Manipulation of beat length and wavelength dependence of a polarization beam splitter using a subwavelength grating

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A polarization beam splitter assisted by a subwavelength grating (SWG) is proposed. The SWG enables nearly 20-fold beat length reduction for TE, which makes the high extinction ratio (ER) possible. On the other hand, the embedded SWG preferably affects the refractive index of the even mode in the coupling region and broadens the bandwidth of the splitter. As a result, the ER of 28.7 dB (24.8 dB) for TE (TM) is obtained, while the insertion loss is only 0.10 dB (0.11 dB) at the wavelength of 1550 nm. The ER is more than 10 dB in the wavelength range of 1450–1625 nm for TE and 1495–1610 nm for TM. © 2016 Optical Society of America

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The silicon-on-insulator (SOI) is a prevailing and compelling platform for photonic integrated circuits, which is CMOS compatible and could realize rather compact integrated devices due to its feature of high index contrast. Simultaneously, strong polarization dependence occurs, which raises new challenge for an on-chip communication system. One solution is to use polarization independent devices, and this requires that all blocks in the system are polarization insensitive, which is not easy in practice [1–3]. Another solution is to utilize a polarization diversity scheme [4], where polarization beam splitters (PBSs) and polarization rotators are crucial and essential components [5–8].

Over the years, many configurations of PBSs have been reported, including multimode interference couplers [9], Mach–Zehnder interferometers [10], and directional couplers (DCs) [11]. Among them, the DCs seem to be the most popular because of their simplicity of structural configuration. However, they usually suffer from a narrow bandwidth since a strict phase-matching condition for the cross-coupling should be satisfied. Bragg-grating-assisted PBSs which are based on contra-coupling could ease the fabrication requirement of the coupling length and have an extinction ratio (ER) higher than 30 dB, but the bandwidths fail to cover the whole C band since the Bragg bandwidth is limited [12,13]. Bent waveguides [14], hybrid plasmonic waveguides (HPWs) [15,16], and polarization-dependent critical guiding conditions [17] have been applied to fulfill a broadband PBS, but they either exhibit an ER less than 20 dB at most or raise a huge challenge to the current fabrication technology.

Subwavelength gratings (SWGs), constructed by the periodic interlayering of two types of materials, have pitches much smaller than the wavelength of light propagating through [18,19]. The structure can be considered as a homogenous medium, and the equivalent refractive index can be tailored by adjusting the duty cycle, which offers a new degree of freedom for the design of novel photonic devices. SWGs have been widely used in many applications, such as waveguide crossings [20], multimode interference couplers [21,22], fiber chip grating couplers [23,24], and polarization-independent directional couplers [25]. With SWGs, the birefringence and dispersion of the device can be manipulated more flexibly through the refractive index engineering method, which enables more possibilities for high-performance devices.

In this Letter, we show the use of a SWG structure to design a PBS with a high ER and a broad bandwidth. A SWG can manipulate the beat length effectively, especially for TE. As shown below, a nearly 20-fold length reduction for TE is demonstrated, which makes it possible to render the beat length of TE half that of TM without an additional fabrication step. Thereby, both of the two polarizations can be separated with a high ER. Additionally, in principle, the embedded SWG affects the refractive index of an even mode mainly and conduces to the bandwidth broadening. Benefited from this design, an ER higher than 10 dB is demonstrated over the wavelength range of 1450–1625 nm for TE and 1495–1610 nm for TM.

The proposed SWG PBS (Fig. 1) is based on the SOI platform with a top silicon thickness of 340 nm. It consists of two strip waveguides, namely A and B, which are covered by air as up cladding. The waveguide width W is set to 500 nm. The gap between them, G, is fixed as 230 nm. S-bends with a radius of 10 μm are implemented at the input and output port to separate the two waveguides. The forepart of the coupling
section of the PBS is embedded in a SWG, the period of which is \( \Lambda \). The high and low refractive index segments are the so-called ridge and groove, the length of which are \( a \) and \( \Lambda - a \), respectively. The upper limit of the period is determined by the Bragg condition. For the wavelength of \( \lambda_{\text{min}} = 1450 \text{ nm} \), \( \Lambda \) should be less than \( \lambda_{\text{min}}/(2n_{\text{eff}}) \approx 269 \text{ nm} \) with an approximate value \( n_{\text{eff}} \approx 2.7 \) assumed. Here, we choose \( \Lambda = 230 \text{ nm} \) as the starting point. The duty cycle, \( f = a/(\Lambda - a) \), has to be kept between 0.25 and 0.75, since the value beyond this interval is hard to fabricate.

The number of the SWG period is \( N \). Thereby, the corresponding length of the SWG region is \( L_{\text{SWG}} = \Lambda \cdot N \). The extent of the SWG on both sides of the coupler waveguides is \( t \), which should be large enough to make the modes see a symmetric refractive index distribution on both sides. Here, \( t \) is set to 300 nm. At the transition between the strip waveguide region and the SWG region, \( t \) gradually changes to \( t' \) to form a taper, which enables light transfer from the SWG mode into the strip waveguide mode efficiently, and vice versa. The length of the taper \( L_t \) is chosen to be the length of nine periods, and \( t' \) is set to 100 nm to ease the fabrication process. Between the SWG and the output s-bend, there is still a segment of strip waveguide (\( L_s \)) to add a freedom to tune the beat length.

The operation of a conventional directional coupler is expounded as follows: one arm of the device is launched, and both the even and odd supermodes are excited. The beat length of these two modes can be calculated by Eq. (1) [26]:

\[
L_x = \frac{\lambda}{2(n_{\text{even}} - n_{\text{odd}})}.
\]

where \( n_{\text{even}} \) and \( n_{\text{odd}} \) are the effective indices of the even and odd modes, respectively. If \( n_{\text{even}} - n_{\text{odd}} \) for TE is twice that of TM, the beat length of TE is half that of TM exactly. Under this condition, the two polarizations can be separated into two output ports with very high ERs.

Besides, for conventional DC based PBSs, power splitting is perfectly obtained only at the design wavelength, because \( L_x \) varies with wavelength due to modal dispersion. This phenomenon can be explained as follows: as the wavelength decreases, both the even and odd modes are more confined in the waveguide, then \( n_{\text{even}} \) and \( n_{\text{odd}} \) tend to be the effective indices of the isolated waveguides. Thus, \( L_x \) increases.

The broadband principle of the proposed PBS can be illustrated as follows: as the wavelength decreases, on one hand, the mode confinement increases which inclines to equate the effective indices, increasing the beat length. On the other hand, the inserted SWG between the coupler waveguides mainly affects the refractive index of the even mode since both the SWG and the even mode are symmetric, while the odd mode has an odd symmetric field in the SWG region, and most of its index perturbation would cancel [26]. The dispersion diagram shows that the effective index of the Bloch mode in SWG grows as wavelength decreases [26]. Hence, the SWG mainly increases the refractive index of the even mode, and the beat length decreases. With these two opposing mechanisms, the wavelength dependence of \( L_x \) can be reduced. This is especially true for the TE mode, since the SWG structure is laterally patterned and affects TE mode majorly.

To optimize the structural parameters, a 3D finite-difference-time-domain (FDTD) method is employed. The refractive indices of silicon and silicon dioxide are \( n_{\text{Si}} = 3.48 \) and \( n_{\text{SiO}_2} = 1.45 \), respectively. The operation wavelength is chosen to be 1550 nm if not specified. To obtain accurate and stable results with an acceptable computation time, we use a nonuniform grid to mesh the structure. The minimum grid sizes are chosen as \( \Delta x = 20 \text{ nm}, \Delta y = 10 \text{ nm}, \) and \( \Delta z = 34 \text{ nm} \) in the \( x, y, \) and \( z \) directions, respectively. The SWG region is considered as a homogenous medium with an equivalent refractive index of \( n_k \). As shown in Fig. 2, when \( n_k \) increases, the beat lengths for both polarizations become shorter, but the slopes of the two curves differ a lot. Thus, this provides an approach to manipulate the beat length as well as the beat length difference between TE and TM by adjusting \( n_k \).

Rytov’s formula can be used to determine the grating parameters roughly [27]:

Fig. 2. Relationship between the beat lengths \( L_x \) and \( n_k \). For a certain value of \( f_x^{TE}(L_x^{TM}/2) \), the corresponding \( n_k \) for TE and TM are named \( n_k^{TM} \) and \( n_k^{TM} \), respectively.
where 

\[ n_{TE}^2 = n_1^2 f + n_2^2 (1 - f) \frac{1}{\Lambda} = \frac{1}{n_1^2} f + \frac{1}{n_2^2} (1 - f). \]  

In our case, \( n_1 \) and \( n_2 \) are the refractive indices of Si and SiO₂. For a grating structure with a duty cycle \( f \), if its equivalent refractive indices for TE and TM, \( n_{TE} \) and \( n_{TM} \), can approximately satisfy \( n_{TE}^2 \) and \( n_{TM}^2 \) in Eq. (2), respectively, the \( f \) for polarization splitting is roughly obtained. Then the length of the strip waveguide \( L_s \) can be adjusted to manipulate the propagation of the residual light. Next, a series of 3D FDTD simulations of PBSs with real grating structures is carried out to optimize the grating parameters. After these steps, the following parameters are chosen: \( \Lambda = 232 \text{ nm}, f = 0.517 \) (i.e., \( a = 120 \text{ nm} \)); \( L_{SWG} = 232 \times 63 \text{ nm} = 14.616 \mu\text{m} \); and \( L_a = 232 \times 9 \text{ nm} = 2.088 \mu\text{m} \), \( L_r = 2.208 \mu\text{m} \). Thus, the coupling region size is about \( 21 \times 1.83 \mu\text{m} \).

It should be noted that even though twice of the beat length for TE is used here, the coupling region length is \( 21 \mu\text{m} \), which is comparable with other PBS schemes that have much smaller gaps. This is because the SWG can reduce the beat length, which is especially true for TE. For a directional coupler which is of the same parameters, merely excluding the SWG structure, the beat length of the TE and the TM are 193.5 and 23.9 \( \mu\text{m} \), respectively. That is to say, nearly a 20-fold beat length reduction for TE is demonstrated. The SWG is a more effective way to manipulate the beat length when compared to methods in other PBSs [11].

Figure 3 shows the optical energy flux density of the TE and the TM mode input, and the polarization beam splitting function of the device is proved. When the fundamental TE mode is launched at the input port of waveguide A, it gradually couples into waveguide B, and then is coupled back into waveguide A again. On the other hand, when the fundamental TM mode is launched at the input port of waveguide A, it couples into waveguide B and propagates to the cross port directly.

The wavelength dependence of the ER and the insertion loss (IL) of the PBS is presented in Fig. 4(a). At 1550 nm, the IL and ER are 0.10 dB (0.11 dB) and 28.7 dB (24.8 dB) for TE (TM). For an ER of 10 dB, the working bandwidth exceeds 175 nm (1450–1625 nm) for TE and is about 115 nm (1495–1610 nm) for TM, much broader than that of PBSs which are also based on gratings [14,15]. The curve for TE is jittering at shorter wavelengths. This is because the refractive index of TE is higher than that of TM. For short wavelength, the Bragg condition is more likely to approach for TE, and some resonances would occur. More simulations have been done to verify this explanation: for the TE mode, the back reflection rapidly grows up to 32.4% at the wavelength of 1410 nm, while it is only 0.5% at 1550 nm.

To demonstrate the enhancement of the wavelength insensitivity brought by the SWG, a conventional DC has also been simulated, which is of the same parameters, merely excluding the SWG structure. Figure 4(b) presents the normalized variation of \( L_x \) (i.e., \( \Delta L_x / L_x \)) as a function of the wavelength. When the wavelength changes from 1500 to 1600 nm, \( \Delta L_x / L_x \) for the conventional DC varies from 26.0% to –20.2% for TE and from 23.1% to –18.2% for TM. However, for the SWG DC, \( \Delta L_x / L_x \) varies from 2.7% to –5.8% for TE and from 18.5% to –14.0% for TM in this wavelength range. The insertion of the SWG reduces the wavelength sensitivity and extends the working bandwidth, especially for TE, which confirms the theoretical prediction.

For the device fabrication, only one-step lithography and etching are needed, which can be readily realized by standard fabrication foundries. Since a DC is usually sensitive to dimension deviations, the fabrication tolerance of the structural parameters of the SWG PBS is analyzed. The IL and ER results as a function of the waveguide width variation \( \Delta W \) (i.e., \( W = W + \Delta W \), \( t = t + \Delta t/2 \), \( G = G - \Delta W \)) are shown in Fig. 5(a). The PBS still maintains an IL lower than 0.80 dB (0.33 dB) for TE (TM) as well as a good ER.
(>10 dB) with the fabrication error of (−20, 30) nm [(−30, 30) nm]. Besides the variation of width, the change of the grating parameters is also important to investigate. The relationship between the transmission and the ridge $a$ is shown in Fig. 5(b). If ER > 10 dB is required, the variation of $a$ should be controlled within the range of (−10, 10) nm for TE and (−20, 20) nm for TM. ILs stay less than 1.60 dB for TE and 0.17 dB for TM for a within (100, 140) nm. We can see that the ER deteriorates rapidly for $a$ deviates from its optimum value, since $a$ affects the duty cycle and, hence, the refractive index greatly.

Figure 6(a) shows the ER and IL as functions of the grating period $\Lambda$ when $L_{SWG}$ stays as a constant of 14.616 $\mu$m. If $\Lambda$ varies in a range of (−20, 20) nm, the ER can stay higher than 10.0 dB (20.6 dB) for TE (TM). The corresponding ILs stay less than 0.86 dB and 0.14 dB for TE and TM, respectively.

The relationship between ER (IL) and the period number $N$ (i.e., the SWG region length) is also studied. From Fig. 6(b), we can see that when $57 < N < 69$, the ER is higher than 10.0 dB (16.6 dB) for TE (TM), while the IL remains lower than 0.93 dB (0.19 dB) for TE (TM). The ER for TE is more susceptible to the variation of the SWG region length than TM since the beat length for TE is shorter than that of TM.

With the assistance of SWG, a polarization beam splitter with a high ER and broad bandwidth is realized. The inserted SWG enables the manipulation of the beat length flexibly and effectively, especially for TE. Nearly a 20-fold length reduction for TE is demonstrated, which makes it possible to render the beat length of the TE mode half that of the TM mode, leading to the separation of these two polarizations with a high ER. Meanwhile, no additional fabrication step is needed. Moreover, the SWG affects the refractive index of the even mode mainly, which conduces to the bandwidth broadening. The ER and IL are 28.7 (24.8 dB) and 0.10 dB (0.11 dB) for TE (TM) at the wavelength of 1550 nm. The ER is higher than 10 dB in the wavelength range of 1450–1625 nm for TE and 1495–1610 nm for TM. Besides, the minimum feature size of this device is 100 nm, which can be easily realized by modern fabrication technology. With the advantage of a high ER and a broad bandwidth, the presented PBS could offer better performance for the polarization diversity scheme. Furthermore, it strongly consolidates the concept that the SWG structure could provide a new approach for the design of high-performance integrated optical devices.

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