First-Order Mode Compact Focusing Grating Coupler for SOI Interconnect

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Abstract—**Compact on-chip grating coupler for first-order TE-like mode in a strip waveguide is proposed. The grating coupler is used in mode-division multiplexing (MDM) systems to couple light from a single-mode fiber to desired on-chip mode without the need of intermediate mode converters.**

Index Terms—**First-order mode, grating coupler, mode-division multiplexing, strip waveguide.**

I. INTRODUCTION

Silicon photonics has allowed a new era of on-chip optical devices and interconnects. Due to the high index contrast between silicon dioxide (SiO_2) cladding and silicon (Si) waveguide, the light is strongly confined to a very small area which allows high density chips to be realized [1]. However, it raises the problem of high modal mismatch between fiber core and on-chip sub-micron cross-sectional waveguide.

Diffractive grating couplers have been proposed for the first time in 1970s [2] and since then it becomes the most widely used method to couple light from fiber to on-chip waveguide and vice versa. To reduce the footprint, a focusing grating coupler has been proposed [3], [4]. In this case, light is focused directly to the center of the waveguide which reduces the required taper length to a few tens of micrometers.

Previously proposed grating couplers offer coupling to/from the fundamental mode on the waveguide with coupling efficiencies above $90\%(0.5\,\mathrm{dB})$ at $1550\,\mathrm{nm}$ with different grating profiles and materials [5], [6].

Coupling to/from higher-order modes is becoming essential to enable testing and investigation of MDM devices without the need for intermediate mode converters.

In this paper, we propose a grating coupler (GC) that couples light from/to the fundamental mode in an optical fiber to/from the first-order TE-like mode in a strip waveguide. It is worth mentioning that the procedure followed in this paper is expendable to higher-order modes as well.

II. LINEAR GRATING COUPLER DESIGN

As the grating width must be comparable to the fiber core diameter to couple the maximum amount of light out from fiber, we can deal with grating region as a slab waveguide. For a GC to first-order mode, both teeth and slot regions are designed to support 2 modes: fundamental and first-order TE-like modes. Figure 1(a) shows the proposed GC, where h_1 and h_2 are the heights of silicon region in tooth and slot regions,

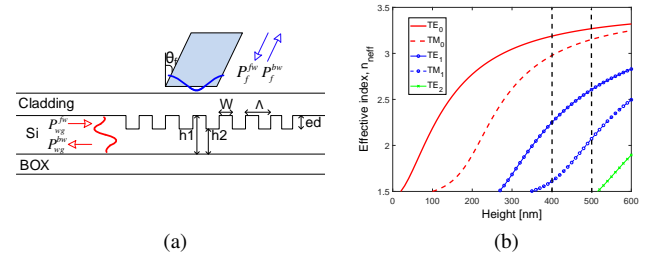respectively. The etch depth is defined as ed $= h_1 - h_2$. The

Fig. 1: (a) Schematic diagram of proposed GC. (b) Mode chart at wavelength $1550\,\mathrm{nm}$ of a slab waveguide.

fill factor of the GC is defined as ff $= w/\Lambda$, where w is the tooth width and Λ is the grating period. The fiber polish angle is θ_f. The Bragg law for constructive interference is [3]:

$$\beta = k_0 n_c \sin(\theta_c) - \frac{2\pi m}{\Lambda}, \qquad (1)$$

where n_c and θ_c are the refractive index and coupling angle in cladding, respectively, m is the Bragg order, and $\beta = 2\pi n_{\mathrm{eff}}/\lambda_0$ is the mode propagation constant in waveguide. Here, λ_0 is the free space wavelength and n_{eff} is the effective index of the grating region for the first-order mode, given by:

$$n_{\mathrm{eff}} = \mathrm{ff} \cdot n_{\mathrm{eff}1} + (1 - \mathrm{ff}) \cdot n_{\mathrm{eff}2}, \qquad (2)$$

where $n_{\mathrm{eff}1}$ and $n_{\mathrm{eff}2}$ are the effective indices of the first-order mode in two slabs with heights h_1 and h_2, respectively. A cladding layer is often employed to protect the device, as shown in Fig. 1(a). However, for some applications such as bio-sensing, air cladding is required.

For an input GC, the coupling efficiency is defined as the ratio between the power coupled into the first-order mode in the waveguide P_{wg}^{bw} and the power in the fundamental TE mode in the fiber P_f^{fw}. Here, fw and bw denote the forward and backward propagation directions, respectively. The insertion loss (IL) and return loss (RL) are defined by:

$$\mathrm{IL} = 10 \log 10 \left(\frac{P_{\mathrm{wg}}^{bw}}{P_f^{fw}} \right), \quad \mathrm{RL} = 10 \log 10 \left(\frac{P_f^{bw}}{P_f^{fw}} \right). \quad (3)$$

respectively. Of course this back reflection is unwanted as it causes Fabry-Perot oscillations by reflecting back and forth between the input and output grating couplers.

The heights of both teeth and slot regions are chosen so that they support first-order mode. Mode chart for slab waveguide is shown in Fig. 1(b). To support two TE-like modes in the grating region, we should have $h_1, h_2 \geq 250$ nm. We choose $h_1 = 500$ nm and $h_2 = 400$ nm, respectively. The corresponding effective indices for the first-order mode in the two slabs is $n_{\text{eff}1} = 2.606$ and $n_{\text{eff}2} = 2.248$, respectively. Using (2) with an initial value of ff = 0.5, we get the effective index of the grating region as $n_{\text{eff}} = 2.413$.

We can choose different combinations for Λ and θ_c to achieve coupling to the first-order mode. As an initial value, we take $\theta_0 = 15°$ which is the angle in air. For a SiO$_2$ cladding with effective index 1.444, the angle in the cladding will be $\theta_c = 10.32°$. This value corresponds to a grating period of $\Lambda = 720$ nm.

2D-FDTD simulation is performed to prove the concept and optimize the coupler parameters as it takes much less computational memory and simulation time. A linear sweeping has been performed for different parameters to choose the best coupling efficiency. With all parameters chosen to get the best coupling efficiency at 1550 nm, the coupling efficiency of the input GC is $53.4\%(-2.725\,\text{dB})$ with back-reflection less than $0.29\%(-25.4\,\text{dB})$, Fig. 2. In this case, the coupling efficiency to TE$_0$, TM$_0$, and TM$_1$ has a maximum value of 0.4%. The taper length required to connect a $12\,\mu\text{m}$ grating to a strip waveguide of 600 nm width is estimated to be hundreds micrometers [3], [4], which increases the footprint significantly.
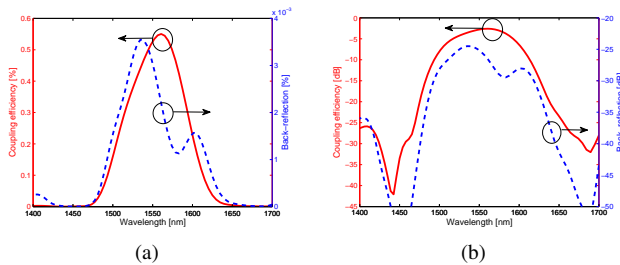

Fig. 2: Input GC coupling efficiency and back-reflection with $1\,\mu\text{m}$ air-spacing between clad and fiber.

III. FOCUSING GRATING COUPLER

To keep the footprint of the grating coupler small, some curvature is introduced to the grating lines. According to the idea demonstrated in [3], a linear grating coupler can be transformed into a compact shape using focusing gratings. This can be done by curving the grating lines to take the form of confocal ellipses with the output waveguide at the focus. The grating lines follow the relation:

$$q\lambda_0 = zn_c \cos(\theta_c) - n_{\text{eff}}\sqrt{y^2 + z^2}, \qquad (4)$$

where q is the grating line number, z is the direction of propagation and the grating lies in the y-z plane. Figure 3(a) shows the mode chart for a strip waveguide of height 400 nm at 1550 nm. Parameters obtained from the linear grating section is used for the focusing grating. At 600 nm, the strip waveguide supports 3 HE modes. The effective index of HE$_{21}$ is 2.104, which matches the effective index in the grating region to reduce back-reflections. An input taper angle of $60°$, shown in Fig. 3(a), and a length of $3\,\mu\text{m}$ have been chosen by sweeping to get the best coupling efficiency to the single-mode fiber. The number of grating periods are found to be 19 periods with period length of 720 nm at the center of the grating, chosen from the linear grating section. A coupling efficiency of 31.7% with $1\,\text{dB}$ bandwidth of 120 nm is obtained.
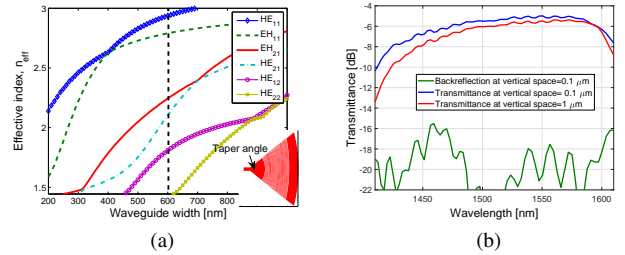

Fig. 3: (a) Mode chart of a strip waveguide at a Si height of 400 nm and a wavelength of 1550 nm. (b) Transmittance from the first-order mode in the waveguide to the fiber.

For the focusing GC, we use a single mode-fiber with core and cladding diameters of $9\,\mu\text{m}$ and $125\,\mu\text{m}$, respectively. The output light from the fiber is simulated as a Gaussian source. The focusing layout dimensions are $17\,\mu\text{m}$ length (grating, input and output tapers) and $20\,\mu\text{m}$ width, which makes it very compact.

Figure 3(b) shows the transmittance to the fiber with two values of the vertical spacing between the cladding and the fiber. As the spacing reduces to 100 nm, the transmittance is improved by $0.5\,\text{dB}$.

REFERENCES

[1] P. P. Absil, P. Verheyen, P. D. Heyn, M. Pantouvaki, G. Lepage, J. D. Coster, and J. V. Campenhout, "Silicon photonics integrated circuits: a manufacturing platform for high density, low power optical I/O's," *Opt. Express*, vol. 23, no. 7, pp. 9369–9378, 2015.

[2] M. L. Dakss, L. Kuhn, P. F. Heidrich, and B. A. Scott, "Grating coupler for efficient excitation of optical guided waves in thin films," *Appl. Phys. Lett.*, vol. 16, no. 12, pp. 523–525, 1970.

[3] Q. Zhong, V. Veerasubramanian, Y. Wang, W. Shi, D. Patel, S. Ghosh, A. Samani, L. Chrostowski, R. Bojko, and D. V. Plant, "Focusing-curved subwavelength grating couplers for ultra-broadband silicon photonics optical interfaces," *Opt. Express*, vol. 22, no. 15, pp. 18 224–18 231, 2014.

[4] Y. Wang, X. Wang, J. Flueckiger, H. Yun, W. Shi, R. Bojko, N. A. F. Jaeger, and L. Chrostowski, "Focusing sub-wavelength grating couplers with low back reflections for rapid prototyping of silicon photonic circuits," *Opt. Express*, vol. 22, no. 17, pp. 20 652–20 662, 2014.

[5] C. J. Oton, "Long-working-distance grating coupler for integrated optical devices," *IEEE Photonics J*, vol. 8, no. 1, pp. 1–8, 2016.

[6] M. Asaduzzaman, M. Bakaul, S. Skafidas, and M. R. H. Khandokar, "Compact silicon photonic grating coupler with dual-taper partial overlaybspot-size converter," *IEEE Photonics J*, vol. 9, no. 2, pp. 1–7, 2017.