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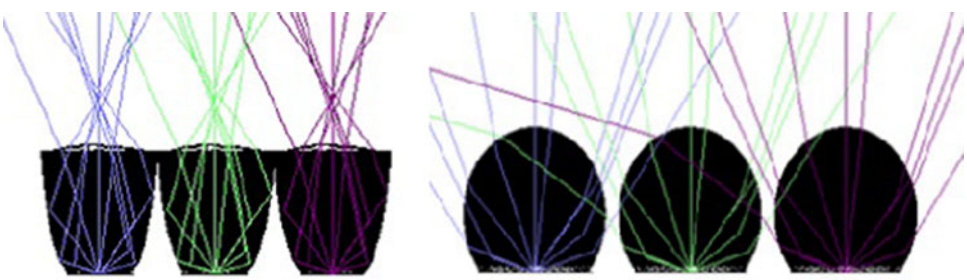

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Performance Comparison of a Freeform Lens and a CDTIRO When Combined With an LED

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Abstract: This paper compares the features and performance of two secondary optics when combined with an LED. The aim and application of the secondary optic are explained in the introduction section. Sections 2 and 3 introduce two optics: A freeform lens and a novel circular dielectric totally internally reflecting optic (CDTIRO), which can provide uniform illumination. The design process, ray tracing simulations and experimental performance of the freeform lens are described in detail in Section 2. The ray tracing simulation and experimental performance of the CDTIRO are presented in Section 3. Section 4 presents a comparison of the features of both lenses and their performance. Both optics can produce over 95% uniformity within an illuminated area. However, the uniformity produced by the freeform lens reduces abruptly compared with the CDTIRO when some parameters such as size and the position of the light source are changed.

Index Terms: Secondary optic, Freeform lens, CDTIRO, uniform illumination and LED.

1. Introduction

Gases - in particular carbon dioxide (CO_2), methane (CH_4) and Nitrous oxide (N_2O) - are produced and enter the atmosphere when fossil fuels are burned in power stations and vehicles [1]. These gases (called greenhouse gases) act as blanket around the planet. The heat is kept inside the earth's atmosphere and increases the global temperature. This leads to environmental disasters including storms, heat waves, floods, and droughts [2], [3]. These problems have motivated the legislation departments of various countries to enact laws and strategies to reduce greenhouse gases emissions. Energy efficiency is at the heart of the European Union's Europe 2020 Strategy for smart, sustainable and inclusive growth and for a transition to a resource efficient economy. The aim of this strategy is to reduce the green house emissions. To achieve this by 2050, the EU should cut greenhouse gas emission to 80% below 1990 level [4], [5] .

Electric lighting accounts for around one-fifth of the electricity consumption, both in the UK and globally [6], [7]. The street lighting system has 7.4 million street lamp posts in the UK and

£3.8 billion of public money is spent annually for this purpose. Moreover many street lighting facilities are outdated and therefore highly inefficient. For example 30% of the light from the lamp posts is wasted as it is dispersed in unwanted directions [6].

Light emitting diodes (LEDs) have great potential for highly efficient lighting that can last more than a decade under continuous use. Between 50% and 80% of energy costs could be saved by switching from traditional light sources to LEDs [8]. In spite of the advantages of LEDs, it is impractical in many cases to use them in street light luminaires directly without a suitable secondary optic due to their lambertian radiation pattern. Normally, the LED produces high light intensity at the centre and low light intensity at the edge of its circular illumination footprint [9]. To overcome this drawback, a secondary optic has been proposed to be combined with the LED to redirect its output rays to the prescribed area. In this decade, several methods have been studied by various researchers to create secondary optics that produce uniform illumination to meet the requirements of particular applications such as street lighting [10].

J. C. Minano and J. C. Gonzalez [11] developed a Simultaneous Multiple Surfaces (SMS) design method to create non-imaging optics in the early 1990. The two dimensional (2D) and three dimensional (3D) spaces of the SMS methods have been used in an imaging lens design. This method allows the construction of two surfaces of the lens simultaneously. It can also be used to provide uniform illumination with an extended light source.

Parkyn [12], [13] proposed a segmented illumination lens capable of providing uniform illumination with different patterns. This can be used on a rectangular target plane for flat and oblique luminaire placement. This lens can be created through the tessellation algorithm of a lighting task on a spherical grid of equal flux. This algorithm produces a faceted surface (non-smooth surface) of the segmented lenses. In spite of providing uniformity, it is not generally a desirable lens for an illumination system due to its faceted surface which is difficult to manufacture.

In general, an optic can produce uniformity by: (i) a single refractive surface and or (ii) a totally internally reflecting (TIR) profile. Providing the uniformity within an very narrow elongated rectangular area by a single refractive surface produces energy losses [12]. Mikhail A. Moiseev *et al.* [12] designed a lens with two clusters to produce uniformity within a narrow rectangular target. Another optic with TIR was designed by Jiang *et al.* [14] to illuminate a rectangular area especially for street lighting.

Since a single LED cannot provide sufficient luminous flux for street illumination. Several LEDs must be mounted on one panel to boost the irradiance. This is called LED array lighting (LAL). Zong Qin *et al.* [15] demonstrated uniform lighting generated by an LED array with a large view angle.

This paper introduces energy mapping and the process of design of two lenses: (i) a freeform lens, and (ii) a CDTIRO. Uniformity can be achieved based on the energy mapping between the light source and the target plane. The freeform lens produces uniformity by using a single refractive surface, whereas the CDTIRO uses the top section and the side profile of the lens.

Simulations and experiments have been carried out on both lenses to evaluate their uniformity. In order to have an accurate comparison between the simulations and the experiments, both systems have the same features including: the refractive index of the optic, the same size of the optic and of the light source; and the same radiation pattern of the light source. In this research, both lenses were fabricated by a Computer Numeric Control (CNC) machinery process due to the high quality achievable. The precision of the CNC machinery optics manufacturing method is within a 5 and 30 micron range. Poly methyl methacrylate (PMMA) was selected as the material for fabrication because of its high transparency (over 92%) and extremely long service life. The maximum permanent operating temperature and melting point of PMMA are 103° and 130°, respectively. Therefore, it is required to fix a heat sink behind an LED to reduce its heating temperature [16].

2. Design Process of a Single Refractive Freeform Lens

In order to achieve uniformity, the design method involves shaping the surface of the freeform lens so that a certain amount of light energy is transferred to the prescribed section on the target plane [17]. Fig. 1 shows six rays ($I_1 - I_6$) emitted from the light source inside the optic and the refracted

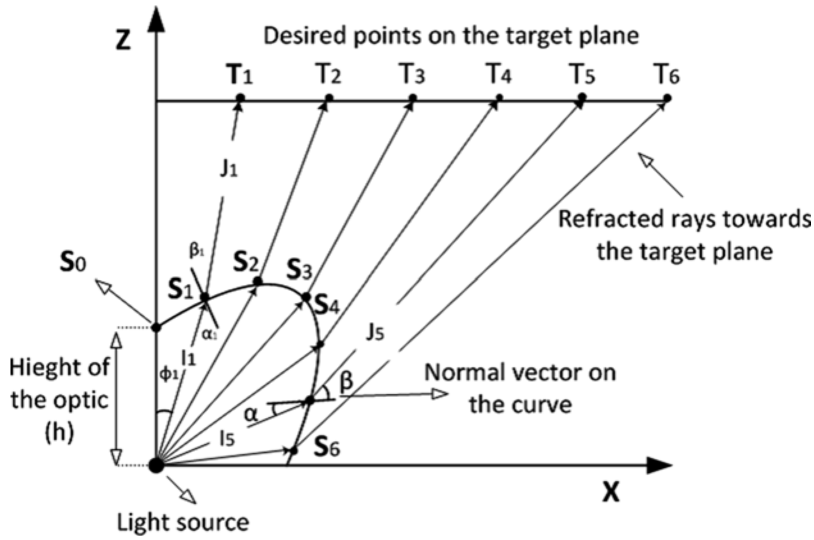

Fig. 1. Energy mapping between the light source and the target plane.

rays at the surface of the optic ($S_1 - S_6$ points). The refraction is based on Snell' laws (Equation 1). The refracted rays ($J_1 - J_6$) reach then the desired points ($T_1 - T_6$) at the target plane.

$$n^{'}\overrightarrow{I_{out}} - n\overrightarrow{I_{in}} = \left| n^{'}I_{out} - nI_{in} \right| \overrightarrow{N} \tag{1}$$

where , n and $n^{'}$ are the index of refraction of the inside and outside the optic, respectively.

In order to create energy mapping, it is necessary to define the position of the desired points on the target plane. First, the amount of luminous flux (Φ) between I_1 and the vertical line (the Z axis) has to be calculated by the following Equation:

$$\Omega_1 = 2\pi(1 - cos\Phi_1) \tag{2}$$

$$\Phi_1 = \int I_v d\Omega_1 \tag{3}$$

where, I_v is the luminous intensity of the light source.

Then the position of the first desired point T_1 can be defined based on Equation 4, the illuminance (E) is the required illuminance on the target plane.

$$T_1 = \sqrt{\frac{\Phi_1}{\pi E}} \tag{4}$$

After finding T_1 on the target plane, the section S_{0-1} (between S_0 and S_1) has to be tilted till the ray J_1 reach the point T_1. In order to provide uniformity at the illuminated area, the level of illuminance (E) should be the same for the other desired points. To design the next section (S_{1-2}) of the lens, the luminous flux (Φ_{1-2}) between I_1 and I_2 has to be calculated. Then the position of the point T_2 can be found. The section S_{1-2} will be tilted to deliver the ray J_2 to the point T_2. The same process is carried out for the rest of the rays to produce the surface of the lens. The curved line of the surface of the freeform can be obtained by connecting S_0 to S_6 points and the freeform lens can be shaped by 360 degree rotation of the curved line around the Z-axis. The number of division on the target plane should be increased when designing the optic to increase the optical performance. The freeform lens shown in Fig. 3 was designed by 900 emitted rays.

A point light source (small LED) has been assumed in Fig. 1. However, high power LEDs (extended light sources) are required in application such as street lighting [17]. Using an extended light source reduces uniformity on the target plane. To keep uniformity the size of the light source and the optic

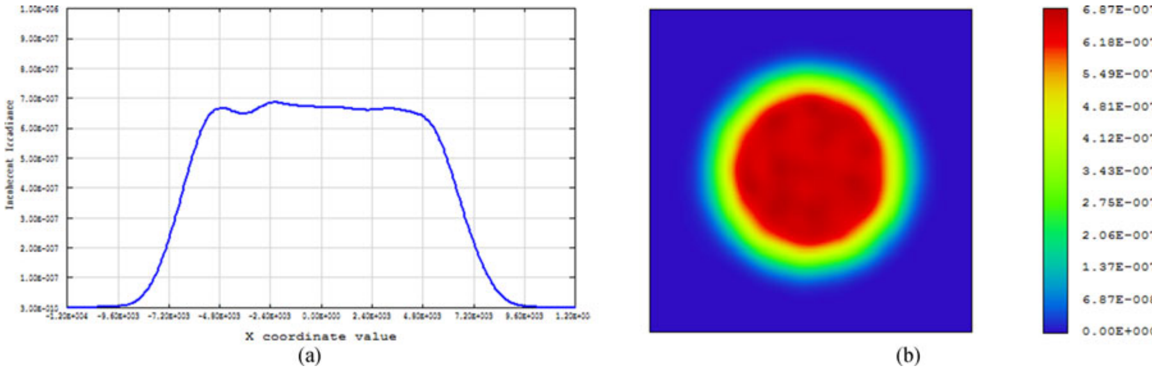

Fig. 2. Uniform illumination provided by the freeform lens. (a) The cross section of the illuminated area. (b) Irradiance distribution at the target plane.

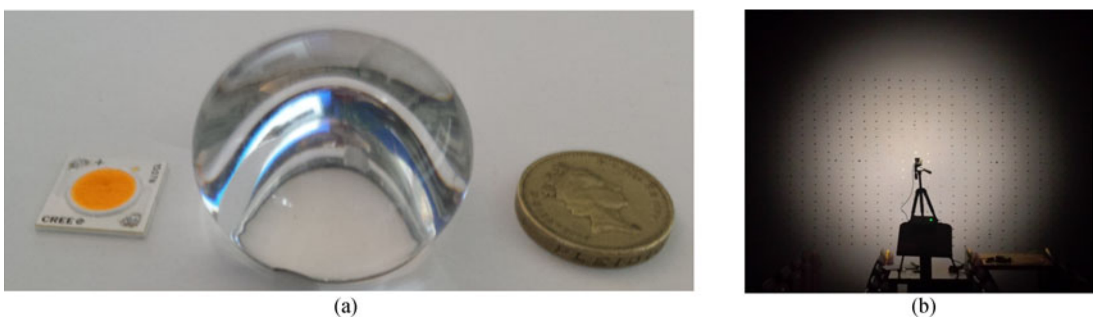

Fig. 3. Uniform illumination provided by the freeform lens. (a) The freeform lens fabricated by PMMA. (b) Irradiance distribution at the target plane.

have to be taken into account. An extended light source acts as an approximate point light source when the size of the optic is five times larger than the light source [17].

Chromatic dispersion should have a minimum effect on the footprint shape and its dimensions; and no effect within the footprint with regards to uniformity. In this research, an extended LED, CREE XLAMP 1507 with a 0.89 cm active area diameter, has been used for both models [18].

A freeform lens with a 2.5 cm height and a 4 cm width was designed to produce uniform illumination within a circular area with 50 cm radius. The distance between the freeform lens and target plane was 1 m. The same distance to the target plane was used for CDTIRO. In the following sections, the simulations and experiments carried out on this freeform lens are explained.

2.1. ZEMAX Simulation Results of the Freeform Lens

The freeform lens has been analysed via ray tracing simulations (ZEMAX software). The simulation data of the LED provided by the CREE company (XLAMP 1507) was used in the ZEMAX software simulation. The uniformity of the light intensity achieved by the freeform lens-LED combination on the illuminated area is presented in Fig. 2.

2.2. Actual Performance of the Freeform Lens

In this section, the experiment carried out to validate the simulation results is described. Fig. 3(a) shows the LED XLAMP 1507, the freeform lens fabricated from PMMA material and a £1 coin (for size reference). High percentage uniformity was achieved in the illuminated area; see Fig. 3(b). In order to investigate uniformity, the light intensity was measured with a light sensor at regular

Fig. 4. CDTIRO fabricated from PMMA.

distance interval shown by the black marks on the target plane (Fig. 3(b)). Uniformity is defined as the ratio of the minimal illuminance over the area weighted average illuminace. Based on the light intensity measured in the simulation and the actual optical performance, over 95% uniformity was achieved within the illuminated area.

3. Circular Dielectric Totally Internally Reflecting Optic

This section discusses performance of a CDTIRO. In contrast to single refractive surface of the freeform lens, the CDTIRO consist of two parts to produce uniformity: (i) the top section and the side profile of the lens. The top section of the CDTIRO is a part of a hemisphere. There is a TIR at the side profile of the CDTIRO. The illumination from the top section and from the curved side profile of the CDTIRO are (E_1) and (E_2), respectively. Two sections illuminates the same area, the total illuminance (E_{total}) includes the effect of both illuminations [19].

$$E_{total} = E_1 + E_2 \tag{5}$$

Fig. 4 shows the CDTIRO used in the experiments. A negligible part of the emitted rays is not TIR. Those at very wide emission angles with respect to the optic axis. The height and radius of the entrance aperture of the CDTIRO are 1.7 cm and 0.9 cm, respectively. This CDTIRO was designed to produce uniform illumination within a circular area with a 35 cm radius. In th simulation and experimental work described below, the CDTIRO was placed at a distance 1 m from the target plane.

3.1. ZEMAX Simulation Results of the CDTIRO Lens

Fig. 5 shows the cross section of the first part of illumination, which has high light intensity at the centre and low intensity at the edge on the target plane. The second part of illumination is the complementary section. The edge of the illuminated area has higher light intensity than the centre of the illumination, as shown in Fig. 6. Uniformity can be achieved by the cumulative effect of the first and second parts of illumination. Fig. 7 shows that over 95% uniformity is achieved in the illuminated area.

3.2. Actual Performance Results of the CDTIRO Lens

The actual performance of the CDTIRO is shown in Fig. 8.

4. Comparison of the Freeform and the CDTIRO Lens

Both optics have the ability to produce over 95% uniformity when using the same LED. However, there are some differences in their features and performances, including:

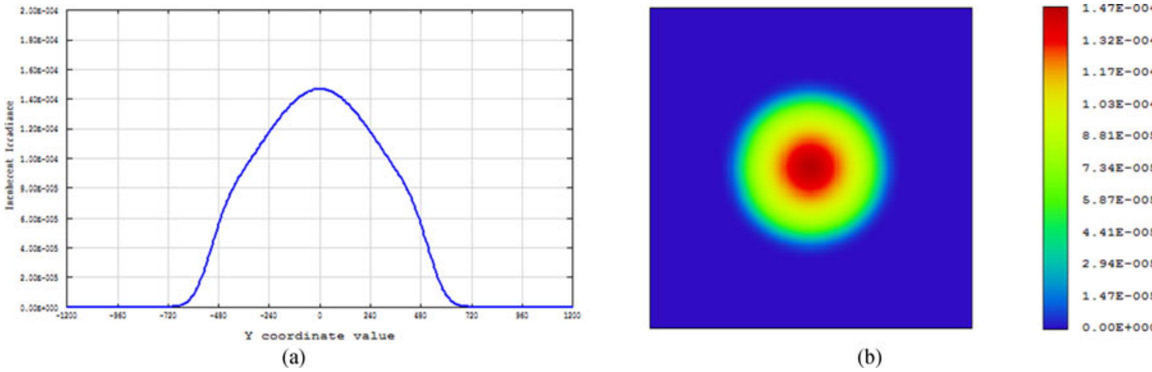

Fig. 5. First part of illumination of the CDTIRO on the target plane. (a) Cross section of the light intensity of the first part of illumination. (b) Irradiance distribution of the first part of illumination.

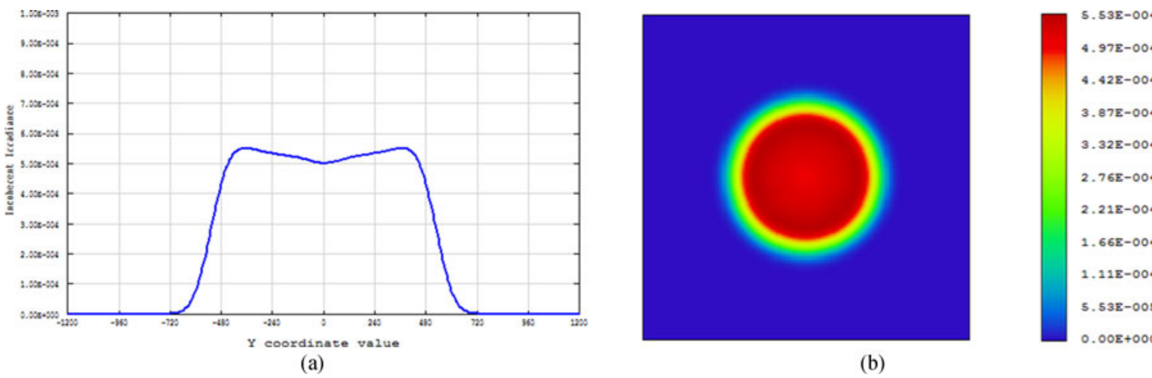

Fig. 6. Second part of illumination of the CDTIRO on the target plane. (a) Cross section of the light intensity of the second part of illumination. (b) Irradiance distribution of the second part of illumination.

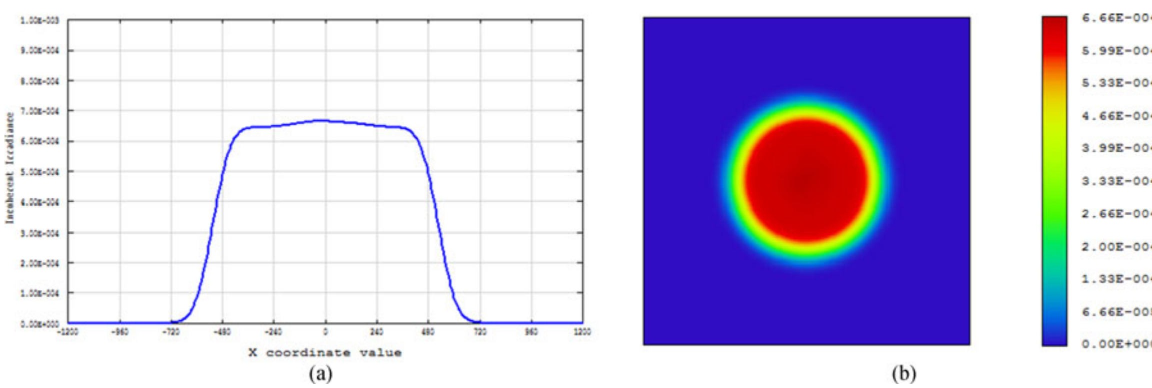

Fig. 7. Total illumination of the CDTIRO on the target plane. (a) Cross section of the light intensity of the total illumination. (b) Irradiance distribution of the total illumination.

1) *Maintenance of uniformity:* Since the footprint of the CDTIRO is a combination of two illuminations this reduces the effects of changing the light source or the size of the optic in the uniformity of illumination.
2) *Collimation:* Due to the TIR at the profile of the CDTIRO, the output rays of the CDTIRO can be collimated more than those of the freeform lens. Thus the level of the light intensity increases. Therefore, the size of the footprint of the CDTIRO is more flexible than that of a single refractive lens while the uniformity remained unchanged.

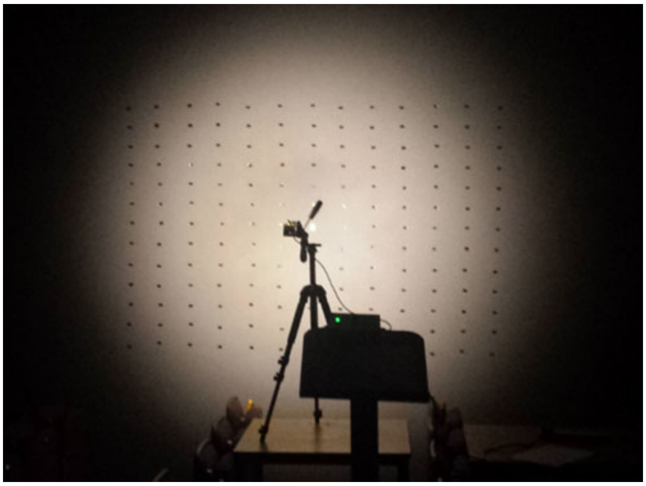

Fig. 8. Uniform illumination provided by the CDTIRO.

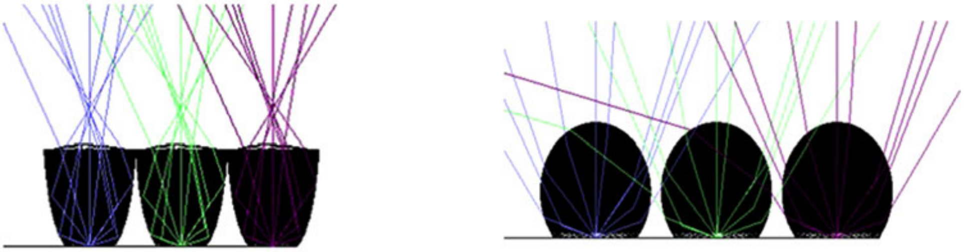

Fig. 9. Compactness of the CDTIROs and the freeform lenses array. (a) Three CDTIROs close together, without shadowing from neighbouring lenses. (b) Three freeform lenses close together, with shadowing from neighbouring lenses.

3) *The average path length within optics:* Due to the internal reflection, the average path length of light within the CDTIRO is 60% larger than that within a freeform lens. This reduces the light efficiency.
4) *Compactness of lenses array:* In contrast to the freeform lens where the rays exit from all parts of the surface, in the CDTIRO light exits from the top section only. This makes it possible to place many CDTIROs closer together without shadowing from neighbouring lenses. For the freeform lenses on the other hand, it is necessary to provide a gap between them in order to keep uniformity of illumination. Otherwise the lenses act like obstacles and uniformity deteriorates as shown in Fig. 9.
5) *Size of the optic:* The CDTIRO can maintain uniformity with smaller size than the freeform lens when using an extended light source.

5. Conclusion

This paper explained the main characteristics of two optics, a freeform lens and a novel CDTIRO. The new optic, the CDTIRO, was created to produce uniformity of illumination by a combination of two sets of illumination. The target area is illuminated two times, by the top section and by the side profile of it. All output rays exit from the top section of lens. Both lenses provide over 95% uniformity within the illuminated area. However, the CDTIRO has several advantages over the freeform lens including: smaller size, better collimation and better compactness when used in arrays.

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