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Silicone optical elements for cost-effective freeform solar concentration

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Abstract: The use of silicone optical elements is demonstrated for a concentrated photovoltaic system. These components show over 96% transmission through most of the solar spectrum and excellent temperature stability. Unique moldability enables the use of complex freeform designs. A light, compact, and cost-effective concentrated photovoltaic system based on silicone optics is proposed. In this system, air-plasma treatment is utilized to overcome the mechanical properties of silicone and difficulties with coating to reduce Fresnel loss. Lens arrays and waveguides are fabricated by injection molding following freeform optical design by LightTools. First-order characterizations are also performed.

1. Introduction

As the global interest in renewable and clean energy becomes more intense, research on solar power generation is accelerating. In particular, the photoelectric conversion efficiency of concentrated photovoltaic (CPV) technology can reach more than 40%, as long as the area of CPV cells can receive high solar concentration (~200x) [1]. For the high solar concentration of CPV solar systems, various types of concentrators have been studied in addition to typical glass lenses such as Fresnel lenses [2], parabolic troughs [3], and micro lens arrays [4]. However, these concentrators still suffer from various problems such as the high cost of the glass lenses, large volume and weight of parabolic troughs, losses due to optical aberrations, low tracking tolerances, and fabrication limitations of the micro-lens array and the Fresnel lenses, which are still difficult to apply to practical high-efficiency CPV solar systems.

Silicone materials have a long history of successful use in a variety of applications such as electronics, medicines, foods, and aerospace industries to name a few. Many of their properties, such as very low ionic impurities, low moisture absorption, chemical compatibility, and a wide range of usable temperatures, make them excellent materials for applications in these markets. Recently, optical quality silicone material based on polydimethylsiloxane (PDMS) was developed for LED applications [5–7]. PDMS has excellent chemical resistance, excellent environmental stability, and high optical transmission in the UV-VIS wavelength range, especially the UV range, in which traditional polymer such as PMMA and polycarbonate (PC) have absorption that causes yellowing effects upon long term exposure [8]. Compared to glass, PDMS products can be thinner, lighter, more compact, and cost-effective. More importantly, PDMS has a significantly better capability of freeform optical design due to its unique and flexible moldability. Freeform optics enhances optical throughput and requires less space to achieve large concentration ratios in solar systems, compared to traditional concentration methods. These properties make PDMS with high optical quality a suitable replacement for existing passive optical elements in solar concentrators. To our knowledge, there is no research in adopting PDMS in such applications.

In this paper, we demonstrated the viability of implementing optical silicone materials in passive optical elements for a solar concentrating system. We designed, fabricated and

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characterized these various optical elements using PDMS based moldable silicone. Freeform optical elements were also designed and fabricated to confirm whether this material could be used for low-cost and high-efficiency CPV solar systems. Figure 1 shows the conceptual design of a compact, low-cost, and high-efficiency CPV panel solar system with freeform optics. In the micro-concentrator, a set of linear acylindrical lens arrays focus the solar direct normal irradiance (DNI) on top of freeform waveguides that collect the light and further concentrate it in the direction perpendicular to the optical axis of the lens array. The light is trapped in the freeform waveguide device due to total internal reflection, and it is directed towards multi-junction CPV cells. A larger silicon PV cell at the bottom of the system collects the diffuse sunlight and stray light from the lenses and waveguides. This design allows concentration over 150x in a compact <40 mm thick device. Due to the number of surfaces and length of the components, a material which is transparent in the solar spectrum with the relatively low refractive index is desired. This minimizes losses due to absorption and Fresnel reflections.

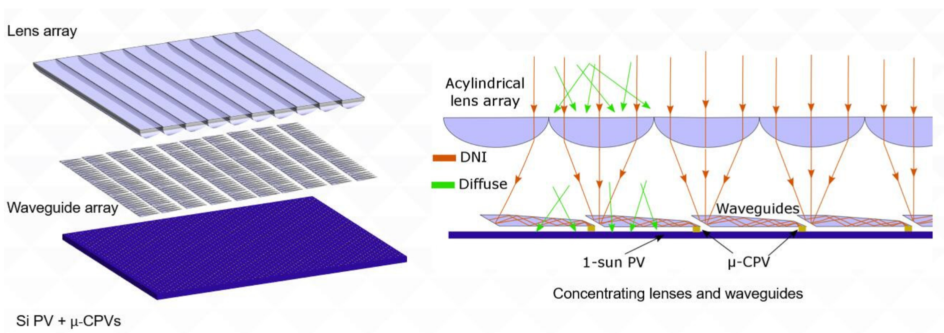

Fig. 1. Lens-waveguide-CPV design, a 3-layer solar panel based on moldable silicone freeform optics.

2. Materials and characterization

Silicone polymer has a number of unique properties that make it a more attractive choice than other organic polymers for solar applications. In addition to the excellent clarity at UV-VIS wavelengths, thermal mechanical stability, chemical resistance, and inherent hydrophobic properties can enhance the stability of the solar system to variations in the external environment. The hardness and the refractive index of the silicone material can be tuned by controlling the proportions of the constituent monomers. The durometer can be as high as 67 shore D, approximately equal to 100 shore A [8]. This not only provides viability for achieving suitable mechanical properties for mass production processes such as casting or injection molding, but also for optimization for solar energy systems. In this study, MS-1001 (Dow Corning) was used as a moldable silicone material. Figure 2 shows the transmission spectrum of MS-1001 with different thicknesses. It has greater than 92% transmission in the UV-VIS and NIR wavelength range (350 nm ~1400 nm) except for one narrow dip near 1200 nm which also coincides with one of absorption peaks in the solar spectrum. It also demonstrates over 96% optical transmission for 8.1-mm thickness in this solar regime. Besides, it has relatively high hardness with 87 shore A durometer [9]. As a comparison, this is harder than automotive tires (70 Shore A). With additional support features incorporated into the single molded piece, they are easily capable of maintaining their shape and functioning properly.

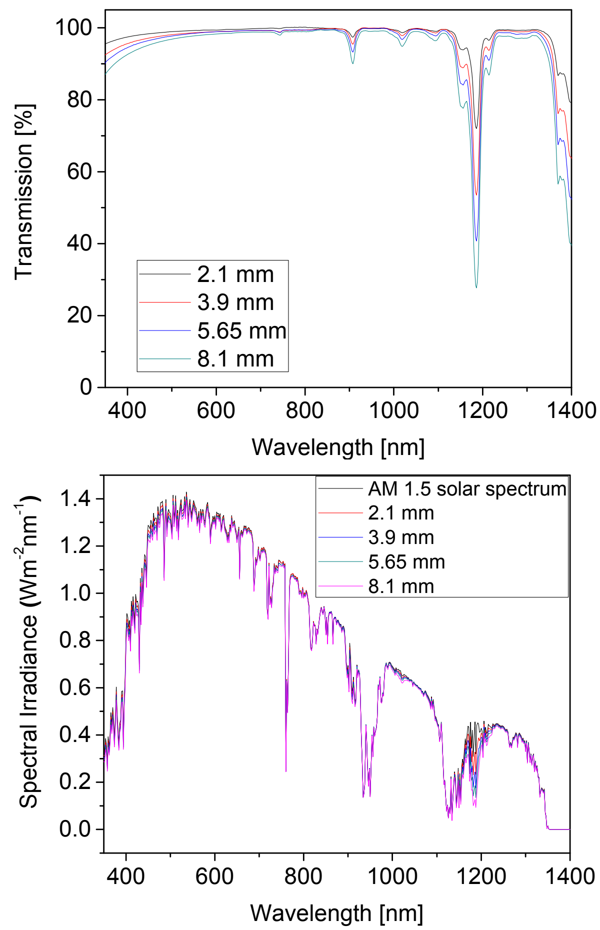

Fig. 2. Transmission spectrum of MS-1001: measured transmittance with UV-VIS spectrophotometer from 350 to 1400 nm with various thickness (upper) and normalized transmittance combined with AM 1.5 solar spectrum (lower).

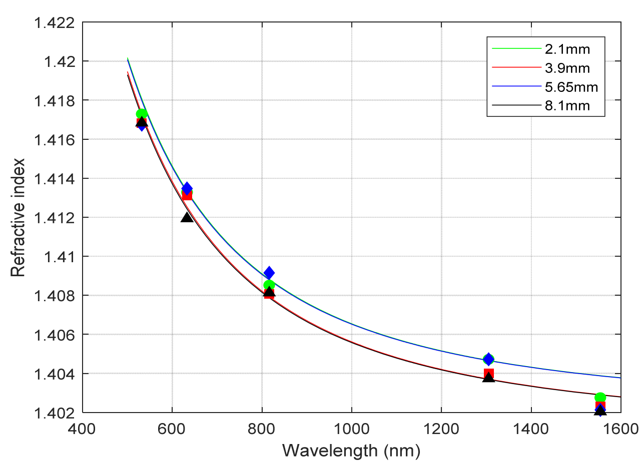

Fig. 3. Refractive index of MS-1001 for several samples with different thicknesses.

As shown in Fig. 3, the refractive index of MS-1001 for different thicknesses was measured at 532 nm, 633 nm, 816 nm, 1305 nm, and 1554 nm, respectively. MS-1001 has very low dispersion with wavelength, which is an important feature to achieve high throughput efficiency with large concentration ratio in a precise, compact CPV solar panel. Moreover, the relatively low refractive index (~1.41) compared to that of glass (~1.5) reduces Fresnel reflection loss at the surface.

Table 1. Comparison of key factors among popular material candidates in solar applications.

Category	Property	PDMS	PC	PMMA	Glass
Optical properties, 2mm thickness	Transmission [%]	94	86~89	89~92	92
	Refractive index	1.41	1.59	1.49	1.5~1.6
	Haze [%]	<1	1~3	2~4	-
	Abbe number	50	34	57	39~59
	Yellowness index	<1	1.0~3.0	1.0~3.0	-
Durability	Heat resistance	Excellent	Poor	Poor	Excellent
	UV resistance	Excellent	Poor	Good	Excellent
Design freedom	Complex/micro design	Excellent	Good	Good	Poor
	Material flexibility	Excellent	Poor	Poor	Poor
	Light weight design	Excellent	Good	Good	Poor

The key factors of popular materials which are widely used in solar applications are summarized in Table 1. PDMS material has better performance in terms of optical clarity, durability and design freedom. Especially, the low yellowness index benefits from strong UV resistance, leading to longer lifetime under strong and prolonged exposure to sunlight. PDMS is a hydrophobic material. Additionally, concerning environmental humidity [10], the Vanlathem, Eric, et al. [8] study showed that no change of refractive index or transparency was detected after exposure to accelerated aging conditions of 85% R.H. 85 °C for up to 2000 hours.

Simple optical elements were fabricated by the double casting method [11] in order to investigate how the silicone material properties appear in real optical devices. A PMMA acylindrical lens array and an optical funnel were used as original masters. A negative mold was made in PDMS (Sylgard 184, Dow Corning) with a 9:1 mixing ratio. After 48-hour, 100°C thermal aging of the negative mold, the replica was obtained by casting MS-1001 onto the negative mold and curing at 70 °C for 1.5 hour. Figure 4 shows the fabricated MS-1001 lens array and optical funnel as well as their PMMA masters.

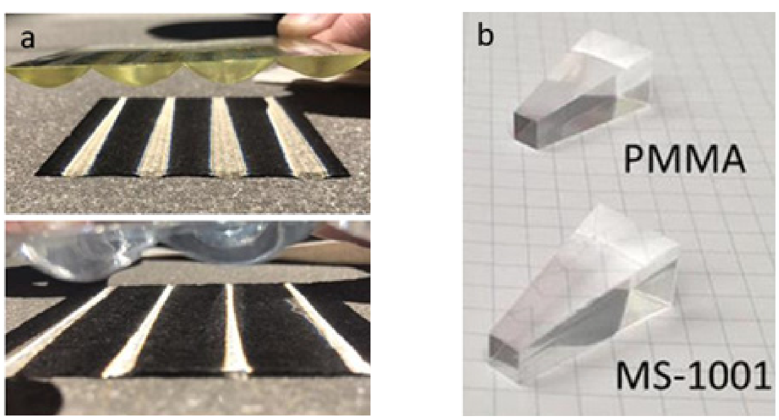

Fig. 4. (a) Upper: PMMA master of acylindrical lenses. Lower: MS-1001 replica. (b) optical funnel.

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The fabricated optical elements were temperature cycled to simulate a practical outdoor environment for 100 cycles between –20 °C and 70 °C. The optical transmittance and the back focal length were measured before and after temperature cycling for the PMMA acylindrical lens array master and MS-1001 replica, respectively. The results are shown in Table 2. The back focal length of both MS-1001 and PMMA lenses has no significant change after the temperature cycling test. There is a significant reduction of transmittance for the PMMA lens in comparison to the MS-1001 lens, indicating less degradation in the MS-1001 case. The optical transmission difference between PMMA funnel and MS-1001 replica was negligible.

Table 2. Characterization of PMMA and MS-1001 lenses for temperature cycling test.

	Back focal length (mm)			Transmittance (%)		
	before cycling	after 100 cycles	Δf/f (%)	before cycling	after 100 cycles	ΔT (%)
PMMA lens	16.2	16.5	+ 1.85	85.44	81.13	–4.31
MS-1001 lens	21.8	21.6	–0.92	87.43	86.24	–1.19

3. Design and simulation of the freeform solar concentrator

Our proposed CPV solar system consists of acylindrical lens arrays, waveguides, and CPV panels as shown in the Fig. 1. Design and simulation of silicone-based acylindrical lens arrays and waveguides for the freeform solar concentrator were performed using LightTools [12] ray-tracing software. The light source was defined by the standard Air Mass (AM 1.5) solar spectrum. The material for the lens array and waveguide was selected to be MS-1002 (Dow Corning, the North American version of MS-1001) which has 1.41 refractive index and approximately 96% internal transmission over the solar spectrum.

The lens array was designed with an acylindrical structure, a linear lens analogous to an aspherical lens in one dimension. These lenses have higher concentration and less aberration than traditional spherical lenses [13]. The final structure of the lens array consists of a glass slab attached to the back side, which acts as back support providing the strength to maintain the shape of the silicone lenses in practical applications. Furthermore, an anti-reflection coating (ARC) over the solar spectrum was applied to the glass to significantly reduce the Fresnel loss at air/glass interface. The size of lens array was 160 x 160 mm^2 with 8 lenses in an array and the designed back focal length was 33.23 mm.

Two freeform waveguide designs (wing-like and horn-like, respectively) were optimized for the CPV concentrator, using a reiterative algorithm to maximize optical efficiency and concentration. In brief, the 18-mm long and 4.45-mm wide waveguides, based on total internal reflection (TIR), were tapered down to redirect and further concentrate the sunlight being focused by the acylindrical lens arrays. For these waveguides, in the lateral plane (parallel to the plane in which the acylindrical lenses rest) a compound parabolic concentrator (CPC) geometry was utilized to focus the light. The CPC structure was 4.45 mm in width and had a 7.9° acceptance angle. As a result, it enabled the light to be concentrated onto 0.7 x 0.7 mm^2 CPV cells. The tapered angle was optimized to obtain high guide efficiency as well as strong mechanical strength. At the input, the angle of the reflecting facet depends on the critical angle of material (45.17° for MS-1002). The wing-like waveguide has one reflecting facet which is easier to fabricate, while the horn-like waveguide has two consecutive reflecting facets with an additional TIR to redirect the light from vertical to horizontal more gradually. This allows for better tracking tolerances but faces more fabrication challenges. Near 94% simulated waveguide efficiency, defined by the power ratio between input and output of the waveguide, was achieved by optimization of the shape of the freeform waveguides. In combination with the acylindrical lens both designs can achieve up to 160x concentration. Besides the improvement of performance, the moldability of silicone also allowed us to include holding/alignment features with the waveguide body in one piece without breaking the total internal reflection condition for practical assembly, which is difficult to achieve with glass. It also reduces the cost of manufacture and mass production, especially for complicated designs. In both of designs, a 2 x 2 x 3 mm^3 small cuboid underneath the waveguides worked as a standoff for practical assembly without break TIR condition. The position of the cuboid was chosen to have minimum impact on waveguide efficiency—less than 0.5% efficiency drop in our designs. Moreover, silicone itself can work as a perfect index-matching adhesive at the interface between the waveguide and the CPV cell for assembly.

The whole system was simulated using non-sequential ray tracing, where stray light and secondary reflection ray paths can be easily be observed to optimize system layout. The system overall length along the optical axis (from the top of the lens to bottom of the waveguide) is 38 mm. The simulated system efficiency was 90.5%. The losses mainly come from Fresnel losses and absorption in the materials.

4. Characterization of freeform optics

Designed acylindrical lens array and freeform waveguides were fabricated by injection molding process at Protolabs, Inc [14]. The molds were machined and polished to obtain optical quality surfaces on aluminum, and the lens array and waveguide were made from MS-1002 material, a new version of MS-1001 recently introduced by Dow Corning.

4.1. Acylindrical lens array

The flexibility of the silicone material is advantageous for making a complex and micro shape, but when a thin and wide structure is produced, bending may occur due to gravity and positioning of the lens. In order to overcome the mechanical properties of the MS-1002 lens array, a slab of glass was bonded to the lens array as back support. Plasma treatment has been widely used to achieve high-strength PDMS/glass bonding by changing the surface energy [15]. In this process, atmospheric plasma treatment was used to bond the lens array and glass plate without any adhesive. Furthermore, back glass plate allowed us to deposit anti-reflection coatings that significantly reduce Fresnel reflection at air/glass interface, which is not feasible on the silicone surface. Scott Borofloat 33 glass was chosen for relatively lower refractive index (~1.47) to further minimize the Fresnel loss at the glass/PDMS interface. Silicone-based lens arrays have light weight which can further reduce assembly cost.

In order to verify the characteristics of the lens array, we collimated a broadband light source (SuperK Extreme EXU-6, NKT Photonics) to enter the lens array and confirmed the linearly focused light as shown in Fig. 5. The real focal length was calculated after a profilometry measurement of radius of curvature. The measured value was 34.89 mm, which is close to the designed value of 33.23 mm within a 5% error. A thermal cycling test (−20 ~70 °C, 100 cycles) was done to verify the stability of the material. After cycling, the bonded lens array was still tightly attached to the back- glass plate without any air gaps and maintained the same optical clarity.

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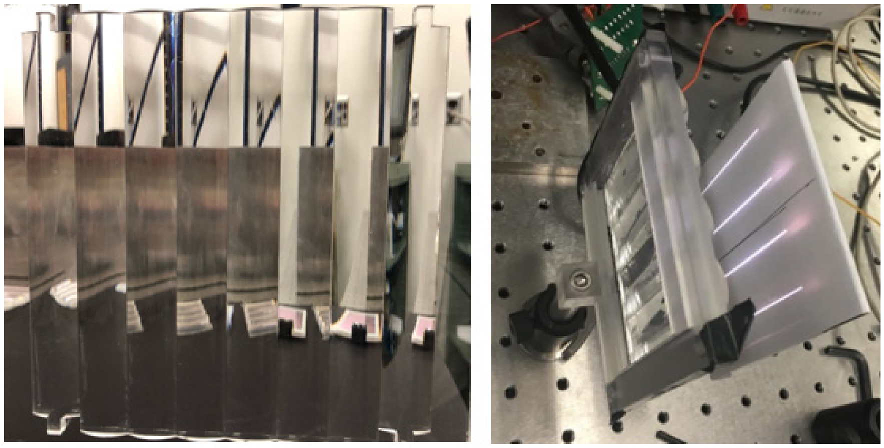

Fig. 5. MS-1002 acylindrical lens array: (left) structure without support glass and (right) structure with backing glass making use of the plasma treatment technique.

4.2. Freeform waveguide

Fabricated waveguides with the two different designs mentioned above are shown in Fig. 6(a)-6(d). The optical efficiency of waveguides was determined using a monochromatic laser source and a Si photovoltaic (PV) cell. Expanded light from the laser was concentrated onto the input facet of the waveguide using a fabricated MS-1002 acylindrical lens array. A PV cell was placed at the output surface of the waveguide. After that, the waveguide was carefully aligned with the lens array to maximize the short circuit current of the PV cell. The short circuit current and open circuit voltage were measured over a range of laser output powers. In order to calculate an optical efficiency, the same measurements were also made without the waveguide. The attenuation of the input power by the waveguide was determined by the attenuation of the laser power that was required for the open circuit voltage of the reference measurement (i.e. without the waveguide) to be the same as the open circuit voltage with the waveguide illuminated at full power. Using this technique, the optical efficiencies of the two designs were determined to be (43.6 ± 0.5) %, Fig. 6(c) and (67.5 ± 0.7) %, Fig. 6(a), significantly different from the simulated values. Since the system was designed for high concentration ratios, its efficiency is very sensitive to alignment of the light source, lens arrays, waveguides and CPV cells. Residual material on the surface of the optical elements after injection molding may also cause scattering loss. Fresnel losses are also present since these initial prototype lens arrays and waveguides do not have ARCs on any surface. Moreover, in the original simulations multifunction CPV cells were used, where performance is enhanced with high concentration as opposed to traditional Si cells where high concentration might reduce conversion efficiency. Further optimization of the design and characterization system, as well as studies on efficiency loss will be pursued in future work.

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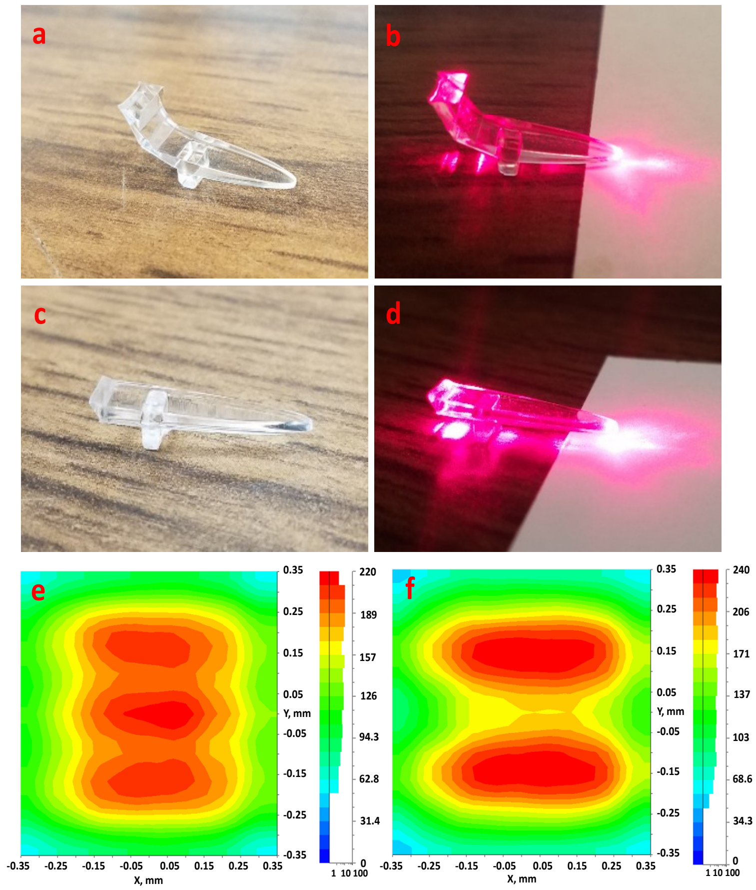

Fig. 6. (a) Horn-like waveguide. (b) Light output through the horn-like waveguide. (c) Wing-like waveguide. (d) Light output through the wing-like waveguide. (e) Systematic optical flux on CPV for MS-1002 wing waveguide. (f) Systematic optical flux on CPV for PMMA wing waveguide.

The simulated systematic optical flux, from the input of acylindrical lens array to the output of the waveguide on CPV, is shown in Fig. 6(e) for an MS-1002 waveguide and Fig. 6(f) for a PMMA waveguide, respectively. Both PMMA and MS-1002 waveguides have 94% waveguide efficiency. The light through the PMMA waveguide is more concentrated on the CPV due to higher refractive index, while the light through MS-1002 waveguide is more uniform which is helpful to reduce irradiance hot spots on the CPV.

5. Conclusions

Moldable silicone is a promising alternative to glass, PMMA, and other polymers for solar energy applications owing to its high clarity, moderate refractive index, low dispersion, and excellent UV resistance. Moreover, unique flexible moldability enables complex freeform optical design for cost-effective manufacture and convenient assembly. Based on these benefits, we confirmed that optical silicone could be used as a solar concentrator after characterizing fabricated optical elements. Temperature cycling test results also show excellent stability to the external environment. Accordingly, a compact and cost-effective freeform solar concentrator which consists of lens array and waveguide based on silicone material were designed and fabricated by injection molding as a proof-of-concept. The acylindrical lens array structure was adopted for high concentration and low aberration. In order to reinforce the strength of the lens array and to reduce Fresnel loss by anti-reflection

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coating, a glass slab was attached on the back side of the lens array by using an atmospheric plasma treatment technique. Two different freeform waveguides were designed and fabricated for the CPV concentrator. Based on the moldability of the silicone material, holding/alignment features was fabricated on the waveguide body in one piece. In initial characterization, it was found that there is a difference between the predicted efficiency of design and the measured value of the fabricated device because of various loss and characterization factor; improvements are the subject of future research.

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