Accurate Diffraction Efficiency Control for Multiplexed Volume Holographic Gratings

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Abstract

We report the method of accurate diffraction efficiency control for multiplexed volume holographic gratings in dry photopolymer films (DuPont HRF-600). Based on the experimental evaluations of the grating formation characteristics in dry photopolymer films, we present the way to develop the practical recording schedules for the fabrication of holographic gratings under accurate diffraction efficiency control. Using this method, we obtained single holographic gratings with the desired diffraction efficiency (variation 2.5%) and high-efficiency equal-strength (47%/47%) double holographic gratings. As a practical application, we demonstrated the centralized optical backplane architecture with uniform fan-outs using the single and equal-strength double holographic gratings we recorded.
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Single and multiplexed volume holographic gratings have been suggested for use in free-space\cite{1} and substrate-guided-wave\cite{2}, \cite{3} board-level optical interconnect systems. The photopolymer-based volume hologram is an attractive option for making high efficiency gratings. The advantage of photopolymers over other types of emulsion, such as dichromated gelatin and silver halides, includes dry-processing capability, long shelf life, and good photospeed\cite{4}. In this paper, first, we briefly review the theoretical model describing grating formation process in dry photopolymer films. Then, based on the experimental evaluations of the grating formation characteristics in dry photopolymer films, we present the way to develop the practical recording schedules for the fabrication of holographic gratings under accurate diffraction efficiency control. Finally, we demonstrate a practical application by using the single and double holographic gratings we recorded.

The dry photopolymer film (DuPont HRF-600) consists of monomers, polymeric binders, and photoinitiators. The monomers are polymerized when exposed to light of a specific wavelength and the percentage of polymerized monomers is proportional to the exposure dosage. We study the formation of double holographic gratings in which the two gratings are
recorded sequentially with non-parallel grating vector orientations. During the first exposure, a 1-D diffusion equation\cite{5,6} in the following describes the monomer concentration $u(\vec{r}, t)$,

$$\frac{\partial u(x,t)}{\partial t} = \nabla [D(x,t)\nabla u(x,t)] - F_o [1 + V \cos (K_r x)] u(x,t), \quad (1)$$

and a 2-D diffusion equation is required during the second exposure,

$$\frac{\partial u(\vec{r}, t)}{\partial t} = \nabla [D(\vec{r},t)\nabla u(\vec{r},t)] - F_o [1 + V \cos (\vec{K}_2 \cdot \vec{r})] u(\vec{r},t), \quad (2)$$

where $\vec{K}_1$ and $\vec{K}_2$ represent, respectively, the grating vector formed by the first and second exposure, $D(\vec{r}, t)$ is the diffusion parameter, $F_o$ is the polymerization factor ($F_o = \kappa I_o$, where $\kappa$ is a constant and $I_o$ is the average irradiance), and $V$ is the fringe visibility. The initial conditions of equation (2) depend on the final conditions of equation (1), and the final monomer concentration after recording can be written in the form of

$$u(\vec{r}, t) = \sum_{i=0}^{\infty} u_i(t) \cos (\vec{K}_1 \cdot \vec{r}) + \sum_{k=0}^{\infty} u_k(t) \cos (\vec{K}_2 \cdot \vec{r}). \quad (3)$$

If the two gratings are orthogonally multiplexed ($\vec{K}_1 \perp \vec{K}_2$), equation (2) can be decomposed into two uncoupled 1-D diffusion equations through a proper coordinate transformation. If the two gratings are non-orthogonally multiplexed, however, the two 1-D diffusion equations are coupled with each other, which implies that the formation of the second grating is affected by the change of the first grating during the second exposure in a complicated way.

We proposed a novel interconnect architecture called the centralized optical backplane\cite{7}. This architecture retains the advantages of bus architecture while at the same time providing uniform optical signal fan-outs. To achieve such fan-outs, single holographic gratings, as shown in Fig. 1 (a), and equal-strength double holographic gratings, as shown in Fig. 1 (b), are required\cite{7}. For these holographic gratings, the reconstruction wavelength is 850 nm, and the
diffraction angles are 45°. Equation (2) is difficult to solve in the case of non-orthogonal multiplexing. Moreover, the diffusion model involves some material parameters\[^6\] that are not available at this stage. Therefore, this model cannot be used directly for diffraction efficiency control, especially in the case of non-orthogonal multiplexing. Experimental evaluations of grating formation characteristics are required to develop the practical recording schedules for the fabrication of holographic gratings under accurate diffraction efficiency control\[^8\].

Holographic gratings were recorded in DuPont HRF-600X014 photopolymer films. The film’s thickness is 20 µm, which along with the 850 nm reconstruction wavelength and the 45° diffraction angle as shown in Fig. 1 satisfies the requirement for a thick phase hologram\[^9\]. The 532 nm line of 0.2 W from a Verdi laser was used for making all exposures. The material has little response at 850 nm, which allows in situ monitoring at this wavelength. The diffracted light from an 850 nm probe laser was monitored to measure the dynamic diffraction efficiency. To examine the dynamic properties of single grating formation in dry photopolymer films, a series of single-grating holograms, as shown in Fig. 1 (a), was recorded with the exposing illumination was stopped before the maximum saturation in the diffraction efficiency was reached. Fig. 2 shows the normalized diffraction efficiency as a function of post-threshold exposure time during and after the exposure. After the termination of the exposure, the diffraction efficiency continues to increase until a saturation value is reached. This increment depends on the diffraction efficiency \(\eta_{\text{stop}}\) at which the exposing illumination is stopped. The data in Fig. 2 show that the value of diffraction efficiency increased, respectively, 5%, 10%, 13%, 13%, 10%, and 8% after the exposing illumination was stopped at 26%, 37%, 48%, 62%, 73%, and 87%. At relatively low diffraction efficiencies, monomer concentration gradients are still weak. When reaching relatively high diffraction efficiencies,
the monomer content available for further diffusion becomes low. Therefore, the postillumination diffraction efficiency increment is relatively small in these cases. To make a single-grating hologram with the desired diffraction efficiency, $\eta_{\text{stop}}$ is a key parameter to control. Fig. 2 can be used as a guide to find the corresponding $\eta_{\text{stop}}$ for the desired diffraction efficiency.

To examine the dynamic properties of double grating formation in dry photopolymer films, a series of double-grating holograms, as shown in Fig. 1 (b), was recorded. The experiments were conducted as follows: (1) the first exposure was stopped when the first grating’s diffraction efficiency, $\eta_{\text{stop}}$, reached a value, e.g., 30%; (2) the substrate was rotated 180°; (3) the film was exposed to the recording beams again to form the second grating. To ensure the stability of the first grating and the repeatability of the experiments, some waiting time is required to guarantee that the second step takes 30 seconds. Fig. 3 shows the normalized diffraction efficiency of the two gratings as a function of second-exposure time. The calculated curves by solving two uncoupled 1-D diffusion equations using the parameters from curve fitting [5],[6] are also shown in Fig. 3 as references. During the second exposure, the diffraction efficiency of the first grating increases to a saturation value, and then rolls down with further exposure. The second grating shows the same behavior but lags behind that of the first grating. Our target is to characterize the crossing point where the two gratings have the same diffraction efficiency $\eta_{\text{equal}}$, which depends on the first grating’s diffraction efficiency $\eta_1(0)$ at which the second exposure is started. As discussed previously, $\eta_1(0)$ is determined by $\eta_{\text{stop}}$. The data in Fig. 3 (a), (b), and (c) show that $\eta_{\text{equal}}$ was, respectively, 26%, 43%, and 47% in the case that $\eta_1(0)$ was 16%, 30%, and 37%. In these cases, the monomer content left
after the first exposure is enough for the second grating to catch up with the first grating, and $\eta_{\text{equal}}$ increases with $\eta_i(0)$. On the other hand, the data in Fig. 3 (d) show that $\eta_{\text{equal}}$ did not exist in the case that $\eta_i(0)$ was 52%, because the monomer content available for the second grating formation was too low. To make a high-efficiency equal-strength double-grating hologram, $\eta_i(0)$ is a key parameter to control. Fig. 3 can be used as a guide to find the optimal $\eta_i(0)$, and then Fig. 2 can be used to find $\eta_{\text{stop}}$ for the corresponding $\eta_i(0)$.

Followed the procedure described above, we obtained the holographic gratings for the demonstration of uniform optical signal fan-outs in a five-board centralized optical backplane as shown in Fig. 4. An 850 nm VCSEL was used at center as the transmitter. As specified by the centralized optical backplane architecture[7], an equal-strength (47%/47%) double-grating hologram was attached to the center of the optical waveguiding plate. The diffraction angles of the holographic gratings were 45°. Each end of the plate had a 22.5° bevel coated with aluminum to provide a nearly 100% reflection efficiency. The fan-out variation was measured to be within 2.5%. This method is straightforward and achieves better uniformity compared with the method that controls the diffraction efficiency by setting exposure time[10].

In this paper, the diffusion model describing the process of grating formation in dry photopolymer films is briefly reviewed. If two gratings are non-orthogonally multiplexed, the process of the second grating formation is coupled with the change of the first grating during the second exposure. Due to the complexity of solving the diffusion equation and the lack of information about material parameters[6], this model cannot be used directly for diffraction efficiency control, especially in the case of non-orthogonal multiplexing. Based on the experimental evaluations of the grating formation characteristics in dry photopolymer films, we develop the practical recording schedules for the fabrication of holographic gratings under
accurate diffraction efficiency control. The method presented in this paper is straightforward and can also be used for accurate diffraction efficiency control for other types of multiplexed volume holographic gratings.

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References


**Figure Captions**

Fig. 1 The vector diagram of the (a) single-grating hologram, (b) double-grating hologram. \( \vec{R} \) represents the wave vector of the reconstruction beam. \( \vec{S} \) represents the wave vector of the diffraction beam. \( \vec{K} \) represents the grating vector formed by the exposure.

Fig. 2 Diffraction efficiency versus post-threshold exposure time during and after the exposure. The monitored diffraction efficiency was, respectively, ■ 26%, ▲ 37%, × 48%, ● 62%, + 73%, and ♦ 87%, when the exposing illumination was stopped.

Fig. 3 Diffraction efficiency versus second-exposure time during the second exposure. At the beginning of the second exposure, the diffraction efficiency of the first grating was, respectively, (a) 16%, (b) 30%, (c) 37%, and (d) 52%. * Curves represent the calculated solutions.

Fig. 4 Uniform optical signal fan-outs in a five-board centralized optical backplane. SH represents single-grating hologram. DH represents double-grating hologram.
Fig. 1
Fig. 2
Fig. 3