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[1] and substrate-guided-wave[2,3] 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.[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 characteristic in dry photopolymer films, we present a way to develop 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.

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[5,6] in the following describes the monomer concentration $u(\mathbf{r},t)$,

$$\frac{\partial u(x,t)}{\partial t}=\nabla[D(x,t)\nabla u(x,t)]-F_0[1+V\cos(K_1 x)]u(x,t), \tag{1}$$

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

$$\frac{\partial u(\mathbf{r},t)}{\partial t}=\nabla[D(\mathbf{r},t)\nabla u(\mathbf{r},t)] -F_0[1+V\cos(\mathbf{K}_2\cdot\mathbf{r})]u(\mathbf{r},t), \tag{2}$$

where $\mathbf{K}_1$ and $\mathbf{K}_2$ represent, respectively, the grating vector formed by the first and second exposure; $D(\mathbf{r},t)$ is the diffusion parameter; F_0 is the polymerization factor ($F_0=\kappa I_0$, where κ is a constant and I_0 is the average irradiance); and V is the fringe visibility. The initial conditions of Eq. (2) depend on the final conditions of Eq. (1), and the final monomer concentration after recording can be written in the form of

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

If the two gratings are orthogonally multiplexed ($\mathbf{K}_1\perp\mathbf{K}_2$), Eq. (2) can be decomposed into two uncoupled 1-D diffusion equations through a proper coordinate transformation. If the two gratings are nonorthogonally 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.[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.[7] For these holographic gratings, the reconstruction wavelength is 850 nm, and the diffraction angles are 45 deg. Equation (2) is difficult to solve in the case of nonorthogonal multiplexing. Moreover, the diffu-

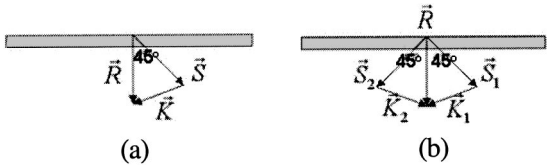

Fig. 1 Vector diagram of the (a) single-grating hologram and (b) double-grating hologram; **R** represents the wave vector of the reconstruction beam, **S** represents the wave vector of the diffraction beam, and **K** represents the grating vector formed by the exposure.

sion 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 nonorthogonal 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-deg 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 enables *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. Figure 2 shows the normalized diffraction efficiency as a function of postthreshold 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 η_{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, η_{stop} is a key parameter to control. Figure 2 can be used as a guide to find the corresponding η_{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 η_{stop} reached a value, e.g., 30%; (2) the substrate was rotated 180 deg; and (3) the film was exposed to the

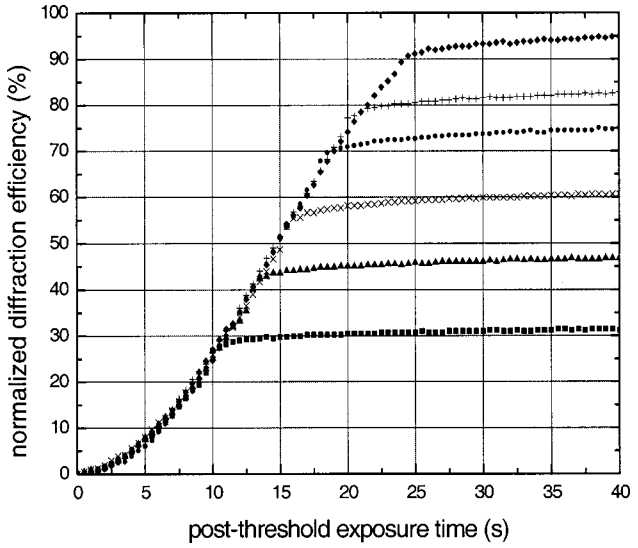

Fig. 2 Diffraction efficiency versus postthreshold exposure time during and after the exposure. When the exposing illumination was stopped, the monitored diffraction efficiencies were, respectively, squares, 26%; triangles, 37%; exes, 48%; solid circles 62%; pluses, 73%; and diamonds, 87%.

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 s. Figure 3 shows the normalized diffraction efficiency of the two gratings as a function of second-exposure time. The calculated curves that result from 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 η_{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 η_{stop}. The data in Figs. 3(a), 3(b), and 3(c) show that η_{equal} was, respectively, 26, 43, and 47% in the case where $\eta_1(0)$ was 16, 30, and 37%. In these cases, the monomer content remaining after the first exposure is enough for the second grating to catch up with the first grating, and η_{equal} increases with $\eta_1(0)$. On the other hand, the data in Fig. 3(d) show that η_{equal} did not exist in the case where $\eta_1(0)$ 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, $\eta_1(0)$ is a key parameter to control. Figure 3 can be used as a guide to determine the optimal $\eta_1(0)$, and then Fig. 2 can be used to find η_{stop} for the corresponding $\eta_1(0)$.

Following the procedure just described, we obtained the holographic gratings for a demonstration of uniform optical signal fan-outs in a five-board centralized optical backplane, as shown in Fig. 4. An 850-nm vertical-cavity surface-emitting laser (VCSEL) was used at center as the transmitter. As specified by the centralized optical back-

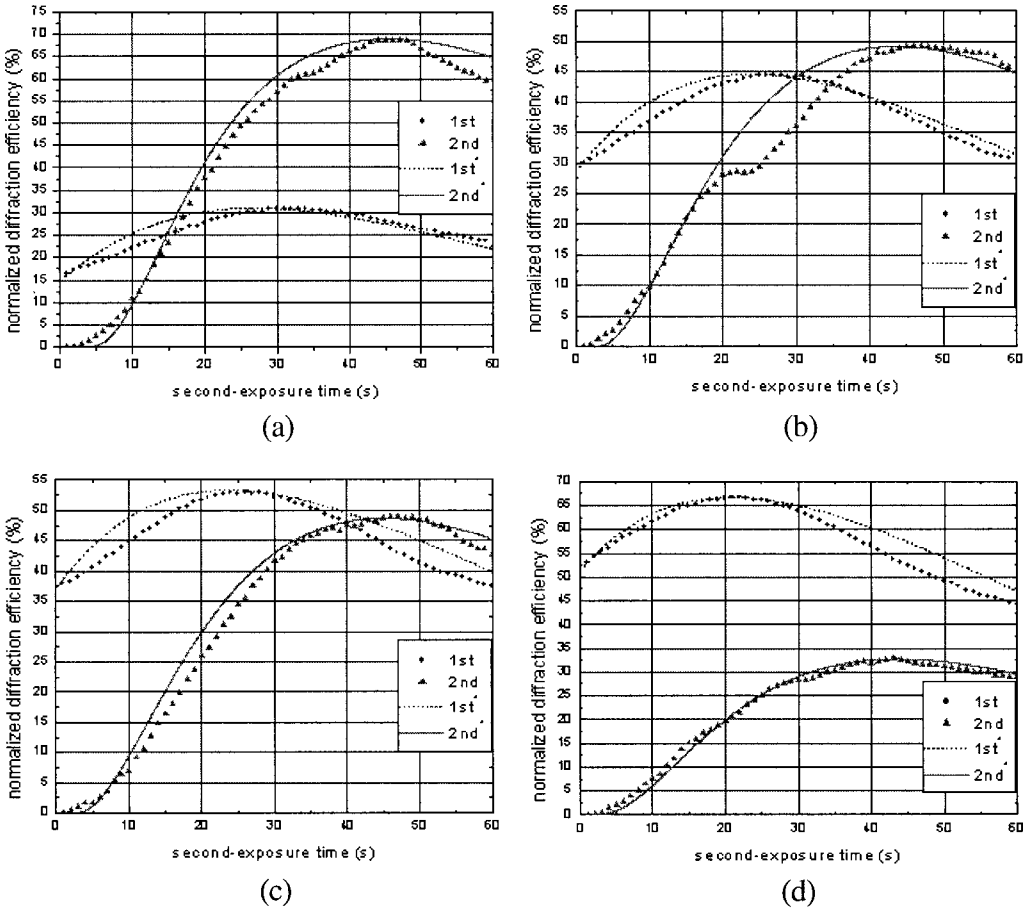

Fig. 3 Diffraction efficiency versus second-exposure time during the second exposure. At the beginning of the second exposure, the diffraction efficiency of the first grating was, respectively, (a) 16, (b) 30, (c) 37, and (d) 52%. The asterisked curves represent the calculated solutions.

plane 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 deg. Each end of the plate had a 22.5-deg 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]

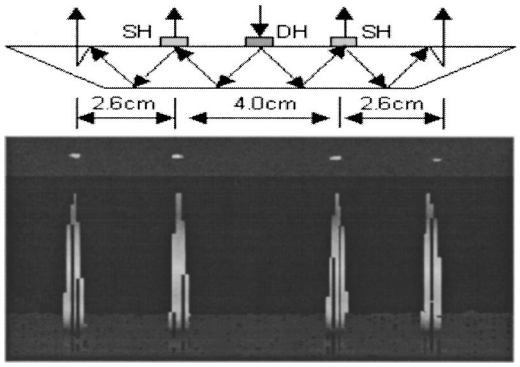

Fig. 4 Uniform optical signal fan-outs in a five-board centralized optical backplane: SH, single-grating hologram; DH, double-grating hologram.

In this paper, the diffusion model describing the process of grating formation in dry photopolymer films is briefly reviewed. If two gratings are nonorthogonally 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 nonorthogonal 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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