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Design and Study of Acrylamide-based Photopolymer Holographic Optical Elements for Solar Application

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1. INTRODUCTION

Currently the world energy usage is 10 TW per year; this is presently supplied by conventional energy resources (fossils fuels etc). By the year 2050 this value is projected to triple to approximately 30 (TW) [1]. Since the fossil fuel resource is depleting rapidly, it is important to find a technology which can meet the ever increasing demand of energy. Solar energy is an attractive renewable energy source as it is a carbon emission free technology.

In order to convert solar energy into usable energy, photo-thermal, photo-chemical and photovoltaic systems can be used. The photo-thermal systems heat up water using sunlight; in photochemical systems the energy in the photon is used to start a chemical reaction; in photovoltaic systems the sun energy is converted into electricity. The photovoltaic solar cells however, are expensive. The proposed use of holographic optical elements in solar concentrators can minimize the amount of expensive photovoltaic material used in solar cells by providing low cost layers which can collect light from a larger area and directs it towards the PV material. HOEs are attractive for use in solar collector/concentrator as they are thin, flat and lightweight. The significant interest in the development of HOEs for solar collectors is demonstrated in the number of publications and development of some commercial technologies.

Holographic Optical Elements (HOE) can be recorded in photopolymer layers to act as holographic lenses, at a significantly reduced cost compared to silicon.
The main aim of our current research is to develop the design and fabrication of low cost solar concentrators utilizing photopolymer HOEs. This follows on from recent work where HOEs have been suggested for use as solar concentrators in the past few years [2-5]. They are capable to diffract light at large offset angle, exhibit Bragg selectivity and offer the potential to create multiplexed gratings. HOEs have also been used for radiant control in buildings to facilitate the optimization of energy use for heating, cooling and day lighting in the past decades [6, 7].
In this paper a novel application for HOE lenses is proposed whereby a photochemical upconversion layer is the solar absorber located at the focal distance of the HOE lens. The aim of using the HOE lens is to increase the localised incident photon flux and thereby increase the overall upconversion efficiency [8].

Long wavelength photons are transmitted through photovoltaic cell to an “upconversion layer”. Upconverted photons are then converted to electrons at the PV cell, increasing the overall electrical power output of the PV cell.
The upconversion quantum yield (photons emitted/photons absorbed) is known to increase at higher incident photon flux. Therefore, a lens array can be introduced between the PV cell and upconversion layer. Also the upconversion layer can be directly attached to the lens (without air gap), or directly to a spacing layer used to position upconversion layer at precise lens position (e.g. at lens focal length). Due to their Bragg selectivity, HOE lenses have the potential to selectively diffract/focus specific wavelength regions of interest.

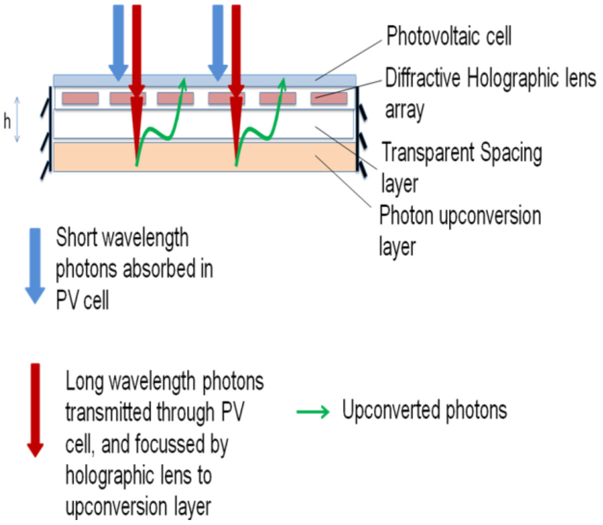

Fig. 1 Configuration of the proposed cell

2. EXPERIMENT

2.1 Photopolymer solution preparation

The material used in this research is a self-developing acrylamide-based water-soluble photopolymer as previously described [9]. The composition of this material is acrylamide, methylenebisacrylamide monomers, triethanolamine initiator, polyvinyl alcohol binder. The components shown in table 1 were mixed well by using a magnetic stirrer.

Table 1 Photopolymer composition

Components	Amount
Acrylamide	0.6g
Methylenebisacrylamide	0.2g
Polyvinyl alcohol (10% wt/v stock)	17.5ml
Triethanolamine	2ml
Erythrosine B dye(0.11%wt/v)	4ml

2.2 Layer Preparation

A specific volume of photopolymer solution is spread evenly on a 50 x 50 mm^2 glass or plastic plate placed on a leveled surface and allowed to dry. The thickness of the sample is controlled by the amount of the solution the samples were left in dark room to dry for usually about 18–24 hours at room temperature.

2.3 Experimental set up

A two-beam holographic optical setup is shown in Figure 2, the angle between the beams was set as 9^0 in order to obtain spatial frequency of 300l/mm. A 532 nm $Nd{:}YVO_4$ laser was used to record off-axis lenses with the focal length of 10 cm. The recording intensity was controlled by a variable neutral density filter. For measuring the diffraction efficiency of the recorded lenses the focusing beam was blocked and the collimated beam was used to probe the recorded HOE. The intensity of the 1^{st} order diffracted beam was measured using an optical power meter (Newport 1830-C) to determine the diffraction efficiency of the recorded lenses.

A vertically polarized Helium-Neon laser (He-Ne) at 633 nm was used as a probe beam at the Bragg angle in order to monitor the angular selectivity of the HOE lenses. When the incident beam is probing the HOE lenses at the Bragg angle the diffraction efficiency is at its maximum.

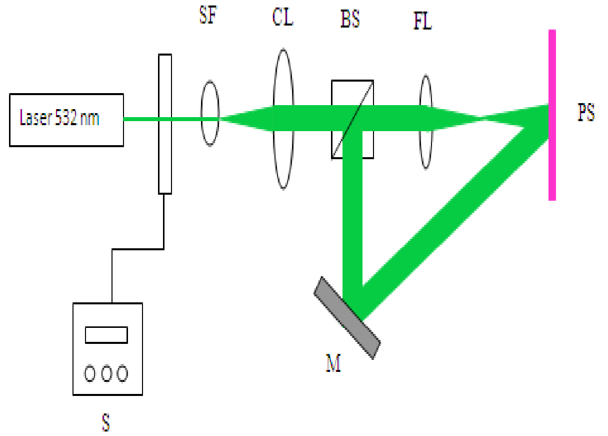

Figure 2 Experimental setup, S: shutter, CL: collimating lens, BS: beam splitter, SF: spatial filter, FL: focusing lens, M: mirror, PS: photopolymer sample.

3. RESULTS AND DISCUSSION

3.1 Diffraction efficiency of HOE lenses and their lifetime

A range of HOE lenses with an off-axis focusing effect were successfully recorded using the arrangement described above at special frequency of 300 l/mm, using different exposure energy. The diffraction efficiency of each HOE lens was determined by using equation (1):

$$\eta = \frac{I_d}{I_0} \qquad (1)$$

The diffraction efficiency of each recorded HOE lens recorded at various exposure times with recoding intensity of 1 mw/cm^2 on 50 µm layers are shown in Figure 3; it can be seen that the diffraction efficiency of over 70% was achieved. The diffraction efficiency of recorded lenses was characterizes after 6 months and it was observed that the diffraction efficiency was decreased by about 50% after 6 months. The decrease in diffraction efficiency could be due to internal processes like the polymerisation of any further active monomer in dark fringes by room light or external factors such as variation in humidity and temperature on the layers which are open to the atmosphere.

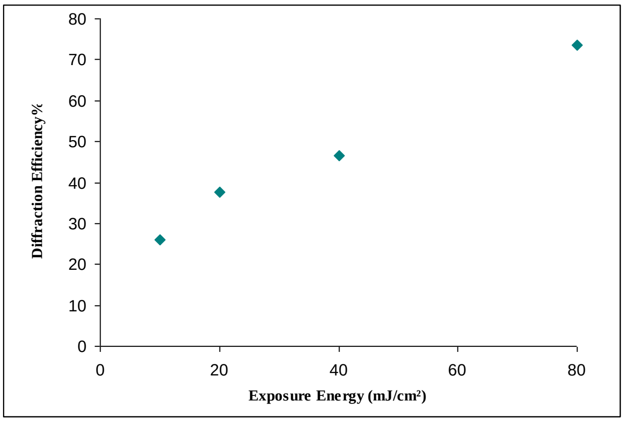

Figure 3 Diffraction efficiency vs. diffraction efficiency of unsealed HOE lenses, recorded with intensity of 1 mW/cm^2 and at the spatial frequency of 300 l/mm was investigated for sample thickness of 50 µm.

However for use of HOE lenses in buildings, it is essential to provide HOE lenses with a longer lifetime, with constant diffraction efficiency not dependent on the environmental conditions; In order to attempt to extend the lifetime a laminated cover layer was introduced to protect the HOE from the effects of the environment. The photopolymer layers were prepared on a plastic substrate and the photopolymer layers were sealed after the drying process. By sealing process the effect of humidity on the layers was limited. As a preliminary test, a HOE was recorded with a recording intensity of 2.5 mW/cm^2 on 30 µm layers and characterized immediately after recording and again after 8 weeks. The diffraction efficiency variation around the Bragg angle is shown in Figure 4.

It can be seen that in the sealed HOEs, there was 25% decrease of the peak diffraction efficiency in the two months. Since it has been observed that the most of the drop of diffraction efficiency in the layer occurs within the first months, it is probate that no further decrease will be observed.

Further characterization is required for sealed samples and the diffraction efficiency of recorded lenses will be studied after 6 months and the results will be compared.

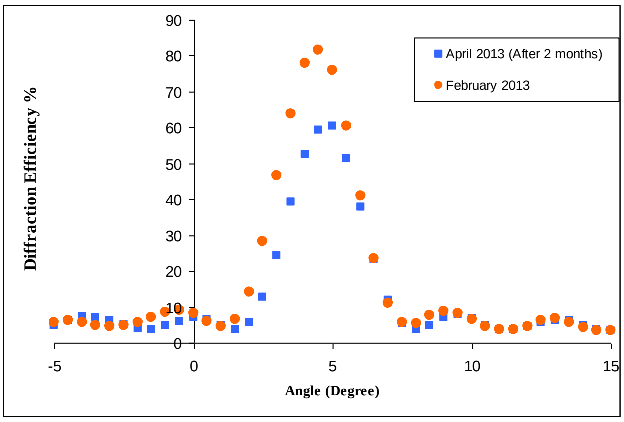

Figure 4 Diffraction efficiency vs. angular selectivity of sealed HOE lenses, recorded with intensity of 2.5 mW/cm^2 and the spatial frequency of 300 l/mm was investigated for sample thickness of 30 µm.

3.2 Dependence of Diffraction efficiency on recording intensities

The HOE lenses were recorded at different range of exposure time and the diffraction efficiency of each lens was characterized. The results in figure 5 show that the diffraction efficiency of HOE lenses recorded with intensity of 1 mW/cm^2 reached the maximum diffraction efficiency of 84% after exposure time of 40 seconds for samples with thickness about 95 µm.

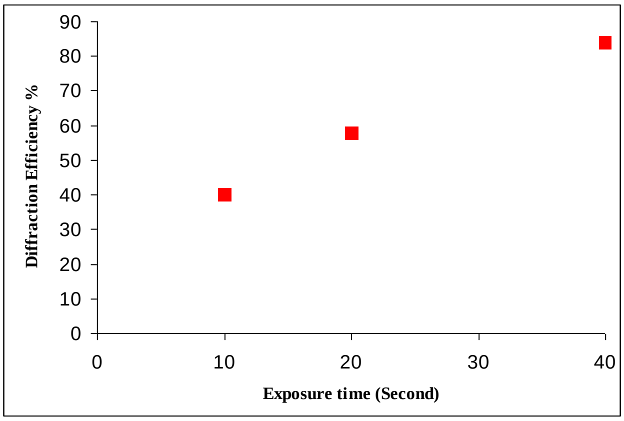

Figure 5 Diffraction efficiency vs. exposure time for HOE lenses at spatial frequency of 300 l/mm with recording intensity of 1 mW/cm^2 was investigated for sample thickness of 95 µm.

3.3 The wavelength selectivity of HOE lenses

The wavelength selectivity of sealed HOE lenses with recording intensity of 2.5 mW/cm^2 on 30 µm layers was investigated. A white light source (Avantes, AvaLight-Hal-S) was used as a probe beam. The diffraction efficiency of lenses at different wavelengths was collected by using an integrating sphere (Avantes, AvaSphere-50-REFL) coupled to fibre optic CCD spectrometer (Avantes, AVASPEC 2048-USB2). The diffraction efficiency (η) of recorded lenses at different wavelength can be determined by measuring the intensity of zero order without HOE lens (I_0) and with HOE lens (I_0'), at the optimum Bragg position by using the equation (2):

$$\eta = \frac{I_0 - (I_0')}{I_0} \times 100 \qquad (2)$$

From the results in figure 6, it can be observed that the HOE lenses achieved the maximum diffraction efficiency of about 54% at wavelength of 460 nm, 60% at wavelength of 540nm and 41% at wavelength of 633 nm.

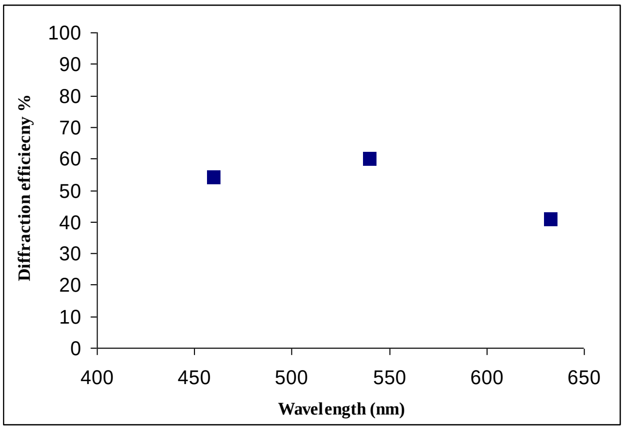

Figure 6 Diffraction efficiency Vs Wavelength for the sealed HOE lenses recorded at intensity of 2.5 mW/cm^2 at various wavelength of 460nm, 540nm, 633nm respectively was investigated for sample of 30µm thickness.

4. CONCLUSIONS

The results show that the acrylamide-based photopolymer holographic optical lenses achieved high diffraction efficiency (above 80%) at relatively low spatial frequency and recording intensities. It can be concluded that sealed HOE lenses are promising for use as solar concentration or windows shading in buildings and environment, but for this to be achieved further improvement of their lifetime will be required. In the future, the angular and wavelength selectivity and diffraction efficiency of multiplexed HOEs will be modelled in order to maximize energy collection for both direct light from a laterally moving source and diffuse light. An exposure schedule will be devised for equalization of the diffraction efficiency of the HOEs so that they can be fabricated for optimum performance using photopolymer materials.

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