πShaper - Refractive Beam Shaping Optics for Advanced Laser Technologies

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Abstract. Laser beam shaping brings to various industrial and scientific laser techniques effects that improve their performance comparing to what can be achieved with using Gaussian or Gaussian-like laser beams: more stability, less tough positioning tolerances make the technologies easier to use, higher efficiency of using of costly laser energy, etc. The task of such a transformation is solved by series of refractive beam shaping optics of field mapping type. This solution is important in irradiating the cathode of Free Electron Lasers, confocal microscopy, biomedical fluorescence techniques, many industrial technologies like welding, cladding, hardening, various laser techniques in photovoltaics, homogenizing of pump radiation by building powerful femtosecond lasers, etc. The refractive beam shapers can be used with TEM00 and multimode laser beams, achromatic design provides the same conditions of beam shaping for several lasers of a certain spectrum range simultaneously, low inherent losses allow to use them with powerful laser sources, particular models can be implemented as Galilean Telescope without internal focusing or as Collimators. This paper will describe the principles of operation, design features of the achromatic refractive beam shapers; there will be presented examples of beam intensity transformation and effects on material processing achieved in several industrial applications.

1. Introduction
The lasers are widely used in various applications in science and industry and their effective using is very important. Typically the intensity distribution of laser sources is described by the Gaussian function provided by physics of creating the laser radiation. From one side, this Gaussian profile provides high energy concentration, however, from another side for many industrial, scientific and life science applications it is not an optimum one because of non-uniform intensity distribution within the laser beam. In plenty of laser techniques a homogenized laser beam is most preferable from the point of view of saving the energy and providing the same conditions of illumination or material treatment in the beam area. Therefore, the task of re-distribution of energy within the laser beam to provide uniform intensity profile is an actual scientific and industrial task. In many cases a solution can be realized on the base of a family of refractive beam shaping systems πShaper.

Unlike other beam shaping solutions, like truncation of a beam by an aperture or attenuation by apodizing filters, integration systems based on arrays of microlenses, micromirrors, prisms or DOE, the πShaper realizes so called field mapping approach featuring by the intensity profile transformation

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in a controlled manner by introducing a pre-determined wave aberration with, after the intensity re-
distribution, its compensation. As result accurate, theoretically almost lossless transformation is
provided and a collimated, speckle-free beam is created.

2. Principles of operation

2.1. Motivation – increasing efficiency of using laser energy

All laser applications have specific features of interaction of material and laser radiation. There is,
however, something common for all single mode (TEM\textsubscript{00}) lasers — the Gaussian function of intensity
distribution. Therefore approximate evaluation of the efficiency of using laser energy can be done by
considering just the geometrical features of the Gaussian function, without taking into account effects
accompanying laser treatment of materials like burning, melting, etc.

The three-dimension intensity profile can be interpreted as a geometrical figure bounded by a
horizontal plane and a surface of the Gaussian function \( I(r) \)

\[
I(r) = I_0 \exp\left(-2\frac{r^2}{\omega^2}\right)
\]

where \( r \) designates a variable beam radius in polar coordinates,
\( \omega \) designates a waist radius of the Gaussian laser beam,
\( I_0 \) is constant.

Fig.1 shows a section of such a figure, its volume has physical sense of energy of the laser beam. Let’s denominate by variables \( E_1, E_2, E_3 \) different parts of that figure:

- \( E_1 \) - an “apex” of Gauss function is an excess of intensity over the working level \( I_h \), very often this is a loss of energy or a source of overheating the central portion of a zone under treatment,
- \( E_2 \) - “tails” of Gaussian distribution, almost always this is a loss of energy or a source of uniwished effects like heat affected zone (HAZ), and
- \( E_3 \) - “effective cylinder” of energy.

By mathematical transformation one can get following formulae to calculate the energy parts \( E_1, E_2 \) and \( E_3 \):

\[
\begin{align*}
E_1 &= 1 - h + \ln h \\
E_2 &= h \\
E_3 &= -\ln h \\
E_1 + E_2 &= 1 + \ln h 
\end{align*}
\]

where \( h = I_h / I_{max} \).

The results of calculations are presented on right diagram in Fig.1.

The unconditional energy loss \( E_2 \), “tails”, can reach a very high level - for example, if a working energy level \( I_h \) is half of maximum (\( h = 0.5 \), very often just this level is considered as a working one) the energy losses are 50 percent of full laser beam energy!
In the case of laser treatment of thin films the energy part $E_1$, “apex” of Gauss, is also considered as a loss of energy because this part exceeds the working energy level $I_w$. Thus both energy parts $E_1$ and $E_2$ are losses, the sum $E_1 + E_2$ has sense of combined losses and minimum of this function is 0.63! In other words, when treating thin films, in the best case, “only” 63 percent of energy is lost and 37 percent is effective!

No doubt, transformation of the original Gaussian shape to “an effective cylinder”, called as a flattop or top hat profile would help to save laser energy and improve those technologies where uniform intensity is most desirable. This transformation is a main function of the $\pi$Shaper systems.

2.2. Design features of the $\pi$Shaper

An idea of the $\pi$Shaper operation is illustrated with Fig. 2. Gaussian (or close to Gaussian) intensity distribution of a TEM$_{00}$ or multimode laser beam is converted to a flat-top distribution (similar to a Greek letter $\pi$) that stays invariable over long distance after the $\pi$Shaper.

![Figure 2. Principle of the $\pi$Shaper operation](image)

![Figure 3. Example of optical layout](image)

This transformation is realized through distortion of the beam wave front inside the optical system under the condition of conservation of energy, this effect is illustrated with a picture in Fig. 3. Mathematically this condition is formulated as follows

$$\int_0^{r_{in}} I_{in}(r) \cdot r \cdot dr = \int_0^{R_{out}} I_{out}(R) \cdot R \cdot dR,$$

(3)

where $r$ is an input beam radius in polar coordinates,
$I_{in}(r)$ is a function of intensity distribution of the input laser beam section,
$r_{in}$ is a max. radius of the input beam subjected to considered intensity distribution,
$R$ is an output beam radius in polar coordinates,
$I_{out}(R)$ is a function of intensity distribution of the output beam,
$R_{out}$ is a max. radius of the output beam resulting after the intensity redistribution.

Another basic principle of a beam shaper is zero wave aberration; this means the aberration introduced by first optical component is then compensated by the second one. Other details of refractive beam shapers of field mapping type like $\pi$Shaper can be found in publications [1,2,3,4,5], here we will emphasize on some features important for their practical using.

An essential design feature of the $\pi$Shaper optical system is in consisting of two optical components and controlled wave front transformation in the space between them due to applying of special optical surfaces, as result necessary intensity redistribution is achieved. Another important feature of the $\pi$Shaper optical design is zero or negligible for practical applications residual wave aberration, this means equal path lengths for all rays of input beam passing through the optical system; this condition is very important for practice since guarantees flat output wave front and avoidance of appearing undesirable interference fringes, this provides also low output divergence and keeping the result intensity profile over long distance after the $\pi$Shaper.

One of important features of the $\pi$Shaper optical systems over other approaches is in their achromatic design that guarantees simultaneous fulfillment of conditions of intensity redistribution and zero or negligible wave aberration for a certain spectral range, as result the achromatic optical
systems provide the same operation at each wavelength of this spectral range. This feature is realized through using materials with different dispersion characteristics.

Providing of the same operation of the achromatic πShaper optical systems at each wavelength of the certain spectral range makes these systems very useful in the applications where several laser sources are applied simultaneously, for example in spectroscopy, fluorescence life science technologies, confocal microscopy. This feature is very important, also, in material processing technologies where various lasers are applied in one technology cycle, for example by manufacturing the solar cells. Another important application example is ultrashort pulse lasers, like femtosecond Ti:Sapphire lasers, where small pulse duration is achieved due to wide spectral bandwidth of a laser source.

To prevent internal focusing of a laser beam all πShaper optical systems realize so called Galilean type telescope, this is a critical point for high power and short pulse laser applications.

The πShaper are capable to work with TEM₀₀ as well as multimode lasers.

Summarizing, the most important features and basic principles of πShaper are:

- telescopic or collimating refractive optical systems that transform Gaussian, or close to Gaussian intensity distribution of source laser beam to a flattop (or top-hat, or uniform) one;
- The initial laser beam can be either a TEM₀₀ or a multimode one;
- The uniform intensity is kept after the πShaper over a large distance;
- There are available telescope models, as well as systems with optical power like collimator;
- The transformation is provided for a certain spectral range, thus πShaper is an achromatic system;
- Galilean design, thus there is no internal focusing of a beam.

Currently the πShaper model line includes many systems capable to work with laser beams of various input size as well as of various wavelengths, Fig.4.

Most of models are implemented as telescopes, thus collimated input and collimated output. However, there are also available collimator type models with a divergent input beam and, hence, combining functions of beam shaping and collimation, this feature might be of interest for fiber laser sources.

An example of a collimating beam shaper is πShaper 37_34_1064, Fig.5, this system is intended to work with powerful, up to 6 kW, industrial lasers like fiber-coupled multimode solid state lasers or diode lasers, fiber lasers.

![Figure 4. Outlook of some πShaper models](image)

![Figure 5. πShaper 37_34_1064](image)

(a) outlook,
(b) mounted on industrial robot.  
*Courtesy of Daimler AG*

Due to their features the πShaper’s are useful beam shaping tools in various laser techniques where working beam sizes are orders of magnitude greater than an operating wavelength, usually they are recommended to be applied when required laser beams sizes are more than 0.2 mm. Low divergence of output beam makes possible further beam size and spot shape manipulation by applying additional lenses, beam-expanders or anamorphic optics.
3. Examples of optical layouts on the base of \( \pi \)Shaper

3.1. Beam Size manipulation with beam-expanders

According to basic design the output beam after refractive field mapping beam shapers is round and has a pre-determined size, for example, in case of \( \pi \)Shaper 6_6 the resulting beam diameter is about 6 mm. For some tasks that’s enough, however most often it is necessary to change the beam diameter. For example, the applications, where it is necessary to illuminate a Spatial Light Modulator or a mask with a collimated laser beam of uniform intensity, usually require expansion of a beam after the refractive field mapping beam shaper. At the same time many scientific and industrial tasks can be successfully solved when a collimated beam of uniform intensity and diameter of about 1 mm is provided, some of them are laser welding, hardening, cladding, etc.

Common features of these beam transformations are varying the beam size and leaving the laser beam collimated. Evidently, this optical task can be easily solved by applying a beam-expander or a beam-reducer of telescopic type with an appropriate magnification factor; the principle optical layouts are shown on Fig.6.

When variable final beam size is required one can apply a zoom beam-expander.

The beam expansion leads to extending of the space where a resulting beam profile is kept stable because the diffraction effects influencing on the beam profile transformation become less strong; another reason is in reduction of residual wave aberration always existing in real optical systems. Therefore, expansion factor is limited rather by capabilities of applied beam-expanders.

In case of beam demagnification it is recommended don’t exceed a factor 10, since too much beam reduction would lead to increasing the residual wave aberrations and, hence, quicker beam profile deterioration when its propagation in space.

3.2. Generation of linear spots with using anamorphotic optics

There are many industrial applications which performance can be seriously improved by applying a linear shape of laser spot, some examples of them are laser cleaning, annealing, hardening, cladding. Therefore, the task of generation of a “laser line” is very important and refractive field mapping beam shapers in combination with special anamorphotic optics can be successfully used as a solution. An example of a layout of such a combined system is shown on the below Fig. 7.

The collimated beam of uniform intensity is emerging from a refractive field mapping beam shaper and is then focused by an anamorphotic optics that is implemented as a pair of lenses, one of them is an ordinary spherical lens and another one is a negative cylinder lens. Due to the inherent astigmatism of the anamorphotic 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. The length and the width of the line are defined by parameters of anamorphotic optics and aspect ratio can be up to 1:1000! The above 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, more detailed description and results achieved are discussed later in the chapter of experimental results.

4. Examples of operation of the refractive field mappers
Essential features of operation of the refractive field mapping beam shapers can be seen in the example of beam intensity re-distribution of a TEM\(_{00}\) laser beam on Fig. 8, here there are presented beam profiles measured with a camera based beam profiler.

In spite of deviation of intensity distribution of the input beam from the perfect Gaussian function the beam shaper provides quite good quality of re-distribution. Due to operational principle a field mapping beam shaper cannot suppress high frequency intensity modulation of original beam; that is why that modulation presents in resulting profile as well. The bright rim in the output spot is result of too much energy in “tails” of that non-perfect Gaussian original beam.

Since the original beam is rather elliptic the horizontal and vertical output profiles have minor difference – there exists some arising of intensity in periphery of vertical profile; that difference is, however, quite weak, and this shows the achromatic beam shaper is capable to smooth away the ellipticity of original beam.

An illustration of the beam shaper influence on the results of material treating is presented in Fig. 9. Here one can see a comparison of engraving of a circular hollow in material used in photovoltaic: with a TEM\(_{00}\) Nd:YAG laser and the same laser with the refractive field mapper.

The difference of engraving results is evident - irregular shape of the hollow with a ragged unwished hole in the center in case of original TEM\(_{00}\) laser, and the good shaped round hollow with a controlled depth when applying the field mapping beam shaper.

Fig. 10 presents results of intensity re-distribution of a multimode beam of 2 kW fiber coupled solid-state laser with using the collimating refractive beam shaper shown in Fig. 5.

Evidently the collimating refractive beam shaper can successfully operate with multimode beams and is capable to manipulate the resulting beam intensity distribution by varying internal settings (distance between components), - either the flattop profile, or a profile with steep edges and intensity downing in the beam centre can be realized. In other words, under certain conditions the beam shapers of field mapping type can realize not only the flattop but also some other profiles, this gives users freedom in choosing an optimum for a particular application profile.
Focusing of a multimode beam after a refractive field mapping beam shaper leads to some useful effects. The Fig. 11 shows a comparison of view of caustics for multimode 2 kW solid state laser, fiber-coupled to 600 micron fiber, by focusing with using the same lens in 2 cases: (a) with ordinary collimator and (b) with the Shaper 37_34_1064 as a collimator. Evidently, there is a difference in the beam profile behaviour in zone of image plane of a fiber end – in case of the beam shaper the caustic is characterized by an extended zone along the optical axis where the intensity profile is uniform and beam size stays almost invariable, this is something like a “pipe of uniform intensity”. This feature makes it possible to achieve more stable and predictable results of welding, brazing, and many other applications where a uniform intensity profile is advisable, while the extended “pipe of uniform intensity” increases a tolerance extent on position of a tool with respect to a workpiece that simplifies applying of a laser technology.

![Figure 11. Caustic view: (a) Ordinary Collimator and Lens; (b) Collimating beam shaper and Lens.](image)

The optical system described in section 3.2 and presented in Fig. 7 was realised in IPG Photonics to generate a linear shape of the spot of multimode 3 kW fiber laser for laser hardening of metal parts, sure, this approach can be applied in many other technologies where a linear spot can improve their performance.

The uniform intensity was provided over the long axis which length was about 10 mm, the line width was about 0.5 mm. Since it was planned to move the linear spot over a workpiece in direction perpendicular to the long axis the intensity profile in short axis wasn’t specified, a main aim was to achieve as narrow as possible line.

Results of numerical calculations for the optical system, Fig. 7, implemented as a Shaper 37_34_1064 with an anamorphotic system are shown in Fig. 12. Results of intensity profile measurements in area of working plane are presented in Fig. 13. Evidently, there exists good correspondence between theoretical and experimental results.

Let us note one important feature of the field mapping beam shapers that is very good seen in this example –

![Figure 12. Computer simulation of beam profile created in optical system described in Fig. 7.](image)

![Figure 13. Results of measurements with using a beam profiler: On left - 3D view of the spot, On right – profiles in sections. Courtesy of IPG Photonics](image)
capability to create not only uniform resulting profiles but some other beam shapes like so called “inverse Gauss” characterized by steep edges and downing of intensity in the centre. Just this “inverse Gauss” profile was achieved in short axis of the final linear spot while focusing the laser radiation of multimode fiber laser, Fig. 13 on right. Thus, depending on settings the field mapping beam shapers provide various beam profiles, and this flexibility is very useful and important in various laser technologies since gives the possibility to choose an optimum intensity distribution for a particular application.

5. Conclusions

Growing complexity and variety of laser applications demand various designs of beam shaping optics. Laser technologies and techniques, where a required final laser beam should have other than Gaussian profile, low divergence and the size orders of magnitude larger than a wavelength, can be improved by applying refractive beam shapers of field mapping type, like $\pi$Shaper, providing collimated beams of uniform intensity. The specific features of refractive field mapping beam shapers provide flexibility in manipulation of the size and the spot shape by applying additional optical components. Low divergence of output collimated beam, near the same like in input beam, leads to extended space after a beam shaper where a resulting beam profile is kept stable, which, in turn, guarantees the long depth of field of a combined optical system. At the same time very high factors of expansion, demagnification as well as high aspect ratios of linear spot shapes become available. These features in combination with inherent capability of field mappers to create not only flattop but also other beam profiles (“inverse Gauss”, etc.) make these devices a convenient tool to build beam shaping optics for various industrial and scientific applications.

6. References

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