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1. Introduction

In photonic integrated circuits, light is highly confined within optical waveguides constructed using semiconductor platforms such as silicon-on-insulator (SOI) and indium phosphide (InP) due to the large refractive index contrast. The waveguides often have width and thickness around or less than 1 μm, while a typical single-mode fiber has a mode size of around 10 μm at 1550 nm wavelength . The significant size mismatch causes a challenge to efficiently couple light between waveguides and optical fibers.

While silicon photonics has many advantages in CMOS-compatibility, low cost, low loss, high index contrast and small foot print, the integration of active components is still lacking. On the other hand, InP is the most essential platform for active optical components due to efficient light generation. Epitaxial growth directly on Silicon is extremely difficult due to lattice constant mismatch and thermal expansion. Monolithic integration of InP laser on silicon has been proposed recently [1] but needs further development. Therefore it is critical to achieve efficient coupling from InP lasers to silicon chips, and from InP lasers to optical fibers.

A few approaches have been proposed. Grating couplers are proposed for coupling between InP waveguide and optical fibers [2,3], which typically have narrow bandwidth. Wafer bonding techniques for heterogeneous integration [4] have been investigated. But it requires sensitive alignment and co-fabrication of silicon and InP. Butt coupling for hybrid integration [5] has also been proposed. However it typically requires an intermediate coupler of different materials, in addition to precise alignment especially in the vertical direction. Recently, 3D integration technique for fabricating InP lasers on silicon chip based on flip-chip bonding was proposed [6,7]. This technique avoids co-fabrication of InP and silicon, as well as thermal expansion mismatch.

In this paper, we study the output coupling from InP chip, and report a design of compact and efficient InP waveguide taper structure based on transformation optics for efficient coupling from a narrow waveguide to a broad opening. This concept could provide an enabling element for both efficient and alignment-tolerant coupling between integrated waveguides for hybrid photonic integrated circuits and from integrated waveguides to optical fiber.

2. InP Output Coupler Design

Figure 1 shows a simplified vertical coupling scheme. Light is confined in a narrow InGaAsP waveguide on top of an InP substrate; a taper structure gradually broadens the waveguide aperture; a slanted mirror is etched at the end of the taper, which reflects the light into vertical direction, for coupling with silicon chip or optical fiber. The efficient coupling depends both on the coupling from waveguide section to the taper section, and the coupling from reflected light to the target device. This paper focuses on the design of compact yet efficient planar taper structure.

Transformation optics is an approach that has recently been adopted for the design of various optical and microwave devices. Under coordinate transformation, the topological variation is effectively equivalent to variation of material parameters such as permittivity and permeability or refractive index absorption coefficient in optics terminology. It has been used for designing microwave waveguide tapers [8], and the fiber-to-chip coupler in SOI platform [9].

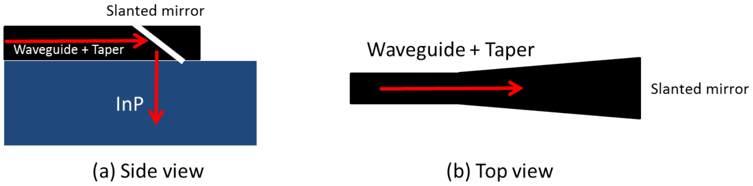

Fig. 1. InP output coupler design concept.

We start with a straight waveguide of width 2 μm, and connect it to a linear taper with end width of 10 μm and length of 20 μm. The effective index of TE mode in the waveguide is about 3.24 at 1550 nm wavelength. Due to the compact size, there is significant scattering loss. Simulations are done in COMSOL to study the propagation behavior. The electric field distribution with the linear taper is shown in Fig. 2(a).

Different transformation mechanisms can be applied to transfer the space from narrow waveguide to a wide opening. Using conformal mapping and neglecting the anisotropy in the permittivity tensor, the permittivity in the taper can be solved with Jacobian matrices [8]. The permittivity is proportional to $al/(a(l-x)+bx)$, where a and b are the end widths of the taper, l is the length of taper, and x is center position along the taper. The field distribution using taper with conformally mapped permittivity is shown in Fig.2(b). Less scattering loss is observed. Another transformation approach based on quasi-conformal mapping is also studied [9], where the isotropic permittivity is defined by solving Laplace equations. The corresponding field profile is shown in Fig.2(c). The field profile at two ends of the taper is almost identical under this transformation.

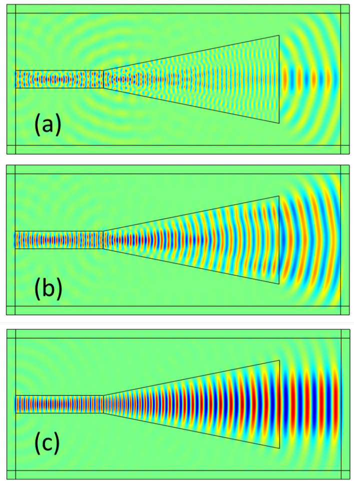

Fig. 2. Simulated electric field distribution for (a) regular linear taper, (b) conformally mapped taper, and (c) quasi-conformally mapped taper.

The permittivity profile under coordinate transformation can be realized experimentally by etching air holes in the taper region. The effective permittivity can be modified by controlling the local filling ratio. The technique has been validated in SOI platform [9]. For simplification, we start with a simple square lattice of air holes with the same diameter of 200 nm, and follow the conformal mapping [8] to calculate the transformed lattice in the taper. The taper with patterned air holes is shown in Fig. 3(a), and the corresponding electric field distribution is shown in Fig. 3(b).

The coupling efficiency of each taper is calculated by the ratio of integrated energy flux through the two plane at the input and output end of the taper. The efficiencies as function of wavelength (1520 to 1580 nm) are plotted in Fig. 3(c). The regular taper without transformation has efficiency between 60 to 70% in most of the range; the conformally mapped taper has an efficiency of over 90%; the mapped taper with air holes has an efficiency higher than the regular taper in most of the range, and an increase of over 10%.

Although the pattern of air holes only approximates the desired permittivity profile, the result already shows promis-

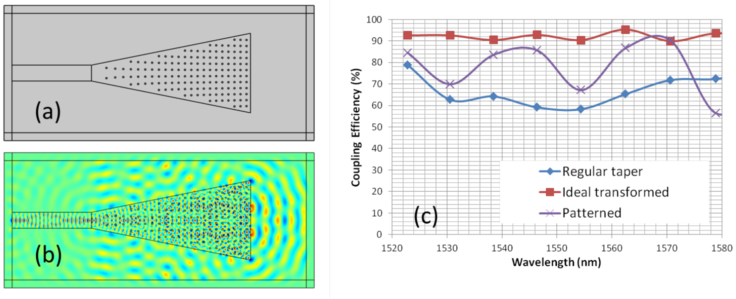

Fig. 3. (a) The taper structure with holes patterned following coordinate transformation approach. (b) Simulated electric field distribution. (c) Simulated coupling efficiency as a function of wavelength for different configurations.

ing improvement in efficiency. Optimization in design parameters will help further improve the performance.

3. Summary

In conclusion, we proposed an efficient and compact InP output coupler design. Tapers based on transformation optics were designed and simulated for improved coupling efficiency. Etched air holes were designed to approximate the required material property and shown to improve the coupling efficiency significantly. This output coupler design has the potential to significantly improve coupling efficiency from lasers and optical fibers to high index contrast waveguides.

References

1. Z. Wang, B. Tian, M. Pantouvaki, W. Guo, P. Absil, J. Van Campenhout, C. Merckling, and D. Van Thourhout, “Room-temperature InP distributed feedback laser array directly grown on silicon,” Nat. Photon. **9**, 837-842 (2015)
2. F. Van Laere, M. Ayre, D. Taillaert, D. Van Thourhout, T. F. Krauss, and R. Baets, “Compact and efficient fiber-to-waveguide grating couplers in InP-membrane,” Proc. SPIE 6182, Photonic Crystal Materials and Devices III, 61820W (April 18, 2006)
3. L. Chen, L. Zhang, C. R. Doerr, N. Dupuis, N. G. Weimann, and R. F. Kopf, “Efficient Membrane Grating Couplers on InP,” IEEE Photon. Technol. Lett. **22**, 890–892 (2010).
4. S. Keyvaninia, G. Roelkens, D. V. Thourhout, C. Jany, M. Lamponi, A. L. Liepvre, F. Lelarge, D. Make, G.-H. Duan, D. Bordel, and J.-M. Fedeli, ”Demonstration of a heterogeneously integrated III-V/SOI single wavelength tunable laser,” Opt. Express **21**(3), 3784-3792 (2013).
5. N. Kobayashi, K. Sato, M. Namiwaka, K. Yamamoto, S. Watanabe, T. Kita, H. Yamada, and H. Yamazaki, “Silicon Photonic Hybrid Ring-Filter External Cavity Wavelength Tunable Lasers,” J. Lightwave Technol. **33**(6), 1241-1246 (2015).
6. P. Contu, C. Stagarescu, A. Behfar, and J. Klamkin, “3D integrated silicon photonic external cavity laser (SPECL),” in Photonics Conference (IPC), 2014 IEEE , pp. 258-259.
7. B. Song, P. Contu, C. Stagarescu, S. Pinna, P. Abolghasem, S. Ristic, N. Bickel, J. Bowker, A. Behfar, and J. Klamkin, “3D integrated hybrid silicon laser,” Optical Communication (ECOC), 2015 European Conference on, Valencia, 2015, pp. 1-3.
8. P. Tichit, S. Burokur, and A. de Lustrac, “Waveguide taper engineering using coordinate transformation technology,” Opt. Express **18**, 767-772 (2010).
9. P. Markov, J. Valentine, and S. Weiss, “Fiber-to-chip coupler designed using an optical transformation,” Opt. Express **20**, 14705-14713 (2012).