Line beam shaping with a tailored anamorphic diffuser

Improving the integrated uniformity of laser lines generated by double sided cylindrical lens arrays

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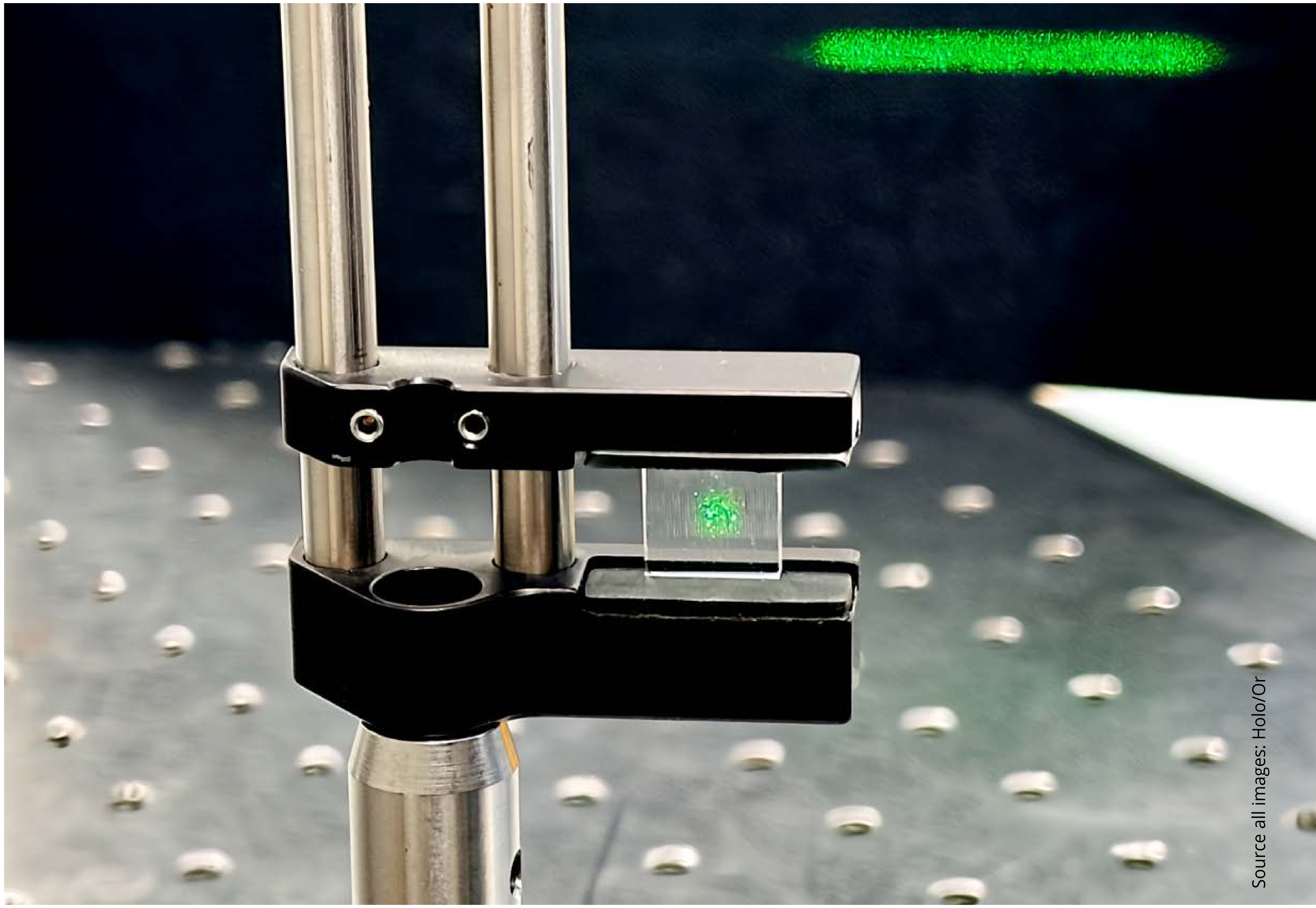
Many applications utilizing lasers require shaping of the laser into a thin flat top line with good uniformity, especially in fields such as microscopy, wafer inspection and laser lift off. Often, multimode lasers are used, due to their lower cost per watt compared to single mode lasers, requiring shaping that is based on diffusers and lens arrays. This article presents a method for improving the narrow-axis integrated intensity uniformity in laser line beam shaping for partially coherent laser sources. The proposed approach involves utilizing a tailored anamorphic diffuser (TAD) to create a controlled mixing of the coherence in both line dimensions, enabling improved uniformity. This method is compared to existing solutions for specific examples. Furthermore, this paper addresses the manufacturing feasibility of the proposed method, highlighting potential fabrication techniques and their practicality.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The need for uniform intensity line shaping in various laser applications

Line shaped laser intensity is often used in scanning or similar application, where the line's thickness is defined as a single unit – without attention to internal intensity distribution along the narrow axis [1, 2], and can thus be described by the value of integration over the intensity along this dimension.

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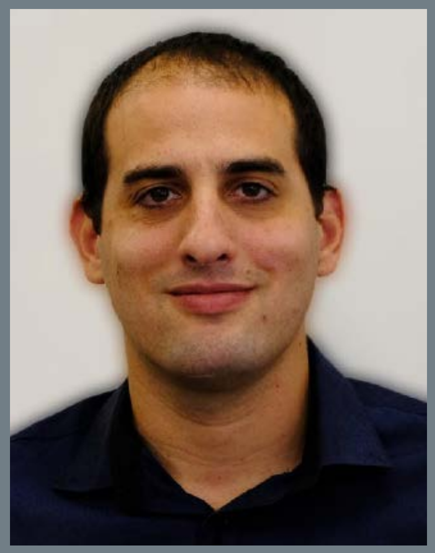

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Unlike the short line axis, the intensity distribution along the long line axis has a strong influence on the performance, for both material processing applications such as laser lift-off and annealing, and for microscopy applications such as or laser wafer inspection in semiconductor industry or cell analysis in laser flow cytometry.

In biomedical imaging applications, a uniform laser line beam is required to illuminate the region of interest in biological tissues and obtain high-quality images with high contrast and resolution. One of the primary biomedical imaging techniques that rely on laser line beam shaping is confocal microscopy. In confocal microscopy, a narrow laser line is used to excite fluorophores in biological tissues, and the resulting fluorescent signals are detected and processed to produce detailed images of the tissue. Any non-uniformity in the laser line beam can result in uneven excitation of fluorophores, leading to artifacts and image distortions.

Uniformity in laser line beam shaping is crucial for wafer inspection in the semiconductor industry. It ensures consistent illumination, enhances defect visibility, improves measurement accuracy, enables effective process control, and simplifies equipment calibration and monitoring. By maintaining uniformity, semiconductor wafer inspection machine builders can significantly enhance the throughput of their machines.

Laser line beam shaping with uniformity is also of utmost importance in the UV laser lift-off process for consistent and controlled separation of the film from the substrate and for maintaining stable and reproducible results in the UV laser lift-off process [3]. Consistency in the beam profile and energy distribution ensures repeatable performance from batch to batch, minimizing process variations and deviations.

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Standard line shaping solutions such as cylindrical lens arrays typically have a purely one-dimensional effect. These approaches are robust and generally work well in non-demanding applications but are suboptimal when uniformity of the line becomes a critical parameter.

Since the nonuniformity in intensity along the long line axis is a function to laser temporal and spatial coherence there is not much that can be done to improve it without increasing line width. However, for partially coherent (high M^2) beams, correct harnessing of the noncoherence can be used to reduce the integrated intensity variations.

Partially coherent laser beams

A partially coherent laser refers to a laser beam that has some degree of randomness or fluctuations in its phase and intensity and belongs to the multimode lasers family. Laser beams with partial coherence may have some speckle in the intensity pattern, or may exhibit some degree of wavefront distortion.

Partially coherent multimode lasers have cost advantage per watt power relative to single mode lasers and are used in vast variety of applications, including materials processing, microscopy, and optical coherence tomography.

There are two main types of partially coherent lasers:

- semiconductor lasers: laser diodes, laser diode bars, and VCSEL arrays. What is common for them is that they are created by multiple emitters and their M^2 value is defined by M^2 of individual emitter multiplied by number of emitters per axis,
- fiber sources: fiber-coupled lasers and fiber lasers. For this type of lasers the maximum M^2 is defined by core diameter and NA of the fiber.

How partial coherence can be harnessed to improve line shaping uniformity

To understand how line shaping uniformity of double sided cylindrical lens arrays can be improved, we must first understand what hurts this uniformity – namely, interference speckles arising due to laser coherence.

M^2 as an indicator of spatial coherence

Spatial coherence is empirically described by the M^2 value. Partially coherent lasers are defined in a range between about 5 and 50 M^2 value per axis. Standard line shapers such as line diffusers increase M^2 values in the long line axis while having no effect on the short axis. The increase in M^2 caused by adding a line diffuser can be inferred from the total divergence angle of the beam due to the combination of natural divergence M^2 and the diffuser angle:

$$M^2 = \frac{\pi\omega\theta}{\lambda}$$

$$\theta_{beam} = M^2\frac{\lambda}{\pi\omega}\theta_{total} = \sqrt{\theta_{beam}^2 + \theta_{diffuser}^2}$$

where M^2 is beam quality factor, θ_{beam} is the natural divergence angle, ω the beam waist size, and λ the wavelength.

The laser beam can be presented as a complex field of amplitude and phase. The amplitude defines beam dimensions, while the phase defines beam divergence.

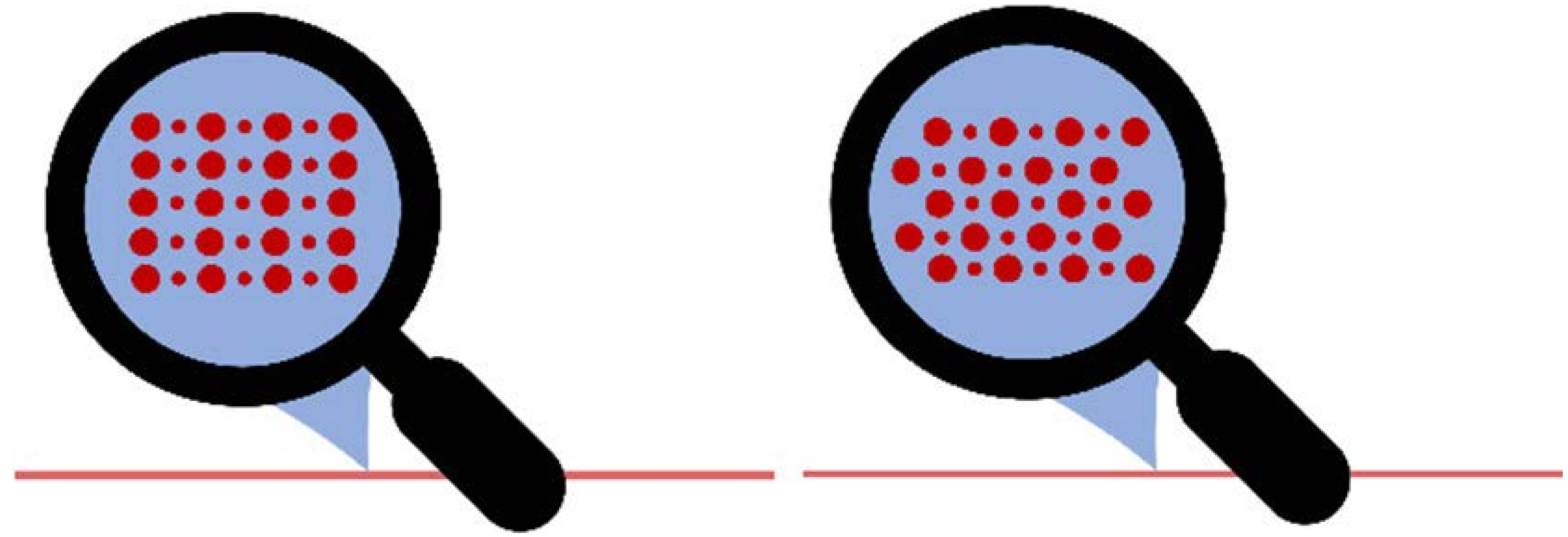

Fig. 1 Schematic illustration of the proposed concept for uniformity enhancement by applying a TAD. Red circles represent intensity of the partially coherent laser beam. Left: effect created by a one-dimensional homogenizer. Right: effect of enhanced uniformity when TAD is added

A diffuser can be represented as pure phase element, so that overall beam characteristics immediately after the diffuser are same beam size as before the diffuser, and a divergence angle that is a combination of original beam divergence and diffuser divergence.

For the equation above, it is clear that when the value of the laser beam's natural divergence θ_{beam} in the narrow line axis is significantly higher (three times or more) compared to the diffuser divergence in this axis θ_{diffuser}, the overall change in divergence angle in the narrow line axis is small. As a consequence, in such cases the line thickness increase due to adding a diffuser to the narrow axis is typically insignificant (10 % or less change). This means that adding a weak diffusion function in the narrow axis of the line has little effect on line width, but as we will see, it has a significant effect on line uniformity.

Improving uniformity by adding anamorphic diffusion

In the case of line shaping using a cylindrical microlens array (MLA), the incident beam is divided into subbeams by the MLA subapertures. Whether the input beam is single mode or multimode, each subbeam closely resembles a plane wave, characterized by uniform amplitude and a flat wavefront. By incorporating a focusing lens, a single line-shaped beam image is formed through the interference of all subbeams. The inherent ordered structure of the one-dimensional MLA gives rise to an array of speckles with equidistant spacing, with typical size determined by the diffraction-limited spot size of the focusing optical system.

Multiple passive solutions were proposed to improve the uniformity of line shaping [4]. What all such solutions have in common is their basis of operation – to add disorder in each subbeam and then output intensity becomes a more randomized one-dimensional speckles with a better fill factor. The lower the temporal coherence of the beam the better the uniformity becomes since the efficiency of the interference creating the speckles is reduced. The highest uniformity achievable by using these concepts is still limited by the one-dimensional speckle physics – i.e, for sufficiently coherent beams, the interference will still create a ripple in the line with a certain amplitude, even if variations in these ripples along the line are eliminated.

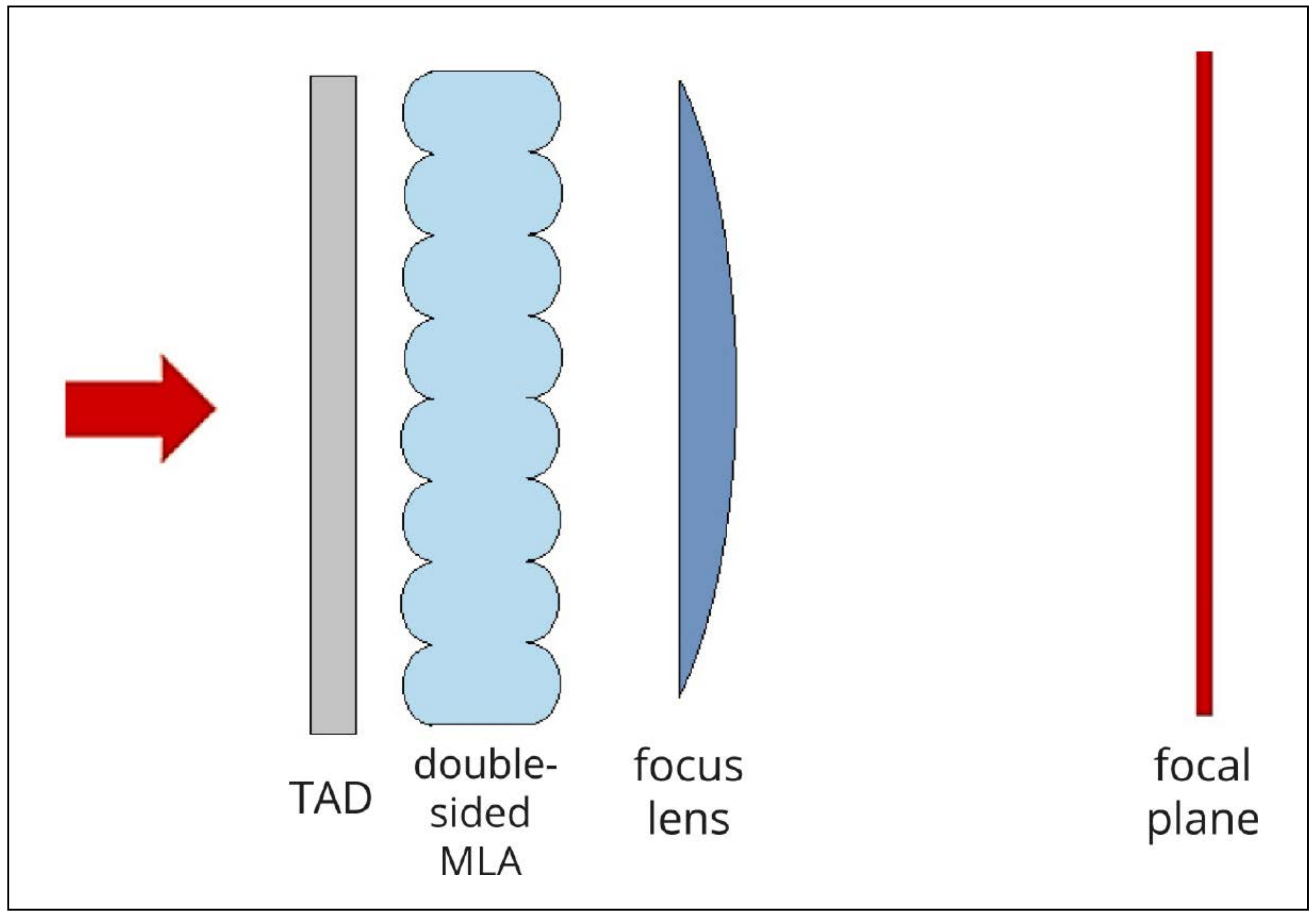

Fig. 2 Schematic optical setup of the case study, including collimated incident laser beam (red arrow), custom TAD, double MLA, focus lens, and output line shaped beam at focal plane of the lens

Here we introduce a novel approach for shaping partially coherent beams into line profiles using a tailored anamorphic diffuser (TAD) to improve the integrated intensity uniformity. A critical requirement of the design is to ensure that the line thickness and the transfer region in the long axis are increased as little as possible, and to a level that is acceptable for the intended application. To fulfill this requirement, the diffuser is designed with tailored diffusion angles for each axis, taking into account factors such as the laser beam quality (M^2), the beam size along each axis, and the numerical aperture (NA) of the microlens array.

To achieve improved uniformity, the optimum method is to introduce an average shift of laser modes approximately 45° relative to the line axis. This shift is necessary to generate random modes in both axes of the line and reduce interference intensity when integrating over the short axis. In practical implementation, we will adhere to an upper limit condition defined by the maximum diffusion angle that ensures an acceptable increase in line thickness while maintaining the desired level of uniformity.

The introduction of the tailored diffuser results in the manipulation of line short-range intensity, as illustrated in Fig. 1. In the left image of Fig. 1, the red circles represent the modes of the partially coherent beam generated along the line by a one-dimensional homogenizer. The intensity distribution is uniform along the short axis but not along the long axis.

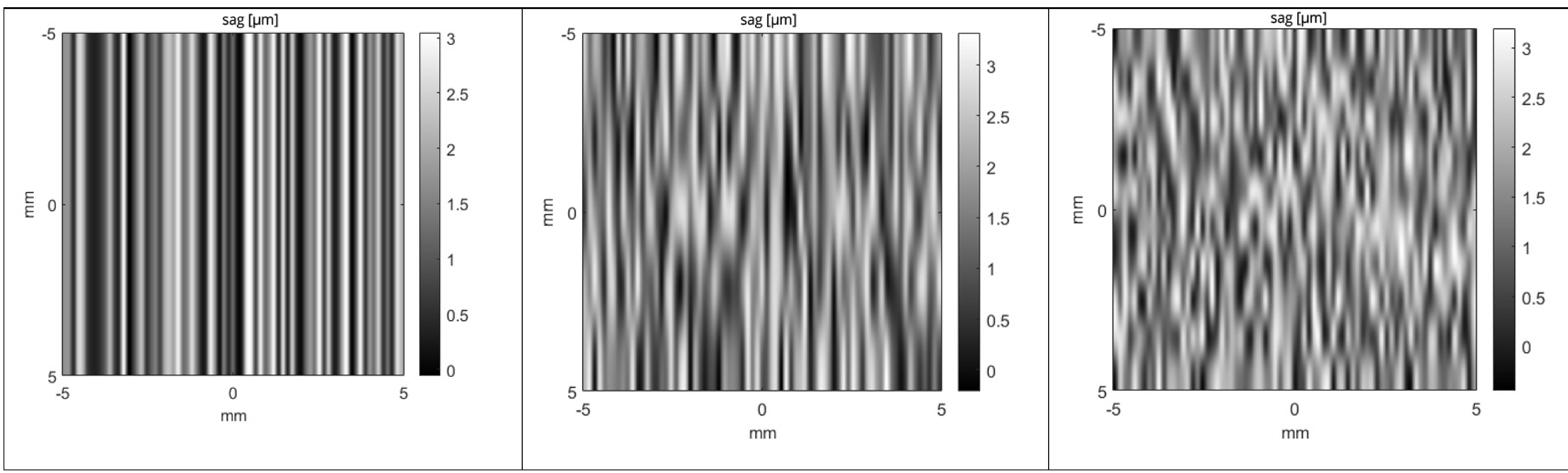

Fig. 3 Diffuser's sag map used for simulation, all diffusers have the same sag range. (a) one dimensional diffuser without optical effect in short axis (case 2). (b) TAD with tailored diffusion angle in short axis, much smaller that of the long axis (case 3). (c) same as b but doubled diffusion angle in short axis (case 4).

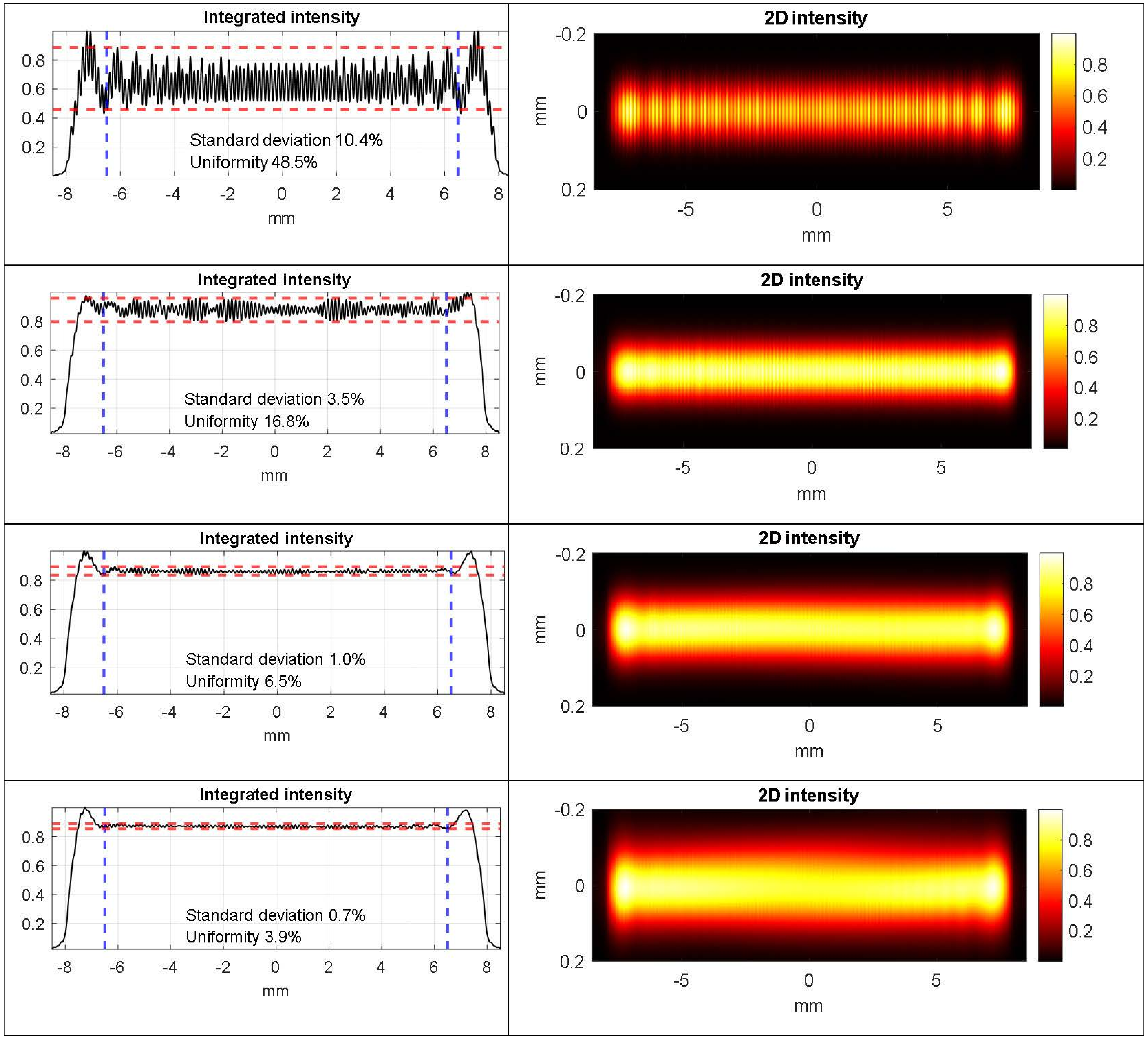

Fig. 4 Integrated and 2D intensity simulation for the four configurations. Top to bottom: standard double-sided lens array, double lens array with 1D diffuser, double lens array with TAD diffuser of 0.104° in narrow axis, double sided lens array with TAD diffuser of 0.208° in narrow axis

By employing a TAD that is specifically designed based on the laser beam's characteristics, such as beam size and M^2 value, it becomes feasible to make subtle adjustments to the intensity distribution. Consequently, the integrated intensity over the long axis exhibits significantly improved uniformity while preserving the thickness of the thin axis. This effect is demonstrated in the right image of Fig. 1.

Specific case study simulation

As a case study to show uniformity improvement we defined the design parameters:

Laser beam parameters:

wavelength 355 nm, beam size FWFM 5 mm, divergence 0.104°, and M^2 20.

Optical system parameters:

homogenizer (9.1° full angle) consisting of double cylindrical MLAs with pitch 0.25 mm and EFL 1.575 mm (ROC 0.75 mm), central thickness 2.3 mm Fourier lens with EFL 100 mm

Target performance:

Line dimensions 15.9 × 0.2 mm at exp(-2)

Fig. 2 presents a schematic diagram of the optical setup employed in this case study. The setup comprises three closely positioned optical elements: the tailored anamorphic diffuser, the MLA homogenizer, and the focusing lens. The output intensity is measured at the focal plane of the focusing lens.

For the purpose of simulation, a physical optics approach employing the Fresnel integral coherent propagation was utilized. This approach considers the free space between the focusing lens and the far field in the focal plane, using a single-mode Gaussian beam input. To showcase the effects of multimode behavior, a convolution method was applied to the coherent output intensity. This well-established technique allows for the demonstration of interference effects associated with partially coherent lasers.

The short axis divergence in the case study is calculated by the diffraction limit formula to be 0.104°. Assuming the upper limit of the line thickness is ~10 % deviation vs the diffraction limited line thickness, the added diffusion angle can be calculated by angular RMS sum between the incident beam divergence and the diffusion angle. The resulted divergence should be equal to 110 % of the incident beam divergence.

Thus, the diffuser's angle is:

$$\theta_{diffuser} = \sqrt{(1.1 \cdot 0.104)^2 - 0.104^2} = 0.048 \text{ [deg]}$$

For the long axis, the added diffuser's angle can be rather large and the limit is that focal spot of each sub beam will be smaller than pitch of the second MLA. A larger angle of diffuser in long axis weakly the affects the width of the edge of the line.

To show enhanced uniformity we simulated four different configurations of the optical system:

1) without an additional diffuser – just a double-sided lens array,
2) one dimensional diffuser,
3) TAD with same diffusion angle as in (2) for long axis,
4) same as (3) but with twice diffusion angle in the short axis

Fig. 3 displays the sag of the first lens array in each of the cases 2 – 4 used in the simulation

Intensity analysis

Fig. 4 displays the performance of the case study system for the four previously defined configurations. The left column represents the integrated intensity over the thin axis, while the right column illustrates the two-dimensional intensity distribution. As anticipated, the case 1 system with just a double-sided cylindrical lens array exhibits the strongest intensity fluctuations. The second configuration shows a significant improvement in uniformity, approximately three times better than the previous configuration, although the intensity fluctuations still exhibit a noticeable one-dimensional nature.

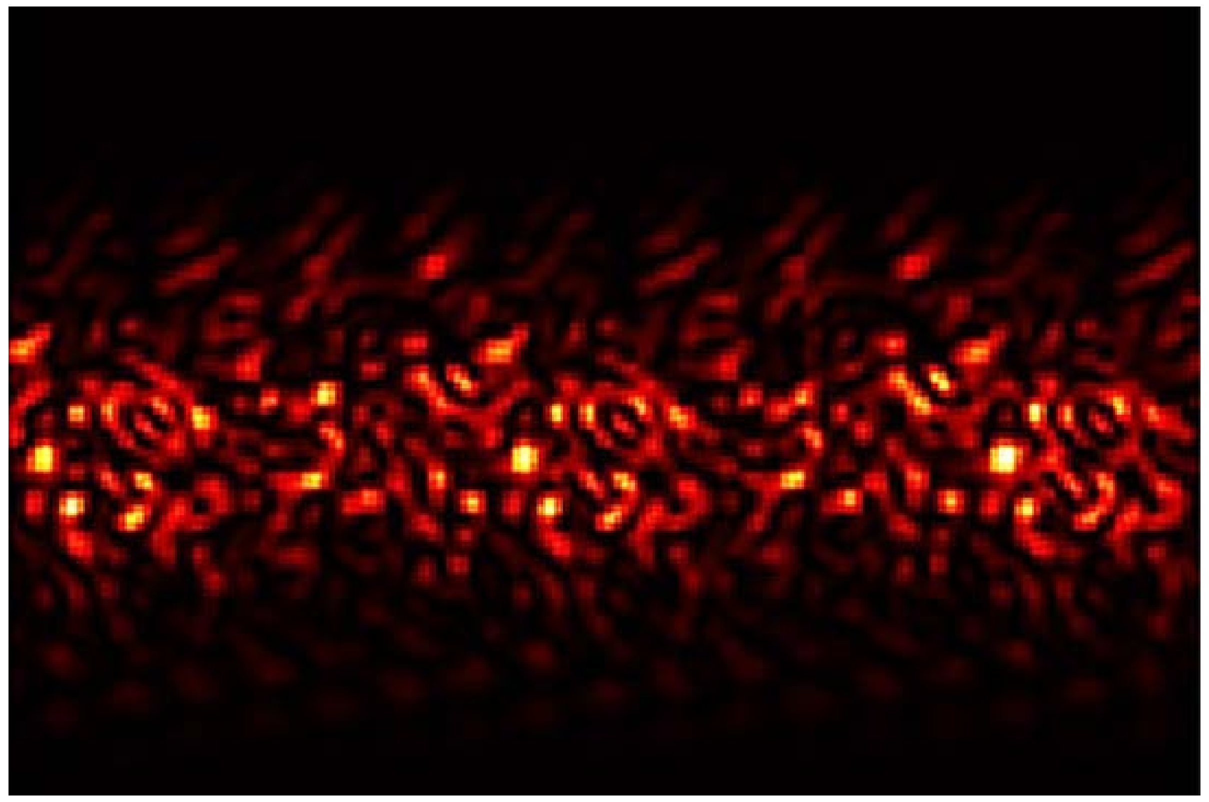

Fig. 5 Simulation – small section along the line shaped beam of the coherent randomly speckled intensity distribution generated by the TAD

In the third configuration, where the TAD is employed, another threefold enhancement in uniformity is observed compared to the second configuration, while still maintaining the line thickness within the specified limit. It is evident that the intensity distribution exhibits effective homogenization in both axes, without the presence of purely one-dimensional horizontal fluctuations observed in the first two configurations.

The last configuration demonstrates the potential to further improve uniformity at the expense of increasing the line thickness to approximately 250 µm.

When comparing the usage of just the homogenizer and the homogenizer with TAD, the improvement is notable. The standard deviation decreases from 10.4 % to 1 %, and the uniformity decreases 48.5 % to 6.5 % of the integrated intensity.

To provide a deeper understanding of the effect, Fig. 5 presents the intensity distribution of the perfectly coherent beam generated in the third configuration, prior to the application of convolution smoothing. It is observed that as the randomization and the average number of speckles along the vertical axis increase, the uniformity in the integrated intensity improves. This enhanced uniformity is directly proportional to the diffusion angle in the vertical axis.

Tailored line diffuser – experimental results

Based on the principles discussed above, we have designed and produced a double-sided lens array that incorporates a TAD surface together with one of the cylindrical MLA surfaces. This was realized using a greyscale lithography method followed by ICP etching to transfer the pattern from the photoresist into the glass.

The pitch chosen was 227 µm, with an effective focal length EFL set to focus on the second side of a fused silica substrate with thickness 2.29 mm, resulting in a diffusion angle of 6.5°. The TAD diffuser component of the first lens array surface was calculated to generate an angle of 0.11° in the narrow axis and 1.1° in the long axis.

The resulting line diffuser was characterized by illuminating it with an $M^2 = 1.5$, 633 nm laser with beam diameter 4 mm, and focused directly into a camera. Two lenses were used – a strongly aberrated biconvex lens with EFL = 30 mm (to observe the entire line in the camera field) and a plano-convex EFL = 150 mm lens for precise measurements of line uniformity and edge sharpness.

From the measurement at EFL = 150 mm, line width was estimated as 0.116°, quite close to designed line width.

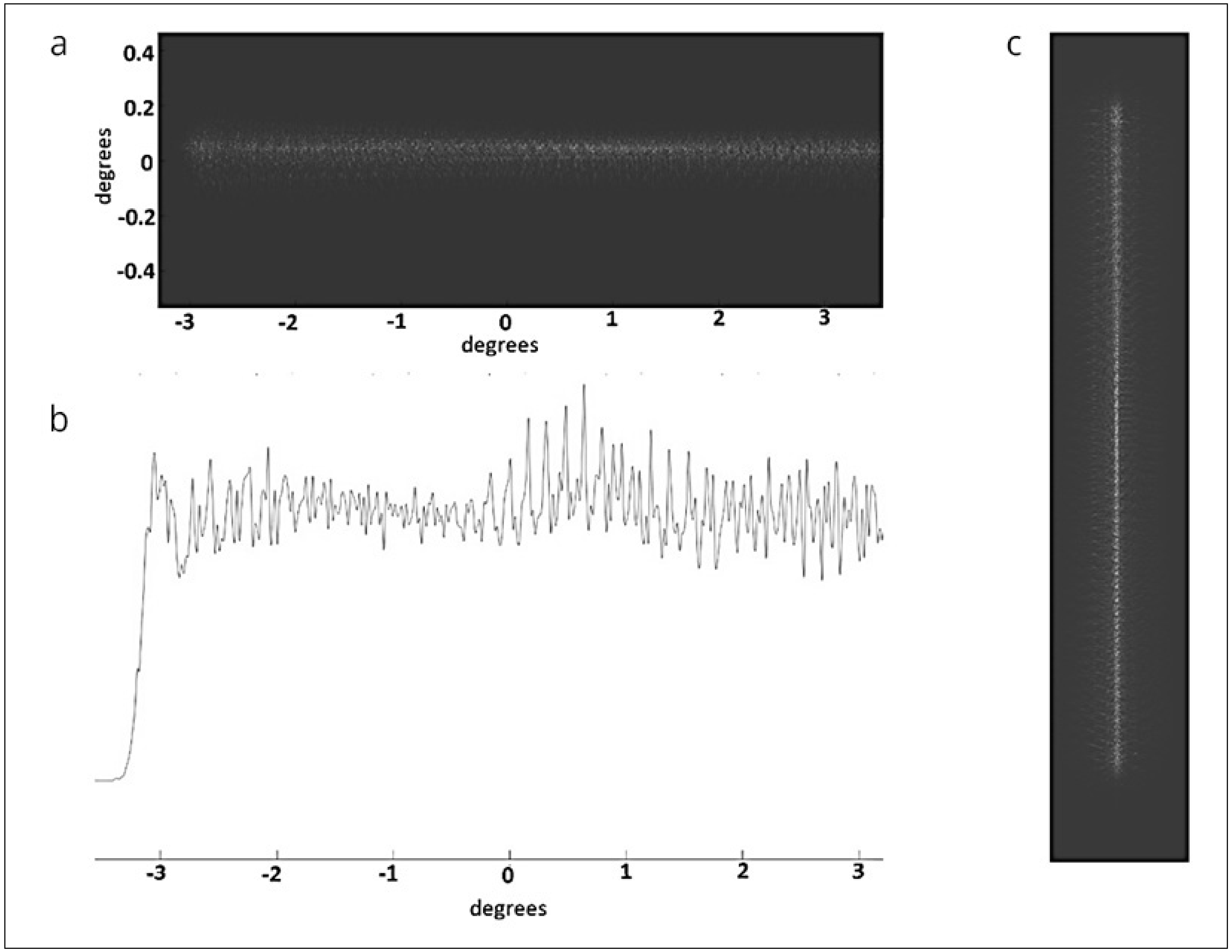

Fig. 6 Measured line of TAD double sided cylindrical lens array diffuser, (a) intensity with EFL = 150 mm lens, (b) full line with EFL = 30 mm lens, (c) integrated intensity profile of (a), integrated over line width

Conclusions

This article has addressed the challenge of improving intensity uniformity in laser beam shaping into line profiles, for partially coherent laser sources. Through the utilization of a tailored anamorphic diffuser, significant improvements in integrated intensity uniformity have been achieved, surpassing the limitations of existing methods.

The comparative analysis demonstrated the advantage of the proposed diffuser. The tailored anamorphic diffuser offers enhanced control over intensity distribution, enabling uniform laser line profile, by considering specific laser beam quality factor value. This theoretical improvement was observed in real experimental result of double sided lens arrays incorporating TAD which showed an integrated intensity profile that has a significantly improved uniformity (peak to average ~15 %) compared to a standard double sided lens array.

The findings of this study open up new possibilities for the development of high-performance laser systems with enhanced precision and efficiency in a wide range of applications, including laser lift-off, laser inspection and detection, and biomedical imaging applications.

[1] R. Delmdahl, R. Paetzel, J. Brune, R. Senczuk, C. Gossler, R. Moser, M. Kunzer, U. Schwarz: Line beam laser lift-off approach for sapphire removal, ICALEO 2012 - 31st International Congress on Applications of Lasers and Electro-Optics, 852-859, DOI: https://doi.org/10.2351/1.5062551

[2] R. Delmdahl, R. Pätzel, J. Brune: Large-Area Laser-Lift-Off Processing in Microelectronics, *Physics Procedia* 41, 2013, pp. 241-248, https://doi.org/10.1016/j.phpro.2013.03.075

[3] O. Haupt, J. Brune, M. Fatahilah, R. Delmdahl: MicroLEDs: high precision large scale UV laser lift-off and mass transfer processes, Proc. SPIE 11989, Laser-based Micro- and Nanoprocessing XVI, 119890I (4 March 2022), https://doi.org/10.1117/12.2610137

[4] Y. Mizuyama, N. Harrison & Riccardo Leto: Despeckling fly's eye homogenizer for single mode laser diodes, *Opt. Express* 21, 9081-9090 (2013), https://doi.org/10.1364/oe.21.009081