Cylindrical array luminescent solar concentrators: Performance boosts by geometric effects

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Abstract: This paper presents an investigation of the geometric effects within a cylindrical array luminescent solar concentrator (LSC). Photon concentration of a cylindrical LSC increases linearly with cylinder length up to 2 metres. Raytrace modelling on the shading effects of circles on their neighbours demonstrates effective incident light trapping in a cylindrical LSC array at angles of incidence between 60-70 degrees. Raytrace modelling with real-world lighting conditions shows optical efficiency boosts when the suns angle of incidence is within this angle range. On certain days, 2 separate times of peak optical efficiency can be attained over the course of sunrise-solar noon.

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1. Introduction

Created in the 1970s [1–3], the concept of a luminescent solar concentrator (LSC) came about to reduce the costs of solar energy. In its basic design, it consists of a transparent waveguide, usually polymethyl methacrylate (PMMA), either homogeneously doped with, or coated with, luminescent material. The luminescent material absorbs incident light and re-emits it, with a proportion of the re-emitted light trapped within the transparent medium due to total internal reflection (TIR), thereby guiding it to the edge of the LSC, where it is collected by optically coupled photovoltaic (PV) cells. The ratio of the incident light collection area and the PV collection area determines the geometric concentration, $C_G$, of the LSC. Another figure of merit is the photon concentration $C_\gamma$ which is defined as:
\[
C_T = C_G \cdot \mu_{opt} = \frac{\phi_{out}}{\phi_{in}}
\]  

where \(C_G\) is the geometric concentration (the ratio of light emitting area and light accepting area), \(\mu_{optical}\) is optical efficiency (the number of photons escaping the emitted surface divided by the number of incident photons), \(\phi_{out}\) is the photon flux out of the emitted surfaces and \(\phi_{in}\) is the photon flux incident on the LSC.

Unlike direct concentrator photovoltaic (CPV) designs, LSCs utilise both the direct and diffuse component of light for concentration, thereby taking away the need for expensive sun tracking systems [4]. These factors introduce the possibility of building-integrated PV (BIPV) designs, as well as retrofitting conventional buildings with LSC solar power, either through PV power or through daylighting.

At module-scale, whilst in absolute power it still lags behind standard crystalline and thin-film silicon PV modules, a yellow-dyed LSC has been demonstrated that it performs closer to its standard test conditions in real life electricity generation than that of standard PV modules [5]. This same dye was also used in an LSC acting as a south-facing face in an office, with the conclusion that LSC integration is compatible and advantageous in terms of visual comfort [6]. Another study quantified the maximum level of coverage an LSC, albeit a red dye doped one, on a facade is 25%, for both interior and exterior viewing [7]. The potential for LSC stained-glass window designs has been reported on, and 3D ray-trace models have been created which have been confirmed experimentally to be useful for optimising LSCs in various shapes and sizes [8]. Curved LSCs can find also applications in building integration, for example being wrapped around a streetlight pole as both an aesthetic and electricity generating structural element [9].

LSCs have also been used for daylighting, whereby incident light is harnessed and wave-guided into a room. A 1.44m² fibre LSC, when illuminated at around 1 sun, can illuminate a room at around 60Wm⁻² [10]. This figure could have been higher had larger diameter fibres been used [11].

LSCs are not yet commercially viable as the optical efficiency remains too low to make it a cost-effective technology. The performance of an LSC stems from either the optical properties of the luminescent material or the light trapping capability of the LSC geometry. Initially addressed by Batchelder et al. [12,13] as an alternative geometry, cylindrical LSCs (CLSCs) offer better photon concentration than planar LSCs due to a greater ratio of PV light collection area to incident light collection area.

CLSCs have experienced a small resurgence in the past decade when it was claimed that a CLSC can outperform a planar LSC of equal volume and collection area by a factor of 1 - 1.9 in terms of optical efficiency [14]. Since then CLSCs have been investigated, albeit not extensively, as standalone devices.

It has been confirmed using raytracing techniques that CLSCs always outperform similarly sized planar LSCs in terms of photon concentration, especially in conditions of isotropic (diffuse) illumination [15]. Furthermore, raytrace modelling at Imperial College has shown that by taking into account the fact that luminophore self-absorption losses are a short range effect, after a certain absorption threshold the increase in geometrical concentration by increasing cylinder length is larger than the loss due to host material absorption and scattering. This means that the effective concentration increase can be theoretically limitless [16]. Other types of luminescent material have been investigated, with rare earth complexes used to eliminate these self-absorption losses by removing the spectral overlap between absorption and emission [17,18]. In practice, the concentration of a cylindrical LSC as a function of length has only been shown with a limited range of lengths of 0-0.2cm [19] and 0-8cm [20]. Hollow CLSCs have been compared with solid CLSCs practically using quantum dot luminophores [19], and with Rhodamine 6G luminophores [21]. Both times were shown to have high optical efficiency.
and photon concentration values than solid CLSCs. Different fibre designs where concentrating geometries are used in tandem with an inner luminescent core within a clear fibre where compared, albeit the investigation was limited to normal incidence light on the fibre [20, 22].

The performance of module-scale LSCs have been investigated outdoors, both in flat-plate, and in fibre array geometries. Investigations were mainly focussed on the performance over the course of a single day [5, 11, 23]. Only one study measures a fibre array CLSC performance over the course of a month [10]. LSC tilt and its effect of performance has been looked at for flat LSC geometries, both in outdoors conditions [23] and in laboratory conditions [8, 24]. Furthermore, whilst the geometrical effect of a cylinder array on external reflections due to angle of incidence of incoming light was touched on [14], there is an absence on the investigation on LSC cylindrical array performance in real world lighting conditions such as the light output as a function of angle of incidence of incoming light.

This paper demonstrates the linear increase in light concentration as a function of cylinder length for length ranges more suited to module sizes, using cylindrical fibres manufactured at Nanoforce Technology Ltd and obtained from LasIRvis Optoelectronic Components Ltd. In confirming this behaviour, it legitimizes the use of long cylindrical LSCs for module-scale size arrays. Secondly, it looks into how a cylindrical LSC array performs as a function of angle of incidence, initially by looking at the path of light through an array of circles, and then by raytrace modelling a cylindrical array in simulated real world lighting conditions, both in terms of sun position and in terms of light spectrum for both direct and diffuse components of incident light.

2. Experimental methods

2.1. Fibre manufacturing and measurement

Cylindrical, homogeneously doped fibre LSCs (FLSCs) were fabricated at Nanoforce Technology Ltd by fibre extrusion. PMMA and the luminescent material Lumogen F Red 305, provided by BASF, were melt-blended in a twin-screw DSM Micro15 micro-compounder. Fibres were drawn through a die in solid state under tension by a rotating drum and air-cooled.

Three fibres were manufactured with a 0.5±0.25% dye load concentration to ensure minimal risk of luminophore agglomeration. This does not remove the risk of uneven spread of the dye within the host matrix during material mixing. They had average diameters of 0.64mm, 0.7mm and 1.12mm with lengths of up to 2metres. Due to the nature of the extrusion process, the fibres suffer non-uniform variations that differ on average 0.18mm from the mean value across the length of a fibre. A low dye load concentration does mean that re-absorption of luminescent light can take a fibre-length to fully redshift the light until it can no longer be absorbed. It was found by using this method of extrusion however that agglomeration occurred at concentrations of around 1.5%. It can be safe to assume that re-absorption/scattering due to the dye could be more pronounced than in other studies, experimentally and computationally. Effects of re-absorption losses caused by the dye could also be masked by the surface waveguide losses due to high non-uniformity.

To measure the light coming out of the FLSC ends, the fibres were coiled in a spiral to avoid overlap, and therefore shading, under a large area (20cm x 20cm) solar simulator. One end of a fibre, which was polished using Thorlabs polishing paper down to 0.3µm grain size, was optically coupled to a silicon photovoltaic (PV) cell using index matching fluid (Cargille acrylic matching liquid, refractive index n=1.49 at 633nm), with the remaining area of the PV masked off as well as being enclosed in a light shield.

Variations in photon flux out of the fibre ends can occur due to the extent of fibre diameter inhomogeneity across its length, agglomeration of the luminescent material which can be mitigated with a low dye load concentration, and the level of polishing of the fibre ends.
2.2. Raytrace model

A Monte Carlo raytrace program, PVTRACE, was used for both 2D and 3D raytracing of light through circles and cylinders [25, 26]. It is run on Python 2.7. The program traces individual photon paths through the constructed geometry in a model environment, using Monte-Carlo processes to determine the outcome of events at each intersection with an object’s surface. Each interaction the photon has with its environment is logged in an SQL file.

SMARTS 2.9.5 [27], which forms the basis of standards ASTM G-173 and ASTM G-177, is used to obtain spectral data for time, day and location for real world light conditions. These are fed into the raytracer. A hemispherical light source is used for diffuse component of incident light, and a planar light source with the relevant solar zenithal and azimuthal angles is used for the direct component.

2.3. PVTRACE real world model setup

The PVTRACE model requires data input for the lighting conditions on an LSC fibre area, namely spectral and angular data for both the direct and diffuse spectral component of incident light from a given time, global position and date. The diffuse component is treated as a hemispherical and isotropic light source on the area (see Fig. 1(b)). For the direct component, the azimuth and zenith angle of incidence is fed in to give a vector property to a planar light source (see Fig. 1(a)). Version 2.9.5 of the Simple Model of Atmospheric Radiative Transfer of Sunshine (SMARTS) [27], developed by Dr. Christian Gueymard, is used to obtain spectral data. The limiting factor of the software is that spectral data given is on the assumption that it is clear sky weather conditions. The sun’s angle of incidence is symmetric on either side of the sun’s solar peak position, which is around midday for all four simulated days. For this reason only morning hours were needed to be investigated.

A horizontal ten-cylinder LSC array was aligned North-South so that the hypothesized performance boosts can be shown over the course of a day due to the Sun’s path across the sky. Each cylinder had a diameter of 1cm and a length of 40cm. Perfect specular mirrors were added to the long sides of the array to approximate an infinite array. The cylinders themselves were modelled as a polymethyl methacrylate (PMMA) host matrix, of refractive index n=1.46, homogeneously doped with BASF’s Lumogen F Red 305 luminescent material. The whole cylinder’s absorption coefficient is set to 9000m$^{-1}$ at its absorption peak wavelength of 576nm.

![Fig. 1. A mid-simulation snapshot of (a) the direct and (b) the diffuse component of light illuminating a cylindrical LSC array, using the PVTRACE raytrace model. The direct light vector is determined by the position of the Sun. The diffuse component is modelled as a hemispherical light source. The spectra for both components of light is obtained from the SMARTS software [27].](image)
corresponds to a dye load concentration of around 1.6%. The cylinder surfaces were modelled as being perfectly smooth. Square rod LSCs were simulated in tandem as a reference to the performance of planar geometries.

Simulations for the direct and diffuse light components were done independently for each given time interval of the day. Each simulation modelled an illumination of 100,000 photons onto the array. The optical efficiency $\mu_{opt}$ of the array is obtained for both direct and diffuse components. These values are weighted by their respective photon flux ratios at that specific time. For example on 10th May 2014, the components of direct and diffuse light contributed 0.85 and 0.15 at 0700h, and 0.91 and 0.09 at solar noon respectively. The definition of optical efficiency in this simulation is the number of photons emitted out of the two ends of the array versus the number of incident photons hitting it.

The location under investigation was London, UK (Lat: 51.5°, Long: -0.13°). Suitable days are needed to demonstrate this light trapping effect, with the criteria being that the Sun’s zenithal angle is within the light trapping range for a significant amount of the sunrise-noon period. Furthermore, the peak light trapping time should be where the effect would be most visible with an efficiency peak that would stick out in comparison to the planar efficiency profile during the morning. Four days were chosen to show light trapping at the beginning and also in the middle of the sunrise-noon period. The peak light trapping angle is halfway through the morning for both 10 March and 10 April 2014, with the sun’s zenithal angle to be within the light trapping region between 0830h - 1000h. For 10 May 2014, the light trapping angle range is between the earlier times of 0730 - 0900h, and for the Summer solstice (21st June 2014), the light trapping angle is between 0700h - 0900h.

3. Determining a linear relationship with fibre length and light concentration

Reabsorption of luminescent light is a major loss mechanism in LSCs [4, 28–31]. It has been shown theoretically that at high optical densities for both coated and homogeneously doped fibres, photons experience multiple re-absorption events. Over 90% of photons are re-absorbed between 1 and 3 times on path length scales shorter than fibre lengths. After a certain length, luminescent light becomes sufficiently redshifted through multiple reabsorption events that it stops getting reabsorbed. Because of this, LSC photon concentration has the ability to increase linearly with fibre length [16], with waveguide surface defects and non-radiative host losses becoming the major loss mechanism. Whilst 1.2m long fibre LSC arrays have been investigated in the literature [10,11], a practical demonstration of the simulated results shown previously by Imperial College [16] has not been attempted.

Two different fibre LSCs are utilised: ones made at Nanoforce Ltd, and a commercially acquired Lumogen Red F 305 fibre LSC from LasIRvis Optoelectronics Ltd. The commercial fibre’s dye concentration is unknown, however it is visibly less than the Nanoforce manufactured fibre LSCs.

In order to determine the amount of luminescence redshifting through a fibre, the emission spectrum of one of its ends is measured whilst a 532nm laser excites various points away from the fibre end. As shown in Fig. 2, when looking at emission spectrum as function of excitation distance away from the measured fibre end, luminescence redshifting caused by re-absorption and re-emission occurs most significantly in the first centimetre of the fibre. The magnitude of the redshifting drastically decreases within the next couple of centimetres of the fibre. Even for a lower dye concentration such as in the LasIRvis fibre LSC, the same effect holds true, with very small redshifting occurring at longer distances.

As shown by experimental data presented in Fig 3, photon concentration is seen to increase linearly as a function of fibre length for up to the manufactured lengths of 2metre for the Nanoforce-manufactured fibres and up to 80cm for the the commercial fibre.
Fig. 2. Demonstrating the short distance effects of luminescence re-absorption and re-emission in fibres doped at high concentration. A spot on a fibre is excited by a 532nm laser. Distances shown are the excitation distance away from the measured end of the fibre. The non-redshifted top surface emission spectrum is shown for reference. The most significant re-absorption and re-emission occurs within the first 1cm of the fibre, as shown by the high redshift for both a Nanoforce-manufactured fibre (a), and a commercially bought Lumogen Red F 305 fibre from LasIRvis Optoelectronic Components Ltd (b).

Fig. 3. Experimental values of photon concentrations of fibres of differing lengths from three sample batches. Nanoforce fibre dye load concentrations are 0.5±0.25wt% with average diameters of 0.64mm, 0.7mm and 1.12mm. The LasIRvis fibre has a diameter of 0.5mm and has a dye load concentration less than that of the Nanoforce manufactured fibres. Photon concentration increases linearly with fibre length up to the 2 metres of manufactured fibre. This agrees with previous raytrace modelling [16].

4. Shading between cylinders

The nature of a non-flat surface of a cylinder means that it will be blocking light onto a neighbouring cylinder when the angle of incident isn’t perfectly normal to the cylinder array. A transparent cylinder, by its curved surface, focusses incident light roughly onto a point. It can be seen in Fig. 4 that at lower non-zero angles of incidence, a cylinder will focus light away from its neighbour [Fig. 4(b)], up until a certain threshold angle where it focuses light back into it [Fig. 4(c)].

To analyse the shading/focusing effects of cylinders on their neighbours, PVTRACE is used...
to raytrace a cylinder cross-section. In this section it is used as a simple 2D model which is not wavelength specific, with fully transparent cylinders in order to demonstrate pathways of light as a function of angle of incidence. A refractive index of $n=1.5$ is used within the circles. In reference to the raytrace figures presented, we analyse the shading/focusing effects on the leftmost circle as a function of incident light angle of incidence.

Looking initially at a two cylinder system, a cylinder focuses all light away from its neighbour, meaning it is essentially opaque to its neighbour, at low angles of incidence. The angle threshold at which light starts to be redirected back into the cylinder’s neighbour is 60°. As seen in Fig. 4(c), by 61°, the redirection of light is already significant. The rate of increase of redirected light decreases as the angle of incidence increases.

This redirection of light into the array is a form of light trapping. The path length of incident light through the LSC is increased, thereby giving it a greater probability of being absorbed by the luminescent material. Fig. 5 visually demonstrates this light trapping effect. This is analogous to texturing surfaces in solar cells to increase scattering for greater absorption in the bulk material.

With two neighbouring cylinders, i.e. a three-cylinder array, having a next nearest neighbour significantly changes the light redirecting behaviour past the 60° angle of incidence threshold. Whilst at angles of incidence of 0-60°, the shading effects are identical, at larger angles there is a two part light direction process. Between angles of incidence of 60-70°, light is redirected to the leftmost cylinder, with peak redirection at 70°. At angles larger than 70° however, the rightmost cylinder diverts incident light that would have been redirected into the leftmost cylinder, away

Fig. 4. Raytracing to determine the shading effects of one cylinder to another. Two circles are illuminated at 0°, 50° and 61° angles of incidence respectively for (a)–(c). Secondary effect ray traces caused by Fresnel reflection, whilst included in the model, are removed from figures for clarity. The focussing effect of a circle geometry can be seen, and at a non-zero angle of incidence, a cylinder will focus light away from its neighbour, thereby rendering it essentially opaque (b). The threshold angle at which the shading circle starts to redirect light back into its neighbour is 60°, and at 61° this redirecting is already quite pronounced (c). The three major paths of light through two circles are: 1) light incident on the desired circle passing through, 2) light being directed into the desired circle by its neighbor, and 3) neighbour directing light away from the desired circle.

Fig. 5. Demonstrating the light trapping effect of a circular array against planar geometry, with incident light coming in at 65°. The path length of incident light is increased through the LSC, thereby giving it a greater probability of absorption. Secondary effect ray traces are removed from figures for clarity.
from it. This is shown pictorially as process 5 in Fig. 6.

Expanding up to a more realistic analysis of a large number of neighbouring cylinders, as shown in Fig. 7, there is the same positive effect of incident light redirecting into a cylinder’s neighbour within the 60-70° angle range, however after this secondary 70° threshold, the amount of light being diverted from the array altogether increases significantly.

The net positive geometrical effect with cylinders, where light is redirected back into the cylinder array by neighbouring cylinders, only occurs in a fine angle range of 60-70°. This geometrical effect should be seen in cylindrical arrays, where its performance should boosted when the zenithal angle of the Sun on the array is within this 60-70° angle range.

Fig. 6. Two circles shading the left (desired) circle with incident light at an angle of 75°. Secondary effect ray traces are removed from figures for clarity. The five main paths of light through the system are: 1) incident light passing directly through the desired circle, 2) light redirected into the desired circle by its nearest neighbour, 3) light redirected into the desired circle from its next nearest neighbour, via its nearest neighbour, 4) light diverted away from a circle’s neighbour, and 5) light from the next nearest neighbour, being redirected into the nearest neighbour but then missing the desired circle. Light path 5 is responsible for the decrease in number of photons reaching the desired circle at angles of incidence greater than 70°.

Fig. 7. Ratio of light entering the left circle to incident light with increasing angles of incidence, with 2 circles, 3 circles and an infinite array of circles, in order to demonstrate shading/light redirection effects. Secondary effect ray traces are removed from figures for clarity. There are two threshold angles, the first being at 60° when light which was initially focused away from the left circle, is then being redirected back into it. The second threshold angle applies to three circles or more, at 70°, when light gets focussed away again from the left circle, which is caused by shading and redirection effects of subsequent circles.
5. Analysis of cylinder geometry effects on LSC performance in real world light conditions

Simulations on these four days demonstrate the advantage of having a cylindrical LSC array compared to a planar geometry LSC. Efficiencies as a function of time of day are shown for cylindrical arrays on the right, and planar arrays on the left, of Fig. 8. There is a visible boost in LSC efficiencies for cylindrical arrays in comparison with planar arrays in the time periods when the angle of incidence of sunlight is within the light redirection range (see Fig. 9). At 70°, where the redirection effect is at its strongest, cylindrical geometry efficiencies are 5% - 10.7% relatively higher than that of planar geometries. Due to lower surface Fresnel reflection losses, diffuse light is more impactful in the cylindrical array than in the planar array.

5.1. 10th March 2014

Efficiencies are shown for the cylindrical rod array in Fig. 8(a) and the planar array in Fig. 8(b). The cylindrical array has a higher total efficiency than the planar array for the whole day, however the efficiency difference between the two geometries is highest in the morning before 0930h. The planar array increases in efficiency, with a plateauing of this increase, from sunrise until noon. When the time of day is linked to the zenithal angle of the Sun, as done so in Fig. 9(a), it can be seen that this peak is due to the light redirection effect of cylindrical geometries, where the profile of the array’s efficiencies matches that of the ratio of incident photons coming into a left hand cylinder as described in Section 4 when overlaying the time of day with its respective solar zenithal angle. Peak redirection in the cylindrical array is at 0900h, which can be seen by an efficiency peak of the direct light component both in Fig. 8(a) and in Fig. 9(a). The cylindrical array’s efficiency is relatively 7% higher than that of the planar array at that time.

5.2. 10th April 2014

Efficiencies are shown for the cylindrical rod array in Fig. 8(c) and for the planar rod array in Fig. 8(d). Overall the cylindrical array outperforms the square array closer to sunrise, but the efficiencies of both are similar closer to noon. The planar array increases in efficiency, with a plateauing of this increase, from sunrise until noon. The efficiency of the cylindrical array however experiences a peak at 0900h, whereby its efficiency is greater even compared to noon. The array’s peak performance is at the maximum redirection angle, beating its performance at noon, which is the peak performance time for planar geometries. At peak redirection time, 0900h, the cylindrical array’s efficiency is relatively 10.7% higher than that of the planar array.

5.3. 10th May 2014

Efficiencies are shown for the cylindrical rod array in Fig. 8(e) and for the planar rod array in Fig. 8(f). Much like the other investigated days, the cylindrical array outperforms the square array closer to sunrise, but the efficiencies of both are similar closer to noon. An efficiency peak is seen at the peak redirection angle at 0800h. By overlaying the solar zenithal angle with the shading/redirection profile and the efficiency profile as a function of time of day, it is seen that the redirection effect angle range matches the efficiency boost at the start of the day. At peak redirection time, 0800h, the cylindrical array’s efficiency is relatively 9.7% higher than that of the planar array.

5.4. 21st June 2014

Efficiencies are shown for the cylindrical rod array in Fig. 8(g) and for the planar rod array in Fig. 8(h). For the Summer solstice, peak redirection happens at 0700h. Whilst the efficiency
Fig. 8. Comparing the efficiencies of circular (left) and planar (right) rod LSC arrays, for the 10th March, 10th April, 10th May between 0700h - 1200h and 21st June 2014 between 0600h - 1200h. For each time segment, the red top sections show the contribution of the diffuse component of the incident light, and the blue bottom sections show the contribution of the direct component of the incident light. Circular geometries outperform square geometries up until 1000h for 10th March, 1000h for 10th April, 0830h for 10th May and 0800h for 21st June 2014. This is due to increased efficiency values for the direct component of incident light, which can be attributed to its angle of incidence being between within the "light redirection" range as explained in Section 4.
peak due to the direct component is easily seen in Fig. 9(d), it is more hidden when taking into account the weighting ratio between the direct and diffuse component at that time, as seen in Fig. 8(g). The redirection effect is still seen when compared to efficiencies for the planar array, with a relatively flat efficiency profile throughout the day. Whilst the cylindrical array has higher efficiencies within the redirection angle range, once the Sun is out of this angle range after 0700h, the planar geometry has higher efficiency values. The cylindrical array’s efficiency is relatively 5% higher than the planar array at 0600h. The planar array’s efficiency at 1030h however is relatively 5.5% higher than that of the cylindrical array.

Fig. 9. Normalised efficiency values for the circular array at different times of the day vs the ratio of incident photons directed into a cylinder from the sun and the cylinder’s neighbours (triangle). Graphs for (a) 10th March, (b) 10th April, (c) 10th May and (d) 21st June 2014. The angle of incidence is matched to the time of day. The efficiency increase/decrease behaviour matches that of the ratio of photons entering a given cylinder relative to the light’s angle of incidence, confirming the impact geometric effects have on a cylindrical array.

6. Discussion

The redirection angle range shifts in timing and duration over the course of the year. For London UK, the four days mentioned were investigated in the knowledge that for a quarter to a third of the day, the Sun’s incident angle on the array would be in this range of interest, in order to more effectively demonstrate the geometrical effect. For the Winter solstice, the Sun is so low in the sky that its zenithal angle never enters the redirection range. This relationship between time of year and Sun’s angle of incidence being with the redirection range is also dependent on the global latitude of the LSC’s location. This efficiency boost by light trapping is yet to be confirmed experimentally.
This efficiency boosting geometric effect of cylinders in an array could be used to optimise LSC arrays in the field, by way of manipulating its orientation and cardinal alignment. This process would be analogous to that of finding the optimal angle for a photovoltaic module given its location and desired maximum performance time/season envelope.

As was shown for LSC performance on 10th April 2014, correct cardinal alignment and tilt could give an array two maximum performance points during the day, which is a characteristic not seen in planar geometry LSCs.

On top of this geometric effect, the geometric concentration of a cylindrical fibre array is greater than to a planar array that covers the same module area by a ratio of $\pi/4$, due to the differences in fibre end areas.

The investigation performed here was on a single layer of thick cylindrical and square fibres of 1cm. It is unknown whether the geometrical boosts seen here would carry on for subsequent layers of cylinders in a multi-layered LSC array.

## 7. Conclusions

Homogeneously doped cylindrical fibre LSCs were manufactured at Nanoforce Ltd and obtained from LasIRvis Optoelectronic Components Ltd. Measurements show a linear increase in photon concentration as a function of fibre length for fibres in the length range of 0.1m - 2m.

2D raytracing of the shading effects of circles onto their neighbours showed that a circle deviates all incident light away from its neighbour when the angle of incidence is in the angle range of $0^\circ - 60^\circ$. After this threshold angle, the circle starts to redirect incident light into its neighbour up until a second threshold angle of $70^\circ$, when light starts to once again get deviated away from the circle’s neighbour. This can be seen as a form of incident light trapping within an LSC. A hypothesis was put forward that this geometric effect can be used to boost the performance of a cylindrical LSC array when the angle of incidence of the Sun on such an array was within this redirection range.

Using SMARTS software for spectral and sun position data, PVTRACE was used to calculate the optical efficiencies of a horizontally placed, North-South aligned cylindrical LSC array in real world light conditions for 10th March, 10th April, 10th May and 21st June 2014 in London, UK. Overall the cylindrical array outperforms the planar array, but efficiencies for both geometries become more equal closer to solar noon, where the incident light angle of incidence is closer to normal. More importantly, the cylindrical LSC array experiences an efficiency boost for the times of the day where the Sun’s incident zenithal angle is within the redirection range of $60^\circ - 70^\circ$, an effect not seen in planar geometry LSCs with identical simulation conditions. At $70^\circ$, where the redirection effect is at its peak, this efficiency boost means that cylindrical rod efficiencies reach a value 5%-10.7% higher than that of planar rods. On 10th April 2014, the cylindrical array experiences two performance peaks, one of them being due to light redirection.

This efficiency boost could be seen as a practical way to improve a cylindrical LSC array’s performance in the field, aligning both its tilt and cardinal direction to give it an efficiency boost in desired time or seasonal periods.

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