A Versatile Spot-Size Converter Design

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A sequence of non-periodic waveguide segments can form a versatile photonic spot-size converter after a necessary parameter optimisation. Optical waveguides with different horizontal cross-sections can be coupled in a compact way but a ground mode can also be transformed in a more general excitation of a multimodal waveguide. An experimental demonstration in Silicon-on-insulator (SOI) is given.

Introduction

Within future photonic integrated circuits (PIC's), waveguides with different cross-sections are likely to coexist. Some functions, especially those depending on non-linearities, need huge power densities and benefit from a waveguide with a small cross-section, often called a photonic wire, whereas interconnection waveguides typically require a larger cross-section due to smaller propagation losses. To keep the overall component footprint small, the coupling between non-identical waveguides should also be kept as short as possible. Nowadays adiabatic tapers (both linear and parabolic) are frequently used to achieve good coupling, see Fig. 1, but need to be very long, to guarantee the adiabatic transition. Non-adiabatic waveguide tapers, also see Fig. 1, have already been demonstrated in optical waveguides with a low refractive index contrast [1]. The work presented here brings the same principle to a high refractive index contrast material system, such as SOI. These material systems are promising candidates for the realisation of PIC's because they offer better light confinement and therefore smaller optical components. An additional advantage of the coupler scheme used here is the possibility to efficiently convert a random multimode waveguide excitation into a single-mode excitation, something an adiabatic taper can not accomplish.

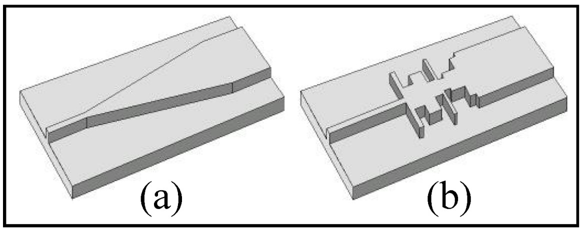

Fig. 1: Scheme of an adiabatic taper (a) and a compact spot-size converter (b).

2-D simulations

As high refractive index contrast easily leads to reflection, a non-paraxial and bi-directional simulation method is necessary to calculate these structures. For speed reasons and easy modal analysis an Eigenmode Expansion (EME) frequency domain method was chosen above a Finite Difference Time Domain (FDTD) method. CAMFR [2] was used, after an effective index transformation on a typical SOI layer structure (0.22 *μm Si*/ 1.0 *μm silica*/

Si-substrate), resulting in an effective index of the core of 2.83 for a wavelength of 1.56 μm. For the TE-mode, the dominant electric field component is parallel to the substrate.

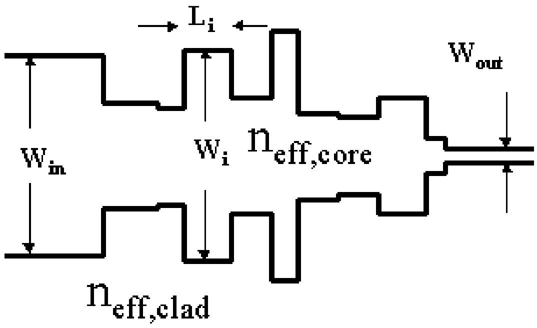

Fig. 2: Scheme of the structure to optimise.

The first configuration studied is the coupling between a broad 10 μm SOI waveguide and a narrow 0.56 μm SOI wire, see Fig. 3. N different waveguide segments lead to a 2N-dimensional [L_1,...,L_N,W_1,...,W_N] parameter space to be searched for optima. Two different optimisation algorithms have been applied: a genetic or evolutionary algorithm and an iterative steepest-descent method. The genetic algorithm starts by generating a set of random structures with as only constraints upper and lower limits for the parameters L_i and W_i. These structures form the starting point for the rest of the genetic calculations. A result is shown in Fig. 3.

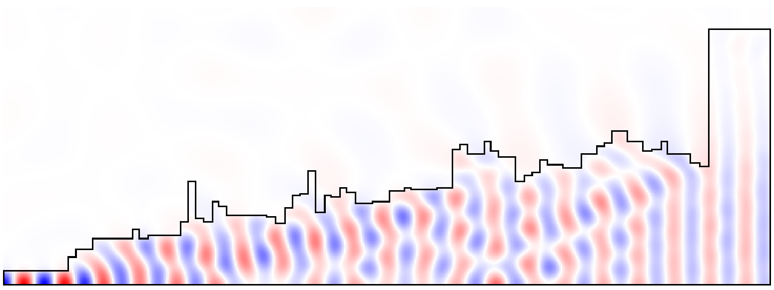

Fig. 3: Field plot (Hy) of a coupler optimised using genetic algorithm with a coupling efficiency of 90%. Because of symmetry, only the upper half of the structure is shown.

When using the steepest descent optimisation more a-priori knowledge is needed. A quasi-adiabatic discretised parabolic taper is the starting point for the iteration. Each iteration begins with a shortening step: the length L_i of every segment is proportionally shortened while the width is kept constant. Then the lengths L_i are kept constant but by changing each width separately a local optimum is searched for using steepest descent optimisation. A result of this method can be seen in Fig. 4.
Another configuration studied is the coupling between a broad dielectric waveguide and a photonic crystal (PhC) waveguide, see Fig. 5. The transmission from a forward Bloch mode in a PhC W1 waveguide (1 row of holes omitted) to each guided mode of a broad 2- μm dielectric waveguide was calculated according to [3]. A genetic algorithm then optimises a coupler structure to change this complex excitation into a ground mode excitation of the broad dielectric waveguide. The resulting structure is composed of 14 sections of

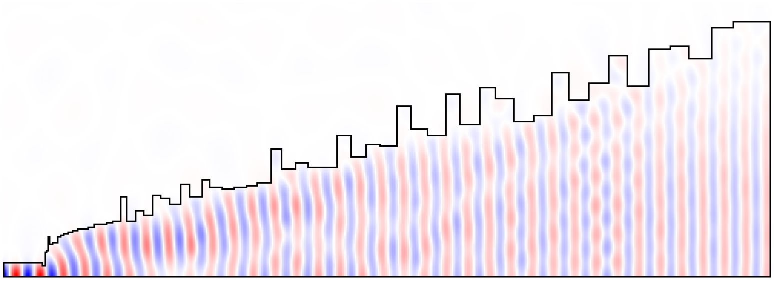

Fig. 4: Field plot (Hy) of a coupler optimised using iterative steepest descent with a coupling efficiency of 95%.

100 nm length and has an efficiency of around 99%. Fig. 5 shows the coupling from dielectric to PhC and back to dielectric waveguide with an overall coupling efficiency of around 98%. The obtained coupler structure has very narrow wing-like features, in which the magnetic field is insignificant. Although their exact role has not yet been understood, they are necessary for the structure to function well. When the three middle wing-like waveguide sections are replaced by sections with as width the average width of the two neighbouring sections, the overall transmission efficiency of the total structure drops below 80

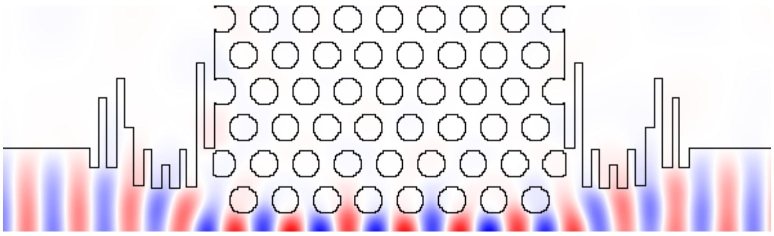

Fig. 5: Field plot of optimised coupling between forward bloch mode of PhC W1 waveguide and a broad dielectric waveguide.

3-D simulations

As the effective index transformation is only an approximation, rigorous 3-D simulations are needed before components can be realised. The commercial tool FIMMPROP (also EME) was used for this purpose. As the structure in Fig. 3 is not easily manufactured due to very small features, a similar structure composed of only 10 sections and optimised in 2-D using a genetic algorithm was calculated in 3-D using an SOI layer structure. A local optimisation in 3-D slightly improved the transmission efficiency to 72%. The total length of coupler is 15.4 μm. A width of 10 μm was chosen for the output because a vertical fibre coupler as described in [4] couples to a waveguide of this width.

Realisation

The above coupler has been realised in SOI using 248 deep UV lithography [5]. Measurements on this component showed a coupling efficiency of around 65%, coming close to the calculated value. A linear coupler with a length of 25 μm performed worse than the compact spot-size converter.

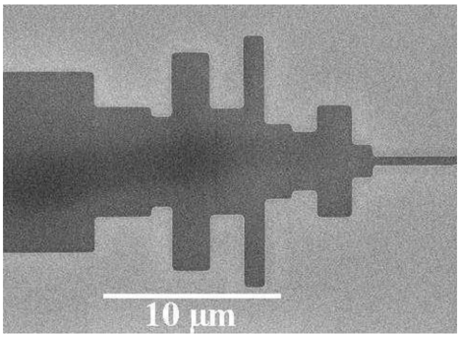

Fig. 6: SEM micrograph of coupler realised in SOI. Widhts of input and output waveguides are respectively 10 *µm* and 0.56 *µm*. Total length is 15.4 *µm*.

Conclusions

Non-periodic segmented waveguides are versatile optical spot-size converters. 2-D simulations in combination with optimisation algorithms show good coupling between the ground modes of waveguides with different widths. Also a complex excitation of an input waveguide can be efficiently converted into a useful monomodal excitation. The same behaviour is also found in 3-D calculations although the achieved efficiency is less in this case. First measurements on components realised in SOI show 65% transmission and a better efficiency than gradual linear tapers of similar, and even longer, length.

Acknowledgements

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