Asymmetric directional coupler type contra-directional polarization rotator Bragg grating: design

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We report contra-directional coupler type polarization rotation Bragg gratings using silicon waveguides. Waveguides incorporating a Bragg grating for polarization rotation and having different widths are placed near to each other. A single grating can separate the backward diffraction light. The structure is optimized considering the field strength ratio between waveguides. A distinct polarization rotation wavelength peak is obtained by 3D-FDTD simulation. © 2019 The Japan Society of Applied Physics

Silicon photonics is considered an important technology to be used in future optical communication systems. Many silicon photonic wavelength filters1 based on Bragg grating have been reported.2–13 In the optical communication technology, as the light signal transmitted through an optical fiber has random polarizations, a scheme to control polarization is required. We have been studying Bragg diffraction which can generate polarization rotated light to be used in wavelength filters to attain polarization insensitivity. Using silicon waveguides, a polarization rotation with high efficiency can be achieved due to its high refractive index contrast. We and others demonstrated many experimental polarization rotation Bragg grating devices using a waveguide with non-vertical side wall, rib waveguide and terrace corrugation structures.14–17 Many types of grating structures such as sampled grating, super structure, chirped period and cavity incorporated devices18–22 can be made possible by using polarization rotation Bragg grating.

Usually, twin grating waveguides are used together with 3 dB coupler to separate the back-diffraeted light from the input light. A contra-directional coupling of diffracted light in asymmetric directional coupler can be used6–13 to simplify the structure for separating the back-diffraction light using single grating. In this report we show that single polarization rotation grating waveguide coupled to another waveguide can separate the polarization rotated and diffracted light. The device is designed by using the finite element method (FEM) to calculate normal modes and three-dimensional finite difference time domain (3D-FDTD) simulation to study the diffraction. We designed the device around 1600 nm for next home system. The device structure is shown in Fig. 1. Two waveguides with different widths incorporating polarization rotation Bragg grating are used. In Fig. 1 polarization rotation Bragg grating is placed in the narrower waveguide. An antisymmetric grating and the waveguide structure asymmetric in the depth direction is required to generate polarization rotation. As in Fig. 1(b) showing a waveguide cross section, a rib waveguide structure with restricted slab area is used as opposed to a figure in Ref. 23. The Bragg diffraction between odd TE and even TM normal modes is selected. The even TM mode light is generated by injecting a light into the wide waveguide. This mode is converted into odd TE mode by the Bragg diffraction which power mainly resides in the narrow waveguide. The polarization rotated light is ejected from the narrow waveguide at the Bragg wavelength. The grating period of \( \Lambda = \lambda_B/(N_{TMe}+N_{TTe}) \) is required for diffraction at wavelength of \( \lambda_B \), where \( N_{TMe} \) and \( N_{TTe} \) are effective indices of even TM and odd TE modes, respectively. This setting avoids using the weak-confined and high-loss odd TM mode. The grating is not placed in the wide waveguide to avoid strong diffraction between even TM and even TE modes.

We use a silicon waveguide core thickness of 220 nm which is often the standard for many foundries. We use 70 nm half etch depth grating. The grating corrugation is 150 nm. The standard waveguide width of 440 nm is used as average width of two waveguides. We optimized the waveguide gap and the width difference to suppress unwanted transfer of the light between waveguides and to obtain sufficient amount of diffraction as will be explained.

Figure 2 shows the main even and additional odd TM modes excited when a light is injected abruptly into the wide waveguide. The relation diagram of even TM and odd TE modes for the main diffraction is shown by a solid-line-arrow in Fig. 2. The presence of the unwanted odd TM mode results in lower main diffraction, wavelength ripple in the through port and crosstalk in the forward drop port. Sub-diffraction at shorter wavelength would be generated when lower effective index odd TM mode is excited and diffracted to odd TE mode as shown by arrow with dotted-line. The peak wavelength of the sub-diffraction is \( \lambda_{SD} = \frac{\Lambda(N_{TMo} + N_{TTe})}{N_{TMo} + N_{TTe}} \), where \( N_{TMo} \) and \( N_{TTe} \) are effective indices of odd TM and TE modes at sub-diffraction wavelength. As the value of \( N_{TMo} \) tends to be smaller than \( N_{TTe} \), the sub-diffraction wavelength is shorter than that of the main diffraction such that \( \lambda_{SD} < \lambda_B \).

The diffraction coefficient \( K \) can be deduced from the overlap of the even TM and odd TE modes in the grating waveguide, so that the field strength in the grating waveguide defines it. The ratio of the TM mode field strengths in two waveguides \( r \) can be used as a guide for the design. The ratio
of maximum field strengths is used for simplicity. The ratio $r$ can be changed by gap width or the waveguide width differences. The graph of Fig. 3 shows the dependency of the diffraction coefficient $K$ between even TM and odd TE modes on the field strength ratio $r$ between waveguides. The ratio $r$ is obtained by FEM. The coupling coefficient is obtained from 3D-FDTD simulation. In Fig. 3 the gap widths of 300, 400, 450 and 500 nm are used with width difference of 200 nm unchanged. The width differences of 100, 140, 200 and 240 nm are used with the gap of 400 nm unchanged. The gap is defined between the wide and average narrow grating waveguide edges. On the other hand, with $K_s$ being the coefficient of diffraction between fundamental TM and TE modes in the single grating waveguide, the $K$ is estimated by $K = rK_s[(1 + r^2)/(1 + r'2)]^{1/2}$ analytically, where $r'$ is the ratio of the odd TE mode field strength ratio in two waveguides. This relation can be used for a simple guide to assess the diffraction strength. For simplicity, it is assumed in Fig. 3 that the field strength ratios of the TE and TM modes is related as $r' = r^{2.6}$ which is obtained from FEM results for 200 nm width difference and 400 nm gap. This function is selected to hold $r' = r = 0$ and $r' = r = 1$ in two extreme cases. For single 340 nm wide grating waveguide, the diffraction coefficient $K_s$ is 0.0768 $\mu$m$^{-1}$. In Fig. 3 we also show the calculated $K$ using this $K_s$ and analytical function of $r$ (described above) which is near those obtained by simulations. Figure 3 verifies that the coupling coefficient $K$ is defined by $r$. A discrepancy between the results of analytical calculation, 3D-FDTD results for gap and width difference might be the field shape difference not taken into account for simplicity. We should be reminded that a small diffraction coefficient is needed to obtain a narrow transmission peak linewidth which requires some effort in a silicon waveguide type device.

When high diffraction efficiency is required larger $r$ value is beneficial as shown in Fig. 3. The maximum excitation...
ratio of the unwanted odd TM mode is \( r^2/(1 + r^2) \) when a light is directly injected into the wide waveguide abruptly. Thus smallest possible \( r \) is beneficial in this regard but this result in smaller diffraction. Adiabatic excitation of the even TM mode is required so that the excitation of the odd TM mode is suppressed. We found that input and output curved waveguides with large radius can be used to obtain this condition as will be explained.

Figure 4 shows the wavelength response of the device obtained by 3D-FDTD method. The total device length is 100 \( \mu \)m. We selected widths of 540 and 340 nm waveguides in simulation. A 400 nm gap between the edges of the wide and the average narrow waveguide is used. The grating pitch is 401 nm. By injecting the TM light into the wide waveguide, a distinct TM to TE conversion wavelength peak near 1600 nm was obtained at the reflection drop port. Strong polarization rotating diffraction was observed despite a small amount of mode overlap in the opposite waveguide. A bump on the peak at 1570 nm wavelength is the diffraction of unwanted odd TM to odd TE mode. The extinction ratio of the main diffraction dip is 9 dB which is limited by the length (180\( \Lambda \)) of the grating that can be used in simulation due to the computer memory and time resource. This amount of the diffraction lowers the peak for 0.58 dB, equal to a polarization conversion efficiency of 87\%. A 200 \( \mu \)m long device is required for 99% (20 dB extinction ratio) conversion efficiency. The FWHM of the peak is 6 nm. The polarization extinction ratio for the reflection drop port is above 32 dB. The optical field obtained by FEM show that \( r \) is equal to 0.255 with these waveguide gap and width difference. This \( r \) value is selected as it was the maximum value to easily suppress the excitation of the odd TM mode to a reasonable level (−20 dB) as shown in Fig. 3 deduced from the sub-diffraction peak height. For the calculation of the sub-diffraction peak height width differences of 100, 140, 200 and 240 nm were used with the 400 nm gap is unchanged. The \( r \) value used in this simulation suggests a diffracted main peak loss of 0.27 dB if the odd TM mode is fully excited but only 0.1 dB of it is observed. This is due to usage of 80 \( \mu \)m radius curved waveguides for the connection to the input and output ports which suppress the excitation of unwanted odd TM mode. If the radius increases, the odd TM mode would become small.

At the input port where the gap between waveguide is large, the optical field of the even TM mode almost entirely resides in the wide waveguide and there is none in the narrow waveguide. The optical field of the odd TM mode mainly resides in the narrow waveguide and there is none in the wide waveguide. Thus, only the even TM mode is excited by injecting the light into the wide waveguide. At the curved waveguide, the gap between waveguides becomes smaller toward the grating section and the even TM local mode shifts its field distribution in two waveguides increasing the light field in the narrow waveguide. The odd TM local mode shifts its field distribution in two waveguides increasing the light field in the wide waveguide. If this structure change is too rapid, a mode conversion from the even to odd TM modes is generated. A larger curvature radius suppresses this mode conversion effect by slow structure change along the propagation distance. Due to reduction of odd TM mode excitation, the sub-diffraction peak height reduces from −13 to −19.5 dB by increasing the curvature radius of input/output waveguide from 20 to 80 \( \mu \)m. We found through simulations that the smallness of \( r \) allows easier achievement of adiabatic like condition to suppress the odd TM mode excitation. The curved waveguide length is 8.8 \( \mu \)m for curvature radius of 80 \( \mu \)m to increase the gap for 2 \( \mu \)m, which is enough to prevent coupling to other waveguide. Thus, this curvature radius size does not contribute much to the total length of the device where the grating section is several hundreds of microns long.

We have proposed the design of an asymmetric directional coupler type contra-directional polarization rotation Bragg gratings using silicon waveguides. Waveguides incorporating a polarization rotation Bragg grating and having different widths are placed near to each other. The diffraction between

![Fig. 4. (Color online) 3D-FDTD simulation result showing wavelength response of the device with 200 nm width difference between waveguides (540 and 340 nm wide waveguides). The gap between waveguides is 400 nm.](image-url)
even TM and odd TE modes is used. The field strength ratio in two waveguides was selected to obtain a diffraction coupling coefficient of sufficient strength and low excitation of unwanted modes. An 80 μm radius input/output curved waveguides were used to obtain adiabatic like excitation of the even TM mode. A distinct polarization rotated wavelength peak was observed at the backward drop port using 3D-FDTD simulation with excess loss under 0.1 dB.

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