Two-channel surface-normal wavelength division demultiplexer using substrate guided waves in conjunction with multiplexed waveguide holograms

Maggie M. Li and Ray T. Chen
Microelectronics Research Center, Department of Electrical and Computer Engineering, University of Texas, Austin, Texas 78759

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We report a wavelength division demultiplexer (WDDM) using collinear surface-normal input and output coupling. The reported device employs polymer-based multiplexed waveguide holograms in conjunction with substrate guided waves. A two-channel WDDM device operating at 700 and 738 nm with diffraction angles of 45° and 50° are demonstrated. The peak diffraction efficiencies of 80% and 77% are measured for these two channels. A crosstalk of −31 dB between the two channels is measured. Variations of the diffraction efficiencies and of the bandwidths as a function of film thickness and index modulation are further considered. A good agreement between theoretical analysis and experimental results is obtained.

Wavelength division multiplexing (WDM) and demultiplexing (WDDM) devices are considered to be two of the key elements for enhancing the transmission bandwidth of optical communications and sensor systems. During the past 20 years, various types of WDMs and WDDMs have been proposed and demonstrated.[1–6] Recently, the technique for producing spatially multiplexed phase gratings in locally sensitized photolime gel (PLG) polymer waveguides for WD(D)M applications has been reported.[7,8] In this letter, we report on the demonstration of a novel two-channel WDDM using collinear surface-normal input and output couplings based on the same polymeric material. The WDDM device presented herein can be integrated with transmitter and receiver modules at the surface normal direction. As a result, pigtailing with fibers from a waveguide edge is not required and the packaging is thus much more rugged and reliable.[9]

The schematic of the two-channel WDDM using PLG-based multiplexed holograms in conjunction with substrate guided waves is shown in Fig. 1. The input laser beams with different wavelengths are coupled into the glass substrate by using a GRIN lens in conjunction with a multiplexed holographic coupler which converts the surface-normal incoming beams into two substrate guided waves with different bouncing angles. The bouncing angles θ_i, $i=1$ and 2, are carefully adjusted based on predesigned phase-matching conditions. Note that each angle θ_i should be larger than the total internal reflection (TIR) angle θ_c of the substrate waveguiding plate employed. After surface-normal optical waves carrying different wavelengths are converted into substrate guided waves, zig–zag guided beams within the glass substrate are generated, as indicated in Fig. 1. Two subsequent holograms (the output holographic couplers shown in Fig. 1) are independently recorded to provide the surface-normal fanouts. Each fanout is then output through a different GRIN lens. It is clear from Fig. 1 that the location and the grating vector of each fanout hologram shall be precisely determined to provide two surface-normal fanout beams at the desired locations with the desired wavelengths.

Based on the spectral requirement of each channel, the space separation between two channels, the thickness of the substrate glass, the diffraction angles for different channels, and the smallest wavelength difference between the adjacent channels can be precisely determined. It is clear that the space separation between the ith and the $(i+1)$th adjacent channels is

$$\Delta d = d_{i+1} - d_i = 2T[\tan(\theta_{i+1}) - \tan(\theta_i)], \tag{1}$$

where T is the thickness of the substrate, θ_i and θ_{i+1} are the diffraction angles of the ith and the $(i+1)$th channels. Equation (1) is only for one bounce of the zig–zag wave within the waveguiding plate.

For a channel with wavelength λ_i, the diffraction angle θ_i is given by

$$\theta_i = 2\ \sin^{-1}(\lambda_i / 2n\Lambda_i), \tag{2}$$

where Λ_i is the grating space for the ith channel, and n is the refractive index of the substrate.

To fabricate a hologram with a desired grating spacing, the two-beam interference method is used.[9] The diffraction efficiency for the ith channel is[10]

$$\eta_i = \sin^2(\nu^2 + \xi^2)^{1/2} / (1 + \xi^2/\nu^2). \tag{3}$$

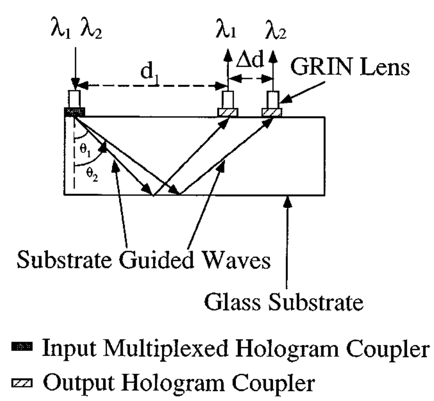

FIG. 1. Schematic of two-channel surface-normal WDDM using substrate guided waves in conjunction with multiplexed waveguide holograms.

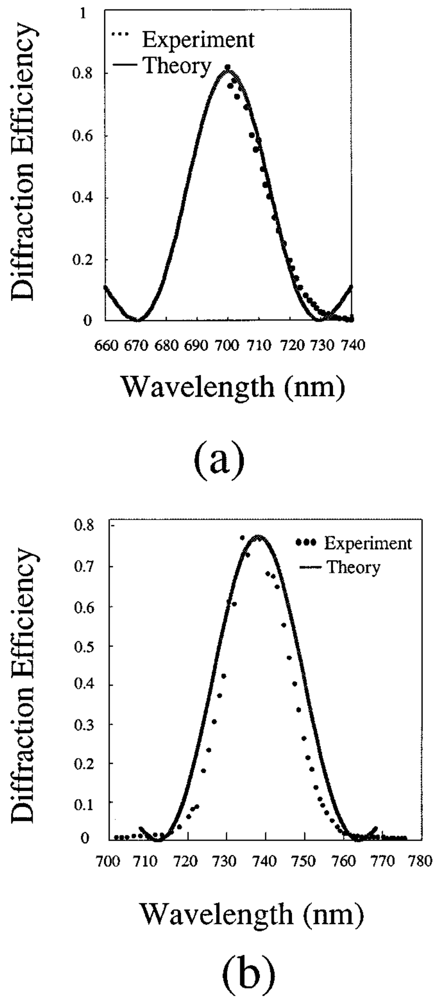

FIG. 2. Theoretical and experimental results for diffraction efficiencies as a function of wavelength at (a) channel 700 nm and (b) channel 738 nm.

For transverse electric (TE) substrate guided waves

$$\nu = \pi \Delta \mathrm{nd}/\lambda (c_r c_s)^{1/2}, \tag{4}$$

$$\xi = \Delta\lambda_i K_i^2 d/8\pi n c_s, \tag{5}$$

$$c_r = \cos\ \phi_0, \tag{6}$$

$$c_s = c_r - (K_i/k_i)\cos(\theta_i), \tag{7}$$

$$K_i = 2\pi/\Lambda_i, \tag{8}$$

$$k_i = 2\pi/\lambda_i, \tag{9}$$

where ϕ_0 is the incident angle of the input signal which is 0° for our surface-normal coupling case (therefore $c_r = 1$), Δn is the modulation of the refractive index of the PLG polymer film which is determined by the exposure dosage, d is the thickness of the hologram film, and $\Delta\lambda_i$ is the wavelength deviation from the channel of center-wavelength λ_i. By using Eqs. (2)–(9), we can calculate the bandwidth of each channel for the center-wavelength λ_i and the corresponding peak diffraction efficiency.

A two-channel device operating at 700 nm with a diffraction angle of 45° and at 738 nm with a diffraction angle of 50° was fabricated. We employed p-polarized Ti-sapphire laser as the light source. The thickness of the glass substrate was 3.2 mm. A film thickness of 20 μm was measured for the polymer thin film employed on top of the waveguiding plate. The refractive index modulation Δn of 0.02 was designed by properly crosslinking the sensitized polymeric thin film.[8] We further derived, from Eqs. (2)–(9), the diffraction efficiencies of the two channels operating at 700 nm with a 45° diffraction angle and 738 nm with a 50° diffraction angle. The results are shown in Figs. 2(a) and 2(b). The peak diffraction efficiencies of 80% and 77% were obtained for the 700 and 738 nm channels, respectively. The 3 dB bandwidths were determined to be 27 nm for the 700 nm channel and 28 nm for the 738 nm channel. We further measured the coupling efficiency of each channel and the results were also shown in Figs. 2(a) and 2(b) where a good match with our theoretical prediction was observed. The experimental data for $\lambda < 700$ nm is not available due to the bandwidth coverage of Ti-sapphire laser. Figure 3 shows us the output spectra of the two channels detected by an optical spectrum analyzer. By comparing with the input spectra (not shown) we can see that the optical properties of the optical system such as distortions or aberrations are very well controlled. We also measured the crosstalk of the two channels and −31 dB was obtained. The system insertion losses were determined to be 2.6 dB for the 700 nm channel and 3 dB for the 738 nm

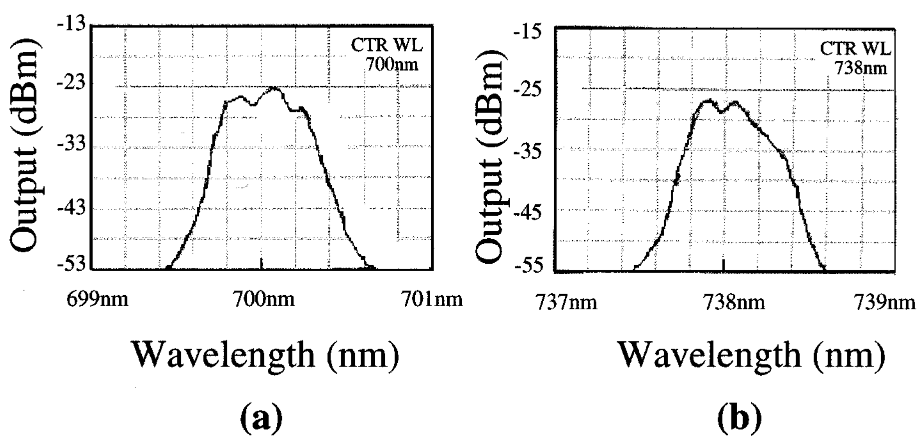

FIG. 3. Output spectra of the two-channel WDDM at (a) 700 nm and (b) 738 nm.

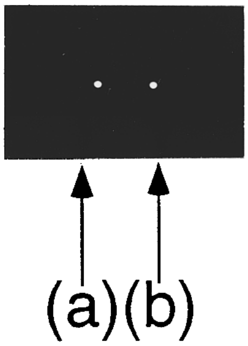

FIG. 4. The output dots of the two-channel WDDM device at (a) 700 nm and (b) 738 nm.

channel, respectively. Two surface-normal output dots corresponding to 700 and 738 nm were illustrated in Fig. 4. Each output spot size is 800 μm in diameter with a channel space separation Δd of 1.2 mm. All the measured device parameters are summarized in Table I. The 3 dB bandwidth is relatively large when compared with our previous result.[8]

TABLE I. Measured device parameters of the two-channel WDDM device reported.

Number of channels	2
Film thickness	20 μm
Index modulation	0.02
Center wavelengths	700 nm and 738 nm
Channel space separation Δd	1.2 mm
3 dB bandwidths	27 nm (700 nm) and 28 nm (738 nm)
Diffraction efficiencies	80% (700 nm) and 77% (738 nm)
Spectral bandwidth of laser beam	1 nm
Crosstalk	−31 dB

This is due to the shortened interaction length which in our case is proportional to the film thickness.

In conclusion, we report a two-channel WDDM based on the polymer multiplexed holograms and the substrate guided modes operating at 700 nm with a diffraction angle of 45° and at 738 nm with a diffraction angle of 50°. The peak diffraction efficiencies of 80% and 77% are theoretically and then experimentally confirmed. The 3 dB bandwidths of 27 and 28 nm are obtained for channels 700 and 738 nm, respectively. A crosstalk of −31 dB between the two channels is measured. A good agreement between the theoretical analysis and the experimental results is achieved. Note that the device scheme presented in this letter provides multiplexibility and demultiplexibility simultaneously without any readjustment. Therefore a truly bidirectional WDM/WDDM system can be provided. Such an approach is compatible with GRIN lens insertion at the surface normal direction, and therefore, the optoelectronic packaging is much more rugged and reliable when compared with the traditional edge-coupling methods.

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