Customised low-angle refractive diffusers for high power laser applications

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ABSTRACT

We describe the design and fabrication of smooth and continuous customized refractive diffusers for the beamshaping of high power lasers, specifically laser systems in which a low diffusion angle is required. Traditional diffusers often have randomised surfaces with strong high frequency peaks in their spatial frequency content. However, these diffusers are not suitable for use in high power laser systems where diffraction angles can approach required diffusion angles. Diffraction angles which exceed diffusion angles present as overall system loss, which in high power laser systems may be unacceptable as they may cause component damage or catastrophic failure.

We show that precise definition of the spatial frequency content of a surface over a lower spatial frequency range allows for the maximisation of diffuser efficiency and performance, even at diffusion angles of only a few milliradians or less. Additionally, the image plane intensity distribution can be extensively shaped in order to obtain favourable processing conditions for numerous systems. By introducing a novel implementation of an Iterative Fourier Transform (IFT) algorithm, we present a method to design and subsequently fabricate highly customised beamshaping diffusers that retain maximum efficiency even when used at low diffusion angles.

This method was subsequently used to design a refractive diffuser for Rutherford Appleton Laboratory's Gemini laser system which imparts a flat top angular distribution having approximately 10mrad full width at half maximum. After manufacture using PowerPhotonic's freeform direct-write fabrication process these diffusers were found to have efficiencies of >96.6% when measured after installation in to the Gemini system, while suffering no performance degradation after approximately 10,000 laser shots with pulse energies around 25J.

Keywords: beamshaping, diffuser, fused silica, high power, materials processing, low angle

1. INTRODUCTION

Customized diffusers for high power lasers operating in both CW and pulsed regimes are highly desirable for a number of different applications, ranging from materials processing to nuclear fusion research. Maximal efficiency is one of the most critical parameters for these systems, thus refractive optics with very low surface roughness and minimized diffractive losses are the most preferred diffuser solution. However obtaining custom refractive diffusers, fabricated in a material that is appropriate for use in both CW and pulsed high power laser systems, can be difficult and prohibitively expensive. Selecting an optical material that is not only capable of handling high pulsed or CW laser power but is also able to be effectively formed in to the appropriate shape can be particularly challenging. Fabrication processes like single point diamond turning and precision moulding can potentially produce custom diffusers in certain materials such as ZnSe and P-SF67, though these materials often have insufficiently high damage thresholds or bulk material absorption for modern high power laser systems [1].

1.1 Basic Diffuser Principles

The principles of refractive diffusers are simple and rely on the fact that the slope distribution of an optical surface directly influences the far-field angular distribution of a light beam transmitted through the surface. If the slope distribution of the diffuser surface can be controlled, then so can the angular distribution of the transmitted beam, thus a surface with a

Gaussian slope distribution will impart a Gaussian angular distribution on the transmitted beam. Commonly the magnitude of the angular distribution imparted on the beam is described with a single angular diffusion value $\theta_{\text{diffusion}}$ associated with an appropriately descriptive threshold value, for example 10mrad half angle divergence at the $1/e^2$ point on a Gaussian distribution.

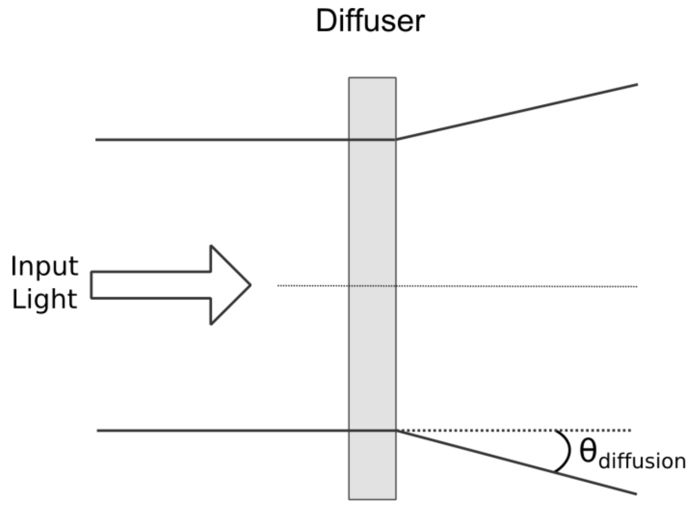

Figure 1: The principle optical function of a diffuser: imparting an angular distribution $\theta_{\text{diffusion}}$ to a transmitted input beam

Most often, as in Figure 2 below, the diffuser element is used in conjunction with a condenser or field lens that converts the angular distribution to a spatial distribution at the focal plane or, equivalently, images the far-field intensity distribution on to a desired image plane.

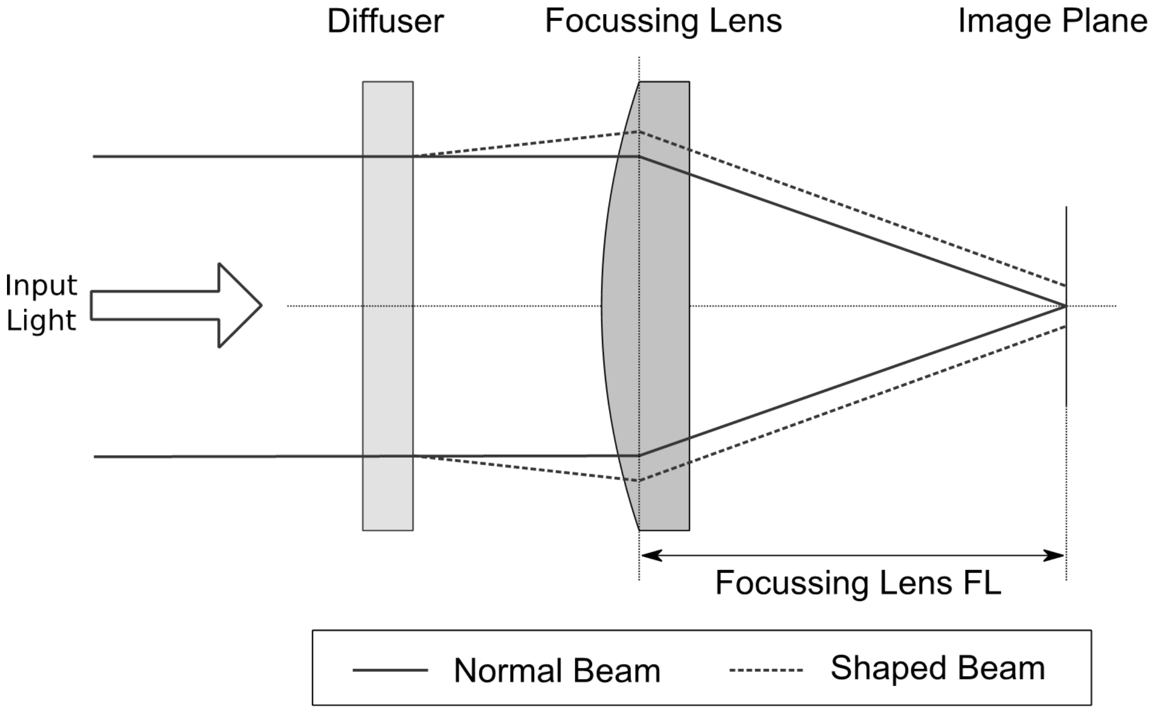

Figure 2: Showing the impact of using a diffuser in a system with a focused beam.

The fundamental optical function of diffusers has been exploited in laser systems since shortly after the invention of the laser for speckle reduction [2] and interferometry [3] amongst other applications. The level of control over the slope distribution in the diffusion surface of cost-effective diffusers has been limited for decades with the majority of diffusers being made using sandblasting, grinding or coatings such as opal with the additional drawback of significant efficiency losses in practice [4]. More angular control is possible when using holographic [5] or diffractive diffusers although both of these solutions are significantly more expensive, and have major limitations on system parameters such as input angle of incidence, output angle of incidence and efficiency. Additionally, it is a challenge for these solutions to produce diffusers with sufficiently low spatial frequency in the modulating medium to allow for maximal efficiency in applications requiring very low diffusion angles.

1.2 Fully Continuous Phase Screen Design

In 1996 Dixit et al, working on improving the Inertial Confinement Fusion (ICF) process at Lawrence Livermore National Labs, described [6] a variant of the commonly used Gerchberg-Saxton Iterative Fourier Transform (IFT) algorithm [7] that could be used to produce efficient, tailored diffuser surfaces. These surfaces were referred to as Fully Continuous Phase Screens (FCPS) and were iteratively calculated such that the resultant slope distribution of the surface would impart a given angular distribution to a transmitted beam, while starting with and subsequently maintaining a smooth and continuous surface profile throughout iteration.

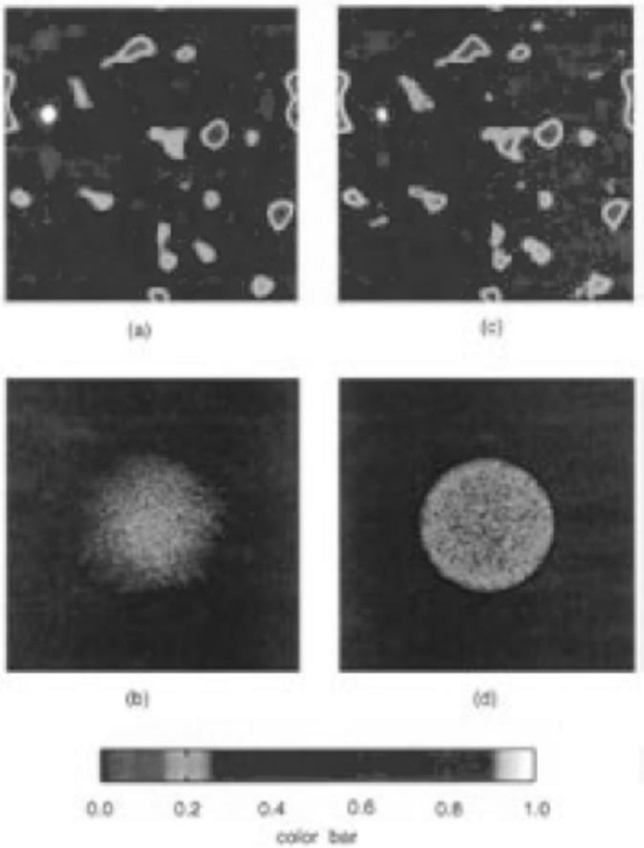

Figure 3: (a) the continuous seed surface, (b) the far-field intensity distribution produced by surface (a), (c) the continuous surface after application of the FCPS algorithm, (d) the far-field intensity distribution produced by surface (c). Taken from [6].

Dixit and his team found that when starting with a continuous seed surface and then running their algorithm with a sufficiently small surface slope modification in between iterations “phase steps”, i.e. regions where phase differences of 2π occur between adjacent pixels in the surface, were not produced. The elimination of the phase steps is critical in maintaining a continuous surface and maximizing transmission efficiency, while the algorithm itself allows for a high level of flexibility and accuracy in defining the far-field angular distribution of a transmitted beam. As can be seen in Figure 3 above, the result of the FCPS algorithm was a highly complex, freeform, continuous surface.

1.3 Minimisation of Diffractive Losses

As previously mentioned, the spatial frequency of the modulations (whether volumetric refractive index modulation or surface modulation) that comprise a diffusing element have an impact on the delivered efficiency of a transmitted beam in to a desired angular aperture. Most of the diffuser manufacturing processes described above have a characteristic spatial frequency content based on the desired angular threshold required. For example, the required diffusion angle $\theta_{\text{diffusion}}$ largely determines the spatial frequency content of sandblasted and ground glass diffusers: the appropriate grit size for processing is chosen to give the desired $\theta_{\text{diffusion}}$ value but this also implicitly creates a set spatial frequency content due to the processing mechanics. In order to minimize diffractive losses for any given angle $\theta_{\text{diffusion}}$, the desired slope distribution must be maintained while allowing for variation in the spatial frequency content of the surface.

If the spatial frequency content of the diffuser element is known, the angle of diffracted light can be approximated by assuming that any given spatial frequency value consists of a sinusoidal structure with a period Λ:

$$\theta_{diffraction} = \sin^{-1}\left(\frac{m\lambda}{\Lambda}\right) \tag{1}$$

where m is the diffraction order and λ is the wavelength of the input beam.

As shown in Figure 4 below, in order to maximize the diffractive efficiency of the diffusing element the diffraction angle $\theta_{\text{diffraction}}$ from any given spatial frequency value within the surface must be lower than the angle $\theta_{\text{diffusion}}$.

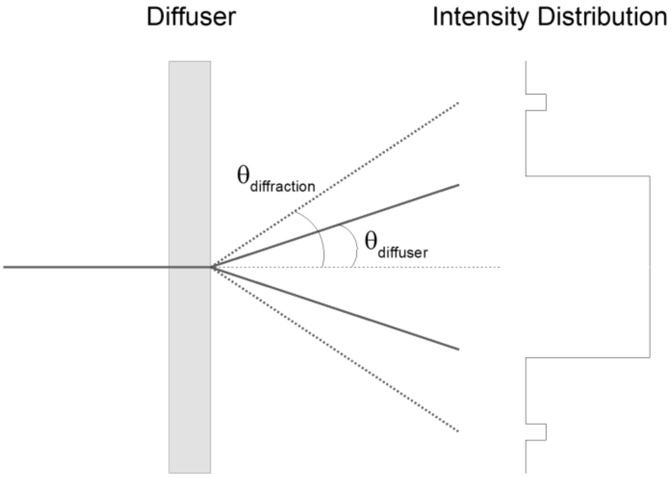

Figure 4: The impact on the far-field intensity distribution when a transmitted beam pass through a diffuser whose spatial frequency means resultant $\theta_{\text{diffraction}}$ is greater than $\theta_{\text{diffusion}}$.

To illustrate the maximum spatial frequency values allowable in a diffuser before incurring diffractive losses, take the example of a generic laser head for materials processing that requires a low-angle diffuser to increase the spot size and Rayleigh length of a focused laser beam:

- λ = 1064nm
- Focussing Lens EFL = 250mm
- Spot size requirement = 0.5mm (HWHM)

From this, we can determine that the HWHM diffusion angle $\theta_{\text{diffusion}}$ is 0.5/250 = 2mrad. In order to calculate the maximum allowable spatial frequency where $\theta_{\text{diffusion}} = \theta_{\text{diffraction}}$, Equation (1) is rearranged:

$$\Lambda = \frac{m\lambda}{\sin(\theta_{diffusion})} \tag{2}$$

It is found that the minimum grating period Λ = 532µm for the first diffracted order which corresponds to a spatial frequency of 1.88 lines/mm. Compare this requirement to typical sandblasted or ground glass diffusers that grit sizes of 10-100µm in diameter, which create diffusers with spatial frequency ranges approximately between 100-10 lines/mm, it can be seen that producing an efficient diffuser using these techniques is not viable. All other standard manufacturing techniques apart from those designed using the FCPS algorithm, including those producing more advanced elements such as diffractive or holographic diffusers, inherently include peaks in their spatial frequency bands that are significantly higher than this example due to the sharp and discontinuous transitions that comprise the diffuser structure.

It is important to note that in cases where the diffuser is being used in high peak or CW power laser applications such as materials processing, ICF and scientific research the impact of diffraction may be significantly enhanced as even losses of a few percent can at the least cause deleterious system heating and at the most cause catastrophic system failure due to stray diffracted radiation.

2. FREEFORM DIRECT-WRITE OPTICAL FABRICATION

Although the FCPS surfaces could be designed and analysed using appropriate simulation tools, manufacture of these surfaces in a truly continuous sense was a significant challenge. They can be approximated by converting the continuous surfaces in to a series of phase steps, but this either largely negates the advantages of the FCPS algorithm by introducing discontinuities or is extremely expensive to implement with traditional manufacturing techniques.

PowerPhotonic’s unique laser direct-write fabrication process allows highly complex, freeform structures to be fabricated in fused silica quickly and economically. A laser acts as the only surface processing tool which negates the requirement for part-specific tooling or masks and allows for the rapid realization of new freeform surfaces designs. The process is essentially made up of two stages: a laser ablation step and a laser polishing step.

2.1 Laser Ablation

The first stage in the PowerPhotonic fabrication process involves the raster scanning of a pulsed laser beam over the surface of a fused silica substrate. The laser pulses ablate a precise volume of material from the substrate, and act to form the desired surface of the required optic.

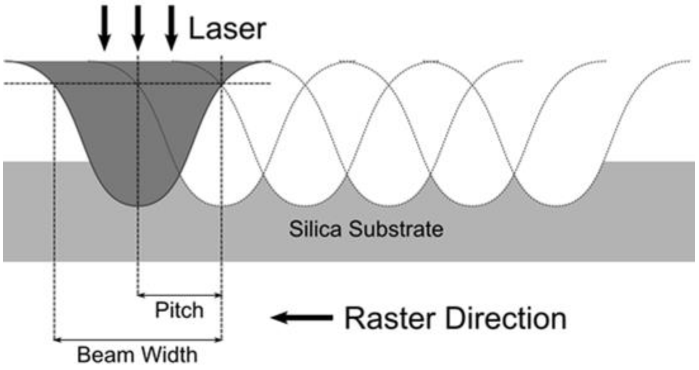

Figure 5: The cutting process showing precise removal of substrate volume using a pulsed raster scanned laser. Diagram not to scale.

In order to create freeform surfaces the pulse energy of each individual pulse is adjusted to alter the volumetric removal on a pulse-by-pulse basis, allowing for completely freeform surface profiles with no symmetry restrictions. Although this process reproduces the desired surface shape highly accurately, it leaves behind a microstructure that must be removed before the element is optically useful.

Figure 6: An illustration of the microstructure left behind after the laser ablation step, with the microstructure shown in black. Diagram not to scale.

2.2 Laser Polishing

The second stage of the PowerPhotonic fabrication process aims to remove the microstructure left behind after the laser ablation step, while simultaneously leaving the desired optical shape completely unchanged. This is achieved using a laser to polish the surface of the glass by raster scanning over the machined surface and melting a very thin layer of substrate. The molten silica reflows under the effects of surface tension which removes the microstructure, the molten fused silica then re-solidifies to leave an extremely smooth and continuous surface while the desired optical shape is unaffected.

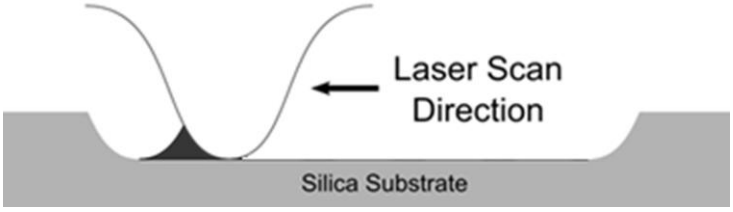

Figure 7: An illustration of the laser polishing process showing removal of the microstructure from the ablation process by raster scanning a laser beam. Microstructure is shown in black. Diagram not to scale.

The ablation and polishing processes can be used together to quickly produce highly complex, freeform surfaces in fused silica. The extremely low surface roughness corresponds to very high efficiency and the laser processing ensures that the laser induced damage threshold (LIDT) of the optical surfaces can be in excess of 100Jcm^{-2} due to the lack of chemical surface changes or micro-cracks.

3. EFFICIENT PRIME DIFFUSER DESIGN

Using the FCPS design algorithm allows for calculation of theoretical beamshaping diffuser surfaces, but does not necessarily take in to account diffractive losses due to spatial frequency content or manufacturing tolerances and limitations. PowerPhotonic have developed a variant of the FCPS algorithm that take both of these in to account and create custom diffusers fit for specific applications. This diffuser product family has been dubbed the Pseudorandom Refractive Intensity Mapping Element (PRIME) diffusers, and the custom PRIME design algorithm has been optimized for the PowerPhotonic fabrication process.

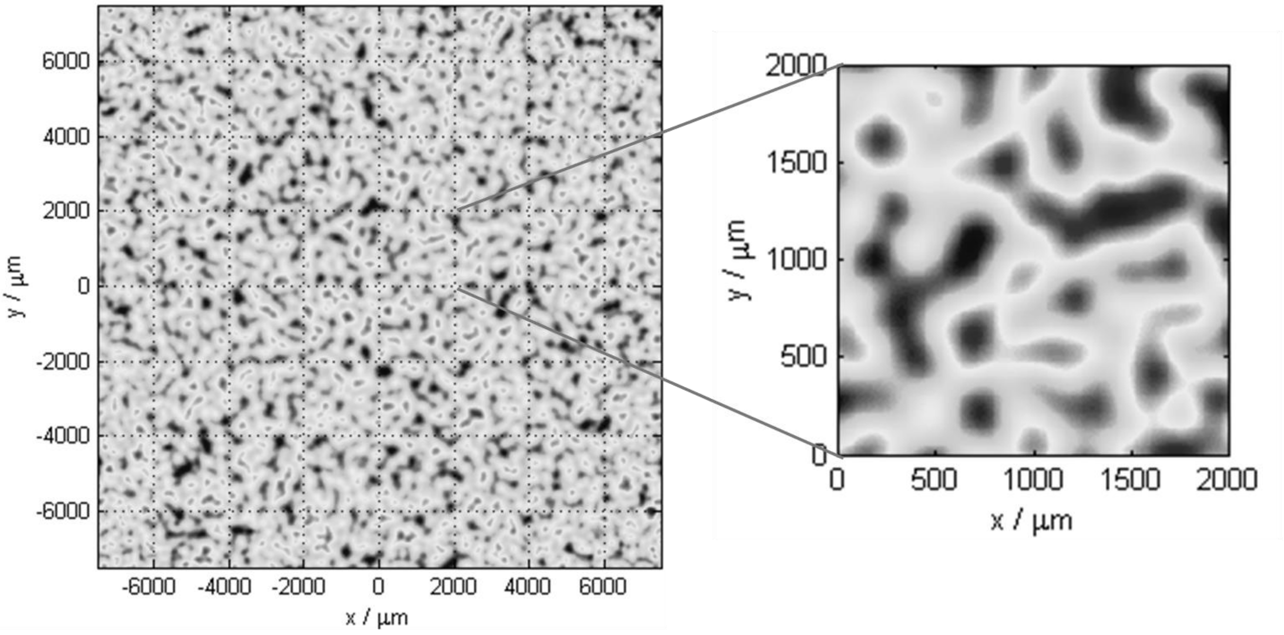

Figure 8: Left: an image of a PRIME diffuser design surface, Right: a zoomed in region highlighting the complex and continuous freeform surface of the PRIME

The main change in the PRIME design algorithm compared to the FCPS algorithm is the introduction of low-pass spatial frequency filtering stages that constrain the spatial frequency content in the resulting surface such that the ultimate optic has minimal diffractive losses while at the same time maximizing the possible beamshaping impact.

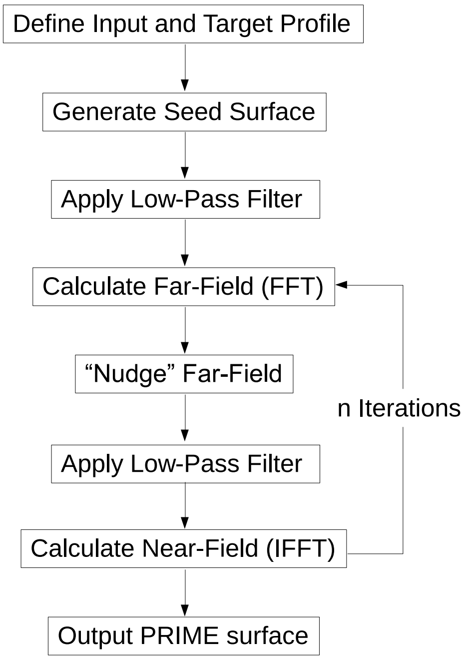

Figure 9: A simplifed flow chart showing the main stages in the PRIME surface generation algorithm.

As can be seen in Figure 9 above, the first stage of the algorithm is to mathematically define the input laser beam parameters and the target intensity distribution. By applying the previously described diffractive angle calculations to the algorithm input parameters, the seed surface is generated using an appropriate spatial frequency filter that ensures minimal diffractive losses. Like the FCPS algorithm the subsequent iterative steps individually apply small changes to the slope distribution of the PRIME surface in order to "nudge" the far-field distribution closer to a target distribution, although the PRIME algorithm applies an additional filtering step to each iteration to constrain the spatial frequency content within known values. This iterative process continues until either the algorithm converges or a pre-defined number of cycles are reached.

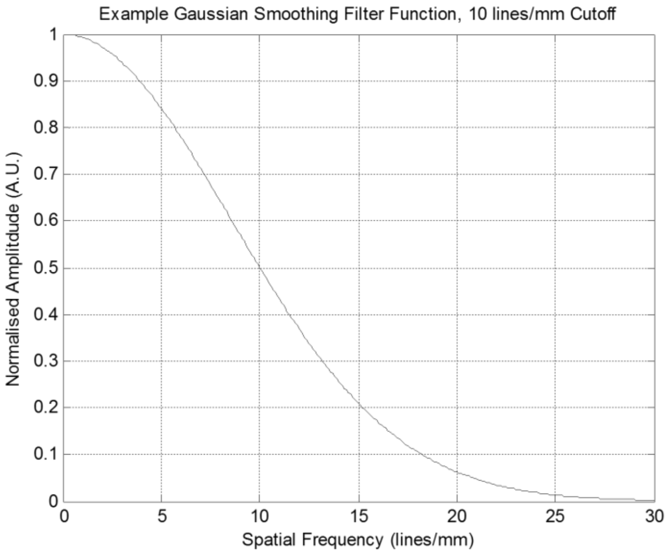

Figure 10: An example of a Gaussian low-pass filter used for PRIME surface design.

Depending on the type of PRIME surface being created, the seed and iteration filtering is conducted using a Gaussian or supergaussian low-pass filter in order to eliminate any ringing in the resulting spatial frequency spectrum, with the cutoff frequency of the filters depending on the input parameters. Using this algorithm in conjunction with the PowerPhotonic fabrication process, PRIME beamshaping diffusers can be designed and manufactured with diffusion angles from 1-150mrad that maximize both efficiency and performance in any given application.

4. EXPERIMENTAL RESULTS

A low angle PRIME was designed and manufactured for the Gemini laser system located in the Central Laser Facility at the Rutherford Appleton Laboratory. This laser system uses a frequency-doubled Nd:glass source to pump a Ti: sapphire gain medium to create ultrashort petawatt peak power pulses [8].

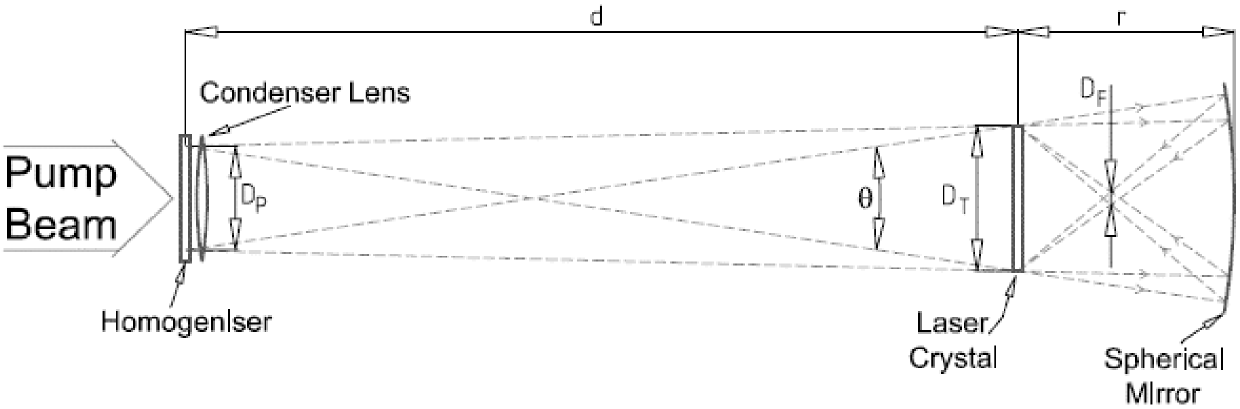

Figure 11: An illustration of the optics involved in the pump beam close to the Ti:sapphire crystal. Taken from [8].

The raw pump beam from the Nd: glass source is very inhomogeneous which significantly detracts from the pump efficiency of the system, where ideally the beam would be homogeneous with high edge steepness.

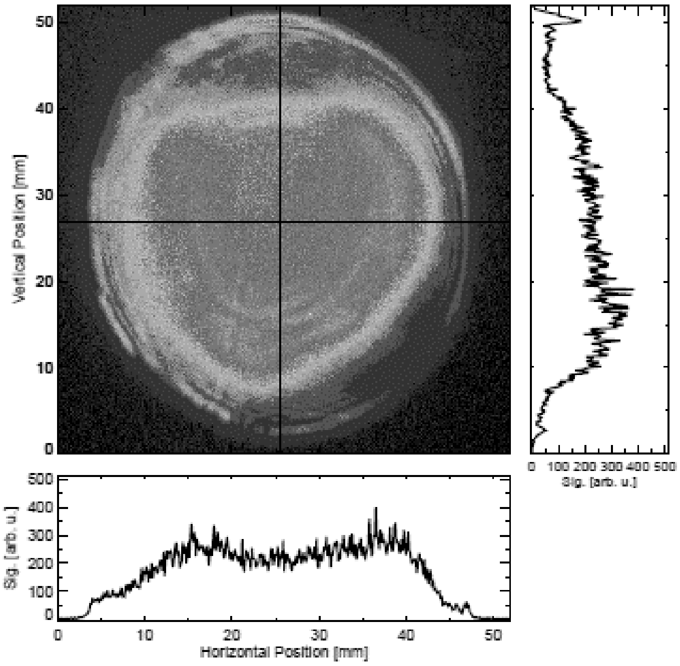

Figure 12: The raw output from the Nd:glass pump source. Taken from [8].

In order to create the desired intensity distribution at the Ti:sapphire plane a PRIME was designed, simulated and manufactured which produced a circular high order supergaussian flat-top of 48mm at the focus of a 4.7m condenser lens.

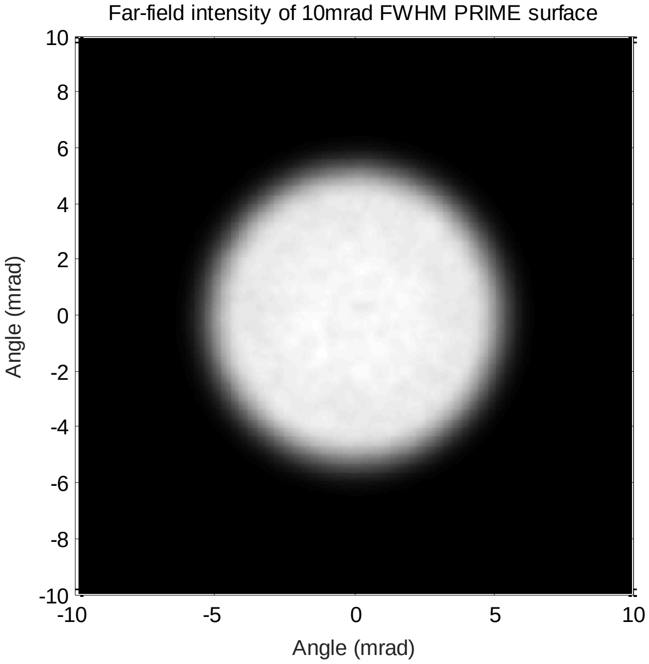

Figure 13: The simulated output of the PRIME design generated for the Gemini laser diffusing element.

After installation in the pump laser beam path, an image of the beam profile was taken during a representative laser shot that showed the output was significantly more homogeneous than the raw output from the Nd:glass source (shown in Figure 14 below).

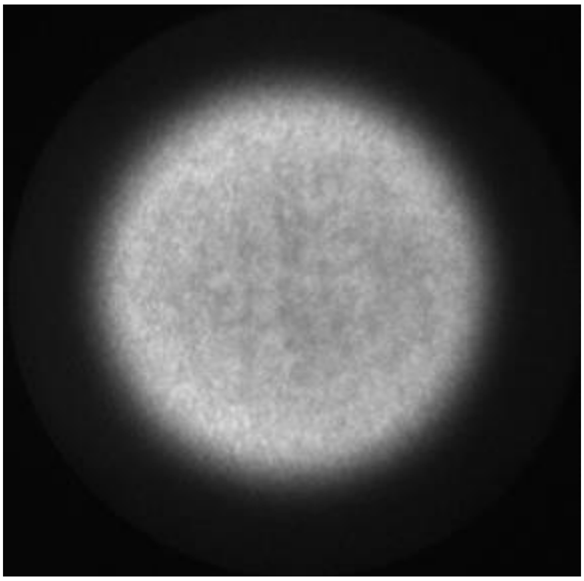

Figure 14: The measured intensity distribution of the Nd: glass pump beam after transmission through the PRIME beamshaping diffuser.

It was found that the efficiency of the system shown in Figure 11, including PRIME diffuser, condenser lens and 3 mirror elements was 96.6% and subsequent analysis and inspection of the PRIME diffusers after approximately 10,000 shots at pulse energies of approximately 25J showed no damage present or change in system performance.

5. CONCLUSIONS

The PRIME algorithm is a custom version of the FCPS algorithm described in 1996 that incorporates additional filtering to ensure both excellent manufacturability and minimal losses due to diffraction when in use. The PRIME diffusers are particularly suitable for use in high peak- and CW-power laser systems due to their fused silica construction, very high LIDT and extremely smooth surfaces.

As evidenced by the results of a PRIME installed in RAL's Gemini laser system, low-angle PRIME beamshaping diffusers can be designed and fabricated by PowerPhotonic that maximize efficiency and performance while maintaining these advantages over extended use cases in one of the world's highest peak power laser installation.

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