Two-dimensional grating coupler with a low polarization dependent loss of 0.25 dB covering the C-band

JINGHUI ZOU, YU YU, AND XINLIANG ZHANG*

Wuhan National Laboratory for Optoelectronics and School of Optical and Electronic Information, Huazhong University of Science and Technology, Wuhan 430074, China
*Corresponding author: xlzhang@mail.hust.edu.cn

Received 28 July 2016; revised 20 August 2016; accepted 23 August 2016; posted 24 August 2016 (Doc. ID 272446); published 8 September 2016

We design and demonstrate a two-dimensional grating coupler (2D GC) with a low polarization dependent loss (PDL) based on the silicon-on-insulator (SOI) platform. Using a grating cell consisting of five cylinders and carefully optimizing the distances between the cylinders, a maximum PDL of 0.25 dB covering the C-band is realized, which is 1.25 dB better than a conventional 2D GC with a single cylinder etching pattern fabricated on the same SOI wafer. © 2016 Optical Society of America

OCIS codes: (130.3120) Integrated optics devices; (230.1950) Integrated optics devices; (230.5440) Polarization-selective devices.

http://dx.doi.org/10.1364/OL.41.004206

Silicon-on-insulator (SOI) is becoming an attractive platform for photonic integrated circuits (PICs) due to the complementary metal oxide semiconductor compatibility and high refractive index contrast [1,2]. Unfortunately, the subwavelength waveguide will cause a serious mode size mismatch with a single mode fiber (SMF), making it challenging to realize highly efficient fiber–chip coupling. Inverse taper and grating couplers (GCs) have been verified as two feasible approaches to solve this problem [3–6]. Compared to inverse taper couplers, GCs have a few advantages in terms of easy fabrication, flexible position, compact footprint, large alignment tolerance, and wafer-scale test. However, the conventional one-dimensional (1D) GC has an inherent defect of strong polarization sensitivity due to the effective refractive index difference between transverse electric (TE) and transverse magnetic (TM) modes, making it helpless for an input light with polarization state unknown. Though a batch of polarization insensitive or polarization splitting 1D GCs have been proposed and demonstrated [7–11], the subsequent polarization beam splitter and polarization rotator are unavoidable considering that most of the silicon PICs are designed for TE mode, and it will not only complicate but also enlarge the PICs. To overcome this dilemma, the 2D GC has been presented [12] and successfully applied to silicon integrated coherent receivers [13,14]. A 2D GC can be briefly considered as a superposition of two orthogonal standard 1D GCs, and it can couple arbitrarily polarized light into the PICs in TE mode with constant coupling efficiency. A multitude of modified 2D GCs have been put forward to suppress the backreflection [15–17], reduce the footprint [18], improve the coupling efficiency [19], and simplify the fabrication processes [20]. However, in all these schemes, the tilted coupling schemes were used, which will make the 2D GC polarization dependent in some degree. This is because an input light with electric field parallel to the symmetry axis (P-polarized) is slightly tilted out of the 2D GC plane, while an input light with electric field perpendicular to the symmetry axis (S-polarized) lies in the same plane as the 2D GC, inducing a coupling spectrum shift [21]. An active scheme based on a phase shifter can reduce the polarization dependent loss (PDL) to a certain extent [21]. Nevertheless, the bandwidth, structure complication, and extra power consumption limit its application. Another 2D GC with rounded diamond-like etching pattern is also proposed to eliminate the PDL, but no descriptions on both of the principles and structures are specified [6].

In this Letter, we propose a 2D GC with an etching pattern consisting of five cylinders to lower the PDL. By adjusting the distances between the cylinders, the coupling spectrum shift is eliminated. For demonstration, the proposed 2D GC is manufactured and a maximum PDL of 0.25 dB is measured at the C-band, which is 1.25 dB better than a conventional 2D GC with single cylinder etching shape. The top view of the single grating cell for the proposed 2D GC is illustrated in Fig. 1. The etching part is formed by five cylinders with same radius of \( R \). One of them is centered in the grating cell, and the other four are distributed along the P- and S-axes with distances of \( dp \) and \( ds \), respectively. As analyzed and demonstrated in [20], the S-polarized coupling spectrum has a redshift compared to the P-polarized coupling spectrum, which is the major origin of the PDL. Thus, we can relief the PDL by moving the S-polarized spectrum back. According to the expression of the peak wavelength \( \lambda \) of a GC [22]:

\[
\lambda = (n_{\text{eff}} - n_{\text{cladding}} \sin \theta)P.
\]
λ depends on the effective refractive index \( n_{\text{eff}} \) of the GC if cladding refractive index \( n_{\text{cladding}} \), coupling angle \( \theta \), and GC pitch \( P \) remain constant. So we can blueshift the S-polarized coupling spectrum by lowering its \( n_{\text{eff}} \), and it can be realized by enlarging the distance \( ds \) between the cylinders lying along the S-axis.

A common SOI wafer with 220 nm top silicon layer and 2 μm buried oxide layer is used in our design. To suppress the backreflection, a coupling angle of \( \theta = 14^\circ \) is adopted. For fabrication convenience, an etching depth of 70 nm is employed, enabling the 2D GC to be manufactured with the same processes of 1D GC [23]. The cylinder radius is selected to be \( R = 110 \text{ nm} \), easily fulfilling the boundary of deep-ultraviolet lithography. Then, \( dp, ds, \) and \( P \) are the remaining parameters to be optimized. Commercial 3D Finite-Difference Time-Domain (FDTD) software from Lumerical Solutions, Inc. [24] is utilized for the optimization. A focusing scheme is introduced [18] to compact the footprint, and the layout is defined as the following equation:

\[
\begin{align*}
\left\{ \begin{array}{l}
n_{\text{eff}} \sqrt{(x - L)^2 + y^2 + \frac{\sqrt{2}}{2} \sin \theta (x - L) + y} = m \lambda \\
n_{\text{eff}} \sqrt{x^2 + (y - L)^2 + \frac{\sqrt{2}}{2} \sin \theta (x + (y - L))} = m \lambda
\end{array} \right.
\tag{2}
\end{align*}
\]

where \( m \) and \( n \) are both integers, and \( L \) is the focusing distance. Each solution \((x, y)\) indicates the center location of a grating cell.

We first fixed \( dp \) to 250 nm, and a sweep of \( ds \) is performed. As shown in Fig. 2, the peak wavelength for S-polarized input light decreases as \( ds \) increases, and it moves back to 1550 nm when \( ds \) increases to 360 nm. The P- and S-polarized coupling spectra are shown in Fig. 3. The PDL defined as the absolute value of difference between P- and S-polarized coupling spectra is illustrated as Fig. 4. A maximum PDL of 0.20 dB locates at 1547 nm covering a broad span from 1530 to 1570 nm. For comparison, a conventional 2D GC with an etching pattern of a single cylinder is also explored at the same time with an etching depth of 70 nm, cylinder radius of 200 nm, and pitch of 612 nm. The calculated coupling spectra are also shown in Fig. 3, and a redshift of 11 nm is observed for the S-polarized coupling spectrum, causing a large PDL. As shown in Fig. 4, the PDL is dramatically increased beyond 1.25 dB at 1570 nm, which is 1.05 dB larger than the proposed 2D GC. For the bandwidth, the conventional 2D GC merely can work at a narrow band from 1550 to 1555 nm while the proposed 2D GC can work from 1530 to 1570 nm if a PDL boundary of 0.20 dB is requested. With the same method, 2D GCs with \( dp = 210, 230, \) and 270 nm are also explored with the corresponding optimum \( ds \) of 340, 350, and 370 nm, respectively. The PDLs are illustrated in Fig. 4. Compared with the conventional 2D GC, all of the proposed 2D GCs show an overwhelmingly superior performance in PDL, especially for the 2D GC with \( dp = 270 \text{ nm} \). However, we should give consideration to another key character of a 2D GC, namely the coupling efficiency. Although the 2D GC with \( dp = 270 \text{ nm} \) has a 0.06 dB better PDL than that with \( dp = 250 \text{ nm} \), it has a 0.22 dB larger coupling loss. Taking both PDL and coupling efficiency into consideration, we select the parameter group of \( dp = 250 \text{ nm} \) and \( ds = 360 \text{ nm} \) in this Letter.

The fabrication tolerance of the proposed 2D GC is also explored. In the fabrication processes, the actual etching depth cannot be completely the same as designed, and the impact of the variations of etching depth is calculated as shown in Fig. 5.
A depth variation of 10 nm will introduce ~13 nm wavelength shift while the PDL stays below 0.30 dB.

In order to validate our design, the proposed 2D GC is fabricated using electron beam lithography (EBL) and inductively coupled plasma (ICP) etching processes. The optical micrograph of fabricated 2D GCs is shown in Fig. 6(a). And the 2D GC is characterized through fiber-to-fiber transmission measurement using a back-to-back configuration [18]. The input light from a broadband optical source is first coupled and focused into the subsequent single mode rib waveguides by the input 2D GC. After transmitting through the connecting waveguides, the light is coupled into the output SMF with an identical 2D GC and measured using an optical spectrum analyzer. The scanning electron microscope (SEM) pictures of the proposed 2D GC are illustrated in Fig. 6(b). At the same time, a focusing conventional 2D CG with 200 nm radius and 612 nm pitch is fabricated on the same wafer as shown in Fig. 6(c). Besides, TE and TM 1D GCs are also fabricated to identify the P- and S-polarization states of the input light.

To obtain a P- or S-polarized input light, the polarization controller before the input SMF is turned to minimize the transmission of the TE or TM 1D GC.

The measured coupling spectra and PDLs of the proposed and conventional 2D GCs are illustrated in Fig. 7. For the proposed 2D GC, the peak wavelengths of P- and S-polarized coupling spectra are both located at 1548 nm with losses of 5.0 and 5.2 dB. As for the conventional 2D GC, the P- and S-polarized coupling spectra have a wavelength difference of 12 nm with peak losses of 4.8 and 4.4 dB. A great amelioration in PDL can be easily observed as shown in Fig. 7. The proposed 2D GC has a PDL under 0.25 dB across a wavelength range of 40 nm while the conventional 2D GC has a maximum value of 1.50 dB at the same band. The experimental results are well in agreement with the simulation results shown in Figs. 3 and 4 except for a loss degradation, which may be caused by the imperfectly smooth edge induced in the etching process. Though the loss of the proposed 2D GC is 0.2 dB higher than the conventional 2D GC, it is at the forefront of 2D GCs that have been presented based on a 220 nm SOI wafer without bottom reflector [12,15,17,18].

In conclusion, a 2D GC with grating cell consisting of five cylinders is proposed to alleviate the PDL for a tilted coupling scheme. By adjusting the distances between the cylinders, the coupling spectrum shift of P- and S-polarized input light is eliminated and the PDL is greatly decreased. For demonstration, the proposed 2D GC is fabricated based on a 220 nm SOI wafer using EBL and ICP etching processes. A maximum PDL of 0.25 dB is measured at the C-band, which is 1.25 dB better than the conventional 2D GC fabricated on the same wafer.

**Funding.** National Basic Research Program of China (2011CB301704); National Natural Science Fund for Distinguished Yong Scholars (61125501); NSFC Major International Joint Research Project (61320106016);
Acknowledgment. We thank He Zhang, engineer in the Center of Micro-Fabrication and Characterization of Wuhan National Laboratory for Optoelectronics, for the support in the EBL and ICP etching processes.

REFERENCES