Beam splitter based on Bragg grating-assisted coupler

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Received March 12, 2014; accepted July 16, 2014; posted online January 26, 2015

We describe a compact beam splitter based on grating-assisted coupler which consists of Bragg grating sandwiched between two parallel waveguides on the silicon-on-insulator platform. The coupled-mode theory is an important method to analyze waveguide structure. The coupling effect is affected by the grating refractive index perturbation due to the phase mismatch between two waveguides with different widths and refractive indices. The power difference between the transmitting and the reflecting directions in waveguide A is nearly 0 when the Bragg wavelength is 1.3464 μm, the index perturbation is 0.245, the period of grating is 0.2 μm, and the distance of two waveguides is 1 μm. At this time, cross couple neighbor waveguides are significantly suppressed. Beam splitter based on grating-assisted coupler is very useful in integrated optical circuits and photonic network-on-chip.

OCIS codes: 250.6715, 250.5300, 230.1950, 230.7370.

doi: 10.3788/COL201513.S12501.

A beam splitter is a key element in the optical communications such as switches, routers, and isolators[1–3]. Conventional beam splitters are based on the use of the natural birefringence of some crystals or on the polarization properties of multilayer dielectric coatings[4,5]. However, these crystals require a large thickness to generate enough walk-off distance between the two orthogonal polarizations owing to intrinsically small birefringence of the naturally anisotropic materials.

Recently, beam splitters using silicon-on-insulator (SOI) structure have attracted increasing attention, for example, multimode interference structures[6–10], directional couplers (DCs)[11–16], Mach–Zehnder interferometers[17–19], and photonic-crystal/grating structures[20–22]. SOI is emerging as a very important material platform for integrated nanophotonics due to the high refractive index contrast between the silicon core and the oxide cladding ($\Delta n \approx 2$). This material system is very well suited for high-density integration of photonic components and circuits which can be fabricated by standard complementary metal oxide semiconductor technology.

In this letter, we theoretically investigate beam splitter based on grating-assisted coupler, which consists of Bragg grating sandwiched between two parallel waveguides on the SOI platform as shown in Fig. 1. A signal beam can be equally split into two output beams using this grating-assisted coupler. The coupled-mode theory (CMT) is one of the most frequently used methods for analytical solutions and strong physical intuition[23–25].

As shown in Fig. 1, the structure of length $L = 150$ μm, includes two parallel slab waveguides with core refractive indices of $n_A = 3.45$ and $n_B = 3.5$. Their widths are $W_A = 0.4$, $W_B = 0.3$ μm, respectively, and the distance between them is $D = 1$ μm. The refractive index perturbation $n_{per} = 0.245$ is a single rectangular Bragg grating of period $p = 0.2$ μm, the width of 0.1 μm, and the fill factor of 0.5.

Grating-assisted couplers have found wide usage in many areas of photonics such as filters, optical switches, wavelength-division multiplexing (WDM) systems, and as feedback mirrors for several laser types. The analysis of the above structure is based on the unified coupled-mode formalism[26], which is a generalization of the case of CMT for pure DCs[27]. The generalized model is derived directly from Maxwell's equations and is based on the

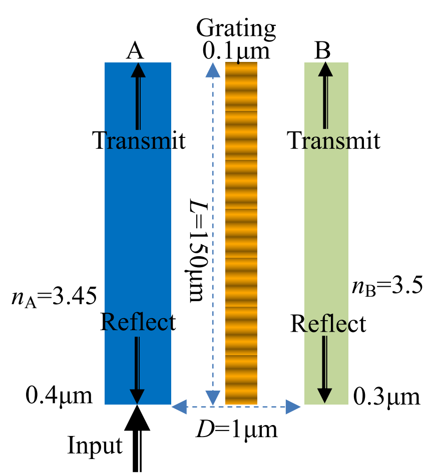
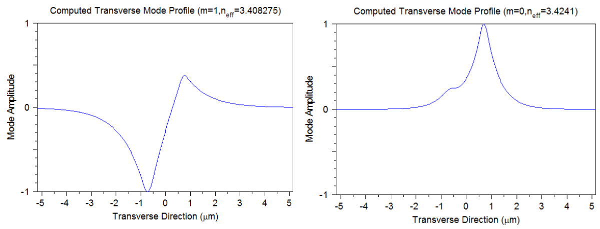


Fig. 1. Schematic structure view of the grating-assisted beam splitter.



(a) (b)

Fig. 2. Mode profile of ridge waveguide without index perturbation: (a) mode in waveguide A and (b) mode in waveguide B.

mode expansion conjecture[28]. As a result, for most practical cases in which most of the energy is trapped within the guiding region of single-mode waveguides, the expansion of the transverse fields is approximately satisfied by superposition of only four guided modes as a function of the z-dependent amplitudes[25,26]. According to Maxwell's equations, the amplitudes consist of propagation constants, coupling coefficients, and other overlap integrals. For the grating to assist coupling, the codirectional or contradirectional coupling between the two ridge waveguides is significantly suppressed or constructed due to the phase mismatch or the phase match by the periodic corrugation[29,30]. The Bragg condition is

$$\beta_{\mathrm{B}}(\lambda) \pm \beta_{\mathrm{A}}(\lambda) = \frac{2\pi}{p}, \tag{1}$$

where the plus and minus signs stand for backward and forward couplings, respectively. β_{A} and β_{B} represent the propagation constants of the transverse electric modes of the ridge waveguides and λ is the Bragg wavelength. Finally, according to a specific set of boundary conditions obtained from wave input into waveguide A, an analytical method of the transfer-matrix method can solve the case of an index perturbation grating between the two waveguides. Then, the time-averaged power flow along the structure is given approximately.

The modes of the ridge waveguides without perturbation are solved using finite-difference method and are shown in Fig. 2.

Obviously, the input direction into the waveguide is important, owing to the stronger interaction between the wave and the grating refractive index region if it

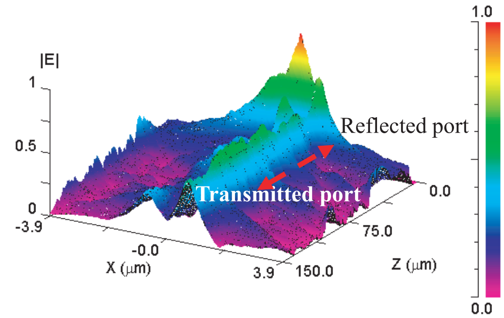
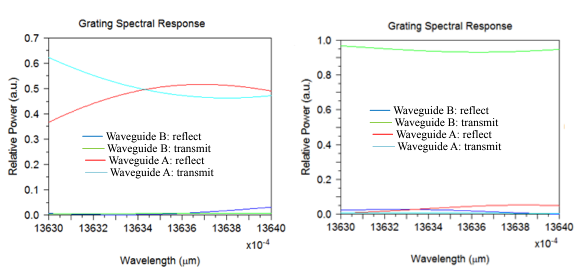


Fig. 4. Distribution of optical field.

occurs at the beginning of the grating. Figure 3 shows the different grating spectral responses when the signal beam inputs waveguides A and B, respectively.

When signal beam inputs from waveguide B, it directly transmits through waveguide B due to the phase mismatch. Consequently, no reflection is obtained, and the codirectional coupling and the contradirectional coupling between two waveguides are significantly suppressed. However, when signal beam inputs from waveguide A, the coupling effect is not obvious due to the phase mismatch between two waveguides with different widths and refractive indices. In contrast, owing to the Bragg grating refractive index perturbation, the reflected beam is significantly strengthened in waveguide A. Particularly, as soon as the Bragg wavelength is 1.3634 μm, both of the powers of the transmitting and the reflecting beams in waveguide A are nearly equal to 50%. At this time, the coupling power to waveguide B is significantly suppressed to zero as shown in Fig. 3(a). The distribution of optical field is shown in Fig. 4. Therefore, when an optical signal is injected from waveguide A, only the power at the Bragg wavelength is simultaneously reflected and transmitted to the two terminal ports of waveguide A, which can be regarded as a half mirror. A subtle amount of power is coupled to neighbor waveguide B. Thus, we can use the grating-assisted coupler to realize beam splitting function.

We first discuss the influence of the coupling length on the Bragg wavelength. As shown in Fig. 5, the Bragg



(a) (b)

Fig. 3. Spectral response for different injection waveguides: (a) signal beams input from waveguide A and (b) signal beams input from waveguide B.

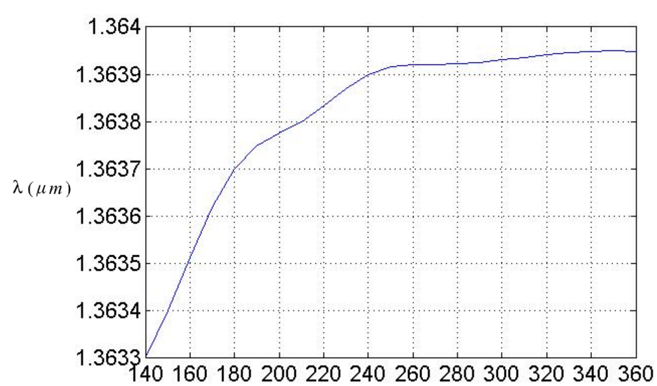


Fig. 5. Wavelength as a function of coupling length L (μm).

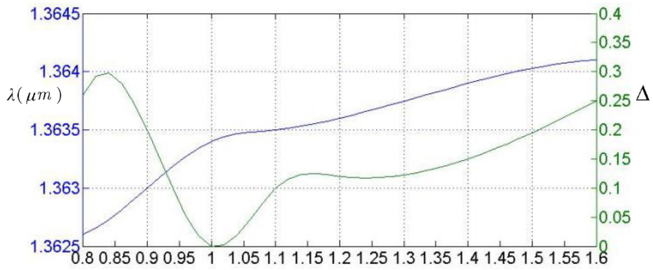


Fig. 6. Wavelength and power difference as function of distance between two waveguides D (μm).

wavelength is not sensitive to the coupling length because the variable scale of wavelength is only 0.7 nm with the increment of the coupling length from 140 to 360 μm. In practice, taking into account the needs of integration with other devices, the length of beam splitter using grating-assisted coupler is generally designed to 150 μm, where the Bragg wavelength is 1.3634 μm.

The gratings are designed to assist equally backward reflecting and transmitting in waveguide A, and to suppress coupling from one waveguide to the other. The distance between the two waveguides is also important. Figure 6 shows the relation between the distance of two waveguides (D), Bragg's wavelength (λ), and the power difference (Δ) of the transmitting and the reflecting directions in waveguide A. As depicted in Fig. 6, increasing or decreasing the distance will suppress or strengthen forward or backward coupling in waveguide A. Therefore, the power difference is increased especially in waveguide A. When the distance between two waveguides is 1 μm, the power difference is zero for which the grating was planned. Simultaneously, with the increment of the distance, the longer the distance between the grating and the injected waveguide A, the longer is the required Bragg wavelength to achieve similar effects.

The power variation along waveguide A as well as the Bragg wavelength is as shown in Fig. 7. A Bragg grating has a monotonically varying refractive index perturbation from 0.2 to 0.26. Then, the power difference acutely fluctuates from 0 (where $n_{\text{per}} = 0.245$) to 0.3 (where $n_{\text{per}} = 0.2$). In other words, the power difference is rather sensitive to the index perturbation. In contrast, the shift of the Bragg wavelength is only

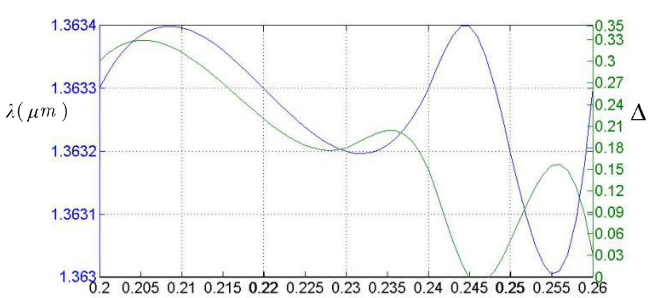


Fig. 7. Wavelength and power difference as function of index perturbation n_{per}.

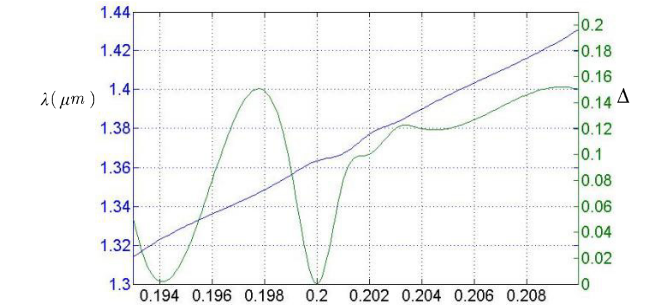


Fig. 8. Wavelength and power difference as function of grating period p (μm).

0.4 nm. The influence of index perturbation of Bragg grating is similar to the distance of two waveguides. Increasing or decreasing the perturbation will significantly affect forward or backward power in waveguide A. Therefore, the power difference is increased especially in waveguide A. As one can expect, no reflection is obtained when the grating vanishes ($n_{\text{per}} = 0$), where the power difference reaches up to its maximum. This is actually the case of an asymmetric DC.

Finally, the influence of grating period on Bragg wavelength and the power difference is shown in Fig. 8. It is noted that changing the grating period for a new wavelength yields Bragg condition Eq. (1). Simultaneously, the power difference obviously fluctuates from 0 to 0.15. Only when grating period is 0.2 μm, and its corresponding wavelength is 1.3634 μm, the power difference between the transmitting and the reflecting directions in waveguide A is equal to 0.

In conclusion, we introduce a beam splitter based on asymmetric grating-assisted coupler. The unified CMT is used to investigate some special aspects of grating-assisted coupling. Specifically, we study the influence of the grating parameters (the coupling length, the distance between two waveguides, refractive index perturbation, and grating period) on beam splitter. The operating principle and simulation results show that the beam splitter based on grating-assisted coupler designed here can equally separate a signal beam into two beams when the Bragg wavelength is 1.3464 μm, the index perturbation is 0.245, the period of grating is 0.2, and the distance of two waveguide is 1 μm. Thus, the power difference between the transmitting and the reflecting beams is 0. Our proposed beam splitter based on grating-assisted coupler is very useful in integrated optical circuits and photonic network-on-chip.

This work was supported by the National Natural Science Foundation of China (No. 60907003), the Foundation of National University of Defense Technology (No. JC13-02-13), the Hunan Provincial Natural Science Foundation of China (No. 13JJ3001), and the Program for New Century Excellent Talents in University (No. NCET-12-0142). The authors gratefully acknowledge helpful discussions with Prof. Zhiping Zhou.

References

1. D. Yi, Y. Yan, H. Liu, S. Lu, and G. Jin, Opt. Lett. **29,** 754 (2004).
2. L. Zhou and W. Liu, Opt. Lett. **30,** 1434 (2005).
3. X. Chen, C. Li, and H. Tsang, IEEE Photon. Technol. Lett. **21,** 268 (2009).
4. M. Born and E. Wolf, *Principles of Optics* (Cambridge University, 1999).
5. J. L. Pezzaniti and R. A. Chipman, Appl. Opt. **33,** 1916 (1994).
6. J. Hong, H. Ryu, S. Park, J. Jeong, S. Lee, E. Lee, S. Park, D. Woo, S. Kim, and O. Beom-Hoan, IEEE Photon. Technol. Lett. **15,** 72 (2003).
7. Y. Jiao, D. Dai, Y. Shi, and S. He, IEEE Photon. Technol. Lett. **21,** 1538 (2009).
8. B. M. A. Rahman, N. Somasiri, C. Themistos, and K. T. V. Grattan, Appl. Phys. B **73,** 613 (2001).
9. A. Katigbak, J. Strother, and J. Lin, Opt. Eng. **48,** 080503 (2009).
10. B. K. Yang, S. Y. Shin, and D. M. Zhang, IEEE Photon. Technol. Lett. **21,** 432 (2009).
11. J. Yang and Z. Zhou, Opt. Commun. **285,** 1494 (2012).
12. J. Yang, Z. Zhou, and W. Zhou, IEEE Photon. Technol. Lett. **23,** 896 (2011).
13. J. Xiao, X. Liu, and X. Sun, Jpn. J. Appl. Phys. **47,** 3748 (2008).
14. X. G. Tu, S. S. N. Ang, A. B. Chew, J. H. Teng, and T. Mei, IEEE Photon. Technol. Lett. **22,** 1324 (2010).
15. T. Yamazaki, H. Aono, J. Yamauchi, and H. Nakano, J. Lightw. Technol. **26,** 3528 (2008).
16. Y. Yue, L. Zhang, J. Y. Yang, R. G. Beausoleil, and A. E. Willner, Opt. Lett. **35,** 1364 (2010).
17. J. Yang, Z. Zhou, X. Wang, D. Wu, H. Yi, J. Yang, and W. Zhou, Opt. Lett. **36,** 837 (2011).
18. D. Dai, Z. Wang, and J. E. Bowers, Opt. Lett. **36,** 2590 (2011).
19. L. M. Augustin, R. Hanfoug, J. J. G. M. van der Tol, W. J. M. de Laat, and M. K. Smit, IEEE Photon. Technol. Lett. **19,** 1286 (2007).
20. Y. Shi, D. Dai, and S. He, IEEE Photon. Technol. Lett. **19,** 825 (2007).
21. X. Ao, L. Liu, W. Lech, and S. He, Appl. Phys. Lett. **89,** 171115 (2006).
22. J. Feng and Z. Zhou, Opt. Lett. **32,** 1662 (2007).
23. D. G. Hall, ed., *Coupled-mode Theory in Guided-wave Optics,* MS 84 of SPIE Milestone Series (SPIE, 1993).
24. N. Lzhaky and A. Hardy, Appl. Opt. **38,** 6987 (1999).
25. N. Lzhaky and A. Hardy, J. Opt. Soc. Am. A **16,** 1303 (1999).
26. A. Hardy, IEEE J. Quant. Electron. **34,** 1109 (1998).
27. A. Hardy and W. Streifer, J. Lightw. Technol. **3,** 1135 (1985).
28. D. Marcuse, *Theory of Dielectric Optical Waveguides* (Academic, 1991).
29. P. Yeh and H. F. Taylor, Appl. Opt. **19,** 2848 (1980).
30. H. Qiu, G. Jiang, T. Hu, H. Shao, P. Yu, J. Yang, and X. Jiang, Opt. Lett. **38,** 1 (2013).