Applying refractive beam shapers in creating spots of uniform intensity and various shapes

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ABSTRACT

Different scientific and industrial laser techniques require not only intensity profile transformation but also creating various shapes of final spots like circles of different diameter, lines and others. As a solution it is suggested to apply combined optical systems consisting of a refractive beam shaper of field mapping type providing a required intensity transformation and additional optical components to vary the shape of final spots. The said beam shapers produce low divergence collimated flattop beam that makes it easy to vary the shape of the beam spot with using either ordinary relay imaging optics, including zoom one, or anamorphotic optics. And the design features of the refractive beam shapers allow controlling the intensity distribution in the final spot (most often flattop one) and providing wide range of spot sizes. This paper will describe some design examples of combined beam shaping systems to create round spots of variable diameter as well as linear spots of uniform intensity. There will be presented results of applying these systems in such applications as laser hardening and others.

Keywords: laser beam shaping, flattop, tophat, homogenizer, achromatic, line generator, laser hardening, uniform illumination, short pulse**.**

1. INTRODUCTION

There exists today a wide variety of scientific and industrial laser applications where the beam shaping optics is applied, as result it is necessary to realize various optical layouts to provide laser beams of required features: collimated and focused, flattop and other intensity profiles, round spots and linear or other shapes, etc. Evidently, it is impossible to make a universal beam shaper capable to fulfil all conditions, however various optical tasks 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 like relay imaging with high, up to 1/200 (!), reduction factor, other approaches are based on applying of beam-expanders/reducers to vary the final spot size or anamorphotic attachments to generate a linear spot shape of required length. Below we will consider some optical layouts built on the base of refractive field mapping beam shapers *πShaper* produced by company MolTech GmbH 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. One can state, also, the refractive field mappers transform the beam profile without deterioration of the beam consistency and increasing its divergence.

2.1 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 *πShaper 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 *πShaper*; other possible applications are Particle Image Velocimetry, Holography, Manufacturing volume Bragg gratings, Particle Size Analysing, field illumination in Confocal Microscopes and many others. 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, flow cytometry, mass spectrometry, and different tasks of material processing.

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 beam-reducer of telescopic type with an appropriate magnification factor; the principle optical layouts are shown on Fig.2.

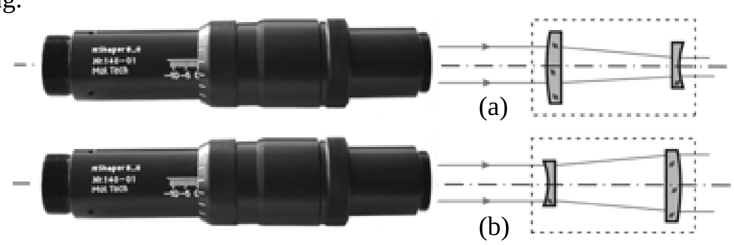

Fig. 2 Examples of (a) reduction and (b) expansion of a beam after the *πShaper* with telescopic beam-expanders.

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.

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

2.2 Relay imaging

When application conditions presume creating of final spots of diameters below 1 mm it is advisable to apply the relay imaging layout when a final spot is created as an image of an output aperture of a the *πShaper*, this approach is illustrated on Fig. 3.

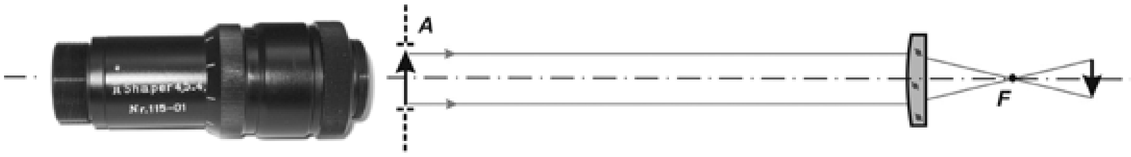

Fig. 3 Relay imaging of the *πShaper* output aperture to the working plane.

Let's assume an aperture *A*, that can be either a real aperture or a virtual one, is at the output of the *πShaper* and is considered as an object (arrow on left side), and a lens installed after the *πShaper* is creating an image of that object (arrow on right side). Because of the *πShaper* operation the object (*A*) is illuminated by a beam of uniform intensity and low divergence, hence each point of the object can be considered as a source of narrow beams with small aperture angles and the image created will have the same relative intensity distribution like the object. Sure, the size of the image depends on the magnification of the relay imaging system. This is just a standard task of relay imaging optics and parameters of this optical layout (distances between components, focal length of the lens) can be calculated using well-known formulae of geometrical optics[6].

As mentioned above the *πShaper* provides a collimated beam of low divergence which intensity profile is kept stable over large distance, therefore the uniformly illuminated virtual aperture *A* can be set at different distances after the *πShaper* and, consequently, different images after the lens will be created. In other words, the relatively extended object space, where the uniform intensity is provided, is projected to the corresponding image space where spots of uniform intensity are created. The length of that image space defines the depth of field (DOF) of the entire optical system including the *πShaper* and the imaging optics, because of extended space of stable beam profile after the *πShaper* this DOF reaches essential values that is very important in many laser applications. It is necessary to note, however, the image size within the DOF will vary according to rules of geometrical optics; sometimes this effect can be used in certain applications, for instance, to vary the final spot size by simple moving the working plane.

All above considerations presumes the lens used for relay imaging is corrected for aberrations and, hence, creates sharp images. Sometimes applying of a simple single lens is enough; however most often it is necessary to use more sophisticated multi-lens optics like microscope objectives or telecentric F-theta lenses.

Realization of the relay imaging approach requires providing a relatively long air gap between a *πShaper* and a lens, this might be critical in case of layouts with high demagnification. Shortening of the entire optical system can be achieved by applying additional beam-expanders between a *πShaper* and an imaging lens, example of such a system will be discussed later in chapter 3.3 of this paper.

There exists one important feature of the relay imaging approach that might be critical in case of operation with short-pulse laser. It is very good seen on the Fig. 3 that the laser beam is focused in back focus of the imaging lens and in case of high peak power pulses the air breakdown could happen, this can lead to creating of plasma preventing the proper realization of a laser effect. This feature should be taken into account while building a particular optical setup; very often, however, this obstacle can be overcome by setting additional field lenses in the optical layout.

The low divergence of the beam after the *πShaper* makes it possible to realize very high demagnification factors, for example the article[8] presents results with 50^x demagnification down to 100 micron spots, other examples showed that and even higher, up to 200^x, demagnification factors can be achieved. This makes this approach very useful in such applications like laser via drilling on PCB or projection of a mask onto a substrate in display technologies, below we will consider an example of relay imaging for irradiation of a photocathode in Free Electron Lasers.

2.3 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. 4.

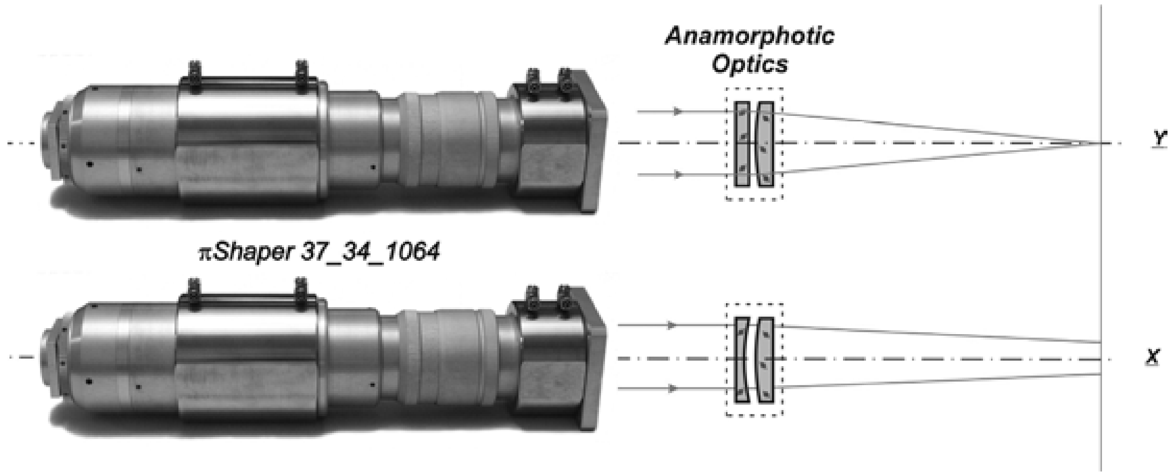

Fig. 4 Generation of “Laser Line” by attaching anamorphotic optics to the *πShaper*.

The collimated beam of uniform intensity is emerging from a *πShaper* 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. 4, 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.

3. EXAMPLES OF LAYOUTS AND EXPERIMENTAL RESULTS

3.1 Apparatus for ultrafast spectroscopy based on a *πShaper* with a beam expander to demagnify the beam

One of methods of ultrafast spectroscopy of reactive nanomaterial dynamics presumes using of a short-pulse infrared laser, for example Nd:YAG, to irradiate a thin, about 1 micron thickness, copper foil coated with a layer of material to be analyzed under high pressure. When irradiated by a laser pulse a piece of that foil of about 1 mm diameter, called as a flyer plate, is cut, accelerated and flies in space up to impingement with a wall; by that impingement the material layer gets high pressure and necessary spectroscopy analysis is carried out. This scientific technique is drastically improved by applying a flattop (top hat) laser beam profile due to uniform acceleration and velocity across the flyer plate and keeping the flyer from breaking up during flight. The details of this technique as well as results achieved with using the optical setup on the base of the *πShaper* are presented in article[5]. Here we consider only the features of the optical layout.

The optical system is shown on the left side of Fig. 5 and includes the laser, attenuator, 10 meter delay line, beam-expander *z1* to provide a proper beam size at the entrance of the *πShaper* and beam-expander *z2* to reduce the spot size down to 0,8 mm diameter. The sequence of measured beam profiles is shown on right side of Fig. 5.

In spite of deviation of the initial laser beam profile from a perfect Gauss the *πShaper* provided the flattop beam with steep edges, the last is very important for the spectroscopy technique realized since guarantees a clean cutting of the flyer plate.

The required 0,8 mm diameter of the flattop laser beam on the target was provided by applying the appropriate beam-expander *z2* with demagnification factor 7,5[x].

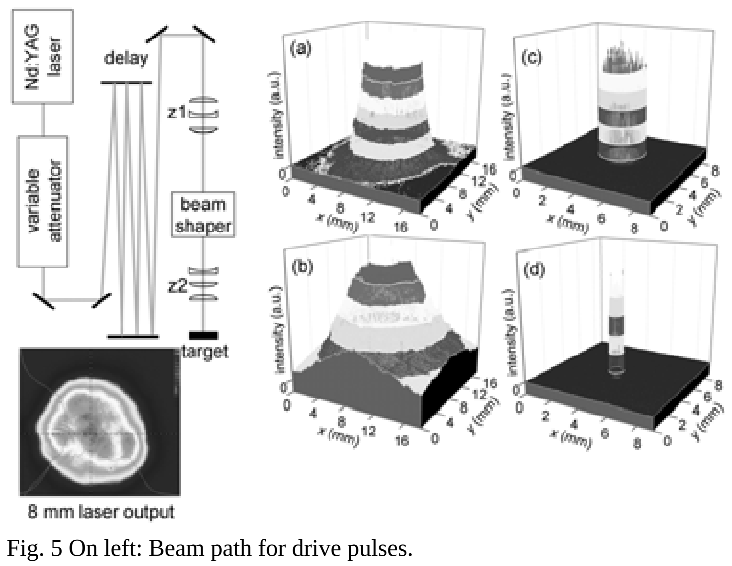

Fig. 5 On left: Beam path for drive pulses.
On right: Images of the beam profile (a) immediately after the laser, (b) after 10 m propagation, (c) after the *πShaper*, and (d) at the target.
Courtesy of Dana Dlott, University of Illinois at Urbana-Champaign, IL, USA.

Since the final collimated beam of uniform intensity has low divergence and, hence, didn't require tight tolerances on positioning the target it was very easy to use it in the described flyer plate technique.

3.2 Optical setup to illuminate a Spatial Light Modulator with an expanded flattop laser beam

A *πShaper 6_6_VIS* is used at the University of Sheffield to reshape the beam from a laser diode so that a spatial light modulator (SLM), in form of a digital micromirror device (DMD), can be illuminated with a highly coherent, uniform-intensity beam. The DMD is used to project the images of computer-generated holograms that are used for research into photolithography on grossly non-planar substrates [7]. The same system can also be used to illuminate a liquid crystal on silicon (LCoS) SLM or to directly illuminate glass holographic masks. It is essential for similar applications to maintain a controlled phase profile across the beam as well as achieving a uniform intensity profile and only field mapping beam shapers like the *πShaper* solve this task successfully and fulfill these conditions simultaneously.

The optical system for DMD illumination is shown in Fig. 6. Input to the system is the distorted TEM_{00} (Gaussian) beam from the laser ($1/e^2$ diameter = 1.6 mm). This beam is spatially filtered using a microscope objective lens and a 25 µm pinhole. The spatial filtering can alternatively be accomplished using a single-mode optical fibre. The beam is then recollimated using an achromatic doublet lens to produce a clean 5.9 mm diameter Gaussian beam (Fig. 7) for input into the *πShaper*. The *πShaper6_6_VIS* has a stated wavelength range of 420-680 nm, whereas the laser operates at 405 nm, however the achromatic optical design of the *πShaper6_6_VIS* makes it possible to operate over an extended wavelength range with some increased reflection losses.

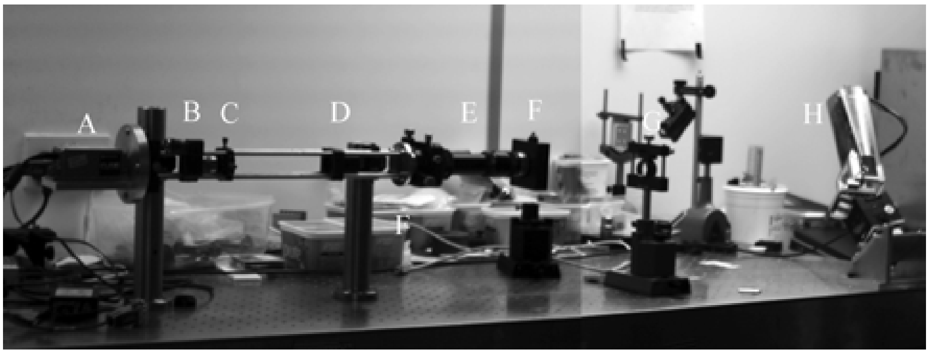

Fig. 6 Photograph of experimental arrangement for illumination of DMD
A – Diode laser module (P_{max} = 50 mW, λ = 405 nm), B – microscope objective, C – pinhole, D – collimating lens (achromatic doublet),
E – *πShaper 6_6_VIS*, F – lens (singlet), G – collimator (achromatic doublet), H – DMD (TI 0.7" XGA ‘DLP’ chip, array size = 14x10.5 mm).
Note that the DMD is tilted over at a 45° angle so that the zero order image reflected from ‘on’ pixels propagates in the horizontal plane.

Fig. 7 Image (directly onto camera) and cross-section of input beam to *πShaper 6_6_VIS* (E), $1/e^2$ diameter = 5.9 mm.

The output from the *πShaper 6_6_VIS* is then further expanded by a 3.5x beam-expander to produce a 21 mm diameter flat top beam that is sufficiently large to illuminate the entire DMD (Fig. 8). An aperture close to the DMD can be used to avoid illumination of areas surrounding the micromirror array. The slight sag in the flat top is presumably due to the non-ideal input beam diameter. Fig. 8 shows, also, a comparison between input and output beam profiles.

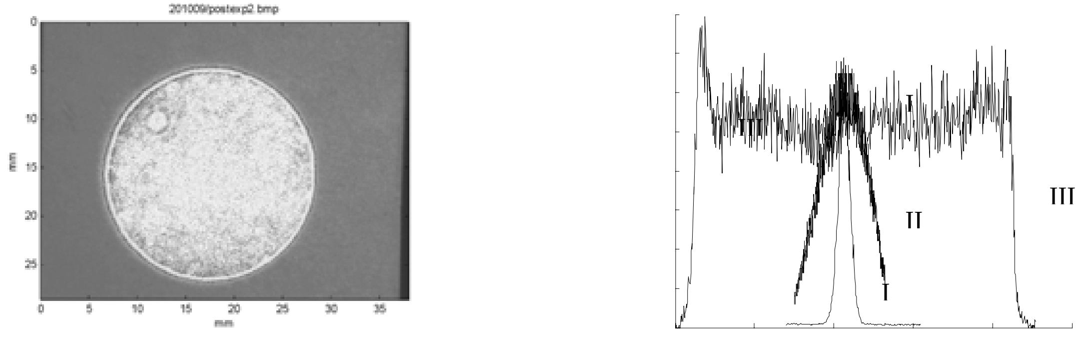

Fig. 8 On left: Spot of expanded laser beam after *πShaper 6_6_VIS* and second expansion (G). Width = 21 mm.
On right: Comparison between laser output (I), *πShaper 6_6_VIS* input (II) and final expanded output (III).
(Note: no correction for background offset in graph III).

By expansion of the beam after the *πShaper* the divergence is reduced proportionally to the magnification factor, as result the final expanded flattop beam has much longer depth of field that makes further work very convenient.

3.3 Relay imaging layout in task of irradiating the photocathode of Free Electron Laser

One more application where refractive field mapping beam shapers are used relates to generation of electron beam in Free Electron Lasers (FEL) by irradiating a photocathode by short laser pulses. To control the process of the electron beam generation it is necessary to vary the intensity profile of the laser beam on the photocathode, for example, to realize the flattop profile.

As a solution just the relay imaging approach can be applied when the output aperture of a beam shaper is projected onto the photocathode, the basic principle was discussed in chapter 2.2 and the specific layout used in ELETTRA-Sincrotrone, Italy is shown in Fig. 9.

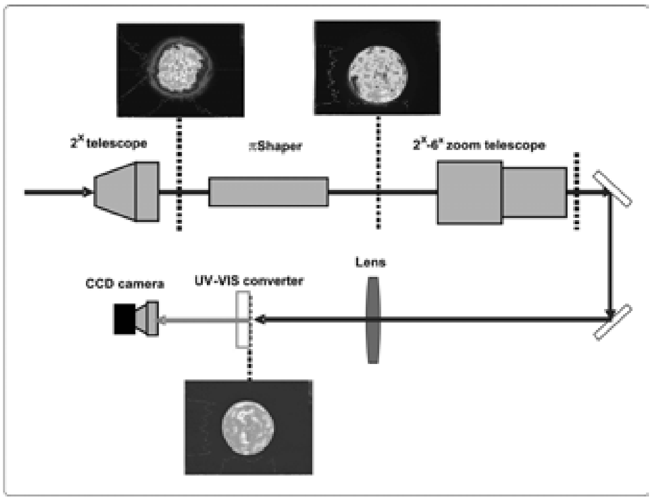

Fig. 9 Experimental layout to create flattop spots of various size on the base of the *πShaper* and relay imaging optics

Here the relay imaging part of optical system was implemented as a combination of a zoom-beam expander and a lens. This combined projecting optics lets it possible not only to create a spot of uniform intensity profile but also to vary its diameter. The beam profiles of a UV laser (triple Harmonic of Ti:Sapphire) were analyzed in various planes of the optical setup by means of a CCD Camera catching the patterns on a UV-VIS Converter. Input and output beam profiles for the *πShaper* are presented in Fig. 10, and the data for image spots are shown in Fig. 11 where the spot outlooks as well as their measured profiles are given for corresponding magnification settings of the zoom beam-expander applied.

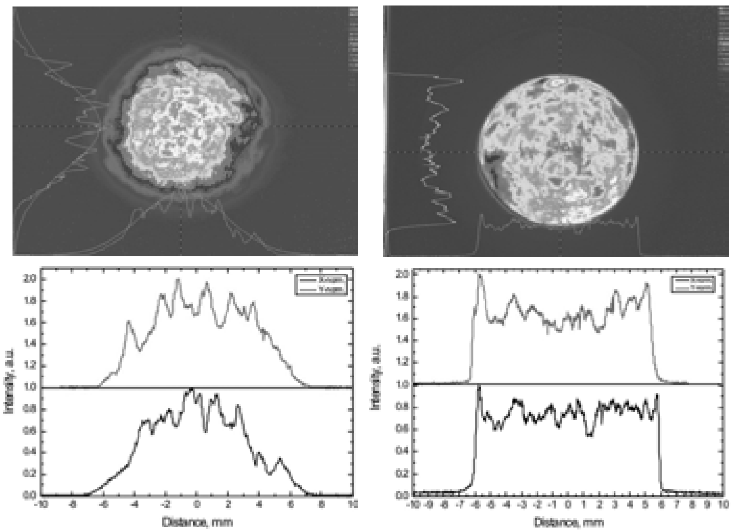

Fig.10 Beam profiles: left – at the *πShaper* entrance, right – at the output.

One can see the input beam is a TEM_{00} one but its intensity distribution is far from a perfect Gaussian profile – there exists strong modulation of intensity over the beam. Nevertheless, the field mapping beam shaper can work with such beams and provide redistribution of the average intensity profile even with suppressing, to some degree, the high frequency intensity modulation, please, compare the profiles on left and right pictures of Fig. 10. Comparing of spot shapes shows the *πShaper* improves, also, the roundness of a spot – irregular shape of the input spot, left pattern, is transformed to a round spot with steep edges shown on right.

Further relay imaging of the output field of the *πShaper* with using the lens and the zoom beam-expander makes it possible to create spots of different size. As shown in Fig. 11 the final spot shapes as well as their intensity profiles are similar to ones of the *πShaper* output.

The high frequency intensity modulation doesn't disappear by the imaging, it becomes, may be, less sharp, however the amplitude of the intensity variation stays essential and more pronounced in case of stronger demagnification, please, compare the patterns for corresponding to 6^x and 2^x. This should be taken into account while developing of real optical systems on the base of the *πShaper* and relay imaging optics.

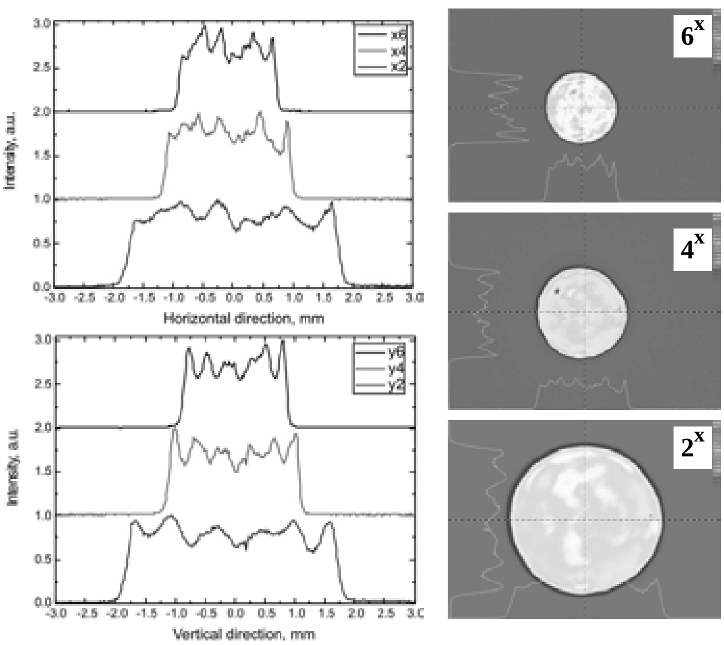

Fig. 11 Beam profiles on the UV-VIS Converter (Fig. 9), data are given for corresponding magnification factors of the zoom beam-expander.

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

The optical system described in section 2.3 and presented in Fig. 4 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. 4, implemented as a *πShaper 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.

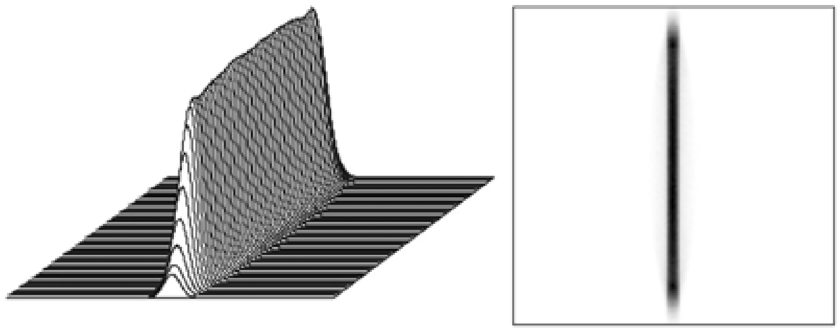

Fig. 12 Computer simulation of beam profile created in optical system described in Fig. 4.

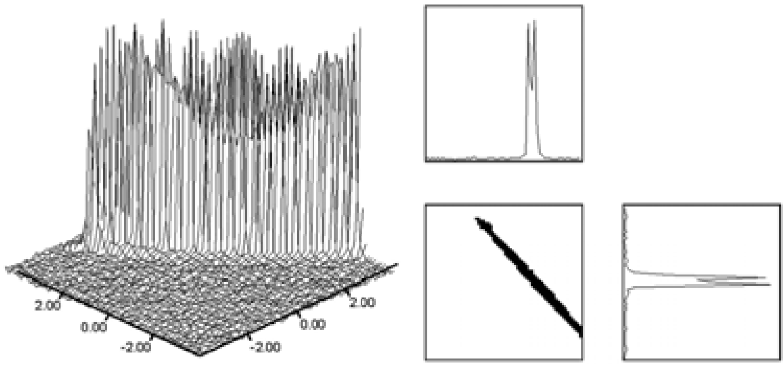

Fig. 13 Results of measurements with using a beam profiler:
On left - 3D view of the spot, On right – profiles in sections.
Courtesy of IPG Photonics

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

4. CONCLUSION

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.

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6. ACKNOWLEDGEMENTS

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