Freeform beam shaping in optical systems of high-power lasers

Alexander Laskin, Vadim Laskin, Aleksei Ostrun


Event: SPIE LASE, 2015, San Francisco, California, United States
Freeform beam shaping in optical systems of high-power lasers

Alexander Laskina\textsuperscript{a}, Vadim Laskina\textsuperscript{a}, Aleksei Ostrun\textsuperscript{b}

\textsuperscript{a} AdlOptica GmbH, Rudower Chaussee 29, 12489 Berlin, Germany
\textsuperscript{b} St. Petersburg National Research University of Information Technologies, Mechanics and Optics, Kronverkskiy pr, 49, 197101, St.Petersburg, Russia

ABSTRACT

Control of irradiance distribution in complex optical systems of modern high-power lasers is of great importance to increase efficiency of optical techniques used to reach high power levels. For example, flat-top or super-Gaussian irradiance profiles are optimum for amplification in MOPA lasers and for reduction of thermal effects in crystals of solid-state ultra-short pulse lasers when pumping by an external multimode laser. Specific requirements to beam shaping optics in these laser systems are providing variable irradiance distributions, saving of beam consistency and flatness of phase front, capability to work with TEM\textsubscript{00} and multimode lasers, resistance to high peak power radiation. Among various refractive and diffractive beam shaping techniques only refractive field mapping beam shapers like $\pi$Shaper meet these requirements. The operational principle of these devices presumes almost lossless transformation of laser beam irradiance from Gaussian to flat-top, super-Gauss or inverse-Gauss through controlled wavefront manipulation inside a beam shaper using lenses with smooth optical surfaces.

This paper will describe some design basics of refractive beam shapers of the field mapping type and optical layouts of their applying in optical systems of high-power lasers. Examples of real implementations and experimental results will be presented as well.

Keywords: beam shaping, flat-top, tophat, superGauss, MOPA laser, short pulse laser, homogenizing.

1. INTRODUCTION

Modern high power solid-state laser systems require effective and flexible transformation of transverse intensity distribution to optimize optical pumping and amplification in MOPA designs\textsuperscript{1,2}. A common problem when optical pumping of crystals of solid-state lasers, for example Ti:Sapphire crystal with multimode radiation of second harmonic of Nd:YAG, is high peak intensity in the crystal centre that leads to thermal lensing and danger of the Ti:Sapphire crystal damage. As result there are limitations of quality and achievable output laser power of ultra-short pulse laser, instability of laser operation. Transforming of that pumping beam to a beam of uniform of intensity or even providing a “concave” (or “inverse-Gauss”) intensity distribution helps to overcome those problems and provide more efficient optical systems of solid-state lasers.

Similar positive effect of beam shaping is important in high power lasers built according to MOPA configuration. With flattop or super-Gauss intensity profile of a beam after seed laser it is possible to achieve higher amplification of the radiation in amplifier due to more efficient use of energy from a pump source, reduce the influence of thermal lensing. As result the higher levels of output power as well as more reliable laser operation can be achieved.

Summarizing one can describe the requirements to beam shaping optics for high-power laser systems:
- high resistance to powerful laser radiation,
- high transmission,
- conserving the structure and low divergence of a laser beam,
realizing beam shaping in general sense, i.e. not only beam homogenizing but also providing other profiles, like super-Gauss, inverse-Gauss,
- it is highly desirable that the variety of these profiles can be realized with the same beam shaper,
- capability to work with TEM$_{00}$ and multimode laser sources,
- adaptability to conditions of particular laser system.

These specific conditions are perfectly fulfilled by the refractive field mapping beam shapers due to their unique features: almost lossless intensity profile transformation, low output divergence, high transmittance and flatness of output beam profile, extended depth of field, adaptability to real intensity profiles of TEM$_{00}$ and multimode laser sources. Combining of the refractive field mapping beam shapers with other optical components, like beam-expanders, relay imaging lenses, anamorphic optics makes it possible to generate the laser spots of necessary shape, size and intensity distribution.

2. DESCRIPTION OF FIELD MAPPING REFRACTIVE BEAM SHAPERS

2.1 Basics of optical design

Under the name “Beam Shaping” there are considered various optical techniques, including ones based on diffractive optical elements, arrays of microlenses or prism, field mapping beam shaping with using mirrors or lenses with special surface shapes$^3$. Among various types of beam shaping the refractive field mapping systems like $\pi$Shaper demonstrate best capabilities to meet the above described requirements. The design principles of refractive beam shapers of the field mapping type are well-known and described in the literature$^{3,7,8,9,10}$, one of implementations is presented in Fig. 1. These beam shapers are typically built as telescopic systems with collimated beams at entrance and exit; they have two optical components and transform the laser beam profile in a controlled manner, by accurate inducing of wave aberration by the first component and further its compensation by the second one, Fig.1, top. The resulting collimated output beam has a uniform intensity and flat wave front. It also has low divergence – almost the same like that of the input beam. In other words, the field mapping beam shapers, like $\pi$Shaper, transform the beam profile without deterioration of the beam consistency and without increasing its divergence.

![Figure 1 Refractive field mapping beam shaper $\pi$Shaper](https://www.spiedigitallibrary.org/conference-proceedings-of-spie/download/9345-93450J-2)
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 to flattop (top-hat, uniform) irradiance distribution;
- almost 100% efficiency;
- high transmittance;
- transformation through controlled phase front manipulation – 1\(^{\text{st}}\) optical component introduces spherical aberration required to re-distribute the energy, then the 2\(^{\text{nd}}\) 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,
- 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 band simultaneously;
- Galilean design, no internal focusing.

Example of beam shaping for Nd:YAG laser is presented in Fig.2.

The achromatic design of the \( \pi \)Shaper is inevitably required for ultra-short pulse laser with duration about 100 fs and less – these lasers have relatively wide spectral band, up to several hundreds of nm, and providing the same conditions of beam shaping for entire working bandwidth is very important.

The Galilean design of telescopic system guarantees avoidance of any internal focusing of a laser beam that is also very important for reliable operation of a beam shaper with high peak power lasers.

2.2 Control of profiles

Operation principle refractive field mapping beam shapers 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. In other words, a variation of input beam size corresponds to variation of output beam intensity distribution, and the size of the output beam stays almost invariable. 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\(^{11}\) and is illustrated in Fig. 3 where measured in real experiments beam profiles are shown.

The data relate to the \( \pi \)Shaper 6.6 which design presumes that a perfect Gaussian beam with 1/e\(^2\) diameter 6.2 mm to be converted to a beam with uniform intensity (flattop) with FWHM diameter 6 mm.

When the input beam has a proper diameter \( D_{in} \) = 6.2 mm, Fig.3 middle column, the resulting beam profile is flat-top, Fig.3 middle bottom. But change of input beam size results in changing of the output beam profile: increasing of diameter leads to a concave intensity distribution with minimum in the beam centre, Fig.3 right column, this distribution is called “inverse-Gauss”; while beams size reduction allows to get a convex profile that approximately can be described by super-Gauss functions, Fig.3 left column.
Figure 3  Experimental spot views and intensity profiles by beam shaping of TEM$_{00}$ laser using $\pi$Shaper 6_6: top - input beams with various diameters $D_{in}$ (1/e$^2$), bottom – output beams.

$D_{in} = 5$ mm
$D_{in} = 6.2$ mm
$D_{in} = 7$ mm
Evidently, a simple variation of laser input beam size allows to generate various profiles and this can be done with the same beam shaper. To vary the beam diameter the ordinary beam expanders or imaging optical systems can be applied. With using a zoom beam-expander one can steady vary the resulting beam profile and provide the intensity distributions being optimum for particular optical systems of high power lasers. A remarkable feature is that variation of beam size at the entrance of a refractive field mapping beam shaping system leads to variation of output intensity distribution but has weak influence on the spot size, so the output beam has stable size but variable profile.

2.3 Creating square shaped flat-top beams
Optical designs of many laser systems presume using square shaped crystals, and to optimize the optical pumping or amplification it is advisable to provide a flat-top beam with square shaped cross section. Design principle\(^3,12\) of refractive beam shapers presumes operation with beams of circular symmetry, therefore output beam is round and square shape is usually realized using a square mask and its further imaging in working space\(^2\). This approach works well but leads to essential, up to 30\%, energy losses; on the other hand image of a mask illuminated by highly coherent laser light is characterized by pronounced diffraction side-lobes. Optimum solution in laser design applications of optical pumping or amplification would be a beam with flat phase front, homogenized intensity, square shape of cross section and smooth edges.

In case of using refractive field mapping beam shapers this solution can be realized by use of birefringent optical materials, for example crystals, to manufacture lenses of a beam shaper. Then, by choosing optimum orientation of polarization of a laser beam, wave plates and birefringent lenses it is possible to redistribute lossless the laser energy and provide square or other beam section shapes. To avoid essential influence on a beam structure and disturbance of its phase front it is advisable to use materials of weak birefringence, for example uniaxial crystals with orientation of crystal optical axis parallel to a beam shaper optical axis.

This design approach is applied in \(\pi\)Shaper models intended to be applied with high peak power short-pulse lasers – lenses are made from sapphire, and due to coincidence of optical axes of crystal and whole beam shaper there exists a tiny birefringence effect that allows realize square-shaped output beam, Fig.4. The edge smoothness depends on input beam size; this point was considered in previous paragraph.

2.4 Imaging technique
When a TEM\(_{00}\) laser beam with Gaussian intensity distribution propagates in space its size varies due to inherent beam divergence but the intensity 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 intensity distributions, for example flattop beams, propagate in space, they get simultaneously variation of both size and intensity profile. Suppose a coherent light beam has uniform intensity profile and flat wave front, Fig. 5, this is a popular example considered in diffraction theory\(^3,6\), and is also a typical beam created by field mapping refractive beam shapers converting Gaussian to flattop laser beam.
Due to diffraction the beam propagating in space gets variation of intensity distribution, some typical profiles are shown in Fig. 3: at certain distance from initial plane with uniform intensity 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 equation

$$I(\rho) = I_0 \left[ \frac{J_1(2\pi \rho)}{(2\pi \rho)} \right]^2$$  \hspace{1cm} (1)

where \( I \) is intensity, \( J_1 \) is the Bessel function of 1st kind, 1st order, \( \rho \) is polar radius, \( I_0 \) is a constant.

Evidently, a flat-top beam is transformed to a beam with essentially non-uniform intensity 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 flat top 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 considered here applications of optical pumping and amplification in designs of high-power lasers it is important to conserve a uniform intensity profile over certain distance. As a solution to the task of providing a necessary resulting spot size with conserving the flat top profile over extended DOF it is fruitful to apply imaging techniques. Essential features of this approach are considered in paper 1, here we emphasize on most important for practice aspects and consider telecentric imaging system shown in Fig. 6, which is also called as a relay imaging system.

The optical system providing telecentricity in both spaces of the Object and the Image is composed from two positive optical components in such a way the back focus of the 1st component coincides with the front focus of the 2nd component, i.e. the optical system presents the Keplerian telescope, which famous feature is capability to create real image. Since the optical power of this telecentric system is zero:

- the flat phase front in the Object space is mapped to the flat phase front in the Image space,
- the transverse magnification of the optical system is constant and doesn’t depend on position of the Object,
- if the Object is located in front focal plane of 1st component its Image is in back focal plane of 2nd component.
From the point of view of geometrical optics an Image is always created by a beamlet of rays emerging from a particular point of an Object, therefore in Fig. 6 there are shown beamlets of divergence $2\alpha$ from couple of Object points. In case of laser beams the divergence of beamlets corresponds approximately to divergence of a laser beam $2\theta$, i.e. is very small for TEM$_{00}$ beams, and the intensity profile behaviour in a telecentric system should be analysed using diffraction theory. Let’s consider transformation of intensity profile on example of the telecentric imaging system in Fig. 7.

Collimated Gaussian laser beam from TEM$_{00}$ laser is expanded to optimum size and then transformed by the $\pi$Shaper to collimated flattop beam, the output of the $\pi$Shaper is considered as an Object plane for the telecentric imaging system. Since the $\pi$Shaper conserves low divergence of laser beam, the intensity profile after it gets transformation due to diffraction that is similar to one shown in Fig. 5. As result near the lenses, Fig. 7, the intensity distribution isn’t uniform, it is typically characterized by appearing some diffraction rings, a particular profile depends on wavelength, beam size and distance from the Object to lenses. According to the diffraction theory the intensity distribution in a certain plane is result of interference of light diffracted from previous plane of observation. One of well-known conclusions of that theory is similarity of intensity distribution in optically conjugated Object and Image planes: if the intensity distribution is uniform in the Object plane, it is uniform in the Image plane as well; and the profile at the $\pi$Shaper output aperture will be repeated in the Image plane of that aperture, herewith the resulting spot size is defined by transverse magnification $\beta$.

A positive lens has a well-known ability to perform two-dimensional Fourier transform and create in its back focal plane intensity distribution proportional to one in far field. This means in the considered case that intensity distribution in back focal plane of 1$^\text{st}$ lens, marked in Fig. 7 as “$F_1=F_2$”, is just “Airy disk” described by Eq. (1).

Summarizing results of this example one can see that uniform intensity after $\pi$Shaper, the Object plane, is transformed to non-uniform intensity in area around the lenses, to essentially non-uniform “Airy disk” distribution in back focal plane of 1$^\text{st}$ lens, and finally is restored to uniform intensity 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 intensity profile is transformed along the beam path, since the intensity distribution in the Image plane repeats the Object plane distribution with taking into account transverse magnification. 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 for transmitting of full light energy through a system and avoid any beam clipping.
3. EXPERIMENTAL RESULTS OF BEAM SHAPING

In this chapter there are presented examples of beam shaping to enhance specifications of ultra-short pulse lasers by improving pumping and optimizing conditions for amplification.

3.1 Improving optical pumping of Ti:Sapphire lasers

One of important applications of the refractive beam shapers is homogenizing multimode radiation from 2<sup>nd</sup> Harmonic Nd:YAG laser when pumping Ti:Sapphire crystals to generate powerful ultrashort pulses. The well-known problem of developing powerful femtosecond lasers is high central peak of intensity distribution of a 532 nm multimode pumping laser that leads to destroying of central part of a Ti:Sapphire crystal, this limits, practically, a maximum power level. Evidently, downing of intensity in the centre of the multimode pumping beam would allow to overcome this obstacle in reaching higher power of a femtosecond laser.

Just this task can be successfully solved by a field mapping beam shaper; result of realization of this approach by one of users is illustrated in Fig. 8.

Intensity distribution of the original multimode beam is quite far from the Gaussian function, it is rather flattop but with a pronounced peak in centre of the beam, just this intensity peak is a source of such a problem like damaging of Ti:Sapphire crystal. Applying of the beam shaper effects downing of intensity in central part of the beam and, hence, eliminating of the central peak and providing more smooth beam profile being optimized for pumping of Ti:Sapphire crystal. As result the output laser power as well as its stability was seriously enhanced.

3.2 Beam shaping in MOPA lasers

As an example of applying the refractive beam shapers in MOPA lasers one can consider the advanced laser system LIFE Lifetest Facility in LLNL, Fig. 9, used for testing the damage threshold of optical components of NIF.

To provide correct measurements of damage threshold it was necessary to realize several laser beams with various wavelengths, pulse energies and durations but with just flattop intensity profiles. A complex laser optical system was applied where the radiation emitted by the oscillator, on left side in Fig. 9, was transformed using the $\pi$Shaper to a beam of uniform intensity and then amplified using high power amplifiers to provide necessary testing modes of the optical components.
4. CONCLUSION
Spatial beam shaping is important in high power laser systems to improve optical pumping of crystals or amplification in MOPA lasers. The lasers are characterized by ultra-short pulse durations and high peak power; therefore beam shaping optics should meet specific requirements like high transmission and resistance. Optimum beam shaping systems are built on the base of refractive field mapping beam shapers \( \pi \text{Shaper} \) featured with low divergence, conservation of beam consistency, variable beam profiles, and operation with TEM\(_{00}\) and multimode beams. Being originally designed to transform Gaussian beams to beams of uniform intensity (flat-top) these beam shapers show high level of flexibility in generation of various intensity profiles like inverse-Gauss, super-Gauss, and this variety of transformations can be realized with using the same field mapping beam shaper. Refractive field mapping beam shapers made from homogeneous optical materials provide round flat-top output beam, but using of birefringent crystals makes it possible to generate square shaped output beam, thus realizing transformation of a round input TEM\(_{00}\) beam to square-shaped flat-top beam with smooth edges – all this properties are important to optimize optical pumping and amplification techniques.

5. REFERENCES

6. ACKNOWLEDGEMENTS
The authors grateful to users of \( \pi \text{Shaper} \) in Lotis, LLNL and for their active and patient work with optics discussed in this paper and kind permission to publish some results achieved during their experiments.