Wavelength-division multiplexing and demultiplexing on locally sensitized single-mode polymer microstructure waveguides

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A four-channel wavelength-division-(de)multiplexing [WD(D)M] device, operating over optical wavelengths of 543.0 to 632.8 nm, has been successfully fabricated on newly developed locally sensitized polymer (photo-lime gelatin) microstructure waveguides (PMSW's). The WD(D)M device exhibits a cross talk of less than −40 dB between adjacent channels and a diffraction efficiency of better than 50%. The angular and spectral bandwidths for the device are ~0.2–0.4° and ~4–10 nm, respectively. Such sensitivities can significantly increase the WD(D)M channel density for optical interconnect architectures. Since the PMSW device can be constructed on a variety of substrates, including insulators, semiconductors, conductors, and ceramics, the demultiplexing technique that we report is suitable for use in a variety of optical-computing, signal-processing, and communication applications.

Wavelength-division (de)multiplexing [WD(D)M] is considered to be a key technology for enhancing the transmission capacity and the application flexibility of optical communication and sensor systems. Various types of wavelength-division multiplexers and demultiplexers have been proposed and demonstrated, including prism, interference filter, and diffraction grating devices.[1,2] In comparison with other WD(D)M devices, grating demultiplexers in thin-film waveguides[3–6] can exhibit high efficiencies, sharp wavelength selectivities, and large channel densities, making them highly suitable for monolithic integration with photodetectors in, for example, the construction of integrated-optic WD(D)M receiver terminals.[5,6]

In this Letter we report, for the first time to our knowledge, the development of a four-channel integrated-optic wavelength-division demultiplexer, using multiplexed waveguide holographic gratings patterned on a locally sensitized single-mode polymer (photo-lime gelatin) microstructure waveguide (PMSW). The device makes use of the fact that the refractive-index profile of the polymer can be tuned by means of mass density changes during wet and dry processing.[7] The creation of a graded-index profile with a high surface index thereby facilitates low-loss (<1-dB/cm) waveguide formation on substrates, such as GaAs, $LiNbO_3$, alumina (Al_2O_3), and beryllium oxide (BeO),[7,8] that would otherwise exhibit excessive loss or leaky-mode behavior. In addition, the polymer waveguide is optically transparent from 300 to 2700 nm, making the polymer-based WD(D)M device described herein suitable for operation at infrared wavelengths in communication applications.

A schematic of the basic waveguide phase hologram demultiplexer is shown in Fig. 1. A guided mode, having wave vector $\mathbf{k}_i$ in the polymer waveguide, is incident upon a slanted phase grating, of wave vector $\mathbf{K}$, that has been selectively defined over a given distance d. The actual WD(D)M device, with a grating length of d = 0.5 mm and Bragg diffraction angles between 25° and 55°, was fabricated on a PMSW. The demultiplexer was formed using a two-step process. First, a single-mode planar polymer waveguide was formed on top of an appropriate substrate. In this case, a thin layer (~3.0 μm) of photo-lime gelatin was coated on a soda-lime glass sample. After waveguide index profile tuning and film hardening,[7] the waveguide was tested, using the prism coupling method. Single-mode propagation was confirmed for optical wavelengths over the range of 543.0–632.8 nm.

Second, holographic gratings were selectively defined within the sensitized polymer microstructure waveguide region. To accomplish this, a layer of photoresist was spin coated on top of the PMSW. Standard photolithography was then used to create an optical window for local sensitization. The local sensitization process was achieved by dipping the sample into an ammonium dichromate solution at room temperature. The masking material was then removed, and within 2 h after drying and stabilization of the sensitized region the sample was ready for dichromated gelatin (DCG) holographic recording and processing.

In order to form the multiplexed waveguide holo-

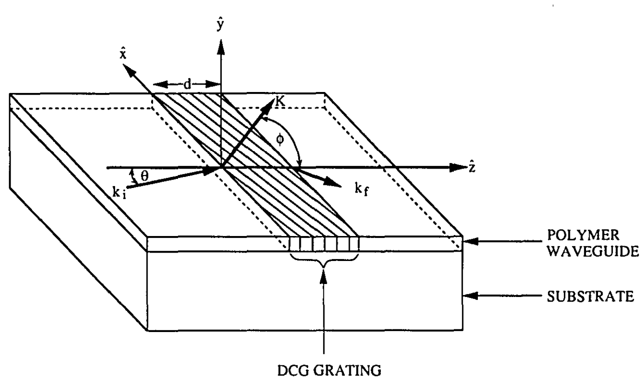

Fig. 1. Model of the polymer microstructure waveguide, with selectively defined DCG phase gratings having slanted fringes.

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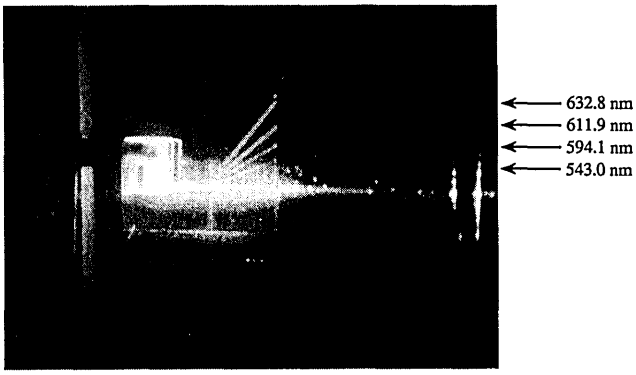

Fig. 2. Four-channel wavelength-division-demultiplexer device using a PMSW waveguide. The diffracted wavelengths are 632.8, 611.9, 594.1, and 543.0 nm.

graphic gratings, to be used in demultiplexing the signal carriers of different wavelengths, a two-beam interference recording method was employed. Each individual holographic grating, having a sinusoidal phase-modulation profile, is recorded such that

$$\mathbf{K}_i = 2\mathbf{k}_{\lambda_i} \sin\left(\frac{\psi_i}{2}\right), \quad (1)$$

where $\mathbf{k}_{\lambda_i}$ and $\mathbf{K}_i$ are defined as

$$\mathbf{k}_{\lambda_i} = N_{\mathrm{eff}_{\lambda_i}} \frac{2\pi}{\lambda_i}, \quad (2a)$$

$$\mathbf{K}_i = \frac{2\pi}{\Lambda_i}. \quad (2b)$$

Here ψ_i is the angle of Bragg diffraction, Λ_i is the ith holographic grating period, $\mathbf{K}_i$ is the ith grating wave vector, and $N_{\mathrm{eff}_{\lambda_i}}$ is the waveguide mode effective index at λ_i. Since the effective index N_{eff} of the PMSW is a function of the wavelength, different recording angles were selected for each different carrier wavelength in order to satisfy the necessary phase-matching conditions of each wavelength. Exposure parameters were adjusted during successive holographic recordings in an attempt to optimize diffraction efficiencies. Each grating is, therefore, designed to be capable of deflecting only one wavelength within a 4–10-nm spectral bandwidth.

The resultant four-channel WD(D)M device, fabricated on a locally sensitized PMSW and operating at λ = 632.8 nm (red), 611.9 nm (orange), 594.1 nm (yellow), and 543.0 nm (green), is shown in Fig. 2. For each wavelength, the TE_0 guided mode is excited by prism coupling into the PMSW structure at a distance of approximately 2–4 mm from the grating interaction region. The cross talk of each individual channel was measured to be approximately −40 dB, while the diffraction efficiency at each wavelength was found to be higher than 50%. It should be possible to achieve much higher diffraction efficiencies for each individual grating if the grating-index modulation profile and the grating interaction length are optimized. While excellent cross-talk figures were obtained, it is conceivable that the presence of substrate radiation modes from each signal carrier, generated by the interaction with other existing gratings or from random fluctuations in grating modulation index and waveguide thickness, will limit the overall WD(D)M device efficiency for closely spaced channels. The angular and spectral sensitivities for the present device were determined to be 0.2–0.4° and approximately 4–10 nm, respectively.

The above results can be compared with values calculated by using coupled-mode theory, as it is applied to a lossless step-index waveguide medium containing slanted phase gratings.[9] The TE-mode (p-light) diffraction efficiency is shown in Fig. 3 as a function of Bragg angle and wavelength. For the calculation it was assumed that there is complete overlap between the guided mode and the index perturbation and that the modulation index has a value of $\Delta n = 0.01$. The diffraction angles chosen for study correspond to those used in actual WD(D)M device described above. We note that the effects of a finite beam width and a graded-index profile were not accounted for in the

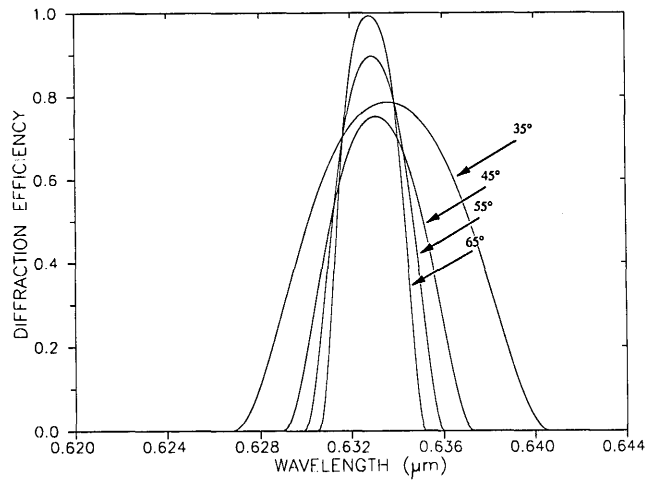

Fig. 3. Diffraction efficiency and wavelength dependence as a function of the diffraction angle ψ. A mode effective index $N_{\mathrm{eff}} = 1.5172$, a center wavelength of $\lambda = 0.6328$ μm, an index modulation $\Delta n = 0.01$, and a grating interaction length $d = 0.5$ mm were used in the calculations.

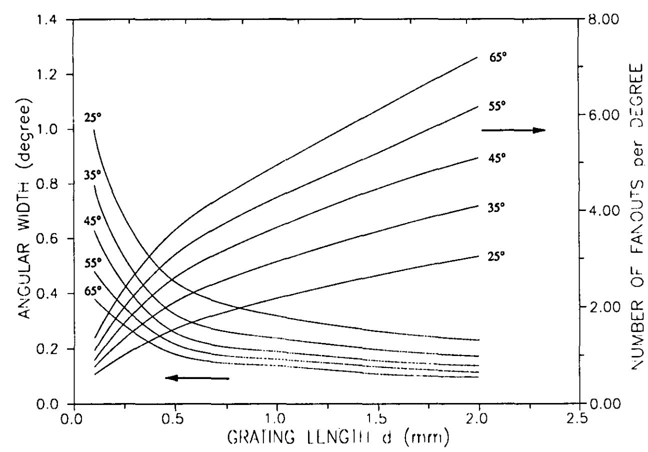

Fig. 4. Angular bandwidth and the fanout density as a function of the grating interaction length.

present analysis. It can be seen that, for a given grating modulation index and a center wavelength of 632.8 nm, there is a decrease in the spectral bandwidth (FWHM) with an increasing Bragg diffraction angle. Alternatively, the diffraction efficiency is periodically modulated, undergoing a transition between a maximum and a minimum value as the diffraction angle is changed. Similar trends are observed at other center wavelengths. We note that the diffraction efficiency at all angles can be improved on by tuning the modulation index during the fabrication process.

The dependence of the angular width and fanout channel on the grating interaction length d is shown in Fig. 4. Once again, a decrease in angular bandwidth can be achieved, but it requires either an increase in the grating interaction length or an increase in Bragg angle. The spectral bandwidth of the device exhibits a similar dependence. Hence, as the angular bandwidth decreases, a greater number of fanout channels can be accommodated within the waveguide. In comparison, the smaller interaction lengths ($\lesssim 60\ \mu m$) often utilized in three-dimensional holographic WD(D)M devices limit the overall channel density that can be achieved.

In summary, a four-channel wavelength-division-demultiplexing device has been fabricated upon locally sensitized polymer microstructure waveguides with the use of multiplexed waveguide holographic gratings in DCG. Because the locally sensitized DCG region is capable of supporting a large number of multiply exposed phase gratings[10] over relatively long interaction lengths, the WD(D)M device has the potential for achieving large channel densities, with excellent angular and wavelength selectivities and low cross talk.

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