Polarization sensitivity of photopolymer-based volume holograms for one-to-many surface normal optical interconnects

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Abstract. Polarization dependence of photopolymer-based volume holograms for substrate-guided-wave optical interconnects with surface normal configuration is investigated. Energy optimization and the trade-off between energy equalization and polarization insensitivity of one-to-many cascaded interconnects are discussed. DuPont photopolymer film HRF 600X001-20 was employed in our experiment. A volume hologram with diffraction efficiency of 91.5%±1.5% is achieved for different linearly polarized optical waves. A 1-to-9 fanout device with ±5% energy fluctuation for a randomly polarized input optical wave at 632.8 nm has been fabricated for evaluating the trade-off under *p* and *s* waves. As the Mylar substrate of the photopolymer films has strong effects in changing incident linearly polarized light into elliptically polarized light, the energy uniformity of a practical device can be improved significantly. The developed theory is applicable to any volume hologram. [S0091-3286(98)02402-7]

Subject terms: optical interconnects; polarization; volume hologram; photopolymer films.

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1 Introduction

DuPont photopolymer films are promising for holographic recording due to their dry processing, long shelf life, and good photospeed.[1–4] The holographic photopolymer emulsion is coated onto a polyester substrate. A removable cover sheet is used as a protecting layer. The films can be imaged by removal of the cover sheet and then laminating the film onto a glass substrate. They have been widely used for volume hologram formation.

The hologram formation mechanism in photopolymer films is known to be a three-step process.[2] First, an initial exposure generates the interference pattern, which causes the initial polymerization and diffusion of the monomers to bright fringe areas from the dark fringe neighborhood in the photopolymer. A higher concentration of polymerization means a higher refractive index. Second, a uniform UV exposure is required for dye bleaching and complete polymerization. Third, a baking process is employed to further enhance refractive index modulation of the hologram formed in the film.

Photopolymer-based substrate-guided-wave optical interconnects employ total internal reflection to direct optical signals within a waveguiding substrate and holographic optical elements (HOEs) to couple optical signals into and out of the substrate. It is an efficient approach for wavelength-division (de)multiplexing (WDDM), optical true time-delay lines, optical backplane buses, and other optical networks.[5–7] In our experiment, DuPont photopolymer film HRF 600X001-20 (20 μm thick) is selected as the recording material because it exhibits a low scattering loss and a high diffraction efficiency.[4] High refractive index modulation in this type of photopolymer film has been reported, and a large dynamic range of diffraction efficiencies as a function of exposure time can be achieved by adjusting the light intensities of the two recording beams.[1,2]

The polarization dependence of holographic interconnects using dichromated gelatin (DCG) was studied by several authors.[8–11] However, the polarization characteristics of photopolymer-based substrate-guided-wave optical interconnects with cascaded holographic optical elements (HOEs) have not been reported. In this paper, the polarization dependence of the diffraction efficiencies of photopolymer-based HOEs is investigated. Polarization-related characteristics for photopolymer-based holographic interconnects with energy-optimized one-to-many surface normal fanouts are demonstrated using a randomly polarized input optical signal. In Section 2, the principle of transmission holograms under *p* and *s* waves is analyzed for DuPont photopolymer films HRF 600X001-20. Optimization of HOE-based substrate-guided-wave optical interconnects is delineated in Section 3 to provide energy-equalized one-to-many surface normal fanouts. In Section 4, we analyze the trade-off between energy equalization and polarization insensitivity for the cascaded volume holograms. Section 5 provides an experimental method to fabricate HOEs and to measure their diffraction efficiencies. Experimental results on a one-to-nine fanout device for a randomly polarized optical signal are given as well. A summary is given in Section 6.

2 Theoretical Background

For a transmission volume hologram with an input optical signal incident at an angle of θ with respect to the surface normal direction, if the polarization of the input optical

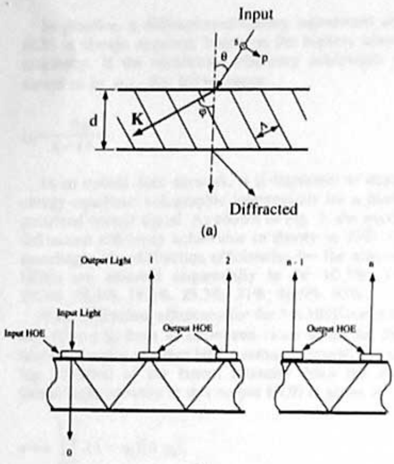


Fig. 1 (a) Schematic diagram for a volume hologram; (b) a typical substrate-guided-wave optical interconnect with surface normal configuration.

signal is either parallel or perpendicular to the holographic grating vector, there should be no cross-coupling. For an s-polarized optical signal, the diffraction efficiency is[12]

$$\eta_s = \sin^2 \gamma_s, \tag{1}$$

where

$$\gamma_s = \frac{\kappa_s d}{(c_R c_S)^{1/2}}, \tag{2}$$

$$c_R = \cos\theta, \quad c_S = \cos\theta - \frac{K}{\beta}\cos\varphi, \tag{3}$$

and

$$\beta = \frac{2\pi n}{\lambda}, \quad K = \frac{2\pi}{\Lambda}, \quad \text{and} \quad \kappa_s = \frac{\pi \Delta n}{\lambda}. \tag{4}$$

The schematic representing such a diffraction is shown in Fig. 1(a). In Eqs. (1) to (4), Δn is the amplitude of the refractive index modulation, θ is the angle of the incident optical signal within the hologram medium, Λ is the grating period, d is the thickness of the grating layer, λ is the free-space wavelength of incident light, n is the average refractive index of the grating medium, and φ is the slant angle of the grating.

For a p-polarized input optical signal, above equations can be used as well by replacing κ_s in Eq. (3) with[12]

$$\kappa_p = -\kappa_s \cos 2(\theta - \varphi). \tag{5}$$

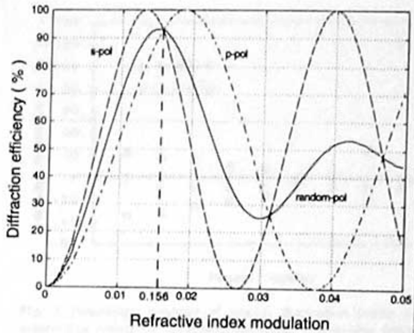


Fig. 2 Theoretical results for diffraction efficiency versus refractive index modulation under p and s waves and a randomly polarized wave at $\lambda = 632.8$ nm for DuPont photopolymer HRF 600X001-20 (20 μm thick).

Figure 1(b) shows a typical substrate-guided-wave optical interconnect with the surface normal configuration. The diffraction angle of the volume hologram is designed to be 45 deg in a glass substrate while the optical signal is incident from the surface normal direction with $\theta = 0$ deg. Figure 2 shows the simulation results on the diffraction efficiencies versus refractive index modulation of p and s waves and a randomly polarized wave. The result is derived for a 20-μm film with a refractive index $n = 1.52$ at $\lambda = 632.8$ nm. It is clear that the diffraction efficiency for s-polarized light is larger than for p-polarized light at low refractive index modulation, and the two curves intersect at $\Delta n = 0.0156$. At this point, 93% diffraction efficiency is achieved for both p- and s-polarized light, which means a polarization-insensitive HOE with high diffraction efficiency can be achieved with the photopolymer films HRF 600X001-20. When the refractive index modulation becomes even larger, the diffraction-efficiency curves start to oscillate.

3 Optimization of Substrate-Guided-Wave Optical Interconnect

For a substrate-guided-wave optical interconnect with an ideal one-to-n energy-equalized surface normal fanout, the diffraction efficiency for the ith output HOE is given by[6]

$$\eta_i = \frac{1}{n - i + 1}, \quad i = 1,2,3,\ldots. \tag{6}$$

In Eq. (6), the subscript i represents the order of the output HOEs in the designed substrate-guided-wave optical fanout device. For example, an ideal one-to-nine energy-equalized fanout device needs, respectively, 11.1%, 12.5%, 14.3%, 16.7%, 20%, 25%, 33.3%, 50%, and 100% diffraction efficiencies for the successive output HOEs. The key to obtain an energy-equalized fanout distribution is to find an appropriate recording dosage that can provide an accurate diffraction efficiency between 11.1% and 100%.

In practice, a diffraction-efficiency adjustment of each HOE is always required, based on the highest achievable efficiency. If the maximum efficiency achievable is assumed to be η_M, Eq. (6) becomes

$$\eta_i=\frac{\eta_M}{n-i+1}. \tag{7}$$

In an optical fiber network, it is important to design an energy-equalized holographic interconnect for a randomly polarized optical signal. As shown in Fig. 2, the maximum diffraction efficiency achievable in theory is 93%. Correspondingly, the diffraction efficiencies for the nine output HOEs are adjusted sequentially to be 10.3%, 11.6%, 13.3%, 15.5%, 18.6%, 23.3%, 31%, 46.5%, 93%.

If the diffraction efficiency for the kth HOE has a deviation of $\pm\Delta\eta_k$ from its optimized value while the diffraction efficiencies of other HOEs remain optimal, the resulting deviation of the fanout intensity from the average fanout light intensity at this output HOE is given by

$$\epsilon=n\prod_{i=1}^{k-1}(1-\eta_i)|\Delta\eta_k|. \tag{8}$$

If the maximum energy fluctuation tolerance of a device with a one-to-n fanout is desired to be $\epsilon_{\max}$, from Eq. (8), the corresponding tolerance of the diffraction efficiency for the kth output HOE is

$$|\Delta\eta_k|_{\max}=\frac{\epsilon_{\max}}{n\prod_{i=1}^{k-1}(1-\eta_i)}, \tag{9}$$

while keeping the other HOEs accurately fabricated.

4 Trade-off between Energy Equalization and Polarization Insensitivity for Substrate-Guided-Wave Optical Interconnect

As the diffraction efficiency varies with the state of polarization of the input optical signal, there exists a trade-off between energy equalization and polarization insensitivity. For an energy-equalized one-to-nine fanout device designed for a randomly polarized optical signal, the equal fanout energy distribution will be changed because of the migration of the corresponding diffraction efficiencies of the output HOEs. For example, as shown in Fig. 2, at $\Delta n=0.0050$, which corresponds to the sixth output HOE, the diffraction efficiency is 23.3% for randomly polarized light, 31% for an s wave, and 16.4% for a p wave. The discrepancy between these diffraction efficiencies causes a serious fanout energy distribution error. Therefore, in designing an energy-equalized fanout device, the polarization of the input beam has to be specified.

Assume the diffraction efficiency of the ith HOE is η_i for an energy-equalized one-to-many fanout under a specific polarization. If a different state of polarization is applied, a deviation of $\pm\Delta\eta_i$ occurs and the diffraction efficiency becomes

$$\eta_i'=\eta_i\pm\Delta\eta_i. \tag{10}$$

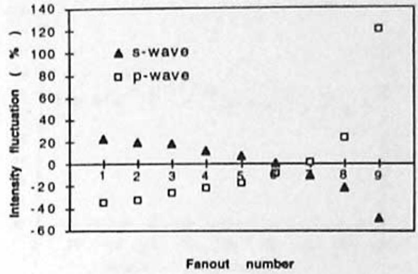


Fig. 3 Theoretical analysis of energy fluctuation under p- and s-polarized waves for an energy-equalized one-to-nine fanout device.

The output intensity from the ith output HOE is

$$I_i=\eta_0 I_{\rm in}\prod_{j=1}^{i-1}(1-\eta_j')\eta_i', \tag{11}$$

where $I_{\rm in}$ is the input light intensity and η_0 is the diffraction efficiency of the input HOE, which is designed to be polarization-insensitive. The average light intensity $I_{\rm av}$ for such a one-to-many fanout device is given as

$$I_{\rm av}=\frac{\eta_0}{n}I_{\rm in}\sum_{i=1}^{n}\prod_{j=1}^{i-1}(1-\eta_j')\eta_i', \tag{12}$$

and the intensity fluctuation ϵ_i occurring at the ith output light signal can be written as

$$\epsilon_i=\frac{I_i-I_{\rm av}}{I_{\rm av}}. \tag{13}$$

Figure 3 gives the theoretical results for an ideal energy-equalized one-to-nine fanout used for randomly polarized light. For an s wave, the energy fluctuation error reaches 50%, and for a p wave, up to 120% energy nonuniformity occurs.

5 Experiment

5.1 *Experimental Setup and Diffraction-Efficiency Measurement*

A two-beam interference method is employed to fabricate HOEs.[13] An argon ion laser operating at 514 nm is used to record holograms. The reconstruction wavelength is set at 632.8 nm. The diffraction angle for each HOE is designed to be 45 deg in a waveguiding substrate, greater than the 41.3-deg critical angle of the total internal reflection for a BK-7 glass substrate. The phase matching condition[12] and Snell's law are applied to calculate the diffraction angle in the hologram medium and then to convert the recording angles to those in the air. The Mylar film shows birefringent properties. During volume-hologram recording, the holographic film should be rotated to make the recording

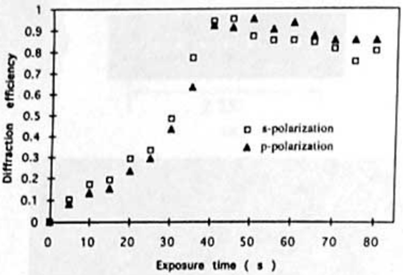


Fig. 4 Experimental results for diffraction efficiency versus exposure time under p and s waves at $\lambda = 632.8$ nm for DuPont photopolymer HRF 600X001-20 (20 μm thick).

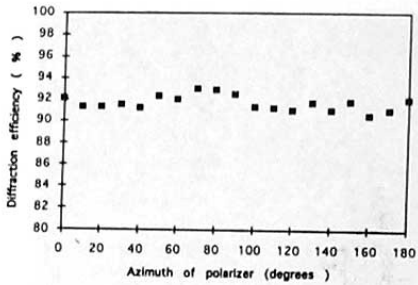


Fig. 5 Diffraction efficiency versus the azimuth of the polarizer for an HOE.

light wave direction parallel to the Mylar's optical axis to enhance the coherence of two interference beams. A recent publication by Blitz and Pernick[14] confirms experimentally that the Mylar support alters an incoming linearly polarized laser beam to an elliptical polarization and distorts the incoming polarization to a comparable degree.

For our experiment setup, the intensity ratio of the two recording beams is set at 1 : 2 and the total intensity of the two beams is 3.1 mW/cm^2. Holograms with exposure times from 0 to 80 at an increment of 5 s are recorded. The holograms are postexposed with 120-mJ/cm^2 UV light and baked for 1 h at 120°C. A He-Ne laser is used to measure the diffraction efficiencies of the HOEs at 632.8 nm. A plastic sheet polarizer (type HN 22, Polaroid Co., Norwood, MA) is employed in our experiment. The diffraction efficiency versus the exposure time under such a recording condition is given in Fig. 4, which shows that when the exposure time is smaller than 40 s, the diffraction efficiency of the HOE for an s wave is larger than that of the HOE for a p wave. This is consistent with simulation results given in Sec. 2. The effect of the Mylar support on the polarization sensitivity is to make the discrepancy of diffraction efficiency between p and s waves at a given refractive index modulation smaller than that predicted in Fig. 2. From Fig. 4, we can see that higher efficiencies (>90%) for both p and s waves occur between 40- and 50-s exposure time, different diffraction efficiencies ranging from 0% to 94% for an s wave are obtained between 0 and 45 s and different diffraction efficiencies ranging from 0% to 93% for a p wave are obtained between 0 and 50 s. When the exposure time is larger than 50 s, the diffraction efficiency for a p wave becomes larger than those for an s wave. Also, the diffraction efficiencies for both p and s waves remain nearly unchanged once the saturation of the modulation of the refractive index is achieved.[2]

Figure 5 shows the diffraction efficiency versus the rotation angle of the linear polarizer, which is rotated every 10 deg from 0 to 180 deg, for an HOE with diffraction efficiencies larger than 90% for both p and s waves. The exposure time of the HOE is 40 s. The diffraction efficiency is within 91.5%±1.5% for different linearly polarized optical signals. Such an HOE can be used in some cases as polarization-insensitive input and/or output couplers in optical interconnects.

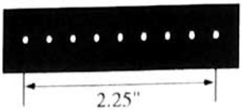
5.2 *Experimental Results on Energy Optimization for a Randomly Polarized Substrate-Guided-Wave Optical Interconnects*

A one-to-nine fanout device was fabricated for an input randomly polarized optical signal operating at 632.8 nm. The exposure time for fabrication of each output coupler corresponds to the average diffraction efficiency of those measured for p and s waves and shown in Fig. 3. The fabrication method is similar to that described in Ref. 6.

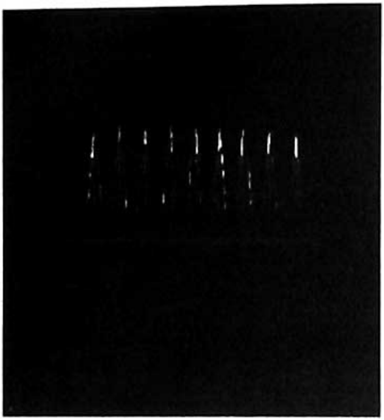
Figure 6(a) shows a photograph of the one-to-nine fanout device under a randomly polarized input optical signal, and its corresponding CCD 2-D intensity profile is shown in Fig. 6(b). The fluctuation of the intensity distribution is measured to be within ±5% with respect to the average intensity. Using p- and s-polarized optical signals, the corresponding intensity profiles are also provided in Figs. 7(a) and 7(b). The maximum energy nonuniformity for a p wave becomes −13%, and for an s wave −24%, which indicates the trade-off between energy equalization and polarization insensitivity. We can also see that, for a p wave, the first channel deviates the most from the average value, while for an s wave, the last one does. Because the Mylar film changes the linear polarization into an elliptical one, the nonuniformities for p and s waves are reduced significantly from those expected in theory. Furthermore, elliptical polarization of each fanout light is observed, while the extinction ratio achievable is ~13 dB (1 : 20), and around 10 deg of rotation of the polarization is also observed.

6 Summary

In this paper, the polarization sensitivity of a photopolymer-based volume hologram is characterized both in theory and in experiment. Energy optimization of cascaded HOEs and the trade-off between equal energy distribution and polarization insensitivity existing in the even fanout device are discussed. A volume hologram with diffraction efficiency of 91.5%±1.5% under various states of

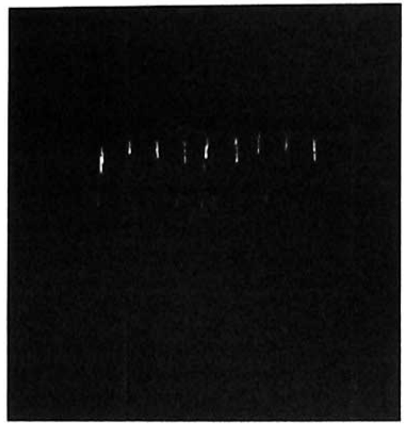


(a)

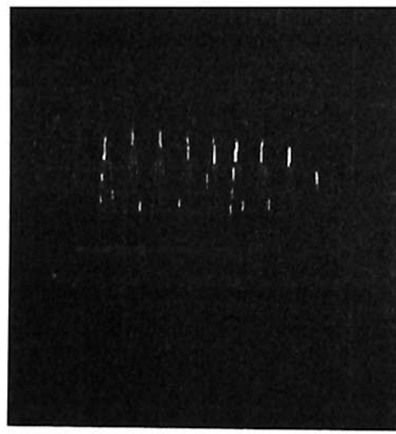


(b)

Fig. 6 Experimental results for a one-to-nine fanout device under a randomly polarized input wave at $\lambda = 632.8$ nm: (a) photograph, (b) two-dimensional CCD intensity profile.



(a)



(b)

Fig. 7 CCD intensity profiles for the one-to-nine fanout device (in Fig. 6) at $\lambda = 632.8$ nm under (a) a p wave, (b) an s wave.

polarization is obtained using DuPont photopolymer film HRF 600X001-20. It is shown theoretically that, when different polarized waves are applied to an energy-equalized fanout device under a randomly polarized input optical signal, severe nonuniformity of fanout energy distribution occurs. Using photopolymer film, this situation can be improved because the Mylar film has strong effects in changing incident linearly polarized light into elliptically polarized light. A one-to-nine fanout device with energy fluctuation $\pm 5\%$ for an input randomly polarized light signal is demonstrated. Up to $\sim 13\%$ and $\sim 24\%$ nonuniformities are observed for p- and s-polarized waves, respectively.

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