Reflecting polarizing beam splitter

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We propose and experimentally demonstrate the use of metal-covered lamellar relief gratings as a polarizing beam splitter operating at a single wavelength near Littrow incidence. We report the characteristics of a grating produced by holography and reactive ion etching that was calculated for operation as beam splitter at $\lambda = 633$ nm (for a He–Ne laser).

Optical polarizing components are elements that modify the state of polarization of light. Classical examples of them are polarizing cubes such as Glan–Thomson prisms, wave plates, Nicol prisms, and Wollaston prisms. Generally they utilize the natural birefringence of such crystalline materials as calcite or quartz and are expensive. Grating structures have interesting polarization properties when their periods are much smaller than or have the same dimensions as the wavelength of light. In the first case one can use effective medium theories to preview the behavior of the structures.[1] In the second case, however, called resonant domain, the Maxwell equations must be solved for each particular case.[2] For volume gratings the coupled-wave theory furnishes a simple analytical solution of the diffraction problem,[3] whereas for surface relief gratings a numerical solution of the rigorous electromagnetic theory is required.[2,4]

Volume phase holograms were recently used to form polarizing beam splitters[5]; however, surface relief components are more interesting for mass production. Some recent papers studied the use of surface relief structures as transmission beam splitters.[6,7] At normal incidence the disadvantage of using these structures is that the light splits into at least three diffraction orders unless a more-complex asymmetric profile of the grating is used.[7] At Bragg incidence the grating behaves somewhat as a volume grating with lower efficiency or requires diffraction angles near 90 deg to optimize the polarization properties of the component.[6]

By analyzing the calculated diffraction efficiencies of perfectly conducting gratings in a Littrow mounting[2] one can see that the first diffracted order of a lamellar grating (square profile) has interesting properties of polarization. For certain grating parameters the greatest diffraction efficiency of the TE polarization can occur just at a null point of diffraction efficiency of the TM polarization. On the other hand, it is known that the reflection (0 diffracted order) of perfectly conducting lamellar gratings can be used to polarize light.[8,9] As the polarizing effect at the reflection is less dependent on the grating parameters and on the incidence angle, as theoretically calculated by Roumiguieres,[8] we can choose a particular grating and conditions to take advantage of both the 1st and the 0 diffraction orders. In this Letter we propose and experimentally demonstrate the use of lamellar gratings in the Littrow condition of incidence as polarizing beam splitters.

A schematic of the proposed operation for such a beam splitter is shown in Fig. 1. An unpolarized light beam (of wavelength λ) is incident in a lamellar metallized grating (of period Λ) at the Bragg angle θ_B, given by

$$\theta_B = \sin^{-1}(\lambda/2\Lambda). \tag{1}$$

The 1st diffracted order, which returns in the direction of the incident beam, should be linearly polarized in the TE direction (electric vector parallel to the grating lines), whereas the reflection (0 diffracted order) should be linearly polarized in the TM direction.

From Ref. 2, the theoretical diffraction spectrum of a perfectly conducting lamellar grating of aspect ratio (depth/period) = 0.35 and filling factor (linewidth/period) = 0.5 represents a maximum of 100% TE polarization (electric vector parallel to the grating lines), while the TM component vanishes. This effect occurs at the Littrow condition of incidence, when the reflected 1st diffracted order returns parallel to the incident beam (it corresponds to the incidence at the Bragg angle of the grating) and under the condition that λ/Λ (incident wavelength/grating period) = 0.74. To obtain maximum diffraction efficiency and avoid loss of energy in other diffracted orders one must choose the period of the structure (Λ) between $\lambda/2$ and $3\lambda/2$ so only two diffracted orders (-1 and 0) will be present for wavelength λ.

From these theoretical results and taking into account the theoretical results of Roumiguieres,[8] to produce a polarizing beam splitter for the He–Ne laser ($\lambda = 633$ nm) it is necessary to use a lamellar grating of period $\Lambda = 860$ nm, depth of 300 nm, and filling factor (linewidth/period) = 0.5. Using Eq. (1),

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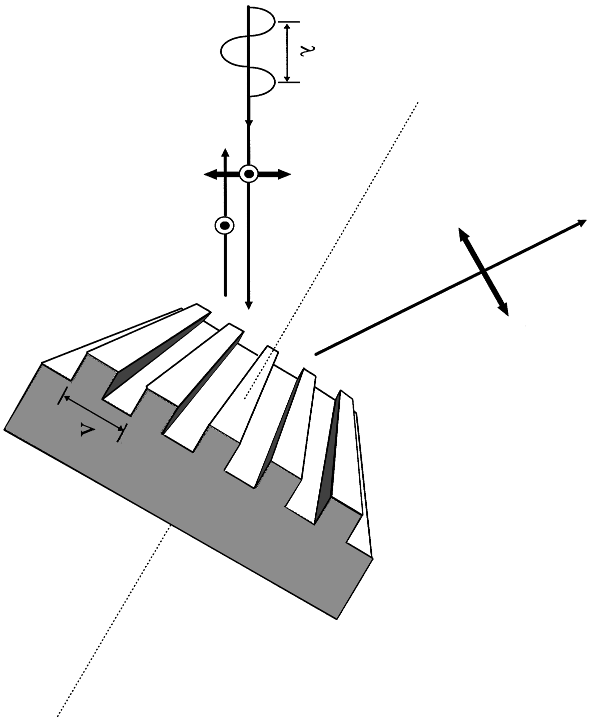

Fig. 1. Schematic of the proposed reflection polarizer beam splitter. The unpolarized light, incident in the metal–covered gating at the Bragg angle, splits into two directions: the −1 diffracted order and the reflected (0) order. The −1 diffracted order is linearly polarized at the TE direction (electric vector parallel to the grating lines), and the reflection (0 diffracted order) is linearly polarized at the TM direction.

we can see that these parameters result in a Bragg angle of ~22 deg that is perfectly realizable for practical applications. Small deviations from the Bragg angle do not significantly change the diffraction spectrum[2]; thus it is possible to separate the diffracted beam from the incident beam by using angles slightly different from Bragg.

We performed several trials, using quartz and Si substrates, to obtain these lamellar structures. Better results, however, were obtained with InP substrates; the recorded profiles matched the required lamellar form better. The sample that presented the better performance was prepared with a positive photoresist film of AZ 1518 (diluted 1:1 in AZ thinner) spin coated onto a previously cleaned InP substrate at 10,000 rpm. These conditions yield a photoresist film thickness of 100 nm. We exposed the film to an energy of 60 mJ/cm^2 in a holographic stabilized setup,[10] using an Ar laser at $\lambda = 458$ nm that produced an interference pattern of the determined period. The grating was developed in AZ 351 developer diluted 1:3 in distilled water until the substrate was reached. After development an O_2 plasma was used with the patterned InP sample to remove any remaining photoresist over the crystal's exposed areas. In the O_2 plasma conditions that we used, a resist layer of ~20 nm was removed. We then etched the sample in a reactive ion etching system, using 20% CH_4 in H_2, rf power 400 W, total gas flow rate 50 SCCM (cubic centimeters per minute at STP), and 40-mTorr pressure for 6 min to obtain the desired depth (300 nm). One could change the time in the O_2 plasma system to obtain different filling factors (linewidth/period of the lamellar grating). After the etching, the sample was coated with Al to increase the reflection and fulfill the theoretical conditions for conducting grating.

We measured the efficiency of the −1 diffracted order of the coated sample at the Littrow condition as a function of the incident wavelength for the two orthogonal polarizations, using an appropriate spectrometer that found the Bragg angle for each wavelength. This spectrum is shown in Fig. 2. Note that the maximum of the efficiency for the TE polarization matches very well the minimum for the TM, and both occur at $\sim\lambda = 630$ nm. Figure 3 shows a scanning electron microscope photograph of the cross section of the grating recorded in this sample. It presents a profile more trapezoidal than lamellar. The period and the depth measured for this sample were 850 and 300 nm, respectively.

We measured the intensities of the 1st and the 0 diffracted orders for each of the two orthogonal directions of polarization (TE and TM) for this grating, as in Fig. 1, using an unpolarized He–Ne laser ($\lambda = 633$ nm) and a simple polarizer placed in front of a linear detector. The measurements were performed with an incidence angle of ~2 deg from the Bragg angle to separate the −1 diffracted order from the incident beam. We normalized the results by dividing the measured intensities by the intensity of the same He–Ne beam reflected in a polished InP sample recovered with an Al film at the same conditions of the grating. The efficiency obtained for the TE polarization of the 1st diffracted order was 59%, whereas for the TM polarization was 0.5%. For the 0 diffracted order we obtained 85% for TM and 3% for TE.

As can be seen from these results, we have only 0.8% undesired polarization in the 1st diffracted order and 3.5% in the 0 order, demonstrating that this sample

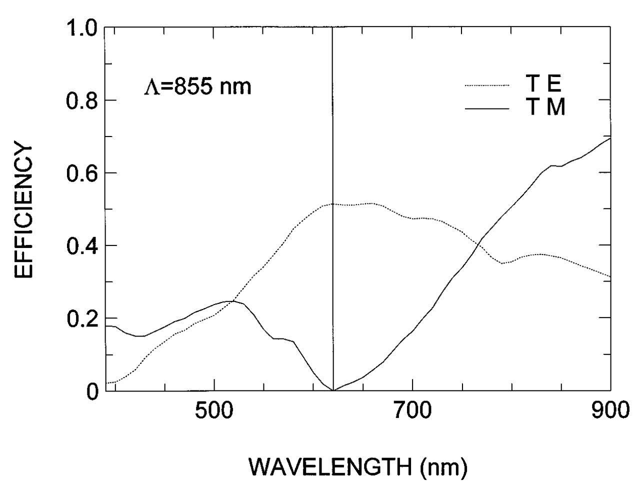

Fig. 2. Diffraction spectrum of the −1 diffracted order for the TE and TM polarization for incidence in the grating under the Littrow condition. The spectrum was obtained with a spectrometer that finds the Bragg angle for each incident wavelength.

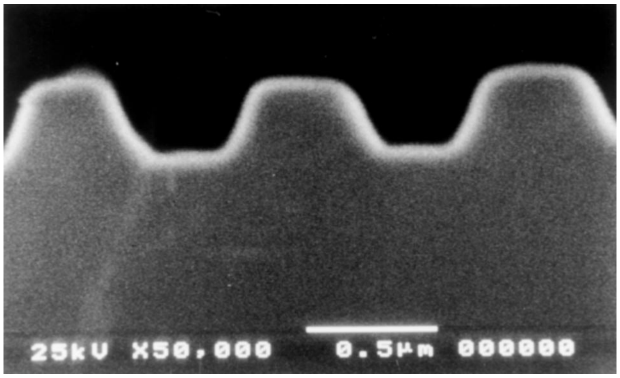

Fig. 3. Scanning electron microscope photograph of the cross section of the grating recorded in InP, showing the spectrum shown in Fig. 2.

performs well, as the diffraction spectrum of Fig. 2 confirms.

By examination of the grating shown in Fig. 3 we can see that the profile is not lamellar. Other samples performed in similar conditions but etched for different times in the O_2 plasma exhibited more lamellar profiles but with filling factors different from 0.5. These gratings, however, demonstrated worse performance as polarizing beam splitters. The determining parameter for this desired polarization behavior seems to be not the strict lamellar shape but the symmetry of the profile.

Although the profile of the grating must be controlled better to match the theoretical parameters and improve the final performance of the component, these results clearly demonstrate the feasibility of the proposed component. In practice, however, this component must be recorded in materials that are not so expensive as InP.

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