Chapter 6

Photopolymer Holographic Optical Elements for Application in Solar Energy Concentrators

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1. Introduction

Making use of the sun's radiation as an alternate energy resource has become increasingly worthwhile in recent years both on a domestic and large industrial scale. Rooftop solar collectors for domestic water heating are now common even in regions where direct sunlight is somewhat limited, and large installations for commercial electricity generation are increasing in sunnier climates. In 2010 in the US there was a 45% increase in the number of grid connected photovoltaic systems installed compared to the preceding year, raising the cumulative grid-connected capacity to 2.15 GW_{dc}. In the same year, the largest solar concentrating plant since the 1980s (75 MW_{a}) was completed in Florida [1].

There are three key technologies for the conversion of solar energy; thermal heating, photovoltaic and thermal to electric.

In thermal heating systems, water is heated directly or indirectly by the sun, typically in insulated tubing on the premises roof, and used for domestic or sometimes for commercial water heating. Photovoltaic cells generate electricity directly and are widely used in domestic and commercial applications.

Thermal to electric involves mechanical heat engines and requires higher temperatures, so to date it has been mostly used in large scale commercial generation plants where concentrating collectors can be used.

However availability of new materials and technologies currently under development may well change the applicability of each technology. For example, a recent paper in Nature[2] describes the use of nanostructured thermoelectric materials and spectrally selective solar absorbers in a solar thermal to electric power conversion system. This has efficiency 7–8 times greater than the previously reported best value for a flat-panel solar thermal to electric (STEG) system and could lead to a much wider use of STEG systems.

Solar collector technologies in current use can be divided into concentrating and non-concentrating types. Concentrators have obvious advantages where the solar conversion surface is expensive (photovoltaics) or requires high temperatures to work efficiently (thermal to electric systems). The most common concentrators currently used in commercial systems are either cylindrical or hemispherical reflectors. They concentrate the light by reflectance off a curved surface either to a line or spot where the solar energy is converted.

The holographic equivalent is a concentrating diffractive optical element, or holographic lens, which will focus the collected light in a similar fashion.

2. Solar application for holographic optical elements

Holographic Optical Elements (HOE) have also been studied for controlling and directing the radiation of the sun with high potential for energy saving.

Photovoltaic energy conversion is very suitable for solar energy generation but the main disadvantage of photovoltaic electrical energy generation is the cost.

In order to solve this problem a significant amount of expensive photovoltaic material can be replaced by an optical concentrator. By providing complex optical functions in thin, low cost layers which can be used with other PV components, benefits could be expected.

HOEs are very good examples of optical concentrators and have been suggested for use as solar concentrators [3]. HOEs are produced by dividing coherent light into monochromic waves with the same polarization and equal intensities. An optical lens is placed in one of the beams and focuses the incident beam; the HOE can be recorded where two beams overlap with each other. HOEs have several unique features such as ability to diffract light through a large angle, and Bragg selectivity. They also have the potential for multifunctionality by multiplexing a number of optical components in the same layer. They are thin, flat and lightweight, making HOEs attractive for solar collector/ concentrator devices.

Another type of HOE has been used for window shading in buildings with a defined orientation [4, 5]; the holograms have been designed and produced to shade the windows of a building with a facade facing 56º east of south. HOEs were recorded at 45º and 60º and tested in a solar simulator for an entire year. The test revealed that the maximum illumination took place at 11 a.m. Comparison of the spectral characteristics proved that the HOES recorded at 45 º are more suitable for window shading. Due to the ammonium dichromate in the HOEs they showed some absorption in the blue spectral range and due to iron ions (which can be found in standard green glass) they showed some absorption in the red.

3. Advantages of HOE solar energy concentrators

The collection of light from a moving source (such as sun) which exhibits a broad spectral range of wavelengths is a complex process. HOEs have the capability to perform a range of functions in one element thus providing a potential solution to this problem without the need for tracking or mechanical movement.

Holographic solar concentrators can use flat optics for the collection of sunlight because they can be designed to have a very wide field of view which would make them attractive for improving power conversion efficiencies in energy conversion devices which have fixed orientations and locations.

HOEs can be designed to redirect, concentrate or block the incident light, such as that from the sun. They may also be designed for wavelength selectivity, so a range of wavelengths can be directed to one position while other wavelengths go to another position and the diffracted light can be focussed in one spot [6, 7].

4. Types of HOEs

Depending on their effect on the incident light holographic optical elements for use in solar energy collection can be classified as:

- Non focussing elements: optical elements that are used simply to redirect light;
- Focussing elements: optical elements that produce a converging wavefront, having the same effect as spherical or cylindrical lenses. The focal length can vary depending on the devices; they can have a dual role in solar collectors by focusing the light and redirecting the beam.

Depending on the geometry of the recording, HOEs can be classified as:

- Reflection HOEs: The incident beam and the diffracted beam propagate on the same side of the hologram; they allow diffuse light to be transmitted whilst the direct beam is diffracted.

In this type of HOE the fringes due to interference between the recording light beams, form planes that are usually parallel to the recording material surface. The spacing between fringes depends on the angular separation between the reference beam and the object beam and on the wavelength of the recording light.

- Transmission HOEs: In a transmission HOE the incident and the diffracted beams are both transmitted through the optical element. The fringes due to interference between the recording light beams can be perpendicular to the layer surface (unslanted gratings) or at an angle (slanted gratings). As in the case of the reflection gratings the spacing between the interference fringes depends on the angle between the two recording beams and the wavelength of recording light.

5. HOEs used in solar concentrators

Prism Solar Technologies manufacture a solar cell concentrator which at present has a limited bandwidth and low conversion efficiency [8]. The sunlight is reflected and concentrated onto the photovoltaic cell (PV) with all components supported by a substrate. The HOE reflector is placed in a waveguide. The waveguide has been used in this application to receive the sunlight and redirect it to the PV cell. The concentrators produce uncompensated aberration such as dispersion and wavelength shift produced by the reflector, so that the spectral bandwidth of reflected band may not be precisely matched to the energy band gaps of the PV solar cells.

Another application of HOEs in light harvesting that could be useful in solar energy collection is reported in [9]. Holographic diffractive optical elements were used in order to increase the light collection from fluorescence-based biochips. The HOEs increased the transmitted fluorescence intensity and also served to filter out the undesired wavelengths. This was possible due to their high angular selectivity. The diffracted intensity of the HOE was measured to be about 50% of that of the incident beam. The diffraction efficiency was relatively low due to a complexity of the recording process that covers a large spatial frequency range (0-2800 lines/mm). It was found that the HOE can collect fluorescent light coming from a spot with the same size as that of the HOE.

Another example of holographic solar application described in [10] uses a sensor and feedback system to maintain 0.5 degree tracking accuracy with one-axis tracking holographic planar concentrators (HPCs). It was found that in the polar one-axis tracking HPC system the efficiency increases by 43.8% compared to non tracking HPC systems due to high overall module optical efficiency and higher levels of irradiance.

Dispersive concentrating systems based on transmission phase HOEs for solar applications are reported in [2]. The authors demonstrate that volume based transmission HOEs can be used advantageously in solar concentrators due to their high diffraction efficiency, low absorption and adjustable dispersion. The ratio of diffracted intensity to incident beam intensity is defined as diffraction efficiency. In solar applications the measurement of the diffraction efficiency as a function of wavelength is essential. The transmissivity of HOEs as a function of wavelength was measured when white light illuminated the phase holograms and due to diffraction the light was split spatially and spectrally. It was determined that a minimum angle of 20° is required between the recording beams for achieving high diffraction efficiency in one diffraction order so that only an off-axis zone plate was suitable. A zone plate with diameter of 8 cm and a focal length of 25 cm was recorded at 488 nm wavelength. The diffraction of efficiency of the recorded zone plate was about 70% for monochromatic light. The shrinkage of the gelatin layer caused a change in the Bragg angle depending on the shape of recorded interference patterns and the intensities of the recording beams.

Volume HOES are suitable for multiplexing; a range of HOES with various angles between the recording beams can be recorded in one photosensitive layer and this allows spatial separation of the red and the blue spectral ranges of sunlight into different areas. Three solar cell systems with various band gaps and multiplexed HOEs were tested [3]. The maximum

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efficiency achieved was 42% since the concentration ratio for diffracted wavelengths was about c= 100.

Holographic solar concentrators have been theoretically modelled [11] and several useful aspects of holographic gratings have been investigated for use in solar concentrator applications. The basic relationships for designing holographic elements have also been presented.

A solar radiation receiver is described in [12]. This combined system uses a holographic film to concentrate the solar radiation and to optimize the efficiency of the sensor. A mathematical model is used to calculate the Volt-Ampere behaviour and the thermal and photovoltaic efficiencies to demonstrate the advantages of the suggested system.

The design and optimization of photopolymer based holographic solar concentrators was recently reported in [13]. The authors demonstrated the recording of broad band spectrally splitting holographic solar concentrator in HoloMer photopolymer material with an efficiency of 70% and an average efficiency of 56.6% for a wavelength range from 633nm to 442 nm. The recorded elements showed a narrow angular selectivity hence tracking would be required for an effective photovoltaic concentrator system.

A simple technique to realize a compact and nearly all-angle solar energy concentrator using a volume holographic element is presented in [14]. The theoretical modelling of the HOE predicts up to a fivefold concentration of energy per unit area of photovoltaic material.

In the following section we present experimental results from the recording of simple focusing holographic optical elements in a photopolymer layer, namely a spherical lens and a cylindrical lens. Furthermore we have explored the possibility of multiplexing a number of elements in the same layer.

6. Experimental

6.1. Photopolymer solution preparation

The photosensitive layer was prepared as previously described [15]. Briefly, 2ml of triethanolamine was added to 17.5 ml stock solution of polyvinyl alcohol (PVA) (10% w/w). Then the monomers, 0.6g acrylamide and 0.2 g of N,N Methylene bisacrylamide and 2ml of initiator, TEA, were added. Finally, 4ml of Erythrosin B dye was added (stock solution concentration - 1.1mM) to sensitise at 532 nm. The solution was made up to 25ml by adding distilled water. Methylene blue sensitised samples of thickness 50 μm were used to record at 633nm.

6.2. Layer preparation

Different amounts of photopolymer solution were spread evenly on a 50x50 mm^2 glass plate placed on a levelled surface and allowed to dry. This resulted in layers of thickness varying between 50 and 120 μm. The drying time was usually 18-24 hours.

6.3. Recording of HOE consisting of a single optical component

A standard holographic optical setup (Fig.1) was used to record transmission gratings and lenses using a 532nm Nd:YVO_4 laser. The recording intensity was controlled by a variable neutral density filter. The inter-beam angle was adjusted to be 9 degrees in order to obtain a spatial frequency of recording of 300 lines/mm. At the end of the holographic recording, the focusing beam was blocked and the collimated beam was used to probe the recorded HOE. The intensity of the diffracted beam was measured using an optical power meter (Newport 1830-C) to determine the diffraction efficiency of the recorded grating or lens respectively.

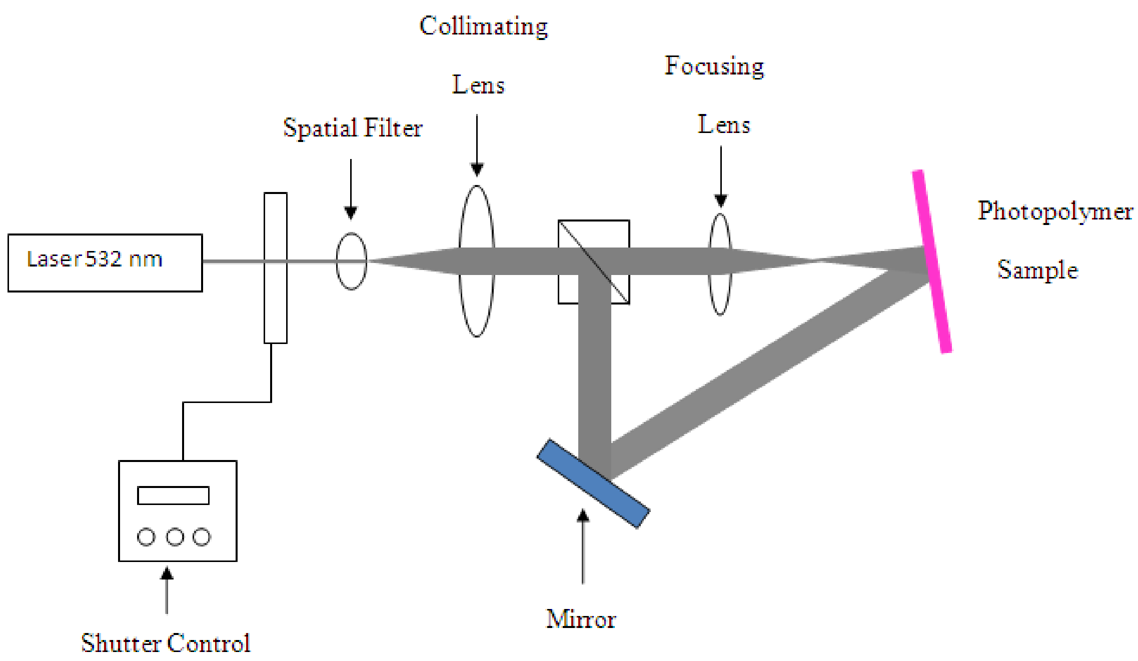

Figure 1. Optical set-up for recording of a single lens HOE.

The recording set up at 633 nm was similar to that shown in Fig. 1. A single off-axis HOE of focal length 5 cm was recorded. The recording intensity of the beams was 1 mW/cm^2 and the average spatial frequency of recording was 650 l/mm.

6.4. Recording of HOEs by multiplexing

The aim of this experiment was to record a holographic optical element which would direct the light in a fixed direction independently of the direction of incoming light.

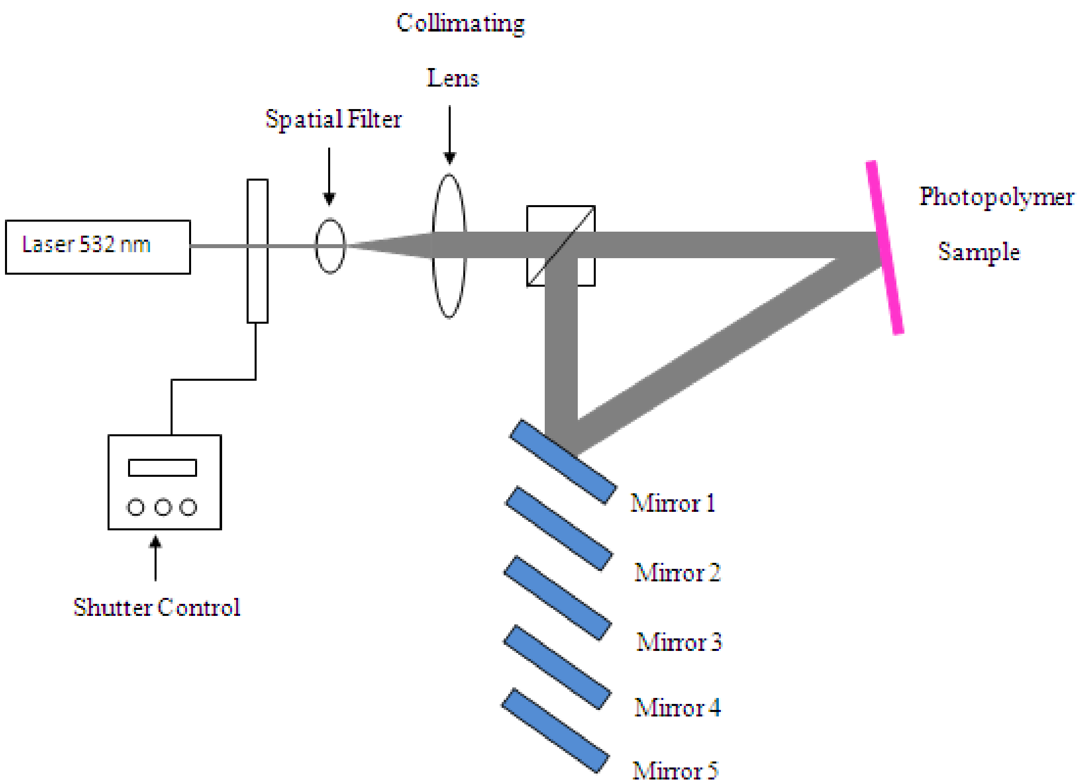

Figure 2. Optical set-up for recording multiplexed HOEs in this case - diffraction gratings of different spatial frequencies. B S (Beam Splitter), C L (Collimating Lens), S F (Spatial Filter), P S (Photopolymer Sample)

Figure 2 shows the experimental set up for the recording of multiplexed transmission gratings. The photopolymer sample was kept at a fixed distance from the beam splitter and the reference beam was varied in direction by using five mirrors fixed at different distances from the beam splitter to reflect the light onto the photopolymer layer. The photopolymer sample was adjusted so that the object beam and the reference beam from mirror 5 overlapped in the plane of the photosensitive medium with the sample normal bisecting the interbeam angle. This ensured the grating was unslanted when recorded by the beam reflected by mirror 5 and the beam transmitted by the beam splitter. The gratings were recorded in the same photopolymer layer starting with the lowest spatial frequency (mirror1). Mirror 1 was then removed and the next grating was recorded in the same area by the light reflected onto the photopolymer layer from mirror 2 and the light transmitted by the beam splitter. This procedure was repeated for the other three mirrors, with mirror 5 corresponding to the largest spatial frequency. Cylindrical lenses were also recorded in the same volume of the recording medium using a cylindrical lens of 15 cm focal length placed in the path of the beam transmitted by the beam splitter so that this light was focused into a thin line just behind the photopolymer sample. In order to find the optimum recording conditions for HOEs with equal diffraction efficiencies the transmission gratings were recorded in two ways. First, the intensity was kept constant and the exposure time varied from one recording to the next. The second approach was to keep the exposure time constant and vary the intensity. The recorded HOEs initially consisted of three gratings utilising mirrors M1, M2 and M5 and then five gratings utilising all five mirrors (M1, M2, M3, M4 and M5).

The spatial frequencies of the recorded gratings using the different mirrors in the recording set up were respectively: M1- 450 lines/mm; M2 - 1065 lines/mm; M3 -1295 lines/mm; M4 -1470 lines/mm and M5 -1700 lines/mm.

6.5. Characterisation of the recorded HOEs

Two procedures were used in order to measure the maximum diffraction efficiencies (η) of the HOEs at different spatial frequencies.

Probing the recorded holograms using Nd:YVO_4 laser beam (532nm)

After the recording of the transmission gratings with the photopolymer sample fixed in the same position, one of the recording beams was stopped and the HOE was illuminated only with the other recording beam, but with intensity much less than that used to record the grating, in order to avoid further polymerization. A photo detector was used to measure the intensities of the diffracted beam, the incident beam and the beam reflected from the photopolymer surface.

The percentage diffraction efficiency (η) was calculated from the equation

$$\eta = \frac{I_d}{I_1 - I_r} \times 100. \tag{1}$$

where I_1 is the intensity of the incident beam, I_d is the intensity of the diffracted beam and I_r is the intensity of the beam reflected from the front photopolymer surface.

Probing the recorded holograms using a Helium-Neon laser (633nm)

Figure 3 shows the experimental set up for measuring the diffraction efficiencies using a Helium-Neon laser beam that has a much smaller diameter than that of the HOE. The Helium-Neon laser was positioned so that it probed the centre of the HOE that was recorded on the photopolymer layer. The photopolymer is not sensitive to light of wavelength 633 nm, therefore further polymerisation does not occur. The photopolymer sample was rotated until the maximum diffracted intensity of the laser beam was observed on a screen behind the photopolymer. The angle of incidence of the probe beam at which the maximum diffraction efficiency is obtained is known as the Bragg angle.

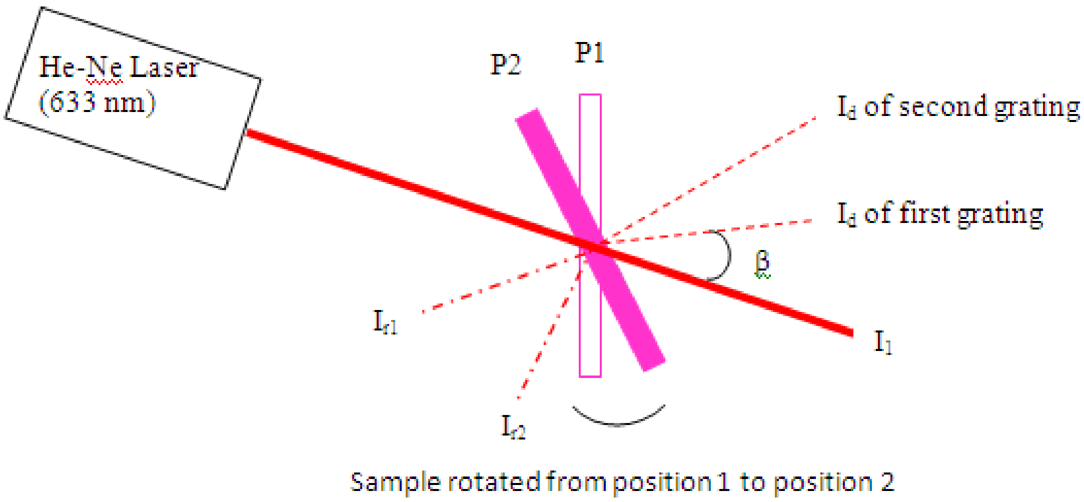

Figure 3. Characterisation of the HOE at 633nm. I_1 is the intensity of the probe beam,

I_d the intensity of the reconstructed or diffracted beam and I_r the intensity of the beam reflected from the photopolymer surface.

The intensity I_d was measured using a photo detector, and equation (1) was used to calculate the diffraction efficiency. In the case of multiplexed gratings the value of I_d for each grating was measured in turn by further rotation of sample until the diffracted intensity maximum for each was obtained at the appropriate Bragg angle.

7. Results and discussion

7.1. Recording of focusing HOEs

The diffraction efficiency of a single lens recorded in a red sensitive layer of thickness of 50 μm as a function of recording time is presented in Fig. 4. It is seen that the maximum diffraction efficiency is nearly 45 % and it is reached after 100 s exposure time.

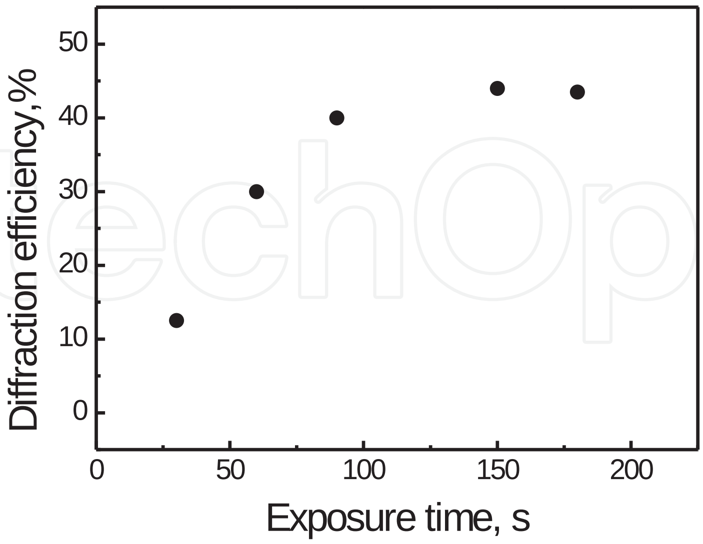

Figure 4. Diffraction efficiencies of single lenses recorded in 50 micrometer layers. Recording wavelength was 633 nm. Recording frequency was 650 l/mm and recording intensity was 1 mW/cm^2.

Much higher diffraction efficiency was achieved in green sensitised layers of thickness 50 μm (Fig.5). The total recording intensity of the beams was 1 mW/cm^2. The spatial frequency of recording was 300 l/mm.

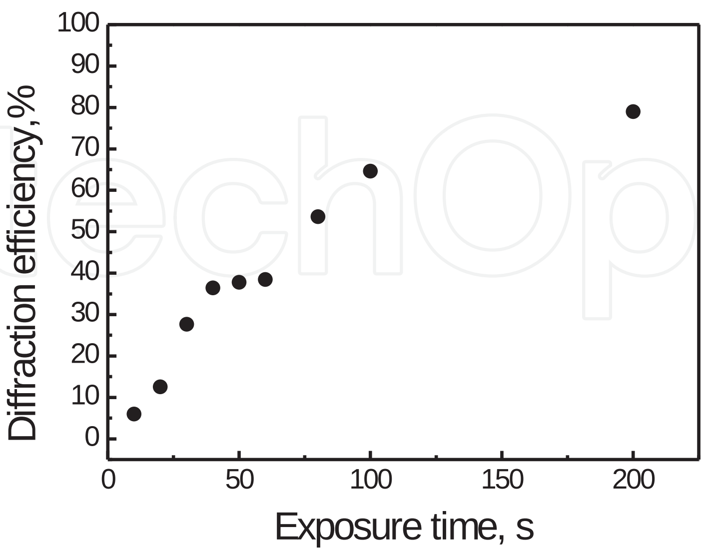

Figure 5. Diffraction efficiency of gratings recorded in 50 μm layers. Recording wavelength was 532 nm.

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7.2. Recording of three multiplexed holographic gratings

Initial experiments were carried out in layers of thickness of 100 μm. In order to find the optimum exposure times required to obtain gratings with diffraction efficiency above 50 %, gratings were separately recorded at 1000, 1500 and 2000 l/mm. At the next stage of the experiment, three gratings of spatial frequencies 2000, 1500 and 1000 l/mm were recorded in the same volume of the recording medium, first by using the measured recording times required to achieve 50% diffraction efficiency at each of the spatial frequencies. This produced gratings with unequal diffraction efficiencies. In order to equalize the diffraction efficiency of the gratings the recording time was varied. The diffraction efficiencies of previously recorded gratings were measured after each exposure to observe how the recording of the gratings at 1500lines/mm and 1000 lines/mm affected the grating recorded at 2000 lines/mm.

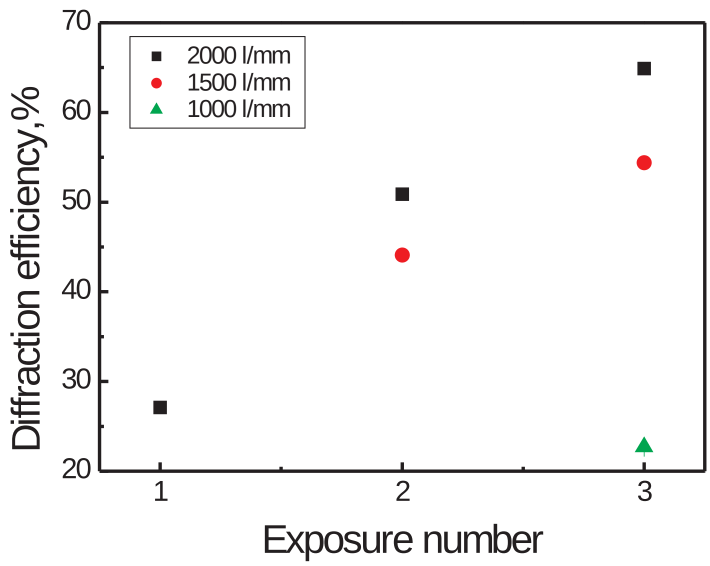

Figure 6. Diffraction efficiency of three gratings multiplexed in the same region of a photopolymer layer of thickness 100 μm.

It is seen from Fig. 6 that the recording of the grating at 1500 lines/mm had a large effect on the diffraction efficiency of the grating previously recorded at 2000 lines/mm. The diffraction efficiency at 2000 lines/mm increased by 23.8% after the recording of the second grating at 1500 lines/mm. It increased a further 14% due to the recording of the third grating at 1000 lines/mm. This shows that the recording of a grating affects the diffraction efficiency of a previously recorded grating. This must be taken into account when the exposure schedule for equalization of the diffraction efficiencies is developed.

This procedure was repeated several times by varying the exposure times, but it was not possible to equalise the diffraction efficiencies of the three gratings and to achieve diffraction efficiency above 50% for all three of them.. From Fig. 6 is seen that the maximum diffraction efficiencies measured at spatial frequencies of 1500 lines/mm and 2000 lines/mm were greater than the set target of 50%. The lower diffraction efficiency at 1000lines/mm was assumed to be due to the dynamic range of the photopolymer layer being consumed.

In order to achieve gratings with diffraction efficiency higher than 50% layers with greater thickness and dynamic range were prepared. The next set of gratings was recorded in layers of 120 μm thickness.

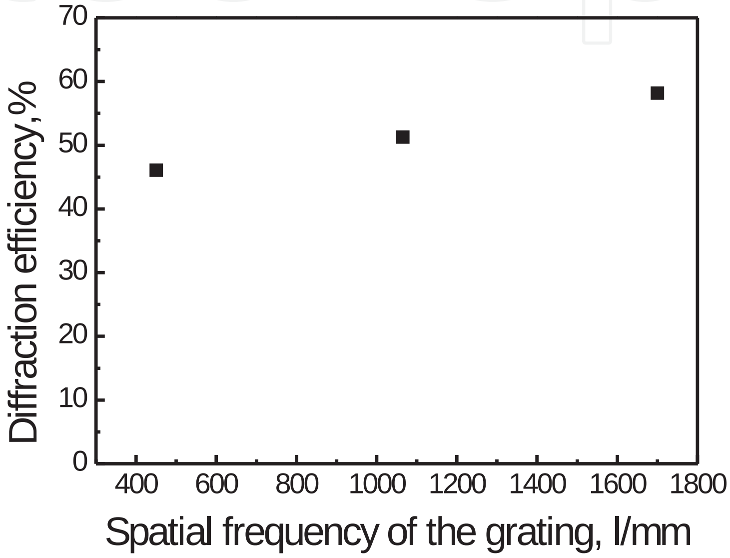

Figure 7. Diffraction efficiency of three gratings multiplexed in the same region of a photopolymer layer of thickness 120 μm.

It can be observed in Fig.7 that the three gratings of different spatial frequencies were successfully recorded with nearly equal diffraction efficiencies around 50%. This confirmed the assumption that in the thinner layers the main obstacle to equalising the gratings with diffraction efficiencies above 50% was insufficient dynamic range of the photopolymer layer. The order of recording and corresponding exposure times for the three gratings were 450, 1065 and 1700 l/mm and 2, 4 and 18 seconds.

7.3. Recording of five multiplexed holographic gratings

After successfully multiplexing three gratings in the same layer the next step was to try to increase the number of holograms and in this way to increase the number of solar light incidence angles that can be exploited. The aim of this experiment was to obtain optimum diffraction efficiencies from five gratings recorded in the same volume of the recording medium. This was achieved by using two different recording conditions, constant intensity with variable expsosure time and constant exposure time with variable intensity. The experimental set-up used was as shown in Fig. 2. The diffraction efficiencies were measured using a He-Ne laser.

The results of these experiments are represented in Fig. 8.

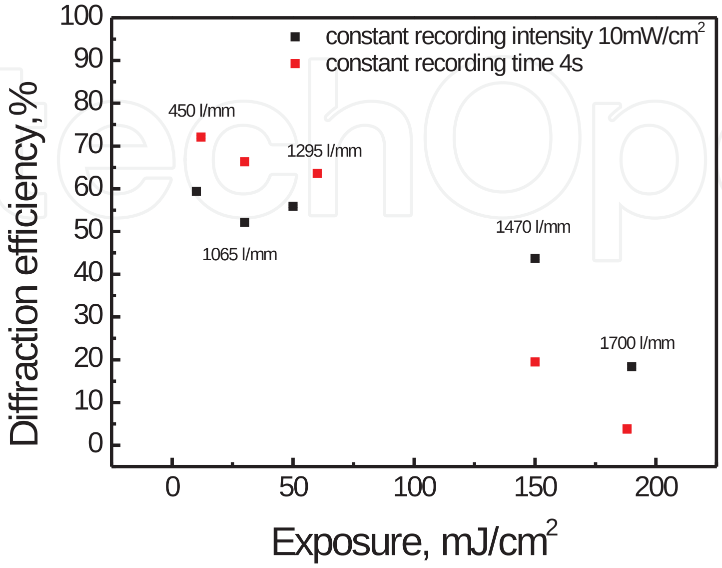

Figure 8. Diffraction efficiencies of five multiplexed gratings recorded by using two exposure schedules- constant exposure intensity of 10 mW/cm² (black symbols) with variable exposure time and constant exposure time of 4s (red symbols) with variable intensity. The order of recording and the exposure times and intensities are given in Table 1.

		Constant Intensity of 10mW/cm²		Constant Exposure time of 4 s	
Grating No.	Spatial Frequency l/mm	Exposure time, s	Exposure energy mJ/cm²	Exposure energy mJ/cm²	Exposure Intensity, mW/cm²
1	450	1	10	12	3
2	1065	3	30	30	7.5
3	1295	5	50	60	15
4	1470	15	150	150	37.5
5	1700	19	190	188	47

Table 1. Exposure time and intensity for recording of the five multiplexed gratings.

From Fig.8 it is seen that recording the gratings with constant intensity produced less variation in the diffraction efficiencies of the recorded gratings. In both cases the dynamic range of the layer is insufficient to produce all five gratings with high diffraction efficiency..

7.4. Recording of five multiplexed holographic lenses

The method of varying the exposure time for the recording of the gratings was repeated with a cylindrical lens in the path of the beam transmitted by the beamsplitter focussing the beam into a long narrow line. The diffraction efficiencies were measured using the He-Ne laser and compared with the diffraction efficiencies measured for gratings recorded under the same conditions with two collimated beams (Fig. 9).

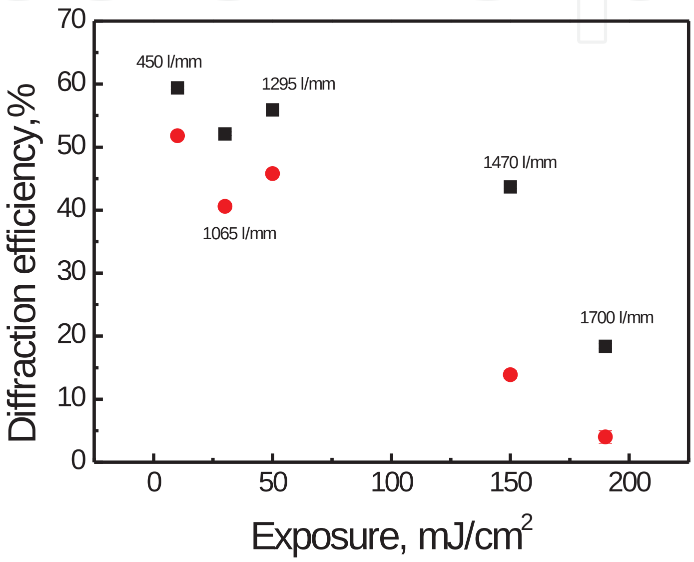

Figure 9. Comparison of the diffraction efficiencies of HOEs of five multiplexed gratings (squares) and five multiplexed lenses (circles).

From Fig. 9 it is seen that the diffraction efficiencies of the first three gratings (recorded at low spatial frequencies) were around the same value above 50% and that the diffraction efficiency is lower for the last two gratings recorded at larger spatial frequencies.

In a further experiment just four lenses instead of five were recorded to reduce the risk of the dynamic range being consumed. The recording conditions were optimised again (Table 2) and are presented in Fig. 10.

		Constant Exposure time of 4 s	
Lenses No.	**Spatial Frequency l/mm**	**Exposure energy mJ/cm²**	**Exposure Intensity, mW/cm²**
1	450	6	1.5
2	1065	13	3.2
3	1295	60	15
4	1700	160	40

Table 2. Recording conditions for multiplexing of four cylindrical lenses in a 120 μm thick photopolymer layer.

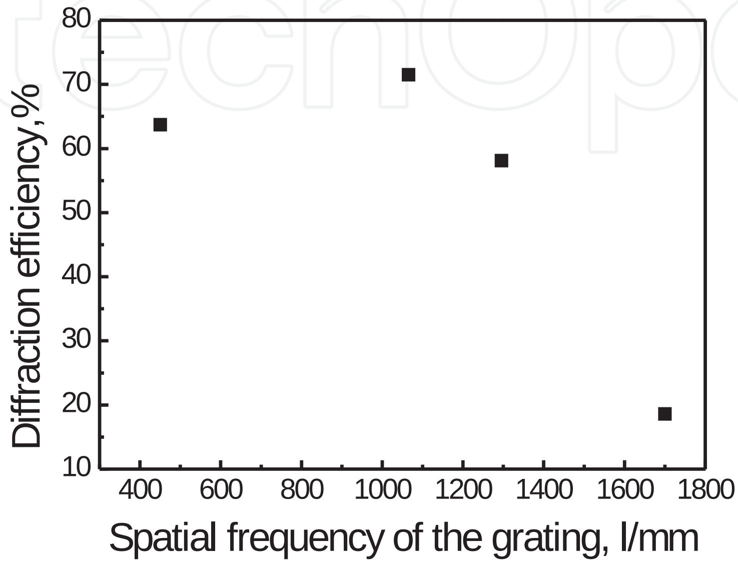

Figure 10. Diffraction efficiencies of multiplexed holographic cylindrical lenses.

8. Conclusions

It was demonstrated that high diffraction efficiency HOE consisting of a single spherical lens can be recorded in a relatively thin photopolymer layer of 50 μm thickness. The advantage of using thin layers and lower spatial frequency of recording in this application is the larger acceptance angle of the optical component.

It was possible to equalise the diffraction efficiencies of three multiplexed gratings at 51.9±3.5 %.

A study of the influence of the exposure schedule – keeping the intensity constant and changing the time or keeping the exposure time constant and varying the intensity, revealed that the first schedule delivered better equalisation of the diffraction efficiency.

Three HOEs - containing five gratings with a range of spatial frequencies from 450 to 1700 l/mm, five cylindrical lenses and four cylindrical lenses, were successfully recorded in the same photopolymer layer. These can be considered as successful first steps in the design and fabrication of holographic solar concentrators fabricated in acrylamide based photopolymer.

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