

BEAM SHAPING OF FOCUSED BEAMS FOR MICROPROCESSING APPLICATIONS

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1. Abstract

Beam shaping of focused laser beams to control intensity distribution in a laser spot is important optical task in various micromachining applications like scribing, PCB drilling and others. Developing of workable optical solutions is based on diffraction theory, and one of important for practice conclusions is that flat-top intensity profile in focal plane of a focusing lens is created when the input beam has Airy-disk intensity distribution. To meet requirements of modern microprocessing machinery the beam shaping optics should be capable to operate with CW and ultra-short pulse lasers, popular F- Θ lenses and microscope objectives, galvo scanners, 3D scanning systems. All these requirements were taken into account and fulfilled while developing refractive field mapping beam shapers Focal- π Shaper, realizing optical approach to optimize conditions of interference near the focal plane and providing variety of profiles: flat-top, donut, inverse-Gauss. Other important features are: extended depth of field similar to Rayleigh length of comparable TEM₀₀ beam, easy integration in industrial equipment, simple adjustment procedure and switching from one profile to another. Flexibility of refractive design allows implementing not only telescopic but also collimating beam shapers compatible with TEM₀₀ fiber lasers. There will be considered design basics of refractive beam shapers, examples of implementations, results of profile measurements and material processing.

2. Introduction

The beam shaping optics becomes more and more popular in various laser applications; at the same time many technical solutions used in industrial laser machinery are based on applying scanning optics as versatile tools of material structuring, image recording, drilling, etc. Usually the optical systems with scanning mirror optics presume working with collimated laser beams entering the 2- and 3-axis galvo mirror scanners, and the focusing is provided by various F-theta lenses. It is well-known that focusing of a laser beam allows creating very small spots required in microprocessing applications; therefore transformation of intensity profiles of focused beams has great importance. As a solution it is suggested to apply refractive field mapping beam shapers, which principle of intensity profile transformation is based on careful manipulation of wave front of a beam with conserving the beam consistency. This approach allows creating a beam, which intensity distribution and phase front are prepared to be transformed to flat-top, inverse-Gauss or donut spots when focused by a diffraction limited lens. Since modern microprocessing applications presume applying of scanning optics we will consider beam shaper designs optimized to be applied just with scanners.

3. Intensity Profile Transformation by Focusing: Theoretical considerations

Focusing of laser radiation by a lens provides concentration of laser energy in a small, typically several microns or tens of microns, laser spots. To provide such small spots, comparable with wavelengths, the focusing lenses should have diffraction limited image quality over entire working field, i.e. the residual wave aberration should be less than quarter of wavelength [4].

Behaviour of laser beam profile in zone of focal plane of a focusing lens is an important issue to be considered for practice. This analysis can be done on the base of diffraction theory, which description can be found in books [1-4], here we emphasize on some important for further consideration features.

The Huygens-Fresnel Principle is the corner stone of the diffraction theory. According to that principle each point of a wave front can be considered as a center of a secondary spherical wavelet and by the light propagating in space the distribution of light in a particular plane or a surface can be defined as result of interference of those secondary wavelets. The rigorous mathematical theory for considering the diffraction effects was built by Kirchhoff, Helmholtz, Maxwell and other scientists in 19th century, for example, usually considerations concerning particular optical effects start from so called Fresnel-Kirchhoff diffraction formula [2]. Since the integral equations of mathematical description are quite complicated and impractical for engineering purposes there are used various simplifications like Fresnel approximation or Fraunhofer approximation [2,3].

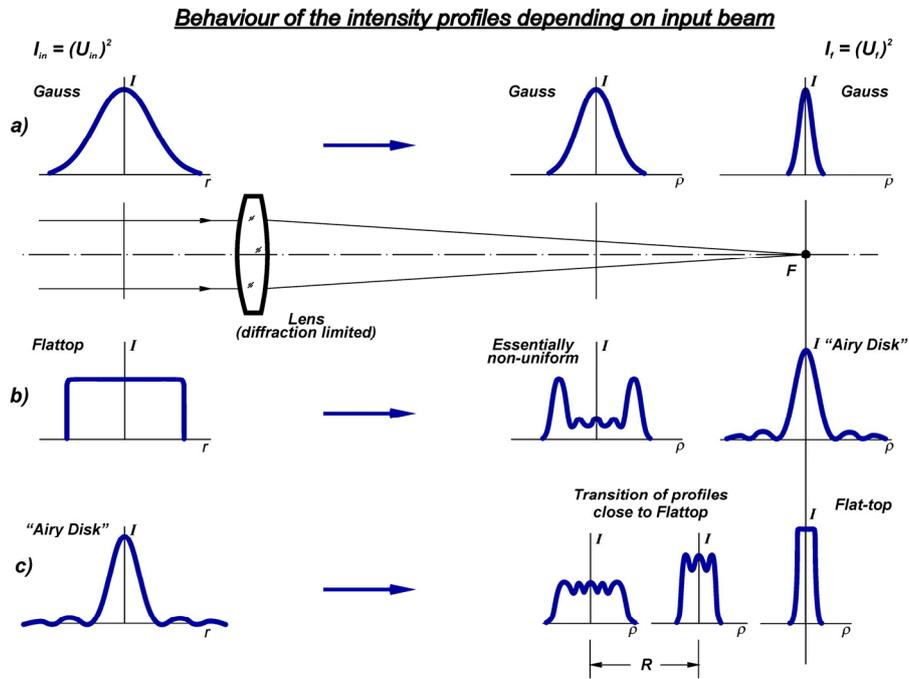


Fig. 1 Focusing of various laser beams by a lens.

case of a focal plane of a lens is proportional to Fourier-image of input field amplitude distribution; examples of this transformation are shown in Fig. 1 and will be considered later. Summarizing analytical considerations concerning the Fourier transform by an optical system of circular symmetry one can express, in polar coordinates, the field amplitude distribution U_f in the lens focal plane by equation

$$U_f(\rho) = B \int_0^{\infty} U_{in}(r) J_0(2\pi r \rho) r dr \quad (1)$$

where U_{in} is field amplitude at the lens input, ρ is polar radius in the lens focal plane, r is polar radius at the lens input, J_0 is the Bessel function of the first kind, zero order, B is a constant. This expression is accordingly referred to as the Fourier-Bessel transform, or alternatively as the Hankel transform of zero order.

In most of laser technologies the result of influence of the laser radiation on material is evaluated with using intensity distribution of a beam. Therefore, for practical usage it is necessary to express the intensity distribution I_f in the focal plane of a lens through the function of field amplitude, for this purpose the well-known relationship [2] can be used

$$I_f(\rho) = [U_f(\rho)]^2 \quad (2)$$

Just the intensity distribution I_f is shown in Fig. 1 where examples of beam profile transformation are depicted.

The case of a beam focusing by a lens has great importance in considering the optical effects in various laser technologies since this is a mostly used way to create laser spots of a necessary size on a workpiece. Usually, analyzing the beam intensity profile in the focal plane of a lens is quite enough; especially when propagation TEM₀₀ laser beams is investigated. However, when an optical system contains beam shapers and intensity distribution transformation while the light propagating becomes more complicated it is necessary to consider intensity profile behavior in other zones of optical system as well, for example very important is the zone surrounding the focus of a lens.

Since the Fourier-transform is just a special case of intensity distribution description being valid for focal plane of a lens only, a complete detailed analysis of the beam profile behavior in zone of the lens focus requires applying of general mathematical descriptions of diffraction theory, for example the already mentioned Fresnel-Kirchhoff diffraction formula. Usually that interference analysis requires quite intensive mathematical computations, using special software for optical calculations. Let us omit the cumbersome mathematical computations and present here results of calculations for the cases most interesting for the practice of laser technologies:

- focusing of a TEM₀₀ (Gaussian) laser beam,
- focusing of a flat-top beam,
- creating a flat-top spot in zone of lens focus.

The results of analysis of intensity profile transformation for these cases are presented in Fig. 1 in form of graphs.

According to the Huygens-Fresnel principle, the intensity distribution in a plane of analysis is result of interference of secondary wavelets. Evidently, while the beam propagating in space the conditions for interference get changes and, hence, that pattern

varies in different planes of analysis. In other words, *in each plane after the lens the intensity profile differs from one of a neighbor plane, and features of this profile variation depends on the initial beam profile at the entrance of the lens.*

The example a) in Fig. 1 corresponds to TEM₀₀ or Gaussian beam being most popular in laser technics, the initial intensity distribution is described in polar coordinates by equation

$$I_{in}(r) = I_{in0} e^{-2r^2/\omega_0^2} \quad (3)$$

where I_{in} is intensity at the lens input, ω_0 is a waist radius of the Gaussian beam, I_{in0} is a constant.

Focusing of such a beam with a diffraction limited lens leads to creating near focal plane a spot with, again, Gaussian intensity distribution and diameter d defined by the equation

$$d = 2\omega'_0 = \frac{2\lambda f}{\pi\omega_0} M^2 \quad (4)$$

where λ is the wavelength, ω_0 is waist radius of focused beam, f is the lens focal length, M^2 is laser beam quality factor.

Essential feature of focusing the Gaussian beam is that its intensity profile stays just Gaussian over all distance of the beam propagation, only size is varying! Result of interference for an intermediate plane (between lens and focal plane) is again the Gaussian intensity profile; this is a well-known feature widely used in laser technics,

But this brilliant feature is valid for Gaussian beams only! In case of any other profile the intensity distribution behavior differs.

This is very good seen in diagrams of the example b), Fig. 1 corresponding to the flat-top initial beam. It is a well-known conclusion of diffraction theory, described in all literature sources by considering photo or astronomic optics, that in the focal plane the intensity I_f is described by the function called as the Airy Disk

$$I_f(\rho) = I_{f0} \left[\frac{J_1(2\pi\rho)}{2\pi\rho} \right]^2 \quad (5)$$

where J_1 is the Bessel function of the first kind, first order, I_{f0} is a constant.

In the space between the lens and its focal plane the interference pattern gets strong variation both in size and in intensity distribution. One can see an essentially non-uniform profile corresponding to intermediate plane of analysis; it differs both from Airy Disk and flat-top functions and is, evidently, useless for practical applications.

As we see the focusing of a flat-top beam never leads to creating a spot with uniform intensity, neither in focal plane nor in intermediate planes:

If an application needs a laser spot of uniform intensity (flat-top or top-hat), no sense to focus a flat-top beam!

This doesn't mean, however, that a flat-top collimated beam cannot be used to create a small laser spot of uniform intensity. When an imaging approach (not focusing!) is applied, it is possible to create flat-top spots of several tens of μm size using imaging optical systems combined from scanning optics and additional collimating system. This technique is out of scope of this paper, some details and examples of imaging in scanning optics are considered in [6,7].

The beam focusing layout c) in Fig. 1 corresponds to very important for practice case of creating a small laser spot with uniform intensity profile just in the lens focal plane. Realizing this approach requires solving of the inverse problem – which intensity distribution should be at the entrance of a lens in order to get a flat-top spot in focal plane? This problem was, for example, discussed in paper [5]. Mathematical computations based on the inverse Fourier-transform technique give a solution that the input beam to have the intensity distribution described just by Airy Disk function, analogous to formula (5) with input beam radius r instead of ρ . Thus, *to generate a flat-top laser spot in the focal plane of a lens the input beam should have essentially non-uniform intensity distribution described by Airy disk function.*

Further analysis shows that the interference pattern in the space between the lens and its focal plane isn't constant; it gets variation both in size and in intensity distribution and flat-top and close to flat-top profiles are created not only in the focal plane but in some regions in space between the lens and its focal plane. Thus, the flat-top profile in focal plane is just a special case of the continuous variation of intensity distribution and, as will be shown later the optimum, from the point of view of practice, working planes are shifted from the focal plane towards the lens. Creating of the beam with Airy Disk intensity distribution is the function of the field mapping beam shaper *Focal- π Shaper* that operate as telescopic optical systems and can be easily integrated in optical layouts with scanning optics.

4. Beam Shaping of focused beams

We discuss in this chapter refractive field mapping beam shaping optics intended to realize the above considered optical approach of creating flat-top spot in focal plane: basic design, features of using the beam shapers and some practical advices.

4.1 Optical design of Focusing Beam Shaper

The refractive field mapping beam shapers like *Focal- π Shaper* provide at the output a beam which intensity distribution is described by Airy Disk function that is an optimum one to create in focal plane of a focusing lens spot with flat-top, inverse-Gauss or donut profiles. Basic idea of the beam shaper operation is shown in Fig. 2.



Fig. 2 Principle of the *Focal- π Shaper* operation.

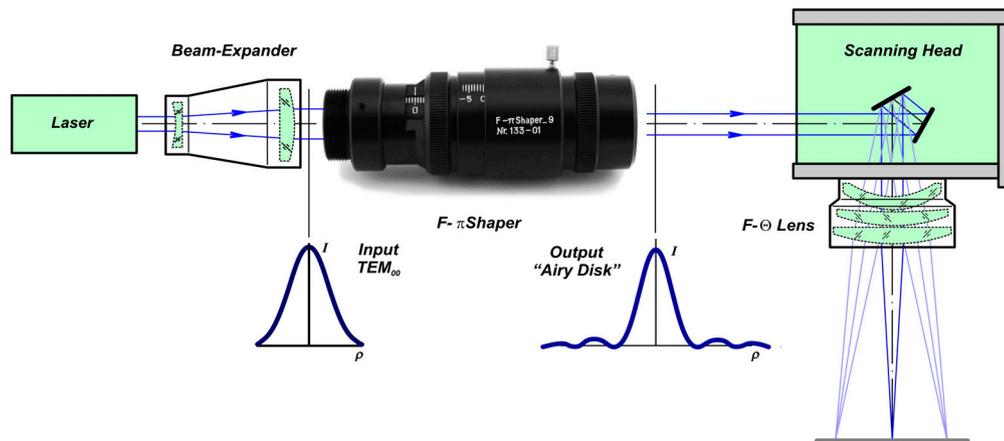


Fig. 3 Optical system with *Focal- π Shaper* and scanning optics.

Most important features and basic principles of the *Focal- π Shaper* are:

- telescopic refractive optical systems transforming the Gaussian to Airy Disk intensity distribution;
- flat-top, donut, inverse-Gauss and other profiles can be generated by the same device;
- operation with input TEM_{00} beams;
- operation in a certain spectral band;
- optical design without internal focusing;
- movable optical components are intended to optimize the final spot profile and to bring the plane of optimum profile in the working plane;
- compact design;
- easy integration to an optical setup and adaptation to a laser source;
- operation with any diffraction limited focusing lens;
- wide range of distances between the *Focal- π Shaper* and the lens.

Example of optical layout of focusing the laser beam with using the *Focal- π Shaper* and scanning optics is presented in Fig. 3. Since the *Focal- π Shaper* operates as a telescope with magnification about 1^x it can be easily integrated in existing equipment. The beam in space between the *Focal- π Shaper* and scanning head is collimated. On the other hand, due to careful handling with wave front in the beam shaper the output profile is stable over long distance. Therefore, the distance between the *Focal- π Shaper* and the focusing lens isn't critical; it can be chosen once but should be invariable during the system operation. Varying the beam size at the *Focal- π Shaper* entrance leads to variation of resulting intensity profile of the final spot, therefore, varying the beam size ahead of the *Focal- π Shaper* is a good mean to provide flat-top, donut and inverse-Gauss profiles. Choosing the plane of optimum profile and bringing it to the working plane of existing equipment is realized by internal focusing of the *Focal- π Shaper*. Thus, the beam shaper the system can be quickly adjusted.

4.2 Beam profile behaviour

The behavior of intensity distribution of a light beam is described by diffraction theory and in common case the intensity is variable when a beam propagation in space: both beam size and its intensity profile are variable. A special case is just the TEM_{00} beam: the Gaussian profile stays stable and only size is variable.

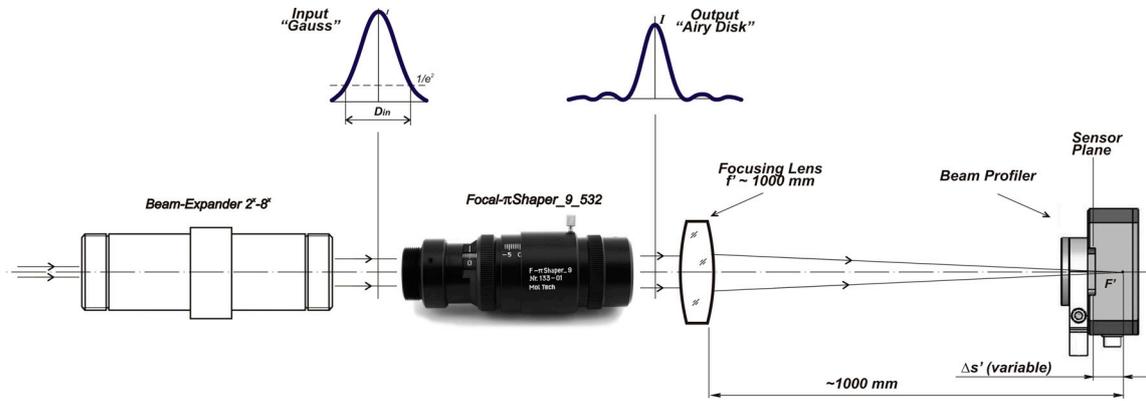


Fig. 4 Experimental optical layout to measure intensity profiles near the lens focal plane.

Since the output beam from the *Focal-πShaper* has not Gaussian but Airy disk distribution its behaviour has to be analysed using the Kirchhoff integral [2,3]. We present in this paragraph comparison of results of theoretical and experimental researches of intensity profile transformation near the focal plane of a lens. The Fraunhofer approximation of the Fresnel-Kirchhoff diffraction formula was used for theoretical calculations; experimental measurements of intensity distributions were made using a camera-based beam profiler.

The experimental setup is presented in Fig. 4: the TEM₀₀ laser beam of $\lambda = 532$ nm is expanded up to $1/e^2$ diameter D_{in} at the *Focal-πShaper* entrance. Output beam with Airy disk intensity distribution is then focused by a lens of 1000 mm focal length, so the resulting laser spots have size of several hundred μ m and can be caught by a camera-based beam profiler. Typical view of measured intensity distributions are shown in Fig. 5: top - Gaussian beam from the laser, middle - expanded beam at the *Focal-πShaper* input, bottom – beam shaper output with a characteristic ring around the central spot – this is typical pattern just for the Airy disk beams.

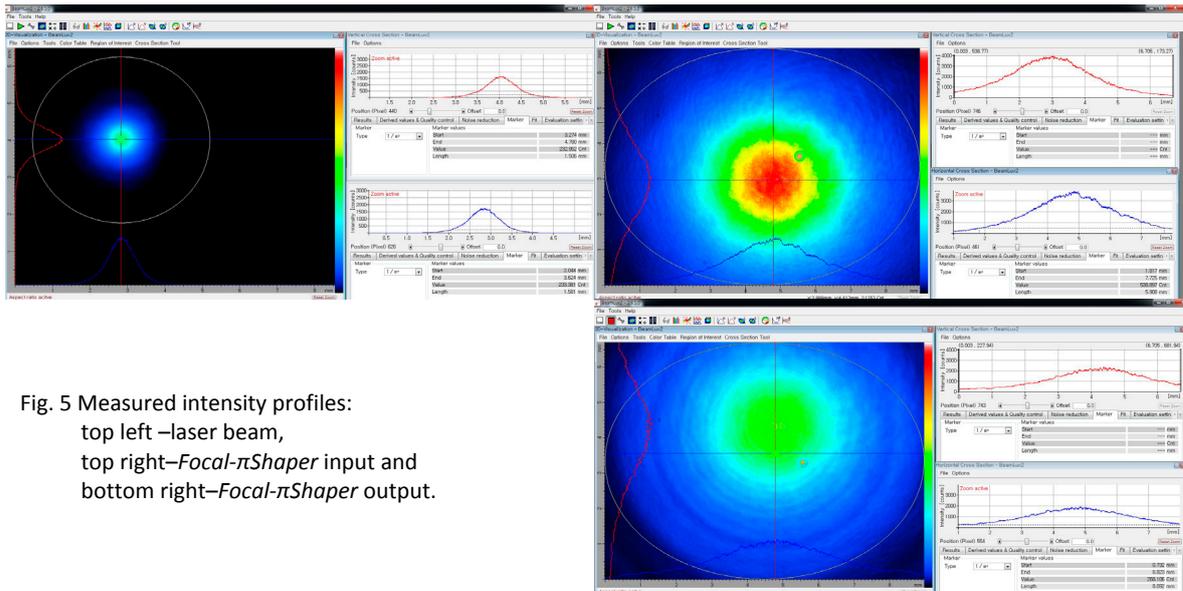
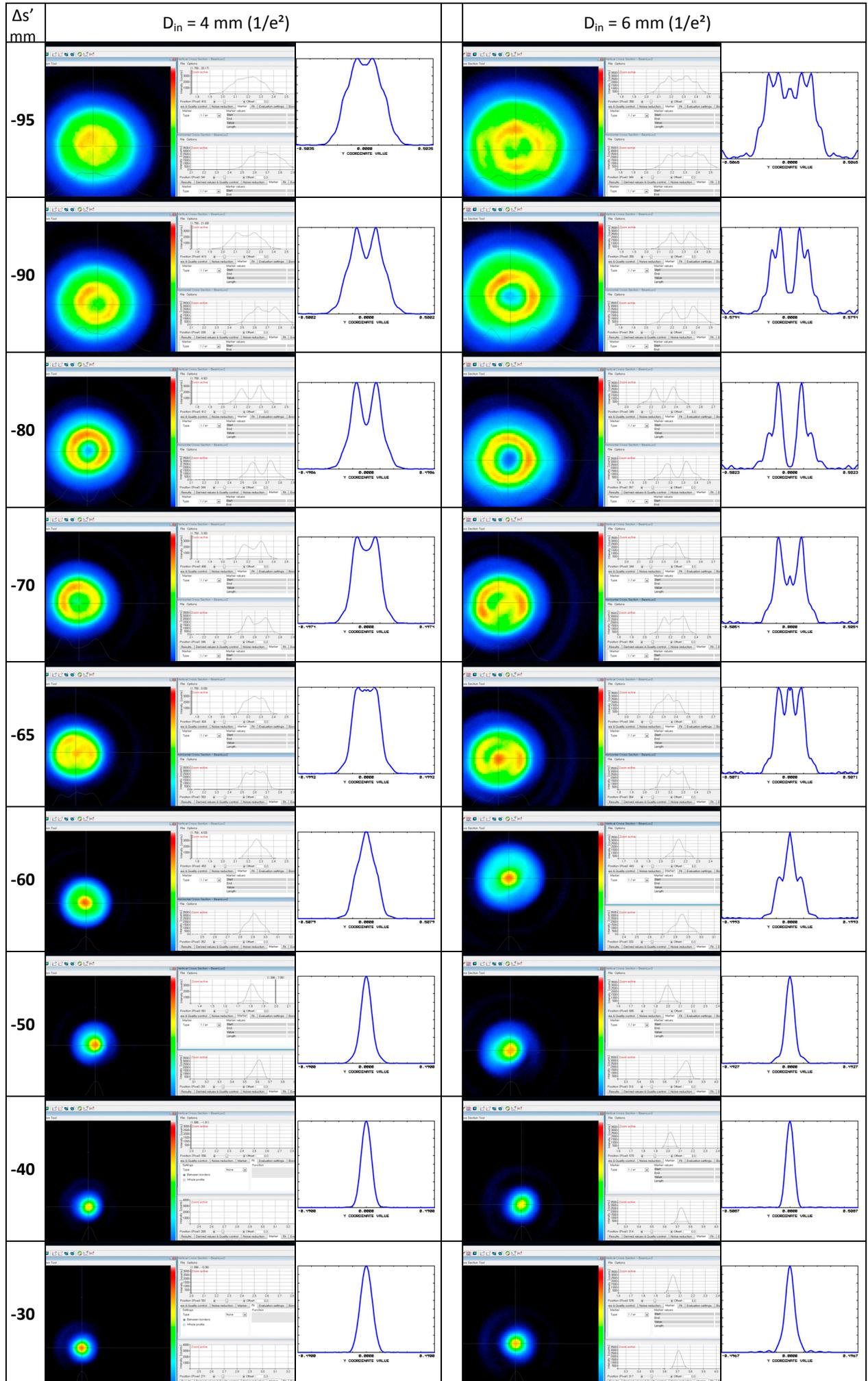


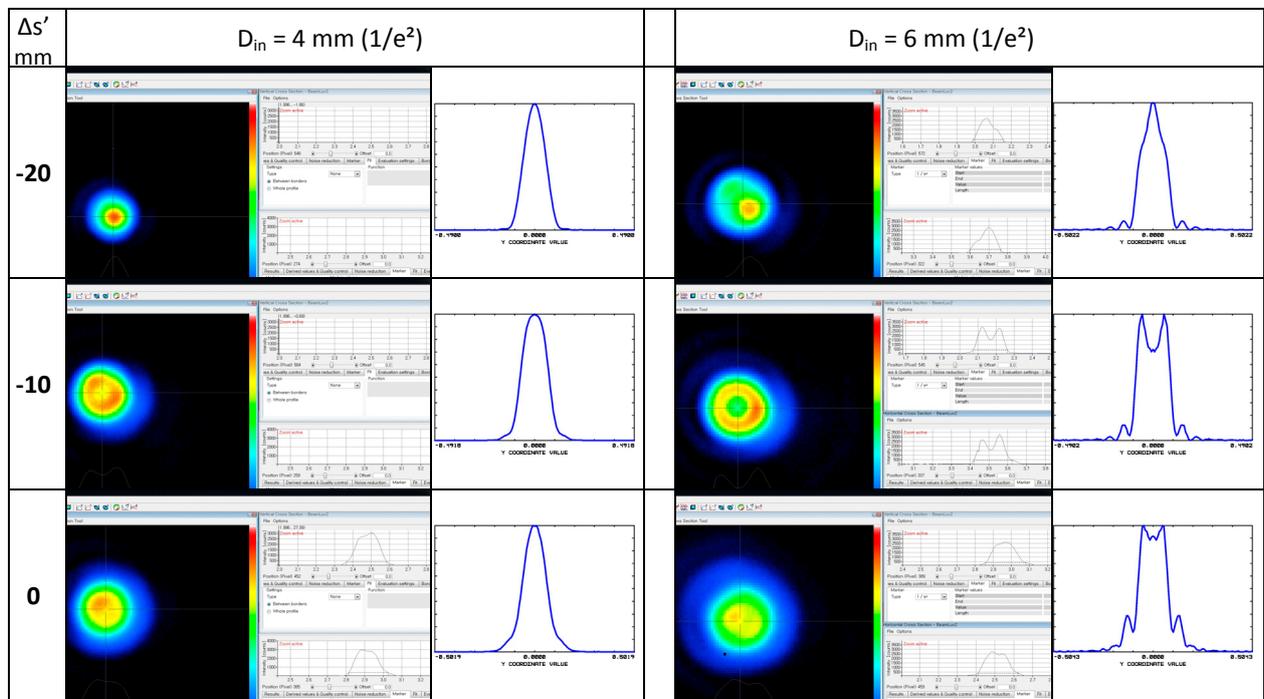
Fig. 5 Measured intensity profiles:
top left –laser beam,
top right–*Focal-πShaper* input and
bottom right–*Focal-πShaper* output.

The measurements of intensity distributions are conducted for input beams with $1/e^2$ diameter $D_{in} = 4$ and 6 mm, the experimental distributions are combined with theoretical calculated normalized profiles and presented in Table 1 for shifts $\Delta s'$ from focal plane. These data allow making some important conclusions about the intensity distribution behavior near the lens focus.

Comparing to an ordinary Gaussian laser beam, which size changes by focusing but intensity distribution stays unchanged and is described by the Gaussian function, the Airy beam is characterized by variation of both size and profile. According to the Huygens-Fresnel principle the intensity distribution in a certain plane is result of a beam interference: in case of Gaussian beam the result is just the Gaussian beam (the Gaussian function is the eigen function of diffraction integral), but in case of a beam after the beam shaper one can observe a sequence of interferometry patterns, and one of them is just a spot with uniform intensity is created in the lens focal plane.

Table 1 Comparison of experimental and normalized theoretical intensity distributions





One should note here that correct analysis approach presumes considering of generalized light beams and characteristics of optical systems. There are some features that are very important for further considerations:

- focus is a characterizer of a lens, one can say that the focus “belongs” to the lens, not to the beam,
- waist of Gaussian beam characterize the Gaussian beam itself (i.e. “belongs” to the beam) and the waist of a focused beam is usually close the lens focus; it is considered in practice that the beam waist coincides with the lens focal plane – this approximation is valid for lasers with short wavelengths, typically less than 2 μm , but should be always checked when longer wavelengths, for example, for CO₂ lasers,
- location of the waist of a general beam should be defined by analysis of beam profile along the optical axis; for example, as will be shown further, the waist of a focused Airy beam is shifted to the focusing lens.

The data of Table 1 show good correspondence between theoretical and experimental data, let’s consider some characteristic features of beam profile behavior.

According to the *Focal- π Shaper* design the input beam to be Gaussian with 6 mm 1/e² diameter, therefore we consider first the data of right columns of the Table 1. The profile in the lens focal plane, corresponding to position $\Delta s' = 0$, is close to flat-top. Since the beam shaper provides approximation of Airy beam the theoretical resulting profile has some deviation from a perfect flat-top in form of side-lobes, while the experimental data with real laser demonstrate a flat-top spot without side-lobes but with some smoothness of spot edges, the central part of spot has uniform intensity.

When shifting the observation plane (moving the camera beam profiler) closer to the lens, the spot size is getting smaller and the intensity distribution is transformed to Gaussian-like function. In particular example the spot in position $\Delta s' = -40$ has minimum diameter and presents the waist of the focused beam. By further shifting of the camera one can see homogenized profiles in positions $\Delta s' = -65$ and $\Delta s' = -95$, as well as with inverse-Gauss and donut profiles in intermediate positions $\Delta s' = -70$ and $\Delta s' = -80$. This profiles sequence “Gaussian-like - homogenized – donut – homogenized” repeats when further moving to the lens, however the spot size is growing as well, and those big spots are rarely interesting in practice and aren’t considered here. Similarly we don’t consider profiles behind the lens focus since that part of focused beam is divergent, the profiles aren’t stable and energy is spreading rapidly.

Evidently, the intensity distribution in zone of a lens focus experiences strong transformation due to essential variation of the beam phase front – the beam changes from convergent to divergent, and the front curvature is extremely high in focal plane [3]. As result the profile created in the focal plane is not stable, it is rather an interesting mathematical solution, but most often it is difficult to use that spot because of short depth of field. As will be shown later the profile in a lens focal plane becomes even more unstable in case of astigmatic laser beams that is typical for solid-state lasers. Therefore, it is usually recommended in practice to operate with spots in planes shifted to the lens where profile transformation is smoother and there exist not only homogenized profiles but also donut and inverse-Gauss that are very important in applications like welding, selective laser melting where uniform temperature profile on a workpiece is optimum.

In order to formulate practical recommendations to work with focused Airy beams we suggest to consider Fig. 6 with schematic presentation of intensity distribution transformation in two cases of beam 1/e² diameter at the *Focal- π Shaper* entrance: 6 mm and 4 mm.

4.3 Laser Beam Expansion by an Auxiliary Lens

As shown in previous paragraph variation of input beam size leads to variation of resulting profile – this is a known feature of field mapping beam shapers like *Focal- π Shaper* [1]. And providing an optimum beam diameter is important while building optical systems of research setups or equipment.

A widely used approach to changing the laser beam size is applying of a beam expander. There are many commercially available models, including fixed and zoom beam expanders, motorized versions. To regret the strong competition among the beam expander manufacturers forces to reduce production costs that is achieved often through simplifying the optical design. For example, the optical systems are properly corrected to operate with axial beam only; therefore there might appear strong aberrations like coma while a beam expander tilt or internal misalignment of optical components. This isn't so "painful" when working with Gaussian beams, because due to the nature of laser radiation the energy is concentrated in a beam centre, so a Gaussian laser beam "forgives" imperfections of optical systems applied. But in case of beam shaping and careful handling with beam wavefront it is necessary to avoid any sources of wave aberrations.

Example of beam expansion of a laser beam using a commercial beam expander is presented in Fig.7.

There is evident distortion of profile in output beam that will influence on resulting intensity distribution by beam shaping of focused beam.

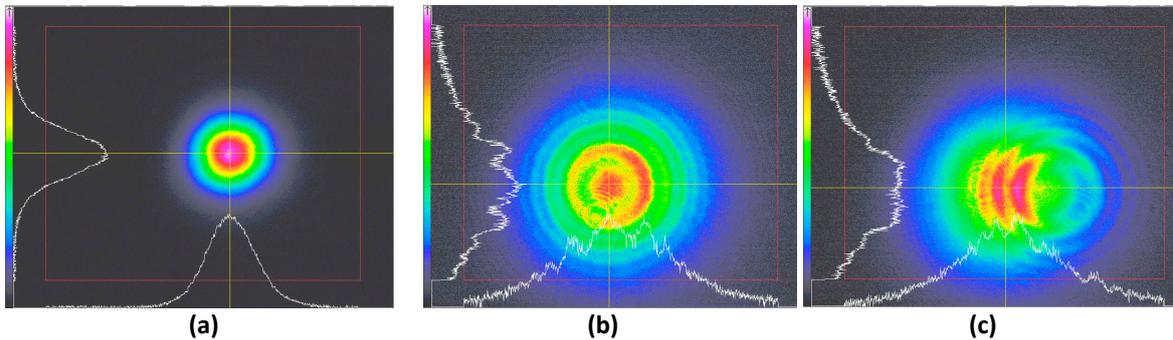


Fig. 7 Profiles by expansion of TEM_{00} laser beam using a beam expander:
(a) input beam, (b) output of *centered* and (c) *slightly tilted* expander.

Therefore, when possible it is recommended to skip using a beam expander ahead of a beam shaper.

Very often by building an optical system of industrial equipment or a research setup it is possible to provide certain space between a laser and a beam shaper. This space can be used to correct the beam size by providing corresponding beam divergence: partially due to natural divergence of laser beam, partially by applying an auxiliary lens at the laser output. This approach is illustrated by layouts in Fig. 8.

Suppose a beam at a laser output has diameter D and divergence 2θ ; we consider here values at $1/e^2$ intensity and D relates not to waist but to beam size at laser exit. The required beam diameter for a beam shaper is D'' , and the distance between the laser and the beam shaper is L . Due to the natural divergence the beam has diameter D' at the beam shaper entrance, so the auxiliary Lens has to introduce certain additional divergence in order to provide the divergence angle $2\theta'$. One should note, the beam shaper has to be capable to compensate this resulting total input divergence angle $2\theta'$, then the maximum allowed angle $2\theta'$ is defined by the beam shaper specifications, in *Focal- π Shaper* it is ± 5 mrad, under some conditions ± 10 mrad.

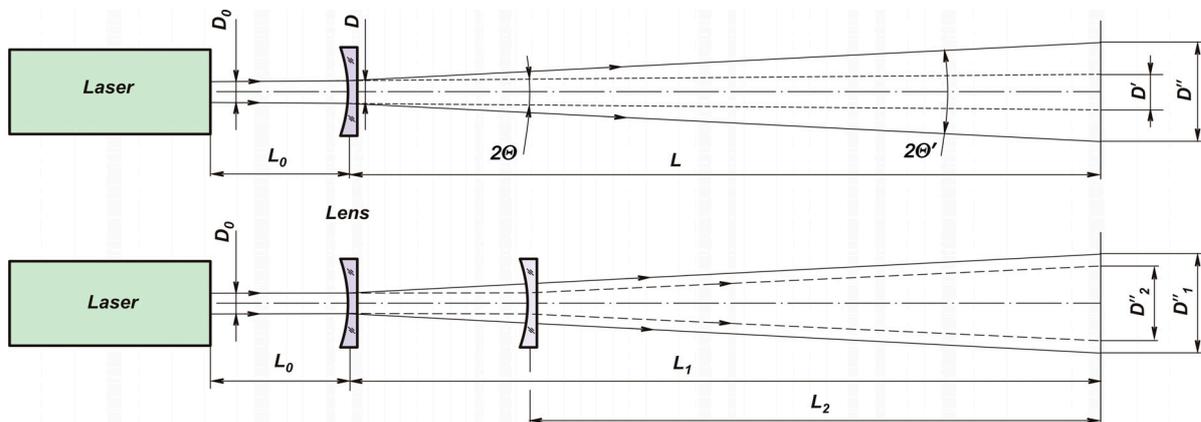


Fig. 8 Layouts to correct beam size using an auxiliary lens.

From the geometry of rays in Fig. 8, one can write

$$2\Theta' = \frac{D'' - D}{L} \quad (8)$$

$$f' = \frac{DL}{D + 2\Theta L - D''} \quad (9)$$

where f' is the focal length of the auxiliary lens.

The Eq. (8) allows evaluating required full divergence angle and check whether this correction approach is realizable with a particular beam shaper. The Eq. (9) is used to calculate the Lens focal length.

Let's consider examples:

- 1) Laser output: $D = 1$ mm and $2\Theta = 3$ mrad (waist $2\omega = 0.5$ mm inside laser, $M^2 = 1.1$); available length $L = 1000$ mm; required $D'' = 5$ mm (for *Focal- π Shaper 9*); then $2\Theta' = 4$ mrad – acceptable by the beam shaper, $f' = -1000$ mm.
- 2) Laser output: $D = 8$ mm and $2\Theta = 0.2$ mrad; length $L = 600$ mm; required $D'' = 5$ mm; then $2\Theta' = 5$ mrad – acceptable by the beam shaper, $f' = 1538$ mm.

In both examples the auxiliary lens to be of low optical power and, hence, doesn't require precise alignment when installed in optical system. In majority of practical cases it is possible to use off-the-shelf lenses.

Moving the auxiliary lens makes it possible to tune the beam size at the beam shaper entrance; this is illustrated by layout in bottom of Fig. 8. From the geometry the resulting beam diameter $\Delta D''$ can be defined by expression

$$\Delta D'' = D_1'' - D_2'' = (L_1 - L_2) \frac{2\Theta L_2 - D_1}{f'} \quad (10)$$

Thus, when certain air gap after a laser is available the optimum input beam diameter for a beam shaper can be adjusted using a single off-the-shelf lens.

4.4 Alignment

As optical devices designed to work with axial beams the refractive field mapping beam shapers operate in relatively narrow angular field, therefore one has to take care for their proper alignment with respect to a laser and other components of an optical system. Due to optical design implementation the *Focal- π Shapers* aren't sensitive to misalignments - typical tolerances are characterized by lateral translation error 0.1 mm and tilt of 5 arcmin with respect to laser beam. Evidently, these tolerances aren't tough and can be provided using ordinary 4-axis mounts. To quicken the alignment procedure it is usually recommended to apply alignment tools like ones described in [8].

Pointing laser beam instability should be analyzed while the beam shaper alignment. It is common to perform adjustments at low power operation mode of the laser to provide safe work conditions and prevent damaging of tools like beam profilers, filters, etc.; then the laser is switched in full power mode for a process. Due to features of laser design there might be deviation of a beam while switching between the low and full power operation modes that would inevitably lead to essential lateral shift of the beam at a beam shaper entrance. This effect becomes more pronounced in case of long air gap between laser and beam shaper, and is very critical for solid-state lasers. Example of this lateral shift is illustrated in Fig. 9: when switching laser power from 0.5 W (left) to 10 W (right) while distance from laser to the *Focal- π Shaper* is 3.5 meter there appears a lateral shift of about 1 mm (!) - this is essential misalignment that results strong distortion of final spot profile.

To avoid this misalignment it is recommended to perform adjustments in full power mode and use beam profilers with dedicated attenuators.

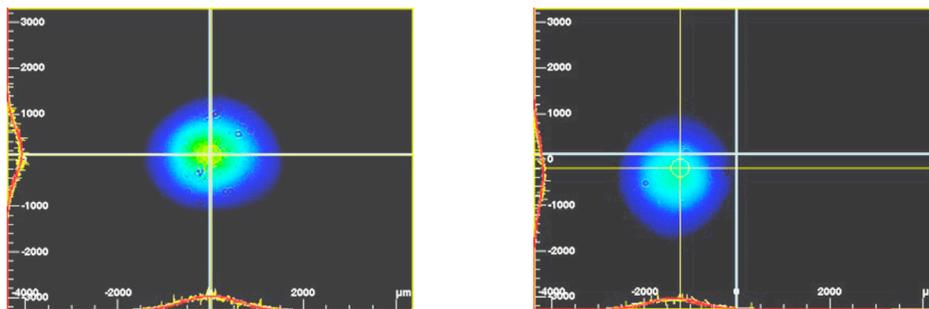


Fig. 9 Pointing error of solid-state laser: *left* – low power, *right* – full power operation modes.

4.5 Influence of astigmatism of input beam

Astigmatism is a physical effect when a focused beam has two separate focuses for two orthogonally related sections, usually meridional and sagittal ones [3, 4]. A laser beam can become astigmatic because of laser design itself, variation of operation parameters (current on pumping laser diodes, repetition rate, pulse duration, etc.) as well as due to astigmatism induced by components of optical system (mirrors, lenses). Astigmatism is an inherent property of radiation of some types of solid state lasers; it is usually suppressed in modern lasers for determined parameters of operation through optimisation of their design, but appears when parameters deviation from those optimum values. Fiber laser and fiber-coupled lasers demonstrate usually weak astigmatism.

Most often astigmatic beams have elliptic shape; it is also possible when a wide collimated beam of several millimetres or centimetres diameter is round but is inherently astigmatic. A simple and effective way to visualize and evaluate astigmatism is the beam focusing and analysis of intensity profiles around the beam waist. Example of profiles before, after and in waist of focused slightly astigmatic Gaussian laser beam is presented in Fig.10:

- the spots before and after the waist are elliptic,
- their long axis are turned at 90° - this is typical behaviour of astigmatic light beams,
- the spot in waist is round.

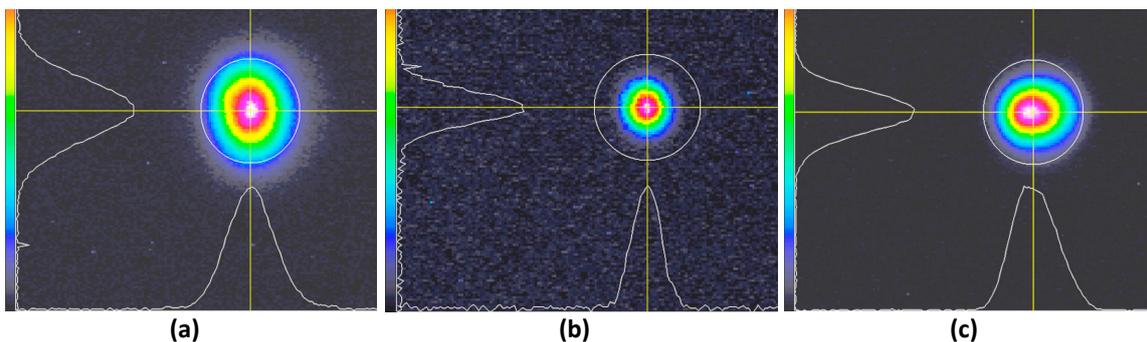


Fig. 10 Profiles by focusing of astigmatic laser beam: (a) before waist, (b) in waist and (c) behind waist.

When working with an ordinary Gaussian beam the influence of astigmatism on a process is not strong, since the spot in the waist is round and certain increasing of its diameter doesn't bring essential change in result of processing. But in case of beam shaping of focused beam astigmatism leads to characteristic change of resulting profile – the circular symmetry of intensity distribution is lost and section profiles have different view. Example of flat-top spot in the lens focal plane is shown in

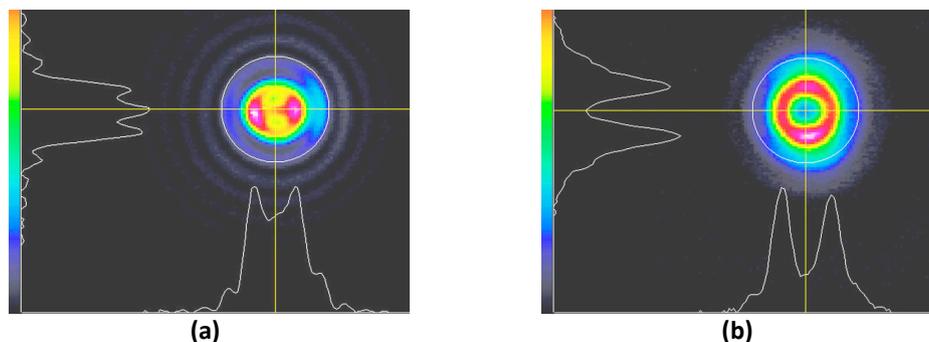


Fig. 11 Profiles of focused astigmatic beam: (a) – flat-top in focal plane, (b) – donut shape.

Fig. 11 (a); in many applications it is possible to work with such a spot and get acceptable processing results, but the unsymmetrical intensity profile has to be taken into account.

Interesting fact is that even in case of astigmatic laser beam the donut spot demonstrates regular round shape, Fig. 11 (b). This feature can be used to simplify the alignment procedure – when a beam shaper is aligned using 4-axis mount it is recommended to put a beam profiler just in the plane of donut spot and use round shape of profile as a criterion of proper alignment.

Astigmatism can be also introduced by components of optical path: lenses, beam expanders, mirrors. Therefore, it is always advisable to simplify the optical system, for example to avoid using of beam expanders as discussed in previous paragraphs.

4.6 Notes to work with F- θ lenses

The considered beam shapers for focused beams are intended to be used with any diffraction limited lens, which wave aberration doesn't exceed $\lambda/4$ value over whole working field. Majority of commercially available widely used in industrial application F- θ lenses fulfil this condition, there are however some features relating to their optical design.

F- θ lenses present multi-lens optical systems providing flat working field – the lens focal plane. Therefore the focal length of

an F- Θ lens isn't constant over whole working field, it depends on the field angle. In popular lenses this focal length difference from the field centre to periphery reaches 10-15%; this variation can be detected by analysing effective spot sizes even with ordinary TEM₀₀ beam.

As shown in previous paragraphs the intensity distribution of focused Airy beam near the lens focus depends on the lens focal length and distance from the focal plane. Therefore there exists certain variation of spot sizes and profiles for spots in centre and periphery of working field. Usually this effect isn't strong but has to be taken into account while evaluation of results of processing.

Telecentric F- Θ lenses have less variation of focal length, and its influence is practically negligible.

5. Experimental Results of Microprocessing

Even edges and reduced heat affected zone (HAZ) are common aims in various micromachining applications. Beam shaping and providing flat-top or other intensity profiles of the laser spot (donut, inverse-Gauss) is one of key techniques of improving those applications, and using the *Focal- π Shaper* brings flexibility in realization of these techniques. We present in this chapter some results of material processing.

5.1 Scribing on glass

The optical layout presented in Fig. 3 was used to improve laser scribing of glass using TEM₀₀ ultrashort pulse laser to create trenches of 6-7 microns width. Comparison of results of scribing with a pure TEM₀₀ laser beam and with *Focal- π Shaper 9_1064* installed ahead of the scanning head is presented in Fig. 12.

The difference in quality of scribing is evident: irregular trench edge and wide HAZ in case of TEM₀₀ beam, and even trench edges, steep walls and practically absent HAZ when *Focal- π Shaper* is used.

Evidently, with using the *Focal- π Shaper* it is possible to enhance the quality and reliability of scribing process.

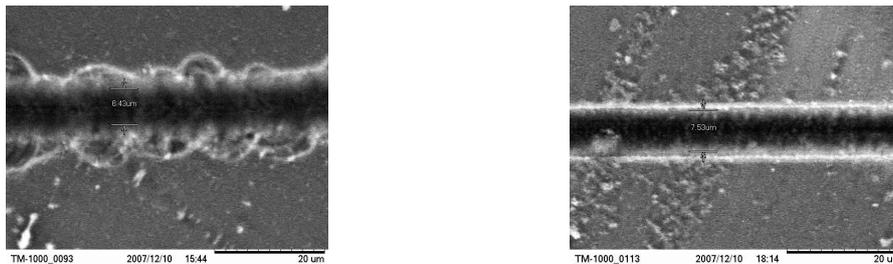


Fig. 12 Scribing by TEM₀₀ femtosecond Laser: *left* - TEM₀₀ laser beam, *right* - after the *F- π Shaper* (Courtesy of Altechna)

5.2 Scribing of thin-film material

Laser scribing of thin layers is widely used in photovoltaics technologies, patterning in display production and many others.

Example of realization of this technique to ablate 210 nm thin film of photovoltaics material is shown in Fig. 13, where

- top screenshot presents initial profile of UV laser ($\lambda=343$ nm, pulse duration 500 fs),
- the central screenshot shows profile of flat-top spot near focal plane of F- Θ lens,
- view of the resulting trench of 40 μm width (100 \times microscopy) is shown in bottom left picture, and
- profile measurements for the resulting trench are presented in bottom right pictures.

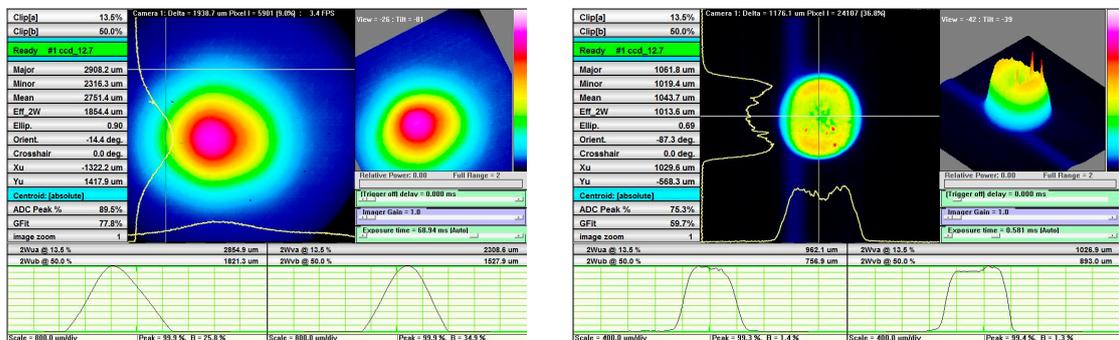


Fig. 13 Scribing by TEM₀₀ UV fs laser:
top left – input beam,
top right – flat-top focused spot,
bottom left – trench view and confocal microscopy.
 (Courtesy of ALPhANOV)

The initial laser beam is astigmatic, therefore the resulting flat-top spot, Fig. 13, centre, has difference of intensity distribution in vertical and horizontal directions. Nevertheless, it is possible to reach high quality trench of 40 μm width with steep edges and not damaged beneath layer.

5.3 Ablation of Silicon

Processing of silicon is important in microelectronics, Fig. 14 presents measured profiles and results of ablation in earlier discussed three characteristic spots: “small flat-top”, donut, “big flat-top”. The profile of initial TEM₀₀ laser with $\lambda = 1030$ nm and pulse duration 8 ps is shown in Fig. 14 (a), it has some imperfections (diffraction fringes) due to beam clipping in previous optical system, nevertheless the resulting intensity distributions in working planes near the lens focus are close to theoretical ones, and the ablation process demonstrates holes with predictable sizes and depths as well as with even edges and steep walls.

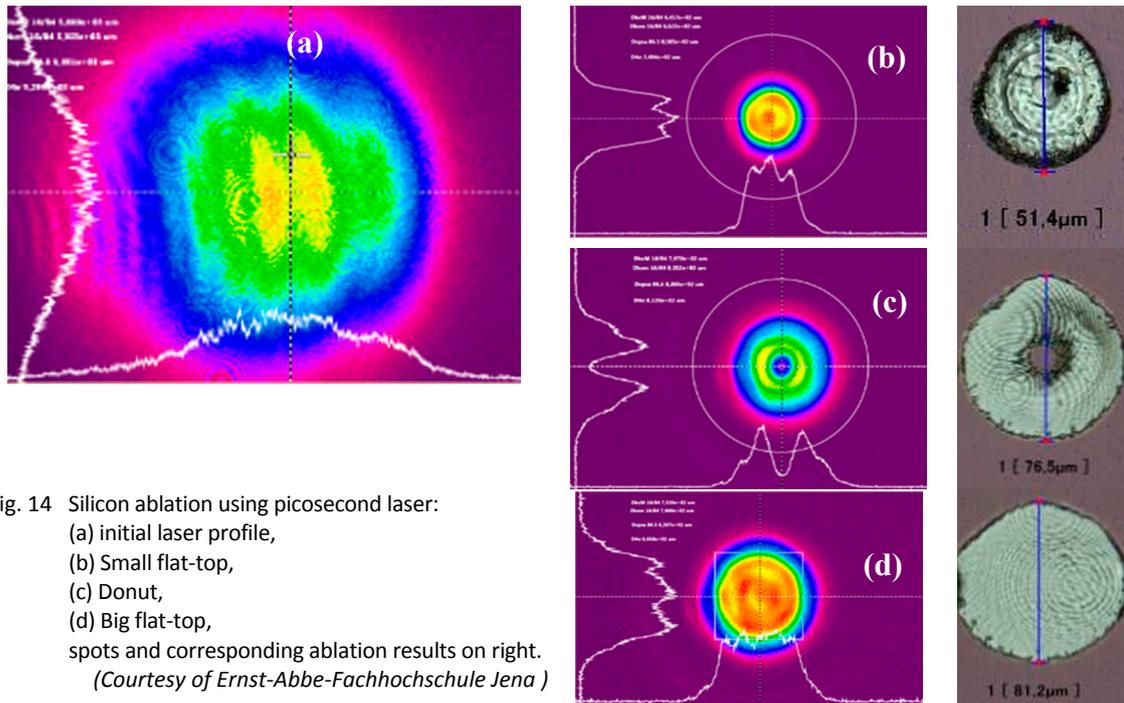


Fig. 14 Silicon ablation using picosecond laser:
 (a) initial laser profile,
 (b) Small flat-top,
 (c) Donut,
 (d) Big flat-top,
 spots and corresponding ablation results on right.
 (Courtesy of Ernst-Abbe-Fachhochschule Jena)

6. Conclusions

Refractive beam shapers of field mapping type transforming a Gaussian beam to a beam with Airy disk intensity distribution provide assured beam shaping of focused laser beams and creating spots with flat-top, inverse-Gauss and donut profiles. The data presented demonstrate good correspondence of theoretical and experimental data. The considered examples of this type of beam shaping in micromachining techniques confirm its applicability in scientific and industrial applications.

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