

REFRACTIVE FIELD MAPPING BEAM SHAPING OPTICS: IMPORTANT FEATURES FOR A RIGHT CHOICE

Paper M1301

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Abstract

There are different kinds of refractive beam shapers of field mapping type used to transform the laser intensity distribution in order to get improvements or special effects in various laser technologies like welding, cladding, hardening, laser techniques in photovoltaics, etc. A right choice of a suitable beam shaper depends on physical specifications of a particular laser application. As a rule, when a final laser spot size is orders of magnitude greater than a laser wavelength, say of millimetre or centimetre scale, it is optimum to apply the beam shapers providing a collimated beam with flattop or another pre-determined output intensity profile. When a final spot size is comparable with the laser wavelength, say tens of microns in micromachining, it is advisable to apply the beam shapers intended to create the required intensity distribution in focal zone of a beam focused. Correspondingly, different kinds of refractive beam shapers, like π Shaper or Focal- π Shaper, should be applied.

This paper will describe important features of intensity profile transformation in optical systems, principles of operation and design features of refractive field mapping beam shapers π Shaper and Focal- π Shaper. There will be presented examples of beam intensity transformation and effects on material processing in several industrial applications.

Introduction

Since the lasers are widely applied in various applications in science and industry their effective using is very important. Typically the intensity profile of laser sources is described by the Gaussian function provided by physics of creating the laser radiation. On one hand, this Gaussian profile provides high energy concentration, however, on the other hand for many industrial, scientific and life science applications it is not an optimum one because of non-uniform intensity distribution within the laser beam⁵. The task of changing

the intensity distribution of a laser beam is solved by so called beam shaping optics¹. Today there are available many optical systems realizing various beam shaping techniques: truncation of a beam by an aperture or attenuation by an apodizing filters, integration systems based on arrays of microlenses, micromirrors, prisms, various types of diffractive optics, various field mapping optical systems; a comprehensive information about beam shaping optics is contained in book¹. Since the main experience of authors relates to applying of refractive beam shapers of field mapping type just these optical systems are considered in frames of this paper. An important feature of the refractive field mappers is in achieving the intensity profile re-distribution due to accurate correction of the beam wave front with saving the beam structure, this principle is a base of optical design of a family of refractive beam shaping systems π Shaper^{3,4,5}, in most of implementations a resulting beam is collimated, low divergent, speckle-free. A fundamental feature, distinguishing the field mapping systems from many other beam shaping techniques, is in capability to create not only flattop (or top hat) but also other intensity profiles, so in addition to the function of a beam homogenization it is provided a freedom to create various intensity profiles that might be required for particular laser technologies.

In frames of this paper there will be considered two basic types of refractive beam shaping optics:

- π Shaper – beam shapers to create collimated beams of uniform intensity which sizes are orders of magnitude greater than a wavelength, and
- Focal- π Shaper - optics to be used together with a diffraction limited focusing lens to create laser spots which size is comparable with a laser wavelength; output profile of F- π Shaper is optimized to realize flattop and other intensity profiles in focus zone of the lens.

Theoretical considerations

Like for any optical systems operation of the laser beam shaping optics of different type obeys the laws of diffraction theory being a base for considering any optical effects. Description of that theory can be found in book², here we mention some basic features that will be important for further considerations.

The Huygens-Fresnel Principle is the corner stone of the diffraction theory. According to that principle each point of a wave front can be considered as a center of a secondary spherical wavelet and by the light propagating in space the distribution of light in a particular plane or a surface can be defined as result of interference of those secondary wavelets. The rigorous mathematical theory for considering the diffraction effects was built by Kirchhoff, Helmholtz, Maxwell and other scientists in 19th century, for example, usually considerations concerning particular optical effects start from so called Fresnel-Kirchhoff diffraction formula². Since the integral equations of mathematical description are quite complicated and impractical for engineering purposes there are used

various simplifications like Fresnel approximation or Fraunhofer approximation².

A well-known and widely used conclusion from the diffraction theory is that the light field amplitude distribution in the special case of a focal plane of a lens is proportional to Fourier-image of input field amplitude distribution; examples of this transformation are shown in Fig. 1 and will be considered later. Summarizing analytical considerations concerning the Fourier transform by an optical system of circular symmetry one can express, in polar coordinates, the field amplitude distribution U_f in the focal plane of a lens by the formula

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

where

U_{in} - field amplitude at the input of a lens,

ρ - a polar radius in the focal plane of the lens,

r - a polar radius at the input of the lens,

J_0 is the Bessel function of the first kind, zero order,

B is a constant.

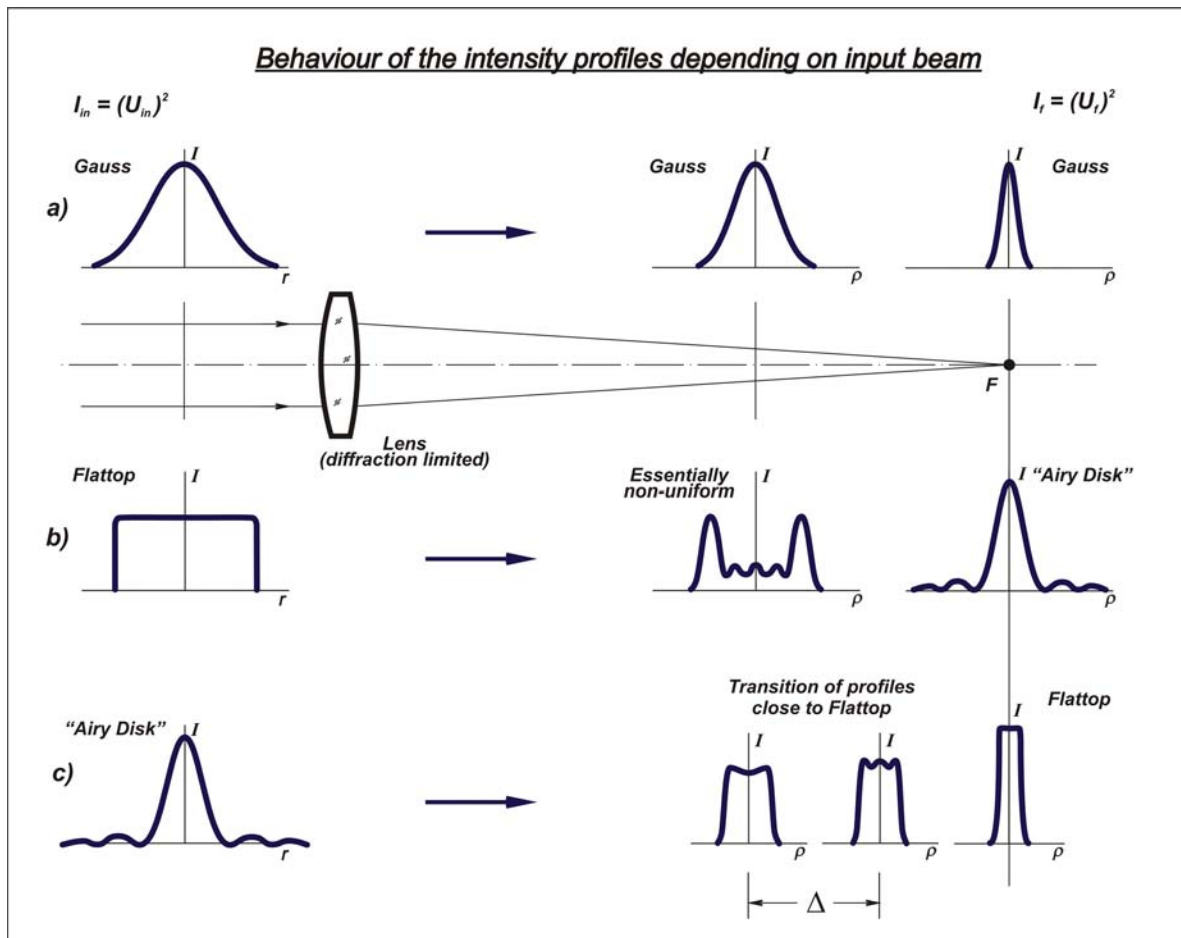


Fig. 1 Examples of the intensity profile transformation when a beam is focused by a lens.

This expression is accordingly referred to as the Fourier-Bessel transform, or alternatively as the Hankel transform of zero order.

In most of laser technologies the result of influence of the laser radiation on material is evaluated with using intensity distribution of a beam. Therefore, for practical usage it is necessary to express the intensity distribution I_f in the focal plane of a lens through the function of field amplitude, for this purpose the well-known relationship² can be used

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

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

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

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

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

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

According to the Huygens-Fresnel principle the intensity distribution in a plane of analysis is an interference pattern created by interference of secondary wavelets. Evidently, while the beam propagating in space the conditions for interference get changes and, hence, that pattern varies in different planes of analysis. In other words, *in each plane after the lens the intensity profile differs from one of a neighbor plane, and features of this profile variation depends on the initial beam profile at the entrance of the lens.*

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

$$I_{in}(r) = I_{in0} \exp(-2 \cdot r^2 / \omega^2) \quad (3)$$

where

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

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

$$d = 4\lambda f \cdot M^2 / (2\pi \omega) \quad (4)$$

where

- λ - wavelength,
- f - focal length of the lens,
- M^2 - laser beam quality factor.

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

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

This is very good seen in diagrams of the example b), Fig. 1 corresponding to the flattop initial beam. In the focal plane the intensity I_f is described by the function called as Airy Disk,

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

where

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

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

As we see the focusing of a flattop beam never leads to creating a spot with uniform intensity, neither in focal plane nor in intermediate planes. In other words: *If a particular application needs a laser spot of uniform intensity (flattop) there is no sense to focus a flattop beam!*

This doesn't mean, however, that a flattop collimated beam cannot be used to get a laser spot of uniform intensity. There will be considered in next chapters a relay imaging approach (not focusing!) that is successfully used to achieve spots of several tens of microns diameter.

The example c) in Fig. 1 corresponds to very important for practice case of creating a small laser spot with uniform intensity profile just in focal plane of a lens. Realizing this approach requires solving of the inverse problem – which intensity distribution should be at the entrance of a lens in order to get a flattop spot in focal plane? This problem was, for example, discussed in paper⁶. Mathematical computations based on the inverse Fourier-transform technique give a solution that the input beam to have the intensity distribution described just by Airy Disk function, analogous to formula (5) with input beam radius r . In other words, to generate a flattop laser spot in the focal plane the input beam should have essentially non-uniform profile. Like in previous cases the interference pattern in the space between the lens and its focal plane isn't constant; it gets variation both in size and in intensity distribution. And the flattop profile in focal plane is just a special case of the continuous variation of intensity distribution!

An important feature of the case of focusing the beam with initial Airy Disk intensity distribution is in creating flattop and close to flattop profiles not only in the focal plane but in some regions in space between the lens and the focal plane. One of these ranges, marked as Δ , is shown in example c), Fig. 1. One can see, there exists a continuous transition from one

practically flattop intensity profile to another similar profile. That Δ -range is, from our point of view, most interesting for practical applications since:

- the flattop profile is stable, deviation can lie in tolerance +/-10%,
- the beam size variation is not essential, below 30%,
- the spot size is only 1.3-1.7 times greater than the spot in focal plane defined by formula (4),
- there is provided a greater depth of field (DOF) comparing to one in immediate proximity to the focal plane; approximately the DOF of that Δ -range is equal to the Rayleigh range of a laser beam with the same conditions of focusing (wavelength, divergence, etc.).

Application requirements to the field mapping beam shapers

From the point of view of spot size the plenty of laser techniques, where beam shaping is used, can be conditionally divided into two groups:

- 1) techniques where a final spot size is order of magnitude greater than a wavelength of the laser radiation, say of millimeter or centimeter scale, and,
- 2) applications with spot size comparable with a wavelength, for examples spot diameters of several microns or tens of microns, usually below 100 micron.

Examples of applications of first group are irradiating the cathode of Free Electron Lasers, the applications, where it is necessary to illuminate a Spatial Light Modulator (SLM), confocal microscopy, biomedical fluorescence techniques, Particle Image Velocimetry, Holography, Manufacturing volume Bragg gratings, Particle Size Analysing various industrial technologies like welding, cladding, hardening, etc.

The applications of the second group are techniques of micromachining, laser marking, various laser technologies in photovoltaics like scribing, microdrilling.

Most often the task for beam shaping optics is to create flattop (or uniform, or top hat) intensity profile. There are, however, techniques where some other profiles like "Inverse Gauss", "Doughnut", Supergauss are required. Depending on an application round, square or linear

spot shapes are needed. A common requirement to any beam shaping system applied in industrial laser technologies is in providing an extended depth of field; it should be, at least, the same like a Rayleigh range of laser beam.

To meet the requirements of modern laser technologies very often just refractive beam shapers of field mapping type can be applied, for example the family of beam shapers π Shaper has two basic types:

- π Shaper – beam shapers to create collimated beams of uniform intensity; these devices are successively applied as solution for the tasks of first group when a spot size to be more than approx. 0.2 mm, and
- Focal- π Shaper - optical devices creating collimated beams with intensity profile described by similar to Airy Disk function; they are an exact solution for the tasks of second group when final spot sizes are below 100 micron.

Design features and examples of application of these refractive beam shapers of field mapping type are described in next chapter.

Description and application examples of the π Shaper

An idea of the π Shaper operation is illustrated with Fig. 2. Gaussian (or close to Gaussian) intensity distribution of a TEM₀₀ or multimode laser beam is converted to a flat-top distribution (similar to a Greek letter π) that stays invariable over long distance after the π Shaper.



Fig. 2 Principle of the π Shaper operation.

This transformation is realized through distortion of the beam wavefront inside the optical system under the condition of conservation of energy and could be illustrated with a picture in Fig. 3. Detailed description of basic operational principles of refractive beam shapers can be found in publications^{1,3,4,5,7,8}, here we will emphasize on some features important for their practical using.

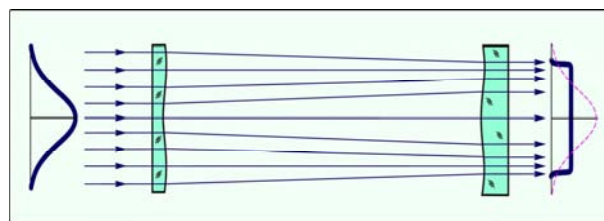


Fig. 3 Example of optical layout of the field mapper.

An essential design feature of the π Shaper optical system is in consisting of two optical components and controlled wavefront 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 π Shaper optical design is providing zero or negligible for practical applications wave aberration for a beam passing through the π Shaper, 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 avoidance of appearing undesirable interference fringes, as well as provides, due to low output divergence, keeping the result intensity profile over long distance after the π Shaper.

One of important features of the π 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 π Shaper 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. Another example is applications based on short 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 π Shaper optical systems realize so called Galilean type

telescope, this is a critical point for high power and short pulse laser applications.

The intensity redistribution could be realized for various light beams including TEM₀₀ laser beams as well as multimode beams.

Summarizing, the most important features and basic principles of π Shaper 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 have either a TEM₀₀ one or a multimode beam;
- The uniform intensity is kept after the π Shaper over a large distance;
- There are available telescope models, as well as systems with optical power like objective or collimator;
- This transformation is provided for a certain spectral range, thus π Shaper is achromatic system;
- Galilean design, thus there is no internal focusing of a beam.

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



Fig. 4 Outlook of some π Shaper models

Most of models are implemented as a telescope, thus requiring collimated input beam and providing a collimated output. However, there are also available collimator type models getting a divergent input beam and, hence, combining functions of beam shaping and collimation, this feature might be of interest for fiber lasers.

Due to their features the π Shaper'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.

According to basic design the output beam after the π Shaper is round and has a pre-determined size. If a particular task requires another final spot size, this can be realized by applying additional optical components like beam-expanders or relay imaging lenses, examples of layouts are shown in Fig. 5 and 6.

By the beam size manipulation with using the beam expanders a final beam stays collimated, i.e. low divergent.

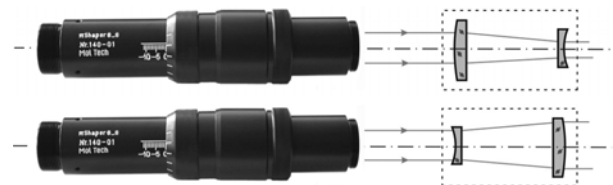


Fig. 5 Examples of reduction and expansion of a beam after the π Shaper with telescopic beam-expanders.

The expansion factor is limited rather by capabilities of 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.

When application conditions presume creating of final spots of diameters below 1 mm it is advisable to apply the relay imaging technique where a final spot is created as an image of an output aperture of a π Shaper, this approach is depicted in Fig. 6.



Fig. 6 Relay imaging of the π Shaper output aperture

Since the π Shaper provides a collimated beam of low divergence it is possible to achieve high reduction factors, down to $1/200^x$, with extended DOF.

One more example of transformation of a beam after the π Shaper is generation of linear spots with using anamorphic optics.

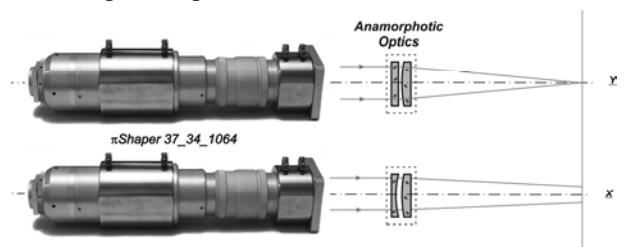


Fig. 7 Layout of a "Laser Line" generation.

The collimated beam of uniform intensity is emerging from a π Shaper and is then focused by an anamorphic 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 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. The length and the width of the line are defined by parameters of anamorphic optics and aspect ratio can be up to 1:1000!

Examples of the π Shaper operation

Example of re-distribution of intensity profile of TEM₀₀ laser beam with a π Shaper is shown in Fig. 8, here there are profiles caught with a camera based beam profiler.

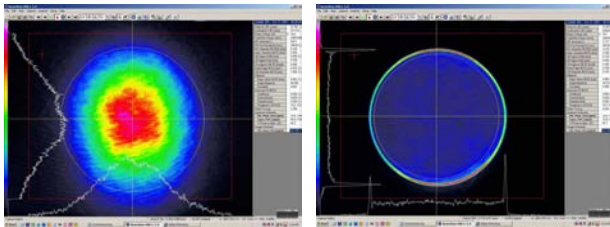


Fig. 8 Intensity profiles:
Left - source beam, Right - after the π Shaper

An illustration of the beam shaper influence on the results of material treating is presented on Fig. 9. Here one can see a comparison of engraving of a circular hollow in material used in photovoltaic: with a TEM₀₀ Nd:YAG laser and the same laser with the π Shaper.

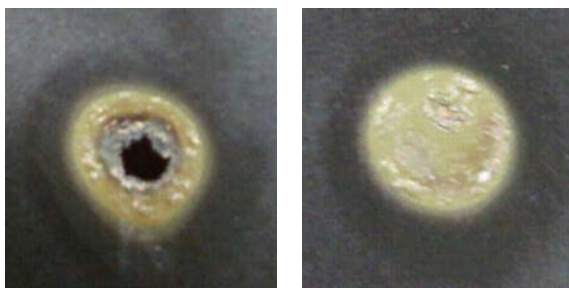


Fig. 9 Comparison of material processing:
Left - TEM₀₀ laser beam, Right - after the π Shaper
Courtesy of EO Technics

The difference of engraving results is evident - irregular shape of the hollow with a ragged unwished hole in the center in case of original TEM₀₀ laser, and the good shaped round hollow with a controlled depth when applying the beam shaper.

Description and application examples of the Focal- π Shaper

The principle of operation of the F- π Shaper is shown in Fig. 10. Its main task is to generate a beam with the Airy Disk intensity distribution in order to create, by focusing with a lens, the flattop, Donut-like, Inverse Gauss and other profiles. This corresponds to the case presented in example c) in Fig. 1.

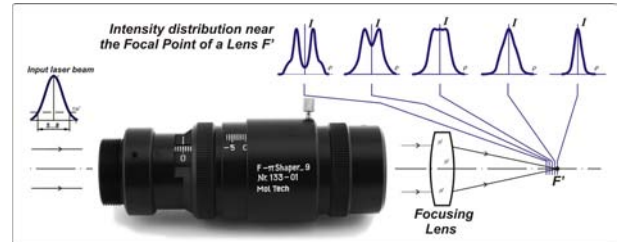


Fig. 10 Principle of the F- π Shaper operation.

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

- telescopic refractive optical systems transforming the Gaussian to Airy Disk intensity distribution;
- operation with input TEM₀₀ beams of various diameter;
- flattop, Doughnut, Inverse Gauss and other profiles can be generated by the same device;
- deviation of the input beam from the perfect Gaussian is possible, however the beam to be just TEM₀₀;
- versions optimized for various wavelengths available;
- operation in a certain spectral band;
- optical design without internal focusing of a beam;
- compact design suitable for scientific and industrial applications;
- easy integration to an optical setup and adaptation to a laser source;
- any focusing lens could be applied; the only condition is the lens to be diffraction limited one,
- the distance between the F- π Shaper and the lens isn't critical, hence
- it is possible to install the F- π Shaper ahead of a galvo-mirror scanning head.

Example of Scribing

The task of scribing with a trench of exact width and even edges is actual for many applications of semiconductor industry, solar cell manufacturing and others. Applying the F- π Shaper allows to improve drastically the performance of these technologies. As an

example the results of laser scribing of glass using TEM₀₀ short-pulse laser are presented in Fig. 11.

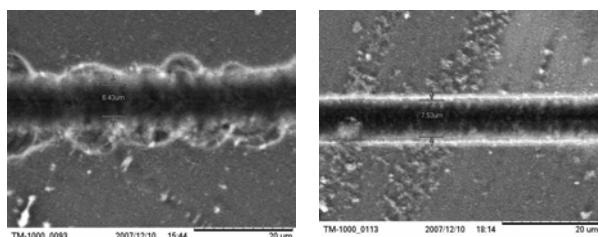


Fig. 11 Scribing by TEM₀₀ femtosecond Laser:
Left - TEM₀₀ laser beam, Right - after the *F- π Shaper*
Courtesy of Altechna

The difference in quality of scribing is evident:

- with TEM₀₀ beam:
 - irregular trench edges,
 - wide HAZ,
- with *F- π Shaper 9_1064*:
 - even trench edges,
 - steep walls,
 - almost without HAZ.

One more example of applying the *F- π Shaper* in photovoltaics technique of scribing of CI(G)S thin-film is presented in publication⁹.

Very often just a flattop profile is considered as a way of improving the particular laser application. In many cases, however, there might be benefits from other profiles, for example by scribing thin-film materials in photovoltaics applying of Inverse Gauss profile with steeper edges makes it possible to get higher quality of a kerf. Hence, the possibility of the *F- π Shaper* to provide various profiles with the same device is a very useful feature for plenty of laser applications.

Evidently, with using the *F- π Shaper* it is possible to enhance the quality and reliability of scribing as well as other micromachining technologies.

Conclusion

Up-to-date variety of refractive beam shapers of field mapping type allows finding a solution for most of laser applications which performance can be improved by the laser beam shaping. A right choice of an optimum beam shaping technique for a particular laser application depends on many features including basic specifications of a laser used (wavelength, mode structure, power, etc.), required intensity profile and size of a final beam.

Most often just the size of the final beam has a decisive importance. As a rule when millimetre or centimetre scale final spot sizes it is reasonable to apply optical solutions based on field mapping beam shapers generating flattop collimated beams, like *π Shaper*. At the same time when spot sizes below 100 micron required just the field mapping beam shapers generating Airy Disk distribution, like *F- π Shaper*, are the right choice.

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