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Polarizing beam splitter based on a subwavelength asymmetric profile grating

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Abstract
In this paper, we propose a broadband compact polarizing beam splitter (PBS) constructed by only a single layer subwavelength asymmetric profile grating. The properties of the grating PBS are investigated by rigorous coupled-wave analysis. It is shown that, over a broadband spectrum of 1.53–1.62 µm, the grating PBS demonstrates high diffraction efficiencies (>97%) with extinction ratio (ER) greater than 16 dB and a comparatively wide angular bandwidth (about 8°). Effects of deviation from the design parameters on the performance of the grating PBS are also presented.

Keywords: diffraction and gratings, polarizing beam splitters (PBSs), leaky-mode resonance (LMR)
(Some figures in this article are in colour only in the electronic version)

1. Introduction
Polarizing beam splitters (PBSs) are basic functional elements in photonic integrated circuits [1] for separating two orthogonally polarized light beams, which play important roles in numerous optical information processing applications such as free-space optical switching networks [2], magneto-optic data storage [3], quantum computation [4], and so on. Conventional PBSs employing the effects of the natural birefringence of crystal, such as Wollaston prisms, Nicol prisms, and Glan–Thomson prisms, require large thicknesses for generating the two orthogonal polarizations and are not suitable for integrated optical circuits. Another method is based on the polarization selectivity of multilayer dielectric structures [5]. However, it provides good extinction ratios only in a narrow angular bandwidth for a limited wavelength range [6]. Recently, an alternative approach, based on the characteristics of photonic crystals, has attracted more and more attention [7]; but the structure of a photonic crystal is too complicated to be fabricated. On the other hand, with the development of nanofabrication technologies, much attention has been diverted to subwavelength gratings (SWGs). SWGs exhibit strong polarizing properties, which can be used as polarizing beam splitters. In the past few years, three kinds of grating PBSs have been proposed and demonstrated. The TE (electric field parallel to the grating grooves) and TM (magnetic field vector parallel to the grating grooves) orthogonally polarized waves are both reflected [8], both transmitted [9], and one reflected and the other transmitted [10]. However, these grating PBSs have the disadvantages of a tedious fabrication process or poor angular sensitivity, which cannot completely fulfil the requirements of modern integrated optical systems. The need for a PBS providing a good extinction ratio, high efficiency in a broad
wavelength range, a larger angular bandwidth and compact size for efficient packaging has brought many challenges, which are still to be overcome. In this paper, based on our previous works [11, 12], a subwavelength grating with an asymmetric profile is proposed as a broadband PBS. Based on leaky-mode resonance (LMR) effects [13], the proposed subwavelength asymmetric profile grating PBS (SAPGPS) may offer the combined merits of high diffraction efficiencies with good extinction ratios over a broad spectrum and comparatively wide angular bandwidth.

2. Structure design and results

A schematic of the proposed SAPGPS is shown in figure 1. The device is normally illuminated by a monochromatic plane wave with both TE and TM polarized components. The TE and TM polarized waves are then highly efficiently separated into the 0th reflected and transmitted orders by the SAPGPS. The asymmetric profile grating is defined by its period ($T$), transition points ($x_1$, $x_2$, $x_3$) and thickness ($t_x$). In this paper, we assume that the SAPGPS is transversely infinite and that the dielectric materials are lossless and dispersion free. Rigorous coupled-wave analysis (RCWA) [14] is adopted to design and optimize the structure. The optimized results are shown in the caption of figure 1.

Several figures of merit are of interest to quantify the performance of the grating PBS [15]. These are the diffraction efficiencies, wavelength bandwidth, polarization extinction ratio and angle of incidence. For the structure in figure 1, the 0th-order reflectivity of the TE wave $R_0^{TE}$ and the 0th-order transmissivity of the TM wave $T_0^{TM}$ should be high. And the extinction ratio (ER) is defined by [16]

$$ER = \min(ER_0^{TE}, ER_0^{TM})$$

in which

$$ER_0^{TE} = -10 \log \frac{R_0^{TM}}{R_0^{TE}}$$

$$ER_0^{TM} = -10 \log \frac{T_0^{TE}}{T_0^{TM}}$$

$ER_0^{TE}$ and $ER_0^{TM}$ are the extinction ratios of the 0th-order of TE and TM waves in unit of dB, respectively.

Figure 2(a) presents spectral properties of the proposed SAPGPS. It has a flat TE stopband from 1.53 to 1.62 µm with reflectance $R_0 > 99\%$, and the TM pass band is nearly flat in the wavelength range of interest with transmittance $T_0 > 97\%$. To clearly illustrate the high reflectance and large bandwidth of the device, we plot the transmittance on logarithmic scales. As can be seen in figure 2(b), there is a transmittance dip at 1.51 µm for the TE polarization, which corresponds to a leaky-mode resonance (LMR) [17]. This shows that the broad reflection band results from the TE leaky-mode resonance. Theoretical analysis shows a maximum (100%) in the zero-order reflectance spectra at resonance in dielectric gratings, and an efficient energy exchange between the reflected and transmitted waves [18]. Physically, LMR arises when the externally propagating diffracted fields couple to leaky waveguide modes by phase matching [19].

Furthermore, high reflectance and large bandwidths are associated with the characteristics of the large refractive index difference among materials and the properly configured top grating profile [20, 21]. The high-index-contrast grating layer can expand the resonances and eventually lead to the formation of broadband reflectance spectra. Moreover, the asymmetric profile of the top grating layer can work to remove the leaky-mode degeneracy of the grating PBS [13], which opens up the possibility of a flat reflection band for the TE polarization.

Compared with the deep-etched fused-silica grating PBS [16], the proposed SAPGPS is highly efficient (>97%) in a bandwidth of 1.53–1.62 µm for both TE and TM polarized waves.
Figure 3. Extinction ratio (ER) of the PBS grating as a function of incident wavelength.

Figure 4. Angular spectrum of the PBS grating at a wavelength of 1.57 µm.

The extinction ratio as a function of wavelength is demonstrated in figure 3. The 0th-order extinction ratios ER\textsubscript{TE} and ER\textsubscript{TM} can be larger than 16 and 20 dB over 1.53–1.62 µm, respectively. Numerical results show that in the wavelength range ER\textsubscript{TM} is larger than ER\textsubscript{TE}, resulting from the low transmittance of the TE wave (see in figure 2(b)), and at resonance, ER\textsubscript{TM} is as high as 37 dB. Figure 3 shows that the proposed grating PBS can work well over the bandwidth 1.53–1.62 µm, and that the TM wave works better than the TE wave.

We also investigated the angular spectrum of the grating PBS. As shown in figure 4, TE and TM polarized waves can achieve high diffraction efficiencies (>95%) in the range of −4°–4°. The angular bandwidth of the zero diffracted order is comparatively wide, which makes the alignment problems encountered in implementing compact micro-optic systems quite moderate.

The finite-difference time-domain method (FDTD), a powerful and accurate method for finite size structure, is adopted to verify this device. The device is normally illuminated by a plane wave with both TE and TM polarized modes at 1.57 µm. Figure 5 shows the simulation results obtained by the FDTD method. As can be seen from the figure, TE and TM polarized waves can be efficiently reflected and transmitted by the grating, respectively.

3. Parameter analysis

In this section, to illustrate the effects of deviation from the design parameters on the performance of the device, we have investigated the response of the proposed structure under variation in period, thickness, and profile modulation.

Figure 6 presents the effects of variation in the grating period \(T\) and thickness \(t_g\). As shown in figure 6(a), with the grating period \(T\) increasing, the reflection band shifts to a longer wavelength, which results from the resonance locations set by the grating period [17]. Also, as can be seen in figure 6(b), changes in thicknesses \(t_g\), say 40 nm, modify the reflection slightly in the wavelength range of interest (1.53–1.62 µm), which is useful in the fabrication of SAPGPBSs.

In addition, we have examined the effects of possible fabrication errors in modulation profile. As shown in figures 7(a) and (b), changes in modulation profile parameters can degrade the performance of the SAPGPBS. Since, in
addition to modulation strength, the state of the LMRs is controllable through the modulation profile [22], the variations of profile modulation can destroy the nondegeneracy of the leaky-mode resonances and the superposition of resonance locations, resulting in a performance deterioration of the SAPGPBS.

4. Conclusion

In summary, we have proposed a SAPGPBS that demonstrates high diffraction efficiencies (>97%) over a broad spectrum of 1.53–1.62 µm with extinction ratios larger than 16 dB and comparatively wide angular bandwidths (about 8°). The combined outstanding merits result from the high-index contrast and asymmetric profile modulation of the grating. Effects of deviations from the design parameters on the diffractive spectra are also demonstrated. Variation in the grating period $T$ or the thickness $t_g$ of 40 nm modifies the diffractive efficiency slightly, but the SAPGPBS shows considerable sensitivity to changes in the modulation profile, which should be taken into account in fabrication of the device. The presented PBS requires only a single poly-silicon subwavelength layer to construct, which makes it easily integrated with other elements at a wide range of wavelengths [23]. The grating PBSs can be potentially used in routing or switching for computer communications or telecommunications.

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