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Volume Holographic Optical Elements as Solar Concentrators

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Abstract

In this chapter, we investigate the possibility to realize a holographic solar concentrator by using a new photopolymeric material as recording medium. Therefore, two different configurations of holographic lenses (lenses with spherical and cylindrical symmetry) are described in terms of both recording process and optical response characterization. Finally, we propose the possibility to use this new photopolymer to realize holographic solar concentrator for space applications.

Keywords: holographic solar concentrator, holographic lens, volume-phase holographic optical elements

1. Introduction

Photovoltaic (PV) electrical energy generation is one of the most sustainable solar energy conversion processes, but its main drawback is the cost. With the current technology, the highest efficiency (37%) is from photovoltaic (PV) cells with triple-junction InGaAs; however, their high cost makes them unattractive. Nevertheless, it is possible to solve this problem by replacing a significant amount of expensive PV material with an optical concentrator. Consequently, in the last 15 years in many fields of application, from the aerospace industry to the domestic applications, people tried to use solar concentration technologies to direct all the exploitable light towards the solar cells. Indeed, solar concentrators, which focus the sun's rays onto the active solar cell area, enable to use solar power also when solar intensity is very weak allowing,

at the same time, smaller active areas of solar cells, reducing the size of the expensive portion of the solar power system [1]. However, so far concentrator systems have low spread in the market due to their high prices mostly induced by (i) complex designs—the small acceptance angle of standard CPVs (e.g. lenses or mirrors) forces to use active solar tracker and (ii) thermal management: the solar cell is excessively heated when illuminated with concentrated solar radiation, and an active or passive cooling system must be taken into account. Holographic optical elements (HOEs) could in part overcome the aforementioned limitations. Holographic PV concentrators were proposed for the first time in the 1980s [2–5]; indeed, holography as an optical technology is much more versatile and cheaper with respect to other concentrating optical systems (lenses or mirrors, for instance). It can also eliminate the need for solar tracking, thus allowing uniform levels of illumination during the course of a day or during different seasons without any moveable parts and so reducing the whole-system complexity [6].

Among holographic concentrators, volume holographic optical elements (V-HOEs) have been proposed for use as solar concentrators [2]. Compared with conventional refractive and reflective optics, V-HOEs can be thinner and more lightweight and have the potential for being very inexpensive in mass production. Moreover, the ability of light manipulation, shown by these diffractive devices, allows replacing standard concentrators with planar optical concentrators for high efficiency and low-cost photovoltaic modules [7]. HOEs have long been suggested for use (i) in a variety of solar collection applications [2–4, 6, 8–10], (ii) in spectral splitting applications to increase the conversion efficiency of PV cells [2, 8, 9] and (iii) in simultaneous concentration and spectral splitting applications [4]. Nevertheless, nowadays, there are only few commercial holographic concentrators, patented by Prism Solar Technologies [11], which work by total internal reflection by means of multiplexed gratings [12]. It has low cost (around 1 $/W), and it is easy to be integrated into buildings, leading to a cost-effective solar building-integrated concentrating system [13].

The simplest V-HOE is a volume holographic grating (VHG), which consists in a photo-induced modulation of the refractive index in a photosensitive thick film and acts as non-focusing element; therefore, it simply redirects the light. VHGs are recorded by interference between two collimated light beams and are different from other diffraction gratings based on surface or amplitude modulation [14]. In particular, the most important advantages offered by VHG are:

- The peak efficiency can be theoretically 100% [15]. In practice, diffraction efficiency of the order of 90% can be easily reached.

- Transmission or reflection gratings can be recorded.

- They require a very rapid and low-cost effective manufacturing.

- The recorded device is easily customizable, and element with multiple optical response can be fabricated (multiplexing).

Additionally, their response can be customized in order to obtain not only grating but also lenses or other optical elements. Indeed, if during the recording process the wavefront of one collimated beam is replaced with a converging one, an interferometric pattern that replaces

the response of the focusing optical systems can be generated, obtaining V-HOEs that act as focusing elements. These optical elements produce a converging wavefront, having the same effect as spherical or cylindrical lenses [16]. Furthermore, lenses can be recorded in off-axis configuration, allowing deflection and focusing of the light at the same time. These considerations led to the idea to use holographic gratings and lenses as light deflectors and concentrators. In the absence of holographic deflector devices, the useful conversion area of the sunlight into electrical energy is only the area occupied by the PV cell, as shown in **Figure 1(a)**.
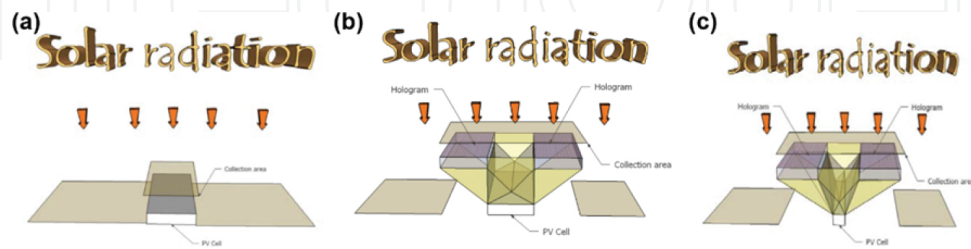
Figure 1. (a) PV module without deflector devices, (b) PV module in the presence of deflector devices and (c) PV module with deflection and concentration of the sunlight.

If a VHG is used as a device to redirect the light, and therefore as a deflector, it is possible to use a configuration like that shown in **Figure 1(b)**. In this arrangement, the incident light on two VHGs is deflected on the same PV cell. Therefore, the collecting surface of the single cell is increased (in this case is tripled), while keeping the constant area occupied by the PV material. To realize a high-efficient holographic solar concentrator, a V-HOE has to be capable not only to deflect the light of the sun but also to concentrate it; in this way the area used by a PV cell can be further reduced, as shown in **Figure 1(c)**.

However, V-HOEs have two characteristics that can affect their performance as solar concentrator: angular selectivity and chromatic selectivity. Due to the angular selectivity, volume holograms have high efficiency only when the incidence direction varies in the plane formed by the two recording beams, and this can be considered as a limitation. Additionally, the efficiency of the volume hologram is related to the wavelength: it is high for a bandwidth centred at a wavelength determined by both the refractive index modulation obtained in the recording material and the angle of incidence. V-HOEs have to be designed in order to present a high efficiency for the spectrum of the sunlight inside the PV conversion range. For multi-junction PV cells, the useful solar spectrum ranges from 350 to 1750 nm [17]. This requirement allows minimizing the amount of solar radiation beyond the conversion range (>1700 nm) that reaches the solar cell. Thus, one of the main problems of concentration refractive systems, namely, the heating of the cell, can be managed. Lower cell temperature results in a higher conversion efficiency and thus lower cost/watt [13, 18].

Regarding the aerospace applications, the solar power conversion is vital to the survival of the satellite, and loss of power, even temporarily, can have catastrophic consequences. With the succession of missions that use the technology of solar concentration, since the Galaxy 11 mission launched in 1999 that made use of mirrors, until contemporary missions, researchers tried to reduce the area, weight and footprint occupied by photovoltaic cells. Note that cost is

a factor usually addressed by means of the mass (weight) of the system [16]. Additionally, among design parameters, some crucial points related to hostile space environment have to be taken into account. For example, it is important to consider the extreme temperature changes at which the concentrators are subject. However, in this field, only few works are reported in literature; therefore, our results could open the way to a new line of research [19, 20].

With this aim, in this chapter, we explore the opportunity to record a holographic solar concentrator by using a photopolymeric material as recording medium. In particular, two different configurations of holographic lenses, namely, a spherical lens and a cylindrical lens, are investigated in terms of both recording process and optical response characterization. As a final point, we suggest the possibility to use this photopolymer to realize holographic solar concentrator for space applications.

2. Theoretical background

A generic V-HOE-based solar concentrator system generates electrical power by using a V-HOE to concentrate a large area of sunlight onto a small PV cell. The efficiency of the whole system can be evaluated as

$$\eta_T = \frac{\iint S(\lambda, \zeta)\eta(\lambda, \zeta)\eta_{PV}(\lambda, \zeta)d\lambda d}{\iint S(\lambda, \zeta)d\lambda d} \tag{1}$$

where S is the solar spectrum (air mass (AM) coefficient, followed by a number, is commonly used to characterize the performance of solar cells. Generally, AM1.5 for earth, AM0 for space), η is the V-HOE diffraction efficiency and η_{PV} is the efficiency of the photovoltaic cells. All the terms are function of the wavelength (λ) and the sun illumination (ζ). The latter is function of the daily and seasonal sun trajectory and of the tilted angle between the V-HOE and PV cell. Thus, in order to evaluate, the performance of the whole system is instrumental to maximize the diffraction efficiency of the V-HOE. Since each point of a V-HOE can be locally seen as a plane holographic grating, the theoretical approach to evaluate the diffraction efficiency of a VHG has been examined.

Figure 2 illustrates the model of a transmission VHG, where a refractive index spatial sinusoidal modulation (Δn) with period Λ is recorded inside a material with a thickness d. The grating is slanted with an angle of φ. θ_i is the incident angle, and θ_d is the diffracted angle considered inside the holographic material. The use of Kogelnik's theory [15] is widely accepted for analytically modelling the behaviour of volume photopolymer holograms. This theory allows relating some volume gratings' physical characteristics, such as thickness, spatial frequency/fringe spacing and depth of refractive index modulation, to their diffraction efficiency and angular/chromatic selectivity.
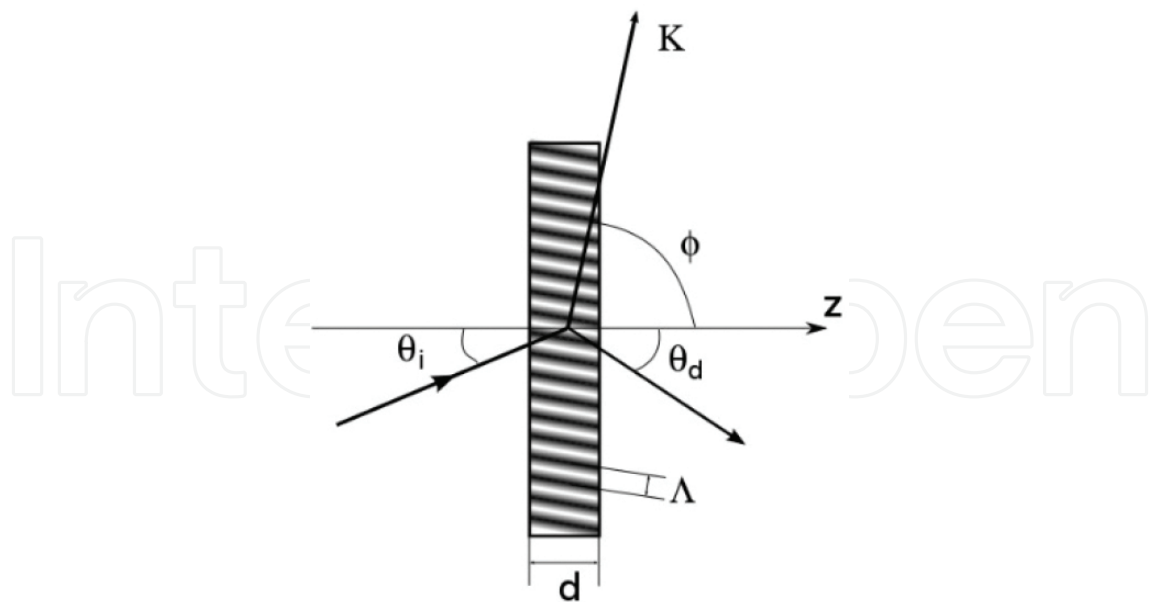
Figure 2. Model of a transmission VHG.

According to Kogelnik's theory, the diffraction efficiency (η) for a lossless material can be theoretically evaluated as

$$\eta = \left(\frac{\pi d \Delta n}{\lambda \chi} \right)^2 sinc^2 \sqrt{\left(\frac{\pi d \Delta n}{\lambda \chi} \right)^2 + \left(\frac{d \cos \theta_i}{2 \chi^2} \right)^2} \tag{2}$$

where the parameters ϑ and χ are defined as

$$\vartheta = K \cos(\phi - \theta_i) - \frac{K^2}{4\pi n} \lambda \tag{3}$$

$$\chi = \sqrt{\cos\theta_i \left(\cos\theta_i - \frac{K}{\beta} \cos\phi \right)} \tag{4}$$

where $K = 2\pi/\Lambda$ is the length of the grating vector normal to the fringes (see **Figure 2**), while n is the average refractive index of the holographic medium (after the recording process) and $\beta = 2\pi n/\lambda$ is the average propagation constant. Eq. (2) allows designing gratings with high diffraction efficiency that operate over large angular and wavelength bandwidth ranges. In particular, when the Bragg condition is satisfied, i.e. $2\beta\cos(\Phi - \theta_B) = K$ (where $\theta_i = \theta_B$ is the Bragg angle), the parameter $\vartheta = 0$ and $\chi = \sqrt{-cos\theta_B \cos(\theta_B - 2\phi)}$. Thus, the diffraction efficiency η can be theoretically evaluated as

$$\eta = sin^2 \left(\frac{\pi\, d\, \Delta n}{\lambda\, \chi} \right) \tag{5}$$

As expected, the angle at which the diffraction intensity is maximum is strictly related to the incident wavelength [14]. While regarding the angular selectivity, hologram diffraction efficiency drops very quickly when the direction of the incident radiation does not fulfil the Bragg condition in the recording plane formed by the two recording beams [13].

For solar applications, a high efficiency is required for the whole useful solar spectrum (350–1750 nm) and for each position of the sun. Eq. (2) can be used to easily quantify how much the Bragg condition is violated either in terms of wavelength or in terms of incident angle (detuning analysis). This analysis is fundamental to design the VHG in terms of d and Δn. In particular, the detuning range can be extended minimizing the recording material thickness in combination with the maximum refractive index modulation Δn available.

It is useful to evaluate the so-called Q factor, defined as

$$Q \;=\; \frac{2\,\pi\lambda d}{n\,\Lambda^2} \tag{6}$$

This parameter allows to estimate if the recorded hologram is a volume and not a surface hologram. Indeed, a holographic grating is considered to be thin (surface hologram) when $Q \leq 1$, thick (volume hologram) when $Q \geq 10$ [21]. However, angular and chromatic selectivity increases when parameter Q increases; thereby, for solar application it is better to adopt a Q value close to the limit of 10. For a VHG, the behaviour is the same in all the points of the hologram. If the solar concentrator is realized by means of a V-HOE, the efficiency and its angular and chromatic selectivity vary at each point of the hologram. However, a V-HOE can be locally seen as a plane holographic grating, so the aforementioned approach can be employed to sample point by point the behaviour of the V-HOE [12, 22]. Obviously, for each local grating, the requirement $Q \geq 10$ has to be satisfied.

It is important to point out that if a V-HOE is used as solar concentrator, in order to determine the image ray direction, the grating equation has to be considered differently from the conventional optics where Snell's law is used [23].

The approach of Kogelnik can be also used to evaluate the dependence of the diffraction efficiency on the polarization. In fact, since solar illumination is randomly polarized, it is necessary to divide the incident optical power into both states of polarization and averaging the respective diffraction in order to evaluate the global efficiency of the concentrator [15, 16]. Thus, Kogelnik's coupled wave theory is enough to analytically predict the effect of the first useful parameters, such as wavelength, incident angle, grating thickness, index modulation and polarization state. However, a rigorous solution of the coupled wave equations is necessary for a completely accurate description of diffraction in gratings [18, 24–26].

3. Recording materials

The use of holographic solar concentrators for space or terrestrial photovoltaic applications is a still limited field of research, although the idea has been known for a long time [2]. Among the known materials are the classic substrates based on silver halide emulsions, recently used to obtain a panchromatic holographic material for the fabrication of wavelength-multiplexed holographic solar concentrators [27] and dichromatic gelatines [28–30], which have shown the best performance in terms of diffraction efficiency and tuning of the refractive index. The most studied holographic materials since the 1970s are those based on polymerization and cross-linking reactions induced by absorption of light, the so-called photopolymers, thanks to the numerous advantages they offer compared with silver halide and dichromatic gelatines. They show high diffraction efficiencies, allow an advantageous real-time monitoring of the recording process, do not require complicated development processes, can be produced from raw materials at low cost and give the possibility to modulate the properties through chemical synthesis. In these materials the grating is registered at a molecular level, and this has a high impact on the resolution. Typically, a photopolymerizable material is composed by a photoinitiator system (photoinitiator or photosensitizer), one or more polyfunctional monomers or oligomers and a polymeric binder. The binder is used to give mechanical stability and must ensure compatibility between all components in order to obtain a homogeneous, transparent material with good optical quality. The formulation can include plasticisers, additives, stabilizers and compounds that increase the photosensitivity of the writing medium. In a system based on radical polymerization, the initiation takes place during the illumination and leads to the production of radicals, which react with the monomers to produce chain initiators. This reaction gives way to the subsequent steps of propagation and growth of the polymer chains. In a writing process, using interference of two laser beams, radical initiation occurs faster in areas of constructive interference, i.e. where the illumination is more intense. Consequently, the polymerization proceeds more rapidly in these regions leading to an increased consumption of the monomers, while the polymerization is limited or absent in the areas of destructive interference (low-light intensity areas). The difference of monomer consumption rate creates a concentration gradient that drives monomer diffusion from dark to illuminated areas [31]. This mass transport proceeds until the monomer is exhausted or no longer able to diffuse through the material, due to the increased viscosity. The polymer concentration distribution will follow the sinusoidal pattern of light intensity. If the refractive index of polymer and binder are different, the result is a permanent modulation of the refractive index, that is, a volume-phase hologram. The refractive index variation is also determined by the density variation of the polymer. At the end of the writing process, a further irradiation of the layer with incoherent light is typically performed, leading to bleaching of the remaining photoinitiator. The first holographic photopolymers were based on liquid mixtures containing acrylamide [32]. Later, polymeric binder such as polyvinyl alcohol or gelatin was used, and diffraction efficiency greater than 80% could be reached [33–35]. This approach was recently used to demonstrate the fabrication of holographic solar concentrators [36]. Also, Sam and Kumar [37] demonstrated the fabrication of holographic solar concentrator in HoloMer 6A photopolymer material with an

efficiency of 70% and an average efficiency of 56.6% for a wavelength range from 633 to 442 nm. The most common formulations include acrylic acid esters and amides, N-vinyl compounds and allyl esters. Holograms with efficiencies exceeding 95% and refractive index variation until 10^{-2} have been recorded using visible laser light [38, 39]. One of the best performing materials (DMP 128) was created by Polaroid Corporation and allows recording of reflection and transmission holograms with a spectral range from 442 to 647 nm. This material is a mixture of acrylic monomers such as acrylic acid and N,N′-methylenebisacrylamide in a matrix of poly-N-vinylpyrrolidone and showed 95% diffraction efficiency and a refractive index modulation of 0.03 in films with thickness up to 30 μm [40]. The radical polymerization has many advantages that it proceeds rapidly and the reaction is irreversible, which allows the realization of a single write. However, the main drawback is the high volumetric shrinkage of the material during polymerization. This shrinkage induces distortions of holograms by altering the characteristics of gratings. Several solutions have been adopted to solve this problem, such as the introduction of nanoparticles in the photopolymeric mixture [41]. An interesting solution is that of cationic ring-opening polymerization (CROP) systems, where the volume shrinkage following the polymerization is balanced by an effect of ring opening which produces instead a volume increase [42]. Aprilis HMD has recently commercialized a high-performance material of this type, characterized by two types of monomers that give rise to orthogonal, not interfering chemical reactions. The cationic polymerization is used to produce the cross-linked matrix, while the acrylic monomers polymerize during the hologram writing stage and diffuse according to the concentration gradient mechanism. A further interesting example is that of Reoxan [43], proposed in the late 1970s as a kind of alternative to the photopolymerizable materials because it contains no polymerizable monomers in the binder (usually polymethyl methacrylate (PMMA)) and a sensitizer of anthracene oxidation in place of a photoinitiator. The photosensitizer transfers the energy of the electronic excited state to oxygen which ends up in a singlet state and reacts with anthracene to form a peroxide. Since this transformation is accompanied by a strong change in the ultraviolet (UV) absorption spectrum, the refractive index of the material is reduced, to form a phase hologram. In the subsequent dark step, an increase of the refractive index modulation is observed due to the slow and uniform diffusion of the remaining anthracene molecules throughout the film and further irradiation and oxidation. These systems show excellent optical properties and high stability and can be obtained as films with thickness from a few microns to centimetres.

3.1. Holographic materials for solar concentrators

In view of possible applications of holographic elements as terrestrial and space solar concentrators, the holographic materials must be able to withstand harsh conditions such as high irradiation and temperatures. In the space they should also withstand much more drastic conditions, due to strong thermal excursions, high vacuum and the presence of high-energy gamma, electronic and protonic radiation originating from the solar wind. In particular high resistance to corrosion by atomic oxygen and a very low outgassing level are required to avoid contamination of the components, although the level of acceptance depends on the destination of use. Currently, no studies are known on the resistance of materials for holographic concen-

trators in these conditions, and their behaviour is therefore yet to be determined. However, there are durability tests on some of the most widely used materials in conventional Fresnel-type solar concentrators, such as elastomers based on silicone and acrylic polymers [44]. The latter represents a significant component of the photopolymer used for holography as a result of the process of photopolymerization of acrylic monomers typically dissolved in a matrix. Polymethyl methacrylate (PMMA) is widely used for the production of lenses for concentrators and protective layers for photovoltaic cells [45], as it guarantees an excellent resistance to UV radiation and a greater than 92% transmittance. The degradation of this type of material in response to UV irradiation mainly takes place with release of an ester radical and subsequent scission of the polymeric chain. Stabilization effects can be induced, for example, by the use of copolymers or through cross-linking of the material [46]. Alternatively, the ultraviolet sensitivity can be reduced by using protective layers or by adding radical scavengers or antioxidants to the formulation of the material. Silicones represent another important class of materials used for the fabrication of solar concentrators. They are characterized by a chemical structure that is less affected by radical photodegradation mechanisms triggered by UV light as in organic polymers. The most widely used polydimethylsiloxane (PDMS) is made of [Si-O]n-type polymeric chains with lateral methyl groups. Since the Si-O binding energy is much higher than that of the C–C bond, PDMS features an excellent stability against UV radiation and resulted very suitable for use in the extraterrestrial environment [47]. Furthermore, a great advantage of this material is the greater optical transmittance compared to PMMA and the tendency to cross-link after irradiation rather than degrade and produce volatile substances, as in the case of acrylic polymers. Starting from these evidences, a promising route towards solar compliant holographic materials is the synthesis of new photopolymers wherein part of the organic material would be replaced with inorganics or hybrid organic/inorganic components, which are less sensitive to thermal and photochemical degradation phenomena. One interesting category from this point of view is that of nanoparticle-polymer composites, that is, photopolymers containing nanoparticles of inorganic species such as SiO_2, ZrO_2 and TiO_2 [48]. The introduction of such nanoparticles was adopted to reduce the shrinkage caused by the polymerization but also helped to obtain higher refractive index modulation [49, 50]. This increase is due not only to the diffusion process of acrylic monomers during the writing process but also to the consequent counterdiffusion of nanoparticles which redistribute in the dark regions of the illumination pattern. Tomita et al. [51] showed that embedding nanoparticles of SiO_2 and ZrO_2 in photopolymers lead to an effective suppression of thermally induced refractive index and dimensional changes. Similar formulations containing zeolite nanocrystals as inorganic dopant are also reported with the aim to improve compatibility between inorganic particles and polymer and reduce the optical losses due to scattering [52]. Dramatic improvement of photostability can be induced on hybrid organic/inorganic materials by the use of similar inorganic porous components, as demonstrated by the case of Maya Blue pigment. This material is made of the organic blue indigo captured within the layers of a phyllosilicate. It remained unchanged for more than 12 centuries and was proved to resist against organic solvents, acids and alkalis [53]. Materials with a high level of interpenetration between the organic and inorganic networks, and no phase discontinuity can be obtained by exploiting the versatility of the sol-gel chemistry [54]. Although high-optical-quality glasses

can be produced under mild conditions, the preparation (hydrolysis and condensation) requires relatively long times to produce a consolidated material [54]. The generic approach is to dissolve the photopolymerizable species in the liquid precursors (typically modified organoalkoxysilanes) of the glassy material in a single reaction mixture, followed by hydrolysis and gelification which lead to the formation of a glassy matrix. By this approach samples of high thickness with good mechanical properties, low shrinking and high thermal and chemical stability can be obtained [55]. Some variants have been proposed to increase the refractive index change after exposure, such as the addition of titanium or zirconium alcoholates to the initial mixture [56] or using low refractive index monomers [57]. A further alternative is to increase the refractive index of the photosensitive material by introducing reactive species with high refractive index species (HRIS) [58]. This solution led to refractive index modulations up to 0,015. A further advantage of this approach seems to be that high refractive index species are dispersed in molecular form with respect to systems containing nanoparticles [59].

4. VHOE-based solar concentrators

Since 1980, several scientific papers have been published to demonstrate that HOEs can provide improvements in solar energy collection over large incident angles and the entire solar spectrum range [2–4, 8, 10, 28, 60]. In particular, Ludman [3] described two configurations with multi-hologram lenses useful to concentrate the sunlight onto an absorber for different sun positions in the day. On the other hand, V-HOEs can be employed to obtain both a concentration and a spatial separation of the solar spectrum. This approach allowed employing different solar cell materials with optimized band gaps achieving high PV efficiency [2, 61].

Ludman et al. [5, 8] demonstrated that a well-designed holographic concentrating and spectral splitting systems can reduce the cooling requirements of the photovoltaic cells. As illustrated in **Figure 3**, PV cells were positioned at right angles with respect to the hologram orientation. This configuration allows eliminating shadow effects and facilitates cooling.
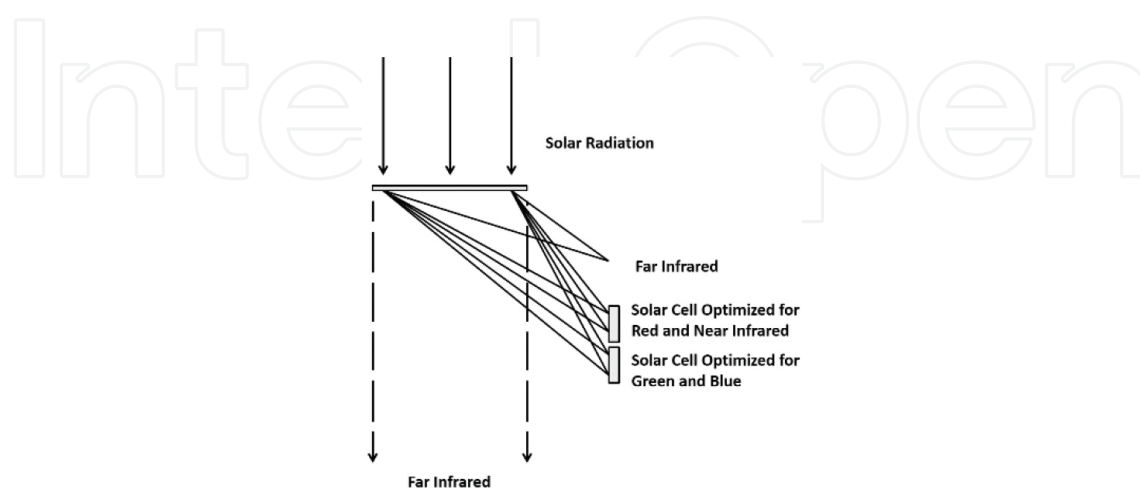
Figure 3. Holographic solar concentrator with spectral splitting systems [5, 8].

The holographic system was designed to direct and concentrate the red and near-infrared spectrum on one photocell and the green and blue spectrum on another one, 2hereas the far-infrared spectrum, which mainly contributes to the heating, is diffracted away from the cells. The authors compared the holographic systems with a Fresnel-based solar concentrator, demonstrating that the holographic system concentrates more total power than the Fresnel system and has a larger relative efficiency and that large heat sinks are not necessary allowing decreasing the bulk and cost.

Muller [62] showed a variety of potential applications in architecture for utilization of solar energy, improvement of room comfort as well as design of solar light and colour effects. The possibility to record more than one transmission hologram (superimposed holograms) on the same holographic medium was detailed described by Bainier et al. [4]. The authors estimated and experimentally measured the energy efficient of a system composed of a PV cell (Silicium- or GaAs-type cell) and a holographic concentrator. In particular, they compared two types of holographic systems: the first concentrator was with a single holographic element, where the maximum of reconstruction wavelength (620 nm) was chosen to be centred in the middle of the range of the PV cells (i.e. 500–800 nm). The second concentrator system was composed of two holographic recordings, where the two maximum of the reconstruction wavelengths (514.5 and 620 nm) were chosen both to well overlap the operating spectrum of the PV cells and to avoid coupling effect. The PV cell was a GaAs with an efficiency of 23%. The authors proposed both a reflecting and transmitting version for the double hologram system. For the transmission, one of the two holograms was superimposed on the same holographic medium. Estimation and experimental evaluation of the energy efficiency of the holographic systems were of 6 and 5% for the single holographic elements and of 11 and 9% for the double holographic element, respectively.

James and Bahaj [63] published a very interesting study on the application of V-HOE-based solar concentrator for solar control of domestic conservatories and sunrooms. They demonstrated that a well-designed V-HOE applied on the glasses of a domestic conservatory can allow keeping the daytime temperatures to an acceptable level. In particular, the authors estimated the temperature reduction inside a conservatory for different configurations of the V-HOEs. Moreover, the angular selectivity of the V-HOEs allows avoiding any actuation of the incident sunlight during the winter months. So, in the winter season, the temperature reduction due to the V-HOEs is inhibited allowing to obtain a comfortable temperature.

In 2010, Hung et al. [64] proposed a superimposed structure with a doubly slanted reflecting hologram fabricated by using 488 and 632 nm laser sources. The slanted structure with an inclination of 30° assures a total internal reflection at the surfaces of the holographic medium. Thus, light emerges at the edges of the holographic plate, where appropriate PV cells can be positioned. From a theoretical point of view, the structure was analyzed as a 1D photonic band gap material. **Figure 4(a)** shows a sketch of the experimental set-up for the doubly slanted layer structures, whereas the diffraction of normally incident white light for the doubly slanted structure is illustrated in **Figures 4(b)** and **(c)**.
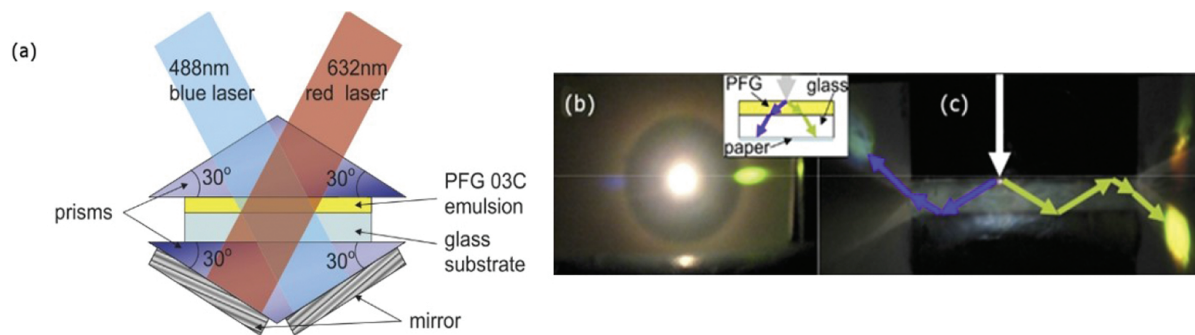
Figure 4. (a) Sketch of the experimental set-up used by Hung et al. [64] for the doubly slanted layer structure. Diffraction patterns evaluated taken from behind (b) and above (c).

Castro et al. [12] reported a detailed study on the design and characterization of a holographic grating used to address the direct sunlight on PV cell with the maximized energy efficiency possible. In particular, they analyzed the effects of incident spectra that vary hourly, daily and seasonally. To maximize the energy collection efficiency during the course of a year, the authors proposed the system based on the structure illustrated in **Figure 5(a)**.
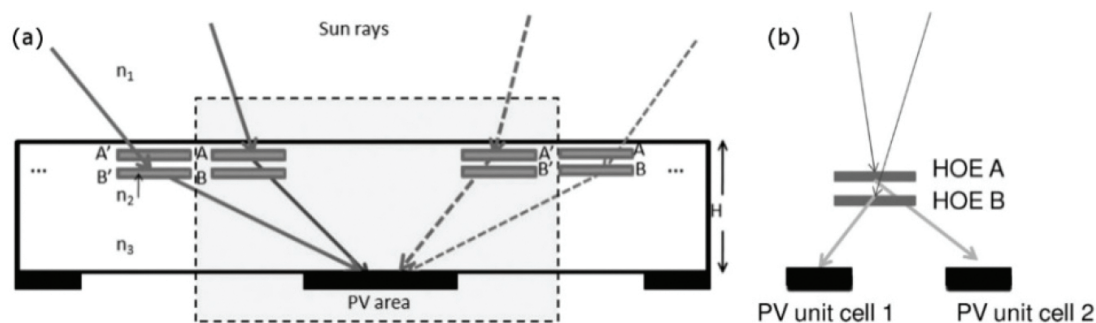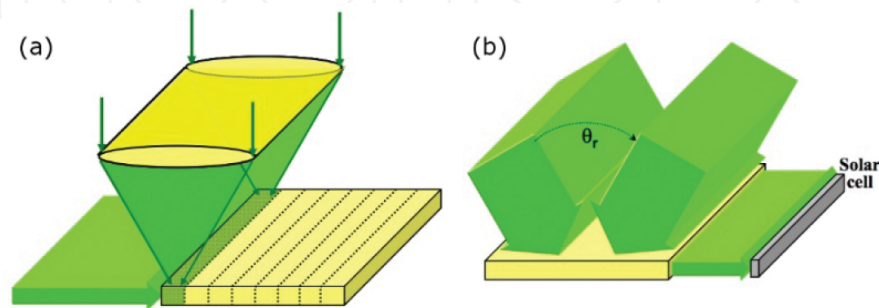

Figure 5. (a) Holographic solar concentrator structure proposed by Castro et al. [12]. Dashed box: unit cell. (b) Holographic design to reduce the optical crosstalk.

The unit cell includes two cascaded holographic grating on each side of the PV cell (holograms A and B). The holograms on each side of the PV cell are conjugated (i.e. A and A' or B and B') to provide peak energy collection at different seasons. In order to reduce the optical crosstalk of the V-HOEs, the two cascaded holograms are designed to diffract light in opposite directions with the incident angles in different quadrants of the Bragg circle (**Figure 5(b)**). Moreover, the geometrical parameters of the system (such as the hologram width and the distance hologram PV cell) are optimized to assure that maximum of the diffracted rays of the sunlight within the solar responsivity spectrum of PV cell can reach the surface of the cell independently of the incident angle. An energy increase due to the concentrator averaged over a particular day of 147% can be obtained, and nearly 50% of the available energy illuminating hologram areas can be collected by photovoltaic cells without the need of tracking.

Hsieh et al. presented a solar concentrator based on a so-called 90° hologram that allows obtaining a compact and wide-angle structure [60]. The conceptual recording set-up is

illustrated in **Figure 6(a)**. In particular, the reference and object beam are an edge-lit and a cylindrical converging beam, respectively. Thus, a combination of a lens and a mirror can be simultaneously recorded in the holographic medium. Then, the medium is shifted, and the recording is repeated obtaining an array of V-HOEs that assure a large angular acceptance. In fact, when the sunlight, assumed as/like a plane wave, impinges on the solar concentrator with different incident angles, the diffracted wave is guided to the edge of the recording medium where a PV cell is positioned (**Figure 6(b)**). The author demonstrated that using a 2 mm thick holographic medium, the proposed architecture increases the collection angle from 0.01° to 6°.

Figure 6. (a) Recording set-up and (b) configuration of volume holographic concentrator [60].

Atencia's group analyzed in detail the design and characterization of a solar PV linear concentrator based on a cylindrical holographic lens [13, 18]. In particular, a simulation tool has been developed to take into account a specific set of designed parameter, such as angular selectivity, bandwidth, optical polarization, PV cell size and so. The possibility to realize a high-efficient system that only requires one-axis tracking was demonstrated.

5. Experimental

5.1. Photopolymer

The recording material was a prototype of photopolymer sensitive to light at wavelength of 532 nm. It was obtained by sol-gel reaction of functionalized alkoxysilanes in acidic conditions and by adding a mixture of acrylic monomers and bis[2,6-difluoro-3-(1-hydropyrrol-1-yl) phenyl]titanocene photoinitiator before thin-film deposition. The mixture was made of halogenated high refractive index species dissolved in phenoxyethyl acrylate and methacrylic acid. Photopolymer was deposited through bar-coating method to obtain 30 μm thickness films. The films were exposed to green light pattern for hologram recording and subsequently to halogen lamp to bleach the unreacted photoinitiator. The final modulation of refractive index showed by this photopolymer is of about 0.02 [65].

In our previous paper, we experimentally demonstrated that this new photosensitive material allows to record volume, holographic diffraction gratings with a very good diffraction efficiency of about 94% [66].

5.2. Recording set-up

The dimensions of an individual HOE range from 1 cm × 1 cm to 10 cm × 10 cm. In a step-by-step exposure process by coherent and monochromatic light (laser), the holograms are produced in patterns on a film, which can have a maximum size of 1 m × 2 m at the present state of technology.

The experimental set-up used to record holographic in-line spherical lenses was a typical Michelson interferometer with a concave mirror with a focal length of 5 cm placed on the object beam. A recording light source emitting at 532 nm (green) with a maximum power of 750 mW in CW and a coherence length up to 100 m was used. The diameter of the hologram was about 4 cm. To record an off-axis holographic cylindrical lens, the experimental set-up was modified, and two beams of equal intensity interfere with an angle α at the surface of the recording medium. A commercial cylindrical lens, with a focal length of 5.08 cm, is placed on the object beam. Finally, to record a volume holographic grating (VHG), two collimated beams interfere with an angle α at the surface of the recording medium.

6. Results and discussions

6.1. Characterization of a volume holographic spherical lens

The volume holographic in-line spherical lens was characterized, and its efficiency η was calculated as the ratio between the power focused by the holographic lens ($P_{f\_Holo\_lens}$) and the power focused by a commercial Fresnel lens ($P_{f\_Fresnel}$) with the same focusing features:

$$\eta = P_{f\_Holo\_lens} / P_{f\_Fresnel} \qquad (7)$$

In particular, both holographic and Fresnel lenses have been illuminated by a beam with a diameter comparable with that of the lenses (≈4.5 cm), and a power metre was positioned at the focal length. The evaluated efficiency was 42%.

The angular selectivity was assessed by measuring the diffracted intensity from the holographic spherical lens as a function of the angle of incidence. Two different laser sources, emitting at 532 and 633 nm, were used in order to consider different behaviours of the lens at different wavelengths. Experimental results of the angular scan at different incident wavelengths are showed in **Figure 7(a)**. As expected, the angle at which the diffraction intensity is maximum increases as the wavelength increases [14]. Additionally, the lens chromatic aberration was investigated. Ideally, an optical lens should focus all of the component colours of white light to a single point. This means that the lens should refract all of the colours of white light in the same way, so they all intersect each other at the same location (or focus). The measurement of axial or longitudinal chromatic aberration is given by the difference of focal length between blue (442 nm), green (532 nm) and red (633 nm), caused by chromatic dispersion.
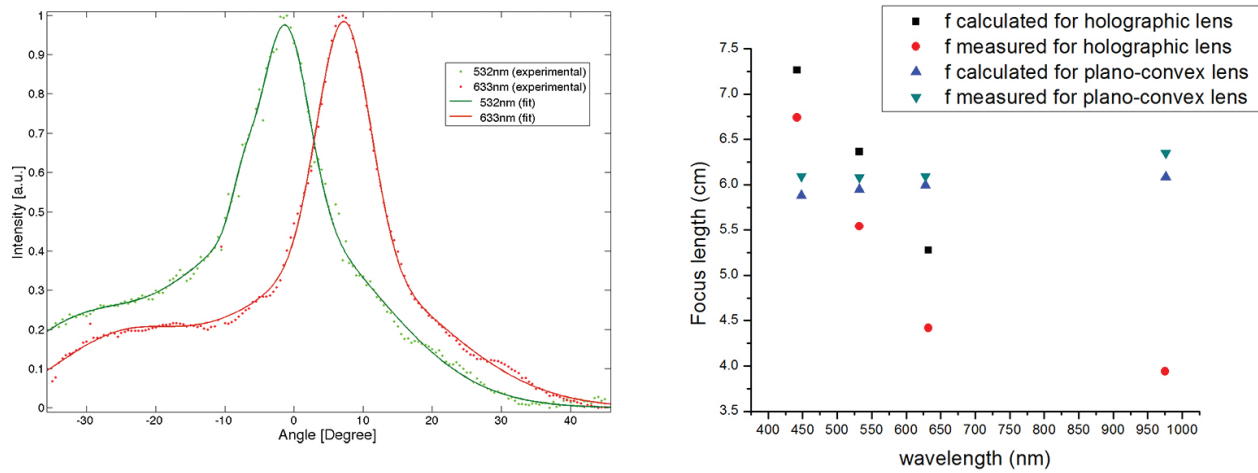
Figure 7. (a) Angular scan of the volume holographic lens at two different wavelengths and (b) focal length for different incident wavelengths both for conventional plano-convex lens and for holographic spherical lens.

The focal length was measured as function of wavelength both for a conventional lens and for a holographic spherical lens. Results are reported in **Figure 7(b)**. The conventional lens was a 2" plano-convex lens with a focus distance of 6 cm. Its theoretical focal length was also evaluated by using a simplified thick lens equation:

$$f = R / (n - 1) \qquad (8)$$

where n is the index of refraction and R is the radius of curvature of the lens surface. The lens used in our experiments had $R = 30.9$ mm, and it was fabricated from N-BK7, so we used the index of refraction for N-BK7 at the wavelength of interest to approximate the wavelength-dependent focal length. Seeing **Figure 7(b)**, it is evident that, while for the conventional lens the focal length slightly increases by increasing the incident wavelength, the holographic lens shows a marked decrease of the focal length by increasing the incident wavelength. Also, this behaviour can be explained by considering the Bragg condition. Indeed, the Bragg angle θ_B increases when wavelength increases. In particular, the focal length is related to θ_B, and so to λ, by the geometrical relationship $f = \dfrac{D/2}{tan(\theta_B)}$, here D is the lens diameter.

Chromatic aberration of the holographic lenses can be reduced in the visible range designing an achromatic doublet by using two holographic elements: a holographic lens and a holographic grating, as proposed by Udupa et al. [67]. Therefore, the combined two holographic element systems behave like a single element holographic achromatic lens.

The beam profile in the focal point of the holographic optical lens was also characterized, and a comparison with the beam profiles both of a conventional lens and of a Fresnel lens was carried out. In **Table 1** the evaluated widths of the beam as four times the standard deviation (4-sigma) for the three different lenses characterized are summarized.

Beam width (4-sigma)	X [μm]	Y [μm]
Holographic spherical lens	4754.62	5279.20
Conventional optical lens	4171.23	4155.35
Fresnel lens	4007.91	4018.47

Table 1. Beam width 4-sigma evaluated for three different lenses.

It is clear that the holographic spherical lens shows a reduced ability to concentrate light at the focal distance with respect to the other two lenses considered. This result can depend from the chromatic aberration that affects the holographic lens.

6.2. Characterization of a volume holographic cylindrical lens

The volume holographic off-axis cylindrical lens was characterized, and its efficiency η was evaluated as the ratio between the power focused by the holographic lens ($P_{f\_Holo\_lens}$) and the power focused by a commercial in-line cylindrical lens (P_{f_Cyl}) with the same focusing features. A beam with a diameter comparable with that of the lenses ($\approx$1.5 cm) was used, and the focused power was measured by a power metre positioned at the focal length. The obtained value for the efficiency was 25%.

Considering that both holographic spherical and holographic cylindrical lenses follow the same theoretical laws; also in the case of cylindrical holographic lenses, it is expected that the focal length as a function of the incident wavelengths follows the same behaviour of that observed for the holographic in-line spherical lens described in the previous section (**Figure 7(b)**). Therefore, a decrease in the focal length of the holographic cylindrical lens is expected by increasing the incident wavelength.

In **Table 2** the evaluated widths of the beam as 4-sigma obtained by the intensity profile of the wavefront acquired at the focal plane of the off-axis holographic cylindrical lens with focal length f = 5.08 cm are summarized.

Beam width (4-sigma)	X [μm]	Y [μm]
Holographic cylindrical lens off-axis	995.84	237.78

Table 2. Beam width 4-sigma evaluated for the off-axis cylindrical lens.

As can be noted from **Table 2**, in the case of the off-axis cylindrical lens, the beam width (4-sigma) along the y-axis is greatly reduced in the focus of the lens, thereby drastically reducing the width along the y-dimension. For that reason, cylindrical lenses are the most commonly suggested to avoid tracking in one direction; indeed, if the incidence direction varies in the perpendicular plane, the angular selectivity is lower, so it is possible to eliminate tracking in this direction [24].

6.3. Solar concentrators in the space

In order to utilize a material in space environment, an appropriate characterization of this material for these applications is required. The first problem is the large temperature range of operation. For this reason, a characterization in temperature was made to verify the possibility to use HOEs described before in the aerospace industry.

In order to characterize the behaviour of the new proposed photopolymer as a function of the temperature, a VHG was recorded with a diffraction angle α of 30° leading a VHG with 1000 lines per millimetre. Experimentally, the diffraction efficiency was evaluated by using the following relationship:

$$\eta = \frac{P_1}{\left(P_0 + P_1\right)} \tag{9}$$

where P_1 is the measured power of the first diffraction order and P_0 is the measured power of the zero diffraction order. With this aim, a He-Ne laser emitting at 633 nm, a motorized goniometer and a power metre were used. Measures were carried out at room temperature (TR = 24°) in a given point of the VHG that was rotated at the Bragg angle. Afterward, the VHG was exposed to a stress in temperature, to verify its behaviour in terms of diffraction efficiency. With this aim, the temperature of the photopolymer, and so of the grating, was increased at 150° for 2 h. Then, the temperature was reported at TR, and the diffraction efficiency at the same previous point of the VHG was measured again. Finally, the temperature was lowered at −80° for 23 h, and the diffraction efficiency was measured again in the same previous point of the grating when the temperature was reported to TR. In **Table 3** the efficiencies measured at TR in initial condition and after two different thermal stresses (increased and lowered of temperature of material) are summarized.

	At room temperature (24°C)	After exposure to +150°C	After exposure to −80°C
η [%]	96.5	93.5	94.3

Table 3. Diffraction efficiency measured as a function of temperature.

Preliminary results confirm that the diffraction efficiency of the VHG subjected to thermal stress does not change significantly. The little variations observed in the diffraction efficiency maybe are ascribed to errors in positioning the red laser for measurement in the same point. Therefore, we can conclude that VHGs do not lose efficiency after a single cycle of thermal stress, and so this very promising material could be successful used for aerospace applications. Of course, further study has to be performed to demonstrate that no changes in the VHG performance are observed even after several cycles of thermal stress.

To consolidate the previous results, a test of outgassing of the photopolymer was carried out. This characterization is very important to evaluate the behaviour of the photopolymer in the absence of pressure (space conditions). In this test, the grating was firstly cleaned with

isopropanol and then was inserted in a chamber connected with a turbo pump variation. The chamber was also connected to a residual gas analyzer (RGA) consisting of a mass spectrometer. Two tests were performed at different pressures. The first one had a base pressure of 2×10^{-8} mbar after 6 days of pumping at room temperature. The results, acquired with a mass spectrometer, reported the presence only of main gas species known that are the contaminants based on the chamber.

The second test had a base pressure 7×10^{-8} mbar after 3 days of pumping at room temperature. Results acquired with the mass spectrometer highlighted the presence of unknown main gas species, with atomic mass units (AMU) up to 100. However, the intensity of the unknown gas is very small and comparable with the contaminants of the same chamber of the test.

Finally, the behaviour of the focal length for different incident wavelengths reported in **Figure 7** can be useful in aerospace application. Indeed, considering that in the infrared region the focal length is very far by the focal length in the visible region (where the PV cell will be placed), the thermal overheating of the photovoltaic cell due to the absorption of infrared radiation is avoided, reducing cooling requirements. All these results confirmed the possibility to use this photopolymer in spatial applications.

7. Conclusions

In this chapter, we experimentally demonstrated that a new photosensitive material can be used to realize holographic solar concentrators.

Two configurations of holographic lenses were investigated: spherical in-line lenses and cylindrical off-axis lenses. The chromatic aberration of the spherical lens was characterized, proving a decrease of the focal length as the incident wavelength increases. Furthermore, the beam profile was characterized for both the proposed holographic lens in their focus. Performances of holographic lenses were compared to those of conventional optics. Some lower performances of holographic lens highlighted with respect to conventional optics, such as higher axial chromatic aberration and lower ability to concentrate light in the focus, are rewarded with a lower size, lower weight and lower cost. However, chromatic aberration can be useful to reduce cooling requirements. Indeed, considering that the PV cell will be placed at the focal length in the visible region, the infrared region will be focalized very far, avoiding the thermal overheating of the photovoltaic cell due to the absorption of infrared radiation.

Finally, a preliminary study of the influence of the thermal stress and the behaviour of the photopolymer in the absence of pressure (space conditions) revealed that the proposed photosensitive material could be suitable in space environment. Therefore, we are quite optimistic that our experimental results can open the way to the fabrication of efficient, cheap and lightweight holographic solar compatible with space applications.

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