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Development and testing of low spatial frequency holographic concentrator elements for collection of solar energy

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ABSTRACT

The aim of this research is to use holographically recorded diffractive optical elements (DOEs) recorded in photopolymer in order to effectively collect and concentrate solar radiation. The potential for recording high diffraction efficiency DOEs with a large angular and wavelength range of operation in acrylamide based photopolymer and the optimum recording conditions have been presented in our previous work (Akbari et al., 2014b, 2014a). Theoretical modelling and experimental test are presented which demonstrate that low spatial frequency components, around 300 line pairs/mm, have an appropriate spectral bandwidth, high efficiency and very limited polarization dependence. Pairs of concentrating off-axis lenses are fabricated in photopolymer and arranged to concentrate light on a c-Si cell. The optical recording process is described and discussed. The results from electrical characterization confirm that with the (two) spherical DOEs (each of area 113 mm^2) in place, the output current of c-Si solar cells is approximately doubled for the solar cells with area of 12 mm^2.

1. Introduction

There are a number of approaches to improving the efficiency of photovoltaic (PV) systems. Concentrating solar energy onto a PV material reduces cell area per unit electrical output and, for certain cell materials and designs, increases PV conversion efficiency (Rabl, 1976). This enables the total system cost to be reduced per unit of energy delivered, (Winston and Hinterberger, 1975; Kennedy et al., 2009; Norton et al., 2011; Wisam et al., 2016; Kabeel and Abdelgaied, 2017). Solar concentration is usually undertaken by imaging optics refractively using lens (Xie et al., 2011; Xu et al., 2016) or reflectively using mirrors (Arancibia-Bulnes et al., 2017) or non-imaging optics (using compound parabolic concentrators (Eames and Norton, 1977; Mallick et al., 2015; Singh and Tiwari, 2017), or luminescent solar concentration, (Goetzberger and Greubel, 1977; Reisfeld et al., 1988; Barnham et al., 2000; Gallagher et al., 2007; Chandra et al., 2015). The limitations of each are mainly determined by concentration ratio required and cost, where imaging optics can achieve much higher concentration of direct radiation to intensities greater than 1000 suns, and non – imaging concentrators such as CPCs have much lower concentration ratios but they have wider acceptance angles.

In this paper we investigate a diffractive solar concentrator which also collects solar radiation over a large area and redirects it onto a smaller area, where it can be converted for example into electrical energy using PV cells. Holographically recorded diffractive optical elements (DOE) are investigated for use in the collection of solar radiation from a moving source, such as the sun, and its redirection onto a fixed detector/convertor for solar concentrator applications.

Holographically recorded volume Diffractive Optical Elements (DOEs) have potential as solar concentrators because of their ability to diffract light at large offset angle, and the potential for multiplexing a number of optical components in the same layer. Recent research has demonstrated different diffractive elements in a variety of arrangements for solar applications that will re-direct and focus incoming light to the desired ‘line’ or ‘spot’ for conversion (Bañares-Palacios et al., 2015; Castro et al., 2010; Ghosh et al., 2015; Hsieh et al., 2011; Hung et al., 2010; James and Bahaj, 2005; Kostuk et al., 2011; Kostuk and Rosenberg, 2008; Sam et al., 2011; Shakher and Yadav, 2000).

A number of researchers have demonstrated novel designs over the years (Sreebha et al., 2015; Belendez et al., 1991; Breitenbach and Rosenfeld, 2000; Mohan and Islam, 2006). For example Sreebha et al., 2015, have reported results on the recording of transmission holographic optical elements in a silver halide material. The wavelength selectivity and focusing properties of the

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recorded holographic lens was used to design a concentrator for dye sensitized solar cells. The fabricated holographic lens was reported to achieve 32.9% energy enhancement with the HOE in place while the dye cells were collecting the yellow radiation of the solar simulator light source.

Breitenbach and Rosenfeld (2000) investigated the optical properties of thin HOEs. The spatial and spectral distributions of light transmitted by the HOE were measured for a range of wavelengths between 300 and 2100 nm and for various angles of incidence. The results demonstrate the capability of HOEs to separate the visible light from the infrared part of solar spectrum. This can be very beneficial in solar applications since daylighting and the solar gain can be controlled individually.

The design of multi-channel HOE has been demonstrated by Mohan and Islam (2006). A range of HOEs were recorded in silver halide recording material using five reference beams in order to concentrate light at a range of incident angles. The maximum efficiency of 15% was achieved for a HOE with the dimensions of 58 mm × 58 mm over an angle-span of 12°. HOEs were recorded by using five reference beams.

A planar concentrator using a low-cost holographic film that selects the most useful bands of the solar spectrum and concentrates them onto the surface of the photovoltaic cell has been demonstrated by Kostuk et al. (2007). The holographic elements have been implemented in 5–25 μm thick layers of dichromated gelatin (DCG). The result show a 25% increase in the output from the cell over the output without the holographic element. However, it can be assumed that stacking multiple gratings or multiplexing several gratings in the same volume could significantly improve the module efficiency.

Photopolymers are excellent materials for producing similar diffractive elements, being thin, lightweight, inexpensive and highly efficient, but challenges remain in reducing the angular selectivity of these relatively thick layers and in applying the technology to natural light in real-world applications. High efficiency diffractive optical elements have been recorded in photopolymer material previously for this and other applications (Fernández et al., 2008; Fimia et al., 1994; Gallego et al., 2008; Gleeson et al., 2008; Guntaka et al., 2002; Jenney, 1970; Martin et al., 1998; Srivastava et al., 2012; Tarjányi et al., 2009). Multiplexing of thick transmission holograms in photopolymer has also been investigated. For example, Naydenova et al. (2013) reported on recording multiplexed cylindrical holographic lenses with high diffraction efficiency in order to direct the light in a fixed direction independently of the direction of incoming light. Bianco et al. (2015), reported on recording an array of three spherical lenses in a sol-gel photopolymer which can be used as solar concentrator.

Altmeyer et al. (2013) demonstrated the potential of multiplexing of thick transmission holograms in photopolymer. The variation of the diffraction efficiency of the multiplexed grating with respect to the angle of incidence and the wavelength are theoretically shown. The experimental results of the angular acceptance of the single and four multiplexed holograms are compared with the simulation results. A maximum diffraction efficiency of 60% was achieved for a layer with thickness 16 μm. This demonstrates the potential for recording multiple high efficiency elements simultaneously in photopolymer layers. However further work is required to design combinations of elements that direct the light in single direction in order to make it useful for solar applications.

Thick transmission holograms and diffraction gratings recorded in acrylamide based photopolymer can be used to change the direction of a light beam with greater than 90% efficiency but are generally only efficient over a small range of angles close to the Bragg angle. Previous work by the authors addressed the issue of increasing the angular working range in photopolymers and demonstrated photopolymer spherical and cylindrical focussing elements that had very high efficiency when measured with monochromatic, linearly polarized laser sources (Akbari et al., 2014a, 2014b). The aim of this work is to test cylindrical and spherical focusing diffractive elements using an unpolarised broadband source, and also to fabricate and test combinations of pairs of elements designed to direct and focus this light onto the same solar cell. Silicon cells are used as the convertor. The relative increase of the output current of c-Si solar cells using the DOEs is investigated using a solar simulator.

2. Materials and methods

2.1. Photopolymer solution preparation

The composition of the acrylamide-based photopolymer used in this study consists of two monomers (Acrylamide and NN'methylene bisacrylamide), an electron donor (Triethanolamine), a dye sensitizer (Erythrosine B, sensitive to light of 532 nm wavelength) and a binder (Polyvinylalcohol) which keeps all of the components suspended. The solutions were mixing for 90 min to ensure that the monomers are completely dissolved The thickness of the layer was 50 ± 5 μm thick, as measured by white light interferometry.

2.2. Layer preparation

0.5 ml of the photopolymer solution was spread evenly using the gravity settling method on a 26 × 76 mm^2 glass substrate and then placed on a levelled surface and allowed to dry for 18–24 h in darkness with temperature and relative humidity ranging between 20–25 °C and 40–60% RH.

2.3. Experimental set-up

2.3.1. Holographic set-up for recording DOEs

In this report, DOEs were recorded using a 532 nm Nd:YVO_4 laser and a Helium-Neon laser (He-Ne) at 633 nm was used as a probe beam. The recording set up is shown in Fig. 1. The S polarized beam was split in two via a non-polarizing beam splitter and re-combined at the photopolymer plate using reflection at a plane mirror. The inter-beam angle was set at 9.14° in air in order to produce gratings with a central spatial frequency of 300 ± 30 line pairs/mm. The exposure time was kept constant at 60 s, thus exposure energy of 60 mJ/cm^2 in a layer of thickness 50 ± 5 μm was achieved. Optical lenses with a range of focal lengths (3–10 cm) were placed in the object beam. In order to maximize the aperture of recorded HOE, it was essential that the object beam and the ref-

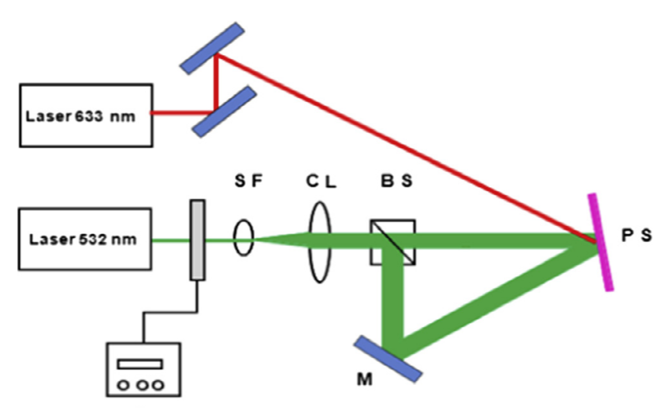

Fig. 1. Experimental set up: S: shutter, CL: collimating lens, BS: beam splitter, SF: spatial filter, M: mirror, PS: photopolymer sample.