Optics Communications 356 (2015) 12–16

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Lens-less bending and concentration of light by volume hologram

Mei-Li Hsieh [a,*], Cheng-Te Peng [a], Hong -Yu Chen [a], Shawn-Yu Lin [b]

[a] Department of Photonics, National Chiao-Tung University, Hsinchu, Taiwan
[b] The Future Chips Constellation, Department of Physics, Applied Physics and Astronomy, Rensselaer Polytechnic Institute, Troy, NY 12180, USA

ARTICLE INFO

Article history:
Received 12 April 2015
Received in revised form
13 July 2015
Accepted 16 July 2015

Keywords:
Holographic optical elements
Volume gratings
Diffractive optics

ABSTRACT

In this paper, a new approach is proposed to realize a lens-less and 90° light-bending by a volume-holographic element, consisting of 3D sub-wavelength index-gratings throughout the sample. In this approach, a top incident plane-wave is diffracted by 90° and guided into a planar volume hologram. Conversely, a side-incident light may be guided and diffracted out of the top sample surface. The diffraction-efficiency η of light was studied in real-time during light-exposure and also in the dark after exposure to observe "dark-enhancement". It is shown that 90° light-bending at normal incidence can be achieved with a high efficiency, $\eta \sim 70\%$, and a small angular-tolerance, $\Delta\theta = 0.02°$. It is further shown, as a proof-of-concept, that a 5° cylindrical-wave top-incident beam may be used to improve angular tolerance to $\Delta\theta = 5°$, but with a reduced efficiency of $\eta \sim 0.80\%$.

Holographic elements have been widely used in optical system to replace traditional optical devices. Examples are compact holographic lens, holographic grating, and holographic concentrator for solar energy harvesting [1–3]. One of the key issues of a holographic element concerns optical properties of the recording materials. However, PQ/PMMA materials has recently been shown to have superior optical characteristics, such as high contrast refractive-index variation, low shrinkage after exposure, environmentally stable and no need for lithographic development [4–7]. Currently, there is an emerging interest in using holographic elements for compact display system with edge-lit hologram [8–10] and for solar harvesting to achieve high conversion-efficiency and enable an easy adoption to a building's non-planar structure. To achieve high conversion-efficiency, a transmission holographic element has been proposed to split solar radiation into regions according to the spectral sensitivity of the cells [11–13]. To enable adaption to building structure, several materials approaches have been developed that include the use of thin-film, polymer, or dye-sensitized photovoltaic cells. Another optical approach is to combine low-cost concentrators with high-efficiency solar cells [14,15]. So far, there is no holographic approach that utilizes 90° holographic recording geometry [16] to enable solar collection with a large collection angle, over the entire solar spectrum and with high concentration factor.

In this paper, we demonstrate lens-less bending and concentration of light by a volume holographic element (VHE). The PQ/PMMA material has a good optical quality and was chosen as the holographic recording material. The recording of index-grating was performed using two different schemes- top incident and 90° incident configurations. The efficiency of light-diffraction was studied in real-time and also in the dark to observe "dark-enhancement". We show that it is possible to achieve 90° light bending with high efficiency $\eta = 70\%$. Furthermore, this 90° bending scheme leads to a concentration factor of 2.5 times, without the use of any external optics. With further improvement in angular tolerance, this 90° light-bending scheme may be useful for compact and efficient solar harvesting.

We first study the optical properties of our PQ/PMMA materials, using a top-incident configuration for optical recording and reading. Fig. 1(a) and (b) illustrates the recording and reading processes, respectively. In Fig. 1(a), two plane-waves were incident from the sample-top with symmetric incident angle, 45°. In Fig. 1 (b), a reading beam at the Bragg angle was incident from the sample-top, and the diffracted beam was retrieved. For this top-incident configuration, the recording and reading laser wavelengths were $\lambda = 514.5$ nm and $\lambda = 632.8$ nm, respectively. The recording wavelength of 514.5 nm was chosen because of its relatively high absorption coefficient of $\alpha = 2\ \text{cm}^{-1}$ in our PQ/PMMA material [17]. Since the reading wavelength is different from the recording wavelength, the reading angle has to be modified in accordance with the Bragg condition [18] and is 60° in air.

Fig. 2(a) shows diffraction-efficiency η vs. exposure-energy measured in real time during light exposure. The testing was repeated for three samples of different thickness $d = 2$, 3, 4 mm, respectively. For $d = 2$ mm sample, its η increases with increasing exposure energy, reaches a maximum of $\eta \sim 35\%$ at $E^{\text{exposure}} \sim 4.2$ J/

* Corresponding author.
E-mail address: mlh@cc.nctu.edu.tw (M.-L. Hsieh).

http://dx.doi.org/10.1016/j.optcom.2015.07.046
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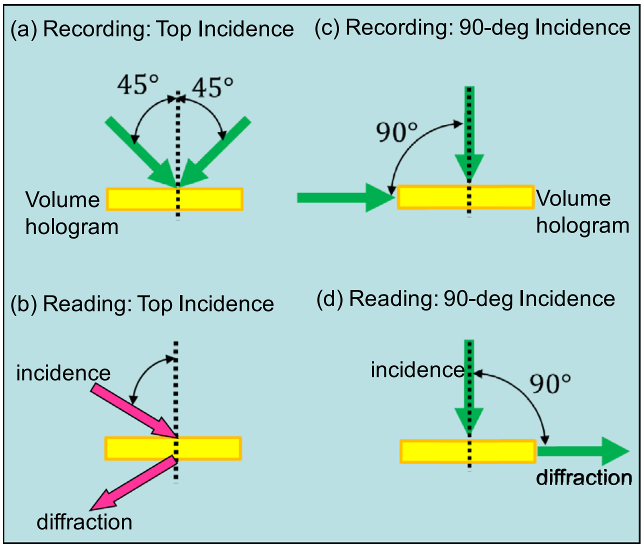

Fig. 1. Our volume hologram recording and reading schemes. (a), (b) schematic of two-beam recording (green arrows) and reading (red arrows) procedures, respectively, for the top-incident configuration; (c), (d) schematic of two-beam recording and reading procedure, respectively, for the 90° incident configuration. The diffracted beam is directed along the planar volume hologram. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

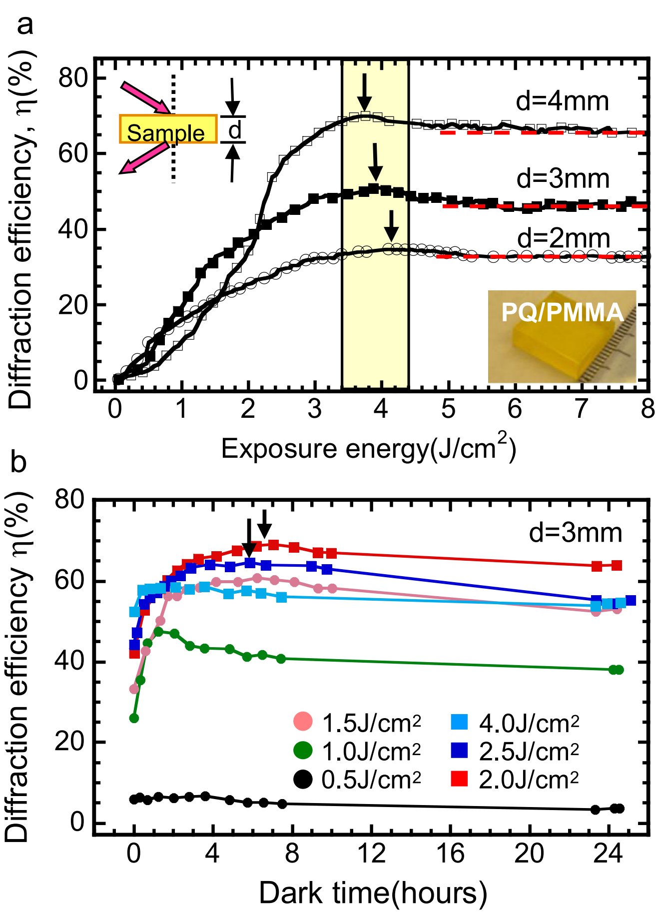

Fig. 2. Optical characterization of diffraction-efficiency η of the diffracted beam. (a) Real-time diffraction-η vs. exposure energy for sample thickness d=2, 3 and 4 mm for the top incident configuration. The maximum-η is indicated by vertical arrows. A photo of the PQ/PMMA photosensitive material is shown in the inset. (b) The measured η as a function of dark-time (t^{dark}) for six samples of the same thickness d=3 mm, but with different exposure-energy $E^{exposure}$=0.5, 1.0, 1.5, 2.0, 2.5 and 4.0 J/cm^2, respectively.

cm^2 and eventually saturates at $\eta \sim 33\%$. For the $d=3$ mm sample, its efficiency follows the same trend and exhibits a higher maximum value of $\eta \sim 51\%$ at $E^{exposure} \sim 3.9$ J/cm^2. The trend continues and the $d=4$ mm sample has an even higher maximum-η of $\sim 71\%$ at $E^{exposure} \sim 3.75$ J/cm^2. This efficiency-characteristic is consistent with that predicted for a volume grating, namely, η is proportional to the square of sin function of sample thickness, i.e., $\eta \propto \sin^2(\kappa d)$ [18]. To first order, it follows that the maximum-η should scale linearly with sample thickness d as was observed. The agreement of our finding with theoretical prediction illustrates that our PQ–PMMA material is uniform and the recorded index-grating is well-defined. We next study change of η of our PQ–PMMA as a function of time after light exposure and in the dark, i.e. dark time t^{dark}. We examine six samples of the same thickness, $d=3$ mm, but with different exposure-energy $E^{exposure}$=0.5, 1.0, 1.5, 2.0, 2.5 and 4.0 J/cm^2, respectively. The data are shown in Fig. 2(b). For all six samples, their η increases with the dark time initially (dark-enhancement), reaches a maximum value at t^{dark}=4 ~8 h and saturate at a steady-state value eventually. The optimum conditions are found to be $E^{exposure}$=2.0 J/cm^2 and t^{dark}=6.8 h for a $d=3$ mm PQ–PMMA sample, such that η can reach a maximum value of 69% with a dark- enhancement of 1.6 times.

Having established the optimum conditions, we now design a new volume-hologram system for solar collection/ concentration purpose. The new recording and reading procedure is called "90° incident configuration" and is shown in Fig. 1(c) and (d), respectively. In Fig. 1(c), one of the recording beams is incident from the top of sample and another from the left side. After recording, in Fig. 1(d), the reading beam is incident from the top and the diffracted beam would be guided along the planar volume hologram and exit from the right side of the sample. Thus, a top incident light is converted into a guided wave with its beam size determined by volume hologram thickness d. For example, let us assume that the size of our sample is 10×5x2 mm^3, and the beam size from the top is 10×5 mm^2, then, the diffracted beam size from the side becomes 10×2 mm^2. Thus, the solar light with 10×5 mm^2 size incident from the top will yield a diffracted beam size of 10×2 mm^2, a concentration factor of 2.5 times. In other words, the diffracted or bent plane wave is narrower, as narrow as the recording plane wave in the holographic plate. Also, a solar-cell is to be placed at the side of the hologram to convert optical to electrical energy. In this 90° incident configuration, our proposed volume hologram approach is promising for achieving light-concentration without the use of any external optical element.

As the first attempt to realize the proposed 90° recording and reading concept, a two plane-waves incidence setup was constructed and shown in Fig. 3(a). Special care was taken to polish the two end faces of the PQ/PMMA material to be optically smooth. In the recording phase, two plane-waves with λ=514.5 nm were incident (green arrows) onto the PQ/PMMA sample. In the reading phase, a plane wave is incident on the top of the sample and the transmitted and diffracted waves measured. Fig. 3(b) shows a photo of our system during the reading process. Light bending by 90° by a volume-hologram was clearly observed. Additionally, CCD photos were taken to better capture the transmitted and diffracted images and were shown in Fig. 3(c) and (d), respectively. The transmission beam is rather weak and has the same size as the incident beam, 5×10 mm^2. On the contrary, the intensity of the diffracted beam is strong, with a smaller beam size of 2×10 mm^2. By diffracting the incident light sideway, a concentration ratio of 2.5 times (or 250%) is achieved. Hence, our holographic approach can give a high solar-concentration without the use of any external optics, offering an universal solution that can be integrated to any solar cells.

In Fig. 4, we show quantitative measurements of diffraction-efficiency of our PQ/PMMA material in 90° recording