Adiabatic transitions for sub-wavelength grating waveguides

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***Abstract*—Sub-wavelength gratings (SWG) enable refractive index engineering in silicon waveguides, with application spanning from fiber-to-chip grating couplers to wavelength demultiplexers. However, the design of adiabatic tapers between these waveguides is challenging and non-intuitive. In this work, a systematic method for designing adiabatic transitions between SWGs is presented for the first time**

Keywords; taper, silicon-on-insulator, Bragg, SWG.

I. INTRODUCTION

Silicon-on-Insulator is emerging as a major fabrication platform for integrated optics, owing to its high contrast that enables compact and highly integrated devices. Recently a new type of silicon waveguide, the Sub-wavelength Grating (SWG), was presented [1]. SWG waveguides are periodic structures with a pitch smaller than wavelength. Diffraction can thus not take place in these structures. The main advantage of these waveguides is that they allow the designer to engineer the effective refractive index in a wide range [1,2]. The refractive index implemented by SWG waveguides depends on the geometrical parameters of the structure (width (*W*), pitch (Λ) and duty cycle (*DC*)), the operation wavelength (λ) and light polarization. In order to work in SWG zone, the pitch of the structure must be smaller than the first order Bragg period, given by:

$$\Lambda < \Lambda_{Bragg} = \lambda / (2 \cdot n) \quad (1)$$

Where *n* is the effective index of the Bloch mode propagating through the structure. While working in SWG zone these structures behave like common waveguides, exhibiting no diffraction effects and low losses.

The use of SWGs has been demonstrated in many applications such as efficient fiber-to-chip couplers [3], mode converters [1], crossings between waveguides [4], arrayed waveguide grating multiplexers [5] and high performance MMIs [6]. Extensive use of SWG waveguides in device design requires adiabatic transitions (tapers) between conventional waveguides and SWGs. However, as illustrated in the following sections, the design of such transitions is challenging and non-intuitive, as significant back-reflections that grow with the taper length can occur. Here we present, for the first time, a systematic method for designing adiabatic SWG tapers. The paper is organized in five sections. In section II the proposed taper structure is described. In section III we detail why a conventional, linear taper is not always an appropriate solution, and present and validate our method for designing SWG tapers. Finally, in section IV the main conclusions are drawn.

II. TAPER STRUCTURE

We consider the general taper structure shown in Fig. 1. This structure is a transition between a silicon wire and a SWG waveguide of a different width. Note that a transition between two SWG waveguides of different widths is a particular version of this structure. Here, w_1 and w_4 are the widths of the silicon wire and the SWG waveguide respectively. The pitch of the SWG waveguide (Λ) and the duty cycle ($DC = b/a$) have been assumed constant along the structure. The parameters of the taper are w_3 and $CoreDC = w_2/w_1$, which are functions of the propagation direction (*z*). In Fig. 1 w_3 and *CoreDC* vary linearly with *z*. This taper shape avoids small gaps that would result from simple changing the duty cycle of the SWG from 1 to b/a.

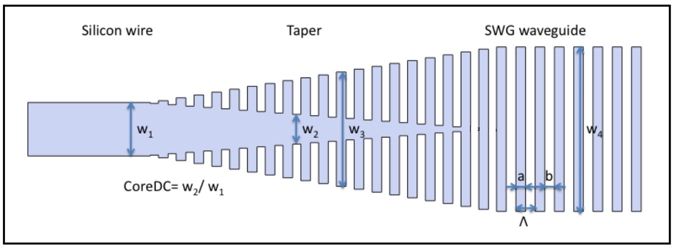

Figure 1. Structure of a taper between a silicon wire and a SWG waveguide.

The analysis has been carried out for TE (in-plane) polarization and using a 2D model obtained through the Effective Index Method. The resulting 2D model has been simulated with the Fourier Eigenmode Expansion Method combined with Bloch mode analysis [7].

III. Design Methodology

The problem can be formulated as the election of the functions *CoreDC*(z) and $w_3(z)$ that maximize power transmission from the silicon wire to the SWG waveguide. The dimensions used in the following design example are w_1 = 0.5µm, w_4 = 3.5µm, Λ = 0.28µm and $a = b$ = 0.14µm. With these values, and a working wavelength of λ = 1.55µm, the SWG waveguide exhibits no diffraction effects.

A. Linear taper

The first approach to the solution is to choose *CoreDC* and w_3 linear functions. Fig. 2 (green line with square markers) shows the taper transmission versus length. Unlike common tapers, transmission reduces as the taper length is increased. This undesirable behavior is caused by the entering of the taper structure in the Bragg zone at some point of its trajectory, causing high-backreflections. In order to avoid this, *CoreDC*(z) and $w_3(z)$ must be designed properly.

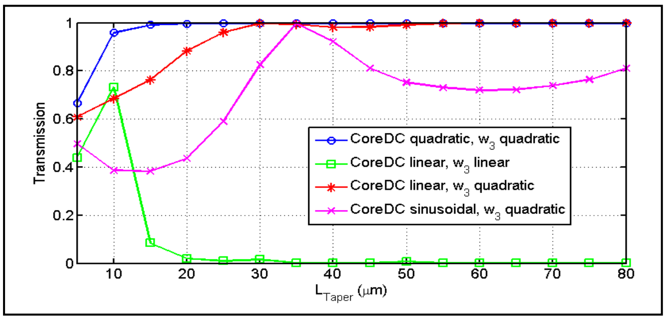

Figure 2. Transmission curves of the designed tapers as a function of length.

B. Choosing adequate shape functions

To minimize back-reflections from the taper, the design method must guarantee an adiabatic transition, while at the same time avoiding the Bragg regime at any point of the taper. Thus, in a first step, a Bloch modal analysis for each combination of *CoreDC* and w_3 is carried out, in order to identify which combinations avoid the Bragg regime. Fig. 3 represents the reflectivity of Bloch mode for each combination of *CoreDC* and w_3. The white area contains the combinations of *CoreDC* and w_3 that yield no reflection, whereas the black area contains the combinations that produce high reflections. The upper-left corner represents the silicon wire waveguide (w_1 = 0.5µm, *CoreDC* = 1), while the lower-right corner represents the SWG waveguide (w_4 = 3.5µm, *CoreDC* = 0). The taper design must connect those points avoiding the high-reflectivity zone. It can be seen how the linear taper goes through the high-reflectivity zone, which explains its spurious behavior.

As an alternative to the linear taper three different tapers are designed, each one avoiding the Bragg zone. The first one varies sinusoidally in *CoreDC* and quadratically in w_3, the second one varies linearly in *CoreDC* and quadratically in w_3, and the third one quadratically in *CoreDC* and in w_3. Their trajectories can be seen in Fig. 3.

To evaluate the performance of the three taper designs, their transmissions are calculated as a function of the length of the taper. In Fig 2 it can be seen that the taper whose trajectory is furthest apart from the Bragg zone (*CoreDC* quadratic, w_3 quadratic) has a better behavior than the other two, obtaining a full transmission with a length of L_{Taper} = 20µm. The proximity to the Bragg zone in the trajectory of the other two tapers (*CoreDC* linear, w_3 quadratic and *CoreDC* sinusoidal, w_3 quadratic) explains their poor behavior.

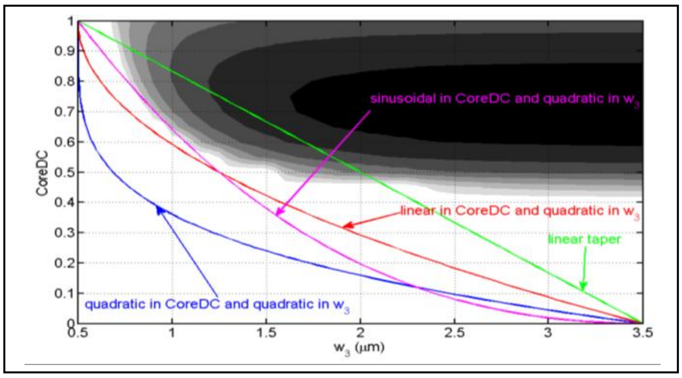

Figure 3. Reflectivity map of a SWG waveguide as a function of CoreDC and w_3 and the trajectories of the designed tapers.

IV. Conclusions

In this work, a systematic method for the design of adiabatic tapers between SWG waveguides has been presented. Our design example focused on a transition between a Si-wire waveguide and an SWG, but the methodology is general and can be readily applied to any SWG transition.

Acknowledgments

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