3D printed optical concentrators for LED arrays

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Abstract

Additive manufacturing methods based on photopolymerization offer a promising potential for fabrication of high quality, highly transparent optical components. One use of these technologies involves fabrication of parts for very specific and narrow applications. In this work, we first performed optical raytracing simulations to model an optimized freeform nonimaging concentrator for a custom-built 12-LED array and then fabricated several waveguide concentrators using 3D printing and characterized their optical characteristics. Our results demonstrate that realizing an irradiance of 17 kW/m² or more with an irradiance nonuniformity of better than 2 % over an area approaching 1 cm² is realistic and that such an approach can rival intensities achieved with powerful lasers over a similar area. We also discuss an application where eight different types of LEDs were coupled into the waveguides to construct a solar simulator.

1. Introduction

Since the advent of high-powered light-emitting diodes (LEDs) with a wide range of emission profiles nearly two decades ago, significant research efforts have been devoted to development of LED-based tunable light sources, particularly for applications where a directional, large-area uniform illumination is required [1–4]. Unlike lasers with coherent and highly-collimated emission characteristics, LEDs emit radiation with a Lambertian distribution that present significant engineering challenges for redistribution of the light flux, particularly when an array of many LEDs is involved. Various methods such as freeform surface methods [5], simulated annealing algorithms [6], and the simultaneous multiple surfaces method [7] have been used to design bright and uniform LED-based light sources. However, few developments have focused on designing concentrated light sources based on LED arrays of many LEDs that can provide exceptionally high and uniform irradiance (as explained later) over a small (≈ 1 cm²) area for applications such as photocuring of

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photosensitive materials, solar simulators, and photoluminescence measurements. One particular challenge is that due to the conservation of etendue [8], the collection efficiency from an array of LEDs is generally very low when designed in a concentrated geometry. Nonimaging concentrators [7, 9–11] offer a viable solution for light concentration from LED arrays in spite of losses and low efficiency collection, but such devices require careful optical modeling to design an optimized freeform concentrator with high efficiency and irradiance uniformity for a given array.

Waveguides or lightpipes are of particular interest when the optical design requires good light mixing and irradiance uniformity [12–14]. A thorough understanding of the optical theory and operation of waveguides has been demonstrated for more than two decades but advances in manufacturing methods have lagged behind. Traditional methods of glass grinding and polishing or glass molding are not always suitable or possible fabrication methods and more advanced techniques such as laser-based fabrication and chemical etching have been implemented [15]. With transparent polymers, injection molding has long been a fabrication method of choice [16]. However, it is evident that sometimes, it is valuable to be able to rapidly prototype optical components based on optimized ray simulations and experimentally test and validate these simulation results on short time scales.

Optical plastics have been playing an increasingly important role in optical devices over the last two decades, with major applications in consumer electronics, lighting, medical, security and automotive fields [16]. Owing their success to their light weight, mass producibility, and high optical transparency, injection molding of plastic optical components has become the method of choice for manufacturing of integrated products [17]. Some successful examples of plastics with desirable optical properties include poly(methyl methacrylate) (PMMA), polycarbonate, and optical polyesters. The quality requirements for optical plastics generally focus on high transparency, refractive index, birefringence, and stability to environmental parameters such as heat resistance, moisture absorption and residual stress [16]. Injection molding however is generally labor and resource intensive and is most suitable for mass production of parts once a final design has been established.

Additive manufacturing (AM), commonly referred to as 3D printing, has been recently identified as a viable and versatile process for fabrication of plastic optical components for prototyping or low-volume and research applications [18–22]. Though many printing technologies use optically transparent materials, processes using photo polymerization are preferred as they are more likely to produce parts with little or no void space, limiting scattering losses. Vat photopolymerization [21], which includes techniques such as stereolithography (SLA) [23], digital light printing (DLP) [24], continuous liquid interface polymerization (CLIP) [23], and multi-photon (MP) techniques [25], and material jetting, which includes techniques such as Polyjet [26], are both capable of producing optically transparent components. However, a comprehensive evaluation of the various optical properties of parts manufactured using these techniques is lacking. For optical components prepared by additive manufacturing, minimizing surface roughness is crucial to prevent scattering losses.
In this work, we show that 3D-printed optical components such as LED-based nonimaging concentrators can achieve performance metrics very close to their theoretical design and therefore rival equivalent optics made by injection molding. Table 1 shows an overview of a few techniques available for fabrication of optically transparent waveguides along with some key parameters. Although conventional glass work and injection molding techniques produce higher quality parts with generally better feature resolution, 3D printing techniques offer the best route for prototyping or low volume work at much lower costs. Furthermore, single waveguides offer a simpler and more efficient optical design for light delivery from an extended LED array than a combination of optical fibers, couplers and imaging optics such as collimation lenses. With the objective of achieving the greatest irradiance with the most illumination uniformity over an area of approximately 1 cm² while using the most compact LED array from commercially available off-the-shelf emitters, we first performed ray simulation modeling using the OpticStudio [29] software to come up with a freeform concentrator within a range of defined parameters. We then 3D printed and processed the model-predicted waveguides using a stereolithography-based commercial 3D printer and performed a series of light irradiance and uniformity mappings at the exit port of the waveguide. The measurement results were in good agreement with the simulation and show that 3D-printed optical parts possess optical qualities that make them suitable for widespread use in optics or prototyping applications. The bulk of this discussion including the simulation work is focused on a compact LED array consisting of 12 nominal LEDs of the same type for demonstrating proof of concept and simplicity. A more interesting case involving 8 LEDs of different wavelengths was also assembled and coupled into the 3D printed waveguides and the findings are briefly discussed in terms of end application as a solar simulator.

2. Design and fabrication

2.1 LED array design

For these measurements, 12 commercially available LED emitters from LEDEngin, part number LZ4–00R308 (see NIST statement in reference [29]), were selected, surface mounted and wired on a custom aluminum-clad printed circuit board (PCB). Each LED emitter consists of 4 individually addressable dies with peak emission flux at 740 nm and a total physical footprint of 7 mm × 7 mm. This small size makes achieving a compact LED array while maintaining the necessary sub-surface PCB wiring to each LED challenging. We coalesced around the design shown in Fig. 1A, where first, each emitter’s contact pads were laid out according to the manufacturer’s recommendation contained in the specification sheet downloadable from the manufacturer’s website and then the 4 individual dies within each emitter were connected in series. Therefore, only two electrical connections were needed to be routed to each emitter within the PCB board. The minimum clearance between each adjacent emitter pair is 1.5 mm, and the total array extent from the left edge to the right edge (or top to bottom) is approximately 37 mm. Each of the 12 emitters is then individually connected to commercial multi-channel LED drivers with regulated dc or ac currents of up to 1000 mA per channel with a current resolution of 1 mA. The ability to individually control each of the 12 LEDs is important because the radiant power of each nominal LED at the same drive current is not the same, sometimes varying by as much as 30%. In order to
get a similar radiant output from each LED, each one needs to be driven at a unique current. The PCB-mounted LED array was placed on a water-cooled heat sink to maintain a stable temperature of 15 °C for all the measurements reported here.

2.2 Ray tracing simulations

The OpticStudio optical design and raytracing program [29], known also as Zemax, includes tools and algorithms for optimizing the shape of a CAD object to satisfy a set of design goals. In non-sequential mode, OpticStudio includes a “Freeform Z” object that simulates a rotationally-symmetric waveguide. It is defined by drawing a cubic spline curve through a series of user defined points, then rotating that curve about the Z axis (the direction of light propagation) to form either a shell or closed volume. Light from a virtual source is introduced at the entrance end of the Freeform Z object and then collected by a virtual detector located at the exit end. The virtual detector can be defined as an array of pixels of known size that populate a rectangular or square field. The output of a pixel is directly proportional to the number of rays that strike it, and the overall array output can be visualized in an irradiance (or radiance) distribution. Optimization of the Freeform Z shape is accomplished by first defining the “merit function”, a set of specifications that numerically indicate how close the system meets a goal and is the figure of merit here. The merit function was set up using non-sequential optimization operands provided by the software. A complete list of the available operands and their settings is detailed in the Optic Studio help files. If the merit function is zero, the system exactly meets the goal. The goal could be maximizing the overall throughput of the Freeform Z object or requiring that the pixel-to-pixel variation in the output of the virtual detector be minimized, or both. As an example, if spatial uniformity at the output is desired, the parameters defining the operand “NSDD” can be set so that the standard deviation of all non-zero virtual detector pixel data is returned along with the individual pixel results. Taking the reciprocal of the standard deviation and then forcing the reciprocal to equal 0 as a requirement in the merit function, a freeform shape is found such that the pixel-to-pixel variation is minimized. Furthermore, an additional operand can be added to find the shape that maximizes the transmitted flux. The final result in the shape would be a compromise between minimum pixel variation and maximum transmitted flux. Variables and constraints are established so that OpticStudio knows which terms to adjust, within the constraints, as it uses the value of the merit function to decide which of two systems is superior while the optimization algorithm drives the merit function value to zero.

A virtual array of 12 source LEDs equal to the actual array used was defined. The individual emitter shape, and angular distribution of the light from an emitter, were culled from datasheets and assumed to be the same for all LEDs. The waveguides were defined to have circular entrance and exit ports but optimized in length and shape. Z = 0 defines the entrance port of the waveguide and the virtual LED array was fixed at Z = −3 mm (top of LED dome) to provide a small air gap between the source array and the waveguide entrance. At Z = 0, the diameter of the entrance was constrained to be 40 mm, a value slightly larger than the 37 mm physical extent of the actual array to maximize the in-coupling. At Z = L, the final length of the waveguide after optimization, the diameter was fixed at 11.28 mm to provide a 100 mm² exit area. The waveguide was defined as a PMMA volume using 6 overall points,
but was constrained to have an overall length not to exceed 152 mm. The software was free to adjust the radius and location of the other points defining the shape along the waveguide length. The virtual detector was located at a standoff of \( Z = L + \frac{1}{2} \text{ mm} \). Other standoffs could have been selected. The merit function for the optimization process was set up to either maximize the coupling efficiency (short concentrator) or to both maximize efficiency and minimize the pixel-to-pixel variation in the output of the virtual detector (long concentrator).

The refractive index of PMMA is approximately 1.5. Light incident on the PMMA-air interface from within the PMMA volume experiences total internal reflection and thus propagates down the waveguide only if the Angle Of Incidence (AOI) at the interface is less than the critical angle \( \theta_c = \cos^{-1}(1/1.5) \), or about 48°, where we have defined the AOI from the light propagation direction along the Z axis of the waveguide. Angles greater than 48° will result in energy transmitted into the air and thus represents an optical loss. The transmitted and reflected power for light normally incident on interfaces is given by the Fresnel equations [30] and is approximately 96 % and 4 %, respectively, at each interface encounter. Thus the optimization algorithm will attempt to maintain angles of incidence less than 48° for any ray throughout the length of the volume if so specified in the merit function as maximum efficiency. Rays which propagate down the guide will not suffer appreciable energy loss in the visible wavelengths unless the ray encounters a scattering center (such as an air bubble or surface roughness), which will deflect it to an AOI greater than the critical angle. For the guided rays and in a short practical length of printed PMMA, the absorption is virtually zero and, thus, the only losses are due to Fresnel reflection. We note that even if the actual absorption was non-negligible, it would not invalidate the fact that the merit function resulted in a geometric shape that minimized the overall loss. Rays that never encounter a PMMA-air interface will always reach the end of the waveguide. Most of the energy loss occurs in the first 1/3 of the length since the slope of the shape is relatively high in that region compared to that at the end of the volume, and the AOI is thus most likely to exceed the critical angle. The final, optimized shape will be a function of the individual source radiances, the number of sources, and their separation. The number of rays used was selected based on a compromise between computer processing time and accuracy in the plots. It was felt that the numbers of rays were of sufficient quantity to illustrate the point of this work and the success of the merit function.

The simulation results are shown in Fig. 2, where two freeform concentrators were conceived. The short concentrator waveguide was designed to achieve the highest irradiance output at the exit port with uniformity being a secondary consideration. The long concentrator was designed with irradiance uniformity at the exit plane having the higher priority over intensity. Figure 2 also shows radiance in angle space plots for these models even though the experimental results in section 3 will be focused on irradiance uniformity mapping. In the radiance plots, the X and Y coordinates are angles computed from the direction cosines of the incident ray relative to the detector’s local Z axis. The light collection efficiencies of these concentrators, defined as the ratio of power measured at the exit port to total radiant power of the LED source, are 11.9 % and 11.2 % for the short and the long concentrator designs, respectively. Although these numbers are low, we have verified that they are much higher than simpler waveguide designs such as rectangular (70 %

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lower efficiency) or circular concentrators (27% lower) by performing separate sets of ray tracing simulation on these fixed geometries.

### 2.3 3D printed waveguides

Solid concentrator waveguides were fabricated by a commercial instrument (Form 2 by Formlabs [29]) using the stereolithography method of additive manufacturing. A laser source with an emission peak of 405 nm cures a liquid resin into a solid plastic part according to the design file. The resin material is a proprietary blend of methacrylated oligomers, monomers and photoinitiators (Formlabs, Clear Resin). The print direction was chosen perpendicular to the long axis of the waveguides with a layer thickness of 50 μm. Other print resolutions were also available but not tested for this work.

Based on the results of the ray tracing simulations discussed above, two types of waveguides were fabricated and post processed. The first, a short waveguide which was designed with the goal of maximum efficiency (intensity) at the exit port, has a length of 80.4 mm, an opening radius of 20.4 mm and an exit radius of 6.03 mm, while the second, a long waveguide which was designed with the goal of maximal uniform illumination at the exit port, has a total length of 133.7 mm, an opening radius of 20.2 mm, and an exit radius of 5.5 mm. These dimensions are slightly different than those determined for the optimized models because we could not export the full computer-aided design (CAD) profile of the model and were forced to reconstruct it in a separate CAD program utilizing cubic spline functions. We verified that the reconstructed design was sufficiently close to the original model to produce a similar outcome. The print times vary depending on the number of layers. For the long waveguide, for example, the total print time was about 12 hours and can be left to take place overnight. The surfaces of as-printed waveguides are rough, with an average root-mean-square (RMS) roughness of 0.97 μm or more as measured within the planar layer of a few test prints and are therefore only partially transparent. To obtain optical clarity and high transmittance, the surfaces needed to be polished. For these waveguides, we first mechanically sanded down all surfaces by hand, starting with a sandpaper grit of 200 and progressively used finer paper up to 2400 grit, with some degree of repetition to achieve a relatively smooth finish. Then the various course and fine surface scratches were chemically polished with a microfiber cloth and plastic polishing products to reveal an optically transparent part, with a mean surface RMS roughness of 81 nm as shown in Fig. 1B. The total sanding and polishing time was about two hours. For the chemical polish work, we used a plastic polish kit by Novus [29], starting out with the heavy scratch remover, followed by the fine scratch remover and finally wiping the part with the clean and shine spray. This sequence can be repeated multiple times to achieve smoother surfaces albeit diminishing returns.

Surface roughness was characterized by a Zygo NewView 6000 3D optical profiler [29], using a 100× objective. The optical transmission data are shown in Fig. 3 for a few polished slabs of various thicknesses and show a transmittance of nearly 90% at wavelengths above 450 nm. These transmittance measurements are in agreement with data reported in other optical plastics, particularly the PMMA and are consistent with the earlier assertion that there is a 4% Fresnel reflection at each air-plastic interface. Therefore, absorption losses...
within the printed parts at 740 nm are minimal and support the reported light collection efficiency values through both measurement and modeling. Once the waveguides were fabricated and postprocessed, they were placed inside a plastic case of similar shape, which was separately 3D printed using a Fused Deposition Modeling (FDM) printer, and the larger input face was placed against the LED array as shown in Fig 1C.

3. Measurement and discussions

In addition to the light intensity at the exit plane, irradiance uniformity is also an important consideration in the design and fabrication of these nonimaging concentrators. We first performed spectral irradiance measurements at the location of the exit port using a calibrated spectroradiometer to determine the total irradiance, and the results are shown in Fig. 4. The short concentrator, which was designed for maximum light collection efficiency, recorded a total irradiance of 16.8 kW/m$^2$ (1680 mW/cm$^2$) when all 12 LEDs were driven at their (near) maximum rated current of 700 mA in dc mode. This value is approximately 17 times the nominal sun intensity of 1 kW/m$^2$ achieved over an area of about 1.14 cm$^2$. The long concentrator delivered a total irradiance of 16.4 kW/m$^2$ over a slightly smaller area of 0.95 cm$^2$.

Both of these values are impressive, considering the significant losses within each waveguide. In addition to the intensity measurements of the two primary polished waveguides, we performed intensity measurements on a third 3D printed short waveguide. For this waveguide labeled as “short concentrator, unpolished sides”, no surface sanding or polishing on the perimeter surface of the waveguide were performed, but some surface preparation was done on the input and output ends to minimize surface reflections/scattering for the light entering the waveguide and leaving it. That waveguide showed a 20 % reduction in peak irradiance, with a total irradiance of 14.1 kW/m$^2$. This measurement shows that surface preparation plays an important role in light transmission through the waveguide and too much surface roughness can change the AOI to angles greater than the 48° limit for total internal reflection to occur at the resin/air interface. Finally, as a point of comparison, we performed an additional irradiance measurement on a highly polished BK7 glass waveguide, with the guide tapering out from an input area of 40 mm × 40 mm to an area of 50 mm × 50 mm. This type of tapered waveguide is more typical of what is found commercially. Although this waveguide has actually the highest efficiency in terms of light collection (88 %) for our particular LED array geometry, the irradiance measurements show that the maximum irradiance achieved (7.78 kW/m$^2$) is still half the 3D printed concentrator.

The collection efficiency of each waveguide was approximately measured as follows: The total radiant power of all 12 LEDs was measured by placing a large 15 cm silicon solar cell against the surface of the LEDs to capture as much of the emitted light as possible coming off the source. A smaller detector of the same type was then placed at the exit port of each waveguide and a power measurement was performed. From the ratio of these two measurements, an approximate efficiency is determined. Our estimate of the efficiency for the waveguides, including an estimated uncertainty, are 12.4 % ± 1.2 % for the short waveguide, 8.4 % ± 0.85 % for the long waveguide and 10 % ± 1 % for the short unpolished waveguide. The efficiency of the short waveguide closely reproduces the predicted efficiency.
from the model of 11.9%, indicating that there are no measurable bulk absorption losses due to voids or impurities and the interfaces have been sufficiently polished. The long waveguide shows a smaller collection efficiency than predicted (11.2%), perhaps due to more scattering losses at surfaces as polishing a longer part with more surface area by hand is more challenging than a smaller part. Also, due to the preliminary nature of this study, we did not fabricate and test a statistically significant number of parts; therefore the reported collection efficiency numbers above are subject to slight changes. The measurements are generally consistent with the predictions of the simulations.

Irradiance uniformity maps were obtained by use of a photodetector with a pinhole aperture diameter of 0.8 mm. The apertured detector was placed on an automated x-y translation stage at a distance of approximately 1 mm from the exit plane of the waveguide (to avoid potential contact between the two devices) and was scanned in steps of 0.5 mm to obtain detailed uniformity maps. During these measurements, all 12 LEDs were operated in pulsed mode with low currents to ensure their stability for the duration of the scan. It has previously been verified that temperature-controlled pulsed LEDs of the kind we have used are output-stable to better than 0.1% over 30 min or more. Each LED current was chosen so that the radiant power from each one is similar, just as assumed in the modeling.

Figure 5 shows the measured irradiance uniformity at the exit plane for the polished short and long concentrators in normalized form, by calculating a percentage nonuniformity by the formulation \( \frac{\text{value}_i - \text{value}_c}{\text{value}_i + \text{value}_c} \times 100 \), where \( \text{value}_c \) is the detector signal at near the center of the map and \( \text{value}_i \) is the signal from each of the other locations \[31\]. Also shown are line profiles in the x direction near the center of each irradiance map. The maps only plot data points up to \(-15\%\) difference from the center. The uniformity map from the short concentrator reveals various warm and cool spots near and around the center of the map with variations of as much as +5% (warmer) and \(-2\%\) (cooler) compared to the center location, consistent with simulation results of Fig. 3 where a pattern of warm and cool patches was predicted. This image is contrasted with the uniformity map of the long concentrator, showing a much smoother map with nonuniformity spots contained to within 2% variation of the center over a central section of diameter 6 mm and to within 5% nonuniformity over a diameter of 7 mm. This behavior was also predicted in Fig. 2 and is therefore considered verified. A 2% spatial uniformity in standards describing qualities of a solar simulator light source, for example, constitutes a class A rating, a particularly high challenge, while a 5% nonuniformity obtains a class B rating \[31\]. The results here show that an excellent irradiance uniformity can be achieved with these waveguides and that they can be used in applications where a homogeneous illumination is a primary requirement.

These waveguides have been designed so that the plane of measurement/end application is at the exit port of the concentrator. As the plane of measurement is pulled back from the exit port of the waveguide, both the light intensity and uniformity worsen significantly. At a distance of just 5 mm away from the exit plane of the long waveguide, the irradiance drops to 55% of its value measured 1 mm from the exit port and to 24% when measured 10 mm away. The uniformity also changes substantially, with the 2% region shrinking to a diameter of less than 3 mm at a distance of 5 mm away. It is possible to model and build other types of freeform waveguides where the working distance is shifted away from the exit face for
other applications with such requirements. Additive manufacturing with optical polymers provides a platform to fabricate and test any optical device with an ease and speed that is difficult to replicate with other methods.

Finally, we briefly demonstrate that the light homogenization properties of such 3D printed waveguides can lead to very useful end applications. We fabricated a new LED plate with a variety of quasi-monochromatic and white-spectra LEDs as shown in the inset of Fig. 6. Of the 12 LEDs on this plate, the four at the center are broad-spectrum white LEDs and the remaining 8 around the perimeter have nominal wavelengths as follows: 460 nm, 523 nm, 590 nm, 623 nm, 660 nm, 740 nm, 850 nm, and 940 nm. These are all 4-die LEDs of the same type as the 740 nm LEDs described earlier and are available from the same manufacturer. The 8 quasi-monochromatic LEDs were all coupled into the long waveguide and operated with appropriate currents such that the synthesized spectrum matched the total irradiance given by the standard solar reference spectrum air mass 1.5 global (AM 1.5G). In the spectral range 400 nm to 1100 nm, the reference total irradiance is \( \approx 756 \text{ W/m}^2 \), and so is the 8-LED synthesized irradiance as shown in Fig. 6. Furthermore, this synthesized spectrum achieves an A rating in terms of spectral shape of a solar simulator based on the criteria specified in the IEC 60904–9 when evaluating the interval irradiance values within the 6 specified spectral bands. Therefore, even with 8 LEDs, this setup passes as a solar simulator by definition.

We also evaluated the uniformity of the irradiance at the exit plane for each of the 8 LEDs. The results, shown in Fig. 7 demonstrate that achieving good uniformity is a bigger challenge. Since there is only one of each type of LED, the homogenization (light mixing) cannot be improved any further by utilizing multiple LEDs of the same type and varying their currents to achieve good uniformity as seen in Fig 5 for the case all identical LEDs. Even so, the irradiance uniformity for the majority of the LEDs are around 15 % and for many research and development of solar cells where quick test results take priority over low uncertainty, this set up could serve as a good resource.

4. Conclusions

We have shown that a commercial 3D printer that fabricates parts with photocurable, optically transparent polymers can be used to engineer high quality optical devices such as a small optical concentrator coupled with an LED-array of 12 surface-mounted high power LEDs. Light transmission properties of these 3D printed structures are comparable to their injection-molded counterparts and the surfaces can be polished to a degree that is sufficient for many applications. Using quasi-monochromatic LEDs with emission peaks at 740 nm and driven in DC mode below their absolute maximum rating, an intensity of \( \approx 17 \text{ kW/m}^2 \) over an approximate diameter of 7 mm in diameter was achieved with an irradiance non-uniformity of under 5 %. For comparison, a class 4 laser system such as a Continuous Wave Ti:Sapphire laser with an optical output of 1 W to 3 W (depending on the model) at 700 nm can provide an intensity in the range of 26 kW/m² to 78 kW/m² over a comparable area, demonstrating that our small, low cost LED array source coupled with a 3D printed waveguide can provide output 22 % to 66% of more costly and complicated laser systems. Furthermore, the LED array can be populated with LEDs of different types and coupled into...
the same waveguide concentrator. Without any additional optimization, we have shown that this setup can serve as a solar simulator with good spectral shape and acceptable irradiance uniformity.

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Fig 1.
A) Layout of the 12-LED array with emission characteristics at 740 nm, B) as-printed short concentrator waveguide, polished short waveguide and polished long waveguide, C) waveguide placed against the array showing the light leakage from the side walls, D) the encased waveguide in operation. The 12 small red LEDs on the top side of the board in A are indicator LEDs only and are not coupled into the waveguide.
Fig 2.
Simulation results: The figures on the left column show the simulated model of the short waveguide, its incoherent irradiance profile at the exit plane and its radiance in angle space. The figures on the right column show the simulated model of the long waveguide where achieving irradiance uniformity was a higher priority in the modeling.
Fig 3.
Light transmittance measurements of a few 3D printed slabs of the cured and polished resin used for fabrication of the optical concentrators.
Fig. 4.
Spectral irradiance measurements at the output plane of various waveguides, including the 3D printed polished short and long concentrators, a short unpolished concentrator and a glass tapered out waveguide for comparison purposes. The total irradiances are integrated values under each curve.
Fig 5.
(left panel) Irradiance uniformity map of the short concentrator in % nonuniformity from the center and a line profile taken along the x direction near the center (right panel) Irradiance uniformity map and a line profile of the long concentrator revealing much higher spatial uniformity.
Fig 6.
(Inset) The design of an LED array with 8 quasi-monochromatic LEDs (the perimeter LEDs) and 4 similar white LEDs in the center. (Main part) With only the 8 monochromatic LEDs utilized and coupled into the long waveguide concentrator, a combined spectrum can be synthesized satisfying an indoor solar simulator spectral and power requirements according to the IEC 60904–9.
Fig. 7.
The irradiance uniformity maps of the 8 LEDs used to construct the solar simulator at the exit plane of the waveguide. The nonuniformity percentage is with respect to a point at the center.
Table 1. Overview of a few techniques for fabricating optical waveguides

| Method                              | Material               | Feature resolution | Processing condition                                                                 | Processing time       | Cost for low volumes |
|-------------------------------------|------------------------|--------------------|--------------------------------------------------------------------------------------|-----------------------|----------------------|
| 3D printing (SLA, this work)        | polymer resin          | 50 μm              | Direct print with support structure, post process: short UV curing, sanding and polishing | Print time: ≈ hours, post process: 2 to 3 hours | low                  |
| 3D printing (microextrusion) [27]    | Ballistic gel          | 150 μm             | Preprinting process: gel preparation, direct print, minimal post processing           | Gel preparation: >12 h, print time: ≈ hours | low                  |
| Family of injection molding techniques [28] | A range of thermoplastic polymers | ≈ 1 μm or lower | Requires mold fabrication, extensive molding process and cycle                     | For a new design: days | Very high            |
| Conventional glass processing       | Glass                  | ≈ 100 μm           | High temperature processes and harsh chemicals, grinding and polishing, limited to simpler geometries | Hours to days         | Medium to high       |