2D simulations of various compact spot-size converters

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Ultra-small waveguides (photonic crystal or wire) promise a way to high-density integrated optics. As a consequence the number of optical connections on-chip between components and between different waveguides will increase. Also the coupling fiber - chip needs to be optimized. A vertical fiber coupler can already couple light into a broad planar waveguide but the following coupling into ultra-small waveguides remains to be solved. Nowadays, adiabatic tapers are used as spot-size converters but easily reach lengths of hundreds of microns. It is believed that couplers could become drastically shorter by applying novel wavelength-scale structures in their designs. Three different designs are investigated in a two-dimensional way.

Introduction

To increase functionality and to lower production cost and especially the cost of packaging, integration of optical components seems the only viable way to follow. Hybrid integration, where different components are fabricated individually and afterwards brought together, is a first step in that direction. But as the alignment of different components in this integration scheme remains a huge cost, it probably will never be useful to integrate a huge number of optical functions. In the end, real integration – as used in electronics – should be applied, where all components are realized in the same material system or, if using different material systems, in a series of entirely wafer-scale processing steps. However, before high-density optical integration can become a reality, different components, like arrayed waveguides, directional couplers, ring resonators or switches, have to become smaller than is possible today. To achieve this, compact waveguides should be used. A first type of such a compact waveguide is a photonic wire, which is a conventional ridge waveguide but with a width, much narrower than normally used. With special corner cavities, bends in these wires can have very small radii while maintaining good transmission, thus allowing miniaturization of existing larger components. The second type of compact waveguide is a photonic crystal waveguide, where the light is not confined by totally internal reflection but by optical bandgap effects in a periodic lattice of refractive index changes [1]. By creating a line defect in such a (mostly hexagonal) lattice, light gets confined and can travel as in a waveguide. Also photonic crystal waveguides can have very small bends and are candidates to form the building blocks for high-density integrated optics.

Coupling problems

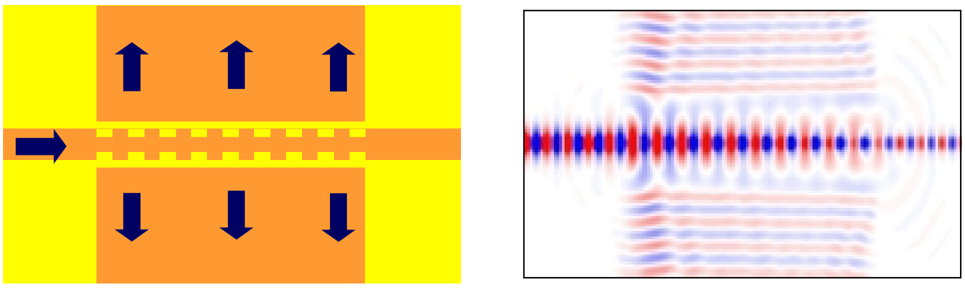
In such an optical chip, a lot of coupling problems might appear. Perhaps not all functions require the same type of waveguides, with for example photonic wires for the pure routing of the light and photonic crystal waveguides only in places where a slow wave, thus a low group velocity is required. At the interface between both types a coupler should provide a nearly perfect transition, as the same interface can appear multiple times within the same chip. Even if within a chip only one type of waveguide is used, the width of that waveguide might vary. One example where this situation occurs is in the case of a vertical fiber coupler [2]. A fiber end is positioned perpendicularly onto the wafer surface and only a few micrometers above it. Underneath a shallow etched second-order grating couples the light into a broad planar waveguide. The width of this waveguide approximately corresponds to the size of the fiber core, which normally is 10 micron. After this out-of-plane step, an additional in-plane coupling is required to couple the broad waveguide into a much narrower waveguide. To tackle both coupling problems, between different widths and between different types of waveguides, adiabatic spot-size converting has been the usual solution [3]. This method however results in long structures with lengths of up to several hundreds of micrometers. It is believed that couplers could become drastically shorter by applying novel wavelength-scale structures in their designs and by relying on phenomena like interference and reflection.

Different designs

Different coupler designs have been studied, all coupling a narrow to a broad waveguide. However, we believe that the methods developed to solve this kind of coupling problem can also be applied to coupling problems between different types of waveguide. To transform a 3-D structure to a 2-D one, the effective index method has always been used. Starting from a layer structure of 0.22µm Si/1.0µm SiO_2/Si-substrate and TE-polarization an effective index of 2.8309 results.

1. In-plane grating coupler

Figure 1 shows a top view of the in-plane grating coupler. A periodic corrugation in the sidewall of a small waveguide acts as a second-order grating and diffracts incoming light in a direction perpendicular to the small waveguide, where the broad waveguide is positioned. By adjusting the period and the depth of the corrugation the diffracted intensity can be maximized. Up to 40% of the light couples to the fundamental mode of the broad waveguide. By applying waveguide mirrors in the small exit waveguide and one of the two arms of the broad ridge waveguides, this number can be increased.

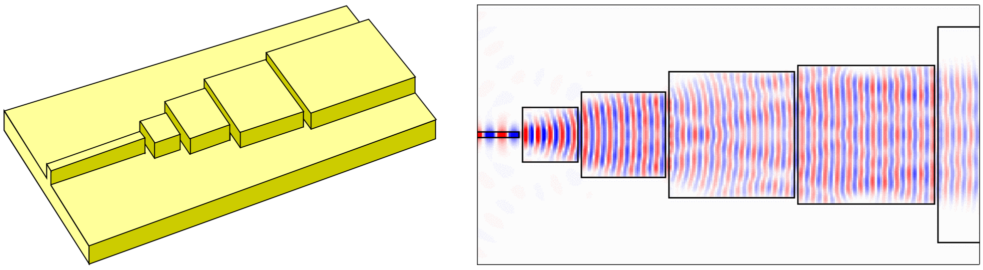


(a) (b)

Fig. 1: (a) 2-D simulation plot of the in-plane grating coupler (b) corresponding field plot (magnetic field perpendicular to surface)

2. Resonator taper

For certain values of the width, a square piece of high refractive index material exhibits high transmission for an incoming plane wave due to Fabry-Perot resonances. By putting different resonators of increasing size behind each other and effective spot-size broadener results. With only 4 resonators and a total length of 20 µm, a waveguide with a width of 0.25 µm and one with a width of 10 µm couple with an mode-to-mode efficiency of 75%. For more resonators this transmission becomes even higher (87% for 8 resonators) and the form of the entire structure resembles an parabolic adiabatic taper.

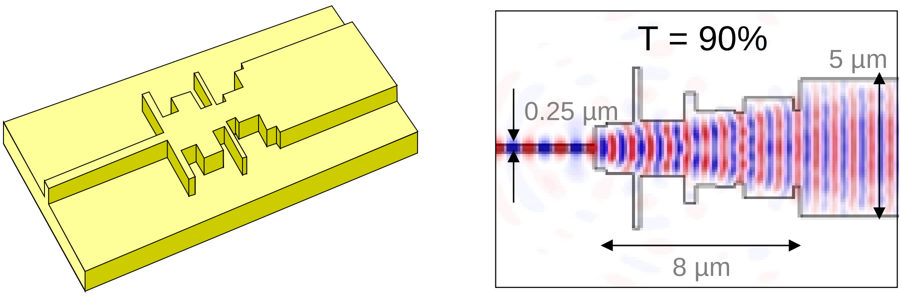


(a) (b)

Fig. 2: (a) schematic 3-D of a resonance coupler (b) 2-D field plot of a similar structure (magnetic field perpendicular to surface)

3. Interference coupler

A third design is called interference coupler and consists of N waveguide sections with varying width and length placed behind other. By taking all 2N parameters independent (N lengths + N widths) and by optimizing the mode-to-mode transmission using heuristic optimization techniques, in particular simulated annealing and genetic algorithms well-performing local optima appear, fig. 3.



(a) (b)

Fig. 3: (a) schematic 3-D view of interference coupler (b) 2-D field plot of a similar structure (magnetic field perpendicular to surface)

This method for reducing losses at an interface between different optical waveguides has been proposed before and realized in a different material system [4]. Although some features in the appearing structures seem rather critical, like the side fins, the solutions are rather robust. For the coupler in fig. 3 (b) with a top transmission of 90% at a wavelength of 1.55µm, the transmission never drops below 80% in the 1.5-1.6 µm wavelength range. Also changes to each length or width don't affect the total transmission in a drastic way. If every length or width is randomly changed with plus or minus n% the average transmission drops to 87% for n = 2, 79% for n = 5% and 69% for n = 10%. Changing just one parameter to a similar amount mostly leaves the transmission unaltered.

The third dimension

All previous calculations were done in 2-D using the effective index transformation. It is well known that results obtained in this way are not always valid for the real 3-D situation due to out-of-plane scattering or substrate losses and due to the simplification involved in replacing a layer structure by just one number. This topic certainly needs more investigation in the future. Nevertheless, we believe that well-performing 2-D structures can form a good starting point when looking for well-performing 3-D structures in an extra optimization step.

Conlusions

Three different compact spot-size converters have been studied, all composed of wavelength-scale structures and all showing decent coupling on length scales much shorter than those normally used when working with adiabatic tapers. Of those couplers the so-called interference coupler performs best although the exact working mechanism is still not fully understood. Further optimization on the three structures can probably increase all the efficiencies involved. Before fabrication can start a thorough look at the behavior of the spot-size converters using 3-D tools seems necessary.

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