Modern techniques of laser material processing require not only simple homogenizing of a beam but also more freedom in manipulation of intensity profile and generating such profiles like super-Gaussian, inverse-Gaussian; and controllable varying of the intensity profile allows to “adjust” a particular material processing technology, improve it or make more efficient. These tasks can be successfully solved with using the field mapping refractive beam shaping optics like $\pi$Shaper which operational principle presumes saving of beam consistency, collimated low divergent output beam, high transmittance, extended depth of field. Varying of the input beam diameter lets it possible to realize either super-Gaussian (smaller input) or inverse-Gaussian (bigger input) intensity profiles of output beam. All variety of profiles can be provided by the same beam shaper unit. There will be considered in the paper the design basics of refractive beam shapers and techniques to vary the output intensity profile, experimental results will be presented as well.

Performance of many modern scientific and industrial laser applications is improved through applying beam shaping optics that is used for creating of different intensity profiles. A choice of optimum spot shape and intensity profile of a laser beam depends on an application: in plenty of techniques just so called flattop (or top hat) profile is requested, some laser technologies, like annealing, hardening, get benefits from linear profile with uniform intensity in one direction and Gaussian in another one, other technologies, like welding, can be improved from so called “inverse Gauss” or “Donut” with minimal intensity in the centre of a spot. A typical approach of beam shaping is realization of a particular beam profile with using a certain beam shaper, which cannot be used for generation of other profiles. There are several diffractive and refractive optical design approaches used to realize various beam shaping effects and only few of them can be used to provide variety of intensity profiles with using the same beam shaper. One of these versatile optical solutions is a refractive beam shaper of field mapping type demonstrating a flexibility in realization of variable intensity distribution by the same device. These beam shapers transform the intensity profile by accurate correction of the wave front of a laser beam and are capable to control output intensity profile due to some interesting features that will be discussed and presented in the paper. There will be considered some optical layouts built on the base of refractive field mapping beam shapers $\pi$Shaper, their behaviour depending on conditions of a particular optical setup, ways of generation various profiles and examples of real applications.

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input beam. In other words, the field mappers transform the beam profile without deterioration of the beam consistency and without increasing its divergence.

For the purpose of further considerations let us summarize main optical features of \( \pi \)Shaper systems being used in this work:

- refractive optical systems transforming Gaussian, or close to Gaussian intensity distribution of source laser beam to a flattop (or top-hat, or uniform) one;
- transformation is realized through the phase profile manipulation in a controlled manner - accurate inducing by the first component of spherical aberrations to achieve the energy re-distribution and further compensation of the aberration by the second optical component;
- the output beam is free of aberration, the phase profile is maintained flat and low beam divergence is provided;
- TEM\(_{00}\) or multimode beams applied;
- collimated output beam,
- the resulting beam profile is kept stable over large distance;
- achromatic optical design, hence the beam shaping effect is provided for a certain spectral range simultaneously;
- Galilean design, no internal focusing.

Example of beam shaping for Nd:YAG laser with using \( \pi \)Shaper is presented in Fig.2. These measured profiles show that the \( \pi \)Shaper not only converts the intensity 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.

Figure 1 Refractive field mapping beam shaper \( \pi \)Shaper

Figure 2 Experimental and theoretical intensity profiles:
Left – Input TEM\(_{00}\) beam,  Right - after the \( \pi \)Shaper  (Courtesy of InnoLas Laser GmbH)
One more important feature of the refractive field mapping beam shapers is that their operational principle presumes the input beam has a certain size, usually defined as diameter at $1/e^2$ intensity level, and a certain intensity profile - Gaussian or similar profiles with peak intensity in the centre. If an input beam size deviates from the pre-determined one the resulting profile varies as well. For example, when a $\pi$Shaper is intended to convert the Gaussian beam to the flattop one and the input beam is essentially smaller, say 2-3 times less than a specified value, the beam shaper operates as an ordinary beam-expander and the resulting profile stays almost the same like at the entrance i.e. Gaussian. This effect is discussed thoroughly in paper\(^6\) and is shown in Fig. 1, bottom profiles. With using the effect of dependence of output beam profile and shape from the input beam size it is possible to build various optical system realizing various shapes and intensity profiles of final laser spots, some of them are considered below.

Capability of the $\pi$Shaper to operate with both TEM\(_{00}\) and multimode laser beams distinguishes these beam shapers from other kinds of beam shaping, obviously, this feature is has great importance in practice.

One of basic design conditions for the $\pi$Shaper systems is zero wave aberration – flat input wave front is transformed to flat output wave front. For proper operation in real applications, for example in industrial equipment, the beam shapers should provide certain tolerances for probable misalignments, like spatial shifts or tilts. Therefore, the real designs should presume providing the same aberration correction level not only for the clear aperture of a system, but also in certain extent outside. The practice of building real beam shaping systems shows the aberration correction should be provided for diameter at least 1.6 times larger than $1/e^2$ diameter of an input Gaussian beam.

In next chapter there are discussed methods of realization of various intensity profiles with the same refractive beam shaper as well as ways of adaptation to conditions of real applications.

**Control of profiles**

**Variable Profiles by Variable Input Beam Size**

The feature of the field mapping beam shapers that output beam profile depends on the input beam size, Fig. 1, can be used as a powerful and convenient tool to vary the resulting intensity distribution by simple changing of laser beam diameter with using an ordinary zoom beam expander ahead of the $\pi$Shaper. This approach is demonstrated in Fig. 3 where results of theoretical calculations as well as measured in real experiments beam profiles for TEM\(_{00}\) laser are shown. The data relate to the $\pi$Shaper \(6.6\) which design presumes that a perfect Gaussian beam with $1/e^2$ diameter 6 mm to be converted to a beam with uniform intensity (flattop) with FWHM diameter 6.2 mm. When the input beam has a proper size, Fig.3a, the resulting beam profile is flattop, Fig.3b. Increasing of input beam diameter leads to downing of intensity in the centre, Fig.3c, 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.3d.

![Figure 3 Experimental and theoretical intensity profiles:](image_url)

- 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 considered intensity profiles correspond to about 10% beam size change; the larger are changes the more pronounced is variation in intensity 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 intensity 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.

Next set of profiles in Fig. 4 demonstrates beam shaping of multimode laser.

![Fig. 4 Beam shaping of powerful multimode laser. (Courtesy of Daimler AG)](image)

Radiation of high power solid-state fiber coupled laser ($\lambda = 1064$ nm, $P = 2$ kW, fiber core diameter 600 $\mu$m) was inputted to the collimating beam shaper $\pi$Shaper 37_34_1064 (see photo in Fig. 7) combining the functions of beam shaping and collimation. The beam emerging from the fiber is divergent and has profile shown in Fig. 4a. Output of the $\pi$Shaper is collimated beam, according to basic design it has flattop intensity distribution, Fig. 4b. Since the input beam for the $\pi$Shaper is divergent there is no possibility to change its size like it was done in previous experiments with TEM$_{00}$ laser. However, the $\pi$Shaper 37_34_1064 has a mean to vary the beam size internally – through changing the distance between its optical components, just that way was used to realize the “inverse-Gauss” profiles presented in Fig. 4c and Fig. 4d. One can see, variation of internal parameters of the beam shaper allows varying the resulting profile.

Evidently, a simple external or internal variation of laser beam size allows generating various profiles with the same beam shaper unit. To vary the beam diameter the ordinary beam expanders can be applied. With using the zoom beam expanders or by choosing the distance between $\pi$Shaper components one can steady vary the resulting beam profile and choose an optimum one for a particular laser technology.

There are many applications where variation of intensity profile helps to optimize a laser technology. For example, the welding of plastics, laser heating and hardening techniques get benefits from providing uniform temperature profile on a workpiece and, comparing to flattop or Gaussian profile, the “inverse-Gauss” intensity distribution is optimum one for this purpose.

The super-Gauss distributions are useful in techniques of spectral laser combining, pumping of DPSS lasers like Ti:Sapphire, MOPA laser designs.

**Adaptation to profiles of real lasers**

According to theory the TEM$_{00}$ laser beams have intensity distribution described by the Gaussian function. But in practice the profiles of real lasers differ from that perfect distribution, they can have extended “wings”, be approximate rather a super Gauss function; it becomes more complicated in case
of multimode beams, for example intensity profile of fiber coupled multimode solid-state laser is better described by a parabolic function. Therefore, to be used with real lasers a beam shaper has to be adapted to these real profiles, and in case of refractive field mapping beam shapers like the πShaper it can be easily realized through varying the input beam size. Examples of this adaptation are shown in Fig. 5.

![Figure 5 Theoretical and experimental Input (on left) and Output (on right) intensity profiles for the πShaper 6_6, Din – input 1/e² diameter, Dout – output FWHM diameter: (a) TEM₀₀, M²=1, Din = 6 mm, Dout = 6.2 mm, (b) TEM₀₀, extended “wings”, Din = 6.5 mm, Dout = 6.4 mm, (c) Multimode, parabolic profile, Din = 5.2 mm, Dout = 6 mm, (d) Measured profiles for the πShaper 12_12: input - multimode Din= 10 mm, output - flattop Dout= 12 mm (Courtesy of Georgia Institute of Technology)](image)

There are shown three cases of a laser beam: a) perfect Gaussian, b) with extended “wings” and c) parabolic profile. The πShaper is designed to transform a perfect Gaussian beam of a pre-determined diameter to flattop one therefore the data in Fig. 4a are predictable. When a beam has extended “wings” it is necessary to increase its 1/e² diameter, then the πShaper performs correct transformation to the flattop profile, Fig. 4b, otherwise the resulting profile would be a kind of super-Gauss. In comparison with the Gaussian distribution the parabolic profile in Fig. 4c is “closer” to a flattop, has shortened “wings”, and in case of Din = 6 mm the output profile would be “inverse-Gauss” (like in Fig. 3c), therefore to get an output beam with uniform intensity it is necessary to reduce the input beam 1/e² diameter. Evidently, this adaptation has to be done externally, for example with a zoom beam expander allowing steady varying of the input beam size.

In the considered examples the variation of input beam diameter is about 10%, it can, for sure, be larger or smaller depending on a real laser. The experimental data in Fig. 4d presents measured profiles of multimode high peak power short pulse laser (λ = 1064 nm, pulse energy 2.7 J, pulse duration 6 ns) which radiation was transformed to flattop profile with using the πShaper 12_12_1064, for correct transformation of that laser beam with parabolic intensity profile its input beam diameter was reduced at about 20%.

Again, the size of resulting beam is stable – by 10-20% size variation of input beam the difference of output beam diameter doesn’t exceed ±3%.

Misalignments and skewed profiles

Proper alignment is important for any beam shaping optics; let’s evaluate influence of misalignments in case of refractive field mapping beam shapers. The Fig. 6 presents results of mathematical simulations as well as measurements of real profiles for the πShaper 6_6 in three cases: perfectly aligned, lateral shift of a beam, angular tilt of the beam shaper.

As discussed in chapter 2 the aberration correction of πShaper systems is provided for a diameter being at least 1.6 times larger than 1/e² diameter of a laser beam. Therefore a small, up to about +/-20% of diameter, lateral shift of a beam with respect to the beam shaper, or vice versa, doesn’t lead to aberration but allows to get an interesting beam shaping effect – the output profile is skewed in direction of the lateral shift, this is illustrated in Fig. 6c. The intensity profile itself stays flat but is tilted in the direction of the shift, and a remarkable feature is that the beam itself stays collimated and low divergent. This skewed profile can be used in applications where a steady increasing or decreasing of intensity is required, for example to compensate attenuation of acoustic wave in acousto-optical devices; such a profile can be also
useful in hardening techniques to sustain a wished temperature profile on a workpiece within a movable laser spot.

As an optical system designed to work with axial beams the πShaper operates in relatively narrow angular field, the data in Fig. 6d demonstrate the intensity profile behaviour by the beam shaper tilt at 1°. The intensity profile stays stable but there is visible degradation of quality on left and right sides of the spot due to aberrations, first of all coma. It should be noted that discussed here 1° tilt of the πShaper 6_6 means about 2 mm (!) lateral shift of one of its ends, no doubts this misalignment can be easily compensated by ordinary opto-mechanical mounts.

These data show that the misalignments have influence on the πShaper operation but sensitivity to these misalignments isn’t tremendous, even with essential lateral shift (up to 0,5 mm!) and tilt (up to 1°!) the resulting profiles are close to flattop. In other words, the tolerance of positioning of a beam shaper is rather not tough and misalignments can be compensated by ordinary opto-mechanical mounts. Since the influence of a tilt on wave aberration of output beam is quite pronounced it is advisable to pay more attention to angular alignment while adjustment of beam shapers.

**Generation of “Laser Line”**

Some laser applications like laser cleaning, annealing, hardening, cladding are realized with using multimode laser sources like fiber coupled solid-state and diode lasers or fiber lasers. At the same time in those technologies just the linear shape of laser spot is preferable and the πShaper in combination with anamorphic after it present a robust solution this task. One of implementations of such a system on the base of the πShaper 37_34_1064 for multi kW multi mode laser is presented in Fig. 7.

According to the basic principle of the πShaper operation the output collimated beam has low divergence and can be further transformed to a
wished profile. In the considered layout the collimated beam of uniform intensity is emerging from the \( \piShaper 37_{34}_{1064} \) 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. 7, but stays unfocused in the perpendicular plane X, hence a spot of linear shape is created. This layout was realized for the task of metal hardening with using radiation of high power fiber laser and a line of 10 mm length and about 0.5 mm width was realized. The data of theoretical calculations as well as experimental results are presented in Fig. 8. Evidently, there exists good correspondence between theoretical and experimental results.

Applying of more sophisticated anamorphic optics after a \( \piShaper \) allows providing linear spots with extremely high, up to 1:1000, aspect ratios; developing of a design of an anamorphic optical system is usually a point for a particular technological project.

It should be noted that the experimental data in Fig. 8 demonstrate also important feature of the \( \piShaper \) when working with multimode lasers - capability to create “inverse-Gauss” profile of focused beam characterized by steep edges and low intensity in the centre.

**Conclusions**

Unique features of refractive beam shapers of field mapping type allow applying these systems as versatile tools to generate various intensity distributions. Being originally designed to transform Gaussian beams to beams of uniform intensity these beam shapers show high level of flexibility in generation of other spot shapes and profiles: inverse-Gauss, super-Gauss, skewed flattop distributions, linear spots with uniform intensity. The beam shapers demonstrate low sensitivity to misalignments and capability to work with both TEM\(_{00}\) and multi mode lasers - these features make them robust solutions in plenty of industrial applications. A remarkable feature of \( \piShaper \) is that this variety of resulting intensity distributions can be realized with using the same beam shaper unit!

**References**


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