Shrinkage-corrected volume holograms based on photopolymeric phase media for surface-normal optical interconnects

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The film shrinkage effect of photopolymeric phase media failed to provide the desired volume holograms for point-to-point optical interconnects. In this letter, we report a compensation method to physically correct the shrinkage effect that resulted from the holographic recording and the postbaking. Dupont photopolymer HRF-600X001 is studied. The correction of the Bragg diffraction angle shift of $1°21'$, which is induced by a 5.25% film shrinkage, is successfully demonstrated with the surface-normal configuration. A shrinkage-corrected volume hologram with 80% diffraction efficiency is experimentally confirmed. The methodology reported herein is applicable to other phase media when the associated film shrinkage data are experimentally determined. *© 1997 American Institute of Physics.* [S0003-6951(97)02229-8]

Recent researchers in the area of optical interconnects have employed various holographic gratings as means of interconnection elements.[1–3] Among all the holographic materials, Dupont photopolymer films (e.g., HRF-600X001), due to their large diffraction efficiency, wide spectral sensitivity, dry-processing, and demonstrated stability, have gained much attention. The Dupont photopolymer films consist of monomers, polymeric binders, photoinitiators, and sensitizing dyes.[4] Upon exposure, the sensitizing dyes absorb light and interact with the initiators resulting in the photo-induced polymerization of monomers. The monomers diffuse and photopolymerize in the photo-induced crosslinking process. This process leads to a higher concentration in the regions having a stronger exposure dosage. Further UV curing and baking processes photopolymerize the residual monomers and enhance the index modulation which has already been reported by many researchers.[5–8] All these processing steps introduce a thickness shift of the holographic films. One immediate result from this thickness variation is the deviation of the input reconstruction angle from the originally designed Bragg condition. A deviation of up to 2.5° has been experimentally reported[8] for the Dupont photopolymer film HRF-150-38. This creates several unwanted side effects. The holographic elements designed for a beam-steering purpose[9] and the surface-normal couplers designed as compatible with the state-of-the-art very large scale integrated (VLSI) technology[10] are two striking examples. The other side effect associated with this thickness variation is the decrease of the diffraction efficiencies at the desired diffraction angles.

In this letter, we study the relative film thickness variation of the Dupont photopolymer HRF-600X001 and present a repeatable compensation method which is capable of counterbalancing the angular deviation effect and therefore eliminates these undesired effects.

The Dupont photopolymer film HRF-600X001 studied in our experiments had a thickness of 20 μm. The structures and properties of this film have been discussed elsewhere.[4] Films to be tested were laminated on BK-7 glass substrates after removal of the protecting cover sheet. The holographic gratings were recorded using the two beam interference method[11] with an argon ion laser operating at 514.6 nm. The intensities of the two recording beams at the surface of the film were 2.21 and 0.67 mW, respectively. The holograms were designed such that the reconstruction beam (at wavelength of $\lambda = 632.8$ nm) incoming from the surface-normal direction was diffracted at 45° within the glass-based waveguiding substrate. After exposure, films were cured for 2 min using an UV lamp (160 W) and baked at 120 °C for different time intervals. Figure 1 shows the angular deviations from the designed Bragg condition (surface-normal) versus the baking time for a hologram after being exposed for 45 s. The sign of the angular deviation is defined such that whenever the film shrinks, it is negative. The change of the angular deviation from negative to positive with the increase of baking time as shown in Fig. 1 suggests that after exposure, the film shrank first, then swelled as the baking time increased. The result implies that the thickness variation of the film during processing is not just a simple monotonous shrinking process as some previous papers claimed.[6,8] After around 150 min of baking, the angular deviation came to a saturated value of about 85 min as seen in Fig. 1. The angu-

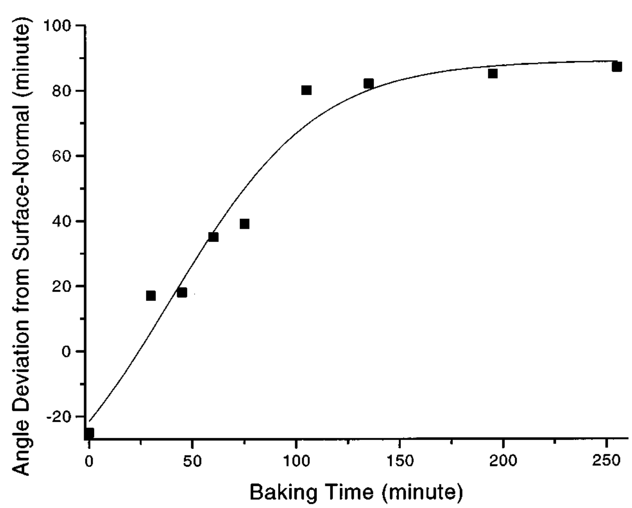

FIG. 1. Variation of angular deviation from the surface-normal as a function of the baking time at 120 °C.

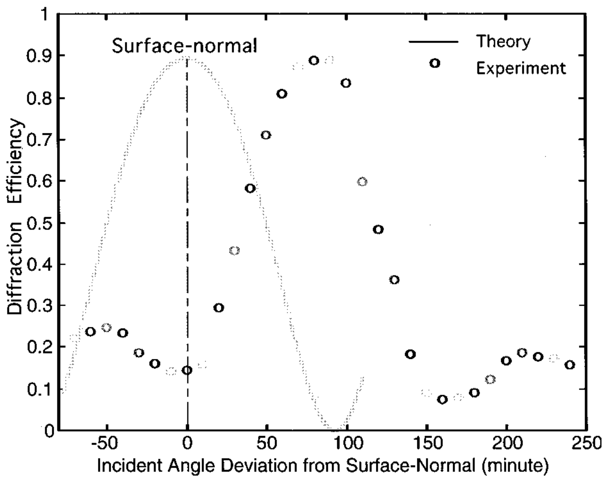

FIG. 2. Variation of diffraction efficiencies as a function of the angular deviation from the surface-normal Bragg condition.

lar deviation from the originally designed surface-normal incident direction is further illustrated in Fig. 2 for a hologram after 45 s of exposure and 150 min of baking. This figure displays the relationship between the diffraction efficiency of the hologram and the angular deviation from the surface-normal direction. The theoretical curve in Fig. 2 is based on the originally designed grating, i.e., a grating with a surface-normal incidence and a 45° diffraction angle. A displacement of about 85 min between the maximum (the Bragg condition) of the two curves can clearly be seen due to the film thickness variation effect.

To study the thickness variation of the films, a model delineating the microstructure of the grating is shown in Fig. 3(a), which schematically defines the related parameters of the film before and after the thickness changes. The detailed Bragg diffraction condition for the gratings in Fig. 3(a) is shown in Fig. 3(b). The thickness change occurs only in the direction perpendicular to the surface of the substrate. In Fig. 3, the θ's are the angles between the slanted holographic gratings and the film surface, Λ and Λ' are the grating periods before and after the baking. Δd is the corresponding thickness variation, $\Delta\theta$ is the change of the angle between the slanted holographic gratings and the film surface due to the shrinkage, and β is deviation of the Bragg angle of the incident beam inside the film. The subscript 1 in the ks denotes the incident beam and the subscript 2, the diffracted beam. It can be easily derived from Fig. 3(a) that

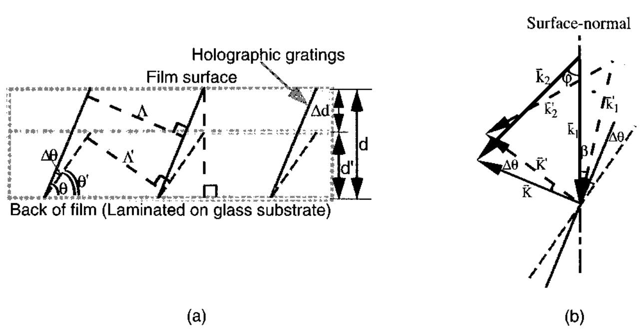

FIG. 3. (a) Schematic of the thickness variations of phase medium before and after processing. (b) Bragg diffraction diagram of the holographic gratings in Fig. 3(a).

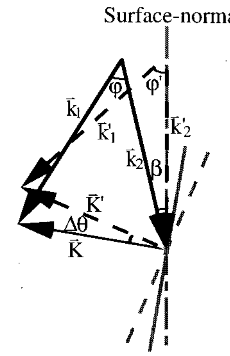

FIG. 4. Bragg diffraction diagram for the compensation study.

$$d' = d\,\frac{\tan\,\theta'}{\tan\,\theta};\quad \Lambda' = \Lambda\,\frac{\sin\,\theta'}{\sin\,\theta}, \tag{1}$$

where $\theta' = \theta - \Delta\theta$ and

$$\theta = \frac{\pi - \varphi}{2};\quad \Lambda = \frac{\lambda}{2n_0\,\sin(\varphi/2)}, \tag{2}$$

where $\varphi = 45°$ is the designed diffraction angle and $n_0 = 1.50$ is the average refractive index of the film. The thickness change in the vertical direction implies that the grating vector, **K**, rotates the same angle as does the grating. By inspecting the geometrical relationship represented by Fig. 3(b), we have

$$\beta + \left[\cos^{-1}\left(\frac{K/2}{k}\right) - \Delta\theta\right] = \cos^{-1}\left(\frac{K'/2}{k}\right), \tag{3}$$

where $k = 2\pi n_0/\lambda$ and $K = 2\pi/\Lambda$. The angular deviation outside the film can be converted into β using the Snell's law. For an angular deviation of 85 min as shown in Fig. 2, Eqs. (1)–(3) can be solved to give $\Delta d = 1.05\,\mu$m, which implies that the Dupont polymer film has a thickness change of 5.25%, which gives a $1°21'$ incident angle deviating from the surface-normal. The change in thickness of the film results in a substantial change in the refractive index. For instance, after 2 h of baking, a refractive index difference of 0.014 has been observed for Dupont OmniDex 706 holographic recording films.[7]

Three different photopolymerization processes influence the thickness variation of the Dupont photopolymer film.[8] They are: (1) the interference patterns of the two recording beams; (2) the sum of the average energy of the two beams; and (3) the UV curing and baking processes afterwards. Experiments have shown that the first process has a negligible effect on the thickness change of the film.[12] Therefore, if two holograms are fabricated under the same condition for processes (2) and (3), the resultant relative changes in the film thickness will be the same.

Consider the phase matching diagram in Fig. 4, which can be treated as Fig. 3(b) after rotating an angle of β equivalent to that of the film shrinkage effect. Again, the dashed lines correspond to the Bragg diffraction after processing and the solid lines to that before processing. By compensating the film shrinkage problem in the recording process, the hologram (the dashed lines in Fig. 4) can be reconstructed surface normally at $\lambda' = 632.8$ nm with a dif-

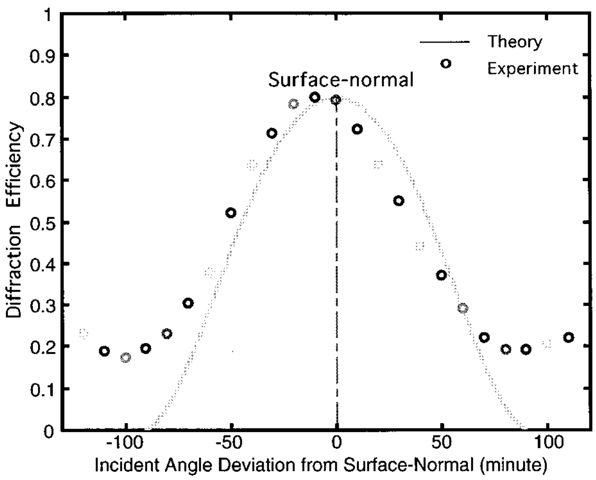

FIG. 5. Diffraction efficiency of a shrinkage-corrected surface-normal hologram as a function of the angular deviation from the surface-normal Bragg condition.

fraction angle of $\varphi' = 45°$. A hologram is recorded with a grating vector **K**, a diffraction angle $\varphi = 44°39'$, and an incident angle $\beta = 54'$ at $\lambda = 632.8$ nm. After being processed under the same condition as for Fig. 2, the film shrinkage effect can be fully compensated by the hologram **K** to achieve the desired surface-normal hologram **K**′ as schematically delineated in Fig. 4.

Fabrication of the hologram is designed to have a diffraction angle of 44°39′, an incident angle of 1°21′, and a reconstruction wavelength of 632.8 nm. The intensity of the two beams was again adjusted to 2.21 and 0.67 mW, respectively. After processing under the same conditions as for Fig. 2, the data representing the diffraction efficiency versus the incident angle relation is shown in Fig. 5. By using the proposed compensation method, a hologram with much small deviation from the desired result can be obtained. The shift of the Bragg angle after compensation is less than $-7'$, which is within the experimental error range when considering the results in Fig. 1. The decrease of the diffraction efficiency for the surface-normal incidence is around 3% with a maximum efficiency of 80%. The methodology presented herein is also applicable to other phase media when the associated film shrinkage data are experimentally determined.

In conclusion, we report, for the first time, a compensation method to correct the film shrinkage effect of the Dupont photopolymer HRF-600X001. An angular deviation of 85′ from the surface normal has been observed in our experiment. A thickness variation of 5.25% resulted from such a deviation. The surface-normal coupling condition is generated after implementing the compensation method. A peak diffraction efficiency of 80% and a deviation angle of less than 7 min are experimentally achieved. The methodology presented herein is also applicable to other phase media when the associated film shrinkage data are experimentally determined.

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