Cross-link optimized cascaded volume hologram array with energy-equalized one-to-many surface-normal fan-outs

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Achieving a uniform fan-out energy distribution is critical to the successful applications of substrate guided-wave optical interconnects. Using Dupont photopolymer film HRF-600X001-20, we investigated the optimum recording beam intensity for obtaining a large dynamic region of diffraction efficiency relative to exposure dosage. Based on the experimental diffraction efficiency curve, 1-to-5 and 1-to-9 surface-normal fan-out devices were fabricated that operated at a wavelength of 850 nm, and output nonuniformities of ±4% and ±10% were obtained for the two devices. © 1997 Optical Society of America

Optical interconnects have been demonstrated to be one of the most important means to overcome the bottlenecks of electrical interconnects.[1,2] Among many optical interconnect demonstrations, substrate guided-wave optical interconnects using holographic optical elements (HOE's) combined with total internal reflection in dielectric or semiconductor substrates are efficient approaches for intramodule and intermodule interconnections, optical clock distributions, and optical backplane buses.[2–5] Several types of one-to-many surface-normal optical interconnect using volume holographic elements integrated upon wave-guiding glasses have been reported.[3–5] Equalization of diffraction efficiencies for holographic memory devices has been reported.[6,7] However, achieving a uniform fan-out energy distribution in substrate guided-wave interconnects and having an input HOE with high diffraction efficiency still remains critical issues to be resolved. Furthermore, the wet-processing requirement affiliated with dichromated gelatin complicates the problem.[8] In practice, the nonuniformity in a one-to-many fan-outs device makes it more difficult to integrate the device with optical detector arrays or other optical signal-processing elements.

Dupont photopolymers are promising holographic films because of their dry-processing capability, long shelf life, good photo speed, and volume phase holographic properties.[9–12] HRF 600X001-20 (20 μm thick) was selected as the recording material because it exhibits lower scattering and higher diffraction efficiency.[12] The hologram formation mechanism in the photopolymer is a three-step process. First, an initial exposure records the interference pattern, which causes initial polymerization and diffusion of the monomer molecules to a bright fringe area from the dark fringe neighborhood 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 index modulation in the hologram formed. Higher refractive-index modulation in this type of photopolymer film has been reported, and one can achieve a large dynamic range of diffraction efficiency as a function of exposure time by adjusting the light intensities of the two recording beams.[9,10]

For a substrate guided-wave optical interconnect with ideal 1-to-n uniform surface-normal fan-outs, as shown in Fig. 1, the diffraction efficiencies for the output holographic optical elements are given by[13]

$$\mathrm{DE}_i = 1/(n - i + 1)\,. \qquad (1)$$

In Eq. (1) the subscript i ($i = 1, 2, 3, \ldots, n$) represents the order of the output HOE's in the designed substrate guided-wave optical fan-out device. According to Eq. (1), an ideal 1-to-5 uniform fan-out device needs 20%, 25%, 33%, 50%, and 100% diffraction efficiencies for the successive output HOE's. For a 1-to-9 fan-out, diffraction efficiencies of the order of 11%, 12%, 14%, 16%, 20%, 25%, 33%, 50%, and 100% are needed for the output HOE's. The key to obtaining a uniform fan-out energy distribution is to find the optimum recording light dosage that can provide an accurate diffraction efficiency between 10% and 100%. Diffraction efficiency adjustment of each HOE is always required, based on the highest efficiency achievable in practice. In our experiment the highest diffraction efficiency used to calculate the designed diffraction efficiencies of the cascaded volume holograms was 90%.

A two-beam interference method[3] was employed to fabricate both the input and the output HOE's. An argon-ion laser operating at 514 nm was used in the hologram recording. The reconstruction wavelength was set at 850 nm, which is the emitting

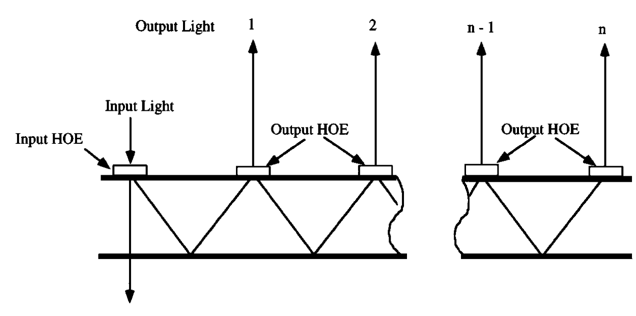

Fig. 1. HOE-based surface-normal fan-out optical interconnect.

wavelength from most commercially available vertical-cavity surface-emitting lasers. The diffraction angle for each HOE was 45°, greater than the 41.3° critical angle of the total internal reflection for the BK-7 glass substrate. We used the Bragg phase-matching condition[14] and Snell's law to calculate the diffracted angle in the hologram medium and then to convert the recording angles to those in the air.[3]

For our experiment setup we investigated various beam intensities and beam intensity ratios to find the optimum recording light power. At a fixed recording intensity and beam ratio, a set of single holograms with exposure times of 0 to 80 at an interval of 5 s were recorded. The holograms were postexposed 5 min under UV light and baked for 1 h at 120 °C. We used a Coherent Ti:sapphire tunable laser to measure the diffraction efficiencies of HOE's at 850 nm. The optimum recording conditions were an intensity ratio of the two recording beams of ~1:1 and a total intensity of the two beams of ~3.0 mW/cm^2. The diffraction efficiency versus the exposure time under such conditions is shown in Fig. 2. We can see that the higher efficiency (>90%) occurs above 40-s exposure time, and different diffraction efficiencies ranging from 0% to ~90% are obtained between 0 and 40 s. This large dynamic region makes it easy to get the accurate diffraction efficiencies required for uniform-fan-out devices. The curve remains almost flat when the exposure time is larger than 40 s. This effect is caused by the saturation of the modulation of the refractive index.[11]

To integrate HOE's with different diffraction efficiencies on one photopolymer film we used a 6-cm-long thin mask with an opening slit of 6 mm. This mask was placed in front of the film during HOE recording. The film was moved a distance of twice the thickness of the substrate sequentially between exposures. The exposure time corresponding to the designed diffraction efficiency at each designed position was obtained from Fig. 2. When an optical signal zigzagged within the glass substrate and was then coupled out by the cascaded volume holograms, absorption and scattering of the optical signal in the waveguiding substrate and the photopolymer film were observed to have changed the fan-out intensities slightly. Several iterations were made to adjust the diffraction efficiencies of the output HOE's to create an even energy distribution for the 1-to-n fan-out.

Figure 3 shows a CCD image of a 1-to-5 fan-out device for which a glass substrate (3.15 mm thick) was employed. Relative to the average among the fan-outs, the intensity distributions from channel 1 to channel 5 were 1.04, 0.99, 0.96, 1.03, and 0.98 (left to right) with a maximum deviation of ±4%. This shows that it is possible to precisely control the output intensity uniformity. In Fig. 4(a) we show the experimental result for a 1-to-9 device. The intensity nonuniformity among the fan-outs is within ±10% [Fig. 4(b)]. This is larger than that of 1-to-5 fan-out device, mainly because the more fan-outs there are, the more difficult it is to control the diffraction efficiencies of the HOE's. For example, it is difficult to control experimentally the neighboring diffraction efficiencies of 11% and 12% precisely. The diffraction efficiency versus the deviation of the input signal from surface normal for the first channel of the 1-to-9 device was also tested. We found that a ±0.5-deg deviation of the input signal from surface-normal position can lead to 10% deviation of the maximum diffraction

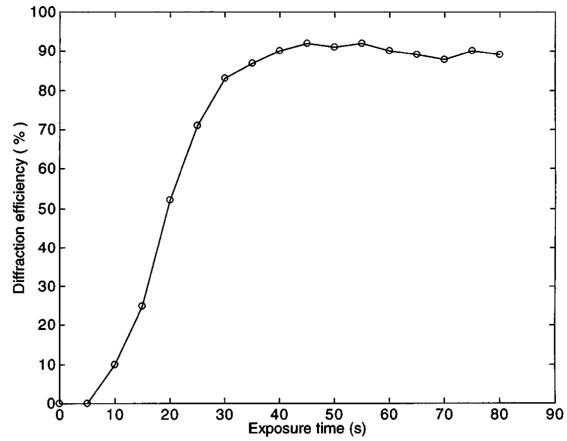

Fig. 2. Diffraction efficiency versus exposure time for Dupont photopolymer HRF 600X001-20 (20 μm thick). The wavelength of the recording light was $\lambda_c = 514$ nm. The ratio of two recording beams was ~1:1. The total intensity of the beams was ~3.0 mW/cm^2. Efficiency was measured at $\lambda_r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

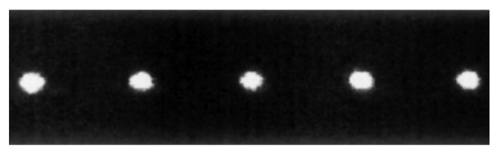

Fig. 3. Far-field image for a 1-to-5 fan-out result at $\lambda = 850$ nm. The intensity fluctuation is within ±4%.

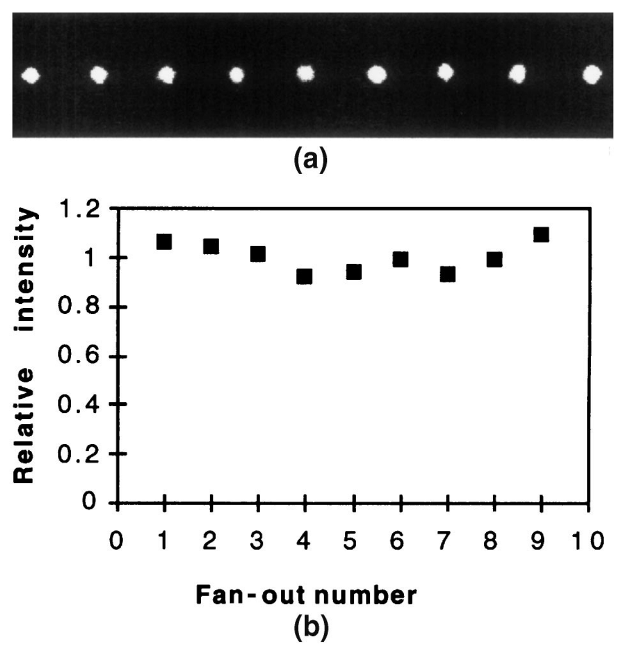

Fig. 4. (a) Far-field image for a 1-to-9 optical fan-out device, (b) relative intensity distribution. The intensity fluctuation is within ±10%.

efficiency. The overall efficiency of the 1-to-9 fanout device is defined as the ratio of the total nine output light intensity entering the device. It is 60%. The diffraction efficiencies of the input HOE's for these two devices are ~90%.

The nonuniformity 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 cleanness of the glass, and the laminating process. Nonideal interface quality between the glass and the photopolymer film cases nonuniform energy distribution as well. Another important factor influencing the output fluctuations of the device is the alignment of the device relative to the input reconstruction laser beam. Furthermore, Dupont photopolymer experienced some degree of shrinkage after UV curing and baking. This shrinkage affects the slanted angle of the hologram gratings, leading to the deviation of the maximum diffraction efficiency from surface-normal incident position.[10] Further improvement should be possible if these effects are taken into consideration.

We have presented the experimental results for the fabrication of one-to-many uniform fan-out devices for surface-normal optical interconnects, using photopolymer-based cascaded volume holograms. Satisfactory results were demonstrated for a 1-to-5 and a 1-to-9 fan-out device at 850 nm. This approach can easily be employed to fabricate uniform-fan-out devices at other wavelengths. It should be noted that the optimum recording condition depends on the reconstruction wavelength, which affects the holographic grating's slanted angle. With the fan-out uniformity problem solved, it is expected that these substrate guided surface-normal optical fan-out HOE's will find wide applications in many integrated-optics and optoelectronic applications. These applications include optical backplane buses, optical clock distribution, and optical true-time-delay lines.[15,16] Use of these uniform-fan-out devices will eliminate the problem of nonuniform power distribution with these optical interconnects and will facilitate the integration of such devices with photodetector arrays for practical system designs. Meanwhile, the uniform fan-out device can also serve as an optical array illuminator,[17] distributing optical power to optical logic gates and bistable devices in optical computing. Furthermore, the uniform-fan-out optical interconnects can be packaged with vertical-cavity surface-emitting lasers, photodetector arrays, and optical processing elements for intermultichip module and intramultichip module parallel optical processing. This approach is under investigation.

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