On the Mechanism of Efficient Coupling into Slow Light Photonic Crystal Waveguides

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Abstract: We investigate effects of evanescent modes on light coupling into low light mode of photonic crystal waveguides. Numerical and experimental results show that group index tapering does not have a dominant role for efficient coupling.

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Efficient coupling between strip waveguides and slow light photonic crystal waveguides (PCWs) is a necessary step toward implementation of slow light PCW based components for practical applications. To achieve high coupling efficiency, several groups have presented adiabatic group index (n_g) tapering, in which, a design parameter of the PCW (hole size, line defect width, etc) is gradually changed from that in the slow light PCW toward the strip access waveguide [1-3]. The operating principle relies simply on reducing the light reflectance (R) at discontinuities based on the effective medium approximation. However, in the case of hexagonal lattices (with air holes), this approximation significantly underestimates the coupling efficiency between two highly mismatched PCWs (e.g. $n_{g,low}$=5, $n_{g,high}$=100, T=1-R=80% [4]). Recently, it was argued that the high transmission is due to the excitation of an evanescent mode on the high n_g side of the interface [5]. The evanescent mode has amplitude comparable to that of the fundamental propagating mode, and its phase is such that it results in a small total field at the interface with the low n_g PCW to satisfy the boundary conditions. Here, we investigate the effect of group index taper on the coupling efficiency against a step coupler. We present experimental results of fabricated PCWs on a Silicon-on-Insulator (SOI) substrate.

A schematic of coupling of a strip waveguide to a high n_g PCW structure with an intermediate low n_g PCW structure is shown in Fig. 1(a). The high n_g PCW is a W1.0 PCW with lattice constant a=395nm. Hole radii for both the PCWs is the same, r=0.26a. We investigate two couplers: a step coupler, which is a W1.116 PCW, and a linear taper, for which the line defect width changes linearly from W1.0 at interface with the high n_g PCW to W1.116 at the interface with the strip waveguide. N is the number of periods in the PCW coupler. SOI with silicon device layer thickness of 230nm is used. Figure 1(b) shoes variations of n_g as a function of wavelength for PCWs with various line defect widths. Note that further widening the line defect width [more than W1.116] does not significantly reduce the group index in the bandwidth of interest ($20<n_g<100$).

We use 3D Finite Difference Time Domain (FDTD) simulations to calculate the coupling efficiency. In order to isolate the effect of the PCW taper from the Fabry Perot oscillations due to reflection at the input and output ports, we only simulate one port (one strip waveguide-PCW taper- high n_g PCW) as shown in Fig. 1(a). In the FDTD simulations, 12 periods of the high n_g PCW are used. We simulate the coupling transmission for step and linearly tapered couplers, for N=8 and 16, as shown in Fig. 1(c). We observe that for any number of periods, the step taper results in higher transmission almost throughout the slow light region. As the number of periods in the taper increases or as the group index increases, both couplers show similar performance. For N=16, when n_g>80, linearly tapered coupler shows a slightly better performance (~within 5%) compared to the step taper. Furthermore, results from adiabatically increasing group index in a chirped PCW on SOI substrate [6] and transmission spectrum measured from GaAs PCW membranes [7] have shown that the disorder-induced scattering completely disrupts transmission for n_g>30. Thus, the adiabatic taper only outperforms the step coupler at n_g values not supported by current state-of-the-art fabrication technology, and only in longer couplers, which are not desirable in the case of compact slow light PCW based devices (which typically require less than 20 periods).

In order to confirm the above claim, we fabricated PCWs on SOI (SOITEC) with a final 230nm top silicon layer and a 3μm buried oxide layer. The length of the high n_g PCW section is 100μm. The pattern was transferred to the device layer through electron beam lithography system, followed by reactive ion etching. Figure 1(d) shows the transmission spectra of direct coupling between strip waveguide and PCW, and also coupling through the step coupler and linearly tapered coupler with 8 and 16 periods. The oscillation amplitude for the direct coupling is 6dB (full swing), while it is about 3dB for coupling with either step or linear couplers. The transmission spectra are blue-shifted by about 20nm, which is due to 15nm expansion in the hole diameter during fabrication. Similar to the 3D FDTD results, the step couplers slightly outperforms the linear tapers in both *N*=8 and 16 cases. Also, as N increases, the performance of the step and linear taper converge together. Since group index tapering is not present in the step coupler, the only explanation for high coupling efficiency between highly group index mismatched PCWs is provided by the existence of evanescent modes at the interface, which helps satisfy the boundary conditions without need for high reflection [5].

In summary, we investigated whether group index tapering or existence of evanescent modes at the boundary of a low n_g and a high n_g PCW has a dominant role in enhancing light coupling between strip waveguide and a PCW operating in the slow-light region. Numerical analysis and experimental measurements showed that the use of short low n_g PCW as an intermediate coupler, in which group index tapering is absent, is advantageous over adiabatically tapered PCW coupler. Our results also indicate that for efficient coupling, a low n_g PCW coupler, much shorter (compared to over 100s of microns of low n_g PCW coupler in [8]) than previously demonstrated, is sufficient.

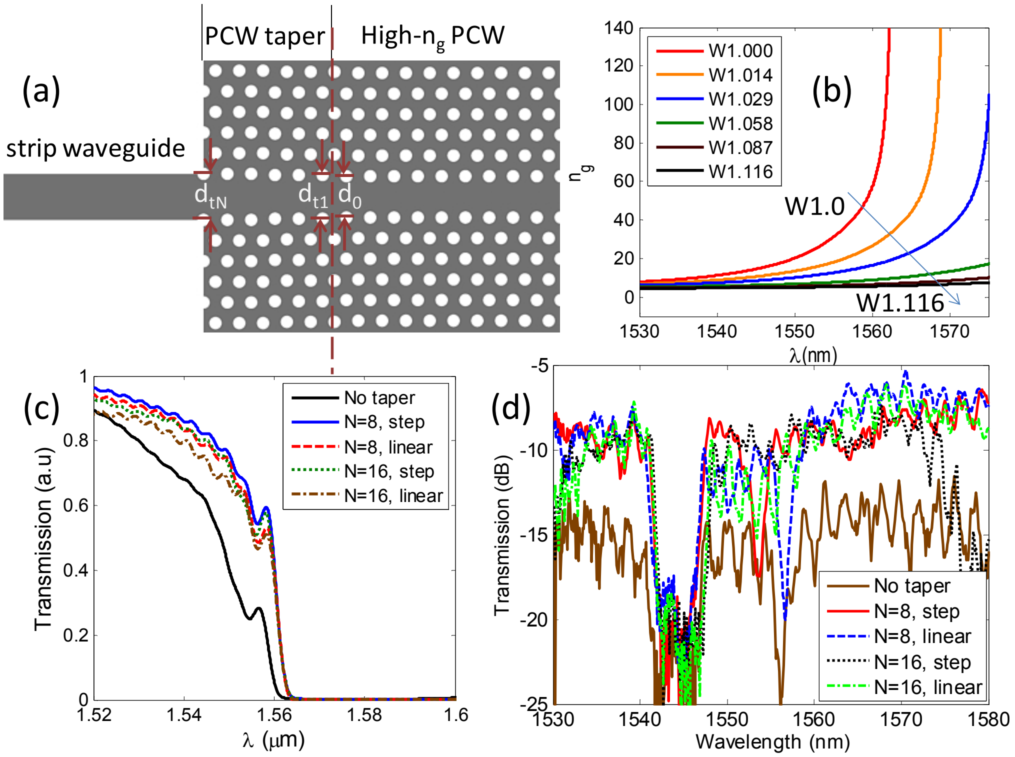

Fig. 1 (a) A schematic of the strip waveguide to high n_g photonic crystal waveguide coupling structure. The PCW on the right side of the interface is assumed to support high n_g propagation at the wavelength of operation. (b) Group index vs. wavelength for infinitely long PCW with different defect line widths. (c) and (d) 3D FDTD simulation results and Measurement results, respectively, transmission vs. wavelength for direct coupling of strip waveguide and PC slab waveguide (no taper) and coupling through PCW tapers, with step and linear profiles, for N=8 and 16.

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