Subwavelength-grating-assisted broadband polarization-independent directional coupler

LU LIU, QINGZHONG DENG, AND ZHIPING ZHOU*

State Key Laboratory of Advanced Optical Communication Systems and Networks, School of Electronics Engineering and Computer Science, Peking University, Beijing 100871, China
*Corresponding author: zjzhou@pku.edu.cn

Received 3 February 2016; revised 9 March 2016; accepted 9 March 2016; posted 10 March 2016 (Doc. ID 258541); published 1 April 2016

This Letter presents both numerical and experimental results of a polarization-independent directional coupler based on slot waveguides with a subwavelength grating. The measured coupling efficiency is 97.4% for TE and 96.7% for TM polarization at a wavelength of 1550 nm. Further analysis shows that the proposed subwavelength grating directional coupler has a fabrication tolerance of ±20 nm for the grating structure and that the coupling efficiencies for the two polarizations are both higher than −0.5 dB (~99%), exceeding the entire C-band (1525–1570 nm) experimentally. © 2016 Optical Society of America

OCIS codes: (130.3120) Integrated optics devices; (050.6624) Subwavelength structures; (050.2770) Gratings.

http://dx.doi.org/10.1364/OL.41.001648

Directional couplers (DCs), consisting of two parallel waveguides separated by a gap, play a fundamental and significant role in many applications, such as on-chip sensors [1,2], power taps [3], microring filters [4,5], and Mach–Zehnder (MZ) switches [6–8]. DCs are widely preferred for their straightforward way of power splitting and negligibly low insertion loss when compared with other splitters, for example, a multimode interference (MMI) coupler (typically 0.3–0.5 dB) [9]. However, DCs suffer from polarization-dependent problems when they are extended to high-contrast systems such as silicon photonics [10]. The beat length for TE greatly differs from that for TM, making the output power unequal for the two polarizations at a certain device length, which limits the polarization-independent coupling and power splitting in silicon photonic integrated circuits.

One solution is to use polarization diversity schemes where polarization splitting and rotating is applied, which increases system size and complexity [11,12]. Another approach is to make the directional coupler inherently polarization insensitive, such as modifying slot waveguide parameters [10,13–15], applying multiple parallel waveguides [16], as well as resorting to plasmonic mode features [17]. Both suffer from either relatively large device size or present a big challenge to the current standard complementary metal–oxide–semiconductor (CMOS) fabrication technology.

Subwavelength gratings (SWGs) are gratings with pitches much smaller than the wavelength of light propagating through them [18]. SWGs can be generally considered as a homogenous medium and their equivalent material index can be tailored by changing the duty cycle, thus providing a new degree of freedom for the design of novel photonic components [19]. Many SWG-based devices with high performance have been reported such as beam splitters [20], fiber-grating couplers [21], MMI couplers [22], colorless directional couplers [23], and fabrication-tolerant polarization splitters and rotators [24].

Here, we propose the use of a SWG to design a polarization-independent directional coupler (PIDC). The key to our approach is to make the effective index difference between odd and even modes identical for both TE and TM modes by adjusting the grating duty cycle. Benefited from this design, polarization independence exceeding the entire C-band is demonstrated both numerically and experimentally while the beat length is ~10 μm.

The proposed PIDC (Fig. 1), designed on a silicon-on-insulator (SOI) wafer with SiO₂ up-cladding, consists of two silicon slot waveguides named A and B, respectively, which are with a certain number of grating pitches with period of Λ at the side close to the gap. The lengths of the low and high refractive index segment, namely, groove and ridge are a and Λ − a, respectively. Owning to the properties of SWGs, the inside neighboring parts of waveguide A and B can be considered as homogenous medium with an effective refractive index nₑ, which can be modified by varying the duty cycle f = (2awₑ)/[Λ(w − wₑ)] (the area proportion of the low-index segment in one period) [25]. Some other parameters are as follows: the waveguide height h is 250 nm; the silicon waveguide width is w, where the gap width is wₑ; and the slot width wₑ is fixed to be 100 nm, which is common in many applications. Both grating groove a and grating depth wₑ are set to be 100 nm for the ease of fabrication. Additionally, an s-bend with a radius of 5 μm is attached to the output port to decouple the waveguides.

The operation principle of the conventional directional coupler is illustrated as follows: light is launched into one arm and excites the even and odd supermodes of the two parallel waveguides. The beat length of these two modes is given as [23]

\[ L = \frac{\lambda}{2(n_{\text{even}} - n_{\text{odd}})} , \]
where $n_{\text{even}}$ and $n_{\text{odd}}$ are the effective indices of the two modes, respectively. If $n_{\text{even}} - n_{\text{odd}}$ can be made identical for TE and TM modes, the beat lengths of both polarizations are equal, leading to polarization-independent performance. Based on this knowledge, the proposed PIDC is realized by properly tuning $n_{\text{even}} - n_{\text{odd}}$.

The 2D finite element method (FEM) and the 3D finite-difference time-domain (FDTD) method were used to design the PIDC and study its characteristics. The operation free-space wavelength is set to 1550 nm, and the refractive indices of silicon and silicon dioxide are $n_{\text{Si}} = 3.48$ and $n_{\text{SiO}_2} = 1.46$, respectively. The inside neighboring parts of waveguides A and B are considered as homogenous media. When $n_k$ decreases (i.e., a grating structure is introduced into a conventional slot waveguide), the beat lengths for both polarizations get longer, but the two curves are of different slopes, as shown in Fig. 2. Thus, this provides a way to manipulate the beat length $L_x$ by the variation of $n_k$, which can be achieved by the adjustment of duty cycle $f$.

Rytov’s formulas are used to determine the grating parameters roughly to achieve polarization independence [26],

$$n_{\text{TE}}^k = n_1^k f + n_2^k (1 - f)$$

$$\frac{1}{n_{\text{TM}}^k} = \frac{1}{n_1^k} f + \frac{1}{n_2^k} (1 - f).$$

(2)

In our case, $n_1$ and $n_2$ are the refractive indices of SiO$_2$ and Si, respectively. For a grating structure with duty cycle $f$, if its equivalent refractive indices for TE and TM, $n_{\text{TE}}$ and $n_{\text{TM}}$, can satisfy $n_{\text{TE}}^k$ and $n_{\text{TM}}^k$ respectively, then the $f$ for polarization independence is obtained. Further, a series of 3D FDTD simulations of PIDCs with real grating structures of varying periods are carried out to optimize the grating parameters. After these steps, the following parameters are chosen: $w = 520$ nm, $w_{\text{g}} = 230$ nm, $f = 0.129$ (i.e., $\Lambda = 370$ nm), and the corresponding $L_x \sim 10$ µm. It can be seen that Eq. (2) is satisfied roughly.

Further simulation is carried out to verify the polarization independence along the light propagation direction. Optical energy flux is integrated over the waveguide cross section and the relationship between coupling efficiency and coupling length $L$ was obtained, which is shown in Fig. 3. The simulated data can be well fitted as a sinusoidal function with the form of $A \sin^2(\kappa \cdot L + \varphi)$, which is the theoretical expression for DC couplers [27]. The introduction of $\varphi$ is to account for the mode transformation from a conventional waveguide to a SWG waveguide. When $L$ is small (less than 3 µm), the simulated data are a little deviated from the fitted curve, while there is good agreement as $L$ becomes large. This is because some distance is needed for the slot waveguide mode to transform into a complete and steady SWG mode. The fitted curves for TE and TM slightly differ. However, the difference remains lower than 2% for all $L$. Several reasons contribute to this divergence. For TE and TM, the grating still exerts a slightly different influence on the coupling process since for short length (e.g., one period long), the accuracy of Eq. (2) is low and the real effective index will deviate from the required $n_{\text{TE}}^k$ ($n_{\text{TM}}^k$). As a result, $\kappa$ and $\varphi$ could not coincide simultaneously for the two polarizations. Also, since fabrication simplicity is considered, for example, $w$ and $w_{\text{g}}$ are both integral multiples of 10 nm, $L_x$ is not critically the same for the two polarizations. Here, 10 µm for TE and 9.81 µm for TM.

For a fully coupled PIDC, the optimal length of the coupling region is 8.4 µm when discounting s-bend length, indicating a compact footprint. The grating region of waveguide B extends until the s-bend ends to make the coupling region transform smoothly. A fully coupled PIDC with an s-bend is presented in Fig. 4 as an example, with optical energy flux density ($P_x$) of TE and TM mode incidence. The input fundamental TE and TM modes are launched at the input port of waveguide A and propagate to the output port of waveguide B.
The coupling efficiency is defined as $P_{B\text{ Out}}/P_{A\text{ In}}$. As shown in Fig. 5, at 1550 nm, the coupling efficiency achieves 98.0% for TE and TM, simultaneously. Furthermore, the 0.5 dB bandwidth, defined as the bandwidth when the coupling efficiency for TE and TM modes are both higher than $-0.5 \text{ dB}$ (≈89%), is as broad as 120 nm. Moreover, the coupling efficiency divergence between TE and TM maintains at less than 1.8%. This broadband performance is much better than that of polarization-independent directional couplers which are also based on slot waveguides, especially for the TE mode [13,15]. The transmission of the bar port varies in the range of 0.3%–7.4% for TE and 0.1%–8.0% for TM while the total transmission is around 98.3%, indicating an insertion loss of about 0.1 dB.

For comparison, a conventional slot directional coupler was also simulated which is of the same parameters of the PIDC, merely excluding the grating structure. At 1550 nm, the beat length $L_\pi$ for TE and TM are 9.76 and 7.13 $\mu$m, respectively, which can also be confirmed by Fig. 2 when $n_k = 3.48$. It means that a fully coupled DC for TE only holds a coupling efficiency of 91% for TM, indicating a distinguished coupling efficiency difference up to 9% ($-0.4 \text{ dB}$).

Fabrication tolerance is also analyzed. Figures 6(a) and 6(b) present the normalized variation of $L_\pi$ (i.e., $\Delta L_\pi/L_\pi$) as a function of $w_d$ and $a$, respectively. For a ±5% variation of $L_\pi$, the tolerance regarding $w_d$ ($a$) is ±20 nm for both polarizations while the PIDC is more sensitive to the $w_g$ variation, as shown in Fig. 6(c). For ±5% (±15%) variation of $L_\pi$, the tolerance is ±10 nm (±30 nm). A conventional slot directional coupler was also simulated which has the same parameters as the PIDC, merely excluding grating structure. Its tolerance about $w_g$ is similar, that is ±30 nm for ±15% variation of $L_\pi$, which indicates that the introduced grating does not bring more sensitivity to the directional coupler. Furthermore, our device is expected to be less sensitive to $w_g$ variation if combined with some fabrication tolerance-enhanced design, for example [9].

The designed directional coupler was fabricated on a SOI wafer with 250 nm thick top silicon and 2 $\mu$m thick buried dioxide. Electron-beam lithography was used to define the structure pattern and an inductively coupled plasma etching process was followed. Then, the chip was covered with a 1 $\mu$m thick silicon dioxide layer as the upper cladding by plasma-enhanced chemical vapor deposition. The top-view scanning electron microscope (SEM) picture of the fabricated directional coupler is shown in Fig. 7, captured before the upper cladding was deposited.

The experimental setup to characterize the fabricated devices is as follows: a tunable CW laser is utilized as the light source and a digital polarization controller is used to adjust the polarization state. Mode converters were also fabricated to efficiently transform energy between the PIDC slot waveguide and the conventional strip waveguide [28]. Light is butt-coupled into the chip and then butt-coupled out to an optical spectrum analyzer through the coupling between the tapered lens fiber and the strip waveguide.

Figure 8(a) shows the measured transmission spectrum of one device for TE and TM polarizations. Because of the reflection of both end facets, the signal-to-noise ratio is degraded by the Fabry–Perot effect. To suppress noise, the robust locally weighted regression method is used to extract the trend lines [29,30], from which coupling efficiency can be derived. The
The measured coupling efficiency of TE and TM are 97.4% for TE and 96.7% for TM at a wavelength of 1550 nm. Broadband operation is demonstrated over a bandwidth of 120 nm (1475–1595 nm) theoretically and exceeds the entire C-band (1525–1570 nm) experimentally. The device is also compact and has a minimum feature size of 100 nm, which can be easily realized by modern fabrication technology. Finally, this on-chip DC not only can be readily integrated with other optical components but also strongly consolidates that the concept of SWG structure could open a new window for the design of high-performance integrated optics devices.

**Funding.** National Natural Science Foundation of China (NSFC) (61120106012, 61177058).

**REFERENCES**