Volume 20 February / March 2023 1

PhotonicsViews

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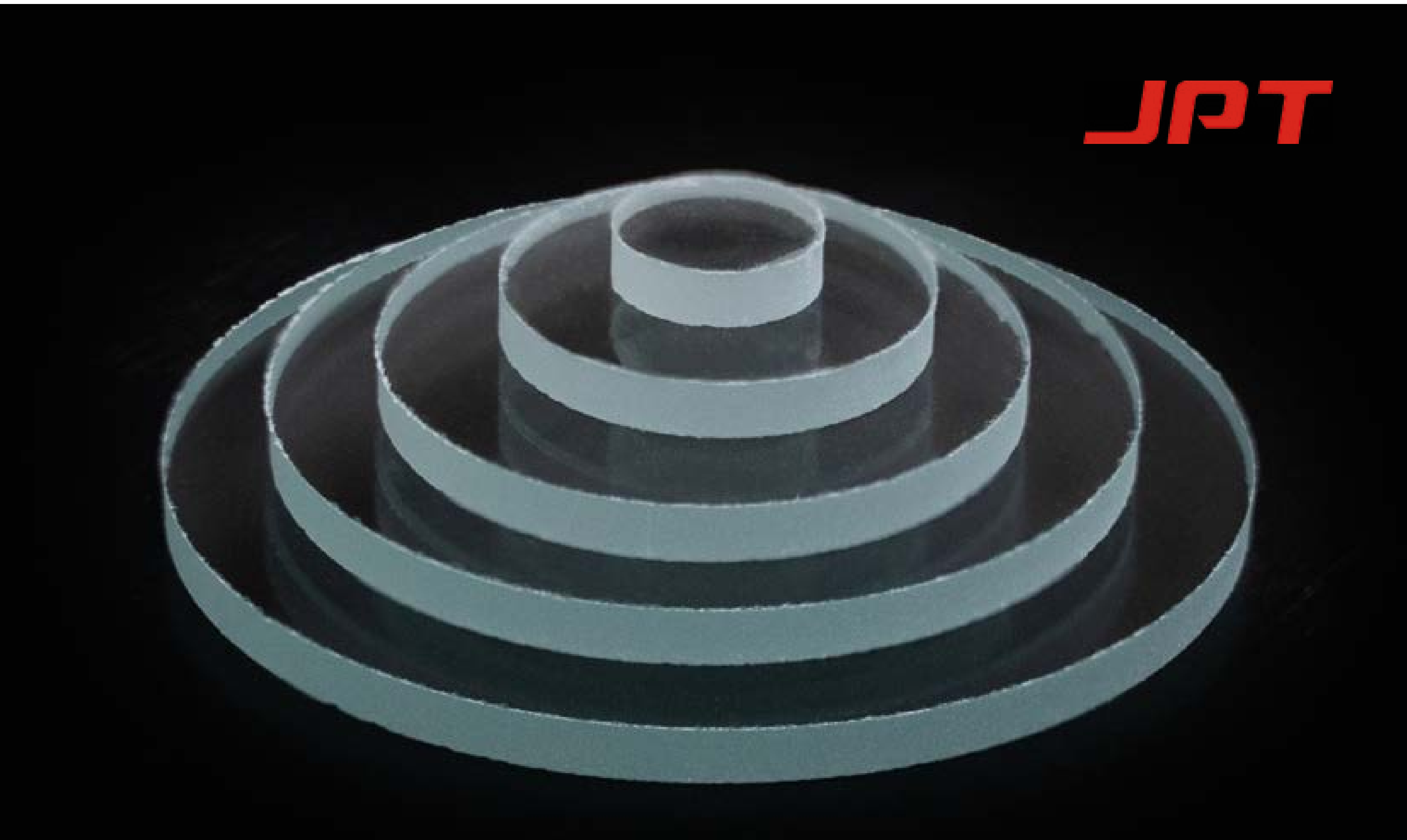

SPECIAL TOPICS

Micromachining of glass and photonics for microfluidic applications

MICROSCOPY
Measure and monitor fine surface irregularities

LASER OPTICS
Thin films polarize a number of new applications

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Let's turn uncertainties into opportunities

What effervescence! What a fever! What a photonics fever!

Photonics is everywhere and for more than ten years it has been recognized as a prime technology in Europe and around the world. New fields are emerging with enormous potential in the short, medium and long term: quantum photonics, magnificently illustrated by the 2022 Nobel Prize in Physics, is now being exploited through the quantum computer, satellite communications are becoming optical, developments are numerous and the production of packaged equipment has started, nuclear photonics probably represents the greatest challenge with medical applications (imaging and treatment such as proton therapy), nuclear waste processing by transmutation and, in the longer term, clean and secure energy production by laser fusion. And do not forget AR/VR, lidar, optical fiber, lighting, surveillance, defense, health, environmental monitoring, semiconductors and photonics on ships, bioimaging and medical optics, large instruments and space applications, optical manufacturing ... it seems that the potential is still immense, if not infinite – let us be optimistic!

Nothing seems to shake these perspectives, even if photonics has to face multifactorial uncertainties: the post-Covid situation, the war in Ukraine, the energy crisis, the climatic and environmental stakes (and the regulation that goes with it), the tensions between China and the USA, etc ... 2023 will probably a complex year to manage. Uncertainties cannot be predicted, but we must be prepared for them. Times of changes are also times for opportunities: let us be ready to seize them, with agility and reactivity. Once again, let us be optimistic and enthusiastic and an actor at the heart of these changes.

States have helped us inhomogeneously through the Covid crisis, and now the energy crisis. The first accelerated the digital transformation of our companies; the second should accelerate the ecological transformation of our models and behavior: do not miss this transition!

To make progress, we can and must rely on academic and industrial clusters, whether regional, national or European. EPIC has done a considerable amount of work over the past ten years to promote the industry and enable more than 800 photonics manufacturers to work, innovate and succeed together. The diversity and excellence of European photonics are our major assets, and we should cultivate them!

Let us go into 2023 together, with acuity, optimism and a smile. Wishing you all the best.

Samuel Bucourt
president and CEO of Imagine Optic
president of Alphanov
member of the EPIC board

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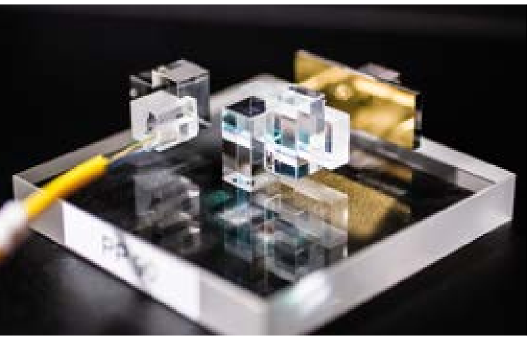
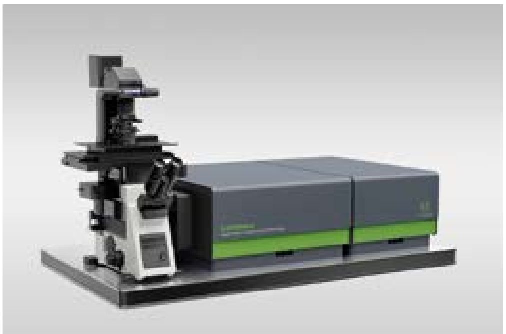
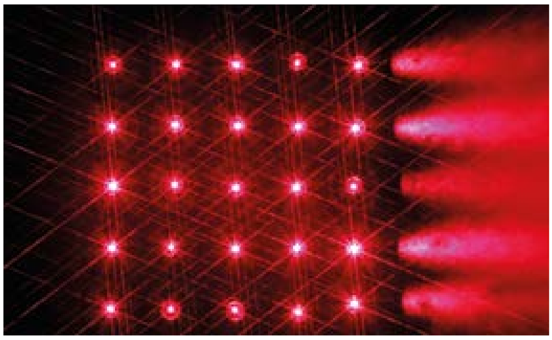

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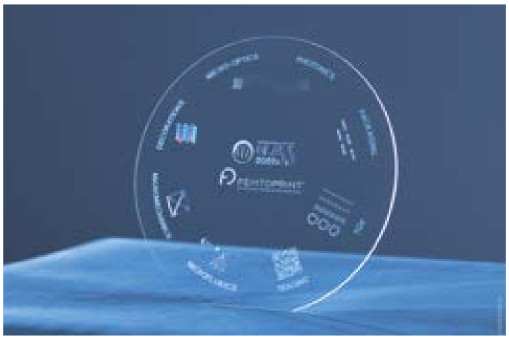
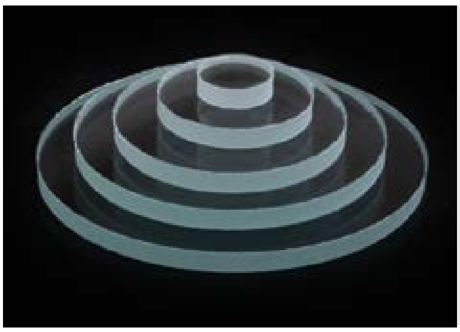
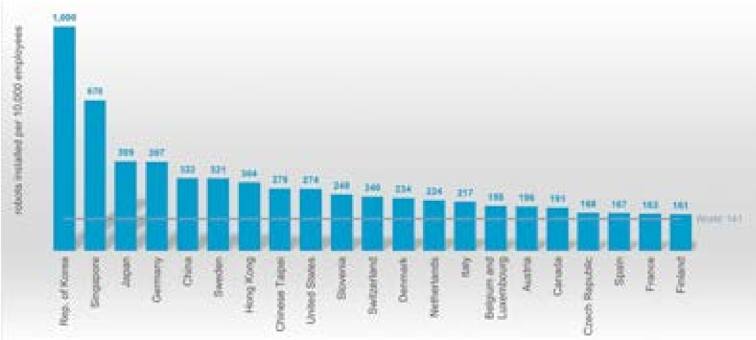




Cover:
Glass processing with a nanosecond fiber lasers with 12 ns pulse width and 40 kW peak power from Shenzhen JPT Optoelectronics

China overtakes US in robot density

China's massive investment in industrial robotics has put the country in the top ranking of robot density, surpassing the United States for the first time.



Driven by numerous robot installations in recent years, robot density in Asia has increased at a CAGR of 18 % since 2016. (Source: IFR)

The number of operational industrial robots relative to the number of workers hit 322 units per 10,000 employees in the manufacturing industry. Today, China ranks in fifth place. The world´s top 5 most automated countries in manufacturing 2021 are: South Korea, Singapore, Japan, Germany and China. These are results from the World Robotics 2022 Report of the International Federation of Robotics (IFR).

"The new average of global robot density in the manufacturing industry surged to 141 robots per 10,000 employees – more than double the number six years ago. China's rapid growth shows the power of its investment so far, but it still has much opportunity to automate," says Marina Bill, president of the International Federation of Robotics.

Driven by the high volume of robot installations in recent years, Asia's average robot density surged by 18 % compound annual growth rate (CAGR) since 2016 to 156 units per 10,000 employees in 2021. The European robot density had been growing by 8 % (CAGR) in the same period of time reaching 129 units. In the Americas it was 117 robots – plus 8 % (CAGR).

The Republic of Korea hit an all-time high of 1,000 industrial robots per 10,000 employees in 2021. This is more than three times the number reached in China and makes the country number one worldwide. With its globally recognized electronics industry and a distinct automotive sector, the Korean economy profits from two large customer industries for industrial robots.

Singapore takes second place with a rate of 670 robots per 10,000 employees in 2021. Singapore's robot density had been growing by 24 % on average each year since 2016.

There is a remarkable gap to Japan (399 robots per 10,000 employees) which ranks third. Japan's robot density had grown by 6 % on average each year since 2016. Germany in fourth place (397 units) is the largest robot market in Europe.

China is by far the fastest growing robot market in the world. The country has the highest number of annual installations, and since 2016 it has each year had the largest operational stock of robots.

The robot density in the United States rose from 255 units per 10 k in 2020 to 274 units in 2021. The country ranks ninth in the world, down from seventh – now head-to-head with Chinese Taipei (276 units) and behind Hong Kong (304 units) and Sweden (321 units).

www.ifr.org

Laser technology for the new space economy

In November, the ESA council meeting at ministerial level in Paris approved a budget increase for the European Space Agency of 17 percent, an increase higher than ever before. The council is chaired by Germany for the next three years in the person of economics minister Robert Habeck. Two weeks later, Dr Anna Christmann, the German government's coordinator for aerospace and commissioner for digital economy and start-ups, visited the high-tech company Trumpf in Ditzingen. The Stuttgart member of the Bundestag explained focal points of European and German projects in the coming years and, for her part, learned about the contributions that laser technology is making.

Presentation of 3D-printed parts for space applications (Source: Trumpf)

During a tour, Trumpf employees showed ongoing metallic 3D printing projects, such as a position control nozzle for a future lunar lander and a high-performance lightweight antenna.

Dr Christian Schmitz, CEO of laser technology at Trumpf, explained other contributions of laser technology to aerospace. For example, aerospace companies use lasers to weld together propellant tank components made of special metal alloys so precisely that the rocket does what it is supposed to do, even under the extreme conditions of launch or flight through the atmosphere. The welding work on the rocket engine itself must also be precise and flawless. In future satellite constellations, VCSEL-based gyroscopes will ensure highly accurate pointing of each of the satellites in low Earth orbit to ensure fail-safe optical communications.

However, special attention is also being paid to 'new space' as an economic factor. For some years now, space travel has been commercialized, combined with an increasing interlocking with traditional industry. This development, known as new space, is the key to future technologies such as autonomous driving, digitally networked industry or a fast, global Internet. The increase in rocket launches and commercial satellites makes this possible. The interplay between new space and classic industry holds great potential and will continue to gain importance in view of the future challenges of our global economy, an opinion shared by Ilan Rozenkopf, expert for aerospace in Europe, McKinsey, Paris, to the participants.

For example, the private sector is providing the momentum for aerospace, albeit to the greatest extent so far in the United States. In 2021, private investors invested more than ten billion dollars in space worldwide. That is a new record and a tenfold increase from ten years ago.

www.trumpf.com

Call for a European photonics strategy

"The European Union will fail to advance towards digital strategic autonomy if it is not at the forefront of technological innovation and manufacturing resilience in both electronic and photonic chips." Prof Gabriel Crean, CEO of the Luxemburg-based Lux Consulting Group, thinks the new European Chips Act is not enough to cover the needs of the photonics industry. "Photonic chips cannot be a simple 'add-on' to the EU Chips Act."

According to Crean, who was talking at the PIC Summit Europe 2022, held in Eindhoven on November 7 and 8 (cf. p. 76), actions must be overlapping and reinforcing. "In other words, they need to be holistic, which means they will be addressing manufacturing capacity, a level playing field, trade restrictions, innovation, and support for training and education."

On top of that, speed is essential to achieve European digital ambitions: "That is why I am ringing the alarm bell now. We have to move fast." Prof Crean warned his audience that the biggest mistake for now would be to underestimate the changes the world has recently gone through. "This change is irrevocable. Covid, Russia's war, the tensions between China and the US, all have resulted in systemic impacts on energy, supply chains, investments. The EU economy faces unprecedented challenges." He calls for strategic autonomy in at least two identified technologies: microelectronics integrated circuits and photonic integrated circuits.

Crean's warnings were directly addressed at the European Commission. Colette Maloney, the Commission's head of microelectronics and photonics, answered with a broader look at the context of the Chips Act, focusing on pilot lines for photonic chips. "But first of all, rest assured that photonics is an integral part of the Chips Act, not an add-on of some sort."

Ms Maloney says the European Chips Act and the 'Chips for Europe Initiative' will bridge the gap between lab and fab. "We will build a virtual platform to reinforce Europe's semiconductor design capacity, enhance existing and develop new pilot lines, build advanced technology and engineer capacity to accelerate the development of quantum chips. Also, we will create a network of competence centers across Europe, and establish a Chips Fund to facilitate access to loans and equity by start-ups, scale ups and SMEs and other companies in the semiconductor value chain.

Of course, Maloney is aware of the fact that all these objectives depend on investments. She says the EU is preparing loans and equity schemes, through EIB and EIC. "On top of that, I want to invite the whole value chain to take part in the workshops we are organizing."

The PIC Summit Europe is a new congress, one of two photonic chip conferences in Europe and will be held annually. It is expected to take place again next year in November. PhotonDelta is the lead organizer of the congress; the program was set up together with the Eindhoven University of Technology and IPSR-I.

Source: PhotonDelta / M. Cazemier

Presentation by Mr Gabriel Crean, CEO of Lux Consulting Group, about the need for a holistic European industrial strategy on photonics

Source: PhotonDelta / M. Cazemier

Presentation by Ms Colette Maloney, head of the microelectronics and photonics unit at the European Commission, about photonics in the EU Chips Act

www.photondelta.com

European pilot line for tandem solar cell photovoltaics

'Pepperoni' is a four-year research and innovation project co-funded under Horizon Europe and jointly coordinated by Helmholtz-Zentrum Berlin (HZB) and Qcells. This project will help advance perovskite/silicon tandem photovoltaics (PV) technology's journey toward market introduction and mass manufacturing. A pilot line will be established at Qcells' European headquarters in Thalheim, Germany. The project began on 1 November 2022.

The solar industry's success in recent years has pushed it toward the current practical limits of efficiency for silicon technology. To go beyond the limits of single-material cells, scientists have proposed adding a complementary one to form 'tandem' solar cells. Pepperoni has selected technology that promises the best ratio of performance over manufacturing costs – silicon/perovskite tandem.

Pepperoni will 'spice up' industrial silicon cells with a perovskite top cell. This tandem design benefits from the industrial expertise of silicon PV and extends the range of attainable power conversion efficiency (PCE) beyond the practical limits of silicon.

Increasing the PCE of solar cells is important for two reasons: in the long run, it is the most effective way to reduce the levelized cost of electricity (LCOE), and in the short term, it is the best way to promote photovoltaics for applications where space is limited, for example on rooftops, facades, or vehicles.

HZB group lead Bernd Stannowski explains: "At HZB we have developed the tandem technology to world-record efficiency level on lab scale. We are now looking forward to cooperating in the consortium with partners from science and industry to scale this new and very promising technology up and transfer it to industry." (Source: Qcells)

Production line for solar cells (Source: Qcells)

www.q-cells.eu
www.helmholtz-berlin.de

PI inaugurates new company headquarters in Karlsruhe

Physik Instrumente have inaugurated their new headquarters in Karlsruhe. The company can now convert more than 1,000 square meters in the existing buildings into production areas in order to be able to better meet the high demand for its high-tech solutions. "PI has grown sustainably in recent years and the global demand for our products and solutions for high-precision positioning continues to rise," explains PI CEO Markus Spanner. "By acquiring and moving to the new building, we are able to create space at the production site in Karlsruhe for the urgently needed expansion of capacity at very short notice." This also means a further increase in employees. As early as 2021, the workforce grew by 170 employees, and a further 240 permanent positions are planned for the current year, most of them in Karlsruhe. "We are looking to fill positions in practically all areas, from production employees to engineers and scientists for research and development," Spanner points out. More than 670 people are currently employed at the Karlsruhe location.

Source: PI

Markus Spanner (pictured left), chief executive officer PI group, Brian Lula, president PI USA, Dr Karl Spanner (on the right), founder of the PI group, in the foyer of the new headquarters.

Around seventy guests from politics and business were invited to the opening of the new headquarters. The Mayor of Karlsruhe, Dr Frank Mentrup, congratulated PI with the words: "A lively culture of innovation is part of Karlsruhe and PI makes an excellent contribution to this. It is a pleasure for me to observe and actively support the innovative strength and dynamic growth of PI in the global high-tech markets."

The investment of around 10 million euros for the acquisition of the building as well as conversion and expansion work at the two Karlsruhe locations is part of the global investment package of over 63 million euros for further capacity expansion.

www.physikinstrumente.com

Lidar startup has secured 10 million euros

Scantinel will use the funding to roll out its frequency-modulated continuous wave (FMCW) lidar devices to customers. Lidar has more accuracy and precision in detecting objects and mapping than other solutions such as radar and RGB cameras. It is also more immune to interference. This makes it ideal for enabling autonomous driving, as well as within logistics – such as conveyor belts and autonomous cranes. However, lidar devices have previously been too large or difficult to produce to be practical alternatives. By using photonic chips, which use light instead of electrons to transfer information in microchips, Scantinel has developed its FMCW lidar solution which has the power, affordability and mass production scalability to enable lidar to be widely used across industry and mobility. The technology delivers a detection range beyond 300 meters with superior resolution and solid-state scanning. Scantinel has signed a number of partnerships with major global automotive, mobility and industrial companies.

The investment by PhotonDelta marks another step in its mission to build a European photonics ecosystem. In April PhotonDelta secured 1.1 billion euros in public and private investment to scale up production, build 200 startups, create new applications for photonic chips and develop infrastructure and talent. Ewit Roos, CEO of PhotonDelta, said: "Photonic chips are a next generation chip technology that will bring new innovations like FMCW lidar on chip to life and we are excited to ride along this journey with Scantinel."

Dr Michael Richter, managing director of Scantinel, said: "The investments from our existing investors Zeiss Ventures and Scania Growth Capital, along with our new investor PhotonDelta will accelerate our product development."

www.scantinel.com

MVTec and Sick deepen strategic partnership

From now on, Sick's automation solutions are also available with MVTec's Halcon machine vision software. The partnership was sealed at the SPS.

Source: David Löh / Wiley

Dr Olaf Munkelt, managing director of MVTec Software (left), and Dr Martin Schenk, senior vice president of product management at Sick, seal the two companies' deepened partnership at SPS in Nuremberg.

On the second day of the SPS trade fair on November 9, Dr Olaf Munkelt, managing director of MVTec Software, and Dr Martin Schenk, senior vice president product management at Sick, signed the contract that deepens their cooperation, which has existed for around ten years. From now on, Sick's automation solutions will also be available with MVTec's standard Halcon software library.

"With the closer strategic cooperation now concluded, we are bringing the strengths of the two worlds of sensor technology and machine vision even closer together. The beneficiaries of the solution from a single source are clearly the users," explains Munkelt.

Sick is a solution provider of sensor-based applications for industrial use. MVTec, in turn, is a provider of software for industrial machine vision with its Halcon, Merlic and Deep Learning software products.

The integration of Halcon into Sick's programming ecosystem provides the answer to the automation industry's increasing need for flexibility and performance. "Our OEMs and integrators [can] participate in Halcon's extensive developments. In particular, our quality control systems benefit from the possibilities Halcon offers, for example with OCR and other image processing algorithms," says Dr Schenk.

www.mvtec.com

www.sick.de

Zeiss is planning a new location in Aalen

A location for two thousand Zeiss employees is being created in East Württemberg. “We are pleased that, together with the city of Aalen, we have been able to find space for our further development,” says Dr Christian Müller, chief financial officer at Zeiss and responsible for business services and infrastructure. Employees from the industrial quality and research (IQR) division are to work at the planned location, most of whom are currently located in Oberkochen. The expansion is part of a long-term growth strategy for the entire Zeiss group: “In East Württemberg alone, also driven by the semiconductor manufacturing technology division, we are planning investments of more than 600 million euros in the coming years,” says Dr. Mueller further.

Zeiss is growing in Jena, Wetzlar, Dresden and at other locations in Germany and worldwide. In East Württemberg, too, the solid growth that has been going on for years is increasingly bringing the research and production site in Oberkochen to its capacity limits. “With the new space in Aalen-Ebnat, we are gaining space for the development of a building infrastructure that, in addition to modern workplaces, will also offer state-of-the-art laboratory and production areas. This ensures our long-term competitiveness and the innovative edge of our research and development capacities. At the same time, they offer the necessary flexibility to gradually lead the building fabric in the main plant in Oberkochen into the future,” says Dr Jochen Peter, member of the management board and responsible for the IQR division.

Zeiss is currently working on the construction plan together with the city of Aalen. “As soon as the plans have taken shape, the first thing we do is inform our employees, and then of course the interested public,” says Dr Mueller.

www.zeiss.de

Jenoptik expands photonics manufacturing capacity in the US

The company has added 7,110 square feet of manufacturing space to its Jupiter, Florida, facility to meet continuing demand for advanced photonic solutions. The expansion will be home to both open and modular cleanroom manufacturing operations.

Construction on the new assembly building will be completed in January 2023. The flexible manufacturing space offers a contamination-controlled environment and can be configured as required for future projects. Jay Kumler, president of Jenoptik Optical Systems in North America, commented, “We are investing in differentiating technologies, advanced equipment and employees, and we are committed to meeting our customers’ expectations for high levels of cleanliness and contamination control.”

The new addition, aptly named Perseverance to honor the group’s work on Nasa’s 2020 Mars Mission, nearly doubles the existing flexible manufacturing area. It is equipped with dedicated test stands and modular class 7 cleanrooms along with raised ceilings that can accommodate an overhead lift to move product, allowing for more production efficiency in a contamination-controlled environment that can be configured as required for future projects.

www.jenoptik.de

Rainer Blatt named 2023 Herbert Walther Award recipient

Optica and the DPG have named Rainer Blatt, University of Innsbruck, Austria, the recipient of the 2023 Herbert Walther Award. Blatt is recognized “for outstanding contributions to quantum optics, quantum information science, especially quantum computing and simulation, as well as precision measurements with trapped ions; and for scientific leadership promoting quantum information and nurturing young scientists.”

The award by the Deutsche Physikalische Gesellschaft (DPG) and Optica (the former OSA) commemorates Max Planck Institute of Quantum Physics’ professor Herbert Walther’s groundbreaking innovations in quantum optics and atomic physics and other wide-ranging contributions to the scientific community.

Blatt is a professor of experimental physics and head of the quantum optics and spectroscopy group at the University of Innsbruck. His research focuses on quantum optics and quantum information. His team is using trapped ions as a means to address fundamental questions in quantum optics, spectroscopy, and quantum information science.

Blatt received his PhD in physics from the University of Mainz, Germany and, through a research grant from the Deutsche Forschungsgemeinschaft (DFG), joined JILA, USA, to work with Nobel Laureate John Hall. He has held positions at the Free University of Berlin, the University of Hamburg, and the University of Göttingen, all in Germany. Since 2003, he has been the scientific director at the Institute for Quantum Optics and Quantum Information (Iqoqi) of the Austrian Academy of Sciences (ÖAW).

A member of DPG and a fellow of the American Physical Society (APS), Blatt serves on many councils, committees and advisory boards. He also supports the next generation of scientists through

Source: Iqoqi, ÖAW / M. R. Knabl

Prof Dr Rainer Blatt

talks and outreach for teachers and high school students. He has received numerous awards and honors, including the Carl Zeiss Research Award, the Stern-Gerlach Medal, the John Stewart Bell Prize, the Micius Quantum Prize, and the Austrian Academy of Sciences Erwin Schrödinger prize.

www.optica.org ▪ www.dpg-physik.de

Alain Rousset is Optica‘s latest advocate of optics

The President of the Nouvelle-Aquitaine region of France is recognized by Optica as its advocate. For more than twenty years, Rousset has demonstrated enthusiastic support for the optics and photonics industry.

The Optica advocate of optics recognition is typically presented yearly to a public official who demonstrates leadership in support of the advancement of light science. Rousset was awarded the advocate in optics recognition at an event hosted by the Institut d’Optique Graduate School (IOGS) on 21 November. The event featured 2018 Nobel Laureate Gérard Mourou, Optica fellow Pierre Chavel and IOGS directeur général Rémi Carminati to celebrate the vibrant French optics industry.

“It is a real honor for me to receive this award. The photonics, laser and microwave sector in New Aquitaine benefits from world-renowned expertise. It brings together companies, universities and research, technology transfer and training centers around major innovation projects,” said Rousset. He was elected President of the Regional Council of Aquitaine in 1998, served on the French National Assembly from 2007 to 2017 and has since been re-elected as President of Nouvelle-Aquitaine. Since assuming office, Rousset has supported the optics community because he believes that “photonics will be in the 21st century what electronics was in the 20th century,” as he told Les Echos Entrepreneurs.

“Président Rousset has been prescient in his support of the optics industry in Nouvelle-Aquitaine. For more than two decades he has championed the scientific and commercial potential of lasers, photonics, and all of the supporting industries that make those technologies possible,” said Elizabeth Rogan, CEO of Optica.

www.optica.org

Source: Evosys

L-R: Ulrike Wolf (Bavarian Ministry of Economic Affairs), Franz Xaver Peteranderl (chairman of the Bavarian chambers of crafts and trades), Lea Sauerwein (Evosys), Elfriede Eberl (chamber of commerce middle Franconia), Frank Brunnecker (Evosys), Robert Schmidt (chamber of commerce middle Franconia), Klaus Josef Lutz (chairman of the Bavarian chambers of industry and commerce)

Evosys receives Bavarian innovation award

The company from the Nuremberg region is the winner of the first main prize of the 2022 Bavarian innovation award. The jury was impressed by the patented AQW laser welding process.

Among nearly 200 innovations, the jury found the patented AQW process from Evosys Laser particularly worthy of the award. The new method of laser welding of plastics combines two laser beam sources and wavelengths. “This approach is aimed in particular at significantly reducing welding times and extending the process window in quasi-simultaneous welding,” explains Lea Sauerwein, responsible development engineer at Evosys. By using two different wavelengths, the input of radiant energy and heat can be better controlled. This enables a more reliable and faster welding process.

The award ceremony took place on Monday, November 21, 2022 at the Swabian chamber of industry and commerce in Augsburg, Germany. The Bavarian minister of economic affairs, Hubert Aiwanger, personally congratulated the winners and awarded them the coveted prize.

“We consider the Bavarian Innovation Award as a great recognition for our efforts in research and development, especially under the challenging conditions of the last few years”, said Frank Brunnecker alongside his co-managing director of Evosys Laser, Holger Aldebert.

www.evosys-laser.com

Winners of the Inspect Awards 2022 received their trophies at the Vision show

The jury of the Inspect award had nominated ten products from dozens of submissions with many exciting innovations and, together with the readers of Inspect, selected three winners in the "vision" and "automation and control" categories. The awards were presented at the Vision 2022 trade show in Stuttgart.

Vision category 1st place
Edmund Optics with the athermal imaging lenses that offer MTF performance of >20 % contrast up to a resolution of 200 lp/mm, corresponding to 2.5 µm pixels. The imaging quality is maintained over the entire maximum image circle (17.6 mm, 1.1" format, 24 MP) and over the entire temperature range of -10 to 50 °C without the need for focusing adjustments. At the same time, the optomechanics are designed to be robust against mechanical shock and vibration.

Vision category 2nd place
Baumer with the freely programmable AX smart cameras. They combine robust industrial camera quality, Nvidia Jetson AI modules and Sony CMOS sensors to create an image processing platform for vision-at-the-edge and AI applications. Based on Linux, the GenICam-compatible all-in-one devices support any programming language and enable the use of various image processing libraries and application programming interfaces (APIs).

Vision category 3rd place
Nerian with the Scarlet 3D stereo camera, which combines a 3D camera and an image processing system in one device. Whether for static environments or hard and critical real-time applications in dynamic environments, the camera delivers exactly the image and depth data needed for numerous machine vision applications. Specifically, this means passive stereo vision at up to 120 fps, with >70 million 3D points per second and up to 5 MP resolution.

Automation & Control category 1st place
Comet Yxlon with the UX50 CT x-ray inspection system, a 450 kV CT system for inspecting large and dense components in the production environment. With its large inspection area, choice of flat and/or line detector and various measuring circuit extensions, it offers a high level of application versatility. Operation via the Geminy software platform supports users with different levels of prior knowledge and reduces training time.


Source: Wiley

Inspect award trophies waiting for the winners in two categories.

Automation & Control category 2nd place
Opto with the imaging module 'profile M' inverted microscope, purely digital and designed for microfluidic tasks as well as automation of biomedical evaluations. Implemented in a plug-and-play imaging module with USB 3.1 or GigE interface and a LED transmitted light condenser. With 5×, 10×, 20× variants in monochrome or color, the module is designed for scanning slides in histopathology and flow cytometry.

Automation & Control category 3rd place
Octum with the Vial.Inspect series to check injection vials for proper condition before filling to ensure that vaccines are only filled into undamaged and uncontaminated vials, which reduces the reject rate. After filling, the systems check that the vials have been properly sealed and printed to ensure 100 % traceability. In the development of this product series, the focus was on maximizing the possible production cycle.

www.inspect-online.com

Quantum Science wins at Warrington Business Awards

A UK quantum company beat two other finalists to take home gold in the innovation award category, recognized for its forward-thinking quantum dot solutions.

The award recognizes Quantum Science's success developing its Infiq quantum dots, which efficiently convert light into electrical signals for infrared sensors. This technology allows the company to manufacture high-performance quantum dots at an affordable price.

Commenting on the win, Dr Hao Pang, CEO and founder of Quantum Science said: "We are over the moon that Quantum Science's work with nanomaterials has been recognized by the judges. We know our quantum dots have the potential to change the world – from self-driving cars to security systems and better smartphone cameras, we are on the cusp of a technological revolution that high-performance quantum dots will push us over."

The Warrington Business Awards were established in 2015 to celebrate business across the Warrington, UK, area. The Innovation category recognizes businesses that have introduced an innovative product within the last two years that demonstrates quantifiable benefits against key performance indicators.


Source: Quantum Science

Quantum Science has been recognized for its forward-thinking quantum dot solutions at the Warrington Business Awards.

https://quantumscis.com

Proof-of-concept grant for Dr Onbaşlı's 'SuperPhoton' project

Koç University's Dr Mehmet Cengiz Onbaşlı was awarded a grant by the European Research Council (ERC) for his project titled "2D topological superconducting single photon detector devices – SuperPhoton".

Source: Koc University

Mehmet Cengiz Onbaşlı

Onbaşli and his team consisting of twelve researchers aim to produce and commercialize new ultrasensitive quantum light sensors, which are critical for the success and proliferation of quantum computers and quantum internet technology, among the most important research fields for the 21st century. Using the superconducting magnetic topological insulator materials they have developed, the team measures the smallest particles of light at extremely low temperatures. With the high-quality production of these functional materials, they aim to commercialize an infrastructure which can act as a pre-pilot production site for Europe and the rest of the world.

www.ku.edu.tr

Management of Toptica Projects expanded

Toptica Projects management board: Armin Zach (left), Frank Lison (middle), and Wilhelm Kaenders (Source: Toptica)

Next to the company founders Dr Wilhelm Kaenders (also managing director Toptica Photonics) and Dr Frank Lison (managing director Toptica Projects), Armin Zach is now board member, responsible for research and technology since October 1, 2022. Toptica Projects was spunoff from Toptica Photonics as a separate entity in 2016.

Zach was one of the start-up members of Toptica Photonics already in 1998. He worked in research and development of semiconductor lasers and ultrafast fiber lasers, where many of the company's products originated. Subsequently, he headed the research and development department of Toptica for fiber lasers and frequency comb technology. As a co-founder of Toptica Projects, he has overseen the company's R&D since its spin-off in October 2016.

Toptica Projects has currently twenty employees at its facilities in Martinsried (Munich), located close to the mothership. Its staff design, develop, manufacture, and support the company's high-tech laser systems, including installations at customer sites in Chile, Hawaii and on the Canary Islands.

www.toptica.com

Kae Nemoto directs new center for quantum technology in Okinawa

On April 22, 2022, the Integrated Innovation Strategy Promotion Council, formulated by the Japanese government, proposed the creation of a Quantum Technology International Collaboration Hub at Okinawa Institute of Science and Technology (OIST), as part of its Vision for the Quantum Future Society. The hub is now one of ten such hubs that exist across Japan. In response, OIST has launched the Center for Quantum Technologies OQT. The center, which was created on October 31, 2022, will drive research and innovation for the Quantum Technology International Collaboration Hub. Prof Kae Nemoto, who leads the Quantum Information Science and Technology Unit at OIST, has been appointed director of the new center.

Source: OIST

Prof Kae Nemoto

"Considering the potential impacts of quantum technologies, the international and interdisciplinary research environment at OIST is important for the future research of quantum science and technology," Nemoto said.

OIST president and CEO, Dr Peter Gruss added, "OIST might be a newcomer in Japan's quantum science and technology fields, but it can help Japan reach the frontiers of quantum technology research due to our ability to attract a wide range of globally recognized researchers." (Source: OIST)

https://quantum-innovation.riken.jp

Ximea strengthens top management

Mike Bode, CEO of Ximea, has been joined at the top of the company by Kevin Toerne as co-CEO of the camera manufacturer with immediate effect. The sales engineer becomes an equal managing director of the camera manufacturer, but retains his function in the sales area.

At the same time, Sam Seidman-Eisler joins the sales team. He will be working at the same location as a sales engineer with immediate effect.

Toerne commented on his promotion: "I am truly honored to join the executive ranks at a company that is so innovative in an industry I have worked in for so many years. I am excited for the opportunities we have to serve the imaging industry and the new products we have coming online and cannot wait to see where we can take our customers and products into the future."

www.ximea.com

Kevin Toerne

Sources: Ximea

Sam Seidman-Eisler

Spectral characterization of VCSELs, microLEDs and AR/VR displays

Manufacturer: Instrument Systems
At the SPIE Photonics West 2023 (USA), the manufacturer will be showcasing its premium-class spectroradiometers and combined measurement solutions with absolutely calibrated cameras.
Products: Different model variants of the spectrally enhanced LumiTop 2D imaging colorimeter are available. The LumiTop 4000 is perfectly suited to the testing of µLED arrays in AFS applications. The 12 MP camera simultaneously measures the individual LEDs of the array and, due to its high measurement speed, avoids the temperature dependence of high-performance LEDs. The LumiTop AR/VR with a periscope lens permits parallel 2-eye measurements for AR/VR headsets, even in confined spaces. The proven LumiTop principle guarantees fast, traceable and highly accurate measurements.
Thanks to its innovative one-shot process, the VTC infrared camera simultaneously measures the spatial polarization of the individual emitters of a VCSEL array and delivers the information necessary to reduce the polarization dependence of the measurement setup. This procedure minimizes the error budget of the VCSEL test system and delivers highly accurate readings for eye safety of the laser source. Manufacturers can then exploit the full performance efficiency of VCSELs / lasers while guaranteeing safe operation.
All systems are available for lab use and – with a focus on faster clocking rates – for production applications.

Instrument Systems GmbH
Kastenbauerstraße 2
81677 München, Germany
phone: +49 89 454 9430
e-mail: sales@instrumentsystems.de
Web: www.instrumentsystems.de

Meet us at SPIE Photonics West, Booth 4106

Low-noise GHz photoreceivers

Manufacturer: Femto Messtechnik
Product: Compact and ultrafast Si and InGaAs photodetectors of the HSPR and HSA-X-S series with integrated GHz amplifier providing a bandwidth range from 10 kHz up to 2 GHz in the wavelength range from 320 to 1700 nm. The optical inputs are optionally free space or FC fiber-coupled. The free space inputs are available with a 1.035"-40 threaded flange or alternatively with a 25 mm round flange to ensure maximum compatibility with common optical accessories.

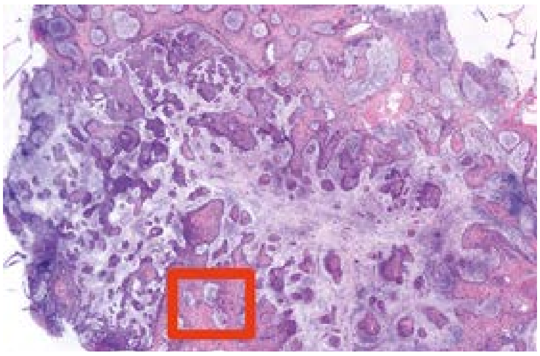
Features: The GHz photoreceivers excel by their low noise with an NEP down to 11 pW/√Hz. The high gain provides a sensitivity of up to 4750 V/W and enables the measurement of fast signals down to the microwatt level. The frequency response is flat and without peaks, resulting in very good pulse transmission, with pulse rise times of down to 180 ps. The high-quality housing offers protection against electromagnetic interference (EMI) and is also designed for use in heavily disturbed environments. All models are equipped with M4 as well as 8-32 UNC threaded holes and can therefore be easily and stably integrated into optical systems with standard post holders.
The HSPR series features an inverted output and has optimized matching with a VSWR of 1.4:1 and so ensures that subsequent devices such as oscilloscopes can also be connected via relatively long cables without impairing the signal quality.
Applications: Spectroscopy, ultrafast-pulse and transient measurements, optical triggering, optical front-ends for oscilloscopes and ultrafast A/D converters.

FEMTO Messtechnik GmbH
Klosterstr. 64
10179 Berlin, Germany
phone: +49 30 2804 7110
e-mail: info@femto.de
Web: www.femto.de

Imaging system for near-instant biopsy results

New technology could enable point-of-care skin cancer diagnosis

Michael Giacomelli, an assistant professor of biomedical engineering and optics at the University of Rochester is developing an imaging system, contained on a portable cart, to shorten the process for getting biopsy results to two minutes. This would enable a surgeon to determine whether a skin lesion is cancerous and, if so, to "treat the patient during the same visit instead of stretching it out over the next month and multiple visits." The system – using two-photon fluorescence microscopy (TPFM) – demonstrated remarkable accuracy in a pilot study. When tested on fifteen biopsies of known nonmelanoma skin cancer, the technology was able to detect basal cell carcinoma with perfect accuracy – 100 percent sensitivity and specificity– and squamous cell carcinoma with high accuracy – 89 percent sensitivity and 100 percent specificity.



Tissue biopsied with a novel imaging system based on 2-photon fluorescence microscopy (TPFM) is showing promising results. (Source: Giacomelli Lab, U. Rochester)

Typically biopsied tissue is excised, fixed, paraffinized, stained, and mounted on slides before being evaluated by a dermatopathologist. "This is how it has been done since the late 19th century," Giacomelli says. "Everybody is on the same page; it works great. The problem is that it is very slow."

He sees potential applications for his system in quickly providing biopsy results for all kinds of diseases. The advantage of using TPFM is that it not only generates high-resolution images but it also uses near-infrared light that penetrates deeper through tissue, making it "advantageous for rapid imaging of fresh, irregularly shaped biopsies with minimal preparation," the researchers note. Giacomelli is now working closely with Sherrif Ibrahim, an associate professor of dermatology at the University's Medical Center, on a larger, 200-patient follow up study, using biopsy samples taken at random at Ibrahim's Rochester Dermatological Surgery in nearby Victor, New York.

"The goal is to analyze how well the technique works in a real-world scenario, where you have a lot people coming in and all kinds of things can show up," Giacomelli says. "We really want to make sure that there is not some bizarre thing that normally has nothing to do with cancer that we somehow confuse with cancer – or something that does have something to do with cancer but we cannot image." (Source: U. Rochester)

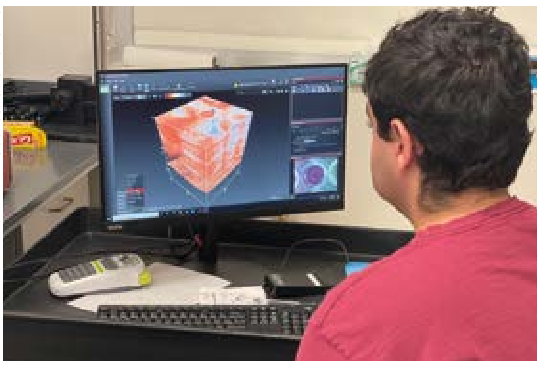
Reference: *V. D. Ching-Roa* et al.: Real-time Analysis of Skin Biopsy Specimens With 2-Photon Fluorescence Microscopy, JAMA Dermatol. **158**, 1175 (2022); DOI: 10.1001/jamadermatol.2022.3628

www.hajim.rochester.edu/bme

Imaging technology to evaluate donor kidneys

Optical coherence tomography is tested to evaluate transplant viability of donor organs

Each year more than 8,000 people die while waiting to receive a kidney transplant. There is currently no reliable method to efficiently determine the viability of donor kidneys, so a team of researchers from the University of Oklahoma and the OU Health Sciences Center, with assistance from LifeShare of Oklahoma as well as researchers and clinicians from the University of Massachusetts Amherst, Worchester Polytechnic Institute and Georgetown Medical Center, will collaborate to investigate using optical coherence tomography (OCT) to evaluate donor kidneys.



Source: U. Oklahoma

Student Andy Keddissi uses the new imaging technology.

Qinggong Tang at the OU Stephenson School of Biomedical Engineering is the OU lead for the four-year study. Tang said there are two golden standards when assessing donor organs for transplant: pre-transplant biopsy score results and post-transplant clinical outcomes. Tang and his team believe that optical coherence tomography scanning technology can aid in predicting both.

OCT is a non-invasive imaging test that uses light waves to take cross-section pictures of tissue, providing what is effectively an optical ultrasound by imaging reflections from within tissue to provide cross-sectional images. The key benefits of OCT are the acquisition of live, sub-surface images at near-microscopic resolution with instant, direct imaging of tissue morphology without the need for preparation of or contact with a tissue sample. "What we want to do is to automate the evaluation process," Chongle Pan from the OU research team said, "so the data coming from the OCT device can be directly analyzed by machine learning algorithms and output a score that is comparable to the score surgeons are currently using." Since OCT is non-invasive, it is possible to scan the whole kidney and get a more complete view of the organ's overall functional capacity.

"Right now, forty percent of donor kidneys are discarded as being unfit for transplant," Tang said. "By our estimate, of that forty percent, there are a substantial amount that are actually usable. We are hoping to decrease the number of discarded kidneys to twenty-five percent and save more people's lives." As a follow-up to this study, Tang hopes to use the same technology to develop OCT scanning protocols to aid in lung and liver transplants. (Source: U. Oklahoma)

www.ou.edu/coe/sbme

Multifocus microscopy with high resolution

A new type of microscope can take 3D images of cells while working in a natural environment

To observe living cells through a microscope, a sample is usually squeezed onto a glass slide. The disadvantage is that it only produces two-dimensional images. Researchers from UiT The Arctic University of Norway and the University Hospital of North Norway (UNN) have now developed what they are referring to as the next generation microscope. The new technology can take pictures of much larger samples than before, while living in a more natural environment.

The technology provides 3D images where researchers can study the smallest details from several angles, clearly and visibly, sorted into different layers, and all layers are in focus. 3D microscopes do already exist, but they work slowly and give poorer results. The most common type works by recording pixel after pixel in series, which are then assembled into a 3D image. Often they cannot handle more than one to five shots a minute. It is not very practical if you are photographing something that moves.

"With our technology, we can manage around a hundred full frames per second. And we believe it is possible to increase this number," says Florian Ströhl, researcher at UiT. The new microscope is a multifocus microscope, which provides completely clear images, sorted into different layers, where you can study the cells from all angles.

Florian Ströhl develops the next generation of microscopes. (Source: K. Rydland, UIT)

Ströhl explains that we are not talking about 3D in the form most of us know it. While in a traditional 3D image you will be able to perceive some kind of depth, with the new technology you are also be able to see behind objects. Ströhl uses an example where you see a jungle scene in 3D at the cinema. "In a normal 3D image, you can see that the forest has a depth, that some leaves and trees are closer than others. With the same technology used in our new 3D microscope, you are also able to see the tiger hiding behind the bushes. You are able to see and study several layers independently," says Ströhl.

The prototype of the microscope is operational. The researchers are currently working on creating an upgraded version that is easier to use. (Source: UiT)

Reference: *F. Ströhl* et al.: Multifocus microscopy with optical sectioning and high axial resolution, Optica **9**, 1210 (2022); DOI: 10.1364/OPTICA.468583

https://en.uit.no

High-throughput computational microscopy imaging

Potential for delineating subcellular structures in large-scale cell studies

Cell organelles are involved in a variety of cellular life activities. Their dysfunction is closely related to the development and metastasis of cancer. The exploration of subcellular structures and their abnormal states facilitates insights into the mechanisms of pathologies, which may enable early diagnosis.

Using conventional microscopes, researchers currently struggle to generate sufficient intrinsic contrast for unstained cells, due to their low absorption or weak scattering properties. Specific dyes or fluorescent labels can help with visualization, but long-term observation of live cells remains difficult to achieve. An approach to achieving label-free, high-resolution, and large FOV microscopic imaging is needed to enable precise detection and quantitative analysis of subcellular features and events.

To this end, researchers from Nanjing University of Science and Technology (NJUST) and the University of Hong Kong developed a label-free, high throughput microscopy method based on hybrid bright/darkfield illuminations. The "hybrid brightfield-darkfield transport of intensity" (HBDTI) approach for high-throughput quantitative phase microscopy significantly expands the accessible sample spatial frequencies in the Fourier space, extending the maximum achievable resolution by approximately fivefold over the coherent imaging diffraction limit.

Based on the principle of illumination multiplexing and synthetic aperture, they establish a forward imaging model of nonlinear brightfield and darkfield intensity transport. This model endows HBDTI with the ability to provide features beyond the coherent diffraction limit. Using a commercial microscope with a 4×, 0.16 NA objective lens, the team demonstrated HBDTI high-throughput imaging, attaining 488 nm halfwidth imaging resolution within an FOV of approximately 7.19 mm^2, yielding a 25× increase in SBP over the case of coherent illumination. HBDTI is expected to provide a solution for cross-scale detection and analysis of subcellular structures in a large number of cell clusters.

Reference: *L. Lu* et al.: Hybrid brightfield and darkfield transport of intensity approach for high-throughput quantitative phase microscopy, Advanced Photonics 4(5), 056002 (2022); DOI 10.1117/1.ap.4.5.056002

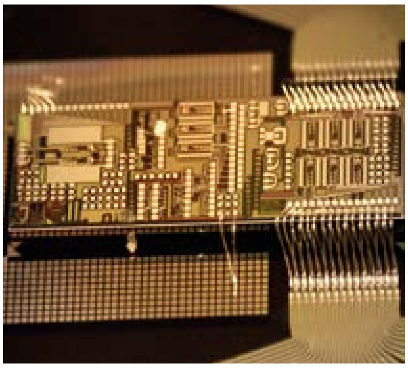
https://scilaboratory.com

Teaching photonic chips to learn

A novel hardware will speed up the training of machine learning systems

Before a machine can perform intelligence tasks such as recognizing the details of an image, it must be trained. Training of modern-day artificial intelligence (AI) systems like Tesla's autopilot costs several million dollars in electric power consumption and requires supercomputer-like infrastructure. Photonic integrated circuits – PICs – have emerged as a possible solution to deliver higher computing performance. However, though they have demonstrated improved core operations in machine intelligence used for data classification, PICs have yet to improve the actual front-end learning and machine training process.

Machine learning is a two-step procedure. Data is first used to train the system and then other data is used to test the performance of the AI system. A team of researchers from the George Washington University (GWU), Queens University, University of British Columbia and Princeton University set out to do just that. After one training step, the team observed an error and reconfigured the hardware for a second training cycle followed by additional training cycles until a sufficient AI performance was reached – e.g. the system is able to correctly label objects appearing in a movie. Thus far, photonic chips have only demonstrated an ability to classify and infer information from data. Now, researchers have made it possible to speed up the training step itself.



New photonic device for training deep neural networks with direct feedback alignment. (Source: GWU / Queens U)

This added AI capability is part of a larger effort around photonic tensor cores and other electronic-photonic application-specific integrated circuits (ASIC) that leverage photonic chip manufacturing for machine learning and AI applications. "It is a major leap forward for AI hardware acceleration. These are the advancements we need in the semiconductor industry as underscored by the recently passed CHIPS Act," Volker Sorger from GWU said. "The training of AI systems costs a significant amount of energy and carbon footprint. For example, a single AI transformer takes about five times as much CO_2 in electricity as a gasoline car spends in its lifetime. Our training on photonic chips will help to reduce this overhead," Bhavin Shastri from Queens University added. (Source: GWU)

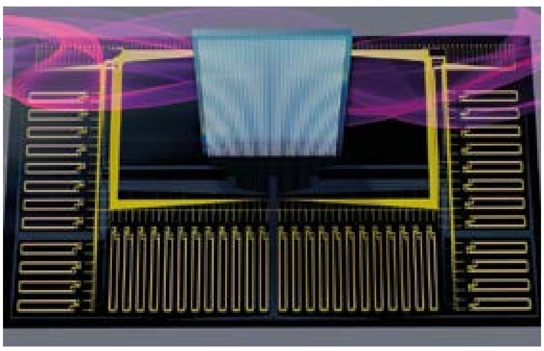
Reference: *M. J. Filipovich* et al.: Silicon photonic architecture for training deep neural networks with direct feedback alignment, Optica **9**, 1323 (2022); DOI: 10.1364/optica.475493

https://sorger.seas.gwu.edu

Deep learning with light

Better shifting of the memory-intensive steps to a central server

Ask a smart home device for the weather forecast, and it takes several seconds for the device to respond. One reason this latency occurs is because connected devices do not have enough memory or power to store and run the enormous machine-learning models needed for the device to understand what a user is asking of it. The model is stored in a data center that may be hundreds of miles away, where the answer is computed and sent to the device. MIT researchers have created a new method for computing directly on these devices, which drastically reduces this latency. Their technique shifts the memory-intensive steps of running a machine-learning model to a central server where components of the model are encoded onto light waves.



Source: A. Sludds, MIT

Illustration of a smart transceiver that uses silicon photonics to dramatically accelerate one of the most memory-intensive steps of running a machine-learning model.

The waves are transmitted to a connected device using fiber optics. The receiver then employs a simple optical device that rapidly performs computations using the parts of a model carried by those light waves. This technique leads to more than a hundredfold improvement in energy efficiency when compared to other methods.

Once the light waves arrive at the client device, a simple optical component known as a broadband Mach-Zehnder modulator uses them to perform super-fast, analog computation. This involves encoding input data from the device, such as sensor information, onto the weight parameters for the input data transformation. Then it sends each individual wavelength to a receiver that detects the light and measures the result of the computation. The researchers devised a way to use this modulator to do trillions of multiplications per second, which vastly increases the speed of computation on the device while using only a tiny amount of power.

"In order to make something faster, you need to make it more energy efficient. But there is a trade-off. We have built a system that can operate with about a milliwatt of power but still do trillions of multiplications per second. In terms of both speed and energy efficiency, that is a gain of orders of magnitude," MIT graduate student Alexander Sludds says. They tested this architecture by sending weights over an 86-kilometer fiber that connects their lab to MIT Lincoln Laboratory. Netcast enabled machine-learning with high accuracy – 98.7 % for image classification and 98.8 % for digit recognition – at rapid speeds.

Reference: *A. Sludds* et al.: Delocalized photonic deep learning on the internet's edge, Science **378**, 270 (2022); DOI: 10.1126/science.abq8271

www.rle.mit.edu

Tunable lenses for virtual reality headsets

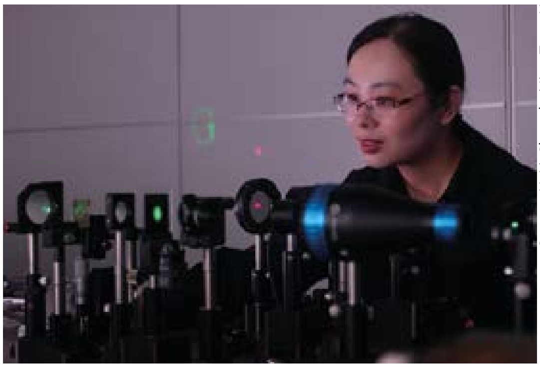
Two liquid crystal elements can be moved in relation to each other

Researchers have developed a thin lens with a continuously tunable focal length. The new lens could one day make visual fatigue from augmented and virtual reality (AR/VR) devices a thing of the past. "Many of the 3D displays used in today's AR/VR devices cause discomfort after long-term use due to the vergence-accommodation conflict," said research team leader Yan Li from Shanghai Jiao Tong University in China who collaborated with Shin-Tson Wu's lab at the University of Central Florida College of Optics and Photonics. "Our lens, which is known as an Alvarez lens, can be used to alleviate this problem. This could provide a more comfortable and more realistic 3D experience that would enable more widespread use of AR/VR headsets."

Vari or multifocal display systems need a tunable lens that can change focus continuously within a large range while also being compact and lightweight enough to be useful in head-mounted AR/VR devices. Li has been working on fatigue-free AR displays and liquid crystal devices for about ten years and recently developed a way to fabricate a liquid crystal-based diffractive optical component known as a Pancharatnam-Berry (PB) optical element that can be used to create a tunable lens that meets these requirements.

"Our method enables PB optical elements with the complicated and irregular phase profiles needed to create an Alvarez lens with high precision, low cost and unprecedented convenience," said Li. "We wanted to see if this ultracompact Alvarez tunable lens could offer a solution to the long-standing vergence-accommodation conflict problem in VR and AR displays."

The researchers used their new approach to create a tunable Alvarez lens made of two planar PB liquid crystal elements. In each element, an ultrathin polymetric liquid crystal layer just a few hundred nanometers thick is coated onto a 1-mm-thick glass substrate. They incorporated this Alvarez lens into an



Source: Y. Li, Shanghai Jiao Tong U

Laboratory setup

AR display system built using off-the-shelf optical elements on an optical table. By laterally shifting the two elements of the Alvarez lens, they were able to continuously tune the depth of the virtual image from near to far distances. (Source: Optica)

Reference: *S. Chen* et al.: Planar Alvarez tunable lens based on polymetric liquid crystal Pancharatnam-Berry optical elements, Opt. Exp. **30**, 34655 (2022); DOI: 10.1364/oe.468647

https://ee.sjtu.edu.cn

Photonic chip allows light amplification

Swiss scientists demonstrated a new principle of light amplification on a silicon chip

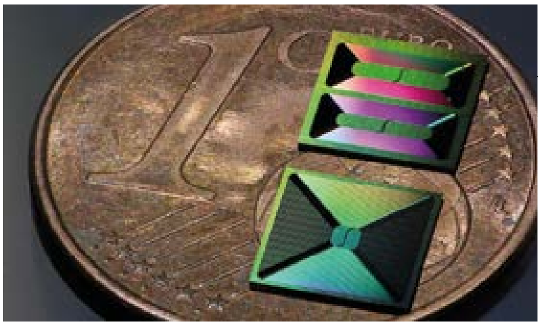
Today, optical amplifiers based on rare-earth ions like erbium, as well as III-V semiconductors, are widely used in real-world applications. These two approaches are based on amplification by optical transitions. But there is another paradigm of optical signal amplification: traveling-wave parametric amplifiers, which achieve signal amplification by varying a small system parameter such as the capacitance or the nonlinearity of a transmission line.

It has been known since the 80's that the intrinsic nonlinearity of optical fibers can also be harnessed to create traveling-wave optical parametric amplifiers whose gain is independent of atomic or semiconductor transitions, which means that it can be broad-band and cover virtually any wavelength. Parametric amplifiers also do not suffer from a minimum input signal, which means that they can be used to amplify both the faintest signals and large input power in a single setting.

Despite their attractive features, optical parametric amplifiers in fibers are compounded by their very high pump power requirements resulting from the weak Kerr nonlinearity of silica. Over the past two decades, the advances in integrated photonic platforms have enabled significantly enhanced effective Kerr nonlinearity that cannot be achieved in silica fibers, but have not achieved continuous-wave-operated amplification.

A new study led by Johann Riemensberger in Tobias Kippenberg's group at the EPFL's Laboratory of Photonics and Quantum Measurements has now resulted in a traveling-wave amplifier based on a photonic integrated circuit operating in the continuous regime. "Our results are a culmination of more than a decade of research effort in integrated nonlinear photonics and the pursuit of ever lower waveguide losses," says Riemensberger.

The researchers used an ultralow-loss silicon nitride photonic integrated circuit more than two meters long to build the first traveling-wave amplifier on a photonic chip 3×5 mm^2 in size. The



Source: T. Kippenberg, EPFL

The photonic integrated circuits used in this study.

chip operates in the continuous regime and provides 7 dB net gain on-chip and 2 dB net gain fiber-to-fiber in the telecom bands. On-chip net-gain parametric amplification in silicon nitride was also recently achieved by the groups of Victor Torres-Company and Peter Andrekson at Chalmers University.

Reference: *J. Riemensberger* et al.: A photonic integrated continuous-travelling-wave parametric amplifier, Nature **612**, 56 (2022); DOI: 10.1038/s41586-022-05329-1

www.epfl.ch

Light-analyzing 'lab on a chip'

Tiny spectrometer is based on 2D semiconductors and operated using artificial intelligence

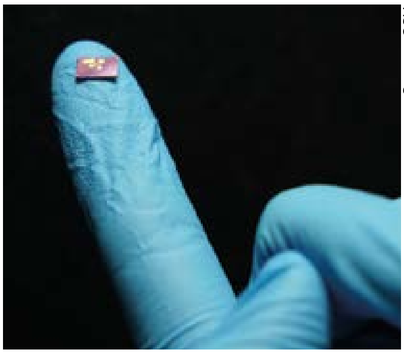
A team led by Aalto University researchers has developed a better tool to measure light, contributing to optical spectrometry in a way that could improve everything from smartphone cameras to environmental monitoring: a powerful, ultrasmall spectrometer that fits on a microchip and is operated using AI.

The research involved two-dimensional semiconductors and the upshot is a proof of concept for a spectrometer that could be readily incorporated into a variety of technologies – including quality inspection platforms, security sensors, biomedical analyzers and space telescopes. "We have demonstrated a way of building spectrometers that are far more miniature than what is typically used today," said Ethan Minot of the Oregon State University College of Science.

Traditional spectrometers require bulky optical and mechanical components, whereas the new device could fit on the end of a human hair, Minot said. The new research suggests those components can be replaced with novel semiconductor materials and AI, allowing spectrometers to be dramatically scaled down in size from the current smallest ones, which are about the size of a grape. "Our spectrometer does not require assembling separate optical and mechanical components or array designs to disperse and filter light," said Hoon Hahn Yoon, who led the study with Aalto University colleague Zhipei Sun Yoon. "Moreover, it can achieve a high resolution comparable to benchtop systems but in a much smaller package."

The device is electrically controllable regarding the colors of light it absorbs, which gives it massive potential for scalability and widespread usability, the researchers say. Yoon said: "Imagine that the next generation of our smartphone cameras could be hyperspectral ones."

"It is exciting that our spectrometer opens up possibilities for all sorts of new everyday gadgets, and instruments to do new science as well," Minot said. In medicine, for example, spectrometers are already being tested for their ability to identify subtle changes in human tissue such as the difference between tumors and healthy tissue. For environmental monitoring, spectrometers can detect exactly what kind of pollution is in the air, water or ground, and how much of it is there. "It would be nice to have low-cost, portable spectrometers doing this work for us," he said. Applications abound as well for science-oriented hobbyists, Minot said. "If you are into astronomy, you might be interested in measuring the spectrum of light that you collect with your telescope and having that information identify a star or planet," he said. "If geology is your hobby, you could identify gemstones by measuring the spectrum of light they absorb." (Source: OSU)



Source: OSU

Spectrometer on a finger-tip

Reference: *H. H. Yoon* et al.: Miniaturized spectrometers with a tunable van der Waals junction, Science **378**, 296 (2022); DOI: 10.1126/science.add8544

https://minotlab.physics.oregonstate.edu
https://qtf.fi

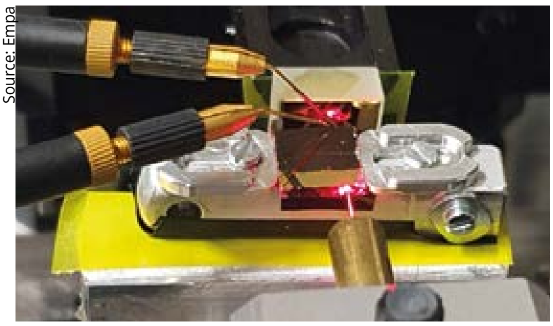
Miniaturized infrared detectors

Monolithic integration of subwavelength IR photodetectors for tiny spectrometers

Miniaturization of infrared spectrometers will lead to their wider use in consumer electronics, such as smartphones enabling food control, the detection of hazardous chemicals, air pollution monitoring and wearable electronics. They can be used for the quick and easy detection of certain chemicals without using laboratory equipment. Moreover, they can be useful for the detection of counterfeit medical drugs as well as of greenhouse gases such as methane and CO_2.

A team of scientists at Empa, ETH Zurich, EPFL, the University of Salamanca, Spain, the European Space Agency (ESA) and the University of Basel have built a proof-of-concept miniaturized Fourier-transform waveguide spectrometer that incorporates a subwavelength photodetector as a light sensor, consisting of a colloidal mercury telluride quantum dot and compatible with complementary metal oxide semiconductor (CMOS) technology.

The resulting spectrometer exhibits a large spectral bandwidth and moderate spectral resolution of 50 cm^{-1} at a total active spectrometer volume below 100 × 100 × 100 µm. This ultracompact spectrometer design allows the integration of optical-analytical measurement instruments into consumer electronics and space devices. "The monolithic integration of subwavelength IR photodetectors has a tremendous effect on the scaling of Fourier-transform waveguide spectrometers," says Empa researcher Ivan Shorubalko. "But this may also be of great interest for miniaturized Raman spectrometers, biosensors and lab-on-a-chip devices as well as the development of high-resolution snapshot hyperspectral cameras." (Source: Empa)



Source: Empa

The experimental setup: a red alignment laser was used to visualize the beam path from the fiber into the optical waveguide and its reflection at a gold mirror. Two microprobes were used to contact the photoconductor, the size of which is in the subwavelength range.

Reference: *M. J. Grotevent* et al.: Integrated photodetectors for compact Fourier-transform waveguide spectrometers, Nat. Phot., online 24. Oktober 2022; DOI: 10.1038/s41566-022-01088-7

www.empa.ch

Lensless camera creates 3D images

Real-time 3D imaging method could improve robot navigation and content for 3D displays.

Researchers at the University of California, Davis, have developed a camera that uses a thin microlens array and new image processing algorithms to capture three dimensional information about objects in a scene with a single exposure. The camera could be useful for a variety of applications such as industrial part inspection, gesture recognition and collecting data for 3D display systems. "We consider our camera lensless because it replaces the bulk lenses used in conventional cameras with a thin, lightweight microlens array made of flexible polymer," said research team leader Weijian Yang, assistant professor of electrical and computer engineering. "Because each microlens can observe objects from different viewing angles, it can accomplish complex imaging tasks such as acquiring 3D information from objects partially obscured by objects closer to the camera."

The camera can produce 3D images in real time because it learns from existing data how to digitally reconstruct a 3D scene. "This camera could be used to give robots 3D vision, which could help them navigate or perform complex tasks such as manipulation of fine objects," said Yang. "It could also be used to acquire rich information that could provide content for 3D displays used in gaming, entertainment or many other applications." The new camera grew out of previous work in which the researchers developed a compact microscope that can image microscopic structures for biomedical applications in 3D.

Although other research groups have developed cameras based on single layer microlens arrays, it has been difficult to make them practical because of extensive calibration processes and slow reconstruction speeds. To make a more practical 3D camera for macroscopic objects, the researchers considered the microlens array and the reconstruction algorithm together rather than approaching each separately. They custom-designed and fabricated the microlens array, which contains 37 small lenses distributed in a circular layer of polymer that is just 12 millimeters in diameter. The reconstruction algorithm they developed is based on a highly efficient artificial neural network that learns how to map information from the image back to the objects in a scene. Once the learning process is complete, it can reconstruct images containing objects that are at different distances away from the camera at a very high speed. The new camera does not need calibration and can be used to map the 3D locations and spatial profiles or outlines of objects.

The researchers are currently working to reduce artifacts, or errors, that appear in the 3D reconstructions and to improve the algorithms to gain even higher quality and speed. They also want to miniaturize the overall device footprint so it could fit into a cellphone, which would make it more portable and enable more applications. Yang says: "With the recent development of low-cost, advanced micro-optics manufacturing techniques as well as advancements in machine learning and computational resources, computational imaging will enable many new imaging systems with advanced functionality." (Source: UC Davis / Optica)

Source: S. Luy, UC Davis

Feng Tian and Weijian Yang developed a camera that uses a thin microlens array and new image processing algorithms to capture 3D information about multiple objects in a single exposure. The raw sub-images from the microarray are displayed on the monitor.

Reference: *F. Tian & W. Yang:* Learned lensless 3D camera, Opt. Exp. **30**, 34479 (2022); DOI: 10.1364/oe.465933

www.ece.ucdavis.edu/~wejyang

Optica Foundation funds research through its 20th Anniversary Challenge

New photonics research to solve environmental challenges and data exchange bandwidth issues

Featuring the Foundation's 20th Anniversary Challenge awardees, this research aims to introduce new, cost-effective ways to test water purity at the source, provide an affordable and real-time system for water contaminant detection, harness heat energy and apply it toward electricity needs, and sense micropollutants in air quality. "This photonics research seeks powerful approaches to address critical environmental issues," said Alan Willner, chair of the 20th Anniversary Challenge selection committee and 2016 Optica (then OSA) president. "The selection committee will excitedly be monitoring the awardees' progress and sharing their findings as they become available."

Recipients of the Optica Foundation 20th Anniversary Challenge prizes in Environment, Health and Information. (Source: Optica)

Environmental work from the 20th Anniversary Challenge includes:

- Portable water sensing, Dismas Choge, University of Eldoret, Kenya
- Real-time water sensing, Ashim Dhakal, Phutung Research Institute, Nepal
- Waste heat as an energy source, Michela Florinda Picardi, ICFO – The Institute of Photonic Sciences, Spain
- Clean greenhouse gas (CO_2 and methane) monitoring, Wanvisa Talataisong, Suranaree University of Technology, Thailand.

From photonic integration and nanotechnology to free-space optical communication strategies, recipients' work advances alternative approaches to traditional optical communications in the light of growing demand.

"As we approach the limits of Moore's Law, we need to seek new ways of addressing the ever-increasing demand for bandwidth," said Andrew Forbes, a member of the 20th Anniversary Challenge selection committee.

Information research efforts from the 20th Anniversary Challenge include:

- Increasing information processing capacity and energy efficiency, Chaoran Huang, Chinese University of Hong Kong, China
- Steering bandwidth with nanotechnology, Mark Lawrence, Washington University in St. Louis, USA
- Solving free-space optical communications challenges in the mid-infrared, Mengjie Yu, University of Southern California, USA

The Optica Foundation launched its 20th Anniversary Challenge to draw out novel ideas from early-career professionals and provide the seed money to investigate impactful hypotheses in the areas of environment, health, and information. Each of the recipients received 100,000 US dollars to explore their ideas and take steps toward addressing critical global issues. Recipients have begun work on these projects and expect to report initial results by the second quarter of 2023.

www.optica.org

New chairman of the IVAM Advisory Board

Prof Dr Harald Kuhn, director of the Fraunhofer Institute for Electronic Nano Systems ENAS in Chemnitz, joins the scientific advisory board of the IVAM Microtechnology Network

Prof Kuhn studied materials science at the Friedrich Alexander University of Erlangen-Nuremberg and also completed his doctorate there. He has many years of international experience in the semiconductor industry and has held various management positions at Siemens and Infineon.

His work focused on automation, research and development, and smart systems. Kuhn has held the professorship for Smart Systems Integration at the Chemnitz University of Technology since 2020. He also took over the function of director at the Center for Microtechnologies located there in 2021.

He is now looking forward with anticipation and clear plans to his new appointment at the industrially-oriented IVAM trade association. "Microtechnology forms the foundation to meeting the central technological challenges of our society, and is an enabler for the development of future technology. Crucial for success is cross-sector networking of know-how between research and industry to drive innovations forward, to quickly transfer them into usable solutions and to jointly maximize opportunities in an internationally competitive environment," Kuhn said.

Prof Dr Harald Kuhn (Source: Fh. ENAS)

"As chairman of the advisory board, I shall be supporting IVAM with all my strength in driving this networking and knowledge exchange throughout our high-tech industry as an 'added value'. I am looking forward to exciting encounters, interesting discussions and constructive cooperation," explained Prof Kuhn as the motivation for his commitment.

www.ivam.de
www.enas.fraunhofer.de

20 years of EPIC

The driving force of European photonics

EPIC annual general meeting and 15th anniversary celebration, Berlin, Germany, 2018

EPIC turns 20 in 2023! We would like to thank all those who have made it possible to reach this point and all the members who have accompanied us over the years. You can find a brief overview of what these two decades have been like below.

At the turn of the 21st century, photonics was synonymous with optical fiber telecommunication and the sector was growing at an explosive rate. But in 2002, the big telecom companies halted the deployment of optical fiber network projects after realizing that their wireless investment could not be recovered through revenues. Thomas Pearsall created the European Photonics Industry Consortium in 2003 as a response to this catastrophe and presented his idea of EPIC to Dr Henri Rajbenbach of the Electronics & Communications unit of the European Commission (EC). The response of the EC was positive, and to help ensure a strong impact, the EPIC proposal was attached as an additional work package to the existing 'Optimist' program. The principal objective, then as now, was to bring together the business and technology leaders in the main sectors of photonics to encourage cross-sector synergies and to develop business partnerships. EPIC started out with 52 company members and, in the first two years of operations, Pearsall organized European-wide workshops on LEDs for automotive lighting, photonic components for telecommunications, organic LEDs for displays and lighting, and laser-assisted manufacturing. Today, EPIC's team arranges between eighty and ninety different events each year on various important topics for its members.

In 2013, Tom Pearsall retired, and Carlos Lee was hired as director general of EPIC. That year saw the first edition of the CEO Award, which went to Nick Martin of AFE Optics (UK). Today, past award recipients are gathered to select the next winner, with the award being presented at the EPIC annual general meeting. Everything that is achieved at EPIC is constant teamwork and the main example of this is the Online Technology Meetings that started in 2020 and were hosted by Jose Pozo with the support of the rest of the team. This format quickly became an important way for members to get the latest information about trending topics, and during the Covid-19 pandemic, EPIC arranged the Photonics World Tour that lasted 24 hours, featuring 72 speakers from 35 countries across 13 time zones!

So for the near future, EPIC has several ongoing Technology Advisory Committees to ensure that it addresses the issues that are critical to the industry in the upcoming meetings.

www.epic-assoc.com

Upcoming EPIC events:

- 31 January 2023
  Pilot Lines & Photonics Innovation Hubs Breakfast, San Francisco, USA
  EPIC VIP'S Networking Lunches & Reception, San Francisco, USA
  EPIC Members Networking Reception, San Francisco, USA
- 31 January – 2 February
  EPIC Members Lunch, San Francisco, USA
- 1 February 2023
  EPIC Executive 5 Miles Run, San Francisco, USA
- 2 February 2023
  EPIC Members 5 Miles Run, San Francisco, USA
- 13 February 2023
  EPIC Online Technology Meeting on Bio-Imaging and Bio-Photonics
- 27 February 2023
  EPIC Online Technology Meeting on Quantum Metrology and Quantum Sensors
- 13 March 2023
  EPIC Online Technology Meeting on Micro LED for Automotive Applications
- 29 – 30 March 2023
  EPIC Annual General Meeting, Helsinki, Finland
- 30 March 2023
  EPIC TechWatch at W3+Fair, Wetzlar, Germany
- 19 – 20 April 2023
  EPIC Meeting on Fiber Sensors at HBK FiberSenting, Porto, Portugal

For the list of all events, visit:
www.epic-assoc.com/epic-events

"We have a number of exciting technology platforms that enable market megatrends"

An interview with Sanjai Parthasarathi, chief marketing officer of Coherent Corp.

In early 2021, II-VI Incorporated joined the race for the acquisition of Coherent Inc. against two competitors – and succeeded. Now, about two years later and six months after completing the merger and the announcement of the rebranding as 'Coherent Corp.', it is time to ask chief marketing officer Sanjai Parthasarathi for a first résumé.

Source all images: Coherent / Wiley

Sanjai Parthasarathi, chief marketing officer, Coherent Corp. (top), interviewed by Oliver Dreissigacker, Wiley

Belated congratulations for your 50th birthday. II-VI was founded in 1971; Coherent Inc. five years earlier. Last summer, you announced the name and branding for the combined company. Can you tell us about the motivation and symbolism or meaning of the new name?

Sanjai Parthasarathi: Our choice of the name Coherent Corp. and our new brand identity signal a broadened scope and vision for the future. We chose the name Coherent because it has the universal meaning of bringing things together, and an appeal that we believe will expand our brand recognition. The "O" in our new logo represents the atom, which is foundational to what makes our products possible.

II-VI had started out manufacturing cadmium telluride products, including lenses, windows and mirrors for CO_2 lasers. What else were your products used for in the early days?

Parthasarathi: Such laser optics were the main uses in the 1970s. Cadmium telluride was also used, and is still used, to make electro-optic modulators for pulse CO_2 lasers. In the early years, these modulators were a key contributor to the company's profitability. The company later added zinc selenide and zinc sulfide to its portfolio of materials and, out of the necessity to fill a gap in the value chain, began polishing and coating these materials into CO_2 laser optics.

In the 1990s, II-VI began to grow not only on its own, but also through numerous acquisitions, among them some photonics and laser companies. So in which sense is the acquisition of Coherent Inc. the logical culmination of this development?

Parthasarathi: Beginning in the 1990s and continuing into the early 2000s, the company saw that there was strong market potential for one-micron, solid-state lasers and fiber lasers. Consequently, the company defined a 10-year roadmap to enter this market.

Recognizing the strategic importance of beam delivery for materials processing, we acquired 75 % of HIGHYAG in 2007 and the remaining 25 % in 2013. With that acquisition, we could work with customers who were in the system business to establish competencies for cutting and welding, while at the same time collaborating with partners who sold YAG lasers, fiber lasers, or direct diode lasers.

In 2010, we acquired Photop Technologies in China, which gave us a product portfolio of one-micron optics and a strategic base in China both for manufacturing and sales in that region. In 2013, we acquired GaAs semiconductor laser product lines, which included pump laser diodes for one-micron industrial lasers. We have since scaled the GaAs technology platform from 3-inch to 6-inch, enabling us to be very competitive in that market space.

Now, with the acquisition of Coherent Inc., we cover the complete value chain in one-micron lasers, from materials to systems and service. We now have a size and scale that allows us to be very competitive at each level of the value chain. The acquisition of Coherent Inc. completes a 20-year strategy, which has provided us with the opportunity to enter the one-micron laser business. Executing on long-term strategies is characteristic of Coherent Corp. and supported by our annual 5-year-plan planning process.

Where do you see the greatest synergies between the offerings of the two former companies?
Parthasarathi: We see sales synergies in automotive, especially in electric vehicle manufacturing, due to our competitive position in fiber lasers that has improved since the amalgamation. We also see sales synergies in life sciences, aerospace and defense, and the semiconductor capital equipment markets due to the complementarity of our product portfolio.

How fast will they bring new technological developments or provide cost savings?
Parthasarathi: Even before the acquisition, we announced a joint marketing program that combined our fiber lasers with our processing heads for welding electric vehicle batteries. Now that the merger is completed, we are continuing to accelerate our market penetration. On the technological development side, it will take some time as we review our combined opportunities and prioritize our investments. On the cost side, we anticipate achieving 250 million dollars in ongoing synergies within three years.

Which product lines and which markets will be the main pillars in the coming years? What new products are currently being added to the portfolio?
Parthasarathi: We will continue to focus our growth in the industrial, communications, electronics, and instrumentation markets. We have a number of exciting technology platforms that enable market megatrends. These include the next evolution of the cloud, sensing, electric vehicles, additive manufacturing, the commercialization of space, and the personalization of health care, to name just a few. We expect to have a series of product announcements leading up to Photonics West.

There are currently many young startups around that provide certain photonic technology for quantum applications. How important will this market become for you and are you already active in it?
Parthasarathi: We are active in certain areas of quantum photonics. Research labs use our lasers to create photon pairs for entanglement studies. We also offer diode modules that are used to cool and trap atoms. On the materials side, we have a long history of working with polycrystalline diamond, and recently we licensed technology to produce crystalline diamond, which has the potential to enable future devices for quantum computing.

The combined company has more than 28,000 staff and over a hundred locations and offices all over the world. How will the number of employees change in the future, which locations will be expanded, and will others be reduced or closed?
Parthasarathi: We are planning to bring the sales teams together at one location in countries where we have multiple sales offices near each other. However, overall, we are expanding in R&D and manufacturing locations.

Are you currently hiring? Where and for which positions and functions? What do you consider the benefits to be when joining Coherent?
Parthasarathi: We are hiring broadly across functions, and we have job openings worldwide. Our combined annual investment in R&D of half a billion dollars is one of the highest in our industry, which we believe will allow us to be a stronger strategic partner to our customers. As a pioneer of innovation with our impacts felt around the world, Coherent is the place to be for those who are curious, innovative, purposeful, and seeking a fulfilling career and rewarding work. It is a great chance to work with and be inspired by the best in the industry, with the thrilling potential to positively impact humanity with what we do.

> "We expect to have a series of product announcements leading up to Photonics West."
>
> Sanjai Parthasarathi

Photonic devices are often tools that lead to energy savings for the manufacturing industry compared to classical manufacturing. Do you have ambitions to realize energy savings in your own operations? Are you producing your own energy? How and where?
Parthasarathi: We recently published our ESG report that details our products that are critical to improvements in global energy efficiency and the increasing sustainability of our locations that produce them. By the end of FY22 – before the closing of the Coherent Inc. acquisition – we had entered into renewable energy contracts for more than 40 sites around the world, including over 35 sites that now cover 100 % of their annual electricity usage with renewable sources. In fact, 100 % of our European sites are now powered by renewable energy sources. We ended the fiscal year purchasing approximately 38 % of our electricity from renewable sources in our facilities. This is just a snapshot of our growing efforts to incorporate sustainable and circular business practices into our operations.

The integration of products from II-VI and Coherent Inc. offers new unique solutions such as remote laser welding solutions for the EV market

We are coming up to the first big industry event of the year – the SPIE Photonics West exhibition. What will be the highlights at the Coherent booth?
Parthasarathi: This will be the first time that we will be exhibiting at Photonics West as a combined company, and we are excited to do so under our new brand. At the show, we will emphasize the benefits of the new Coherent Corp. We will show the breadth of the combined portfolio for applications in various market verticals – life sciences and scientific instrumentation, precision manufacturing and semiconductor capital equipment. We will also address some exciting new and rapidly growing areas such as optical sensing, micro-LEDs and AR/VR in various end markets.

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Questions by PhotonicsViews editor-in-chief Oliver Dreissigacker

Meet Coherent Corp. at Photonics West, Booth 4805 www.coherent.com

"We need lights, but we need more intelligent lights"

EPIC interview with Stephan Berlitz, head of light and innovation at Audi

Jérémy Picot-Clémente

Source all images: Audi

EPIC's photonics technologies program manager Jérémy Picot-Clémente talks to Stephan Berlitz, head of Audi lighting development.

What is the background to you becoming head of Audi lighting development?
While studying a degree in electro engineering at the technical university of Munich in the late 1980s, I worked as an intern for a small research company investigating the effect of light on the growth of tobacco plants. This was my first introduction to light, and I got to know quite a lot about simulated sun illumination, light wavelengths and intensities and lighting measurement. Then in 1989, I went to work for BMW in their new lighting laboratory for external lighting where I worked on light distribution and measurement with regard to lighting regulations – a very important topic as one third of all automotive regulations relate to the intensity and glare of a vehicle's external lighting.

In 1992, after my degree, I went to work for a supplier of automotive lighting. In 2000, I started at Audi's lighting development department with responsibility for developing lighting innovation. I have been at Audi ever since, and in 2020 I was appointed head of development lighting and vision systems.

What have been the main landmarks in Audi lighting over the last twenty years?
Audi's aim in respect of lighting has always been to pioneer and enhance road safety, increase functionality and provide its customers with styling and customization options. In 1994, we incorporated second-generation xenon headlights in the Audi A8, with tiltable modules available from 2003. Then in 2004, we were the first to introduce LED headlights in the daytime running light of the Audi A8. In 2008, we introduced the first full LED headlights in the Audi R8 and in 2013 we were the first to introduce matrix LED headlights that operate in tandem with a camera on the windshield that detects other vehicles or localities. The control unit partially switches off individual LEDs or dims them in many stages so that the head lights can hide other vehicles, but fully illuminate the areas between and next to them. In 2014, a laser was incorporated as an additional high beam in the Audi R8 LMX.

In 2016, we were also the first to incorporate OLED rear lights which have the advantage of producing highly homogeneous red light that can be divided into individually dimmable segments. This was followed in 2020, with digital OLED rear lights connected to the on-board power supply control unit via a bus system, thereby making significantly more functions available - one of which is Audi's proximity indication: when the Q5 is standing still and another road user approaches from behind to

less than two meters, all OLED segments are activated.

What is the situation regarding patents?
While Audi has many patents, the general philosophy has been to make the technology easy to adopt by other OEMs – partly to reduce costs, and in the case of the 'dynamic turn signals' because of regulations. Lighting technology for us is about safety and we are proud of the contribution we have been able to make over the last twenty years to improving road safety.

How do you see the future?
Over the next ten years, LEDs will continue to be the dominant lighting technology with digital OLEDs providing homogenous rear lighting. However, automotive lighting is entering a new era because of the need to adapt to two megatrends: digitization and car-to-x communication [communication between vehicles and infrastructure]. Originally, vehicle lighting in road traffic primarily served the safety of all road users, but the digitization of headlights and rear lights has enabled Audi to expand the perspectives from driver-centric safety to comprehensive external communication and personalization. Digital OLED technology in particular will define the future by not being just a conventional light source. Its development points in the direction of exterior displays that not only increase safety and enable even more personalization, but are also meant to improve communication with the outside world. However, flexible digital OLED rear lights are a step ahead of that. They have a flexible substrate that allows them to go from a two-dimensional structure to a three-dimensional one. That not only sharpens the form, but it also makes it possible to integrate digital light design within the exterior of the lights, enabling symbol displays for additional communication with the outside world.

In summary, we need more lights, but we need more intelligent lights that can be adapted for each driving situation. The focus in future will be on safety and communication with light projected all around the vehicle with a lot more displays. The main difference between our lighting and that of our competitors is that we are more safety orientated and, being a premium brand, we must think about premium solutions. This means maintaining Audi's distinctive style and the having the right light for the right situation.

What are your main challenges going forward?
The major challenge in pushing the automotive world to have better and more efficient lighting has been the need to comply with regulations. Homologation is important but statutory provisions around the world vary on the minimum spatial, lighting and anti-dazzle requirements. Generally speaking, as the scope for functionality and styling expands, the complexity of the approval process also increases, and it always requires an individual, country-specific assessment. In the case of the dynamic turn signal, we were able to convince the regulatory authorities that this idea is a gain for road traffic safety. As a result, we succeeded in launching a world first and many competitors subsequently adopted this function.

While regulations are necessary, the fact remains that we could do a lot more than we are allowed to, and over the next few years a major challenge will be to persuade the regulatory authorities that we know what we are doing and to realize the full potential of lighting development.

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Author: Dr Jérémy Picot-Clémente, European Photonics Industry Consortium, Rue Hamelin 17, Paris, France; e-mail: jeremy.picot-clemente@epic-assoc.com, Web: www.epic-assoc.com, jeremy-picotclemente

Organization

EPIC – European Photonics Industry Consortium

EPIC is the world-leading photonics industry association representing more than 800 members across 35 countries. EPIC promotes the sustainable development of organizations working in the field of photonics, EPIC fosters a vibrant photonics ecosystem by maintaining a strong network and acting as a catalyst and facilitator for technological and commercial advancement. EPIC publishes market and tech-neology reports, organizes technical workshops and B2B roundtables, supports EU funding proposals, advocacy and lobbying, education and training activities, standards and roadmaps, pavilions at exhibitions.

www.epic-assoc.com

Laser technologies for micro and nanofluidics systems

New opportunities for the biological and chemical industries

Jérémy Picot-Clémente

Among the various micro and nanofabrication technologies, ultrafast laser processing is a promising tool for the fabrication of micro/nanofluidics due to its flexibility, versatility, high fabrication resolution and three-dimensional fabrication capability. In this article, we review the progress made to date by companies working with ultrafast laser processing for the fabrication of micro and nanofluidics systems.

In the last decade, the research and development of micro and nanofluidics have made extraordinary progress in revolutionizing lab-on-a-chip systems for the biological and chemical industries. Thanks to the properties of microfluidic technologies, such as rapid sample processing and the precise control of fluids with much improved detection limits, these systems can improve on traditional experimental approaches by providing faster and more accurate biological and chemical analysis, and thereby improved diagnosis.

Background

In the 1990s, governments began exploring the possibility of incorporating microfluidic chips into a portable and miniaturized laboratory known as a lab-on-a-chip (LOC) as an alternative to the model of centralized laboratories processing clinical samples with expensive equipment. LOCs can provide low-cost point-of-care (POC) diagnostics as exemplified by the recent development of desktop polymerase chain reaction (PCR) and at-home rapid antigen tests for Covid-19.

▲ **Fig. 1** The Quantum X systems can recreate 3D vascular structures to mimic in vivo environments and processes. The simple vascular model contains two types of dyed water for demonstration purposes. (Source: Nanoscribe)

According to Precedence Research, the global microfluidics market is projected to increase from 18 billion US dollars in 2021 to around 62 billion by 2030, at a CAGR of 16.5 % [1]. The main market drivers are increased demand for POC devices, low-volume sample anal-

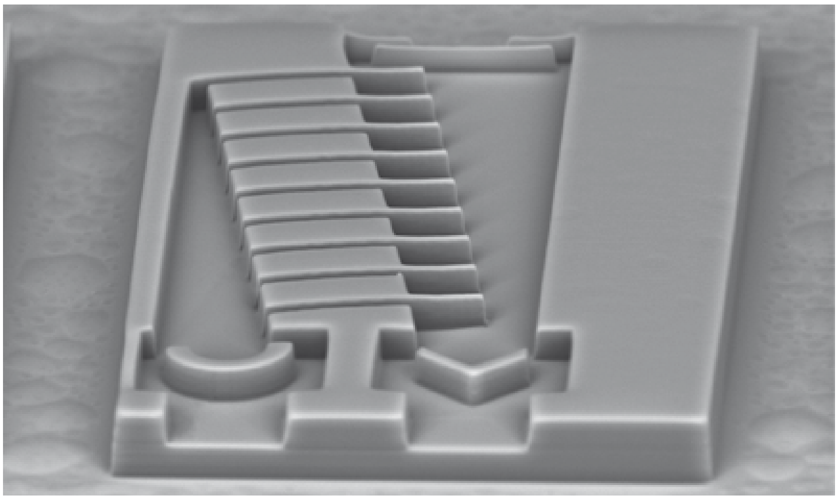

Fig. 2 Microfluidic reactor: microfluidic structures with high complexity and with tunable channel width enabled by 2PP using a MPO 100 3D laser lithography system. (Source: Heidelberg Instruments)

ysis, and in-vitro diagnostics as well as high-throughput screening methodologies and the development of advanced lab-on-a-chip technologies.

Other key factors propelling market growth for microfluidics are rising technological advancements in diagnostic devices and the worldwide increase of chronic diseases. In terms of revenue, the medical technology segment led the global microfluidics market due to the three major benefits offered by microfluidics for POC diagnostics: smaller sample volumes, faster turnaround times, and lower test costs. Lab-on-a-chip applications will continue to grow due to their high detection speed while being able to maintain the same sensitivity level during RNA or DNA amplification.

Microfluidics fabrication

Major lab-on-a-chip research began in the late 80s with the development of microfluidics, which comprises channels of nanometer dimensions typically smaller than several hundred nm, and microfabrication processes to produce polymer chips called soft-lithography. In the 1990s, soft lithography, a technique involving the replication of various structures by using elastomeric stamps or molds, was superseded by various types of lithography such as electron-beam lithography (EBL) and nanoimprint lithography that could create patterned structures of nanoscale feature sizes, with high-accuracy and flexibility in replication, to a processing resolution below 10 nm.

However, these techniques have several drawbacks, including their cost, fouling and clogging of the microchannels, difficulties in creating graded or hierarchal configurations and providing nanochannel connectivity. As a way of overcoming these issues, ultrafast laser manufacturing has emerged in the last decade as a promising alternative for the fabrication of nanofluidics due to its flexibility, versatility, high fabrication resolution and 3D fabrication capability.

Ultrafast laser processing

Ultrafast lasers are a category of pulsed lasers with an ultrashort pulse duration from a few picoseconds to several tens of femtoseconds. They have extremely high peak intensities that can modify transparent materials by multiphoton absorption that allow the fabrication of complex 3D configurations, which are impossible to achieve with planar technologies. One type of ultrafast laser processing for nanofluidics fabrication is known as two photon polymerization (2PP), a type of additive laser processing based on the two-photon absorption (TPA) phenomenon in which two photons are absorbed practically at the same time by a photoinitiator molecule to excite it to a higher energy level. Polymerization is typically induced by a femtosecond laser beam focused through a high NA objective in a small volume of photocurable resin or negative-tone photoresist and non-irradiated areas are washed away by specific solvents to construct sub-100 nanometer 3D structures.

A second type of ultrafast laser processing for nanofluidics fabrication is known as subtractive laser processing, of which there are two types: laser ablation and laser-assisted etching. Femtosecond laser nanoablation can be used on a variety of materials achieving nanohole arrays with sub-200 nanometer diameters due to the collaboration of multiphoton absorption and the threshold effect. Femtosecond laser-assisted etching (FLAE) on the other hand is usually only applied to photosensitive glass or fused silica and consists of femtosecond laser direct writing followed by chemical etching.

Fabrication in Europe using two photon polymerization

Looking to the future of LOCs and POCs, one gap that has yet to be addressed is compatibility with advancing microscopy analysis. Photonics for label-free imaging has matured over the last decade from lab-based proofs-of-concept to clinical practice, such as in refractive index sensing and optical coherence tomography (OCT). Yet these new imaging standards are not integrated into industry-ready LOCs. Label-free imaging is critical for specific applications such as tissue, organ, and body-on-a-chip to minimize sample destruction while providing high-contrast, high-resolution live-cell imaging to elucidate details at subcellular size scales. With this background, Germany-based **Nanoscribe** has developed the Quantum X product line – a 2PP platform enabling semi-automated, aligned 3D printing onto pre-patterned substrates or directly into prefabricated

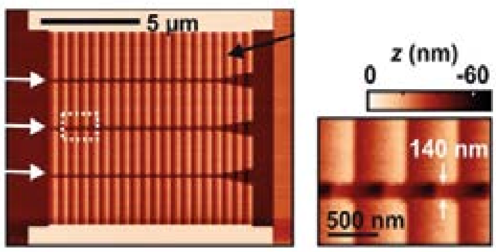

Fig. 3 Nanofluidic rocking ratchets fabricated with single-nanometer accuracy by NanoFrazor patterning. Courtesy of IBM Research (publications in Science and PRL 2018)

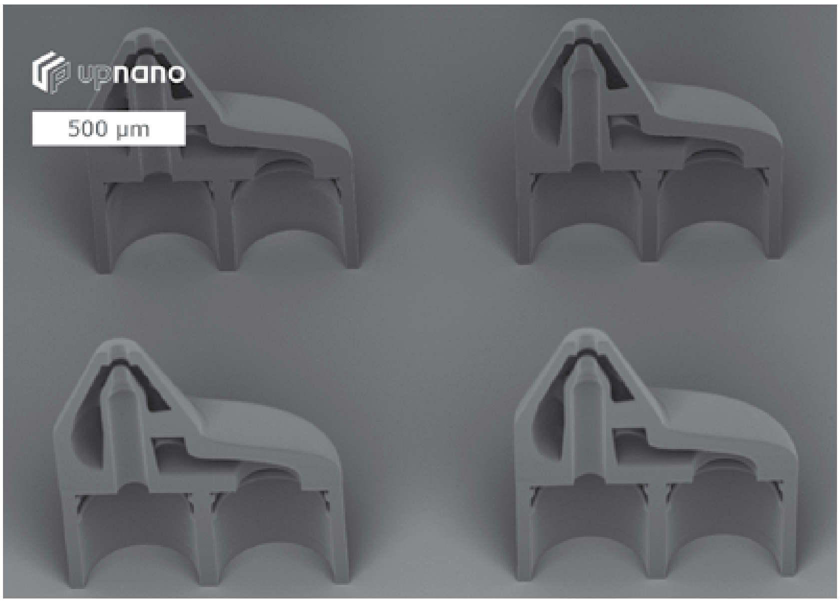

Fig. 4 Microfluidic nozzle printed on a NanoOne printing system, with connector elements and channels with a diameter of 50 µm (Source: UpNano)

microfluidic chips [2]. As regards substrates, the Quantum X system can fill in the literal physical gaps that conventional lithography cannot achieve, such as printing converging (XY) and sloping (Z) microfluidic channel sections. And with the chips, the alignment module of the Quantum X system can precisely fabricate complex structures over patterned substrates, such as electrodes, that allow users to print polymer cell scaffolds into multielectrode array chips.

Especially interesting is printing into microfluidic channels to advance lab-on-a-chip (LOC) applications. Instead of fluorescent markers and dyes that damage samples, users benefit from advanced label-free techniques by integrating photonics into LOCs, i.e. printing lenses inside the chip for optofluidic sensing. Furthermore, in addition to polymers, hydrogels can be used for 2PP bioprinting.

Another company using 2PP technology is **Heidelberg Instruments**, who have launched the MPO 100, a 3D laser lithography system based on 2PP that closes the gap between conventional laser lithography and thermal scanning probe lithography (t-SPL) for nanopatterning. The use of 2PP for the manufacturing of microfluidics enables the printing of real 3D microfluidic systems that is not possible with classical 2D or 2.5D technologies. The MPO 100 can be used either to print the microfluidic systems completely or to print 3D structures in (even buried) 2D microfluidic systems. Secondly, moving parts like springs or valves can be printed in a single process step without the need for assembly. Lastly, 2PP allows the fabrication of structures with dimensions around 100 nm, allowing the printing of both micro and nanofluidic systems.

Advanced applications such as nanofluidic structures or biomimetic substrates for cell growth can be achieved with Heidelberg's NanoFrazor Explore, a thermal scanning probe lithography tool that incorporates a precisely engineered 3D topography that harnesses Brownian motion to separate particles down to 1 nm of size difference by guiding them in opposite directions. Nanofluidic cells with nanoscale ratchet-like surface structures can sort nanoparticles down to 1 nm difference in radius and are very promising for diagnostics and protein purification.

Vienna-based company **UpNano**, a spin-out of the Technical University of Vienna, is also commercializing an ultrafast nano and microscale 3D printing system based on 2PP called the NanoOne [3]. The device uses multiphoton lithography and can achieve extremely precise 3D polymeric parts with a volume ranging from 10^2 to 10^{12} cubic micrometers at nano and microscale resolution. UpNano's proprietary 'adaptive resolution' printing approach combines ultrafine channels and 'large-volume' connector elements for supply lines and hoses while the interaction of hardware and software allows the resolution of the printing system to be adapted to the requirements of the component. This enables the printing of fine elements with the highest resolution, while the voxel is widened up to a factor of ten for areas of internal bulk or where resolution is not the focus, thereby providing unprecedented economic efficiency. NanoOne's high resolution and versatility makes it ideal for applications in the medical field, for example the 3D printing of microneedles, which require defined features like the cannula or reservoir and tight tolerances.

Fabrication in Europe using subtractive laser processing

As we have seen, an alternative to two photon polymerization is femtosecond laser-assisted etching (FLAE), a 3D printing technology that uses light as a powerful ink source. The beam, focused inside glass, locally modifies the refractive index and density of the material. Depending on the exposure parameters, waveguides can be formed to realize complex integrated optical components or three-dimensional structures with additional chemical etching. As an example, the Swiss company **Femtoprint** has developed an ultrafast laser processing system for the fabrication of 3D shapes in glass with high precision, sub-micron resolution, and with an additional polishing step for optical surface quality [4] (cf. p. 56).

Another company working with subtractive laser processes is the French

Fig. 5 3D microfluidic mixer for X-ray applications: determination of electronic structures during chemical reactions. (Source: Femtoprint, courtesy of SLAC)

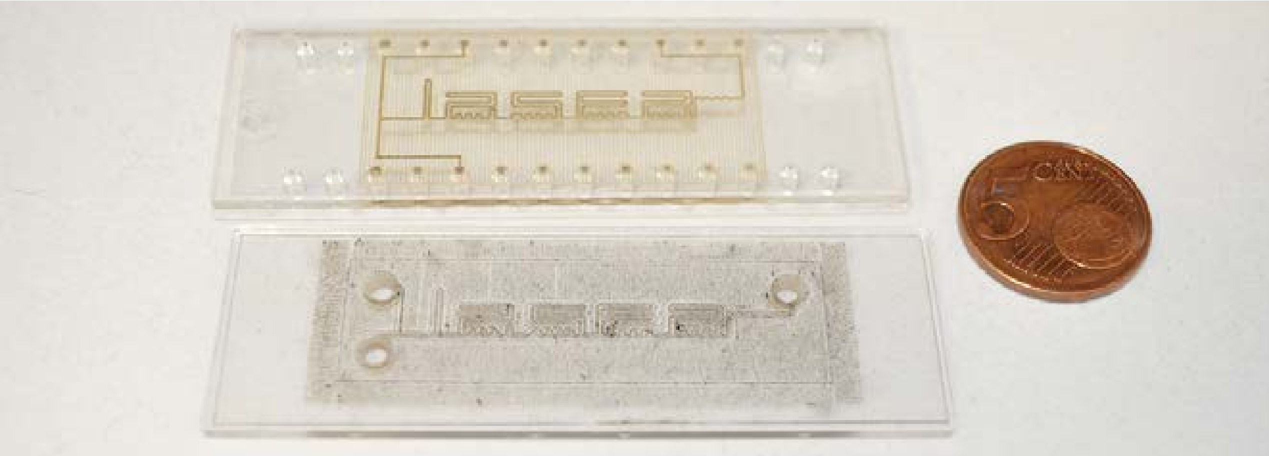

Fig. 6 Microfluidic chip manufactured with a U shape beam (top) and a Gaussian beam (bottom; source: Cailabs, [5])

company Cailabs, a specialist in light shaping, who have partnered with Lasea, a multinational femtosecond laser micromachining manufacturer to develop a unique U shape beam-shaping module, based on multiplane light conversion [5, 6] (cf. p. 32). The edges of the U shape are fifteen times sharper than a Gaussian beam, with a diameter of 62 µm in the processing plane, and the U profile enables the sample to see a homogeneous profile while scanning. Lasea has integrated the beam-shaper on an industrial optical chain with a 100 µJ 1,030 nm femtosecond laser. The sealing of polymer substrate microfluidic chips can then be optimized, leading to an important increase in terms of the quality (aesthetic) of the channels as well as a process speed increased by a factor of nine.

At a European scale, **Phabulous** is a pilot line and one-stop-shop that provides an array of services to companies looking to develop micro and free-form optics, enabling applications such as beam shaping [7]. It offers access to state-of-the-art technology and expertise, helping businesses to create innovative optics solutions to meet their specific needs. With the support of all the partners, companies can benefit from improved efficiency, reduced costs and faster time to market.

Remaining challenges

Despite the progress made in ultrafast laser processing to date, the fabrication of nanochannels with controlled sizes and well-controlled surface properties responsive to fluidic transport is still a challenge. Critical issues include the fouling and clogging of channels, the integration of nanofluidic systems with microchannels and nanochannel connectivity. There is also a deficiency of cost-effective nanofabrication techniques that can offer device-to-device reproducibility. However, with the growing demand for micro and nanofluidics systems for LOCs and POCs, it is just a matter of time before improved fabrication techniques generating even smaller critical dimensions with higher precision and repeatability are developed.

DOI: 10.1002/phvs.202300004

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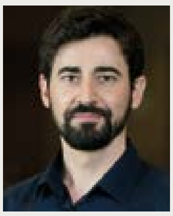
[7] *S. Amairi-Pyka:* The Future of Micro-Optics in Europe, PhotonicsViews **17** (2020) 3, June / July, 20 – 22; DOI: 10.1002/phvs.202070306

Author



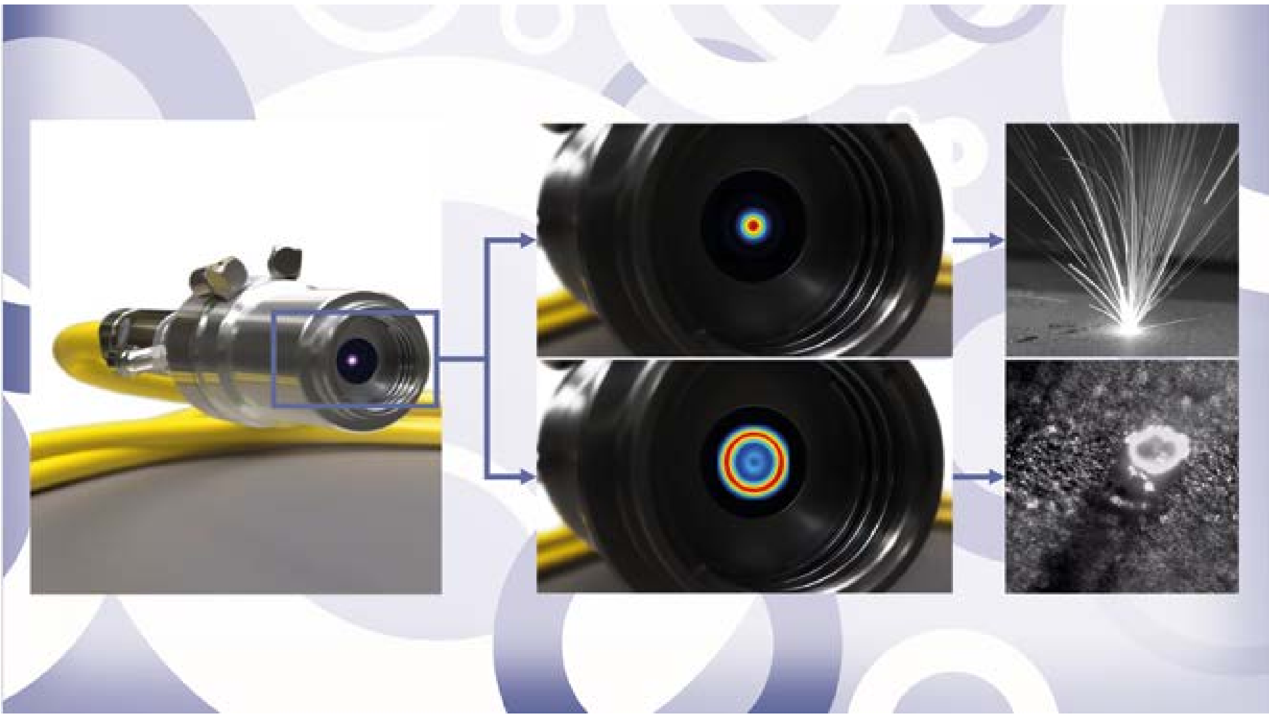
Jérémy Picot-Clémente is a physicist specialized in optics and a program manager at the European Photonics Industry Consortium (EPIC). After a PhD in physics/optics and an MBA, he decided to explore the industry for several years through various missions in managing photonics systems integration, for several applications and in different companies. At EPIC, Jeremy is in charge of the development of the optics and micro-optics fields, and all related technology and applications. He has a strong interest in new technology involving photonics, such as AR/VR, lidar, 3D sensing and imaging devices.

Dr. Jérémy Picot-Clémente, EPIC – European Photonics Consortium Industry, 17 Rue Hamelin, Paris, France;
e-mail: jeremy.picot-clemente@epic-assoc.com, Web: www.epic-assoc.com jeremy-picotclemente

Donut worry

How laser powder bed fusion matures dramatically due to ring-shaped beams

Andreas Rudolf



▲ All-fiber beam shaping allows to rapidly switch the beam profile coming directly out of the fiber connector.

The latest application studies demonstrate how ring-shaped ('donut') laser beams overcome major obstacles in the laser powder bed fusion of metals. This includes key improvements in productivity and cost, a significant reduction of soot and spatter, the stable processing of difficult-to-print and crack-prone materials, and the ability to improve and spatially tailor material properties.

Since its invention in 1996, powder bed fusion laser beam melting (PBF-LB/M) has become the dominant process in the field of metal additive manufacturing. The technology has matured and found its way into many traditional manufacturing chains, but it still lacks a larger leap in production speed to achieve mass adoption in cost-sensitive markets like automotive and machinery manufacturing. The laser source plays a key role on this path. To highlight the potential of beam shaping for powder bed fusion, nLight hosted an expert forum with invited speakers at Formnext 2022. While the individual presentations have already been published online [1], this article discusses the results, enabling a new generation of high-productivity PBF-LB/M tools.

Challenges with Gaussian-shaped beams

Laser powder bed fusion is typically performed with diffraction-limited Gaussian beams, emitted from industrial single-mode fiber lasers. The typical focused spot size on the powder bed is of the order of 80 µm. While such a Gaussian beam is ideal to print fine details such as contours and thin walls, it comes with severe limitations. Due to its high central peak intensity, the center of the generated melt pool is prone to overheating – one could also say that the metal is not just selectively melted but boiled.

Consequently, both the keyhole and the melt pool surface undergo rapid fluctuations, which are the source of all the parasitic particle emissions such as soot, spatter, and liquid breakup.

On the process side, this can lead to weld defects and ultimately to part defects, posing a major threat to consistent quality. It also limits the ability to scale the laser power up because the total rate of particle emission scales accordingly and easily exceeds the maximum extraction capacity of the gas flow system – especially in multilaser machines employing two, four or even more lasers.

While the melt pool center exhibits too much power, the edges are underexposed due to the low-intensity wings of the Gaussian beam. The hatching lines must be tightly spaced to prevent a lack of fusion at the edges, which limits the build rate. In total, the laser power is used inefficiently as it is partly wasted both in the center and at the edges, which limits the scan speed. Furthermore, the narrow melt pool around the deep keyhole causes an inhomogeneous temperature distribution and high cooling rates. Especially in crack-sensitive, hard-to-weld materials like tool steel, this leads to hot cracks across multiple layers, rendering the processing of such materials nearly impossible.

Given these obstacles, it has been very difficult to employ higher laser powers in practice. Defocusing the beam is a commonly used solution for lasers above 500 W. While this enlarges the beam size and lowers the peak intensity, the overall shape stays the same which is causal to most of the limitations laid out above. Furthermore, the process stability suffers, because the process is driven by the beam far outside of its Rayleigh length where its size is highly sensitive to any disturbances of the optical system.

In short, Gaussian beams create a strongly fluctuating keyhole within a narrow melt pool and disadvantageous temperature fields. This causes massive particle emission, which limits productivity and degrades part quality – both deciding success factors in driving up the industrial adoption of PBF-LB/M.

Ideally, the process could be driven with different beam profiles that are adaptable in their shape and diameter and can be switched on-the-fly, without adding complexity to the free-space optical delivery system. Studies both in simulation and application have found that ring-shaped beams and saddle-shaped beams (i.e. ring beams with some intensity in the center) create stable melt pools with a near rectangular cross-sectional shape.

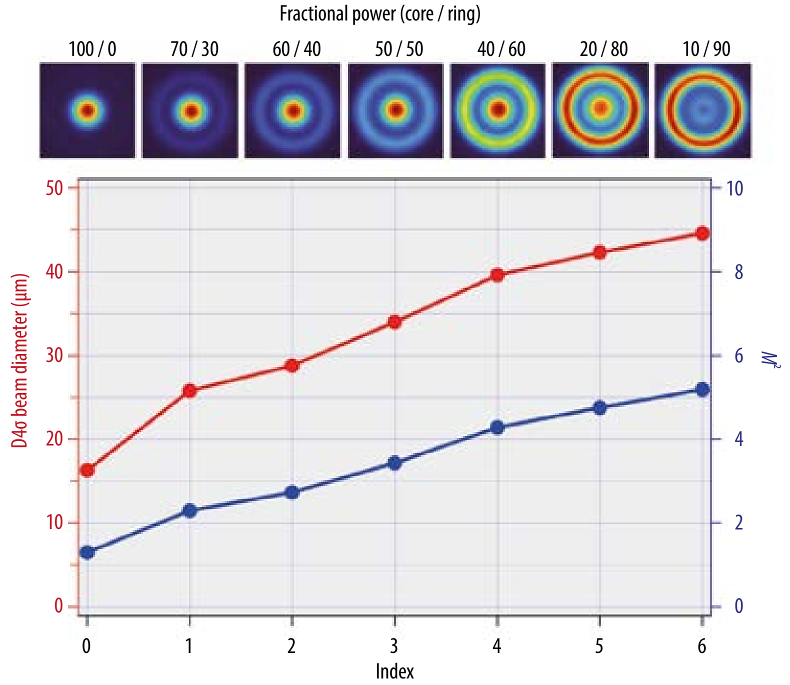


Fig. 1 Switchable beam profile settings ('indexes') of the nLight AFX fiber laser. The top images show near-field spatial profiles for the indicated divisions of power between the central single mode core and the surrounding ring. The graph shows the calculated D4σ beam diameters and the corresponding M^2 values.

Flexible ring-shaped beams via all-in-fiber technology

To provide such beams and flexibility, nLight has developed the Corona fiber laser family. It employs a unique beam shaping technology that allows the output beam profile to be switched on-the-fly within less than 25 ms. All beam shapes can be commanded electrically via the laser communication interface, just as easily as the laser power or modulation rate. A version optimized for PBF-LB/M called AFX has been released that is capable of emitting both a standard single mode Gaussian beam (core size 14 µm) for fine details and six ring and saddle-shaped profiles (outer diameter 40 µm) for larger features, see Fig. 1. The corresponding beam diameter (second moment, D4σ) ranges from 15 – 45 µm, which translates into a range of 75 – 225 µm on the powder bed assuming a typically used optical magnification of 5×. The maximum laser output power currently amounts to 1.2 kW, while an enhanced version with even higher power will be released shortly.

The following sections will discuss various aspects of PBF-LB/M of this flexible laser source. To connect the dots and to provide an overarching framework, Fig. 2 visualizes the manifold relations and dependencies of the various process parameters, the material physics and the observable benefits.

Stabilized melt pool dynamics

The dynamics in the melt pool are changed fundamentally when processing the powder bed with a ring-shaped beam: due to the lack of power in the center, no overheating occurs and all power is efficiently used for homogenous melting.

In simulation studies, Lars Vanmunster from KU Leuven found a significant reduction of the melt pool length, which leads to less balling and humping of the re-solidified track. Further simulation studies by Dr Marcin Serdeczny from Flow Science revealed that the evaporation pressure and the resulting velocities of the melt pool liquid are much lower when applying a ring beam, indicating a calmer melt pool with less ejection.

During extensive trials in AlSi10Mg, Jan Johannsen from Fraunhofer IAPT found that with a donut profile no protrusion or cracking occurs over a wide range of process parameters.

Company

nLIGHT

nLIGHT Inc. is a leading provider of high-power semiconductor and fiber lasers used in a broad range of applications in the industrial, microfabrication, and aerospace and defense markets. nLIGHT fiber lasers are used for high-power industrial material processing, including cutting and welding and additive manufacturing. nLIGHT is headquartered in Camas (WA, USA), with additional sites in Hillsboro (OR, USA), Longmont (CO, USA), Farmington Hills (MI, USA), Torino (Italy), Vienna (Austria), Lohja (Finland), Shanghai (China) and Seoul (South Korea). Its fiber lasers are sold worldwide through direct sales and a global distributor network. nLIGHT (LASR) is publicly traded on the US Nasdaq stock exchange.

www.nlight.net

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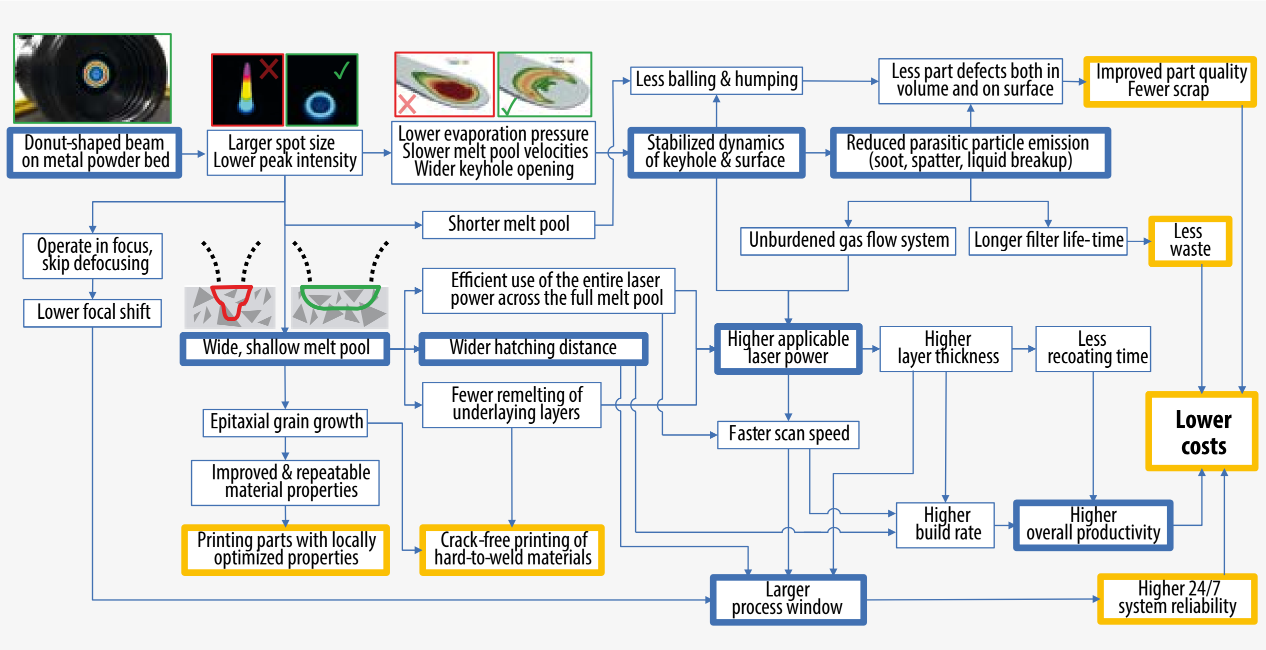

Fig. 2 Visualization of the complex interplay of process parameters, material physics and benefits in PBF-L/M when using ring-shaped laser beams. Bold blue boxes mark important milestones while orange boxes denote key benefits for end users.

Due to the stable melt pool, one can easily assume that – with a ring beam – the powder fusion process is entirely driven by conduction welding, completely suppressing any keyhole welding. Prof Lianyi Chen from the University of Wisconsin-Madison has shed light on this question. In-situ x-ray imaging of melt pools has been performed by his group. While with a Gaussian beam many pores both from the top and bottom of the keyhole are observed, almost no pores are generated by a ring beam, which mitigates volume defects and ensures high density. Furthermore, no liquid droplet detachment from the melt pool is observed with a ring beam.

Reduced particle emissions

One of the most obvious and best studied benefits of ring-shaped beams is the significant reduction of soot and spatter emission. While the reduction is apparent in pure visual observation and video sequence, various spatter detection and analysis methods can be used to quantify the amount.

Dr Hongqiang Chen from GE Research employed a particle counting system directly attached to the gas flow system, allowing live measurement of the soot emission. In Inc718, soot emission was reduced by 2.2× (~45 %) – and that is while processing with a 2.5× higher build rate compared to a Gaussian beam. Richard Rothfelder from Friedrich Alexander University Erlangen-Nuremberg (FAU) used tungsten particles as tracers in titanium powder, enabling easy counting of tungsten spatter in microscopic and µ-CT scans. With ring-beam shaping, he found a mean reduction of the tracer particles of 75 %. Prof Katrin Wudy from the Technical University Munich (TUM) developed an algorithm for video image analysis that determines both the amount and the velocity of spatter, observing reductions of up to 50 % each for certain parameter combinations in SS316L.

Several direct benefits follow from the reduced particle emission. Firstly, the laser power can be increased because the gas flow system is burdened with a lower particle load. Secondly, part quality is enhanced due to less particles being spread over the powder. Thirdly, wastage and the cost of replacing particle filters are reduced.

Improved melt pool geometry

Wide, flat and shallow melt pools are observed in all ring beam studies and visually prove the efficient use of the full laser power across the entire melt pool. This includes the non-overheated keyhole, stable fusion even at the edges and reduced re-melting of previously processed layers.

The near-rectangular cross-section of the melt pool indicates that the solidification vectors are more uniformly oriented upwards, leading to an epitaxial grain growth, compared to a rather anisotropic growth created by a Gaussian beam. This has been shown experimentally by Marco Beckers from Aconity3D through EBSD studies, revealing a sharp grain texture over many layers due to less competitive growth of the dendrites. As a result, the mechanical properties are significantly improved, such as the ductility being doubled – even after heat treatment. Moreover, the ability to switch rapidly between different beam profiles allows the texture and material properties to be tuned, which enables spatially-optimized material properties. This has already been successfully demonstrated, even in a complex geometry, by applying this procedure to the printing of turbine blades.

The melt pool shape is also critical when processing crack-prone materials. With shallow, wide melt pools, hardly any cracks occur – even compared to a defocused Gaussian beam of a similar diameter. Tim Lantzsch from Fraunhofer ILT reported on currently ongoing print trials with ASP2012 tool steel with promising first results, while Kenneth Davis from Amaero already succeeded with crack-free printing of H-13 tool steel at previously unachievable productivity as high as 45.8 cm^3/hr.

Larger process window

The process window is typically spanned by the limits of the main processing parameters of laser power, scan speed, hatch distance and layer thickness. As already described, the limits of all these parameters are shifted when applying ring-shaped beams, leading to a more generous process window with higher productivity. Specifically, the studies of KU Leuven, TUM, IAPT, ILT, Amero, Aconity3D, GE Research mentioned previously explicitly confirm the finding of a significantly increased process window while maintaining the highest part density in the range of ≥99.5 %. It seems counter-intuitive that ring beams – with their shallow melt pool – allow high layer thicknesses. This is another positive consequence of the stabilized melt pool as it tolerates higher laser power which scales up its depth. Very large layer thicknesses of 150 µm have already been demonstrated, with the potential for up to 300 µm through future power increases. By switching the beam profile on-the-fly with respect to the required feature resolution, the economics can be optimized even for parts that incorporate a large variety of fine and volumetric sections.

Outside of the melt pool dynamics, ring beams enlarge the process window in yet another way: while Gaussian beams are defocused to create a larger beam diameter, the ring beam is already large enough in its focal plane, where its size is most insensitive to disturbances of the optical system, for example through contamination. A ring beam is therefore more stable against focal shift, which benefits the reliability of the overall printing system, especially for print jobs that run for many hours or even days.

Higher productivity, lower costs

The cost and time of producing parts via PBF-LB/M are still considered to be too high. Major bottlenecks are the laser-driven powder melting process itself and the deposition of new powder layers by the recoater. As ring beams enable an increase of all main process parameters, both these iterative steps are accelerated. Specifically, the combined increase of scan speed and hatching distance decreases the time needed to melt an entire layer, while increasing the layer thickness reduces the total number of layers and thereby saves recoating time. By maximizing these parameters together with the laser power, large productivity increases over state-of-the-art Gaussian parameter sets have been demonstrated. To name a few examples, Fraunhofer IAPT reported a build rate of more than 100 cm³/hr in AlSi10Mg, marking a 3× increase over commercially available machines from large and renowned OEMs. In Inc718, GE Research reported a 2.5× increase of the build rate while Aconity3D achieved cost and time savings of ~75 % in a specific use case of printing turbine blades.

*

We kindly acknowledge the contributions of our invited speakers at the nLight expert forum during Formnext 2022: Lars Vanmunster (KU Leuven), Richard Rothfelder (FAU Erlangen-Nürnberg), Kenneth Davis (Amaero), Prof Dr Lianyi Chen (U Wisconsin-Madison), Dr Marcin Serdeczny (Flow Science), Prof Dr Katrin Wudy (TU Munich), Dr Hongqiang Chen (GE Research), Jan Johannsen (Fraunhofer IAPT), Tim Lantzsch (Fraunhofer ILT), as well as Marco Beckers and Martin Buscher (both Aconity3D).

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[1] nLight YouTube channel: www.youtube.com/c/nLIGHTInc

Author

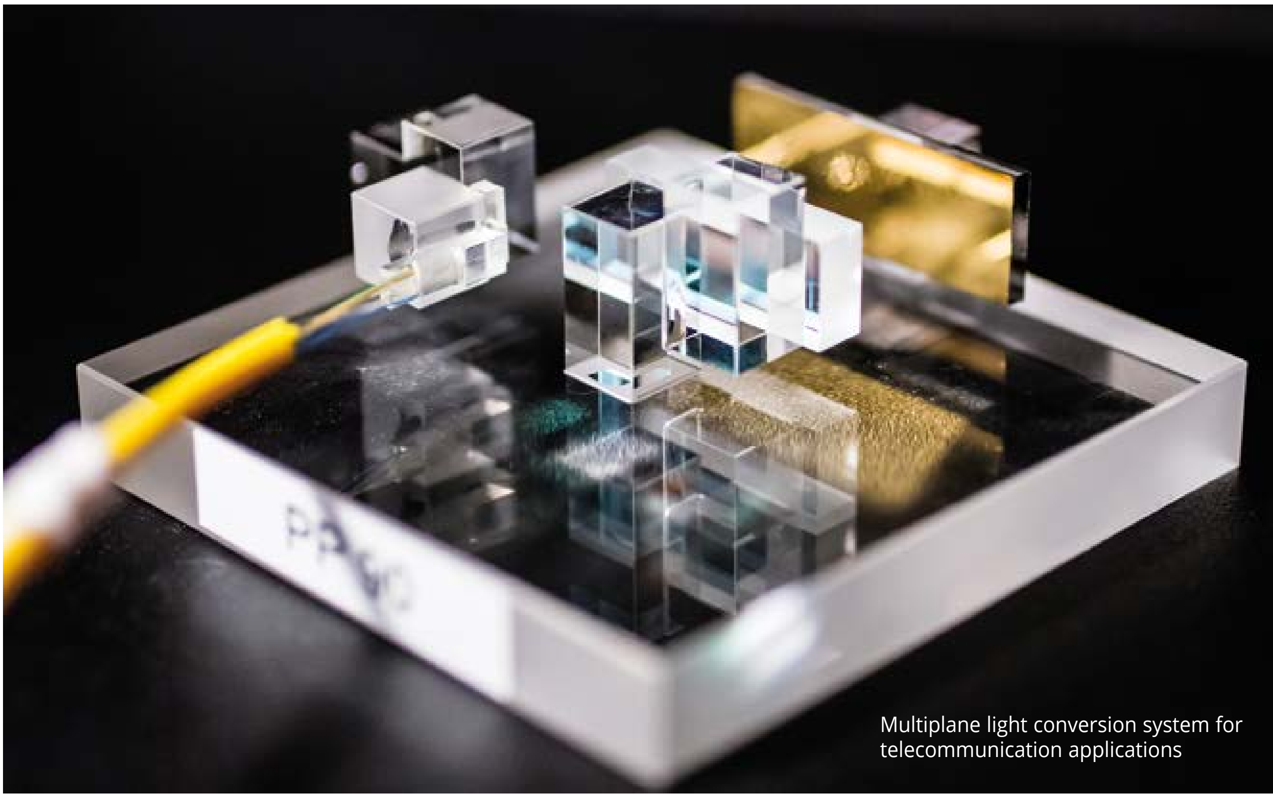
Andreas Rudolf manages the market development of additive manufacturing at nLight, supporting customers in maximizing the performance and reliability of their tools. Prior to nLight, he worked for Precitec, heading the corporate product management and leading the pre-development team focused on laser cutting of thick metals. In 2013, he earned his PhD in physics at the Technical University of Darmstadt, for which he conducted research on fiber amplifiers, strong magnetic field configurations, optical sensors and remote sensing.

Dr. Andreas Rudolf, nLIGHT, Inc., 4637 NW 18th Ave, Camas WA 98607, U.S.A; e-mail: andreas.rudolf@nlight.net, Web: www.nlight.net nlight andreas-rudolf-6a306b173

Beam shaping to scale up micro-processing

Combining multiplane light conversion with an industrial femtosecond laser to increase performance

Gwenn Pallier & Jean-François Poisson



Source: Cailabs

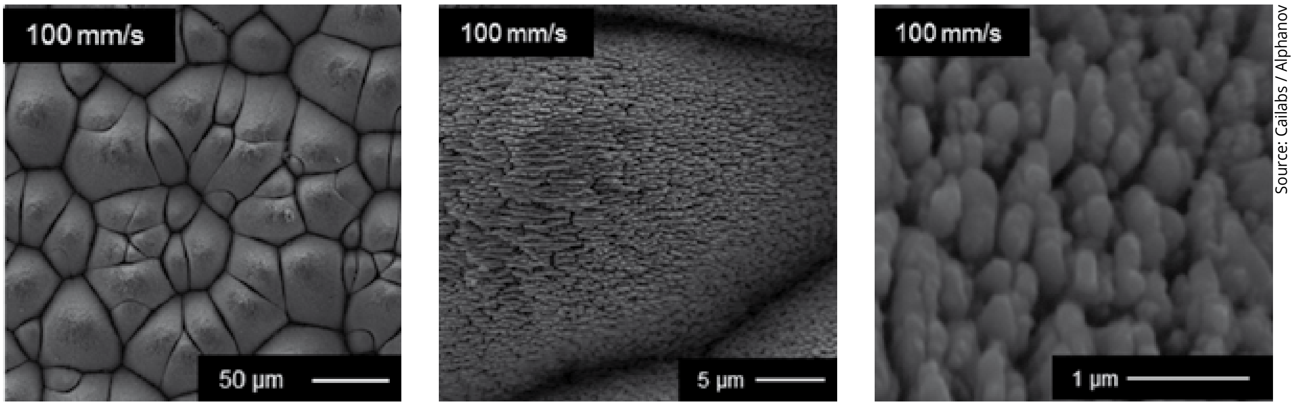
Multiplane light conversion system for telecommunication applications

Many industrial microprocessing applications that use femtosecond lasers have been developed in a variety of sectors, including medical and semiconductors. To access new large-scale applications such as surface texturing however, robust industrial-grade beam shaping solutions need to be combined with femtosecond lasers. Cailabs and Light Conversion have developed a partnership to demonstrate the quality and robustness of their solution using a Canunda-Pulse beam shaper and a Carbide laser.

Many industrial applications have been developed since the laser was invented in the 1950s. The first major application was laser welding with continuous-wave lasers. With the development of pulsed lasers, new smaller-scale applications emerged, and microprocessing – or machining at a micrometer scale – was developed. Today, microprocessing enables very large volumes to be produced for a wide range of markets: medical (e.g. the production of medical devices); semiconductors (e.g. the selective ablation of thin layers on chips); and even luxury goods (e.g. watch decoration).

Having experienced very strong, continuous growth for many years, new microprocessing markets are now emerging, and the strong development of surface texturing is expected. Many phenomena take place on the surface of objects: heat exchange, friction, fluid flow, to name just some. Machining the surface of an object to fulfil its purpose is therefore an essential requirement, and microprocessing allows very specific textures to be applied, for example to modify tribological properties, to improve aerodynamic properties, or to create hydrophobic or hydrophilic regions.

Using femtosecond lasers to perform this type of surface texturing gives high-quality results with incomparable precision. The extremely short



Images at different scales of Stainless steel 316L to generate a deep black effect, results obtained with Alphanov

pulse duration means that the material is vaporized without having time to generate thermal effects around the ablated area. These lasers can perform different types of surface texturing: geometrically organized, self-organized, and based on interference patterning.

The challenges of microprocessing

While the surface texturing performance obtained is extremely satisfactory, developing these applications on an industrial scale still faces two main challenges. First, in order to texture large and sometimes complex surfaces (curved), the machine must be able to cover large surfaces, which is greatly facilitated by a fiber laser. However, the output of high average power industrial femtosecond lasers is currently delivered through free-space. Second, it is necessary to increase process efficiency, which implies using higher energy and more powerful lasers. However, simply using these lasers is not enough, as applying more energy to the surface will result in a significant decrease in process quality. The solution is therefore to optimize the use of the available energy by shaping the laser beam.

Femtosecond laser beam shaping

Various technologies can be used to perform laser beam shaping. Each uses different optical principles and laws and has manufacturing techniques with different constraints, which results in beam shaping systems with very different behaviors. While identical intensity profiles can be obtained using different technologies, the behavior of the beam, and especially that of its phase profile, may be very different for each case: just because the same intensity profile is observed in a plane, that does not mean that it is the same beam.

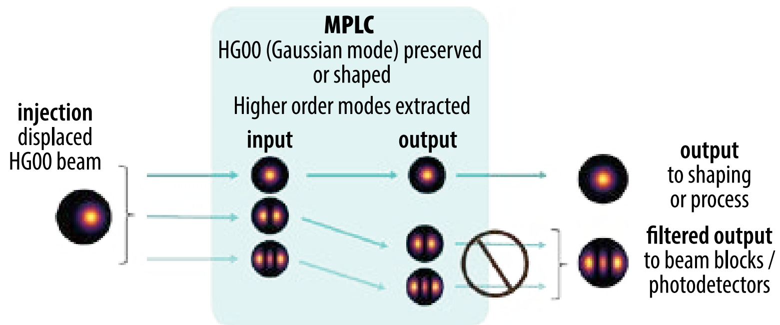
Three main beam shaping techniques exist for single-mode lasers with a very short pulse duration. The first uses basic ray tracing laws, for example Fresnel's law, which we can see in beam shaping systems such as aspheric lenses. The second relies on the laws of physical optics, of diffraction, found in diffractive optical element (DOE) systems. The third and final technique uses laser mode propagation laws, found in multiplane light conversion systems.

Multiplane light conversion (MPLC)

MPLC is a beam shaping technique invented at the Laboratoire Kastler Brossel (LKB) in Paris and subsequently developed by Cailabs. It consists of shaping a laser beam by using multiple phase plates one after the other with sufficient propagation between each. Implementing an MPLC device in an industrial context is generally done reflectively: the beam travels back and forth between two mirrors, one of the mirrors being textured. The MPLC can take one or more beams at input and output, and can have either fiber or free-space inputs and outputs. Finally, the light is converted without any theoretical loss.

The multiple phase plates provide great control and flexibility of the intensity profile at the system output, as well as of the phase profile. This makes it possible to obtain a flat phase profile in the process plane which satisfies an important requirement for industrial use: a stable depth of field. The depth of field obtained with an MPLC system can reach the theoretical limits and is therefore only limited by the steepness of the profile, which is in turn limited by the numerical aperture of the optical chain. Furthermore, due to the propagation laws used, MPLC provides another key property for the industrialization of beam shaping: the shape is preserved over the whole field of view of an F-Theta lens, thus preserving machining quality over a large machining area. MPLC also preserves the polarization and spectrum, and therefore the pulse duration of the input laser.

Finally, an important feature has been developed to allow the industrial use of MPLC with femtosecond



Mode cleaning feature principle (Source: Cailabs)

Carbide laser from Light Conversion

Canunda-Pulse beam shaper from Cailabs

lasers: mode cleaning. Regardless of the technology, it is impossible to maintain a high-quality beam profile on a single-mode beam if it presents offset instabilities, which is the case for all free-space femtosecond lasers, especially if they have to propagate along a long optical chain that includes mirrors and lenses on an optical table.

Based on the control of modes in an MPLC, mode cleaning ensures stable beam shaping under all circumstances. The system projects the input beam onto a base of orthogonal modes: part of the energy is on the main mode, TEM_{00} (Gaussian), and part of the energy is on the higher order modes. If the input beam has defects (astigmatism, ellipticity, etc.) or if it is not stable in time (tilt, shift, etc.) these defects will be identified as energy to be projected onto the higher order modes. The energy in the main mode follows an initial path in the MPLC, is shaped, and leaves the system.

The same shape, based on a Gaussian beam, is preserved at output. The energy of the higher modes follows another path, is filtered, and does not leave the system. Any deviation from the perfect profile, either statically or dynamically, will result in a decrease in transmission, but there will be no change in the output profile. This allows good process quality to be maintained under all circumstances.

Industrial femtosecond lasers

Light Conversion designs and manufactures a wide range of industrial femtosecond lasers with an average power ranging from 6 to 80 W and energy per pulse ranging from 100 µJ to 4 mJ. These lasers are available in several wavelengths, up to the fifth harmonic, and their flexibility is such that when a laser is produced for a given wavelength, it is still possible to access the fundamental wavelength (1,030 nm) and any others (e.g. for a Carbide UV 343 nm laser, the 1,030 nm and 515 nm wavelengths are available for use).

Light Conversion's laser sources can be mounted in several directions (horizontal, vertical, sideways) and are not sensitive to movement or vibration (each source produced undergoes vibration tests with accelerations up to 4 g). They are energy efficient and only require a simple water/air or water/water cooler (supplied) for temperature control. All of these properties make them particularly suitable for industrial use.

Compatibility of the laser with the beam shaping system

To demonstrate that industrial beam shaping using Cailabs' MPLC technology is compatible with an industrial femtosecond laser developed by Light Conversion, the two companies set up a partnership. A Carbide laser with an output power of up to 60 W at 1,030 nm was used, delivering pulses of 100 µJ with pulse duration of 190 fs. The laser was also used at a wavelength of 515 nm.

Company

Cailabs

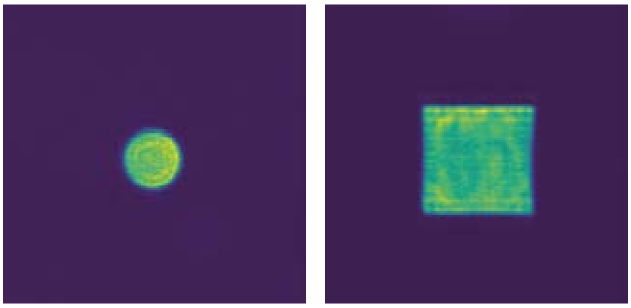
The company was founded in 2013 and is a French deep-tech enterprise that designs, manufactures and sells innovative photonics products for telecommunications and industrial lasers. A leading player in complex light shaping, its technology is currently covered by 19 patents. Its innovative components are used in various fields, from aeronautical wiring to factory local area networks, including laser manufacturing. They have contributed to several world records (in particular, the fiber optic throughput record held by the Japanese operator KDDI).

www.cailabs.com

Light Conversion

Founded in 1994 with roots at the Vilnius University Laser Research Center, the company became a pioneer in femtosecond optical parametric amplifiers (OPAs) and Yb-based femtosecond laser sources. With proven competence in laser design and manufacturing, state-of-the-art R&D facilities, and close ties to research programs, Light Conversion offers unique solutions for today's industrial, scientific, and medical challenges. The reliability of our femtosecond lasers has been proven by hundreds of systems operating 24/7 for more than ten years in the industrial market.

https://lightcon.com



Left: intensity profile of a *t*/*L* = 0.1 round top hat at 1,030 nm, right: intensity profile of a *t*/*L* = 0.33 round top hat at 515 nm (Source: Cailabs)

The beam shaping module used was a Canunda-Pulse that generated a round top hat profile with a steepness (transition region from 90 % to 13.5 % of maximum energy divided by the length of the plateau at 90 % of maximum) of 0.1 at 1,030 nm. A beam shaper that could generate a steepness of 0.33 at 515 nm was also used. The characterization setup included the Carbide laser, an injection telescope to obtain a waist of 500 µm at the input of the beam shaping module, the Canunda-Pulse beam shaper and a telescope to re-image the beam onto a camera at the module output.

Conclusion and next steps

It was demonstrated that it was possible to shape a femtosecond laser beam into a stable and robust round and square top-hat profile at both 1,030 nm and 515 nm, which maintained the same characteristics over time. It should be noted that the top-hat profile increased the steepness of the beam by a factor of 17. Following on from this compatibility demonstration, which was supported by a webinar with a live demonstration performed at Cailabs, two further steps will be taken: process testing will be conducted in Light Conversion's application laboratory, and compatibility testing of other shaping systems will be performed, such as beam splitting combined with shaping, or at even lower wavelengths.

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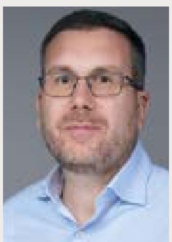
Authors

Gwenn Pallier holds a master's degree in optical engineering from the Institute of Optics in Paris, as well as in fusion science from the École Polytechnique in Paris. Passionate for optics, she has previously worked in the space and defense industry. She is now product line manager at Cailabs in charge of the development of the industrial applications of the MPLC-based beam shaping systems.



Jean-François Poisson started his career in the laser world in 2001 with a market leading company as project manager for standard and customized micromachining turn-key solutions. He then moved to a sales engineer position for the same product range in the same company, and later with a beam analysis solutions manufacturer. Jean-François has now been in charge of sales of light conversion products for the French speaking territories in Europe for two years.

Gwenn Pallier, Cailabs, 1 rue Nicolas Joseph Cugnot, 35000 Rennes, France; phone: +33 6 66 62 87 02; e-mail: gwenn@cailabs.com, Web: www.cailabs.com, gwenn-pallier-48230263, cailabs ■ Jean-François Poisson, Light Conversion UAB, Keramiku st. 2B, 10233, Vilnius, Lithuania; phone: +33 6 74 48 07 78; e-mail: jf.poisson@lightcon.com; Web: www.lightcon.com; jean-françois-poisson-9a3b6714a, light-conversion

Measure and monitor fine surface irregularities

Maintaining the quality of film surfaces using 3D laser confocal microscopes

Suzue Izumi


Source: shutterstock

Surface treatment is applied to the film used in food packaging, industrial materials, and medical applications to add various surface functions, such as transparency, gloss, waterproofing, antifouling, and non-adhesiveness. This article provides examples to demonstrate how laser microscopes can be used to check the quality of various film surface properties.

The film for food packaging, for example, requires various functions. The film must maintain the freshness and quality of the contents, be easy to handle, and resist contamination. The demand for surface functions continues to increase, along with the need to confirm quality through roughness measurements of the surface's fine irregularities. 3D laser confocal microscopes have proven to be an effective solution for measuring the roughness of fine irregularities on the film surface to maintain the quality of the film surface during production.

Comparing the surface condition of yogurt lids

The first example using a laser microscope investigates the surface condition on the back of two yogurt pot lids – one with high water repellency and one with low water repellency. The level of water repellency impacts the adhesion of yogurt to the lid, as yogurt will stick to a lid with low water repellency but will not stick to a lid with higher water repellency.

The lids are composed of multiple film layers. This includes an aluminum layer with strong reflective properties. To correctly capture the shape of the outermost surface of the film, it is important to take data that is not affected by strong reflection from the lower aluminum layer. A high-magnification objective lens with a shallow depth of focus reduces the effect of strong reflection from the lower layer. It also enables data to be acquired just from the outermost surface of the film.

The LEXT OLS5100 3D laser confocal microscope is adapted to a laser wavelength of 405 nm and uses a dedicated LEXT objective lens that suppresses aberrations. Accurate 3D data can be acquired over the entire field of view with this setup.

3D data acquisition using the laser microscope makes it visually clear that the highly water-repellent yogurt lid has spherical convex aggregates of various sizes randomly scattered on the base surface. In comparison, the lid with low water repellency has no conspicuous convex shape. This difference is shown in Fig. 1.

The surface condition of a sample with high water repellency is like the surface of lotus leaves and broccoli. These surfaces have a fine uneven shape called a fractal structure – a form where similar shapes can be seen at different scales of magnification. This structure repels water so that the droplets flow down. Inspired by these natural shapes, this fractal structure is also applied to highly water-repellent yogurt lids.

Acquiring roughness data of the yogurt lids in a wider area

Acquiring data from a wider area shows the distribution this characteristic convex shape has on the back of the highly water-repellent yogurt lid. While a high-magnification objective lens is effective for acquiring data only on the outermost surface of the back of the lid, the range of one field of view is too narrow to capture all the data. Using the stitching function on a laser microscope enables individual images captured using a high-magnification objective lens to be connected to create a high-resolution image with a wider field of view (Fig. 2).

Fig. 3 shows that the appearance of the convex aggregates randomly scattered in one field of view (right image) has a similar distribution even when the field of view is widened (left image). The convex aggregates have a fractal structure.

The images above show visually that the surface states of highly water-repellent films and low water-repellent films differ greatly. It also shows that convex aggregates exist in highly water-repellent films. Lastly, it shows that the convex aggregates have a fractal structure where similar convex aggregates are scattered, even when the images are stitched together and observed in one wide field of view. These results were used to quantify the surface condition of these two lids by measuring their surface roughness.

Quantifying the surface condition

A stylus-type surface roughness tester that acquires one-line data is often used for roughness evaluation. Yet for shapes with locally scattered irregularities, such as on highly water-repellent surfaces, the roughness value varies greatly depending on the line traced by the stylus. Contact with the stylus can also damage the sample, presenting a risk during measurement. In comparison, a 3D laser confocal microscope can obtain surface data without contact. It does so by scanning the laser beam. This process makes it possible to obtain more surface shape information than the one-line data from the stylus (Fig. 4).

The acquired data from the wide field of view (about 700 µm) was used for the surface roughness measurement. To obtain suitable data for surface roughness evaluation, it is important to have a field of view that contains at least ten characteristic uneven shape components that can most affect the surface function of the sample.

For the highly water-repellent sample above, this means that if each convex aggregate seen in the one field of view (50× objective, about 250 µm) is a characteristic shape component that provides a water-repellent function, at least ten convex aggregates must be captured in a wider field of view. To collect more than ten convex aggre-

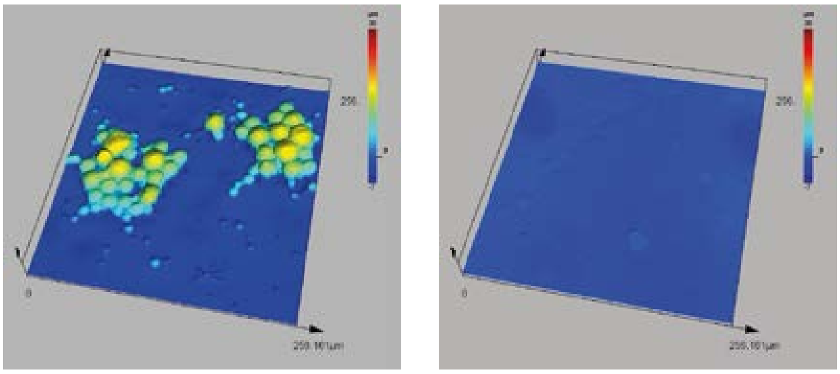


Fig. 1 Visual 3D data of the two yogurt lids taken with the OLS5100 laser confocal microscope. Left: yogurt lid with high water repellency (50× objective, about 250 µm). Right: yogurt lid with low water repellency (50× objective, about 250 µm).

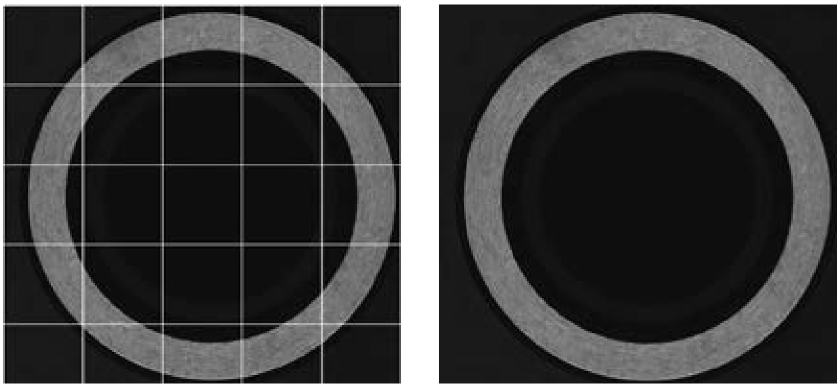


Fig. 2 Left: individual 2D images before stitching. Right: 2D image after stitching.

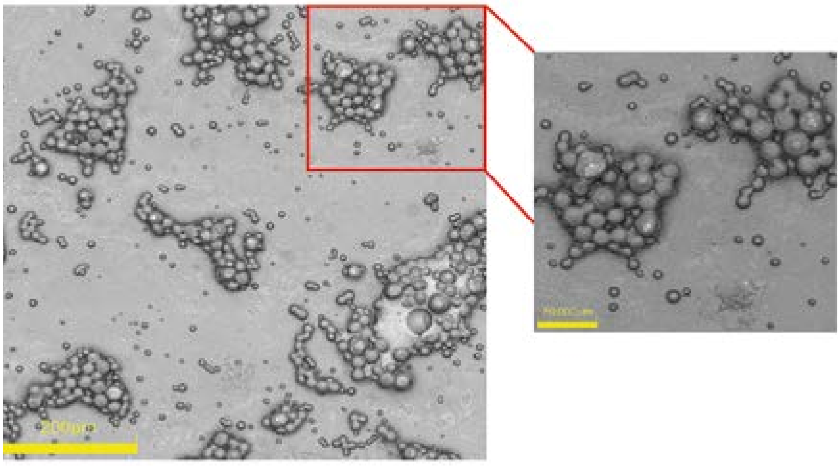


Fig. 3 Left: 3 × 3 images (50× objective, about 700 µm), stitched using the OLS5100 3D laser confocal microscope. Right: one field of view (50× objective, about 250 µm).

Sample	S_p [µm]	S_v [µm]	S_z [µm]	S_a [µm]	S_{dq}	S_{dr} [%]
High water repellency_50×z1_3×3	28.419	9.597	38.016	4.297	2.082	31.562
Low water repellency_50×z1_3×3	2.044	7.434	9.478	0.471	0.127	0.561

Table 1 Surface roughness measurement results for the back surface of yogurt lids, using the 50× objective lens.

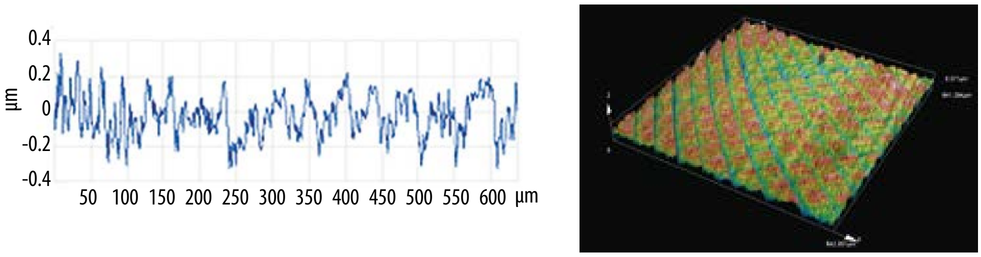


Fig. 4 Left: data from a stylus-type surface roughness tester provides information from only one line. Right: the OLS5100 3D laser confocal microscope acquires information from an entire plane.

gates, widefield data with 3 × 3 stitched images was used to evaluate the surface roughness.

Surface roughness measurement results of the yogurt lids

Using the 50× objective lens, the laser microscope obtained the following results for the back surface of the two lids (see table 1). The parameters to note are S_p, S_z, S_a, S_{dq}, and S_{dr}:

S_z is the maximum height, and S_p is the maximum mountain height. If you look at the S_z value, you can see the size of the unevenness from the average surface. S_z is the sum of the maximum mountain height (S_p) and the maximum valley depth (S_v). What we pay attention to here is that the difference between S_p and S_v is large only in S_p. The data from this example shows that the highly water-repellent lid has many convex shapes from the average surface.

S_a is the arithmetic mean height. This parameter shows the average value of the height difference from the average surface. The highly water-repellent lid with a large S_a value has larger unevenness.

S_{dq} is the root mean square gradient. This parameter shows the average size of the local gradient of the surface irregularities. The highly water-repellent lid with a large Sdq value has larger unevenness, which reduces the gloss of the surface.

S_{dr} is the expanded interface area ratio. This parameter shows the rate of increase in surface area. The higher the water repellency, the larger the undulations and the larger the surface area.

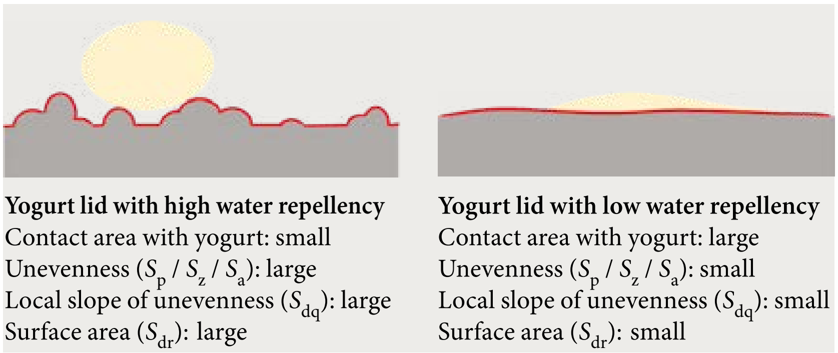


Fig. 5 Yogurt lid with high (left) and low (right) water repellency

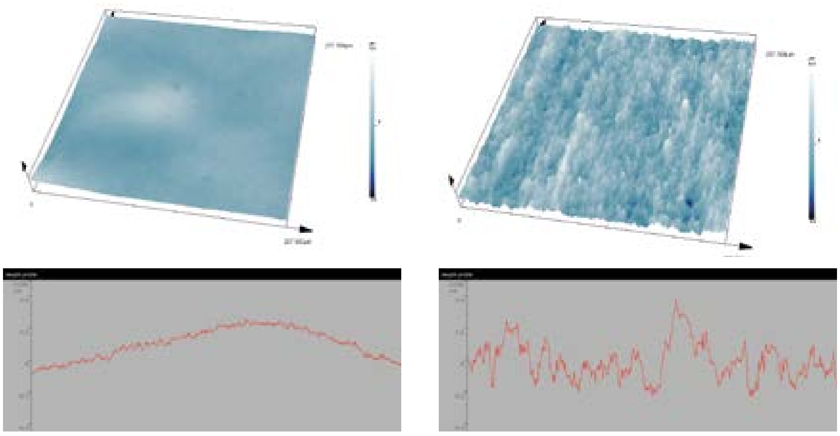


Fig. 6 Left: Polyethylene film (food wrap), 50× objective. Right: Antistatic film, 50× objective. Visual 3D data taken with the OLS5100 3D laser confocal microscope.

Key takeaways from the surface roughness data

Forming the surface of the water-repellant lid into a fractal structure reduces the contact area between the yogurt and the lid. This surface shape causes the yogurt to form droplets that do not stick to the film. The reduction in the contact area means that the surface area of the film is large and uneven. In contrast, the lid with low water repellency has a small, even surface area that creates a large contact area. We can conclude that the yogurt sticks to this lid because the adhesion increases as the contact area increases. The relationship of the level of water repellency to the surface roughness data is given in Fig. 5.

Comparing the surface condition of polyethylene film and antistatic film

Another example of using a laser microscope investigates the amount of static charge on polyethylene film (food wrap) and antistatic film by comparing their surface conditions. Antistatic film reduces the buildup of static electricity. This film helps to protect sensitive electronics from electrical energy formation that can damage the components.

The OLS5100 laser confocal microscope scans the film surface with a 405-nm purple laser beam to acquire 3D data. Paired with a dedicated LEXT objective lens that adapts to a wavelength of 405 nm and suppresses aberrations, the system can clearly capture fine patterns and defects that are difficult to capture with conventional optical microscopes and general laser microscopes.

Fig. 6 shows that the surface of the polyethylene film does not have a particular shape and has gentle irregularities. In comparison, the antistatic film has jagged irregularities of sub-µm to several tens of nm periodically.

Quantifying the surface condition of the antistatic film and polyethylene film

The difference in the visual unevenness of these two film surfaces was quantified by measuring the surface roughness using the same 3D laser confocal microscope. In this step, it is important to select a lens suitable for the sample under observation to obtain reliable measurement results.

The OLS5100 microscope can easily determine – measured values are not guaranteed – whether the selected lens

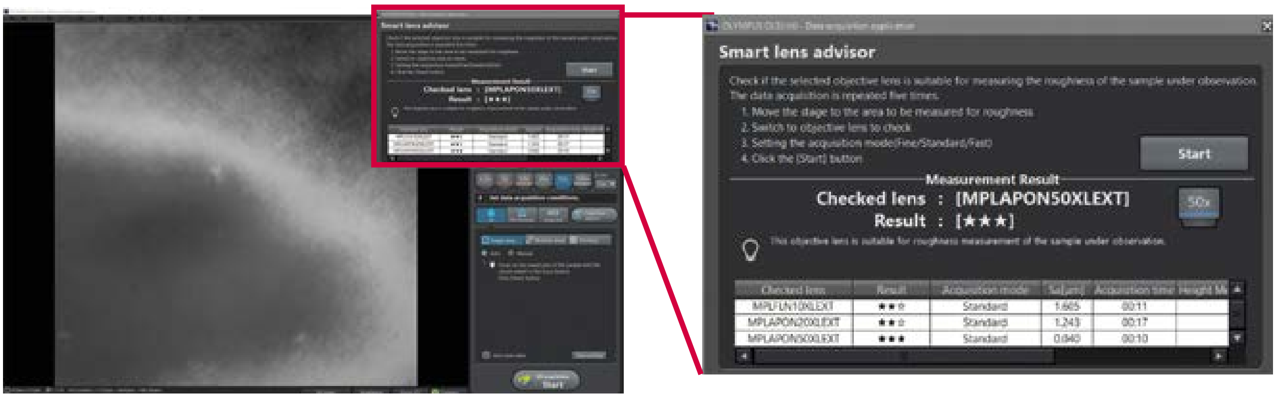


Fig. 7 The Smart Lens Advisor on the OLS5100 laser confocal microscope confirms the objective lens is suitable for the measurement.

Sample name	S_q [µm]	S_z [µm]	S_a [µm]	S_{dr} [%]	S_{al} [µm]
Polyethylene film _50×	0.06	0.477	0.043	0.076	30.553
Antistatic film _50×	0.122	1.152	0.097	0.84	8.424

Table 2 Surface roughness measurement results of polyethylene film and antistatic film, using the 50× objective lens.

is suitable for the sample thanks to the Smart Lens Advisor. In this example, the system determined the dedicated LEXT 50× objective lens was suitable for the roughness measurement of the film (Fig. 7).

Using the 50× objective lens, the microscope obtained the following results for the two films (see Table 2). The notable roughness parameters in the measurement are S_q, S_z, S_a, S_{dr}, and S_{al}:

S_q is the root mean square root height, S_z is the maximum height, and S_a is the arithmetic mean height. These parameters indicate the size of the unevenness from the average surface. In this example, the antistatic film with a larger value indicates that the unevenness is larger.

S_{dr} is the expanded interface area ratio. This parameter shows the rate of increase in the surface area. In this example, the polyethylene film with a small S_{dr} value has a small surface area. In comparison, the antistatic film has a larger surface area due to the large unevenness on the surface.

S_{al} is the autocorrelation length. While most parameters evaluate roughness in the height direction, S_{al} is one of the few parameters that focuses on the lateral direction, such as the density of streaks and particles. A smaller S_{al} value indicates a steeper shape and finer grain. A larger S_{al} value indicates that the surface has a more gradual uneven shape. We can conclude that the antistatic film with a smaller S_{al} value has more fine-grained shapes on the uneven surface.

Key takeaways from the surface roughness data

The three main factors that determine the amount of static electricity are contact area, friction force, and humidity. Here we focused on the contact area, which is closely related to surface roughness. In general, a larger contact area between objects generates more static charge.

In this experiment, we can see that the antistatic film with a small contact area between objects generates less static electricity compared to the polyethylene film with a large contact area. The large unevenness of the antistatic film lowers the contact area compared to the smoother surface of the polyethylene film. The relationship of the charge amount to the surface roughness data is shown in Fig. 8.

Conclusion

These examples show how 3D laser confocal microscopes can precisely measure the surface roughness of films used to package food, electronics, and other important items. With noncontact measurement and 3D data acquisition over a wide area, inspectors can easily confirm the quality of surface treatment on film during production. Smart microscope features, such as dedicated objective lenses that reduce aberrations, image stitching, and lens selection tools, further streamline the measurement workflow.

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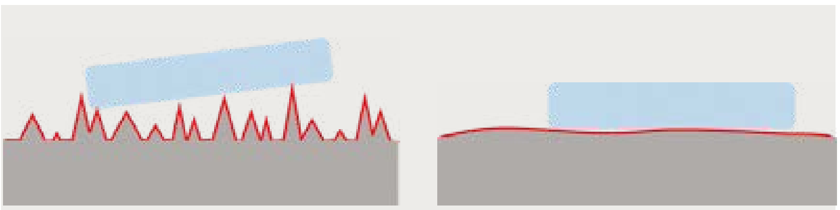

Antistatic film
Charge amount: small
Contact area with an object: small
Unevenness (S_q/S_z/S_a): large
Surface area (S_{dr}): large
Fineness (S_{al}): small

Polyethylene film (food wrap)
Charge amount: large
Contact area with an object: large
Unevenness (S_q/S_z/S_a): small
Surface area (S_{dr}): small
Fineness (S_{al}): large

Fig. 8 Surface roughness illustrations for antistatic film (left) and polyethylene film (food wrap; right)

Author

Suzue Izumi is a marketing specialist for metrology solutions at Evident. Since joining Evident in 2001, she has performed many demonstrations as a laser confocal microscope specialist. In addition to visiting laser confocal microscope users in Japan to provide technical support for system operations and data analysis, she also provides application support globally.

Suzue Izumi, EVIDENT CORPORATION, Shinjuku Monolith, 3-1 Nishi-Shinjuku 2-chome, Shinjuku-ku, Tokyo 163-0910 Japan, e-mail: suzue.izumi@evidentscientific.com, Web: www.evidentscientific.com

Time-resolved microscopy made easy

New confocal microscope for dynamic structural biology with single-molecule FRET

Maria Loidolt-Krüger

Source all images: PicoQuant

Fig. 1 Single photon counting confocal microscope Luminosa

Quantitative single molecule and time-resolved fluorescence techniques offer new insights into many samples in life and materials sciences. So far, their adoption has been slow because expert knowledge was required for correct data acquisition and analysis. Now, PicoQuant have developed a new confocal microscope called Luminosa. It combines state-of-the-art hardware with cutting-edge software to deliver high-quality data while simplifying daily operation. The software includes context-based workflows for each technique. This article shows how it streamlines single-molecule Förster resonance energy transfer (smFRET) experiments.

Single photon counting and timing opens a new dimension

The confocal fluorescence microscope has become increasingly popular over the last four decades, and today is a workhorse instrument routinely used in molecular, cell, and developmental biology to visualize dynamic processes and cellular structures. Besides imaging, point measurement methods such as fluorescence correlation spectroscopy (FCS) or smFRET are gaining popularity for biophysical studies. One more advance that has caught attention recently is the addition of time-resolved methods.

Measuring the fluorescence lifetime of a fluorophore opens an extra dimension of information, which is complementary to spectral information. The fluorescence lifetime is characteristic for each fluorophore and can thus act as an identifying feature for multiplexing. It can also be influenced by the smFRET process, such that the shortening of the donor lifetime in the presence of an acceptor reports on the FRET efficiency.

Until now, the threshold for adapting time-resolved fluorescence methods was perceived as rather high, requiring expert knowledge. The new Luminosa microscope has been created to lower this threshold and to enable quick incorporation of these methods into a researcher's toolbox. They can offer new insights into various research areas such as:

- Dynamic structural biology at the single molecule level
- Cellular mechanisms driven by phase separation
- Environmental sensing
- Mapping dynamics and structure of cellular membranes
- Characterization of functional nanovesicles

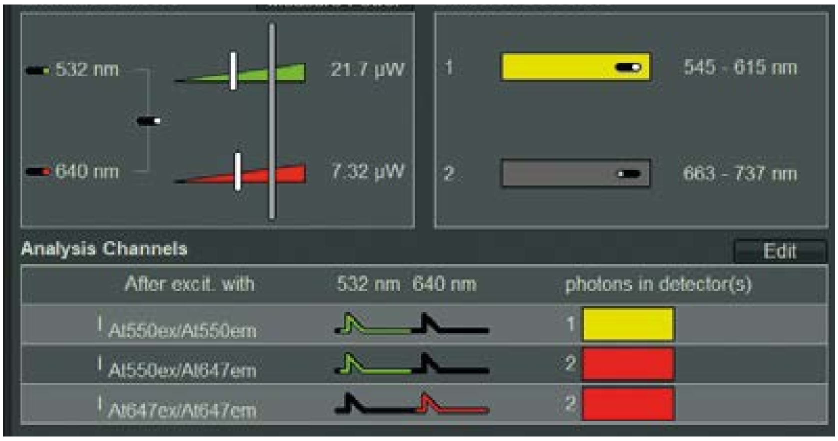

Fig. 2 Screenshot of hardware and analysis settings for a smFRET experiment with 532 and 640 nm pulsed interleaved excitation and dual-channel detection, yielding three logical analysis channels.

- Studying chemical reactions at the single molecule level and
- Characterization of advanced materials.
- Increasing quality and reproducibility

Across these research areas, scientists regularly have trouble reproducing other scientist's experiments [1]. One of the possible reasons is that microscopy methods employed are often not described in sufficient detail. One potential way to increase the accuracy, precision, reproducibility and quality of experiments is to limit human error by automation of microscopy, i.e. motorization of hardware parts and integration of sensors into smart software. This also increases the ease of use of imaging systems, all in all saving researchers precious time and materials. Moreover, automation boosts the throughput and even opens up new experimental possibilities such as time lapse imaging, multi-position imaging, or multi-point time traces.

Cutting-edge hardware for best results

Luminosa has been designed for best performance in the lifetime domain. The microscope is also optimized for single photon sensitivity, enabling experiments at the single molecule level. Experience with PicoQuant's confocal MicroTime 200 system guided the optical design of the new microscope, and helped the selection of the best hardware components. The optical design is optimized for the highest sensitivity by incorporating only the minimum number of optical elements of the best quality.

The user can either choose a galvo scanner for high speed or bypass it with the click of a button and use a piezo objective scanner instead. This option is not available on other confocal microscopes. Piezo scanning prevents loss of signal at the scanning mirrors and yields approximately 20 – 30 % more photons, depending on the wavelength. The user can also select either PMA hybrid detectors with better timing resolution or SPAD detectors with higher sensitivity for their individual set-up.

Intuitive workflows for simple day-to-day operation

The Luminosa system software was created from scratch. Its design permits quick and easy workflows for experiments, which allow the users to focus on their samples. Clearly arranged interfaces showing only those parameters that are relevant for each application promote reproducible measurements yielding consistent datasets. The Luminosa software includes smFRET routines, FCS, and time-resolved imaging methods, as well as the ability to define custom measurement and analysis modes.

The system can perform a sample-free auto-alignment at the click of a button, which takes less than a minute. The resulting alignment is so precise that FCS measurements are directly possible without further optimization, so it is easy to ensure that the microscope is always in the same excellent condition.

To start out, the user chooses which measurement technique to use in the next experiment. A clearly arranged software interface shows only those parameters that are necessary for that type of measurement, thereby minimizing the risk of accidental errors. The hardware is automatically configured correctly upon selection of the fluorophores present in the sample. Analysis channels are then assigned based on the experimental context. Similar functionality is already available in most commercial LSMs, but here additional parameters important for time-resolved measurements – such as the laser repetition rate – are now set as well and reduce the amount of expert knowledge required by the user. Saving and loading of settings guarantees the repeatability of measurements. Furthermore, the appropriate metadata is saved alongside the actual data, and can even be searched later.

The excitation laser power calibration allows setting and displaying the excitation intensity in µW as shown in Fig. 2, without requiring an external power meter. It lasts less than ten seconds and can be performed in between measurements even while the sample is present. Reference [2] underlines the importance of illumination power in reproducibility, as photobleaching, phototoxicity, etc. cause variability in the results. This issue is so significant that QUAREP-LiMi's first working group is dealing with illumination power.

Several online previews are displayed in real time while the measurement is running. This allows researchers to

Company

PicoQuant

PicoQuant was founded in 1996 by four young scientists and engineers who set themselves the goal of developing optical instrumentation designed by scientists for scientists. The company focuses on offering innovative and high-quality products for international researchers working in various scientific fields. By staying true to this standard, the company became world leader in the field of time-resolved optical measurements. The company's portfolio covers a broad range of products, instrumentation, and applications.

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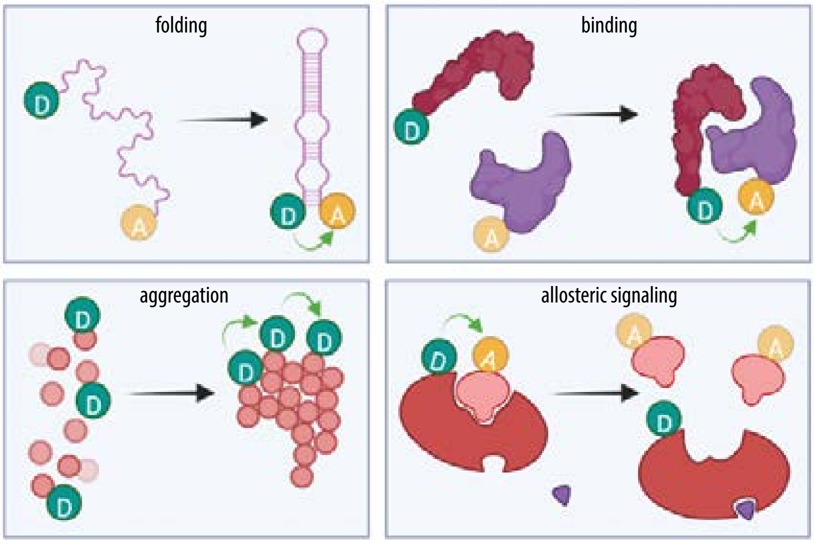

Fig. 3 Exemplary applications of smFRET method to study protein and DNA functions (created in biorender.com)

judge the quality of the sample, and to ascertain the correct settings of the acquisition parameters. A new feature enabled by online analysis is dynamic help messages, which aim to improve data quality.

The new software incorporates GPU-accelerated algorithms for fluorescence lifetime imaging microscopy (FLIM), FCS and single molecule detection. Their high speed enables automated analysis routines that take information about the experiment type, hardware configuration, fluorophores, and data dimensions into account, so the initial results are obtained without user interaction. However, raw data is saved unchanged and can be re-analyzed with different parameter settings later.

smFRET for dynamic structural biology

Single molecule studies – and more specifically smFRET methodologies – have become a standard tool for studying dynamic structural changes in proteins and nucleic acids. These methods can reveal dynamic events on time scales covering several orders of magnitude from nanoseconds to several seconds. This allows, for example, the study of chain dynamics, binding, folding, allosteric signaling, oligomerization, and aggregation, as illustrated in Fig. 3. The results nicely complement structural data obtained using other methods such as electron microscopy or NMR, so they can now be entered into the archiving system for integrative structural models, PDB-Dev [3]. The power of these methodologies is highlighted by the study of Intrinsically Disordered Proteins whose biological relevance has been increasingly studied over recent years.

smFRET measurements can be performed with molecules freely moving in solution as well as with molecules immobilized on the coverslip surface. Luminosa offers a dedicated workflow for each modality.

The hardware is automatically configured correctly upon selection of the FRET pair in use, i.e., excitation wavelengths and power are set, pulsed interleaved excitation of both donor and acceptor is enabled, and the correct detectors and emission filters are chosen, as illustrated in Fig. 2. Further, the analysis channels are assigned based on the experimental context: donor emission after donor excitation, sensitized acceptor emission after donor excitation, and acceptor emission after direct acceptor excitation as control. Different stop conditions for the acquisition can be selected. For example, for molecules in solution, these are the number of bursts, total time, or reduction of burst rate. This promotes the collection of consistent data sets with adequate statistics.

Four live previews of the data are shown during acquisition: a histogram of FRET efficiency (E) vs. stoichiometry (S), a burst histogram, an intensity time trace and a TCSPC histogram with online fitting of the donor and acceptor lifetime decays. E and S are calculated online and displayed in an E/S histogram. The data is corrected with four factors, according to the standard procedure of the community as described in [4]. These factors are

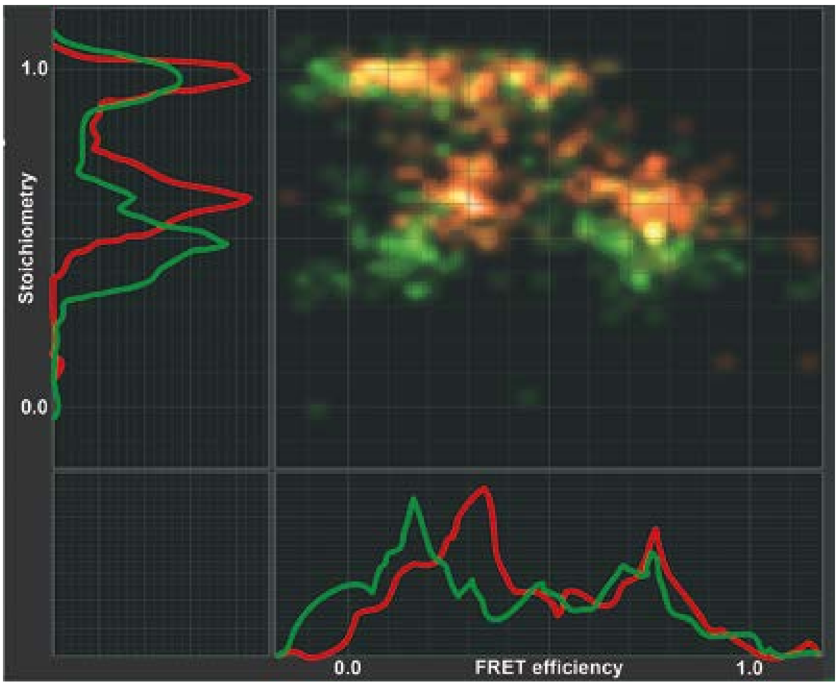

Fig. 4 E/S histogram displaying values of individual FRET bursts as single dots. Corrected values are shown in green and uncorrected values in red.

the spectral crosstalk α, the excitation flux β, the detection efficiency γ and the direct excitation δ. Both corrected and uncorrected data are shown as in Fig. 4, so that the influence of the correction procedure can be assessed. The factors can be manually changed later.

The fluorescence signal is collected while the molecules move through the stationary laser focus, which defines the observation volume together with the confocal pinhole size. The observation time window, i.e. the burst duration, is determined by the observation volume. Diffraction-limited observation volumes yield high photon count rates with short inter-photon times, which enables monitoring of fast molecular dynamics. Expanding the observation volume increases the burst duration, as shown in Fig. 5. This allows observation of slower molecular dynamics and measurement of slower diffusion properties of larger particles. In general, “larger confocal volumes, in combination with high irradiances, yield the highest number of photons per burst”, according to [5]. Luminosa offers the ability to increase the observation volume from three to six times larger than diffraction limited, depending on the excitation wavelength. A click of a button in the software decreases the excitation beam diameter, underfilling the objective lens, adjusts the optical path and the size of the confocal detection pinhole correspondingly, to increase the effective observation volume.

When studying molecules immobilized on a surface, one can first choose either the piezo scanner to gather more signal or the galvo scanner for a faster scan speed. The sample is automatically kept in focus, while tiling and stitching enables the imaging of a large area, as seen in Fig. 6.

After acquisition of an image tile, an algorithm automatically detects the positions of single molecules according to selectable criteria. Then the molecules are targeted one after the other and intensity time traces are recorded from each until the pre-defined stop criteria are met. Afterwards, the next image tile is scanned. In this way, datasets with adequate statistics can easily be obtained.

Discussion and outlook

Luminosa’s automated workflows increase the system’s ease of use and limit human error, thereby saving researchers’ time and materials. Importantly, the values of parameters set automatically can be saved as metadata whereas in manual systems one would have to note these by hand. Taken together, this improves accuracy, reproducibility, quality and precision compared to systems that are operated manually. However, it is still important to review configurations and setups such as dye database entries or thresholds that discard events to ensure that these fit to a new experiment.

A lot of expert knowledge went into defining the workflows and parameter settings so that this knowledge is not required by each user anymore. Even so, some knowledge is still necessary to prepare samples in a suitable way and to correctly interpret the results obtained.

PicoQuant continues to develop new fluorescence microscopy tools, such as spectrally resolved FLIM which combines lifetime and spectral information for truly parallel multi-target imaging, as detailed in [6] and [7]. PicoQuant also actively participates in research projects in collaboration with academia to explore new microscopy concepts and methods. For instance, the NG-FLIM project will realize a microscope system with very high spatial and temporal resolution, which allows membrane receptors in live cells and tissues to be observed faster, easier and more accurately than before. Different optical methods will

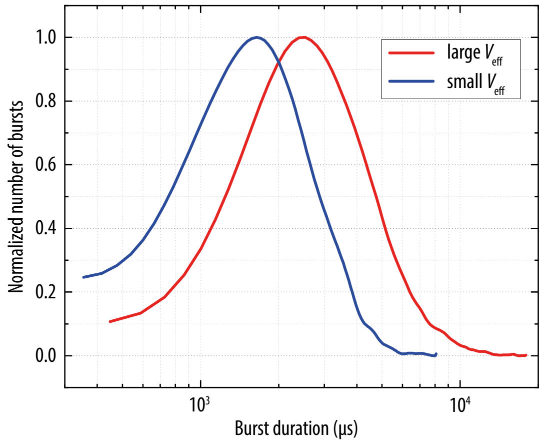

Fig. 5 Comparison of burst durations measured with a large (red) or small (blue) observation volume.

be combined to improve image contrast, and deep learning-based data analysis will be applied for automated data evaluation. This project is a collaboration between PicoQuant, Nanotag Biotechnologies, Arivis, the University of Göttingen and the University Medical Center Göttingen. It is funded by the Federal Ministry of Education and Research in Germany in the “Photonics Research in Germany” program (project 13N15324). As another example, entangled two-photon absorption could potentially be applied to chemically selective fluorescence microscopy. This concept is currently being investigated by PicoQuant in collaboration with the Fraunhofer Institute for Applied Optics and Precision Engineering, M Squared Lasers and the Friedrich Schiller University Jena,

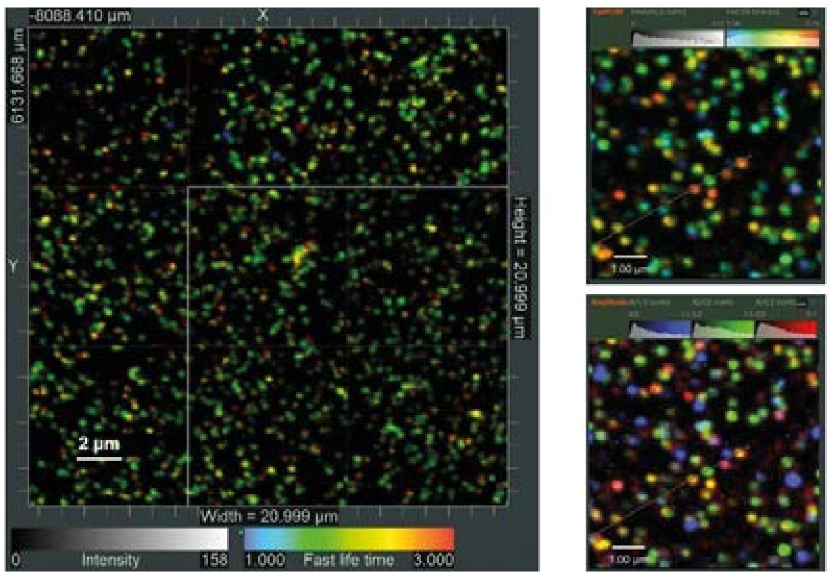

Fig. 6 Single DNA origamis labeled with Cy3B and Atto647N immobilized on a surface. An area of 21 × 21 µm was imaged with nine tiles stitched together. Right: FLIM analysis results of a single image tile. Top: average lifetime, bottom: multiexponential fitting overlay. Samples courtesy of Acuna group, Department of Physics, University of Fribourg.

within the LIVE2QMIC research project (13N15953) supported by the Federal Ministry of Education and Research of Germany

Conclusion

PicoQuant's new Luminosa confocal fluorescence microscope enables researchers to easily apply single molecule and time-resolved fluorescence microscopy methods in a wide range of life and materials science studies without requiring years of microscopy expertise. Thanks to many new software features in combination with state-of-the-art hardware, and in particular better integration of the hardware and software, the system quickly delivers high-quality data in a reproducible manner. This allows researchers to confidently adapt new methods such as smFRET to view their samples from a new angle.

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Author

Maria Loidolt-Krüger studied biophysics at the University of Kaiserslautern and did her diploma thesis and doctorate in the group of Prof Stefan Hell at the Max Planck Institute in Göttingen, focusing on STED microscopy development. Directly afterwards, she joined PicoQuant in 2018 as an application specialist for microscopy. In 2022, she became scientific content creator for PicoQuant. In parallel, she works as a part-time lecturer at the HTW Berlin, teaching about light microscopy.

Dr. Maria Loidolt-Krüger, PicoQuant GmbH, Rudower Chaussee 29, 12489 Berlin, Germany; phone: +49 30 1208820 629, e-mail: krueger@picoquant.com, Web: www.picoquant.com
dr-maria-loidolt-krüger-b3b50196 Maria39244565

A safe way to better vision

WaveLight relies on laser sources and laser beam analysis from MKS Instruments

Source all images: WaveLight

There are many challenges in the development and production of laser systems for medical applications – and the safety requirements are significant. It is no wonder that medical technology manufacturers choose their suppliers very carefully. WaveLight, a subsidiary of Alcon and a global player in refractive surgery, successfully uses products from MKS Instruments in the development, production and maintenance of its high-quality laser systems.

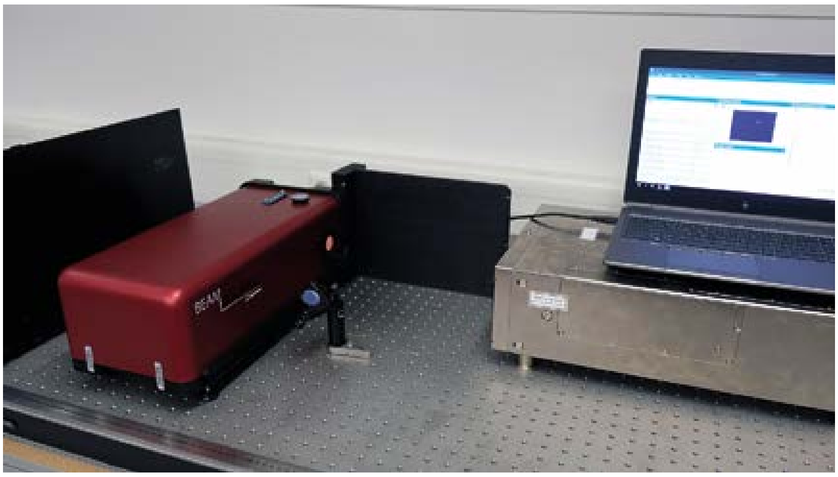
▲ Cornea cap cutting laser

Spectra-Physics laser sources have been integrated into WaveLight FS200 femtosecond laser systems for over ten years, and Ophir solutions for measuring laser power and energy as well as for laser beam analysis are employed throughout the process from development to maintenance. Millions of patients benefit from this collaboration.

Refractive surgery requires the very highest quality

The number of people with ametropia is on the rise, and many of them feel so restricted by it that they decide to have their vision corrected by laser treatment. Refractive surgery is thus becoming more and more important worldwide. One of the foremost companies in modern diagnostic and surgical technology for correcting refractive errors using eye lasers is WaveLight. A subsidiary of Alcon, itself among the top ophthalmology companies, WaveLight develops and produces high-quality laser and diagnostic systems at three locations in Germany. Several thousand of these systems have been put into operation worldwide since the launch of the WaveLight Refractive Suite, which consists of the FS200 femtosecond laser and the EX500 excimer laser, and millions of patients have been operated on with the Refractive Suite.

This resounding vote of confidence is no coincidence: WaveLight pays great attention to precision and quality in both development and production. Laser sources are tested and selected accordingly, so the requirements for the laser measurement technology are correspondingly high.



The beam profile of the femtosecond lasers is checked with the Ophir BeamSquared analysis system.

The long path from development to approval

An essential component of a laser system is the laser source itself. During the development of the WaveLight Refractive Suite, the development engineers first combed the market to see if suitable laser sources were available as standard. For the cutting of the flap, i.e. the incision in the cornea, WaveLight was looking for a laser source in the infrared spectrum with a power of one to two watts and a pulse width in the femtosecond range. The developers found what they were looking for at MKS, selecting a Spectra-Physics laser source. After careful testing, the team decided on the standard pulsed laser source which then had to be adapted to meet WaveLight's individual requirements. The dimensions of the laser, the integrated interfaces and the power supply were all optimized to meet its needs – which is a process that should not be underestimated! It takes a few months to go from the experimental setup in the laboratory to the prototype, and it usually takes one to two years just to get the first pre-series product ready for testing. After five years, the laser system had been approved for Europe, and after a further three years, it even had worldwide approvals. An advantage here is that the MKS production facility for Spectra-Physics lasers in Rankweil, Switzerland, is certified according to the EN ISO 9001 and EN ISO 13485 quality standards for the design and manufacture of medical devices.

Mario Klafke, head of R&D corneal refractive therapy at WaveLight said: "You have to remember, it is not enough just to have an excellent prototype. It is essential to successfully complete the full approval process and to ensure that the product's quality remains high when manufactured in series. But many processes can be greatly simplified if you have the right certifications. We worked very closely with the MKS developers while setting up the first Spectra-Physics laser sources and avoided quite a few pitfalls."

Metrological testing of the quality parameters

When it comes to assessing the quality of a laser source, the measurand generally used is the laser's ability to be focused, as described by the beam propagation ratio M^2. This is why there is an additional MKS product in use, not only for production and incoming goods inspection at Spectra-Physics but also to adjust the laser source at WaveLight: Ophir BeamSquared. In less than a minute, this fully automated, camera-based instrument reliably measures the beam profile of continuous-wave and, as in this case, pulsed lasers. With regard to the laser source for the femtosecond laser system, there is an obvious advantage in using the same system for testing on both the manufacturer's and the customer's sides, but Ophir products are also used to measure the excimer lasers used to ablate the inner corneal tissue. Mario Klafke explains: "Our number one priority is the quality of our laser systems. Ophir measurement technology is therefore in daily use at our company — each and every laser system is meticulously tested, first in the manufacturing process and again during commissioning and maintenance. To do this, our worldwide service team uses exactly the same products as our manufacturing team does, ensuring comparable results every time."

Companies

WaveLight

WaveLight is a subsidiary of Alcon, a global leader in eye care. WaveLight is a leader in the development and production of advanced diagnostic and surgical technology for the correction of refractive errors by using ophthalmic lasers. The product portfolio also includes an electronic guidance system to position intraocular lenses during cataract surgery and eye tracking systems for eye lasers. Around 280 specialists work continuously at the Erlangen, Pressath, and Teltow sites to ensure the company's success.

www.wavelight.de

MKS – Photonics Solutions Division

Spectra-Physics, Ophir and Newport are brands within the MKS Instruments Photonics Solutions Division. This division provides a full range of solutions including lasers for precision industrial and scientific research applications, laser and LED measurement, beam profiling, precision motion control, optical tables and vibration isolation systems, photonics instruments, temperature sensing, opto-mechanical components and optical elements. MKS Photonics Solutions enhance our customers' capabilities and productivity in the semiconductor, advanced electronics and specialty industrial markets.

www.mks.com

WaveLight attaches great importance to precision and reliability in the production of its laser systems in Pressath, Bavaria.

WaveLight uses Ophir 3A-FS thermal sensors and Ophir PE50U pyroelectric sensors to measure the laser power and laser energy respectively. The latter have a higher damage threshold due to a special coating. At the same time, as OEM sensors, they are specifically calibrated to the employed wavelength of 193 nm, further increasing their absolute measuring accuracy. WaveLight relies on these camera-based instruments with their large-format LT665 silicon cameras to complete the measurement of the laser system and determine the beam profile. Ophir's comprehensive software was one of the key factors for choosing its measurement technology, as Mario Klafke puts it: "The measurement accuracy was an important criterion for us, and various functions of the BeamGage software plus the direct interface to the PC also made our work easier."

Continuous quality assurance

The WaveLight Refractive Suite has now been on the market for more than ten years, and several million operations have been performed with these laser systems. Here, the fundamental requirement is outstanding quality. This is where the intense collaboration between the development teams from WaveLight and Spectra-Physics, along with the meticulous measurements of the laser systems taken with Ophir measuring devices, has really paid off. "We view the cooperation with MKS as very positive. Of course, when dealing with any supplier, challenges will arise from time to time – but here they have always been resolved constructively and with a focus on service. This is not only true for Europe; on-site service in other regions also works very well," explains Mario Klafke.

*

This case study was prepared in cooperation with WaveLight by Dagmar Ecker, MBE.

Technical Contacts:

WaveLight GmbH
Mario Klafke
Am Wolfsmantel 5
91058 Erlangen
Germany
phone: +49 9131 6186 0
e-mail: mario.klafke@alcon.com
Web: www.wavelight.de

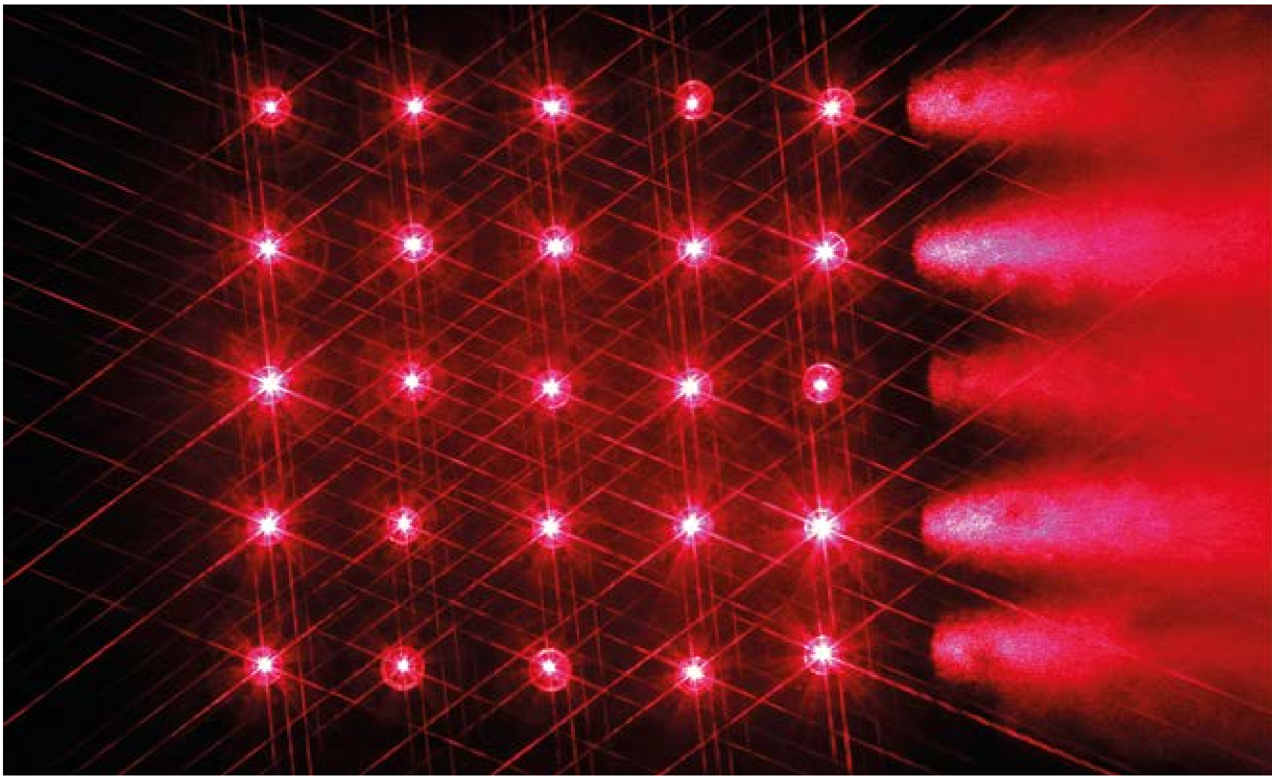
MKS Instruments – Spectra-Physics
Dr. Boris Ruffing
Guerickeweg 7
64291 Darmstadt
Germany
phone: +49 6151 708 239
e-mail: boris.ruffing@mksinst.com
Web: www.spectra-physics.com

MKS Instruments – Ophir
Roland Heinze
Guerickeweg 7
64291 Darmstadt
Germany
phone: +49 1511 4359279
e-mail: roland.heinze@mksinst.com
Web: www.mks.com/b/ophir

Programmable photonics for coherent transceivers

On-the-fly DSP functions in the optical domain

Ana González & Jim Theodoras



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The implementation of coherent systems in communications involves the post-processing of the optical transmitted signal after photodetection due to the need to mitigate transmission impairments. This processing is currently performed in the electrical domain using a digital signal processing device (DSP), which increases latency, and costs in the form of power consumption and additional equipment. The use of programmable photonics in coherent systems opens the door to correcting the main transmission impairments in real-time inside the photonic chip, allowing adaptive processing through time fluctuations.

▲ Abstract representation of a complex modulation format allowed by coherent transmission

As digital signal processing becomes an ever more important part of optical technologies, it is also becoming more burdensome. Each year, DSPs take a greater share of overall power consumption and cost. This had led to efforts to offload DSP functions through optical means, and wherever possible to totally avoid DSPs altogether. However, if a function is moved from a programmable DSP algorithm into the optical domain, it must retain its programmability. The photonic processor discussed here has the ability to implement a wide variety of DSP functions while retaining rapid re-programmability, to either complement or even totally displace DSPs in optical applications. In this article, we discuss what a photonic processor is, how it can be programmed to realize DSP functions, and give real-world examples of use cases.

Photonic processors

A field-programmable photonic gate array was described in [1] for use in optical communications. In this use case, a variety of common optical transceiver elements were placed around a central matrix of waveguide switches. These waveguide switches were treated as on/off elements with some inherent variable optical attenuator capabilities. A closer look at the switching elements reveals them to actually be Mach-Zehnder interferometers (MZI) with heaters on each leg. The ends of three sets of MZIs are connected as a 3-port node and arranged into hexagonal structures (see Fig. 1). These MZIs arranged in such a configuration are not just a simple switching matrix, but rather can be thought of as a powerful analog computing element or gate that can perform mathematical processing of an optical signal [2].

Discrete signal processing relies on the feeding forward and the feeding backward of multiple copies of a signal with various amplitudes, phases, and positions in time. The programmable hexagonal mesh of MZIs is a perfect match to emulate a wide variety of discrete signal processing architectures. For example, finite impulse response (FIR) filters can be formed by a cascade or lattice of MZIs. Infinite impulse response (IIR) filters can be realized by forming optical ring cavities out of the interconnected MZIs. Combining FIRs and IIRs in cascades, lattices, and transversal configurations with feedback and feed forward yields a powerful and programmable discrete signal processing engine in the optical domain.

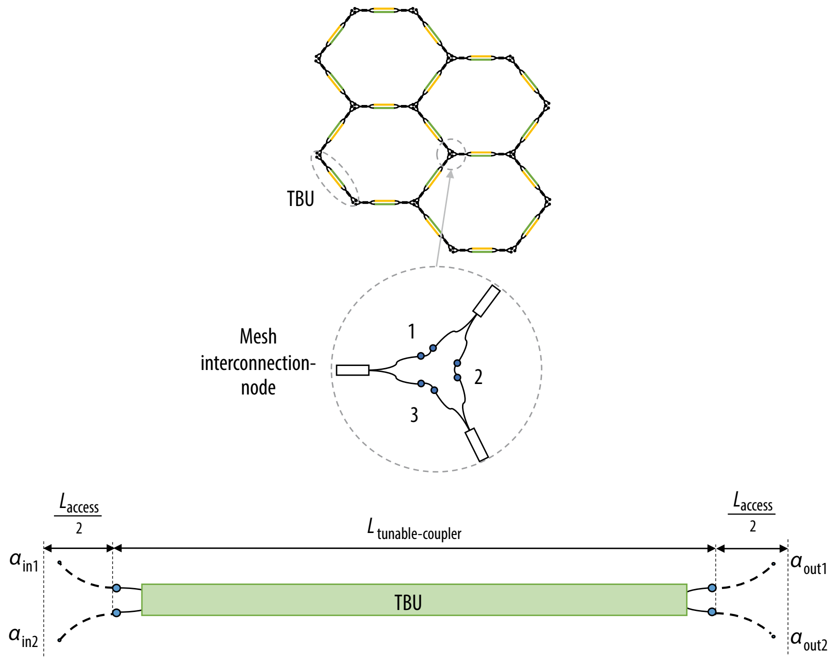

Fig. 1 Interconnection nodes in the mesh and representation of a tunable basic unit (TBU)

DSP functions that can be implemented

Tunable FIR filters can be emulated using programmable photonics by unbalanced Mach-Zehnder interferometers (UMZIs) and FIR transversal filters. UMZIs find multiple applications, including linear phase filters and group delay compensators.
Tunable IIR filters are ring cavities either 1-input/1-output implementing notch filters, or 2-input/2-output periodic filters implementing both IIR notch and FIR + IIR bandpass filters. Other complex filters such as CROWs and SCISSORs can be constituted by using IIR filters as building blocks. IIR filters can be employed for dispersion compensators and true time delay lines.
Multiple input/output linear transformations inside the hexagonal matrix involve mode transformations, which can be described in terms of multiple input/multiple output linear optics transformations given by an $N \times N$ unitary matrix. These include, among others, switching, broadcasting, mode combiners, MIMO channel equalizers and splitters.

DSP functions that cannot be implemented

What about DSP functions that cannot be implemented in the central switching matrix itself? Just as in the case of the programmable optical transceiver, various functional blocks can be arranged around the perimeter of the switch matrix. A signal can then be routed back and forth between functions implemented in the central matrix and those implemented outside of the matrix in the order that is needed by the intended mathematical function.

A good example of this would be optical delay lines (see Fig. 2). Rather than trying to implement a very long-time delay inside the matrix, the signal can be routed to the perimeter of the matrix where a long coil of waveguides is located and then back again.

Coherent implementation using DSPs

One of the earliest use cases – as well as currently the most successful – of DSPs being used as a game changer in optical communications is coherent transmission. Direct detection (DD) schemes only detect intensity modulations formats. Instead, in coherent systems, photodetectors produce a current pro-

Companies

iPRONICS

iPRONICS is developing the first general-purpose photonic processor that shares a common hardware platform based on photonic integrated circuits that is reconfigurable by software. This cost-effective solution enables the same hardware to be applied to limitless commercial applications with increasing needs in computational power, including 5G communication, data centers, artificial intelligence, autonomous driving, quantum computing, and Internet of Things.

https://ipronics.com

HGGenuine

The Top 10 optical transceiver manufacturer has shipped over eighty million transceivers in 2021. It is a subsidiary of HG Tech, a manufacturing conglomerate listed on the Shenzhen Stock Exchange with a market capitalization of nearly $ 3 B. HGGenuine is a pioneer in optoelectronic device development with advanced end-to-end production lines, and vertical integration capabilities from chip, device, transceiver to subsystems. It has opened a new $ 100 M datacom factory bringing manufacturing floorspace up to nearly 1 M square feet, and recently announced a large and rapidly-growing internal silicon photonics team.

https://en.genuine-opto.com

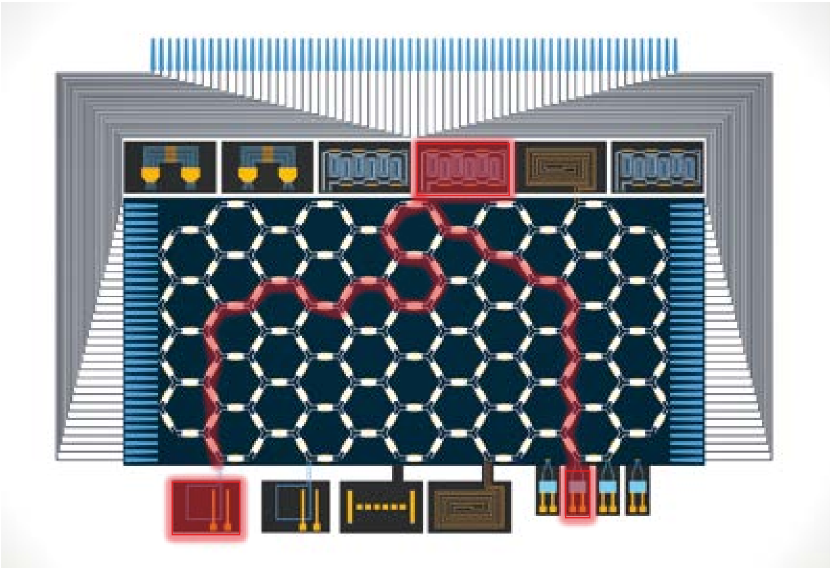

Fig. 2 Schematic representation of the programmable photonic device showing a more efficient delay line using a high-performance building block.

portional to the optical field, enabling the transmission of advanced modulation formats and the effective mitigation of transmission impairments with complex dynamics. However, the optical/electronical conversions needed to process the data through a DSP increase latency and limit capacity.

In coherent detection, the link signal and a local oscillator are combined prior to detection (see Fig. 3a) resulting in a beating electrical field. At the photodetector, the photocurrent is given by equation (1) in Fig. 3b containing a direct detection term and a beating term that is proportional to the optical field, making it possible to code information in amplitude, phase, and frequency.

Challenges to providing a cost-efficient coherent system for applications other than long-haul transmission come from the basic sources of degradation: a) relative intensity noise (RIN), b) phase noise and c) polarization mismatch. RIN limits the maximum power that the local oscillator can deliver. Common mode RIN can be overcome by using a balanced receiver, which increases the cost and complexity.

Fluctuations due to combined phase noises from the source and the local oscillator degrade the performance of both homodyne and heterodyne systems. Phase noise is corrected by the DSP in the detector, increasing latency and power consumption due to the O/E conversions and processing in the electrical domain. Another impairment is the fluctuations of the state of polarization of the signal over time that might cause complete signal fading – see $e_s \cdot e_{lo}$ in equation (1), Fig. 3. The current solution is to use a polarization diversity scheme at the receiver, i.e. to add a polarization beam splitter after the combiner and sending each mode to a different photodetector, incorporating an FIR filter again in the electrical domain, before re-combining and obtain the output current.

The first method of homodyne coherent RX uses an optical 90° hybrid, which is usually the reference for implementation in long-haul core networks with coherent detection. However, the imbalances in responsivities require these responsivities to be balanced after detection using the DSP. The main drawback for real deployment in access networks is the optical 90° hybrid, which is still a complex and expensive device.

Offloading DSPs by using optical processing

As highlighted in the previous section, expensive instrumentation is needed to overcome these transmission impairments, which prevents coherent systems from being applied for edge network applications such as access, IoT, and industrial scenarios. Using a programmable photonic device, it is possible to offload the DSP of some of the processes mentioned above, increasing

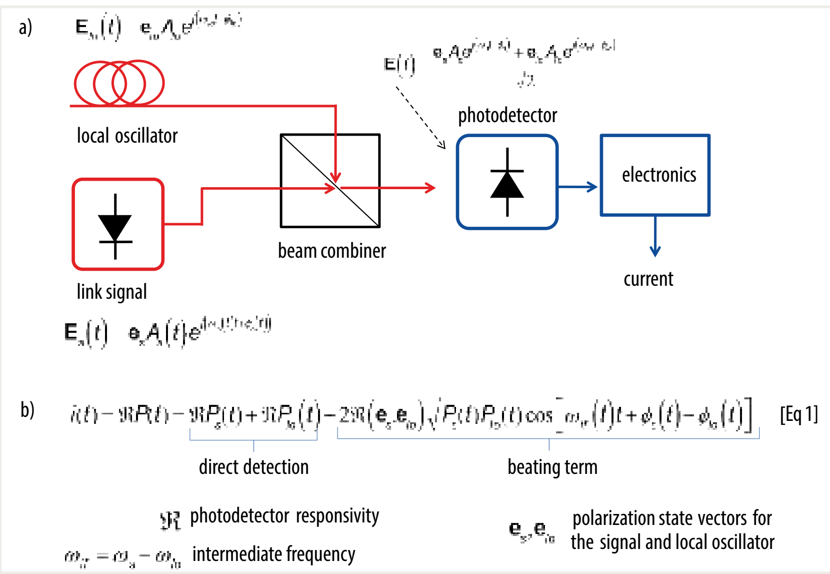

Fig. 3 (a) Coherent detection scheme where the electrical field of the local oscillator $E_{lo}(t)$ and the electrical field of the received signal $E_s(t)$ are combined, resulting in an electrical field $E(t)$ that is detected at the photodetector, and (b) photocurrent generated at the photodetector containing a direct detection term and a beating term.

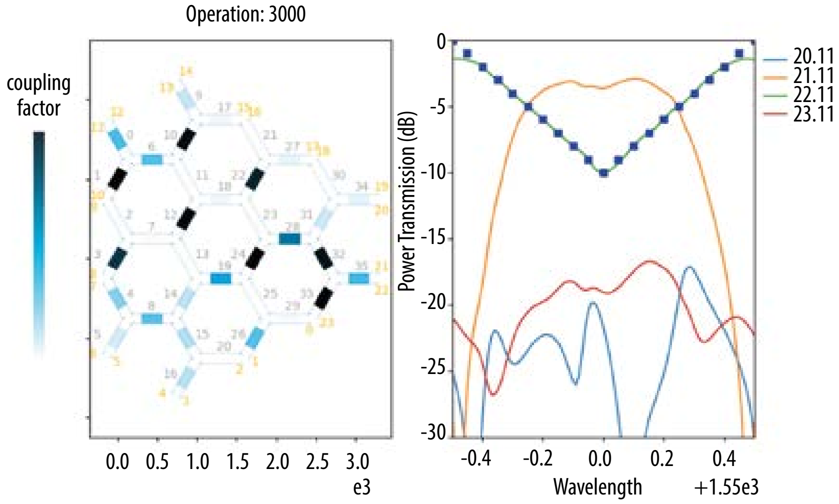

Fig. 4 Adaptative reconfigurable V-shape profile equalizer between 0 and -10 dB for 1 nm, centered at 1,550 nm, programed in a waveguide mesh arrangement.

efficiency by reducing power consumption and latency.

1. **Photonic processors can emulate a tunable 2 × 4 or 2 × 8 hybrid** with perfectly balanced power-splitting behavior, and emulate tunable power equalizers to match the requirements of balanced detection, reducing all the associated costs. It would allow the device to perform 90° hybrid operation with exactly balanced splitting by reconfiguration. In Fig. 4, we show the profiles of an automated adaptive reconfigurable equalizer that can be programed in a waveguide mesh arrangement when the selected optical channel travels through ports 11 (input) and 22 (output). Interested readers might check reference [3] for more details.
2. **Phase noise can be removed by emulating an FIR filter in the mesh.** This filter can be reconfigured over time to adapt to noise fluctuations of the source and the optical oscillator [4].
3. Components required to **compensate for the impairment in the fluctuations of the state of polarization of the signal over time** such as a polarization beam splitter can be added as a functional block surrounding the programmable mesh.

Powerful energy-efficient photonic processing

Before DSPs were fast enough for optical applications, discrete processing in the optical domain was used wherever possible. These early attempts at optical processing were often fixed waveguide solutions, requiring lengthy fabrication runs every time a parameter changed. DSPs offered a more flexible solution when they became available, but as their size grows so does the power they consume. The time of the photonic processor has arrived. By offloading the functions of the DSP that can be done in the optical domain, the DSP will only be given those tasks that cannot yet be performed by the photonic processor. Furthermore, the photonic processor is both programmable and reconfigurable on the fly. By marrying the capabilities of electronic DSPs with photonic processors, new potential will be unleashed.

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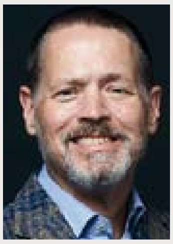
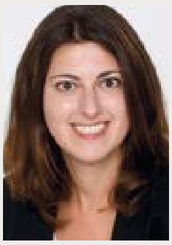


Jim Theodoras is currently VP of R&D at HG Genuine USA, where he oversees the design and manufacture of optical transceivers for data communication applications. He has over thirty years of industry experience in electronics and optics, spanning a wide range of diverse topics. Jim is a past president of the Ethernet Alliance and past optical liaison editor for the IEEE Communications Magazine, and is a frequent contributor to industry publications, standardization efforts, and MSAs.



Ana González is director of strategic partnerships at iPronics. Her role is to investigate new applications and identify potential partners for the commercialization of programmable photonic integrated circuits (PICs) including relationships with the supply chain and supporting customer operations. Ana was R&D manager at EPIC (the European Photonics Industry Consortium) and has a solid network within the PIC industry as well as significant experience interacting with new adopters of PIC technology.

Jim Theodoras, HG Genuine USA Co Ltd, 2025 Gateway Pl Ste 128, San Jose, CA 95110, USA; phone: +1 214 563 8744; e-mail: jimtheo2@genuine-opto.com, Web: https://en.genuine-opto.com ■ Dr Ana González, iPronics Programmable Photonics, S.L., Camino de Vera s/n. Edificio 9B, 46022 Valencia, Spain; e-mail: ana.gonzalez@ipronics.com, Web: https://ipronics.com, in GonzalezAnaBelen

X-ray emissions during laser machining of cylindrical micro-components

Innovative laser 'turning' operations for the manufacture of precision components

Roswitha Giedl-Wagner & Thomas Lang

Fig.1 Processing setup in GL.smart

Source all images: GFH

Ultrashort pulse lasers are the perfect tool for the micromachining of components for a wide range of applications. Even hard and brittle materials can be processed with high precision in state-of-the-art machines like the GL.smart from GFH. With pulse lengths in the pico and femtosecond range, an irradiation >10^{12} W/cm^2 is incident on the workpiece with the potential to generate ionizing radiation. This article deals with the x-ray emissions recorded during laser turning operations and the corresponding safety measures.

The advantages of laser micromachining with ultrashort pulse lasers are numerous. Since laser machines have been classified as "systems for the generation of ionizing radiation" according to the German Radiation Protection Act and for CE compliance, laser machine tool builders are well advised to evaluate the potential of x-ray generation during processing of materials in their systems. By doing so, they can adapt the layout of the machine enclosure and choose an appropriate material to fulfill not only laser safety requirements but also to shield the operator from the potential hazard of the ionizing radiation that may be emerging during machining and ensure that the dose rate at 100 mm distance from the touchable surface stays below 10 µSv/h in case the laser irradiation lies above 1×10^{13} W/cm^2 and 1 µSv/h for irradiation levels below that.

The customer, as the future operator of the machine, has the duty to notify the radiation protection authorities of the intended use of a laser machine four weeks ahead of the start of operation, if the possible irradiation exceeds 1×10^{13} W/cm^2. For this notification, a radiation protection officer with the necessary qualifications has to be appointed, and the machine's x-ray safety has to be confirmed by an independent expert

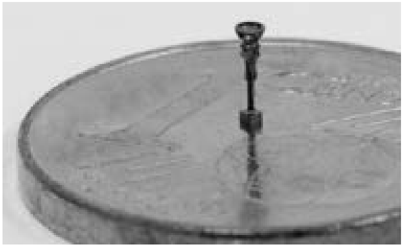


Fig. 2 Machined demonstrator

acceptable to the responsible authorities. Notification is not necessary if the laser irradiation is below this threshold, however it is still necessary to comply with a dose rate of below 1 µSv/h.

Many industrial ultrashort-pulse laser processes operate below the thresh-

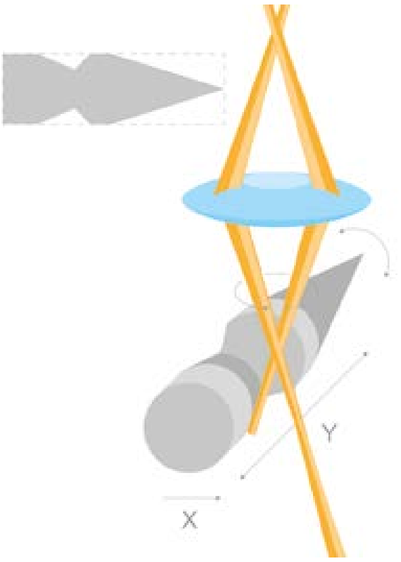


Fig. 3 Sketch of the process setup

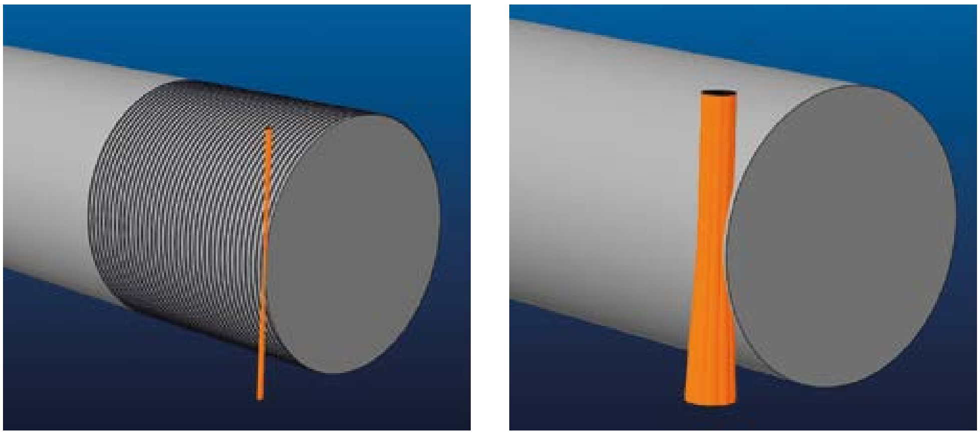


Fig. 4 Sketch of laser beam on metal rod; left: laser beam without rotation showing machined grooves; right: laser beam rotating at defined diameter

old for the generation of x-ray emissions. This varies for different materials and depends, among other things, on the laser wavelength [1]. Some processes such as laser drilling and cutting provide inherent shielding so that any emissions occurring are attenuated within the workpiece itself. It has to be noted also that the infeed is typically done with an energy ramp so that at the beginning of the process the threshold for the onset of x-ray emission might not be exceeded. Once the laser has removed the surface and reached a certain depth, not only the shielding starts but also the irradiation depends on the irradiated surface. As the angle of incidence is likely to differ from the starting condition of normal incidence, the irradiated area increases, thereby lowering the laser irradiation. In the case of laser turning, the workpiece only provides limited shielding and makes laser irradiation exceeding the threshold for the emergence of x-rays possible during process steps such as roughing operations for high volume material removal. Therefore, emissions occurring during laser machining of cylindrical workpieces have been investigated here.

Machining layout

The machine used for the study was the GL.smart. It was equipped with an ultrashort-pulse laser with a wavelength of 1.03 µm, a pulse duration of 1 ps, an average power of up to 64 W on the workpiece and a repetition rate of 200 kHz to 800 kHz. The laser power can be divided by a beam splitter to be guided to the two machining heads for parallel machining. A pulse energy of 80 µJ up to 180 µJ on the workpiece is focused down to 24 µm, resulting in an irradiation of 5.1×10^{13} W/cm^2 up to 1.1×10^{14} W/cm^2 at normal incidence. The machined specimen was clamped in a precision chuck in the spindle and was rotated at up to 3,000 rpm. Linear and axial feed-in was done with X and Y axes (see sketch in Fig. 3). With the opposed spindle on a swivel axis, the part may be handed over for cutting to length or further processing steps (see Fig. 1), like material removal in the cup as done for the defined demonstrator in Figs. 2 & 6.

The laser beam itself can be moved on a circular path with an in-situ adjustable diameter and angle controlled by the special GL.trepan optics. Fig. 4 illustrates the difference of a stationary beam tangentially machining the rod (left) and the rotating beam removing the material. An integrated galvo scanner can be used for layer-by-layer material removal. The demonstrator blank under study was a rod of 1.5 mm diameter made of heavy metal. Apart from laser turning operation, also drilling, cutting and ablation processes were used to realize the desired geometry.

DIS-1 dosimeters are used to monitor the dose rates close to the touchable surface. A so-called Lixmeter from the company CalvaSens, a Si-based sensor for x-ray emissions of the dose rate $\dot{H}'(0.07)$ with photon energies of 3 keV up to 50 keV with a measuring area of 1 cm^2, was placed at 110 mm distance from the laser-material interaction zone at an angle of ≥20° to record the ionizing radiation during machining. This short distance was due to the confined space in the machine used. The housing of the machine is made of steel exceeding 2 mm thickness. The viewing window is composed of a sandwich of an x-ray radiation protection glass and a laser safety window.

Recorded emission during demonstrator machining

The normalized dose rate $\dot{H}'(0.07)$ recorded at 110 mm distance during laser turning, cutting, drilling and ablation of the heavy metal rod is shown in Fig. 5. Starting off with the trimming of the rod to a defined length, a short but high peak appears. Such short peaks seem to happen with every infeed of the laser but do not last very long.

The following steps of contouring the outer geometry in a series of roughing operations lead to far lower dose rates. In these process steps, the beam is rotated

Company

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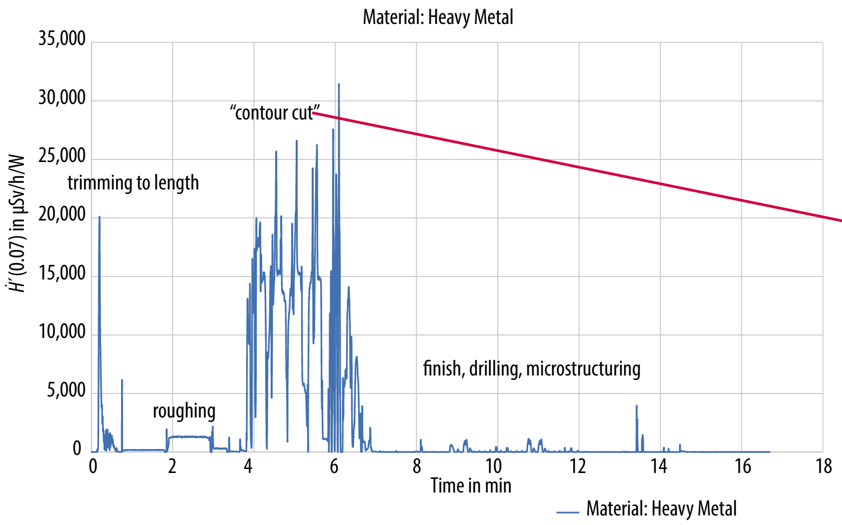

Fig. 5 Dose rate measured with Lix meter during machining of demonstrator normalized to the laser power

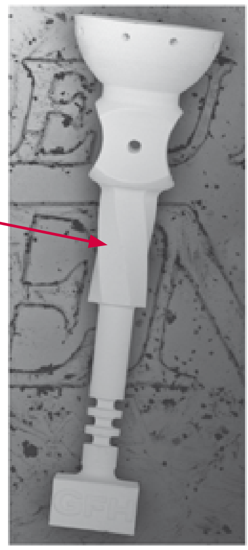

Fig. 6 Demonstrator

on a defined diameter, and it is to be noted that part of the material is likely to be removed in larger particles (i.e. 'bulk' material). The rotation speed of the work piece is adapted to the process step and volume to be removed. The laser turning with the laser infeed tangential to the work piece does allow a real roughing start with a low-quality surface to increase the material removal rate at the beginning. In the subsequent finishing steps, the surface may be dressed to the required quality up to a level close to polishing, as was published in [3].

The next and highest emission peaks may be attributed to the machining of the twisted cut faces. The rotation speed is reduced in this process step, and, in contrast to standard laser cutting, there is no cut kerf to provide intrinsic shielding as a complete material layer is cut off. The following finishing, drilling of the microholes and ablation steps delivered comparatively low dose rates, with occasional small peaks during infeed operations such as machining the grooves.

In almost all process steps, the laser 'tool' is tuned by the trepanning optics GL.trepan to adjust the tool diameter and use an inclination angle helping to create perpendicular shoulders. In a worst-case study in the same machine and setup to identify the process parameters for maximum x-ray emissions, machining of a heavy metal rotating rod with a rotating beam and a stationary beam (Fig. 4) was investigated. The x-ray emissions during turning with the stationary beam were actually slightly higher than using the rotating beam.

It also turned out that the process to generate high dose rates during laser turning may be compared to the planar ablation processes to some extent. The machined grooves in planar machining typically have an interline distance of approximately the spot diameter for maximized x-ray generation. It appears to be similar in laser turning. The feed forward is adapted to the rotation speed of the part so that the grooves on the cylinder were separated. Readings of the external DIS-1 dosimeter confirmed that no x-ray radiation levels were detected outside of the machine beyond what is expected for background radiation.

Comparison of laser turning with normal incidence machining of a cylinder

The laser irradiation incident on the workpiece defines how much ionizing radiation may be generated for the specific material, pulse length and wavelength, with the maximum achieved in the focal plane [1, 2]. During laser turning (or tangential machining as it has also been referred to), the conditions change during feed-in and with reduced diameter so that the real irradiation is typically lower compared to the theoretical maximum value in the focal plane for normal incidence. On the other hand, the changing angle of incidence may lead to an increase in laser absorption. With a beam rotating at a specified diameter, it is also likely that part of the laser pulse does not impact on the material and does not remove any material.

In order to investigate the different scenarios of normal incidence and tan-

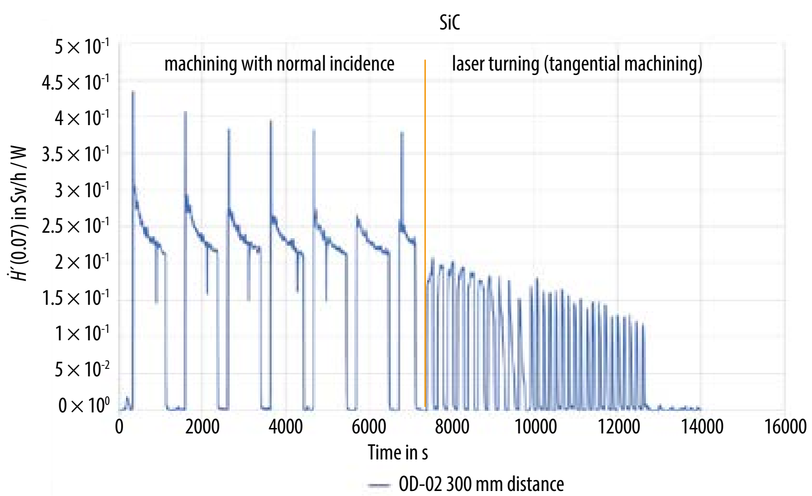

Fig. 7 Dose rate $H'(0.07)$ during machining of a SiC rod normalized at laser power

gential incidence machining, a silicon carbide rod was machined with a 70 W laser @ 1.03 µm with an irradiation (normal incidence) of 7.7 × 10^{13} W/cm^2. The rod was rotating while the laser was scanned along the rod in the first case with a normal incidence, and in the second case in a laser turning operation with tangential infeed. The normalized dose rate $\dot{H}'(0.07)$ was recorded with the OD-02 dosimeter at a distance of 450 mm. Using the quadratic relationship between the dose rate and the distance, the emissions were converted to a distance of 300 mm (see Fig. 7). The focal plane was adjusted to the reduced diameter during machining at normal incidence by using an optical measurement after a defined process step. This interrupted laser machining and subsequently x-ray emission, which is shown in the micrograph.

It can be seen that the level of x-rays generated is slightly higher during machining at normal incidence compared to the tangential machining, for which the true irradiation is below the value for normal incidence due to the larger irradiated surface. The difference may also be attributed to a lower material removal rate during tangential machining. There are a few more open questions as to what influence the different processing parameters and strategies have on the onset of x-ray emissions which will be addressed in further investigations. Comparing the results with the predictions of the model presented in [1] reveals that the emissions are still well within the expected dose rates. With further improvement of the model and experimental confirmation, it may become a valuable tool for the dimensioning of enclosures.

Summary

Laser machining of cylindrical micro components is becoming more interesting in a variety of industries. As with many other applications utilizing ultrashort pulse lasers, x-ray emissions may be generated during laser processing, which is also the case for laser turning. In this case, there are process regimes with noticeable ionizing radiation, but nevertheless, with an appropriate enclosure fully shielding the emissions such as in the GL.smart, the machine can be operated safely. Further investigations will be carried out to verify the findings, improve the understanding of the underlying mechanisms and keep ahead of the steadily increasing average power of the lasers.

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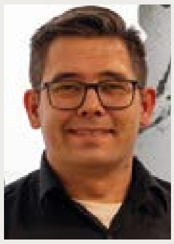
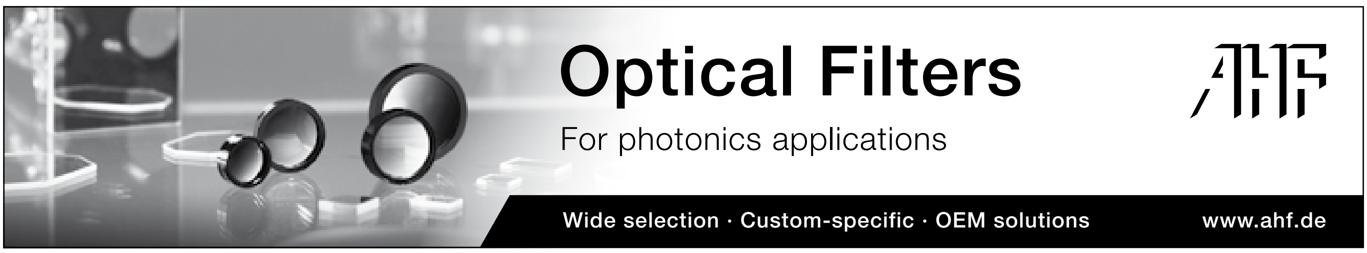
Authors

Roswitha Giedl-Wagner studied electrical engineering and obtained her PhD at the University of Hull in Great Britain, studying grating formation in fiber transmission systems and polymer films using excimer lasers. After two years at SEL Alcatel, she worked for Delphi Diesel Systems developing laser drilling for injection nozzles and joined the GFH team in 2005, staying in the field of laser micromachining. She is responsible for the publicly funded R&D projects at GFH and takes care of laser and radiation safety issues.



Thomas Lang studied mechanical engineering and mechatronics at the University of Applied Sciences in Deggendorf, Germany. For the first eight years of his career he designed and built mold tools and special purpose machines in the plastics industry at Jander, Kirchberg. After three further years at HB-Feinmechanik, Deggendorf, as a project manager in the field of chemical and food extrusion he returned to GFH in 2016 where he had started his engineering career with an internship in 2004. Since then, he has been developing laser processes with a focus on laser turning and clamping devices.

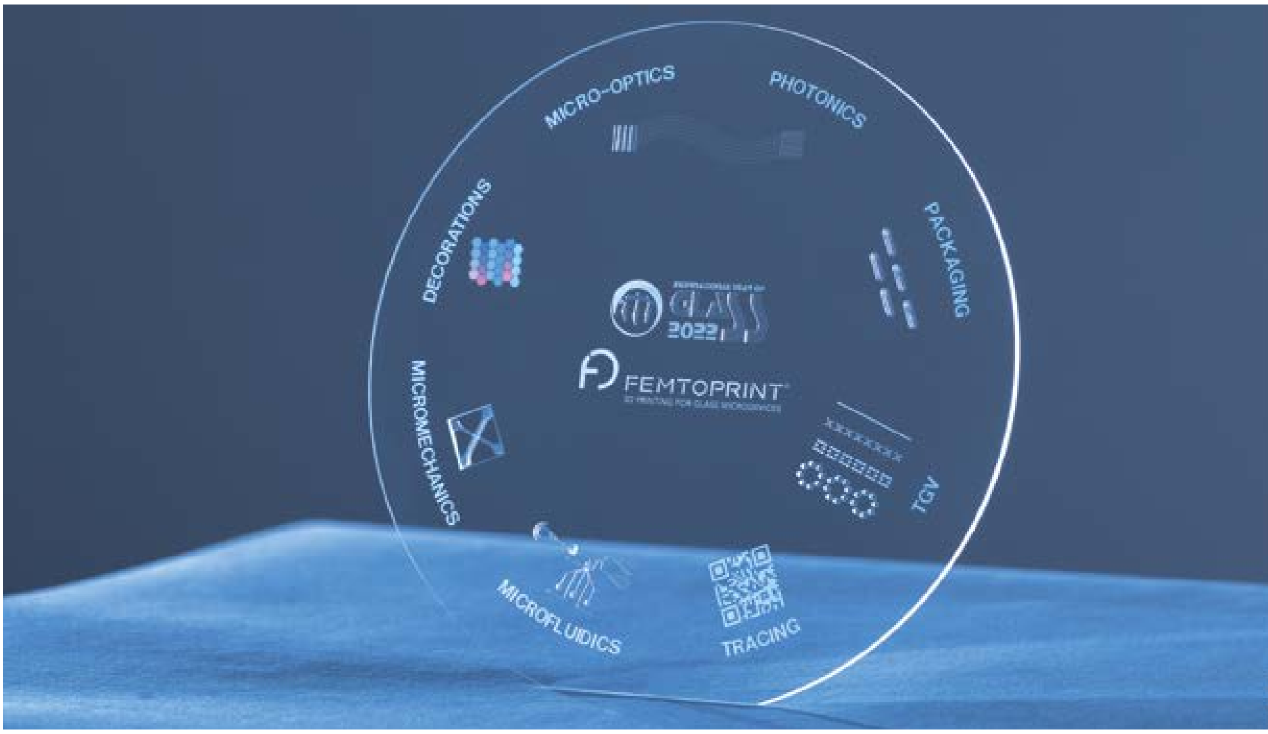
Prof. Dr. Roswitha Giedl-Wagner, GFH GmbH, Großwalding 5, 94469 Deggendorf, Germany; phone: +49 991 2909 2171, e-mail: roswitha.giedl-wagner@gfh-gmbh.de; Web: www.gfh-gmbh.de



Laser-based glass micromachining for integrated photonics

The new frontier for wafer-scale precision manufacturing

Rolando Ferrini



Source all images unless otherwise noted: Femtoprint

In the last ten years, laser-based glass micromachining has become a mature technology, which is now out of the R&D labs and is finally deployed in industry as a scalable micro-manufacturing process to produce innovative optics and photonics devices. Micro-optics, integrated photonics, optical communication, innovative displays, photonic and quantum computing are among the fields that are looking at this potentially ground-breaking technology for the precision manufacturing of disruptive miniaturized devices.

The current miniaturization of photonic systems requires access to advanced micro-fabrication technologies able both to guarantee high resolution and cost-effective industrialization while maintaining and possibly increasing the amount and quality of functionalities. On the one hand, our laser-based glass micromachining platform allows 3D freedom in design and fabrication, as well as the possibility of monolithically integrating several functionalities within a single photonic system and thereby avoiding complex assembly steps, while allowing for a high level of complexity. On the other hand, it enables access to fast prototyping and pilot production while guaranteeing the ability to up-scale to volume production.

The current megatrends in integrated photonics push for the miniaturization of the pixel dimensions at the chip level as well as the use of single mode fibers for transmission. This imposes more and more stringent requirements on both precision and tolerances for fiber-to-chip alignment in order to comply with the performance standards set for the final products (e.g. for losses). In addition, monolithic integration and scalability are going to create a major impact in product development and

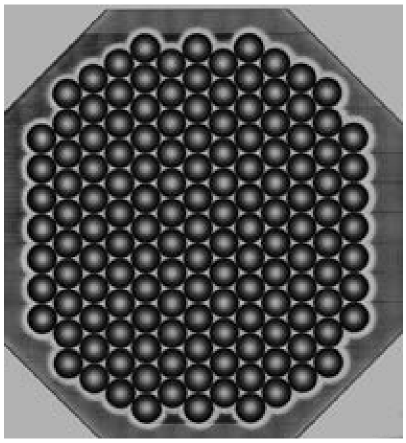


Fig. 1 Detail of a fully processed micro-lens array.

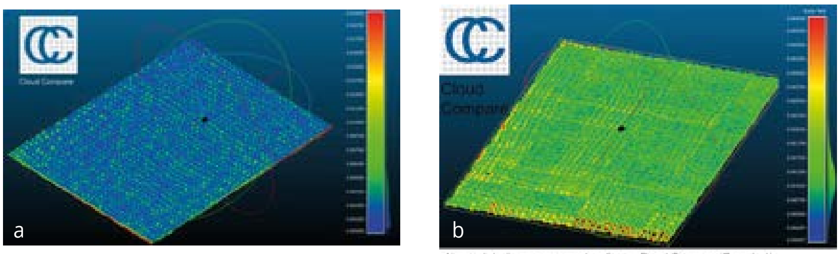


Fig. 2 Surface deviation from nominal geometry (a) before and (b) after surface treatment (Source: CSEM, www.csem.ch)

manufacturing. Combining several components in a single photonic system is of paramount importance to minimize its footprint, improve the overall performance and reduce the cost per function.

The following three classes of building blocks are usually combined for both fiber-to-chip and chip-to-chip connectivity: free-form micro-optical components up to miniaturized optical systems, high precision fiber alignment elements (V-grooves, ferrules, 2D hole arrays), and waveguides or photonic wire connections for signal routing.

Free-form micro-optical components up to miniaturized optical systems

The fabrication of free-form micro-optical components faces important technological challenges that usually grow in the absence of symmetries, when the dimensions drop below the millimeter range and/or when the devices are arranged into densely packed arrays. While in the nanometer range there are few effective options, microdevices, i.e. devices with typical dimensions from a few microns to a few millimeters, still pose significant technological issues. In this context, laser-based glass micromachining is a fully 3D innovative manufacturing technique that has proven to be successful in the fabrication of arrays of free-form microlenses, with good performance both in shape accuracy and surface quality. This approach can produce 3D surfaces with just a few microns or less deviation from the nominal shape and also a surface quality with roughness in the nanometer range. As an example, we present fabricated, fused silica, spherical microlens arrays and a free-form microdiffuser as well as a miniaturized optical system.

Our manufacturing technique belongs to the so-called selective laser-induced methods that rely on a combination of ultrafast laser micromachining and chemical material processing. Typically in a first step, the desired 3D shape is patterned within the glass substrate by a focused ultrafast laser that sweeps a tightly-focused beam which locally modifies the material structure. The maskless method enables the generation of 3D shapes without the restrictions that are usually encountered, for example when using lithography. The exposure to femtosecond laser pulses triggers a nonlinear absorption process that causes a glass densification within the laser voxel. The voxel is the volume at the vicinity of the focusing point where the optical power density has reached a certain value, thus allowing the nonlinear densification effect. The shape accuracy that can be achieved during this first writing step is defined by the dimensions of the laser voxel combined with its movement precision, which are in the range of a few microns and submicron, respectively. The laser-induced material modification triggers a very large etching selectivity, which is exploited during the subsequent wet etching step when all the excess material is removed and the device is released from the bulk of the glass substrate [1, 2]. The combination of the laser writing and the etching step in relation to the overall dimensions will eventually define the minimum feature size and the shape accuracy of the resulting microdevice, which are typically of the order of a few microns or below. However, a surface quality with micron-scale inhomogeneities may still not be suitable for many applications, particularly in optics and photonics. Additional surface processing is therefore used to reduce the surface roughness to the nanometer range. Note that besides micro and miniaturized optical elements, the same manufacturing technique also enables the integration of micromechanical and microfluidic components that may all be monolithically combined and integrated into the final system [3]. This is particularly appealing when complex and precise assembly may become a major concern.

Fig. 1 shows an array of about a hundred spherical microlenses arranged in a closely-packed hexagonal pattern manufactured on a fused silica substrate. The lenses with a diameter of 500 µm and a radius of curvature (RoC) of 650 µm presented a sagitta (SAG) of 50 µm. The array was characterized via white-light interferometry by measuring a few lenses placed close to the center and to the top, bottom, left, and right portion of the array. The average RoC was measured to be in the order of 625 ± 5 µm, while the SAG matched the nominal value within ±1.5 µm. The average surface roughness (S_a) was measured to be smaller than 5 nm.

Fig. 2 shows an optical diffuser based on an array of free-form microlenses: the 2.5 mm × 2.5 mm element consists of free-form microlenses of various diameters ranging between 50 and 70 µm and variable SAGs up to 70 µm. The surface profile of the entire array was measured with a laser confocal scanning microscope and the deviation of the real device from the nominal shape was calculated

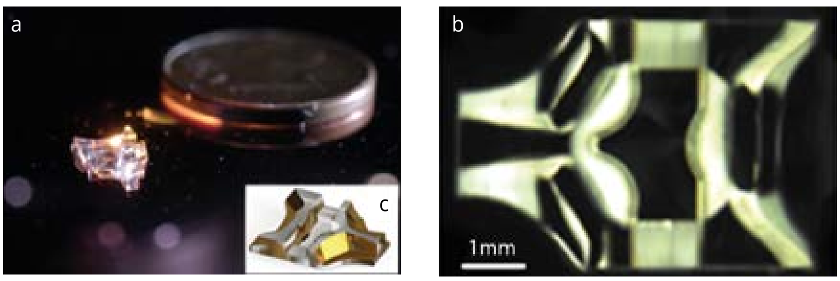


Fig. 3 (a), (b) Pictures and (c) sketch of the miniaturized glass photonic system

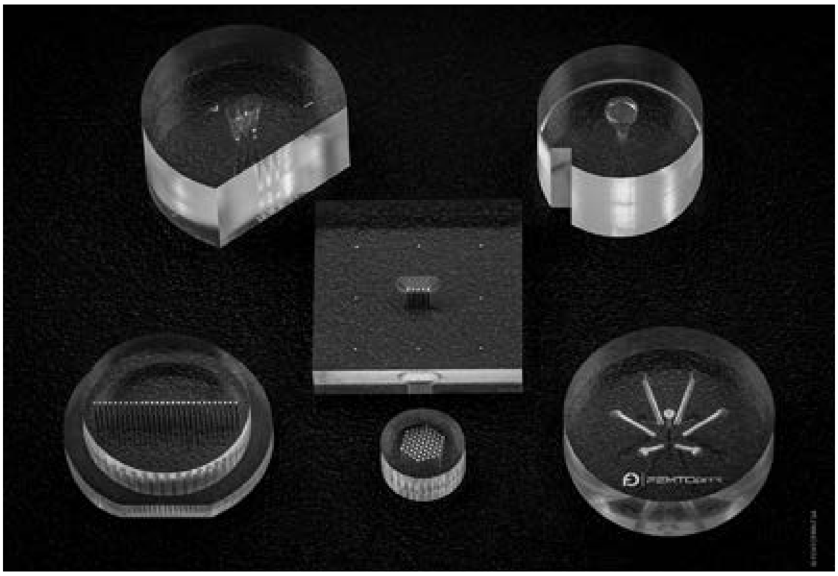


Fig. 4 Ferrules and 2D fiber hole arrays micromachined in glass with the Femtoprint laser-based technology.

using the Cloud-Compare software package. The average deviation before the final surface processing is 0.08 µm with a standard deviation σ = 1.27 µm. These values increase after the surface treatment and grow to 0.15 µm and 1.71 µm, respectively. While in this case the surface treatment induces a deviation from the nominal shape, S_a drops drastically from approximately 250 nm to 20 nm or less.

The examples above clearly show that, on the one hand, our manufacturing technology is already well suited to the wafer-scale fabrication of (free-form) micro-optical components. On the other hand, it can also be effectively applied to produce high-quality glass masters to be used in high-volume imprint manufacturing in plastics, such as replica, casting, and injection molding. Moreover, 3D laser-based micromachining can be successfully extended to the fabrication of miniaturized optical systems in the few millimeters range, where standard macro and microfabrication processes usually have limitations.

Fig. 3 shows a miniaturized photonic system combining refractive and reflective optical elements that was developed and built to be integrated into a hybrid fluidic-optronic CMOS retina chip to improve its sensitivity in the optical detection of particle matter in air through the measurement of light scattering upon laser irradiation [4]. The optical system consists of front spherical elements, internal free-form reflectors, and flat back diopters. These components are combined into a compact, monolithic element that must provide both optical performance and stable mutual alignment. The monolithic optical device has a small footprint, and the surfaces of all optical elements must have optical-grade quality. In particular, the miniaturized system includes out-of-plane microlenses, which are challenging to produce using standard microfabrication methods. Also, free-form mirrors would require diamond turning, for example, which is a very slow and expensive technique. Using our laser-based micromachining technology combined with surface treatment, it was possible to fabricate the optical component with surfaces characterized by $S_a \approx 5 - 15$ nm, providing minimal surface scattering.

High-precision fiber alignment elements

In datacom and telecom applications, if 1D V-grooves yield a mature solution for fiber-to-chip connectivity, there is a clear trend to move towards 2D fiber arrays, which allow the integration of many more channels per surface unit, thereby increasing the level of miniaturization, improving the transmission speed, and reducing the overall energy consumption [5]. The fabrication of high precision ferrules for 2D fiber arrays still faces important technological challenges due to the lack of fabrication processes that can effectively handle dimensions in the range from a few microns to a few millimeters with resolution and accuracy below 1 µm. The challenge is even more important when the substrate material must be very few millimeters thick since conventional microfabrication processes are typically not adequate. Laser-based micromachining applied to glass has the potential to provide a disruptive solution building on the unique physical-chemical material properties for the targeted applications. First of all, glass is very stable in time and has a low coefficient of thermal expansion, making it an ideal candidate when thermal effects must be avoided. Secondly, glass is also used to produce optical fibers, thus ensuring a perfect material match.

High-precision ferrules (Fig. 4) can be fabricated in glass using our micromanufacturing technology. Machined surfaces show a typical average roughness (R_a) in the order of 100 nm, well below what can be achieved by standard fabrication methods like ablation or milling. In particular, 2D fiber hole arrays were fabricated through 4.7 mm thick silica substrates with a pitch of 1 mm in X and Y. Along Z, each hole presents a sequence of three cylinders (cf. Fig. 5) with increasing diameters designed to host an optical fiber. The smallest section is the most critical: being the guiding section of the bare fiber, it determines the functionality of the entire assembly. The other sections are intended to improve the robustness of the assembly by hosting the coating and the jacket as well as to avoid direct exposure of the bare fiber to the surrounding environment. For this reason, they do not require a very high resolution. Finally, the transitions between the different sections are made conical both to ease fiber

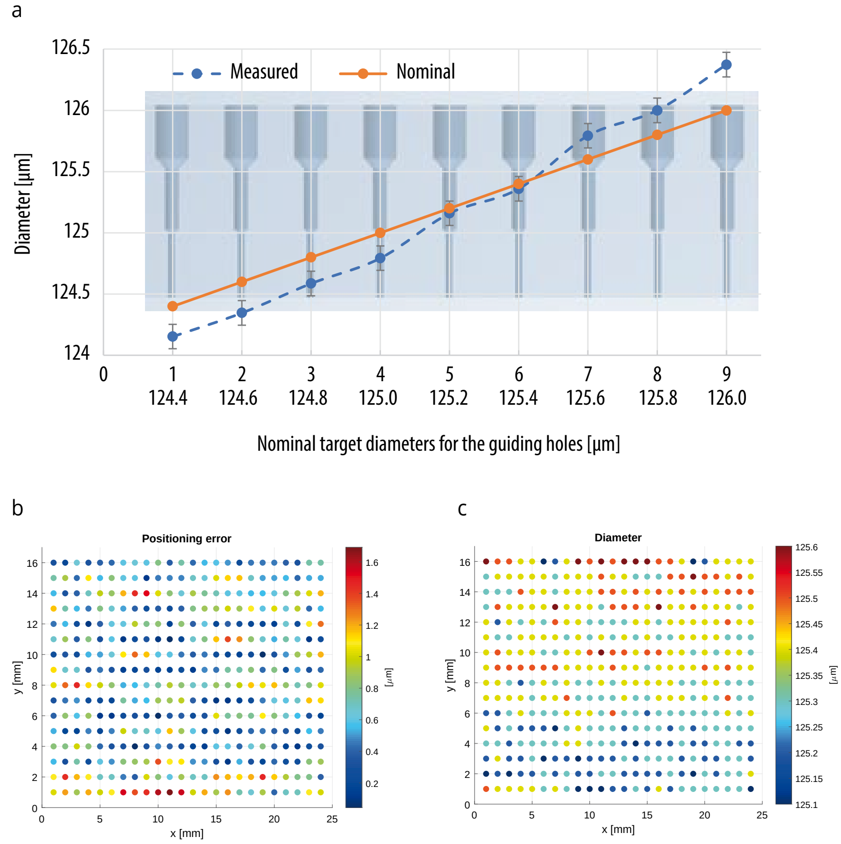


Fig. 5 (a) 2D fiber hole array with varying hole diameters. 2D arrays with (b) 11 × 16 and (c) 24 × 16 identical holes with a nominal diameter equal to 125.5 µm.

insertion and to avoid any mechanical damage during the assembly process. Three different sets of 2D arrays were fabricated.

Fig. 5a shows an array with nominal hole diameters for the guiding section ranging from 124.4 µm to 126.0 µm with a step of 0.2 µm. Each hole was repeated three times. These arrays were built and tested to assess shape accuracy after laser machining. The diameters were measured mechanically with ±0.1 µm resolution. On the Y axis of the graph, we report the measured diameter for each hole. The trend highlighted by the blue line confirms that shape accuracy <0.5 µm is achieved.

Fig. 5b presents a larger array of 11 × 16 identical holes with a nominal diameter of 125.5 µm. The array was designed to study the repeatability of the process with a larger number of holes. The graph shows the variation of the diameter measured with the same mechanical method described above. The mean value matches the nominal dimensions well with a maximum spread below ±0.4 µm. The same experiment was repeated three times and the results were confirmed. The measured diameters were all in the range of 125.5 ± 0.5 µm with a standard deviation <0.2 µm.

Fig. 5c refers to an even larger array of 24 × 16 identical holes intended to assess the position accuracy with respect to fiducials. An optical measurement method was used to detect the perimeter of each hole and then measure the relative distance with precision <2 µm. The graph shows the deviation of the actual hole position with respect to the nominal position, in X and Y. The maximum deviation observed is 1.6 µm, which is within the resolution of the instrument, confirming the accuracy of positioning. The same experiment was repeated five times with an average hole positioning error of ±0.7 µm and standard deviation <0.4 µm.

In conclusion, our laser-based micromachining technology was used to fabricate high-precision fiber alignment elements with the ability to control the diameter of each hole and its position accuracy with a precision <1 µm and <2 µm, respectively. With the latter precision in shape accuracy and positioning, the 2D fiber hole arrays produced can be qualified as a 'grade B' product, guaranteeing an average attenuation level <0.12 dB for telecom applications according to the IEC international standard.

Waveguides and photonic wire connections

As illustrated above, our technology is based on glass modifications induced by non-linear absorption processes within the laser voxel. These localized modifications may have multiple consequences depending on the laser parameters used. In particular, the refractive index of the material can be locally increased by a factor of 10^{-2} to 10^{-3}, thus inducing the creation of 3D waveguides (Fig. 6) within the bulk of the glass [6]. These can be used as photonic wire connections within photonic integrated circuits or their package and assembly components to guarantee effective fiber-chip or chip-to-chip connectivity. With respect to other fabrication technologies, our approach makes photonic wire connections possible that are fabricated with a high-precision, one-step writing process and directly embedded in the glass. In addition, the material properties of glass naturally guarantee thermal stability with respect to heat dissipation in optoelectronic systems.

Our technology enables the fabrication of both single and multi-mode waveguides (specifically at telecom wavelengths) with the possibility of

- fully free-form bending in 3D
- tapering for adiabatic mode conversion and efficient fiber-to-waveguide coupling,
- combining with both ferrules and V-grooves for precise micromechanical fiber alignment,
- monolithically integrating with micro-optical elements for optimized fiber coupling,
- adding alignment markers for easy assembly and packaging.

In particular, it is possible to fabricate single-mode waveguides at telecom wavelengths (1,310 and 1,550 nm) with mode field diameters ranging from 3 to 12 µm and propagation losses which can be as low as <0.7 dB/cm. To keep losses at bends in the order of 1 dB or less, the radius of curvature is currently limited to 20 – 30 mm. However, the ability to shape the waveguides in 3D in the glass volume is a unique property for the design of optical circuits when compared to other technologies. The material choice also adds another important degree of freedom. If our laser-written waveguides are routinely fabricated in fused silica, other glass families such as borosilicates offer optimized thermal properties for silicon

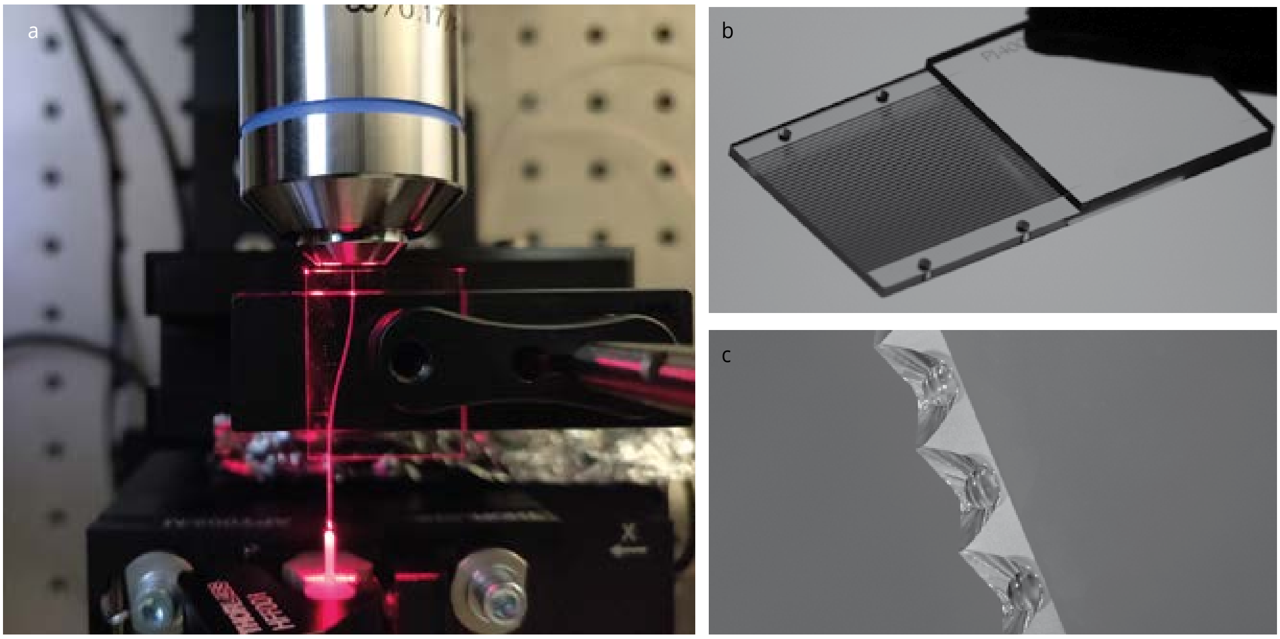


Fig. 6 (a) Free-form 3D waveguide laser-written within the bulk of the glass. High-precision monolithic integration of (b) V-grooves and (c) edge microlenses with laser-written waveguides (continuing on the right side of the glass slabs: not visible in the picture due to the low contrast), aligned with micrometer precision to the micromechanical and micro-optical elements.

photonics applications and better performance in terms of refractive index contrast and losses.

Finally, the ability to combine waveguides and photonic wire connections with high-precision micromechanical alignment elements such as V-grooves and ferrules (Fig. 6b), as well as with microlenses (Fig. 6c) or microlens arrays paves the way to the fabrication of fully integrated photonic systems in glass. In this respect, the added value of our technology resides in the monolithic combination of all these elements with micrometer precision, thus not suffering from the assembly errors that are a common issue in multistep, multimachine processes with registration limitations. The micrometer resolution of our technology enables self-alignment of all the elements of a glass photonic circuit within ±1 µm, which opens up a wealth of design options for the development of glass optical components and photonic systems in integrated photonics.

Conclusions

In conclusion, our laser-based micromanufacturing technology offers a fully industrialized platform for the fabrication of free-form micro-optical components, miniaturized optical systems, high-precision micromechanical fiber alignment elements, and photonic waveguide connections in glass. Moreover, it can be further exploited to monolithically integrate not only optics and photonics microelements but also fluidic and mechanical microcomponents, which may have interesting implications when precise alignment or co-packaging becomes critical.

*

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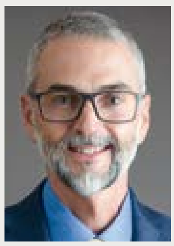

Rolando Ferrini is the head of the Femtoprint subsidiary located in Neuchâtel, Switzerland, and devoted to optics and photonics microdevices. He obtained his PhD degree in physics at the Università degli Studi di Pavia, Italy. He then worked for more than a decade as a research associate at EPFL in Lausanne before joining CSEM as group leader MicroNano Optics in Basel. In 2020, he founded the European Phabulouμs pilot line for the manufacturing of free-form micro-optical components.

Dr. Rolando Ferrini, FEMTOprint SA, Via Industria 3, 6933 Muzzano, Switzerland; e-mail: rolando.ferrini@femtoprint.ch, Web: www.femtoprint.ch rolando-ferrini, femtoprint-sa

Thin films polarize

TFPs with special functions open up a number of new applications

René Sattler

Source all images: Laser Components

Exceptional applications require exceptional solutions. With today's expertise and technical possibilities, complex layer designs can be built on thin-film polarizers to provide functions and applications that were previously not considered for these optics – for example as 'luminosity boosters' in projectors or as 'efficiency boosters' when generating frequency-doubled laser beams.

Linear polarization is used in laser technology for numerous different applications. The most well-known example is certainly thin film polarizers (TFPs), which are used together with half-wave plates to variably attenuate linearly polarized high-power lasers. However, with the rapid pace at which laser technology is advancing, new requirements are constantly emerging and with them new ideas on how to benefit from polarizers in previously unconventional ways. Racking their brains during development and using high-tech measurement systems in manufacturing technology, suppliers can discover new worlds of products and innovative fields of application.

Here are some examples of novel applications developed at Laser Components in close cooperation with customers.

Trichroic TFPs for RGB projectors

RGB projectors are primarily known for their use in the entertainment industry. However, they are also used in other industries, in the positioning of components for example. In positioning applications, the contrast of the projection is crucial so that the position marks can be easily recognized, even in daylight. A higher contrast can be achieved via a classic TFP by combining two linearly polarized lasers of the same wavelength. The ability to mix any of these three colors – red (640 nm), green (520 nm), and blue (450 nm) – at the same time is trickier. This can also be achieved with TFPs, but only if they work to the same extent for all three wavelengths rather than the usual single one. This requires complex coating designs in which the layer thicknesses must be precisely controlled. With such a trichroic polarizer, two linear polarized beams with either different wavelengths (RGB) or the same wavelengths can be combined at will. If the same wavelengths meet, the resulting common beam then has both polarizations again but twice the intensity. With different colors, the desired RGB mixing effect is also achieved (Fig. 1).

Multiple TFPs for excitation lasers

Lasers are often used to excite certain materials, i.e. to make them fluoresce. Very clearly defined wavelengths are

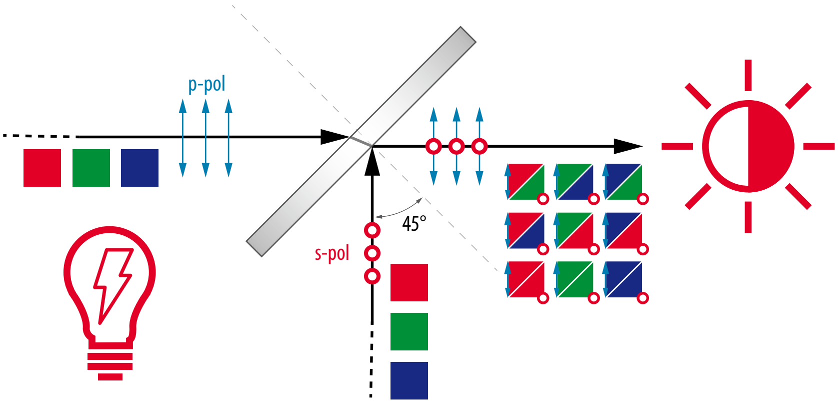

Fig. 1 A TFP is used to increase contrast and mix colors in an RGB projector.

used, depending on the application. The same rule applies here, too: the higher the energy, the greater the effect. In this respect, the solution for this application is similar to that of the first example. The difference here is that the fluoresced light must be captured and further processed and the losses of the fluoresced light must be low to ensure accurate measurements. In addition, all – or as many as possible – wavelengths of the fluoresced spectrum should be captured. The optics must therefore ensure that the polarization effect only occurs at the specified wavelengths while the reflectivity for the fluorescence wavelengths should be as high as possible (Fig. 2).

TFPs in the resonator

Frequency doublers are often used to generate laser beams with shorter wavelengths, so-called harmonics. The resonator for beam generation then contains not only the active medium but also a crystal that halves the original wavelength. For a 1,064 nm wavelength, for example, the active medium would be an Nd:YAG crystal and the wavelength would be reduced to 532 nm. The whole frequency doubling process is very energy consuming. Classically speaking, only a few percent of the laser power circulating in the resonator ends up being used as a laser beam. Even less power is usable from the frequency-doubled laser (half the wavelength). TFPs with additional transmission can reduce these losses. In contrast to the previous examples, the aim here is to allow a certain wavelength (1,064 nm) to 'pass through' as completely as possible while coupling out the s-pol of another wavelength (532 nm; Fig. 3). The advantage of this is that considerably more energy of the target wavelength can be used, while the energy of the original wavelength remains almost completely in the resonator and is available for the generation of the harmonics.

Large broadband TFPs for petawatt lasers with extremely short pulses

The foundations for tomorrow's technology are being laid in today's giant petawatt facilities. The laser pulses in the femtosecond range (10^{-15} s) with which these plants operate place their own unique demands on the polarizers. With such extremely short time periods and the huge amounts of energy involved, Heisenberg's energy-time uncertainty relation must be considered. The pulses therefore always have a very broad spectrum which should also be covered by the polarizer. The efficiency of these broadband TFPs does not compare to that of the previous applications. It is especially important to maintain the pulse length of a few femtoseconds, which means that the TFP must cover the whole spectrum of the pulse. A higher extinction rate is then achieved by using multiple components.

There are also the challenges that apply to almost all optics in these systems. In addition to a high damage threshold, the coating must have a high degree of homogeneity across the entire surface (e.g. 300 × 200 mm) to guarantee the same optical properties throughout. Defects are not tolerated.

How do TFPs work?

Every electromagnetic wave can be decomposed into two linearly independent polarizations. If the wave is then reflected on a mirror or TFP, the polarization part – the electric field of which is perpendicular to the reflection plane – is called the s-pol and its counterpart the p-pol. Thin-film polarizers are often used in photonics to split light into these polarizations or to combine two polarized light beams. In these optics, one polarization is almost completely transmitted, while a large part of the other is reflected. This effect is achieved by the coating of the optics, which alternates between high and low refractive index materials and creates interference that causes certain wavelengths to be transmitted or reflected, which is the basic principle of all dielec-

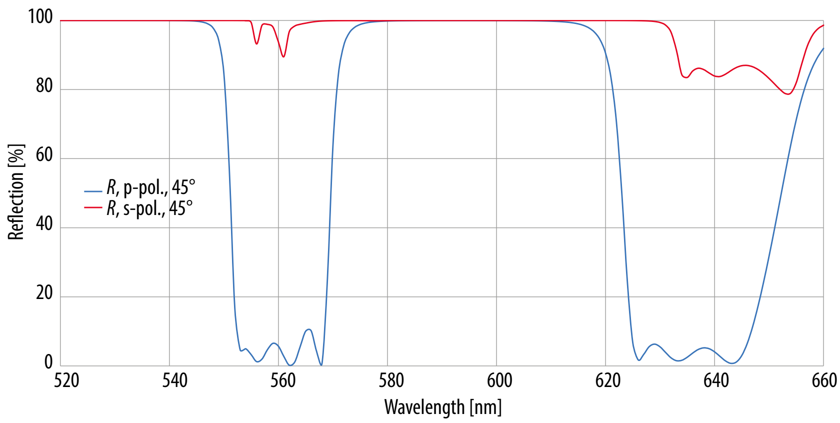

Fig. 2 TFP as used for excitation lasers: polarization is limited to specified wavelengths (blue) while reflectivity for all other wavelengths (red) is a high as possible.

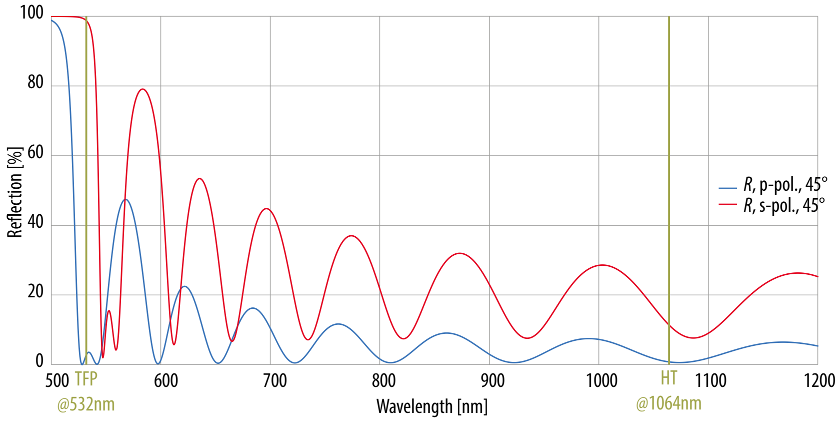

Fig. 3 TFP for resonators: high s-pol reflectivity at 532 nm (left) while higher wavelengths (e.g. 1,064 nm p-pol) are transmitted.

trically coated optics. A phenomenon occurs that is crucial for polarizers: the refractive index contrast of the effective refractive indices of the layer system changes with the angle of incidence. If the angle becomes larger, the contrast for the p-component decreases. The larger refractive index contrast for the s-pol results in a wider reflection range than for the p-pol. This creates an intermediate range in which the s-pol has already been reflected while the p-pol is still transmitting, which allows both polarizations to be effectively separated from each other. This works especially well at the Brewster angle (for quartz about 56°) because the p-pol is almost completely transmitted at this angle.

The layer thicknesses are based on the wavelength λ of the light. In 'classic' optics such as simple mirrors, the dielectric coatings consist of $\lambda/4$ stacks in which low and high refractive index materials alternate. Silicon dioxide (SiO_2) is usually used as the low-refractive material, while tantalum pentoxide (Ta_2O_5), for example, is used as the high-refractive material. The number of layers in mirrors can be used to determine how strongly they reflect certain wavelengths.

Monitoring is essential

It is crucial that the layer thicknesses be deposited with nanometer precision during production. Deviations of just a few nanometers can significantly shift the central wavelength of the calculated design and even lead to a completely different spectral curve. For manufacturers such as Laser Components, it is therefore crucial to precisely determine the thickness of each individual layer during the coating process. Today, this is usually done by in-situ broadband monitoring (BBM) during which a spectrometer records the light from a white light source that is transmitted through test optics. The unfiltered light that passes through an empty hole in the substrate holder serves as a reference value (Fig. 4) and allows the layer thicknesses to be determined within half a nanometer. In contrast to conventional monochrome monitoring, BBM uses the entire visible spectrum between 400 nm and 1,000 nm. The wavelength range can be extended with additional light sources and detectors if necessary, for examply with an IR source for wavelengths between 1,100 and 2,000 nm.

No technology without know-how

This type of monitoring is a basic technical prerequisite to produce TFPs specific to an application, such as for the examples mentioned above. Such polarizers require complex designs with varying layer thicknesses, the design and production of which requires in-depth knowledge of the subject matter. It is firstly important to understand the applications and the environment in which they are intended to be used. This is the only way to determine what the polarization optics must achieve.

Based on these specifications, software is used to calculate appropriate designs. These ideal values are then revised by experienced coating developers who know exactly what the processes and equipment in their company can do. The result is viable optics, the specifications of which precisely match the requirements of the application.

In the end, it is all teamwork: the requirements must be clearly defined by the client, and there must be people on the manufacturer's side who are willing to leave the beaten path and explore unusual new avenues.

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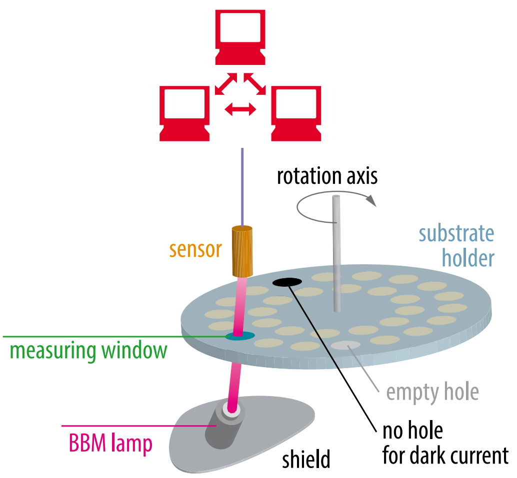


Fig. 4 Schematic diagram of a broadband monitoring system

Author

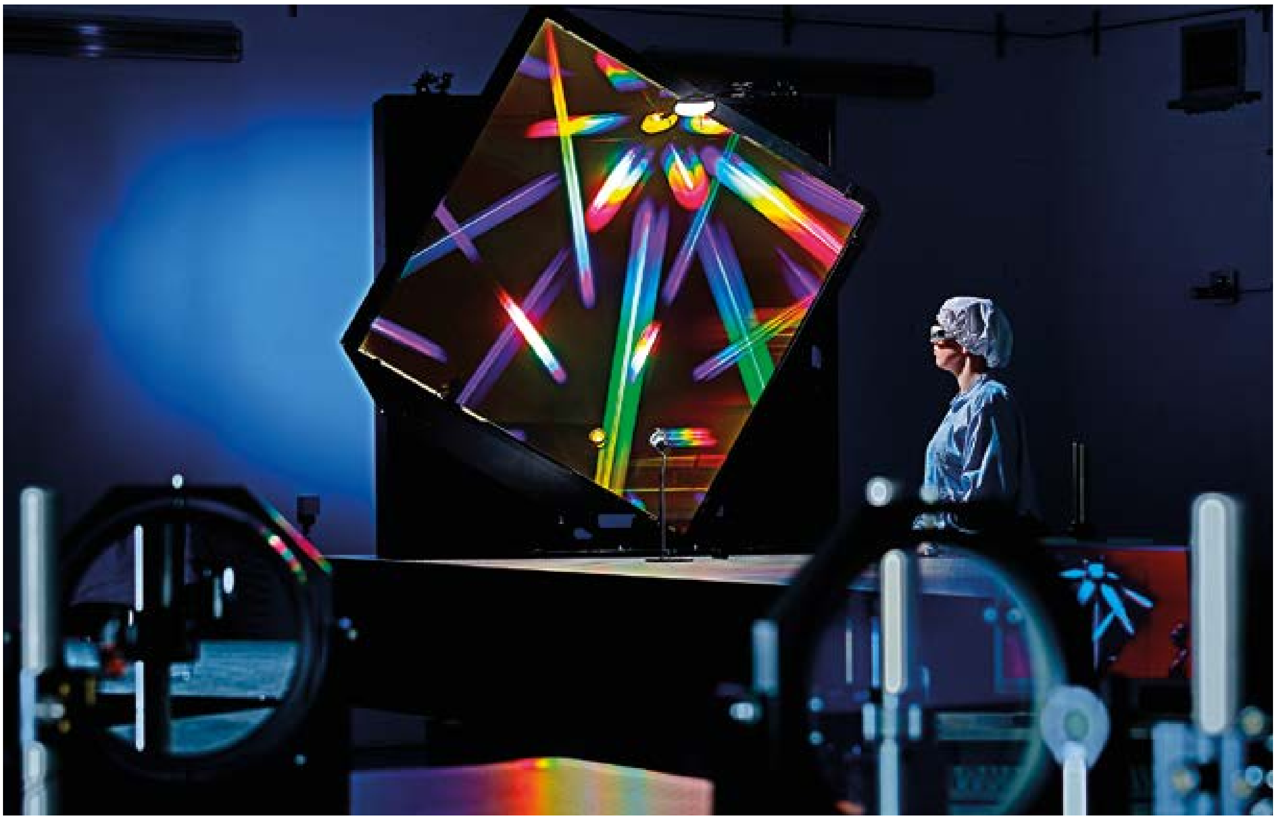
René Sattler is a product engineer and key account manager for laser optics at Components Germany. He has 17 years of experience in sales of complex technologies, with more than 12 years in the field of laser optics. After studying physics in Rostock and Hanover, he graduated from Laser Zentrum Hannover (LZH) with a thesis on high power lasers for gravitational wave detection.

René Sattler, LASER COMPONENTS Germany GmbH, Werner-von-Siemens-Str. 15, 82140 Olching, Germany; phone +49 8142 2864-763, fax +49 8142 2864-11; e-mail r.sattler@lasercomponents.com, Web: www.lasercomponents.com, rene-sattler

Resource-efficient generation of large-area micro and nanostructures

High-quality, large area diffraction gratings originated by diode laser-driven interference lithography

Benedikt Bläsi, Martina Müller, and Harald Rossmeier



Lasers are widely used in various manufacturing processes. In order to achieve sustainable production, it is important to reduce the environmental impact caused by the laser operation. One major improvement is the step from gas lasers to diode lasers.

▲ The large-scale interference lithography setup at the Fraunhofer Institute for Solar Energy Systems ISE (Source: Fh. ISE)

Replacing gas with diode lasers reduces the energy consumption of the light source by up to a factor of 1,000. Gas lasers usually also require substantial cooling, either wasting thousands of liters of water every operating day or increasing energy consumption when a closed cooling circuit is used. This article addresses large scale interference lithography as an important application, where gas lasers were the light source of choice until the arrival of solid-state lasers and novel diode laser solutions in recent years.

In interference lithography, high-end lasers are used to originate micro and nanostructures on areas up to the square meter scale [1, 4]. Large area gratings or engineered diffusers can be used in displays, LED lighting or in solar cells [2]. Lasers emitting at wavelengths <445 nm with extreme requirements of stability, beam profile, coherence and output power are needed for large area interference lithography.

For 3D AG, a tooling and industrial manufacturing company specialized in processing nano and microstructures, large area originations are needed to obtain seamless surface areas – both for research and for industrial clients. The laser used in the lithography setup is one of the core elements to produce high quality structures. The template originated by interference lithography in glass is later replicated by 3D AG using

Fig. 1 Toptica's TA-SHG pro system comprises a high-power, tunable, frequency-doubled diode laser, a high power semiconductor (TA) and an integrated frequency doubling stage (SHG pro) with digital control DLC pro (right). (Source: Toptica)

electroforming processes, and the nickel replicas serve as templates for industrial manufacturing processes. This first glass master is crucial for the high fidelity and functionality of the structure in subsequent steps and final products.

Experimental setup – interference lithography

Interference lithography is based on the superposition of two or more coherent waves on a photoresist-coated sample. Typically, a laser beam is split, expanded, spatially filtered and then superimposed on the sample. Therefore no mask is required and the achievable exposed size only depends on the beam diameter as long as the exposure stability can be maintained. In a subsequent wet chemical development step, the pattern recorded in the photoresist is transformed into a surface relief structure.

At Fraunhofer ISE, an L-shaped optical table with 10 and 12 m length enables beam expansion up to very large areas (up to 1.2 × 1.2 m). For such large area processes, the exposure times can reach up to five hours. The phase between the interfering waves needs to be kept stable during this time, which implies extremely high thermal and mechanical stability of the setup as well as high laser coherence and stability. As an example, vibration amplitudes or position changes of more than 20 nm over the exposure time would be detrimental [6]. In this work, we evaluated a Toptica DLC TA-SHG pro emitting at 390 nm with a single frequency output power of 1 W. No water cooling is required due to its high energy efficiency. This not only makes installation and operation easier, but also contributes to the overall stability. Large area structures for various applications such as diffraction gratings, solar cells and LEDs could be successfully originated using this laser system.

Versatile functionalities of structured large area surfaces

Large-area and seamless micro and nanostructures are needed for a wide range of applications. In display technology they can be used as diffusers or antiglare surfaces, as grating couplers or to polarize light. In lighting technology, surface structures lead to enhanced LED outcoupling or light steering. In the highest efficiency solar cells, gratings-based light trapping makes optimum use of the solar radiation.

If seamless and homogeneous large-area structures are needed in the product, the mastering technology must fulfil these requirements. High-end mastering technologies, such as electron beam lithography or extreme ultraviolet (EUV) lithography, are extremely expensive and not feasible for large areas. Interference lithography is very well suited for such requirements.

Companies

3D AG

3D AG is an independent full service company based in Switzerland with thirty years of experience in micro and nanotechnology. From designing banknote security features to the creation of tools for display manufacturing, 3D AG explored and acquired a wide knowledge in the processing of structures for various functionalities. 3D AG focuses on manufacturing durable molds by electroforming and has developed various in-house processes, such as a high precision step-and-repeat UV imprint technology. The 3D AG expertise is customized to upscale micro and nanostructures from the laboratory to industrial manufacturing.

https://3dag.ch

Toptica Photonics

Toptica has been developing and manufacturing high-end laser systems for scientific and industrial applications for more than twenty years. The portfolio includes diode lasers, ultrafast fiber lasers, terahertz systems and optical frequency combs. Toptica today has 450 employees in six commercial entities with a consolidated group revenue of 100 million euros (about $107M).

www.toptica.com

Institute

Fraunhofer Institute for Solar Energy Systems ISE

Fraunhofer ISE in Freiburg, Germany, is the largest solar energy research institute in Europe. The institute is committed to promoting sustainable, economic, safe, and socially just energy supply systems based on renewable energies. Its research provides the technological foundations to supply energy efficiently and on an environmentally sound basis in industrialized, threshold and developing countries. Focusing on energy efficiency, energy conversion, energy distribution and energy storage, the Institute develops materials, components, systems and processes.

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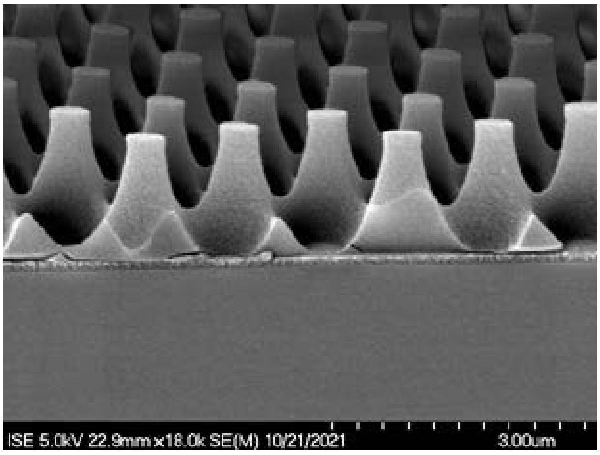

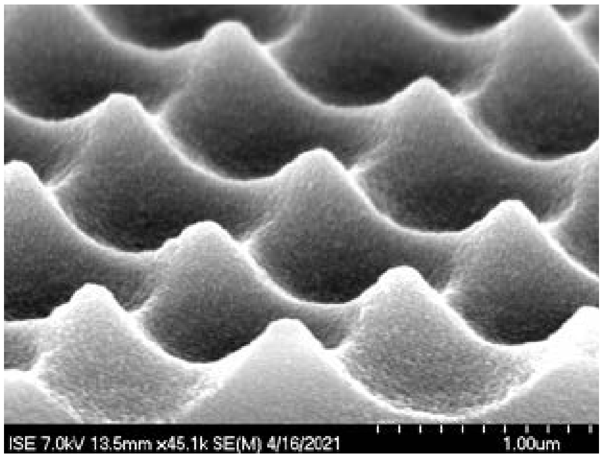

Fig. 2 Examples of large area structures fabricated during the evaluation. The left SEM image shows a diffraction grating designed to cause a very bright color appearance. The hexagonal grating in the right image is designed to trap light in triple-junction solar cells with efficiencies >35 %. (Source: Fh. ISE)

Microreplication techniques are typically used to integrate such functional structures into products. The basic idea is that firstly a master structure is researched and designed to then be originated – the origination being the initial and most important step to guarantee proper industrial replication in further processes. The quality and fidelity of the structure is crucial for a successful application. Clean room facilities are an elementary environment for a high performance laser interference setup, as provided by ISE using the Toptica DLC TA-SHG pro for the engineering of the experimental setup described here. A master origination not only needs true structure fidelity, but a defect-free surface because defects can hinder functionality or visually disturb the surface area.

3D AG has specialized in the later replication of masters to obtain high fidelity copies (nickel shims) of the master structure by electroforming. To make the glass surface conductive, a gold layer is sputtered onto the glass master at the ISE facilities. Electroforming nickel shims from such sputtered masters maintains the origination effort through the creation of a nickel shim family with multiple generations. The first copy is an Au-Ni alloy with a thickness of 300 µm ± 10 µm. This rigid tool, a precise replica of the glass master, serves as a template for multiple generations. Defect inspection can only be conducted in the reflective view of the sputtered surface or in the first Au-Ni master. As the process is very delicate and sensitive, the exposure is repeated multiple times. The best result is chosen to produce multiple pure nickel shims as tools for industrial replication of the structure.

One of these nickel tools is used as a stamper for further processes such as nanoimprint lithography for the industrial replication of the structure in other materials. Other industrial processes are roll-to-roll (R2R) or roll-to-plate (R2P) applications. Shims of various thicknesses can be made, mostly of 80 µm – 200 µm, depending on the chosen application. In many cases, the nickel templates can also be welded to sleeves to better facilitate high volume production.

Conclusion

The solid-state laser at 390 nm has proven to be a reliable modern tool to substitute legacy gas laser systems. Homogeneous high-quality structures can be originated seamlessly by interference lithography on large areas. Solid-state laser technology is therefore well suited for this type of high-end lithography process, paving the way to innovative products in display technology, lighting, or solar energy conversion.

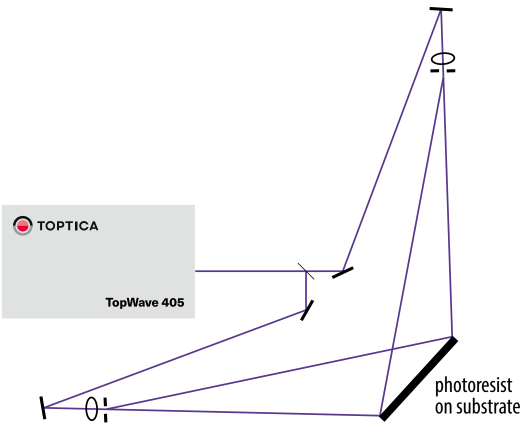

Fig. 3 Sketch of a large area interference lithography set-up (Source: Toptica)

relevant wavelength range	257 – 445 nm
wavelength stability	unlocked: typ. <5 pm drift in 8 hours locked: <0.003 pm drift in 8 hours (depending on reference)
coherence lengths	>>100 m
spatial mode, beam quality	TEM_{00} $M^2 \leq 1.2$
optical output power	0.5 – 3 W (depending on wavelength)
energy consumption	typ. <100 W

Table Characteristics of the laser system as discussed in the text

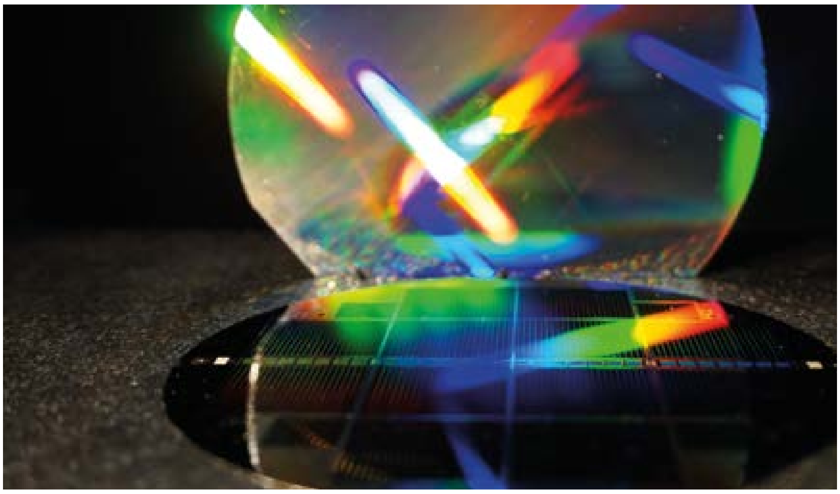

Fig. 4 Interference lithography-based diffraction gratings enable multijunction solar cells to achieve the highest efficiencies [5]. (Source: Fh. ISE)

The flexibility of modern solid-state lasers is seen as a plus for interference lithography as it opens up the accessibility of a great choice of wavelengths (VIS to DUV) and output power levels (see Table).

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Authors

Benedikt Bläsi received his MSc from University of Durham (UK) in 1995 and his PhD from Freiburg University (Germany) in 2000, for his work on interference lithography for optically-functional nanostructures. He is co-founder of Holotools GmbH (since 2014 part of Temicon). In 2004 he was a visiting fellow at University of Technology Sydney, Australia. Since 2005 he is head of the group 'cleanroom and microtechnology' at Fraunhofer ISE. Since 2019 he serves as an associate editor for the journal Optics Express. His main research focus is on photon management for photovoltaic systems, displays and lighting applications.

Martina Müller is owner and CEO of 3D AG, a 3rd generation family business specialized in optical and functional nanostructures, the development of high security features for banknotes, for product and brand protection, as well as the production of new products with optical elements, such as displays, smart glasses or biomimetics. Martina's educational background in chemistry, art and business enables interdisciplinary creativity, inspired by research and experienced in logical evaluation and strategy.

Harald Rossmeier began his career at Toptica in 1999 after graduating with an engineering degree in physics from the University of Applied Sciences in Munich. He played a leading role in the development of industrial OEM diode laser systems and later took over the role of product manager for this segment. In 2011, he moved to the US to drive the application and business development in Biophotonics and Semicon for Toptica. Since his return in 2014, he resumed the position of product manager OEM diode lasers, focusing on providing high-end solutions for industrial lithography and holography applications.

Dr. Benedikt Bläsi, Head of Team Microstructured Surfaces, Fraunhofer ISE, Heidenhofstr. 2, 79110 Freiburg, Germany; phone: +49 761 4588-5995, Web: https://www.ise.fraunhofer.de ■ Martina Müller, CEO, 3D AG, Laettichstrasse 4a, 6340 Baar, Switzerland; phone: +41 41 768 25 17; e-mail: m.mueller@3dag.ch, Web: https://3dag.ch ■ Harald Rossmeier, Senior Product Manager OEM Diode Lasers, Biophotonics & Materials, TOPTICA Photonics AG, Lochhamer Schlag 19, 82166 Gräfelfing, Germany; phone: +49 89 85837-0; e-mail: harald.rossmeier@toptica.com, Web: www.toptica.com

GRIN pad polishing

3D-printed hardness-gradient polishing tools for micro-optics synchro-speed polishing

Oliver Fähnle, Kerstin Kern, Jan Allaart, Henrik Surberg, Jens Bliedtner, Christian Schulze, Sebastian Henkel, Volker Heineck, Jürgen Bode, and Michael Wagner

A new concept for CNC polishing pads is given by the gradient index (GRIN) pad polishing tools. Instead of gluing polishing foils as a layer onto metallic tool holders that have the spherical surface to be polished, 3D-printed GRIN pads are applied directly to the CNC tool axis.

▲**Fig. 1** Traditional synchrospeed polishing method applying spherical polishing pads made of metal and of the exact workpiece radius, covered partially by flower-shaped polishing foils (left). A satisloh SPS-100 CNC optics polishing machine machine (right)

The use of micro-optical systems – usually with diameters and radii ranging from dozens of micrometers to a few millimeters – has increased tremendously, with applications ranging from medical optics for endoscopy and implants, to optical transmission systems such as fiber coupling, space missions or laser diode beam shaping devices, and virtual reality applications such as lidar. Due to their small dimensions, it is hardly possible to apply on-machine, in-situ, in-process quality control during their manufacture [1]. The application of stable manufacturing processes is therefore crucial. Two dif-

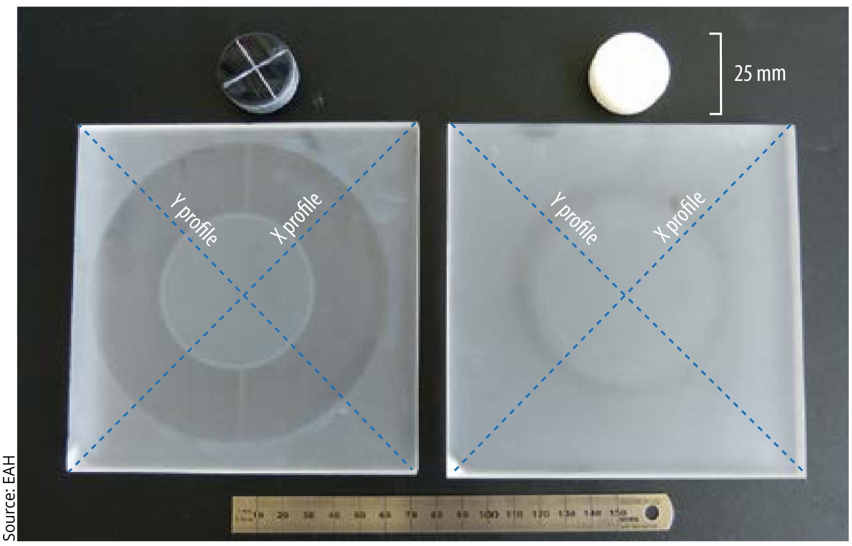

Fig. 2 Two polishing pad materials have been developed, the black one (on the left) featuring substantially higher wear rates than the white one (on the right). This can be seen in the two circular grooves polished into two 130 mm diameter N-BK7 samples. Polishing was stopped after 20 minutes with the black pad causing more than 4× higher volume removal than the white pad.

Fig. 3 Novel GRIN polishing pads for synchrospeed polishing are currently under investigation: (a) a full material synchrospeed polishing pad (b) a lightweight synchrospeed polishing pad and (c) a special, full material synchrospeed polishing pad in two dimensions for lens diameters of 9 mm and 4 mm. Smaller pad dimensions are currently under investigation.

ferent approaches are feasible to achieve this: (a) the invention and development of new fabrication technologies such as direct 3D printing of optical elements or the application of metasurfaces, and (b) inventions and developments to enable the application of established state-of-the-art fabrication technology to also be used for the production of microlenses. This paper reports on an experimental study towards the implementation of the latter.

The state-of-the-art in the mass production of macroscopic spherical optics is the CNC machine-based, synchrospeed polishing method, first published by Erhard Brück in 1981 [1]. Spherical surfaces are polished by area contact with tool diameters twice the size of the lens diameters with both rotating in the same direction. If the ratio of the rotary speeds of tool and lens equals the cosine of the inclination of the tool rotary axis with respect to the workpiece axis, relative speeds between tool and workpiece surface are almost constant for each point within the clear aperture, resulting in constant stock removal over the entire surface to be polished. This is a prerequisite for stable mass production [2] (Fig. 1). One essential feature of synchrospeed polishing is the preparation of the lateral pad surface shape to generate stable wear distribution within the clear aperture. This is done by calculating the tool assignment for the optical component and deriving the corresponding polishing foil geometry to achieve a constant removal rate over the entire component surface, as shown in Fig. 1. Unfortunately, this feature prohibits the application of synchrospeed for micro-optics polishing since the required polishing foil microshapes can hardly be generated.

Recently, a new approach to solve this problem called GRIN pad polishing, has been developed and experimentally tested in a first-light study. As shown in Fig. 2, two different polishing pads (black and white) have been developed and 3D-printed, featuring two different types of plastic material of substantially different hardness. While both differ substantially in material removal rates during polishing (applying a water-based cerium oxide slurry on N-BK7), both enable the generation of P3 optical surface roughness levels below 2 nm RMS (1.8 nm RMS using the black pad and 1.4 nm RMS using the white pad). Therefore, both materials can be printed into one single GRIN synchrospeed polishing pad as shown in Fig. 3. These 3D-printed tools remove substantially more material in the black flower-shaped part and almost no material within the part in between (the white part of the pad). These 3D synchrospeed pads are mounted on a flat interface to the CNC tool axis, omitting the need to use the traditional, metallic synchrospeed tools of the workpiece radius. The required workpiece radius can easily be generated directly into the 3D-printed pad. Two different 3D-printed synchrospeed pad designs are currently under investigation: (a) the full material GRIN pad shown in Fig. 3a, and (b) a lightweight-structured GRIN pad shown in Fig. 3b, where the white part of the pad is only partially formed to guarantee mechanical stability during polishing. Finally, Fig. 3c shows a miniaturized polishing pad, the construction of which is enabled thanks to the <10 µm lateral resolution of 3D-printing multiplastic and hardness gradient GRIN pads.

In conclusion, GRIN pad polishing, a new class of 3D-printed synchrospeed polishing pads, has been developed and tested during a first-light experiment. These new tools enable the replacement of spherical, metallic polishing foil carriers by cost-efficient, 3D-printed, planar pads, possibly enabling their use for the synchrospeed polishing of microlenses. Their process windows in terms of smallest radii processable, tool lifetimes and industrial applicability are currently under investigation in the labs of the Applied Universities of EAH (Jena, Germany) and OCB (Buchs, Switzerland) as well as in industry.

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OST Ostschweizer Fachhochschule Campus Buchs (OCB)
Departement Technik
Dr Oliver Fähnle, Dr Kerstin Kern, Jan Allaart, Prof Dr Henrik Surberg
Werdenbergstrasse 4
9471 Buchs, Switzerland
phone: +41 58 2573359
e-mail: oliver.faehnle@ost.ch
Web: www.ost.ch

Ernst-Abbe-Hochschule (EAH)
SciTec Department
Prof Dr Jens Bliedtner, Christian Schulze, Sebastian Henkel, Volker Heineck
Carl-Zeiss-Promenade 2
07745 Jena, Germany
phone: +49 3641 205 444
e-mail: jens.bliedtner@eah-jena.de
Web: www.eah-jena.de/scitec

Satisloh Gmbh
Precision Optics
Dr Jürgen Bode, Michael Wagner
Wilhelm-Loh-Str. 2–4
35578 Wetzlar, Germany
phone: +49 6441 912326
e-mail: juergen.bode@satisloh.com
Web: www.satisloh.com

Case study: power supply units

Fine-tunable switching power supplies as laser drivers

Denny Vogel & Tino Becker

Endurance and stress testing ensures the quality of laser LEDs.

Source: iStockphoto/golubovy; all other images: Systemtechnik Leber

LaCoSys Laser Control Systems specializes in manufacturing optoelectronic products. The company's electronics experts have started integrating fine-tunable Cotek power supply units into their customers' laser test systems. Featuring technology much like that found in laboratories, these power supplies have a great advantage: they not only provide voltage, they can also a deliver a precisely calibrated amount of current.

Laser and laser diode manufacturers count on LaCoSys test systems to assure the quality of laser diodes installed on their production lines or test benches. Their objective is to minimize the failure rate and to rule out early failures altogether. After all, it is annoying when a service technician has to set out yet again to replace a faulty laser diode.

This is why manufacturers conduct burn-in tests. This method involves stress-testing laser diodes on a special burn-in board for up to 100 hours at or above their rated operating conditions to identify components that will fail prematurely, before their expected lifetime elapses. These operating conditions may include temperature, voltage/current, operating frequency and other parameters with specified thresholds.

The availability of variable output voltage and output current is crucial to these tests. To achieve meaningful results, both have to be precisely adjustable over the full 0-to-105 percent range via a digital or analog interface. Conventional power supplies do not offer this feature, so LaCoSys engineers opted for a fine-tunable Cotek power supply when they began building their new burn-in testing system. This can be set to voltage-regulated rather than current-regulated operating mode. With its current-regulated output, this power supply unit is the perfect choice to power a high-performance laser diode driver. This is one unique selling point on the market, the other being the power supply's great flexibility in accommodating a wide range of extensions.

The design and function of laser test systems

Laser and laser diode manufacturers are keen to test their products directly on a test bench as part of this quality assurance regimen – mainly by conducting burn-in tests. Today's laser diodes figure prominently in diverse use cases and come with a wide variety of wavelengths and power ranges. Anything goes, from laser pointers with a few milliwatts to car-body welders with multiple kilowatts. The laser is becoming an increasingly important tool in industry, medical engineering and research. Much of its growing significance is down to recently developed power classes and wavelengths. These advances enable use cases that would have been inconceivable just a few years ago. Laser diode manufacturers with state-of-the-art production lines are able to execute the entire manufacturing process. They can grow the laser crystal, separate and dice wafers, and coat and package the diode by attaching the crystal to the heat sink and affixing a mounting bracket.

A laser is tested and inspected repeatedly in the course of these many process steps. However, it can only be characterized at full power at the end of the process chain. Some laser diode manufacturers carry out elaborate tests prior to delivery to rule out potential defects during these production steps and to assure the lasers' quality, particularly their service life. These trials include burn-in tests to detect early failures and other quality issues to ensure faulty lasers never leave the plant.

The purpose and benefits of burn-in testing

Burn-in test systems for high-performance lasers consist of one or more test chambers in which laser diodes can be operated safely. A cooling system keeps the lasers' temperature in check. Sensors in the test chamber provide information on power levels and many other parameters. A high-power laser diode driver serves as the energy source for the laser. It is regulated and monitored via an industrial controller. A human machine interface (HMI) enables the operator to set and view all key values such as current, operating mode, and test time. This type of system benefits the laser diode manufacturer by fully automating the testing and inspection process. These automated tests entail applying different currents to simulate various operating modes and load cases. This serves to model pulsed and continuous wave applications as well as 'real-world' scenarios. All data captured during this process is stored alongside the laser diodes' production data in a customer-specific database.

Burn-in test systems for high-power lasers consist of one or more test chambers.

Test accuracy and product quality hinges on the power supply unit

The core component of these test systems is the energy source. It determines how meaningful the results will be and, by extension, the attained product quality. This is why the current or voltage source has to be as versatile, accurate, and reliable as possible. Only expensive power supplies designed for lab use had been able to meet that requirement until LaCoSys engineers discovered power supplies units made by Cotek, a manufacturer based in Taiwan. They were finally able to develop a new low-cost energy source for burn-in systems based on a power supply unit suited for industrial use. With variable current and voltage output ranging from 0 to 105 percent, these power supplies are versatile and precise enough to meet the requirements of a burn-in system.

Conventional power supplies, on the other hand, are usually only variable within a limited range of the nominal voltage, for example, ±5 percent. Some manufacturers also allow current to be varied, but only to a limited degree within a certain range.

However, laser diode manufacturers who run the LaCoSys test systems on the test bench need the complete I–V characteristic for quality assurance and laser diode characterization. The current must be precisely adjustable from 0 to 500 amps for this fundamental characterization of high-power laser diodes throughout the optical power range. In this case, a steep I–V characteristic curve is unsuitable for voltage control because even a few millivolts variance at the voltage source would result in considerable changes in the amount of current.

A typical laser diode has a slope of 1 to 2 amps per millivolt at the operating point. At 22 volts and a voltage regulation accuracy in the typical range of 0.5 percent, this would amount to 11 millivolts. As a result, the current change would range from 10 to 20 amps. This simple example clearly illustrates why the abil-


The Cotek AEK-3000 power supply takes on the role of a laser driver in the new LaCoSys burn-in test system.

Company

Systemtechnik Leber

Systemtechnik Leber, a Burger Group company, is a leading provider of solutions for drive engineering, digital electronics, fieldbus and communication technology, power electronics and individual power supplies as well as power controllers. The enterprise and its experienced engineering team develops concepts, electronics, hardware and software for prestigious medical engineering, aviation, industrial automation, automotive and consumer electronics companies at its location in Franconia, Germany. On permanent rather than temporary contracts, its workforce also supports customers in all phases of development, from prototyping to product launch. Leber's clientele includes high-profile corporations such as VW, Siemens and Airbus.

www.leber-ingenieure.de

The new LaCoSys laser test system: the SmartPowerXL laser driver with a power range of 3,000 – 12,000 watts.

ity to regulate current is so important to controlling optical power at the laser diode with exacting precision.

How the power supply unit works

Cotek power supplies are currently the only units of their kind to meet this requirement for the I–V characteristic curve. Systemtechnik Leber, a German electronics company, distributes these units and adapts them to the given use case. "A real USP on the market, this was a decisive factor in the development of our new burn-in laser test system," says LaCoSys managing director Tino Becker. "After all, the ability to precisely control the voltage and current output and adjust it via a digital or analog interface over the full 0-to-105 percent range is such an important prerequisite for the accuracy of tests conducted with this system. Conventional power supplies do not offer this particular option."

The technology of the AC/DC inbuilt power supply models of the Cotek AEK range with 3 kW is similar to that of laboratory power supplies.

This burn-in system comes with AEK series 3 kW, AC/DC power supply models built in. These units' technology is similar to that of laboratory power supplies. They enable the test systems to take precise readings of the current for each ampere.

Cotek power supplies have the advantage that they can be switched to operate in current-regulated mode in addition to the customary voltage-regulated mode. This current-regulated, precisely controllable output enables engineers to implement the perfect high-power laser diode drivers. In addition, output power can be readily scaled up to 15 kilowatts by connecting power supplies in parallel. The power supply units' internal protection circuits guarantee reliable and safe operation.

Trials with dummy laser diodes and in the test lab

The first test runs prior to integrating a Cotek unit into a laser power supply were conducted on LaCoSys' premises using a test rig. Their engineers kicked things off by putting the current and voltage regulation to probing tests using dummy laser diodes. Experts from both companies convened at the Leber lab in Nurnberg to subsequently analyze, discuss, and assess the results of these tests. Then the new system's performance was optimized by applying these findings, which also helped answer questions about the synchronization and wiring of the interface.

Once the prototype was ready to go, LaCoSys engineers took advantage of yet another opportunity to conduct tests jointly at the LaCoSys plant and on site at Systemtechnik Leber. They chose the best variant after testing and comparing various configurations on location. The winning configuration was re-examined in the STL test laboratory and tested under load.

The second development phase involved testing the power supply units in parallel and individually at LaCoSys using dummy diodes as well as actual lasers. These trials served to re- test and optimize interactions at the interface and the timing. LaCoSys engineers were then able to develop the first power supplies for the company's customers and conduct further field tests.

The insights gained in these field tests flowed back into the product during the last development phase. Engineers put the finishing touches to the interface with a final revision and opted for an RS485 industry standard-compliant external interface. They implemented algorithms in the software to ensure uniform utilization of the power supply units and to enable intelligent power management. This significantly increases efficiency when operating multiple power supply units in parallel under partial loads.

These efforts culminated in a modular, scalable and reliable power source for state-of-the-art, high-performance burn-in systems. LaCoSys' new laser test system – the SmartPowerXL laser driver with a 3,000 to 12,000 watt power range and integrated Cotek power supplies – has since gone into production.

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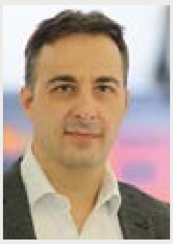
Authors



Denny Vogel is a power supply expert at STL Systemtechnik Leber. He regularly presents innovations and trends in this sector as a guest speaker and author. Before joining STL, he worked with various different companies in technical sales, among them Emtron electronic, where he was a consultant for industrial power supply applications.

Tino Becker is the founder and CEO of LaCoSys. He was previously a developer in various companies, among them Lasos Lasertechnik where he was responsible for the development of strategic micro-electronic and software projects, and also the semiconductor and component manufacturer Jenoptik Laser where he was responsible for the development of hardware and software for laser controls and systems.

Denny Vogel, Systemtechnik Leber GmbH & Co. KG, Haimendorfer Str., 90571 Schwaig, Germany; phone: +49 911 2153 7268, e-mail: denny.vogel@leber-ingenieure.de ■ Tino Becker, LaCoSys GmbH, Ernst-Ruska-Ring 17, 07745 Jena, Germany; phone: +49 3641 224 1514, e-mail: tino.becker@lacosys.com

Full articles now online and in PhotonicsViews issue 2/2023

Holographic recordings without compromise

Tunable lasers help streamline the fabrication of holographic optical elements

Widely tunable continuous-wave optical parametric oscillator (OPO) systems help meet the demands on holographic optical elements (HOEs) for many use cases, including head-up displays and augmented-reality devices. The wide tuning range allows for direct adjustment of the replay wavelength with little to no need for modification of the holographic recording geometry. HOEs fabricated using these OPO systems in conjunction with advanced photopolymer materials offer precisely controlled replay properties and exceptional diffraction efficiency.

Holographic optical elements are versatile alternatives and complements to conventional refractive and reflective optics. With few exceptions, the manufacturing of HOEs based on holographic recording requires monochromatic light with a long coherence length and narrow linewidth, typically provided by lasers operating in a single longitudinal mode. The wavelength of the recording light is a key process parameter as it directly affects the spectral behavior and selectivity of the HOE at replay. Widely tunable continuous-wave optical parametric oscillator devices are becoming increasingly popular in applied holography, offering unparalleled wavelength coverage in the visible and near-infrared (NIR) spectral range in a single device with coherence and stability properties that match holography's stringent requirements.

Meta Materials Inc

Stefan Trotzky
505-3292 Production Way
Burnaby, BC V5A 4R4
Canada
e-mail: stefan.trotzky@metamaterial.com
Web: https://metamaterial.com

Hübner Photonics

Niklas Waasem
Wilhelmine-Reichard Str. 6
34123 Kassel
Germany
niklas.waasem@hubner-photonics.com
Web: https://hubner-photonics.com

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https://doi.org/10.1002/phvs.202300010

Silver jubilee for the Laser MicroJet

Three awards for the technology kicked off the success of start-up company Synova in 1997

Combining light and water created a hybrid method of laser machining superior to other technologies, trade-marked as Laser MicroJet. The water cools the cutting zone so that hard and brittle materials can be machined without any thermal damage.

Synova's history begins when Bernold Richerzhagen, after obtaining his master's degree in mechanical engineering from RWTH University Aachen in 1989, applied for a position in a research project at the EPFL's Applied Optics Laboratory to develop a laser-based dental tool for the removal of caries. His invention was based on the fusion of laser and water to drill tooth enamel. The laser beam was guided by total reflection within a fine water jet in the manner of an optical fiber. The laser provided the heat for ablation while the water cooled the material. This water jet-guided laser offered the advantage of a parallel cylindrical laser beam without any beam divergence that is inherent in other laser processes.

DaVinci system for shaping diamonds (Source: Synova)

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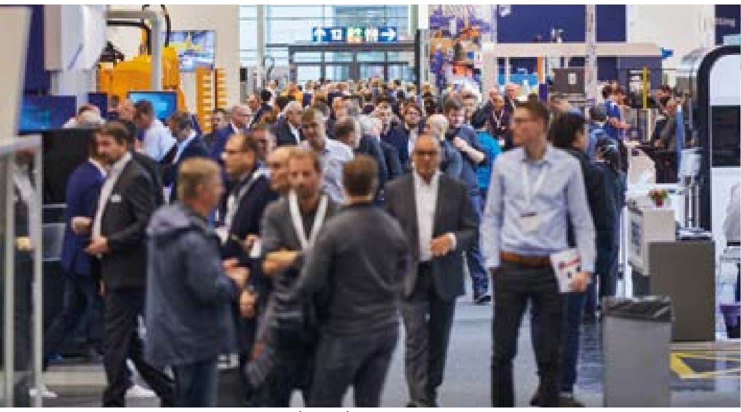
Synova S.A.

Route de Genolier 13
1266 Duillier (Nyon)
Switzerland
phone: +41 21 552 2600
fax: +41 21 552 2601
e-mail: sales@synova.ch
Web: www.synova.ch


Source: Mack-Brooks


Source: Landesmesse Stuttgart

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https://spie.org/photonics-west

February 22 – 24, 2023
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Lisbon, Portugal
https://photoptics.scitevents.org

March 7 – 8, 2023
LEF 2023
Fuerth, Germany
www.lef.info

March 22 – 24, 2023
LASER World of PHOTONICS China
Shanghai, China
www.world-of-photonics-china.com

March 29 – 30, 2023
W3+ Fair
Wetzlar, Germany
https://w3-fair.com

March 29 – 30, 2023
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https://epic-assoc.com

April 17 – 21, 2023
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www.hannovermesse.de

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Read event previews and reviews on www.wileyindustrynews.com/en/events

"AM is shaping the future of industrial manufacturing"

Review: Formnext 2022, 15 – 18 November, Frankfurt, Germany

This year's exhibition was very much in tune with the times. As the coronavirus pandemic continues and new political and economic challenges emerge as a result, additive manufacturing can play a key role in decentralizing manufacturing processes and production, making supply chains more resilient, and facilitating resource and energy-efficient production in order to get innovative new products onto the market faster.

A glance at the figures shows just how important Formnext has become. With 802 exhibitors – the corresponding figure in 2021 was 606 – and 51,148 square meters of booked exhibition space, the performance of the world's leading exhibition for additive manufacturing and modern production was virtually on a par with pre-Covid levels. And with the lineup of eager experts and executives expanding by 65.6 % to 29,581 – up from 17,859 in 2021 – Formnext was going strong in its eighth year with attendees from 96 nations and a remarkably high proportion of international visitors (51 %) and exhibitors (58 %).

Leading international companies such as 3D Systems, Additive Industries, AddUp, Arburg, BigRep, Carbon, Desktop Metal, DMG Mori, Dyemansion, EOS, Farsoon, Formlabs, GE Additive, HP, Keyence, Markforged, Materialise, Renishaw, Ricoh, Siemens, Sisma, SLM Solutions, Stratasys, Trumpf, Voxeljet, XJet, and Zeiss presented more efficient production systems and an array of innovations. In addition, numerous well-known international corporations, including BASF, Covestro, Evonik, GKN Sinter Metals Components, Henkel, Höganäs, Linde, Mitsubishi Chemical, Nikon, Oerlikon, Sandvik, SMS Group, and many more presented innovative solutions for every stage of the process chain. The numerous world premieres and innovative developments included novel AM technologies and new and improved systems, as well as new materials ranging from wood to ceramics, software solutions, service offerings, post-processing solutions, and more.

Partner country France

France cemented its status as one of the world's most important suppliers and users of additive manufacturing solutions. In total, more than forty French companies, associations, and research institutes were represented at Formnext. French AM manufacturers such as AddUp, Lynxter, Constructions3D, Pollen AM and VLM Robotics, material manufacturers Fabulous and Constellium, and numerous other exhibitors showcased their exciting innovations and impressive additive manufacturing expertise.

Source: Mesago / M. Kutt

Formnext 2022, Halls 11 & 12, Messe Frankfurt

The 2023 edition of Formnext is scheduled to take place on 7 – 10 November in Frankfurt am Main, Germany.

https://formnext.mesago.com

"Boost of innovation"

Review: 10th Laser World of Photonics India, 7 – 9 December 2022, Bombay Exhibition Centre, Mumbai

Laser World of Photonics India 2022 was spread across 5,000 square meters, with almost ninety exhibitors from eight countries. Around 5,800 visitors attended the trade fair and the supporting programs to see the futuristic solutions on display at the exhibition grounds.

"We are delighted with the response to this latest edition of Laser," Bhupinder Singh, CEO, Messe München India says. "Across multiple applications and user industries, laser is recognized as a powerful solution. However, several challenges – like cost and compatibility of the machinery to Indian market conditions – prevent its mass adoption. We are glad to see some solutions emerge at this year's fair, and we are confident of creating more networks and partnerships for this industry in the future editions."

Dr Martin Lechner, executive director Messe München, adds: "Today, the Indian manufacturing landscape is among the most vibrant in the world. This is reflected in the footfall and dynamic participation at Laser World of Photonics India 2022. Our trade fairs in Munich and Shanghai have catalyzed growth in this industry on a global scale, and we are glad to see the show in India delivering value to all stakeholders in the Indian industry."

One of the major highlights of the 2022 edition was the industry-academia partnership through the IEEE Photonics Society – IEEE Bombay Section at IIT Bombay in the form of Photonics and Lasers – Industry Meet (PLAIM), which brought together global experts and researchers to deliberate on emerging trends, opportunities and challenges confronting the industry. Supporting programs designed to fulfil the needs of the growing manufacturing industry accompanied the three-days event.

Source: Messe München

Laser World of Photonics India 2022 in Mumbai

The 11th international conference and exhibition on 3D printing & additive manufacturing technologies brought together engineers, scientists, designers, and educators to share knowledge, best practices, challenges, and applications of 3D printing and additive manufacturing.

The next instance of 'Laser India' will be from September 13 – 15, 2023 at the BIEC, Bengaluru.

www.world-of-photonics-india.com

"Cork was a complete success"

Review: 5th European Machine Vision Forum, 27 – 28 October 2022, Cork, Ireland

The Forum in Cork was hosted by the Tyndall Institute. Prof Peter O'Brian and speakers from partner institutes provided participants with an insight into the Irish machine vision ecosystem, which includes academic and industrial activities. This included the presentation by Prof Martin Glavin, University of Galway, who spoke about vision systems for driver assistance and autonomous driving.

Another highlight of the conference program was the keynote speech on terahertz light-field imaging by Prof Ullrich Pfeiffer from the University of Wuppertal. He spoke about the challenges in beam generation as well as beam acquisition and evaluation. He discussed new approaches to solutions that could also provide new impetus in the visible light spectrum. Also exciting was the presentation by Christian Kludt, Fraunhofer IOSB, on light field inspection. Other topics at the Forum included multi/hyperspectral image acquisition as well as real-time 3D data acquisition, and components for image acquisition.

In addition, there was an exhibition by numerous companies with posters and smaller exhibits. Among the exhibitors were Midwest Optical Systems and Advantech.

The sixth European Machine Vision Forum will be held in Wageningen, the Netherlands.

www.emva.org

Source: David Löh / Wiley

5th European Machine Vision Forum in Cork, Ireland

"Everything the community hoped for"

Review: 1st PIC Summit Europe, 7 – 8 November 2022, Eindhoven, The Netherlands

The European integrated photonics value chain – including academics, startups, policymakers, and the industry – assembled in the Netherlands.

PhotonDelta CEO Ewit Roos, one of the initiative-takers of the event, looks back with joy: "It was everything we hoped for. Together with global stakeholders from the field, we were able to offer a diverse and compelling program that addressed the most important topics that need to be discussed. We are incredibly proud of the successful first edition of this international photonic chip conference and want to thank the amazing speakers, the attendees, the sponsors, and our partners for making it possible."

The program consisted of lectures, panel debates, workshops, and informal meetings. It also hosted the IPSR-I autumn meeting, co-organized with MIT and the Tech Tour 'photonics & electronics', attracting important investors to the scene. Representatives of the European Commission, universities, the Dutch national government, and the industry shared their visions throughout the two days.

PIC Summit Europe 2022 is a new congress, one of two photonic chip conferences in Europe and will return annually. It is expected to take place again next year in November 2023.

www.photondelta.com

Source: PhotonDelta

Day 2 at Eindhoven University of Technology

Preview: W3+ Fair Wetzlar 2023

W3+ FAIR CONVENTION WETZLAR

29 – 30 March, 2023, Buderus Arena, Wetzlar, Germany

The cross-industry platform for enabling technologies calls companies from optics, photonics, electronics and mechanics to the economically strong high-tech region of Central Hesse once again to jointly drive new innovations. Exhibitors such as OptoTech, Schunk, Carl Zeiss, IMT, Keba, Universal Photonics, QED, Trioptics, the Dutch Technology Alliance and – new – Hamamatsu, Vario Optics and Harmonic Drive will use the trade fair to present their latest products.

In addition to the multidisciplinary exhibition, visitors can learn about current trend topics at the accompanying conference en-tech.talks. Renowned speakers will give talks on the topics of medtech and life science, technology and quality assurance, production of the future, and digitalization and management. An EPIC TechWatch will also be given a stage, bringing user companies to the trade show to formulate their needs for cutting-edge technology. The lecture program will be complemented by a Start-up Pitch, where the VDI and IHK Hessen innovativ will provide a technology portfolio of the region. 'Microtechnology for optical devices' is the theme of the IVAM joint booth. The Thuringia joint booth will present high-tech from Germany's other strong optical region around Jena. The Competence Center Ultraprecise Surface Processing UPOB will host its 13th High Level Expert Meeting (HLEM 2023) on asphere metrology.

The W3+ Fair Wetzlar 2023 is supported by many long-standing expert partners, including Wetzlar Network, EPIC, IVAM, Spectaris and OptecNet Deutschland.

https://w3-fair.com

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CH-9444 Diepoldsau
Tel. +41(0)71 737 74 00
Fax +41(0)71 737 74 10
info@zuendoptics.com
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D-04318 Leipzig
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SCANLAB GmbH
Siemensstr. 2 a
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Prismastr. 5
CH-9444 Diepoldsau
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Am Fleckenberg 20, 65549 Limburg
+49 (0) 6431 9860 – 0
info@bm-optik.de / www.bm-optik.de

Optics Balzers AG
Balzers, Liechtenstein
Phone +423 388 92 00
info.mbo@materion.com
www.materion.com/balzersoptics

ZÜND precision optics

Zünd precision Optics ltd
Prismastr. 5
CH-9444 Diepoldsau
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info@zuendoptics.com
www.zuendoptics.com

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+49 (0) 6431 9860 – 0
info@bm-optik.de / www.bm-optik.de

Optics Balzers AG
Balzers, Liechtenstein
Phone +423 388 92 00
info.mbo@materion.com
www.materion.com/balzersoptics

ZÜND precision optics

Zünd precision Optics ltd
Prismastr. 5
CH-9444 Diepoldsau
Tel. +41(0)71 737 74 00
Fax +41(0)71 737 74 10
info@zuendoptics.com
www.zuendoptics.com

Windows, optical

B&M Optik GmbH
Am Fleckenberg 20, 65549 Limburg
+49 (0) 6431 9860 – 0
info@bm-optik.de / www.bm-optik.de

ZÜND precision optics

Zünd precision Optics ltd
Prismastr. 5
CH-9444 Diepoldsau
Tel. +41(0)71 737 74 00
Fax +41(0)71 737 74 10
info@zuendoptics.com
www.zuendoptics.com

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Editorial:
Dr. Oliver Dreissigacker (od; responsible), Stephanie Nickl (sn)
Phone: +49 (0)6201 606-181 / -030

Boschstr. 12, 69469 Weinheim, Germany
Fax: +49 (0)6201 606-328
e-mail: photonicsviews@wiley.com
www.photonicsviews.com

Contributing Editors:
Dr. Christel Budzinski (cb)
Carsten Heinisch
Jan Oliver Löfken

Copy editing: Matthias Erler, David Jayne

Subscriptions:
Wiley GIT Reader Service
65341 Eltville, Germany
Phone: +49 (0)6123 9238 246
Fax: +49 (0)6123 9238 244
e-mail: WileyGIT@vuservice.de
Our service is available for you from Monday to Friday 8 am – 5 pm (CEST)

Advertising:
Änne Anders (responsible)
Boschstraße 12, 69469 Weinheim, Germany
Phone: +49 (0)62 01 60 65 52
Fax: +49 (0)62 01 60 65 50
e-mail: aanders@wiley.com

Nicole Schramm (Executive)
Boschstraße 12, 69469 Weinheim, Germany
Phone: +49 (0)62 01 60 65 59
Fax: +49 (0)62 01 60 65 50
e-mail: nschramm@wiley.com

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