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Refractive Index Engineering of High Performance Coupler for Compact Photonic Integrated Circuits

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Abstract

Subwavelength gratings are periodical structures with pitches small enough to locally synthesize the refractive index of photonic waveguides, which allows direct control of optical profile as well as easier fabrication process. Several examples of refractive index engineering by subwavelength grating are presented, such as vertical coupling binary blazed grating coupler, polarization beam splitter, and polarization independent directional coupler, which show better performance when compared to their conventional counterparts.

1. Introduction

Coupler is a basic building block in many photonic integrated circuits. The efficient fiber-chip coupling as well as polarization independent coupling between waveguides is crucial issue, raising much concern in recent years.

Subwavelength gratings, constructed by the periodically interlayering of two types of materials, have pitches small enough to locally engineer refractive index [1, 2]. The refractive index, theoretically, can vary in a wide range between that of the two materials by tailoring duty cycle. With subwavelength grating, the design of effective refractive index is no longer restricted to the variation of waveguide width or some fixed etch depths as conventional devices do, but a new freedom is opened up. In the following sections, we would show how a rectangular-pillar grating coupler could approximate a triangular-ridge one with ease fabrication and how grating in a directional coupler is exploited as homogenous medium to eliminate polarization dependence.

2. Vertical coupling binary blazed grating coupler

A blazed grating can blaze all diffracted light into a single diffraction order while suppress others [1]. As a result, the directionality and coupling efficiency of the grating are enhanced and it is often applied in normal incidence situations. However, the conventional saw-tooth profile demands grey-scale lithography in fabrication process. Through refractive index engineering method, the triangular shape ridge in each period can be imitated by multiple rectangular pillars of a certain height but different widths, and this binary quantization grating is the so called binary blazed grating (BBG). BBGs can be easily fabricated by modern lithography technology while possessing a higher coupling efficiency when compared with conventional blazed grating due to shadowing effect and waveguide feature [3].

As shown in Fig. 1(a), every period of a BBG is divided into M equal sub-periods. The optimum number of M is fixed as 4. Each ridge's width is modulated to obtain the blaze effect. H_1 is the height of the common blazed grating, h_i (i = 1, 2, 3, 4) is the height of each discrete multilevel grating (Fig. 1(b)). The fill factor of each sub-period f_i (i = 1, 2, 3, 4) is defined as the ratio between the pillar width and the sub-period width. According to the localized effective refractive indices theory of binary gratings, the fill factors can be obtained:

$$n^{TE}_{eff(i)} = \sqrt{\varepsilon^{TE}_{eff(i)}} = \sqrt{f_i n_2^2 + \left(1 - f_i\right) n_1^2} \qquad (1)$$

$$n^{TE}_{eff(i)} = \frac{h_i}{H_2} n_2 + \frac{H_2 - h_i}{H_2} n_1 \qquad (2)$$

$$h_i = \frac{1}{2}\left[\frac{H_i}{M} n_2 + \frac{H_i}{M}\left(i-1\right)\right] = \frac{\left(2i-1\right)H_1}{2M} \qquad (3)$$

According to Eq. (1)-(3), f_i should be:

$$f_i = \frac{\left[\frac{2i-1}{2M}\frac{H_1}{H_2}\left(n_2 - n_1\right) + n_1\right]^2 - n_1^2}{n_2^2 - n_1^2} \qquad (4)$$

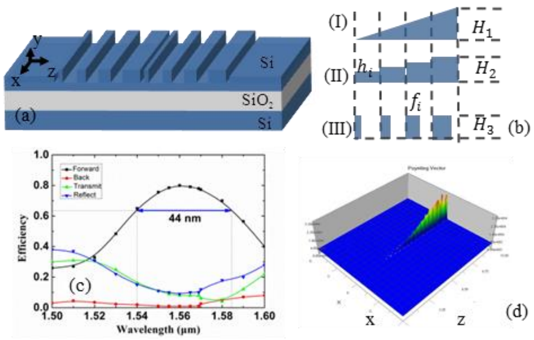

Fig. 1(a) Schematic (b) wavelength dependence and (c) power distribution of the BBG.

Based on this knowledge, we have designed a high-efficiency vertical grating coupler [4]. The optimized parameters are as follows: the grating etching depth is 350 nm, and a 160nm-thick slab waveguide is left, grating period is 545 nm, and the BOX layer thickness is 2.43 μm. In this structure, f_1~f_4 are 0.075, 0.293, 0.6 and 1. As illustrated in Fig. 1(c), the efficiency can reach 81% at the wavelength of 1560nm with a 1dB bandwidth of 44 nm. The optical field distribution is presented in Fig. 1(d). This perfectly vertical grating coupler holds a coupling efficiency higher than that of chirped grating couplers without bottom mirrors under normal incidence [5, 6].

The concept of BBG can then be extended to the polarization splitting field where normal incidence is also applied [3], the design of which follows the descriptions in the above section as well. The configuration of the PBS is shown in Fig. 2(a) and the key of this structure is that the upper grating is optimized for TE mode and the lower one is for TM. With the assistance of binary grating structure, the incident TE (TM) light could be efficiently coupled by the upper (lower) grating while the other polarization light would leak to the substrate.

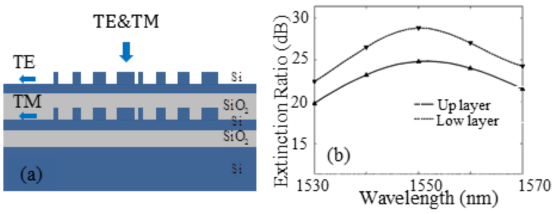

Fig. 2(a) Configuration of the PBS (b) wavelength dependence of extinction ratio.

Extinction ratio higher than 20 dB in the wavelength range of 1530-1570 nm is demonstrated in Fig. 2(b). The coupling efficiencies are 58% (50%) for TE (TM) at 1550 nm. The proposed PBS avoids grey-scale lithography and can couple light and split them efficiently. It enables vertical coupling and owns comparable or even higher coupling efficiency than other grating polarization beam splitters which require tilted fiber placement [7, 8], revealing the high performance introduced by the subwavelength grating.

3. Polarization independent directional coupler

For a conventional directional coupler, light is launched into one arm and even and odd supermodes are excited. The beat lengths of these two modes are as follows:

$$L_\pi = \frac{\lambda}{2(n_{even} - n_{odd})} \qquad (5)$$

where n_{even} and n_{odd} are the effective indices of the two modes, respectively. Because of huge birefringence on SOI platform, the beat lengths for TE and TM diverge a lot, which limits the polarization-independent coupling and power splitting in photonic integrated circuits. From Eq. (5), it can be derived that the beat lengths of both polarizations can be identical by properly tuning $n_{even} - n_{odd}$..

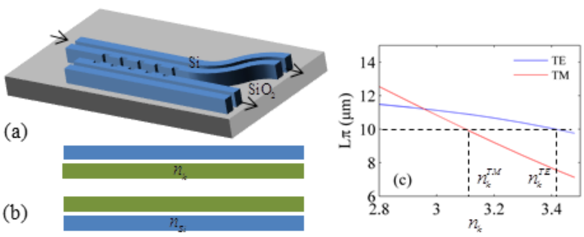

Fig. 3 (a) Schematic (b) equivalent homogeneous medium structure (c) relation between L_π and n_k

Recently, we report a grating assisted polarization independent directional coupler (PIDC) which consists of two slot waveguides with subwavelength grating inside (Fig.3) [9]. It has a period of 370 nm and can be considered as homogenous medium with equivalent refractive index of n_k.

As shown in Fig. 3(c), when n_k increases, the beat lengths of both modes augment but are of different rate. If the duty cycle is chosen properly, e.g. n_k for TE and TM equals n_k^{TE} and n_k^{TM}; the same L_π can be achieved.

Fig. 4(a) presents the simulation result of PIDC's wavelength dependence. At 1550 nm, the coupling efficiency reaches 98.0% for both polarizations and is higher than -0.5 dB (~89%) in a wide range of 120 nm. Moreover, the coupling efficiency divergence between TE and TM keeps less than 1.8%. As shown in Fig. 4(b), the measured coupling efficiency of TE and TM are 97.4% and 96.7%, respectively at 1550 nm. In the range of 1525-1570 nm, the difference between the two modes is less than 0.4 dB. This broadband performance is much better than that of polarization-independent directional couplers which are also based on slot waveguides, especially for TE mode [10, 11]. This confirms the positive impact afforded by the grating.

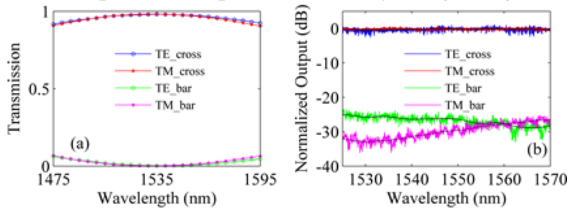

Fig. 4 (a) Simulation and (b) experimental results.

4. Conclusions

Some recent applications of refractive index engineering with subwavelength grating are proposed: efficient vertical coupling fiber-chip grating couplers, polarization beam splitters with high coupling efficiency and high extinction ratio and high performance polarization independent directional couplers. The idea of refractive index engineering with subwavelength grating opens a new freedom and acts as an efficient tool for the design of novel high performance photonic components. This concept is also expected to spread to other photonic integrated circuits.

Acknowledgements

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References

[1] Z. Zhou, and T. J. Drabik, Journal of the Optical Society of America A **12**, (1995) 1104.

[2] P. J. Bock, P. Cheben, J. H. Schmid, J. Lapointe, A. Del âge, S. Janz, G. C. Aers, D. Xu, A. Densmore, and T. J. Hall, Opt. Express **18**, (2010) 20251.

[3] J. Feng, and Z. Zhou, Opt. Lett. **32**, (2007) 1662.

[4] L. Yu, L. Liu, Z. Zhou, and X. Wang, Opt. Commun. **355**, (2015) 161.

[5] X. C. X. Chen, C. L. C. Li, and H. K. T. H. Tsang, Ieee Photonic. Tech. L. **20**, (2008) 1914.

[6] G. Roelkens, D. V. Thourhout, and R. Baets, Opt. Lett. **32**, (2007) 1495.

[7] Y. Tang, D. Dai, and S. He, IEEE Photonic. Tech. L. **21**, (2009) 242.

[8] J. Zou, Y. Yu, and X. Zhang, Opt. Express **23**, (2015) 32490.

[9] L. Liu, Q. Deng, and Z. Zhou, Opt. Lett. **41**, (2016) 1648.

[10] Y. Ma, M. Sung, and D. Huang, Appl. Optics **49**, (2010) 6979.

[11] N. Cheng, Y. Ma, P. Fu, C. Chin, and D. Huang, Appl. Optics **54**, (2015) 436.