A Two-Dimensional Dual-Wavelength Routing Network with 1-to-10 Cascaded Fanouts

Jian Liu, *Student Member, IEEE,* and Ray T. Chen, *Member, IEEE*

***Abstract*— A two-dimensional (2-D) wavelength-division demultiplexing device [WD(D)M] is demonstrated to separate and to distribute optical signals of different wavelengths by use of substrate-guided wave optical interconnects. In our experiment, two stacked input holographic gratings are fabricated to steer two optical wavelengths into two different routing directions and to zigzag within a waveguiding substrate. Input coupling efficiencies of 70% and 76% are experimentally confirmed at the input wavelengths of 780 and 790 nm, respectively. Two arrays of 1-to-10 cascaded output holographic grating couplers are employed to couple out the optical signals with surface-normal fanouts. The crosstalk is measured to be < -30 dB. The fanout energy fluctuation is within $\pm 10\%$ for each wavelength.**

***Index Terms*— Network, optoelectronic interconnects, photopolymer films, volume hologram, wavelength-division multiplexing.**

I. Introduction

WAVELENGTH-DIVISION (de)multiplexer (WD(D)M) is a pivotal bandwidth enhancement component in optical fiber communications and optical sensor systems. Various types of optical WD(D)M have been proposed and demonstrated [1]–[13]. These include gratings [1], thin film filters [2], fused-fiber coupler [3], waveguide-type [4], [5], Bragg-reflector-in-fiber devices [6], Fabry–Perot interferometer-type filters [7], holographic optical element (HOE) based transmission-type demultiplexers [8]–[10], and polarization-independent optical filters [11]–[13]. These approaches can only be used for wavelength filtering or separation. When the WDDM's are applied to the fiber-to-home network [14] or multisensors system [15], it is necessary for them to be able to route separate wavelength channels and to distribute each channel to many users.

Photopolymer-based substrate guided wave optical interconnects, using photopolymer volume holograms combined with total internal reflection (TIR) in waveguiding substrates, have been demonstrated as efficient approaches for intra- and intermodule interconnections, optical clock distributions, optical backplane buses, and optical networks [16]–[18]. In this paper, by means of photopolymer-based substrate guided wave optical interconnects, a two-dimensional (2-D) WDDM serving the functions of wavelength separation and one -to-many fanouts is demonstrated. In our design, stacked volume holograms are employed as the input couplers to steer input optical signals with different wavelengths to their desired directions and then coupled-out by output HOE arrays. This 2-D network configuration having both the input and output HOE's integrated on one waveguiding plate fulfills simultaneously wavelength separation, routing, and optical signal distribution. Experimental results of routing and distributing two optical channels at wavelengths of 780 and 790 nm are presented.

Manuscript received October 8, 1997. This work was supported by the Ballistic Missile Defense Organization, by the Army SSDC, by the Center of Optoelectronics Science and Technology (COST), by the Office of Naval Research, by Cray Research, by DuPont, Lightpath, and by the Advanced Technology Program (ATP) of the State of Texas.

The authors are with the Microelectronics Research Center, Department of Electrical and Computer Engineering, University of Texas at Austin, Austin, TX 78758 USA.

Publisher Item Identifier S 1041-1135(98)01509-2.

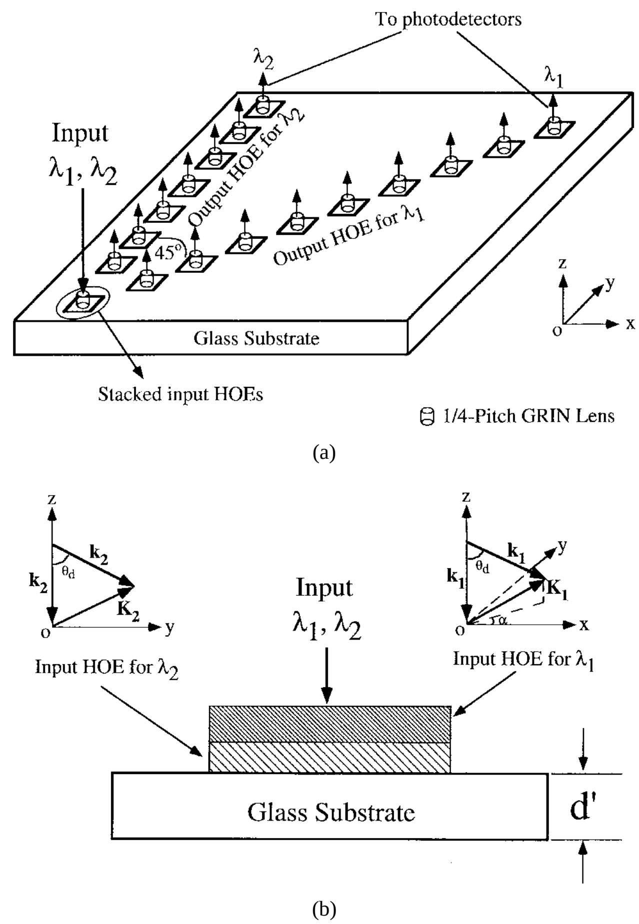

Fig. 1. (a) Schematic diagram of a 2-D WDDM distributing network and (b) two stacked volume holographic input couplers and their phase matching diagrams.

II. Design of a Two-Dimensional WDDM Network

Fig. 1(a) shows a schematic diagram for a 2-D WDDM network. The input and the output volume holograms are

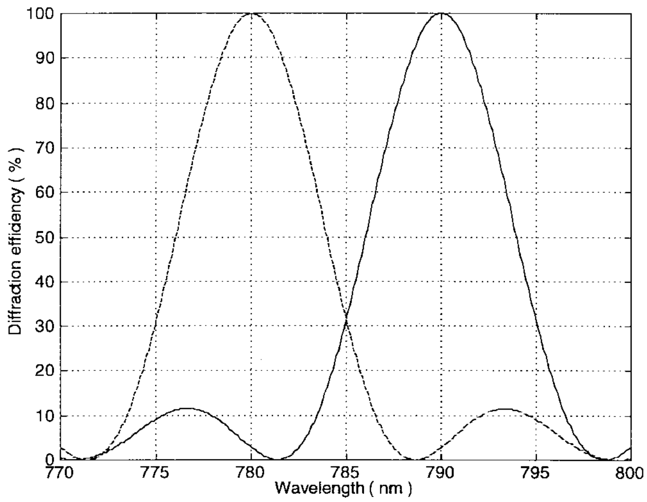

Fig. 2. Simulation results of diffraction efficiencies versus the wavelength deviation from central wavelengths 780 and 790 nm of an s-wave.

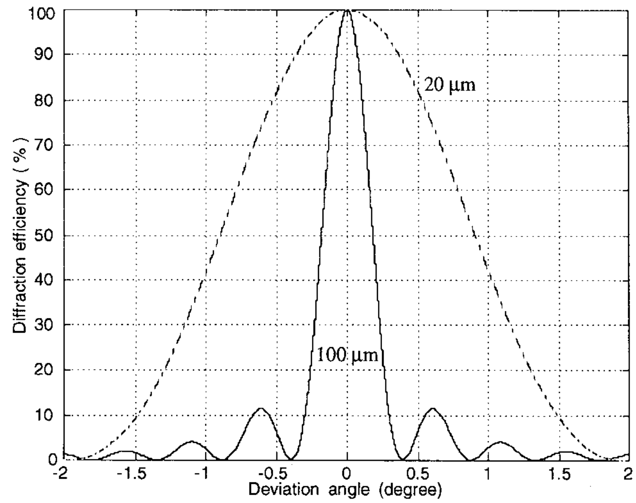

Fig. 3. Diffraction efficiencies versus the incidence angle deviation at 790 nm. Similar results are obtained for 780 nm.

integrated on the same waveguiding substrate at their designated positions. Two stacked volume holograms are used as the optical wavelength routing filters to couple two input optical signals λ_1 and λ_2 into their designed routing directions with an angle of 90°–α between them in the XY plane as indicated in Fig. 1(b). The bouncing angle within the waveguiding substrate is greater than the critical angle of the substrate. The two stacked volume holographic gratings and their phase matching diagrams are given in Fig. 1(b), in which the input wave vector $\mathbf{k_1}(|\mathbf{k_1}| = 2\pi n/\lambda_1)$ is phase-matched with the grating vector $\mathbf{K_1}(|\mathbf{K_1}| = 2\pi/\Lambda_1)$, and so does the $\mathbf{k_2}(|\mathbf{k_2}| = 2\pi n/\lambda_2)$ and the $\mathbf{K_2}(|\mathbf{K_2}| = 2\pi/\Lambda_2)$. n is the average refractive index of the holographic medium. The angle between the two projected grating vectors in XY plane is 90°–α. The separated optical signals propagate within the waveguiding substrate with total internal reflection and are distributed to their respective destinations, and then coupled out surface-normally by the two arrays of cascaded volume holograms. Many users may share the same source with this distributed 2-D WDDM. It is promising for this 2-D configuration to be used for filtering and distributing wavelength channels centered at 0.8, 1.3, and 1.55 μm. It is also possible to realize multiple-wavelength channels separation and distribution by stacking more input holographic gratings and by integrating more arrays of output couplers at the desired wavelengths and positions. To get a small channel wavelength spacing, it is important to fabricate the input couplers with a narrow bandwidth, and to make the output couplers capable of accommodating a larger angular deviation to couple the optical signal out of the waveguiding plate.

For a typical substrate guided wave optical interconnect with the surface-normal configuration, the diffraction angle of the volume hologram is designed to be 45° in a quartz substrate while the optical signal is incident from the surface-normal direction with $\theta = 0$. The deviation of operating wavelengths and the incident angle θ are evaluated using coupled wave theory [19]. Fig. 2 shows the simulation results of diffraction efficiencies versus the wavelength deviation from central wavelength 780 and 790 nm of an s-wave with refractive index $n = 1.52$ for DuPont photopolymer films. The film thickness is 100 μm. The corresponding refractive index modulation Δn is determined to be 0.0033 for a 100% diffraction efficiency at 790 nm. From Fig. 2, we can see that the 3 dB bandwidths [full-width at half-maximum (FWHM)] is 8 nm for the 100-μm-thick film. Fig. 3 shows the diffraction efficiencies as a function of the incident angle deviation at 790 nm (similar results are obtained at 780 nm). The parameters used are the same as those in Fig. 2 except that $\Delta n = 0.0166$ for 20-μm-thick film. The angle deviation tolerances at half maximum of the diffraction efficiency are 1.7° and 0.4°, respectively. To demultiplex and distribute two wavelength channels at 790 and 780 nm, we employ 100-μm-thick films as input wavelength channel routing filters and 20-μm-thick films as the output coupler arrays.

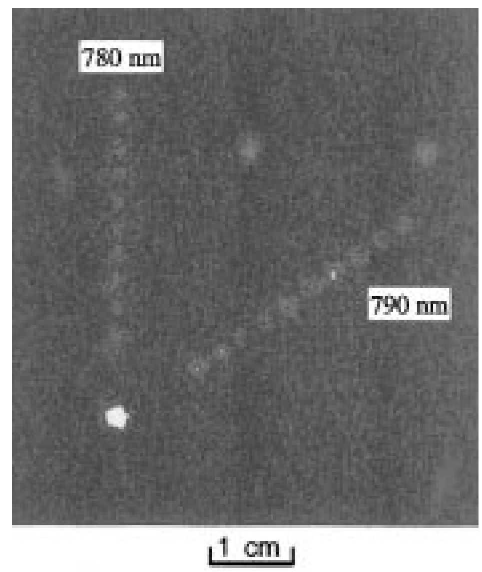

Fig. 4. Experimental results of the 2-D WDDM device while operating at 790 and 780 nm. Oblique fanouts are for 790-nm channel. Vertical light spots corresponds to the 780-nm channel fanouts.

III. Experiment

In our experiment, an Argon ion laser operating at 514 nm is used to record the volume hologram. A Ti : Sapphire tunable laser is employed to carry out the measurement. To demonstrate the conceptual 2-D WDDM network shown in Fig. 1(a), we choose Dupont photopolymer HRF 150- with 100-μm film thickness as the input holographic grating couplers. Two stacked holographic films are sequentially laminated on a quartz plate. The thickness of the substrate is $d' = \sim 1.6$ mm. The bouncing angle within the substrate is 45°. The angle between the two routing directions is designed to be ~45°. One holographic grating is designed to deflect the optical signal at $\lambda_1 = 790$ nm, and the other is for $\lambda_2 = 780$ nm. Two arrays of output holographic grating couplers are also fabricated along the desired routing direction for reconstruction wavelength at 780 and 790 nm, respectively, by employing DuPont photopolymer film HRF 600 with a 20-μm film thickness. By taking advantage of the fact that the collimated laser beam has a Gaussian intensity profile during hologram recording, we are able to record the output couplers with relatively uniform fanout distribution for both arrays.

Fig. 4 shows the experimental results when the device operates at 780 and 790 nm simultaneously. The diffraction efficiencies of the input holographic grating couplers are measured to be 70% and 76%, respectively. The 3-dB angular deviations of the volume holograms are measured to be within 0.5°. The two wavelengths are succesfully separated and directed to their designed directions by the two stacked input holographic grating coupler. Each wavelength channel has ten fanouts. The energy distribution nonuniformity is measured to be within $\pm 10\%$. The crosstalks between two channels are measured to be smaller than $+30$ dB. It is obvious that this 2-D network configuration provides a robust, reliable, surface-mountable, and cost-efficient device with combined functions of wavelength demultiplexing and distributing.

IV. Conclusion

We demonstrated a cost-efficient and user-sharing 2-D wavelength demultiplexing and distributing optical network, with which optical signals at 790 and 780 nm are separated and diffracted into the waveguiding plate in two different routing directions by two stacked DuPont holographic gratings with a 100-μm thickness, distributed within the glass substrate with total internal reflection, and coupled out of the substrate to each user by output holographic grating with 20-μm thickness. By using two different kinds of photopolymer films, we may obtain narrow band filtering function for input couplers and large angular tolerance for output couplers. The crosstalks are measured to be < -30 dB, and the nonuniformity of the fanout energy distribution is within $\pm 10\%$. The relatively uniform fanout energy distribution is pivotal to the integration with photodetector arrays for practical system designs. The monolithic integration of the input and output couplers on a waveguiding substrate provides a robust architecture against environmental and mechanical perturbations. Furthermore, it is possible to realize multiwavelength channels routing and distribution involving 0.8-, 1.3-, and 1.55-μm wavelengths by stacking holographic gratings as input wavelength seperating and routing couplers and by integrating arrays of output couplers at desired wavelengths.

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