Ultra-low-loss Waveguide Crossing Arrays Based on Imaginary Coupling of Multimode Bloch Waves

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Abstract: We experimentally demonstrate ultra-low-loss waveguide crossing arrays showing loss down to 0.04 dB/crossing. They rely on a low loss, focusing Bloch wave that is stabilized by radiative scattering, via a radiative form of coupling.

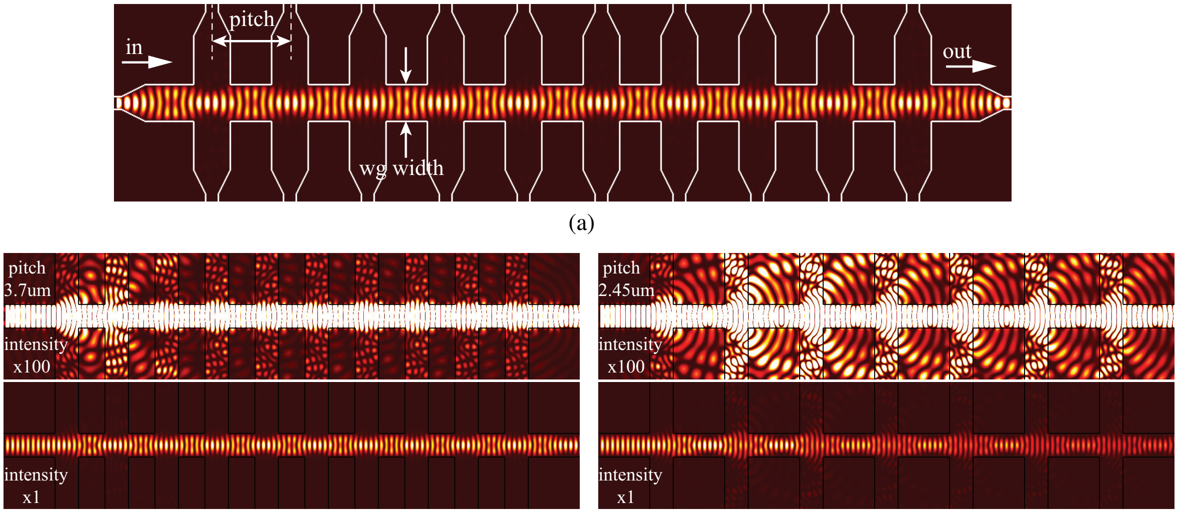
OCIS codes: (230.7370) Waveguides; (130.3990) Micro-optical devices; .

1. Introduction

Silicon photonic circuits promise to enable energy efficient chip-scale photonic interconnects for CPU-to-memory communication. As device density and complexity increase in a planar photonic circuit, efficient waveguide crossings become essential. For some network topologies, the number of waveguide crossings required rises quickly and tolerable levels of loss and crosstalk per crossing accordingly drop to very small limits. A multitude of work has considered crossing designs [1–9], including resonant [1], MMI-like [2, 3, 6, 8, 9], multi-layer [5], and adiabatic [4, 7] designs.

In previous work, Popovic *et al.* proposed an efficient approach to design a crossing array by constructing a low loss Bloch wave in a matched periodic structure, that avoids contacts, and using non-adiabatic, tapered excitation structures to efficiently excite these low-loss Bloch waves [8]. The field focuses periodically, and the crossing waveguides are placed at those points. The loss-avoiding breathing modes can provide as low as 0.04 dB per crossing, with the tapers contributing a similar loss. Fig. 1a shows a 2D simulation from [8] illustrating the concept. Fig. 1b shows a fundamental mode excitation settling into the low loss Bloch mode after scattering at the first few periods, while Fig. 1c shows large losses in a periodicity mismatched structure. Other applications include electrically and thermally contacted devices.

In this paper, we experimentally demonstrate this concept showing near-theoretical performance with loss as low as 0.04 dB/crossing (1%/crossing), and under 0.1 dB measured over a wide wavelength range exceeding 100 nm.



(a)

(b) (c)

Fig. 1. (a) Ultra-low-loss crossing array concept. (b) Low-loss breathing field achieved by matching structure periodicity and the periodicity of the low-loss breathing optical field (top: 100x oversaturated intensity to show detail, bottom: normal intensity scale). (c) High propagation loss in a periodic structure due to substantial mismatch between the structure periodicity and the periodicity of the low-loss breathing optical field (from [8]).

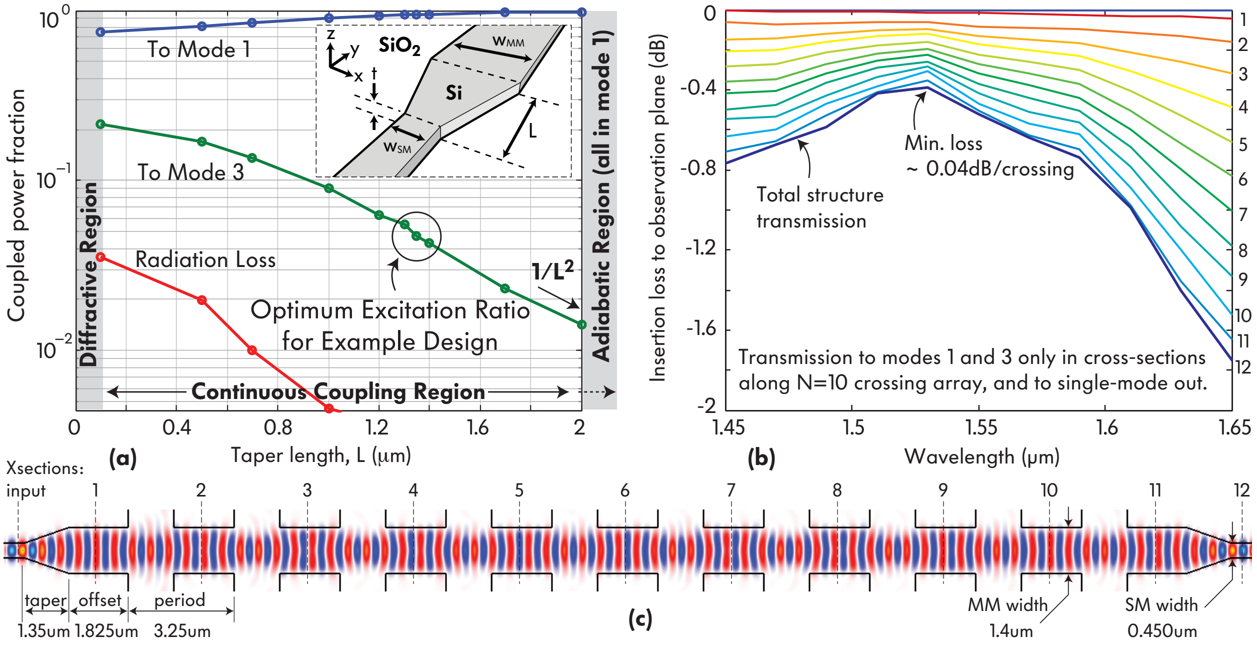


Fig. 2. (a) A short, non-adiabatic symmetric taper as a "directional coupler" between the 1^{st}- and 3^{rd}-order modes, allowing efficient excitation a breathing Bloch mode of the crossing array; coupling and loss vs. length. (b) Simulated transmission after 1-10 crossings, and through entire structure including tapers (3D FDTD). (c) Field from 3D FDTD simulation (dimensions shown differ slightly from the design used for fabricated devices).

2. Design Approach

The waveguide crossings presented here are designed in a 220 nm silicon device layer. To excite the low loss breathing mode, the period of the crossing array is designed to match the difference in (effective) propagation constants of the 1^{st}- and 3^{rd}-order eigenmodes of the waveguide, $\Lambda = 2\pi/(\beta_1 - \beta_2)$. In a multimode waveguide without crossing guides, there are two resulting Bloch waves. With crossings, scattering loss at the crossings radiatively couples these two modes to preserve a low-loss mode that avoids the crossings, and a suppress one that acquires high scattering loss. Launching the fundamental (Fig. 1b), in a periodicity matched structure, the low loss Bloch wave "survives" as the wave spatially propagates along the crossing array.

If the fundamental mode is launched into the multimode guide, the first few crossings strongly scatter until the low loss wave is established (Fig. 1b). We can observe the fraction of mode 1 and 3 present in the converged low loss wave. A non-adiabatic taper can be designed to excite that optimum ratio of 1^{st} and 3^{rd} eigenmodes from a singlemode input, to minimize loss. Fig. 2a shows 3D FDTD simulation results of a simple linear taper design, showing coupling to mode 3, and corresponding radiative loss. as the wave transits into the low-loss breathing supermode.

Figure 2b shows the simulated transmission, and its spectral dependence, after 1-10 crossings (observation planes labeled in Figs. 2b (right) and 2c), and through the entire structure including tapers, using 3D FDTD. The theoretical transmission is ~ 0.4 dB (0.04 dB/crossing) at the design wavelength. Figure 2c shows the simulated Bloch wave.

3. Experimental Results

Crossings arrays with $N = 10, 50, 150$ and 250 crossings were designed and fabricated through ePIXfab [10] (Figs. 3a and 3b). Dimensions of a structure nearly identical to the targeted design are shown in Fig. 2c. Due to precompensation for bias in the lithography, the width of the multimode waveguide section was varied in layout from 1450 nm to 1510 nm, with other dimensions remaining at design target. Figure 3c shows the total insertion loss experimentally measured in these devices, normalized to a plain single mode waveguide. Thus, input and output grating coupler responses are normalized out of the spectra. The data represents insertion loss of the array, including the non-adiabatic tapers and the crossings. For each waveguide width, the slope of insertion loss versus number of crossings gives the loss per crossing (not including the tapers) over the wavelength range (Fig. 3d). A device with waveguide width 1510 nm shows a loss per crossing of 0.04 dB at $\lambda = 1505.8$ nm. Scanning electron micrographs of the 1510 nm wide structure (Fig. 3b) confirm that its measured width is near the targeted 1400 nm. The other major source of difference from

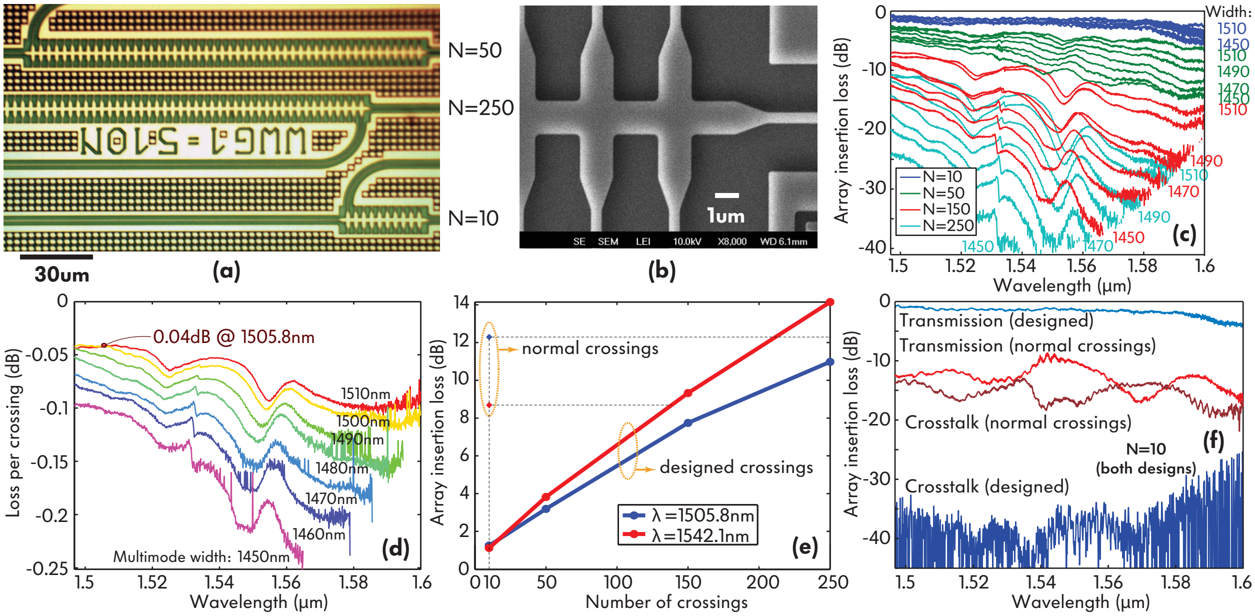


Fig. 3. (a) Optical micrograph of three waveguides with 50, 250 and 10 crossings. (b) SEM detail of crossing arrays. (c) Spectral insertion loss of arrays with 10, 50, 150 and 250 crossings (waveguide width varies from 1450 nm to 1510 nm). (d) Insertion loss/crossing vs. wavelength of crossing arrays with different waveguide width. (e) Insertion loss vs. number of crossings in designed crossing array of waveguide width 1510 nm compared with an array of 10 normal crossings, at $\lambda = 1.5058\,\mu$m where the designed crossing achieves the lowest loss of 0.04 dB/crossing, and at $\lambda = 1.5421\mu$m where the normal crossing array has the lowest loss. (f) Transmission and crosstalk spectra of designed and normal crossing arrays with 10 periods.

theoretical design is error in the device layer thickness. The demonstrated loss of 0.04 dB/crossing matches theory, with minimum loss wavelength shifted down by about 25 nm.

Comparing this optimal design with a plain, single-mode 10-crossing array, at the multimode crossing's peak wavelength ($\lambda = 1505.8$ nm, blue), a 250-crossing array has lower insertion loss than the single-mode 10-crossing array (Fig. 3e). Figure 3f shows the transmission and crosstalk of a 1510 nm wide 10-crossing design and a single-mode 10-crossing array. Apart from a 13 dB improvement in transmission, our designed crossing array also has a suppressed crosstalk that's over 35 dB, 20 dB below that of a normal crossing array.

In conclusion, we experimentally demonstrated waveguide crossing arrays with ultra-low losses of 0.04 dB/crossing, near the theoretical performance of this design. These structures also offer capabilities for electrically and thermally contacted, and suspended photonic structures with minimized scattering loss.

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