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Recording multiple holographic gratings in silver-doped photopolymer using peristrophic multiplexing

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Abstract. Plane-wave transmission gratings were stored in the same location of silver-doped photopolymer film using peristrophic multiplexing techniques. Constant and variable exposure scheduling methods were adopted for storing gratings in the film using He–Ne laser (632.8 nm). The role of recording geometry on the dynamic range of the material was studied by comparing the results obtained from both techniques. Peristrophic multiplexing with rotation of the film in a plane normal to the bisector of the incident beams resulted in better homogenization of diffraction efficiencies and larger $M/\#$ value.

Keywords. Photopolymers; holography; holographic multiplexing.

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1. Introduction

Holographic data storage (HDS) has been considered as a promising data storage technology since 1960s because of its outstanding characteristics such as parallel storage and retrieval, high density storage and fast data transfer rates. One of the important parameters that characterize a recording material in terms of its suitability as a holographic memory is the dynamic range, that is, the number of holograms with a diffraction efficiency of 100% which can be stored in a material with a specific thickness [1]. It is the storage capacity of a recording material and is characterized by the parameter M number ($M/\#$). Developing suitable recording media with large dynamic range is important to achieve a practical holographic data storage system. The quest for an ideal holographic recording medium has increased in recent years. Poly(vinyl alcohol) (PVA) acrylamide-based photopolymers have been widely studied because of their excellent properties like high sensitivity, high diffraction efficiency (DE), large dynamic range ($M/\#$) and real-time imaging capabilities [2]. Multiplexing techniques such as angle, peristrophic (rotation), shift and wavelength multiplexing are commonly used to store numerous pages of data in the recording media [3–8]. Various research groups have reported holographic multiplexing studies in acrylamide-based photopolymer layers with different compositions and film thicknesses (100 μm–1 mm). Sherif *et al* have reported $M/\#$ of 3.6 while recording 30 holograms in a 160 μm thick acrylamide-based photopolymer film [4]. Fernandez *et al* have developed 700 ± 10 μm thick acrylamide photopolymer layer and peristrophically multiplexed 90 gratings which gave $M/\#$ of 12 [9]. Initial studies on peristrophic multiplexing in silver-doped photopolymer layer was reported earlier [10]. In the present study, efforts were made to completely utilize the dynamic range of the silver-doped films by storing more number of gratings. Peristrophic multiplexing techniques with rotation of sample normal to the recording media (peristrophic method I) and along the plane of incidence to the recording media (peristrophic method II) were employed to record gratings in the film by constant and variable exposure scheduling methods. For holographic data storage (HDS) applications, the multiplexed gratings should have uniform DE so that the electronic detector array can detect all the signals effectively. Hence studies were carried out to determine proper exposure scheduling technique to record gratings with uniform DE. The DE and $M/\#$ values obtained from both the peristrophic methods were compared to analyse the role of recording geometry on the storage capacity of the photopolymer layer.

2. Methodology

The photopolymer film was developed in our lab by gravity settling method. It consists of acrylamide (AA) as polymerizable monomer, methylene blue (MB) as sensitizer dye, triethanolamine (TEA) as radical generator, silver nitrate as cross-linker and a binder of poly(vinyl alcohol) (PVA). The details of film fabrication are discussed in our previous paper [10]. The optimized film Ag2 [10] was used in the present study. The film was 130 μm thick (measured using Dektak 6m stylus profiler). The optical absorption spectrum of the film was recorded using JASCO-V-570 spectrophotometer. The film had good spectral sensitivity in the red region of the spectrum and He–Ne laser with 632.8 nm emission was used for recording and reconstruction of gratings. Double-beam holographic recording set-up was used to record plane-wave transmission gratings in the film [10].

For peristrophic multiplexing studies, the film was mounted on a rotational stage and was kept normal to the bisector of the recording beams. In peristrophic method I (figure 1), the rotation of the film about an axis normal to the plane of incidence was performed. The film was rotated in a direction perpendicular to the plane of incidence after each recording. This rotation shifts the reconstructed image away from the detector, permitting a new grating to be recorded at the same location and viewed without interference. In the case of peristrophic method II (figure 2), the rotation of the film was carried out about an axis along the plane of incidence. The film was rotated along the plane of incidence after each recording. This rotation causes reconstruction from the stored grating to come out in a different direction, allowing another grating to be recorded at the same location. The multiplexed gratings were reconstructed using He–Ne laser (632.8 nm). Diffraction efficiency was calculated as the ratio of the intensity of the first-order diffracted beam to the incident probe beam intensity.

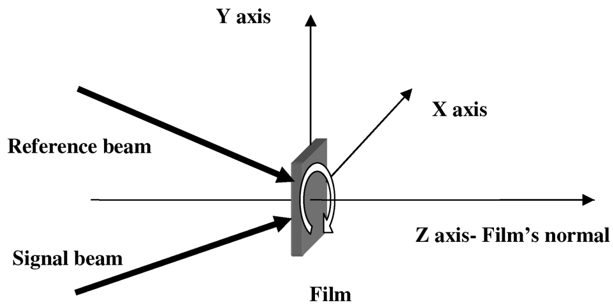

Figure 1. Peristrophic method I.

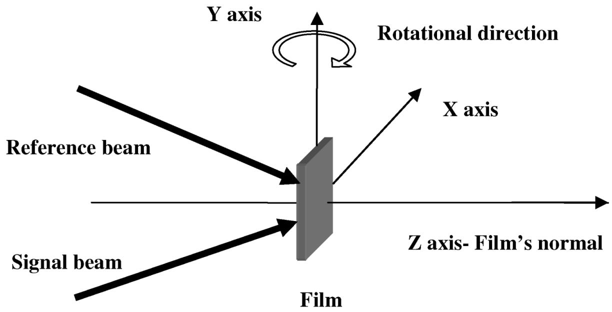

Figure 2. Peristrophic method II.

3. Results and discussion

3.1 *Peristrophic method I*

Initially, gratings were recorded with a constant exposure energy of 1 mJ/cm^2. A combined exposure intensity of 0.4 mW/cm^2 was used to record the individual gratings and the beam intensity ratio was 1 : 1. Twenty plane-wave gratings were recorded with an angular separation of 5° in the film by this method. This angle was chosen so that the first-order diffracted peak of each grating would not contribute to or detract from the diffraction efficiency of neighbouring gratings. The stored holographic gratings were then reconstructed using He–Ne laser (2 mW, 632.8 nm). Figure 3 shows the variation of diffraction efficiency with grating number. The first recorded gratings had high DE values, while the last gratings had very low values. Efficiency of the first grating was 16% while that of the twentieth one was 2×10^{-3}%. The mean DE (DE$_\mathrm{m}$) was approximately 3%. The maximum efficiency η_i was seen to decrease as the number of recorded gratings increases which may be due to the consumption of the dynamic range of the photopolymer film as each new grating is recorded. The dynamic range ($M/\#$) was calculated using the expression, $M/\# = \sum_{\mathrm{i}=1}^{\mathrm{M}} \eta_\mathrm{i}^{1/2}$, where η_i is the maximum diffraction efficiency of each recorded grating and the sum is over M holographic gratings stored in the same location of the film [1,5]. The dynamic range ($M/\#$) used to record the gratings by

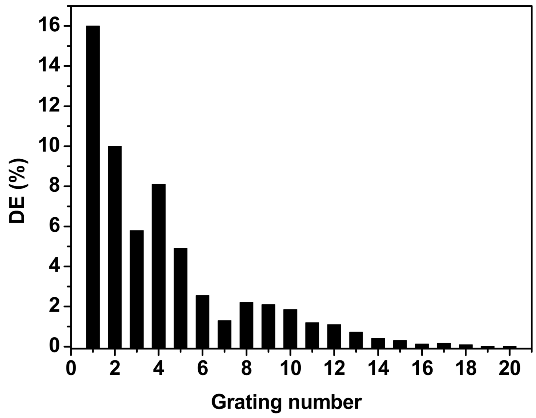

Figure 3. DE vs. grating number.

constant exposure scheduling was equal to 2.7. It is found that multiplexing studies at constant exposure will not result in uniform gratings, which is very essential for holographic data storage. When the gratings are recorded in the photopolymer film, the monomer and dye are being consumed and therefore the material becomes less sensitive. Hence, it is necessary to increase the exposure time for the last gratings so that they also attain the same diffraction efficiency as the first recorded gratings. Efforts were made to equalize the diffraction efficiency of the recorded gratings by adopting exposure scheduling method designed to share all or part of the available dynamic range of the recording material among the gratings to be multiplexed. In this case also, gratings were recorded using the same recording parameters used in constant exposure scheduling method. Exposure energy was increased in steps by increasing the exposure time while recording gratings. Twenty gratings were recorded in the same volume of the film by adopting variable exposure scheduling scheme. The diffraction efficiencies of the recorded gratings were determined by reconstructing the gratings using He–Ne laser. The variation of diffraction efficiency with grating number for the recorded gratings is shown in figure 4. The exposure scheduling scheme used for recording gratings is shown in figure 5. The range of DE was 3–6% and $M/\#$ was obtained as 4.2 and mean DE was 4.5%. Variable exposure method resulted in the recording of nearly uniform gratings with larger $M/\#$ values than constant exposure scheduling.

3.2 *Peristrophic method II*

Plane-wave transmission gratings were recorded in the film using peristrophic method II with the axis of rotation along the plane of incidence to the recording medium. All the recording parameters were the same as in peristrophic method I. Twenty gratings were recorded in the film by variable exposure scheduling method. Figure 6 shows the variation of diffraction efficiency with grating number and the corresponding exposure scheduling scheme is plotted in figure 7. The range of DE was 0.6–2% and $M/\#$ was obtained as 2.5. The mean DE was 1.6%. In this case,

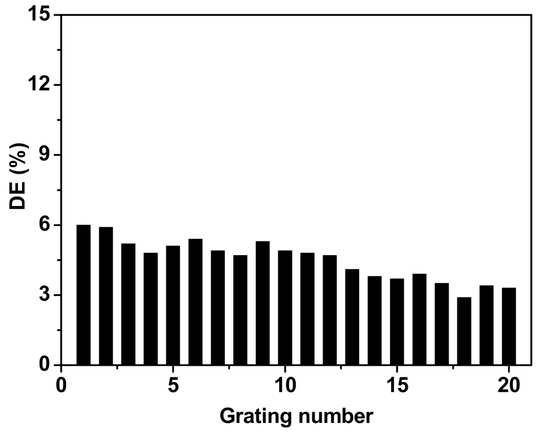

Figure 4. DE vs. grating number.

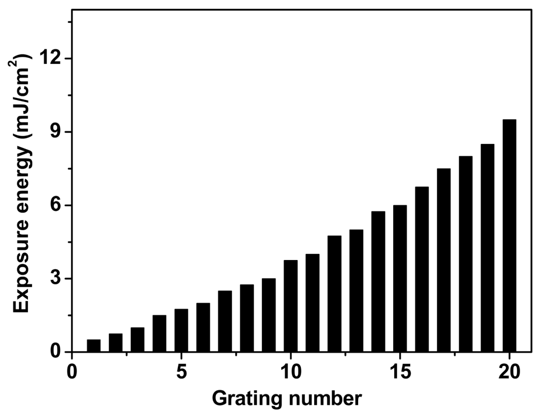

Figure 5. Exposure scheduling scheme for peristrophic method I.

the recorded gratings have nearly uniform DE, but the $M/\#$ value is smaller than that obtained from peristrophic method I. In peristrophic method I, recording of same number of gratings had resulted in $M/\#$ of 4.2. Thus, peristrophic method I is more suitable for data storage applications as it makes better use of the available dynamic range of the recording material.

4. Conclusions

Peristrophic multiplexing techniques were employed for storing multiple transmission gratings in silver-doped acrylamide-based photopolymer film using He–Ne laser. Variable exposure scheduling method resulted in the recording of gratings with nearly uniform diffraction efficiencies and larger $M/\#$ values. Peristrophic method I, with axis of rotation normal to the recording medium was found to be

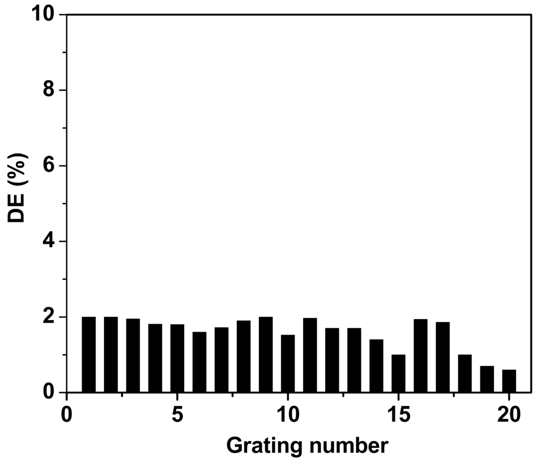

Figure 6. DE vs. grating number.

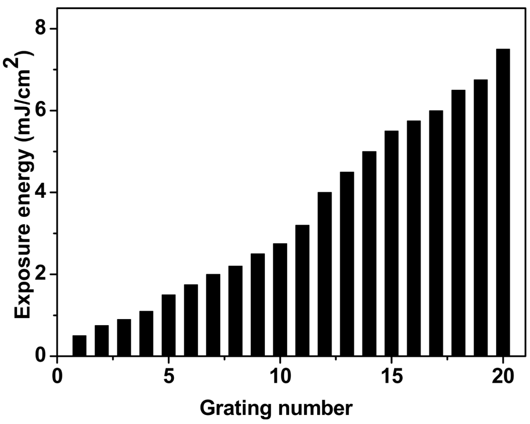

Figure 7. Exposure scheduling scheme for peristrophic method II.

more suitable for multiplexing as it resulted in the recording of nearly uniform gratings with higher diffraction efficiency and dynamic range.

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