

Five-channel Surface-normal Wavelength Division Demultiplexer Using Substrate Guided Waves in Conjunction with Polymer-based Littrow Hologram

Maggie M. Li, Ray T. Chen and Chunhe Zhao
 Microelectronics Research Center
 Department of Electrical and Computer Engineering
 University of Texas, Austin, TX 78759
 Tel: 512-4717035

Abstract—In this paper, we report on a 5-channel wavelength division demultiplexer (WDDM) using substrate-guided waves in conjunction with polymer-based Littrow hologram operating at 700, 710, 720, 730 and 740nm, respectively. An average cross talk of -40dB between adjacent channels is measured. The diffraction efficiencies of 69%, 78%, 83%, 77%, and 69% are both experimentally and theoretically confirmed for the five-channel WDDM device. Further study aiming at reducing the wavelength channel separation to 1nm is also provided for the future work. Device length of 6.4cm corresponding to propagation distance of 9.05cm is required to achieve such a goal.

Wavelength division (de)multiplexing [WD(D)M] devices are considered to be the key elements for enhancing the transmission bandwidth of optical communications and sensor systems. During the past 20 years, various types of WD(D)Ms have been proposed and demonstrated[1-6]. Recently, WD(D)Ms based on photo-lime gel (PLG) polymer-based waveguide holograms using surface-normal coupling technique, has been reported[7,8]. In this paper, we report on the demonstration of a 5-channel WD(D)M using surface-normal input and output couplings based on the Littrow holograms packaged with GRIN rod lenses. The WD(D)M 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 5-channel WDDM using PLG-based Littrow hologram in conjunction with substrate guided waves is shown in Fig.1.

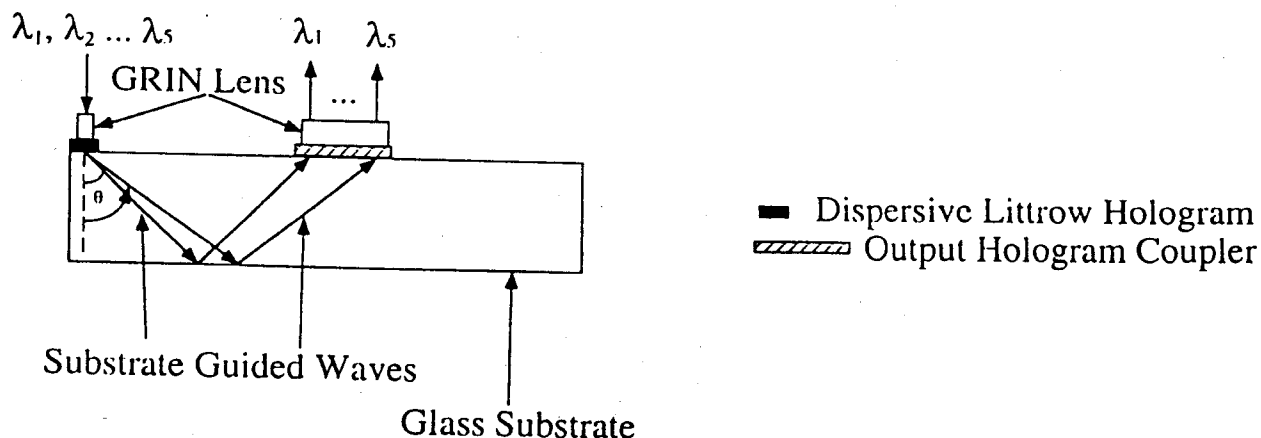


Fig.1 Schematic of the demonstrated 5-channel surface-normal WDDM using substrate guided waves in conjunction with dispersive littrow hologram.

The input laser beams with different wavelengths are coupled into the glass substrate by a Littrow holographic grating which converts the surface-normal incoming beams into five substrate guided waves with different bouncing angles. A Littrow hologram with the diffraction angle θ_0 and the peak diffraction efficiency η_0 at 720nm is designed based on the required phase-matching condition. Therefore the center-channel (the third channel in our case) of the WDDM device operates at 720nm with a bouncing angle $\theta_3 = \theta_0$. 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. A wide band holographic coupler is recorded to provide the surface-normal fanouts. It is clear from Fig.1 that the location and the grating vector of each fanout hologram coupler shall be precisely determined to provide the five surface-normal fanout beams at the desired locations with the desired wavelengths.

For the center-channel λ_0 of the Littrow hologram at which the maximum diffraction efficiency is designed, the diffraction angle θ_0 is given by

$$\theta_0 = 2 \sin^{-1}(\lambda_0 / 2n\Lambda) \quad (1)$$

where Λ is the grating spacing for the Littrow hologram, n is the refractive index of the substrate. From the coupled mode theory, the diffraction efficiency of the Littrow hologram is[10],

$$\eta = [\sin^2 (v^2 + \xi^2)^{1/2}] / (1 + \xi^2/v^2) \quad (2)$$

For transverse electric (TE) substrate guided waves,

$$v = \pi \Delta n d / \lambda_0 (c_r c_s)^{1/2} \quad (3)$$

$$\xi = -\Delta \lambda K^2 d / 8\pi n c_s = \Delta \theta K d \sin(\varphi - \phi_0) / 2c_s \quad (4)$$

$$c_r = \cos \phi_0, \quad c_s = c_r - (K / k_0) \cos(\theta_0) \quad (5)$$

$$K = 2\pi/\Lambda, \quad k_0 = 2\pi/\lambda_0 \quad (6)$$

$$\varphi = 0.5 (180^\circ - \theta_0) \quad (7)$$

where ϕ_0 is the incident angle of the input signal which is 0° for our surface-normal coupling case (therefore $c_r = 1$), φ is the angle between the grating vector and the incident beam, 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 $\Delta \lambda$ is the wavelength deviation of the channel λ_i from center-wavelength λ_0 . By employing Eqs.(1)-(7), we can calculate the corresponding diffraction efficiencies for the five different channels.

For desired wavelength channel separation $\Delta \lambda$ of the device, its space separation can be derived. From Eq.(4), we have

$$\Delta \theta = \theta_i - \theta_0 = -\Delta \lambda K / 4\pi n \sin(\varphi - \phi_0) \quad (8)$$

It is clear that the space separation between the i th channel and the center-channel is

$$\Delta d = d_i - d_0 = 2T[\tan(\theta_i) - \tan(\theta_0)] \quad (9)$$

where T is the thickness of the substrate. Eq.(9) is only corresponding to one bounce of the zig-zag wave within the waveguiding plate.

To fabricate a hologram with a desired grating spacing, a two-beam interference method is used [11]. A 5-channel WDDM device operating at 700, 710, 720, 730, and 740nm is fabricated. For the input Littrow grating shown in Fig.1, the center wavelength is designed at 720nm with the diffraction angle of 45° . We employ P-polarized Ti-Sapphire laser as the light source. The thickness of the glass substrate is 3.2mm. A polymer thin film having a $20\mu\text{m}$ measured thickness is applied on top of the waveguiding plate. The refractive index modulation Δn of 0.02 is experimentally controlled by properly cross-linking the sensitized polymeric thin film[9].

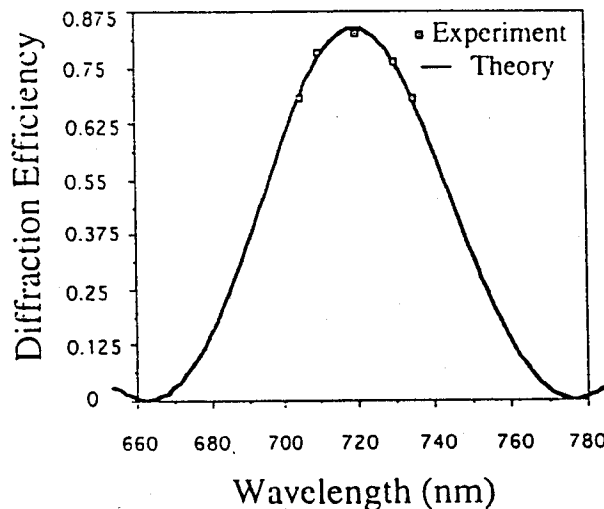
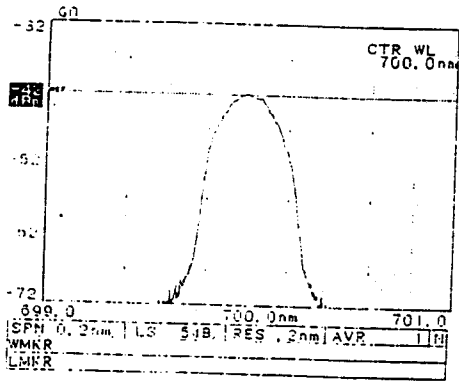
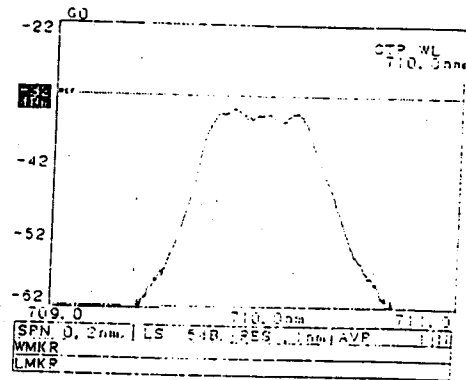


Fig.2 Theoretical and experimental results of diffraction efficiencies as a function of wavelength.

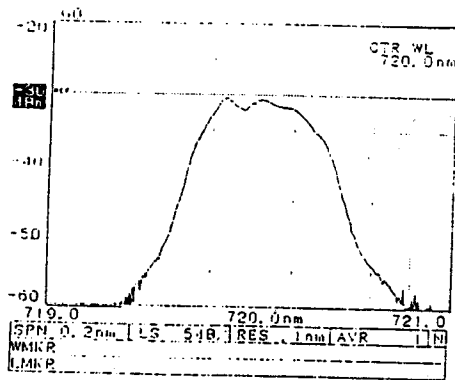
Based on the above parameters, we further derive, from Eqs.(1)-(7), the diffraction efficiency of the Littrow hologram as a function of the wavelength. The result is shown in Fig.2. The peak diffraction efficiency of 83.5% is obtained. Coupling efficiencies of 69%, 78%, 77%, and 69% for the other four channels operating at 700nm, 710nm, 730nm, and 740nm are also determined. These theoretical results are well-matched with the measured data shown in Fig.2. The characteristic of off-peak symmetry is maintained. Figs.3(a)-(e) show us the output spectra of the five channels detected by an optical spectrum analyzer. Note that the 3dB bandwidth of each output beam is equivalent to that of the input beam (not shown).



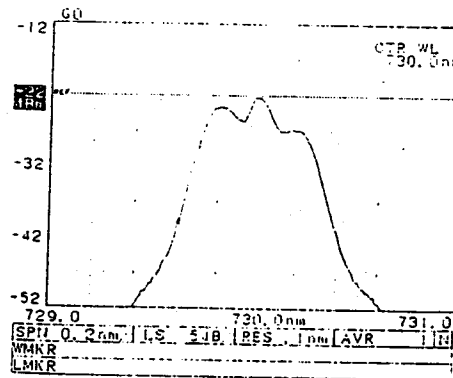
(a)



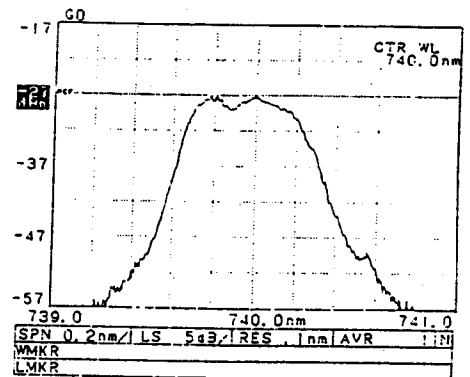
(b)



(c)



(d)



(e)

Fig.3 Output spectra of the 5-channel WDDM at (a) 700nm, (b) 710nm, (c) 720nm, (d) 730nm, and (e) 740nm.

We also measure the average cross-talk of the two adjacent channels and a cross talk of -40 dB is experimentally confirmed. The system insertion losses are determined to be 2.5 dB for the 720nm channel, 2.7dB for the 710nm and 730nm channels, and 3 dB for the 700nm and 740nm channels respectively. Five surface-normal output dots through the GRIN lens corresponding to the five channels operating at 700, 710, 720, 730, and 740nm are further illustrated in Fig.4 using a polaroid camera.

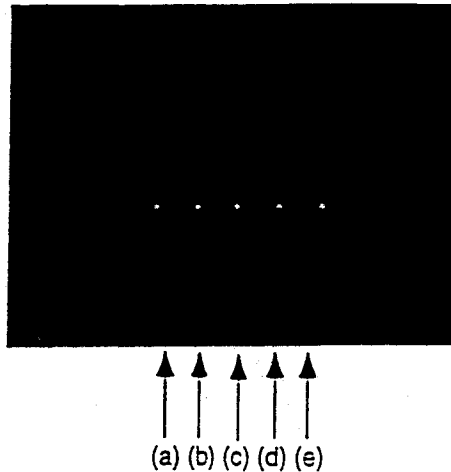


Fig.4 The output dots of the 5-channel WDDM device at (a) 700nm, (b) 710nm, (c) 720nm, (d) 730nm, and (e) 740nm.

If a smaller channel separation is required for the WDDM device, more than one reflections of the guiding waves in the substrate are needed. We study the relationship between device length and channel separation by using Eqs.(8) and (9) both theoretically and experimentally for our WDDM device. The results are shown in Fig.5.

It is clear that a device length of 0.64cm is required for the 10nm wavelength channel separation. To reduce the wavelength channel separation to 1nm, the device length should be 6.4cm corresponding to a propagation distance of 9.05cm. Further experimental result will be presented in a separate publication in the near future.

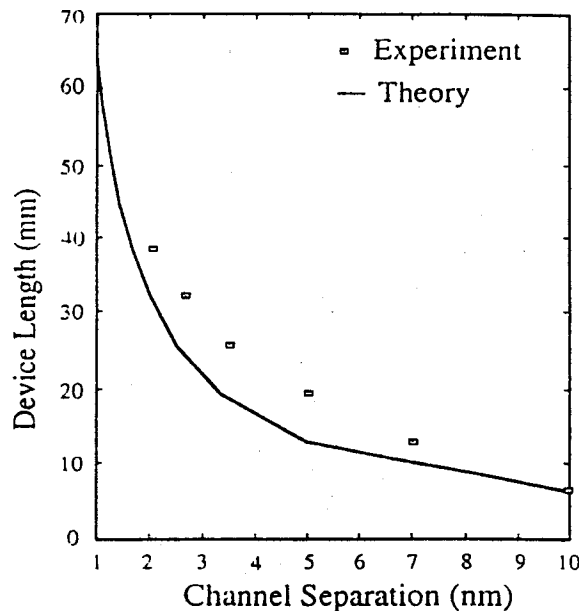


Fig.5 Theoretical and experimental results for the relationship between the device length and the channel separation corresponding to the grating vector of our device.

In conclusion, we report on a five-channel WDDM operating at 700, 710, 720, 730, and 740nm using a polymer-based Littrow hologram and substrate guided waves. The device length is 0.64cm. The diffraction efficiencies of 69%, 78%, 83.5%, 77%, and 69% are theoretically and then experimentally confirmed for 700, 710, 720, 730, and 740nm wavelength channels, respectively. An average cross-talk of -40dB between two adjacent channels is measured. The relationship between device length and channel separation is also studied. A good agreement between the theoretical analysis and the experimental results is achieved. Note that the device scheme presented in this paper provides multiplexibility and demultiplexibility (time reversal) simultaneously without any readjustment. Therefore a truly bi-directional WDM/WDDM system can be provided. Such an approach is compatible with GRIN lens insertion at the surface normal direction. As a result, the optoelectronic packaging is much more rugged and reliable when compared with the traditional edge-coupling methods.

This research is sponsored by AFOSR, BMDO and ARPA.

REFERENCES:

- [1] W. J. Tomlinson, *Appl. Opt.* 16(8), 2180 (1977).
- [2] A. C. Livanos, A. Katzir, A. Yariv, and S. C. Hong, *Appl. Phys. Lett.* 30(10), 519(1977).
- [3] H. Ishio, J. Minowa, and K. Nosu, *J. of Lightwave Tech.* 2(4), 448 (1984).
- [4] I. Nishi, T. Oguchi, and K. Kato, *J. of Lightwave Tech.* 5(12), 1695 (1987).
- [5] H. Obara and Y. Hamazumi, *Electron. Lett.* 28(13), 1268 (1992).
- [6] A. E. Willner, C. J. Chang-Hasnain, and J. E. Leight, *IEEE Photonics Tech. Lett.* 5(7), 838 (1993).
- [7] Y. T. Huang, D. C. Su, and Y. K. Tsai, *Opt. Lett.* 17(22), 1629(1992).
- [8] M. M. Li, K. C. Liu, and R. T. Chen, Submitted to *Appl. Phys. Lett.*
- [9] R. T. Chen, H. Lu, D. Robinson, and T. Jansson, *App. Phys. Lett.* 59(10), 1144 (1991).
- [10] H. Kogelnik, *The Bell Sys. Tech. J.* 48(9), 2909 (1969).
- [11] R. T. Chen, S. Tang, M. M. Li, D. Gerold, and S. Natarajan, *Appl. Phys. Lett.* 63(14), 1883 (1993).