# Five-channel surface-normal wavelength-division demultiplexer using substrate-guided waves in conjunction with a polymer-based Littrow hologram

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We report on a five-channel wavelength-division demultiplexer using substrate-guided waves in conjunction with a polymer-based Littrow hologram operating at 700, 710, 720, 730, and 740 nm. An average cross talk of −40 dB between adjacent channels is measured. Diffraction efficiencies of 69%, 78%, 83%, 77%, and 69% are both experimentally and theoretically confirmed for the five-channel device. We also present further study aimed at reducing the wavelength channel separation to 1 nm and find that achieving such a goal requires a device length of 6.4 cm corresponding to a propagation distance of 9.05 cm.

Wavelength-division (de)multiplexing (WDDM) 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 WDDM device have been proposed and demonstrated.[1–6] Recently WDDM devices based on photo-lime-gel polymer-based waveguide holograms and the use of surface-normal coupling techniques were reported.[7,8] In this Letter we report on the demonstration of a five-channel WDDM device using surface-normal input and output couplings based on two Littrow holograms packaged with graded-index rod lenses. 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 five-channel WDDM device using a photo-lime-gel-based Littrow hologram 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 a Littrow holographic grating that converts the surface-normal incoming beams into five substrate-guided waves with different bouncing angles. A Littrow hologram with diffraction angle $\theta_0$ and peak diffraction efficiency $\eta_0$ at 720 nm is designed based on the required phase-matching condition. Therefore the center channel (third channel in our case) of the WDDM device operates at 720 nm with a bouncing angle $\theta_3 = \theta_0$. After surface-normal optical waves carrying different wavelengths are converted into substrate-guided waves, zigzag guided beams within the glass substrate are generated, as indicated in Fig. 1. A wideband holographic coupler is recorded to provide the surface-normal fan-outs. It is clear from the figure that the location and the grating vector of each fan-out hologram coupler will be precisely determined to provide the five surface-normal fan-out beams at the desired locations with the desired wavelengths.

For the center-channel wavelength $\lambda_0$ of the Littrow hologram at which the maximum diffraction efficiency is designed, the diffraction angle $\theta_0$ is given by

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

where $\Lambda$ is the grating spacing for the Littrow hologram and $n$ is the refractive index of the substrate. From the coupled-mode theory the diffraction efficiency of the Littrow hologram is[10]

$$\eta = [\sin^2(\nu^2 + \xi^2)^{1/2}]/(1 + \xi^2/\nu^2). \tag{2}$$

For TE substrate-guided waves,

$$\nu = \pi\Delta nd/\lambda_0(c_r c_s)^{1/2}, \tag{3}$$

$$\xi = -\Delta\lambda K^2 d/8\pi n c_s = \Delta\theta K_d \sin(\varphi - \phi_0)/2c_s, \tag{4}$$

$$c_r = \cos\phi_0, \qquad c_s = c_r - (K/k_0)\cos(\theta_0), \tag{5}$$

$$K = 2\pi/\Lambda, \qquad k_0 = 2\pi/\lambda_0, \tag{6}$$

$$\varphi = 0.5(180° - \theta_0), \tag{7}$$

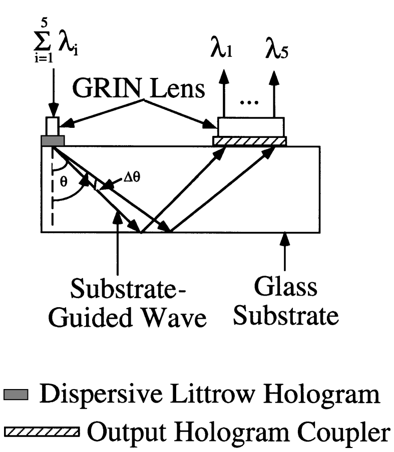


Fig. 1. Schematic of the five-channel surface-normal WDDM device using substrate-guided waves in conjunction with a dispersive Littrow hologram. GRIN, graded-index.

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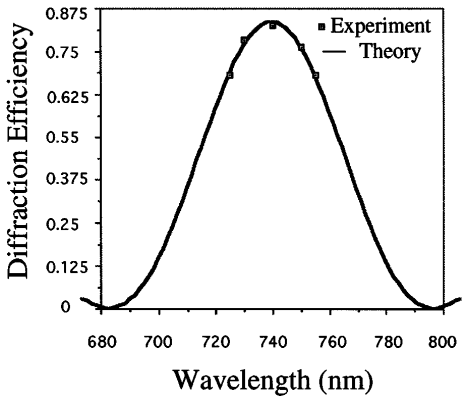


Fig. 2. Theoretical and experimental results of diffraction efficiencies as a function of wavelength.

where $\phi_0$ is the incident angle of the input signal, which is 0° for our surface-normal coupling case (therefore $c_r = 1$); $\varphi$ is the angle between the grating vector and the incident beam; $\Delta n$ is the modulation of the refractive index of the photo-lime-gel 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 $\lambda_i$ from the center wavelength $\lambda_0$. By employing Eqs. (1)–(7) we can calculate the corresponding diffraction efficiencies for the five different channels.

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

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

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

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

where $T$ is the thickness of the substrate. Equation (9) corresponds to only one bounce of the zigzag wave within the waveguiding plate.

To fabricate a hologram with a desired grating spacing, we use a two-beam interference method.[11] A five-channel WDDM device operating at 700, 710, 720, 730, and 740 nm is fabricated, and for the input Littrow grating shown in Fig. 1 the center wavelength is set at 720 nm with a diffraction angle of 45°. We employ a $p$-polarized Ti:sapphire laser as the light source. The thickness of the glass substrate is 3.2 mm. A polymer thin film having a 20-$\mu$m measured thickness is applied on top of the waveguiding plate. We control the refractive-index modulation $\Delta n$ of 0.02 by properly cross linking the sensitized polymeric thin film.[9] 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. A peak diffraction efficiency of 83.5% is obtained, along with coupling efficiencies of 69%, 78%, 77%, and 69% for the other four channels operating at 700, 710, 730, and 740 nm, respectively. As Fig. 2 shows, these theoretical results are in good agreement with the measured data, and the characteristic of off-peak symmetry is maintained. Figure 3

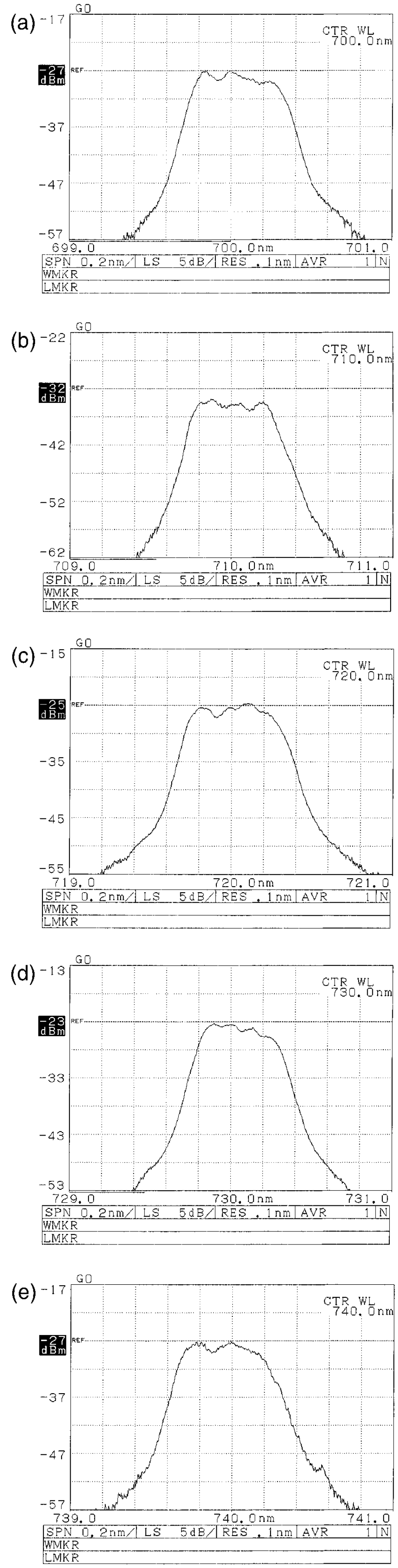


Fig. 3. Output spectra of the five-channel WDDM device at (a) 700, (b) 710, (c) 720, (d) 730, and (e) 740 nm.

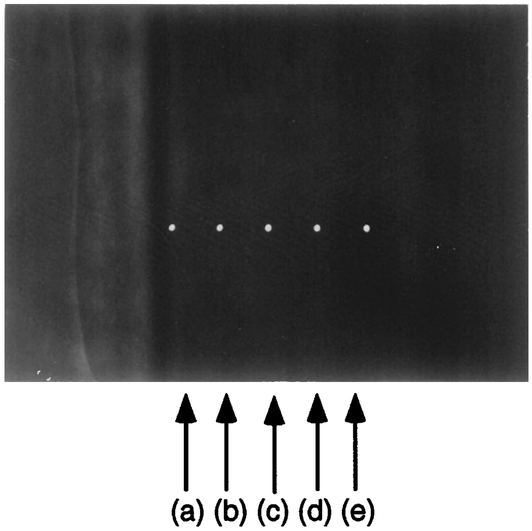


Fig. 4. Output dots of the device at (a) 700, (b) 710, (c) 720, (d) 730, and (e) 740 nm.

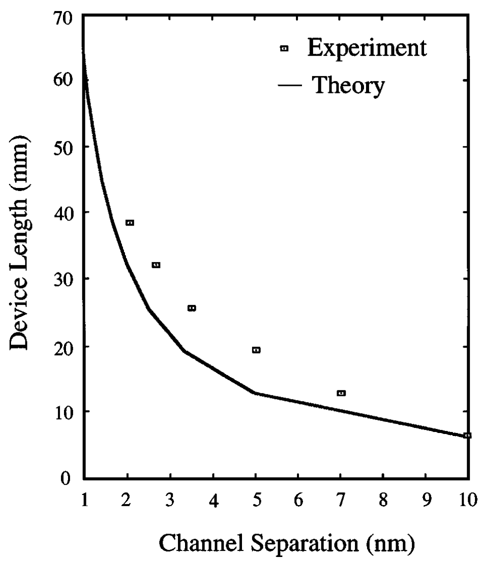


Fig. 5. Theoretical and experimental results for the relationship between the device length and the channel separation corresponding to the grating vector of our device.

shows the output spectra of the five channels detected by an optical spectrum analyzer. Note that the 3-dB bandwidth of each output beam is equivalent to that of the input beam (not shown). 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 720-nm channel, 2.7 dB for the 710- and 730-nm channels, and 3 dB for the 700- and 740-nm channels. Five surface-normal output dots through the graded-index lens corresponding to the five channels operating at 700, 710, 720, 730, and 740 nm are illustrated by the Polaroid camera photograph in Fig. 4.

If a smaller channel separation is required for the WDDM device, more than one reflection 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 0.64 cm is required for the 10-nm wavelength channel separation. To reduce the wavelength channel separation to 1 nm, we need a device length of 6.4 cm, corresponding to a propagation distance of 9.05 cm.

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

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