Five-Channel Polymer Waveguide Wavelength Division Demultiplexer for the Near Infrared

M. R. Wang, G. J. Sonek, R. T. Chen, and T. Jannson

Abstract—**A five-channel wavelength division demultiplexer (WDDM), fabricated in polymer gelatin waveguides, and operating over a 100 nm bandwidth centered at 770 nm in the near infrared, is demonstrated. The device has a maximum diffraction efficiency of 80% at 730 nm, a spectral bandwidth of 17 ± 3 nm per channel, and effectively utilizes a portion of the large optical transparency bandwidth (~2400 nm) of the photo-lime gelatin polymer material at laser diode wavelengths. High channel density WDDM devices at longer infrared wavelengths should be possible.**

To date, several different wavelength division multiplexing (WDM) and demultiplexing (WDDM) devices have been proposed and demonstrated [1]-[5] for use in lightwave systems. In particular, a technique for producing multiple phase gratings in locally sensitized photo-lime gelatin polymer waveguides for WDM applications, has recently been reported [6]-[8]. An efficient four-channel visible wavelength demultiplexer has also been demonstrated [8]. While the above device has demonstrated the feasibility of fabricating and processing locally sensitized polymer films into high density optical interconnection and signal processing elements, it has not adequately taken advantage of the near-infrared optical transparency bandwidth available with photo-lime gelatin polymer microstructure films.

Herein, we report on the development of a new five-channel, single-mode planar polymer waveguide, wavelength division demultiplexer, for use in the near infrared wavelengths. The device, which demultiplexes five discrete wavelengths from 730 to 810 nm, in 20 nm increments, shows the potential for high diffraction efficiency, low cross-talk, and compatibility with GaAs and AlGaAs laser diodes for use in signal processing and interconnection applications. The concepts presented herein should also make possible the development of WDDM devices at the wavelengths of 1.3 and 1.55 μm, respectively, for fiber-optic communication systems.

The fabrication and processing procedure for producing a visible WDDM device has been described in detail elsewhere [8], but is also applicable to the development of demultiplexers which operate in the near-infrared and IR wavelengths. In essence, a thin-film, step-index, polymer slab waveguide is formed, on an appropriate substrate, through a series of gelation, spin-coat, and slow-dry processing steps. The refractive index profile of the polymer waveguide is then tuned, via a carefully controlled wet and dry process using an alcohol immersion technique, to produce a graded-index waveguide. A local sensitization process, consisting of polymer prehardening, ultraviolet exposure, and ammonium dichromate polymer sensitization, is subsequently used to sensitize selectively masked portions of the polymer waveguide. In this way, a single holographic phase grating, or multiply exposed phase gratings, having the proper Bragg diffraction angles, can be processed in the locally defined polymer film.

In the present device, a polymer film, having a thickness of ~3 μm, was fabricated on top of a soda-lime glass substrate using the aforementioned techniques, and selectively processed to accommodate five phase gratings within an interaction region measuring ~0.19 mm. The effective refractive index of the core, and the refractive index of the substrate region, are estimated to be 1.5175 and 1.512, respectively, at a wavelength of 632 nm. The gratings were designed to selectively demultiplex signals at the center wavelengths of 730, 750, 770, 790, and 810 nm, respectively, by holographically exposing the sensitized films at the appropriate phase-matched Bragg diffraction angles. In addition, the gratings were designed to have a full-width half-maximum (FWHM) spectral bandwidth of ~10-19 nm, for an interaction length of ~0.2 mm. In order to test the resulting five-channel device, light from a tunable Ti:Al_2O_3 laser was prism coupled into the polymer waveguide, output coupled with a second prism coupler, and detected with a Si photodiode. Diffraction efficiencies, spectral bandwidth, and degree of crosstalk were measured by continuously scanning the laser wavelength from 718 to 842 nm. Propagation losses and crosstalk effects were measured by positioning the output prism coupler in such a way that all diffracted and undiffracted beams could be coupled out of the waveguide simultaneously.

The resulting five-channel demultiplexer is shown in Fig. 1(a) and (b), respectively, for the fundamental TE_0 mode of the polymer waveguide. The device schematic of Fig. 1(a) shows a multiplexed hologram that has been selectively defined in a region of the graded index polymer film. A coupling prism is used to excite the waveguide mode at the wavelength of interest. After interaction with the grating region, the five diffracted, and one undiffracted, beams continue to propagate within the slab waveguide. As seen in Fig. 1(b), five discrete channels, corresponding to the near infrared wavelengths from 730 to 810 nm, are created by the polymer WDDM. The diffraction efficiency of each channel is measured by monitoring the diffracted power with respect to the amount of power remaining in the undiffracted beam, seen as the bright streak in the lower portion of Fig. 1(b). Using the prism coupling technique, the propagation losses for the polymer film were also examined before and after refractive index profile tuning. The results for a typical polymer film on top of a glass substrate are shown in Fig. 2. Prior to index tuning, the planar polymer film was found to support three slab modes, while only the fundamental TE_0 mode was observed after the tuning process. This behavior is commensurate with the conversion of the polymer step-index profile to that of a narrow

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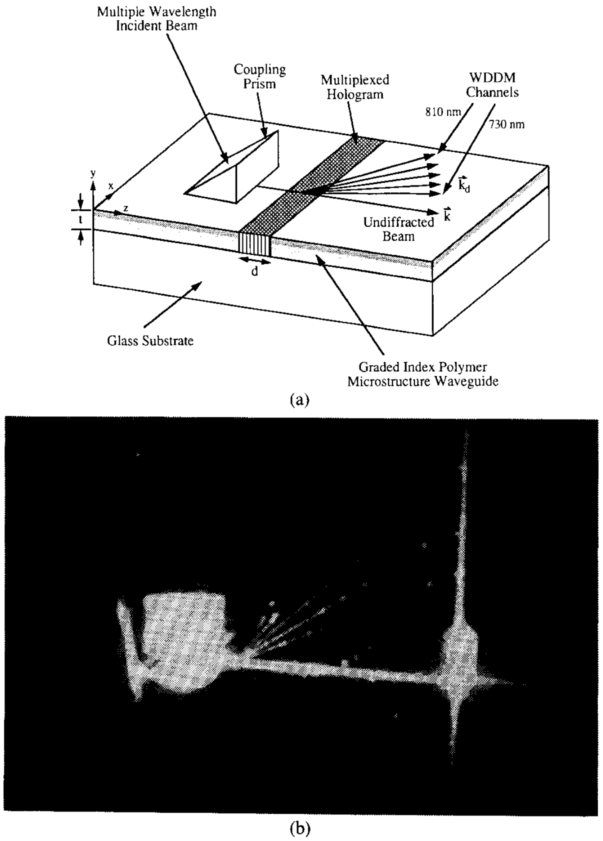

(b)

Fig. 1. (a) Schematic of a multiplexed hologram and graded-index polymer film, used to form a demultiplexer device and (b) photograph of a five-channel near infrared demultiplexer, operating at the design wavelengths of 730, 750, 770, 790, and 810 nm, respectively. The polymer waveguide mode at each channel wavelength is excited with a prism coupler and diffracted at the phase-matched Bragg angle condition.

graded-index core region, and the lowering of the surface refractive index, after successive wet and dry processing steps [6]. From the logarithmic plot in Fig. 2, it can be seen that the propagation loss, in the present waveguide, increased slightly from ~0.94 dB/cm to ~1.22 dB/cm, as a result of film processing, for waveguides exceeding 3 cm in the length. Such waveguides have, in fact, been routinely fabricated over substrate lengths exceeding 20 cm. The tuning process has been found to introduce some film defects that can, occasionally, result in larger losses. In general, however, only a small increase in loss is observed. The attenuation for the preprocessed TE_1 and TE_2 waveguide modes were found to be in the 0.5-2 dB/cm range.

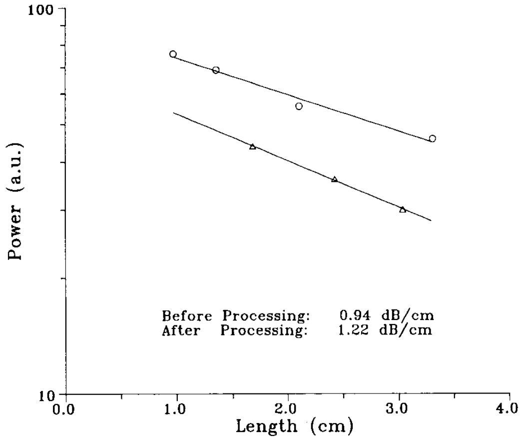

Fig. 2. Propagation losses for the photo-lime gelatin polymer waveguide, measured before (circles) and after (triangles) refractive index profile tuning. Losses for the TE_0 mode are ~0.94 and 1.22 dB/cm, respectively.

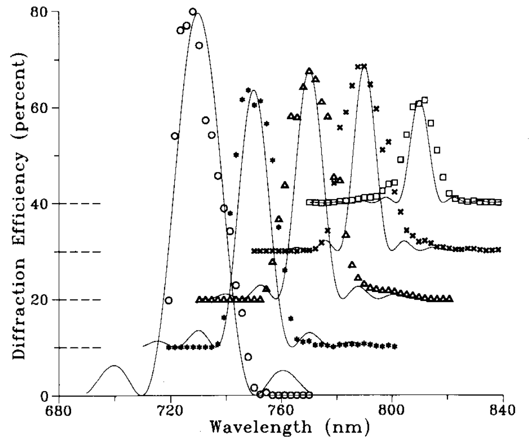

Fig. 3. WDDM diffraction efficiency, as a function of wavelength, for each of the center channel wavelengths. Data points represent experimentally measured diffraction efficiencies for a single wavelength channel, with adjacent channel signals blocked. Theoretical efficiencies (solid lines) are calculated from coupled-mode theory using a different grating modulation index for each channel. Channel wavelengths are centered around 730 (circle), 750 (star), 770 (triangle), 790 (cross), and 810 (square) nm, respectively. The curves have been offset, vertically, for clarity, as indicated by the baseline marks.

The demultiplexer diffraction efficiency, as a function of incident laser wavelength, is shown in Fig. 3. For this measurement, the output prism coupler was placed ~2 mm away from the grating interaction region, such that the angular coupling constraints of all five diffracted beams could be satisfied. In this way, a continuous wavelength scan for all five gratings could be obtained. Channel responses were obtained by monitoring individual diffracted channel signals, and blocking all other adjacent channel signals. These results are compared with the diffraction efficiencies calculated from coupled mode theory, for a lossless step-index waveguide medium having slanted phase gratings [8], [9], which appear as the solid curves in Fig. 3. The curves are calculated from the efficiency expressions, given by

$$\eta = \frac{4\kappa^2(\hat{k}\cdot\hat{k}_d)^2}{\frac{C_i}{C_d}\vartheta^2 + 4\kappa^2(\hat{k}\cdot\hat{k}_d)^2} \cdot \sin^2\left[\frac{1}{2}\left(\frac{\vartheta^2}{C_d^2} + \frac{4\kappa^2(\hat{k}\cdot\hat{k}_d)^2}{C_i C_d}\right)^{1/2} d\right] \tag{1}$$

where

$$C_i = \frac{\beta_{mz}}{\beta_m} \tag{2}$$

$$C_d = \frac{\sigma_z}{\beta_1} \tag{3}$$

$$\vartheta = \frac{\beta_1^2 - \sigma^2}{2\beta_1} \tag{4}$$

$$\kappa = \frac{2\pi^2}{\lambda^2} \int_{-\infty}^{\infty} n_0(y)\, \Delta n(y) E_m(y) E_1(y)\, dy. \tag{5}$$

Here, d is the grating interaction length, t is the polymer waveguide thickness, λ is the free space wavelength, n_0 is the waveguide bulk index, Δn is the grating modulation index, β_m and β_1 are the incident and diffracted guided mode propagation constants, and E_m and E_1 are the corresponding mode profiles which obey the orthogonality relationship:

$$\int_{-\infty}^{\infty} E_m(y) E_1(y)\, dy = \frac{\delta_{m,1}}{\beta_m} \qquad m, 1 = 0, 1, 2, \cdots \tag{6}$$

δ is the dephasing constant, used to describe the effects of Bragg detuning by an amount σ from the diffracted propagation constant β_1, while κ accounts for the overlap between the locally defined grating and the waveguide mode. Using the above expressions, the angular and spectral bandwidth for each diffraction angle and center wavelength is calculated as a function of the waveguide mode effective index, the grating modulation index, and the grating interaction length.

From Fig. 3, it can be seen that the diffraction efficiency at the Bragg angle of 25° achieves a maximum value of ~80% at 730 nm, while the efficiency for the adjacent channel, having a Bragg angle and signal wavelength of 33° and 750 nm, respectively, is ~54%. The efficiencies for the other three channels are much smaller, assuming values of ~48, 39, and 22% at 770, 790, and 810 nm, respectively. Each of the curves appearing in Fig. 3 has been offset, vertically, for clarity. As expected, the efficiency for each of the five demultiplexer channels decreases rapidly at wavelengths detuned from the center Bragg wavelength. The measured FWHM spectral bandwidths for all five channels, obtained by scanning over the entire laser tuning range, are found to be between ~14–20 nm. These bandwidths are, in fact, slightly broader than the 10–19 nm bandwidths expected from the individual, singly exposed grating responses, and those predicted from coupled mode theory. For example, spectral bandwidth measurements for the 730 and 750 nm channels yield values of 17.1 and 17.0 nm, while the 790 and 810 nm channels have bandwidths of 17.7 and 13.3 nm, respectively. The crosstalk for the two most efficient channels, measured at the center wavelengths by successively blocking adjacent channel signals, are determined to be −26.0 and −14.8 dB, respectively. Other channel crosstalk figures are found to vary between −10.2 and −18.5 dB, depending on the presence, or absence, of sidelobe features lying to either side of the central diffraction maxima. We note that crosstalk figures in excess of −40 dB can be achieved, if the grating interaction length can be increased to larger than 0.5 mm [8]. As shown in the data of Fig. 3, no distinct symmetric sidelobe features are observed for any of the channels, even though such features are theoretically predicted.

From Fig. 3, it can be seen that the experimental and calculated values for the response of the WDDM at each of the center wavelengths are in good agreement, if different grating modulation indexes are used to model the multiply exposed gratings at the given interaction length of 0.19 ± 0.02 mm. Values between the range of 7.9×10^{-4} and 1.4×10^{-3}, were used for the modulation index in the calculation, and are found to correspond closely to those expected from the experimentally measured DCG grating exposure fluxes [10]. Discrepancies between calculated and experimentally observed data can be attributed to several factors, including the use of the graded-index waveguide structure specific to this work, the presence of a finite and converging beam width, and the modulation parameters generated in the IR. The decrease in channel performance with increasing wavelength, for example, is derived from the larger diffraction angle, effects of cross-coupling, and the possible saturation of the DCG film after multiple holographic exposures. Similarly, the absence of distinct sidelobe features are likely to be due to variations in the waveguide modal propagation constant, or the grating constant, within the index-tuned polymer film. At present, these are the only limitations to realizing higher channel densities and uniformly higher efficiencies at the longer 1.3 and 1.55 μm infrared wavelengths.

In conclusion, a five-channel WDDM device, operating in the near infrared, and having a spectral bandwidth of 17 ± 3 nm/channel has been demonstrated in the newly developed polymer gelatin waveguide material system. Sharper wavelength selectivities, and higher channel densities, are expected, if the grating interaction length, index modulation parameters, and film processing steps can be optimized.

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