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Shrinkage- and refractive-index shift-corrected volume holograms for optical interconnects

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The Bragg mismatching condition for volume holograms occurs because of the changes in the thickness and the refractive index of holographic recording materials during the recording and reconstruction procedures. We propose an improved compensation method to physically correct these effects in the fabrications of volume holograms for optical interconnects. In order to show the validity of this method, Slavich photographic plate VRP-M is used to fabricate optical interconnects. The correction of the Bragg diffraction angle shift of about 2.10°, which is induced by 6.14% film shrinkage and 0.06 refractive index shift, is successfully demonstrated with the surface-normal configuration. A shrinkage- and refractive-index shift-corrected volume hologram with 23% diffraction efficiency is experimentally confirmed. The methodology proposed is applicable to other phase media when the associated film shrinkage and refractive-index shift data are experimentally determined. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1502022]

Thick recording materials such as silver halide emulsion, dichromated gelatin, and photopolymer, can be used to record volume holograms for optical interconnects. The thickness and the refractive index of these recording materials can change significantly after optical exposure and postprocessing. According to the coupled-wave theory,[1] the diffraction properties of a volume hologram are strongly dependent on the wavelength of the reconstructed light, the thickness, and the refractive index of the recording material. Thus, the operation characteristics of thick volume holograms are strongly influenced by the shifts in the thickness and the refractive index of the photographic film, especially when the operating wavelength is different from that of the recording beam such as for optical interconnect applications. There are several articles proposed to reduce the influences of the thickness shift.[2–6] Some are related to the procedures of the postprocessing.[2–5] Recently, Zhao *et al.*[6] proposed a corrected condition in the geometry of optical setup for recording volume holograms, and he demonstrated its feasibility with Dupont photopolymer HRF-600X001. There is no reference related to how to simultaneously correct the influences of the thickness shrinkage as well as the refractive-index shift. In this letter, an improved compensation method to physically correct the influences due to both the thickness shift and the refractive-index shift is proposed, based on Zhao's technique. In addition, volume holograms for optical interconnects are fabricated with silver halide emulsion to demonstrate its validity.

The geometry of optical configuration for recording a volume hologram is shown in Fig. 1. Two light beams R_1 and S_1 with wavelength λ_1 are incident on a recording material at θ_{r1} and θ_{s1}. The recording material consists of a substrate with refractive index n_s and a photographic film with refractive index n_{f1} (at λ_1) and thickness d_1. Their refractive angles in the photographic film are θ'_{r1} and θ'_{s1}, and the spacing of the interference fringes is Λ_1. After the exposure, the recording material is postprocessed for developing. Then the thickness of the photographic film and its refraction index may shift to different values. Assume the thickness, the spacing of the interference fringes, and the slant angle are changed from (d_1, Λ_1, ψ_1) to (d_2, Λ_2, ψ_2), as shown in Fig. 2. In order to satisfy the Bragg matching condition for volume holograms, the recording and reconstruction conditions must be carefully designed. For optical interconnect applications, this problem becomes more serious because volume hologram are always fabricated by the technique of shorter-wavelength construction for longer-wavelength reconstruction.[7] Thus, the reconstructed light with wavelength λ_2 $(>\lambda_1)$ must be incident at a specially designed angle θ_{r2}, as shown in Fig. 3. If the outgoing signal

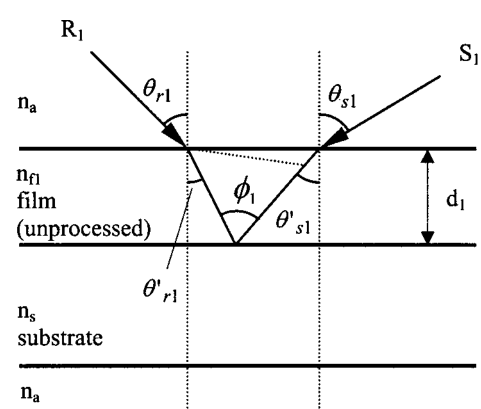

FIG. 1. Geometry for recording a volume hologram.

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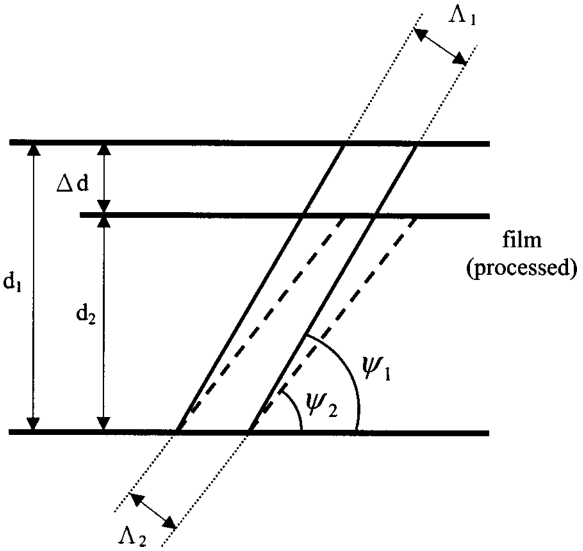

FIG. 2. Schematic representation of thickness shift of photographic film before and after processing.

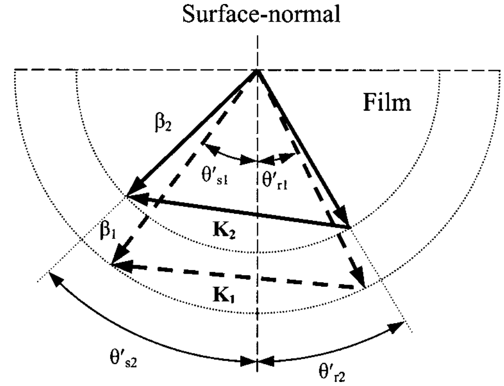

FIG. 4. K-vector diagram for the compensation study.

wave S_2 with diffracted angle θ_{s2} is desired, then the angles θ'_{r2} and θ'_{s2} can be calculated with Snell's law, and the angles θ'_{r1} and θ'_{s1} can be derived with the K-vector diagram for Bragg matching condition,[1] as shown in Fig. 4. Here, K_1 is the grating vector of the volume hologram before processing, its initial and end points are on the circular arc with radius $2\pi/\Lambda_1$. And K_2 is the grating vector of the volume hologram after processing. Since a light beam with wavelength λ_2 is used to reconstruct this volume hologram, its original and end points are located on another circular arc with radius $2\pi/\Lambda_2$. Finally, the values of θ_{r1} and θ_{s1} can be calculated by using Snell's law again. Hence, we have

$$\theta_{r1}=\sin^{-1}\left\{\frac{-n_{f1}}{n_a}\cos\left[\psi_1+\sin^{-1}\left(\frac{\lambda_1}{2n_{f1}\Lambda_1}\right)\right]\right\}, \tag{1}$$

and

$$\theta_{s1}=\sin^{-1}\left\{\frac{n_{f1}}{n_a}\cos\left[\psi_1-\sin^{-1}\left(\frac{\lambda_1}{2n_{f1}\Lambda_1}\right)\right]\right\}, \tag{2}$$

where

$$\psi_1=\tan^{-1}\left\{\frac{(-1)d_1}{d_2}\cot\left[\frac{1}{2}(\theta'_{r2}-\theta'_{s2})\right]\right\}, \tag{3}$$

$$\Lambda_1=\frac{\lambda_2\sin\psi_1}{n_{f2}(\sin\theta'_{r2}+\sin\theta'_{s2})}, \tag{4}$$

$$\theta'_{r2}=\sin^{-1}\left(\frac{n_a}{n_{f2}}\sin\theta_{r2}\right), \tag{5}$$

$$\theta'_{s2}=\sin^{-1}\left(\frac{n_a}{n_{f2}}\sin\theta_{s2}\right), \tag{6}$$

n_{f1} and n_{f2} are the refractive indices at λ_1 and λ_2, respectively. It is obvious from Eqs. (1) and (2) that θ_{r1} and θ_{s1} can be calculated if the experimental conditions of n_a, n_{f1}, d_1, n_{f2}, d_2, θ_{r2}, and θ_{s2} are specified. These equations serve as design formulas for the precompensated volume holograms.

Optical interconnects with the specifications of $\theta_{r2}=0°$, $\theta_{s2}=45°$, and $\lambda_2=632.8$ nm are fabricated. A solid-state laser with 532 nm wavelength is used to record the interference fringes on the Slavich photographic plate (VRP-M) whose optimal exposure is 30 μJ/cm^2. After the optical exposure, it is processed with the technique presented by Sazonov and Kumonko[8] (with SM-6 developer and PBU-Amidol bleach). An ellipsometer (Model: nkd-6000™, Aquila Instruments Ltd.) and a surface profiler (model: Dektak 3030, Veeco Instruments Inc., Sloan) are used to measure the refractive indices and the thickness of this film before and after processing, respectively. The measured results are shown in Fig. 5. From this figure, we obtain $n_{f1}=1.6046$ (at 532 nm), $n_{f2}=1.6647$ (at 632.8 nm), $d_1=5.70$ μm, and d_2

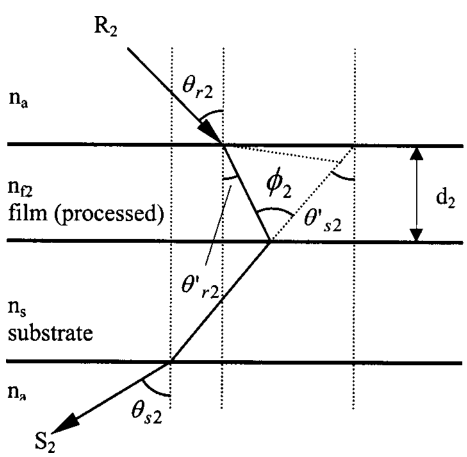

FIG. 3. Geometry for reconstructing a volume hologram.

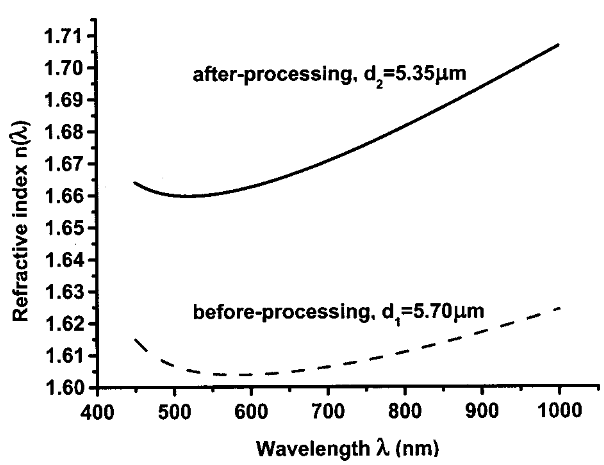

FIG. 5. The measured relation curves between the refractive index vs the wavelength of Salvich VRP-M film before and after processing.

TABLE I. Calculated values for four possible uncompensated conditions.

Conditions	θ_{r1}	θ_{s1}	θ_{s2}
(i)	−2.20°	39.26°	46.15°
(ii)	−2.18°	39.23°	46.11°
(iii)	−3.39°	40.81°	48.04°
(iv)	−3.38°	40.80°	48.03°

$=5.35\ \mu$m, respectively. Substituting these data and $n_a=1$ into Eqs (1)–(6), the conditions $\theta_{r1}=-1.46°$ and $\theta_{s1}=38.31°$ are obtained.

Let us consider the conventional cases. First, assume we consider only the thickness shrinkage of the photographic film, then we have two conditions (i) $d_1=5.70\ \mu$m, $d_2=5.35\ \mu$m, $n_{f1}=n_{f2}=1.6046$, and (ii) $d_1=5.70\ \mu$m, and $d_2=5.35\ \mu$m, $n_{f1}=n_{f2}=1.6647$. In addition, if we even do not consider both the thickness shrinkage and the refractive index shift of the photographic film, then we may have another two conditions (iii) $d_1=d_2=5.70\ \mu$m, $n_{f1}=n_{f2}=1.6046$, and (iv) $d_1=d_2=5.70\ \mu$m, $n_{f1}=n_{f2}=1.6647$. We use these four possible uncompensated conditions to calculate the values of θ_{r1}, θ_{s1}, and θ_{s2}. And they are calculated and listed in Table I. In these four cases, θ_{s2} does not equal to 45° as originally designed. We have plotted the relation curves of the diffraction efficiency versus the deviation of the incident angle from the surface-normal direction, as shown in Fig. 6(a) for conditions (i) and (iii) and Fig. 6(b) for (ii) and (iv), respectively. The theoretical and experimental curves have been added in both Figs. 6(a) and 6(b) for comparisons. It is seen that the experimental curve shows good correspondence with the theoretical curve. It is noted in Fig. 6 that the incident angle for matching the Bragg condition (maximum diffraction efficiency) are deviated from the surface-normal direction by −0.81°, −0.78°, −2.10°, and −2.09° for conditions (i), (ii), (iii), and (iv), respectively. If both the thickness shrinkage and the refractive index shift have been taken into account, then there should be no angle deviation.

According to the coupled-wave theory, it can be calculated that if the product of the index modulation strength n' and the thickness d_2 (in micron unit) of the photographic film is larger than 0.24, then the diffraction efficiency will be larger than 90%. In our experiments, the thickness of the photographic film is so thin that the maximum diffraction efficiency is only about 23%. If the thickness d_2 could be increased to 18.77 μm and other data would remain unchanged, the diffraction efficiency would be enhanced to 90%.

The influences owning to shifts in the thickness and the refractive index of holographic recording materials have been discussed. An improved compensation method to physically correct these effects in the fabrication of volume holograms for optical interconnects has been proposed. Moreover, volume holograms for optical interconnects are fabricated with silver halide emulsion photographic material to show the validity of this method. The methodology proposed is applicable to other phase media when the associated film shrinkage and refractive-index shift data are experimentally determined.

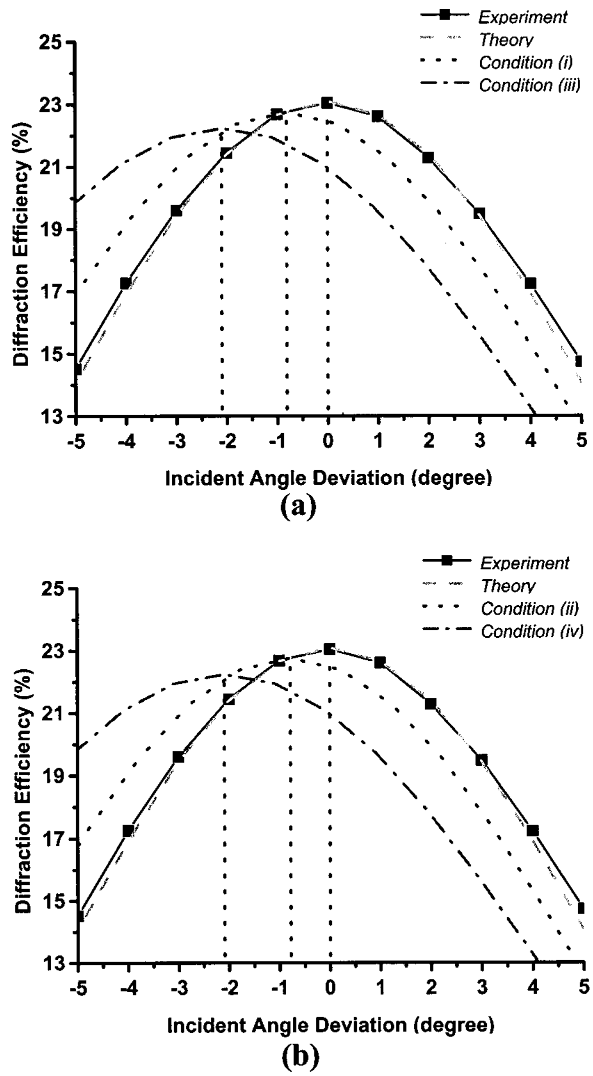

FIG. 6. Variations of diffraction efficiency as function of the angular deviation from the surface-normal Bragg condition for (a) conditions (i) and (iii); and (b) conditions (ii) and (iv).

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