A Novel Wavelength-Division-Demultiplexer with Optical In-Plane to Surface-Normal Conversion

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***Abstract*— We present a novel surface-normal optical wavelength-division-demultiplexer (WDDM), working at 750, 770, 790, 810, 830, and 850 nm wavelengths. The device is based on the integration of a polymer-based planar waveguide, a substrate waveguiding plate, and waveguide holograms. The unique optical in-plane to surface-normal conversion converts the difficult three spatial and three angular edge coupling problem into a planar surface one, resulting in a reliable miniaturized optoelectronic packaging containing a photodetector array and the WDDM. A six-channel wavelength-division-demultiplexer with equally spaced collinear surface-normal outputs are designed and demonstrated in a polymer-based planar waveguide in conjunction with holograms on a glass substrate.**

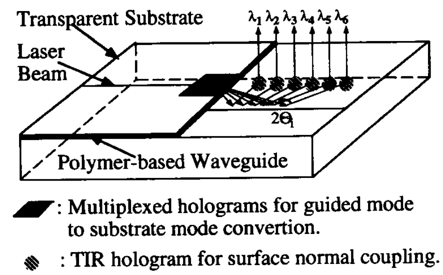

Fig. 1. Schematic diagram of the in-plane to surface-normal WDDM.

IT IS AN established strategy to employ wavelength division multiplexing (WDM) techniques for increasing network capability and functionality. As one of the key optoelectronic components, many types of optical wavelength division demultiplexers (WDDM) have been proposed and demonstrated. These include integrated Mach–Zehnder demultiplexers [1], [2], waveguide grating demultiplexer [3], [4], and holographic grating demultiplexer [5]–[7]. Since all these demultiplexers are fabricated or packed in a planarized geometry, while the photodetector array employed receives optical signals perpendicular to the substrate surface in most cases, the optoelectronic packaging associated with the array of photodetectors is very challenging and expensive. Precise angular and spatial control is required for both optical coupling and packaging. A wavelength division demultiplexer with the optical in-plane to surface-normal conversion can be a very useful approach to provide effective optical coupling and stacked packaging between an in-plane WDDM and a photodetector array.

In this letter, we present a novel optical wavelength-division-demultiplexer with the unique optical in-plane to surface-normal conversion capability. The device is based on integrating a planar waveguide, a substrate waveguide and waveguide holograms, which provides a compact miniaturized face-to-face packaging between the photodetector array and planar optical channel devices. The optical wavelength-division-demultiplexing is provided by multiplexed holograms in planar waveguide region, and the optical in-plane to surface-normal conversion is conducted within the substrate through substrate surface holograms. The conversion of a planar guided mode to substrate modes generates an additional degree of freedom in designing integrated optical wavelength-division-demultiplexer. More importantly, precise angular control is no longer required for the optical coupling and packaging associated with the photodetector array. To our best knowledge, it is the first compact optical wavelength-division-demultiplexer that provides the optical in-plane to surface-normal conversion.

The schematic diagram of the device is shown in Fig. 1. It consists of a polymer-based planar waveguide fabricated on the surface of a light transparent substrate. Multiplexed waveguide holograms are employed at the end of the planar waveguide to convert the planar guided wave into substrate guided modes preserving total internal reflection (TIR). The bouncing angle designed is different for each wavelength for wavelength division demultiplexing. A linear substrate surface hologram array is further employed to convert the substrate guided modes into a linear array of surface-normal beams. A look-down photodetector array can be stacked on the surface of the device substrate with effective optical coupling and aligning.

There are two types of holograms involved in this optical surface-normal WDDM. The first type, planar waveguide multiplexed holograms (see Fig. 1), diffracts the planar guided wave into many substrate modes, corresponding to different wavelengths, respectively. The second type of hologram, the TIR holograms, is a transmission hologram that converts a substrate guided mode into a surface-normal output beam. Using dichromate gelatin (DCG), a photolime gel polymer doped with ammonium dichromate (~4% $(NH_4)_2Cr_2O_7$), up to 60 planar waveguide holograms can be recorded in the same emulsion area due to the large index modulation [5] (up to 0.2). Nearly 100% optical coupling efficiency can be achieved with a hologram interaction length of 1 mm [5]. For the second

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type, TIR holograms, optical coupling efficiency as high as 82% has been reported [7].

A multiplexed waveguide hologram (shown in Fig. 1) is designed to diffract a planar guided wave, carrying wavelength λ_i, into the substrate with a bouncing angle Θ_i, satisfying

$$\Theta_i = \tan^{-1}[i] \qquad i = 1, 2, 3, 4, 5, \text{ and } 6. \tag{1}$$

As a result, a uniform separation between the two nearest surface-normal beams can be obtained as

$$S = 2d[\tan(\Theta_i) - \tan(\Theta_i - 1)] = 2d \tag{2}$$

where d is the thickness of glass substrate. Both the thickness, d, and bouncing angle, Θ_i, can be chosen to have the spatial separation (S) matching the separation of the detector array. Note that the bouncing angle, Θ_i, is designed to be larger than the critical angle (41.8°) of TIR within the optical glass substrate ($n = 1.5$).

The thickness of the single-mode waveguide can be found by employing the Helmholtz beam propagation method [8] and/or the effective index method [9], when the indices of polymer, substrate and operating wavelength are known.

Design of the waveguide holograms is accomplished by constructing a grating vector such that a specific phase matching condition can be met. For the waveguide holograms employed herein, most of the theory can be borrowed from the well-developed theories for holographic gratings [10], [11]. The multiplexed holograms employed here are formed by sequentially recording single gratings that have been designed operating at a specific Bragg diffraction angle and a specific wavelength.

To construct the two types of holograms employed, the recording and reconstruction conditions shown in Fig. 2(a) and (b) are required. Because of the strong blue absorption band of the holographic material (DCG), we choose $\lambda = 488$ nm as the recording wavelength provided by an Ar+ laser (INNOVA 200). The reconstruction wavelengths can be designed in a wide range from 500 to 1500 nm, which can be different from the recording wavelength. The discrepancy for recording and reconstruction phase-matching condition for the waveguide multiplexed holograms is indicated in Fig. 2(a), while that for TIR substrate hologram is illustrated in Fig. 2(b). In Fig. 2, K_1 and K_2 are the propagation vectors of the two recording beams. K_3 and K_4 are the propagation vectors of the guided transmission wave and diffracted wave, respectively. K_i is the holographic grating vector associated with the wavelength λ_i. K_5 is the propagation vector of the substrate transmission wave through TIR, and K_6 is propagation vector of the surface-normal diffracted wave. The refractive index ($n = 1.5$) of the holographic polymer is selected to match the index of glass substrate. Such index match is important to reduce the undesired interface reflection.

The techniques to construct the multiplexed waveguide holograms and TIR hologram array can be found in our previous publications [5], [11], [12]. The multiplexed waveguide holograms demultiplex each transmission wave of wavelength λ_i into a substrate guided mode with a diffraction angle ξ_i. The TIR substrate waveguide hologram converts a substrate mode

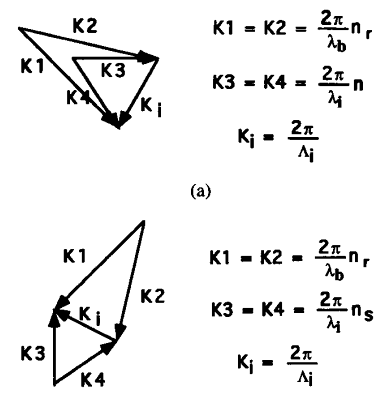

Fig. 2. The recording and reconstruction phase-matching diagrams for (a) multiplexed holograms and (b) TIR holograms. λ_b = recording wavelength, Λ_i = grating spacing, n = holographic polymer index.

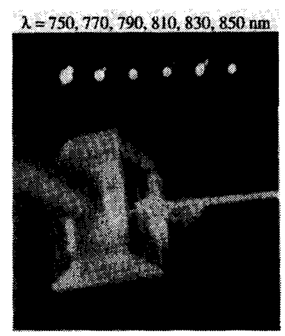

Fig. 3. Photograph of the six-channel WDDM with the optical in-plane to surface-normal conversion. The nearfield profiles of the six surface-normal demultiplexed beams are also shown. The separation between the two nearest beams is 2 mm.

with a bouncing angle, $\Theta_i = 90° - \xi_i$, into a surface-normal output beam. Note that each TIR hologram is not multiplexed in space (shown in Fig. 1), diffracting only one substrate mode at a given wavelength into a surface-normal beam.

Six waveguide holograms are superimposed at the end of a polymer-based planar waveguide as shown in Fig. 1. The prism-coupled planar guided wave having six different wavelengths are converted into an array of six substrate guided beams with six different bouncing angles. The bouncing angles are fabricated according to (1) for wavelengths $\lambda_i = 750$, 770, 790, 810, 830, and 850 nm, respectively. An optical glass, BK-7 with the index match to DCG photopolymer ($n = 1.5$), was employed as the substrate with thickness of 1 mm. Reconstruction of the surface-normal optical demultiplexer is shown in Fig. 3, where the near field pattern of the six surface-normal beams, projected surface-normally from the substrate surface, is also shown on the top of Fig. 3. The six input laser beams with $\lambda_i = 750$, 770, 790, 810, 830, and 850 nm were provided by a Titanium: Sapphire tunable laser (Coherent 870). Prism coupling technique is employed to couple the input laser beam into the planar waveguide. And the phase matching angle of the input is set for the TE_o mode of the planar waveguide.

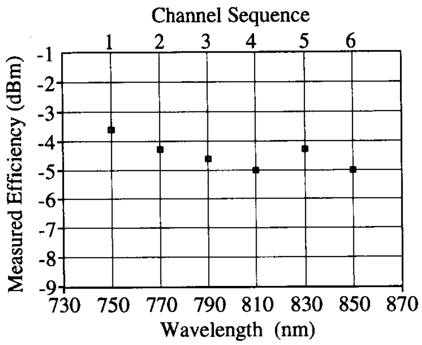

Fig. 4. Measured throughput efficiency of the six surface-normal demultiplexed beams with 3.5 mW input at each given wavelength.

The measured throughput efficiency ($10\ \log_{10}[P_{\rm out}/P_{\rm in}]$) for the six surface-normal beams is shown in Fig. 4. Variations among the six channels is within 1.5 dB. The measured coupling efficiency of the six TIR holograms are all above 50%. The coupling efficiency could be improved by using thicker holographic emulsion. The diffraction efficiencies of the multiplexed waveguide holograms were in the range of 18–25%. Precise control of the hologram recording process are important for uniform diffraction efficiencies.

In summary, we have investigated the first six-channel WDDM with optical in-plane to surface-normal conversion for effective coupling and reliable packaging. Two types of waveguide holograms were employed on the same surface of substrate where the planar waveguide is fabricated. The non-uniformity of the throughput efficiency among the demultiplexed surface-normal beams is determined to be within 1.5 dB. This result represents an effort to eliminate the two dimensional nature of conventional planar lightwave circuits. Such a surface-normal WDDM provides an effective optical face-to-face coupling and packaging for a photodetector array. Based on this novel optical in-plane to surface-normal conversion, advanced technologies including vertical cavity surface emitting laser [13], flip-chip bounding, thin film lift-off devices [14] and the optical fiber v-groove bounding technique [15], [16] can be directly employed to fabricate cost-effective, compact optoelectronic integrated circuits for advanced optical fiber networks employing WDM.

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