Efficient Tapering to the Fundamental Quasi-TM Mode in Asymmetrical Waveguides

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Abstract—**The tapering problem of the fundamental quasi-TM mode in thin asymmetrical waveguides is investigated. Mode conversions are found to be at the origin of the failing adiabatic tapers. We propose and investigate three non-adiabatic taper solutions, a focusing grating coupler, a lensed taper and a discontinuous taper, which circumvent these mode conversions.**

Keywords-taper; quasi-TM; polarization; integrated photonics; asymmetrical waveguide; Silicon Photonics;

I. INTRODUCTION

Optical waveguides are the fundamental building blocks of integrated photonic devices. Besides waveguide loss, substrate loss, optical confinement and footprint one has to deal with polarization issues when designing a waveguide. In high index contrast platforms such as Silicon-On-Insulator (SOI), thin (subwavelength) waveguides are used resulting in quasi-polarized modes which differ substantially in effective refractive index (birefringence), optical confinement and waveguide loss. Besides the traditional optical communication application for integrated circuits where polarization diversity is required, interest in using the quasi-TM polarization is rising. One advantage is that because of a weaker optical confinement and because of a large evanescent field at the top of the waveguide, the quasi-TM mode is more suited for field interactions with deposited and bonded materials or for biosensing [1]. Another example is where the quasi-TM polarization is used to excite plasmons in a gold clad layer [2]. All these applications can result in highly asymmetrical waveguide structures. The problem is that asymmetrical waveguide circuits, unlike symmetrical ones, don't transmit any quasi-TM polarized light if adiabatic tapering from a multi-mode waveguide to a single-mode waveguide is present.

II. ADIABATIC MODE CONVERSIONS

All calculations have been performed for an SOI strip waveguide with a thickness of 220nm. When the top cladding of the waveguide is equal to the bottom cladding, we speak of a symmetrical waveguide. This vertical symmetry introduces a plane along which the mode is purely polarized, resulting in quasi-TE and quasi-TM modes. For waveguides where top and bottom cladding are different or in the case of a rib waveguide,

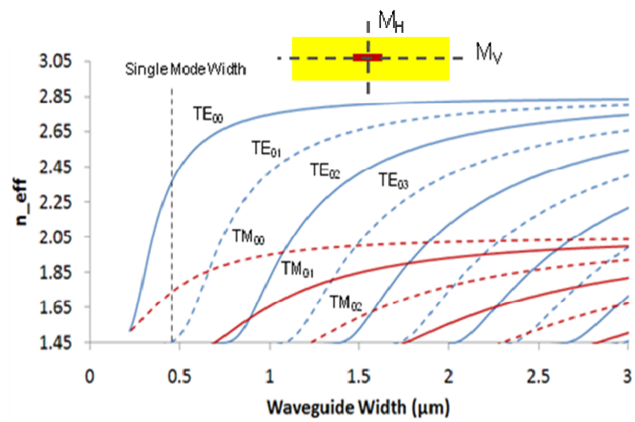

Figure 1. Adiabatic Mode Profile of a symmetric waveguide.

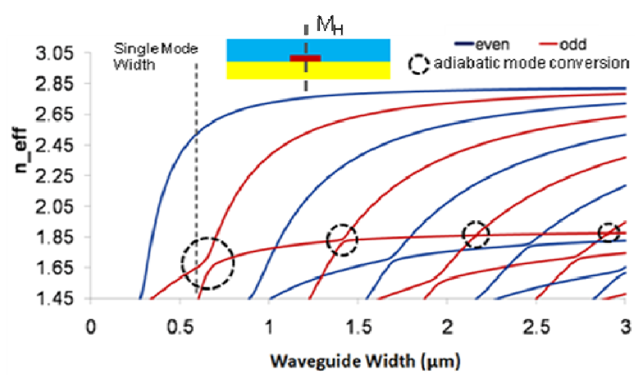

Figure 2. Adiabatic Mode Profile of an asymmetric waveguide.

the symmetry is broken and one cannot make a distinction between different quasi-polarized modes. As a convenience we shall use quasi-polarized mode naming in these asymmetrical waveguides referring to the quasi-polarized counterpart of the mode in the symmetrical case. Fig. 1 and 2 show the effective refractive index as a function of the waveguide width for all guided modes of respectively a symmetrical waveguide and asymmetrical waveguide. In a symmetrical waveguide two symmetry planes are present by which the modes can be classified. Using the vertical symmetry (M_V), modes are split into quasi-TE and quasi-TM modes. The horizontal symmetry (M_H) subdivides these polarizations into even and odd modes. In an asymmetrical waveguide the symmetry plane for quasi-polarization classification disappears such that quasi-TE and quasi-TM modes can couple to each other in adiabatic tapers. The circles in Fig. 2 show the mode conversions from the fundamental quasi-TM mode to higher order quasi-TE modes. The latter are not guided in a single-mode waveguide what explains the breakdown of adiabatic tapering.

III. Non-Adiabatic Tapers

We will investigate different solutions which circumvent the mode conversion problem for tapering to the fundamental quasi-TM mode in an asymmetrical strip waveguide.

A. *Focusing Fiber-To-Chip Grating Coupler*

With a focusing grating coupler, see Fig. 3(a), one can couple and at the same time focus the light into a photonic wire [3]. This approach is experimentally verified and an efficiency of 13% is demonstrated for coupling from an optical fiber to the fundamental quasi-TM mode of a 220nm thick SOI single-mode photonic 500nm wire. The etch depth of the grating is 70nm and the top cladding is air, making the waveguide highly asymmetrical. The 1dB and 3dB bandwidth were respectively 45nm and 80nm.

B. *Lensed Focusing Taper*

Another way of avoiding the mode conversion problem due to adiabatic tapering is to use a focusing effect as is done in focusing grating couplers. This focusing effect can also be obtained by using in-plane lenses. These lenses can for example be fabricated in silicon using doping or by etching. The lenses considered here are made by etching 70nm of the 220nm high silicon area as shown in Fig. 3(b). Since the effective index of the etched area is smaller, a focusing lens has a concave shape. One can now design bi-concave and plano-concave lenses. From lensing theory it is known that the latter result in fewer aberrations when using them for focusing purposes. 2D effective index FDTD simulations were performed for focusing from a 10µm waveguide to a 450nm waveguide using bi-concave lenses. For a radius of curvature ranging from 5µm to 10µm, the focal length ranges from 9µm up to 23µm and the efficiency increases from 85% up to 90% respectively. The use of plano-concave lenses roughly doubles the focal distance but no significant improvement in efficiency was seen. The increase in efficiency for larger focal distances can be explained due to matching of the focused light to the diffraction of a 450nm waveguide. 3D-FDTD simulations were performed as well but these show a decrease in efficiency to about 30%. This is mainly due to the etch step which will scatter the light since the TM mode has the largest field intensity at the top and the bottom of the waveguide.

C. *Discontinuous Taper*

By avoiding the waveguide widths in a taper for which mode conversions take place, one can design a discontinuous taper as shown in Fig. 3(c). By optimizing the waveguide widths of the discontinuous sections of the taper with a 3D vectorial mode solver, 90% efficiency has been obtained for tapering from a 10µm waveguide to a 450nm waveguide of the fundamental quasi-TM mode.

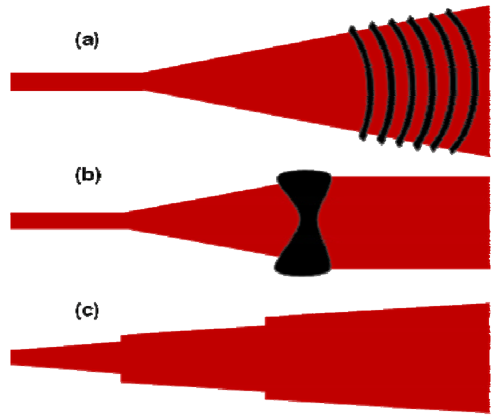

Figure 3. Non-Adiabatic tapers: (a) Focusing Grating Coupler (b) Lensed Focusing Taper (c) Discontinuous Taper

IV. Conclusion

We have found that asymmetrical adiabatic tapers exhibit a lot of mode conversions and are unsuitable for tapering of the fundamental quasi-TM mode. 13% coupling efficiency has been measured for a focusing grating coupler that couples and focus the light into a single-mode waveguide. 2D and 3D-FDTD simulations predict respectively 90% and 30% taper efficiency for a lensed focusing taper. According to 3D vectorial mode solving, an optimized discontinuous taper can have 90% taper efficiency. In symmetrical waveguides, process variations can break the symmetry resulting in mode conversions. In general one should avoid the waveguide widths near a mode conversion. For the same reason it is desirable to not make an adiabatic taper unnecessary long for symmetrical waveguides.

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