Ultra-Compact Tunable Multi-Mode Converter based on Tilted Bragg Gratings in SOI Waveguides

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***Abstract*—We propose an elite mode converter using a tilted contra-directional Bragg grating in SOI strip waveguide, with merits of a compact footprint and a tunable multi-mode conversion. The device footprint is less than 10 μm, with an insertion loss less than 1 dB.**

***Index Terms*—Silicon photonics, modes, Bragg gratings**

I. Introduction

Mode converters are considered essential elements for mode-division multiplexing (MDM) systems. Various mode converters have been proposed using different approaches, such as tapers, Bragg gratings, metasurface structures, and etched polygonal trenches. However, there are some challenges like compound structure and large device footprint, which reached 60 μm when using two cascaded Bragg gratings with different designing parameters for each grating [1], and 24 μm when using polygonal slots [2], besides the complexity in arranging the dimensions and vertices of the slots. Although subwavelength gratings shrink the device length down to 7 μm [3], selecting dimensions of such a pattern, including width, tilt angle of subwavelength gratings and length, are complicated and unique for each mode order.

There is a special type of gratings at which the gratings are tilted along the transverse direction, this type of grating has been implemented in polymer waveguides to achieve power coupling between the fundamental and first-order TE modes [4]. However, multimode polymer waveguides have relatively large dimensions and are not compatible with CMOS fabrication technology.

In this paper, we propose, analyze, and optimize a simple general mode converter using a silicon strip waveguide with a tilted contra-directional Bragg grating. The most important feature in the proposed design is the validity to convert from one mode to another arbitrary mode based on a systematic and simple mathematical argument. Another feature is the ability to convert from one mode to muti-modes simultaneously at different operating wavelengths, using a single device, without any change to its design. Furthermore, it is possible to adjust the couplings with different modes at unique operating wavelength in the same device by applying thermo-optic effect on the device, in order to control the refractive index of silicon material. Recently, the same concept has been proposed in wavelength-division multiplexing systems based on a silicon grating assisted coupler, and achieved tuning shift up to 25 nm experimentally [5].

II. Device Principle

The proposed mode converter, shown schematically in Fig. 1, consists of a multimode silicon strip waveguide of width $w = 1500$ nm, height $h = 220$ nm, with grating depth $d = 60$ nm. The lower Box and the above cladding layers are made from silica (SiO_2) with a thickness of 2 μm each. This structure is compatible with SOI platform.

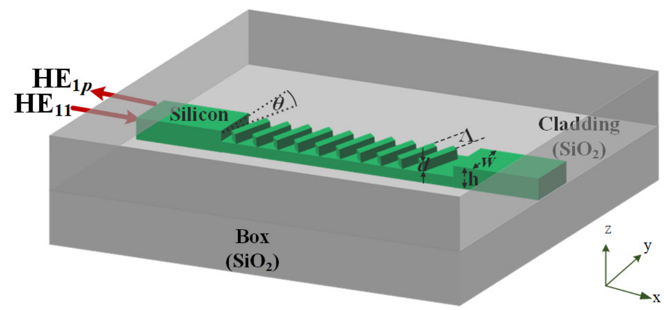

Fig. 1: Schematic structure of proposed mode converter consisting of tilted Bragg gratings on SOI.

Basically, coupling between mode number μ and mode number ν depends on two main factors. The first one is the phase matching condition: $\beta_\mu + \beta_\nu = 2\pi/\Lambda$, where β_μ and β_ν are the propagation constants of modes number μ and ν, respectively, and Λ is the period of the grating. The second factor is the coupling coefficient, $\kappa_{\mu,\nu}$, which can be expressed in a normalized form as follows [4]:

$$\kappa_{\mu,\nu} = \frac{\iint \psi_\mu^*(y,z) e^{i2\pi y \tan(\theta)/\Lambda}\ \psi_\nu(y,z) dydz}{[\iint |\psi_\mu(y,z)|^2 dydz \cdot \iint |\psi_\nu(y,z)|^2 dydz]^{1/2}}, \quad (1)$$

where ψ_μ and ψ_ν represent the electric field profiles of the two coupled modes and θ is the tilt angle of the grating plates with respect to the y-axis. It should be noticed that the integration in the numerator is performed in the perturbed region only in the y-z plane, whereas in the denominator, the integral involves the whole transverse plane.

III. Numerical Results

In this section, 3D-FDTD simulation is performed to investigate the performance of the proposed device.

We start by optimizing the parameters of the tilted grating. First, Λ is calculated properly to satisfy phase matching

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between the two selected modes, knowing their respective propagation constants.

Next, knowing the field profiles of these modes, $\kappa_{\mu,\nu}$ is obtained from (1) for different values of θ. Figure 2 represents the relation between $\kappa_{\mu,\nu}$ and θ for a set of output modes, HE_{1i}, where $i \in \{1, 2, \ldots, 5\}$. It is obvious that, the variation of coupling coefficients depicts not only the grating effect, presented by the exponential function argument in (1), but also the field profile of the tested modes inside the grating region. Both factors produce the kind of periodicity change with nulls and peaks at different tilt angles.

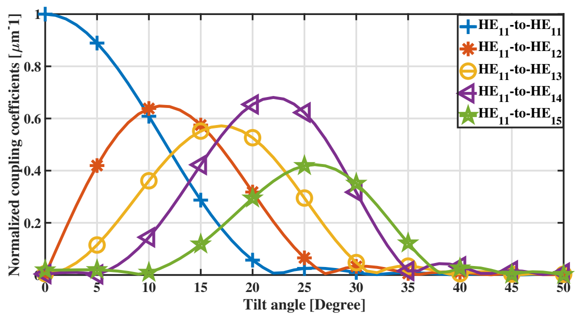

Fig. 2: Normalized coupling coefficients between fundamental HE_{11} and HE_{1i} versus grating tilt angle.

It is found that for each output mode there is an optimal value θ_{opt}, at which the coupling coefficient is maximized. This optimal value of tilt angle increases with the mode order. Moreover, multiple couplings can be found at any tilt angle larger than zero, consequently it is expected to get multiple mode converters through a single device. However, owing to the phase matching condition, those couplings occur at different operating wavelengths.

The total number of gratings N is then determined using 3D-FDTD sweep to return the maximal reflection output, and consequently the corresponding device length L can be directly calculated. For the sake of simulation, we choose to design a mode converter that converts from HE_{11} to HE_{13} at operating wavelength of 1550 nm, by following the previously illustrated procedures, the design parameters are Λ = 318 nm, θ°_{opt}= 16°, N = 28 and L = 9.33 μm. It is worth noticing the very short length of the proposed device compared with that of traditional-grating-based and tilted-thick-trench-based converters, respectively [1], [2]. In addition, the simulated reflection spectrum of the tested mode converter is shown in Fig. 3. It is also clear that transmission losses are limited to 0.9 dB, and the corresponding crosstalks (due to other guided modes) is -15.7 dB, for HE_{11}-to-HE_{13} converter at 1550 nm.

It is worth noticing that the proposed device offers multi-mode converter with different central wavelengths, as shown in Fig. 3, that can match the wavelength grid of MDM systems. If one needs to manipulate mode converter at a single wavelength, e.g., 1550 nm, the wavelength adjustment is implemented by tuning the spectrum via thermal power. This

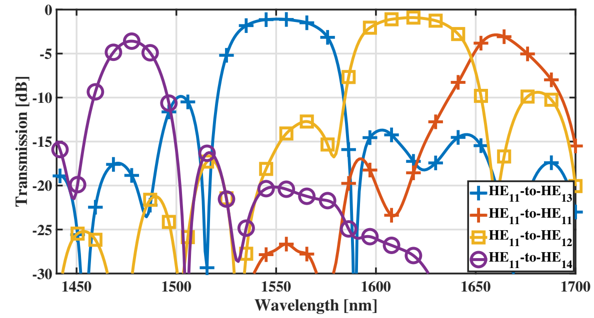

Fig. 3: Simulated reflection spectra: for HE_{11}-to-HE_{13}.

thermal power affects the refractive index of silicon waveguide, and subsequently a red shift appears in its spectrum.

IV. Conclusions

A backward HE multi-mode converter based on tilted Bragg gratings has been proposed. The tilted gratings have been designed to obtain a high coupling efficiency between the fundamental mode and different spatial modes. The proposed structure has been simulated via 3D-FDTD. Our proposed mode converter is of short length (< 10 μm), low transmission loss (~ 1 dB), and low modal crosstalk (≤ -15 dB).

Moreover, our proposed design obtains not only a mode converter with good spectral range and relatively short length, compared with previously proposed configurations, but also the luxury of using the same device as muti-mode converter, whether at different operating wavelengths, by default, or at same operating wavelength by controlling the spectrum thermally.

Acknowledgment

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