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ORIGINAL ARTICLE

# Fabrication of high-performance lens arrays for micro-concentrator photovoltaics using ultraviolet imprinting

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## Abstract

Micro-concentrator photovoltaics (micro-CPV) is a cutting-edge CPV approach aimed at increasing the efficiency and reducing the cost and carbon footprint of solar electricity by downscaling concentrator solar cells and optics. The reduced size of micro-CPV provides several advantages over conventional CPV, including shorter optical paths and lower temperature and resistive losses in the cell, resulting in higher electrical efficiencies. This may increase the energy yield per area compared to conventional CPV or silicon modules. Cost reduction is achieved through material savings and the use of continuous manufacturing methods enabled by the tiny size of cells and optics, such as roll-to-roll (R2R) and roll-to-plate (R2P) ultraviolet (UV) imprinting for optics production. However, adapting these processes to large-area arrays of Fresnel micro-lenses with no wasted areas and high efficiency remains a challenge. In this study, we present a comprehensive methodology for the development of micro-CPV optics with full area coverage—from design and mastering to up-scaling, tooling, and replication. The methodology involves designing a non-rotationally symmetric elementary insert tailored to ultraviolet imprinting. Crucially, multiple inserts are originated via precision machining and recombined to form a single array master mold without wasted areas. The master is then replicated into a flexible working stamp for UV imprinting of Fresnel lens arrays, utilizing different UV curable materials. The functional characterization of the lenses demonstrates an optical efficiency of 80% at 178X under collimated white light, representing the highest effective concentration achieved using UV-imprinted Fresnel lenses. Furthermore, initial reliability tests confirm the absence of degradation during thermal cycling or outdoor exposure. This methodology paves the way for continuous high-throughput manufacturing of micro-lens arrays using R2R or R2P methods, presenting a significant step forward in micro-CPV.

**Keywords** Solar energy · Concentrator photovoltaics · Building-integrated photovoltaics · Micro-concentrator optics · UV imprinting

## 1 Introduction

In concentrator photovoltaics (CPV), optical systems are used to concentrate sunlight onto solar cells with the double aim of increasing the power conversion efficiency of solar cells and reducing the required area of semiconductor, which takes most of the cost and environmental impact of solar panels because of the high carbon footprint of their manufacturing. Micro-concentrator photovoltaics (micro-CPV) is a trend in CPV to reduce the size of the solar cells below 1 $mm^2$, consequently making the rest of the components proportionally smaller [1, 2]. The reduction in size provides benefits such as better optical efficiency and thermal management, reduced series resistance losses, a lower bill of materials, and the ability to use alternative low-cost and high-throughput manufacturing methods. Although optical alignment between parts now requires sub-millimeter precision, angular tolerance is the same as in classical CPV optics because all dimensions are scaled. However, to exploit these advantages, technological innovations in the manufacture and assembly of the various components are necessary. On

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the one hand, a precise and inexpensive placement method of micro solar cells is required as an alternative to prohibitive serial pick and place, *e.g.*, via fluidic self-assembly or transfer printing processes, which are currently being developed by related mainstream industries such as those of LED lighting and micro-LED displays [3, 4]. On the other hand, a high-throughput, high-quality manufacturing process is needed for large-area lens arrays as an alternative to the conventional batch-based molding of silicone-on-glass or polymethyl methacrylate (PMMA) with long (expensive) cycle times. Hot embossing of PMMA can reach high yields, but it has not yet achieved very good surface qualities [5, 6]. Potentially inexpensive alternative processes enabled by the reduced thickness of micro-CPV lenses include roll-to-plate (R2P) or roll-to-roll (R2R) ultraviolet (UV) imprinting, where a roller mold is used for the continuous fabrication of micro or nanostructures on rigid substrates or films of large area via UV curing of photoresins [7]. The possibility to use roll-to-roll UV imprinting to manufacture CPV lenses has already been demonstrated by several publications: linear Fresnel lenses with a geometric concentration of 4 suns (X) (that is, the ratio between the area of the lens and that of the receiver cell) [8] and radial Fresnel lenses with concentration ratios of 16X [9] and 128X [10]. This technology, in addition to being highly scalable and cost effective, allows the inclusion of antireflective (AR) coatings and other surface functionalization to add UV filtering, self-cleaning, or anti-soiling properties [11], both on the structured part of a Fresnel lens [12] and on the flat side of the lens array [10].

UV imprinting or UV embossing is a molding process for the manufacturing of microstructures in UV-curable materials [13]. This technology is employed in industrial applications for manufacturing of devices such as active-matrix organic light-emitting diodes (AMOLED) devices, flexible solar cells, or microfluidic devices [14, 15]. UV imprinting is a scalable technology suitable for producing structures within a wide range of dimensions, from the nanoscale to the millimeter scale. It provides high resolution and low roughness estimated to be down to 10 nm and, as such, is well suited to manufacture Fresnel optics.

The UV imprinting fabrication process is suitable for high-efficiency Fresnel optics for micro-CPV. However, it involves several challenges: first, the optical modeling and geometric design of the Fresnel lens considering the UV imprinting process and material properties and, secondly, the manufacturing of a precision mold for the non-rotationally symmetric shape of a Fresnel lens array with no wasted areas, which cannot be diamond turned directly [9]. Characterization of individual micro-CPV lenses is required to assess optical efficiency, concentration ratio, or the optimal focal distance to provide feedback on the manufacturing process quality. Optics on films are difficult to characterize and must be stretched accordingly. Having the optics on film is also not always beneficial; as the final form will be flat, the film must be laminated on a substrate which can incorporate losses and reduce the longevity. Ideally, these lenses could be manufactured by roll-to-plate or even by large-scale plate-to-plate processes on glass substrates.

In this publication, we present the fabrication of high-performance Fresnel lens arrays via plate-to-plate (P2P) UV imprinting process in two different UV curable resins. We start off with the design of the Fresnel lens and continue with the manufacturing of the metallic master array. Finally, to prove the effective mold design, Fresnel lens arrays are produced on rigid silica substrates by UV imprinting. The goal is to achieve the highest possible optical efficiency at the intended geometric concentration of 178X. This work served as the basis for scaling up the fabrication of microlens arrays via R2R UV imprinting, as described in [10].

## 2 UV imprinting process

### 2.1 Plate-to-plate UV imprinting of micro-CPV Fresnel lens arrays

For the fabrication of the Fresnel lens arrays, a low pressure wafer-based UV imprinting process was employed using a soft working mold. The steps involved in the preparation of this mold are as follows. First, a brass master mold containing the negative contour of the Fresnel lens design is produced (process described in Section 4). Subsequently, this mold is replicated in PDMS (polydimethylsiloxane) by a common soft lithography process [16]. Subsequently, the PDMS replica is again replicated using a perfluoropolyether (PFPE, Fluorolink MD700, Solvay) to create the working molds. For this, the PFPE precursor is mixed with 2 wt.% of 2-hydroxy-2-methylpropiophenone (Sigma Aldrich) applied as a photoinitiator. The mixture is then degassed under vacuum before being poured onto the PDMS replica substrate. Afterwards, the mixture is photopolymerized under UV illumination using a PET foil as the blanket, preventing oxygen inhibition of the free radical photocuring reactions. The resulting PFPE substrate is then used as a working mold to form Fresnel lens arrays on fused silica substrates (P2P process). In this process, the PFPE soft mold is placed with the Fresnel structure facing upwards, and then, a photocurable optical resin is applied by blade coating Fig. 1a). Subsequently, the coated mold is covered with a fused silica wafer, and the sandwich is placed under a thick quartz plate transparent to UV light; this plate applies a low pressure that does not deform the soft mold but helps filling the lens cavities on it. In continuation, the whole assembly is exposed in a UV chamber to a UV lamp providing 80 mW·cm$^{-2}$ (UVASPOT 400/T, Honle) for 1 min (Fig. 1b) whereby the resin is cross-linked and the mold lens structures are

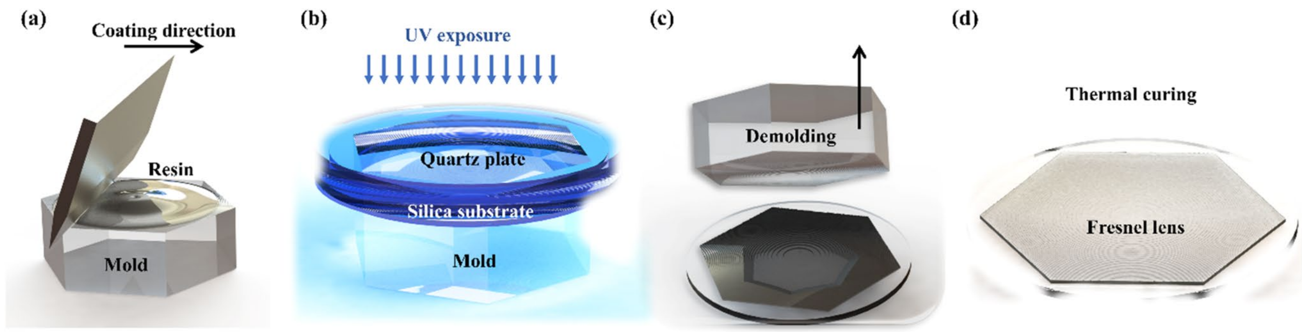



**Fig. 1** UV imprinting process for the manufacturing of Fresnel lenses for micro-CPV. Each step is shown: **a** blade coating, **b** UV imprinting, **c** demolding, and d thermal curing (optional)

transferred to the substrate. Finally, the resulting Fresnel lenses are obtained by carefully peeling off the soft flexible mold (Fig. 1c). Optional but recommended is a post-baking step (> 100 °C) for complete curing of the optical material (Fig. 1d), increasing the chemical strength and improving the optical properties. Since the objective of this study was to obtain the best possible lens performance, 250-µm thick fused silica wafers were used as a rigid substrate for the lenses due to their very high transmittance.

## 2.2 Selection of UV-curable materials for CPV

UV-curable materials can be selected depending on their processing characteristics (*e.g.*, suitable viscosity, high curing speed, high adherence to the substrate, low adherence to the mold, or reduced shrinkage after curing) and their optical properties (mainly refractive index, dispersion, and spectral transmittance). After considering different optical-grade resins, OrmoComp, a hybrid organic–inorganic sol–gel resin from Microresist GmbH, and the acrylate-based FOL 1.2 resin from Film Optics LTD were selected. These materials have interesting characteristics such as high transparency with high resistance to degradation or yellowing during UV exposure (tested), good adhesion to different substrates such as polymers and glass (datasheet), compatibility with soft silicone molds (tested), good replication of deep structures of 100 µm (datasheet), low shrinkage after curing (5–7% for OrmoComp acc. datasheet), and high hardness (75 Shore D for OrmoComp acc. datasheet).

The measured spectral transmittance of a 100-µm thick layer of candidate resins cured on a 250-µm thick fused silica substrate is shown in Fig. 2a, along with the quantum efficiency of standard triple-junction solar cells, which are typically used in micro-CPV modules. A very high transmittance

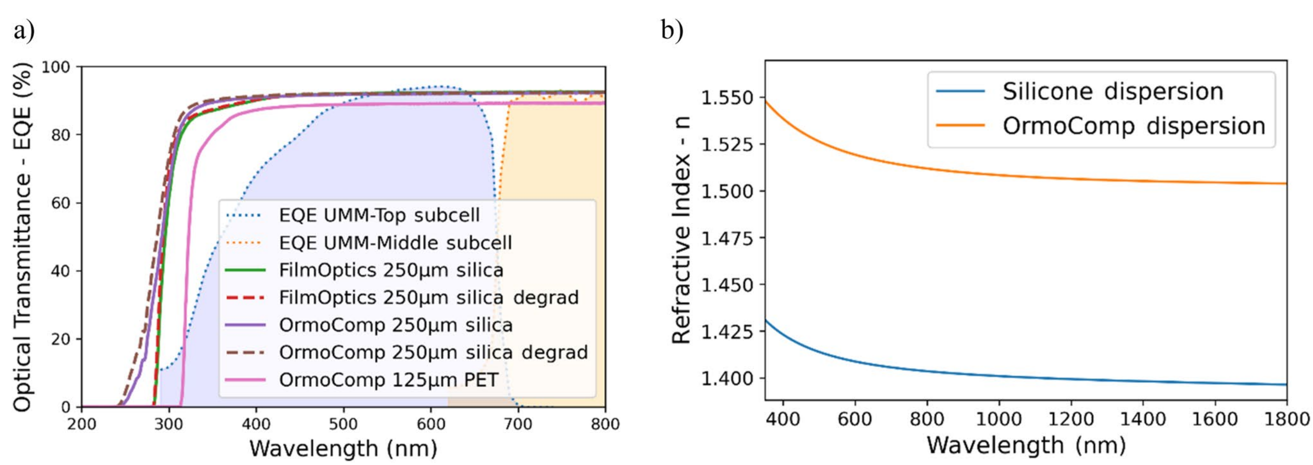



**Fig. 2** **a** Optical transmittance measurements of 100-µm thick OrmoComp and Film Optics sheets before and after ("degrad") outdoor UV degradation, both on 250-µm thick fused silica wafers. A measurement of OrmoComp resin on 125-µm thick PET is also included. The external quantum efficiency (EQE) of an upright metamorphic (UMM) solar cell is also plotted to show the importance of high UV transmittance of these materials. **b** Material dispersion curves of an optical silicone (PDMS) typically used for CPV lenses and the OrmoComp resin. Both curves show a similar dispersion, but with a different mean refractive index

is attained from the UV region through the visible to the near infrared (NIR) regions. Because the energy yield of multi-junction solar cells depends on UV light more significantly than that of Si cells, a high UV transmittance of the optics is desired.

Standard qualification test sequences for CPV modules are defined in the IEC 62108 norm, but cover qualification and type approval of the entire module design prior to commercialization. In our case, we only aimed at a preliminary validation of the sandwich of materials in terms of robustness against the most typical stresses experienced by CPV optics in real operation: UV dose and large temperature changes. Flat samples of the photoresins were mounted on a two-axis tracker and an outdoor exposure test was performed during 60 days of autumn in Madrid, which cumulated a dose of direct normal irradiation higher than 100 $kWh/m^2$ for times where the direct normal irradiance exceeded 600 $W/m^2$ to guarantee a sufficiently high dose of UV. No evidence of visual defects, yellowing, or change in spectral transmittance was detected (Fig. 2a, noted in the legend as "degrad"). Longer-term exposure tests that meet a dose closer to the 500 $kWh/m^2$ recommended by IEC 62108 would be carried out once a functional module prototype is constructed. Furthermore, a thermal cycling test with a duration of 7 days was carried out for OrmoComp and FOL 1.2 resins on silica and flexible polyethylene terephthalate (PET) substrates. In each cycle, the samples were kept at a temperature of + 65 °C for 14 h and -20 °C for another 6 h, without humidity control. After the cycling, the resins on fused silica showed no delamination, but one sample on a flexible substrate was warped. This is not considered a failure because rigid substrates are always required in the real module design. These stress tests demonstrated the technical feasibility of the candidate materials in terms of robustness for solar applications.

The dispersion of the photocurable materials employed in this work is very similar to that of optical polydimethylsiloxane (Wacker Elastosil Solar 3201 silicone) commonly used for silicone-on-glass Fresnel lenses in conventional CPV modules (Fig. 1b). The solar Abbe number $\nu_{\text{solar}}$ describes the dispersion of the material for solar applications: the higher the Abbe number, the lower the chromatic aberration and the higher the achievable effective concentration [17, 18]. For OrmoComp the $\nu_{\text{solar}}$ is 17.1, versus 18.3 for polydimethylsiloxane (PDMS).

In addition to lower (better) dispersion, another important material property for CPV is the thermal sensitivity of the refractive index dn/dT, which gives an indication of the optical losses that may be encountered outdoors because of the daily and yearly variations of operating conditions. For OrmoComp, $dn/dT = -2.0\ 10^{-4}\ K^{-1}$, which is lower than that of PDMS ($dn/dT = -3.6\ 10^{-4}\ K^{-1}$) and leads to lower optical efficiency losses for large temperature ranges. This parameter was not provided by the manufacturer for the Film Optics resin.

## 3 Fresnel lens design optimized for UV imprinting

### 3.1 Lens array design

The design consists of an array of hexagonal Fresnel lenses with facet heights of 50 µm, curved facets, a draft angle of 5°, and a circumscribing diameter of 16.6 mm. The lenses are designed to be used with solar cells with an active area of 1 $mm^2$. The area of each single lens is 178 $mm^2$ resulting in a geometric concentration ratio of 178X. The height of 50 µm was defined as a compromise between ease and fidelity of replication with UV imprinting and low optical losses due to the Fresnel facet drafts. A low facet height facilitates resin filling during imprinting and demolding of the cross-linked structures. However, a low height also increases the number of Fresnel facets needed and hence the optical losses due to the unavoidable tip rounding and to the increase of inactive areas of positive draft angle. The height of the facet is also limited by the viscosity of the resin, which for the resins selected in this work should exceed 100 µm. The draft angle was designed to be 5° to ease the machining of the master mold, as well as to ease the demolding of the lens facets out of the soft mold after the UV imprinting process.

The optical efficiency is the ratio between the radiant flux impinging on the receiver cell and that available on the lens aperture. As such, it is a figure of merit of the transmission of the lens at a given geometric concentration (ratio between the lens and receiver areas). The main sources of losses are Fresnel reflection at material interfaces, bulk absorption, and geometric losses; the latter are mainly caused by the draft angle and tip rounding of the Fresnel facets. In contrast, the effective concentration is the ratio between the lens aperture and the area of the light spot cast by the lens when exposed to reference direct normal irradiance (AM1.5D spectrum as defined in IEC 60904–3 and the same angular extent as the solar disc). The spot area is defined as the circle that contains 99% of the energy transmitted by the lens in the vicinity of the receiver. Therefore, this figure of merit defines how far we can reduce the size of the solar cell (*i.e.*, increase the geometric concentration) without significant light spillage (*i.e.*, maintain the optical efficiency). In this case, the main limitations are chromatic aberration, the angular size of the Sun, and all surface defects that may affect the optical path of light (roughness, waviness, and the difference between the design and the real achieved lens profile).

The Fresnel lens design was realized on the basis of a refractive index ($n$) of 1.52 corresponding to that of the OrmoComp resin. The second resin used in this work from Film Optics has a slightly different refractive index ($n = 1.49$). Nevertheless, optical simulations carried out prove that this difference does not cause significant optical losses, as shown in the next section.

### 3.2 Performance modeling via ray tracing

The parameters of the light source for the simulation are the solar reference spectrum for direct light AM1.5D (IEC 60904–3) and the Sun's angular radius of 0.267°. Furthermore, an ideal receiver capable of absorbing all the light rays incident on it has been considered. The optical efficiency is estimated using a 1 $mm^2$ receiver to emulate the design case with 178X geometric concentration. To calculate the effective concentration ratio, the software defines a mesh of bins that captures the spatial distribution of the irradiance in the receiver. The diameter of the circle that contains 99% of the transmitted power defines the receiver size.

Optical ray-tracing simulations of an ideal design (with zero draft angle and no tip rounding) showed an optical efficiency of 91.9% at the intended concentration of 178X. This efficiency value includes realistic losses due to Fresnel reflection at material interfaces, bulk absorption, wavelength-dependent transmittance, and refractive-index dispersion. The results of the simulations for a concentration of 178X using a 250-μm-thick silica wafer as the lens substrate are shown in Table 1. The efficiency loss due to the use of the Film Optics material with a slightly different refractive index is only 0.5%. When the 5° draft angle and the 3-μm tip/valley rounding are added to the simulation, the optical efficiency is reduced to 88.6%: a loss of 1.9 percentage points (pp) due to the draft angle and a loss of 1.4 pp due to rounding. Regardless of the lens material and the rigid support considered, the main source of optical loss would be the Fresnel reflection at the outer optical interface. This reflection can be greatly reduced by adding AR coatings [6].

To conclude, the effective concentration ratio is equal to 466.6X for the OrmoComp lens and 428.5X for the Film Optics lens. Note that this difference is explained because the design of the lens was optimized for OrmoComp resin.

## 4 Precision mold development for non-rotationally symmetric Fresnel lens arrays

Manufacturing precision optical molds for Fresnel lenses typically involve single-point diamond turning (SPDT). However, it is not possible to directly turn a radial Fresnel lens array because grooves are not rotationally symmetric, unless a wasted area is allowed between lenses (filling factor below 1). This is not an option in CPV because it directly impacts the power conversion efficiency of the module. The pioneering work on R2R-based UV imprinting of linear Fresnel lenses took advantage of the linear symmetry to directly machine a brass roller mold using a 5-axis ultra-precision machining system [8], but the radial Fresnel lenses were circular and spaced far apart from each other, so the optical array had a large wasted area [9]. A most recent approach uses the same system to manufacture an array of 7 hexagonal Fresnel lenses without waste area. These lenses are not radial, but consist of six linear Fresnel parts that together form a hexagonal lens [19].

In our work, a mold for a 6 × 4 array of hexagonal Fresnel lenses with no wasted areas (filling factor equal to 1) was manufactured with a novel method. Each Fresnel lens structure was cut via SPDT on a different hexagonal brass prism (see Fig. 3b). These bolts were previously shaped via electro-discharge machining (EDM). Subsequently, these bolts were assembled into the full array composed of 24 lenses held together by a rigid metallic bed (see Fig. 3b). Unfortunately, our EDM supplier did not achieve the required tolerance when cutting hexagonal shapes, which resulted in gaps of around 100–150 μm (see Fig. 3c). These gaps do not significantly influence the performance of single lenses, but can cause misalignments between lenses that complicate the manufacturing of a micro-CPV array [20]. The resulting lens pitch error is presented in the next section. To prevent this type of shape inaccuracies, it is suggested to use ultra-precision milling instead of EDM. However, these errors were considered

**Table 1** Ray-tracing simulation optical efficiency results for a concentration of 178X with both photoresins

| Resin and substrate | Modeled optical efficiency @178X (%) | Modeled effective concentration (X) |
|---|---|---|
| *Film Optics, 5° draft, silica 250 μm* | 90.0 | 428.5 |
| *OrmoComp, 5° draft, silica 250 μm* | 89.7 | 466.6 |
| *Film Optics, 5° draft, 3 μm rounding, silica 250 μm* | 88.6 | 428.5 |

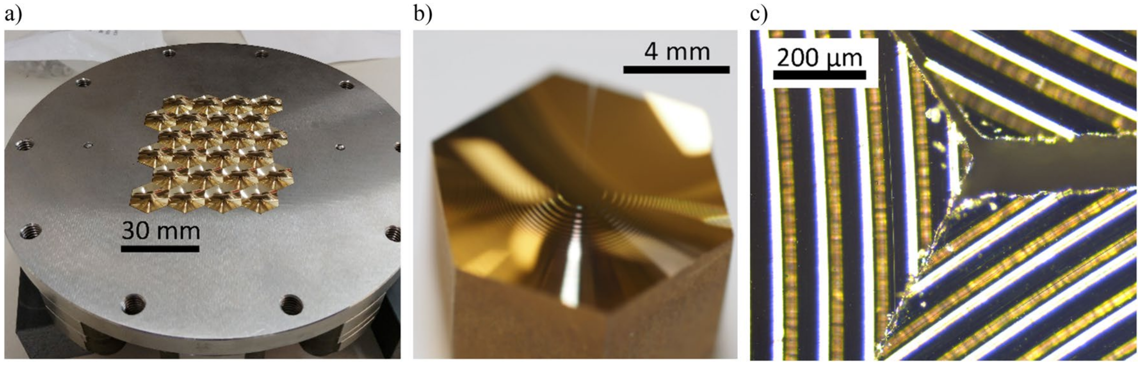



**Fig. 3** Photo of the metallic master with inserts (**a**) and photo of a single insert (**b**). **c** Microscopy image of a gap between the inserts

acceptable, and the process was continued by producing soft PDMS molds from this master.

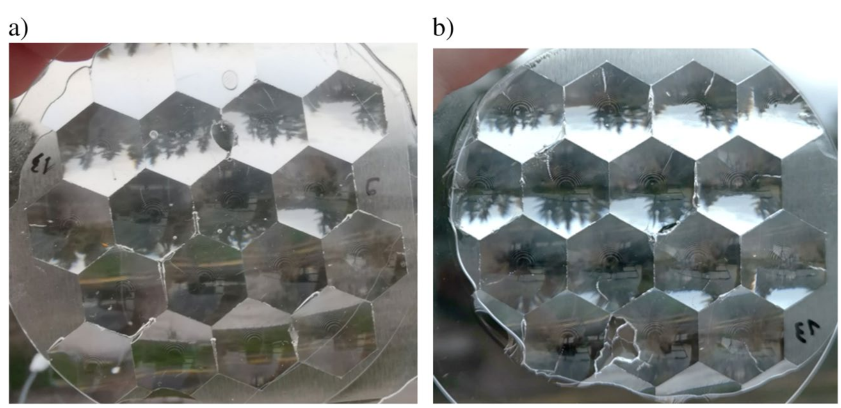
In order to produce the working mold for imprinting the lenses (process described in Section 2.1), the metallic master shown in Fig. 3a was copied twice: first to obtain a positive intermediate template and subsequently to obtain the negative relief of the soft working molds. Therefore, the brass inserts were also cut with negative relief. The process is explained in detail in [10].

Replication processes inevitably introduce a certain loss of quality, especially with respect to surface roughness and tip rounding on the lens facets. However, soft molds allow demolding by peeling action using an effective lower detachment force, which in turn reduces the risk of damage by fracture of the imprinted structures. During UV imprinting, an issue to take into account is the thermal heating caused by the high-intensity UV lamp and the associated thermal expansion of the mold. This problem was mitigated by optimizing the exposure time and the distance at which the mold-substrate assembly was exposed to the UV light source. However, the expansion of the mold during the UV irradiation is deemed compensated for by the volume shrinkage of the material during curing, which is in the range of 5–7% depending on the material (lower for Film Optics, higher for OrmoComp). We note that the thermal expansion of the mold and the shrinkage of the resin were not considered or compensated for during the design phase of the lens facets geometry, which leaves room for improvement of the results presented below.

## 5 Results and discussion

The presentation of the results is divided in two parts: metrology and functional characterization through optical efficiency measurements. The same two optical configurations modeled via ray tracing were now experimentally characterized. Images of the Fresnel lenses imprinted using the two photocurable resins on 250-µm-thick fused silica substrates can be seen in Fig. 4a, b. Some visual defects, such as trapped air bubbles, are visible at the edges of the hexagonal lens arrangement. This points to some further optimization of the process parameters needed with regard to effective degassing and air bubble elimination from the photoresin. Nevertheless, sufficient

**Fig. 4** Photos of the Fresnel lens arrays manufactured with Film Optics (**a**) and OrmoComp (**b**) photoresins supported on fused silica wafers



quality lenses were obtained with each replication of the array to allow a performance comparison between both configurations.

## 5.1 Metrology of final lenses

Metrology measurements were performed using a Leica DCM 3D multislit confocal scanning microscope. The tip rounding of the final lenses was between 3 and 5 µm and the surface roughness ($R_a$) was between 5 and 8 nm. These figures are close to the original figures measured for the master inserts: $R_a$ between 3.4 and 5 nm (measurements provided by the manufacturer) and tip rounding of 3 µm (measured on PDMS copies using the confocal microscope). A summary of the measurements is given in Table 2. The results show that the tip rounding does not increase significantly compared to the master, meaning that UV imprinting can generate Fresnel structures with high fidelity. The $R_a$ increases slightly but still provides enough quality for optical applications (< 10 nm). The increase is due in part to the extra intermediate steps required to manufacture the soft working mold.

It is expected that the shrinkage of the UV resin upon curing also introduces form errors. The shrinkage grows with the thickness of the facet, with a maximum shrinkage of 3% at the tip. The comparisons shown in Fig. 5a, b have been used to determine the root mean square error (RMSE) of the form of each UV-imprinted lens profile with respect to the mold design. In both cases, a notable increase in RMSE is observed from the inner (center) to the outer facets of the lenses. Near the lens center (wider facets, lower slope angle), the theoretical design is reproduced with a lower form error keeping a groove height, curvature, and draft angle reasonably similar to the mold design. Form RMSE for the first 3 inner facets is 2.6 µm and 3.3 µm in average, for the samples made with OrmoComp and Film Optics resins, respectively (or 5.3% and 6.6% with respect to the facet height). However, near the edges, the replication process smoothens the facets at the sharp peaks and valleys due to the high viscosity (2–2.5 Pa·s at 24 °C) of the photoresins, significantly increasing form errors and surface roughness (OrmoComp RMSE = 12.3 µm, Film Optics RMSE = 10.2 µm). Improving this effect will probably require further process optimization, including resin formulations with a lower viscosity.

**Table 2** Metrology of master inserts and UV imprinted lenses: surface roughness $R_a$, tip rounding, and draft angle

| Sample | Best Fresnel facet | | Draft angle |
|---|---|---|---|
| | $R_a$ (nm) | Tip rounding (µm) | |
| *Master inserts* | 3.4–5 | 3 | 5° |
| *OrmoComp on silica* | 8.00 | 3 | 4° |
| *Film Optics on silica* | 5.00 | 3 | 2.5° |

Shrinkage affects not only the profile of the lenses but also the pitch between lenses throughout the array. The XY micro-positioning stage of the confocal microscope was used to visually identify center positions in both types of arrays. A lens pitch error of 66 µm and 121 µm has been measured for OrmoComp and Film Optics resins, respectively (in the range of 1% of the lens diameter). This error would cumulate throughout the array and introduce non-negligible optical losses when concentrating light on a matrix of 1-mm$^2$ solar cells at the design concentration of 178X (cell width of 1 mm), because the optical axes will become slightly misaligned. This shrinkage, typical in optical molding, is usually compensated for by originating a slightly larger mold.

In contrast to the sources of loss described, shrinkage also has the side benefit of reducing the effective draft angle

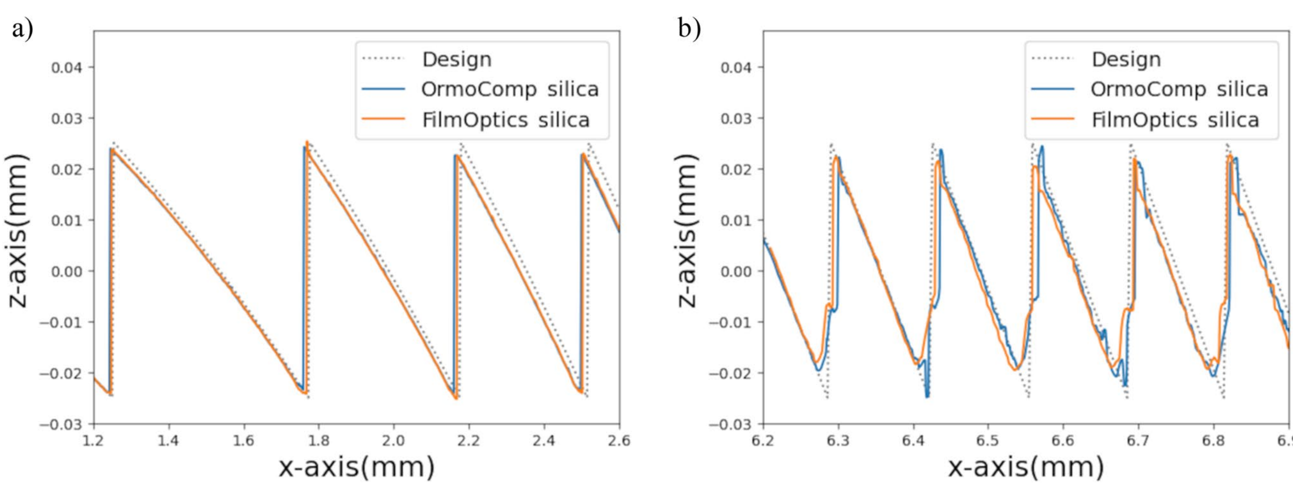



**Fig. 5** Comparison of the surface profile of the UV-imprinted lenses and the theoretical design for the central (**a**) and external (**b**) parts

from the design value of 5° to 4° and 2.5° for OrmoComp and Film Optics resins, respectively. As a result, the optical loss caused by inactive areas at the interfaces between facets is reduced.

### 5.2 Optical efficiency

The optical efficiency under white light with the angular and spectral properties of sunlight is the ultimate figure of merit of concentrator optics. The experimental results shown in this section have been measured using the Solar Added Value CPV flash solar simulator Helios 3198, which generates a collimated light beam with the solar reference spectrum for direct light AM1.5D [21]. A more detailed description of the setup can be found elsewhere [22, 23].

Since micro-CPV solar cells are very small (≤ 1 $mm^2$), a very accurate alignment is carried out iteratively repeating multiple micrometric scans in 3 orthogonal axes, using an automated three-axis positioning platform. A rotating stage is added for angular alignment. A Matlab code controls the setup, and the measurements are automated for both single lenses and arrays. The characterization process for micro-CPV lenses is described in more detail in [24]. In Fig. 6 the results of a focal distance scan are plotted for the OrmoComp and Film Optics lenses on fused silica. This focal distance scan provides a measurement of the mechanical tolerance of this optical architecture.

Optical efficiency measurements involve a systematic sequence. First, each lens in the array is measured under a low concentration factor of 6X (that is, using a solar cell with an area of 30 $mm^2$). With such a large solar cell, the measurement result is very similar to the direct optical transmittance of the lens. Lenses with the best results are selected

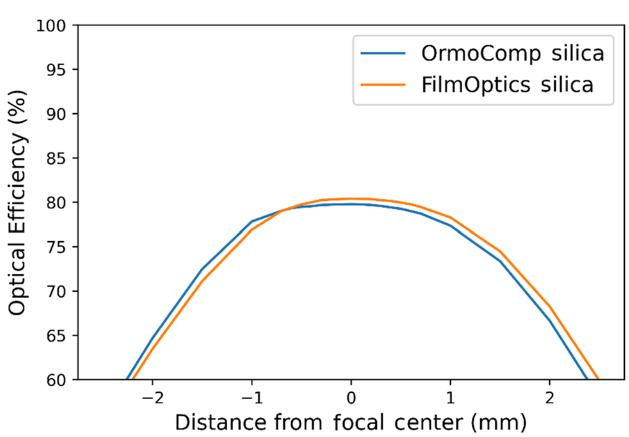



**Fig. 6** Results of the optical efficiency focal scan for UV-imprinted lenses on silica. Both materials perform equally well on the silica substrate, with optical efficiencies of around 80% at the intended geometric concentration of 178X

and measured under the design geometric concentration of 178X with a 1 $mm^2$ solar cell. As measurements are very time-consuming because of the required preliminary alignment, only the best lenses from each array were selected. For all the measurements, we used the same type of solar cells: upright metamorphic (UMM) triple junction solar cells with a Germanium substrate.

### 5.3 Discussion

Table 3 summarizes the results of the optical efficiency. These are the highest efficiency results for UV-imprinted Fresnel lenses for concentration to date [9]. Efficiency values approaching 80% are close to the industrial standard of silicone-on-glass Fresnel lenses, which reach typical values of 84–88% [6]. Furthermore, the performance is quite stable across hundreds of microns of focal distance variation at 178X, as shown in Fig. 6. This provides a budget for mechanical tolerance in the manufacturing of practical CPV modules. Both resins perform equally well, as expected from the simulation results. The difference in optical efficiency is in the range of the measurement error of ± 1% in optical efficiency [[25], p. 61]. In a continuation work [10] in which a scalable R2R UV imprinting was used to manufacture the same Fresnel lenses, the optical efficiency reached 68.7% (see Table 3). This is more than 10 pp lower than the values achieved using P2P. We point out the reasons below.

The target optical efficiencies presented in Table 1 show that there is room for improvement for UV-imprinted lenses. Several approaches can be followed to reduce the defects and optical losses. Firstly, with regard to the imprinting process, the air bubbles trapped between the mold and the liquid photocurable resin can be reduced. They originate when the air in the mold cavities is not efficiently evacuated through the liquid resin or soft mold during the imprint process. The effect has been observed in both the P2P and the R2R processes. This issue can be improved by fine-tuning the viscosity, temperature, and dwell time of the imprinting process to favor air release.

Another source of defects, as mentioned above, is the additional replication steps performed to manufacture the working molds that contributed to the increase

**Table 3** Optical characterization results of the best lenses manufactured on silica and PMMA substrates

| Lens array | Optical efficiency at 178X (%) |
|---|---|
| *OrmoComp on silica (P2P)* | 79.8 |
| *Film Optics on silica (P2P)* | 80.4 |
| *Film Optics on PET (R2R) from* [10] | 68.7 |

in roughness. In these aspects, the difference between the P2P and R2R UV imprinted lenses is noteworthy. The lenses produced by P2P showed an $R_a$ of 5–8 nm (see Table 2), whereas those produced by R2R showed a roughness within the range of 35–50 nm [10]. These high values of roughness cause scattering off the optical surfaces and consequently lower the optical efficiency. The R2R process also generated a larger tip rounding in the Fresnel facets than the P2P process, 7 μm [10] vs 3 μm (see Table 2). However, the impact on efficiency loss of this tip rounding is lower than that of the modest quality of surface roughness.

In addition, the mold design did not consider any compensation to counteract the volume shrinkage of the resins upon curing. After shrinkage, the replicated facets deviate from the ideal shape and produce a shift in the focal distance. The shift is not the same for every facet, so the concentrated light spot becomes blurred and the effective concentration ratio is reduced. In other words, the optical efficiency is reduced for a receiver with a geometric concentration ratio of 178X.

Regarding the impact of the substrate on the results, note that a realistic substrate for solar applications, such as 4-mm thick float glass, will slightly reduce the optical efficiency as a result of the higher volume of light absorption. Ray-tracing simulations show that the loss would be in the range of 0.5 pp. However, AR coatings can significantly increase optical efficiency by reducing Fresnel reflection losses at the outer air-substrate interface from 4 to 1%.

The improvement and optimization of the imprinting process to reduce the defects mentioned could bring optical performance on par with other technologies such as PMMA injection molding and silicon on glass (SoG) lenses [6, 26]. Upscaling their fabrication through continuous R2R or R2P manufacturing processes would enable low-cost fabrication of micro-CPV lens arrays, which would pave the way for micro-CPV to become a source of cheap and very low-carbon solar electricity [9].

## 6 Conclusions

A comprehensive process flow has been presented and demonstrated for the development of high-performance Fresnel lens arrays for micro-CPV applications using a scalable UV imprinting process. The methodology starts with the design of a non-rotationally symmetric Fresnel lens insert (negative shape) tailored to UV imprinting process constraints. Multiple inserts are fabricated using EDM and SPDT and then recombined to form a single array master mold without wasted areas, which is subsequently copied using soft lithography into a PDMS intermediate template and then a PFPE working mold. This working mold is then used to imprint the lens array on a fused silica substrate using UV-curable resins. The process was demonstrated for a Fresnel lens array with 50-μm aspheric facets designed to work at a geometric concentration of 178X on 1 $mm^2$ solar cells with a target optical efficiency of 88.6% according to ray-tracing simulations. Two different photoresins were tested. The metrology of the UV-imprinted lenses revealed a tip rounding in the range of 3–5 μm and a surface roughness between 5 and 8 nm, indicating excellent replication capabilities. However, form errors increase near the lens edges, probably because of the high viscosity of the photoresins, showing room for process improvement. The optical efficiency of the lenses under white light reached 80% for both resins, demonstrating CPV industry-standard performance. The best lens achieved 80.4% at 178X, which is to our knowledge the highest effective concentration achieved using UV-imprinted Fresnel lenses. It is expected that further process optimization could bring the optical efficiency closer to the theoretical target value: reducing trapped air, better adapting facet height to resin viscosity, compensating mold design for shrinkage after curing, and reducing gaps between inserts (via improvements of EDM shape accuracy or switching to ultraprecision milling). The robustness and compatibility of the materials were preliminarily tested by outdoor exposure (UV aging) and thermal cycling, which showed no significant degradation in terms of spectral transmittance or visual inspection. Thus, despite the identified defects and areas for improvement, the presented methodology using P2P UV imprinting demonstrates the potential to match the performance achieved by established technologies such as silicone-on-glass or PMMA lenses. It also serves as groundwork for the development of continuous, high-throughput manufacturing processes for micro-lens arrays, such as R2R or R2P UV imprinting, which are enabling technologies for the cost reduction of high-performance micro-CPV technology.

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## Declarations

**Competing interests** The authors declare no competing interests.



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