

LOW LOSS FIELD-MAPPED LASER BEAM HOMOGENIZER

Paper (1304)

Michael Scaggs¹, Nadeem Rizvi², Andrew Goater², Gary Owen², Gilbert Haas³

¹ Neoteric Concepts, LLC, 1612 Eastlake Way, Weston, FL 33326, USA

² Laser Micromachining Ltd., OpTIC Technium, St. Asaph Business Park, Denbighshire LL17 0JD, UK

³ Haas Laser Technologies, Inc, 37 Ironia Rd, Flanders, NJ 07836, USA

Abstract

A new type of laser beam homogenizer has been developed which “field-maps” an illumination by using spherical, cylindrical, axicon or prism optical segments, or in some applications combination of these various elements, and placing the optical segments in a configuration whereby light passing through each optical segment directs the light to overlap at a homogenized plane with the desired shape (rectangle, square, rectangular or circular ring illumination). The geometry of the homogenized field is limited only by the fabrication techniques used in segmenting and how the segments are physically arranged. This optical concept could be called a Fresnel Homogenizer as it functions like a Fresnel lens. Fabricated in its basic form from spherical or cylindrical lenses, the lenses can be either negative or positive, depending upon the type of illumination, size and numerical aperture required. Typical fly’s eye homogenizers require 5 optical elements this new homogenizer is comprised of a single element; thereby significantly reducing the losses in the system due to diffraction and reflectance.

Introduction

Light beam homogenizer designs used for decades are largely based upon lenticular lens arrays that date back to the 1940s and 1950s. A more recent design is from the late 1980s that comprises a pair of crossed-cylindrical lenticular lens structures coupled with a condensing lens [1]. The 1980s design has 10 optical surfaces which represents a significant source of optical loss, long beam path (typically ~ 1.5 meters) and high cost from having so many optical elements. Further, this design requires careful and precise alignment of the light beam in relation to the optics comprising the homogenizer, in particular angular rotation of the lenslets and their positioning in the X-Y plane of the optical axis. Interestingly, none of these designs are capable of producing a homogenized ring illumination which is useful for ablating polymer insulation from metal bonding pads in microelectronic fabrication of multichip modules and memory chips. Burghardt et al developed a dual line homogenizer

which was a great step in increasing the efficiency and versatility of laser beam homogenizers for microelectronic applications [2].

Gray scale lithography techniques have made it easier to obtain ring illumination and other complex homogenizer shapes [3]. While these homogenizers provide great versatility, they are limited in size (< 15 mm input aperture) and are expensive unless purchased in very large quantities and therefore are less favorable for typical excimer and other high power lasers.

Homogenizers are divided into two categories: imaging and diffractive (non-imaging) [3]. A diffractive homogenizer is shown in figure 1. An imaging homogenizer is illustrated in figure 2.

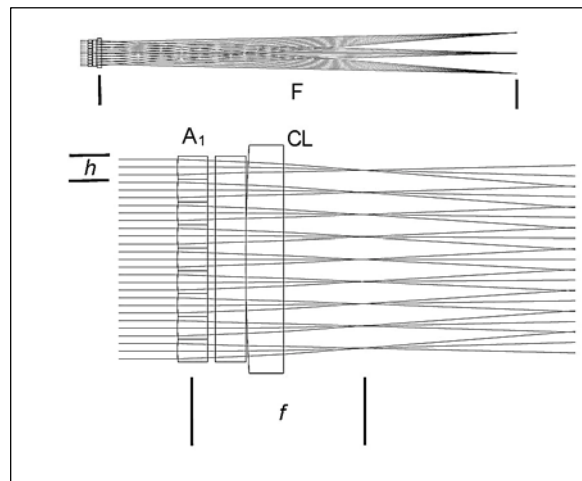


Figure 1 Diffractive (non-imaging homogenizer)

The diffractive homogenizer is most easily fabricated by using a pair of crossed cylindrical lenses (A_1) with focal length f , lenslet width h as shown in the figure 1. All of the sub apertures created by the crossed lens array are then superimposed at the focus F of the spherical condenser lens.

The size of the homogenized field is therefore defined by the following equation:

$$H = \left| \frac{hF}{f} \right| \quad (1)$$

An imaging homogenizer is generally comprised of 2 pairs of crossed cylindrical lenses (A1 & A2 with focal lengths f_1 and f_2) and followed by a Fourier transform lens (CL).

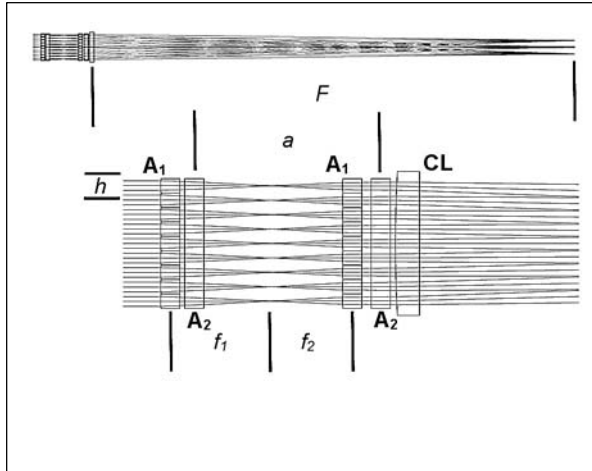


Figure 2 Imaging Homogenizer

The homogenized field of an imaging homogenizer is defined by:

$$H = \frac{hF}{f_1 f_2} [(f_1 + f_2) - a] \quad (2)$$

In both of the classic type of homogenizers, one has to pay attention the Fresnel number of the system as this has a significant effect upon the homogenized field. The Fresnel number is defined by:

$$N_f \approx \frac{hH}{4\lambda F} \quad (3)$$

The Fresnel diffraction is directly related to the Fresnel number and the higher the Fresnel number, the sharper the edges of the profile and the less variation in intensity due to diffraction. Fresnel numbers in the range of > 10 to > 100 are most commonly used in homogenizer design [4].

Field-Mapped Beam Homogenizer

A novel approach has been developed which reduces the number of optical elements required to make a laser beam homogenizer.

The field-mapped homogenizer, in its basic form, is fabricated from spherical or cylindrical lenses. The lenses can be either negative or positive, depending upon the type of illumination, size and numerical aperture required. The lenses are then segmented from larger lens elements in a predetermined way and then specific segments are selected and repositioned in a mapped order so that the light passing through each lens segment recombines at the desired homogenized plane. Figure 3 illustrates this process with 3 plano-concave lenses to form a 1 x 3 segment homogenizer for simplicity of explanation.

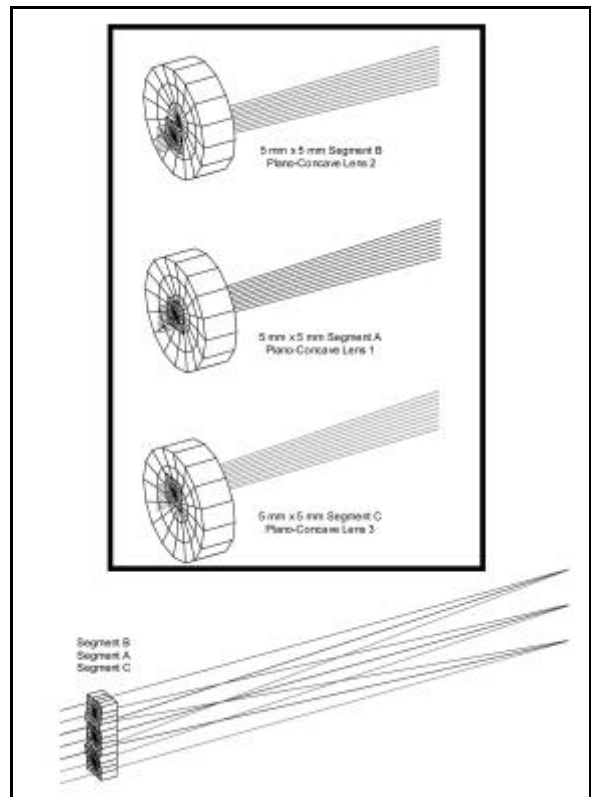


Figure 3 Field-Mapped Homogenizer

The 1 x 3 segment homogenizer in figure 3 would produce a 15 mm x 15 mm homogenized field at two times the absolute focal length of the negative spherical lens used, i.e., if the plano-concave lens prior to segmenting had a focal length of -100 mm, then the homogenized field would be + 200 mm away from the array after segmenting and mapping. Specifically, segment "A" is extracted from the center of lens 1 which has coordinate values (-2.5 mm, -2.5 mm) and

(2.5 mm, 2.5 mm) and defines the 5 mm x 5 mm square lens segment. It is assumed here that the center of each of the larger lenses, prior to segmenting, would have coordinate value (0 mm, 0 mm). Next, segment “B” is extracted from lens 2 with coordinate values (-2.5mm, 0) and (2.5 mm, -5.0 mm). Lastly, segment “C” is extracted from lens 3 with coordinate values (-2.5 mm, 0) and (2.5 mm, 5.0 mm). In the assembled array segment “B” would be the top lens, segment “A” the center lens and segment “C” the bottom lens.

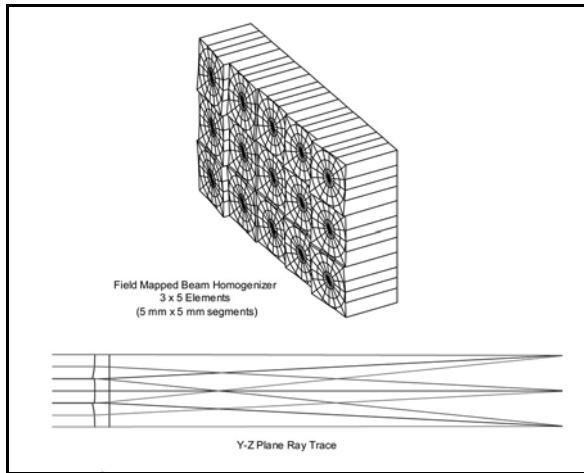


Figure 4 Field-Mapped Beam Homogenizer with 3 x 5 elements

Although there are innumerable ways to segment the lens and achieve a field-mapped illumination, the most efficient for utilizing stock optics and therefore reduced cost of manufacturing, is to segment with a 50% offset from the center segment as described above. This, then, results in a length (L) from the optic to the homogenized field defined as follows:

$$L = \left| \frac{2r}{n-1} \right| \quad (4)$$

Where r is the radius of curvature of the segment and n is the index of refraction of the lens material. This equation assumes a plano-convex or plano-concave design. Although there is no reason a convex-convex or concave-concave design couldn't be used, there is no performance advantage to do so and having a plano-convex/concave surface combination simplifies fabrication.

When the radius of curvature of the lens segments are positive, the homogenized field size is equal to the segment size:

$$H = h \quad (5)$$

When the radius is negative, the homogenized field size at the homogenized focal position L is:

$$H = 3h \quad (6)$$

Again, this assumes a 50% offset of the lenslets from the center element as mentioned earlier.

The ray trace at the bottom of Figure 3 illustrates the controlled refraction which forms at a common, homogeneous plane with a focal length of 200 mm. The cross-sectional view of the array (figure 4 ray trace) resembles a Fresnel lens. By definition each lens segment can be considered a Fresnel zone but as such are not configured in the traditional manner.

The field-mapping can be applied to prism or conical forms. Figure 5 shows an example of an axicon based field-mapped ring illumination homogenizer. The top graphic in figure 5 shows an isometric view of a segmented axicon where each section has a different conic constant that allows the light to be overlapped at a fixed distance from the array. For the given example the focus of the homogenized ring is about 120 mm and produces a 3 mm wide ring. The spot diagram at the bottom of the figure shows how the light transforms after the array over a range of +/- 120mm. This illustrates the flexibility of the basic concept. Likewise, segmenting and mapping rectangular cylindrical lens segments, positive or negative, will produce a rectangular ring illumination.

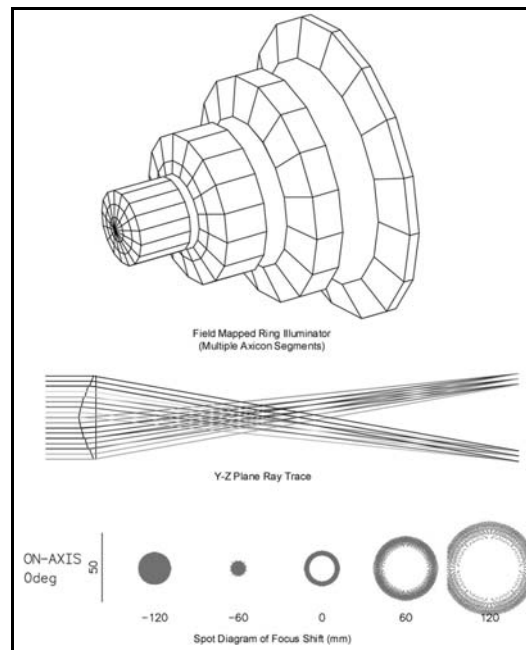


Figure 5 Field-Mapped Ring Illumination



Figure 6 Field-Mapped 3x9 Element Homogenizer

A microelectronic application, for example, may require the illumination of the outer region of a circuit that is 13 mm x 21 mm; where metal bonding pads need to be cleared of an insulating polymer. In a typical excimer laser optical system, one might require an ablation fluence of 500 mJ/cm² in order to expose the metal bonding pad. A field of 13 mm x 21 mm would therefore require 1.36 J of energy on target for the given fluence. This is very unrealistic for current excimer laser technology at any reasonable cost. Since the bonding pads are on the periphery of the chip, one need only illuminate the outer perimeter and not the entire die of which most of the laser's light would be blocked by the illumination mask. Existing homogenizers would have to illuminate the entire 13 mm x 21 mm area or at lower energy and process the die in steps. This is impractical in most cases due to the added time of step and repeating the circuit with an accompanied mask change.

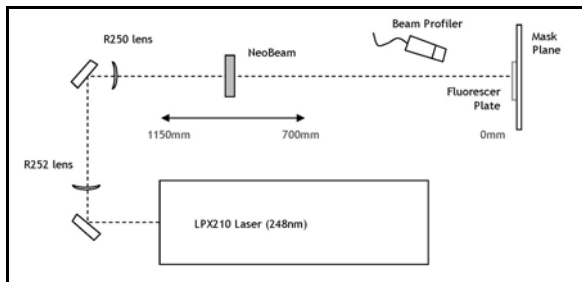


Figure 7 Optical Setup

In order to achieve a rectangular ring illumination with field-mapping, segments from several plano-convex cylinder lenses are mapped to a homogenized field that forms a rectangular ring of 13 mm x 21 mm as an annulus. A typical width of the annulus could be 3 mm. In this example the field-mapped ring illuminator would only require 465 mJ at the mask to achieve the

needed 500 mJ/cm² fluence to expose the bonding pads. This is very much achievable with current excimer technology and clearly improves the overall efficiency of the laser's energy over larger areas that are simply not possible with other homogenizer designs.

Experimental Setup

A 3 x 9 element field-mapped beam homogenizer was designed and constructed to work with a 248 nm Lambda Physik LPX 210 excimer laser.

The spherical segments of the homogenizer were sized and cut to accept the nominal beam size from the excimer or 10mm x 30mm and to produce a 10mm x 10mm homogenized field at a nominal distance of 1000 mm. The segments were cut to 3.33mm x 3.33mm and the radius of curvature of each element was -250 mm.

With $r=-250$ and the index of refraction n for fused silica at 248 nm is 1.508 and using equation 4 gives a homogenized distance length of 984 mm. Since this is a plano-concave design the homogenized field size is 3 times the segments size. Given our segment size of 3.33mm x 3.33mm our homogenized field size is nominal 10mm x 10mm from equation 6.

Figure 6 shows the actual homogenizer used in the system. The unit requires a fraction of the space more traditional designs take. This unit is only about 60mm x 40mm x 13mm. Alignment is simple in that the device need only be positioned in the X and Y axis of the beam and rotated to be parallel to the optical axis of the beam. As well, the unit can be orientated with the concave surface facing the laser or the plano surface. The orientation has no impact on the homogenized field.

In this design (plano-concave) there is no focussed pupil to worry about down stream of the device so this is beneficial for protecting mirrors between the mask and homogenizer. Figure 7 gives the basic layout of the optical system used to test the homogenizer.

A relay lens system was used to improve the light collection and to provide some level of divergence control prior to illumination of the field-mapped beam homogenizer. Figure 8 shows a 3-D profile of the raw excimer beam prior to illumination of the homogenizer. In addition, a qualitative measurement beam profile of the laser before and after the homogenizer was taken with fax paper (figure 9).

Results

Figures 10, 11 and 12 are 3-D beam profiles of the homogenized field-mapped beam measured at 700 mm, 950 mm and 1150 mm from the optic. The optimum distance was found to be 950 mm which closely agrees the optimized optical design software distance of 956 mm.

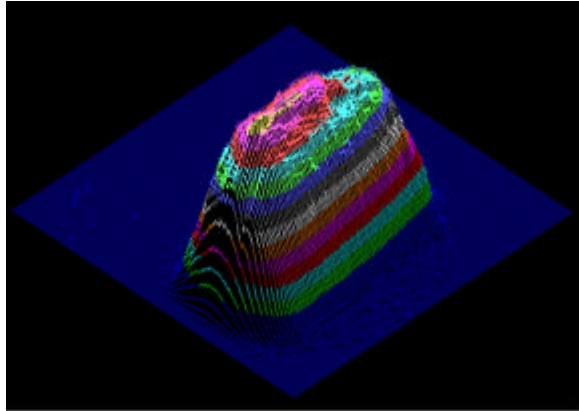


Figure 8 Raw Excimer Beam 3-D Profile

	With Lens Pair	Without Lens Pair
Input		
Output		

Figure 9 Fax burns of the input and output of the field-mapped homogenizer

Figures 14 and 15 are plots made with Zemax to model the homogenizer with a simulated excimer beam approximating those of an LPX 210. Both of the 2D plots and the false color plot are reasonably close to what was experimentally measured when one takes into account the divergence from an excimer is specified at the 50% energy level and is therefore an average. In the optical design software the divergence is a fixed value from a finite number of rays traced.

The energy throughput of the homogenizer was measured at >83%. The homogenized field illuminated a test reticule to check imaging using a 10X, 0.1NA objective. Figure 13 shows the image resolution from this reticule. The finest resolved features of 2.5 μm lines and 2.5 μm spaces were machined in polycarbonate with the reticule set at the optimized 950 mm position.

Unfortunately the relay lens did not improve the divergence enough to make a noticeable difference in the profile. The relay lens did cause the homogenizer to be slightly under filled and if anything degraded the homogenization in the long axis.

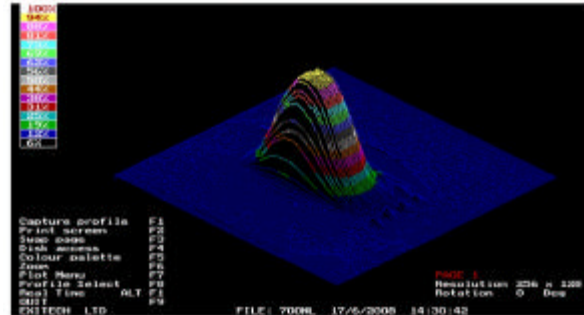


Figure 10 Field-Mapped Profile measure @ 700mm

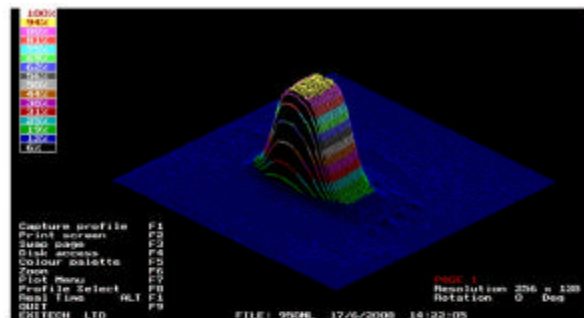
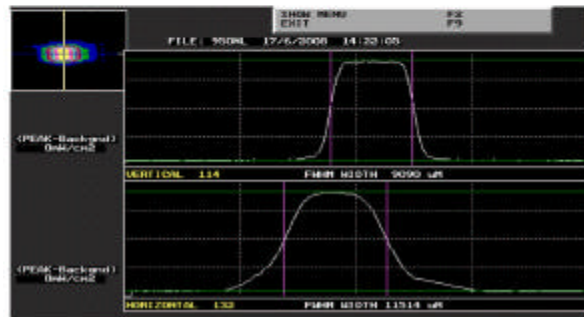


Figure 11 Field-Mapped Profile @ 950mm



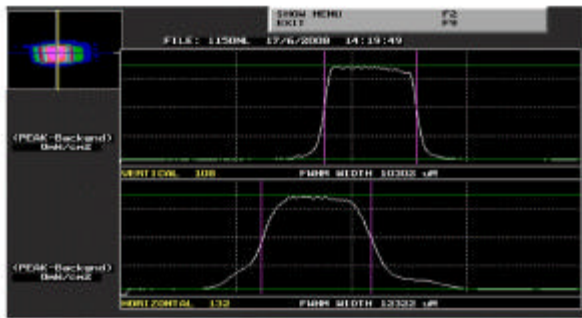
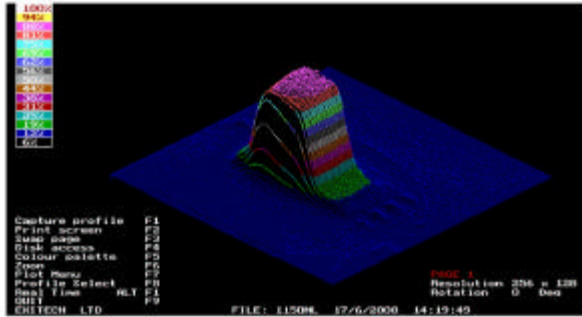


Figure 12 Field-Mapped Profile @ 1150mm

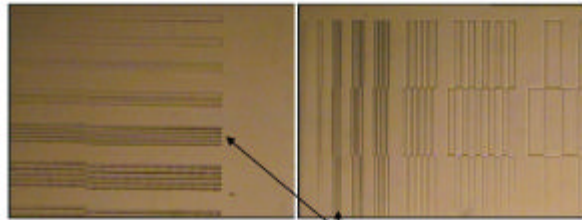


Figure 13 Dense features machined in polycarbonate (2.5µm lines, 2.5µm spaces).

Conclusions

The field-mapped homogenizer appears to be optically equivalent to a diffractive homogenizer in terms of performance and functionality with the added benefit of reducing the optics required from 33% to 50%, depending upon the design used.

From a manufacturing point of view the field-mapped beam homogenizer requires half to a quarter the number of lens segments needed to construct, dependent upon the fabrication method. In the case of both the diffractive homogenizer and the imaging homogenizer each lens segment is made from a single lens. If one has an 11 x 11 array, this requires 22 lenses for a diffractive homogenizer and 44 lenses in a non-imaging design; using cylindrical segments.

Imaging and non-imaging homogenizers have efficiencies of <50% so the 83% throughput measured

with the field-mapped homogenizer is a significant improvement.

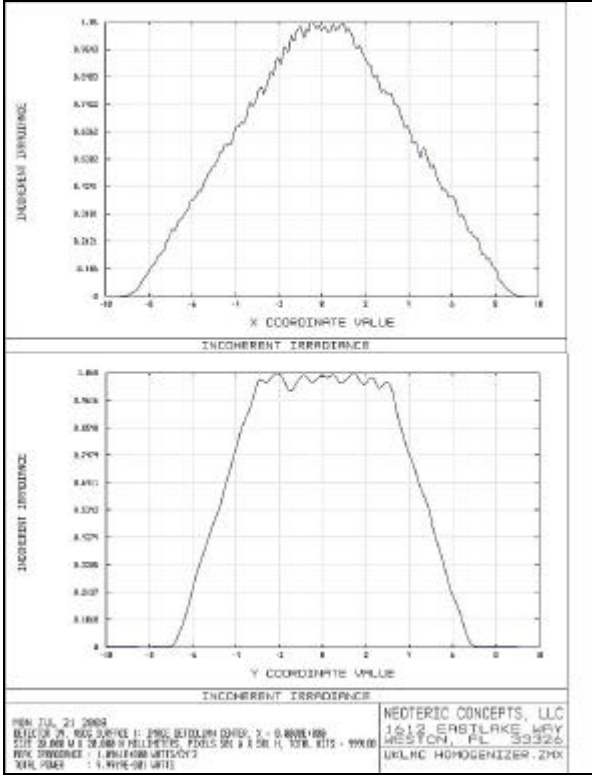


Figure 14ZD plot of field-mapped beam homogenizer profile from Zemax optical design software

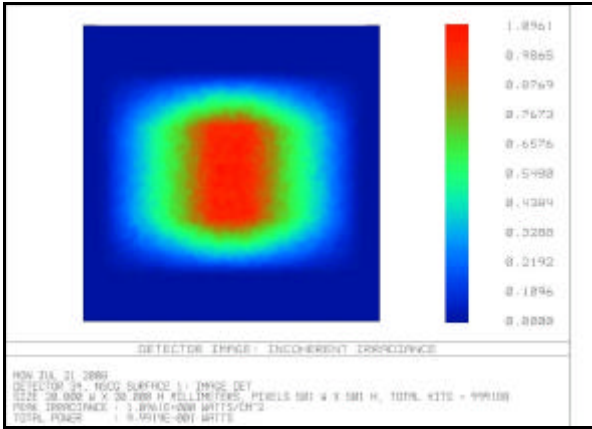


Figure 15 Zemax false color profile of modelled field-mapped beam homogenizer

In the field-mapped homogenizer multiple segments are extracted from a single lens which reduces the overall cost of the segments. The 3x9 array used in this work was made from 8 spherical lenses. In

contrast, an equivalent diffractive homogenizer would require 27 individual lenses to make the same array.

As stated earlier, the field-mapped design reduces the number of optical components needed by at least the condenser lens as the field-mapping eliminates the need of the condenser thereby providing a 50% optic reduction.

Clearly the asymmetric beam divergence of the excimer impacts the quality of the homogenizer which is the case in the traditional designs as well. This is best handled by employing a crossed cylindrical design where the segment size of the long axis array is 2 times that of the short axis to compensate for the nominal 2 time divergence difference between the axis. Alternatively, reducing the beam divergence helps to significantly sharpen the edge profile but care must be taken to keep the segment sizes large enough to avoid interference effects to due coherence and minimizing Fresnel diffraction.

Future work will include a design that is fabricated with diamond turning techniques with the goal to average the divergence over the optic and to further reduce the cost to manufacture the homogenizers.

References

- [1] Fahlen et al, Optical Beam Integration System, US Patent 4,733, 944, March 29, 1988
- [2] Burghardt et al, Device for Homogenizing A Light Beam, US Patent 5,414,559, May 9, 1995
- [3] Brown et al (2000), Multi-aperture Beam Integration Systems, in Laser Beam Shaping Theory and ATechniques, CRC Press, Taylor & Francis Group, 273-311
- [4] Sercel et al (2006), Practical UV Excimer Laser Image System Illuminators, in Laser Beam Shaping Applications, CRC Press, Taylor & Francis Group, 113-155