

# Field Mappers for Laser Material Processing

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## ABSTRACT

The native shape of the single-mode laser beam used for high power material processing applications is circular with a Gaussian intensity profile. Manufacturers are now demanding the ability to transform the intensity profile and shape to be compatible with a new generation of advanced processing applications that require much higher precision and control.

We describe the design, fabrication and application of a dual-optic, beam-shaping system for single-mode laser sources, that transforms a Gaussian laser beam by remapping – hence field mapping - the intensity profile to create a wide variety of spot shapes including discs, donuts, XY separable and rotationally symmetric. The pair of optics transform the intensity distribution and subsequently flatten the phase of the beam, with spot sizes and depth of focus close to that of a diffraction limited beam. The field mapping approach to beam-shaping is a refractive solution that does not add speckle to the beam, making it ideal for use with single mode laser sources, moving beyond the limits of conventional field mapping in terms of spot size and achievable shapes.

We describe a manufacturing process for refractive optics in fused silica that uses a freeform direct-write process that is especially suited for the fabrication of this type of freeform optic. The beam-shaper described above was manufactured in conventional UV-fused silica using this process. The fabrication process generates a smooth surface (<1nm RMS), leading to laser damage thresholds of greater than 100J/cm<sup>2</sup>, which is well matched to high power laser sources. Experimental verification of the dual-optic field mapper is presented.

**Keywords:** Beam delivery, Beam shaping, High power laser, Optical fabrication, Micro-optics, Collimation

## 1. INTRODUCTION

High-power laser beamshaping involves converting an input beam, whose properties are generally determined by the laser source, into a well-defined output beam, whose properties are determined by the laser machining process. Beamshaper design principles are well-established [1] and commercial beamshapers based on mature optical fabrication processes are readily available [2].

Although a large range of standard beamshaping products already exists, the requirement space is even larger. Consequently, designing a laser system based on catalogue beamshaper elements typically involves either compromising system performance or increasing system complexity compared to what could be achieved using an optimal design.

Typical requirements driving beamshaper selection and design are:

- Flexible choice of output beam profile
- Insensitive to input beam
- Large depth of focus
- Brightness preservation
- Speckle-free
- High peak power handling
- High efficiency
- Single, thin optical element
- On-axis operation
- Ease of integration into standard process head

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The type of beamshaper used in any given laser system depends on the laser source being used, with the requirement at the process plane determining whether the beamshaper system consists of one optic or more. The selection criteria is largely delineated by modal content; the  $M^2$  value of a laser gives a good indication of the beamshaper requirement, as shown in Table 1.

Table 1. Beam shaper selection based on laser source modal content.

| Laser Source             | Beam Shaping |                                                                       |
|--------------------------|--------------|-----------------------------------------------------------------------|
| Single Mode              | Field mapper |                                                                       |
| Multi-mode<br>$M^2 > 2$  |              | Pseudorandom diffuser                                                 |
| Multi-mode<br>$M^2 > 10$ |              | Diffracting lens array<br>Imaging lens array<br>Pseudorandom diffuser |

In this paper, we are concentrating on single mode laser sources. Field mappers map adjacent patches from a known input field distribution into adjacent patches in a defined output beam profile. This is distinct from the alternative class of beamshaping optics, the beam integrator, examples of which are the two types of lens array, and the pseudorandom diffuser in Table 1. In this case, the beam is sampled by the sub-apertures and then overlaid, and the final spot shape is identical to the lenslet aperture shape. Field mappers provide smooth, speckle-free output beam profiles, and can be used to generate a phase-flat (minimum divergence) output profile when depth of focus at the process plane is critical. They are, however, sensitive to input beam dimensions and profile. The beam shaper must therefore be carefully matched to the input beam, and, as discussed, below, any changes in position, size, or profile, will affect the output beam.

## 2. FIELD MAPPING BEAMSHAPERS

PowerPhotonic design and manufacture refractive fused silica field mappers for use with single mode laser sources. These optics transform a Gaussian laser beam by remapping the intensity profile to create a wide variety of spot shapes including discs, donuts, squares and rectangles. They can be used as a single or dual optical system depending on the required spot size and depth of focus. They are very high efficiency optical elements with excellent flat top performance and they do not introduce any speckle or interference effects. There are (at least) three different types of field mapping solution characterized by use, performance and output specifications. These are here referred to as Type 1-3.

### 2.1 Type 1: single optic field mapper (T1FM)

The T1FM uses a single optic to transform the far field of a laser beam to the required intensity distribution. The T1FM solution adds divergence to the beam and therefore has a larger focused spot size compared to the same system without the field mapper. The phase of the T1FM beam is not flat, which reduces the axial range over which the image will retain the desired distribution; in essence the depth of focus is reduced compared to the unshaped beam. The performance of a T1FM can be estimated by calculating a characteristic parameter [1] of the system,  $\beta$

$$\beta = \frac{2\sqrt{2\pi}r_{\text{spot}}r_{\text{beam}}}{f\lambda} \quad (1)$$

where  $r_{\text{beam}}$  is the input beam radius at the  $1/e^2$  threshold,  $r_{\text{spot}}$  is the output spot radius at the  $1/e^2$  threshold,  $f$  is the focal length of the focusing lens and  $\lambda$  is the laser beam wavelength. Alternatively,  $r_{\text{beam}}$  and  $r_{\text{spot}}$  are characteristic length scales of the input and output profile. The larger the  $\beta$  parameter, the more uniform the spot that can be achieved; with values  $\beta > 16$  providing good performance and values of  $\beta > 32$  providing excellent performance. Values  $\beta < 4$  will not produce acceptable results. This becomes clear when Eqn. 1 is expressed in the form

$$\beta \approx 4 \frac{w}{d_{DL}} \quad (2)$$

where  $w$  is the characteristic length parameter of the output and  $d_{DL}$  is the diffraction limited spot size in the absence of any beam shaping optics. Now  $\beta < 4$  is an attempt to operate below the diffraction limit of the system, whereas  $\beta > 16$  is 4x diffraction limited operation, and  $\beta > 32$  is 8x diffraction limited operation.

## 2.2 Type 2: dual optic field mapper (T2FM)

The T2FM uses a pair of optics that generate a collimated beam with a shaped intensity distribution. The first optic reshapes the intensity distribution of the beam to give the desired output, while the second optic flattens the phase of the beam. This leads to a collimated, shaped beam with a long axial range over which the desired intensity distribution can be found in the near field. The far field of the beam differs from the desired intensity distribution, therefore a focusing lens cannot be used in a T2FM system [2].

## 2.3 Type 3: dual optic field mapper (T3FM) with near diffraction limited performance

The T3FM system, like the Type 2 system, consists of 2 optics: a field mapping optic and a phase correcting optic. However, the fundamental difference is that the T3FM generates an intermediate field distribution that does not correspond to the ultimate focused spot requirement. Specifically, the T3FM system generates a field distribution that is the Fourier transform of the required field distribution. The required field distribution is only generated at the focal plane of a focusing lens, giving the T3FM system the significant advantage of allowing for very small focused shaped spots without the requirement for a large and expensive image relay system.

# 3. DESIGN OF TYPE 3 FIELD MAPPERS

The T3FM is a 2 stage optic where both the amplitude and the phase of the beams are independently controlled. The T3FM is capable of near diffraction limited performance; reducing spot diameter and increasing depth of field of flat top beams, where the dependence of the depth of field ( $z'$ ) on focal length is

$$z' \propto f^2 \quad (3)$$

The design path for the T3FM is to form, in the plane after plate B, a complex-amplitude field that is the inverse Fourier transform of the desired final field. We illustrate this using the example of a square flat top at the target plane. Figure 1 is a schematic of the T3FM system, and Figure 2 the fields at the three planes labeled in Figure 1. The refractive surface profile of plate A is constructed such that the field formed at plate B, which is the combination of the input field distribution (field 1 in Figure 2) and the profile of plate A together propagated a distance  $L$ , has a sinc profile (Figure 3) (we form an Airy pattern for a circular flat top). Plate B corrects the phase of the complex-amplitude distribution (field 2 in Figure 2) and the focusing lens generates a Fourier transform of this distribution in the target plane (field 3 in Figure 2).

In practice, the sinc or Airy pattern needs to be truncated due to the finite size of the optics. The impact of the truncation at plate B can be quantified by propagating the truncated field to the focus of the lens. The number of “rings” in the pattern (defined in Figure 3) determines the quality of the field formed in the target plane. Figure 4 shows theoretical examples of the final target profile for the case where two (Figure 4a) and three (Figure 4b) rings are formed at plate B. Although in Figure 1 plate B is in the front focal plane of the focusing lens, in practice plate B can be positioned anywhere if the phase correction applied by plate B is suitably adjusted. This is limited only by the ability of manufacturing process to realize the surface.

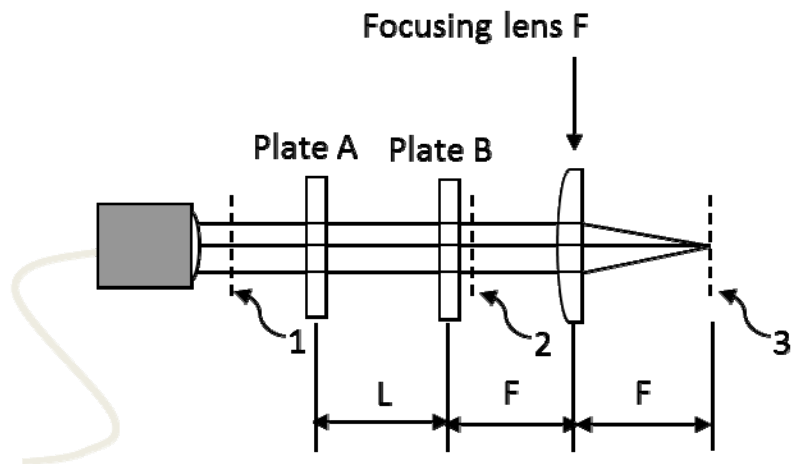


Figure 1. A schematic representation of the Type 3 field mapper system.

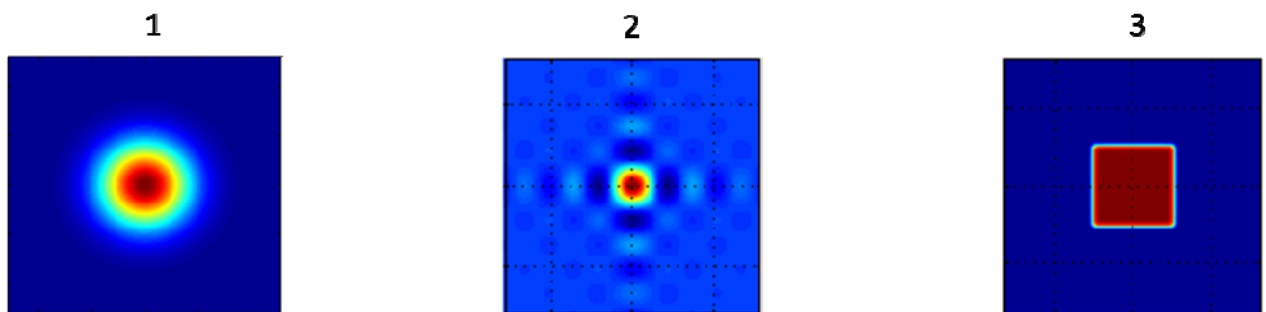


Figure 2. The input beam profile at plane 1; the intermediate profile at plane 2; and the final profile at plane 3, the back focal plane of the lens.

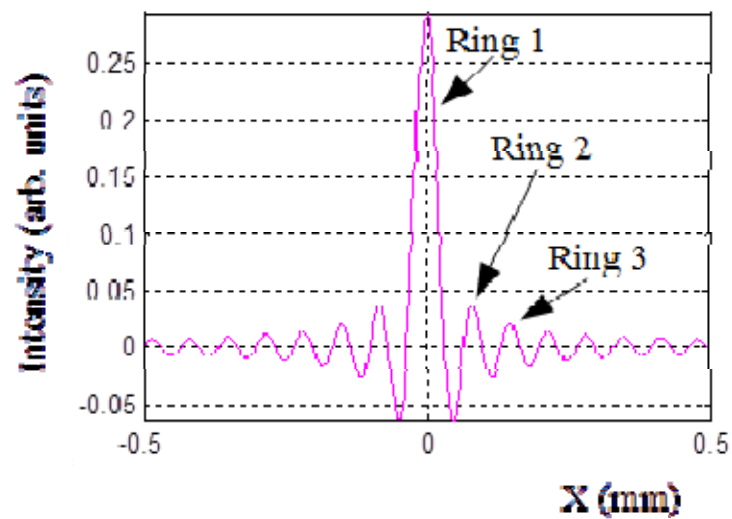


Figure 3. The ideal (non-truncated) beam profile at plane 2.

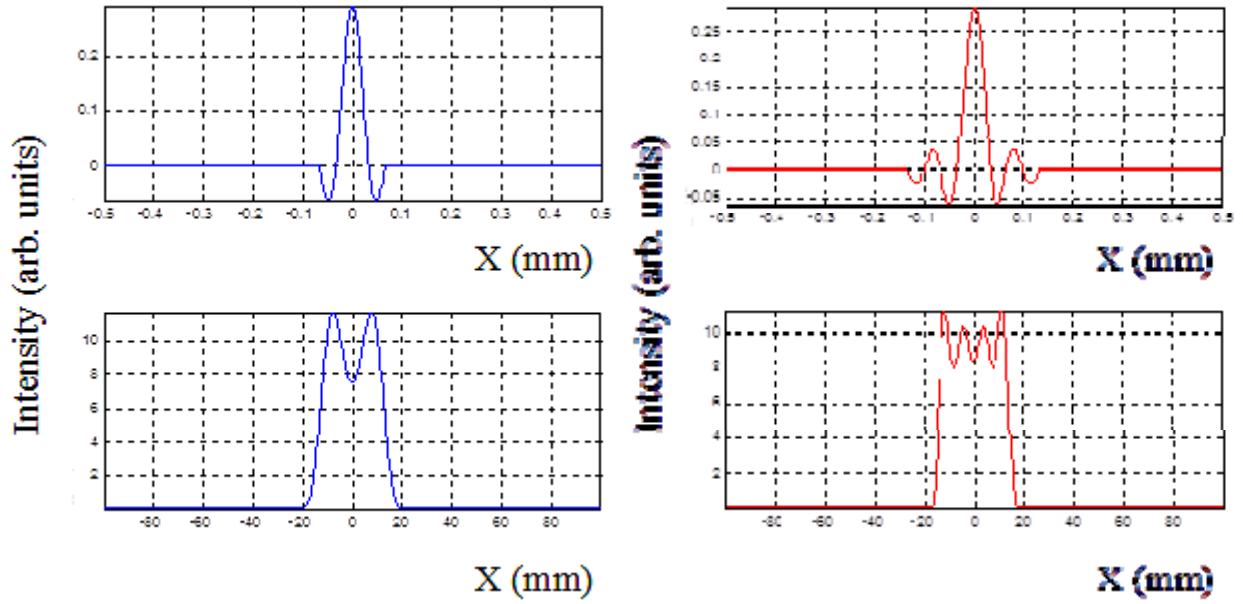


Figure 4. (a) The beam profile at plane 2 truncated to two ring (top) and the profile at plane 3. (b) The beam profile at plane 2 truncated to three ring (top) and the profile at plane 3

To explore the performance of the T3FM, we designed two pairs of optics following the prescriptions in Table 2. The input beam is circular Gaussian, but can be of the form circular or elliptical Gaussian beam, any beam profiles separable in  $x$  and  $y$ , or any rotationally symmetric beam profiles. The final beam profile can be flat circular or square, any other shape separable in  $x$  and  $y$ , or any other rotationally symmetric shape. Following Eqn. 2,  $\beta \sim 20$  for the circular flat top, representing a final spot that is 5x the diffraction limit of the optical system. Figure 5 illustrates a typical surface profiles of the two plates: plate A is (a), (c) and e, plate B is (b), (d) and (f).

Table 2. Beam shaper selection based on laser source modal content.

| Parameter                      | Circular flat top | Rectangular flat top |
|--------------------------------|-------------------|----------------------|
| Wavelength, $\lambda$          | 1.03 $\mu$ m      |                      |
| Beam diameter ( $1/e^2$ ), $d$ | 4.95 mm           |                      |
| Focal length of lens, $f$      | 40mm              | 50mm                 |
| Plate separation, $L$          | 100mm             |                      |
| Flat top diameter / width      | 0.15mm            | 0.50mm               |

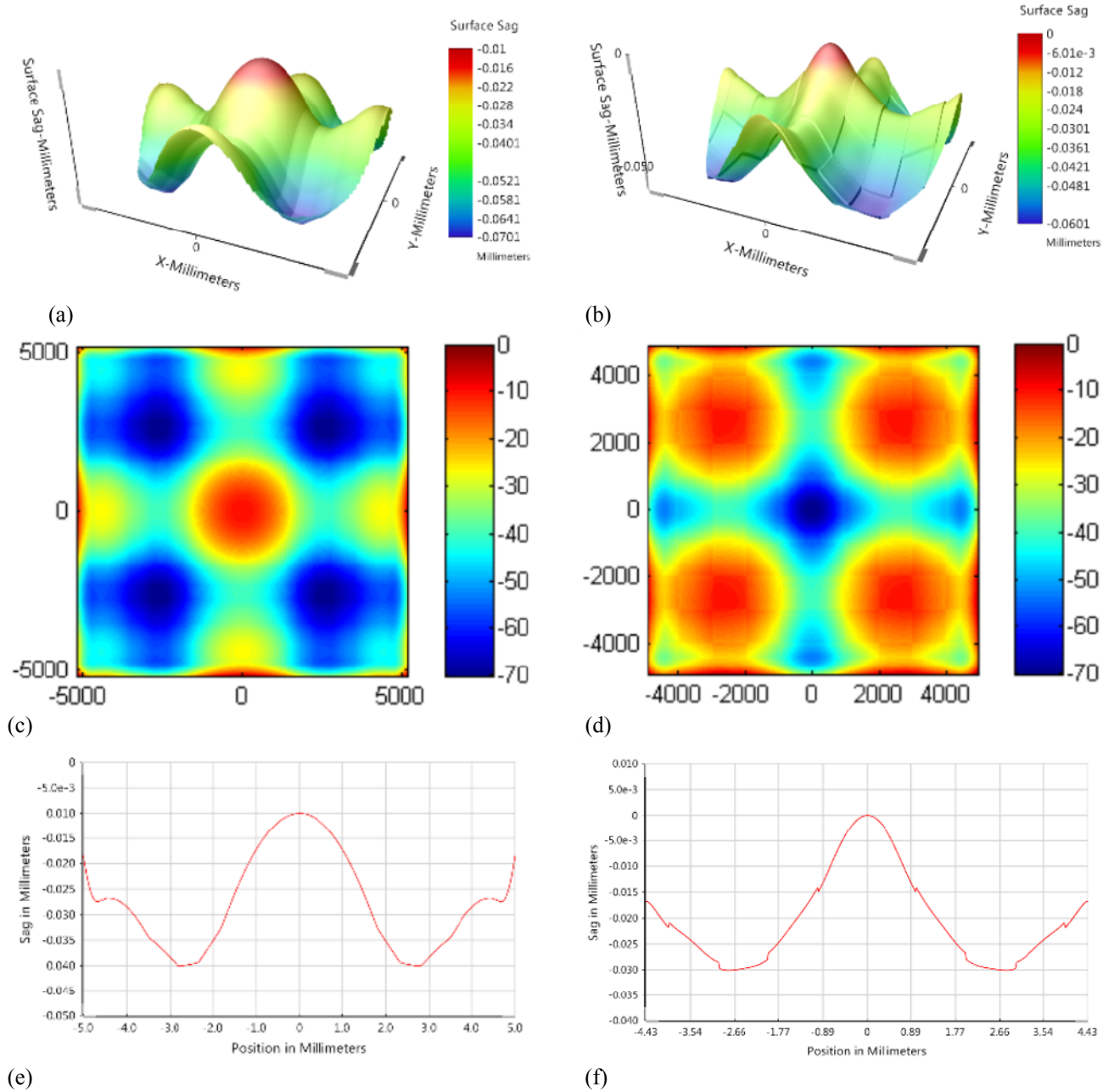


Figure 5. Plate A (a) sag 3D sag profile, (c) 2D profile and (e) line scan through the optic centre; similarly for (b), (d) and (f)

#### 4. FREEFORM DIRECT-WRITE OPTICAL FABRICATION

PowerPhotonic's optical products are fabricated using a unique, laser-based freeform direct-write process. A laser material removal process first generates a programmed net shape in the fused silica substrate material. Then a second laser-based process locally reflows the material to remove cutting marks, resulting in an ultra-smooth, low-scatter, refractive surface.

Since no part-specific tooling or masks are required, realizing a new component design does not incur the level of NRE required for mask-based processing. The manufacturing process is short, so prototype parts can be generated rapidly,

cutting both lead time for custom micro-optics when compared to other free-form grayscale fabrication processes [3][4][5]. The same wafer-scale manufacturing process that is used to make one-off prototypes, is used to manufacture volume parts, so once proven, a new design can be directly scaled up to volume manufacture.

The process is entirely freeform, with no symmetry restrictions, and is easily capable of making the complex surfaces required by many beamshapers. Fabrication in fused silica, plus laser surface smoothing, results in parts with excellent power handling and damage resistance properties, which are ideally suited to high-power laser applications.

The two pairs of T3FM optics were manufactured in Corning 7980 fused silica. The central structure of plate B for the circular flat top, measured using a Taylor Hobson CCI MP-HS (0.2 Angstrom RMS repeatability, <0.1% step height repeatability), is shown in Figure 6. The scaling error in all cases is less than 0.5%. The RMS surface error is less than 500nm; typically we would reduce this to < 50nm through process pre-compensation. The refractive profile is inverted w.r.t Figure 5(b); it appears on the opposite face of the substrate than that used in the model.

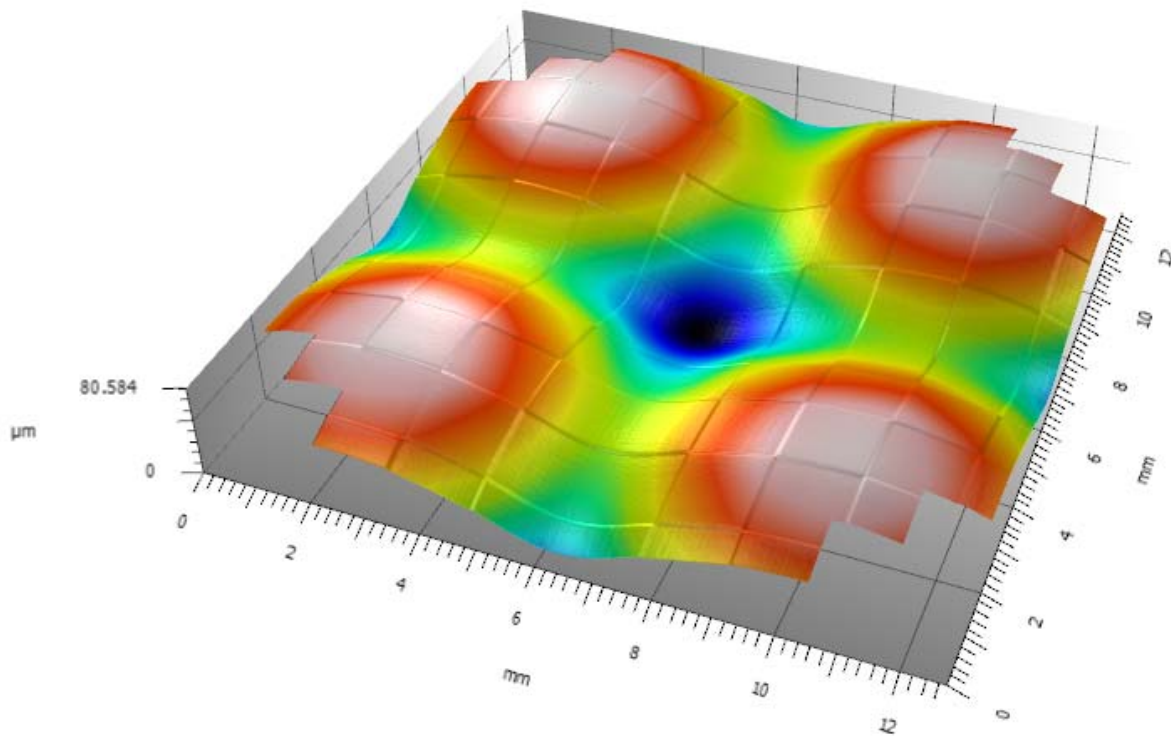


Figure 6. The central region of the plate B. Note the  $\lambda/2$  phase changes.

## 5. PERFORMANCE

The circular flat top T3FM was optically tested using a 1m focal length lens to maximize the size of the spot on the camera. The source was a Qphotonics 15 mW single-mode diode-laser coupled to a fibre. This is collimated to a 4.955mm diameter Gaussian using a Thorlabs 25 mm EFL air space triplet with integrated FC connector. The beam was collimated, and we assumed a plane-wave beam-waist after plate B.

Figure 7 shows the through focus performance for a range of 0.91m to 1.08m about the focal plane located 1m from the lens. The depth of field is estimated at 30mm. The estimate of beam diameter is 0.7mm throughout the depth of field. This scales to the design diameter of  $30\mu\text{m}$  for a 40mm lens.

A large depth of field is relevant in the case of beam scanning. A further series of tests looked at incorporating the T3FM into a polygon scanner configuration. Over the range of the camera translation (approximately 130mm, corresponding to a scanning angle of  $\pm 18^\circ$ ) the beam profile size was maintained ( $200\mu\text{m}$  for a 300m focal length lens, which scales to a diameter of  $27\mu\text{m}$  for a 40mm lens), see Figure 8.

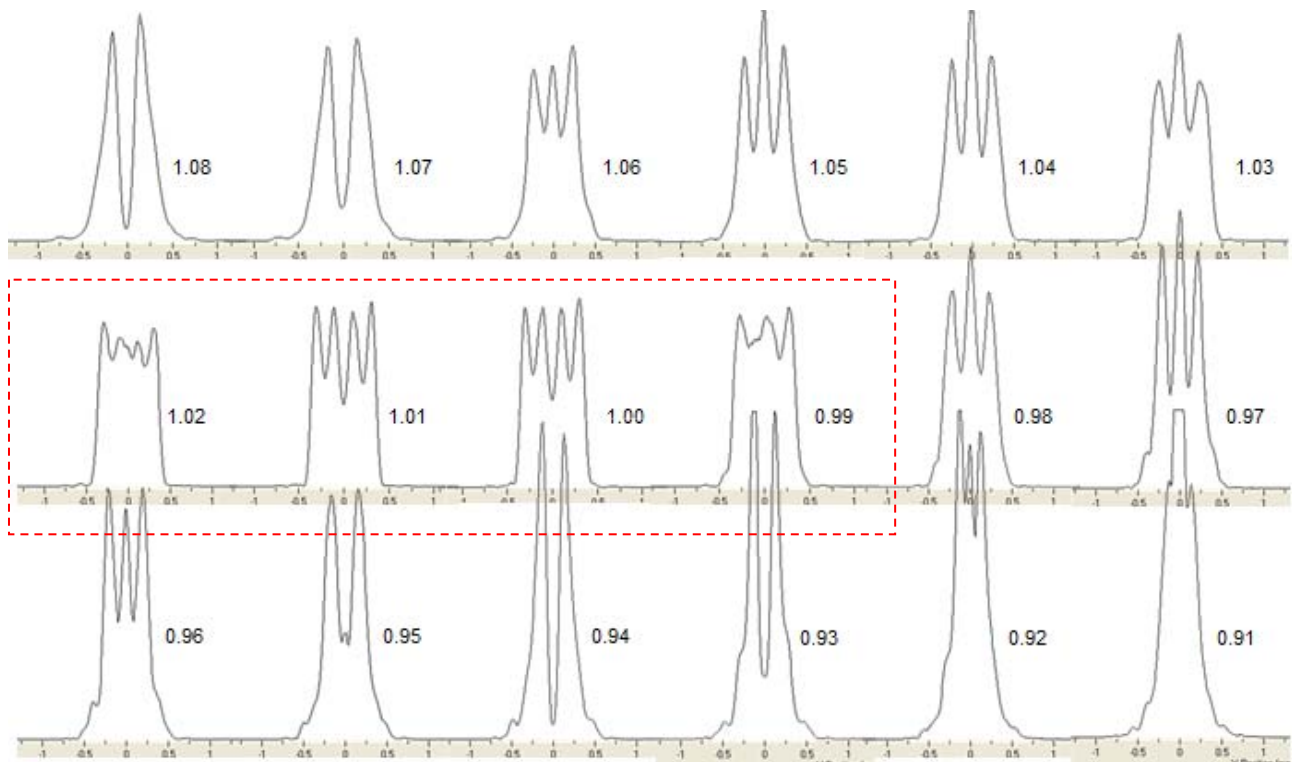


Figure 7. Through focus beam profiles for the circular flat top T3FM using a 1m focal length lens. The red box demotes the (qualitative) depth of field

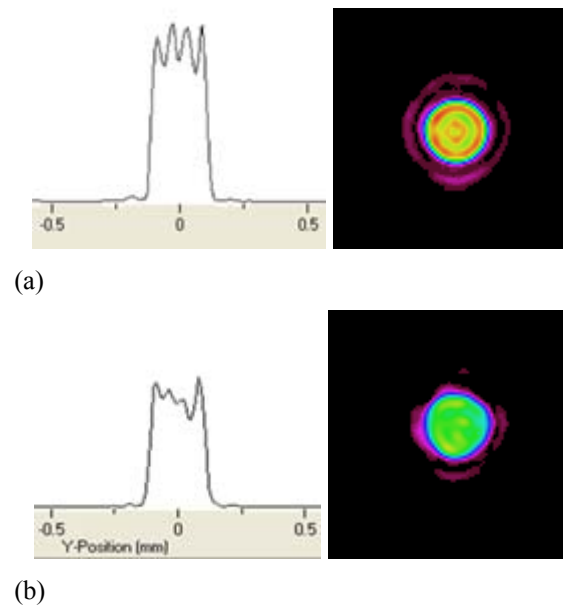


Figure 8. Beam profiles (a) on-axis and (b) at  $18^\circ$  deflection. Focal length 300mm

The second T3FM was designed to produce a  $50 \times 50 \mu\text{m}^2$  spot with an  $f = 50\text{mm}$  focusing lens, therefore it would produce a  $250 \times 250 \mu\text{m}^2$  spot for an  $f = 250\text{mm}$  focusing lens. The laser source was a 20W EP-S SPI laser used with a 75mm BEC. The beam profiles are in Figure 9. The measured spot width is within  $\pm 2\%$  from design. The edge width is  $\sim 60\mu\text{m}$ . The inhomogeneity *excluding* the corner peak (figure 2[d]) is  $\pm 12.5\%$  ( $\pm 2b/a$ ), and including the corner peak  $\pm 20.5$ . Future work will focus on improving homogeneity, although it is worth noting that in many material processing applications the increased intensity in the corners may be desirable.

The most stringent alignment tolerance surrounds the centring of plate B relative to plate A. For an X/Y range of  $\pm 1.5\mu\text{m}$  the impact was noticeable, however at  $\pm 5\mu\text{m}$  the impact was unacceptable. Outwith this, we are seeking to improve the ripple in the flat top profile; modelling suggests that truncation of the Airy profile is responsible for the ripple in the output.

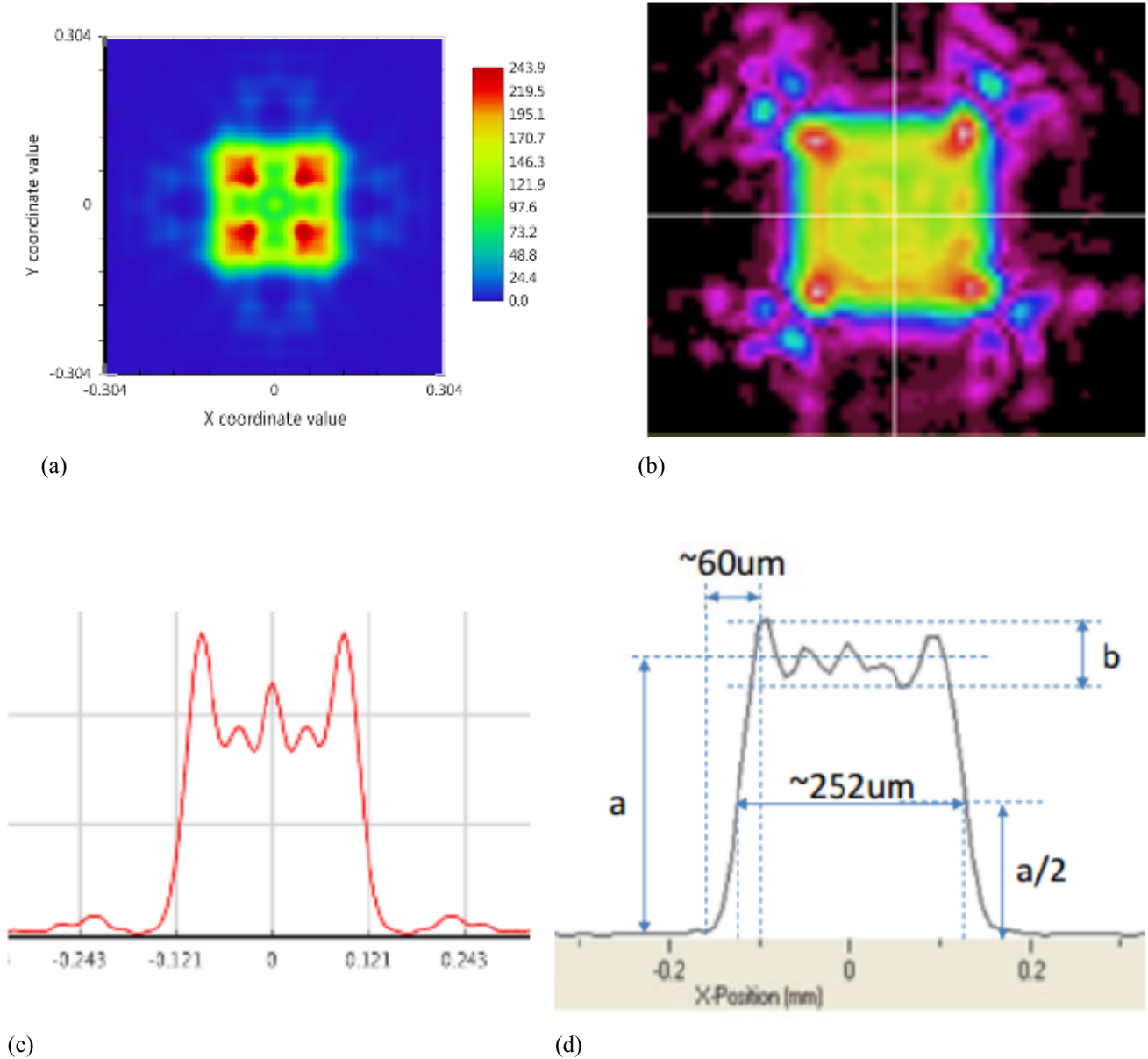


Figure 9. The (a) theoretical beam profile and (b) the measured beam profile in the focal plane. Line profiles through (c) the theoretical beam profile and (d) the measured beam profile in the focal plane.

## 6. CONCLUSION

High power applications place stringent demands on laser beamshaping optics, which must provide high efficiency while handling high peak ( $\text{GW}/\text{cm}^2$ ) and average ( $\text{kW}/\text{cm}^2$ ) power densities. Integration into standard process heads strongly favours compact beamshaper designs, ideally single, thin, elements with smooth, low-scatter surfaces. These requirements particularly favour the use of refractive designs fabricated in fused silica.

For spatially-coherent beams, such as low- $M^2$  fibre lasers and DPSS, field mappers offer the best possible performance, in terms of efficiency and output beam uniformity. Achieving this performance requires stable, well-characterized beam properties, and a beamshaper geometry that is closely matched to the source beam width. The T3FM system is ideal for beams with high spatial coherence, and where there is a requirement for near-diffraction limited performance and/or a large depth of field.

We have successfully demonstrated the T3FM in the generation of circular and square flat top profiles, both in laboratory conditions, and with commercial laser sources. Beam profile size, and inhomogeneity where measured, are within acceptable ranges for most laser material processing applications. Our goal now is an improvement in homogeneity and the alignment procedure, although this has been successfully transferred to laser users.

The Type3 field mapper can be realized as a pair of thin optical elements, for ease of integration into industrial laser process heads, enabling a dramatic increase in system functionality with minimum additional engineering effort. PowerPhotonic's freeform direct-write process is an ideal fabrication technology in this case, delivering low loss fused silica optics with low scatter and high damage threshold. A key feature of this process is the ability to make application-specific beamshapers, providing the greatest possible design freedom, and in particular enabling prototype designs to be fabricated and evaluated without incurring NRE costs for masks or other hard tooling. This wafer-based process provides an economic route to beamshaper realization, from first trial parts all the way through to volume manufacture. It allows optical designers and manufacturers of material processing system to produce application-specific beam profiles without having to make the compromises otherwise imposed by designing with catalogue beamshaper components.

Combining high efficiency, high damage resistance, compact construction, and enabling rapid realization and evaluation of application-specific beam profiles, PowerPhotonic's unique fabrication capability is enabling freeform refractive optics to become a practical, flexible and economic platform for beamshaping in high-power laser systems

## 7. ACKNOWLEDGEMENTS

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