

Substrate-mode holographic polarization-division multi/demultiplexer for optical communications

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Based on the diffractive properties of a transmission-type phase volume hologram, a new type of polarization-division multi/demultiplexer for optical communications is presented.

In optical fiber communications, multiplexing schemes such as wavelength-division multi/demultiplexing¹ and polarization-division multi/demultiplexing^{2,3} have been presented for large transmission capacities. A typical polarization-division multi/demultiplexer using a conventional polarization beam splitter is not easy to integrate into the fiber system. To solve this problem, we present a new type of polarization-division multi/demultiplexer using a substrate-mode hologram. In this device we use the polarization-selective property of holographic elements, and these types of polarization-selective elements have been investigated and fabricated.⁴⁻⁶

The architecture of this new substrate-mode holographic polarization-division demultiplexer is depicted in Fig. 1. It consists of an input coupling grating G_1 , an output coupling grating G_2 , a substrate, and graded-index (GRIN) lenses. The input signal wave is collimated by the GRIN lens GR_1 and then is normally incident upon the first grating G_1 at A. Either s - or p -polarization fields can be diffracted completely by G_1 into the substrate, and the other one is forward transmitted through the substrate and coupled normally into the GRIN lens GR_2 . The diffraction angle is designed so that it is larger than the critical angle in the substrate; therefore the diffracted wave is totally reflected at B toward G_2 at C. This wave is again totally reflected at C, and the reflected wave from C satisfies the Bragg condition of

G_2 . The propagation direction of the reflected wave is parallel to that of the wave diffracted by G_1 . Thus if the structure of G_2 is the same as that of G_1 , then the diffracted wave of G_2 will be parallel to the input signal wave; that is, the output signal wave is normally guided into GR_3 . The detail of the wave propagation at E is shown in the upper right circle of Fig. 1. According to the functions operated by G_1 and G_2 , they are transmission-type phase volume gratings with the same structures. Only when the input and the output beams are interchanged does this demultiplexer become a multiplexer.

Here, dichromated gelatin (DCG) and short-wavelength recording for the long-wavelength reconstruction technique are introduced to design a polarization-division-multi/demultiplexer for the operating wavelength of 1.3 μm . Some important factors will be discussed in the following, and an optimum condition is derived:

(i) *Diffraction Efficiency.* If the Bragg angle of a transmission-type phase volume grating is set to be 0° (i.e., the normal is incident upon the grating), then the diffraction efficiencies for s and p polarizations are given as⁷

$$\eta_s = \sin^2 \left[\frac{\pi n_1 d}{\lambda_r} \frac{1}{(\cos \theta_d)^{1/2}} \right] = \sin^2 \nu_s, \quad (1)$$

$$\begin{aligned} \eta_p &= \sin^2 \left[\frac{\pi n_1 d}{\lambda_r} \frac{1}{(\cos \theta_d)^{1/2}} \cos \theta_d \right] \\ &= \sin^2 (\nu_s \cos \theta_d) = \sin^2 \nu_p, \end{aligned} \quad (2)$$

respectively. θ_d is the diffraction angle in the phase volume grating, n_1 is the index modulation strength, d is the hologram emulsion thickness, and λ_r is the reconstruction wavelength. The necessary condition for our device is that either η_s or η_p is 1 and that

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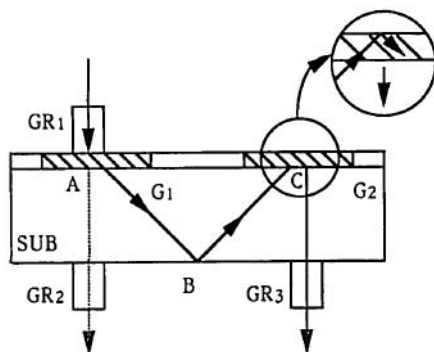


Fig. 1. Architecture of the substrate-mode holographic polarization-division demultiplexer: GR, graded-index lens; G, coupling grating; SUB, substrate.

the other one is 0. This will exist when

$$\nu_s = (m + 1)(\pi/2), \quad \nu_p = m(\pi/2), \quad (3)$$

where m is a positive integer.

(ii) *Index Modulation Strength.* In practice, n_1 depends on the exposure, and it is difficult to fabricate DCG with $n_1 > 0.08$. In general, our thickness d of hologram emulsion fabrication from DCG is $17 \mu\text{m}$. Introducing the conditions $n_1 < 0.08$ and $d = 17 \mu\text{m}$ into Eqs. (1)–(3), we get $n_1 = 0.054$ and $\theta_d = 60^\circ$. Considering fabrication variations in gelatin thickness and index-modulation strength, we can reach $\eta_s > 90\%$ and $\eta_p < 3\%$ for a grating, and a dual grating can make this device reach the extinction ratio of 900:1.^{5,6}

(iii) *Recording Geometry.* In the $\mathbf{K}$ -vector diagram shown in Fig. 2, K_{r1} and K_{r2} are the wave vectors of the reconstruction and the diffracted wave, respectively, at a wavelength λ_r , and K_{c1} and K_{c2} are wave vectors of the construction reference wave and the object wave, respectively, at a wavelength λ_c . This device will be fabricated under the conditions $\theta_{r1} = 0^\circ$ and $\theta_{r2} = \theta_d = 60^\circ$, and θ_{c1} and θ_{c2} can be calculated from the geometrical relations in Fig. 2.

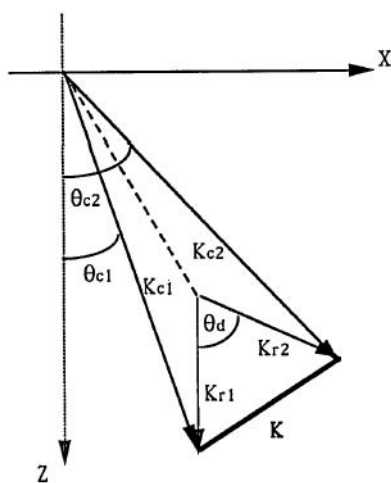
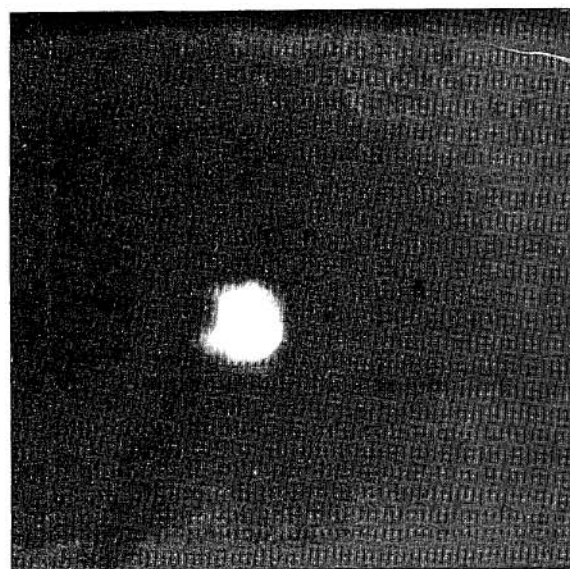


Fig. 2. $\mathbf{K}$ -vector diagram of shorter-wavelength construction for longer-wavelength reconstruction.

To demonstrate the feasibility of this device, we made a polarization-division demultiplexer. In our experiment, the gelatin reduced from Kodak 649F photoplates and the simplified processing technique presented by Georgekuty and Liu⁸ are used for preparing DCG recording material, and an argon-ion laser with wavelength 488 nm is used for exposure. The refractive indexes of emulsion and substrate are 1.54 and 1.517, respectively. From the geometrical relations in Fig. 2 it is easy to obtain $\theta_{c1} = 19.2^\circ$ and $\theta_{c2} = 40.8^\circ$ in the emulsion. Because the angle θ_{c2} is larger than the critical angle of the air-emulsion interface, a 45° – 90° – 45° prism with refractive index 1.517 is used for coupling during the exposure. The distance between G_1 and G_2 is $\sim 3.5 \text{ mm}$, and the thickness of the substrate is 1 mm. Polarization-



(a)



(b)

Fig. 3. Transmission images for (a) s -, (b) p -polarization input signals.

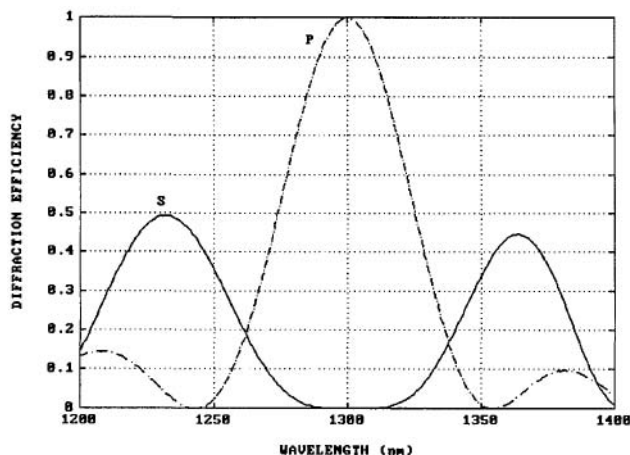


Fig. 4. Calculated efficiencies of the device versus the coupling wavelength for the center wavelength of 1.3 μm .

division demultiplexing experiments are performed with the setup shown in Fig. 1, in which GRIN lenses are omitted for convenience and an infrared CCD camera is used to detect the output signal wave. Figures 3(a) and 3(b) show the transmission images when the input signal waves are *s*- and *p* polarizations, respectively. The hologram insertion loss for the polarizations is lower than 0.3 dB, and the coupling loss from the experimental polarization-preserving fiber to the GRIN lenses is 0.15 dB. The coupling loss from the GRIN lens to the hologram is less than 0.1 dB from normal index-matching coupling. The cross talk of this device for *s*- and *p*-polarization output channels is -14 and -15.1 dB, respectively. The calculated bandwidth characteristics of diffraction efficiencies for *s*- and *p*-polarization fields are shown in Fig. 4. It shows $\sim 100\text{-nm}$ bandwidth, so it is practical to be integrated with wavelength-division multi-demultiplexers to enhance transmission capaci-

ties. Finally, the polarization-division multi/demultiplexer for the operating wavelength of 1.55 μm can be fabricated similarly.

A new type of polarization-division multi/demultiplexer for optical communications using substrate-mode holograms and polarization properties of volume phase grating is presented. The feasibility of this device is demonstrated; it can be made with low insertion loss, low cross talk, normal input/output coupling, and compact monolithic structure, and it can be fabricated by a visible exposure technique.

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