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A four channel polarization and wavelength separation element using substrate-mode stacked holograms

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A four channel polarization and wavelength separation element using substrate-mode stacked holograms is proposed based on the diffraction efficiency characteristics for polarization and the wavelength selectivity of a transmission-type phase volume grating. We fabricated a sample device and measured its polarization selectivity, output spectrum, and insertion loss of each channel to demonstrate its performance. © *1996 American Institute of Physics.* [S0003-6951(96)04525-1]

Wavelength division multiplexing (WDM)[1] and polarization switching devices are considered to be two of the key elements for signal multiplexing and switching in optical communications or optical interconnects to enhance the transmission capacities and signal switching ability. Various types of wavelength division multi/demultiplexer[2–4] and an optical switching device that consists of holographic polarization beam splitters and a ferroelectric liquid crystal for polarization switching[5,6] have been proposed. Although some holographic polarization selectors proposed[7,8] have the properties of polarization and wavelength selectivity, they didn't mention the combination performance. In this letter, we propose a four channel polarization and wavelength separation element using substrate-mode stacked holograms. It has some merits, such as normal input/output coupling, high polarization and wavelength selectivity, and compact, lightweight structure. It is also easy to be combined with a ferroelectric liquid crystal or a dichroic liquid crystal switch to form an active polarization and wavelength selector.

The structure of this four channel polarization and wavelength separation element using substrate-mode stacked holograms is shown in Fig. 1(a). The system consists of eight holograms. The first four, labeled G'_{ij}, are placed in a stack illuminated by the incident beam. The other four, labeled G_{ij}, are distributed on a sheet of glass which conducts the separated beams by total internal reflections. The first index of the subscript, i ($i=1,2$), refers to the wavelength, and the second index of the subscript, j ($j=x,y$), refers to the polarization state of the dominated diffracted light. The gratings G'_{ij} are stacked together to form a stacked grating G_s, as shown in Fig. 1(b). Although G_{ix}, G_{iy}, G'_{ix}, and G'_{iy} have the same structures, the grating planes of G'_{ix}, and G_{ix} are parallel to the x axis, and those of G_{iy} and G'_{iy} are parallel to the y axis. Hence the s and p polarizations of input beams for gratings G_{ix} and G'_{ix} are along x and y axis, and for G_{iy} and G'_{iy} gratings, the s and p polarizations are along y and x axes, respectively.

According to Kogelnik's coupled-wave theory,[9] if the Bragg angle of a transmission-type phase volume grating is set to be 0° (i.e., normal incident upon the grating), the diffraction efficiencies for s and p polarizations are given as

$$\eta_s=\sin^2\left[\frac{\pi n_1 d}{\lambda_r}\frac{1}{\sqrt{\cos\ \theta_d}}\right]=\sin^2\ \nu_s \tag{1}$$

and

$$\eta_p=\sin^2(\nu_s\ \cos\ \theta_d)=\sin^2\ \nu_p, \tag{2}$$

respectively. Where 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. From Eqs. (1) and (2), it is very easy to obtain the conditions that either η_s or η_p is 1 and the other is 0.

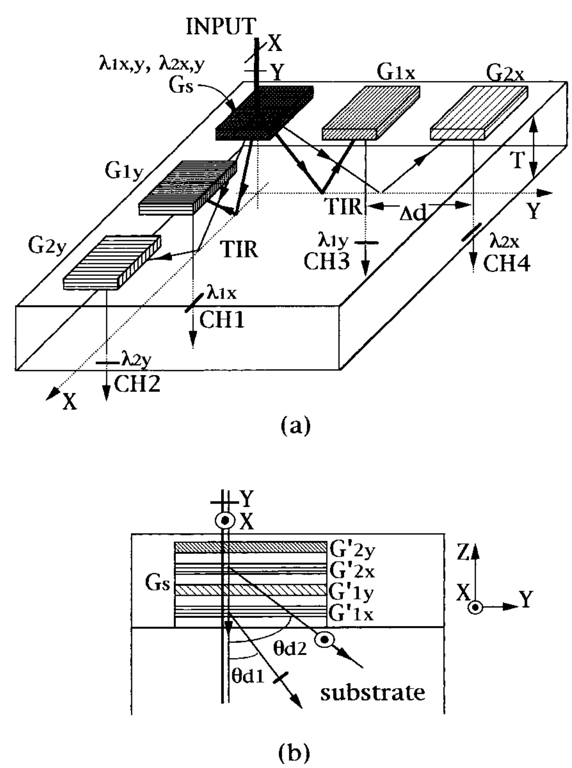

FIG. 1. The structure of (a) this four channel polarization and wavelength separation element, and (b) the stacked holograms.

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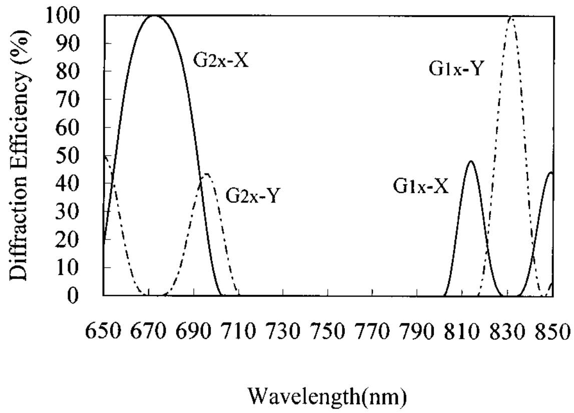

FIG. 2. The calculated wavelength sensitivity for transmission-type phase volume gratings of G_{1x} and G_{2x}. G_{1x}-$X(Y)$: the diffraction efficiency of *X(Y)* polarization for G_{1x}, G_{2x}-$X(Y)$: the diffraction efficiency of *X(Y)* polarization for G_{2x}.

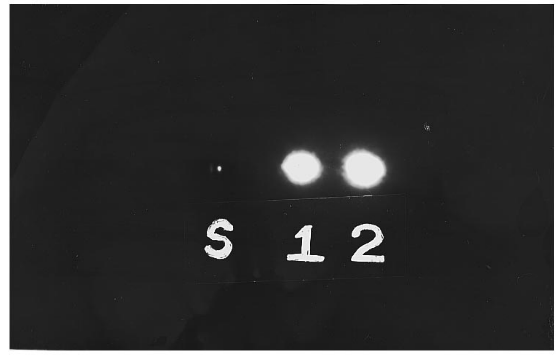

FIG. 3. The photography of the outputs for λ_{1x} (label 1) and λ_{2y} (label 2), respectively. *S*: the incident position.

These will occur (i) as $\theta_d=60°$ and $n_1=\lambda_r/(\sqrt{2}d)$, then $\eta_s=0$ and $\eta_e=100\%$, and (ii) as $\theta_d=48.2°$ and $n_1=(\sqrt{3}\lambda_r)/(\sqrt{2}d)$, then $\eta_s=100\%$ and $\eta_p=0$.

As shown in Fig. 1(a), the input beams with polarizations being parallel to *x* and *y* axis of wavelength λ_1 and λ_2 incident normally on the stacked gratings G_s. The optical signal of wavelength λ_i is diffracted by G'_{ij} into the substrate under Bragg conditions and this diffracted light propagates within the substrate with m_i times of total internal reflection before arriving at G_{ij}. The light is again totally reflected in G_{ij}, and normal coupled out through the substrate on the Bragg conditions of G_{ij}. Since the *s*- and *p*-polarization diffraction efficiencies of G_{ij} and G'_{ij} with diffraction angles satisfy the above conditions (i) and (ii), the light paths are as shown in Fig. 1 and it is clear that this device separates light with the different wavelengths and different polarization states to four channels. Here λ_{ix} and λ_{iy}, represent the light components with respect to wavelength λ_i, and their polarizations are parallel to the *x* and *y* axes, respectively. The channel separation Δd between the two wavelengths is about $2T(m_2 \tan\theta_2 - m_1 \tan\theta_1)$ when we use the substrate of thickness *T* and the different polarizations were separated in the different directions. Assume the diffraction efficiency of G_{ij} for wavelength λ_{ij} at near Bragg condition incident is $\eta_{ij}(\lambda_{ij})$. We could estimate approximately the insertion loss as $-10\log[\eta_{ix}^2(\lambda_{ix})\cdot\Pi_{(c,j)\neq(i,x)}[1-\eta_{cj}(\lambda_{ix})]$ dB.

In our experiments, the conditions of $\lambda_1=831$ nm, $\theta_d=48.2°$, $\lambda_2=672$ nm, $\theta_d=60°$, and $d=17$ μm for the gratings were chosen to show the feasibility of this device. The dichromate gelatin is exposed by a He–Cd laser with 441.6 nm for fabricating phase volume gratings. From the coupled-wave theory, the strengths of the modulated refractive index should be 0.034 and 0.048 for λ_1 and λ_2, respectively. These two index modulation strengths are easy to achieve in dichromate gelatin. In fiber optical communication applications for $\lambda_1=1300$ nm and $\lambda_2=1550$ nm, the similar calculation shows that higher index modulation strengths of 0.094 and 0.065 are required for the gratings with thickness of 17 μm. Figure 2 shows the wavelength sensitivity of the stacked gratings G_{ix} and G_{jy} for the above conditions. This simulation result is calculated by using the coupled-wave theory for *s* and *p* polarizations as wavelength from 650 to 850 nm. The experimental diffraction efficiencies of *s* and *p* polarization are 89%, and 0.7% for the grating G_{1x} and 0.5% and 85% for G_{2x}, and the extinction ratio for the diffraction beams are 127:1 and 1:170, respectively. Figure 3 shows the double exposure of the two output beam images for λ_{1x} (label 1) and λ_{2y} (label 2), respectively. The device dimension is about 5 cm×5 cm. The channel separation is about 10 mm and the beam diameters are about 8 mm for both wavelengths. The output spectrum of these two wavelengths was measured by Advantest TOS345 optical spectrum analyzer in Fig. 4. Similarly, we also obtained two output beam images for λ_{1y} and λ_{2x}, which are not shown here. The insertion losses measured with different input for channels 1, 2, 3, and 4 are 1.01, 1.45, 1.2, and 1.54 dB, respectively.

A four channel polarization and wavelength separation element using substrate-mode stacked holograms is presented in this letter. It is based on the diffraction efficiency characteristics of wavelength and polarization selectivity of a transmission-type phase volume grating. In order to investigate its feasibility, an element for operating wavelengths at 672 and 831 nm was fabricated, and its performance was demonstrated. It is compact, lightweight and has normal input and output coupling usage. This element could also work with dichroic liquid crystal or ferrioelectric liquid crystal to be a wavelength selector or a polarization switching device.

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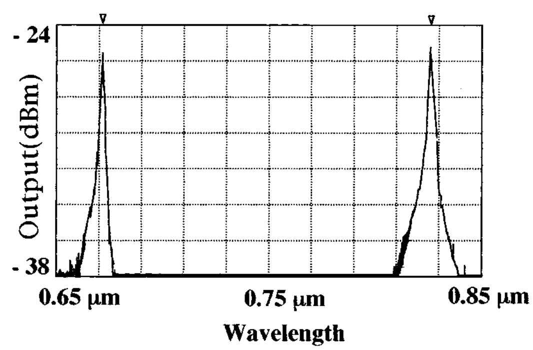

FIG. 4. The spectrum of the output channels for λ_{1x} and λ_{2y}.

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