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A wavelength and polarization selector made of holographic polarization beamsplitting cubes for optical communications

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We present a combined wavelength-polarization selector made of holographic polarization beamsplitting cubes in series. Each unit cube comprises a pair of prisms and a transmission-type phase volume hologram. The assembled selector, when examined with an intensity modulated beam of known polarization state, demonstrated our designated target. © *1997 American Institute of Physics.* [S0003-6951(97)03014-3]

A polarization-selective element is essential in optical information processing, magneto-optical pickup, and optical switching.[1–6] A conventional polarization-selective element is made of birefringence crystals or a pair of right-angle prisms sandwiched with a special multilayer dielectric film. Several holographic polarization-selective elements were proposed in recent years.[3–7] Kostuk *et al.* proposed a substrate-mode guiding holographic polarization-selective element using a transmission-type phase volume hologram with large diffraction angle.[6] The element requires an additional input coupling hologram which, in turn, needs the same diffraction efficiencies for different polarization states, making the element difficult to fabricate. The Kato *et al.*[3] and Huang[7] groups presented holographic polarization-selective element with a smaller diffraction angle which can be used in multichannel optical switching systems. We have also introduced yet another type of polarization-selective element made of substrate-mode stacked polarization-selective holograms that can be used as a four channel polarization and wavelength separation element.[8] In this letter, we further propose a design of using holographic polarization beamsplitting cubes in series for wavelength and polarization selection in optical communications.

The structure of a unit holographic polarization beamsplitting cube is shown in Fig. 1(a). It consists of a pair of right-angle prisms and a transmission-type phase volume hologram (H). The normal incident beam travels in the first prism without changing direction and strikes the sandwiched hologram at 45°. According to Kogelnik's coupled-wave theory,[9] the diffraction efficiencies of a transmission-type phase volume hologram for the *s*- and the *p*-polarization states near Bragg condition are

$$\eta = \frac{\sin^2(\sqrt{\nu^2 + \xi^2})}{(1 + \xi^2/\nu^2)}, \qquad (1)$$

where

$$\nu = \nu_g = \frac{\pi n_1 d}{\lambda \sqrt{|\cos\theta_{r1}\cos\theta_{r2}|}} \quad \text{for } s \text{ polarization}, \qquad (2a)$$

$$\nu = \nu_p = \nu_g \cos(\theta_{r1} - \theta_{r2}) \quad \text{for } p \text{ polarization} \qquad (2b)$$

and

$$\xi = \frac{-\Delta\lambda \mathbf{K}^2 d}{8\pi n \cos\theta_{r2}}, \qquad (3)$$

respectively, where ν is the coupling coefficient, ξ is the detuning factor, λ is the reconstruction wavelength, $\Delta\lambda$ is the wavelength shift with respect to the central wavelength λ, $\mathbf{K}$ is the grating vector, d is the grating thickness, n_1 is the amplitude of the index modulation, and θ_{r1} and θ_{r2} are, respectively, the reconstruction and the diffraction angles in the phase volume hologram. From Eq. (2), it is seen that there is no diffracted light of *p*-polarization state since ($\theta_{r1} - \theta_{r2}$) = ±π/2. Based on the last ±π/2 condition, if the grating vector $\mathbf{K}$ [Fig. 1(b)] recorded on the hologram is such that its Bragg angle is $\theta_{r1} = 45°$, then the direction of the diffracted beam S will be perpendicular to that of the reconstruction beam R in the emulsion as is shown in Fig. 1(b). Consequently, the *s*-polarization state is 90° diffracted since the *p*-polarization state passes through the hologram without changing direction.

In this letter, two types of holograms were purposely developed for the readily available 632.8 nm He–Ne laser line and 780 nm GaAs/GaAlAs diode laser line. These are called $H1$ and $H2$, respectively. The holograms were recorded on laboratory-made dichromated gelatin (DCG) using He–Cd laser 441.6 nm line and the technique of the longer wavelength reconstruction with the shorter wavelength recording. The final thickness of the fixed emulsion layer is 12 μm (α-step measurement), and its averaged refractive index (n) is 1.52. Their index modulation strengths for high polarization extinction ratio are chosen to be 0.0186 and 0.0229, respectively. These holograms were cemented between the hypotenuse faces of two right-angle $BK7$ prisms ($n = 1.517$) with Norland 65 UV curing optical cement ($n = 1.52$). The wavelength and polarization selective characteristics of $H1$ and $H2$ cubes were investigated with prepared polarization states of the two wavelengths (632.8 and 780 nm). The diffraction efficiency is affected by the Bragg detuning factor. And the results of the diffraction efficiency versus wavelength of these two holograms are shown in Fig.

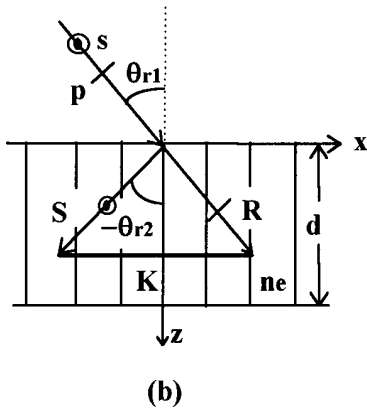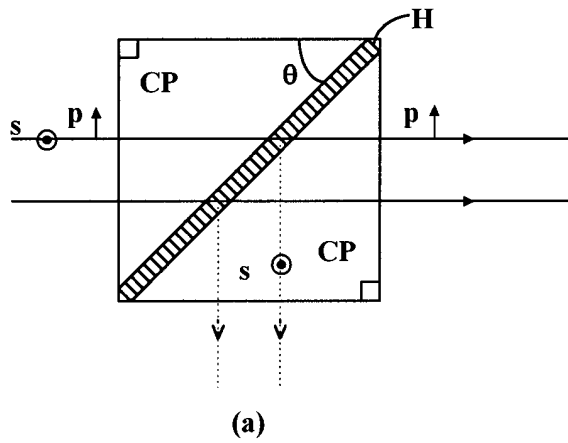[a)]Electronic mail: t7503@cc.nctu.edu.tw

(a)

(b)

FIG. 1. (a) The structure of a holographic polarization beamsplitting cube. CP stands for the coupling prism, s and p the s and the p-polarization states, and H the hologram. (b) Reconstruction geometry in the emulsion of a volume phase hologram. R and S represent the reconstruction and the diffraction beams, θ_{r1}, and θ_{r2} the reconstruction and diffraction angles, and **K** the grating vector.

2. The circles and dots represent the experimental data of the s and the p polarizations, respectively. The full width at half maximum (FWHM) of 632.8 and 780 nm peaks are, respectively, ~30 and ~40 nm. The continuous lines marked H1 and H2 are the theoretical diffraction efficiency curves for the s and the p polarization from Eqs. (1) and (2). The theoretical diffraction efficiency curves for the p polarization
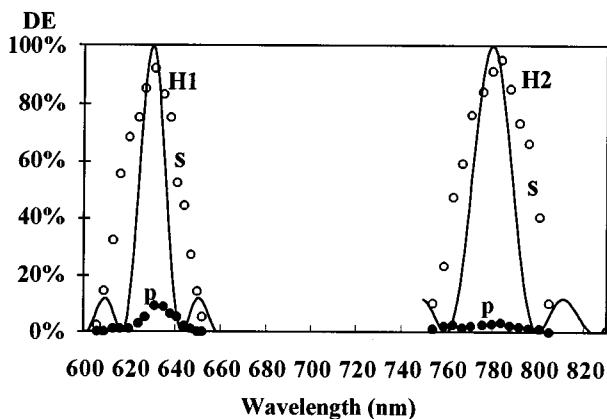

FIG. 2. Experimental diffraction efficiencies of H1 and H2 vs wavelength. S polarizations are shown in open circle and p polarizations in dots. The smooth curves show the theoretical predictions of Eqs. (1) and (2).
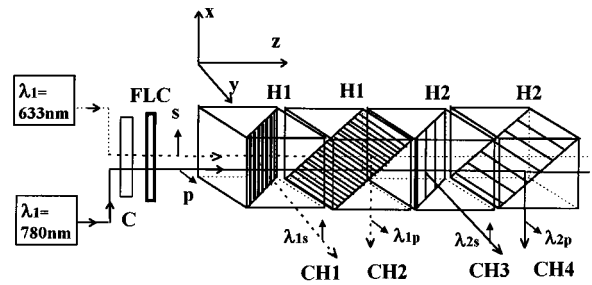

FIG. 3. The experimental setup for wavelength and polarization selectivities of the assembly using holographic polarization cubes in series. C stands for the chopper, FLC the ferroelectric liquid crystal, and H1 and H2 the holograms.

are nearly zero and hence are close to the ordinate and hardly seen in Fig. 2. These curves are qualitatively comparable to the experimental data. Therefore, these H1 and H2 holographic cubes can serve as a wavelength dependent polarization-selective element. Holographic polarization beamsplitting cubes for other wavelengths (such as those used in fiber communications) can be possibly made with the same techniques.

In order to demonstrate the overall performance of these holographic cubes as a wavelength and polarization selector, we assembled two H1 and two H2 holographic cubes in series. The structure is shown in Fig. 3. The hologram planes
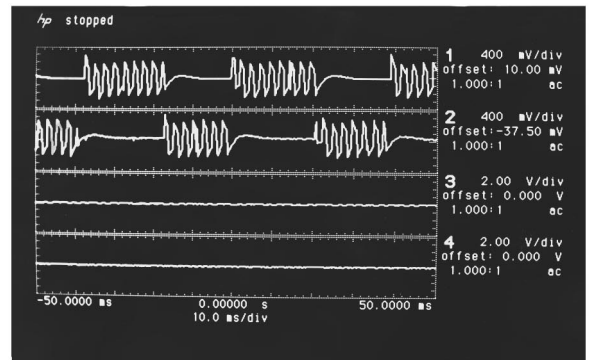
(a)
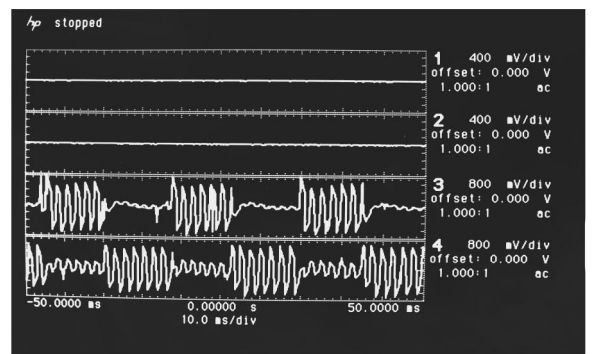
(b)

FIG. 4. (a) Oscilloscope readout for each channel of the assembly using 632.8 nm input beam. (b) The channel readout for the 780 nm input beam.

of incidence of the first two $H1$ cubes were arranged to be perpendicular to each other. The hologram planes of the following two $H2$ cubes were also perpendicular to each other. It demonstrated that different wavelength input beams were diffracted selectively with the specific polarization states by the individual channel in the assembly. In Fig. 3, the input laser signals were incident from the left to the assembly. A chopper (C) and a ferroelectric liquid crystal (FLC) were inserted between the laser and the assembly for the carrier signal intensity and polarization modulation. The outputs from each channel of the assembly were monitored by an oscilloscope. Figure 4(a) shows those for the 632.8 nm input beam. The carrier signals produced by the chopper action enveloped by the FLC in alternating phases only appeared in channels 1 and 2, consistent with the character of $H1$ cubes. There were no signal outputs in channels 3 and 4 as was expected. Figure 4(b) shows the signal outputs of the 780 nm input beam in channels 3 and 4, reflecting the proper functioning of $H2$ cubes. There were no signal outputs in channels 1 and 2.

In summary, it is clear that the assembly of our holographic polarization beamsplitting cubes in series is a practical wavelength-polarization selector that can be useful in optical communication.

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