Applying of refractive beam shapers of circular symmetry to generate non-circular shapes of homogenized laser beams

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ABSTRACT

Creating of non-circular laser spots, for example of linear, elliptical or rectangle shape, with uniform intensity profile is important in various laser techniques in industry, scientific and medical applications. This task can be successfully solved with applying of refractive beam shaping optics of field mapping type in combination with some additional optical components. Due to their unique features, such as: low output divergence, high transmittance and flatness of output beam profile as well as extended depth of field, the refractive field mappers provide a freedom in further manipulation with intensity profile and shape of a laser beam. Typically design of refractive field mapping beam shapers has circular symmetry; therefore creating of non-circular spot shapes requires applying anamorphic optical components (cylinder lenses, prism pairs, etc.) ahead of or after a beam shaper. As result it becomes possible to provide various combinations of spot shape and intensity profiles, for example: roof-like spot with uniform intensity in one direction and Gaussian or triangle profile in another direction, linear spots with aspect ratio up to 1:1000, elliptical spots of uniform intensity, etc. Applications include flow cytometry instrumentation, particle image velocimetry, particle size analyzing, hardening, cladding, annealing, and others.

This paper will describe some design basics of refractive beam shapers of the field mapping type and optical layouts for creating laser spots of non-circular symmetry. Examples of real implementations will be presented as well.

Keywords: beam shaping, flattop, tophat, line generation, flow cytometry, hardening, cladding

1. INTRODUCTION

Along with growing interest to beam shaping systems as solutions for a wide variety of scientific and industrial laser techniques there appear new demands to these optics and very often applications can benefit not only from manipulation of intensity profile but also from providing of a certain shape of laser spot. For example, performance of the flow cytometry technique can be enhanced when a beam has “roof-like” intensity profile with uniform intensity in one direction and Gaussian in another one; at the same time such industrial technologies like annealing, hardening can benefit from using linear spot with high aspect ratio. Simultaneous shaping of the laser beam intensity profile and its shape can be solved by applying a combination of an existing beam shaper and additional optical components used to manipulate a beam size or spot shape. And the refractive beam shapers of field mapping type[1,2,3,4] demonstrate a high level of flexibility in realization of this approach. Since the refractive field mapping beam shapers transform the laser beam profile in a control manner by accurate introducing and further compensation of wave aberration the resulting collimated output beam of a uniform or another intensity profile has low divergence comparable to one of input beam. In other words, the field mappers transform the beam profile without deterioration of the beam consistency and increasing its divergence. This feature is very important for further manipulation with a resulting beam and makes it possible to realize various optical layouts with using anamorphic optical components like cylinder lenses and prism pairs. In this paper we will consider some optical layouts built on the base of refractive field mapping beam shapers *πShaper* and present examples of real applications.

2. OPTICAL DESIGN CONSIDERATIONS

The design principles of refractive beam shapers of field mapping type is well-known and described in literature[1,2,3,4], for purposes of further considerations let us summarize the main optical features of the *πShaper* systems being used in this work:

- telescopic or collimating refractive optical systems that transform Gaussian or similar intensity distribution of a source laser beam to flattop (or top-hat, or uniform) profile of resulting collimated beam;
- the intensity profile transformation is realized through the phase profile manipulation in a control manner;
- the output phase profile is maintained flat, hence output beam has low divergence;
- optical systems of beam shapers consists of two refractive optical components, variation of the distance between the components is used to adjust a *πShaper* in a real optical setup;
- TEM_{00} or multimode beams applied;
- Output beam is collimated and resulting beam profile is kept stable over a large distance;
- achromatic optical design, hence the beam shaping effect is provided for a certain spectral range simultaneously;
- Galilean design, thus there is no internal focusing of a beam.

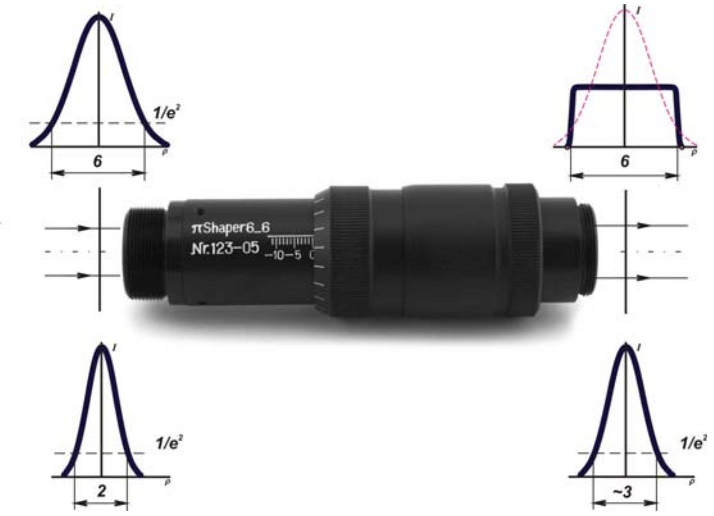


Fig. 1 Refractive field mapper *πShaper*.

An example of *πShaper* is shown on Fig.1.

Most often just telescopic optical systems of refractive field mapping beam shapers are realized, hence the input and output beams are collimated. The *πShaper* systems have paraxial beam size magnification in range 1.5^x - 1.7^x, so they operate as beam-expanders of special type and, consequently, have angular magnification $1/1.5^x$ - $1/1.7^x$ and reduce the divergence angle in paraxial domain. In calculations for real optical layouts one can consider the output divergence is approximately the same like one of input beam.

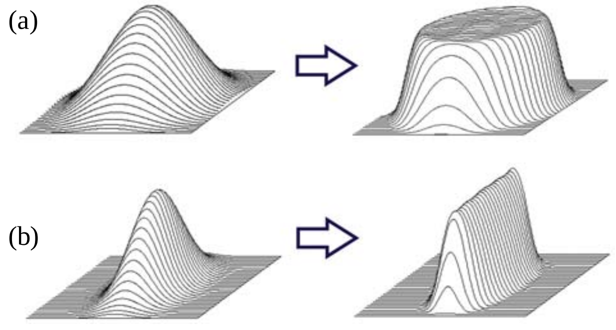


Fig. 2 Beam profile transformation with *πShaper*.
(a) round Gaussian to Flattop, (b) elliptic Gaussian to Roof-like

One can state, also, the refractive field mappers transform the beam profile without deterioration of the beam consistency and increasing its divergence.

There is one more important feature of the refractive field mapping beam shapers – 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 differs from the pre-determined one the resulting profile deviates from the flattop as well, for example, when an input beam is essentially smaller, say 2-3 times less than a specified value, the beam shaper operates as an ordinary beam-expander, so the output beam is about 1.5 times expanded but the resulting profile stays almost the same like at the entrance i.e. Gaussian. This effect is demonstrated on Fig. 1, see the charts in the bottom. It can be used, for example, to generate a Roof-like beam profile with uniform intensity in one direction and Gaussian in another one – this is easily achieved when an elliptic input beam with a long axis of proper length (according to a *πShaper* design), Fig. 2. 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 in this chapter.

2.1 Beam shape manipulation with anamorphic beam-expanders after a *πShaper*

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 *πShaper 6_6* the resulting beam diameter is about 6 mm. If a particular laser technique requires an elliptic flattop spot the beam after the *πShaper* can be squeezed by a telescopic cylinder beam reducer, like shown on Fig. 3, or another anamorphic optical component like a pair of prisms. Of course, when necessary the beam can be also expanded with using an appropriate cylinder beam-expander.

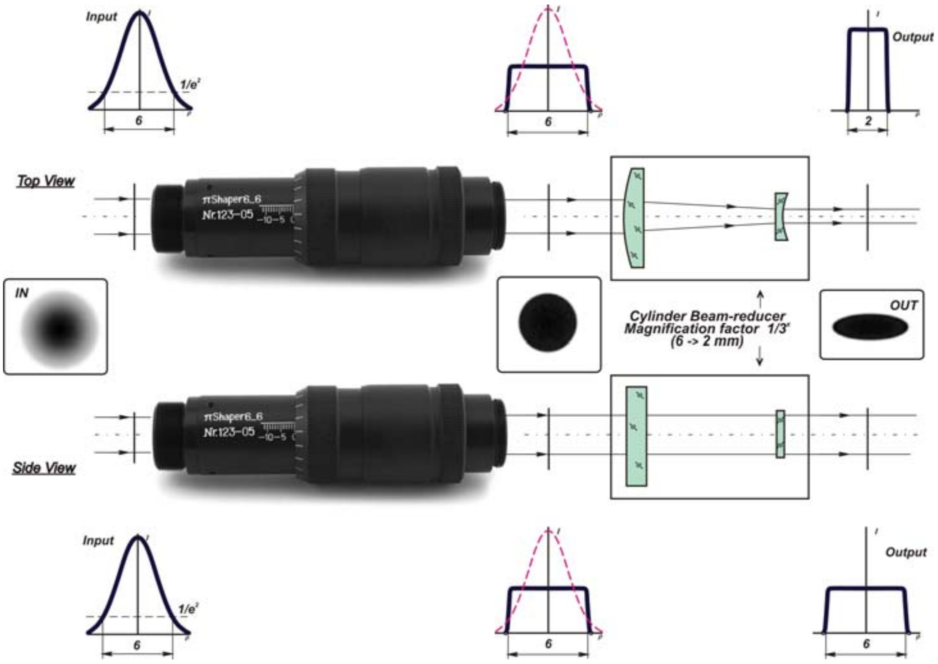


Fig. 3 Creating elliptic final flattop spot with using a cylinder beam-expander.

The resulting beam stays collimated so the flattop profile and elliptic spot shape are provided over a large distance; this means this system has extended depth of field (DOF).

In case of beam demagnification it is recommended don't exceed a factor 5, since too much beam reduction would lead to increasing the residual wave aberrations and, hence, quicker beam profile deterioration when its propagation in space.

Examples of real optical setups will be considered later in the section of experimental results.

2.2 Creating spot with the Roof-like profile

As discussed above the Roof-like beam profile can be provided if an input beam is elliptic that can be easily realized by applying an anamorphic optical components, like a cylinder beam-expander or a pair of prisms, ahead of a *πShaper*, this approach is shown at Fig. 4. A circular laser beam is transformed to elliptic one that is then entering the *πShaper*, the resulting beam has uniform intensity in the direction of long axis of input beam, at the same time the intensity in perpendicular direction stays Gaussian one.

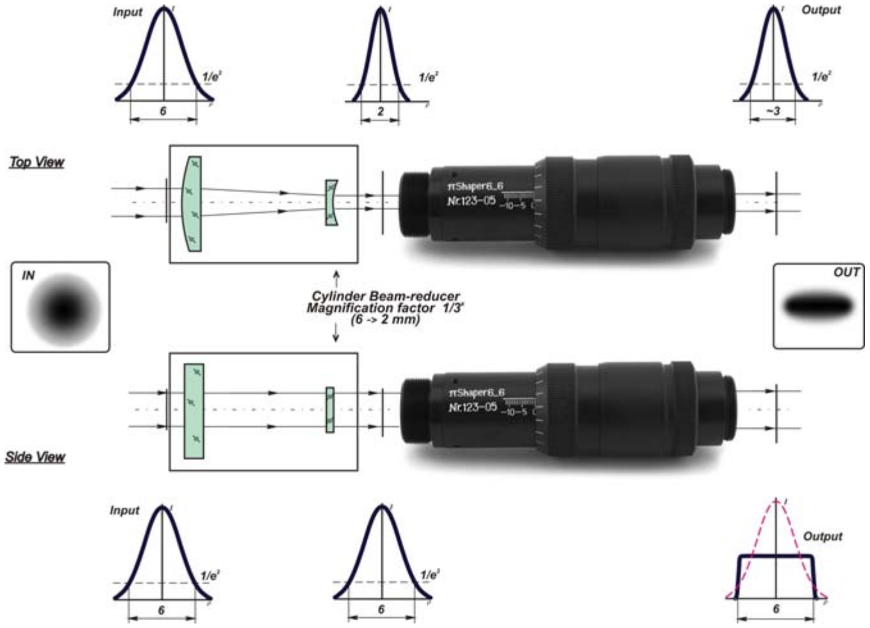


Fig. 4 Creating the Roof-like profile.

2.3 Creating the Linear spot

This approach is based on the layout considered in the previous chapter 2.2. Since the Roof-like profile has Gaussian intensity distribution and saves the phase relationships of TEM_{00} beam in short axis it is very good suited to realize a Line-like profile by applying a cylinder lens focusing the beam in that short axis, this layout is demonstrated in Fig. 5. The resulting spot is linear and featuring by uniform intensity along its length and Gaussian profile in width, the layout in Fig. 5 is based on the *πShaper_6_6*, hence the length of the Line is 6 mm.

Evidently, the beam stays diffraction limited in the direction of focusing, so it is possible to realize as narrow as possible width, of microns or tens of microns scale, by applying an appropriate focusing anamorphic optics like a simple or cylinder lens or more sophisticated diffraction limited optical system of short focal length. As result very high, more than 1000:1, values of the aspect ratio of final linear spot can be achieved!

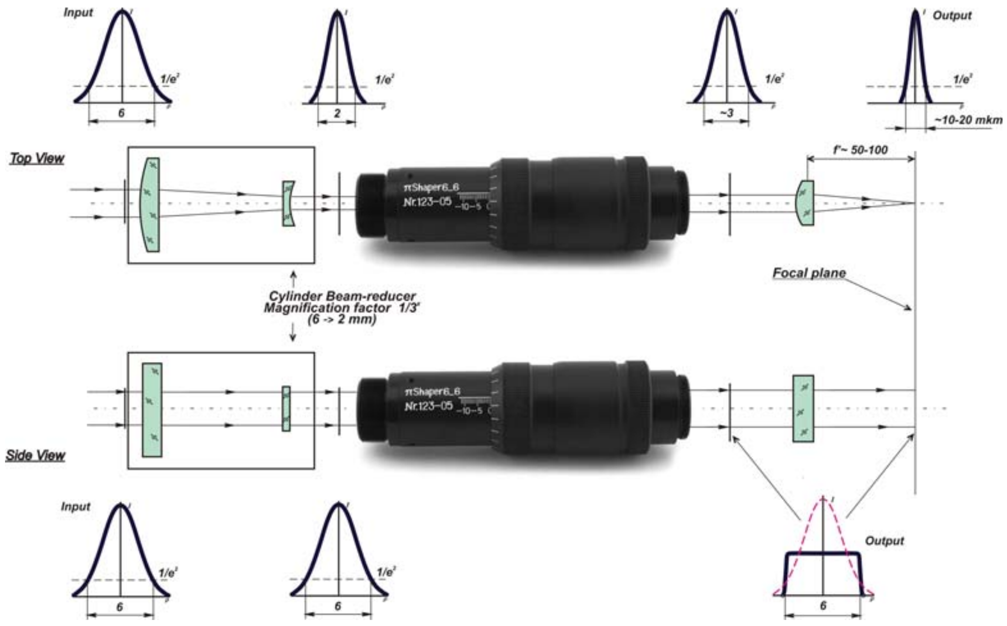


Fig. 5 Creating the Linear spot

2.4 Creating the extended laser Line

Further development of the optical system considered in previous chapter can be done in order to realize extended linear spots, see the Fig. 6.

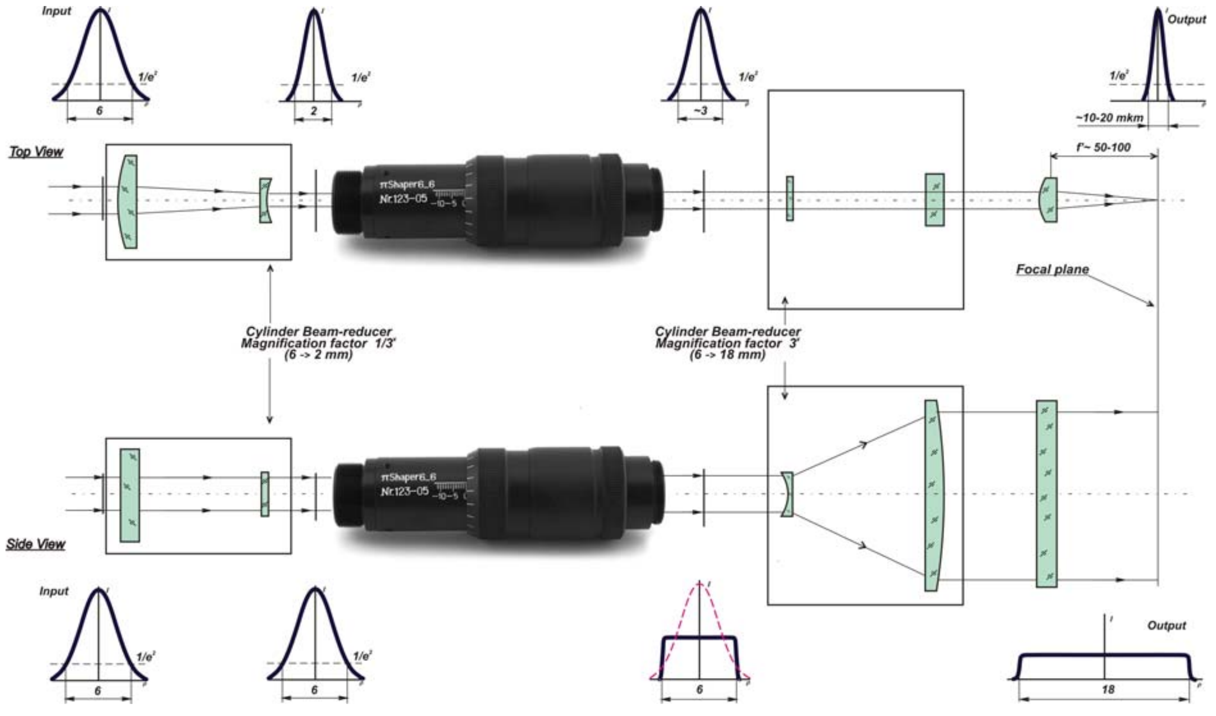


Fig. 6 Creating the extended Linear spot

Here one can use the feature of the refractive field mapping beam shapers like *πShaper* that the output beam is collimated and has approximately the same divergence like at the *πShaper* input. Hence, it is possible to apply telescopic beam expanders in order to expand or de-magnify the beam[5]. Without limitations both ordinary telescopes of circular symmetry and anamorphic optical systems with cylinder lenses or prisms can be applied.

Simple expansion of entire output beam after the *πShaper* would lead, simultaneously, to longer length and narrower width of the linear spot, in other words this is a way to increase the aspect ratio of a final linear spot. If a task requires simple extending the Line length without changing the width, then it is necessary to apply an anamorphic beam-expander like a telescope of cylinder lenses like one shown in Fig. 6.

2.5 Creating the Linear spot with using relay imaging optics

A number of laser applications require a final linear spot which size is featured by the length of scale of millimetre or several hundreds of microns. As discussed in paper[5] it is reasonable in such a case to use so called relay imaging approach when the output aperture of the refractive field mapping beam shaper, like *πShaper*, is projected to the working plane with using an imaging lens. This approach can be used also to generate linear spots, when an imaging lens is combined with anamorphic optical components; an example of realization of such a layout is shown in Fig. 7.

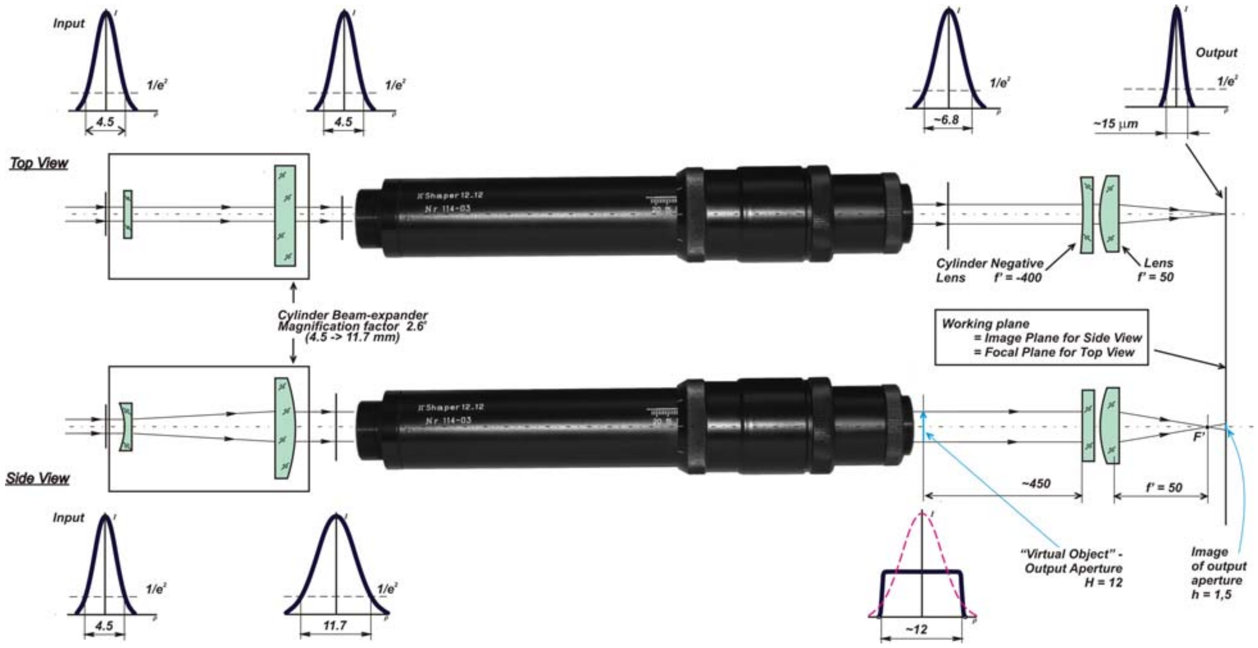


Fig. 7 Relay imaging to generate the Linear spot

This layout is based on the *πShaper 12_12*; the input beam is elliptic with Gaussian profiles in both axes, transformation of circular Gaussian beam to the elliptic one is provided through applying a cylinder beam-expander; the output beam has a Roof-like profile. The relay imaging optical system after the *πShaper 12_12* is implemented as a combination of a convex-plano spherical lens of 50 mm focal length and a negative cylinder lens of -400 mm focal length.

It is assumed the working plane is just the plane where the image of the output aperture of the *πShaper 12_12* is created; according to the rules of optics that image plane, in common case, is located after the focal plane of the imaging lens. To get a narrow width of a final spot it is reasonable to focus the Roof-like beam after the *πShaper* in the section where that beam has Gaussian profile, top view in Fig. 7, and bring into coincidence the focal plane of that section and working plane of the entire system. Evidently, this can be achieved by applying a negative cylinder lens with an appropriate focal length that is, typically, an order of magnitude larger than focal length of imaging spherical lens.

2.6 Generation of linear spots from multimode beams

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 those technologies can be improved by applying a linear shape of laser spot and the field mapping beam shapers in combination with anamorphic are a working solution for this task, one of working realizations is presented in Fig. 8.

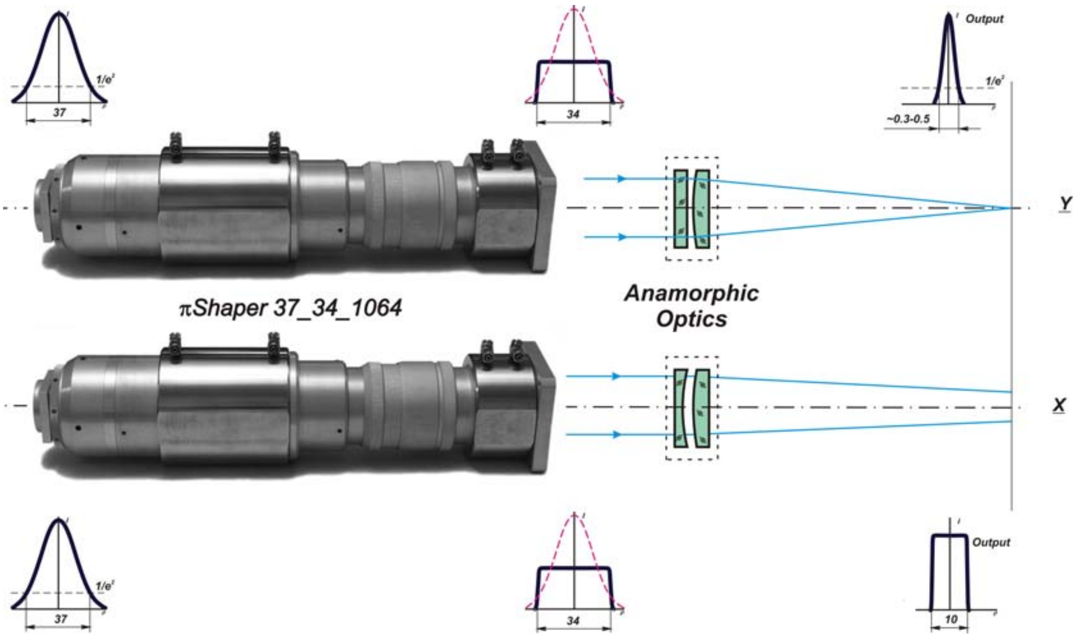


Fig. 8 Generation of “Laser Line” from multimode laser beam.

The collimated beam of uniform intensity is emerging from a *πShaper* 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. 8, but stays unfocused in the perpendicular plane X, hence a spot of linear shape is created. 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.

3. EXPERIMENTAL RESULTS

3.1 Generation of elliptic flattop spot

Sequence of beam profiles in an experimental setup realizing the optical layout according to Fig. 3 is presented in Fig. 9. Components used are:

- laser, λ=532 nm, TEM_{00}, $1/e^2$ diameter about 1 mm,
- beam-expander,
- *πShaper 6_6_532*,
- Pair of prisms.

One can see the original laser beam is TEM_{00} but its profile deviates from a perfect Gaussian, nevertheless the *πShaper* provided the acceptable flatness of output flattop beam, with steep edges. Squeezing of the beam after the *πShaper* with using a pair of prisms gives the elliptic final flattop spot with axes lengths 6.8 and 1.7 mm, i.e. the aspect ratio is 1:4.

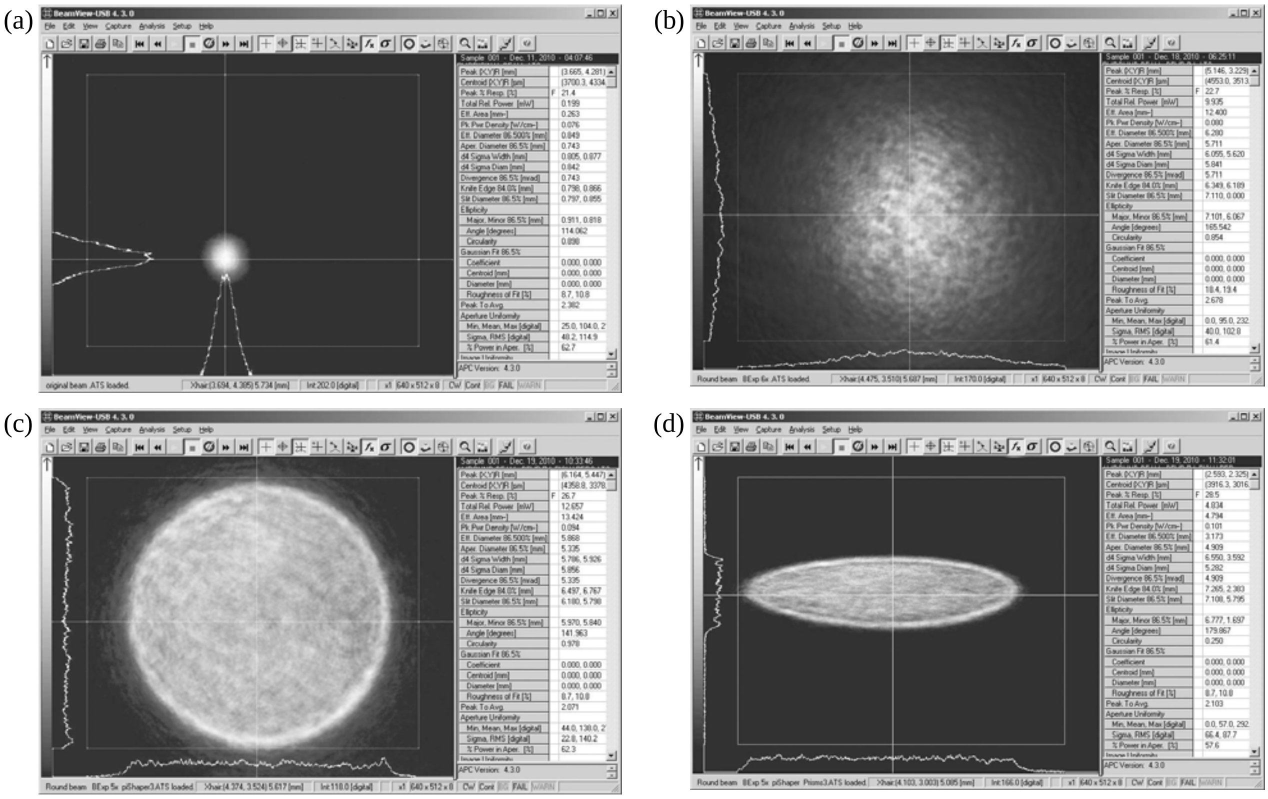


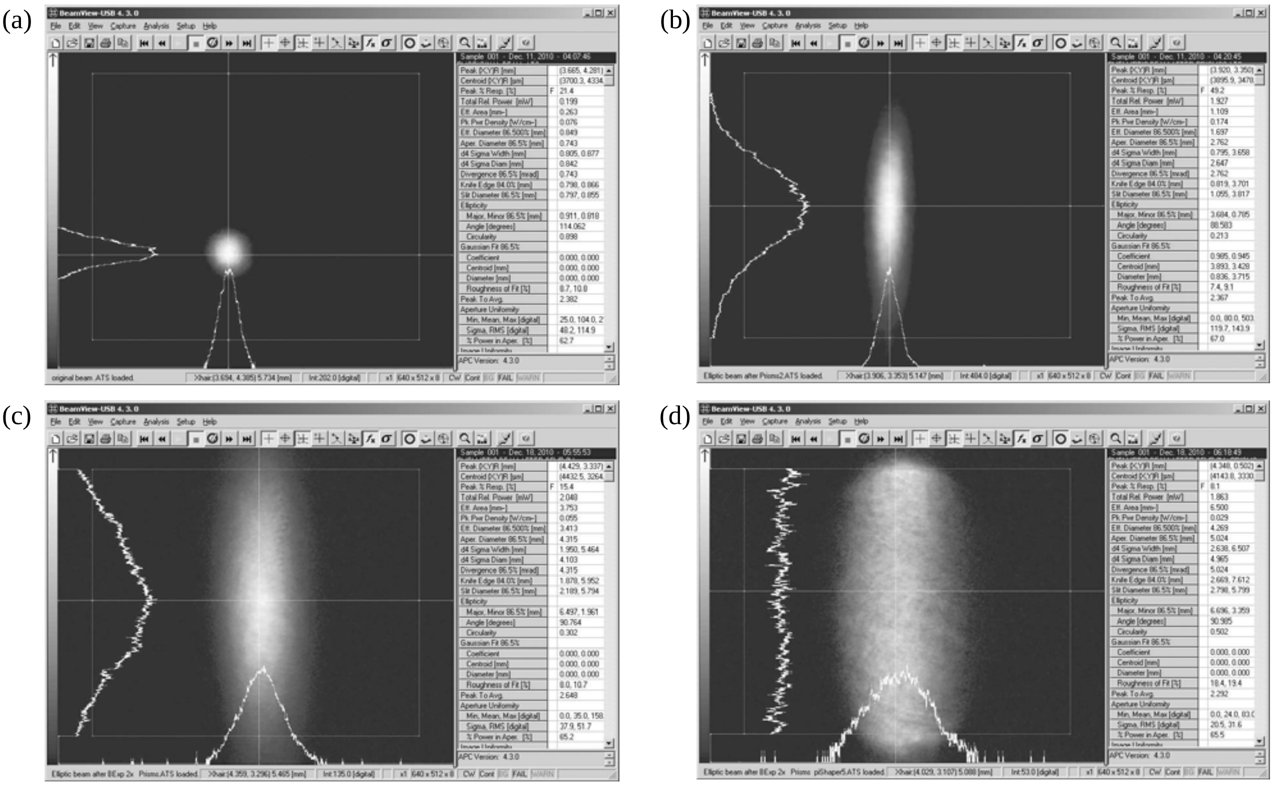
Fig. 9 Creating the elliptic flattop spot; optical layout according Fig. 3.
Beam profiles: (a) after laser, (b) after 6^x magnification by Beam-Expander, (c) after *πShaper*, and (d) after Pair of Prisms.

3.2 Generation of a spot with the Roof-like intensity profile

The optical layout described in paragraph 2.2 of this paper, Fig. 4, was implemented as a combination of following optical components, in sequence:

- laser, λ=532 nm, TEM_{00}, $1/e^2$ diameter about 1 mm,
- pair of prism, magnification 2.5^x,
- beam-expander, magnification 2^x,
- *πShaper 6_6_532*.

Beam profiles are presented in Fig. 10.



	(a)	(b)	(c)	(d)
Sample	001 - Dec. 11, 2010 - 04:07:46	001 - Dec. 11, 2010 - 04:20:45	001 - Dec. 18, 2010 - 05:55:53	001 - Dec. 18, 2010 - 06:18:49
Peak [X,Y]R [mm]	(3.665, 4.281)	(3.920, 3.350)	(4.429, 3.337)	(4.348, 0.502)
Centroid [X,Y]R [µm]	(3700.3, 4334.	(3895.9, 3470.	(4432.5, 3264.	(4143.8, 3330.
Peak % Resp. [%]	F 21.4	F 49.2	F 15.4	F 8.1
Total Rel. Power [mW]	0.199	1.927	2.048	1.863
Eff. Area [mm²]	0.263	1.109	3.753	6.500
Pk Pwr Density [W/cm²]	0.076	0.174	0.055	0.029
Eff. Diameter 86.500% [mm]	0.849	1.697	3.413	4.269
Aper. Diameter 86.5% [mm]	0.743	2.762	4.315	5.024
d4 Sigma Width [mm]	0.805, 0.877	0.795, 3.658	1.950, 5.464	2.638, 6.507
d4 Sigma Diam [mm]	0.842	2.647	4.103	4.965
Divergence 86.5% [mrad]	0.743	2.762	4.315	5.024
Knife Edge 84.0% [mm]	0.798, 0.866	0.819, 3.701	1.879, 5.952	2.669, 7.612
Slit Diameter 86.5% [mm]	0.797, 0.855	1.055, 3.817	2.189, 5.794	2.798, 5.799
Ellipticity				
Major, Minor 86.5% [mm]	0.911, 0.818	3.684, 0.785	6.497, 1.961	6.696, 3.359
Angle [degrees]	114.062	88.583	90.764	90.905
Circularity	0.898	0.213	0.302	0.502
Gaussian Fit 86.5%				
Coefficient	0.000, 0.000	0.985, 0.945	0.000, 0.000	0.000, 0.000
Centroid [mm]	0.000, 0.000	3.893, 3.428	0.000, 0.000	0.000, 0.000
Diameter [mm]	0.000, 0.000	0.836, 3.715	0.000, 0.000	0.000, 0.000
Roughness of Fit [%]	8.7, 10.8	7.4, 9.1	8.0, 10.7	18.4, 19.4
Peak To Avg.	2.382	2.367	2.648	2.292
Aperture Uniformity				
Min, Mean, Max [digital]	25.0, 104.0, 2	0.0, 80.0, 503.	0.0, 35.0, 158.	0.0, 24.0, 83.
Sigma, RMS [digital]	48.2, 114.9	119.7, 143.9	37.9, 51.7	20.5, 31.6
% Power in Aper. [%]	62.7	67.0	65.2	65.5

Fig. 10 Beam profiles in the system according Fig. 4:
(a) after the laser, (b) after the Pair of Prisms 2.5^x, (c) after the Beam-Expander 2^x, (d) after the *πShaper 6_6_532*.

Expansion of the elliptical beam after the Pair of prisms is required to provide the proper beam size along its long axis. Final spot at the output of the *πShaper 6_6_532* has a Roof-like profile with uniform intensity in vertical direction and Gaussian function in horizontal direction.

3.3 Generation of linear shape of spot of fiber laser for laser hardening

The optical system described in paragraph 2.6 and presented in Fig. 8 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.

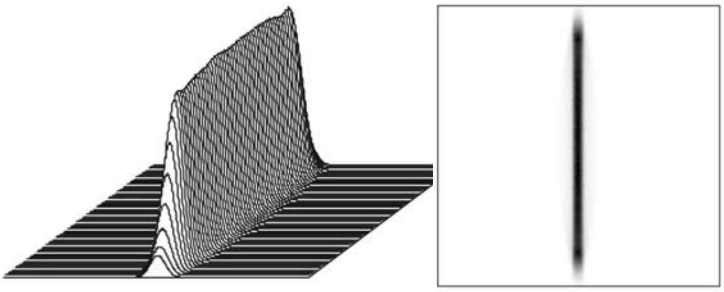


Fig. 11 Computer simulation of beam profile created in optical system described in Fig. 8.

Results of numerical calculations for the optical system, Fig. 8, implemented as a *πShaper 37_34_1064* with an anamorphic system are shown in Fig. 11. Results of intensity profile measurements in area of working plane are presented in Fig. 12.

Evidently, there exists good correspondence between theoretical and experimental results. Here one can see also one important feature of the field mapping beam shapers like the *πShaper* – capability to create not only uniform resulting profiles but some other beam shapes like so called “inverse Gauss” characterized by steep edges and low intensity in the centre, this feature is described, for instance, in the paper[4]. 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. 12 on right.

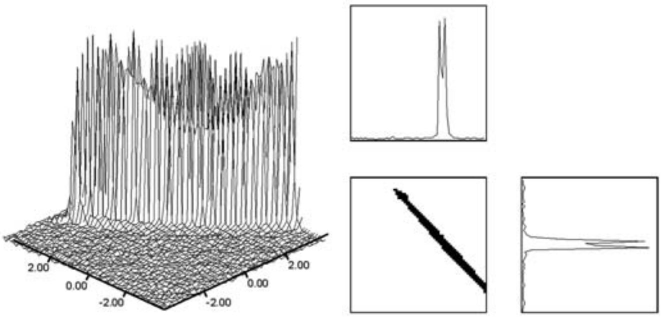


Fig. 12 Measurements with using a beam profiler:
On left - 3D view of the spot, On right – profiles in sections.
Courtesy of IPG Photonics

4. CONCLUSION

Despite the circular symmetry of optical design of the refractive field mapping beam shapers these systems are capable to generate non-circular shapes of homogenized laser beams. This unique feature is possible due to their operational principle presuming low divergence of output collimated beam that 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. Applying of additional optical anamorphic components like cylinder lenses or prisms makes it possible to create elliptic and linear spots with flattop, Roof-like, “inverse Gauss” intensity profiles. This extends the range of capabilities of refractive beam shapers and makes these devices a convenient tool to build beam shaping optics for various industrial, medical and scientific applications.

5. REFERENCES

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