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Volume 17
June / July 2020
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PhotonicsViews

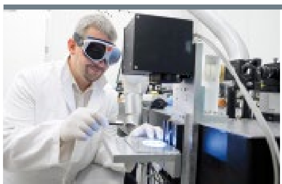
OPTICS • PHOTONICS • LASER TECHNOLOGY

Fiber Coupling

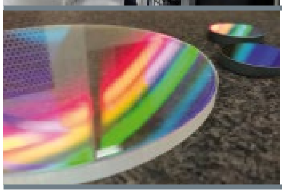
to polarization-maintaining fibers and collimation

Focus:

SLT



Laser Micromachining
Smooth Surfaces by Pulsed Laser Processing



Optical Components and Systems
Resonant Waveguide Gratings

published in media partnership with EPIC European Photonics Industry Consortium

WILEY

The Laser Boosts Digital Manufacturing

60 years and going stronger than ever …

It is only a question of time until we will be able to buy the first lasers that can switch between cw and (ultrashort) pulsed operation at kilowatt average power levels. The technology is ready and will allow us to perform most of the known laser applications with one and the same device. We should therefore prepare to take advantage of this to increase the flexibility, productivity and quality of manufacturing. The ability to perform everything from micro to macro materials processing with the same laser on one and the same machine bears an enormous potential for digital manufacturing and is particularly attractive for small and medium-sized enterprises.

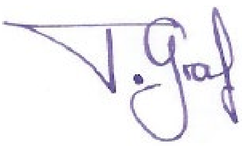
The development of such versatile laser machines requires novel approaches to system engineering to be able, for instance, to simultaneously increase the feeding rates, the dynamics, and the precision of machines and to integrate the handling and the supplies required for the different processes. Additionally, the systems should be equipped with a suitable artificial intelligence, for example to autonomously decide on the optimum sequence of the various processing steps and the optimum processing parameters.

The Stuttgart Laser Technology Forum SLT 2020 was once again meant to give an outlook to the future of laser technology with a series of keynotes on the subjects above, and highlighting the current developments and achievements: the latest developments in the field of laser sources were to be discussed along with the latest advances in fiber-based beam delivery, optical scanners, and real-time process control. In the field of materials processing, presentations were confirmed on fascinating new applications that benefit from the recent developments of modern laser systems, their applications ranging from high-precision drilling to the fundamentals of additive manufacturing, welding, and cutting.

The mission of the SLT is to address laser technologies for materials processing in a fundamentally scientific and yet comprehensible manner with a strong contribution by international and German research institutions and to exemplify the scientific conclusions through presentations on corresponding industrial implementations.

The live event had to be canceled this year due to Covid-19, but fortunately, this issue of PhotonicsViews brings you up to date with no less than nine technical articles based on the presentations planned for SLT 2020.

I wish you inspiring reading!



Prof. Dr. Thomas Graf
Institut für Strahlwerkzeuge (IFSW)
University of Stuttgart

SLT 2020 postponed

new date:
21 – 22 June, 2022

www.twitter.com/photonicviews

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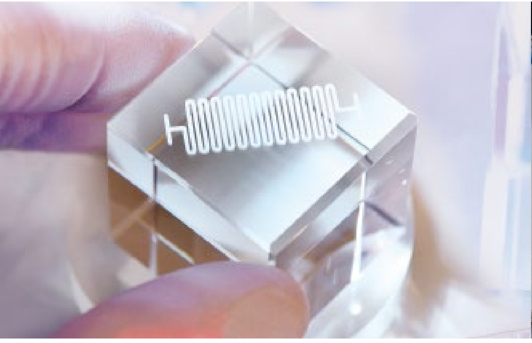
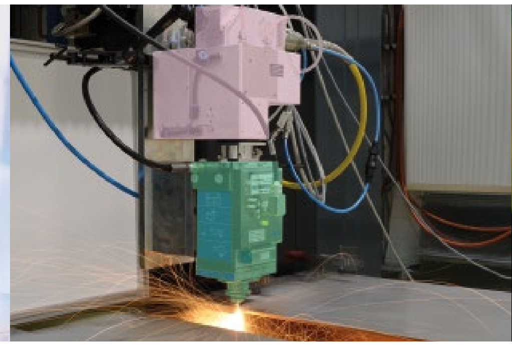
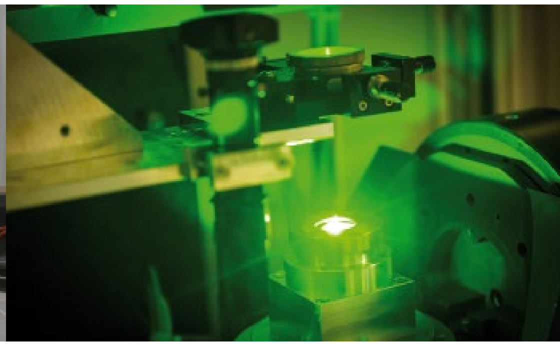
PhotonicsViews
OPTICS • PHOTONICS • LASER TECHNOLOGY

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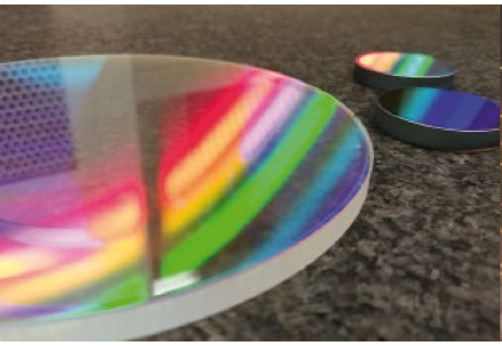


Cover:
Fiber coupling to polarization-maintaining fibers and collimation – measured fiber parameters help to chose the best coupling and collimation optics, p. 32
(Source: Schäfter+Kirchhoff)

Edmund Optics' Opens New Indian Office

The provider of optical and imaging components Edmund Optics recently opened a new office in the Bangalore district of Karnataka, India. Along with it comes a full-service website and technical support from local engineers to provide improved service to local customers and underline EO's commitment to the region. The company has expanded its global presence rapidly over the past decade and will be leveraging the global infrastructure already in place to benefit Indian customers.

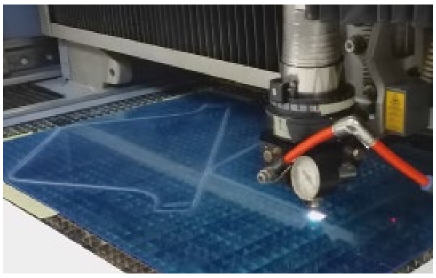
For over a decade, EO has conducted business in India through the support of sales representatives and distributors. During this time, the company proactively partnered with businesses developing products to support life-changing applications in the market, such as a medical device company that helps Indian citizens by bringing necessary eye care to rural regions of the country.

"Asia has already been a primary focus of Edmund Optics for many years, not only for the purpose of serving customers but also to build relationships and connect with the market," stated Timothy Paul Kennedy, director of Edmund Optics India and senior director of sales and marketing, Asia. "We are dedicated to better understanding the dynamics of the multitude of cultures in the region."

www.edmundoptics.com

The India team, from left to right: Adarsha Sarpangala (imaging key account manager), Deepthi Sasikumar (technical engineering manager), Dasharatha Rana (business development engineer. (Source: Edmund Optics)

Helping in the Fight Against COVID-19



A Luxinar laser cutting Perspex to make face shields (Source: Luxinar)

Laser manufacturer Luxinar is supporting a number of its customers, partner organizations, and colleagues in the fight against coronavirus.

A major partner, Ron Dearing University Technical College in Kingston upon Hull, has supplied Perspex sheets to Luxinar so that colleagues in the company's applications laboratories can laser cut and engrave visors. This is in support of the Hull school's initiative to create face shields for key healthcare workers battling coronavirus.

Also, in response to the UK's National Health Service call for 3D-printed parts, colleagues at Luxinar are using printers that they have either borrowed or made in-house to produce face masks for NHS health workers throughout the country. Luxinar is supplying the materials and the 3D-printed parts are being sent to a company for assembly and sterilization.

www.luxinar.com

TEKA: A Quarter Century of Clean Air

On 1st April 1995, Erwin Telöken and Jürgen Kemper applied to register the company TK, now known as Teka Absaug- und Entsorgungstechnologie, and thereby laid the foundations for an enterprise which now markets suction and filter equipment throughout the world. It all started with a small black box which held a lot of potential. Working initially as a two-man business, they developed and built their first suction unit for dental and laboratory technology.

Nowadays, with a workforce of some 150 employees worldwide, the suction equipment manufacturer boasts a broad portfolio, from mobile and stationary units, through indoor air solutions for hall filtration and on to complex system solutions for sectors such as the automotive, metalworking and electronics industries.

Teka's managing director Erwin Telöken (r.) and his son Simon (Source: Teka)

www.teka.eu

Coherent opens "Center of Excellence for Fiber Lasers" in Finland

Coherent has expanded its fiber laser operation in Tampere, Finland, and designated the facility as a "Center of Excellence for Fiber Lasers". Fiber lasers themselves have been produced at this location since 2003. Now, in order to further streamline the production flow, Coherent will combine stand-alone fiber laser source assembly and testing at the same site with the manufacture of fiber laser components, laser engines, and combiners.

Coherent's new "Center of Excellence for Fiber Lasers" in Tampere (Source: Coherent)

This center will become the source for all HighLight fiber lasers series, comprising industrial high-power fiber lasers with output powers ranging from 1 to 10 kW and a wide range of beam qualities – including single-mode, multimode, and adjustable ring mode – delivering superior results in a variety of challenging welding tasks. Coherent places particular focus on a new generation of lasers that offer additional benefits, such as a full range of adjustable output powers and dual beam, ring mode, with truly independent center beam and ring beam power control.

The center brings together Coherent's fiber laser manufacturing and testing expertise into more than 53,000 ft² (5,000 m²) of production floor space, including more than 10,000 ft² (1,000 m²) of cleanroom devoted to fabrication of critical optical components. The location will also house an applications lab featuring the full range of Coherent fiber lasers, industrial welding heads, and analysis tools for weld seams.

www.coherent.com

Big in Japan

Jenoptik acquired the remaining 33.42 percent of the shares in Jenoptik Japan Co. Ltd. from its joint venture partner Kantum Ushikata Mfg. Co., Ltd. and thus transferred the joint venture to a wholly-owned subsidiary at an undisclosed price.

Jenoptik Japan, based in Yokohama, has ten employees and generates sales in the single-digit million euro range. The company was founded in 2005 as a joint venture with Kantum and initially started as a sales company for diode lasers. Today its business comprises photonic components, systems and machines from Jenoptik, in addition to diode lasers, above all laser systems, optics and industrial measurement technology.

"Japan is a strategically very important market for our internationalization. We can build on a good foundation and advance the further development in Japan. We will continue to invest primarily in our sales organization and our footprint in Japan. We would like to thank our long-standing partner Kantum for the many years of joint partnership," said president & CEO Stefan Traeger.

With photonic technologies, Jenoptik focuses on OEM customers and system suppliers (tier ones) with production facilities in and outside Japan and is further expanding its proximity to customers. Under the motto "More International", the photonic technology group is structuring and strengthening its international business and sees growth opportunities mainly in Asia.

www.jenoptik.com

Palomar's New Global Headquarters

To meet growing customer demand for its advanced photonics and microelectronic device packaging solutions around the world, Palomar Technologies has moved to a new global headquarters and expanded its facilities to over 110,000 square feet.

"Since acquiring SST International [renamed to SST Vacuum Reflow Systems] in 2015, our global business has rapidly developed with a new customer base and these new facilities make it possible for Palomar to meet the growing global demand for our entire product line," said Bruce Hueners, CEO and president for Palomar Technologies and SST. "Additionally, our Innovation Center, which specializes in contract assembly and process development, has grown substantially and these new facilities will provide a top-notch laboratory, precision manufacturing, and training facilities."

The new headquarters in Carlsbad, CA. (Source: Palomar Technologies)

Palomar has its roots in the aerospace and defense industry and expanded across the segments automotive (lidar and power modules), medical semiconductor/biophotonics, microwave, RF/wireless, 5G, Datacom, telecom and industrial segments, and a few niche markets.

www.palomartechnologies.com

Applied Photonics Award 2020

Fraunhofer IOF has announced the young researcher award "Applied Photonics Award 2020". Students and doctoral candidates can apply from April 1st until June 30th, 2020. The young researcher award of the Fraunhofer Institute for Applied Optics and Precision Engineering IOF will be presented during the Photonics Days 2020 in Jena on September 22th, 2020. Prizes are awarded for the best final theses in the field of applied photonics.

The award recognizes new ideas in the field of applied photonics at an early stage of a researcher's career and is given to final theses that deal with innovative and economically exploitable optical technologies for sustainable living and business. The field of study is irrelevant; non-physicists are also explicitly invited to apply.

This award is handed out for the best final theses

Source: Fh. IOF

related to applied photonics. Besides the prize money, the winners receive the opportunity to present their final theses to a specialist audience and network with representatives of high-ranking companies in the optics and photonics industry for their later career.

All bachelor, master, and diploma theses, as well as dissertations in German or English, that were registered at a German university or technical college in 2019 and evaluated as passed by the supervisor/reviewer until the application is submitted, are eligible to participate.

www.applied-photonics-award.de

OIF and EPIC sign MoU to Strengthen the Photonics Industry

The Optical Internetworking Forum (OIF) and the European Photonics Industry Consortium (EPIC) signed a memorandum of understanding to strengthen the photonics industry on an international level, bringing together members and knowledge to better serve the industry. The collaboration is focused on cooperative activities involving industry endorsement of standards and technology roadmaps. It encourages cooperation between the members, including participation at events, writing joint articles, collaboration on information exchange and promotion, and advisory mandates to develop an efficient and sustainable industry. Dr. Jose Pozo, CTO of EPIC, said: "Having OIF on board as a partner brings the opportunity for EPIC members to form global alliances with the companies driving the standards in electro-optical digital communication. The main goal of this cooperation is to facilitate the communication between different parts of the value chain towards building an optical platform compatible with the 112-Gbps standard for serial electrical links, which is currently being developed by OIF."

"The collaboration helps us promote the development and deployment of interoperable networking solutions and services by creating Implementation Agreements for optical networking products, network processing elements and component technologies," said OIF president Nathan Tracy.

www.oiforum.com
www.epic-assoc.com

IFR Elects Milton Guerry as New President, Klaus Koenig Appointed Vice President

The executive board of the International Federation of Robotics (IFR) elected Milton Guerry of Schunk USA as new president. Klaus Koenig of Kuka Robotics has been appointed as IFR's new vice president.

Guerry has held the position of IFR vice president since December 2019 and prior to that for a two-year term. He succeeds Steven Wyatt of ABB, Switzerland, who is leaving ABB. He held the rotating post of president since December 2019.

Guerry heads the Schunk USA team as its president based in Morrisville, NC. He joined Schunk in 2000 and has held various leadership roles, assuming his current role as president in 2007. Milton is a member of the Robotic Industries Association's (RIA) board of directors. He began his career in the automotive industry in a number of functions.

Klaus Koenig serves as CEO of Kuka's robotics division based in Augsburg, Germany. He joined Kuka AG in


(Source: IFR)
Milton Guerry


(Source: Kuka)
Klaus König

July 2017 as COO. Before, he had held various leadership positions in the German automotive industry. During his career he also took on international jobs, with multi-year assignments operating out of Canada and Italy. Klaus holds a degree in mechanical engineering from RWTH University, Aachen, Germany.

https://ifr.org

Physik Instrumente – The Next Generation

Physik Instrumente (PI) has implemented a quiet and long-planned generational


(Source: Physik Instrumente)
Markus Spanner, PI's managing director since January 2020

change in its management. After 42 years as managing director, Dr. Karl Spanner has now ultimately handed over the management of the company to his son, Markus.

"Our technologies have enormous potential to make our customers' applications even more successful," says Markus Spanner, who is managing director since the beginning of the year. He has held managerial responsibility as managing director finance and controlling at PI over the last eleven years.

Markus Spanner has established an extended management team to take a structured approach to achieving the new targets. He will be assisted by Dr. Peter Schittenhelm (COO), Dr. Markus Czanta (CTO), Stéphane Bussa (CSO) and Heiko Brehm (CFO).

PI employs more than 1300 people all over the world.

www.physikinstrumente.com

Applied Photophysics' New CEO, President

The board of directors of Applied Photophysics has appointed Tim Flanagan as CEO and board member. Additionally, Marc Neglia has been appointed president to lead operations in the Americas and will also be an executive member of the board of directors. Tim succeeds Paul Walker who has been acting as interim CEO for the past year and will resume his previous role as a non-executive member of the board.

Tim Flanagan has over 25-years of leadership experience in the life sciences tools markets and has previously held senior roles in Bioquell, GE Life Sciences, MicroCal, Bio-Rad, and Beckman Coulter.

Marc Neglia has more than 25 years of senior leadership experience, which


(Source: Applied Photophysics)
Tim Flanagan

includes a decade of leading sales teams that have delivered strong growth in the biotech and scientific sectors. He holds a BS in electronics engineering from Thomas Edison State University and an MBA from Drexel University.

www.photophysics.com

Florian Lendner Manages GFH Alone

Anton Pauli, who was CEO of GFH for many years, departed on December 31, 2019, from the company's management. Florian Lendner has been managing the company alone since the beginning of the year. As acting shareholder, Mr. Pauli will still assist as a consultant.

Main shareholder Prof. Dr.-Ing. Hans Joachim Helml has gratefully thanked Mr. Pauli for his outstanding performance as managing director and its positive-associated development that made GFH a global leading company in the laser micro machining industry. „We are convinced that Mr. Lendner will carry on this success story and that he and his team will continue developing the company customer and market orientated," says Prof. Helml.

GFH GmbH was founded in 1998 and is headquartered in Deggendorf, Lower Bavaria, Germany. The company's competencies range from process development to prototyping and small series production in micro-technology to the development and construction of special machines according to customer specifications.

www.gfh-gmbh.de


(Source: GFH)
Florian Lendner

Coherent Appoints Andy Mattes as New CEO, Mark Sobey New EVP and COO

(Sources: Coherent)

Dr Andreas "Andy" W. Mattes (l.), Mark Sobey, PhD

Andreas "Andy" W. Mattes, previously senior advisor at McKinsey & Company and president and CEO of Diebold Nixdorf, has been named as the company's new president and CEO, and a member of the board of directors, by Coherent and its board. The April appointment follows the announcement a year ago that Dr John R. Ambroseo will retire from his positions as president and CEO and member of the board no later than April 2021. Ambroseo becomes a special advisor to the company until the end of next year, ensuring a smooth and successful transition.

On Andy Mattes' recommendation, the board has also appointed Dr Mark Sobey, a 13-year senior executive of the company, as new executive vice president and chief operating officer, effective immediately.

"Following an extensive and thorough search, we are delighted to welcome Andy Mattes as new CEO, ushering in an exciting new chapter of the company's long and storied history", said Dr Garry Rogerson, Coherent's chairman of the board. "Andy is a proven leader and has significant experience running and growing global technology businesses, including hardware, software and services."

Rogerson added, "We thank John for all he has done over the past 18 years as CEO to bring us to where we are today. I am looking forward to working closely with Andy Mattes in the years to come."

Mattes, a US-German national, is an experienced global technology business executive with more than thirty years of management experience. He most recently served as a senior advisor at McKinsey, where he focused on advising international businesses on high-impact transformations, agile change and positioning companies for growth. Prior to this, he served as president and CEO of publicly traded Diebold Nixdorf, a multinational financial and retail technology company. Under his leadership, Diebold Nixdorf became the largest ATM provider worldwide, through a re-shifting of the company's focus to services and software along with the successful execution of one of the largest US-German cross-border corporate mergers. Prior to this, he spent more than five years in executive leadership positions at Hewlett Packard, including leading worldwide sales and running the Americas enterprise services business, and over twenty years at Siemens. He has also served on numerous boards of private and public technology companies over the past twenty years.

www.coherent.com

Sam Rubin to Head LightPath

Vertically-integrated global manufacturer, distributor and integrator of proprietary optical and infrared components and high-level assemblies LightPath Technologies announced that Sam Rubin joined the company as president and CEO effective March 9, 2020. He has also been appointed as a member of the board of directors and will stand for election at the next annual stockholder meeting to be held in November 2020. Mr. Rubin succeeds LightPath's current president and CEO, J. James Gaynor. Mr. Rubin was formerly general manager at Thorlabs.

In Mr. Rubin's prior senior executive role at Thorlabs, he was responsible for the imaging systems division, a standalone organization with its own sales and marketing, as well as global responsibility for all of Thorlabs' life science activities.

Prior to joining Thorlabs, he co-founded XLight Photonics, an optical communication startup, which was later sold to a telecommunications private equity firm. Rubin holds a BSc in electronic engineering from Ben Gurion University, an MBA from NYU, and is a graduate of the executive education, program for leadership development at Harvard Business School.

Robert Ripp, chairman of the board, said, "Sam has demonstrated leadership in managing complex organizations and improving their performance. He has successfully increased revenue and profit growth in multiple assignments. Sam is also very capable of providing a strategy that we believe will better position LightPath for the future and will deliver enhanced value."

www.lightpath.com

Essilor Reorganizes, Integrates with Luxottica

(Source: Essilor)

Paul du Saillant

In view of recent world changes, it has become necessary for Essilor to speed up its integration with Luxottica in order to build a more resilient, flexible and agile combined organization. To this end, Paul du Saillant, 61, has been appointed CEO of Essilor. He succeeds Laurent Vacherot, 64, who has decided to retire.

Du Saillant has named a single combined management committee in order to optimize the integration process. This younger and more focussed executive team brings together ample experience of the combination with Luxottica in many key areas.

In parallel, the board of directors of Essilor SAS is being streamlined to five members from the previous fifteen, with a view to simplifying decision processes and reducing the overlap with the EssilorLuxottica board.

"I would like to warmly thank Laurent for leading our Company in several key roles over the past 28 years. He leaves it in very good shape", commented Essilor chairman Hubert Sagnières.

Du Saillant has served as Deputy CEO of Essilor since 2019 and as COO from 2010 to 2019. He joined the group in 2008 as director of strategy. Prior to this, he was COO of Lhoist Group and senior EVP of Air Liquide. He holds a degree from École Centrale de Paris.

www.essilorluxottica.com

Osram Appoints Kathrin Dahnke as CFO After Ingo Bank's Transfer to AMS

Osram CFO Ingo Bank has been appointed CFO of AMS AG as of May 1, 2020. AMS, a sensor and semiconductor specialist based in Premstätten, Austria, successful launched a takeover offer in 2019 for all the outstanding shares of Osram Licht AG. Osram and AMS had agreed to possibly expand the number of AMS board members through the course of the acquisition with the appointment of an Osram board member.

The acquisition remains subject to regulatory approvals. These approvals and subsequent completion are expected before the summer.

"I would like to thank Ingo Bank very much for his achievements over the past three and a half years. He has been a major asset for Osram, making a significant contribution to the realignment of the company from a lamp manufacturer to a high-tech lighting concern. His financial expertise and his knowledge of the lighting industry will be of great benefit in the continuing process of combining Osram and AMS," said Peter Bauer, chairman of the Osram supervisory board, and continued: "The appointment of Ingo Bank to the AMS board is an important step for the future integration of the two companies and ensures continuity in management."


Ingo Bank
(Source: Osram)

In mid-April, the supervisory board of Osram Licht AG appointed Kathrin Dahnke (59) as new member of the management board. Effective April 16, she succeeded Ingo Bank and became responsible for the financial business of the high-tech company. Dahnke was most recently a member of the management board of the Neuss-based conglomerate Werhahn KG, which operates in the fields of building materials, consumer goods and financial services.

"Kathrin Dahnke has extensive experience with medium-sized as well as listed companies in transformation. She has gained great recognition in the industry as a versatile and crisis-tested financial manager and supervisory board member," said Bauer. "We are delighted that she is taking on the continuing challenges facing our company with her proven financial expertise."


Kathrin Dahnke
(Source: Osram)

In her career to date, the business graduate has worked in various industries, including Beiersdorf AG, Westdeutsche Landesbank and the former Gildemeister AG, always with a clear focus on the financial sector. Through her membership of the supervisory boards of Fraport AG, B. Braun SE and Knorr-Bremse AG, she also brings extensive and comprehensive industry knowledge to her new position.

www.ams-osram.com

New MPL Microphotonics Research Group

Pascal Del'Haye has been heading up the new microphotonics research group at the Max Planck Institute for the Science of Light, MPL, in Erlangen since January this year.

The main research focus of the group will be on integrated microphotonic devices and nonlinear optics in whispering gallery mode microresonators. These resonators are tiny rings with diameters around the size of a human hair that can store light for up to a million roundtrips. The long photon storage times in these resonators allow them to "charge" these devices with circulating optical powers of up to a Megawatt, which enables studies of a large variety of nonlinear optical effects. In integrated optical circuits, the optical microresonators can convert a single wavelength laser into an optical frequency comb, which can be used as an optical rulers with applications ranging from distance measurements to precision spectroscopy and channel generation in telecommunications networks.


Pascal Del'Haye
(Source: MPL)

An additional research area of the group is the study of the interactions of counterpropagating light in ring resonators. Their effect can be used for the realization of chip-integrated optical diodes, gyroscopes, and photonic switches.

https://mpl.mpg.de

Gurevich Heads Laser Center Muenster

Evgeny Gurevich joined the Laser Center FH Münster (LFM) at the University of Applied Sciences in Muenster, Germany, in October 2019 as a new director and was appointed associate professor in laser technology at the department of engineering physics following the retirement of Prof. Dickmann.

Prof. Gurevich was born in 1977 in St. Petersburg, Russia, where he graduated in physics at the State Technical University in 2000. He obtained his PhD degree in physics at the University of Muenster in the field of gas discharge physics in 2004. After two postdoctoral positions at the Max Planck Institute for Dynamics and Self-Organization in Goettingen and the ISAS Institute for Analytical Sciences in Dortmund, he was appointed as an assistant professor at Ruhr University Bochum in 2012. Here he supervised a group at the chair of applied laser technologies working on material processing with ultrafast lasers and the generation of nanoparticles upon laser ablation.

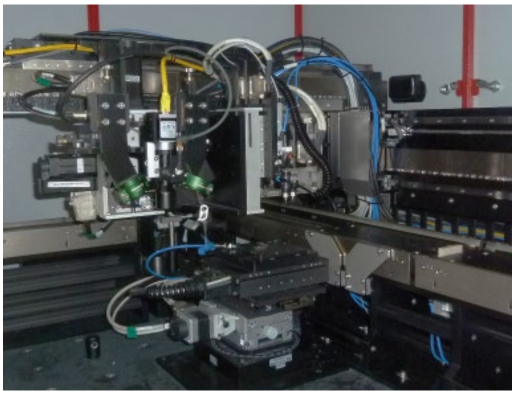

Evgeny Gurevich
(Source: W. Gerharz / FH Münster)

During the last ten years, he mainly focused his research on experimental and theoretical studies of laser-matter interaction, especially on physical mechanisms of formation of laser-induced nanostructures.

www.lfm-online.de

Pick and Place Station

Manufacturer: nanosystec.
Supply: Pick and place station "Nano-Place" for demanding micro assembly tasks that uses various precision assembly technologies like gluing, eutectic bonding, soldering, welding, etc.
Features: The gantry configuration offers a large unobstructed working area with easy access for loading the components to be processed. In order to achieve the most productive solution, the design and process flow will be tailored to the application: *Gluing* with epoxy and subsequent UV curing is widely used for the permanent placement of lenses, prisms, mirrors, VCSEL's and similar elements. The resin is dispensed by either time/pressure units, jetting dispensers or volumetric instruments. – *Eutectic bonding* combines the precise placement with high thermal conductivity. Typical examples for such devices include opto-electronic chips which are sensitive to temperature changes, such as modulators, Silicon Photonics assemblies or semiconductor laser dies. – *Selective laser soldering* is the right choice for attaching extremely thin wires to miniature contact pads or insert heat-sensitive components into PC boards. – *Laser welding* joins two parts without filling material. This joining technology provides maximum mechanical strength and is widely used for space applications. – *Micro ablation* can be integrated into the process flow as an additional inline process.
The powerful machine vision capability allows for measuring the position of the objects in all dimensions with less than 1 µm error. The motion control elements match this performance: Linear optical encoders provide 5 nm resolution for controlling the linear motors. Depending on the processes, the station changes the tooling automatically. A variety of device grippers allow for the ideal adaptation to the respective gripping task: pneumatic or electrical parallel grippers with two jaws, vacuum grippers or combinations of these.



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Website: www.nanosystec.com

Self-aligning Raman Imaging Microscope

Manufacturer: WITec.
Supply: New generation of the confocal Raman microscope "alpha300 apyron" that can – thanks to the newly developed "AutoBeam" technology – self-align and self-calibrate. This substantially reduces the researcher's experimental workload by requiring less user input, enhancing reproducibility and eliminating potential sources of error.
Features: Software-driven automation allows the microscope to be operated completely remotely, whether in an environmental enclosure such as a glove box, or from another location. This is made possible by a complete set of "AutoBeam" opto-mechanical components, a new and versatile tool kit that can be configured individually. New functionalities include polarization-dependent measurements with motorized polarizer and analyzer rotation, push-button spectrometer connection and signal maximization, and automated adjustment of both iris diaphragms.
Available with a wide variety of excitation wavelengths from the ultraviolet through the visible into the near infrared, the microscopes can be equipped with up to three ultra-high throughput "UHTS" spectrometers and their accompanying range of detectors. Raman imaging and correlative measurements are defined, executed, saved and evaluated with "Suite FIVE" software and intuitive "EasyLink" handheld controller.
The user-friendliness makes advanced confocal Raman imaging accessible to researchers of all experience levels and fields of application. Scientists working in materials science, environmental science and microparticle analysis, life science, food science, geology, pharmaceutics and many other fields will benefit from automated alignment routines that provide consistently optimized performance. The alpha300 apyron accelerates both the experimental setup and subsequent measurement workflow.

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Industry's Smallest Slide with Anti-Cage Creep Technology

Manufacturer: PM.

Product: New "MSR" series of miniature slides. They have been developed according to the raising demand for smaller, compact linear slides for use in dynamic

and accurate application and allow an increased output in micro-assembly machines and pick-and-place machines. The MSR miniature slide can also be used in applications for repetitive minor movements in tight spaces in combination with relatively high loads.

Features: The miniature slide is offered in six particular sizes with different lengths and strokes, from a rail width of 4 mm and a stroke starting at 5 mm to a rail width of maximum 15 mm and max. travel of 112 mm. The smallest miniature slide "MSR 4" has an overall height of just a 4 mm and overall width of 7 mm and 10 mm length. All parts are manufactured from corrosion-resistant steel; for the bearings high-precision cylindrical rollers are used. These rollers are arranged in a crisscross pattern, i. e., that each roller is oriented at a 90 degrees angle relative to the one next to it, and being kept in a stainless steel cage. This design enables the slide to support loads and moments from all directions and it also contributes to high stiffness. The maximum acceleration is determined at 200 m/s^2 and maximum load capacity is 7.819 N. The integrated anti-cage creep mechanism "ACCI" will retain the roller cage in position under the most demanding conditions, like high accelerations and vertical mounting orientation. ACCI guarantees that the stroke always can always be achieved, even under the harshest environments. For easy mounting and high precision, the miniature slide table and center rail have a standard attachment hole pattern with countersunk and treaded holes. Thus the user can mount the slide easily and simply into the application. All the miniature slides are in-house preloaded by means of geometry pairing of the cylindrical rollers within tolerances of just 0.5 µm. This results in nearly frictionless motion with a high precision stroke and a smooth running behavior. –

PM is a technologically driven family business that is active worldwide in the field of precision linear guides, linear slides and customized motion systems. The linear guides and slides are known for their high precision, low friction and smooth running performance. Another main business is the supply of engineered-to-spec motion systems. The products are made in the Netherlands and meet the strictest quality requirements.

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Ultra-Low-Noise Semiconductor Lasers

Manufacturer: Thorlabs.

Product: Ultra-low-noise 1550 nm semiconductor lasers "ULN15PT" with PM fiber and temperature tuning.

Features: The product line offers an unrivaled combination of high output power (> 100 mW), narrow linewidth (< 100 Hz), and ultra-low relative intensity noise (RIN < –165 dB/Hz). Based on a patented Fiber Bragg Grating (FBG) external cavity design, these lasers provide output centered at 1550 nm. Each laser is packaged in an extended 14-pin butterfly housing featuring two thermoelectric cooler elements for precise laser and FBG control and stabilization. Offered in both polarization maintaining and single mode fiber variants, these lasers can be optimized for wavelength tuning by temperature or current depending on the application. The new lasers complement the extensive offering of single frequency lasers, which span wavelengths from 671 nm to 11 µm.

Applications: Remote sensing, optical comb generation, and RF/microwave photonics.

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Coherent Passes 50,000 Laser Milestone for Sapphire OPSLs

Coherent has now passed the milestone of 50,000 units shipped for the company's "Sapphire" family of compact CW visible lasers. As the first solid state alternative to bulky and energy inefficient gas lasers at the critical 488 nm wavelength, these lasers enjoyed early strong success mainly in life sciences and related instrumentation. However, the power scaling and wavelength scaling inherent to "Sapphire's" optically pumped semiconductor laser (OPSL) technology has enabled the company to continuously expand the product lineup with new wavelengths and power levels over the laser's 20-plus year history to meet the demands of new and changing applications. For example, "Sapphire" is currently offered with a choice of nine different standard wavelengths between deep blue (458 nm) and orange (594 nm) to support new applications in metrology and other techniques in diverse industries including semiconductors. Yet all of these compact lasers still feature exactly the same form and fit, which has proved a particularly popular advantage for OEM customers with products often tied to quite different life cycles. In addition to standard products, custom versions of "Sapphire" with unique wavelengths and other output properties continue to be developed for OEM customers.

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Bitelecentric Lenses for Highest Requirements

Manufacturer: Sill Optics.
Product: Three new lenses for large sensors used in industrial machine vision with different field sizes. The bitelecentricity of the optics ensures smallest angles on the sensor and optical vignetting and shading effects are avoided. They satisfy the high performance demand and also ensure a color correction for broadband illumination or color sensors.
Features: The lenses "S5LPJ1762" and "S5LPJ6162" are designed for a sensor size of 24 mm and a pixel size of 3.45 µm (e.g. Sony ImX387). "S5LPJ1862 "is recommended for 17.6 mm sensor diagonal and 3.45 µm pixel size (e.g. Sony IMX253). Furthermore, all three lenses are applicable for the latest Sony series "Pregius S" for 2.74 µm pixel size and 19.2 mm sensor diagonal (e.g. Sony IMX530). To ensure the compatibility with color sensors or a VIS broadband illumination, these lenses are color corrected for 400 to 700 nm, that means only a small lateral color aberration over the complete VIS range is visible. For NIR applications, transmision has been optimized up to 900 nm. All mentioned lenses are available with C-Mount, M35x0.75 and M42 mount.

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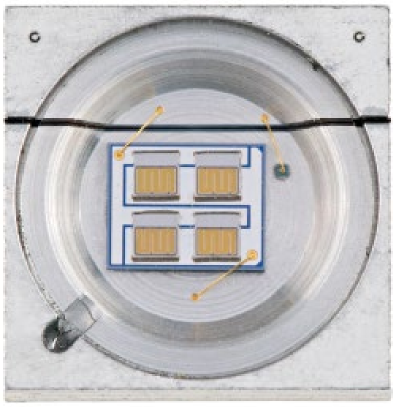
UV-C LEDs for Disinfection and Sterilization

Manufacturer: Seoul Viosys.
Distribution: IMM Photonics.
Supply: Powerful UV-C LEDs "CUD8AF1D" and "CUD8AF4D" (1chip or 4chip SMT devices) with 19 mW and 60 mW high power output, respectively, at 275 nm.
Features: The view angle for both LED types is 120 degrees. The aluminum metal body ensures high thermal conductivity. The small size and low energy consumption of the UV-C LEDs allows for quick and easy integration into existing design concepts.
The main applications of UV-C LEDs are the disinfection and sterilization of surfaces, water and air. Possible fields of application are household appliances, sanitary facilities, analytical equipment, spectroscopy and medical technology.



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Flicker Measurement with Enhanced Frequency Range

Manufacturer: Gigahertz-Optik.
Supply: Spectral light meter "BTS256-EF" with flicker measurement function for lamps and luminaires in general lighting. The versatile and reliable measurement device now has an enhanced flicker frequency range up to 40 kHz.
Features: The newly updated device offers a wide selection of measuring quantities relevant in general lighting and hence acts as universal measuring device in its field. Besides illuminance and spectrum, there are many additional, more specialized properties of light sources that need to be measured like their performance in context with human centric lighting (HCL), their flicker properties, their efficiency in plant growth and many more. Now, the device has been updated to record and analyze even higher flicker frequencies than before: It supports signal sampling with up to 40 kHz. Furthermore, this enhancement does not only apply to brand-new devices: By applying the latest firmware and software updates, this new feature also becomes available for devices that have been out in the field for many years. Updates are offered on request.

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Compact Ultrafast Laser Lowers Costs for Microscopy and Other Applications

Manufacturer: Coherent.
Supply: Completely new suite "Axon" of compact fixed-wavelength femtosecond lasers, designed from inception to deliver lower cost, reduced complexity, and smaller footprint. The lasers address demanding applications such as multiphoton microscopy (MPE), nanoprocessing, semiconductor metrology, and THz spectroscopy.
Features: The first two models of the compact (212 mm × 312 mm × 62 mm) air-cooled laser have output wavelengths of 920 nm and 1064 nm, with other wavelength versions expected soon. All "Axon" lasers feature the same form, fit and function, including 1 W of average power with integrated, software-controlled GVD pre-compensation. To further simply adoption of this laser, its output matches the existing femtosecond laser oscillators: short (< 150 fs) pulse width, a clean temporal profile and 80 MHz pulse repetition rate.
Applications: The 920 nm laser is designed for GFP and related imaging probes, and Ca^{2+} indicators such as GCAMP. The 1064 nm version matches well with red shifted Ca^{2+} indicators and red fluorescent proteins. Other applications include two-photon polymerization, material nanoprocessing and semiconductor and thin film metrology. The 1064 nm model is also an excellent tool for supercontinuum generation thanks to its high fidelity femtosecond pulse quality.

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Inexpensive and Environmentally Friendly LEDs

FET Open project ENABLED develops sustainable light sources from bacterial production

LEDs from bacterial production – the basis for this vision is being laid at the Institute of Biochemistry at Graz University of Technology, where Gustav Oberdorfer (pictured) and his team are designing proteins with the help of simulation software. "For this project, we're analyzing fluorescent protein structures from nature and testing how we need to modify them so that they bind different fluorescent organic molecules," explains Oberdorfer. LEDs emit short-wave blue light which is then absorbed by a layer of inorganic lighting materials and converted into light of longer wavelength. The entire spectrum then results in the white light as we perceive it.

Oberdorfer developed the idea for the project together with cooperation partners from Spain and Italy who worked on the topic independently of each other and were able to achieve promising success. Rubén Costa from the Madrid Institute for Advanced Studies (IMDEA) developed a stable organic LED coating as an alternative to conventional LED coatings, which usually consist of problematic rare earth minerals. The mixture consists of organic polymers in which he and his team managed to embed fluorescent proteins. These fluorescent proteins are found in marine organisms and are used by them as a light source for hunting, communication and self-protection. The luminosity that can be achieved with such devices is however still too low to use them in lamps that illuminate entire rooms.

Researchers of the department of chemistry at the University of Turin led by Claudia Barolo are in turn dealing with the synthesis of organic dyes that have a good light emitting efficiency and are used in organic light-emitting diodes (OLEDs). However, many of these dyes are costly and complex to synthesize. As part of the FET Open project, Barolo and her team are now looking for a suitable dye that can be produced with minimal effort and that can be modified so that it can be incorporated into proteins as an artificial amino acid.

The FET Open project ENABLED now brings together the successes of all groups. The goal is to use bacteria to develop completely new artificial fluorescent proteins. To this end, the Graz biochemists first simulate thousands of different hypothetical proteins that are to bind specifically to the synthetic dyes. A handful of these proteins – namely those closest to the structure of naturally fluorescent proteins – are then ordered as synthetic DNA constructs. The next step is to investigate whether

(Source: Lunghammer / TU Graz)

Gustav Oberdorfer has been researching at the TU Graz Institute of Biochemistry since February 2018.

these proteins really bind the dyes for which they were designed. As soon as this is confirmed, these new, artificial fluorescent proteins will be integrated into the polymer matrix and tested for their suitability with regard to bio-LEDs.

"The plan is that we will 'harvest' the proteins from the bacterial cell; in other words, we will be able to grow some part of the light sources," said Oberdorfer, hoping for a proof of principle at the end of the project in four years' time.

www.tugraz.at

Mobile NIR Spectroscopy Solution First Shown at Virtual Lab Show

Powerful combination of sensor, data analytics, and molecular expertise

Trinamix, a wholly-owned subsidiary of BASF SE, launched a mobile near-infrared spectroscopy solution. The company offers all the required functions in a single, handheld device: mobile and robust hardware, precise data and material analytics and excellent molecular and chemical expertise.

Informed and healthy life decisions are ones that everyone tries to make, but sometimes the visible information presented to the eyes is just not enough. The new mobile NIR spectroscopy solution aims to improve on-the-spot decision-making and is now affordable and accessible beyond factory and laboratory applications.

Trinamix has developed a proprietary measurement device, including an in-house produced infrared semiconductor, to quickly and accurately analyze the molecular structure of different materials in a wavelength range up to 2.5 µm. These IR semiconductors are very small and have a high detectivity, and as such enable the creation of this miniaturized near-infrared spectrometer: a "lab in your pocket".

Applications range from agriculture to food and beverage testing as well as chemical and industrial processes. Inbound control, quality checks, in-the-field analytics, material sorting and identification are among the use cases that Trinamix can support. The company's production capabilities are designed for high-volume production runs all the way up to consumer electronics-level supply demands.

Mobile near-infrared (NIR) spectroscopy solution (Source: Trinamix)

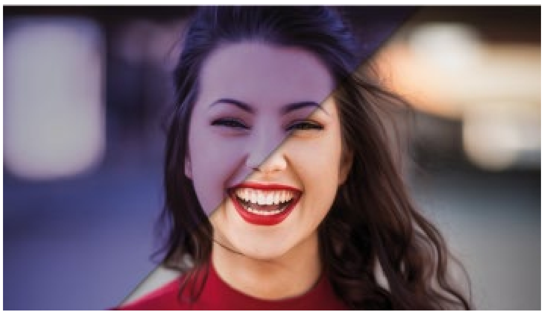
Trinamix presented its mobile NIR spectroscopy solutions online at the Virtual Lab Show from March 31 – April 3.

www.trinamixsensing.com

The Most Advanced Spectral ALS Sensor

Precise light-source identification and accurate white-point balancing in all lighting conditions

At the CES Las Vegas, AMS launched its AS7350, described by the company as the market's most advanced spectral ambient light sensor (ALS) for high-end mobile phone cameras. The new sensor enables the highest quality images even in situations with extreme color contrast, or under non-ideal/mixed light source conditions, enabling professional grade photography using a consumer device. For the first time, the AS7350 achieves this by enabling light source identification via spectral reconstruction to achieve unprecedented automatic white-point balancing accuracy under any light conditions.



The AS7350 spectral ALS sensor provides precise light-source identification and enables accurate white-point balancing in all lighting conditions. (Source: AMS)

By accurately identifying ambient light conditions, the AS7350 promises unparalleled image quality even in high color contrast scenes, and helps vendors continue on the path to delivering professional-grade camera quality in mobile devices. Reiner Jumpertz, vice president and general manager of the color & spectral sensors business line at AMS, says, "For many consumers, camera performance is the decisive factor in choosing a premium mobile phone: they research the models deeply, guided by professional tests and user reviews. In what we believe is a turning point for professional picture quality using consumer devices, smartphone vendors can now use the AS7350 spectral ALS to detect and identify ambient light sources to obtain extremely accurate white balance information – above and beyond normal RGB sensors – thereby delivering world-class picture quality to their customers."

Professional photographers understand the effects of different illumination sources on the quality of a photograph and its color rendering. White-point balancing, adjusting the image's treatment of color for the distorting effects of ambient light is one of the core functions of advanced photography. Providing advanced white-point balancing capabilities to consumer devices enables imaging quality previously reserved for the professional camera market.

The AS7350 identifies any type of light source. The spectral ambient light sensor features eleven channels: eight equally spaced in the visible, one flicker, one NIR, and one clear channel, all in a tiny 3.1 × 2.0 × 1.0 mm LGA package. The flicker channel detects artificial light sources with flicker frequencies from 50 Hz to 3 kHz and beyond.

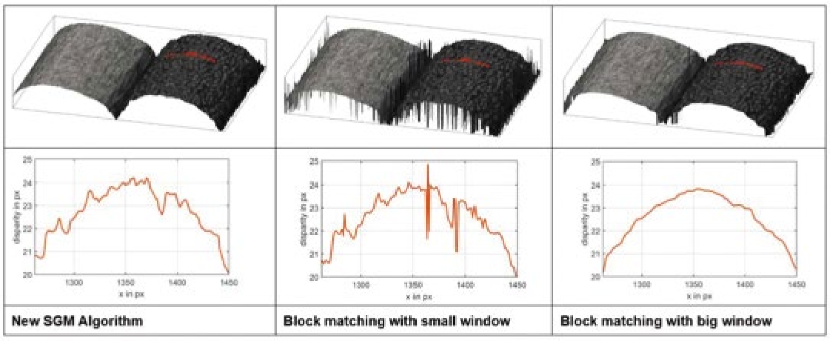
https://ams.com

New Reconstruction Algorithm Sharpens Accuracy of 3D Machine Vision Imaging

Semi-global algorithm superior to existing block-matching in uncovering defects

Chromasens, a provider of linescan machine vision technology, introduced an advanced 3D reconstruction method to its CS-3D-API (application programming interface) library that empowers integrators to build, deploy, and scale higher value 3D imaging systems capable of improved detection of extremely small defects. Based on the semi-global matching algorithm (SGM), it combines global and local stereo methods for more accurate, pixel-wise matching at low runtime.

Chromasens 3D stereo linescan cameras have been unlocking new insights far beyond the capabilities of standard 2D cameras for over a decade, especially in the semiconductor and automotive sectors. By measuring the precise location, shape, volume, surface angles, and degrees of flatness of objects under inspection at extremely high resolutions, these cameras ensure manufacturers of defect-free products ranging from ball bearings to fresh fruit.



The semi-global matching (SGM) algorithm is more accurate at object borders, fine structures and in weakly textured terrain (left), than the existing block-matching (BM) approach (center and right; source: Chromasens)

The new semi-global matching algorithm represents an alternative to the traditional block matching (BM) method used previously with the company's 3D stereo cameras to match corresponding pixels between two images. The primary difference between the two methods is how a matching cost (energy) is computed. For BM, the cost is computed with normalized cross-correlation, while SGM utilizes a specialized Census transformation. As a result, prior knowledge about a surface structure can be incorporated, making the SGM algorithm more accurate in generating 3D point clouds that better identify object borders, and reconstruct fine structures and weakly textured terrain, without artifacts.

www.chromasens.de

New Photon Source for Encrypted Communication

Quantum-enhanced optical systems operating within the 2 to 2.5 µm spectral region

Two of Chromacity's ultrafast laser systems were used in breakthrough research into quantum-enhanced optical systems, which could drive advances in encryption, communication and measurement.

A group of researchers, led by Dr Matteo Clerici at the University of Glasgow's James Watt School of Engineering together with colleagues from the UK, Japan and Germany have demonstrated a new method of generating and detecting quantum-entangled photons at a wavelength of 2.1 micrometers.

The unique, non-classical properties of entangled photons are used in applications including quantum key distribution, allowing uncrackable communications between two parties.

Methods of entangling photons at shorter wavelengths of between 700 and 1550 nanometers are already well-established. However, those wavelengths are vulnerable to interference from the sun's light when they are transmitted over open air, making them difficult to use in applications such as secure satellite-to-ground and satellite-to-satellite communications.

The Glasgow-led team's new method of generating entangled photons further into the infrared at two micrometers wavelength will overcome these problems for the first time.

(Source: Chromacity)

Dr Matteo Clerici, senior lecturer at the University of Glasgow, said: "What we have been able to do is carve out a band in the electromagnetic spectrum where the entangled particles we produce are less likely to be affected by background solar radiation when they're transmitted across free space".

This innovation has benefited from the expertise of UK photonics companies. In partnership with Covesion Ltd, Dr Clerici and his team have developed a new type of non-linear crystal made from lithium niobite. The two entangled photons are generated when short pulses of light from the Chromacity 1040 laser system (pictured) pass through the crystal.

Dr Christopher G. Leburn, commercial director and co-founder of Chromacity, explained how the company's ultrafast laser systems supported the research: "Two of our systems have been involved in this exciting research. Our Chromacity 1040 is the workhorse that allows the generation of entangled photons at 2 µm, while our OPO has been used as a tool to help push the development of single photon detectors used to detect the entangled photons. We are thrilled to see how a mix of our technologies is clearly having a real impact on important cutting-edge research."

Reference: *S. Prabhakar* et al.: Two-photon quantum interference and entanglement at 2.1 µm, Sci. Adv. 6, eaay5195 (2020); DOI: 10.1126/sciadv.aay5195

www.chromacitylasers.com

First All-Optical Stealth Encryption Technology

End-to-end solution includes encryption, transmission, decryption, and detection

BGN Technologies, the technology transfer company of Ben Gurion University of the Negev, Israel, introduced the first all-optical "stealth" encryption technology that claims to be significantly more secure and private for highly-sensitive cloud computing and data center network transmission. The new all-optical encryption innovation was introduced at the Cybertech Global Tel Aviv conference in Israel.

"Today, information is still encrypted using digital techniques, although most data are transmitted over distance using light spectrum on fiber optic networks," said Dan Sadot, professor and chairman of the Cathedra for Electro-Optics at BGU who heads the team that developed the technology.

Using standard optical equipment, the research team essentially renders the fiber-optic light transmission invisible or stealthy. Instead of using one color of the light spectrum to send one large data stream, this method spreads the transmission across many colors in the optical spectrum bandwidth – one thousand times wider than digital – and intentionally creates multiple weaker data streams that are hidden under noise and elude detection. The researchers demonstrated that they can transmit weaker encrypted data under a stronger inherent noise level which cannot be detected.

The solution also employs a commercially available phase mask, which changes the phase of each wavelength. That process also appears as noise but destroys the coherence or ability to recompile the data without the correct encryption key. The optical phase mask cannot be recorded offline, so the data is destroyed if a hacker tries to decode it.

"Basically, the innovation is that if you can't detect it, you can't steal it," Sadot said. "Because an eavesdropper can neither read the data nor even detect the existence of the transmitted signal, our optical stealth transmission provides the highest level of privacy and security for sensitive data applications."

"The novel, patented method invented by Prof. Sadot and his team is highly useful for multiple applications, such as high-speed communication, sensitive transmission of financial, medical or social media-related information, without the risk of eavesdropping or jamming data flow," said Zafrir Levy, senior vice president exact sciences and engineering, BGN Technologies. "In fact, with this novel method, an eavesdropper will require years to break the encryption key. BGN is now seeking an industry partner to implement and commercialize this game-changing technology."

This all-optical technology is an extension of the digital optical encryption method originally invented by Prof. Sadot and his team in collaboration with Prof. Zalevsky of Bar Ilan University.

www.ee.bgu.ac.il

A Supercontinuum Laser for Detection of Skin Cancer

New LC-OCT medical imaging device detects cancer cells early, fast, without biopsies

The new LC-OCT medical imaging device by Damae Medical uses NKT Photonics SuperK supercontinuum white light lasers to detect skin cancer at an early stage, faster, cheaper, and without the need for biopsies. It eliminates unnecessary surgery and it saves lives.

Skin cancer is the most frequent cancer type and it is becoming increasingly common. Currently, a doctor or dermatologist makes a diagnosis, starting with a visual examination of the skin surface. If they observe anything suspicious, they take out a biopsy. The biopsy is examined under a microscope to determine if cancer cells are present.

(Source: Damae Medical)

The LC-OCT diagnostics system for onco-dermatology

The current method is not ideal. It is painful, costly, time-consuming, and unreliable to some extent: around sixty percent of the biopsies do not show signs of cancer while around twenty percent of skin cancers are missed at an early stage.

The LC-OCT device is a new handheld imaging probe that looks deep into the skin, both the dermis and epidermis, in real-time. The device offers high-resolution images to the dermatologist who immediately can tell cancer cells from healthy cells reliably, painlessly, fast, and inexpensively.

Damae Medical has developed the device based on the line-field confocal optical coherence tomography (LC-OCT) imaging technology, powered by the SuperK supercontinuum laser.The broad spectrum of light from this laser enables the delivery of high-resolution images that replace the need for biopsies. Instead, LC-OCT produces "optical biopsies".

The two companies have worked together under the Eurostar financing program to combine the cutting-edge LC-OCT technology, developed by Damae Medical, with the supercontinuum laser technology provided by NKT.

Anaïs Barut, CEO of Damae Medical, explains, "This cooperation is the natural extension of a fruitful collaboration initiated three years ago with the development of LC-OCT. The project has paved the way for the industrial scale-up of an unprecedented combination of technologies in the field of medical imaging."

"It is truly exciting to see how our SuperK white light lasers are enabling this entirely new field of medical imaging. With their broad white light, they ensure the high-resolution images dermatologists need", says Jesper Toft Olesen, product line manager at NKT Photonics. "Damae's device can save lives and we are proud to deliver the advanced lasers that make it all possible."

Throughout Europe, Damae Medical is currently undergoing clinical trials to validate the accuracy of LC-OCT diagnostics in onco-dermatology. It will be released for sale later this year.

www.damaemedical.fr
www.nktphotonics.com

Breast Screening to End Unnecessary Biopsies

New mammographic imaging system determines benign or malignant breast lesions

Scientists from the Horizon2020 project SOLUS have developed a non-invasive, multimodal imaging system that uses ultrasound and light technologies to easily differentiate between benign or malignant lesions – without having to perform a biopsy. Similar to a pregnancy ultrasound appointment, a clinician scans the breast with a handheld "smart optode" pen probe that combines light and sound to collate blood parameters and tissue constituents.

Doctor assisting a patient during mammography (Source: Tyler Olson / Shutterstock)

Using diffuse optical imaging – a method that has provided breakthroughs in neuroscience, wound monitoring, and cancer detection – scientists can monitor changes in concentrations of oxygenated and deoxygenated haemoglobin, collagen, lipids and water present in a suspected tumor against a pre-programmed set of results.

While mammography is accurate in detecting breast lesions, many women encounter false positive results and the clinicians have to resort to invasive procedures, such as biopsies, to make an accurate diagnosis. The SOLUS scanner, however, can produce an accurate, while-you-wait diagnosis. Aiming for 95 percent sensitivity and 90 percent specificity, it combines commercial ultrasound imaging and elastography with novel diffuse optical imaging approaches. The new system gathers diagnostic information by sending pulses of infrared light and ultrasound a few centimeters into the breast tissue.

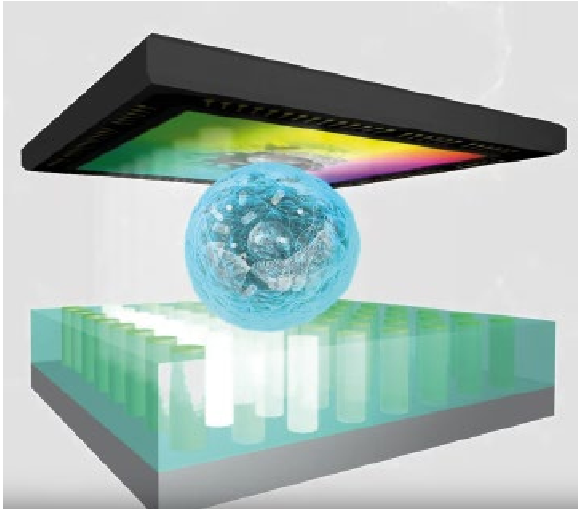
"Our team developed a multiwavelength time-domain optical mammography that was used in clinical studies on more than four hundred patients. Now an upgraded version has just entered clinics for the monitoring of neoadjuvant chemotherapy of breast cancer," said Prof. Paola Taroni from Politecnico di Milano, Italy.

Peter Gordebeke, research manager from the European Institute for Biomedical Imaging Research said: "While SOLUS is developing biomedical imaging technologies to improve the diagnosis of breast cancer, we are making good use of diffuse optics for breast cancer and other medical diagnostics applications."

www.solus-project.eu

A New Approach to Optical Microscopy

Development of the first chip-sized optical microscope with superresolution capabilities



A model of the ChipScope microscope: the specimen lying on the nanoLED surface is scanned and the shadow image is recorded by the detector (top; source: ChipScope)

The conventional light microscope underlies the fundamental laws of optics, so resolution is limited by diffraction to the Abbe limit – structural features smaller than 200 nm cannot be resolved.

In the ChipScope project, researchers use a structured light source with tiny, individually addressable elements. As depicted in the image, the specimen is located on top of this light source, in close vicinity. Whenever single emitters are activated, the light propagation depends on the spatial structure of the sample, very similar to what is known as shadow imaging in the macroscopic world.

To obtain an image, the overall amount of light that is transmitted through the sample region is sensed by a detector, activating one light element at a time and thereby scanning across the sample space. If the light elements have sizes in the nanometer regime and the sample is in close contact to them, the optical near field is of relevance and superresolution imaging may become possible with a chip-based setup.

Some innovative technology is required to realize this alternative idea. Several partners in the ChipScope project are applying their expertise in the corresponding fields of research. The structured light source is created from tiny light-emitting diodes, which are developed at the TU Braunschweig, Germany. To date, no structured LED arrays with individually addressable pixels down to the sub-µm regime were commercially available. So within the framework of the EU-funded ChipScope project, the first LED arrays based on gallium nitride (GaN) with pixel sizes down to 1 µm have now been demonstrated by the researchers. Controlled structuring of such LEDs down to the sub-µm regime is extremely challenging. It is done by photo and electron beam lithography, where structures in the semiconductor are defined with high precision by optical shadow masks or focused electron beams.

As a further component, highly sensitive light detectors are required for the microscope prototype. Here, professor Angel Dieguez' group at the University of Barcelona has a high level of know-how and has developed so-called single-photon avalanche detectors (SPADs), which can detect very low light intensities down to single photons.The first tests with those detectors integrated into a prototype have already been conducted and have shown promising results. In addition, a way to bring specimens into close proximity of the structured light source is vital for proper microscope operation.

An established technology to realize this utilizes microfluidic channels, where a fine system of channels is structured into a polymer matrix. Using high-precision pumps, a liquid is driven through this system and carries the specimen along to the target position. This part of the microscope assembly has been contributed by the Austrian Institute of Technology. (Source: ChipScope / FSRM)

www.chipscope.eu

EPIC Again Innovative in Creating Business Opportunities

Hosting more than 30 online events from April to June

At a time when events are being postponed and travel is being restricted, EPIC reacted with agility and flexibility to the needs of its members and with an open ear for their business and technology-related concerns. EPIC has created a series of online events, such as webinars and online meeting, including live streamed Online Technology Meetings.

Understanding the issues that businesses were facing, EPIC kicked off their online events calendar in March with the "EPIC Members Online Meeting on Coronavirus Impact and Possible Concerted Actions". More than fifty EPIC members from fifteen countries joined the online meeting to talk about the impact on their businesses and to talk to each other about the challenges they were facing. What followed where several webinars. The "EPIC Members Webinar on Working from Home and Managing Remote Teams" was EPIC's way of sharing their experiences working with remote teams, managing thirteen employees spread across eight countries.

What could also not be missing from the event calendar was, of course, how photonics is to face and defeat viruses like this new coronavirus. The webinar on "Towards a Prototype of an Anti-Virus UVC-LED-based Respiratory Mask" showed how photonics is used to develop innovative respiratory masks capable of killing the virus by exposing the airflows to the suitable amount of light. Further, during the "EPIC Webinar on Biosensors for Virus Detection", a discussion was held on how a photonic integrated circuit-based biosensor can help to detect a virus in a cost-effective, real-time and user-friendly way.

EPIC has taken it even further by adding fifteen Online Technology Meetings to the events calendar. Based on their favorite question: "What can you do for the others? And what can they do for you?", they bring together component suppliers, system integrators and end-users, discussing topics on different photonics technologies and applications.

The meetings are moderated by the highly skilled technology team and are held in small groups online but can also be viewed live on YouTube. The feedback received from the industry has been extremely good as stated by Simon Schwinger, senior manager business development at Jabil Optics: "The EPIC team is improving from one event to the next one, not only in the physical but also in the online world. Their efforts make connecting and interacting even faster with their meetings participants. Keep up the good work EPIC team!"

Past events are still available on the EPIC Photonics YouTube channel www.youtube.com/c/EPICPhotonics. Upcoming (online) events can also be viewed on

www.epic-assoc.com

Upcoming EPIC events:

EPIC events are renowned for excellent networking, creating new connections and strengthening existing ones. Connecting EPIC members means building trust within the photonics industry.

- 3 – 4 September – EPIC World Industrial Quantum Photonics Technology Summit at University of Glasgow, Glasgow, United Kingdom
- 10 September – EPIC VIP Networking Reception at CIOE, Shenzhen, China
- 16 – 17 September – EPIC Meeting on Fiber Sensors at HBM FiberSensing, Porto, Portugal
- 21 September – EPIC VIP Networking Reception at ECOC, Brussels, Belgium
- 24 September – EPIC Networking Lunch at Laser World of Photonics India 2020, Bengaluru, India
- 20 – 21 October – EPIC Meeting on 3D Printing of Metal at Siemens, Finspong, Sweden

www.epic-assoc.com/epic-events

Basil Garabet Joins EPIC Board of Directors

Benno Oderkerk, CEO of Avantes and president of EPIC (right), welcomes Basil Garabet, CEO of NKT Photonics, to the EPIC board of directors. (Source: EPIC)

At the EPIC Annual General Meeting, held online on 16 April 2020 because a face-to-face meeting was not possible, it was announced that Basil Garabet, president and CEO of NKT Photonics since 2015, has joined the EPIC board of directors. Basil holds an MSc in lasers and their applications and has extensive 37-year international management experience from leading positions in the photonics industry. Previously with JK Lasers, EM4, Altitun, Melles Griot, Pirelli, and Lasertron, Basil has built and revitalized companies towards profit and growth throughout his career.

Basil Garabet said: "Over the years, EPIC has built a strong network of companies across the entire spectrum of the European photonics industry. Today, EPIC is a leading advocate in the industry with its trusted experts and leaders. I am privileged to be a member of the EPIC board of directors and look forward to the commitment towards the growth of the photonics industry. I am very excited to work with EPIC towards this development."

"It is a privilege to have Basil join our board of directorsand to add his expertise and knowledge of the laser industry to the EPIC association and its members. EPIC's model of connecting the European photonics community worldwide is built on collaboration and partnerships and we look forward to working with Basil to further promote photonic technologies and innovations in Europe," said Benno Oderkerk, president of EPIC.

Garabet's further colleagues in the EPIC board are Christian Bosshard (CSEM), Jan Meise (AMS Technologies), Martin Schell, (Fraunhofer Heinrich Hertz Institute HHI), Maurizio Gattiglio (Prima Electro & Convergent Photonics), and Samuel Bucourt (Imagine Optics).

www.epic-assoc.com/board-governance

EPIC Hires More Staff to Service Its Members

Sharara Qasemová, event manager (Source: EPIC)

Dr Susette Germer, public relations manager (Source: EPIC)

With this changing world, the European Photonics Industry Consortium is expanding its team to continue creating attractive networking events. Whether it is in person,as planned for fall 2020, – or online, hosting more online meetings and webinars than ever –, EPIC is a leading facilitator for new business in the photonics industry and has hired two new team members to service the industry and its members.

Sharara Qasemová joined as event manager in mid-April. She has taken over from Neringa Noreikienė, who is on maternity leave. Sharara is an experienced event manager with an extensive portfolio of project accomplishments and we are sure she will be a great addition to the marketing and events team.

To lead the marketing and events team, EPIC also hired Dr Susette Germer as public relations manager. Susette is a natural scientist with a PhD in physics, she graduated from the TU Bergakademie Freiberg and TU Dresden. In her role at EPIC, she will be responsible for member engagement and leading the marketing and events team to ensure we are hosting the best events.

www.epic-assoc.com

The Future of Micro-Optics in Europe

Addressing the importance of micro-optics manufacturing in the photonics industry and its remarkable economic growth

Sana Amairi-Pyka

Micro-optics is set to become one of the main technology platforms in Europe for photonics with the potential to reach the same manufacturing maturity level of micro-electronics. These ambitions, together with good profit margins and the predicted exponential growth in business opportunities, make micro-optics a very attractive proposition for investment.

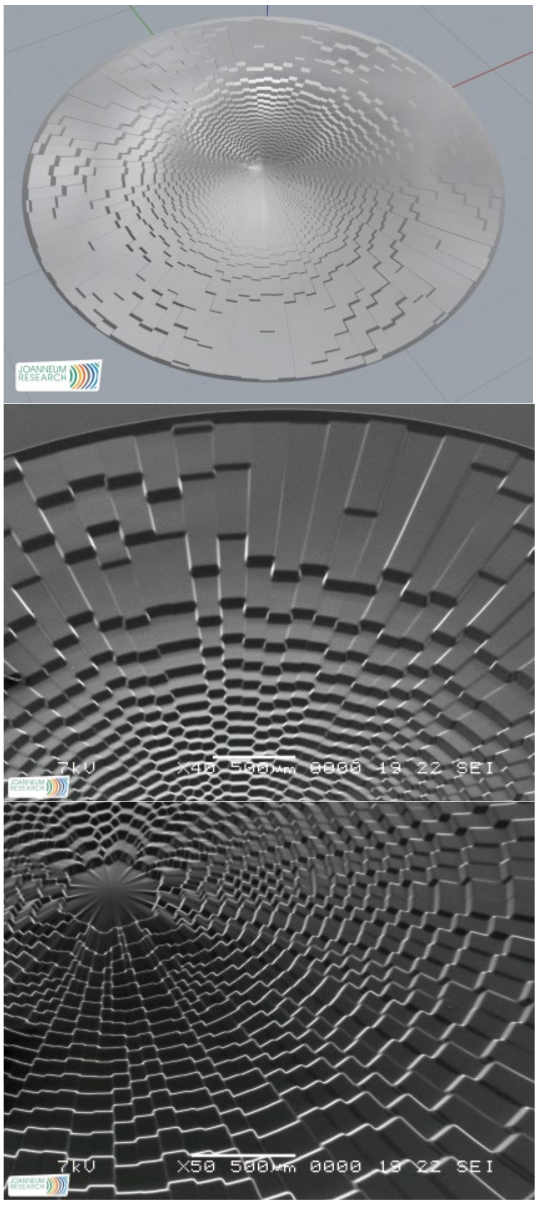


Fig. 1 Calculated design of freeform micro-optics for hexagonal light distribution (top). SEM images of master structures produced by maskless grayscale laser lithography (middle and bottom; sources: Joanneum Research Forschungsgesellschaft)

Europe currently has a 15.5 % share of the global photonics market, making it the world's second largest manufacturer of photonics products after China [1]. With the exodus of volume manufacturing for the telecom and consumer electronics market to Asia, the European photonics sector has focused mainly on niche markets where the region's strengths of training, innovation and R&D can be best exploited. According to Dr. Juan Carlos Miñano, CEO, and Dr. Pablo Benítez, CTO of Limbak, micro-optics is a breakthrough in optics manufacturing in the same way as aspheric and free-form manufacturing have been. Aspheric manufacturing added degrees of freedom for the optical design by allowing not only spherical surfaces but also rotational non-spherical surfaces; free-form added more degrees of freedom by allowing even non-rotational symmetric surfaces. Micro-optical manufacturing goes one big step beyond by also allowing surfaces with slope discontinuities.

One of the most growing markets in Europe is micro-optical manufacturing.

Micro-optics manufacturing is driven by the increasing need for miniaturization of optical components as well as for new optical functionalities in the form of free-form micro-lens arrays (FMLAs). One major motivation is the revolution in lighting sources producing highly asymmetric light distribution, and therefore more uniform illumination over large areas such as on trains, roads, and supermarket racks. Their small size and low weight reduce manufacturing and packaging costs and allow the design of more compact and aesthetically pleasing devices.

Highly developed FMLAs are essential for new optical functionalities and displays for AR/VR applications such as headsets, making them closer to users' eyes by radically decreasing the size of headsets and making them lighter and less bulky, as well as for automotive displays. These attributes are important for high volume applications such as indoor and automotive lighting solutions as well as to enable innovative concepts for electric vehicles and autonomous driving. An example of freeform micro-optics for hexagonal light distribution, produced by the Institute for Surface Technologies and Photonics at Joanneum Research, can be seen in Fig. 1.

"An exponential growth is expected in the sensor and illumination sector within the next five years," says Dr. Toralf Scharf, director of technology at Suss MicroOptics. Furthermore, applications such as laser material processing and distortion correction for imaging are benefiting from this technology. According to Roy McBride, managing director and co-founder Powerphotonic, "we anticipate strong growth over the next five years because the benefits of including micro-optic based beam shaping are real and commercially compelling. We have customers today who have realized significant gains in their industrial laser material processing quality and speed as a direct result of utilizing our micro-optic free-form based beam shapers."

The importance of micro-optical manufacturing for the EU economy

The EU has been investing heavily in R&D in high-tech since 2013, which is seen as a key factor in enhancing growth, competitiveness, better and better-paid jobs, greater social cohesion and a smart, sustainable and inclusive economy. This policy has paid off, as according to the European Commission's 2019 Innovation Scoreboard [2], the EU has moved ahead of the US in innovation performance for the first time. In photonics, there has been an increasing focus on manufacturing with the investment of 49 million euros for pilot lines to provide the manufacturing sector with support for innovation and the facilities needed to get ahead in global markets [1]. The reasons for prioritizing manufacturing are twofold. Firstly, as Europe has found to its cost through the relocation of large swathes of its manufacturing base to Asia, a healthy manufacturing sector and associated R&D is essential for keeping brains in Europe and, through "the multiplier effect", for creating highly qualified jobs. Secondly, as photonics manufacturing requires relatively few workers and state-of-the-art facilities for FLMAs are not yet ready in China, Europe has a golden opportunity to occupy a big share of the micro-optics market.

According to Dr. Rolando Ferrini, head of micro/nano optics and photonics at CSEM, having a reliable and standardized fabrication value chain for micro-optics will be of paramount importance to bring this technology to the same manufacturing maturity level of micro-electronics. Succeeding in this will allow companies to reduce production costs and to lower technology barriers that currently prevent the adoption of this technology by SMEs and, to a certain extent, LMEs that are not experts in the field. With this, micro-optics could become one of the main technology platforms in Europe for photonics, with a strong impact on several industrial sectors from suppliers and producers up to end users.

Fig. 2 Kick-off meeting, EU project PHABULOuS in Neuchatel 15 – 16 January 2020 (Source: CSEM)

PHABULOuS, the new European pilot line for free-form micro-optics

In recognition of the strategic importance of micro-optics for the European economy and the urgent need to ramp up FLMA production in Europe, an EU funded consortium of 19 companies and research organizations was formed in 2018 to create the infrastructure for a self-sustainable pilot line for the manufacture of FMLAs. This initiative, known as PHABULOuS, is an EU-funded pilot line, led by the Swiss research and technology organization CSEM, providing highly advanced and robust manufacturing technology for optical free-form microstructures and has two basic aims. The kick-off meeting of this project took place in January 16, 2020 at CSEM in Neuchâtel; see group photo (Fig. 2).

Phabulous

Funded by: PHOTONICS21 PHOTONICS PUBLIC PRIVATE PARTNERSHIP

The first aim of PHABULOuS is to strengthen Europe's leading position as a technology and machine provider for the production of micro-optics, based on a value selling model that retains the high-cost and high-value technology portfolio in Europe. The second aim is to develop easily accessible, world class manufacturing facilities to enable European companies to implement micro-optical components in their products and to compete advantageously with their global competitors. The PHABULOuS pilot line has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No. 871710.

Opportunities for investment in micro-optics manufacturing

While the business potential of micro-optics cannot yet be compared to electronics, most leaders in European photonics see European micro-optics as a sector ripe for investment.

Firstly, by 2024 the PHABULOuS pilot line will have the capacity to serve up to a hundred companies (mainly SMEs) for low to full rate production of FLMAs. These companies will be highly competitive due to a significant reduction in time to market, which will allow them to release products earlier than the rest of the pack, to benefit from increased revenues, to corner higher market shares and to open new markets for their products.

Secondly, the new production technology and increased capacity will give European SMEs huge opportunities for the penetration of micro-optics in many business sectors, ranging from lighting to consumer electronics, automotive, security, sensing, medical, photovoltaics and wearables. In the industrial sector, the use of micro-optic free-form based beam shapers is already providing significant quality and speed gains in laser material processing. As knowledge of these successes grows, a wider uptake of this technology is expected across a broader range of laser material processing applications and also for distortion correction in imaging applications. Early successes in the commercial deployment of micro-optics in high-end mass markets have already proven the economic case of using micro-optics over other competing technologies as well as allowing end-users to optimize the throughput-yield-quality balance to their competitive advantage. Consequently, in the next five years, exponential growth is expected for micro-optics in high-end mass markets, particularly in the sensor and illumination sectors as well as for several applications in the automotive sector.

Thirdly, rates of return are expected to be high as companies will focus mainly on fast moving, high price segments such as sensing, medical, automotive lighting and luxury segments where profit margins are reasonably high.

And finally, micro-optical manufacturing is a breakthrough process because it allows surfaces with slope discontinuities and even a non-rotational symmetric surface, and consequently the number of future applications is potentially enormous. Although the full range of applications has yet to be determined, as more application fields emerge, the accumulated experience, know-how and improved competitiveness gained from FMLA manufacture will enable European SMEs to successfully exploit these new markets.

With the enormous deployment of solid-state light sources in a wealth of devices and products, the demand for micro-optics can only increase. In response, the PHABULOuS pilot line will provide Europe with a reliable, standardized and mature fabrication value chain for micro-optics that will reduce time to market and enable companies to reduce production costs, thereby giving them a competitive advantage over their global competitors. This micro-optics infrastructure will have a strong impact on all parts of the value chain and on a wide range of industrial sectors including the consumer electronics, automotive and medical markets.

We would like to thank for their input:

- Dr. Rolando Ferrini, head of micro/nano optics and photonics at CSEM, and coordinator of the pilot line PHABULOuS.
- Dr. Juan Carlos Miñano, and Dr. Pablo Benítez, CEO and CTO of Limbak, respectively
- Dr. Toralf Scharf, director of technology at Suss MicroOptics
- Dr. Daniela Karthaus, head of lighting pre-development optics at Hella
- Roy McBride, managing director and co-founder of Powerphotonic
- Prof. Dr. Paul Hartmann, director of the Institute for Surface Technologies and Photonics, Joanneum Research

[1] https://www.photonics21.org/download/ppp-services/photonics-downloads/PPP_Impact_Report_2017_final_C3.pdf
[2] https://ec.europa.eu/docsroom/documents/36084

Organization

EPIC – European Photonics Industry Consortium

EPIC is the world-leading photonics industry association representing over 500 members across 33 countries. EPIC promotes the sustainable development of organizations working in the field of photonics, we foster 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 technology reports, organizes technical workshops and B2B roundtables, supports EU funding proposals, advocacy and lobbying, education and training activities, standards and roadmaps, pavilions at exhibitions.

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Author

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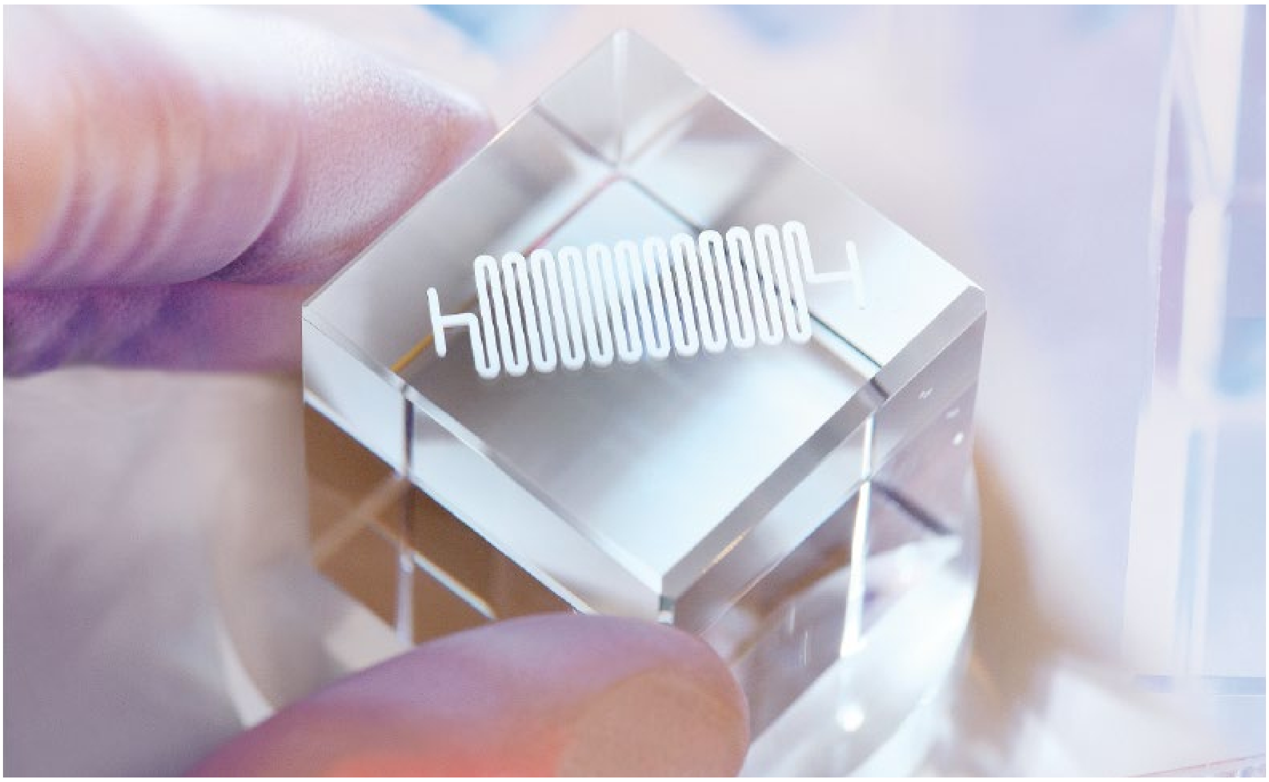

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Cutting Glass, Sapphire, Ceramics and Other Brittle Materials

USP lasers enable a non-contact, high-yield process that is compatible with green sustainable manufacturing

Hatim Haloui, Tony Lee, and Ludger Müllers

Over the past decade, glass has become an increasingly sophisticated structural and functional component in uses as varied as flat panel displays, automobiles and architecture. For the manufacturer, this has created a drive to enhance the physical characteristics of the glass itself, to develop more advanced coatings, and also to improve the process for cutting glass in terms of higher precision, greater speed, reduced environmental impact, and lower cost.

In particular, the massive acceleration in smartphone and tablet technologies has created a need to cut tough, chemically strengthened glass with tight curves and small cutout holes that are beyond the limits of traditional mechanical cutting. In this article, we see how ultrashort-pulse (USP) lasers enable this cutting in a non-contact, high-yield process that is compatible with green sustainable manufacturing and that often requires no post-processing whatsoever.

The same processes are also suitable for tough materials like sapphire, as used in camera phone windows, and starting to gain traction for automotive glass components. As a result, eventual adoption in architectural glass applications seems an inevitable future development.

Direct cutting – ablation

Ultrashort-pulse (USP) lasers compress the output into pulses that are in the picosecond (or even femtosecond) range. USP lasers can be used to cut even the toughest glass by two different processes: direct ablation and filament cutting. In direct ablation, the laser is focused on to the glass and each pulse vaporizes a tiny amount of the glass. (To cut thicker glass, the focus is systematically stepped deeper into the glass target.) There are several advantages to using USP lasers rather than traditional lasers with longer pulse widths. First, the process is relatively cold, resulting in minimized peripheral thermal damage – the heat-affected zone (HAZ). This is because of reduced thermal conduction; the short pulse time means that most of the pulse energy is ejected with the vaporized material, before it has time to spread further into the glass. Each pulse also only carries a small amount of energy. And because these lasers can

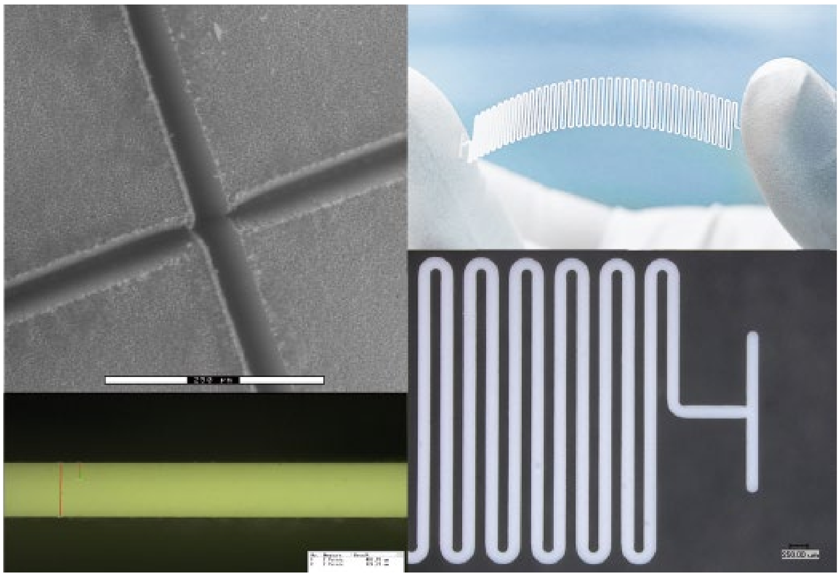

Fig. 1 Hyper Rapid NXT infrared picosecond laser, left: scribing of ceramic with a thickness of 400 µm, cutting speed >100 mm/s (left). Right: cutout of a meander structure in a 500 µm thick ceramic, cutting speed >10 mm/s, HAZ <10 µm.

operate at multi-MHz pulse repetition rates, the process can still be quite fast, with material removal rates exceeding 1.5 mm^3/s.

In addition, the high peak intensity during the short pulse duration means that the interaction between the laser photons and the glass includes a non-linear component. In simple terms, even if the material is nominally transparent at the laser wavelength it can be ablated with a UPS laser. This eliminates the cost and complexity of using a short pulse and a short wavelength. As a result, picosecond (ps) infrared lasers, such as the Hyper Rapid NXT from Coherent, are now the first choice in many glass and ceramic material ablation applications. Taking advantage of the low tensile strength in these ceramic materials, shallow laser surface scribes allow controlled crack propagation and very high throughput with high-quality material separation – see Fig. 1.

Filament cutting – Smart Cleave

The uniquely high peak intensity of ps lasers like Hyper Rapid NXT, combined with the capability to run the laser in burst mode, can be used to drive a very different glass cutting process called filamentation cutting, which leverages the power of the laser to achieve much higher cutting rates than ablation. The Coherent patented embodiment of this process is called Smart Cleave and can be used for a wide range of brittle and optically transparent substrates, from soft borosilicate glasses to chemically hardened glass used in smart phone displays, as well as sapphire. There are numerous advantages of filamentation cutting, including the ability to produce curved shapes and cutouts, cutting speeds of up to 1000 mm/s, and superior edge quality devoid of stress, which eliminates the need for post-processing.

In technical terms, the high peak intensity created by a focused, ultrafast laser produces self-focusing of the beam due to some physics called the "nonlinear optical Kerr effect". This self-focusing further increases power density until, at a certain threshold, a low-density plasma is created in the material. This plasma generation is driven by the subsequent pulses in the burst, and lowers the material refractive index at the center of the beam path and causes the beam to defocus. If the beam focusing optics are properly configured, this focusing/defocusing effect can be balanced to repeat periodically and form a stable filament that extends over several millimeters in depth through an optically transparent material. Coherent manufactures laser, sub-systems, and complete machines based on USP laser technology; both glass and sapphire can be cut by the Hyper Rapid NXT in thicknesses up to 5 mm when integrated in an automated cutting machine such as the Coherent Exact Cut 430 or the META 2C. In order to achieve a continuous cut, these laser-generated filaments are produced close to each other by a relative

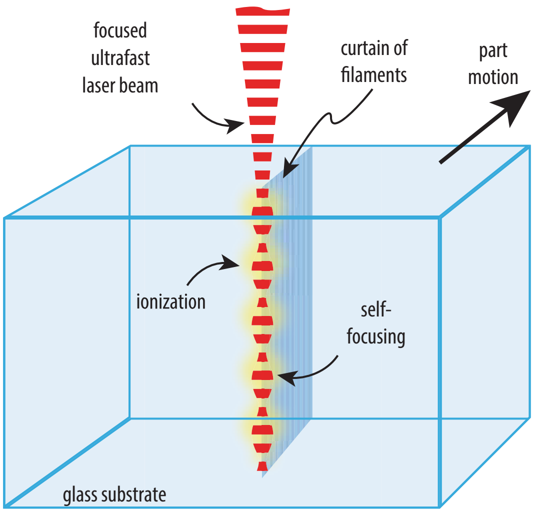

Fig. 2 In filament cutting, the self-focusing of a USP laser enables a very fast cutting process for glass up to several mm thick, leaving very smooth edges with no cracking or chipping.

Company

Coherent

Founded in 1966, Coherent Inc. is one of the world's leading providers of lasers and laser-based technology for scientific, commercial, and industrial customers. With headquarters in the heart of Silicon Valley, California, and offices spanning the globe, Coherent offers a unique and distinct product portfolio and services that touches scientific research, instrumentation, microelectronics, and materials processing.

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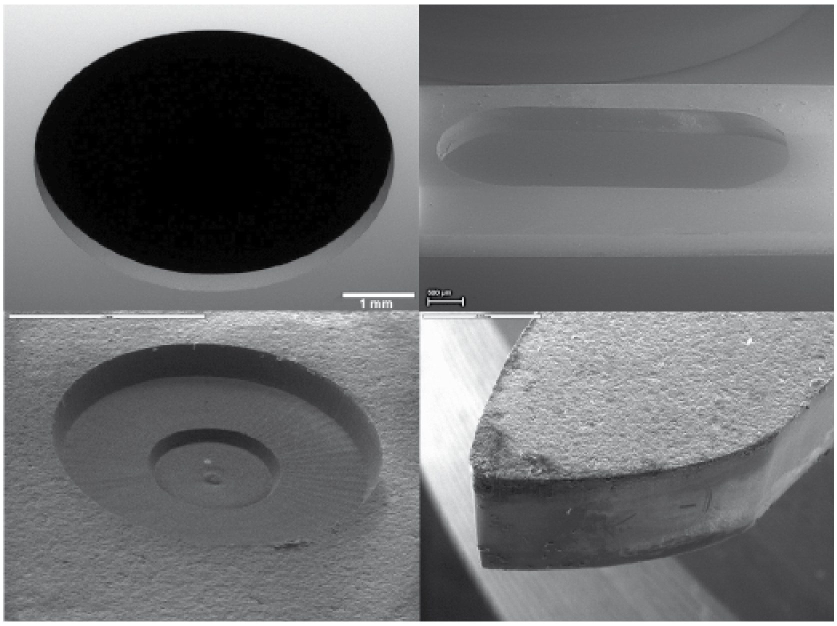

Fig. 3 Even extremely hard materials like sapphire can be cleanly cut with a USP laser. Top left: Hole cutting with 5 mm diameter using the Hyper Rapid NXT infrared laser and the Smart Cleave technology, processing time <1 s. Top right: feature cutting with a Hyper Rapid NXT green laser using the ablation technique. Bottom right: gear cutting in 500 µm thick sapphire. Bottom left: machining of blind holes of different diameters in sapphire with highly accurate depth control.

movement of the work piece with respect to the laser beam, leaving a curtain of microvoids (perforations) in the glass – see Fig. 2. In the case of strengthened glass, the glass may then spontaneously separate along this line. For other glasses, a localized thermal shock is used to cause physical separation – either a jet of cold air or a low-power carbon dioxide laser. The typical filament diameter is in the range of 0.5 to 1 µm, enabling very high precision cutting. In order to combine high-speed beam movement with micrometer precision, Coherent has developed advanced laser triggering to deliver closely spaced "bursts" of pulses. This enables the burst rate to be matched to the scan speed, with no difference in the cutting effect between straight cuts and tight corners. Hyper Rapid NXT is the first USP laser to bring this feature – called Pulse EQ – to materials processing.

Compared to mechanical cutting, there are several advantages to Smart Cleave. It can cut strengthened glass as easily as regular glass, and even sapphire – see Fig. 3. There is no chipping or microcracking and no residual edge stress, so no post-processing is required. Edge stress would otherwise increase the breakage potential in touch screens.

Cutting glass outlines

Today, most smartphones and tablets have screens with some type of shaping beyond a simple rectangle; at a minimum they usually have tightly rounded corners. Filament cutting is the method of choice for the screen outline where it produces a typical edge roughness <0.5 µm in a single pass. In addition, the absence of residual edge stress in the cut glass is important in touch screen applications. The reason is that even when pressure is applied in the center of a glass panel, any break will virtually always propagate from the edge, so edge stress or microcracks that could focus stresses must be avoided. Filament cutting is also used for the larger sapphire windows used for the latest smartphone cameras.

Looking forward, filament cutting is now in the early stages of adoption for automotive applications, primarily for the rearview and side mirrors, again because these increasingly have shaped profiles. Another advantage here is that cutting always had to precede coating, e.g., with a TCO (transparent conductive oxide and/or metal). But Smart Cleave can be used either before or after the coating with no impact on quality.

Displays – cutting smaller holes

There are several purposes for cutting holes in displays, including to accommodate microphones, electronic buttons and so forth. These holes can be cut in one of three ways, depending on the hole diameter. For holes with a diameter >5 mm, filament cutting is the preferred method since it is much faster than the ablation alternative. In the 2 – 5 mm diameter range, ablation is typically used for trepanning the hole; trepanning refers to cutting a hole by first cutting the outline and then removing the central plug by gravity or forced air. For the smallest glass through holes (e.g. 1 – 2 mm), the best results are obtained by complete ablation. The focused laser is moved repeatedly over the entire area of the hole until it is completely removed.

Summary

In the age of photonics, optically transparent materials like glass have inevitably become key components in many industries and products. And not surprisingly, photonics-based technology, such as USP lasers, is providing the means to manipulate these materials with new precision and levels of performance.

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joined Coherent in 2005 after studying microsystem technology at the University of Freiburg and laser technology at the University of Applied Sciences Koblenz. Now he is senior manager for application technology. With many years of experience in the micromachining sector with short and ultrashort-pulsed lasers, he has the responsibility for advanced process engineering, process development. and key accounts worldwide.

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Fast Beam Oscillations Improve Laser Cutting of Thick Materials

State of the art and outlook

Andreas Wetzig, Patrick Herwig, Madlen Borkmann, Cindy Goppold, Achim Mahrle, and Christoph Leyens

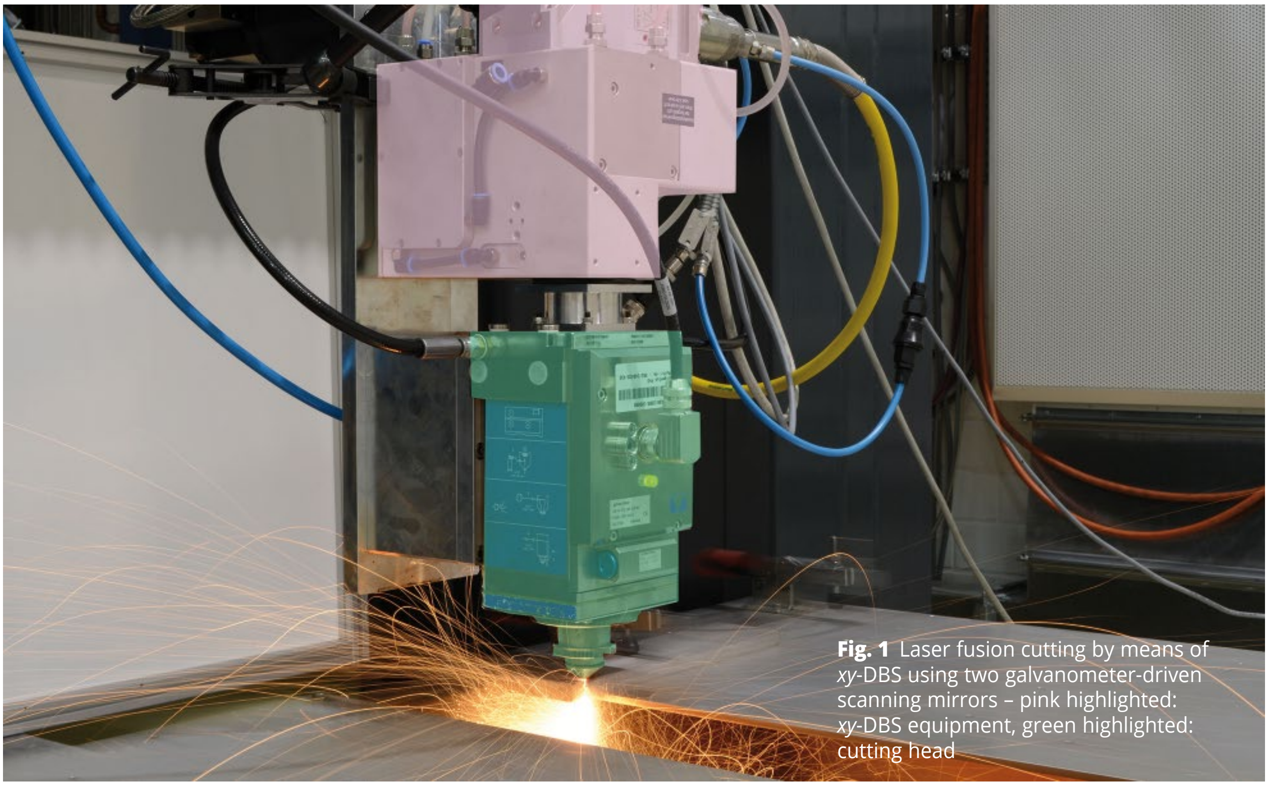


Fig. 1 Laser fusion cutting by means of *xy*-DBS using two galvanometer-driven scanning mirrors – pink highlighted: *xy*-DBS equipment, green highlighted: cutting head

Source all images: Fh. IWS

We provide here an overview of the capabilities of oscillating beams to improve solid-state laser fusion cutting of thick-sheet AISI 304 stainless steel and present results of the so-called dynamic beam shaping (DBS) technique, which relies on fast and commonly harmonic oscillations of the laser focus at frequencies in the kHz range.

Improvements of cutting edge quality and maximum cutting speed have been demonstrated for planar *xy*-DBS. For the first time, piezo-driven gimbal mirrors were utilized as a promising substitute for the galvanometer-driven mirrors in commercially available standard configurations. In addition, a novel fast adaptive mirror setup was used for oscillations of the focal plane along the propagation axis of the beam with amplitudes of several millimeters. The initial results of this vertical *z*-DBS are encouraging and the opportunities of the fast oscillations in all three spatial dimensions will be discussed in this article. Alternative concepts for fast beam oscillations will also be considered related to their suitability for manufacturing.

Laser beam cutting as an established and widespread material processing technology is considered the most cost-efficient technology for versatile cutting of metals with a thickness of up to 15 mm. High brilliance solid-state laser sources have played a vital role for the market development. It was reported that the number of commercially available cutting machine systems has more than doubled since the introduction of fiber and disc laser technology [1]. Challenges still exist for thick-section fusion cutting of stainless steels and non-ferrous alloys to meet user expectations in terms of process performance and cut edge quality. Conventional solutions with a static laser beam possess only a limited number of easy-to-control influencing parameters. The position of the focus plane in relation to the surface of the material is often identified as the most critical factor for performance and quality for a given setup of beam caustic, laser power and gas flow configuration. Obviously, the solution of multicriteria optimization problems becomes difficult with only one critical parameter at hand. A promising remedy is the application of oscillating beams, commonly referred to as the dynamic beam shaping (DBS) method despite the fact that the beam profile itself remains unchanged. The DBS approach – being well established in electron and laser beam welding – also seems to be promising for thick-section laser beam cutting

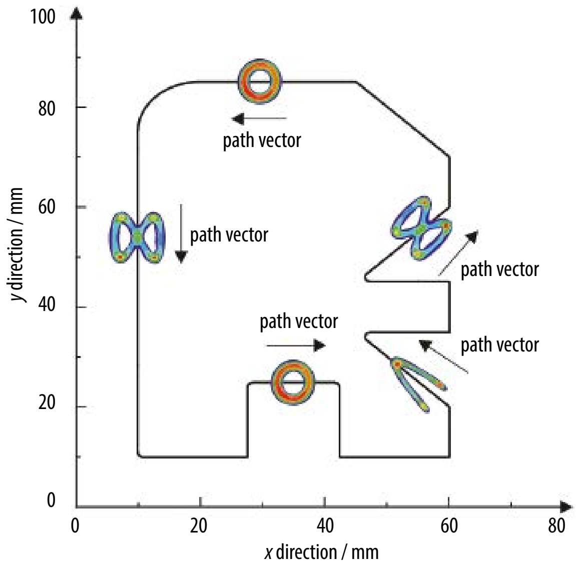


Fig. 2 The DBS control system allows the alignment of the oscillation pattern to the path vector. Suitable patterns like circle, eight, or horse shoe to achieve different process targets are shown here.

due to the many additional degrees of freedom which can be used to alter the characteristics of the cutting process. However, corresponding experimental studies have been strongly related to the development stage of appropriate system technology so far. Early investigations demonstrated the capability to control the inclination angle of the cutting front by longitudinal 1D-oscillations (x-DBS) of the beam to achieve a high coupling efficiency for 1 µm laser wavelength [2]. Later, 2D-oscillation patterns (xy-DBS) were applied to improve the overall process performance [3-5]. Current efforts are focused on the development of oscillation strategies along the propagation axis of the beam in the z direction (z-DBS). Combined with 2D-oscillations in $x\,y$ direction, it will be most likely be possible to develop sophisticated 3D-oscillation strategies with additional power modulations in order to achieve the highest degree of flexibility in beam control. Starting as an exciting field for fundamental research, the DBS technology has recently found its way into the commercial laser cutting market: one leading cutting machine manufacturer has integrated an oscillation module into one of their latest models [6].

Experimental setup

An overview of available and already tested oscillation devices including main parameters of interest is given in Table 1.

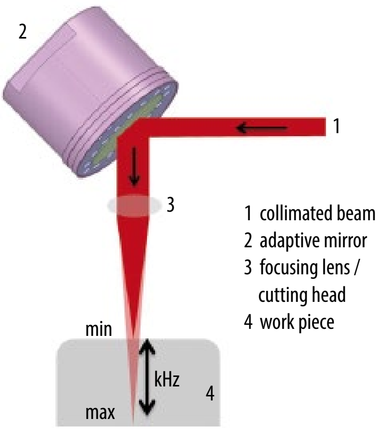
The conventional technical solution for laser beam oscillation in x and y direction uses a separate scanner unit with two integrated galvanometer-driven scanning mirrors. This device is positioned in the optical path of the collimated part of the laser beam, and can be combined with most commercially available cutting heads. The typical setup of such a solution is shown in Fig. 1 with the scanning mirror unit placed on the top of a standard cutting head. The core element is the controller with its ability to define frequencies, amplitudes, and phase shifts for and between both axes. As a result, various patterns of energy density distribution are available in the geometrical shapes of circles, eights, horseshoes, rectangles, etc. The specified pattern can be aligned with the motion vector along the desired cut contour, and oscillation parameters can be adapted in response to changing process conditions, such as changes in direction, cutting speed, or laser power on the fly. Fig. 2 schematically shows the capability of the control unit for 2D laser fusion cutting to generate freely selectable patterns at different positions along the cut contour to ensure consistent cutting quality.

As a promising alternative, piezo-driven gimbal mirrors are now available for xy-DBS instead of galvanometer driven mirrors. The adjustable parameters of amplitude and frequency are similar to those of galvanometer driven mirrors, see Tab. 1. Piezo-driven gimbal mirrors have already demonstrated high performance at up to 3 kW laser power. The main advantage results from the compact design and the low total mass of this novel scanning concept

Direction		*xy* oscillation		*z* oscillation
type of drive		galvanometer	piezo	piezo
construction size l × w × h in mm³		200 × 200 × 150	25 × 25 × 50	50 × 50 × 50
mass		10 kg	0.5 kg	1.0 kg
laser parameters	aperture	21 mm	18 mm	25 mm
	tested laser power	10 kW	3 kW	6 kW
	laser power for cutting	3 kW	3 kW	4 kW
oscillation parameters	maximal oscillation frequency	4 kHz	4 kHz	4 kHz
	amplitude at 4 kHz*	±75 µm	±300 µm	±10 mm
	amplitude at 2 kHz*	±380 µm	±300 µm	±10 mm

*calculated for a focal length of 125 mm

Tab. 1 Overview of different oscillation devices



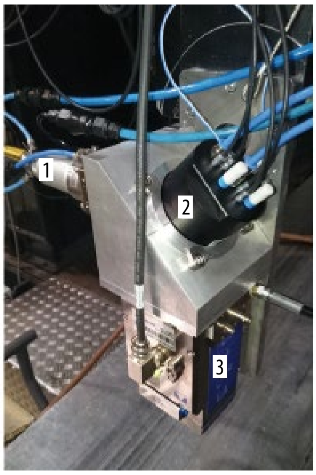


Fig. 3 Adaptive mirror for fast *z*-DBS, schematic (left) and in the lab (right)

compared to a conventional scanning mirror unit. The two-axis gimbal mirror replaces the plain bending mirror, which is needed for the optical setup anyway.

A novel fast adaptive mirror solution was also developed to allow for oscillations of the focal plane along the beam propagation direction in the range of several mm and with frequencies up to 4 kHz, the so-called *z*-DBS. The mirror pre-focuses the collimated beam up to a focal length of 2 m, which allows maximal oscillation amplitudes of 20 mm in combination with this cutting head configuration. The amplitude and frequency of this piezo-based mirror could be adjusted according to the cutting conditions under real-time conditions. The parameters and properties can be taken from Tab. 1 as well. The fast adaptive mirror can also be used instead of the plain bending mirror, which saves space and mass for the whole opto-mechanical setup (see Fig. 3).

A state-of-the-art fiber laser with maximum 4 kW power was used in different optical configurations for all cutting experiments on thick-section stainless steel that are presented in this paper.

Results

xy-DBS for laser fusion cutting

Cutting experiments were carried out on 12 mm thick AISI 304 stainless steel sheets in the form of linear cuts with a constant laser power of 3 kW. Oscillation frequencies were varied between 100 Hz and 4 kHz. The evaluation criteria of the cutting performance were the highest possible feed rate, the roughness of the cut edge surface, and the amount of dross, which is usually considered to be more important than a low surface roughness. The best results of *xy*-DBS were achieved by stretching the DBS pattern along the cutting direction. Whether an eight-shaped or a linear longitudinal oscillation pattern in feed direction is favored depends upon the kerf width that is set. Results are presented here that were achieved under the additional constraint of the smallest possible kerf width. These results are compared with the performance of conventional laser cutting with a static laser beam. Usually, two opposing objectives are pursued in conventional laser cutting: cutting with maximal cut speed or cutting with best edge quality. The compilation of the results including microscopic views of the cutting edges is shown in Fig. 4. On the one hand it is found that *xy*-DBS yields double the feed rate when compared with the high quality static beam cut, and even slightly higher feed rates when compared with the static beam cut at maximum cutting speed. On the other hand, the amount of dross and its height is considerably reduced when compared with both the maximum cutting speed and quality cut achieved with a static beam. The quality cut with a static beam only has some minor advantages of the smoothness of the cut edge. In order to reach these results, the optical setup – including the focal position – was adapted for each of the three considered cases.

z-DBS for laser fusion cutting

Cutting experiments with *z*-DBS were performed on 10 mm thick sheets as linear cuts with a constant laser power of 4 kW in order to study the influence of oscillations of the focal layer plane on the processing results. For that purpose, the amplitude was varied in a range between 1 and 6 mm with the zero focal position in the upper half of the material

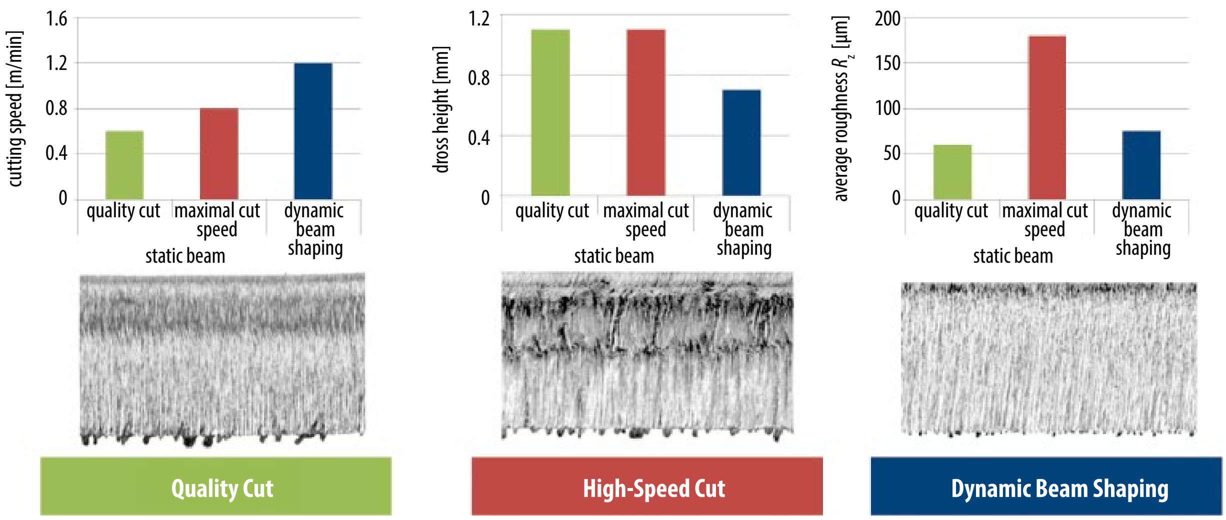


Fig. 4 Comparison between state-of-the-art highest cutting speed and highest quality cut processes with DBS cutting

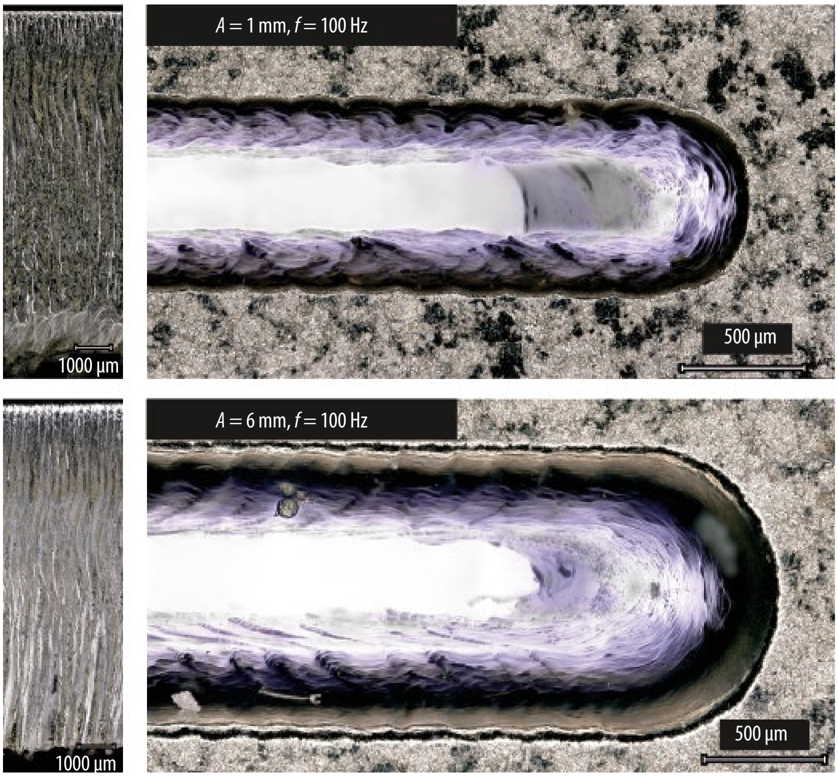


Fig. 5 Appearance of kerf and cut edge while utilizing *z*-DBS

thickness at frequencies from 100 Hz to 1 kHz. The cutting speed was kept constant at a value of 1.3 m/min to reach a through-cut for each of the tested parameter constellations. High-resolution microscopic views of selected kerf geometries for different values of the oscillation amplitude demonstrate the strong impact of this factor on the kerf shape and size, see Fig. 5 on the right-hand side. In particular, it was found that the kerf width at the top surface strongly correlates with the applied oscillation amplitude. Furthermore, the striation structure and overall topography of the cut edge is also changed as a function of oscillation amplitude, see Fig. 5 on the left-hand side. It is obvious that the well-known issue of the so-called boundary layer separation of the gas flow with insufficient blow-out of the melt in the range of the lower cut edge (amplitude $A = 1$ mm) is effectively suppressed by the adjustment of the oscillation amplitude and the kerf size, respectively (amplitude $A = 6$ mm).

Discussion

The application of beam oscillation methods in laser beam cutting offers many opportunities to alter the process performance, the cut edge properties and the cut kerf geometry. The underlying physical mechanisms causing these effects are considered to be quite complex, so an improved understanding will be needed to find the optimal parameter settings. The strong effect of the oscillation amplitude on the cut kerf width on the upper side of the sheet and also the cut kerf shape are obvious and highly reproducible options. This also confirms the common knowledge in conventional cutting that the kerf width always correlates to the beam size at this particular position. The kerf width is probably the most crucial parameter in laser beam cutting because it determines the laser-induced melting rate and also the coupling efficiency of the high-pressure gas flow to blow the molten material out of the kerf. A high-quality cut at high processing speeds requires an equilibrium between these two subprocesses. In conventional cutting, the focal layer position can be effectively used for kerf width control. In thick-section laser beam cutting with high brilliance solid-state laser sources, it is often recommended to locate the focus layer in the lower half or even lower third of the sheet thickness. As a result, due to reduced effective beam intensities in the upper part of the kerf, the melting capability of the laser beam is reduced, and the achievable cutting speeds decrease. In contrast, using the flexibility of DBS methods, the cut kerf shape can be independently controlled from the particular focus position by

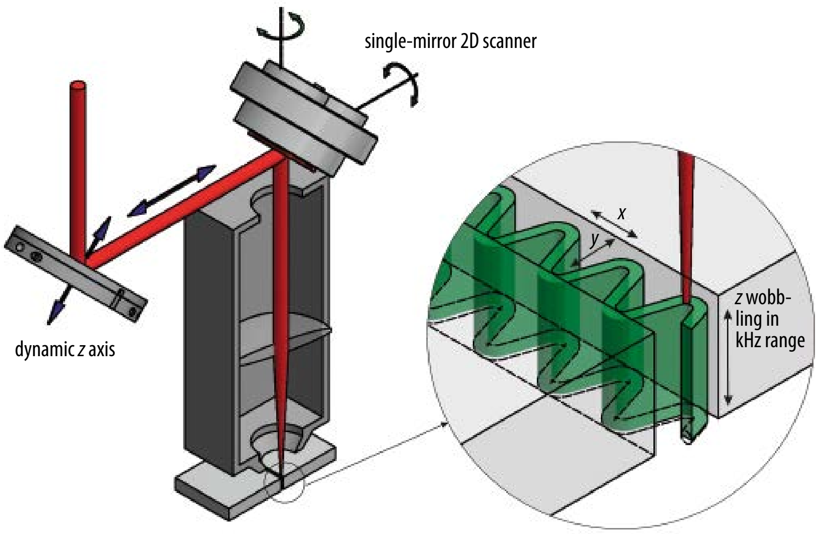


Fig. 6 Schematic illustration of the experimental setup for fast 3D beam oscillations in *x, y* and *z* direction

the specified oscillation amplitudes. So high focal layer positions can be selected to ensure high beam intensities in the upper part of the kerf to reach higher cutting speeds. In addition, adjustment of oscillation frequencies and oscillation patterns enables a tailoring of the energy deposition along the interaction zone of the cut front. The locally and temporarily modulated energy density will not only affect the cut front shape and coupling efficiency of the laser radiation but also the temperature distribution of the melt, and in this manner the flow properties (viscosity, surface tension) and the flow behavior of the melt in interaction with the gas flow. All of these phenomena are believed to have a strong impact on striation formation, cut edge roughness and dross attachment. Deeper insights into cause-and-effect relationships also seem to require clarification of the boundary layer characteristics of the applied high-pressure gas flow [7]. Nevertheless, the current empirical process knowledge and the proven benefits of DBS already justify the increased demands for system technology and process design, and motivate further work on DBS technology and its application in laser beam cutting.

Summary and outlook

Dynamic beam shaping (DBS) of the laser focus in the *xy* plane as well as along the beam propagation axis in *z* direction has a high potential for improved laser fusion cutting in terms of dross reduction, smoother cutting edge surfaces, higher feed rates, adjustable kerf width, and an enlarged process window. The recently started joint Fraunhofer-DFG project FastShape, a collaboration between Fraunhofer IWS and IFSW Stuttgart, is aiming to gain knowledge about the physical effects of fast beam oscillations, for example, by real-time X-ray studies of the cutting process and 3D reconstruction of the cutting front [8]. Furthermore, efforts will be made to apply laser powers of up to 8 kW instead of 3 kW. Future research will be conducted towards cutting trials with DBS in *xz* and *yz* planes as well as 3D fast beam oscillations in all spatial directions, see Fig. 6 (patent pending). In addition, the effect of DBS will be clarified for oxygen cutting.

For the physical deflection of the laser beam, single mirror, dual-axis systems are preferred over two galvanometer-driven mirrors in order to achieve high compactness and low cost. Currently, piezo and servo-driven mirrors are under development. The former have already been tested as described and the latter will soon be available for this particular application. An alternative approach is to use coherent beam combining (CBC) technology that enables fast changes of power distribution within the laser focus in the MHz range [9]. High-power fiber lasers that are equipped with this CBC technology are under development and are going to enter the market for material processing. One of the first lasers with an output power of more than 12 kW will be soon available for cutting experiments under lab conditions.

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Institute

Fraunhofer IWS

The Fraunhofer Institute for Material and Beam Technology of Dresden has been focusing on R&D in laser material processing for more than 25 years. All kinds of industrial lasers are available at IWS, which are utilized for structuring, heat treatment, cladding, additive manufacturing, joining, and cutting of workpieces made of metals, non-metals, and laminates. Fraunhofer IWS concentrates on the development of industrial laser processes and system technology that enables innovative laser manufacturing processes.

www.iws.fraunhofer.de

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Patrick Herwig studied mechatronics to MSc degree. He received his PhD in mechanical engineering at the TU Dresden. After five years of research activities of system technology, he now leads the laser cutting group at Fraunhofer IWS. His team focuses on efficiency and quality improvements for conventional laser cutting processes and the development of new technologies such as laser remote cutting.

Cindy Goppold is research associate in the laser ablation and cutting department at the Fraunhofer IWS in Dresden, Germany. She earned her master of engineering in laser and opto-technologies at the University of Applied Sciences Ernst Abbe Hochschule Jena, Germany. Her current research interests focus on the development of new approaches for the conventional laser beam cutting of metals.

Christoph Leyens studied and graduated in materials science and engineering, earned his PhD, and was finally promoted to Professor of materials for aerospace – RWTH Aachen being his alma mater. He worked at DLR as acting director of the Institute of Materials Research before he accepted a full professorship in metallurgy and materials technology at BTU Cottbus in 2004, and for materials technology at TU Dresden in 2009. In 2016, he was appointed director of Fraunhofer IWS.

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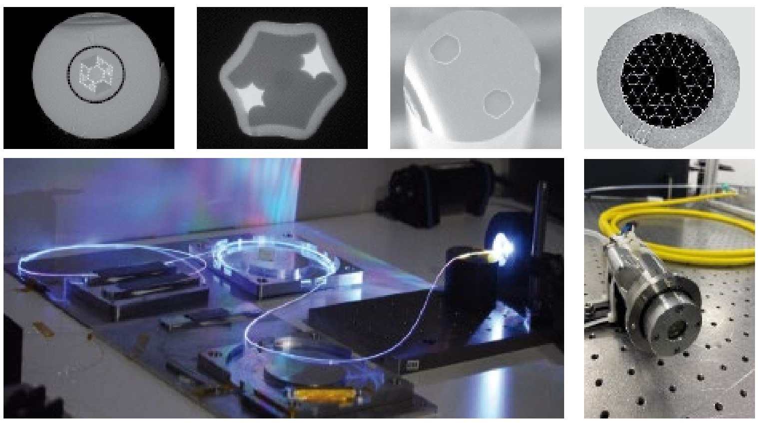
Preview

New Microstructured Optical Fibers for Innovative Lasers and Beam Transportation

SLT

L. Bigot, P. Roy, T. Taunay, F. Benabid, and E. Mottay

The French 4F consortium has obtained new results on microstructured optical fibers for the development of Ytterbium active fibers with a large core and for the transport of intense laser beam via hollow-core photonic crystal fibers. In the case of active fibers, several methods to obtain fiber preforms have been tested (MCVD, OVD, powders, sol-gel), as well as suited designs. The fiber specifications are targeted for optimum laser performances, such as a mode field diameter larger than 30 µm, a polarization extinction ratio greater than 15 dB, no air clad and a cladding absorption at 976 nm larger than 10 dB/m. Bending radius is also limited to a relatively small diameter (about 20 cm). The fiber will allow a laser operation exceeding 150 W. The fiber for beam delivery consists of inhibited-coupling guiding fiber and allowing guidance of high levels of pulse energy and average power.



(Source: Amplitude Laser)

Read the article in issue 4 / 2020 (August / September)

Fiber coupling to polarization-maintaining fibers and collimation. Measured fiber parameters help to chose the best coupling and collimation optics.
(Source all images: Schäfter+Kirchhoff)

Fiber Coupling to Polarization-Maintaining Fibers and Collimation

How measured fiber parameters help to choose the best coupling and collimation optics

Anja Knigge, Mats Rahmel, and Christian Knothe

A stable measurement setup is fundamental for any successful measurement. A major cause of frustration and error is the need to continuously readjust optomechanical equipment because of continuous instabilities. But first decisions have to be made about which components to use. Detailed measurements of fiber parameters like e.g. an effective numerical aperture allow a better understanding which other fiber optic components are suitable for the application at hand. In-depth knowledge about the different parameters is key for this procedure. The online product configurators on the new Schäfter+Kirchhoff website provide this information quickly and easily and help narrow down the search to the most relevant choices.

The use of fiber optics has proven to increase both stability and convenience significantly when compared with standard free-beam setups. These modular, complex and self-contained setups also often increase laser safety and reduce the laser safety classification.

The defined interface between a laser source and the more sensitive environment of the measurement setup provides the physical separation that enables a mechanical and thermal decoupling, suppressing mutually negative effects.

Single-mode and PM fibers

Single-mode fibers are specialized fibers that transmit light in the transverse fundamental mode LP_{01}. The field distribution (mode field) of the light exiting the fiber is close to Gaussian. For standard single-mode fibers, the light is guided

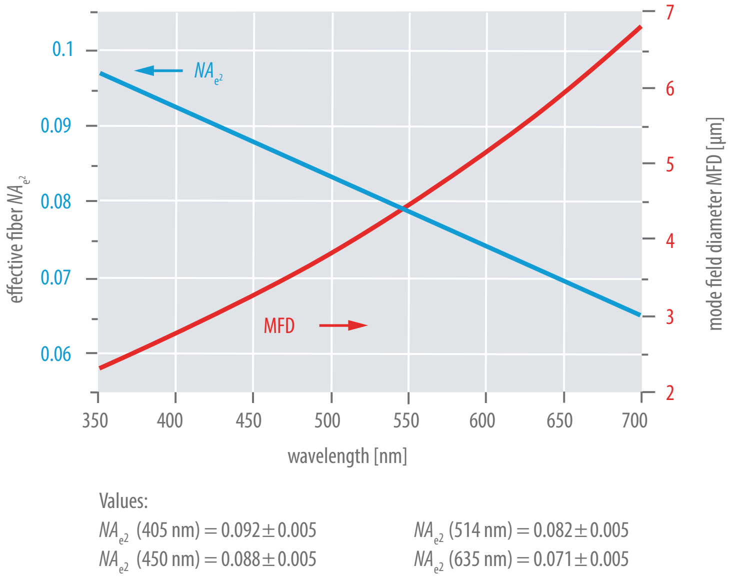


Fig. 1 Effective numerical aperture NA_{e^2} and the corresponding MFD for an RGB fiber that can be used between 400 nm and 640 nm. The NA_{e^2} decreases significantly with increasing wavelength.

in two principle states of polarization. Imperfections in the fiber do lead, however, to random power transfer between the two principle states of polarization so that the polarization is not maintained.

Polarization-maintaining single-mode fibers (PM fibers) are rotationally non-symmetric because of integrated stress elements, for example, that break the degeneracy of the two principle states of polarization (SOP). Light is guided either in the so-called „fast", or the „slow" axis and linearly polarized light coupled into one of these axes is maintained.

Single-mode and PM fibers are characterized by their numerical aperture *NA*, their mode field diameter (MFD) and their cutoff wavelength λ_0.

It is only at wavelengths above this cutoff that the coupled light is guided in a single mode and not in multiple modes, where the beam and intensity profiles are no longer stable nor Gaussian.

The MFD is wavelength-dependent and inversely proportional to the fiber *NA*. While fibers used for telecommunication in the infrared region, around wavelengths of 1550 nm, are characterized by fairly large mode field diameters of around 10 µm, the MDF in the UV is small, e.g. 3 µm for 405 nm and a fiber with nominal $NA = 0.12$.

Nominal vs. effective *NA*

The fibers obtained by most manufacturers usually come with a so-called nominal numerical aperture (nominal fiber *NA*) that is defined by the refractive indices of fiber core and cladding.

For a typical single-mode or a polarization-maintaining fiber, the nominal value is $NA = 0.12$.

This *NA* specification corresponds to the Gaussian angle distribution at a 1 – 5 % level, but in most cases, this is either not a measured value, the nominal *NA* is given with a large bandwidth or the level on which the *NA* was measured is not given or inaccurate. Often, the *NA* is measured in the preform but not for the finally drawn fiber. Some manufacturers measure the MFD, which allows recalculation of the *NA*, but only for one single wavelength. This measurement is usually given with a large error margin. Since the fiber *NA* is crucial for choosing corresponding fiber-optic components, these rough values should be substituted for actual measured values. This is done with an effective fiber numerical aperture defined on the $1/e^2$ level. For fiber coupling purposes, this effective fiber NA_{e^2} is more convenient than the nominal fiber *NA* defined by the refractive indices since Gaussian beams are also generally defined by their $1/e^2$ diameter.

Schäfter+Kirchhoff defines an effective fiber NA_{e^2} which corresponds to the divergence of the power distribution emitted by the fiber taken at the $1/e^2$-level of the Gaussian angle distribution and measures this value for each fiber batch and for a number of wavelengths. This value is the designated effective numerical aperture NA_{e^2}. For a PM fiber with cutoff 405 nm for example, the manufacturer gives a nominal *NA* of 0.12 defined somewhere between 1 – 5 % level. This corresponds to an effective NA_{e^2} of 0.079 to 0.098 with an uncertainty of almost 20 %. However, an actual measurement reveals that the measured value for the effective NA_{e^2} for 405 nm actually is 0.070 ± 0.005 providing a much more precise information.

These detailed measurements show that for short wavelength fibers, the numerical aperture varies with wavelength and is not constant as it is assumed in the standard model and for telecommunication fibers. For single-mode fibers and for polarization-maintaining fibers, the effective NA_{e^2} typically decreases with increasing wavelength λ. This makes it essential to measure the *NA* for a number of wavelengths. If the *NA* or the MFD is measured or given for a single wavelength, the significant change with wavelength is completely missed.

Wavelength dependence of the effective NA_{e^2}

In order to illustrate how much the effective NA_{e^2} changes with wavelength, its values are measured for a broadband RGB fiber that is designated for use between 400 and 640 nm. Fig. 1 shows the NA_{e^2} profile between 400 and 640 nm. The effective NA_{e^2} decreases with increasing wavelength and has significantly different values for 405 nm ($NA_{e^2} = 0.092$) and 635 nm ($NA_{e^2} = 0.071$). The almost linear relationship between NA_{e^2} and the wavelength can be seen by extrapolating the measured values.

Besides the effective NA_{e^2}, the MFD is also shown. The MFD is calculated

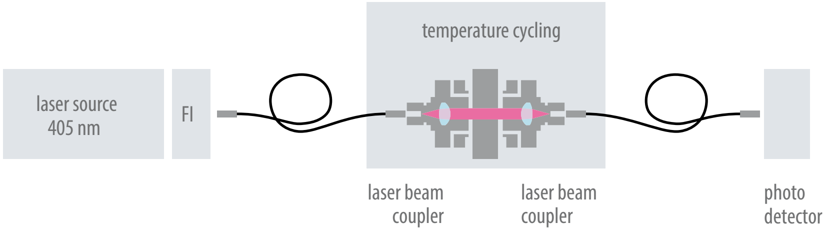


Fig. 2 Test setup for measuring the stability of two laser beam couplers (f= 4.5 mm, λ = 405 nm) during successive temperature cycling between 15 and 35 °C.

(and not measured directly) from the obtained values of NA_{e^2} for each wavelength λ using

$$\mathrm{MFD} = \frac{2 \cdot \lambda}{\pi \cdot NA_{e^2}}$$

It is also important to note that the values for the effective numerical aperture change from fiber batch to fiber batch making it necessary to constantly remeasure for each new role.

The NA_{e^2} curves and other useful information can be obtained for each Schäfter+Kirchhoff fiber cable using the new fiber cable product configurator. By choosing the operating wavelength, the fiber type (single-mode or PM), fiber cable properties (e.g. vacuum-compatible, 900 µm buffer or 3 mm cable) and fiber connectors (with end cap, amagnetic connectors, FC or other connectors) the product configurator finds the adequate fibers and gives a short overview about the most important features. Fiber cables can be compared using the comparison function. Once the adequate fiber is found, key information can then be downloaded and used as basis for deciding other fiber optic components e.g. the correct fiber coupler to couple into this fiber or the correct fiber collimator to collimate the light exiting this fiber cable.

Fiber coupling

When coupling into single-mode fibers, the laser beam couplers should produce a diffraction-limited spot that matches the mode field diameter and the numerical aperture of the fiber in order to achieve maximum coupling efficiency. It is only when this condition is met that fiber coupling with high coupling efficiencies of up to 85 % are achieved.

The adequate focal length can be chosen using

$$f' = \frac{0.5 \cdot \varnothing_{\mathrm{beam}}}{NA_{e^2}}$$

Where f' is the optimum focal length, $\varnothing_{\mathrm{beam}}$ is the beam diameter on the $1/e^2$-level, and NA_{e^2} the effective numerical aperture at the coupling wavelength λ.

For a nominal fiber NA, the adequate focal length is determined by

$$f' = \frac{F_{NA} \cdot \varnothing_{\mathrm{beam}}}{NA}$$

The nominal fiber NA corresponds to the Gaussian angle distribution at a 1 – 5 % level requiring the factor F_{NA} to correct for the different definitions of the NA. F_{NA} is 0.76 for 1 %, 0.66 for 3 %, and 0.61 for 5 %.

A focal length that was chosen too large is inefficient, since the focused laser spot is larger than the mode field diameter. When using a focal length too small, the convergence angle of the focused laser spot is larger than the maximally acceptable divergence angle of the fiber – the coupling efficiency is diminished. For an optimally chosen focal length, apart from losses due to Fresnel reflection at both fiber ends of about 4 % each, an ideal Gaussian beam is coupled almost completely.

It becomes clear that an accurate value for the effective fiber NA_{e^2} has a high impact on the value for the optimum focal length.

For example, for a beam diameter $\varnothing_{\mathrm{beam}}$ of 0.72 ($1/e^2$-level), wavelength 405 nm and a standard fiber with nominal NA of 0.12 (given on the 1 – 5 % level), the optimum focal length is calculated to be f' = 3.7 – 4.6 mm. Using the actual measured value for the effective numerical NA_{e^2} for this fiber (NA_{e^2} = 0.07), the optimum calculated focal length is f' = 5.1 mm.

The coupling efficiency can be calculated as the overlap between the MFD and the Gaussian spot. An overlap of 1 means, that apart from losses due to Fresnel reflection at both fiber ends of about 4 % each, imaging aberrations, and stray loss and beam distortion (8 %), as well as transmission loss (1 %), an ideal Gaussian beam is coupled almost completely (max. coupling efficiency ≈80 %). The overlap between the MFD of the fiber is 0.99 using an optics of focal length f' = 5.1 mm whereas the overlap is only 0.94 for an optics with focal length f' = 4 mm, the next best choice. Please note that optics are not available for each focal length and that 4 mm would the best choice for the calculated range. The choice based on the inaccurate nominal values for fiber NA such leads to a possible decrease in coupling efficiency of 6 %.

Of course, these are theoretical considerations. In reality, optics quality also plays an important role. For applications with multiple wavelengths achromatic or apochromatic optics should be chosen that allow for a large coupling efficiency for two or more wavelengths, whereas for single wavelengths aspheres are appropriate as well. Please note that for coupling into PM fibers, the polarization direction of the laser source must be aligned with the polarization axis of the fiber as well. This procedure is described in detail in [1].

Proven stability

The high stability of fiber coupling using a laser beam coupler is demonstrated in temperature stability tests using different focal lengths and wavelengths. The test setup is depicted in Fig. 2. The light emitted by a temperature-stabilized laser diode beam source with integrated Faraday isolator is guided to the test setup using a polarization-main-

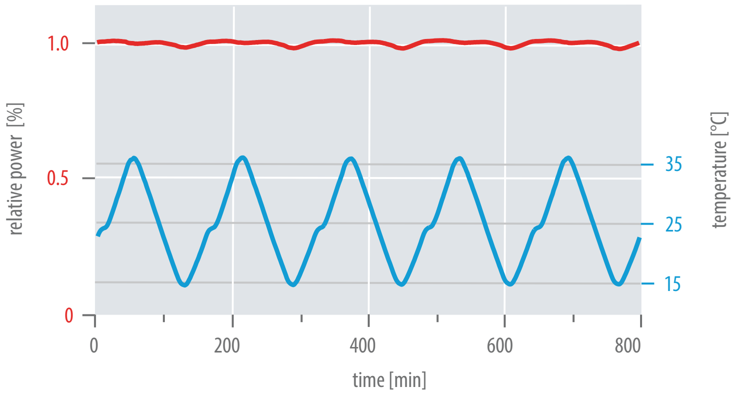


Fig. 3 The relative power (normalized with respect to the mean power) shows a repetitive pattern following the temperature (below) and has a maximum deviation of ±1.5 %.

taining fiber, collimated by a laser beam coupler, and then coupled back into a polarization-maintaining fiber using a second laser beam coupler, with both placed 12 mm apart. The recoupled power is monitored using a photodetector. The coupling setup is placed on a thermo-controlled plate, to vary the temperature between 15 and 35 °C in successive cycles with a rate of 0.5 °C per minute. The temperature of the coupling system is monitored by a temperature sensor placed on one of the two laser beam couplers. In order to minimize any temperature impact on the measurement equipment, the laser source as well as the photo detector and the data logger are all placed on a thermo-controlled plate at a constant temperature of 25 °C.

Fig. 3 shows the typical results of the relative transmitted power over five measurement cycles using a focal length of 4.5 mm and a wavelength of 405 nm. The power is normalized with respect to the mean power acquired over all measurement cycles. The power deviation from the mean power is ±1.5 %. The repetitive pattern in the relative power caused by the temperature cycling is demonstrated more clearly in Fig. 4, in which the relative power (normalized to the maximum) is plotted against the temperature of the laser beam couplers. The maximum coupling efficiency is reached a little above 25 °C and it decreases faster towards lower temperatures than higher temperatures, with the smallest slope near the requested operating point (25 °C). The respective power curves for each measurement cycle are almost coincident and the power variation at points with equal temperatures is <1 %, which demonstrates the reproducibility of the pointing stability during temperature cycling and the long-term stability of the fiber-coupling.

The maximum deviation with respect to the maximum power here is 3 %.

Choosing the right collimating optics

Fiber collimators are designed for collimating radiation exiting optical fiber cables. They can also be used in reverse-mode as fiber incouplers. They are suitable for single-mode and polarization-maintaining fiber cables leading to collimated beams with a Gaussian intensity profile. Just as finding the right coupling focal length in many applications the optimum focal length of the fiber collimator has to be chosen in order to get a certain collimated beam diameter. The designated collimated beam diameter $\varnothing_{beam}$ (defined on the $1/e^2$-level) is calculated using

$$\varnothing_{beam} = 2 \cdot f' \cdot NA_{e^2}$$

with f' being the focal length of the fiber collimator and NA_{e^2} being the effective fiber numerical aperture.

The new online product configurators for fiber couplers and collimators allow to insert fiber information and

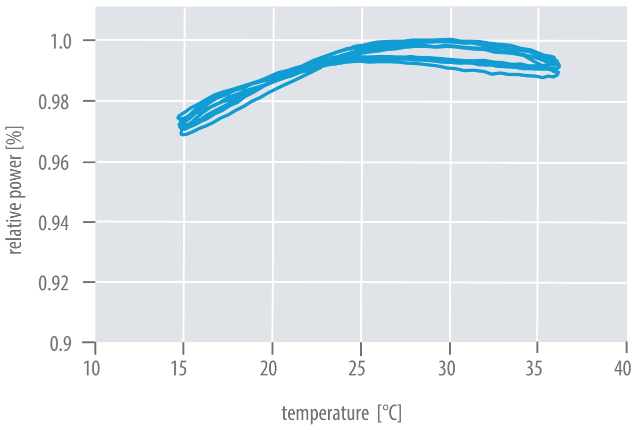


Fig. 4 The relative power curves (normalized with respect to the maximum power) are almost coincident and confirm the high reproducibility of the pointing stability during temperature cycling. The maximum deviation is only 3 %.

features like wavelength, *NA*, or purpose (coupling or collimation) and then adequate fiber collimators and couplers are shown. Using the fiber properties, the corresponding beam diameters and the Rayleigh range are calculated. If a certain beam diameter is needed, sliders are used to adjust the limits and the large selection of possible collimators is narrowed down to the best choices. This makes selecting quick and easy. The comparison function is used to compare key features. For each fiber collimator / coupler, further information and a data sheet can be downloaded.

Just as for the focal length of the coupling optics accurate values of the numerical aperture of the fiber here also have a large impact on determining the right collimating optics in order to get a certain beam diameter. For example, in order to get a beam diameter ($1/e^2$-level) of 1 mm the focal lengths are calculated to be $f' = 5.1 - 6.3$ mm for a nominal *NA* of 0.12 (1 – 5 % level), whereas using the actual measured values of NA_{e^2} for 405 nm leads to a focal length f' of 7.1 mm. Just to illustrate: the wrong choice of focal length $f' = 5.1$ mm in reality leads to a beam diameter of only 0.71 mm.

Apart from the right focal length, the right choice of optics type also plays a role. Monochromic optics that are corrected for spherical aberration are a great choice or single wavelength application. Unlike for in-coupling, very few selected aspheres can also be used that provide a good quality collimated beam profile. Achromats are a great choice for multiple wavelength applications.

Conclusion

Fiber optics can significantly increase the stability and convenience of measurement setups and allow large breadboard setups to be replaced by stable, compact, transportable, sealed fiber-optic systems. The stability of any fiber-optic system strongly depends on the long-term stability of the laser beam couplers used for both coupling in and out of PM fibers. Power stability during temperature cycling, with a typical maximum deviation of 3 %, was achieved in a test setup for laser beam couplers with a focal length of 4.5 mm at 405 nm and at temperatures between 15 and 35 °C. This high stability is fundamental for the successful use of fiber optic equipment. Accurate measurements of the effective fiber numerical NA_{e^2} provide the basis for choosing the most appropriate coupling and collimating optics. Suitable fiber cables can be selected using the online fiber cable product configurator on the new Schäfter+Kirchhoff website that also provides the NA_{e^2} curves for downloading. These values can then be used as basis to put into the fiber coupler and collimator online product configurator that narrows down the search quickly and easily in order to find the most adequate coupler or collimator.

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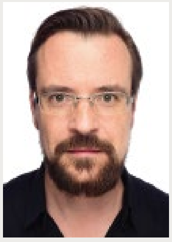

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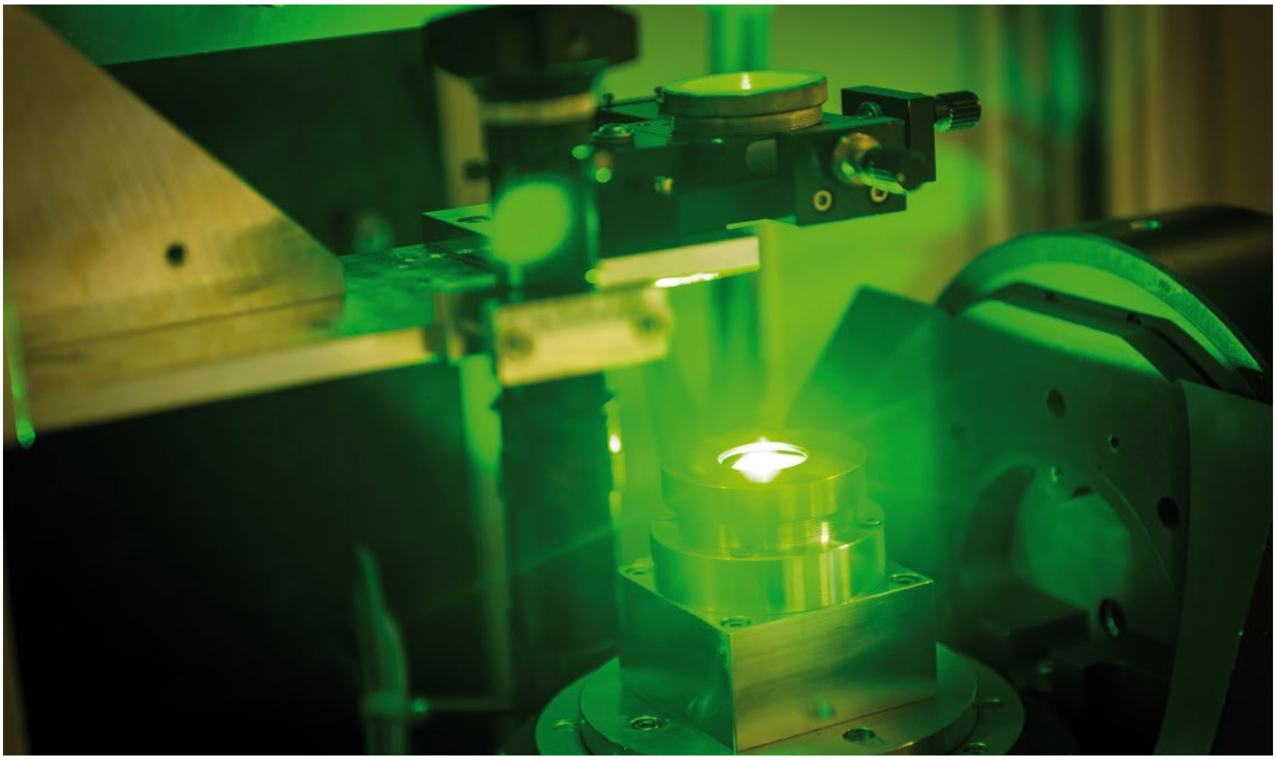
X-Ray Protection in an Industrial Production Environment

Industrial implementation of the requirements of the German Radiation Protection Act

Christian Freitag and Roswitha Giedl-Wagner



Source all images: LightPulse Laser Precision

With the classification of ultrashort-pulse laser processing systems as "systems for the generation of ionizing radiation" in the German Strahlenschutzgesetz (Radiation Protection Act), their operation is usually no longer possible without a license and without notification of the authorities. This article deals with the implementation of the legal requirements resulting from this classification in an industrial production environment.

Using ultrashort-pulse lasers for materials processing offers many advantages compared to laser sources with longer pulse durations: minimum heat input, a mechanical precision in the micro-meter range and the ability to process transparent materials are just a few of them [1]. The typical pulse duration of industrial laser sources used for materials processing is in the range of 300 fs to 10 ps. Using such short pulse durations, an irradiance of more than 10^{13} W/cm² is easily achieved. With such high laser irradiances, the electron temperatures in the generated plasma reach several keV which results in bremsstrahlung with emissions in the keV X-ray order.

This emission of X-ray radiation when ablating material with ultrashort-pulse lasers was already investigated in the 1980s [2]. Although it is an already known effect, it has recently come increasingly into focus with the increase in the average power of ultrashort-pulse lasers into the kW range. Since the dose rate increases proportionally to the average power, X-ray emission from processes using higher average laser powers can represent a serious health risk. Accordingly, research activities in this area have increased strongly in recent years.

Legall et al. (2018) measured the spectral X-ray emission for different target materials using an ultra-short-pulse laser with a wavelength of 1030 nm. X-ray photons with energies up to 25 keV were detected [3]. These results were confirmed by Behrens et al. (2019) [4]. Further research was carried out on the influence of processing parameters on X-ray emission by Legall et al. (2019) [5]. It was found that the intra-line separation and the scanning direction have an influence on the measured X-ray dose when using a beam scanning scheme. An analytical model to estimate the expected X-ray dose when laser processing with ultra-short-pulse lasers under industrial conditions was presented by Weber et al. (2019) [6]. Using the presented model, it was concluded that shielding with a 2 mm sheet of iron is, to current knowledge, sufficient to attenuate the radiation level generated during processing with a 1 kW ultrashort-pulse laser to a safe level. This prediction was recently confirmed by Legall et al. (2020) [7].

The potential health risk posed by the X-rays generated during material processing with ultrashort-pulse lasers led to a reaction from the legislator. The new German Radiation Protection Regulation came into force on December 31, 2018, which also applies to material processing stations equipped with an ultrashort-pulse laser. This article deals with the effects of this regulation on a German company.

Legal requirements

Part C of the German Radiation Protection Regulation states: "…The operation of systems for the generation of ionizing radiation in which ionizing radiation can be generated by the incidence of laser radiation according to § 2 paragraph 3 sentence 1 of the Regulations on Artificial Optical Radiation on material is exempt from licensing and notification if the irradiance of the laser radiation does not exceed $1 \cdot 10^{13}$ watts per square centimeter **and** the local dose rate in 0.1 meter from the touchable surface does not exceed 1 micro Sievert per hour." One of the consequences of this regulation is that companies have to acquire a license for the operation of every processing station that is operated with an irradiance exceeding $1 \cdot 10^{13}$ W/cm². This level is easily possible using an ultrashort-pulse laser.

An application must be submitted to the authorities to obtain this license and should include:

- The appointment of a radiation protection officer and a radiation protection commissioner who have the necessary technical qualifications
- Documentation including, amongst other things, the annual maintenance plan, planned materials to be processed, a safety report and a hazard assessment
- Proof of coverage against radiation damage provided by the insurance company
- Radiation protection training and a list of the persons working with the system
- A test report according to the measurement specifications
- Documentation of the continuous dosimetry

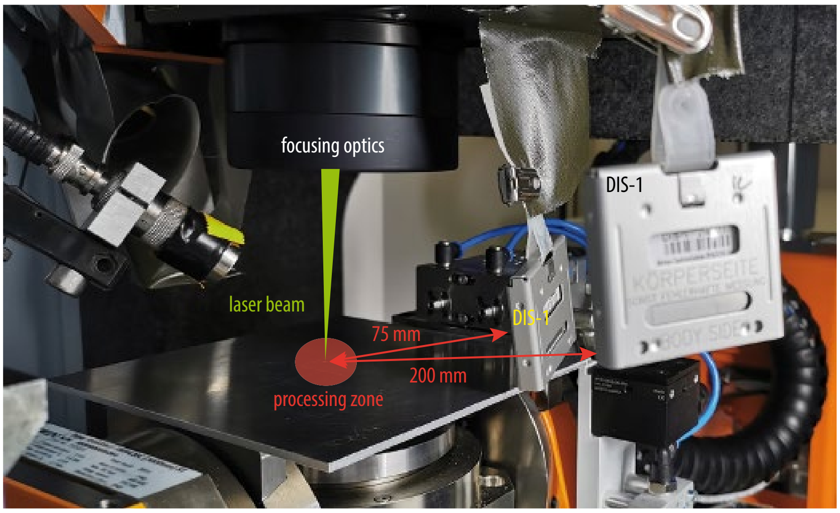


Fig. 1 Overview of the experimental setup. The laser beam is focused on the workpiece surface with focusing optics. Two type DIS-1 dosimeters are placed close to the processing zone at distances of 75 mm and 200 mm.

A critical point is the test report according to the measurement specifications, where an X-ray test qualifying the housing must be performed. The aim is to guarantee the X-ray safety of the housing so that there is no danger to the operator. Of special interest are the doses $H(0.07)$ and $H(10)$ and the corresponding dose rates $\dot{H}(0.07)$ and $\dot{H}(10)$. These describe the absorbed X-ray energy per mass at a depth in the body of 0.07 mm and 10 mm, respectively. The first value mainly considers X-ray photon energies around 5 keV; the latter photon energies at about 30 keV [6]. The corresponding dose rates consider the absorbed X-ray energy per mass and time. The legal limit for $H(0.07)$ is an accumulated dose of 50 mSv within one year and for $H(10)$ an accumulated dose of 1 mSv within one year. The legal requirement that the local dose rate at 0.1 meter from the touchable surface should not exceed 1 µS/h assumes the $\dot{H}(10)$ dose rate.

In the following, an X-ray test of a housing is presented as an example of a real application case.

Experimental setup

The tested laser processing station was a GL.compact from GFH. This station is equipped with an ultrashort-pulse laser with a pulse duration of 900 fs, a wavelength of 515 nm, a maximum average power of 35 W, a repetition rate of 200 kHz, a maximum pulse

Companies

LightPulse LASER PRECISION

Lightpulse Laser Precision is a start-up from Stuttgart and offers services for micro material processing with ultrashort-pulse lasers. This includes the development and adjustment of machining processes, the production of prototypes and the contract manufacturing of series. In addition, consulting services on the technology are also offered. Due to our long experience in material processing with ultrashort-pulse lasers, Lightpulse Laser Precision is your ideal partner for the implementation of even the most demanding applications.

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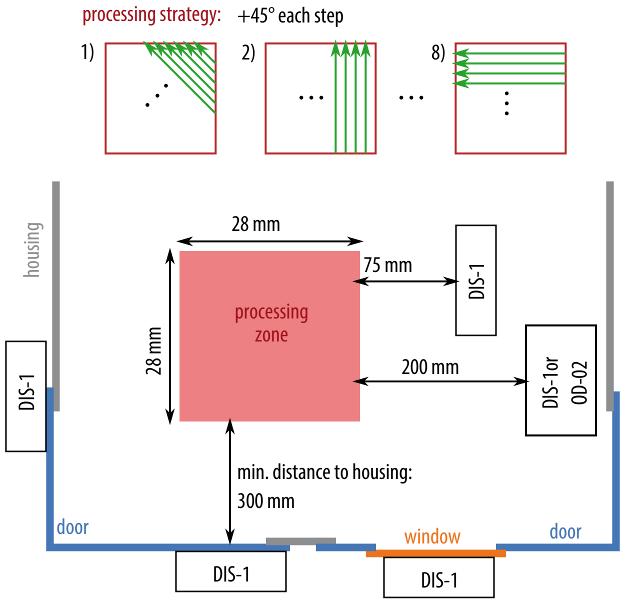
GFH GmbH

GFH GmbH is one of the global leaders and technology pioneers in the design and engineering of high precision laser micro machines with ultrafast lasers. It has more than 20 years of experience in laser micromachining. A range of serial production solutions with customized automation can be offered, as well as special machines purpose-built for specific applications. The in-house precision manufacturing department provides feasibility studies, sample and serial production.

https://gfh-gmbh.de

Fig. 2 A sketch of the arrangement and a depiction of the processing strategy for the housing test is shown here. The housing completely encases the processing zone. The minimum distance of the processing zone from the housing is 300 mm. The housing has two doors, one of which is equipped with a laser safety window. Additional DIS-1 dosimeters are installed at critical points of the housing. For preparatory studies, an OD-02 dosimeter was installed instead of the DIS-1 dosimeter at a distance of 200 mm. The processing strategy shows the hatching direction for the different processing steps within the processing zone. The hatching direction is turned in 45° steps after each processing step.



energy of 174 µJ and a focal spot diameter of 10 µm. This results in a maximum intensity at the focus of $4.7 \cdot 10^{14}$ W/cm².

A scanner system was used for beam movement since, according to current knowledge, hatching causes the highest X-ray dose. The laser generated plasma is shielded least using a hatched scanning process. An overview of the experimental setup is shown in Fig. 1. The beam is focused on the workpiece with focusing optics. Two DIS-1 dosimeters from Mirion Technologies were placed inside the station near the processing zone, one at a distance to the processing zone of 75 mm and one within a distance of 200 mm. A sketch of the setup and the processing strategy is shown in Fig. 2. In addition to the dosimeters placed inside the stations, dosimeters were placed outside at the critical points of the housing. One dosimeter was placed at the laser safety window and one dosimeter was placed on the housing at the shortest distance to the processing zone. The minimum distance from the processing zone to the housing is 300 mm. Another dosimeter is placed at a transition between the housing and a loading door, as this is a potential weak point. The housing itself is made out of 2 mm thick steel. The laser security window is 3 mm thick, additionally secured by a lead glass pane with a lead equivalent value of 1.5 mm. A protruding flange is installed at the openings, for example at the transition from the housing to the door, so that a direct view of the laser plasma is always blocked by at least 2 mm steel.

Material selection

As a preparation for the housing test, the generated X-ray dose was measured for two different materials, steel and tungsten, since both materials showed similar dose rates in previous studies [3]. The dose rate was measured as a function of the irradiance. The irradiance was varied by changing the pulse energy. The average laser power was kept constant at 3.5 W by changing the repetition rate accordingly. A constant average laser power is important, since the dose rate increases linearly with the average laser power [6]. To keep the pulse overlap constant, the movement speed of the laser beam was changed according to the repetition rate. The dose rate was measured using an OD-02 dosimeter from STEP Sensortechnik and Elektronik Pockau. It was placed inside the processing station at a distance of 200 mm from the processing zone. The measured dose rate as a function of the irradiance can be seen in Fig. 3.

The dose rate is about a factor of ten higher when processing tungsten compared to steel. For this reason, tungsten was used for the subsequent housing test. It can also be seen in Fig. 3 that there is a linear correlation between the dose rate and the irradiance. The dose rate is maximum at maximum irradiance, and the maximum irradiance was used for the housing test.

Hatching strategy

Previous studies showed that the scanning direction has a significant influence on the measured X-ray dose [5]. As a further measure in preparation for the housing test, the process was examined for the dependence of X-ray emission on the hatching angle. The dose rate was again measured using the OD-02 dosimeter during a scanning process with eight different orientations of the hatching pattern. The dosimeter was again placed inside the processing station at a distance of 200 mm from the processing zone. Squares with a size of 28 × 28 mm were ablated on tungsten. The orientation of the hatching pattern was rotated by 45° after each processing step. The total process time was 250 s, so the hatch pattern was rotated approximately every 30 s.

The measured dose rate as a function of the processing time can be seen in Fig. 4. The individual process steps are separated and numbered by red dotted

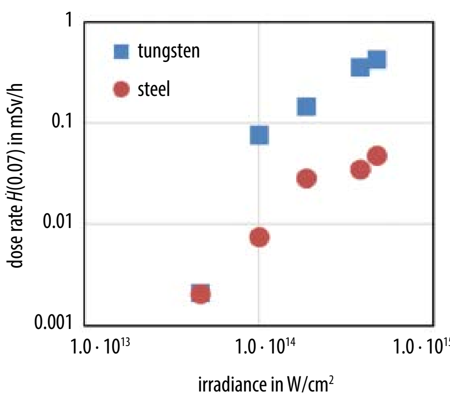


Fig. 3 Dose rate $\dot{H}(0.07)$ as a function of the irradiance. The dose rate was measured for two different materials, steel and tungsten. The process parameters were: average laser power 3.5 W, pulse duration 900 fs, wavelength 515 nm, focal spot diameter 10 µm. The pulse energy, repetition rate and the movement speed of the beam were varied.

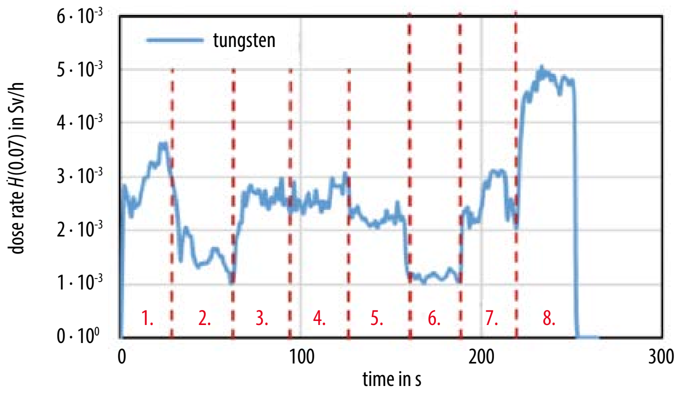


Fig. 4 Dose rate $\dot{H}(0.07)$ as a function of the processing time. The OD-02 dosimeter was placed at a distance of 200 mm from the processing zone. The processed material was tungsten. The hatching pattern was rotated by 45° every 31 seconds. Each of these processing steps is marked by a red number and separated by red dotted lines. The average laser power was 35 W, the repetition rate 200 kHz, the pulse energy of 174 µJ and the focal spot diameter 10 µm. This results in a maximum intensity at the focus of $4.7 \cdot 10^{14}$ W/cm².

lines. There is a strong dependence of the dose rate measured on the hatching direction with respect to the dosimeter. With optimum alignment of the hatching direction, up to five times more X-rays are recorded than with the most unfavourable alignment. Furthermore, it can be seen that the maximum dose was not generated during the first pass but only during the eighth process step. There the alignment of the dosimeter to the hatching direction seemed to be optimum. The positioning and hatching direction during step 8 are depicted in Fig. 2. This strategy of rotating the hatching direction in 45-degree steps was used for the housing test. Such a rotation pattern ensures that all dosimeters (inside and outside the station) are exposed to the same radiation dose over time. In this way a comparable measurement result can be achieved.

X-ray test of the housing

The maximum average laser power of 35 W was used for the housing test. The total duration of the measurement was 96 minutes. The dosimeters were read out every 16 minutes. Please note that the dosimeters were not reset after each read out. In this way, the temporal development of the dose can be tracked.

The measurement results for the two dosimeters located inside the station are shown in Fig. 5. In Fig. 5a the accumulated dose $H(0.07)$ is shown, in Fig. 5b the accumulated dose $H(10)$ is shown. A high $H(0.07)$ dose was measured at a distance of 75 mm to the processing zone. After one hour, a dose of 102 mSv was achieved. The legal limit is 50 mSv, which is already exceeded close to the processing zone and without shielding after half an hour. Increasing the distance to 200 mm (again without shielding), the $H(0.07)$ dose already drops significantly. After one hour, a dose of about 2 mSv was measured. These measurements confirm that keeping a sufficiently large distance to the processing zone already significantly reduces the dose.

The accumulated dose of $H(10)$ at a distance of 75 mm was 1 µSv after 16 minutes and stayed constant afterwards. At a distance of 200 mm the $H(10)$ dose was 0 µSv for the whole duration of the measurement. A reliable measurement is difficult at such low values because the readout accuracy of the $H(10)$ dose of the DIS-1 is 1 µSv. As the accumulated dose of $H(10)$ at 75 mm distance did not increase over the prolonged exposure it can be assumed that the readout of 1µSv is not representative for the real emission but caused by the readout resolution.

The insufficient readout accuracy is problematic in that the legal limit is 1 µSv per hour. However, since at a distance of 200 mm the measured $H(10)$ dose was 0 µSv, it can be expected that outside the housing, which has a minimum distance to the processing zone of 300 mm, no X-ray emission relevant for the $H(10)$ dose will be present.

Three dosimeters were placed at critical points on the outside of the housing (window, housing with the shortest distance to the processing zone, transition between housing and door). All of these dosimeters measured a $H(0.07)$ dose of 0 mSv and a $H(10)$ dose of 0 µSv. Although, as shown before, inside the housing, a significant amount of $H(0.07)$ dose was measured, no X-ray radiation could be detected outside the housing. The housing therefore provides sufficient shielding against the X-ray radiation generated during laser processing with an ultrashort-pulse laser.

Arising costs

The need to apply for a licence as well as the conditions required for the granting of the licence cause additional costs in a company. For the license application, the preparation of a test report, the attendance of a radiation protection course to act as radiation protection offi-

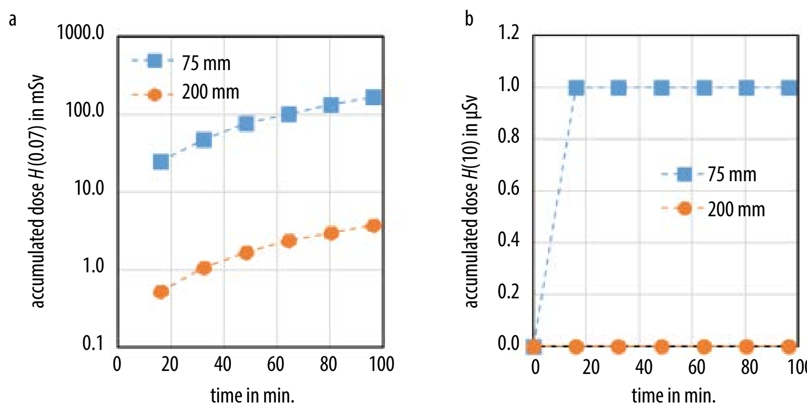


Fig. 5 Accumulated dose $H(0.07)$ as a function of the time measured with the two dosimeters within the station (a). Accumulated dose $H(10)$ as a function of the time measured with the two dosimeters within the station. In both cases the average laser power was 35 W, the repetition rate 200 kHz, the pulse energy of 174 µJ and the focal spot diameter 10 µm (b). This results in a maximum intensity in the focus of $4.7 \cdot 10^{14}$ W/cm². The processed material was tungsten.

cer as well as the issuing of the license, a one-time cost of approximately 6,000 euros is incurred. The radiation protection course has to be revisited every five years. This is a cost estimate based on the current situation (March 2020) and the examination of the radiation-proof designed GL.compact. The costs in individual cases may vary considerably. If the testing process is further standardized, the time for the housing test and therefore the costs may be reduced. The testing process may be more complex and thus more cost-intensive for other, more complex systems than the GL.compact. Additional costs of about 650 euros per year arise for the continuous dosimetry as well as the insurance coverage. In addition, the resulting administrative costs for the radiation protection organization must be taken into account. All in all, the necessary administrative effort and costs for companies should not be underestimated when commissioning an ultrashort-pulse laser processing station.

Summary

Since the entry into force of the German Radiation Protection Regulation, a licence is now required for the operation of ultrashort-pulse laser processing systems. This requires a report on the radiographic test of the housing. Such a test was described in an actual application example and the difficulties illustrated with the current method. The housing consisted of 2 mm of steel. Protruding flanges were implemented at potential weak points, like the opening between a door and the housing. The laser safety window was additionally secured by lead glass. These security measures were sufficient, so that no X-ray emission was measured outside the housing even though a significant amount of X-ray emission was generated during ultrashort-pulse laser processing.

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[5] *Legall* et al.: Applied Physics A **125** (2019) 570

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Smooth Surfaces by Pulsed Laser Processing with Bursts

Making use of the effects of successive pulses

Andreas Michalowski, Fabian Nyenhuis, and Gerhard Kunz

(Source all images: Bosch)

The aim in ultrashort-pulsed materials processing is generally to keep interactions between the effects of the individual laser pulses to a minimum in order to minimize quality-reducing effects and to avoid exceeding process-specific thresholds. A contrasting approach aims at exploiting the interaction of consecutively applied laser pulses with the respective material response. In this case, it is possible to use particularly high average laser powers as well as bursts that feature time intervals of only a few nanoseconds.

The main reason for introducing ultrashort laser pulses into production is the outstanding precision and flexibility of this technology. For some years, the biggest drawback was the relatively low productivity caused by the low average laser power of the available beam sources. Since beam sources with high average power have become available, it has been a challenge in many applications to use the available power for higher productivity while maintaining high quality. In the case of the laser ablation of highly absorbent materials, especially metals, increasing laser power often results in a rather abrupt transition from a very smooth surface quality to very rugged surfaces that are heavily oxidized and usually no longer meet the quality requirements. The cause of this undesired effect was identified as the accumulation of heat on the material surface [1, 2].

Contrary to a widespread opinion held for many years, a significant portion – about one third – of the incident pulse energy remains as heat in the work piece during material processing with ultrashort laser pulses [3, 4]. As a result, when using high repetition rates and high pulse overlap, high temperatures can occur locally on the material surface, although the work piece as a whole heats up only slightly. Therefore the real advantages of ultrashort-pulse machining are lost. Approaches to avoid this unwanted effect consist, for example, of advances in the field of scanner technology or beam shaping.

Another problem can occur with very short times between pulses. Due to interactions with the ablation products of the preliminary pulses, the ablation volume per pulse can be significantly reduced [6, 9]. In some cases, however, it may also be possible to use the accumulation effects to one's advantage [5 – 8].

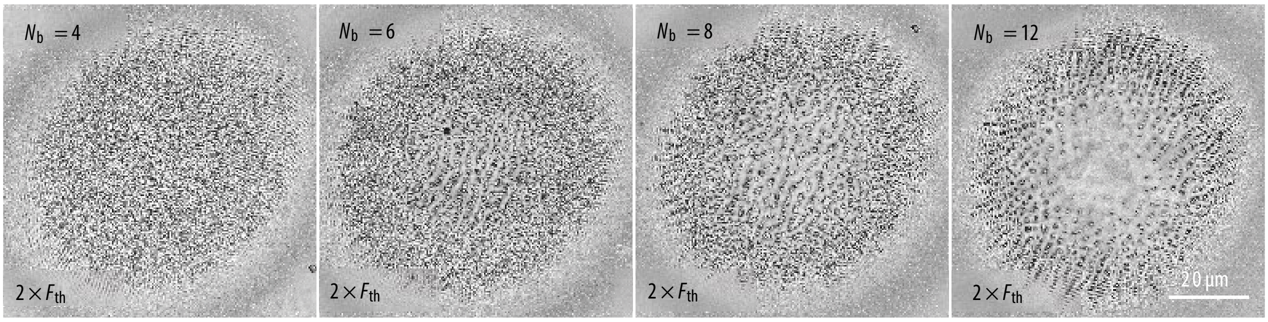

Fig. 1 Iron surfaces irradiated with ≈100 pulses at 1030 nm and 1 ps pulse duration divided into burst packages of different pulse numbers N_b. The average fluence of each pulse is twice the ablation threshold F_{th}, the time spacing of the pulses inside the burst was 12.5 ns. The time spacing between the burst packages was set to one millisecond to enable heat dissipation between the bursts. As the number of pulses in the bursts increases, solidified melt becomes more clearly visible, with N_b = 12 even producing a smooth surface in the central area.

Processing of metals

An interesting application of the heat accumulation effect is the purposeful and defined production of melt films on the material surface. Here it is advantageous to apply the energy in the form of pulse packages, so-called bursts. A typical burst is characterized by a sequence of pulses with a smaller time spacing t_B followed by a larger time spacing t_R. Within the burst, t_B is typically some nanoseconds and thus several orders of magnitude smaller than t_R (usually about 1 µs), which is defined by the repetition rate of the laser system. The heat input into the material at the surface can be controlled by a suitable choice of the pulse energy of the single pulse in the burst, the time spacing between the burst pulses and the number of pulses within each burst.

Fig. 1 shows scanning electron microscope images of an iron surface irradiated with about a hundred pulses, where the number of pulses within each burst was varied while adjusting the number of burst packages to keep the total number of pulses approximately constant.

The energy of each individual pulse was chosen so that the mean fluence was twice the ablation threshold of 0.075 J/cm^2 (unpolished iron, multiple pulses).

While the typical ripple structure on the iron surface is observed, solidified melt in the center of the irradiated area can be seen more and more clearly as the number of pulses in the burst increases. At twelve pulses in the burst, a closed solidified melt film remains in the center, which has smoothed out the ripple structure. In principle, it is therefore possible to realize a kind of laser polishing with ultrashort pulses. Both material ablation and the formation of ripples can be minimized by reducing the energy of each pulse within the burst so that the fluence of each pulse is below the ablation threshold. Due to the heat flow into the bulk material, however, for small fluence it is necessary to reduce the time spacing between the pulses so that the melt film does not solidify immediately between the pulses. The maximum length of the time spacing depends on the thermal diffusivity of the material, which is comparatively large for metals.

The effectiveness of this approach can be clearly seen from the surfaces shown in **Fig. 2**, where a scratched iron surface has been irradiated. The

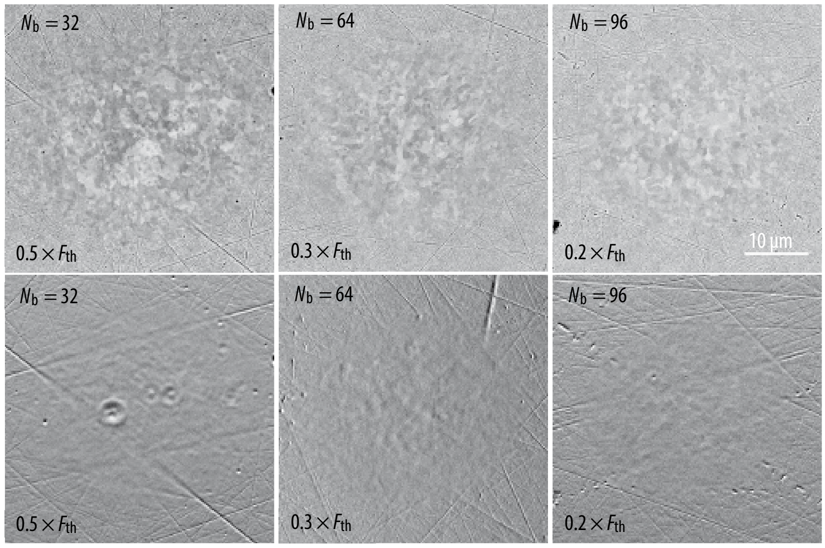

Fig. 2 SEM images (upper row) and topology (lower row) for irradiated iron at a pulse duration of 1 ps and a wavelength of 1030 nm. From left to right, the number of pulses N_b in the burst increases while the average fluence of each pulse is reduced. Due to the short time of 625 ps between the pulses, the smoothing effect can be achieved even though the fluence of each pulse is clearly below the ablation threshold. This allows smoothing out scratches on the sample without causing additional ablation damage to the surface. The microscope images show a grain structure with very small grains which, as expected, indicates a very fast cooling process.

Company

Bosch Research

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average fluence is well below the ablation threshold, the time spacing of the pulses in the burst was set to 625 ps and the number of pulses in the burst was increased. The scratches on the surface are significantly smoothed without damaging the surface by ripple or visible material removal.

It is also possible to adjust which structural sizes will be smoothed and which are to be kept by suitable selection of the burst parameters. Fig. 3 left shows an example of the subsequent smoothing of the characteristic bump structures that typically occur in laser milling of steel at higher average power and a too low feed rate. The melt film thickness and the duration of the liquid phase were large enough to completely smooth the relatively large bumps after just ten scans. The visible parallel lines have a waviness of less than one micrometer. If the parameters are adjusted in such a way that the melt film is thinner and more short-lived, it is also possible to smooth particularly fine unwanted structures that are superimposed on a more coarse functional structure (Fig. 3 right).

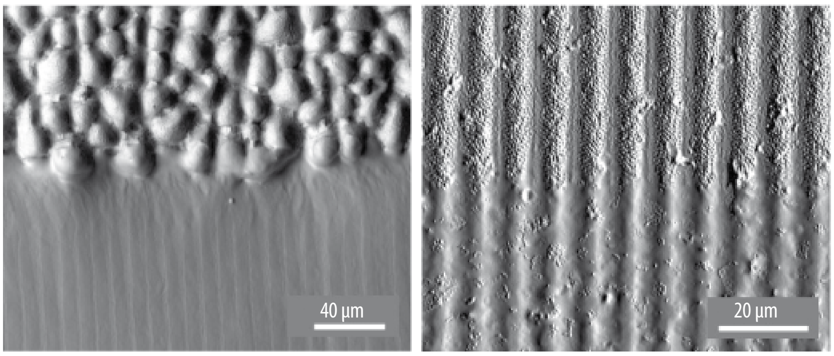

Fig. 3 By selecting the appropriate parameters, the structure size to be smoothed can be adapted to the specific application. The left illustration shows an example of the subsequent smoothing of bumps, which typically occur during laser milling of steel when too much heat accumulates (upper area: bumps, lower area: subsequently smoothed). On the right is an example of smoothing a DLIP structure without removing the DLIP structure itself (time spacing 625 ps, pulse duration 1 ps, wavelength 1030 nm).

Processing of silicon

This smoothing effect is not limited to metals. In laser milling of silicon, the energy-specific ablation volume towards shorter pulse durations increases significantly. However, at pulse durations of about 1 ps and below, similar to metals at high fluences, a damaged surface with a high roughness is observed. This damage can be avoided by using bursts, whereby a double pulse already produces the desired smoothing effect (Fig. 4 left). Nevertheless, in this case it makes sense for productivity reasons to work with more pulses in the burst, since an increasing number of pulses leads to a higher energy-specific ablation volume (Fig. 4 right). The reason for this is presumably both the significant difference in the absorption behavior of bursts compared to single pulses and the more efficient removal of the molten surface layer, e.g. liquid material that is displaced from the laser material interaction zone in the form of melt droplets [6].

High average ablation rates and very smooth surfaces can be achieved when laser milling silicon (Fig. 5) if the process parameters are suitably adjusted. In this example, the roughness achieved on the surface is well below one micrometer. With suitable processing strategies, the ultrashort pulsed laser is an attractive tool for the production of complex surface topologies in hard semiconductors, as demonstrated here for silicon.

Discussion

The selective use of burst makes it possible to combine the high intensities that arise during material processing with ultrashort laser pulses and a controllable accumulation of heat. This enables the low-damage removal of material during laser milling of different materials, whereby subsequent smoothing effects can remove damage to the surface. In the case of silicon, bursts can increase productivity and enable working at a high average power. A smoothing effect could possibly also be achieved by using pulse durations of a few nanoseconds. However, a big

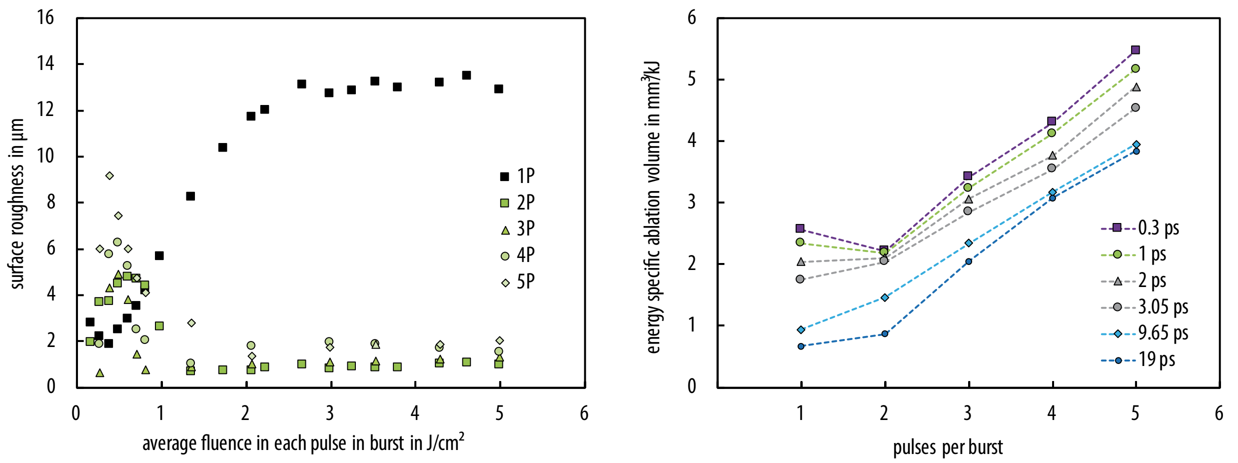

Fig. 4 For pulse durations below 1 ps, laser milling of silicon with bursts results in a much smoother surface than without (left). The energy-specific ablation volume increases significantly with an increasing number of pulses in the burst, illustrated here for an average fluence of 2.06 J/cm² (each pulse in the burst; right). The reason for this is presumably a changed absorption behavior caused by the previous pulses and, *in particular*, the more efficient removal of the liquid melt films. The experiments were performed at a wavelength of 1030 nm with 20 ns time spacing of the burst pulses.

advantage of the burst approach is the ability to make use of high intensity or specific melt formation, depending on need. Damage that typically occurs at high average laser power can be smoothed out again afterwards. This shows that the selectively switchable burst is a further step towards a universal laser beam source for material processing.

*

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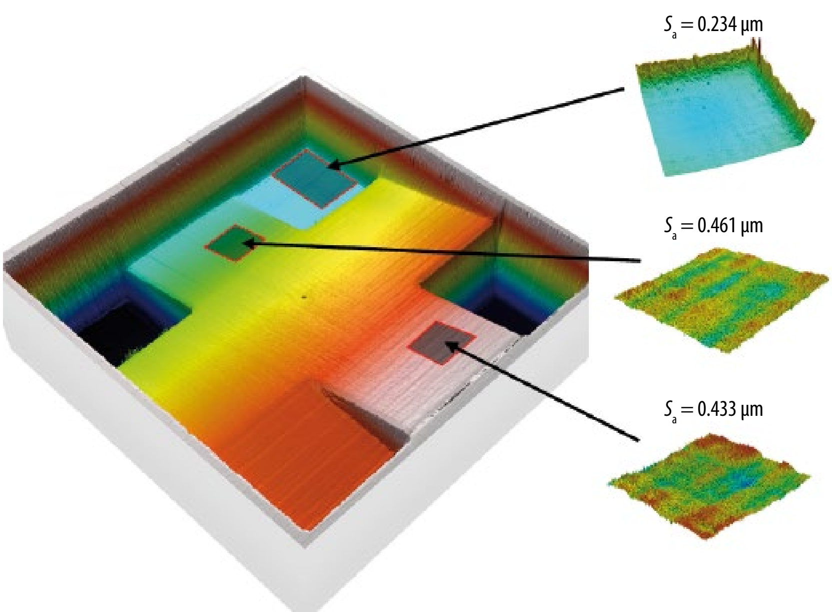

Fig. 5 In this example of laser milling of silicon, a relatively large volume (12 mm³) was removed with high precision and low roughness by using suitable parameters and high average power (pulse duration 300 fs, wavelength 1030 nm).

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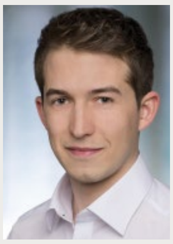
Authors

Andreas Michalowski has more than 15 years' experience in ultrashort-pulsed laser material processing. At Bosch Research, he is responsible for this technology as a senior expert for process fundamentals and simulation. He studied physics at the University of Dortmund and subsequently obtained his doctorate at the Institut für Strahlwerkzeuge at the University of Stuttgart.



Fabian Nyenhuis studied physics at the University of Hannover with a focus on non-linear optics and photonics. In 2017, he moved to Stuttgart for his master's thesis on the ultrashort pulse processing of battery foils at the research campus of the Robert Bosch GmbH. As a Bosch PhD student, he is researching the potential of highly repetitive ultrashort pulse lasers in advanced materials processing.

Gerhard Kunz studied mechanical engineering at the University of Stuttgart and completed his master's thesis on the high volume micromachining of silicon with ultrashort laser pulses. Since 2015 he has been pursuing this work at Bosch Research, focusing on process development for the industrial implementation of laser applications.

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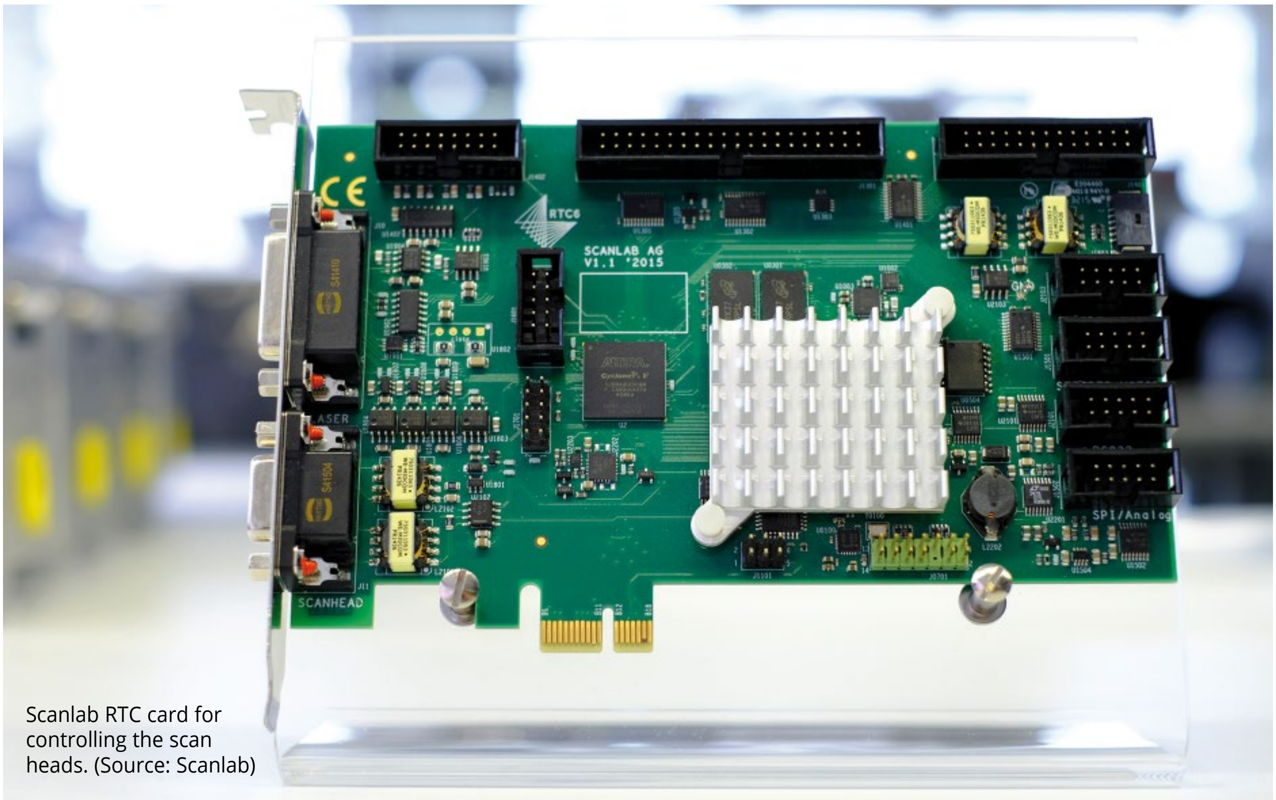

Scanlab RTC card for controlling the scan heads. (Source: Scanlab)

Micro-Drilling with a 5-Axis Precession Bore System

Practical experience using green and infrared lasers at Posalux

Udo Heinzel and Holger Schlüter

Relentless miniaturization in both consumer electronics and mechanical engineering has brought countless changes to the fabrication of such electronic components as PCBs, control elements, and sensors. This development also affects demands placed on laser processing machines used in micromachining. Difficult-to-handle materials such as polymers and ceramics present a special challenge. The following will describe how machine builder Posalux deals with these growing requirements. Today's processing limits can be newly defined by employing a precession bore system with a green laser.

The electronics industry consistently miniaturizes not just its products, but also the devices used to test them. Known as advanced probe cards, these aid in the testing of ICs and assert the most stringent demands on machining. The main component of any probe card is a guide plate consisting of a mechanical substrate with thousands of micro drill-holes. Those drill holes must securely and precisely position the probe card's contact pins to establish accurate contact with the connectors of the semiconductor chip being tested. But mechanical drilling is no longer precise enough for current advanced probe cards. Even worse, variable geometries are needed nowadays. Hence, the benefits of laser-based machining are obvious: drill hole quality is superior, enhanced bore geometries can be used, and processing times shrunk substantially.

Industrial demand for laser drilling by the micromachining sector has grown noticeably in recent years. Posalux tested the benefits of using a green laser versus an infrared (IR) system. Particularly interesting under these aspects is the availability of a scan system designed for 515 nm laser beams, which enables the generation of finer lateral structures.

Posalux has been supplying high-precision micromachining technologies for high-volume production for several decades. These micromachining tools find use in automotive manufacturing, medical technology, electronics fabrication, and the watchmaking industry.

Quest for ever more precision

To meet the increasing demands of micromachining, Scanlab extended its precsys product family to include a system designed for green lasers with

Fig. 1 The precsys 515 micromachining subsystem. (Source: Scanlab)

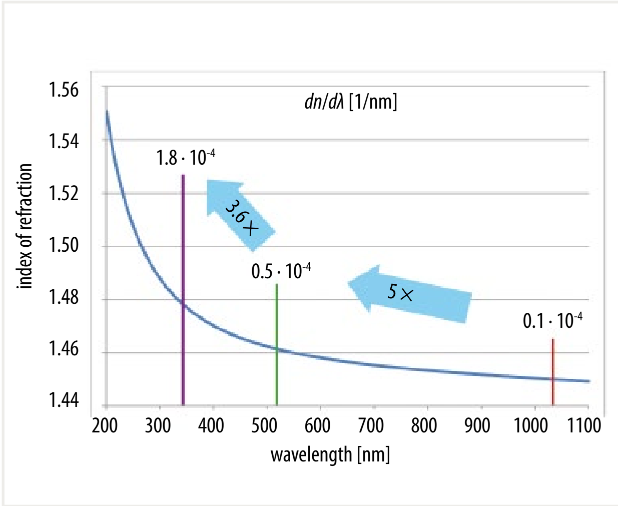

Fig. 2 Refractive index and dispersion of fused silica as a function of wavelength. (Source: Corning / Zemax material catalog)

a wavelength of 515 nm. Compared to IR laser systems at 1030 nm, it is exactly half the applied wavelength. This substantially reduces the spot size, thereby enabling much more precise lateral processing of difficult materials. Higher aspect ratios are obtainable at the identical beam divergence.

The dispersion of fused silica and the bandwidth of the deployed laser source play a key role when evaluating the system's spot size and spot quality. Fig. 2 shows that the change of the refractive index over wavelength at 515 nm is five times higher than at 1030 nm. For 343 nm, this value is a further 3.6 times higher than at 515 nm.

In other words, the refractive index of fused silica changes at varying rates across the laser's bandwidth, thereby introducing chromatic aberration. With classical scan lenses, such color errors can be compensated for by using a glass with a different dispersion. For ultrashort-pulse (USP) lasers, one such glass that could compensate for chromatic aberration is CaF_2.

But modern f-theta lenses for USP lasers typically do not use CaF_2 due to limitations in manufacturability and limited temperature stability. So, even with modern f-theta lenses, color errors remain that result from the USP laser's bandwidth. These color errors depend on the field size, so the largest errors occur at field edges (see elliptical spot on the right in Fig. 3 for 515 nm and 343 nm).

This effect also applies to the scan lenses used in the precsys. The effect is particularly strong at 343 nm, so Scanlab decided not to develop a 343 nm drill head.

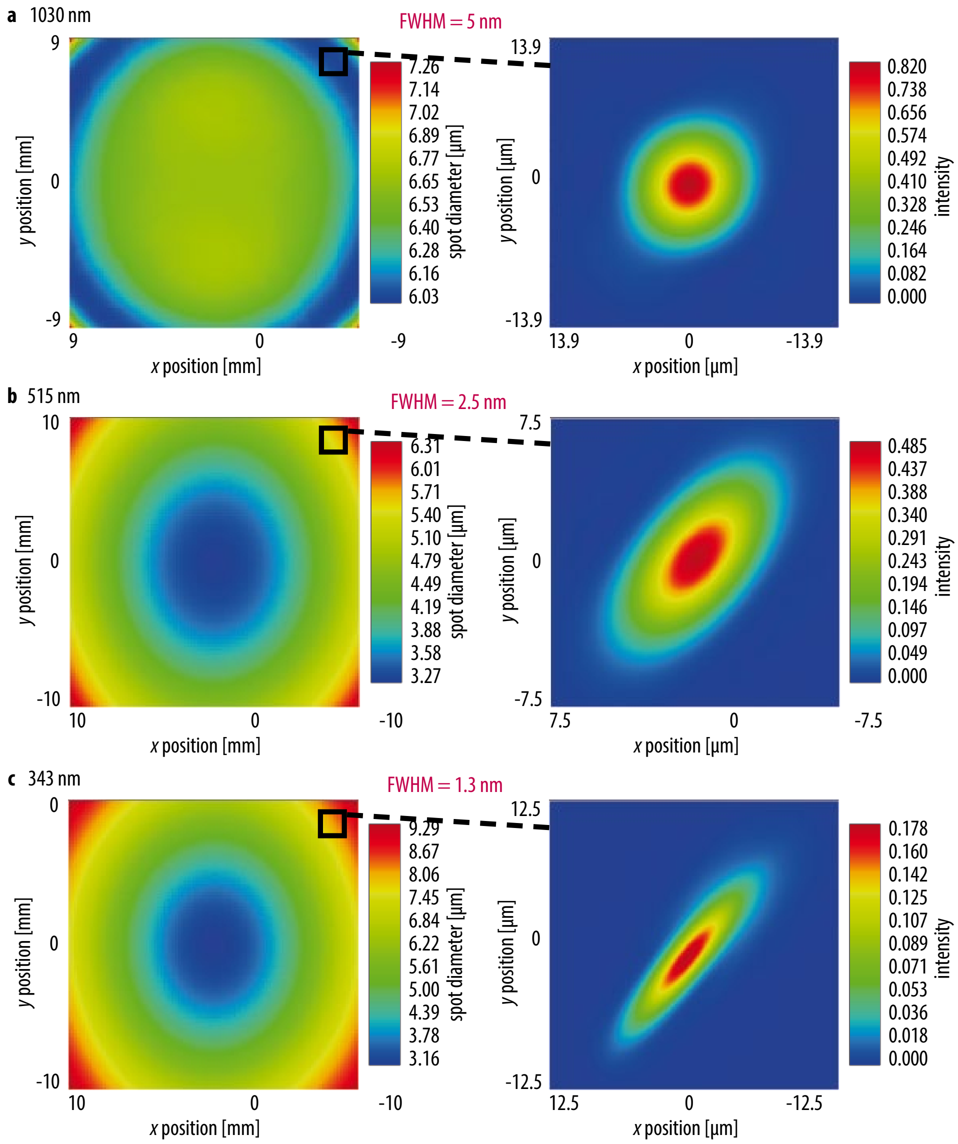

Fig. 3 Variations of the processing spot size (left) and processing spot at field edge (right) for three different wavelengths. The shorter the laser wavelength, the stronger the effects on spot quality at working field edges due to the change of the refractive index over wavelength of fused silica and the laser's bandwidth. Spot dimensions of –9 mm to 9 mm (a) and –10 mm to 10 mm (b, c), respectively, and f = 65 mm, M^2 = 1. (Source: Scanlab / Posalux)

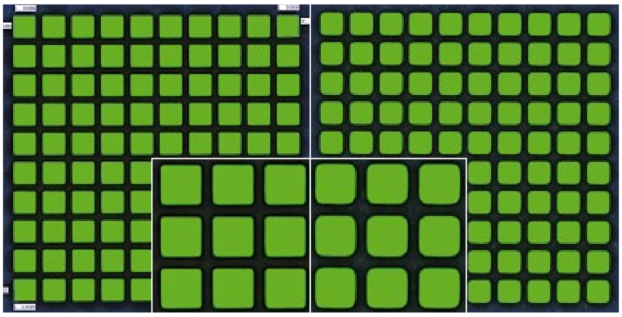

Fig. 4 Entry side of square holes with 30 µm edge lengths in a 250 µm thick Si_3N_4 ceramic substrate, made using a 515 nm laser (a), and a 1030 nm laser (b). (Source: Posalux)

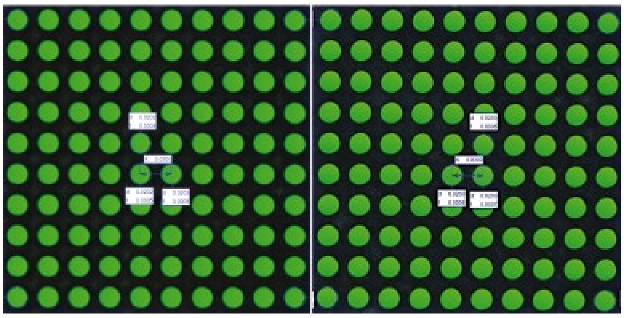

Fig. 5 Round holes with 20 µm diameter in a 250 µm thick Si_3N_4 ceramic substrate: entry side (a), exit side (b). (Source: Posalux)

Repeatability as key to success

Posalux integrated the new galvo-based precsys 515 five-axis subsystem into its machine design and subjected it to comprehensive testing. The scan head's extensive beam-positioning capabilities (in the x, y, z, α, and β directions) provide maximum flexibility for developing new process strategies so that elliptical or linear traversal paths can be defined in 2D or 3D. Meanwhile, all members of the precsys product family now utilize a new approach to servo control that offers even higher rotation frequencies and process speeds during drilling operations. The following documented process examples reflect actual customer requirements and were fabricated by Posalux under real production conditions. Repeatability and precision have the utmost priority here and must be reliably assured throughout everyday production.

Fig. 4 shows the entry side of square holes in a Si_3N_4 ceramic substrate. Holes generated using the 515 nm laser constantly result in a 3 µm edge radius and these systems fully meet the current stringent needs of customers. In contrast, holes drilled using a 1030 nm laser only achieved an edge radius of 5 µm.

A further application example involved drilling round holes. **Fig. 5** shows round drill holes with a diameter of 20 µm in a Si_3N_4 ceramic substrate. The aspect ratio is 12.5 : 1. Here too, processing was with a green 515 nm laser.

Additional measurements were performed to better evaluate process results. **Fig. 6** shows the measured diameters and roundness of 1300 holes drilled using the precsys in a femto laser machine

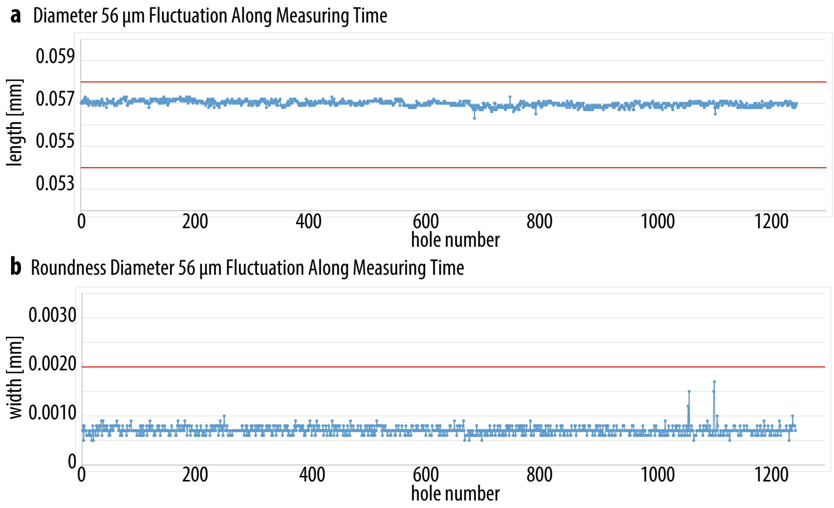

Fig. 6 Measured diameters (a) and roundness (b) of 1300 holes drilled using a 515 nm laser. Measuring points are shown in blue, tolerance limits (red curves) were set to ±2 µm (a and b). (Source: Scanlab)

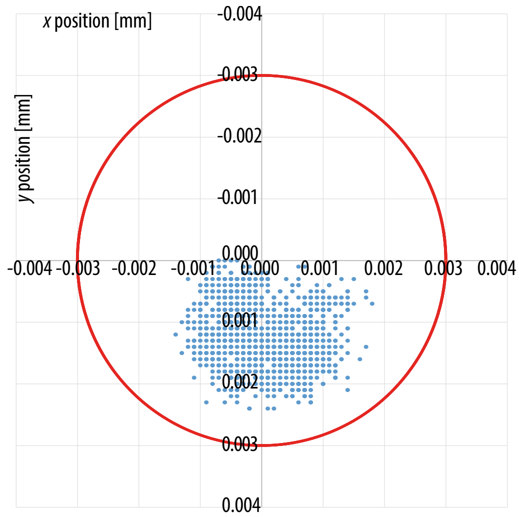

Fig. 7 Positional accuracy on the entry side. Plotted absolute positions (blue) of holes.Also shown is the position tolerance limit of ±3 µm. (red circle) from Fig. 6. (Source: Scanlab)

from Posalux. Readily apparent is that the results remain well below the 2 µm tolerance limit (red lines in graph).

The absolute positions of drill holes in the workpiece are depicted in Fig. 7. Again the results remain well below the definded limits, of – in this case – a position tolerance limit of ±3 µm.

All these operations and samplings confirm that using a 515 nm laser permits the fabrication of much smaller structures than is achievable with a 1030 nm IR laser. The diameters, roundness, and positions of drilled holes fulfill the highest precision requirements.

Outlook

Such application examples offer a well-founded insight into the technological advances that will soon also affect other sectors, in addition to the electronics industry.

Numerous difficult-to-process materials are coming into focus. These include sapphire, ceramics and glass, as well as the synthetic rubies used, for example, by the watchmaking industry. Further application trials are underway for double valve caps in the automotive sector, as well as in medical technology. The limits in miniaturization and feasibility have yet to be reached.

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Company

SCANLAB

With over 35,000 systems produced annually, SCANLAB GmbH is the world-leading and independent OEM manufacturer of scan solutions for deflecting and positioning laser beams in three dimensions. Its exceptionally fast and precise high-performance galvanometer scanners, scan heads and scan systems find application in industrial materials processing and the electronics, food and beverage industries, as well as biotech and medical technology.

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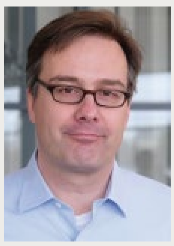

Holger Schlüter studied physics at the RWTH Aachen, Germany, and finished his PhD in engineering at the Fraunhofer ILT, also in Aachen. He worked for twelve years in various leading positions at Trumpf and stayed eight years of that in the United States. He then worked for five years as COO and CTO at Technolas Perfect Vision, a maker of surgical laser systems. After a short period as CEO of Highyag, Dr. Schlueter joined Scanlab as head of business development in 2015.

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Resonant Waveguide Gratings – Versatile Devices for Laser Engineering

Accurate tailoring of the spectral, temporal and spatial parameters of your laser systems

Martin Rumpel, Tom Dietrich, Frieder Beirow, Thomas Graf, and Marwan Abdou Ahmed

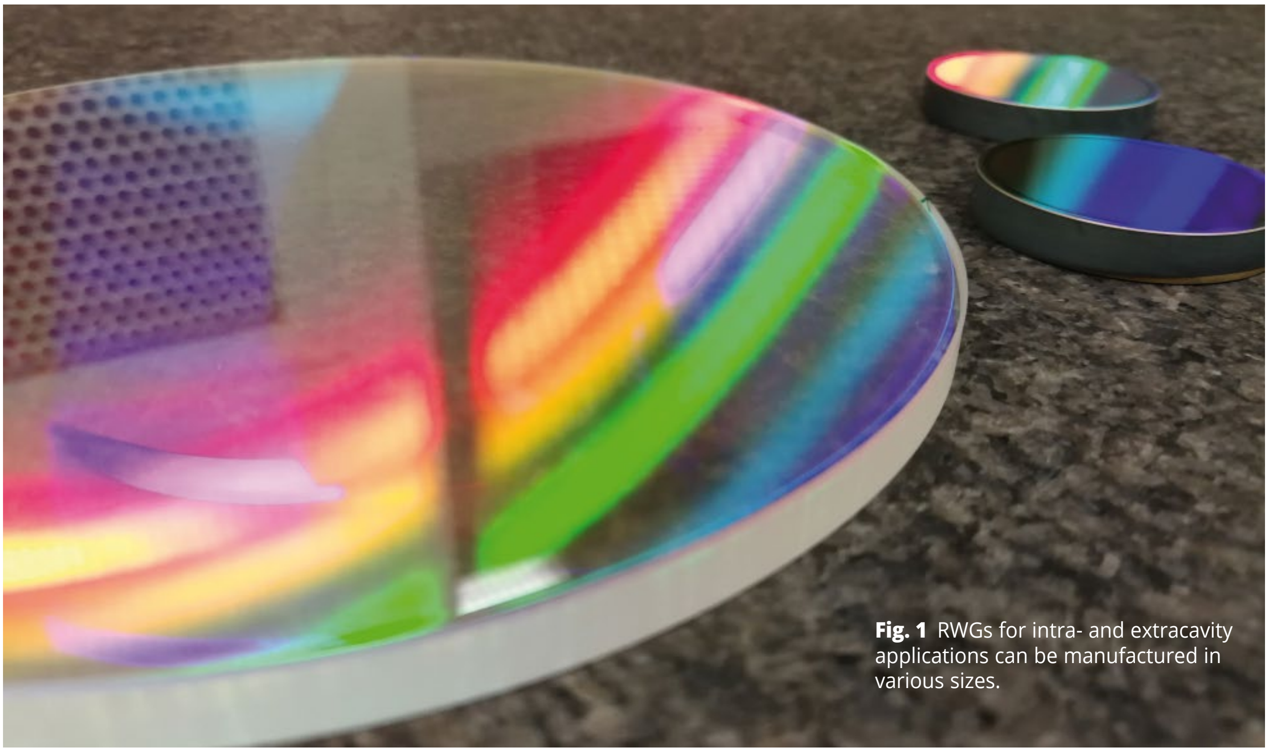

Fig. 1 RWGs for intra- and extracavity applications can be manufactured in various sizes.

Source all images unless otherwise noted: Martec Photonics

Resonant waveguide gratings (RWGs) have been developed by various international groups for over 35 years now and have been successfully implemented in many different laser sources (gas, disk, fiber, rod, microchip, or diode lasers). These devices offer high versatility in their application and high efficiency in reflection, transmission or diffraction. RWGs can withstand power and energy levels as required in modern laser sources and applications.

Realizing a laser resonator that offers good beam quality at high output power and high efficiency can be challenging due to thermal effects, non-linear effects and damage thresholds of the optical-mechanical components used in the laser system. The design process is of course dependent on the laser architecture used, e.g. if a disk, fiber, slab, rod, microchip, or diode laser is to be realized. Nonetheless, commercially available sources today include lasers delivering continuous wave (cw) beams of several tens of kilowatts of power (mostly fiber and disk lasers), pulsed laser beams with pulse durations ranging from milliseconds to femtoseconds and energy levels of several J/cm^2 (microchip lasers and rod lasers) or ultrashort pulsed lasers with average powers reaching the kilowatt level and pulse durations in the femtosecond range (fiber, slab and disk MOPA systems). Discussing the design aspects of all these laser sources in detail would of course go greatly beyond the scope of this article. The scope is therefore to introduce to the reader how RWGs can be used in the design of laser resonators, especially if a designer needs to influence certain properties of the emitted laser beam, such as stabilization of its state of polarization and/or wavelength, or even allow these states to be tunable. Thin-film polarizers, birefringent filers or Brewster plates combined with etalons are usually used for these tasks. RWGs can provide these properties within one single optical component (Fig. 1). Furthermore, RWGs are particularly promising, thanks to their versatility, as they can be implemented in the

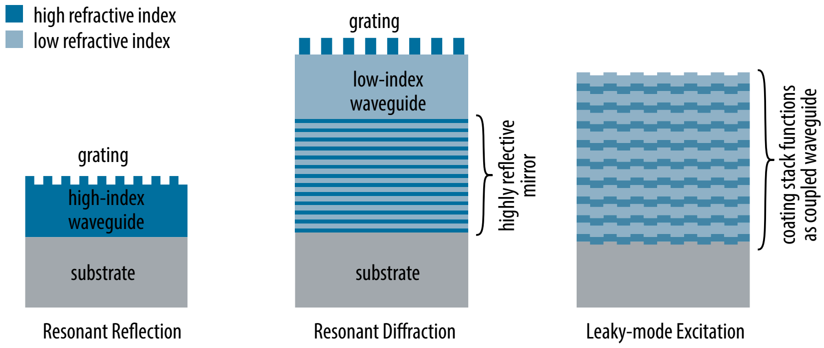

Fig. 2 Design examples of resonant waveguide gratings (RWGs).

laser resonator at almost any position, i.e. as an output-coupler, folding mirror, cavity end-mirror or even as part of the laser active medium. And since a single RWG can combine various tasks of polarization and wavelength stabilization, the resonator design can be simplified. The RWG presented here are passive components, yet with a special resonator design, they can perform tasks of compensating thermally induced shifts of the beam path in resonators. Usually, expensive active components need to be used to achieve this, such as motorized mirror mounts and feedback control loops. In the following sections, we will therefore describe the physical setup of RWGs, briefly introduce their operating principle, present some examples how they can be used as an intracavity device for a laser resonator to fulfill a certain task of polarization and/or wavelength stabilization, introduce an example of how RWGs were used to actively stabilize the laser cavity of a thin-disk laser and, finally, mention a few extra-cavity applications of RWGs.

Physical setup of RWGs

RWGs consist of a planar dielectric waveguide in combination with sub-wavelength diffraction gratings. The waveguides are usually manufactured by deposition methods such as evaporation or sputtering, and the grating first by using a lithography technique to create the grating lines (e.g. interference-beam or electron-beam) and then a subsequent etching process to transfer the grating lines into the material (e.g. reactive ion etching or ion beam etching). The waveguide can be of single-layer or multilayer design, where the latter is also referred to as a coupled waveguide. The grating can only be introduced to the top of the waveguide layers or at all interfaces of the multilayer waveguide. In most applications where the RWG is used as a component of the resonator or a component in the subsequent beam path, a suitable substrate is needed to give mechanical stability. Yet, since the functionality of the RWG lies within the waveguide layers in combination with a sub-wavelength grating, it can also be realized as layers that are deposited on an laser active medium, for example.

In Fig. 2, cross-sections are schematically shown for three examples of RWG structures, which support three distinct resonance effects as will be shown in the following section. The RWG on the left comprises a single-layer waveguide of high refractive index where a grating is introduced to the top. The RWG in the center comprises a single-layer waveguide of low refractive index that sits on top of a dielectric mirror (i.e. a stack of alternating layers of low and high refractive index) and a grating of high refractive index is added on top of the waveguide. Finally, the RWG on the right example comprises a multiple corrugated RWG where the grating was first etched into the substrate and the coating was applied subsequently.

For all designs, the grating period is chosen to be in the sub-wavelength range, meaning the grating period is smaller than the target wavelength of the application. Materials used for the waveguide layers are typically Ta_2O_5, Nb_2O_5, HfO_2, TiO_2 and SiO_2.

Operating principle of RWGs

The mechanism of operation of the RWG presented in Fig. 2 involves the coupling of parts of an incident free space electromagnetic field to modes of a planar waveguide. This can be accomplished by means of a sub-wavelength diffraction grating. Special combinations of wavelength, polarization and AOI exist in which resonance phenomena between the individual fields of the modes, incident beam and its reflected, diffracted or transmitted parts. The resonances then lead to unique spectral properties of the RWG in terms of reflectivity, diffraction or transmission. Three different effects can be distinguished in the designs presented in Figs. 3 – 5. First, the resonant reflection is characterized by a narrow spectral peak of the reflectivity of (theoretically) 100 %. Second, the resonant diffraction leads to obtaining a diffraction efficiency of (theoretically) 100 % in the -1^{st} diffraction order. Third, the excitations of leaky modes in a coupled waveguide can be used to generate a transmission of up to 100 % through a RWG. Figs. 3 – 5 show the spectral responses of these types of RWGs if, for example, they are designed to operate at a wavelength of $\lambda = 1030$ nm. The plots distinguish between both orthogonal states of polarization as defined on a linear grating: TE polarization (electric field parallel to grating lines) and TM polarization (magnetic field parallel to grating lines).

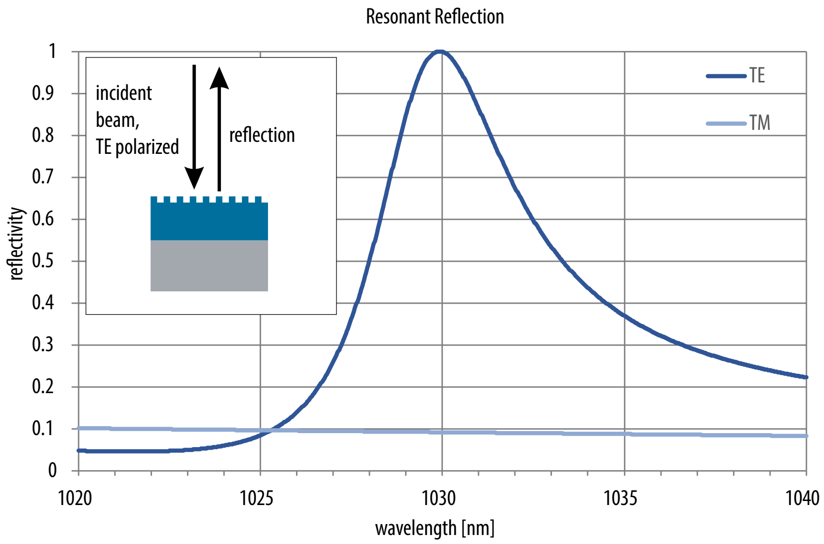

Fig. 3 Phenomena of resonant reflection in RWGs.

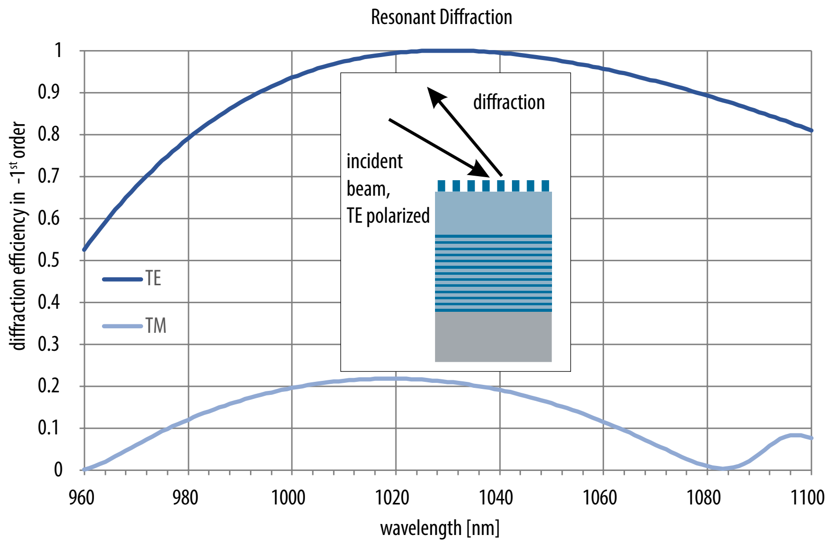

Fig. 4 Phenomena of resonant diffraction in RWGs.

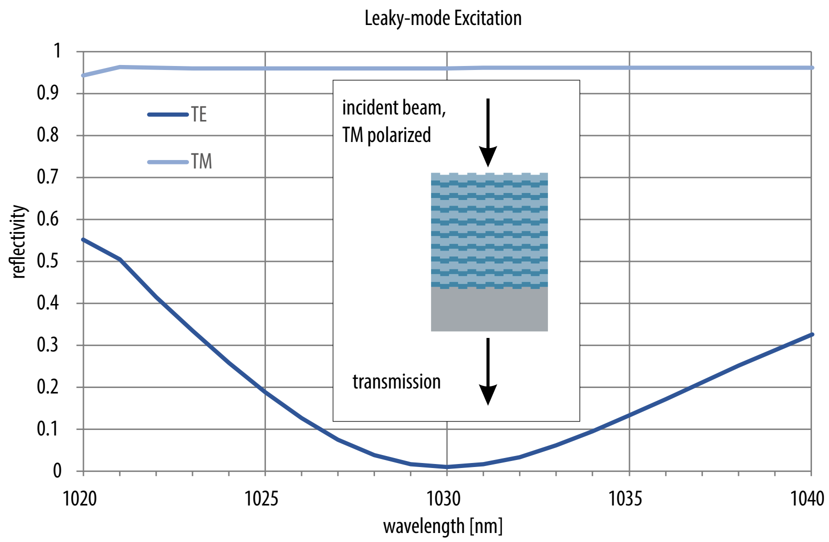

Fig. 5 Phenomena of leaky-mode excitation in RWGs.

RWGs for intracavity stabilization of polarization and/or wavelength

One prominent example to demonstrate the potential of RWGs is using them to stabilize linear polarization and the laser emission wavelength for the purpose of achieving a high efficiency for the intracavity second harmonic generation (SHG). To achieve optimal nonlinear conversion, the stabilization of the fundamental wavelength (e.g. λ = 1030 nm for a Yb:YAG thin-disk laser) as well as its spectral bandwidth is necessary, since the gain bandwidth of Yb:YAG is wider than the wavelength acceptance bandwidth of most nonlinear SHG crystals. Further, high purity of polarization of the infrared beam is beneficial to achieve optimal phase matching in the SHG crystal. Using the RWG for this purpose in an Yb:LuAG thin-disk laser was demonstrated for fundamental-mode [1] and multi-mode [2] operations. An LBO crystal provided by Cristal Laser*) was used for the intracavity SHG. The resonator setup for the multi-mode experiments is shown schematically and in a simplified version in Fig. 6, the exact details are described in [2]. The thin-disk laser resonator consists of two arms; one is designated to the frequency conversion and the other to the polarization and wavelength stabilization. The RWG allows the latter arm to be simplified.

In summary, in fundamental-mode operation ($M^2 \approx 1.3$), the RWG enables the stabilization of the emission bandwidth of the Yb:LuAG thin-disk laser to only 25 pm (FWHM) at 620 W of output power, whereas the free running spectrum at the same pump power level had a spectral bandwidth of close to 2 nm. In multimode operation ($M^2 \approx 20$), for output beams of 1 kW, the RWG enabled the stabilization to an emission bandwidth of 185 pm, compared to around 1.5 nm of the free running spectrum. Additionally, for both the fundamental-mode and multimode resonator, a clear linear polarization was observed. This made it possible to obtain very high conversion efficiencies to the second harmonic process when introducing the LBO crystal to the cavity. It was possible to generate laser beams of 400 W in fundamental-mode operation with an optical efficiency (i.e. infrared pumping power to green laser emission) of 40.7 %. The peak power density on the RWG, when considering the Gaussian intensity distribution and the elliptical beam profile on the RWGs surface, was 133 kW/cm². In multimode operation, beams with an output power of 1 kW could be generated with a conversion efficiency of 51.6 %. These experiments demonstrated the great benefit of the RWG over the state-of-the-art solution for the intracavity SHG.

Another example is the use of RWGs to generate beams with radial polarization, which can have advantages in laser drilling or cutting thanks to the optimal light-matter interaction. The RWG

*) www.cristal-laser.com

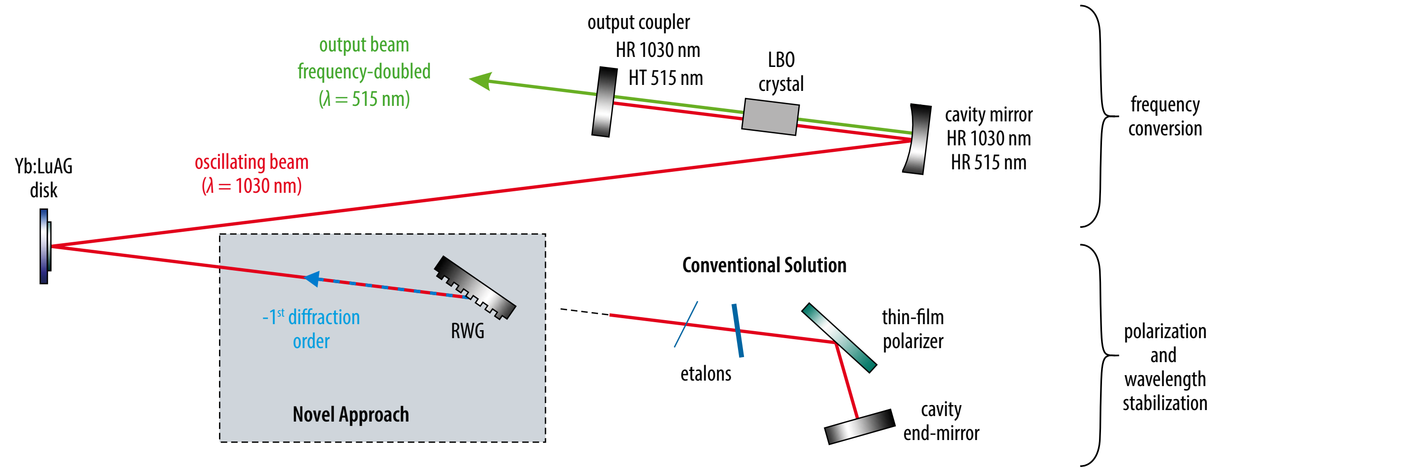

Fig. 6 Thin-disk laser resonator with RWGs for intracavity frequency conversion, details see [2]. HR: highly reflective; HT: highly transmissive

could be successfully implemented here as a radially polarizing output-coupler to the resonators of a thin-disk laser operating in mode-locking scheme [3] as well as a cavity end-mirror to a thin-disk laser operating in cw mode [4]. The RWGs designed for these objectives utilized circular grating lines. When using the RWG as an output coupler, it was designed such that, for an operating laser wavelength of $\lambda = 1030$ nm, a reflectivity of 96 % is realized for beams of radial polarization (which corresponds to TM polarization for linear gratings). Beams of azimuthal polarization (i.e. TE polarization for linear gratings) experience a reflectivity of less than 75 %. When using the RWG as a cavity end-mirror, it was designed to have >99.9 % of reflectivity for radial polarization (TM) and around 60 % for azimuthal polarization (TE). Fig. 7 shows the measured spectral reflectivities of the RWG used in the mode-locked resonator and shows a schematic of the simplified setup in the inlet, as well as the measured intensity lobes. It was possible to realize a radially polarized Yb:YAG, passively mode-locked, thin-disk laser oscillator that provided an average output power exceeding the 100 W power level. With a pulse repetition rate of 78 MHz and a measured pulse duration of 0.97 ps, this corresponds to a pulse energy of 1.6 µJ and a peak power of 1.45 MW. Similarly, in a different thin-disk laser setup, it was possible to generate cw radially polarized laser beams with up to 980 W of output power and an optical efficiency of 50.5 %. A high degree of polarization purity was achieved throughout the complete range of power. The calculated and measured spectral reflectivities of the RWG used here, as well as a simplified schematic of the resonator and the measured intensity lobes of the emitted beams, are shown in Fig. 8. Using a custom-built 2D Stokes polarimeter, a degree of radial polarization of around 96 % (1 kW cw) and 97 % (100 W average power, mode-locked) could be quantitatively measured.

RWGs for stabilization of thermally-induced beam pointing

In high-power thin-disk lasers, common limitations in scaling the output power result from thermally induced wavefront distortions. Among them is the problem caused by the convection of heated ambient air in front of the laser crystal, commonly known as the formation of an “air wedge” in front of the laser crys-

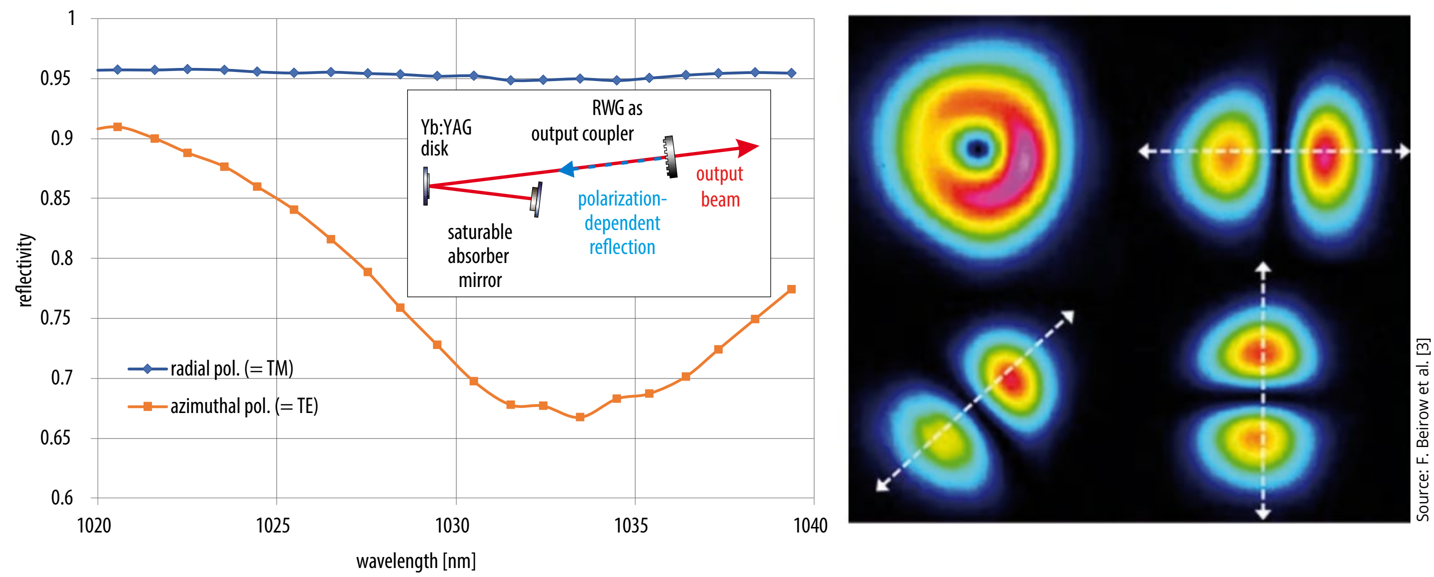

Fig. 7 Spectral characteristics of the RWG and simplified schematic of the resonator (left) and measurement of the emitted intensity lobes (right) as shown in [3]. The arrows indicate the transmission axis of a linear polarizer that was put into the beam path.

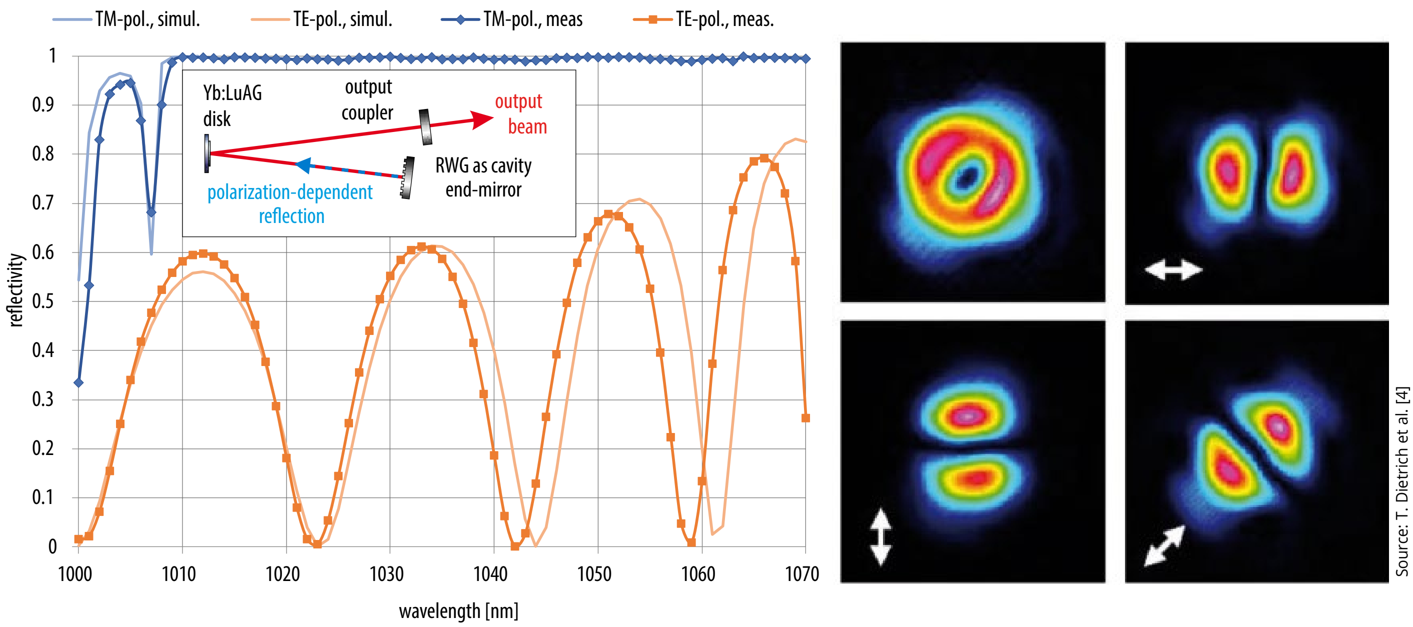

Fig. 8 Spectral characteristics of the RWG and simplified schematic of the resonator, left, and measurement of the emitted intensity lobes at 1kW of output power, right, as shown in [4]. The arrows indicate the transmission axis of a linear polarizer that was put into the beam path.

tal [5]. As a result, severe pump-power-dependent misalignments can be created in thin-disk laser resonators. Especially in fundamental-mode operation, the air wedge is particularly pronounced and limits the output power unless a continuous realignment of the resonator is possible during operation. The angular misalignment due to the air wedge in front of the disk effectively leads to a vertical displacement of the oscillating laser beam, which can be observed by a shift of the position of the laser mode with respect to the pumped region on the disk. However, by exploiting the spectral dispersion of RWG, this misalignment instability can be passively compensated for if the RWG is used as a cavity end-mirror in a Littrow configuration $\theta_{Littrow}$, which means the -1^{st} diffraction order is fed back into the resonator and is collinear with the incident beam to the RWG. The grating lines have furthermore to be oriented perpendicular to the predominant (vertical) direction of convection (Fig. 9). In this configuration, a tilt of the beam induced by the air wedge in front of the thin-disk crystal changes the angle of incidence on the grating surface, which then corresponds to the Littrow condition with a slightly shifted wavelength. Hence, the laser oscillation will simply shift to the wavelength leading to the highest gain for the circulating radiation. By this, it was possible to almost triple the output power of a fundamental mode Yb:LuAG TDL pumped at $\lambda = 969$ nm in comparison to the free running layout, i.e. a laser resonator without the RWG. The compensation mechanism described can also be observed in the emission spectrum of the output of the laser, which is shifted from $\lambda = 1030.026$ nm at 129 W of pump power to $\lambda = 1029.750$ nm at 1066 W of pump power. This corresponds to a total shift of 276 pm. The exact details are given in [5].

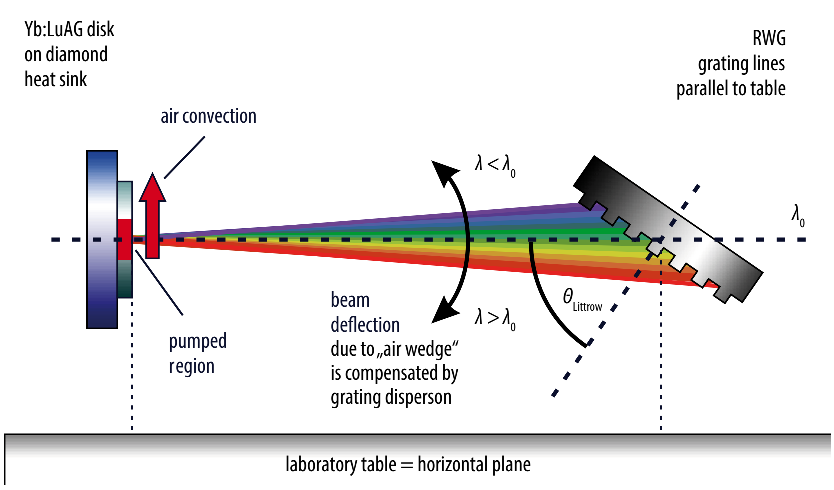

Fig. 9 Schematic of the compensation mechanism due to diffraction at the RWG as shown in [5]. λ_0 indicates the wavelength without thermally induced shift.

RWG for extracavity applications

RWGs can also be used for dispersion control, for example for the stretching and compression of pulsed laser beams. Over the years, pulse compression gratings that are characterized by diffraction efficiencies of more than 99 % in the -1^{st} diffraction order at $\lambda = 1030$ nm could be realized [6]. This enabled compressors to be built with an overall efficiency of more than 96 % (i.e. four grating passes). The damage threshold of the RWG depends on the proper design as well as the materials used. So far, RWGs could be produced with damage thresholds of 0.8 J/cm^2, single-shot, measured at $\lambda = 1030$ nm and a pulse duration of 550 fs [7]. For pulse durations of 12 ns, a damage threshold of 2.95 J/cm^2 was measured at the same wavelength. Other possible applications can be using RWGs for spectral beam combining tasks or to serve as a polarization converter.

Summary

RWGs are versatile devices to tailor the spectral, spatial, temporal, and polarization characteristics of a laser beam emitted from a laser resonator. Due to their versatility in design, RWGs can serve as intracavity devices at various positions in the resonator, i.e. as an output coupler, a folding mirror or cavity end-mirror, but also as an extracavity device. We have shown examples where RWGs were used to greatly improve the efficiency of the intracavity SHG by replacing etalons combined with thin-film polarizers. We also showed how RWGs allowed the generation of laser beams with radial polarization from thin-disk lasers operated in cw or mode-locking. A further example presented the ability to utilize the diffractive nature of the RWGs to realize a passive compensation of dynamic beam pointing effects caused by an air wedge in front of the laser disk. Finally, we mentioned RWGs used for the stretching and compression of high-power laser pulses, where diffraction efficiencies for reflective gratings of more than 99 % have been demonstrated.

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Machine Learning for Process Monitoring Systems

Examples from laser materials processing to additive manufacturing

Thomas Grünberger

Fig. 1 Data-driven approach, different steps from digital values via machine learning to AI-based process intelligence (Source: Plasmo, Adobe Stock)

Machine learning (ML) as part of artificial intelligence will be a key technology of the future in many areas of our life, so also in laser materials processing. This data-driven approach will use digital twins – digital equivalents of real parts covering the whole process chain. Optical process monitoring systems observe process steps in real time yielding in a digital process twin as part of the twin. ML will enable us to extract information from data, assisting experts in answering questions from “Ship the part?” to “How I can produce a part with a lot size of one at a given quality level?”

Process monitoring is a well-established technology in laser materials processing. Different sensor technologies measuring different values of the process are available, and optical sensors are frequently used for in-situ measurement (Fig. 2). Diode-based systems measure process emissions at different wavelengths (Fig. 2 left), 2D gray scale cameras measure, for example, the size of the melt pool in the visible or near infrared area, later ones – if calibrated – enable the measurement of temperatures, temperature distributions and cooling down rates (Fig. 2 middle). 3D measurement systems based on triangulation (Fig. 2 right) or displacement sensors based on OCT (optical coherence tomography) enable absolute geometric measurements in 3D. Additionally, other sensor technologies are available (e.g. acoustic sensors), machine parameters and process parameters are also acquired, and all synchronized with sensor data to do extended data analysis.

All these technologies can be used for additive manufacturing as well, for example for DED (directed energy deposition) and PBF (powder bed fusion) processes.

Turn on the light in your process

Automated laser welding plants are welding 24/7 the whole year, while additive manufacturing machines print parts for several hours up to several days. Due to safety reasons, many laser processes cannot be visually inspected by users, and it is impossible to do this for long hours. So process monitoring systems acquire measurements from the process and – if visualized properly – give you a deeper insight into your process online and – if stored – offline, enabling process documentation, process analysis, and process optimization.

These stored measurements and/or calculated features of the measurements are a digital representation of the manufacturing process, so analog to the digital twin this can be called digital process twin.

This data and these features can be proven against limits for modeling the decision “part OK / part not OK”, which can be seen as comparing the actual process twin to a digital footprint (reference part).

Fig. 2 Basic optical sensor technologies for laser materials processing (Source: Plasmo)

If the additive manufacturing quality standards for different parts do not yet exist, the modeling of OK / NOK then becomes a future task. Nevertheless, the digital process twin can be used to avoid beginners' mistakes, to develop and optimize process parameters and to assist proof process stability. So the added value is a faster time to market. Process stability is an important measure of quality, because process stability means that you are able to build a part with a consistent quality. Last but not least, calibrated measurement systems allow you to make processes comparable from machine to machine, so you can answer questions according scalability of the process.

Machine learning, artificial intelligence

The following definitions are used in this section: artificial intelligence (AI) tries to model human intelligence in aspects of cybernetics. Weak AI systems assist human experts in their work.

- Statistics tries to explain what happens, while data mining and machine learning are based on statistics
- Data mining – often used as a synonym for big data computational environments – tries to explain why something happens (e.g. a root cause analysis)
- Machine learning tries to explain what will happen in future, how processes can be optimized, and how certain situations can be avoided. Machine learning is a first step for modeling human intelligence and is part of AI.
- Deep learning is a special method of machine learning using deep neural networks and is mainly used for analyzing images

Basics about machine learning and deep learning can be found in [1] and [2]. Machine learning and especially deep learning were enabled by the availability of high computational power such as the usage of the graphical processing unit GPU, and big storage systems such as cloud computing. Developing these data-driven approaches in a company firstly needs new professions like data scientists, secondly new computational environments like virtualization, and thirdly discussions over SQL versus no SQL databases and massive parallel programming versus distributed file systems. These topics cannot be handled in this paper, although further details can be found in [3].

Machine learning is a special "programming" method, where an algorithm is trained only using data, and no dedicated programmed algorithm is used. Different methods can be defined depending on the data available and the idea of training (cf. Fig. 3).

Reinforcement learning does not need value paired input/output data and is based on human reinforcement learning by "learning and doing" using positive and negative feedback. Reinforcement learning is normally not used in classic data analytics. If annotated data is available, i.e., if there are paired input/output values, supervised training can be performed. Typical tasks are classification tasks (e.g. part OK / part NOK) or regression tasks (e.g. predict the density of a part based on process and geometry parameters).

If no annotated output data is available or new information has to be extracted from the data, only input data is used to train the models. The main task for this approach is finding clusters in the data.

A vision of Plasmo is an AI-based system for laser processes and especially for additive manufacturing. The common consensus in the community for the time to realize "push one button and print" is around nine to ten years. Therefore, AI-based systems maybe a possible solution. Setting up such expert systems that enable process intelligence requires several steps (cf. Fig. 1).

The foundation is a digital environment and the usage of assistance systems (e.g. digital learning, augmented and virtual reality). In the next step, data has to be analyzed and visualized in dashboards to perform statistical process control and to extract knowledge by human intelligence. As an example, the

Fig. 3 Basic training methods and their application (Source: Plasmo)

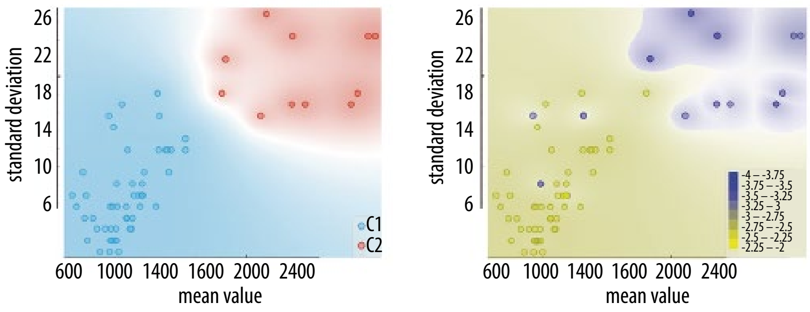

Fig. 4 Clusters found by unsupervised k-means (left) and the corresponding process parameter focal distance (right; source: Plasmo)

distribution of detected defects can be plotted. If clusters are found, the reason can normally be easily identified and corrected. This saves resources and can avoid downtime.

If annotated data is available, supervised learning techniques can be trained to improve classification and regression tasks. Evolutionary programming [4] can be used to automatically find parameterizations, for example for OK/NOK classification tasks.

Unsupervised methods can be used to extract unknown information yielding in an expert system providing as named by Plasmo "process intelligence".

Example of unsupervised learning for process optimization

Strip welding machines are used to weld coils to an endless sheet (I seam butt joint), for example to run endless heat treatment processes in steel plants. In this application the lot size can be one, means, no welding of a combination of input and output sheet (e.g. material, thickness) was done before and will not be done in future. The quality criteria for these welds are very high because there would be a long downtime in the plant if a seam should break. Typically, a combination of different sensor technologies (cf. Fig. 2) is used in such machines.

In a real production environment, there was a problem with the number of bad welds that were detected as NOK by the quality inspection systems, but rewelding needs time and there may be a downtime if rewelding is not successful. The question was: can any potential for process optimization in the data of the monitoring systems be seen? The data of diode-based monitoring systems like the Plasmo ProcessObserver is often used for process optimization (due to the high sampling rates and the different characteristics available that are based on physics and can be calculated from the data).

In the first step, these characteristics are the mean value of the signal intensity of one weld (corresponding to the form of a cross-cut of the seam) and the standard deviation (corresponding to the fluctuations in the process e.g. cold welds, changing gap and edges or pollution). Fig. 4 (left) shows the distribution of the welds (one dot represents one weld with a given combination of mean value / standard deviation in the scatter plot). K-means [1] is used as an unsupervised training method, and automatically found two clusters (C1 and C2) which are colored blue and red. These clusters describe the boundary of good welds / bad welds quite well (right upper corner means less penetration depth and an nonconstant process). In this application, process parameters like laser power, velocity and focal position are available for each weld, so a correlation of the clusters with process parameters can be done. Fig. 4 (right) shows the high correlation of the clusters with the focal position, so the reason for the bad weld is the low value of the focal position of -3.5 to -4 (blue dots). A final analysis with the customer yielded the following result: the user lowered the focal distance to melt more material in case of a height mismatch: this was not optimal and reduced the overall quality of the welds. Switching to higher focal positions reduced the number of bad welds to an acceptable ratio.

An example of an unsupervised search for irregularities in AM

Diode based monitoring systems are widely used for additive manufacturing (AM) processes. Many of these processes are layer based, by accumulating the different characteristics of the diode signals according to the laser position digital process twins per characteristic can be calculated.

In this example, thirteen parts are built using six different process parameters changing in height for all parts every 4 mm. The process is monitored using an on-axis and an off-axis diode. The characteristics of moving average and signal dynamics (a special Plasmo feature for detecting process stability) are calculated, so four digital process twins are calculated at the end (average and signal dynamics on and off-axis). Fig. 5 (left) shows one layered graphic of the characteristic signal dynamics off-axis.

Finding irregularities means manually stepping through all images (there are several thousand in typical jobs) and looking for irregularities in each characteristic. This is very time consuming, so a semi-automatic or automatic method is preferred. One possibility is using deep learning to automatically look for irregularities (by unsupervised training of OK reference images and testing against other images). Another approach is to calculate the mean value and standard deviation of these four characteristics for each part in the

Company

plasmo Industrietechnik

plasmo is a global high-tech provider of automated quality inspection systems for thermal joining processes in the metal working industry. Established in 2003, it has its headquarters in Vienna and has a network of international subsidiaries and distributors. The company's expertise includes the monitoring and control of welding and laser brazing processes, including data analysis software. A wide range of services with comprehensive engineering rounds off the portfolio.

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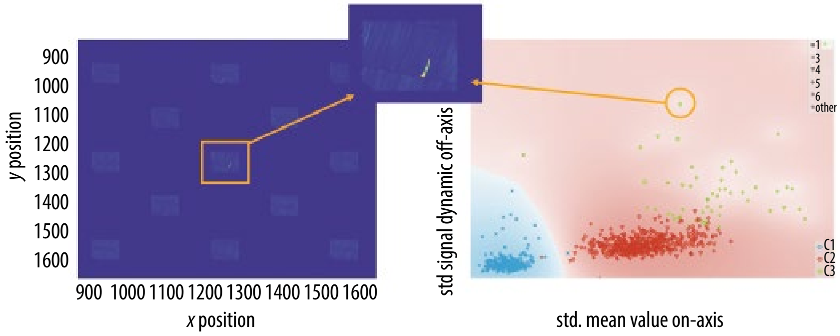

Fig. 5 Digital process twin signal dynamics off-axis layer 25 and clusters (left), zoom of center part (middle) and three k-means clusters of the eight-dimensional problem (right; source: Plasmo)

image, giving us an eight-dimensional problem. Using unsupervised clustering based on k-means, we obtain three clusters (Fig. 5 right). The blue cluster C1 corresponds to known process changes (unit energy), the red cluster C2 to nominal process and the green cluster C3 to unknown irregularities. The form of the markers corresponds to the six process changes.

By selecting the green markers we obtain the irregularities – Fig. 5 (middle) shows one found irregularity. As an additional result, we can see that we obtain very unstable processes for process parameter set 6 (systematic behavior); the irregularity shown is a stochastic one.

Summary and outlook

Process monitoring systems together with process and machine parameters are appropriate tools to “turn on the light in the laser process”. Faster time to market by avoiding beginner mistakes, optimize processes using the digital process twin reduce cycle time and avoid downtime, processes are comparable from machine to machine (scalability). This added value holds for classic laser welding and for additive manufacturing processes: in classic laser welding, a modelling of part OK / NOK is possible where quality standards are available.

Machine learning as part of artificial intelligence enables new data-driven programming paradigms (supervised and unsupervised learning). Plasmo uses supervised learning to develop improved models for classification, regression, and automatic parameterization tools. Additionally, use unsupervised learning to identify clusters and to extract new information from process data, as shown in the examples above.

Special know-how and experience is quite helpful and available at Plasmo to select appropriate algorithms needing less training data, in generating training and test data sets and in data plausibility checks and correlation checks of input variables.

We use deep learning for the evaluation of camera-based images. Particularly in battery welding, a combination of diode and camera-based sensors is helpful for some applications to reduce false positive and false negative evaluations.

As in all applications, machine learning is a tool, and the users will not notice that machine learning is being used.

Plasmo also works with partners on concepts for future platforms, where data from experiments, metallurgic tests, simulation runs and measurements are stored. AI-based methods will enable designers to check if and how parts can be produced using additive manufacturing. This will hopefully push AM to the next level.

*

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Advanced Process Monitoring in Additive Manufacturing

In-process temperature field measurement for laser metal deposition and laser powder bed fusion processes

Dieter Tyralla and Thomas Seefeld

(Source all images: BIAS)

Laser-based additive manufacturing processes like laser metal deposition (LMD) and laser powder bed fusion (LPBF) are becoming more and more popular in industry. In demanding applications, however, every part has to be tested non-destructively in a subsequent step. Online process monitoring can provide detailed documentation for each part and has the potential to reduce the post-process inspection costs. BIAS has developed an advanced monitoring approach for in-process temperature field measurement using a coaxial two-channel pyrometric camera.

Additive manufacturing is increasingly being used in industrial production due to its unique design possibilities and the high functionalization of parts. Laser metal deposition (LMD) is generally used for the generation of large parts or for hybrid production that generates functional elements on semi-finished products. A consistent layer is generated by the deposition of neighboring welding beads and a layer-by-layer repetition generates the three-dimensional geometry. The quality of the resulting parts depends on the quality and geometry of each single bead. An appropriate relation of energy per unit length and powder mass per unit length is necessary for a consistent width and height of the bead, which is mandatory for a uniform layer geometry. Hence, the temperature field of the process zone is a suitable indicator for the current process behavior [1].

However, temperature measurement is demanding because of high temperature ranges and welding speeds. In addition, the additive process requires a direction-independent observation. Common methods for temperature measurement are coaxial pyrometer measurement and lateral camera observation that correlates grayscale values with temperature. Single-spot measurements limit the variety of information from the process zone to only one temperature value [2], as compared to camera-based measurements. The coaxial integration of IR pyrometers and cameras is limited, however, because of the optical properties of common lenses used in LMD. An issue of temperature measurement in powder-based processes is the fluctuating attenuation of the thermal emissions from the process zone by the powder flow, spatter and by welding fumes. So the utilization of different materials, surface conditions, state of matter and even temperature ranges may affect the thermal emissions of the process zone and lead to deviations in the measured temperature. Two-channel pyrometers are preferred because of their emissivity-corrected measurement and independence of attenuation by powder, spatter, and fumes.

In contrast to LMD, laser powder bed fusion (LPBF) is a powder-bed 3D printing method using a high-intensity single-mode laser to melt and consolidate metallic powders in very thin lay-

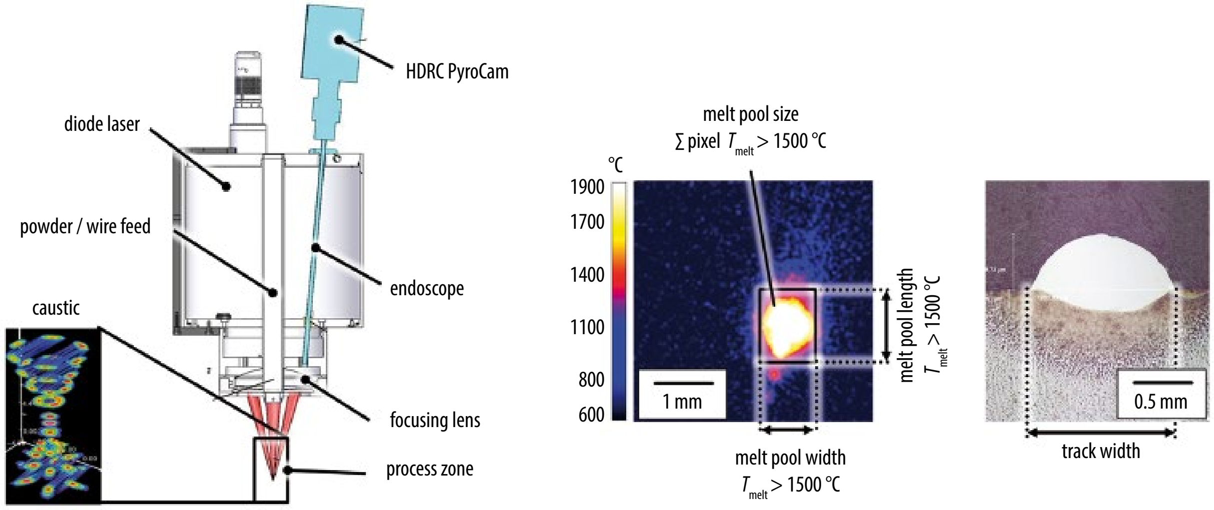

Fig. 1 Cross-section view of the LMD processing head with an integrated monitoring system (left), coaxial view of the measurement system with evaluated thermal values and the corresponding cross-section (right) [Tyralla 2020 / BIAS ID 200280]

ers and generate components of higher geometrical complexity and accuracy, although limited to smaller typical component sizes when compared to LMD. LPBF machines employ closed build chambers with scanner-based optics, and LPBF processes feature smaller laser spot sizes traveling at a higher welding speed, all of which often makes in-process monitoring more challenging. BIAS has recently demonstrated a high-precision dimensional measurement approach for monitoring the quality of powder recoating and consolidation [3]. In LPBF, the temperature field in the process zone indicates the energy balance and can be used to identify applicable parameters [2], so in-situ thermal monitoring is desirable.

Coaxial temperature field measurement in LMD

This work demonstrates thermal process monitoring for LMD by a novel two-channel pyrometer camera that combines the advantages of camera-based observation and emissivity-corrected temperature measurement. The camera has already been applied for the verification and optimization of thermal process simulations [4] and enables the determination of different temperature field-related values, such as melt pool geometry [5] or temperature gradients [6]. Furthermore, it was used for closed loop control in the wire-based cladding process [7].

The camera (PyroCam, IMS Chips) was integrated into a direct diode laser processing head (Profocus, OSCAR PLT). The special design allows the feeding of wire-based and powder-based filler material through the center of the process head. The laser is induced coaxially in a circle and ensures high powder feed efficiency. An endoscopic system is integrated into the process head for thermal process monitoring. The set-up (Fig. 1) has been shown in detail in previous publications [5].

The PyroCam is used for in-situ temperature field analysis. The measurement system compares the radiation at central wavelengths of 661 nm and 667 nm for emissivity-corrected temperature measurement. The temperature calibration of the whole optical path was done by the camera vendor. The accuracy of the temperature measurement is specified to be within 2 % in the range of 600 to 1900 °C. A frame rate of 200 Hz was applied.

Different thermal indicator values are obtained from the thermal images. Therefore, the melt pool is identified in the PyroCam images with the help of the melt temperature which is taken from the literature and specified between 1480 and 1530 °C for the material used. A LabView-based algorithm detects bright areas of pixels with a value that is higher than the melt temperature. The recognized melt pool has to be assembled from more than ten pixels to avoid an incorrect detection.

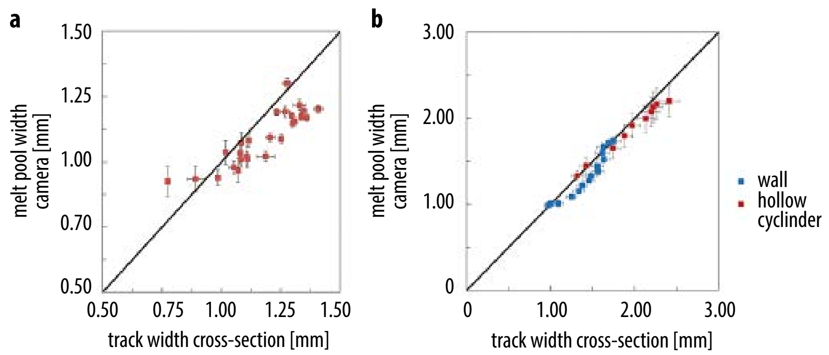

Fig. 2 Comparison of the melt pool width measured by PyroCam and the track width determined by metallographic cross-section for single-track laser cladding (a) and additive manufacturing of simple wall and cylinder geometries (b) [Tyralla 2020 / BIAS ID 200285]

Institute

BIAS – Bremer Institut für angewandte Strahltechnik GmbH

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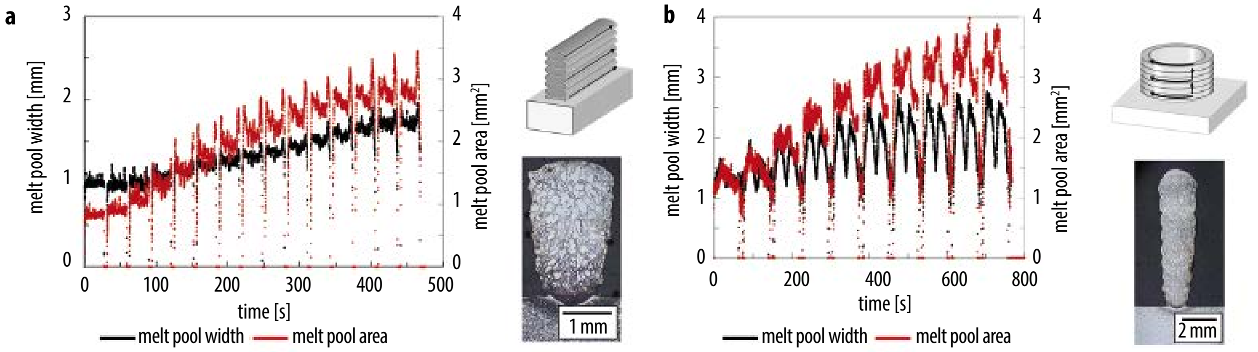

Fig. 3 Thermal monitoring of additive LMD process by PyroCam. Melt pool width and melt pool area for wall build-up (a) and cylinder build-up (b) [Tyralla 2020/BIAS ID 200286]

If more than one area is detected, the one with the highest number of pixels is chosen for further evaluation. The detected size is evaluated with regard to the expansion in the x direction and in the y direction, which equals the melt pool width and length. The melt pool area is determined by summarizing the number of pixels with the melt temperature or above. In addition, the algorithm enables the evaluation of the temperature profiles and temperature gradients of the cross and longitudinal sections (Fig. 1). The lateral resolution of the PyroCam images is 33.6 µm/pixel.

Different experiments were carried out to demonstrate the capability of this novel system for process monitoring and to determine the accuracy of the method. Therefore, single tracks and typical geometries of additive manufacturing were produced and observed by the PyroCam. The single-track experiment investigated the changes of melt pool geometry under variation of the process parameters due to an online observation by the PyroCam. The thermal images were evaluated by the melt pool width. The corresponding track width was determined in a metallographic cross-section and was used as a reference value. The correlation of the melt pool width measured by the camera and the metallographic track width indicates the accuracy of the measurement method (Fig. 2a). Here, the camera values are plotted versus the reference values. The graph demonstrates a high accordance between the values. The deviation is less than 4 % and shows that the system enables the precise measurement of the seam geometry already in process and ensures the recognition of quality variations by thermal process monitoring.

Common sources of build-up mistakes in additive manufacturing were investigated for typical wall and thin-walled cylinder geometries and observed by thermal process monitoring. A constant laser power often leads to heat accumulation in wall build-up because of the small heat sink of the wall geometry and the poor heat conduction. For the first time, the heat accumulation can be visualized online by an emissivity corrected temperature field measurement due to coaxial integration. For a wall of fifteen layers, the melt pool width and the melt pool area increase for higher layer numbers (Fig. 3a). Similar behavior can be observed for the constant energy input during build-up of a hollow cylinder. The melt pool width increases because of the heat accumulation in the structure and leads to a higher wall thickness. The melt pool width and the melt pool area for a cylinder of ten layers (Fig. 3b) shows a different representation in contrast to a wall experiment. Here, the evaluation algorithm matches melt pool dimension in the y-direction with the width and so impedes the correct determination on a circular welding path. In this case, the melt pool area is more applicable for process monitoring because of the direction-independent evaluation approach. The comparison demonstrates high accordance of the online melt pool width measurement and metallographic determination of track width in the build-up process too

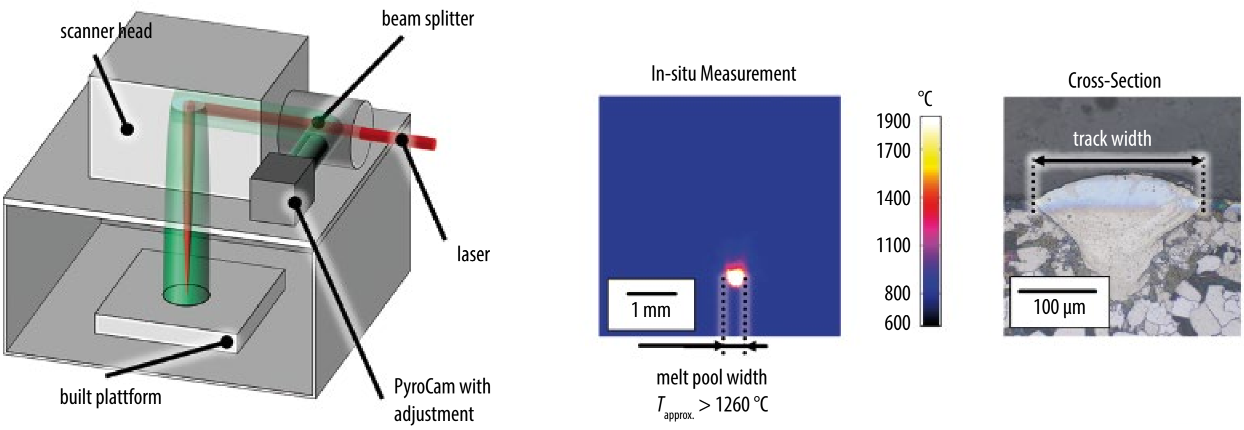

Fig. 4 Schematic representation of coaxial integration of the temperature field measurement system in LPBF (left), coaxial view of the measurement system with evaluated thermal values and the corresponding cross-section (right) [Tyralla 2020 / BIAS ID 200281]

(Fig. 2b). The deviation is less than 2 % for the additive manufacturing of a wall and a cylinder structure.

Coaxial temperature field measurement in LPBF

The investigation of the temperature measurement for LPBF used a commercial LPBF machine (Realizer SLM 250) with a build-up area of 250 mm by 250 mm. A single-mode fiber laser applied a maximum laser power of 200 W at 1070 nm. The laser spot diameter was 50 µm. The nickel-based powder material 2.4665 (TruForm HX, Praxair) was used with a particle size between 15 µm and 45 µm. A special f-theta lens with a high transmission of laser radiation at 1070 nm and thermal radiation at 650 nm enabled simultaneous processing and measurement. In addition, the mirrors of the scanner unit were coated for higher reflectivity in the spectral ranges mentioned above for thermal process monitoring. The pyrometric camera was integrated coaxially into the beam path using a beam splitter as illustrated in Fig. 4.

Fig. 5 shows the comparison between the melt pool geometry which was measured in-situ by PyroCam and the track width which is determined in cross-section by metallography. The graph demonstrates good accordance of the melt pool width within a deviation of 3 % in the case of 50 mm/s and 100 mm/s (red marks). Due to limitations of the experimental setup, however, chromatic aberration deteriorated the accurate measurement of the melt pool width for higher welding speeds of 200 mm/s and above (blue marks).

Summary

A two-channel pyrometer camera was integrated into a novel direct diode laser LMD process head and a scanner-based LPBF machine. This setup enabled emissivity-corrected temperature field measurement and the in-situ evaluation of various thermal indicator values. Coaxial observation ensured a high lateral resolution and the accuracy of the melt pool geometry measurement was demonstrated by a comparison between the in-process measured melt pool width and the metallographically determined track width. In LMD, the average deviation was only 4 % in laser cladding and less than 2 % for the additive manufacturing of wall and cylinder geometries. In a more challenging LPBF environment, a comparable accuracy could successfully be demonstrated for larger melt pool sizes at low welding speeds, while limitations that demand further adaption of the scanner-based set-up were found when measuring smaller melt pool sizes at higher welding speeds.

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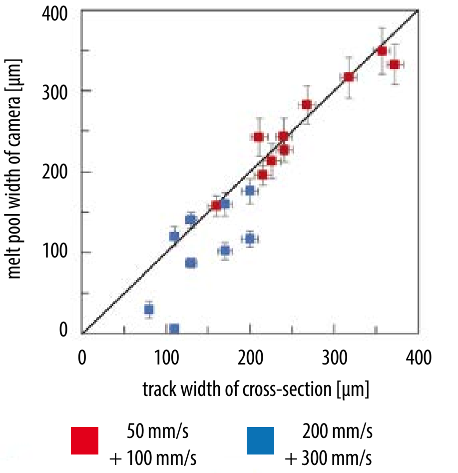

Fig. 5 Comparison of PyroCam measured melt pool width and metallographically determined track width in LPBF [Tyralla 2019 / BIAS ID 200071]

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Fig. 1 4D data center solution for data storage and future machine learning capabilities at shop floor level, available for generation 6 of the WeldWatcher software. (Source all images: 4D GmbH)

Process Monitoring in E-Mobility Applications

Examples of hairpin welding, ablation and cell-to-cell welding with WeldWatcher 6

Christoph Franz and Oliver Bruchwald

With an increasing demand for laser welding applications related to e-mobility, the range of material combinations, system setups, wavelengths used, beam qualities and frequencies has risen drastically. There is a multitude of different processes and parameters that all aim at the same goal: hundreds of connectors in batteries, electric drives, and cable connections must be functional for years in each car. Not a single one may fail or increase its electrical resistance and all of them need to be welded and inspected in the shortest time. Online process monitoring systems contribute to achieve these ambitious goals, so their capabilities and limitations as well as some vivid examples are discussed in this article.

There are several systems available on the market that capture or measure and analyze physical properties and/or emissions emerging from the area where the interaction between laser light and material takes place. None of these effects and values alone stand for “seam quality”, which is typically defined by mechanical, geometrical and metallurgical properties of the solidified seam. The process characteristics such as emitted visible and thermal radiation, the geometrical values of the melt pool or the penetration depth of the laser forming the keyhole only provide indications of how the desired quality might be achieved.

So process monitoring must not be categorized as a direct quality measurement method; in any case it is a valuable indication of how stable the process itself is running, in the best case it is the tool to spot potential root causes of errors.

System setup

The practice of 4D is to integrate one or multiple different sensors into the optical path of the processing laser to capture the emitted process radiation. Depending on the monitoring requirements, which are predefined by the process itself, three different sensor types and six different sensor sensitivities are available. Sensor types range from visible light (VIS) detectors and back reflec-

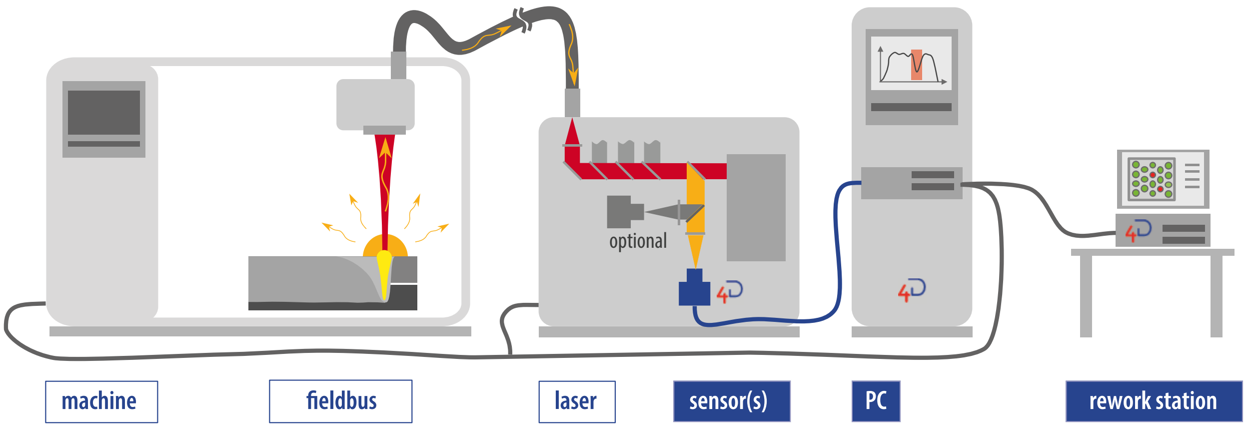

Fig. 2 Typical system integration: here, Integration of two sensors into the laser with four optical paths to be monitored by only one WeldWatcher system.

tion detectors to near-infrared (NIR) detectors, which are all customized for the individual user's machine and process properties by the WeldWatcher experts. It is the expertise of 4D as well to select the best sensor sensitivities and filter settings, a determining influence on the success of the process monitoring.

Contrary to the popular misconception that lasers generate a plasma that can be measured, lasers in the vast majority of laser welding applications in e-mobility primarily generate a keyhole (deep penetration welding only) and a metallic vapor plume. The surface of the liquid metal, including the walls of the keyhole and its surrounding melt pool surface, as well as the volume of the metal vapor in and outside of the keyhole, emit light according to Planck's law. As a result, both VIS and NIR sensor types capture a mix of thermal surface radiation that is attenuated by the metal fume and volumetric radiation of the hot metal vapor rising from the keyhole. Furthermore, all radiation depends on the material properties and alloy composition and on the influence of oxides floating in the melt pool (emission coefficient). Emitted near infrared light is thermal radiation as well however; a correlation to a "temperature" is often impossible since the current emission coefficient is unknown in most cases.

Some of the laser light is not absorbed at the metal surface but reflected, depending on the surface angle. Access to this process information can be ensured by additionally using a back-reflection detector.

Different positions for the integration are possible. We recommend to integrate into the laser source when possible as shown in Fig. 2. This approach, typical for 4D, offers numerous advantages in the laser's housing: no oil, no dirt, no dust, stable temperatures, no vibrations, and cables are easy to integrate. The mechanical integration time is often below thirty minutes without touching the laser cell or working space, which enables quick trials in already active production lines. There are many laser types, such as disk lasers and a huge number of fiber lasers, which offer the integration of a 4D WeldWatcher into the laser source itself (Fig. 3). In some cases, especially for most single-mode fiber lasers, such an integration is often not possible. The second-best solution is to integrate the sensor into the laser scanner head (Fig. 4). Suppliers of these optics and 4D itself offer integration adapters for most systems to apply WeldWatcher sensors to the camera port while maintaining the functionality of these positioning cameras. The experience of 4D gained over decades typically results in setups that eliminate the need to use lookup tables for the field of view to compensate for intensity changes when jumping from one position to another.

As shown in Fig. 2, the whole system integrates into the fieldbus of the machine to assign part and seam numbers for a 100 % traceability. All data is stored in a database that connects to the customers network if required and can also be used to visualize parts and welding positions for rework stations.

Fig. 3 New compact fiber sensor to directly integrate into most IPG YLS sources (no beam switch required)

Fig. 4 New head sensor (IP 67) and new robot cable and connectors

Company

4D

Celebrating the 25th year after the company's foundation in 1995, the laser process monitoring experts of 4D support customers worldwide with their comprehensive experience. While focusing on independent laser process monitoring solutions only, 4D's total amount of installed WeldWatcher® systems just recently exceeded 1400.

www.4d-gmbh.de

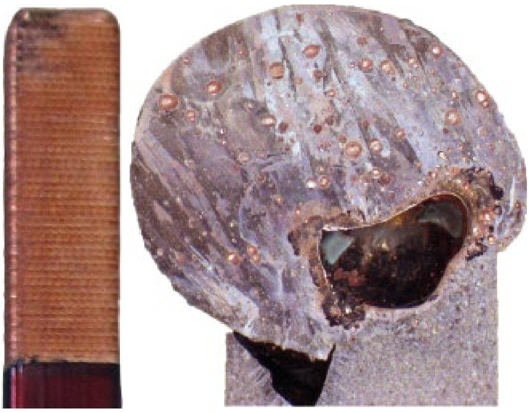

Fig. 5 (left) partial remains of the isolation can be detected. This could potentially cause poor welding results, as shown in the cross-section (right).

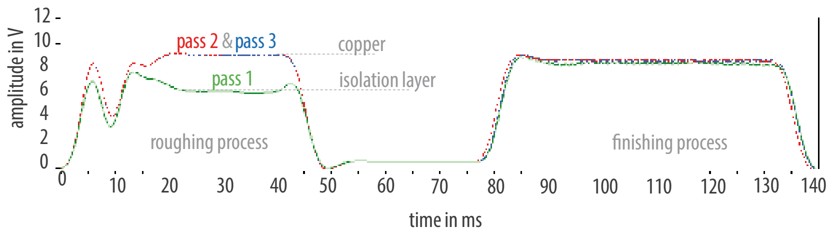

Fig. 6 Distinction between removal of the isolation layer and ablation of the base material

The newly available InlineView assists workers to quickly visualize the whole workpiece on any PC connected to the same network.

Why process monitoring in e-mobility?

At least in one aspect, automated laser welding is not different to any other manufacturing processes: when welding thousands of seams per shift, users must stop their fully automatic machines when the laser process is suddenly or gradually exceeding previously set limits. Such an approach allows operators to find systematic faults directly where and when they occur, rather than at the end of the line where quality inspection takes place and the line is still running, producing more and more parts with the same faults.

After quality inspection, there are typically two approaches to ensure economic efficiency: declare faulty parts as scrap or perform a repair procedure and re-inspect them. There is a special consideration, however, when it comes to joining components in e-mobility: the batteries and electric drives on the production line where laser welding takes place are already high-value items. From an economics point of view, these parts would have to be repaired if faults occur. Unfortunately, from a technical point of view, repairing these parts is difficult or even impossible. So instant awareness of faults produced in the currently running machine is crucial.

An online process monitoring solution often shifts the moment of fault detection from the end of the line to the moment of occurrence. Thus, faulty cell connectors or hairpin connections can be immediately rewelded or simply exchanged instead of disassembling the whole part further down the production line. Furthermore, the statistic evaluation of all welding positions from the previous production run may help to maintain optimal process parameters, before a faulty part is produced.

The following paragraphs show some examples to demonstrate the capabilities of process monitoring in three relevant e-mobility applications.

Hairpin ablation

In order to increase the copper fill ratio and heat transfer, solid copper hairpins are usually used in the stator of electric motors for e-mobility instead of conventional wound coils. These hairpins are coated with an electrical isolation that must be completely removed without damaging the copper material prior to welding in order to ensure a reliable connection. The ablation process is commonly carried out by using short-pulse lasers.

The WeldWatcher provides online monitoring of the laser ablation and cleaning processes: the removal of the coating layer generates a characteristic process emission that can be reliably distinguished from the process emissions of bare and clean copper. Therefore, it is possible to determine if the cleaning process was successful or if traces of the isolation – which may affect the welding process, still remain on the pin's surface (Fig. 5).

Fig. 6 shows the post-processed signal for a typical short-pulsed hairpin cleaning process that consists of a roughing and a finishing phase. The whole cleaning process was performed three times in order to demonstrate the changes in the related signal behavior and amplitude.

During the first roughing process, the major cause for the specific process emissions in the spectrum under review is the removal of the isolation layer,

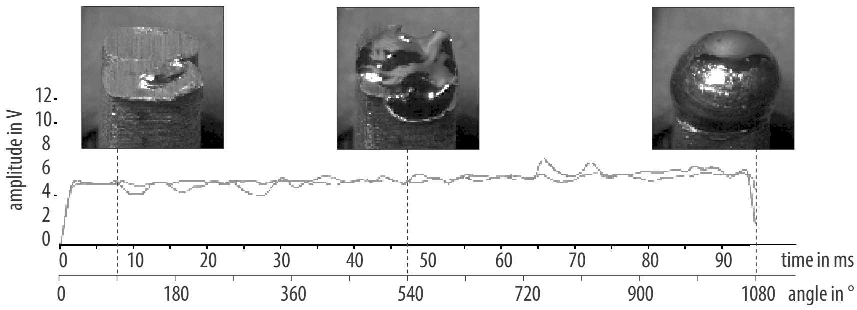

Fig. 7 Hairpin welding – references without faults

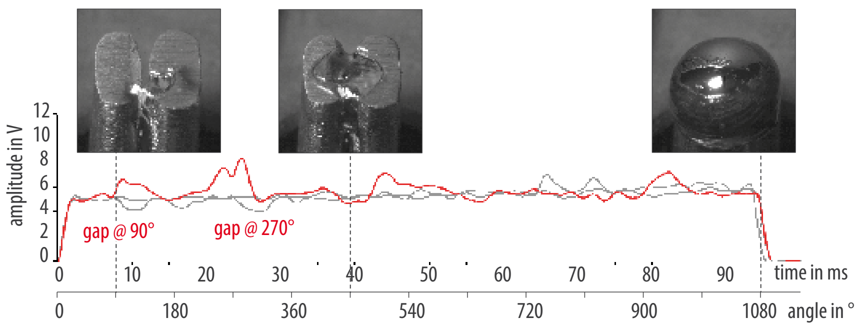

Fig. 8 Hairpin welding – misalignment with 0.2 mm gap

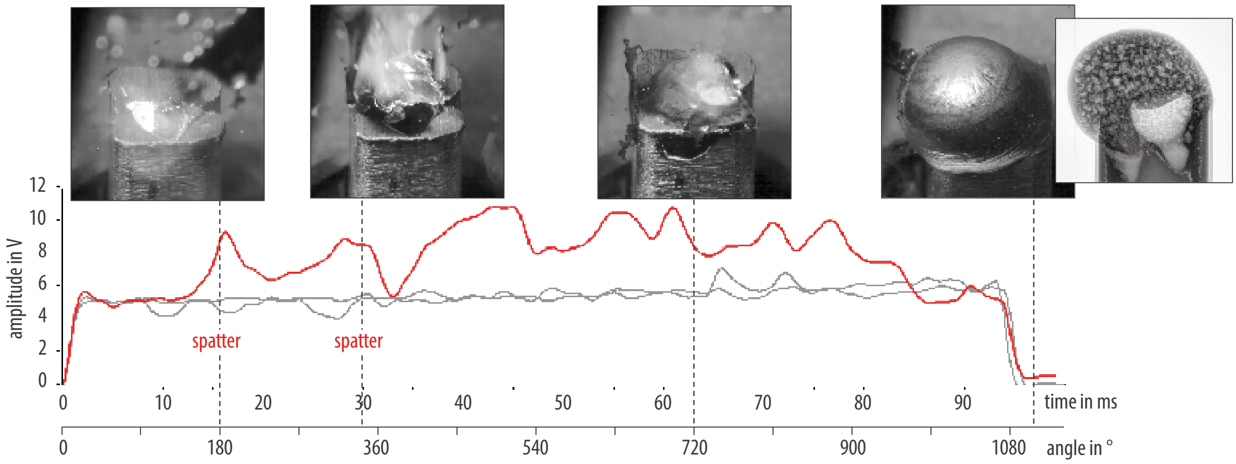

Fig. 9 Hairpin welding – remaining traces of isolation between the hairpins cause massive melt pool ejections

which causes a signal of ≈6 V. During the following finishing process, the signal's amplitude is much higher because the process emissions already include a significant amount of the ablated base material. This means that the majority of the isolation layer was already removed during the preliminary roughing process. Pass 2 and 3 show almost identical signal behavior that correlates with the ablation of the clean copper base material.

Hence, the direct detection of incompletely removed isolation can be achieved in line, even with very little remains of the organic isolation material as shown in Fig. 5. Accidental welding of pins with remains of the isolation can be prevented automatically in most cases by applying simple limits. This approach significantly increases the economic efficiency since fewer motors must now be rejected.

Hairpin welding

After ablating the isolation layer, and after mechanical forming and assembly into the stator, it is necessary to achieve an accurate and strong connection with low transition resistances between the numerous hairpins of the motor. Years ago, copper welding was a challenging task – now various promising approaches such as the usage of green or blue lasers exist that lead to industry-ready results.

Nevertheless, even minor changes in positioning and of process parameters may affect the welding results in a way that – in the case of hairpin welding – leads to power and performance loss or a reduced lifetime of the electric engine.

Monitoring the welding process of copper hairpins can be seen in Figs. 7 – 9. In these examples, a conventional 4 kW IR-laser was used to join the hairpins with three simple circles. In order to correlate the WeldWatcher signal with the actual weld condition, images of the weld pool were acquired by a high-speed camera.

A faultless reference welding generated a smooth signal in the range from 4 and 7 V (Fig. 7).

A misalignment that results in a gap of 0.2 mm between the hairpins leads to significant peaks in the signal at 90° and 270° due to the changes in absorption and process emissions (Fig. 8). After the first circle, the melt pool covers the gap and the expected peak at 450° and 630° are only weakly defined. The final result looks similar to the reference welding. In many cases, the WeldWatcher is able to detect gaps resulting from clamping wear over time and indicates the clamping position that should be re-tuned to fulfil the required quality standards before gaps become too large to pass QA.

Remaining traces of the isolation layer between the hairpins are vaporized when hit by the laser beam and may cause a massive eruption in the melt pool. Fig. 9 shows an example where the remaining isolation leads to significant melt pool ejections and devolatilizing causing the WeldWatcher to mark this weld as NOK.

Surprisingly, the final result looks similar to the reference welding and would be considered as OK during optical inspections. An additional CT scan showed a huge amount of pores that decrease the mechanical stability and increase the transition resistance of this connection.

This motor would have been rejected immediately after the welding of this pin. Processing all other remaining hairpins (around 150 in total) can be stopped immediately, saving cycle time. All other production steps between laser welding and QA can be saved as well for this part.

Welding dissimilar materials

An issue still to be dealt with, and especially in the production of batteries and battery packs, is how to connect dissimilar materials (such as copper, aluminum and steel) while ensuring the required quality is maintained. Laser welding of dissimilar materials is proven to work for very thin foils (e.g. using ultrashort-pulse laser technology) as well as for thicker sheets (e.g. using standard cw laser technology) and provides the option of online process monitoring.

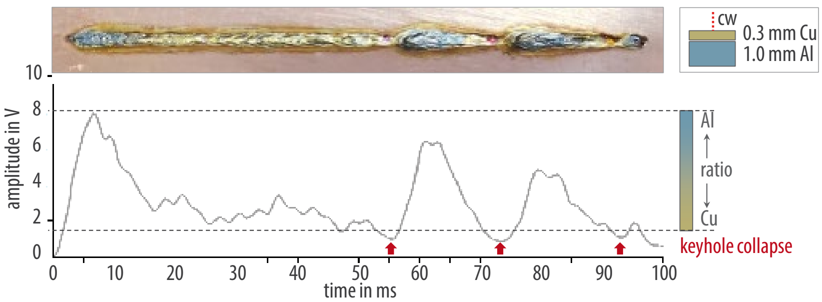

Fig. 10 Estimation of the Al/Cu ratio in the melt pool

Fig.10 shows the signal of a cw laser welding process with a 0.3 mm copper sheet on a 1.0 mm aluminum sheet. According to the sensor filter setup, the spectral emission of aluminum was given a much higher weighting than the spectral emission of copper.

During the first 15 ms, the melt pool contains a high amount of aluminum and the signal shows an appropriate peak. In the following 40 ms, a relatively homogenous weld with a significantly lower amount of aluminum in the melt pool was achieved, and the signal shows a smooth behavior at a lower signal level. From 55 ms on, a periodic incoupling can be seen whereby the collapse of the keyhole leads to a significant drop in the signal's amplitude down to 1.0 V. These results show that it is possible to roughly estimate the Al/Cu ratio in the melt pool.

The system is also capable of recognizing process instabilities provoked by any influence on the laser process. Such influences typically arise from gaps or contamination from oil or dust on the workpieces, but also fluctuations of the air flow, fume extraction, transmission loss on the cover glasses or thermal shift of the lenses lead to process fluctuations that the WeldWatcher does recognize. All these other influences need to be known to be able to detect the cause of single unpredicted events. Or in other words: stable process monitoring requires stable processes.

Summary and outlook

Gaps, dust, misalignment, spatter, cover glass contamination, power loss are just a few of many issues that often cause trouble in production and need to be detected on occurrence. Especially when it comes to high volume production, process monitoring systems provide the potential to significantly empower a fully automatic production line to stop producing faulty parts where and when these errors happen. Economic efficiency needs to be proven since such a system cannot fully replace other quality assuring concepts.

These three e-mobility examples show how various different user requirements can be fulfilled. In hairpin ablation, the WeldWatcher may stop pins from being transported to the welding stage if the isolation is not fully removed and a failing welding process can be prevented. In the example of hairpin welding, the user's desire is to prevent the production line from producing more faulty motors before the final QA finds out that there is a systematic error in the production line. And in the last example, battery cell welders can inspect 100 % of the numerous cell connectors of a module, where misconnections as a result of gaps or poorly mixed materials need to be identified and re-welded.

With InlineView and the 4D data center solution (Fig. 1), new powerful enhancements towards visualization, data acquisition and machine learning will be available in the near future.

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Christoph Franz joined 4D in 2017 and became CEO in 2018. He started his process monitoring career at the Fraunhofer ILT, Aachen in 2004, entered the industry as product manager to start the development of the camera-based SCeye process monitoring solution in 2012 at Scansonic MI, Berlin, and became unit manager shortly afterwards. Back to his roots, he now leads 4D with his passion to monitor laser processes.

Oliver Bruchwald studied mechanical engineering at the Leibniz University Hanover and completed his PhD in online process monitoring and non-destructive testing in 2017. In the same year, he joined the 4D team as RnD engineer with his focus on new sensor technologies.

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Powerful disk lasers in the green wavelength spectrum are the perfect copper welding tool for automakers and their suppliers. (Source all images: Trumpf)

A Green Wave for Electric Cars

Powerful green laser light meets all the requirements of the industry

Stefanie Bisch and Sebastian Zaske

Automakers and suppliers are searching for standards for electric car production. Experience has shown that green laser light is the perfect welding tool for electric components made of copper.

Electric mobility is the biggest trend in the worldwide automotive industry. Fueled by a combination of technological progress, statutory requirements and evolving customer demand, electric cars have long ceased to be a niche phenomenon and are now on the verge of becoming a genuine mass-market mainstream offering. This has prompted automakers, suppliers and machine makers to search for the best way to produce each e-mobility component in high volumes and to a consistently high standard. In some of these areas, no single manufacturing technology has yet emerged as an established standard, one example being the joining and welding of copper electrical components in the battery, motor and powertrain. But a tool is now available that meets all industry's requirements in this area: powerful green laser light offers high productivity, reliable processes, high-quality welds and reproducible results.

Choose lasers, choose green!

Copper – and to a lesser degree aluminum – is an ideal choice for electrical connectors due to its high electrical and thermal conductivity. It conducts electricity and heat better than any other commonly used industrial metals. Unfortunately, however, copper absorbs very little light in the infrared, which is exactly the wavelength region in which most industrial lasers operate. Working at a wavelength of around one micrometer, these lasers have a tough time processing copper: at room temperature, copper reflects 95 percent of infrared light and only absorbs between 3 and 5 percent. As well as being very inefficient, this also poses a hazard, since the reflected laser light can adversely affect or even damage its surroundings. The risk increases further if the chamber is narrow and confined or if temperature-sensitive components are located close to the weld point.

As the temperature of the copper increases, so does the rate at which it absorbs infrared laser light, climbing as high as 20 percent. Getting the welding process started requires significant energy input. The material heats up and, as soon as the melting temperature is reached, the rate of radiation absorption suddenly increases, producing a spike in energy that is difficult to control. This complicates the production process by causing a delay in the onset of welding that cannot be precisely reproduced even when using identical parameters – so it is impossible to be sure in advance where the weld seam will start. In addition, the excess energy leads to erratic processes with spatter along the entire weld path – something that is completely unacceptable in a confined environment full of sensitive electronics, especially when manufacturing electric cars.

With green laser light, all these problems disappear. Scientists have long known that copper absorbs short-wavelength laser light significantly better than long-wavelength light. But only in the past few years have beam sources come onto the market that can deliver this light at the power levels required for industrial welding. Modern industrial disk lasers that operate in the green spectrum (515 nanometer wavelength) can now deliver two kilowatts of power output. At room temperature, copper absorbs 40 percent of this green laser light – a rate of absorption that is eight times higher than for near-infrared wavelengths. This significantly improves welding, leading to more stable processes, smoother bead surfaces, low-spatter formation and more consistent penetration depths.

Benefits for copper

Green light offers specific benefits when it comes to processing this challenging metal.

For one thing, it enables users to carry out reproducible heat conduction welding of copper – something that is currently impossible with near-infrared lasers. Penetration depths of up to 500 micrometers can be achieved in industrial settings using heat conduction welding with a two-kilowatt laser power output. Green light also makes the heat conduction welding process completely spatter-free, helping to create a smooth, polished weld seam surface. Since there is no keyhole formation and therefore no metal vapor, the seam is free of pores. This increases the conductivity of the join.

Deep penetration welding of copper is another area where green light's strengths come to the fore. With a laser power of two kilowatts, green light once again enables users to achieve consistent weld depths of up to 1.5 millimeters This kind of weld depth consistency is currently unachievable with near-infrared lasers. What's more, the higher absorption rate means welding can also be performed with defocused laser light. The green laser then produces a wedge-shaped keyhole that gets wider toward the top, creating a seam form that makes it easy for vapor to escape. This results in stable, low-spatter processes and an even weld seam surface.

Another benefit to using green light is that relatively little heat is transferred to the part being welded. Absorption is high, which means the processing time is relatively short, so minimal heat is lost into the material. The part distorts less and is subjected to a lower thermal load. What's more, users do not have to resort to beam oscillation (wobbling) to achieve high seam quality, but can simply stick to linear welding. This allows for a high feed rate and thus higher productivity. It also makes the process simpler because fewer parameters need to be defined.

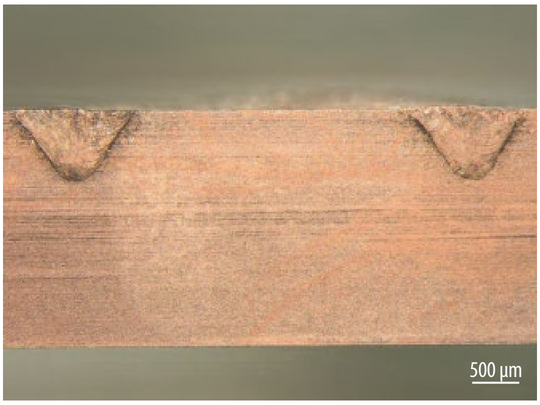
Numerous tests have demonstrated that the copper's surface properties have no effect on welding results with green light. In other words, it makes no difference whether the copper is polished, sanded, untreated, or heavily oxidized. The process is not affected by the degree of oxidation, superficial scratches or highly reflective, mirror-finish surfaces. In an industrial setting, this means that, in many cases, users can do without upstream surface preparation processes such as sandblasting or tin coating if they use green laser light.

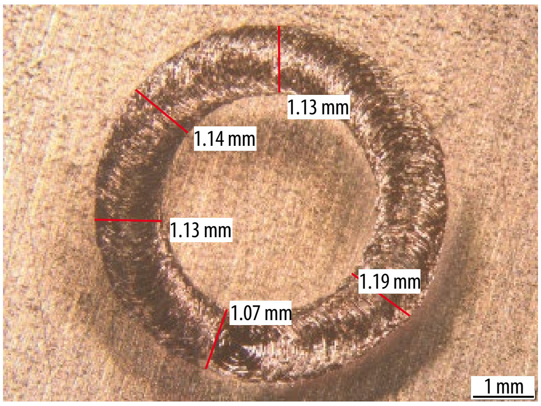
As well as being an excellent choice for processing copper, green laser light is also suitable for other widely used industrial metals such as aluminum, steel and gold. That makes the green laser particularly interesting for users who wish to process a range of materials with a single beam source.

Applications in electric car manufacturing

The field of component manufacturing for electric cars offers numerous applications for powerful green laser light – from the battery and powertrain to the power electronics. Four key applications offer particular promise:

- **Battery foil welding**: Battery cells consist of stacked layers of very thin copper and aluminum foils. Each foil is welded to a tab made of the same material before the cell is filled with electrolyte. Two key challenges arise during battery foil welding: first, air between the foils





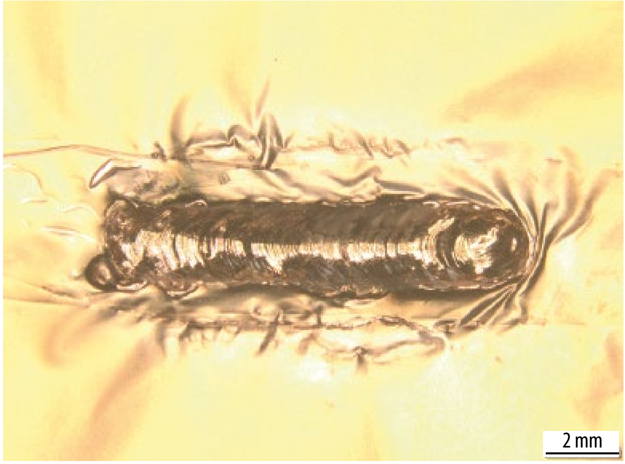
Busbar welding with copper sheets measuring 0.5 by 2 millimeters: an even weld seam surface and consistent penetration depth in a welding time of just 0.42 seconds.

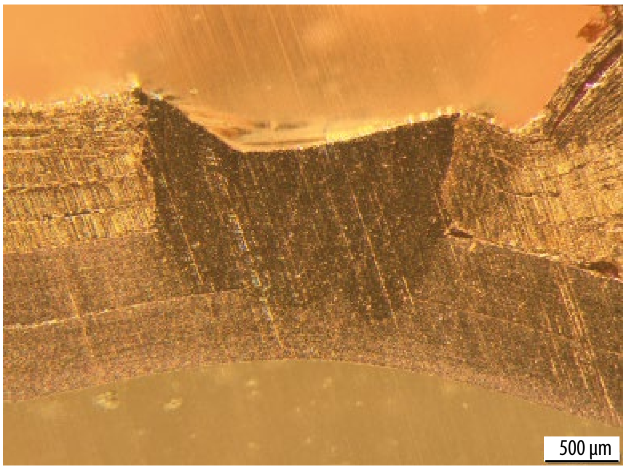
Company

Trumpf Lasers

Trumpf's mission is to further develop and digitally connect production technology, to make it even more efficient, precise, and future-proof. From drilling the finest holes no wider than a hair, to welding panels in ship building, the disk lasers from Trumpf have been used in tens of thousands of installations around the world. Whether it be a continuous wave or ultrashort-pulse laser, disk laser technology demonstrates its advantages in the respective sector with both high pulse energies and high average powers.

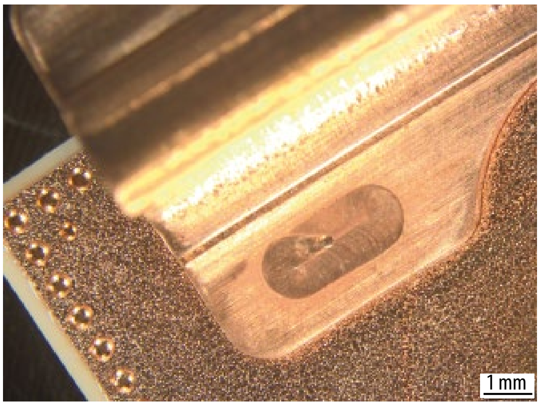
www.trumpf.com





Welding a hundred 6-micrometer battery foils to a 2 × 0.5-millimeter copper tab: a large, pore-free bonding surface and a smooth top bead with minimal spatter formation.

that can potentially lead to well spatter and, second, the low thermal capacity of the foils combined with the high thermal conductivity of the tab. The challenge is to ensure that the foils do not burn before enough heat has reached the tab. Using green laser light, users can achieve a large, pore-free bonding surface and reduced spatter formation, especially with copper foils. Unlike ultrasonic welding, laser welding is a non-contact process. This offers various advantages, including considerably easier access to the welding point and no accumulated abrasion in the foil. What's more, the forces applied to the sensitive foils are low, minimizing the risk of damage. The number of foils that can be welded to a single tab is up to four times higher with laser welding than with ultrasonic welding.



Connecting copper contacts to DBC substrates: green laser light offers a controlled penetration depth that keeps the DBC substrate intact. scanning optics guide the light to the exact processing point even when space is tight.

- **Welding cell connectors:** The welding process used to connect battery cells often brings together different materials. A typical combination is welding copper to aluminum or vice versa. By creating a weld seam in a meandering motion using green laser light, users can achieve a large bonding surface with a high tensile strength of significantly more than 600 Newtons for connections between different materials. The high laser power enables high feed rates and high productivity with minimal heat input to the underlying part. The high process speed also helps suppress the formation of undesirable intermetallic phases.
- **Busbar welding:** Copper busbars are used in applications such as battery modules and power electronics. They are generally welded in an overlap joint. With a power output of two kilowatts, the green laser is the ideal choice for quickly and reliably welding copper sheets measuring 0.5 by 2 millimeters, for example. To further increase the cross-section and thus the conductivity of the join, a circular geometry can be used instead of a linear weld seam.
- **Welding contacts for DBC substrates:** DBC substrates for power electronics are heat-sensitive. They are generally contained in an extremely confined space, which makes access difficult. Scanning optics can be used to position green laser pulses precisely at the weld point. The rapid welding process means that very little heat enters the contact and the surrounding structure, so the thermal stress load is low. Penetration depth can be precisely controlled and reproduced – and the heat-sensitive DBC substrate remains intact while the contact is being formed. There is also significantly less spatter thanks to the green laser radiation. Spatter can lead to short circuits and the destruction of the entire component, especially in the case of power electronics components.

Beam quality makes the difference

In principle, similarly good results should be achievable with blue laser light (450 nanometers), which is next to green on the wavelength spectrum. Technically speaking, it makes no significant difference whether green or blue light is used in terms of the resulting coupling behavior in copper. But what does make a difference is the choice of beam source. Currently available beam sources for blue are based on gallium nitride diode material, which has not yet proven its durability for laser material processing in industrial settings. In contrast, disk lasers with a green wavelength use the same diode material as infrared disk lasers, which have been proven in the field for many years. Green lasers are also superior to blue lasers in terms of the power output that is currently achievable. However, the biggest advantage of green light from disk lasers compared to blue light from the diode is its significantly better beam quality of up to 2 mm · mrad with a small numerical aperture of 0.1. To obtain higher laser power output from blue diodes, manufacturers currently resort to spatial addition of diode material. However, this results in significantly lower beam quality. For many industrial applications in electric vehicle construction – which require delicate weld seams and a correspondingly small focus – blue light is therefore out of the question.

Yet the primary reasons for green's supremacy over blue are practical ones: the high beam quality of green light hugely simplifies the way machines are designed and enables the use of focusing optics with a longer focal length. This means the optics do not have to be right above where the work is carried out. They can be guided above the workpiece at enough of a distance to allow easier access to narrow work areas, reduce contamination and extend their service life. The significantly longer Rayleigh length (i.e. larger depth of focus) paves the way for far greater tolerances in terms of working distance. Green light requires less precision than blue light when it comes to both fixtures and part tolerances.

In addition, green lasers enable the use of scanner optics. Combined with long focal lengths, these provide a larger scan field. For example, programmable scanner optics with a focal length of 265 millimeters cover a scan field of 140 × 100 millimeters. The advantage is that neither the part nor the optics have to be moved. Simply moving the scanner mirrors is all it takes to process a part – or even several parts at a time – and achieve high productivity. No additional axes are necessary.

Transmission losses for blue laser light in fiber-optic cables are higher than for green laser light by a factor of 1.4. Available products on the market with blue laser light are typically supplied with 5 meter long fiber-optic cables. This makes it easier to integrate green lasers in machines. It also makes it possible to use a single laser for several different machines via multiple outputs, which increases productivity enormously. Green lasers also have the advantage of an extensive range of industry-standard optics, machines, process monitoring solutions and software, which have been comprehensively tested and are already available.

Based on these advantages and all the applications described above, green light from industry-proven disk lasers is the perfect choice of tool for all copper-processing manufacturing tasks, especially in the electric car industry.

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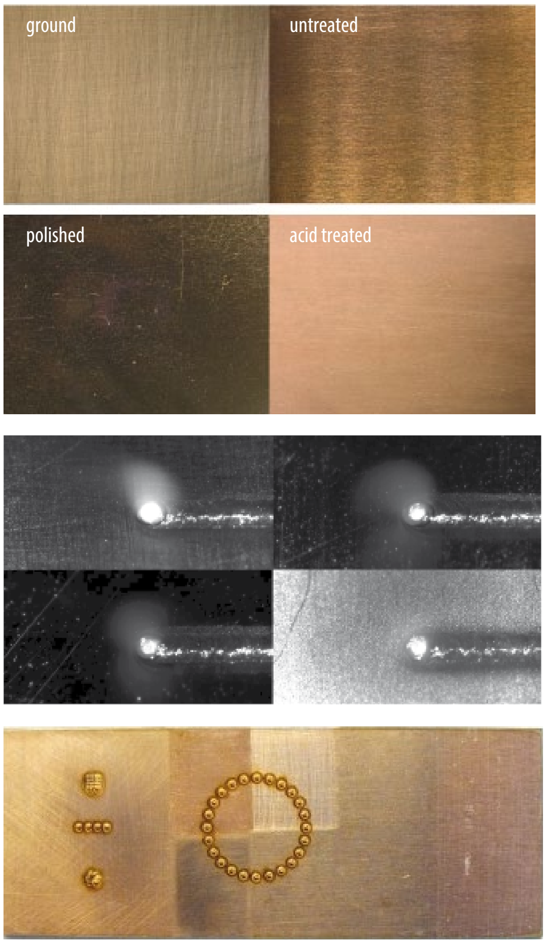
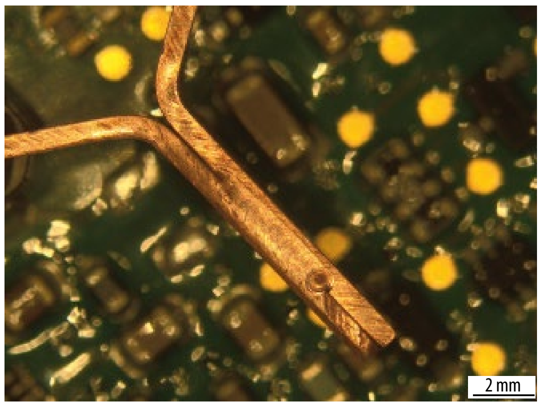


The surface of the copper makes no difference to green laser light. The results are the same for polished, sanded, untreated or etched surfaces – and green light even takes scratches and varying degrees of oxidation in its stride.



Light of a green wavelength reduces spatter formation to a minimum during laser welding, as seen with this electronic component.

Authors

Stefanie Bisch works as a product manager for the laser and machine tools manufacturer Trumpf in the area of high power lasers since 2015. She is responsible for the portfolio of high power disk lasers with green wavelength and works closely with customers, sales and development to understand the market requirements and to develop market-oriented products. She graduated from the University of Heidelberg in 2015 with an MSc degree in physics.

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Coherent

Founded in 1966, Coherent is one of the world's leading providers of lasers and laser-based technology for industrial, commercial, medical and scientific customers. With headquarters in the heart of Silicon Valley, California, USA, and offices spanning the globe, Coherent offers a distinct product portfolio for applications in microelectronics, materials processing, life sciences, and scientific research.

We service market-leading companies in numerous industries and our roster of customers includes several Noble laureate scientists. The breadth of Coherent's success stems in part from the company's unmatched technology portfolio: UV optical systems, high power fiber lasers, ultrashort pulse lasers, solid state lasers, direct diode lasers and much more.

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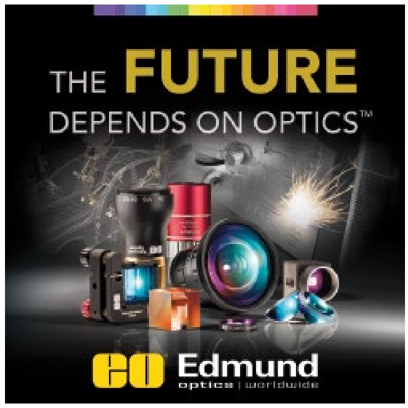
The Future Depends on Optics

Edmund Optics® (EO) is a leading global supplier of optics, imaging, and photonics technology that serves a variety of markets including Life Sciences, Biomedical, Industrial Inspection, Semiconductor, and R&D since 1942. EO designs and manufactures a wide array of optical components, multi-element lenses, imaging systems, and opto-mechanical equipment, while supporting OEM applications with volume production of stock and custom products. With locations in more than nine countries across the globe including manufacturing and design, EO employs over 1000 employees and continues to expand.

An extensive portfolio of over 35.000 products is supported by a huge inventory of standard parts with fast delivery, making sure customers can get what they need when they need it.

EO takes pride in helping customers from prototype to volume production, and specializes in creating cost-effective solutions that meet our customer's specifications, timelines, and budgets. Whether requirements include stock optics, a build-to-print custom optical component, expert application engineering to optimize the design, or a completely custom design to customer-supplied requirements, our engineers can create great solutions for each unique optical challenge. Every step of the way, Edmund Optics® is committed to ensuring product and procedural quality.

As well as high quality products, EO offers free technical resources and engineering support to meet the needs of its customers. From an extensive online technical resource library of application notes, videos, calculators, FAQ's and published articles, to technical support via phone, email or chat – EO is committed to bringing its customers project to success.



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GWU-Lasertechnik – Best of Photonics

GWU-Lasertechnik Vertriebsges. mbH has more than 30 years of experience in supplying crystals, optics and accessories for lasers and laser applications. Moreover, GWU is a well-known manufacturer of tunable laser sources.

GWU offers all common laser crystals (Nd:YVO4, Nd/Yb:YAG, …) and optical non-linear crystals (BBO, LBO, …) with a broad variety of specifications. Besides the well-established materials, innovative crystals with outstanding properties are available. Crystals and optical components are manufactured by GWU's partner Castech Inc. Periodically-poled frequency conversion crystals manufactured by HC Photonics provide the ability for high conversion efficiency even for cw and low power applications. These PPLN crystals are available as bulk or waveguide chips. The portfolio also comprises ready-to-use PPLN devices, optionally fiber-coupled.

The assortment of optical components is completed by windows, prisms, waveplates, polarizing optics and various standard items. High-quality isolators, acousto- and electro-optic devices can meet even demanding requirements. All laser components can be configured in flexible design, free-space or fiber-coupled and can be equipped with driving electronics.

No matter if individual pieces are required or cost-efficient numbers in in small, mid or large batches with in-time delivery are needed: GWU's dedicated service helps to find the best core components for your application. As GWU is not only a distributor but also a well-known manufacturer of laser devices, a wide knowledge and in-field experience can be shared to the advantage of its customers.

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The World Leader in Fiber Lasers

IPG Laser GmbH is the German subsidiary of IPG Photonics, the world leader in fiber lasers. For 30 years we have been developing and manufacturing the most reliable high-performance fiber lasers, systems and amplifiers for diverse applications across numerous markets. Our extensive product lines of low, mid and high-power lasers and amplifiers are used in materials processing, communications, medical and advanced applications, as well as in entertainment and scientific applications.

IPG fiber lasers continue to replace traditional laser technologies in many of these application areas while also expanding the range of laser applications with new, revolutionary technologies. Examples include a new High Peak Power option for cw lasers, tunable Adjustable Mode Beam lasers, and an inline weld monitoring system. Because IPG is the most vertically-integrated fiber laser developer and manufacturer, we are able to meet our customers' unique requirements, accelerate development and improve component yields as well as manage costs, all while maintaining high performance and quality standards. Quite simply, IPG fiber lasers and systems are disrupting the market by empowering our customers with the most cutting edge application capabilities today.

IPG is a global company with manufacturing facilities in the US, Germany, Russia and Italy and regional sales offices in many countries in Europe, Asia and South America. Our products are available globally to OEMs, system integrators and end users across a wide range of diverse markets.

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Laser Safety Made in Germany

Highest Quality Made by Laservision

laservision, as one of the leading manufacturers of laser safety products, secures and further develops this position through innovative products and services, based on the requirements of its customers.

Since 1987, the name laservision has been synonymous with first class quality of laser safety products customers can rely on. The highest quality standards apply to laservision products are monitored with state-of-the-art testing and measurement equipment. ISO-certified processes guarantee the reliability, precision and durability of laservision products at any time. The extensive portfolio of laservision includes laser safety eyewear with glass and plastic filters for almost all laser applications within the industrial, medical and R&D sectors. Furthermore, laser safety cabinet windows, barriers, curtains and movable walls are offered customer-specific and standard.

Manufacturing competence throughout the entire process allows us to guarantee high-quality and reliable products, as well as advisory measures and personal service. We operate according to our three core brand values “quality, innovation and customer orientation”.

Comprehensive expertise, long-standing experience and a passionate dedication are the perfect combination to ensure the continued advancement of exceptional innovation at laservision. With a high level of technical knowledge and new ideas laservision continuously meets the safety challenge of rapid advancement in laser technology.

laservision

From individual product development to qualified advisory services, protection of health is the core focus at laservision, in line with the uvex group’s brand mission: protecting people.

Company

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Innovative and Flexible

Leister Technologies has been a global leading provider of plastic welding equipment for over 70 years. With comprehensive theoretical and practical knowledge in a wide range of plastics processing techniques, Leister is able to confidently apply multi-faceted, “big picture” solutions with ease. As one of the first companies to develop and manufacture laser systems for plastic welding, our expertise and partnerships within the industry have consistently provided thousands of clients an efficient and effective pathway to fulfilling their plastic joining needs.

Leister’s innovative laser systems open up new possibilities in the automotive, medical, sensors, electronics and micro-system technology industries for plastic joining. We specialize in finding customized, cost-effective solutions ranging from common joining problems to the most critical and complex customer demands. As an example, Leister’s patented and award-winning GLOBO Optic is an exclusive technology module that can weld three-dimensions plastic components in a single step to eliminate the complex tooling requirements of other joining technologies. In addition to our laser technologies, our highly-trained specialists can assist in the design and component construction, material selection, process optimization and equipment integration for new and existing manufacturing platforms.

LEISTER
LASER PLASTIC WELDING

Company

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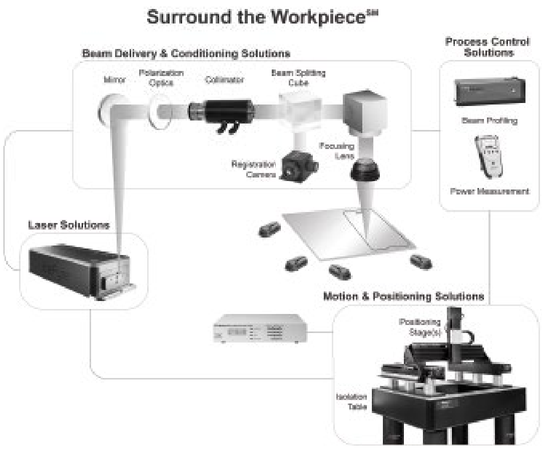
Helping Customers Solve for Success

MKS Instruments is a global provider of instruments and solutions to measure, monitor, deliver, analyze, power and control critical parameters in advanced manufacturing and research applications. Spectra-Physics, Ophir and Newport are brands within the MKS Instruments Light & Motion division. ESI is a brand in our Equipment & Solutions division. Spectra-Physics combines groundbreaking laser technologies with deep application expertise to deliver industry leading lasers for precision industrial and scientific research applications. Ophir specializes in laser and LED measurement products, including laser power and energy meters and laser beam profilers. Ophir also provides high-performance IR thermal imaging lenses and optical elements as well as optics for CO_2 and high-power fiber laser material processing. Newport provides a full range of solutions including motion control, optical tables and vibration isolation systems, photonic instruments, optical and opto-mechanical components. MKS Light & Motion solutions enhance our customers' capabilities and productivity in the semiconductor, industrial technologies, life and health sciences, research and defense markets. The Equipment & Solutions segment provides laser-based manufacturing solutions for the micro-machining industry that enable customers to optimize production. Our market is composed primarily of flexible and rigid PCB processing/fabrication, semiconductor wafer processing and passive component manufacturing & test. Our solutions from both divisions support our Surround the Workpiece[SM] offerings, in which we deliver leading products and services in the lasers, photonics, and optics markets.



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Precision Linear Guides and Frictionless Slides

PM is the leading European manufacturer of standard and customised precision linear bearings, linear slides, miniature slides, rotation bearings, sub-assemblies and engineered-to-spec motion systems. We are a family-owned company in the Netherlands and employs more than 200 people. Known as a trusted partner for hundreds of global players operating semiconductor industry, optical and metrology sectors, medical technology to industrial automation, space and defense industries.

PM has over 50 years in-depth manufacturing knowledge and critical products are made in house. We offer all manufacturing capabilities for extremely small sized products up to large machining capabilities necessary for vacuum chambers and accurate large machine elements and frames.

Our product portfolio of linear bearings includes ball, cross roller and needle roller linear bearings. Besides linear bearings, we are specialised in linear slides and we offer various miniature slides. Our newest innovation is our extremely compact cross roller linear slide MSR which includes anti-cage creep technology and offers a highly accurate movement at high speeds.

Other products are the compact and flat rotary table bearing for precise rotary motion and the gonio bearings which offer precision and low friction curved motion, originally developed for use in optical lenses applications

Furthermore, our portfolio includes customised XY-stages, positioning systems and advanced motion systems with accuracies at sub-micron level. Our expertise enables us to find solutions that meet the specific requirements of a wide variety of industry applications. Assembly of our products is done in conditioned low-dust assembly rooms, for semiconductor and medical customers we offer ultrasonic cleaning, assembly and qualifying in cleanroom classes 6 and 7.

Company

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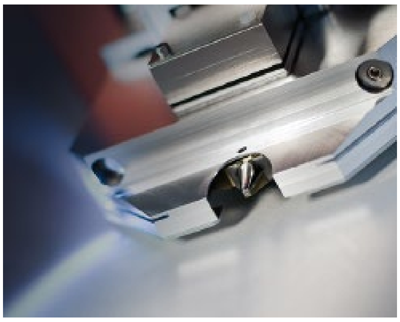
Competence in Beam Diagnostics

PRIMES develops and produces market leading systems for laser beam characterization in industrial applications. Our spectrum of high-precision, durable products is put to use in numerous branches, such as automotive industry, industrial machinery, additive manufacturing as well as for R&D and laser manufacturing. Our company is an important player on the global market, represented by 12 distributors and a new PRIMES subsidiary in Japan. We have a clear customer focus and offer worldwide consulting. PRIMES provides robust, industry proven, ready-to-use-systems for industrial environments.

They are easy to integrate in production processes due to standardized interfaces. Thanks to the in-house design of hard- and software we can offer optimal solutions for a wide variety of laser measuring tasks as well as for nearly all major laser and machine builders. Our core competence comprises beam diagnostic devices for use in the processing area of systems with multi-kilowatt laser power and high densities.

As an ISO 9001 certified company, precision is our standard. Our calibration lab has experience with most laser applications and calibrates measuring devices from all manufacturers. Our spectrum of beam sources – from CO_2 to solid-state lasers – offers the perfect conditions for this.

PRIMES is an established partner for customer specific developments from idea to delivery. With 4 to 6 patents each year, we are constantly showing our capacity for innovation, intensified by an extensive R&D network. With a global installation base of more than 20,000 systems, PRIMES has gained highest reputation in the market. Our commitment to innovation and customer focus is our key to success.



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High-Quality Optical Components

The company Schäfter+Kirchhoff GmbH is based in Hamburg, Germany and was founded over 60 years ago. From here we manufacture high quality optical products that are delivered to customers all around the world.

Our current product lines are polarization-maintaining fiber optics, lasers for machine vision and line scan cameras. A special focus is set on the winning combination of high optical and high mechanical precision, which is the basis for the high quality, stability and durability of our products.

One example of successful opto-mechanics is the 60SMS laser beam coupler, which is used to couple into polarization-maintaining fibers. This demanding task requires very high precision and quality in order to reach long-term stable and high coupling efficiencies. Further fiber optics components are available for the wavelength range 360-2100nm.

Another field of opto-mechanics is Machine Vision that uses laser line or spot generators as well as line scan cameras. Ruggedized solutions for industrial purposes are only possible by using high-quality optics, mechanics and electronics. This is true for defined and thin laser line geometries or especially small laser spots as well as complete line scan camera based scanner systems. The Corrosion Inspector, e.g., is an automated and objective analysis tool for corrosion phenomena that offers a fast and precise evaluation according to international norms. The line scan cameras used are also supplied as OEM components and offered with different interfaces.

Our extensive know-how and highly qualified, strongly committed employees are the driving force behind the company. To have sales, research and development, as well as manufacturing so closely knit together, ensures a quick and efficient response to customer needs.

Company

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www.SuKHamburg.com

More Than 125 Years of Modern Lens Manufacturing

Sill Optics is a medium-sized company in Germany, which has specialized in the production of high quality optical components with a total value € 26 mio. Its philosophy is: "100 % Made in Germany". Since the foundation in 1894, enormous technical skills and extensive knowledge of manufacturing have established. Sill Optics takes the word "precision" seriously and certifies its quality to DIN EN ISO 9001:2015 since 1996.

Currently Sill Optics employs more than 240 people. The majority works in the manufacture of coated aspherical and spherical lenses, mounts and assembly. A 100 % inspection by qualified staff with state-of-art measurement devices guarantees the quality of our finalized lenses.

Our product portfolio in laser optics includes focusing lenses and beam expanders as well as standard and telecentric scan lenses. We also offer precision fused silica aspheres with focal lengths from 20 mm to 400 mm. Our laser optics cover the wavelength range from 193 nm to 1980 nm.

Besides laser optics, we also produce lenses for machine vision. We are specialized in single and double sided telecentric lenses and offer lenses with coxial illumination or an integrated tunable lens. Furthermore our portfolio includes telecentric LED condensers and a some entocentric CCD lenses.

We are specialized in the custom specific production of small and medium quantities for various niche markets in laser optics and machine vision. Our flexibility enables the fully development from your idea to a final prototype or series product. All design and production steps are realized inhouse. Furthermore, there is a catalog with a choice of standard products.

Company

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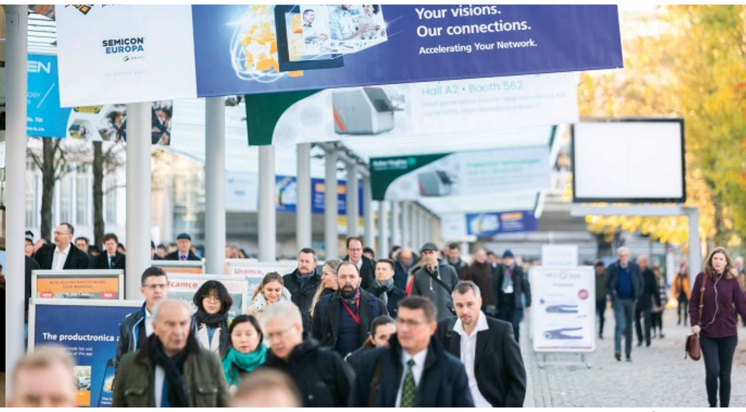
Source: Messe Düsseldorf



Source: Messe München

new / next date

May 12 – 14, 2020 → **November 17 – 19, 2020**
Optatec
Frankfurt, Germany
www.optatec-messe.de

May 27 – 28, 2020 → **October 28 – 29, 2020**
chii2020
www.chii2020.com

June, 16 – 18, 2020 → **June 21 – 22, 2022**
SLT'20
Stuttgart, Germany
www.slt.uni-stuttgart.de

June, 16 – 18, 2020 → **June 21 – 23, 2022**
LASYS
Stuttgart, Germany
www.messe-stuttgart.de/lasys

June, 16 – 19, 2020 → **September 15 – 18, 2020**
EPHJ 2020
Geneva, Switzerland
https://ephj.ch

June, 23 – 25, 2020 → **May 4 – 6, 2021**
Sensor+Test
Nuremberg, Germany
www.sensor-test.de

June, 26, 2020 → **June, 10 – 12, 2021 and online: 26 June 2020**
EMVA Business Conference
Sofia, Bulgaria
www.business-conference-emva.org

new / next date

July 3 – 5, 2020
LASER World of PHOTONICS CHINA
Shanghai, China
www.world-of-photonics-china.com

July 3 – 5, 2020
productronica China
Shanghai, China
productronica-china.com

August, 11 – 13
SIAF Guangzhou & Asiamold 2020
www.spsinchina.com
www.asiamold-china.com

September, 9 – 11
22nd China International Opto-electronic Exposition CIOE
Shenzhen, China
www.cioe.cn

September, 20 – 24 → **December 6 – 10, 2020**
European Conference on Optical Communication ECOC 2020
Brussels, Belgium
www.ecocexhibition.com
https://ecoco2020.org

September, 23 – 24
W3+ Fair Rhine Valley
Dornbirn, Austria
https://w3-messe.de/en/Rhine_Valley

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Laser Micro Material Processing Influenced by Wavelength and Digitalization

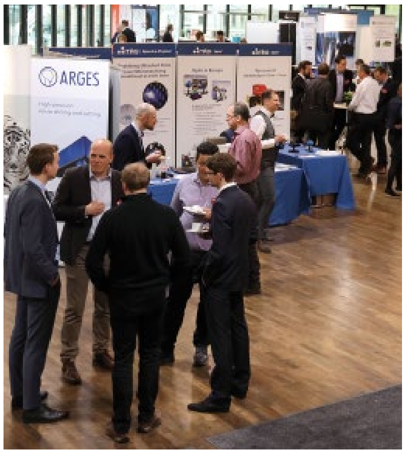
Review: LEF Seminar 2020, 10 – 11 March, Fürth, Germany

The "23rd seminar on lasers in electronics production and precision engineering" took place in March this year, with a diversified lecture program on the welding of copper with visible wavelengths, ultrashort-pulse processing with different wavelengths, smart production systems, intelligent inline process monitoring as well as "pecha kucha" presentations on non-destructive testing (NDT).

Highlights were the talks of the opening speakers Prof. Randolf Hanke (Development Center X-ray Technology EZRT / Fraunhofer Institute for Integrated Circuits IIS, on the future of NDT and X-rays in the context of Industry 4.0), Berndt Zingrebe (retired CEO of Sill Optics, talking about sixty years of affinity with lenses – changes in production), Dr. Jan-Philipp Weberpals (Audi AG, on laser remote welding of aluminum: holistic provision of data for the process chain) and Dr. Fabian Wein (Friedrich-Alexander-Universität Erlangen-Nürnberg, on process-oriented design optimization – opportunities and limitations).

Unfortunately, all those who registered were able to participate in the event as planned due to various travel restrictions caused by the increasing spread of the Coronavirus. In the end, more than one hundred participants made their way to Fürth. As a consequence, digital transformation made up not only a large part of the seminar program this year, but because of the special situation, one lecturer was connected with the audience remotely and gave his talk from afar for the first time in the history of the seminar – digitalization made it possible.

Regardless of the unfavorable conditions, the attendees took the opportunity to intensively discuss the potential of laser micro material processing for the technological challenges of the future. The accompanying exhibition provided the ideal backdrop for this, where 17 exhibitors presented their products and services, as did the traditional evening event. This time, magician and mentalist Tom Duval astonished the visitors during the evening event with his tricks



Overlooking the accompanying exhibition at the foyer of Stadthalle Fürth during LEF 2020 (Source: BLZ / S. Roth)

and gave rise to conversations the next day as well.

The "24th seminar on lasers in electronics production and precision engineering" will take place in Fürth on March 16 and 17, 2021. More information will be available via the LEF website in the fall of 2020.

www.lef.info

Preview: 22nd China International Opto-electronic Exposition CIOE

CIOE
CHINA INTERNATIONAL
OPTOELECTRONIC
EXPO

9 – 11 September 2020, Shenzhen, China

Registration is open for the most influential optoelectronics event in China: the 22nd China International Optoelectronic Exposition will be held at the new Shenzhen World Exhibition Convention Center. Featuring 160,000 square meters exhibition area and nearly 3,000 exhibitors, it showcases components, devices, equipment and various optoelectronic applications to global optoelectronic professionals and buyers from within the optoelectronic ecosystem. With the restructured floor plan, it integrates six sub-expos under one roof covering information and communication, precision optics, laser technologies, infrared applications, optoelectronic sensors and photonics innovation.

The CIOE Information and Communication Expo covers optical chips, optical devices, fiber-optic cables, optical modules, and optical equipment, which are in great demand in infrastructure projects such as 5G, data centers, IIoT and AI. The other flagship sub-expo is Precision Optics, Lens Camera Module Expo, which shows the entire optics supply chain including optical materials, components, optical imaging measurement and optical instruments, optical processing equipment, sapphire and touch-screen manufacturing.

China's only infrared show, CIOE Infrared Applications Expo, displays the role of photonics for the worldwide fight against Covid-19. It presents IR products and technologies from infrared material and components, infrared thermal imaging technologies and devices to THz monitoring and imaging, to meet the need for mass temperature screening in public places. The CIOE Opto-electronic Sensor Expo will showcase the new products and technologies of lidar, millimeter-wave radar, 3D sensing, visual sensing, fiber-optic sensors, the Internet of Things and other related sectors. The Lasers Technology Intelligent Manufacturing Expo will focus on fine processing, particularly the application scenario of ultra-fast lasers in consumer electronics, hard brittle and flexible materials processing, and in 5G. The latest advanced photonics research-incubated products or technologies will be presented at CIOE Photonics Innovation Expo by national research institutes and universities.

International leading opto-electronic enterprises will exhibit at CIOE 2020 to attract around 80,000 buyers and industry peers.

www.cioe.cn

Preview: W3+ Fair Rhine Valley

23 – 24 September 2020, Dornbirn, Austria

Provided that Austria further relaxes the regulations as expected, the W3+ Fair Rheintal will take place as planned. For the second time, the high-tech platform is calling experts from the optics, photonics, electronics and mechanics sectors from the four-country region of Austria, Switzerland, Liechtenstein and Germany. Together, the experts are looking for new technological solutions that are used, for example, in areas such as medical technology, tools and machinery and automotive. Key exhibitors have confirmed their participation, including Swarowski Optik from Austria, Optotech from Germany, WZW Optic from Switzerland, Universal Photonics from the USA as well as ILT Fineworks from the Netherlands.

Looking to the future will be a central theme: the new, W3-accompanying high-tech congress N-Tec Talks will be held under the motto “The day after Corona – prospects, opportunities and measures for high-tech industry after the crisis”. The congress on enabling technologies took place for the first time at the W3+ Fair Wetzlar in Germany in February 2020. In the Rhine Valley, everything will revolve around current know-how and best practice examples in the three subject areas of product technology, procurement and production, and management. Speakers from associations and companies will present their concepts for a new beginning, which will be of equal interest to product managers, developers or buyers.

Another novelty: in 2020, the W3+ Fair be held in conjunction with the Tech.Con trade fair, the platform for industry, trade and production companies in the Lake Constance region. This creates a wide range of topics and ensures a cross-industry mix of experts on site.

In order to meet the increased safety requirements in Corona times, organizer Fleet Events has put together a comprehensive package of measures that can be implemented as required. These include controlled numbers of visitors in the hall as well as wider aisles, increased cleaning cycles and the recommendation to all participants to wear face masks.

“We are confident that the event will take place in September. After the Corona break, we are expecting a strong response – many companies and partners are very much looking forward to resuming personal contacts. Dornbirn will thus become the hotspot of the high-tech industry in the Rhine Valley region during the two days of the trade fair,” project director Jörg Brück is certain.

Important associations and institutions such as EPIC, Swissphotonics, Photonics Austria, Spectaris and IVAM will be partners in 2020. It is planned to use the W3+ Fair as a platform for the first personal meetings of members. Due to the forced break, the industry’s need for direct contacts and the resumption of regular business operations has increased significantly. For this reason, the organizer is providing more space for networking.

The W3+ Rhine Valley has been carefully chosen: The transnational region with its focus on research and development is one of the top ten of Europe’s 1200 high-tech locations. This is where the cross-industry concept of the W3+ Fair is particularly effective. User sectors such as aerospace, automotive, medical technology, life science, tools & machinery benefit from the cooperation just as much as the high-tech industries themselves. At the premiere in September 2019, more than one hundred national and international exhibitors met with more than a thousand trade visitors.

https://w3-messe.de/en/Rhine_Valley

Preview: European Conference on Optical Communication ECOC 2020

New date: 6 – 10 December 2020, Brussels, Belgium

Due to the current circumstances regarding Covid-19 the decision has been taken by the ECOC Management Committee and ourselves to postpone the event from September to December. In light of uncertainties regarding international travel, in response to requests from local authorities, the organizers decided to postpone ECOC 2020 conference to 6 – 10 December 2020 / exhibition dates 7 – 9, also in Brussels, Belgium.

The conference and exhibition will be held at the Brussels Expo in Brussels, Belgium, and will once again showcase the latest products and services, as well as provide an unrivaled opportunity to meet and network with key suppliers and industry leaders. Over 6000 colleagues, customers and peers are expected, along with more than 330 exhibitors, for three days of networking, sharing ideas, learning and developing new business leads. The 2019 event took place in Dublin, Ireland, with 6569 visitors and 337 exhibitors from around the globe.

ECOC is the largest conference on optical communication in Europe, and one of the most respected and long-standing events of its kind in the world. ECOC 2020 will be the 46th edition, which indicates the stability and the attractiveness of this conference as one of the world’s major events in the field, providing a prime forum for new developments and results in optical communication techniques and networks.

The programme will consist of a set of high-level plenary speakers, tutorials, invited papers, workshops, symposia, and most importantly, parallel sessions with your contributions, technical papers, demonstrations and posters. The programme will highlight new breakthroughs in the field of optical communications in different areas such as: fibers, fiber devices and amplifiers, waveguide and optoelectronic devices, subsystems and network elements for optical networks, transmission systems, backbone and core networks, access and local area networks.

As has been the case at ECOC 2018 and all even years, Brussels will also host a CLEO Focus Meeting within the ECOC 2020 programme.

www.ecocexhibition.com
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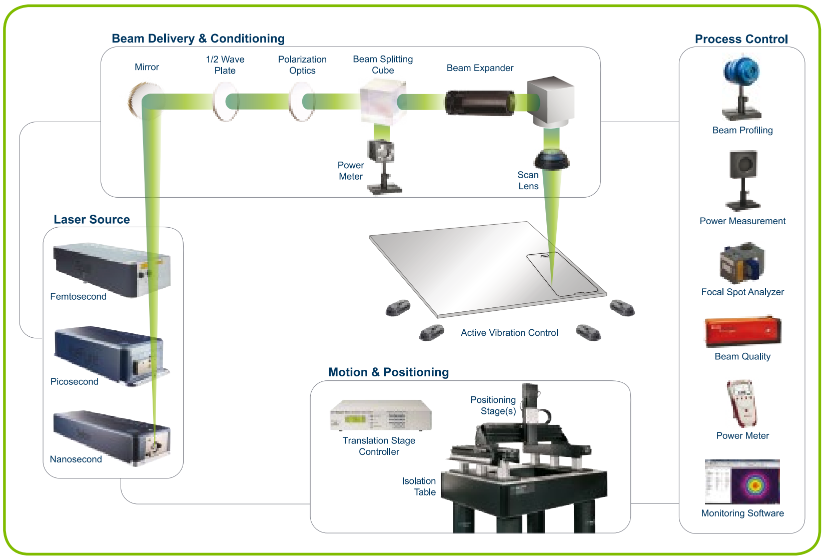

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