ELSEVIER

Cascaded energy-optimized linear volume hologram array for 1-to-many surface-normal even fan-outs

J. LIU, C. ZHAO, R. LEE, R. T. CHEN

Optimization of fan-out energy distribution for substrate guided wave optical interconnects with a surface-normal configuration is addressed in this paper. Up to nine optimized waveguide holograms are independently fabricated on the same substrate. Energy fluctuation affected by the deviation of the designed diffraction efficiency is theoretically analysed. Using DuPont photopolymer film HRF-600X001-20, we demonstrate 1-to-5 and 1-to-9 surface-normal fan-out devices operating at 850 nm. The output non-uniformities of ±4% and ±10% are experimentally confirmed for the two devices, respectively. © 1998 Elsevier Science Ltd.

KEYWORDS: optical interconnects, volume holograms, fan-out

Introduction

Optical interconnects have been demonstrated to be one of the most important alternatives to overcome the bottlenecks of the existing high bandwidth electrical interconnects[1,2]. Among many optical interconnect demonstrations, substrate guided wave optical interconnection, using holographic optical elements (HOEs) together with total internal reflection is an efficient approach for intra- and inter-module interconnects, optical clock distributions, and optical backplane buses[2–5]. Several holographic optical elements for 1-to-many surface-normal optical interconnects have been reported using dichromated gelatin (DCG) integrated on wave guiding plates[3–5]. However, achieving an equalized fan-out energy distribution and an input HOE with a high diffraction efficiency is still required. Furthermore, the wet-processing requirement affiliated with DCG complicates the problem[6]. In practice, the non-uniformity of a 1-to-many fan-out device makes it more difficult to integrate with optical detector arrays and with other optical signal processing elements.

In this paper, the optimization of a cascaded fan-out energy distribution for substrate guided wave optical interconnects with a surface-normal configuration is addressed. A method is developed to integrate a cascaded volume hologram array on a glass substrate using DuPont photopolymer film HRF 600X001-20, and experimental results are demonstrated at an operating light wavelength of 850 nm.

Hologram formation in DuPont photopolymer films

DuPont photopolymers (DuPont Holographic Materials, Wilmington, Delaware, USA) are promising holographic films due to their dry processing, long shelf life, good photo-speed, and large index modulation[7–10]. The holographic photopolymer is usually coated from solvent onto a clear support, typically a Mylar polyester film. A removable cover sheet is used as a protecting cover. Photopolymer thicknesses are available from 10 to 100 μm.

The hologram formation mechanism in the photopolymer films is known to be a three-step process. First, an exposure initiates the interference pattern, which causes initial polymerization and diffusion of the monomer molecules to bright fringe areas from the dark fringe neighbourhoods in the photopolymer. A higher concentration of polymerization means a higher refractive index. Second, a uniform UV light is required for dye bleaching and complete polymerization. Third, a baking process can further enhance the refractive index modulation of the hologram formed in the photopolymer film. It is shown that the dynamic properties of diffraction efficiency versus exposure time can be controlled by the two recording beam intensities, which are related with the polymerization rates and the diffusion rates in the photopolymer films[8]. Before saturation, if the two recording beam ratio is 1:1 and the recording intensities are relatively low, the diffraction

---

The authors are in the Microelectronics Research Center, Department of Electrical and Computer Engineering, University of Texas at Austin, Austin, Texas 78758, USA. Received 23 April 1997. Accepted 7 July 1997.

regions are too low. On the other hand, if high intensities are employed, it causes the diffusion rates to be less than the polymerization rates in the dark fringe regions, and the resulting diffraction efficiency curve shows a decrease when the diffusion processing stops through the rigidity of the polymerized portion of the film. For an optimum recording light intensity, a smoothly increased diffraction efficiency curve with a saturation region should be obtained, resulting from the monomer diffusion rates compatible with the polymerization rates in the dark fringe regions in the photopolymer film. In our experiment, HRF 600X001-20 (20 μm thick) is selected as the recording material because it exhibits lower scattering and higher diffraction efficiency[10]. Higher refractive index modulation in this type of photopolymer film has been reported, and a large dynamic range of diffraction efficiency as a function of exposure time can be achieved by adjusting light intensities of the two recording beams[7,8].

Designing principle and theoretical analysis

For a substrate guided-wave optical interconnect with ideal 1-to-n energy-equalized surface-normal fan-outs, as shown in Fig. 1, the diffraction efficiencies for the output holographic optical elements are given by[11]

$$\eta_i = 1/(n - i + 1) \tag{1}$$

In (1), the subscript i ($i = 1, 2, 3, \ldots, n$) represents the order of the output HOEs in the designed substrate guided wave optical fan-out device. For example, an ideal 1-to-5 energy equalized fan-out device needs 20%, 25%, 33%, 50% and 100% diffraction efficiencies. For a 1-to-9 fan-out design, diffraction efficiencies of the order of 11%, 12%, 14%, 16%, 20%, 25%, 33%, 50% and 100% are needed for the output HOEs. The key to obtaining an energy equalized fan-out distribution is to find an optimum recording light dosage which can provide an accurate diffraction efficiency between 10% and 100%.

If diffraction efficiency for the kth HOE has a deviation of diffraction efficiency of $\pm\Delta\eta_k$ from its designed value while diffraction efficiencies of other HOEs remain accurate, the resulting deviation ε of fan-out intensity over average fan-out light intensity occurs at the kth output HOE and is given by

$$\varepsilon = n\prod_{i=1}^{k-1}(1 - \eta_i)\,|\Delta\eta_k| \tag{2}$$

If the tolerable energy fluctuation of a device with 1-to-n fan-outs is desired to be ε_t, from (2), the corresponding deviation of diffraction efficiency for the kth output HOE is allowed to be

$$|\Delta\eta_k|_t = \frac{\varepsilon_t}{n\prod_{i=1}^{k-1}(1 - \eta_i)} \tag{3}$$

Figure 2 shows the maximum fluctuation of diffraction efficiency tolerance for each channel of the 1–9 fan-out device ($n = 9$) which is caused by a maximum energy fluctuation of 10% and 5% for the designed device. It is shown that the tolerance of deviation of diffraction efficiency for the first few fan-out channels is much less than for the last few channels. For example, for a 10% maximum energy fluctuation at the last fan-out, the diffraction efficiency change for the first channel is restricted to be within ±1%, which can be carefully achieved.

In reality, the diffraction efficiency adjustment of each HOE is always required based on the highest efficiency achievable. If the maximum efficiency achievable is η_M, (1) becomes

$$\eta_i = \eta_M/(n - i + 1) \tag{4}$$

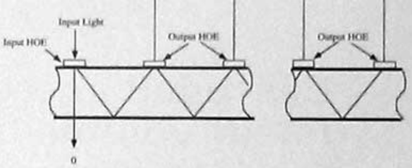

Fig. 1 HOE based surface-normal fan-out optical interconnect

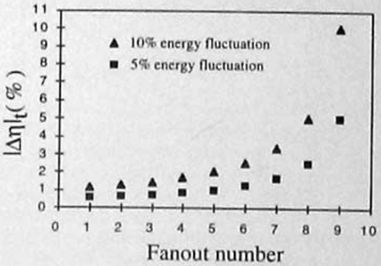

Fig. 2 Maximum deviation of diffraction efficiency allowable for each fan-out channel

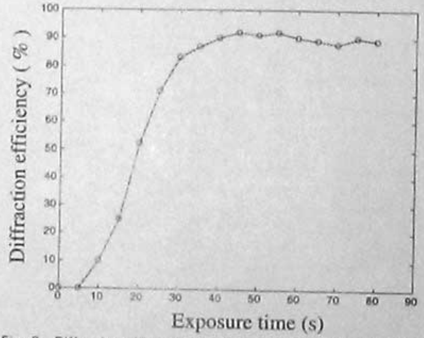

Fig. 3 Diffraction efficiency versus exposure time for DuPont photopolymer HRF 600X001-20 (20 μm thick). The film thickness is 20 μm. The recording light wavelength is $\lambda_c = 514$ nm. The ratio of two recording beams is about 1 : 1. The total intensity of the beams is ~3.0 mW cm^{-2}. Efficiency is measured at $\lambda_r = 850$ nm

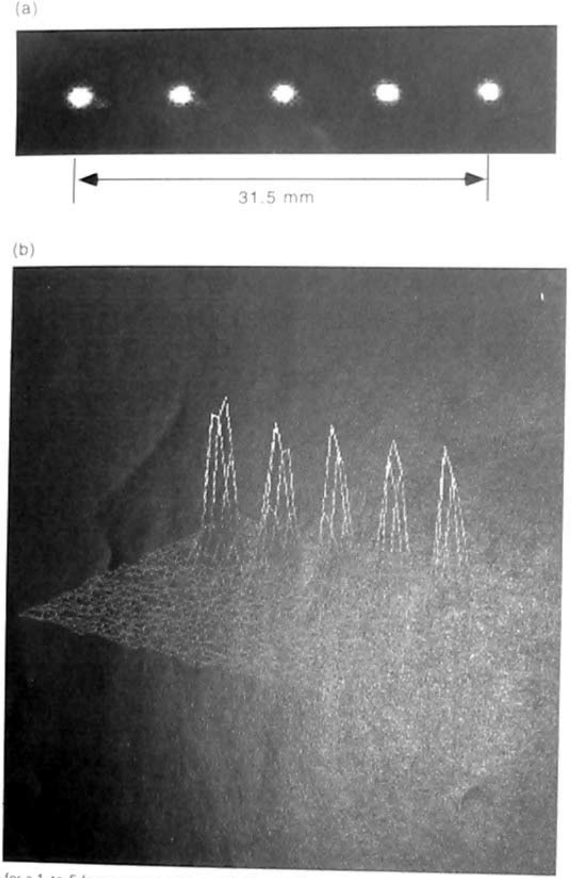

Fig. 4 (a) Far field image for a 1-to-5 fan-out result at $\lambda_r = 850$ nm. (b) Three-dimensional profile for a 5 fan-out energy distribution. The intensity fluctuation is within ±4%

Assume the maximum efficiency that can be routinely achieved experimentally is 90%, the corresponding diffraction efficiencies for the 1-to-9 fan-out device are determined to be 10%, 11%, 13%, 15%, 18%, 23%, 30%, 45% and 90%, respectively.

Experiment

A two-beam interference method[3] is employed to fabricate both input and output HOEs. An argon ion laser operating at 514 nm is used in the hologram recording. The reconstruction wavelength is set at 850 nm, which is the emitting wavelength from most of the commercially available vertical cavity surface emitting lasers (VCSELs). The diffraction angle for each HOE is designed at 45°, greater than the 41.3° critical angle of the total internal reflection of a BK-7 glass substrate. The Bragg phase matching condition[12] and Snell's law are applied to evaluate the diffracted angle in the holographic medium and then to convert the recording angles to those in air[3].

For our experimental set-up, different beam intensities and beam intensity ratios are investigated to find optimum recording light intensities, by which the diffusion rates of monomer molecules in the photopolymer film are close to the polymerization rates in the dark fringe areas as discussed above. At a certain fixed recording intensity and beam ratio, a set of single holograms with exposure times from 0 to 80 s at intervals of 5 s are recorded. The holograms are post-exposed UV light with 100 mJ cm^{-2} and are baked for 1 hour at 120°C. A Coherent Ti:sapphire tunable laser is used to measure the diffraction efficiencies of HOEs at 850 nm under s-polarization. An optimum recording condition is found to be that the intensity ratio of the

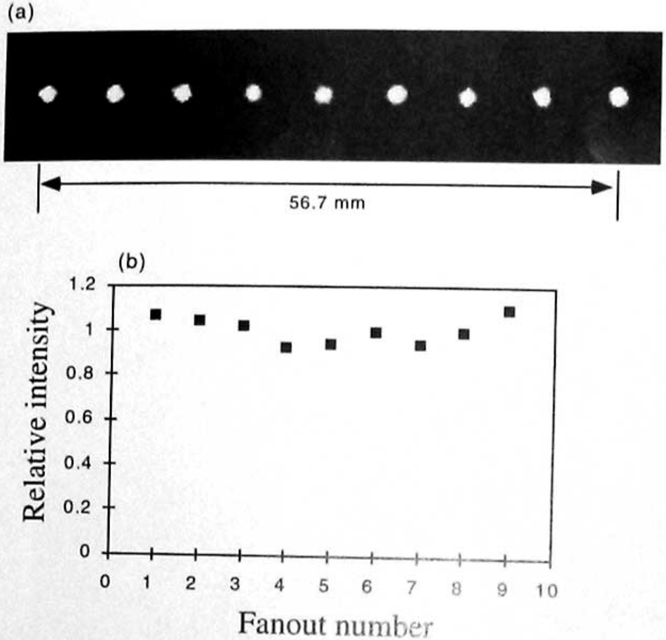

Fig. 5 (a) Far field image for a 1-to-9 optical fan-out device; (b) relative intensity distribution measured. The intensity fluctuation is within ±10%, $\lambda_r = 850$ nm

two recording beams is 1:1 and the total intensity of the two beams is ~3.0 mW cm^{-2}. The diffraction efficiency versus the exposure time under such a condition is given in Fig. 3. We clearly observe that the higher efficiency (>90%) occurs at the 40 s exposure time, and different diffraction efficiencies ranging from 0% to ~90% are obtained between 0 s and 40 s. This large dynamic region makes it easy to get the accurate diffraction efficiencies required for energy equalized fan-out devices. The curve remains almost flat when the exposure time is larger than 40 s. This is caused by the saturation of the modulation of the refractive index[9].

To integrate HOEs with different diffraction efficiencies on one photopolymer film, a 6 cm-long mask with a slit of 6 mm across is used. This mask is placed in front of the film during the HOE recording. The film is translated twice the thickness of the substrate sequentially between exposures. The exposure time corresponding to the diffraction efficiency at each designed position is obtained from Fig. 3.

Figure 4 shows the CCD image of a 1-to-5 fan-out device at 850 under s-polarized light, for which a glass substrate (3.15 mm thick) is employed. The intensity distributions from channel 1 to channel 5 are 1.04, 0.99, 0.96, 1.03, 0.98, with a maximum deviation about ±4%. This shows that it is possible to control the output intensity uniformity precisely. In Fig. 5, we show the experimental result for a 1-to-9 device. The intensity non-uniformity among the fan-outs is within ±10% (see Fig. 5(b)). This is larger than that of the 1-to-5 fan-out device, mainly due to the fact that the more fan-outs, the more difficult to control are the diffraction efficiencies of the HOEs. For example, it is difficult to control experimentally the diffraction efficiencies of neighbouring channels having 11% and 12% precisely. The diffraction efficiency versus the deviation of the input signal from the surface-normal for the first channel of the 1-to-9 device is also tested. We found that a ±0.5° deviation of the input signal from the surface-normal position can lead to a 10% deviation of the maximum diffraction efficiency. The diffraction efficiencies of the input HOEs for these two devices are measured to be about 90%.

The non-uniformity of the fan-outs of the devices is caused by the deviation of the required diffraction efficiency of the HOE at the recorded position, the cleanliness of the glass, and the laminating process. Non-ideal interface quality between the glass and the photopolymer film also causes non-uniform energy distribution. Another important factor influencing the output energy fluctuations is the alignment of the device relative to the input reconstruction laser beam. The DuPont photopolymer experiences some degree of shrinkage after UV curing and baking. This shrinkage affects the slanted angle of the hologram gratings, which leads to the deviation of the maximum diffraction efficiency from the surface-normal incident position[8]. Figure 6 shows the deviation angle of the maximum

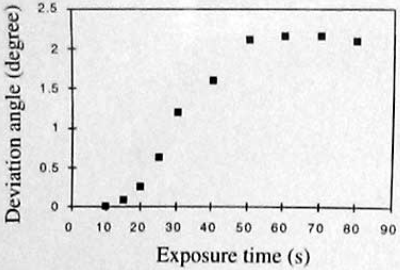

Fig. 6 Angle of maximum diffraction efficiency deviated from the surface-normal incident position versus exposure time for DuPont photopolymer HRF 600X001-20, $\lambda_r = 850$ nm

diffraction efficiency as a function of the exposure time. The recording conditions are the same as those in Fig. 3. We can see that the angle deviated from the surface-normal incident position increases as the exposure time (which controls the diffraction efficiency as shown in Fig. 3) increases. The higher the diffraction efficiency, the larger the deviation angle. Up to 2.1° deviation angle is determined for those HOEs with ~90% diffraction efficiency. It seems that the deviation angle saturates at higher diffraction efficiency. Further improvements can be made by taking these effects into consideration.

Summary and discussion

We present the design considerations and the experimental results for the fabrication of a 1-to-many energy equalized cascaded fan-out device for surface-normal substrate guided wave optical interconnects. Satisfactory results are demonstrated for 1-to-5 and 1-to-9 fan-out devices at 850 nm. This approach can be easily employed to fabricate energy equalized fan-out devices at other wavelengths. It should be noted here that the optimum recording condition depends on the reconstruction wavelength which affects the holographic grating slanted angle. With the fan-out energy equalization problem solved, it is expected that these substrate guided surface-normal optical fan-out HOEs will find wide applications in many integrated optics and optoelectronic applications. These include optical backplane bus, optical clock distribution, and optical true-time-delay lines[13,14]. By employing these energy equalized fan-out devices, the non-uniform power distribution concerned with these optical interconnects is no longer an obstacle. This also eases the integration of such devices into photodetector arrays for practical system designs. Meanwhile, the energy equalized fan-outs device can also serve as an optical array illuminator[15] distributing optical power to optical logic gates and bistable devices in optical computing. Furthermore, the energy equalized fan-out optical interconnects can be packaged with VCSELs, photodetector arrays, and optical processing elements for inter multi-chip module (MCM) and intra MCM parallel optical processing. This approach is currently under investigation.

Acknowledgements

This work is supported by AFOSR, BMDO, ONR, Cray Research, the ATP program of the state of Texas, and DuPont.

References

1 **Goodman, J.W., Leonberger, F.I., Kung, S.Y., Athale, R.A.** Optical interconnection for VLSI systems, *Proc IEEE*, **72** (1984) 850–866
2 **Tocci, C., Caulfield, H.J.** *Optical Interconnection* Artech House, Boston (1994)
3 **Chen, R.T., Tang, S., Li, M.M., Gerald, D., Natarajan, S.** 1-to-12 surface-normal three-dimensional optical interconnects, *Appl Phys Lett*, **63** (1993) 1883–1885
4 **Li, M.M., Chen, R.T., Tang, S., Gerald, D.** Angular limitations of polymer-based waveguides holograms for 1-to-many V-shaped surface-normal optical interconnects, *Appl Phys Lett*, **65** (1994) 1070–1072
5 **Tang, S., Chen, R.T.** 1-to-42 optoelectronic interconnection for intra-multichip-module clock signal distribution, *Appl Phys Lett*, **64** (1994) 2931–2933
6 **Georgekutty, T.G., Liu, H.K.** Simplified dichromated gelatin hologram recording process, *Appl Opt*, **26** (1987) 372–376
7 **Gambogi, W., Steijn, K., Mackara, S., Duzik, T., Hamzavy, B., Kelly, J.** HOE imaging in DuPont holographic photopolymers, *Proc SPIE*, **2152** (1994) 282–293
8 **Rhee, U., Caulfield, H.J., Vikram, C.S., Shamir, J.** Dynamics of hologram recording in DuPont photopolymer, *Appl Opt*, **34** (1995) 846–853
9 **Piazzolla, S., Jenkins, B.K.** Holographic grating formation in photopolymers, *Opt Lett*, **21** (1996) 1075–1077
10 **Zhou, H.J., Morozov, V., Neff, J.** Characterization of DuPont photopolymers in infrared light for free-space optical interconnects, *Appl Opt*, **34** (1995) 7457–7459
11 **Chen, R.T., Lee, R.** Holographic optical elements (HOEs) for true-time-delays aimed at phased array antenna applications, *SPIE Proc*, **2689** (1996) 176–187
12 **Kogelnik, H.** Coupled wave theory for thick hologram gratings, *The Bell Sys. Tech. J*, **13** (1969) 2909–2947
13 **Natarajan, S., Chen, R.T., Tang, S., Mayer, R.A.** High speed optical backplane bus with modulation and demodulation capabilities, *SPIE Proc*, **2153** (1994) 344–351
14 **Chen, R.T., Zhou, C., Zhao, C., Lee, R.** Photopolymer-based waveguide holograms for optoelectronic interconnects applications, *Critical Reviews of Optical Science & Technology*, **63** (1996) 46–64
15 **Kubota, T., Umebara, N., Iida, K., Shimura, T., Kuroda, K.** Generation of an ultrahigh-repetition-rate pulse by an array illuminator, *Opt Lett*, **21** (1996) 1667–1669