Refractive beam shapers for material processing with high power single mode and multimode lasers

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ABSTRACT

The high power multimode fiber-coupled laser sources, like solid state lasers or laser diodes as well as single mode and multimode fiber lasers, are now widely used in various industrial laser material processing technologies like metal or plastics welding, cladding, hardening, brazing, annealing. Performance of these technologies can be essentially improved by varying the irradiance profile of a laser beam with using beam shaping optics, for example, the field mapping refractive beam shapers like piShaper. Operational principle of these devices presumes transformation of laser beam irradiance distribution from Gaussian to flattop, super-Gauss, or inverse-Gauss profile with high flatness of output wave front, conserving of beam consistency, providing collimated output beam of low divergence, high transmittance, extended depth of field. Important feature of piShaper is in capability to operate with TEM_{00} and multimode lasers, the beam shapers can be implemented not only as telescopic optics but also as collimating systems, which can be connected directly to fiber-coupled lasers or fiber lasers, thus combining functions of beam collimation and irradiance transformation.

This paper will describe some features of beam shaping of high-power laser sources, including multimode fiber coupled lasers, and ways of adaptation of beam shaping optical systems design to meet requirements of modern laser technologies. Examples of real implementations will be presented as well.

Keywords: beam shaping, flattop, multimode, high power laser, fiber-coupled, welding, hardening, cladding**.**

1. INTRODUCTION

Growing popularity of high power lasers in material processing is accompanied with variety of demands to control the laser irradiance profile and spot shape. The applications like metal or plastics welding, cladding, selective laser melting, hardening, brazing, annealing get benefits from providing flattop or inverse-Gauss irradiance distribution of a laser spot with round, elliptical or linear shape. The complexity of requirements is also increased due to variety of laser sources: solid-state, diode or fiber lasers can be TEM_{00} or multimode, free space or fiber-coupled, CW or pulsed, the laser power spans from few watts to several kW.

There are several beam shaping techniques that are applied in modern laser technologies: truncation of a beam by an aperture, attenuation by apodizing filters, integration systems based on arrays of microlenses, micromirrors, prisms, various diffractive optical elements; but very often using of these techniques with modern powerful lasers is limited by efficiency or resistance to high power laser radiation. To meet these requirements the up-to-date beam shaping solutions can be built on the base of the field mapping refractive beam shapers like *πShaper*, which operational principle implies transformation of laser irradiance distribution from Gaussian to flattop, super-Gauss, or inverse-Gauss, conserving of beam consistency, low divergence of collimated output beam, high transmittance, extended depth of field, capability to operate with TEM_{00} or multimode lasers, implementations as telescopes or collimators.

This article describes basic principles and important features of refractive beam shapers as well as some optical layouts that can be built on their base to meet requirements of modern laser technologies.

2. DESCRIPTION OF FIELD MAPPING REFRACTIVE BEAM SHAPERS

2.1 Basics of optical design

The design principles of refractive beam shapers of field mapping type, like *πShaper*, are well-known and described in the literature[1,4,5,6,7,8]. Most often these devices are implemented as telescopic systems with two optical components, it is implied that wave fronts at input and output are flat, the transformation of irradiance profile from Gaussian to uniform is realized in a controlled manner, by accurate introducing of wave aberration by the first component and further its compensation by the second one, Fig.1, top. Thus, the resulting collimated output beam has a uniform irradiance and flat wave front, it is characterized by low divergence – almost the same like one of the input beam. In other words, the field mappers transform the irradiance distribution *without deterioration of the beam consistency and without increasing of beam divergence*.

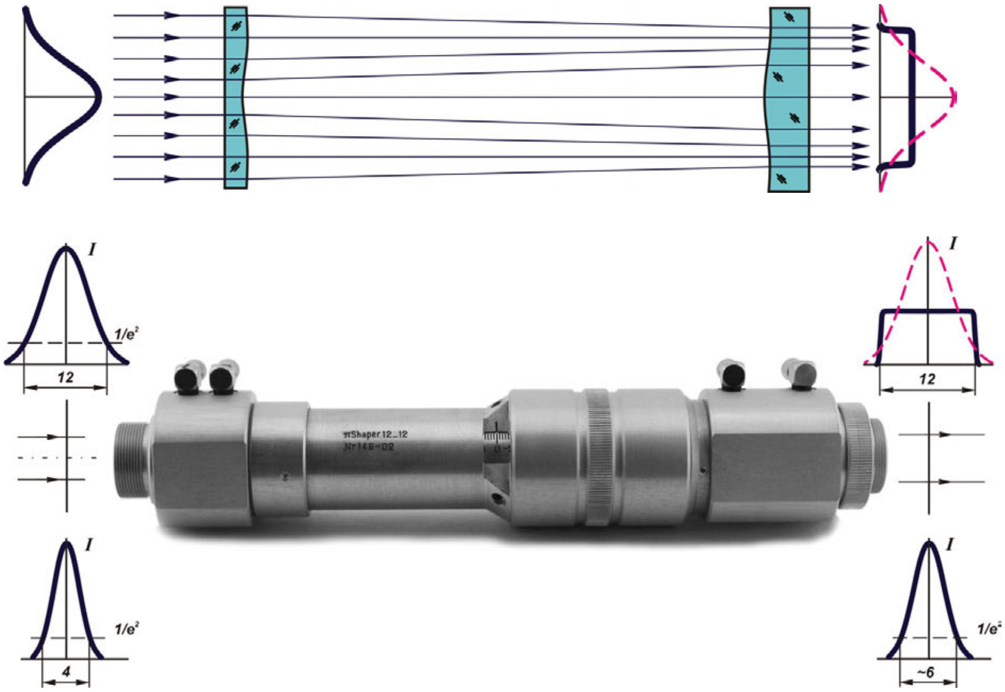

Figure 1 Refractive field mapping beam shaper *πShaper*

Shortly the main optical features of refractive field mappers are:

- refractive optical systems transforming Gaussian to flattop (top-hat, uniform) irradiance distribution;
- transformation through controlled phase front manipulation – 1st optical component introduces spherical aberration required to re-distribute the energy, then the 2nd optical component compensates the aberration;
- output beam is free of aberrations, the phase profile is maintained flat, hence, low divergence is provided;
- TEM_{00} and multimode beams applied;
- collimated output beam,
- the resulting beam profile is kept stable over large distance;
- implementations as telescopic or collimating optical systems;
- achromatic optical design, hence the beam shaping effect is provided for a certain spectral range simultaneously;
- Galilean design, no internal focusing.

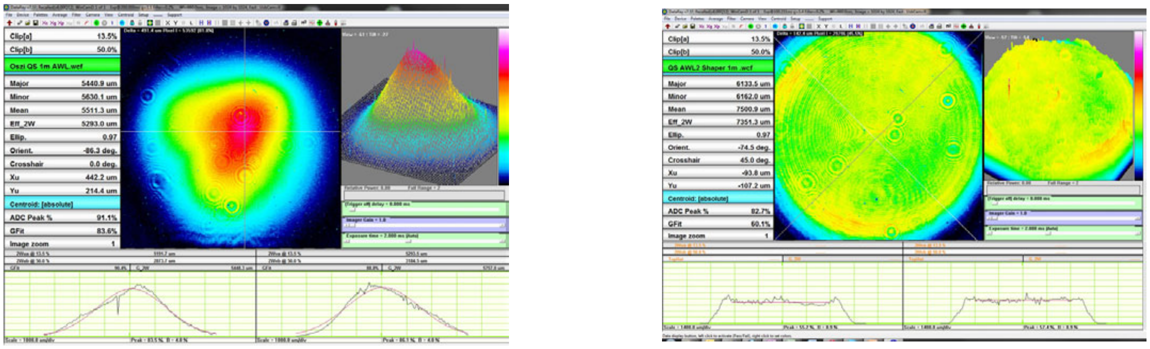

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Figure 2 Example of beam shaping: Left – Input TEM$_{00}$ beam, Right - after the *πShaper*
(Courtesy of InnoLas Laser GmbH)

Example of beam shaping for Nd:YAG laser is presented in Fig.2. These measured profiles show that the beam shaper not only converts the irradiance profile but improves also the spot shape – one can see the slightly distorted input beam is transformed to a flattop output beam with regular round spot shape.

2.2 Collimating beam shapers – solution for TEM$_{00}$ and multimode fiber or fiber coupled lasers

One of characteristic trends in modern laser material processing technologies is in expansion of using fiber delivery of laser radiation – both fiber lasers and fiber coupled diode or solid state lasers. At the same time the growing power demands lead to applying not only TEM$_{00}$ but also multimode laser sources, today a laser with power of several kW is considered as a usual device in majority of material processing techniques.

A remarkable feature of field mapping beam shapers is capability to meet these challenging demands of modern industrial applications and realize collimating optical systems combining the functions of beam shaping and collimation: *divergent Gaussian beam is converted to collimated flattop*. Example of collimating beam shapers is shown in Fig. 3

Figure 3 Conversion of divergent Gaussian beam from fiber to collimated flattop.

In contrast to many other beam shaping techniques the physical principle of operation of refractive field mappers doesn't require the input beam to be obligatory a TEM$_{00}$ one, i.e. to have a common phase front. The beam shapers like *πShaper* work perfect with multimode beams as well, the only condition is that the irradiance distribution of input beam to be similar to Gaussian function, i.e. to have irradiance characterized by peak in center and decreasing towards periphery, for example parabolic, Fig.9, a. Gaussian-like irradiance profiles are typical for high power multimode solid-state lasers, as well as for fiber coupled multimode solid-state and diode lasers. Therefore collimating refractive beam shapers converting laser radiation from a fiber directly to a collimated beam with uniform irradiance profile meet the demands of modern industrial technologies like welding, cladding, hardening. Capability to work simultaneously with TEM$_{00}$ and multimode lasers allows switching easily from one laser source to another.

2.3 Adjustment features

Any beam shaping technique implies introduction of aberrations in a certain way and, therefore, requires fulfilment of some pre-determined conditions for proper transformation of a laser irradiance distribution. Like in other beam shaping techniques in case of refractive field mapping beam shapers it is necessary to take care for an input beam size, its irradiance profile and proper alignment of a beam shaper. These features were discussed in paper[9]. Here we can state that the requirements of beam shapers like *πShaper* are not tough, for example, alignment of a *πShaper 6_6* to be done with tolerances about 0.1 mm for lateral shift and about 10 arc minute for tilt, while the tolerance of input beam diameter is about 10%. Evidently, proper alignment of a *πShaper* can be done with using ordinary opto-mechanical alignment devices like 4-axis mounts, while the input beam size can be provided by widely used zoom beam expanders. That feature of refractive beam shapers that *variation of input beam size leads to variation of output irradiance distribution* is used to realize various irradiance distributions and achieve some interesting effects of beam shaping; this topic is discussed in the chapter “Control of profiles”.

Another important feature of the beam shapers like *πShaper* is capability to compensate divergence/convergence of input beam through changing the air gap between components and easy adaptation to lasers with deviated from perfect Gaussian irradiance profile; all these features have great importance in practice.

2.4 Working distance and propagation of flattop beams

It is usual to characterize beam shaping optics by the working distance – the distance from last optical component to a plane where a target irradiance profile, flattop or another one, is created. The working distance is an important specification for diffractive beam shapers and refractive homogenizers (or integrators) based on multi lens arrays. But in case of the field mapping beam shapers the output beam is *collimated* and, hence, instead of a definite plane where a resulting irradiance profile is created, there exists certain space after a beam shaper where the profile is kept stable. In other words, the working distance isn’t a specification for the field mapping beam shapers, it is better specify the depth of field (DOF) after a beam shaper where resulting irradiance profile is stable. This DOF is defined by diffraction effects happening while a beam propagating and depends on wavelength and beam size.

When a TEM_{00} laser beam with Gaussian irradiance distribution propagates in space its size varies due to inherent beam divergence but the irradiance distribution stays stable, this is a famous feature of TEM_{00} beams that is widely used in practice. But this brilliant feature is valid for Gaussian beams only! When light beams with non-Gaussian irradiance distributions, for example flattop beams, propagate in space, they get simultaneously variation of both size and irradiance profile. Suppose a coherent light beam has uniform irradiance profile and flat wave front, Fig. 4, this is a popular example considered in diffraction theory[2,3], and is also a typical beam created by field mapping refractive beam shapers converting Gaussian to flattop laser beam.

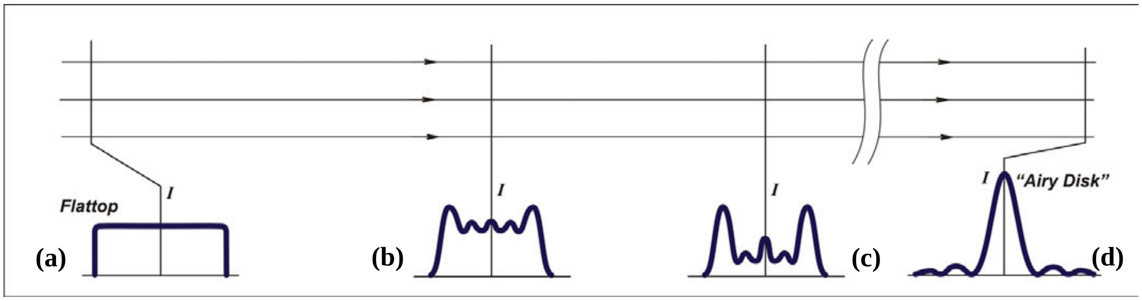

Fig. 4 Irradiance profile variation by a flattop beam propagation.

Due to diffraction the beam propagating in space gets variation of irradiance distribution, some typical profiles are shown in Fig. 4: at certain distance from initial plane with uniform irradiance distribution *(a)* there appears a bright rim *(b)* that is then transformed to more complicated circular fringe pattern *(c)*, finally in infinity (so called far field) the profile is featured with relatively bright central spot and weak diffraction rings *(d)* – this is the well-known "Airy disk" distribution described mathematically by formula

$$I(\rho) \quad = \quad I_0\, [J_1(2\pi\rho)/(2\pi\rho)]^2 \qquad (1)$$

where I is irradiance, J_1 is the Bessel function of 1st kind, 1st order, ρ is polar radius, I_0 is a constant.

The "Airy disk" function is result of Fourier-Bessel transform for a circular beam of uniform initial irradiance[2].

Evidently, even a "pure" theoretical flattop beam is transformed to a beam with essentially non-uniform irradiance profile. There exists, however, certain propagation length where the profile is relatively stable, this length is in reverse proportion to wavelength and in square proportion to beam size. For example, for visible light, single mode initial beam and flattop beam diameter 6 mm after a *πShaper 6_6* the length where deviation from uniformity doesn't exceed ±10% is about 200-300 mm, for the 12 mm beam it is about 1 meter.

In case of multimode lasers strength of diffraction effects, like rings, is typically less and depends on beam spatial coherence. Approximately it is possible to consider a multimode beam as a combination of single mode beamlets, which overlapping leads, on the one hand, to less pronounced diffraction rings, on the other hand, to larger beam divergence, as result the character of variation of irradiance profile differs from one for a TEM_{00} laser.

There are many laser applications where conserving a uniform irradiance profile over certain distance is required, for example holography, interferometry; the extended DOF is also very important in various industrial techniques to provide less tough tolerances on positioning of a workpiece. As a solution to the task of providing a necessary resulting spot size with conserving the flattop profile over extended DOF it is fruitful to apply imaging techniques that are considered in next chapter.

3. IMAGING OF FLATTOP BEAMS

Imaging technique is a powerful tool to building complex beam shaping systems on the base of refractive beam shapers like *πShaper*, essential features of this approach are considered in paper[11]. Here we emphasize on most important for practice aspects.

Example of imaging layout is shown in Fig. 5, here the output of the *πShaper* is considered as an *Object* plane. Since the *πShaper* conserves low divergence of laser beam, the irradiance profile after it gets transformation due to diffraction, similar to one shown in Fig. 4. As result before and immediately after the imaging lens, Fig. 5, the irradiance distribution isn't uniform, it depends on wavelength, beam size and distance from the *Object* to the lens.

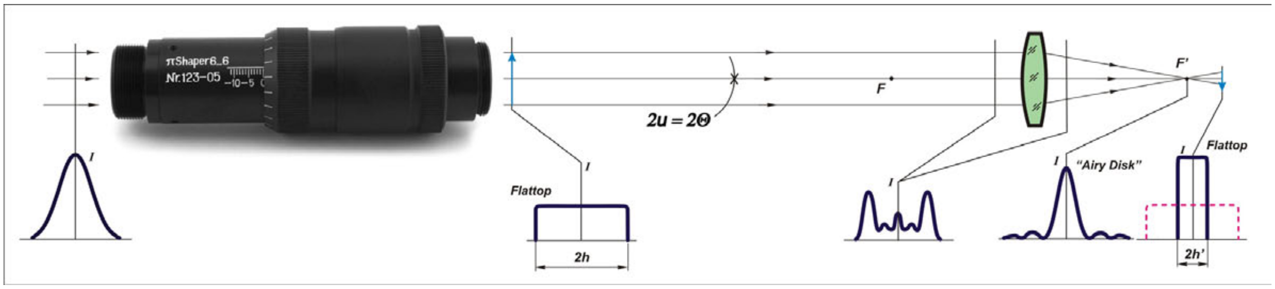

Fig. 5 Irradiance profile transformation of flattop laser beam in imaging layout

According to the diffraction theory the irradiance distribution in a certain plane is result of interference of light diffracted from previous plane of observation. The result of interference in the considered imaging layout is that irradiance distribution in the *Image* plane, being optically conjugated with the *Object* plane, will be similar to one of the *Object* plane. Hence, *If the irradiance distribution is uniform in the Object plane, it is uniform in the Image plane as well*; and the profile at the *πShaper* output aperture will be repeated in the *Image* plane of that aperture, herewith the resulting spot size is defined by transverse magnification β of imaging optical system.

In the example in Fig. 5 the imaging optics is shown just a lens singlet, but for high quality imaging more sophisticated optical systems should be applied, for example aplanats (with correction of spherical aberration and coma), microobjective lenses or other multi-component optical systems. Calculation of parameters of a particular imaging setup can be done with using well-known formulas of geometrical optics, described, for example, in book[3].

A positive lens has a well-known ability to perform two-dimensional Fourier transform[2] and create in its back focal plane irradiance distribution proportional to one in far field. This means in the considered case that irradiance distribution in focal plane, marked in Fig. 5 as *F’*, is just “Airy disk” described by formula (1), evidently essentially non-uniform.

Summarizing results of this example one can see that initial uniform irradiance after *πShaper*, the *Object* plane, is transformed to non-uniform irradiance in area around the imaging lens, then to essentially non-uniform “Airy disk” distribution in back focal plane of that lens, and finally is restored to uniform irradiance profile in the *Image* plane as result of interference of diffracted beam. An important conclusion for practice is that *it doesn’t matter how the irradiance profile is transformed along the beam path, since the irradiance distribution in the Image plane repeats the Object plane distribution with taking into account transverse magnification*. This conclusion is valid not only for flattop beams but also for any other irradiance profile. For instance, the *πShaper* allow realizing also such profiles like “inverse Gauss” or super-Gauss[9] and these profiles can be successfully reproduced in the *Image* plane as well.

Since the *Image* is a result of interference of light beams being emitted by the *Object* and diffracted according to physics of light propagation, it is necessary to take care of full light energy transmitting through an optical system and *avoid any beam clipping*.

Another important feature of imaging of low divergent laser beams is extended DOF; this effect is illustrated in Fig. 6.

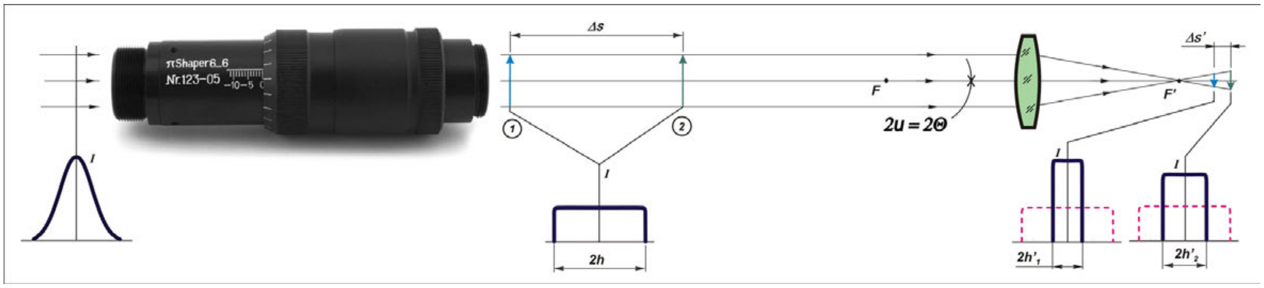

Fig. 6 To evaluation of depth of field in imaging layout.

The *Object* at the exit of the *πShaper* can be implemented as a physical aperture or iris diaphragm, then the *Image* will have very sharp edges and repeat the shape of that aperture. If no apertures applied and output collimated beam simply propagates towards the imaging lens the *Object* has no a definite plane and whole space after the *πShaper*, where the irradiance profile is flattop, will be mapped to a corresponding space on the *Image* side. As discussed in paragraph 2.4 that length Δs of stable profile in the *Object* space depends on wavelength and beam size, it can achieve values of several hundreds of mm or several meters depending on applied laser and *πShaper*. Hence, the beam profile is stable over relatively long length $\Delta s'$ in the *Image* space as well, in other words the extended DOF is provided. The DOF length can be approximately evaluated with taking into account that longitudinal magnification of an imaging system is equal to square of the transverse magnification[3].

4. CONTROL OF PROFILES

As discussed in previous chapter, in *πShaper variation of input beam size leads to variation of output irradiance distribution*. This feature is used as a powerful and convenient tool to vary the resulting irradiance distribution by simple changing of laser beam diameter, for example, with using a zoom beam expander ahead of a beam shaper it is possible to provide flattop, inverse-Gauss or super-Gauss irradiance distributions[9].

The inverse-Gauss irradiance distribution is optimum for the applications where uniform temperature profile on a workpiece is required, for example, welding of plastics, laser heating and hardening techniques, selective laser melting.

At the same time the super-Gauss distributions are useful in techniques of spectral laser combining, pumping of DPSS lasers, MOPA laser designs.

In spite of circular design of beam shapers it is also possible to realize some non-circular symmetry profiles, for example, elliptical input beam is transformed to "roof" profile characterized by uniform irradiance in one direction and Gaussian in another one, Fig. 7. The "roof" profile is useful in cases when a particular task requires very high aspect ratio of linear spot, then focusing of the output beam in "Gaussian" section leads to narrow line.

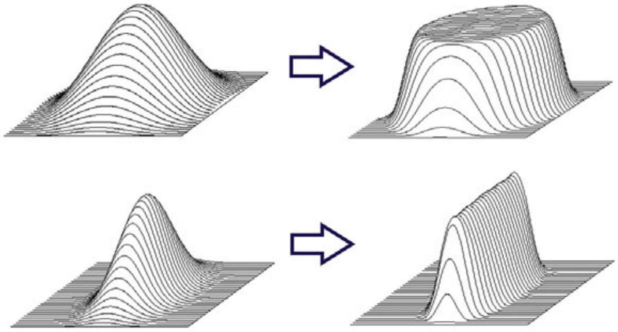

Fig. 7 Top - round Gaussian beam is transformed to round flattop, Bottom - elliptic Gaussian beam is transformed to roof-profile.

A remarkable feature is that various profiles realized with the same beam shaper unit.

The approach of variation of resulting irradiance profile through *external* changing the input beam diameter with suing a zoom beam expander is illustrated in Fig. 8 where results of theoretical calculations as well as measured in real experiments beam profiles for TEM_{00} laser are shown.

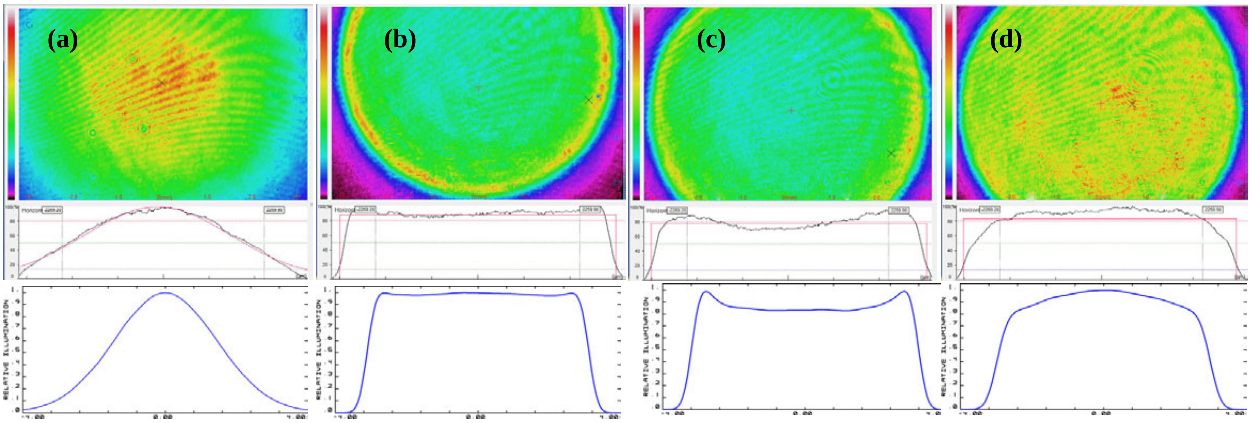

Fig. 8 Experimental and theoretical irradiance profiles:
a) TEM_{00} Input beam, D_{in} = 6 mm (1/e^2), b) Flattop output profile when by D_{in} = 6 mm (1/e^2),
c) Concave output profile ("Inverse Gauss"), D_{in} = 6,5 mm (1/e^2) d) Convex output profile ("superGauss"), D_{in} = 5,5 mm (1/e^2)
(Courtesy of IPG Photonics)

The data relate to the *πShaper 6_6* which design presumes that a perfect Gaussian beam with 1/e^2 diameter 6 mm to be converted to a beam with uniform irradiance (flattop) with FWHM diameter 6.2 mm. When the input beam has a proper size, Fig. 8a, the resulting beam profile is flattop, Fig. 8b. Increasing of input beam diameter leads to decrease of irradiance in the centre, Fig. 8c, sometimes this distribution is called as "inverse-Gauss"; input beam size reduction allows getting a convex profile that approximately can be described by super-Gauss functions, Fig. 8d. The considered irradiance profiles correspond to about 10% beam size change; the larger are changes the more pronounced is variation in irradiance profile.

An interesting feature of the field mapping beam shapers is in stability of the output beam size – variation of input beam diameter results in variation of irradiance profile while the output beam diameter stays almost invariable. This is very important in practice and brings element of stability while searching for optimum conditions for a particular laser application.

Another way to vary the output beam profile is changing the beam size *internally* by varying the distance between beam shaper components, this approach is illustrated in Fig. 9, where input and output beam profiles of multimode fiber coupled solid state laser are shown.

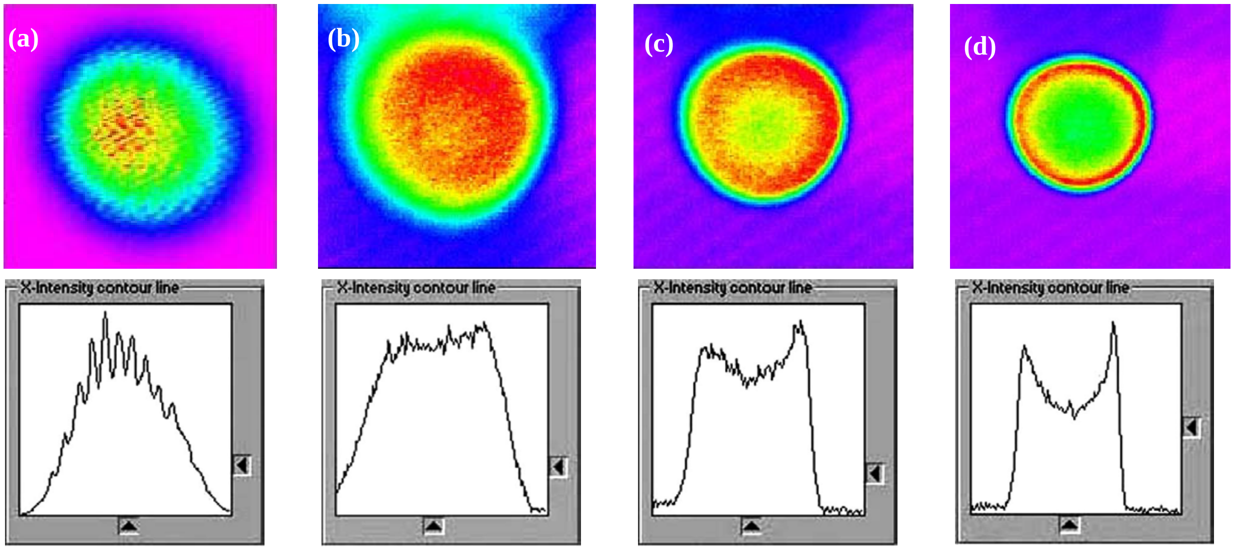

Fig. 9 Beam shaping of powerful multimode laser. *(Courtesy of Daimler AG)*

Radiation of high power solid-state fiber coupled laser ($\lambda = 1064$ nm, P = 2 kW, fiber core diameter 600 µm) was inputted to the collimating *πShaper* combining the functions of beam shaping and collimation. The beam emerging from the fiber is divergent and has Gaussian-like (parabolic) profile shown in Fig. 9a. Output of the *πShaper* is collimated beam, according to basic design it has flattop irradiance distribution, Fig. 9b. Variation of output beam profile is realized through *internal* changing of distance between optical components, as result the presented in Fig. 9c and Fig. 9d inverse-Gauss profiles were realized.

Evidently, simple external or internal variations of laser beam size allow generating various profiles with the same beam shaper unit.

5. CONTROL OF SPOT SHAPES

According to basic design the output beam of refractive field mapping beam shapers is round and has a pre-determined size. However, in majority of practical cases it is necessary to either to enlarge or de-magnify the beam or change its shape to elliptical or linear. Since the output of refractive beam shapers is a collimated low divergent beam, that manipulation of laser spot shape can be easily realized with using beam expanders, imaging optics or anamorphic optical systems[9,10,11].

Example of imaging optical system for micromachining to create square laser spots of uniform irradiance is presented in Fig. 10. The system is built from ordinary components used in micromachining applications: laser, beam expander, galvo-mirror scanning head and F-theta lens. The TEM$_{00}$ laser beam at the entrance of the *πShaper 6_6* has circular shape and Gaussian irradiance distribution, Fig. 10, on left; therefore the round collimated beam after the *πShaper* has uniform irradiance profile, Fig. 10, centre.

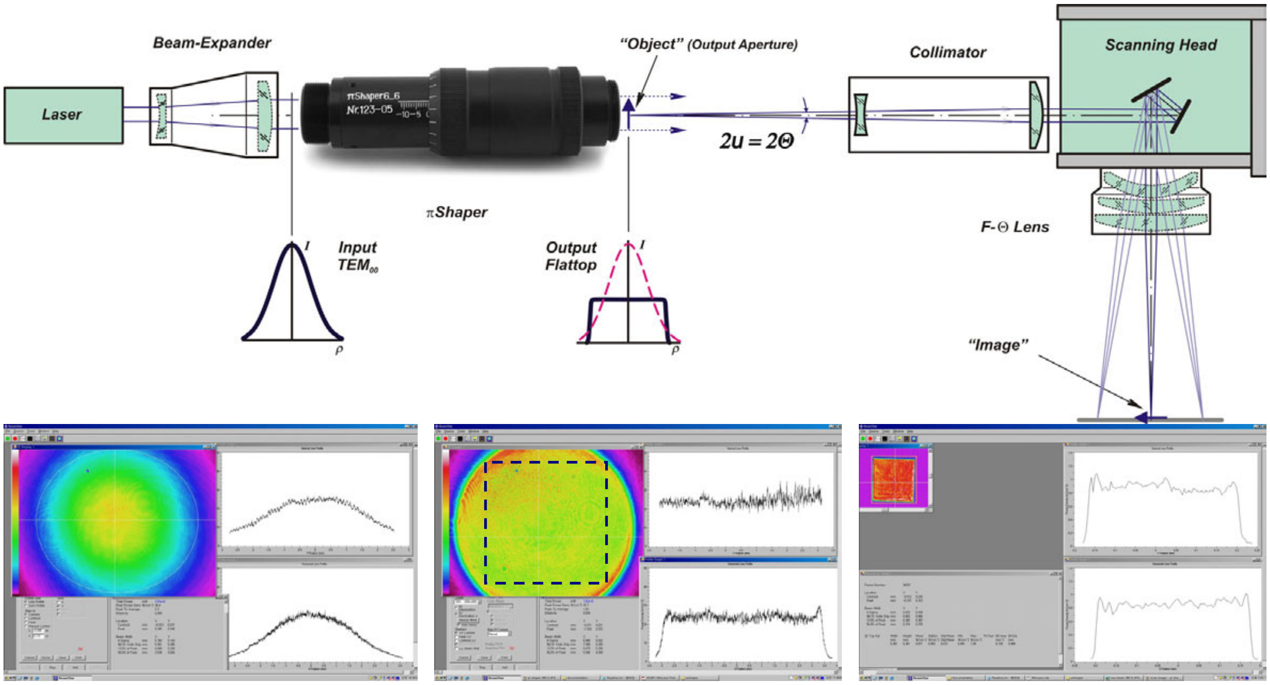

Fig. 10 Creating square spots with using *πShaper* and imaging system: Top – Optical layout,
Bottom: Left – input beam, Centre - *πShaper* output, Right – final square spot 50 x 50 μm^2.

The *πShaper* output is imaged onto a workpiece with using imaging optics composed from an additional collimator and the mentioned F-theta lens: the the *πShaper* output is considered as an *Object* , then the *Image* is created in the focal plane of the F-theta lens. Since the task is to create a square spot, a square aperture is installed at the *πShaper* exit, it is shown in Fig. 11, centre by a dashed line. Imaging of that square aperture with using the Collimator and F-theta lens gives a resulting 50 x 50 μm^2 spot of square shape and flattop irradiance profile, Fig. 11, on right. Please, pay attention to *high steepness* of the spot edge, which is very important in such applications like drilling blind vias in PCB or repair of display pixels.

Some laser applications like laser cleaning, annealing, hardening, cladding are realized with using multimode lasers like fiber coupled solid-state and diode lasers or fiber lasers. At the same time just linear shape of laser spot is preferable in those technologies and the *πShaper* in combination with anamorphic after it present a robust solution. Example of implementation on the base of the *πShaper NA0.1_12_1064* for multi kW multi mode laser is presented in Fig. 11.

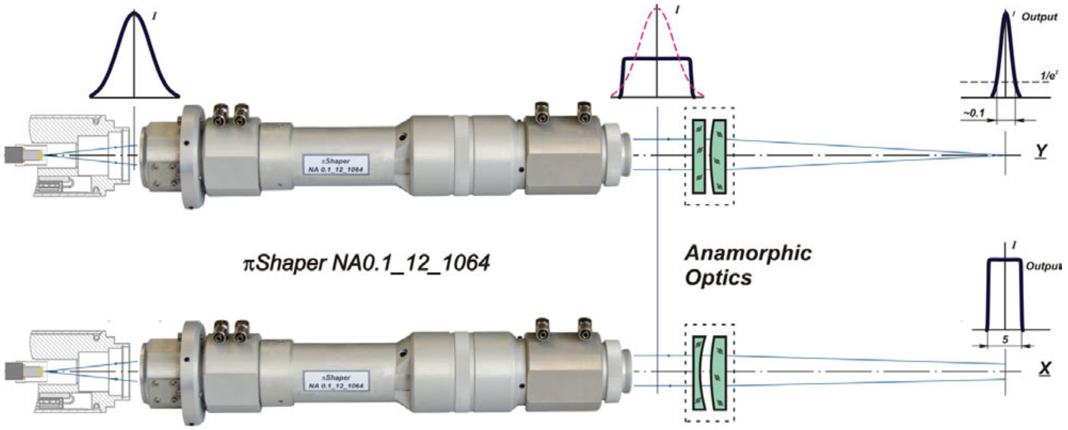

Fig. 11 Generation of "Laser Line" from multimode laser beam.

The collimated beam of uniform irradiance is emerging from the collimating beam shaper and is then focused onto a workpiece by an anamorphic optics that is implemented as a pair of lenses: one positive spherical lens and one negative cylinder lens. Due to inherent astigmatism of the anamorphic optics the beam is focused in one plane, *Y* in Fig. 11, but stays unfocused in the perpendicular plane *X*, hence a spot of linear shape is created. The data of theoretical calculations as well as experimental results are presented in Fig. 12.

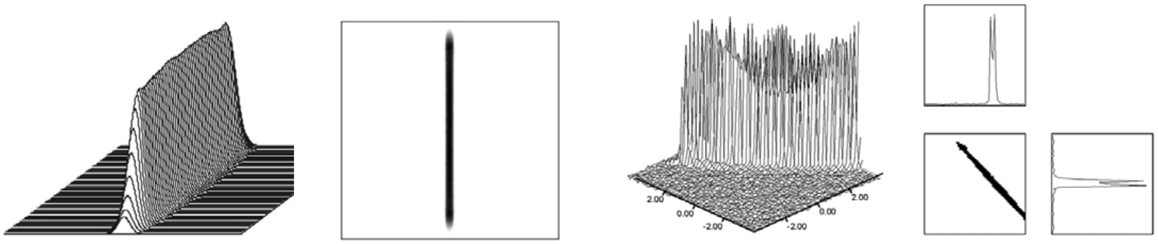

Fig. 12 To “Line” generation: Right - computer simulation, Left – measured profiles in layout according to Fig. 11
(Courtesy of IPG Photonics)

Evidently, there exists good correspondence between theoretical and experimental results. Applying of more sophisticated anamorphic optics after a *πShaper* allows providing linear spots with extremely high, up to 1:1000, aspect ratios. Example of one of such a beam shaping system is shown in Fig. 13.

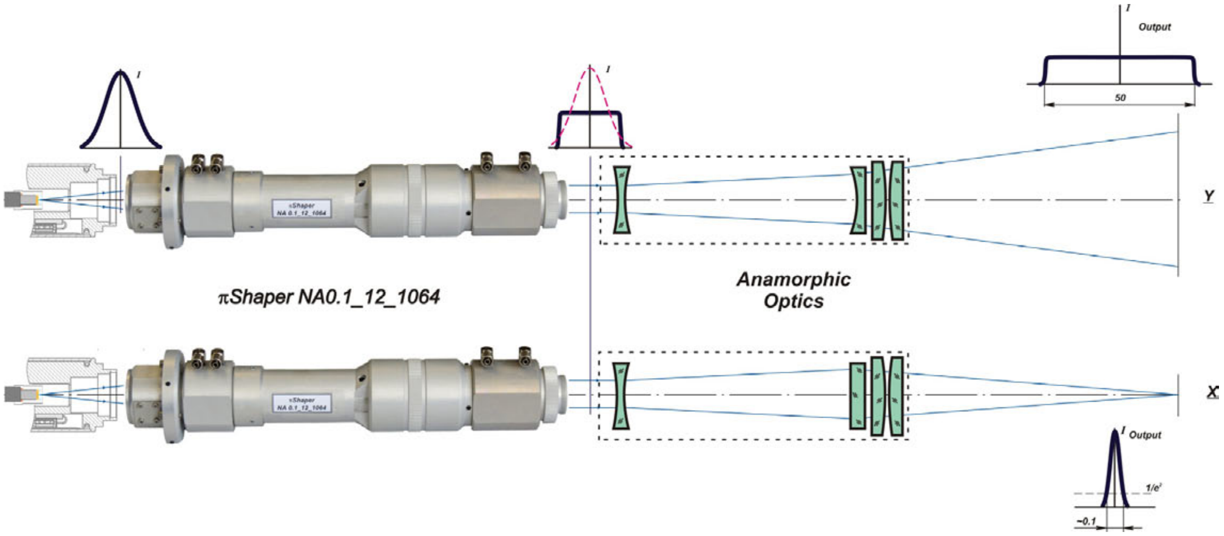

Fig. 13 Generation of “Laser Line” with aspect ratio 1:500.

Collimated laser beam after the *πShaper* is entering into an anamorphic optical system that focuses the beam in section *X*, and expands it in section *Y*, as result a Linear spot is created. High numerical aperture of the anamorphic system in image space provides narrow line width, therefore high aspect ratio 1:500 of the Line is provided. Developing of an anamorphic optical system design is usually a point for a particular technological project.

5. CONCLUSION

Optical approach realized in refractive beam shapers of field mapping type allow applying these systems as versatile tools to generate various irradiance distributions. Being originally designed to transform Gaussian beams to beams of uniform irradiance these beam shapers show high level of flexibility in generation of other profiles: inverse-Gauss, super-Gauss, as well as various spot shapes: round, square or linear. A remarkable feature of *πShaper* is that this variety of resulting irradiance distributions and spot shapes can be realized with using the same beam shaper unit.

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7. ACKNOWLEDGEMENTS

The authors are thankful to *πShaper* users in IPG Photonics, Daimler AG and InnoLas Laser GmbH for their active and patient work with *πShaper* and kind permission to publish some results of experiments.