Holographic solar energy systems: The role of optical elements

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Abstract

The use of holographic optical elements for solar energy applications has increased interest in the recent years because of their potential to reduce production cost, their ability to select certain bandwidths of the solar spectrum and their suitability for architectural integration. Among the different typologies of holograms, volume holograms are the most widely utilised devices due to their high efficiency (up to 100%) and also because they have two important characteristics: angular selectivity and chromatic selectivity, which are crucial for the design of systems addressed for lighting, solar shading or solar concentrators. In the present article, an analysis of the main existing holographic solar energy systems is presented, with emphasis on the characteristics of the optical element.

Keywords: Holographic Optical Elements (HOE); Solar energy; Photovoltaics; Solar Concentration; Building Integration

1 Introduction

The Holographic Optical Elements (HOEs) for solar energy applications can be used in combination with Photovoltaic (PV) cells or solar thermal absorbers, in order to generate electricity or heat respectively. On the other hand, HOEs can be used in applications related to the aesthetics of the building or in applications about temperature or lighting control.

Among the different types of holograms, thin holograms, both amplitude and phase, are not suitable for applications with white light (sun) because the issue of very low efficiency arises, with maximum values (after bleaching process) of 33%. Despite the fact of presenting greater chromatic and angular selectivity than thin holograms, almost all the elements used in the holographic solar energy applications are volume and phase holograms. With this type of holograms, efficiencies up to 100% can be reached for certain wavelengths and directions of light incidence.

Over the different solutions using volume holograms, reflection and transmission elements can be found. According to the way that these elements operate, they can be classified into non-concentrator elements (they only modify the direction of the sunlight, but they do not concentrate it) and concentrator elements. The holographic elements can exist alone or combined with other holographic elements, refractive elements and/or reflective, or light-guide systems.

Dichromated gelatines and photopolymers are the most commonly used recording materials for this type of applications. Although designs in silver halide materials are reported in the literature as laboratory studies, these materials are not suitable for use in field conditions because of their blackening tendency.

It should be noted that, in many cases, the holographic element would operate in a range of wavelengths different than the recording wavelength for which the holographic material is sensitive. Therefore, a photosensitive material presenting index modulations sufficient to diffract with high efficiency in a wavelength different to the recording one is required.

In the case of solar applications, it is essential to consider that solar radiation changes direction during the day and over the year. As the distance from the Sun to the Earth is very large, it can be assumed that the Sun is a point source and the sunrays are collimated (source at infinity) for each point of its trajectory.

The solar spectrum varies considerably the energy flux for each of the wavelengths. This fact determines, jointly with the angle of incidence, the performance of the holographic solar energy system.

1.1 Key characteristics of the volume holograms

For the comprehension of the different designs which will be described in the following sections, it is necessary to consider three typical characteristics of volume holograms: angular selectivity, chromatic selectivity and chromatic dispersion. These characteristics strongly depend on the recording geometries and the holographic material [1].

1.1.1 Angular selectivity

Volume holograms only present maximum efficiency (defined as the quotient between diffracted and incident fluxes) for a range of incidence angles near the direction that satisfies the Bragg condition. This range of angles can be higher or lower depending on the material thickness and the spatial period of the recorded interference. In general, this is a disadvantage since the hologram does not work with maximum efficiency for all the incoming light inclinations, requiring a solar tracking system or cascade design elements or multiplexed gratings.

It should be taken into account the fact that the angular selectivity of the volume hologram is not equal for all the directions of incidence, but it shows higher selectivity when the illumination angle is varying in the recording plane direction (Fig. 1(a)). In the perpendicular plane, the efficiency decays softer when incident directions go away from the optimal reconstruction angle; thus, it is possible to design systems that require tracking only in one direction (azimuth tracking or sun height tracking).

The angular selectivity can also be an advantage, so that a hologram can deflect radiation entering a building depending on the season and time of day, blocking or using it for lighting.

<Fig. 1>

In Figure 1(b), an example of angular selectivity curves for a transmission volume hologram on the major and minor angular selectivity directions is illustrated. When the direction of illumination, in the reconstruction, varies in the plane perpendicular to the recording one (XZ plane), the angular selectivity is 20 times lower than when it varies in the plane parallel to the recording plane (YZ plane). Therefore, the system is much more tolerant (maintains high efficiency) when the illumination direction varies in the XZ plane than when it varies in the YZ plane.

1.1.2 Chromatic Selectivity

When a volume hologram is lighted with white light, each wavelength of the incident radiation is diffracted with different efficiency, which decreases when moving away from the wavelength for which the hologram is designed.

In Fig. 2, an example of diffracted spectrum depending on the wavelength for a volume hologram is shown. The width of the curve, as occurs with the angular selectivity, depends on the spatial period of the interference recorded and the thickness of the material. Figure 2(a) corresponds to an ideal case, with the largest spatial period possible within the range of volume hologram. In general, the diffracted spectral bandwidth is lower, as it can be seen in figures 2(b) and 2(c).

This property, which in principle can be considered as disadvantage, can be utilized to adapt the diffracted spectrum to the sensitivity of the PV cells, improving the performance and preventing wavelengths that produce overheating. It also allows the same element to be used for two different functions, for example, lighting and concentration or generation of electricity and thermal power generation.

<Fig. 2>

With regard to transmission and reflection holograms, the difference between them is that the latter has higher chromatic selectivity and lower angular selectivity.

From the above mentioned, in solar energy applications, in order to determine the efficiency of a holographic system, it is necessary to consider the efficiency of the hologram for each wavelength and also the curve of the solar spectrum. In case that the energy is collected in a PV cell, the curve of the spectral sensitivity should be also taken into consideration.

1.1.3 Chromatic dispersion

The wavelengths efficiently diffracted by the volume hologram propagate with different direction. If the hologram concentrates the rays, each wavelength focus is spatially separated. This dispersion can be an advantage, by using several PV cells optimized for different spectral ranges; thereby, improving system efficiency.

The purpose of the present manuscript is to review and analyze different holographic devices for solar applications. The contents are structured regarding the type of holographic element used. In section 2, configurations based on volume and phase transmission holograms are presented, distinguishing between holographic gratings and holographic lenses, and considering configurations with only one holographic element and devices composed by different holographic elements. In section 3, designs with volume and phase reflection holograms are described. Finally, in section 4 the main conclusions are stated.

2. Systems using volume phase transmission holograms

2.1. Non-concentrating optical systems

Normally the non-concentrating elements are utilised for solar illumination management applications in buildings. In this regard, the holograms may operate as selective shading technology or as daylight element. Depending on the characteristics of the holographic grating, the optical element can also be used as temperature control system, avoiding near infrared incident bandwidths.

2.1.1. Systems with one holographic element

A system which utilises a single holographic grating for daylight applications is the one reported in [2]. This device was designed to operate under covered sky; thus, it mainly works by the diffuse fraction. The objective of this specific system is to redirect diffuse light coming from the zenithal region of the sky towards the interior of the building. The system, called zenithal light-guiding glass, consists of a photopolymer which records the interferential pattern placed between two glass panes (mechanical stability and protection against humidity). The holographic device is though to be used on façades or roofs only receiving diffuse irradiance because direct sunlight could cause glare and chromatic dispersion.

Some of the first holographic daylighting systems, proposed ten years ago, showed low efficiency for white light; a simulation study presented by Papamichael et al. [3] about holographic glazing for illumination of an office revealed that, after analysing several scenarios corresponding to different holographic gratings for different angles of incidence representative of several months, the holographic glazing only improves the illumination at the back of the office with very low performance. This phenomenon is attributed to the angular and chromatic selectivity of the single holographic optical element included.

2.1.2 Systems with various holographic elements

A system reported by Müller [4], in which three gratings operating for three angles of incidence incorporated into a double glass pane window, allows improvement of the lighting in the interior space without any movable part or control. This system, named sun-directing glass, deflects light in the horizontal plane and in the vertical plane by combining the HOE with acrylic material inside the double glass and reflectors at the ceiling. The reflectors play an important role because they can redirect the light to some specific areas where higher intensity is needed or they can diffuse the light by using a white material. This technology was applied in a demonstration project in office buildings in Cologne, in 1994. The results demonstrated significant lighting energy savings in comparison to a reference configuration without light control for the case of using aluminium reflective lamellas at the ceiling [2].

Stojanoff *et al.* [5] presented an improved device constructed with three holographic gratings. These elements diffract solar radiation with incidence angles between 22º and

80º with respect to the normal of the window, and they direct it with an inclination of 15º to the ceiling of the room to be illuminated. Each one of the three acts for a different range of the solar spectrum, at red, green and blue. At the room ceiling, the wavelengths of the three ranges are overlapped resulting in white light (figure 3).

<Fig. 3>

A summary of the different non-concentrating solar energy holographic systems described above and in section 3 regarding reflection holograms is included in Table 1.

2.2 Concentrating optical systems

The efficiency of a solar PV system can be improved if the light is concentrated onto the PV cell. Furthermore, in this way, less cell surface is needed, reducing the global cost (environmental and economical) of the system [6].

2.2.1 Concentrating optical systems with holographic non-concentrating elements

A hologram recorded from two plane waves does not concentrate radiation, but it splits beams at the output. This type of elements, which are called holographic gratings, can be combined with refractive elements to concentrate the energy, or they can be combined with guidance systems that redirect radiation to the solar generator. In these cases, the concentration ratio of the system is defined as the ratio between the total surface area through which the solar radiation penetrates and the area used to collect this radiation. Such systems are called Holographic Planar Concentrators (HPC).

2.2.1.1 Systems with one holographic element

An HPC which utilizes a single holographic element was proposed by Zhang *et al.* [7] (Figure 3). One module of this system consists of a holographic volume and transmission grating and one PV cell. In this case, at the cell will arrive the direct sunlight and the diffracted by the hologram that is guided by total internal reflection in the substrate. Because of the chromatic selectivity, not all the wavelengths will be efficiently diffracted and the energy of the transmitted wavelengths will be lost (without deviation) by the grating. If the lost energy corresponds to wavelengths for which the response of the cell is low or zero, the system performance will not be affected. May even design the hologram so that it transmits wavelengths that would cause overheating in the cell; thereby, increasing system performance.

The geometrical concentration ratio of the system in figure 4 is 2x, although if the size of the cell is reduced the concentration ratio would increase. The range of angles of incidence for which the hologram deviates the rays in order to arrive onto the cell, depends on the ratio between the size of the hologram, the size of the cell and the distance between both. For optimal operation, the holographic gratings must diffract in directions that fulfil total internal reflection for all the useful wavelengths.

<Fig. 4>

2.2.1.2 Systems with combination of various holographic elements

For some cases, in order to take advantage of a greater fraction of solar radiation, the planar holographic elements are combined in such a way that each one would be efficient in a different range of wavelengths. This occurs in a design reported by Kostuk et al. [8], in which a system with two gratings in cascaded configuration was proposed (Figure 5). The first grating deflects the long wavelengths towards right, making them to arrive at one PV cell of spectral sensitivity adapted to this range. The second one deflects the radiation of short wavelengths towards left where there is another cell sensitive to this range of wavelengths. Thus, two types of different cells, placed at the edges of the system, are utilized with spectral sensitivity curves matching with the diffracted wavelengths of the gratings, increasing in this way the efficiency of the cells and avoiding overheating and other possible negative effects. The range of the angles of incidence of the radiation for which the system is efficient depends on the geometry of the system and on the characteristics of the employed holographic gratings.

<Fig. 5>

The same authors proposed one version of this system, utilizing also Compound Parabolic Concentrators (CPC), which increases the concentrating factor and reduces the required PV cell area. The concentrators are located at the edges with their aperture area substituting the PV cells of the previous designs and placing the cells at their base (exit). In the previously cited work, Zhang et al. [7] investigated the use of three cascaded gratings in an arrangement similar to figure 4 to extend the concentrated spectrum.

Another application of the cascaded holographic elements is the increase of the range of the incidence angles for which the system is efficient. An example is the design of Castro *et al.* [9] in which cascaded holographic elements are combined in such a way that the system is efficient over the whole year (Figure 6). The cascaded gratings do not have the task of operating in different wavelength ranges, but in ranges of different angles of incidence. In this type of systems, with cascaded elements, the selection of the angle between beams in the recording is essential for avoiding coupling between diffracted beams in the reconstruction [7].

<Fig. 6>

As it can be observed in Fig. 6, gratings A and A´ are conjugated and they operate for a range of angles of incidence of the solar radiation in one side and in the other side with respect to the normal of the system. The same occurs with B and B´, but they are working for angles of incidence more inclined. A and B (and thus, A´ and B´) are operating for angles of incidence of different sides with respect to the normal, to avoid coupling between the gratings, i.e., grating B would have efficiency for the direction in which the rays exit from A. If this occurs, at the exit of B the rays would not have adequate inclination for reaching the PV cell.

By means of this system, the sun tracking in one direction could be avoided so that the system only has to follow the solar azimuth movement, but not the solar height. For this purpose, the holograms should be located in such a way that the direction of the lowest angular selectivity coincides with that of the solar altitude. If the holograms are oriented with the direction of low angular selectivity coinciding with that of the azimuth movement of the sun, a system, which does not require tracking to any direction, could be achieved, despite the fact that the global efficiency would decrease [10].

This system can be extended by using up to three cascaded gratings. Moreover, each of the gratings could be efficient in a different range of wavelengths, in such a way that the diffracted light in each range would focus to cells with different curve of spectral response [7]. The geometrical concentrating ratio for these systems is low, similar with that which is obtained in a system with single grating as the one proposed by the same author. The behaviour of the system, in both cases (the one that operates without tracking, as well as, the other that works with single-axis tracking), depends on the angular selectivity of the holograms. The recording material used was dichromated gelatine.

Castillo *et al.* [11] also proposed a system with only one-axis tracking, at the direction of the zenith variation of the sunrays. The holograms, for this reason, are oriented with such a way that the direction of the lowest angular selectivity coincides with the azimuthal trajectory of the sun. For this case, ¨two-adjacent holographic gratings¨ configuration with a bifacial cell was proposed. In Fig. 7, the trajectory of the rays for perpendicular incidence of the solar radiation is illustrated. Grating 1 deflects the radiation towards the cell at the left, while grating 2 towards right. In addition, due to the chromatic dispersion, each range of wavelengths is directed to one different part of the bifacial cell (in the figure, the long wavelengths affect the lower part and the short ones the upper part). Furthermore, with the bifacial cells and the holograms it is also possible to collect albedo.

<Fig. 7>

This type of system is called DA-HPC (Dual Aperture Holographic Planar Concentrator), due to its capacity to work with incident solar light from both sides of the system. The company Prism Solar Technologies uses DA-HPC for the design of their commercial solar panels [12]. In the study of Russo *et al.* [13] a comparison of this type of systems with a conventional PV system can be found, revealing that the DA-HPC yield outperforms the conventional one by 73%. Moreover, Castillo *et. al* [14] investigated the effect of the holographic elements on the output of the CIGS cells, which are also utilised by the solar holographic panels commercialized by Prism Solar.

2.2.2 Concentrating optical systems with holographic concentrating elements

If in the recording of the volume holograms, one or both waves that interfere are spherical waves, the hologram behaves such as a lens, concentrating incident light in the reconstruction in one point at the exit (spherical holographic lenses). If one of the waves is cylindrical (coming from a linear focus) and the other is plane, at the exit of the hologram the diffracted light is concentrated onto one line similar to the one utilized in the recording (cylindrical lenses). Generally, tracking for systems using cylindrical lenses could be less demanding in the direction corresponding to the focusing line.

The chromatic dispersion of volume holograms causes different focus position for every wavelength, which can be utilized for disposing various cells with different spectral response.

As occurs with gratings, a holographic concentrator must present high efficiency for the widest possible bandwidth, and it is necessary its coincidence with the spectral response of the PV cell. In many cases, depending on the type of the PV cell used, it is convenient the fact that the concentrator does not diffract infrared wavelengths, since in this way cell overheating or the use of a cooling system are avoided.

2.2.2.1 Systems with one holographic element

Ludman *et al.* [15, 16] reported the design of a cylindrical lens in dichromated gelatine, in such a way that the concentration ratio could reach 20x (Figure 8). The chromatic dispersion is utilized for collecting the diffracted energy in separated cells each one with spectral response at different wavelengths. The efficiency of the system depends on the recording wavelength and used cell. The theoretical simulations predict the highest efficiency (41%) for recording wavelength of 632.8 nm and in-tandem cells, one of GaAs and one of InGaAs. This efficiency is calculated as the product of the solar spectrum, the efficiency of the holographic element and the spectral efficiency of the cell. The authors estimated that the substitution of Fresnel lenses by this type of holographic element in existing concentrating systems (Sandia Baseline Module 3) would reduce the cost of energy production by half.

<*Fig. 8*>

Zhang *et al.* [17] proposed another geometry that takes advantage of the chromatic dispersion of the holographic elements to improve the output of the system. In that case, one spherical holographic lens concentrates solar radiation on one point, which position depends on the wavelength. Every holographic lens is combined with two types of PV cells (Figure 9). In the same work, one prototype with holograms recorded in dichromated gelatine is designed and constructed, in such a way that the final system (with one GaAs PV cell and one high-bandgap-energy PV cell) reaches an electrical conversion efficiency of 31%, improving around 12% the electrical efficiency which is achieved by a GaAs PV cell without hologram.

<*Fig. 9*>

All these prototypes require solar tracking, due to the angular selectivity of the holographic lens. In order to extend the range of directions of incidence for which the system is efficient, Hsieh *et al.* [18] studied the design of a holographic element combined with a planar waveguide, as shown in Figure 10. The main problem of this system is that for each direction of incidence, operates efficiently only a very narrow region of each area; for this reason, it seems to have a constant but low efficiency.

<*Fig. 10*>

A configuration with cylindrical holographic lenses was reported by [4] and [2] for solar shading and PV power generation. The holographic lens concentrates the direct irradiance to the PV cells (or to a reflector), shading the interior space, and the diffuse irradiance passed through the system for lighting. The system was designed considering single-axis tracking. A demonstration of such system with 90 m^2 of holographic glass panels (azimuth tracking) was built for the IGA Stuttgart Expo 93 International Garden Exhibition. However, no data regarding performance and characteristics of the hologram was included.

In 2013, Chemisana et al. [19] presented a similar configuration with single cylindrical lens design for building integration (Figure 11), functioning as a solar energy concentrator in combination with crystalline silicon cells. The holographic element was designed so as to act for a bandwidth that corresponds to the spectral response of the cell. The study was completed with efficiency measurements taking into account single-axis tracking in the highest angular selectivity direction, showing a clear improvement in the proposed system compared to a bare cell. The system reached an electrical efficiency of 17.9% with a geometrical concentration ratio of 3.5x. Further analysis about such system topology is detailed in reference [20].

<F*ig. 11*>

Stojanoff et al. [21] proposed a system for building integration that combines shading and PV power generation, by concentrating diffracted light on solar cells. This dual application was obtained by placing the holographic film on a parabolic substrate. This configuration was implemented onto the façade of the factory of solar cells of Shell, in Gelsenkirchen, Germany.

Vorndran *et al.* [22] proposed a hybrid system with a holographic lens, taking advantage of the chromatic selectivity to diffract a narrow spectral band through an aperture of a receiver, for example, a PV panel or an algae bioreactor. The transmitted wavelengths are collected in a second receiver (for example, a different PV cell with broad bandwidth or a thermal pipe). The holographic lens studied is a uniaxial lens formed by the interference of a planar and a spherical wavefront. It should be taken into account that this element has low efficiency at the central part of the lens, because the volume condition is lost, but this does not affect the performance of the system if the non-efficient portion of the lens has the same size as the first receiver aperture. The power distribution among both receivers can be selected by modifying the design of the central part of the lens to deviate the transmitted wavelengths to the second receiver.

2.2.2.2 Systems with combination of various holographic elements

Ludman [23] designed a holographic lens recorded with two spherical waves. In this way, when it is illuminated with collimated solar light, each zone of the lens works with a different inclination of daily solar irradiance. Thus, solar tracking in one direction during day is avoided. Since it has the same problem with the system of Hsieh *et al.* [18] which was previously described, in order to increase the concentration factor, a second holographic lens in cascade is added, in such a way that the radiation that does not diffract the first lens is diffracted by the second one. Complete design with a holographic three-stage system was proposed, ensuring in this case that the optical efficiency of the holographic system is around 70% and the system may efficiently concentrate the visible spectrum in a daily angular variation of about 100°. The concentration factor that they claim that it is achieved is 4x, but since the lenses in cascade are not decoupled (the wave diffracted by the first is again diffracted by the second one and fallen out of the cell), it seems that the system can't work properly. Moreover, experimental data is not reported [23].

A similar design, with three cascaded holographic lenses, was proposed by Xuechang *et al.* [24]. In this case, each holographic lens does not act by zones but the whole of its surface operates for a given inclination of the solar radiation. This system presents some critical points which address the device not to work adequately: the first lens does not meet the conditions of volume hologram (the angle between beams in the recording at the centre is zero), so its efficiency is expected to be very low; the three lenses will diffract the light in the same direction; therefore, the diffracted light of the first would be diverted by the second outside of the cell.

Fröhlich *et al.* [25] presented a configuration of a solar concentrator with two arrays of compound uniaxial lenses, each one with a grating and a biaxial holographic lens. Each uniaxial lens operates in line at a different range of solar spectrum. The gratings and lenses distribution minimizes cross-coupling between elements. The system collects the radiation focused by each lens in a different cell: GaAs for the spectral range around 800 nm and $Al_xGa_{1-x}As$ for radiation centred at 550 nm (Figure 12). The holographic lens only needs to be efficient in a range of wavelengths for which the cell used is sensitive. Theoretical simulations predicted a global conversion efficiency of the proposed system equal to 22.4%.

<Fig. 12>

Stojanoff *et al.* [5] also suggested the use of uniaxial lenses with different cells arranged along the optical axis of the lens, by using the different position of the foci for each wavelength. In this case, the holographic lenses should have low chromatic selectivity, so that the efficiency could remain high for the wavelength range in which each cell is sensitive. Taking into account that for the case of a compound holographic lens the diffractive efficiency is the product of each component, the diffracted spectrum width is stretched compared with a single holographic lens, losing global efficiency.

Gordon *et al.* [26] proposed a system with modules formed by two biaxial cylindrical holographic lenses combined with two different types of PV cells, sensitive to different spectral range. One of the cylindrical lenses diffracts in the spectral range that matches with one of the cells placed off axis and transmits the rest of the spectrum to the other placed at the axis of the lens. The same occurs with the other holographic lens and PV cell pair. The simulation of this system predicts an electrical conversion efficiency of approximately 30%. The same design, but multiplexing the two lenses in the same material, diffracting in two different directions for the same angle of incidence was considered. The authors affirmed that in this way, system tolerance to errors in the sun tracking alignment is higher and cell illumination is more uniform.

This idea of multiplexing several lenses in the same plate was already pointed out by Bloss *et al*. [27] and Bainier *et al*. [28]. To get multiplexed lenses in the same volume with high efficiency, a material capable of achieving high refractive index modulations is required [29] and it is necessary to choose geometries that avoid cross-coupling between lenses.

In some cases, the holographic elements are combined with refractive elements in order to achieve higher concentration. For example, the work of Russo *et al*. [30] dealt with the combination of a refractive lens and a transmission hologram. In this case, the hologram is designed to compensate the aberrations introduced by refractive lenses and to distribute focal points for each wavelength on a flat surface.

Table 2 sums up the concentrating system typologies described in sections 2.2 and 3, incorporating their most relevant characteristics. It should be noted that in some of the references the information described is very qualitative and no data about technical features is included, as for instance, the concentration ratio.

3. Systems using volume phase reflection holograms

The most immediate application in the frame of solar energy management of volume phase reflection holograms (holographic mirrors) is the shading in buildings. Stojanoff [21] designed asymmetric reflection holograms so that they can block sunlight at certain times of day (the hologram is optimized for a certain sun angle). The spectral properties, the central wavelength that is transmitted and the bandwidth, are designed according to the geographical location and the orientation of the windows. For instance, the hologram could reflect incidence infrared wavelengths at certain angles in order to prevent the heating of the building. In this study, Stojanoff proposed the utilization of symmetrical reflection holograms arranged as venetian blinds that are mounted on the exterior surface of the building. In the same work, Stojanoff [21] also proposed holographic mirrors on curved substrate to concentrate diffracted light in chemical reactors. This investigation is specifically developed in [31].

A transparent holographic shading system was also examined in reference [2]. The device is intended for temperate climates, where the reflecting holographic elements avoid part of the direct irradiance for certain selected angles of incidence to pass into the interior space while adequate illumination is ensured because diffuse light is transmitted though the hologram. The system is not efficient for all the angles of incidence; therefore, if it is desired to operate under proper designed conditions, solar tracking is required. A demonstration system was installed at the REWE supermarket headquarters in Cologne, Germany.

The reflection holograms could also be used in closed terraces or greenhouses [32], where the holographic element is placed between two glasses in each of the surfaces of the greenhouse or terrace. The holographic element can be designed according to the inclination of the surface and its orientation so that in winter it would allow the entire spectrum to pass and in summer it would reflect part of it, in such a way that the interior temperature would be controlled. In this study [32], a design method of holograms for two typical greenhouses in Britain is proposed and the temperature obtained in each one is determined, as a function of the percentage of the greenhouse that it is covered by the holographic elements.

There are designs only for concentrating the light onto PV cells with reflective elements [26]. Cassegrain concentrator [33] combines a holographic reflection grating substrate placed onto a hyperbolic glass with a parabolic mirror. The reflection hologram is designed so that the reflected spectrum is adjusted to the sensitivity of the cell. This type of system requires sun tracking, since the efficiency of the reflective elements, as occurred with those of transmission, dependents on the direction of the illumination beam.

Other designs use holographic mirrors to concentrate a narrow bandwidth in a photochemical reactor. The system of Quintana et al. [34] utilizes a holographic parabolic mirror recorded on plane substrate to concentrate UV radiation. As indicated in the beginning of section 3, Ortner et al. [31] constructed a holographic mirror on parabolic substrate to concentrate a bandwidth of 70 nm centred at 550 nm.

Based on the idea of matching the reflected spectrum with the sensitivity of the cell, Wu *et al.* [35] designed a folded holographic PV system (figure 13). The system consists of two different PV cells, each one absorbing in different spectral range, in combination with two reflectors and one reflection holographic grating that redirect wavelengths that have not been absorbed in each PV cell to the other one. This system can collect the direct and diffuse irradiation. The authors define a parameter, Improvement over the Best Bandgap (IoBB), to characterize this kind of designs that split the solar spectrum in different spectral bands. In this case, IoBB evaluates the improvement of the system conversion efficiency compared to that of the best performing bare cell under the same spectrum, and its value is around 21% with direct light and 15% with diffuse light for this folded system.

<Fig. 13>

Iurevych *et al.* [36] simulated the performance of reflection holograms in a system to generate electrical energy from PV cells and thermal energy. The wavelengths for which the reflection hologram is efficient are led by total internal reflection to the PV cell (Figure 14). The hologram should not be efficient for the infrared range, so that these wavelengths would pass through the system and utilized to heat the thermally conductive fluid. Solar movement produces a change in diffracted wavelength range.

<Fig. 14>

The problem of reflection holograms is that the spectral range for which they are efficient is much narrower than for those of transmission. Stojanoff *et al.* [33] achieved considerable augmentation (more than double) by altering the processing stages of the DCG in order to achieve a differential shrinkage of the emulsion. Hull *et al.* [37] proposed the use of stacked reflection gratings to broaden the diffracted spectrum. Another solution is to multiplex several holograms on the same material, each one operating at different spectral range, as described above for the transmission lenses. In this case, the maximum efficiency that reaches each grating could decrease [38]. This solution is relatively unexplored in the literature.

Villamarín *et al.* [39] presented a design of a solar PV concentrator that combines diffraction in holographic reflection gratings, specular reflection and total internal reflection. In this way, the sunlight is redirected to the PV cell for a wide range of inclinations of the incident sunrays increasing the acceptance angle of the system (Figure 15).

<Fig. 15>

4 Conclusions

In the present study, different designs of holographic solar devices proposed in the literature are described and analyzed. The applications range from climate control and interior lighting to solar thermal and PV configurations for the production of heat and electricity.

Among holograms, operating either by transmission or reflection, the volume and phase are the type which is most widely used. Holographic gratings for solar applications are primarily recorded in dichromated gelatines or photopolymers.

For all the configurations, it should be taken into account the fact that volume holograms diffract efficiently only for a range of inclinations of the beam illumination, for this reason a tracking system is needed. The tracking can be eliminated by multiplexing several holograms in the same material or by providing multiple holograms in cascade, so that each one acts for different range of inclinations for each region of the spectrum, which means a complex design, and in most of the proposed solutions the overall system performance reduces. It should be taken into consideration the fact that the angular selectivity is lower in the direction perpendicular to the recording plane; thus, in this direction the solar tracking could be minimized or eliminated if cylindrical lenses instead of spherical lenses are used.

Another characteristic of volume holograms is the chromatic selectivity. In certain applications, it may be an advantage, for example in the case of designing combined

elements, so that the wavelengths that do not diffract the hologram can be used for another application. Therefore, designs that perform the dual function of air conditioning and lighting of buildings are obtained, or can generate solar PV and thermal energy with the same system. Another advantage could be the removal of the infrared wavelengths, which causes overheating of the PV cells decreasing their performance.
In case that it is desirable to take advantage of the whole solar spectrum for the same application, the chromatic selectivity may be a disadvantage, but again multiplexed or cascade arranged elements could be adopted as solution.

Furthermore, it must be taken into consideration the fact that the direction of diffraction depends on the wavelength. This chromatic dispersion in most cases is an advantage since systems with different PV cells can be designed, each of them operating at a different range of wavelengths; thereby, increasing system efficiency.

From all the designs proposed in the literature, only a few are in commercial operation, such as the device offered by the company Prism Solar [12], or some designs proposed by the team of Stojanoff [5, 21, 33].

From the different systems analysed, it can be concluded that the characteristics of the volume holograms have a crucial influence on the potential suitability in terms of their use in certain solar applications. Each solution requires a careful design process and analysis in which it is essential a thorough understanding of the physical behaviour of gratings and holographic lenses.

Acknowledgements

This research has been supported by the Diputación General de Aragón (Consolidated Group TOL, T76) and the Spanish Ministries of Science and Technology (grant FIS2012-35433) and Economy and Competitiveness (grant ENE2013-48325-R).

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Table captions

Table 1. Non-concentrating optical systems

Table 2. Concentrating optical systems

Figure captions

Figure 1. (a) Diagram of recording and reconstruction of a volume holographic grating. The YZ plane is the recording one (b) Monochromatic diffracted efficiency (η_1) curves vs. angle of incidence when it varies at the YZ plane or at the XZ plane.

Figure 2. Curves of the chromatic selectivity for volume holographic gratings recorded in material of 30 microns thick, with the angle between the beams of 10° (red dashed line), 20° (blue dashed line), 30° (green solid line) which shows that the diffracted spectrum is narrower at higher angle beam.

Figure 3. Schematic of the system of Stojanoff et al. [5] for illumination of interiors.

Figure 4. Scheme of the system proposed by Zhang et al. [7].

Figure 5. Scheme of the system proposed by Kostuk et al. [8], with two cascaded gratings, each one diffracting a different spectral range.

Figure 6. (a) Scheme of the system investigated by Castro et al. [9] with two cascaded gratings, so that the system could be efficient for a wide range of illumination direction. (b) A detail of the reconstruction for gratings A and B, which shows that each one works for a range of different directions of illumination.

Figure 7. Schematic of the system proposed by Castillo et al. [11], consisting of two adjacent gratings in combination with a bifacial cell.

Figure 8: Holographic element set-up proposed by Ludman et al. [16]. The diffracted spectrum is split onto cells with different spectral response.

Figure 9. Layout of the system proposed by Zhang et al. [17] using two PV cells.

Figure 10. Schematic of the system proposed by Hsieh et al. [18], where the same holographic element is recorded on different areas of the plate and with a guided reference beam.

Figure 11. Registration and reconstruction under solar illumination by the cylindrical lens proposed by Chemisana et al. [19]

Figure 12. The system proposed by Fröhlich et al. [25] in which two uniaxial compound lenses are combined, each one working to concentrate different bandwidths.

Figure 13. Folder holographic photovoltaic system designed by Wu et al. [35].

Figure 14. Schematic of the hybrid (thermal and photovoltaic) system proposed by Iurevich et al. [36]

Figure 15. Schematic of the solar concentrator proposed by the Andalusian Holographic Institute [39].

Table 1

NON-CONCENTRATING OPTICAL SYSTEMS			
		T / R*	**Main Characteristic**
Single HOE	Kischkoweit-Lopin [2]	T	Building integration: Illumination control
	Papamichael *et al.* [3]	T	Building integration: Illumination control
	Stojanoff *et al.* [21]	R	Building integration: Illumination control and chemical reactors
	Kischkoweit-Lopin [2]	R	Building integration: Illumination control
	James and Bahaj [32]	R	Building integration (greenhouse): Illumination and temperature control
Combined HOEs	Müller [4]	T	Building integration: Illumination control
	Stojanoff *et al.* [5]	T	Building integration: Illumination control

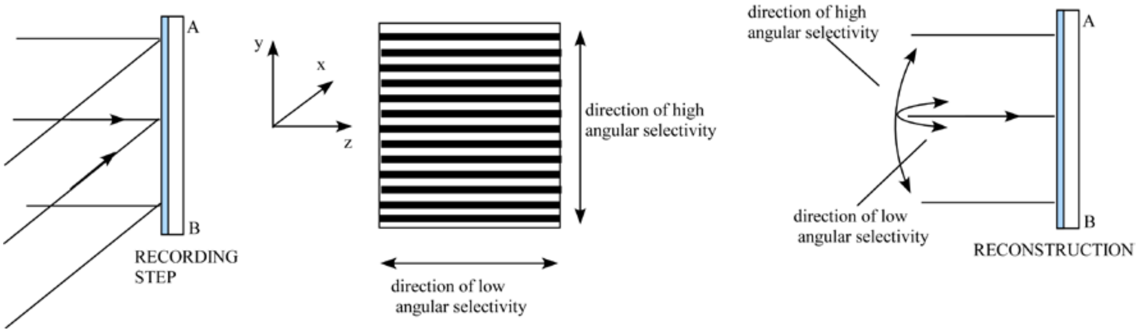
*T: transmission hologram, R: reflection hologram

Table 2

CONCENTRATING OPTICAL SYSTEMS				
		T / R*	**Main Characteristic**	**CR****
Single HOE	Zhang *et. al.* [7]	T	PV generation	2x
	Ludman *et al.* [15, 16]	T	PV generation	20x
	Zhang *et. al.* [17]	T	PV generation	1x (deducted)
	Hsieh *et al.* [18]	T	PV generation	5x
	Müller [4]	T	PV generation/solar shading	Not indicated
	Kischkoweit-Lopin [2]	T	PV generation/solar shading	Not indicated
	Chemisana *et al.* [19]	T	PV generation/building integration	3.5x
	Stojanoff *et al.* [21]	T	Shading and PV generation; parabolic HOE	3x
	Vorndran *et al.* [22]	T	PV generation/chemical reactors	Not indicated
	Quintana *et al.* [34]	R	UV concentration	36x
	Stojanoff *et al.* [21]	R	Photochemical reactor; parabolic HOE	Not indicated
	Wu *et al.* [35]	R	PV generation in 2 spectral bands	2x
	Iurevych *et al.* [36]	R	PV generation and fluid heating	2x
Combined HOEs	Kostuk *et al.*[8]	T	PV generation in 2 spectral bands	Not indicated
	Zhang *et. al.* [7]	T	PV generation/cascaded gratings	2x
	Castro *et al.* [9]	T	PV generation/cascaded gratings	2x
	Kostuk *et al.* [10]	T	PV generation/cascaded gratings	2x
	Castillo *et al.* [11]	T	PV generation with bifacial cells	2x
	Prism Solar [12]	T	PV generation with bifacial cells	2x
	Russo *et al.* [13]	T	PV generation with bifacial cells	2x
	Castillo *et al.* [14]	T	PV generation with bifacial cells	2x
	Ludman [23]	T	Fluid heating	4x
	Xuechang *et al.* [24]	T	PV generation	Not indicated
	Fröhlich *et al.* [25]	T	PV generation in 2 spectral bands	49x
	Stojanoff *et al.* [5]	T	PV generation in 3 spectral bands	Not indicated
	Gordon *et al.* [26]	T	PV generation in 2 spectral bands	2x
	Bloss *et al.* [27]	T	PV generation with 3 multiplexed holographic lenses	100x
	Bainier *et al.* [28]	T	PV generation with 2 multiplexed holographic lenses	Not indicated
	Russo *et al.* [30]	T	PV generation; refractive lens + holographic grating	Not indicated
	Gordon *et al.* [26]	R	PV generation in 2 spectral bands	2x
	Stojanoff *et al.* [33]	R	PV generation with parabolic mirror	Not indicated
	Hull *et al.* [37]	R	PV generation	Not indicated
	Villamarín *et al.* [39]	R	PV generation	3x

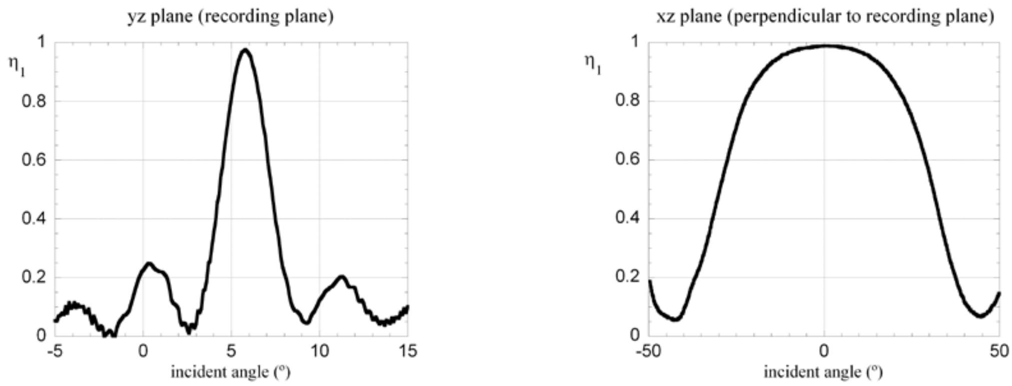
* T: transmission hologram, R: reflection hologram
** CR: geometric concentration ratio

Figure 1



A
B
RECORDING
STEP
y
x
z
direction of high
angular selectivity
direction of low
angular selectivity
direction of high
angular selectivity
direction of low
angular selectivity
A
B
RECONSTRUCTION

(a)



yz plane (recording plane)
η_1
1
0.8
0.6
0.4
0.2
0
-5
0
5
10
15
incident angle (°)
xz plane (perpendicular to recording plane)
η_1
1
0.8
0.6
0.4
0.2
0
-50
0
50
incident angle (°)

(b)

Figure 2

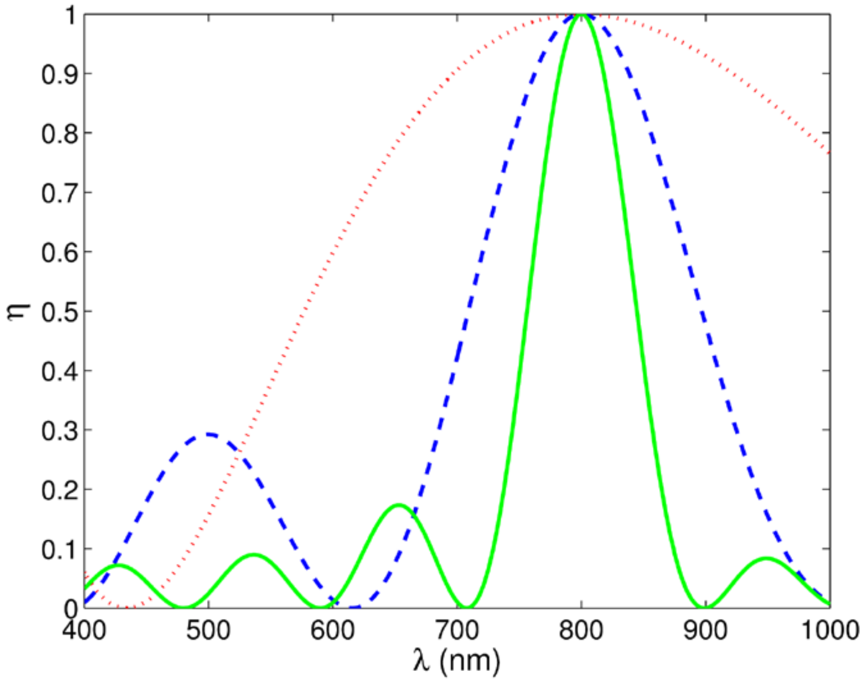


Figure 3

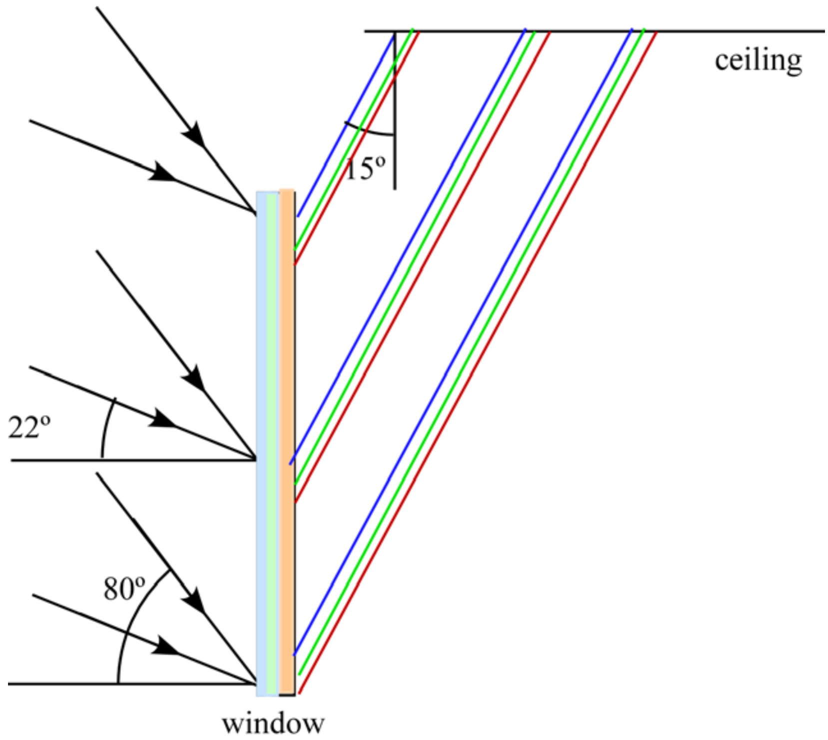


Figure 4

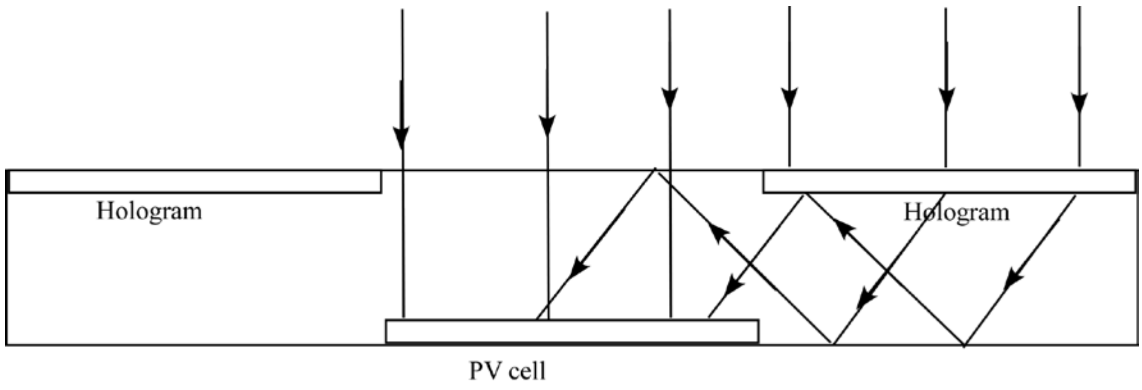


Figure 5

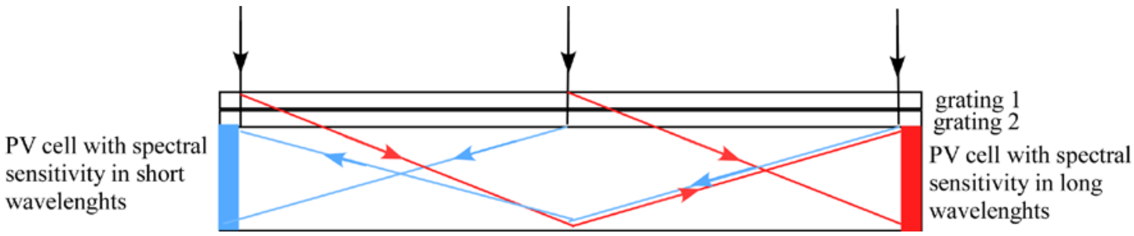

grating 1
grating 2
PV cell with spectral sensitivity in short wavelenghts
PV cell with spectral sensitivity in long wavelenghts

Figure 6

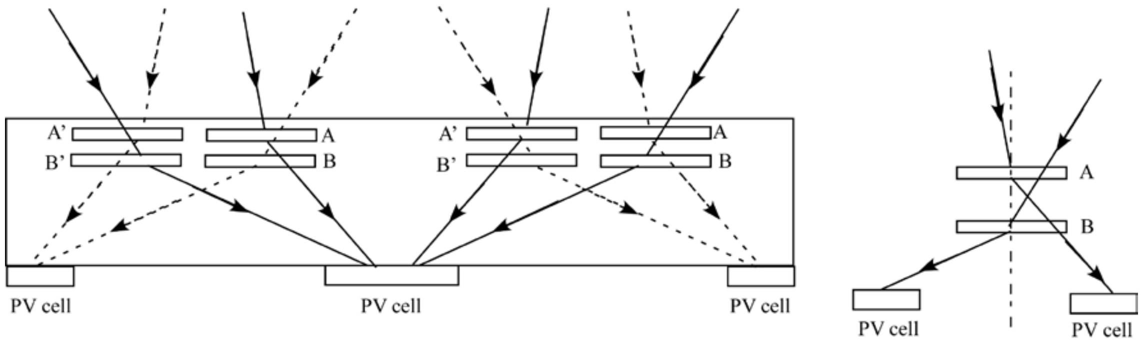


Figure 7

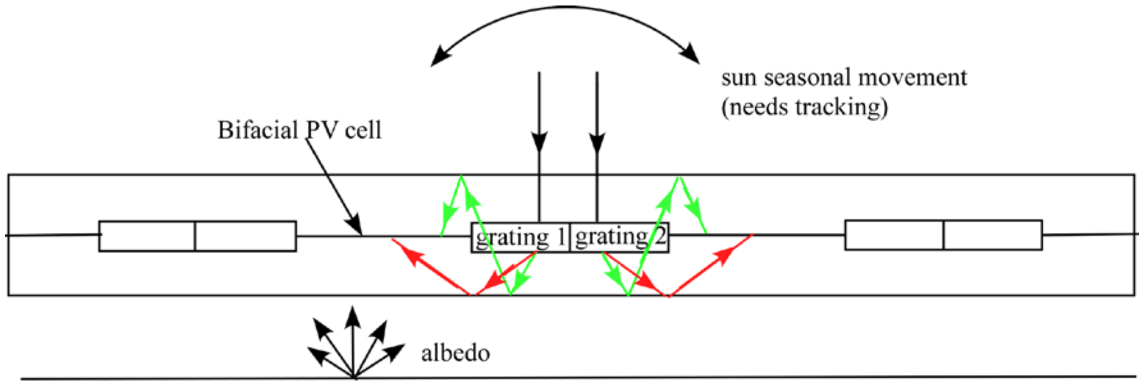

sun seasonal movement
(needs tracking)
Bifacial PV cell
grating 1
grating 2
albedo

Figure 8

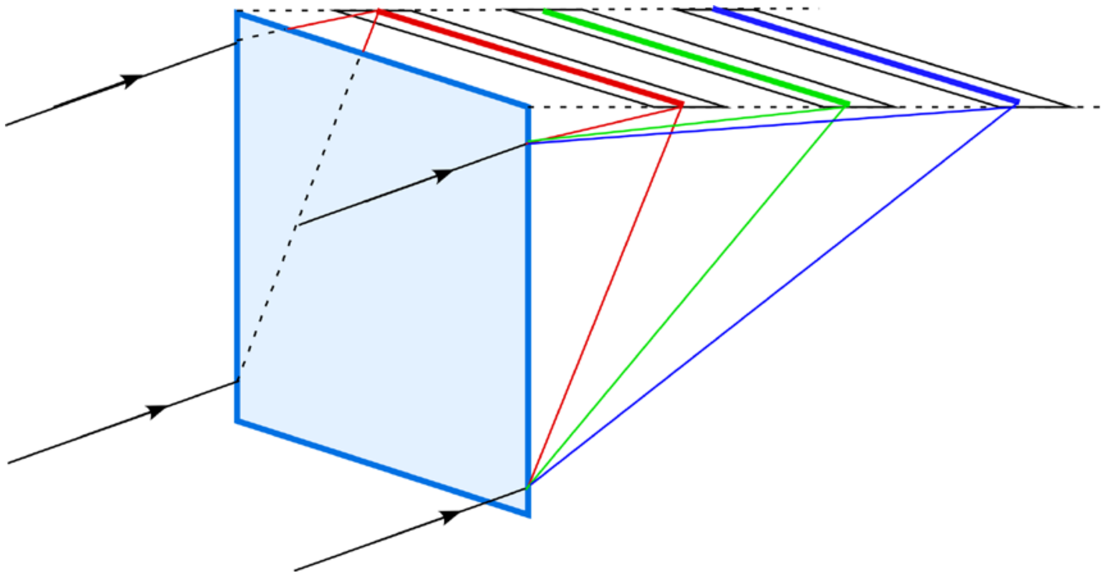


Figure 9

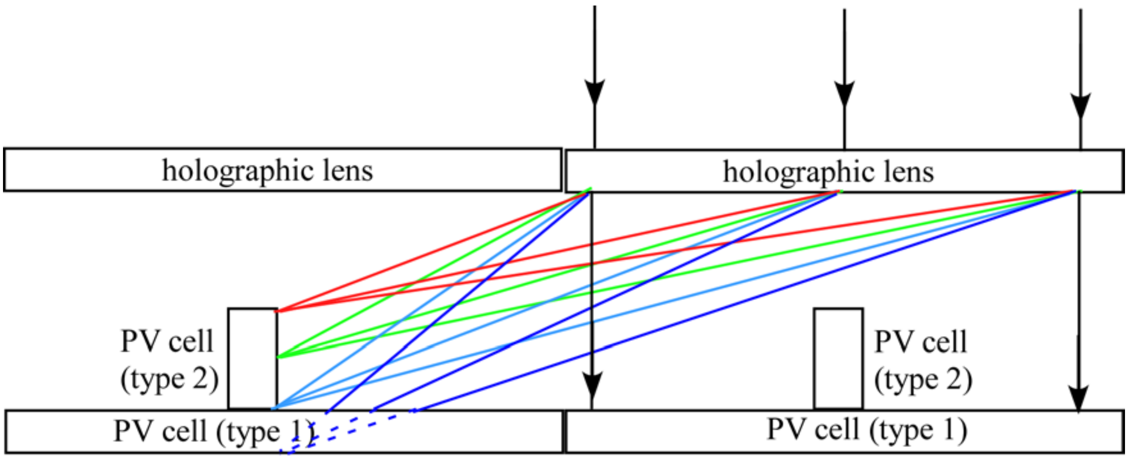
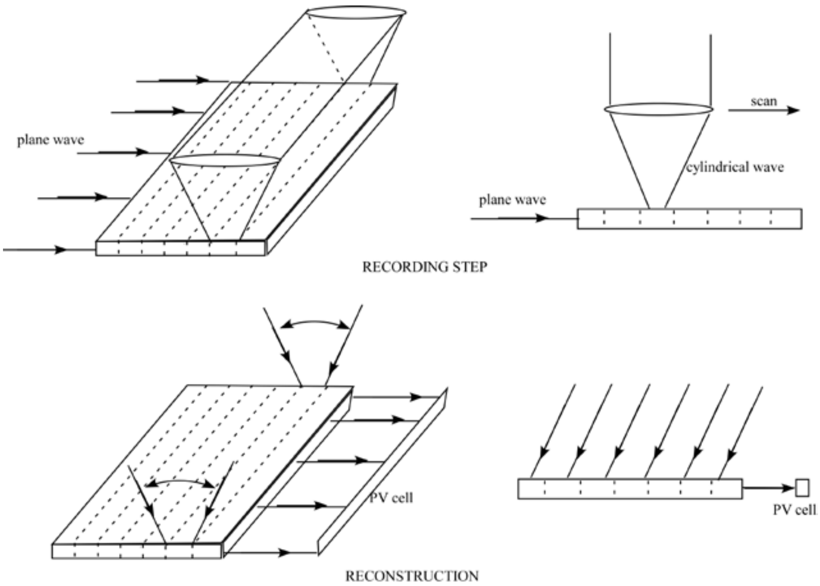

holographic lens
holographic lens
PV cell
(type 2)
PV cell
(type 2)
PV cell (type 1)
PV cell (type 1)

Figure 10



plane wave
scan
cylindrical wave
plane wave
RECORDING STEP
PV cell
PV cell
RECONSTRUCTION

Figure 11

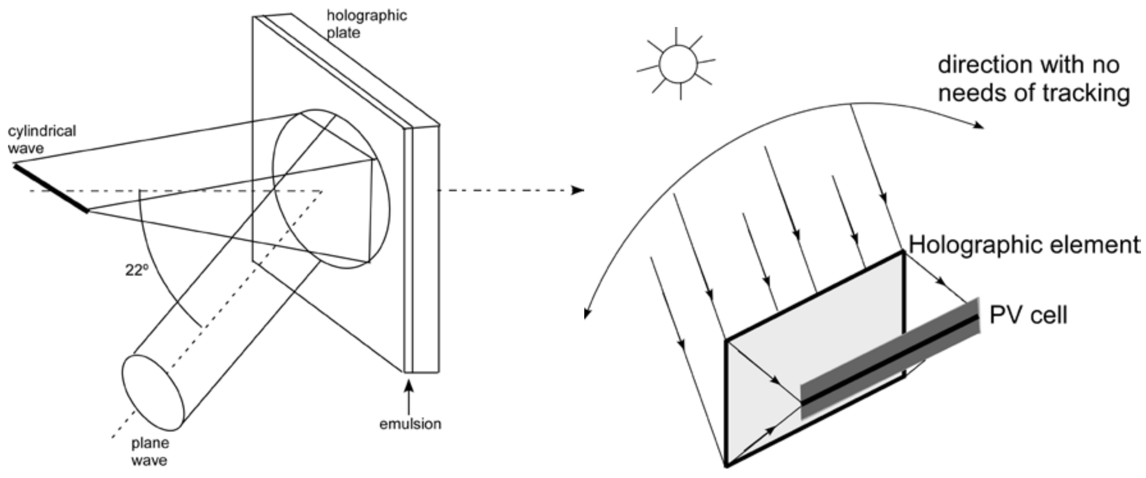

holographic
plate
cylindrical
wave
22º
plane
wave
emulsion
direction with no
needs of tracking
Holographic element
PV cell

Figure 12

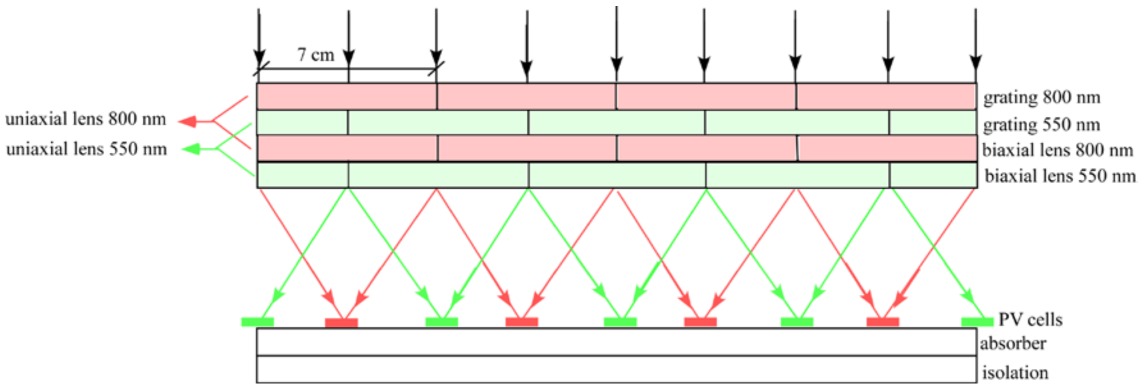

7 cm
uniaxial lens 800 nm
uniaxial lens 550 nm
grating 800 nm
grating 550 nm
biaxial lens 800 nm
biaxial lens 550 nm
PV cells
absorber
isolation

Figure 13

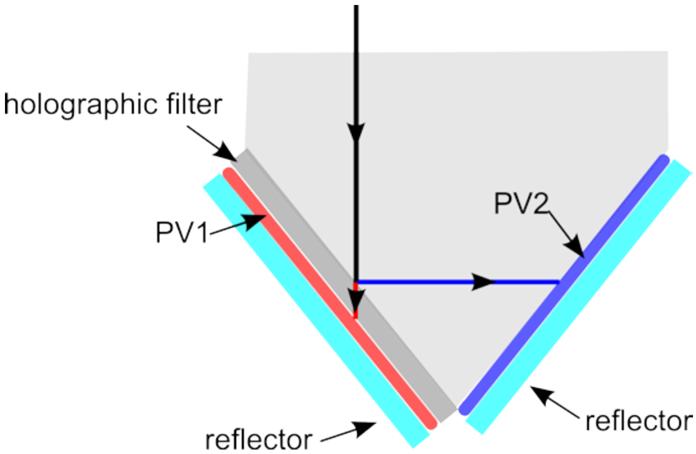


Figure 14

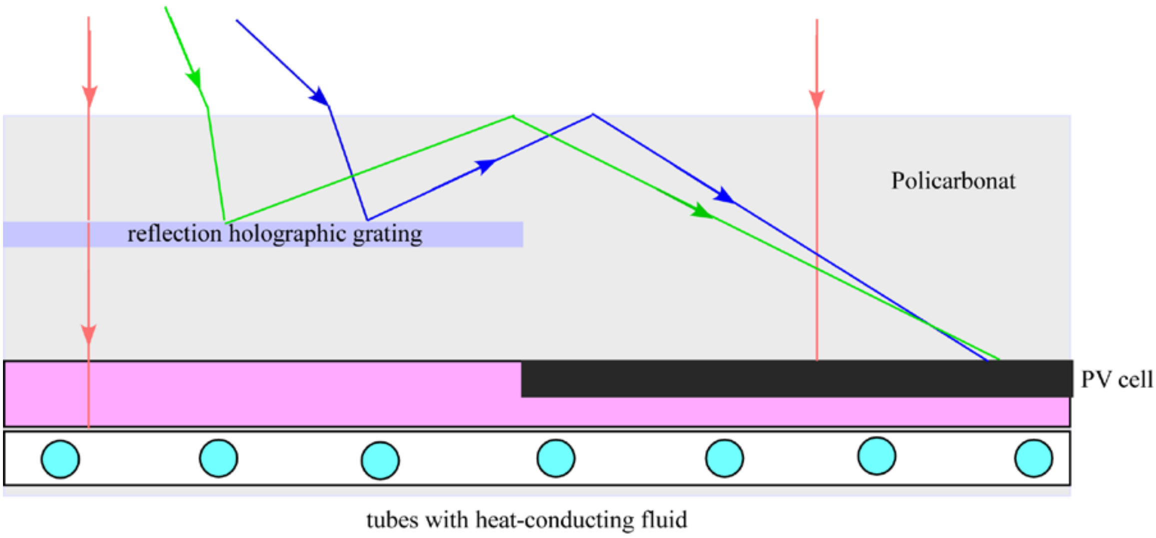
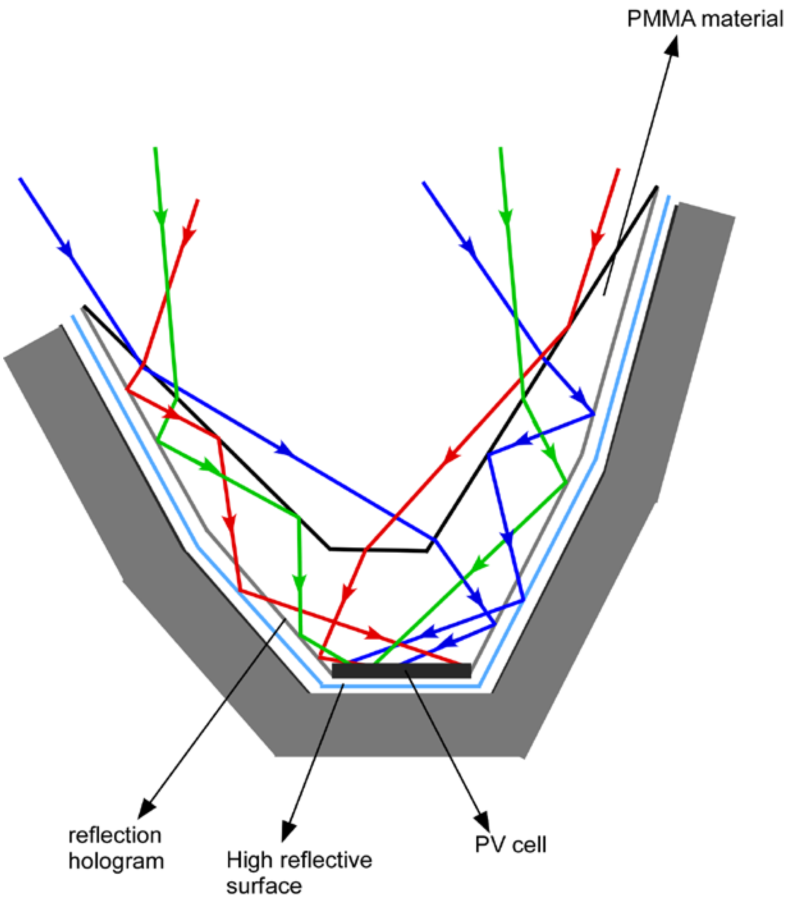

Policarbonat
reflection holographic grating
PV cell
tubes with heat-conducting fluid

Figure 15


PMMA material
reflection hologram
High reflective surface
PV cell