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Compact polarizers with single layer high-index contrast gratings

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HIGHLIGHTS

- A single-layer broadband polarizer was designed for the telecommunication wavelength band.
- High polarization efficiency, high extinction ratio with a broad wavelength range were obtained.
- The extinction ratio of transmission for the central wavelength was 114 dB.

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ABSTRACT

A single-layer broadband polarizer has been designed for operating in the telecommunication wavelength band. The rigorous coupled-wave analysis (RCWA) is applied to study the optical spectrum for the optimized structure. High polarization efficiency, high extinction ratio with a broad wavelength range (1.45–1.75 μm) are obtained. Both of the transmission efficiencies of TM-polarization and reflection efficiencies of TE-polarization are over 95%. The extinction ratio of transmission is over 30 dB in the 1.45–1.75 μm wavelength range, and the value is 114 dB for the central wavelength. The designed polarizer may lead to potential application in optical communication and infrared imaging polarimetry.

1. Introduction

Wire-grid polarizer is an important optical element, which has been studied for several decades due to its simple structure, compactness, and integrated capability with other devices [1–3]. It is widely used in many fields such as optical communication [2], liquid crystal displays [4,5] and imaging systems [6]. Subwavelength metal gratings (SWMGs) and dielectric multilayer stacks (DMSs) are the most commonly used polarizer in practical applications [7–17].

It has been well known that the MGs with period much smaller than the wavelength of incident light, will transmit the TM polarization (polarized light that has an electric field vector perpendicular to the grating slits), but reflect and absorb the TE polarization. Such SWMGs support the lowest TM mode, but cut off fundamental (guided) TE mode. Based on the strong form birefringence of SWMGs, many important polarization-control devices are designed and fabricated [7–12]. But metal will not only increase the absorption of the incident light, but also arouses the influence of heat transfer. To overcome the absorption of metal material, DMS polarizes are proposed and fabricated with using the thin film technology [13–19]. However, DMS polarizers require many layers with precious control of layer thickness and refractive indices although they can provide wide bandwidth and large extinction ratio, more important drawback of these polarizer is that the element can only be used at oblique incident angle [14,18].

The considerable development over the last decade of new modeling tools and fabrication technologies has led to the possibility of investigating a new type of gratings with sub-wavelength periodicity called high-index contrast gratings (HCGs) [20–22]. By surrounding the high-index medium with low-index materials, HCGs have drawn a lot of attention due to their capability of providing versatile spectra properties, with a simple and compact structure [23–27]. The high refractive index contrast allows for very strong confinement of guided modes, and ultimately, for a very high degree of integration in silicon-based fabrication technology that is hardly achievable using traditional integrated optical material systems [28].

In this paper, we designed a novel subwavelength polarizer with all dielectric materials, which are nearly lossless materials. The polarizer profiles are optimized by use of RCWA. The transmission of TM polarization and reflection of TE polarization are both over 95%. The extinction ratio of transmission is over 30 dB in

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the considered wavelength range. It is interesting to note that the broadband reflectivity does not result from a resonance, as the period of the grating is subwavelength but not half-wavelength. The optimal refractive index value for grating ridge is 3.48 which is achievable with silicon material. The properties of high refractive index contrast and low optical absorbance make it very easy to be integration in other optical devices.

2. Polarizer design

The proposed structure has a large refractive index difference among materials, Fig. 1 shows the configuration of the HCG-based polarizer that consists of lines of high-low index material surrounded by two low index layers. A monochromatic plane wave is incident from the air with an incident angle θ. The TE polarization wave will be strongly reflected while TM polarization wave will propagate through the grating. The structural parameters depicted in Fig. 1 determine the transmission and reflection properties of the grating. These parameters are grating thickness d_g, refractive index of the material for the grating ridge, grating periodicity Λ, duty cycle f, i.e. the fraction of high refractive index material in one grating period, low-refractive index material thickness d_l, and the refractive index n_l. n_c is the refractive index of the top cladding layer, which is fixed as $n_c = 1$ in this paper.

The relationship between the grating period and the incident wavelength is the key element of deciding the performance of polarizer [6,7]. When the grating period is much larger than the incident light wavelength ($\Lambda \gg \lambda$), the waves travel in straight lines with no bending around the edges of objects. That is realm of geometric optics. When the grating period is much smaller than the incident light wavelength ($\Lambda \ll \lambda$), the grating diffraction efficiency is relatively stable, and exist only the zero-order diffraction propagation wave, the rest orders are not carry energy. When the grating period is close to the incident wavelength ($\Lambda \approx \lambda$), it is called resonance domain.

From the grating's equation, assuming normal incidence, it is observed that a sufficient and necessary condition for the diffracted mode to exist is given by

$$\left| m\frac{\lambda}{\Lambda} \right| < 1 \tag{1}$$

where m is the diffraction order, if m is equal to 1, means only zero-order diffraction propagation wave exists.

In HCGs, reflection and transmission are not caused by diffraction as the only diffraction order found in the transmitted or reflected beam is the 0th. In fact, from Eq. (1), the ratio λ/Λ is bigger than one for sub-wavelength grating periodicity. In these structures, reflection and transmission are the result of coupling of the radiative optical mode to the photonic bandgap (PBG) modes of the photonic crystal structure constituted by the HCG [20,22]. High order diffracted modes are diffracted at grazing angle. These modes can couple to PBG modes of the structure if the parallel components of the wave vectors coincide. Therefore, the waveguide mode is a lossy mode, because it can couple to a radiated mode. This conditions on the wave vector may be fulfilled in the region above the light line of the dispersion characteristic of the HCG structure.

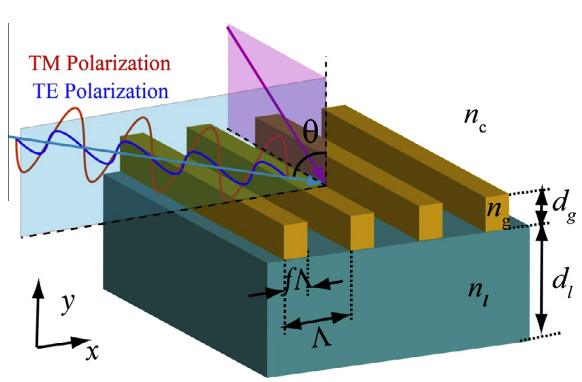

Fig. 1. Schematic view of the polarizer based on HCG.

3. Simulation results and analysis

Fig. 2a and b illustrate the diffraction efficiency of the polarizer as a function of fill factor (f) and incident wavelength when $\Lambda = 1$ μm for TE and TM polarizations, respectively. The calculations for these spectra are done using rigorous coupled-wave analysis (RCWA) [29,30]. RCWA is well known rigorous methods for solving diffraction problems involving optical periodic structures. Using this technique, the field is expanded into space harmonics, reflected and transmitted fields and their corresponding diffraction efficiencies can be calculated. The parameters used in the simulation are: $n_g = 3.48$ (Poly-Si), $d_g = 250$ nm, $n_l = 1.5$ (SiO_2) and $d_l = 200$ nm. In general, the variations of the fill factor play an important role on the reflection of TE polarization light and the transmission of TM polarization in the corresponding wavelength range. The diffract efficiency of the polarizer can still remain very high values (above 90%) even the fill ratio is changed from 0.1 to 0.25 for TM polarization, and the transmission of TE polarization is very low in this range which can be seen from Fig. 2a. To realize the goal of the proposed polarizer with high transmittance for TM polarization and low transmittance for TE polarization in the 1550 nm wavelength band, $f = 0.27$ should be chosen which can be seen from Fig. 2.

The various design parameters play interesting roles on the final optical spectrum. The grating period determines the location of the center wavelength, and this effect is shown in Fig. 3. The band shifts to longer wavelengths proportionally to Λ, and for $\Lambda = 1.04$ μm, the polarizer shows the best performance. It can be seen that the transmission is kept above a very high value (>90%) over the whole wavelength band 1.45–1.75 μm even the period is increased from 0.5 μm to 1 μm for TM polarization. Besides, we can obtain much large period tolerance in the optical communication wavelength band, which provides a favorable advantage for the fabrication process. For the TE polarization, the transmission is still kept over a very low value ($R < 10\%$) when the period is increased from 0.9 μm to 1.1 μm.

Grating thickness (d_g) determines the intensity of modulation, or grating strength. However, this strength cannot increase indefinitely and there is an optimum point where the grating effect is strongest. Fig. 4 shows the effect of d_g, this map quantifies the characteristics relative to d_g which is especially useful for high-refractive-index contrast elements, the optimized performance occurs for $d_g = 0.24$ μm. As this parameter can be precisely controlled by epitaxial growth or plasma deposition techniques, the optimized design can be easily fabricated. From Fig. 4 it is observed that the transmission initially decreases by increasing d_g, then increases. This behavior is caused by the change of the resonant wavelength of the structure while changing the grating period.

The high index material used for the grating ridge is essential to obtain the high extinction ratio. This is shown in Fig. 5, which consists of contour plots of transmission as a function of wavelength and n_g. Keeping all the other parameters the same, the transmission for TM polarization light becomes low when $n_g > 3.5$.

Fig. 6a illustrates the calculated transmittance spectra for TE and TM polarizations with the optimal parameters. One can find that the polarizer shows $T > 95\%$ for TM and $T < 5\%$ for TE over a $\sim$0.25 μm