

Improved Modeling of an InP-Based Spot-Size Converter

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Integrated Spot-Size Converters (SSCs) are crucial for reducing the coupling loss between InP-based Photonic Integrated Circuits and optical fibers. Previously we reported a novel 2D simulation tool for SSCs based on the continuous limit of the Coupled-Mode Theory. In this paper we present the 3D extension of this model. This model is illustrated with a SSC structure in which the vertically etched taper is replaced by a laterally tapered layer in the upper part of the converter, which is easier from a fabrication point of view.

Introduction

For III/V semiconductor optical integrated circuits fiber-chip coupling is a bottleneck. SSC, used to adapt the spot-size of the waveguide on the chip to the spot of a single mode fiber, are promising for bringing down the packaging costs of such IC, for a review see [1].

In a SSC the effective refractive index changes strongly, also the index contrast is high. This combination makes it difficult to simulate SSC converters with Beam Propagation Models (BPMs).

An other scheme works with eigen-mode propagation in a piecewise uniform approximation of the structure, see [2]. Previously we have discussed the continuous limit of this model in the 2D case see [3,4]. Here we will extend the simulations to the 3D case.

Model

We take the propagation of the light in the z direction. The field profile $\Psi(z)$ is given by,

$$\Psi(x, y, z) = \sum_i a_i \psi_i(x, y) \quad (1)$$

Here a_i stands for the complex amplitude of mode ψ_i , which includes the phase information. The summation runs over the number of modes. In a non-uniform

$$\frac{\partial a_i}{\partial z} = -i\beta_i a_i - \sum_j \left\langle \frac{\partial \psi_j}{\partial z} \middle| \psi_i \right\rangle a_j \quad (2)$$

waveguide the propagation of the field is governed by,

Here β_i stands for the propagation constant of the i^{th} mode and $\langle \psi | \phi \rangle$ stands for the overlap integral between ψ and ϕ . This is the continuous version of the Coupled-Mode

theory. Equation (2) is the basis of the simulation tool we developed for SSCs. The interpretation of Equation (2) is that changes in the modal field couple to the other modes.

The simulation tool first computes for every mode the overlap of the z derivative of the modal field with the other modes for a number of points along the taper. To compute the modes we use the 2D bend mode solver from BBV software. Finally, we numerically integrate Equation (2) using a Runge-Kutta scheme. This scheme is implemented in Selene from BBV software using the provided scripting tool.

Mode labeling

The coupled-mode theory uses the modal profiles and their derivatives, the modes must be labeled in such a way that modal profiles will not be interchanged. When a 2D waveguide is deformed a mode labeling on bases of the effective index will not do, because two modes with distinct modal profile can exchange order in effective index. This is illustrated in Fig. 1.

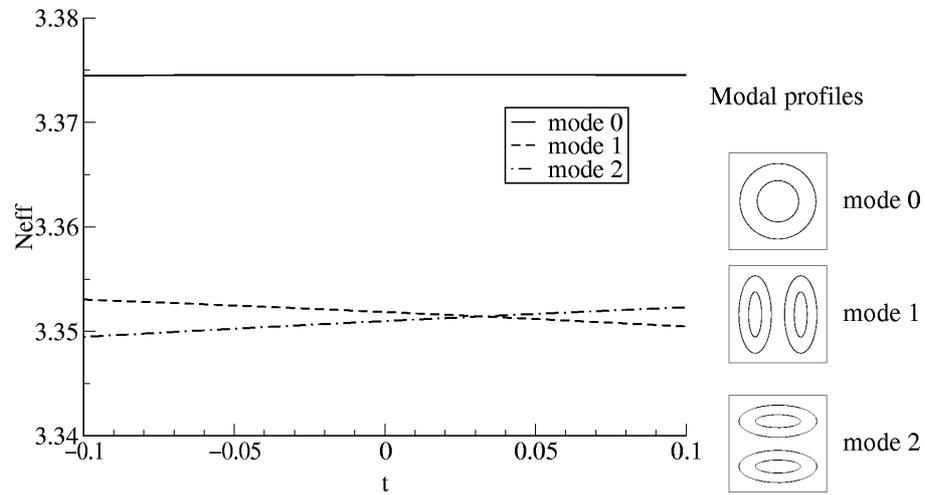


Figure 1: Modes in rectangular waveguide of various aspect ratios.

In Fig. 1 for a rectangular waveguide with a refractive index of 3.39, a background index of 3.17, a width of $3+t$ and a height of $3-t$, the first three modes are calculated for $-0.1 < t < 0.1$. It can be seen that the mode with two maxima in the horizontal direction has a higher effective index than the mode with two maxima in the vertical direction, for t smaller than 0.032. For t larger than 0.032 this relationship is reversed. The fact that the crossing of the effective index of the first and second order mode is located at $t=0.032$ instead of at $t=0$ is due to the fact that the TE polarization breaks the symmetry between the lateral and transversal direction.

The labeling of the modal profiles can be done by following the effective index of the modes along the SSC and using the linear extrapolation of the effective index to label the modes. Alternatively the modes in an every cross-section can be overlapped with the

modes in the previous cross-section. The first method is much more efficient from a calculation point of view.

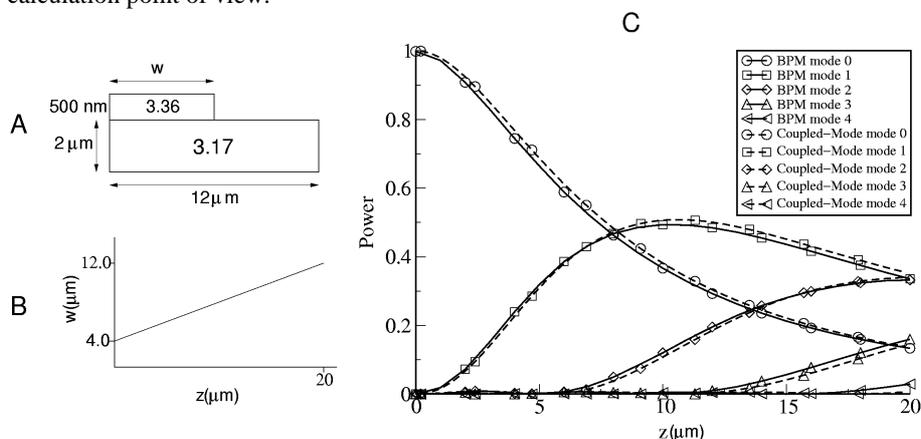


Figure 2: In A) the cross section of the waveguide structure is shown. B) shows the width of the upper layer as a function of the position. C) shows the simulation results for a BPM and the Coupled-Mode Theory.

Test of Model

As a test we simulated the power in 5 of the modes in a waveguide structure as shown in Fig. 2A. The upper layer is asymmetrically tapered from 4 μm to 12 μm in 20 μm, see Fig. 2B. Here the core index was 3.36 and the index of the block below the core was 3.17. The simulation was done for TE polarized light of 1.55 μm. We compared the results with a five mode analyses of the field computed by a BPM for the same taper. The agreement is almost perfect as can be seen in Fig. 2B.

Simulation of SSCs

Our SSC, as shown in Fig. 3A, consists of a 600 nm InGaAsP(1.3) waveguide layer with refractive index 3.39. On a N-doped InP ($n_{N-InP}=3.15$) substrate a 5 μm undoped InP ($n_{InP}=3.17$) layer is deposited, which can form a waveguide which is matched well to a glass fiber mode when a 15 μm wide and 5 μm deep ridge is etched. With a 2D mode solver we find that the coupling loss from this large waveguide to a single mode fiber (gaussian spot half-width of 5 μm) is 1.5 dB. Previously [5,6] we have used a vertical taper in the film layer to make the transition between the normal, high contrast, waveguide to the fiber matched waveguide. This approach was hindered by inhomogeneities in the fabrication of the vertical taper. Therefore we would rather use a lateral taper which could simply be fabricated by a normal dry etch.

To simulate the performance of a SSC we use the 3D Coupled-Mode. In this case a 3D BPM will need a very fine grid because large field changes will take place in small width changes as will be shown. Three modes are used in the computation. The results for both TE and TM light of 1.55 μm are shown in Fig. 3B. Fig. 3A shows the taper profile used. In the region of the lateral taper the fiber-matched waveguide is reduced to a width of 4 μm. This is done to increase the effective index difference between the

modes and thereby reducing the coupling. After the lateral taper the fiber-matched waveguide is tapered up to $14\ \mu\text{m}$ such that it matches optimally to a fiber.

Because most of the spot-size conversion takes places between a width of $0.9\ \mu\text{m}$ and $0.7\ \mu\text{m}$, as can be seen in Fig. 3B, this design will not be tolerant to changes in the waveguide width due to the photo lithography. The tolerances could be relaxed by incorporating an $600\ \text{nm}$ InGaAsP(1.1) layer below the normal layer and first taper the normal film away such that the light is forced into this additional layer. Followed by a lateral taper in this InGaAsP(1.1) layer such that the light is forced into the fiber matched waveguide. This would, at the expense of an additional mask and etch step, increase both the fabrication tolerances and the efficiency of the SSC.

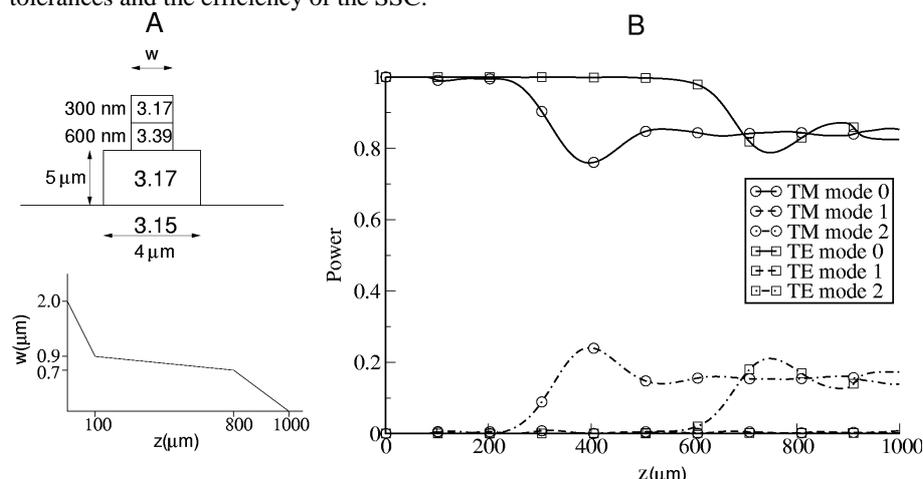


Figure 3: Structure and simulation of lateral SSC.

Discussion

We have shown that a continuous 3D version of the Coupled-Mode theory can be used to simulate SSCs. We have shown that this approach is equivalent to a BPM for simple structures.

References

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