Efficient, narrow profile waveguide crossings based on rapid adiabatic coupling

Josep M. Fargas Cabanillas*, Bohan Zhang and Miloš A. Popović†
Department of Electrical and Computer Engineering, Boston University, 8 St. Mary's Street, Boston, MA 02215, USA
**jofa@bu.edu, †mpopovic@bu.edu*

Abstract: We demonstrate an efficient silicon waveguide crossing based on the rapid adiabatic coupling (RAC) concept. Insertion loss and crosstalk are under 0.05 dB and -50 dB in simulation and under 0.3 dB and -17 dB in experiment across a 100 nm bandwidth.

Adiabatically tapered guided-wave devices in silicon photonic circuits – realizing 3 dB splitters, crossings and "escalators", mode converters, polarization splitters, polarization rotators, etc. – are known for their fabrication tolerant and broadband properties [1]. These benefits come at the expense of device length (often exceeding 200 μm in SOI). We have recently shown that much shorter, "rapid" adiabatic devices, rivaling direct-coupling based (but narrowband) designs in size while maintaining the benefits of adiabatic operation, can be designed by exploiting a new principle and previously unexplored degree of freedom [2]. In addition to adiabatic evolution of the cross-section, we add an orthogonal, transverse displacement or bending of the geometry. This transverse bending, without changing the adiabatic evolution, can exactly zero out the dominant unwanted mode coupling and thus reduce device length by up to an order of magnitude, to lengths comparable to the best non-adiabatic devices [2]. Unwanted (crosstalk) couplings caused by different sidewalls of the structure are engineered to cancel while leaving untouched the mode/cross-section evolution. We presented the first application of this method to demonstrate an ultra-short, broadband 2×2 3-dB coupler [3].

In this paper, we apply the rapid adiabatic coupling (RAC) principle to the design and experimental demonstration of a waveguide crossing (rapid adiabatic crossing, RAX). Two key parameters for crossings are insertion loss and crosstalk to the cross-waveguide. Among waveguide crossing designs [4–7], a compact and efficient one is a geometry that intersects two MMI waveguides at right angle [4, 7]. However, a number of large-scale photonic integrated circuits based on beam splitter networks, for multimode beam forming, optical neural networks, and optical FPGAs for example, may require crossing waveguides to exchange ports – where a parallel-waveguide directional coupler like geometry of crossing consumes low or essentially zero excess space, while orthogonal crossings and associated waveguide routing may take up considerable chip area. Hence, in this work we propose a narrow-profile, co-linear crossing design aimed at low loss, fabrication sensitivity and crosstalk over wide bandwidth by using adiabatic design [1] enhanced with the rapid adiabatic synthesis concept [2]. The design top view layout is shown in Fig. 1(a).

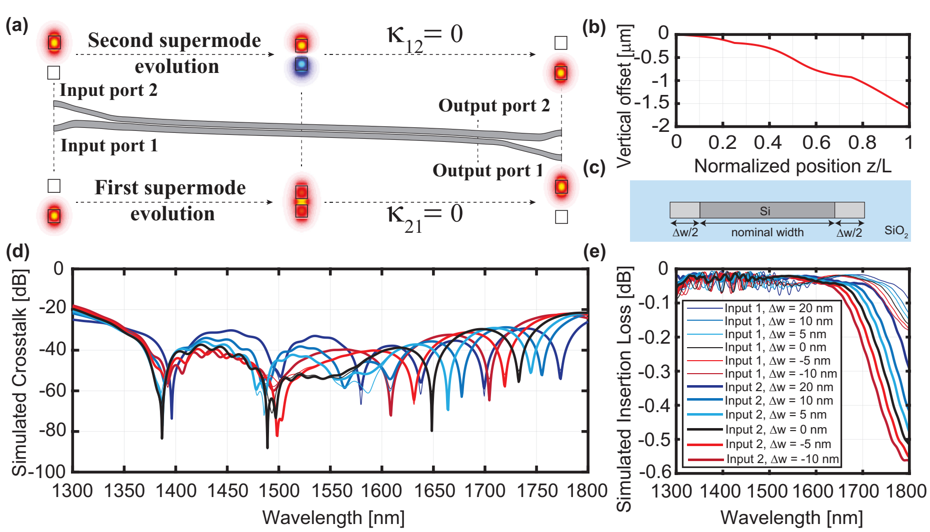

Fig. 1: (a) Rapid adiabatic crossing (RAX) schematic. (b) Transverse offset versus normalized position along the device from (a) synthesized to have the zero-coupling RAC condition. (c) Waveguide cross-section on SOI illustrating deviation from nominal width. (d,e) Simulated crosstalk and insertion loss (IL) vs. wavelength respectively for several widths deviating from nominal.

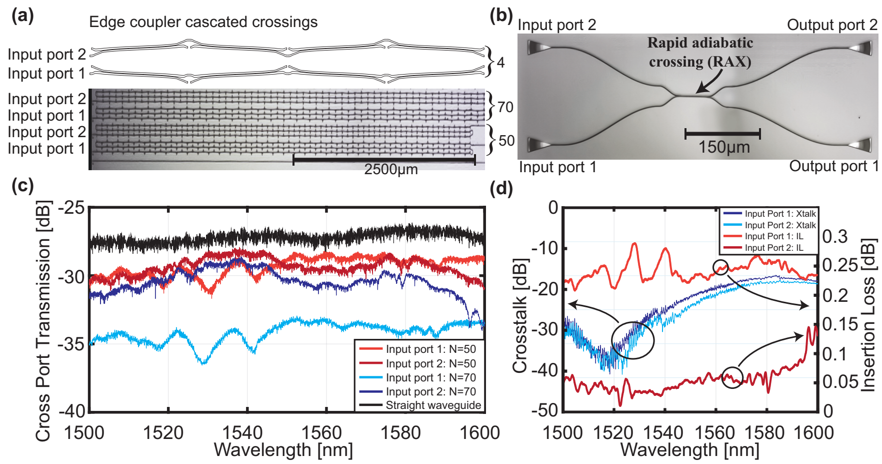

Fig. 2: (a) Illustration and micrograph of 4, 70, and 50 (top to bottom) cascaded RAXs. (b) Micrograph of a RAX connected to grating couplers. (c) Cross port transmission for the structures from (a). (d) Experimental crosstalk and insertion loss obtained from structures (a) and (b).

Our crossing has two input ports (left) and two output ports (right), where insertion loss is loss in transmission to the cross port (ideally no loss) and crosstalk is remaining transmission to the bar port (ideally zero). In Fig. 1(a) the fields of the first and second supermodes (symmetric and anti-symmetric) are shown in the first, middle and last cross-sections of the device, the mode evolution of each showing the crossing function. The key to rapid adiabatic coupling is bending the structure in the transverse direction precisely to frustrate (zero out) the coupling between the first and second supermodes at all points along the device [2]. Fig. 1(b) shows the bending of the outline of the lower sidewall, i.e. its displacement relative to an initial straight structure. The cross-section at each point, z/L, is unchanged, only laterally shifted. There is a small transition at the start and end of the device to taper the asymmetrical input and output waveguide widths to equal bus widths – this does not affect crosstalk because the waveguides are far enough apart.

Fig. 1(c) shows the cross-section of one of the waveguides of the device on SOI. The RAX is simulated in FDTD, and crosstalk and IL are obtained for both input ports while accounting for deviations from nominal design due to fabrication errors [Fig. 1(d,e)]. Simulated crosstalk for the nominal design does not exceed -37 dB across a 300 nm bandwidth. Sweeping the waveguide width error from -10 to 20 nm, the worst-case crosstalk over a 350 nm bandwidth was -30 dB, showing the device's robustness to fabrication variations. Maximum IL is 0.075dB over 300nm bandwidth.

Fig. 2(a) shows a micrograph and an illustration of cascaded RAX devices for loss measurements. We measured a set of 50 and 70 cascaded RAX devices and extracted the transmission [Fig. 2(c)]. Using those values, the IL per device from both input ports 1 and 2 is extracted and shown in Fig. 2(d). Input ports 1 and 2 have a maximum IL of 0.28 and 0.14 dB, respectively. Fig. 2(b) shows a micrograph of a RAX connected to grating couplers. The crosstalk for both input ports is shown in Fig. 2(d). The minimum crosstalk is -38 dB and the maximum is -17 dB. Crosstalk and IL are higher than predicted by simulation, and further studies will be made to investigate the reasons.

In conclusion, we showed the first design and experimental demonstration of a rapid adiabatic coupling based waveguide crossing (RAX). It has a narrow footprint that provides nearly no excess width compared to uncoupled waveguides. We expect further work to allow experimental performance closer to the theoretical designs. Still, the theoretical simulated performance improve over recent results shown in a similar 220nm SOI platform. Our RAX has -50dB instead of -37dB crosstalk and 0.05dB instead of 0.15dB IL from 1500 to 1600nm [7].

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