Group velocity independent coupling into slow light photonic crystal waveguide on silicon nanophotonic integrated circuits

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ABSTRACT

Slow light in photonic crystal waveguide can significantly enhance the light-matter interaction, which is a promising approach toward building ultra-compact photonic devices. However, optical coupling from strip waveguide to slow light photonic crystal waveguide is challenging due to the group velocity mismatch between these waveguides. This issue can be addressed by designing a photonic crystal taper that allows the defect guided mode in photonic crystal waveguide to slow down gradually when it enters the photonic crystal waveguide from strip waveguide, thereby minimizing the group velocity mismatch. By using the photonic crystal taper design, experimental results show coupling efficiency can be enhanced by more than 20dB in normal group velocity region with 5dB less fluctuation as compared to the control group, which does not have photonic crystal taper. Enhancement right before photonic bandgap cutoff can be up to 28dB. Measurement results show excellent agreement with two-dimensional (2D) finite-difference time domain (FDTD) simulation.

Keywords: photonic crystal waveguide, slow light, silicon photonics, waveguide coupling.

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1. INTRODUCTION

Slow light in photonic crystal waveguides has been an active subject of research during the pass decade. Due to the enhanced linear and nonlinear light-matter interaction [1], ultra-compact photonic devices for various applications including optical communication and on-chip spectroscopy have been demonstrated. For optical communication devices such as modulators and switches, the interaction length can be significantly reduced due to the reduced group velocity. Examples of these devices include thermo-optic modulators [2] , thermo-optic switches [3] , and electro-optic modulators which utilize carrier effect [4, 5] or Pockels effect [6]. Based on slow light enhanced absorption, on-chip absorption spectrometers for underground water pollution detection [7] and hazardous gas sensing [8] in photonic crystal slot waveguide have also been demonstrated. All of theses devices require operating at the slow light region near the bandedge of the defect guided mode. However, coupling efficiency between strip waveguide and photonic crystal waveguide drops significantly with the decreasing group velocity of the guided mode in photonic crystal, which can significantly weaken the advantage of slow light devices. To address this issue, many works have been done to minimize the coupling loss between strip waveguide and photonic crystal waveguide. Optimizing the strip-photonic crystal waveguide interface [9] has shown excellent coupling efficiency in guided mode away from the bandedge. However, this approach cannot maintain its efficiency for slow light mode near the bandedge, where the guided mode starts to show reduced group velocity [10, 11]. Using quarter-wave transformer design at the strip-photonic crystal waveguide interface can facilitate coupling into slow light mode [12], but the narrow band nature of the transformer will limit its usage in practical applications. Hetero-group velocity design has also been theoretically suggested to improve the bandwidth of coupling, but such structure requires a photonic crystal waveguide of several hundred microns, which can occupy significant amount of chip real estate. By contrast, adiabatic group velocity tapering which offers smoother group velocity transition and compact footprint can be a promising approach for coupling [13]. As theoretically suggested recently [14], it is possible to have efficient coupling between strip waveguide and photonic crystal waveguides with coupling efficiency nearly independent to the group velocity of the guided mode in photonic crystal waveguide [15]. In this paper, we present our experimental study on about the effect of adiabatic group velocity taper on the coupling efficiency between strip and photonic crystal waveguides.

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2. DESIGN & SIMULATION

The schematic of the slow light photonic crystal waveguide (highlighted in blue) with the photonic crystal taper (highlighted in green) is shown in Fig. 1(a), which comprises a standard W1 line-defect-induced photonic crystal waveguide with a unified lattice constant of a=405nm and two photonic crystal tapers (symmetric) with gradually changing air hole size. The control group, which has identical slow light waveguide (blue) but without photonic crystal taper, is shown in Fig. 1 (b). Both waveguides have the same number of periods. The silicon slab thickness and the air hole diameters are chosen to be h=230nm and d=180nm, respectively, such that the W1 photonic crystal waveguide supports single mode operation. The dispersion relation (photonic band diagram) and group index (n_g) versus wavelength relation of the defect-guided mode are calculated using a three-dimensional (3D) plane-wave expansion (PWE) method as shown in Fig. 1(c) and (d). The simulated band diagram shows a guided mode from 1522nm to 1567nm, which falls inside our experiment observation window.

The choice of air hole diameters (d_n, n=1,2,…8) to create the photonic crystal tapers is based on an empirical equation $d_n = 144.15 + 8.19n - 0.46n^2$, which can create a smooth group velocity taper. The choice of air hole diameters in the taper region is plotted in Fig. 2 (a). To have a better understanding on the effect of group index taper, we calculate the group index (n_g) of each period of the taper as a function of wavelength using a 3D PWE method as shown in Fig. 2 (b). One can see from the group index dispersion relation in Fig. 2 (b) that this gradual increment of hole size results in a gradual increase of group index for the guided mode. Compared to butt coupling, the guided mode sees a smoother transition in group index as it enters the photonic crystal waveguide. As a result, the guided mode coupled from the strip waveguide can slow down gradually over the eight periods of taper region as it enters the slow light waveguide. Coupling out of the slow light photonic crystal waveguide to a strip waveguide is simply the reverse process. Under this design, the group velocity mismatch between a strip waveguide and a slow light photonic crystal waveguide is significantly reduced, which should lead to significant improvement of coupling efficiency.

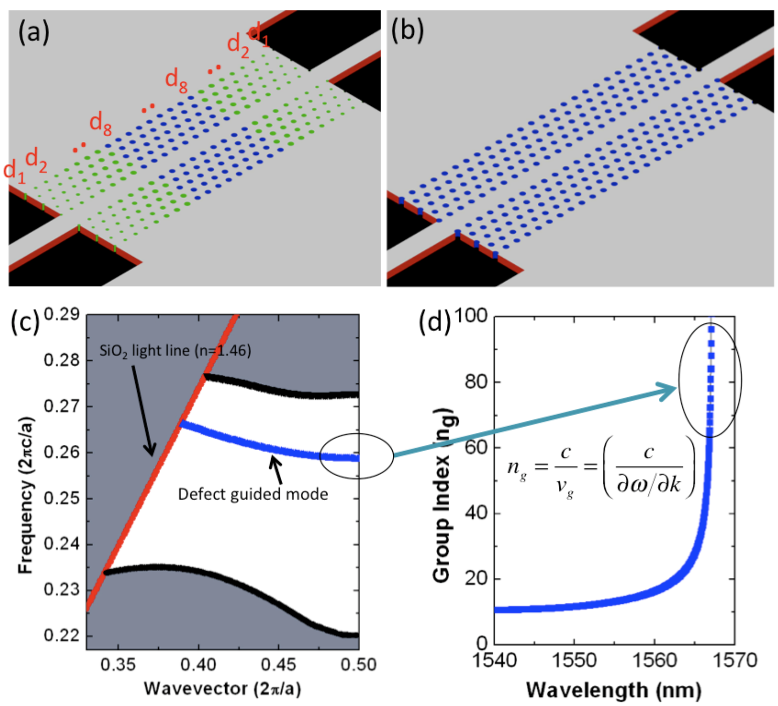

Figure 1. (a) Schematic of the device structure which shows input and output strip waveguides (red), photonic crystal taper with gradually changing hole sizes (green, not to scale), and the slow light photonic crystal waveguide (blue) (b) Control group: same slow light photonic crystal waveguide as in (a) with same total periods but without group index taper. (c) Dispersion relation of the defect-guided mode in the slow light photonic crystal waveguide, as highlighted in blue in (a) and (b) (d) Group index of each periods of the photonic crystal waveguide shown in (a).

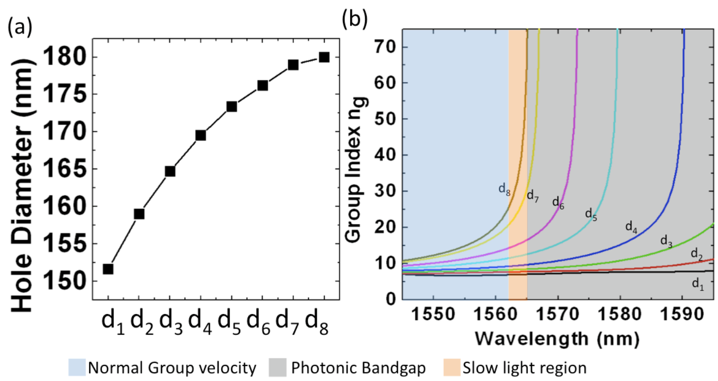

Fig. 2. (a) The hole diameters of d_1, d_2,…d_8. (b) Group index (n_g) versus wavelength relation for different hole diameters in (a).

Transmission through the photonic crystal waveguide devices is simulated by 2D FDTD as shown in Fig. 3. Although the group index taper is only eight periods (3.24µm long) of the photonic crystal waveguide, this coupling structure has a dramatic impact on coupling efficiency into a slow light mode. For a photonic crystal waveguide without any taper, coupling efficiency starts to drop well before the band edge. By contrast, when photonic crystal taper is included in the photonic crystal waveguide, coupling efficiency remains nearly the same as its peak value even in the slow light region. Additionally, this coupling structure reduces the fluctuation of coupling efficiency due to reduced Fabry-Perot reflections.

3. DEVICE FABRICATION

Photonic crystal waveguide devices were fabricated on a Unibond silicon-on-insulator (SOI) wafer with a 230nm top silicon layer and a 3um buried oxide (BOX) layer. 45nm of thermal oxide was thermally grown as an etching mask for pattern transfer. Photonic crystal waveguides, photonic crystal tapers, and strip waveguides are patterned in one step with a JEOL JBX-6000FS electron-beam lithography system followed by reactive ion etching. Photonic crystal waveguide devices were formed in a non-membrane configuration with the patterned silicon photonic crystal waveguide core supported by the 3µm BOX as bottom cladding layer. The hole dimension and the width of photonic crystal waveguides can be precisely controlled with errors less than 2nm and sidewall roughness ~5nm estimated by scanning electron microscope (SEM) inspection. Photonic crystal waveguide devices with and without a photonic crystal taper were fabricated on the same chip with an identical fabrication process. SEM images of the fabricated structure are shown in Fig 4.

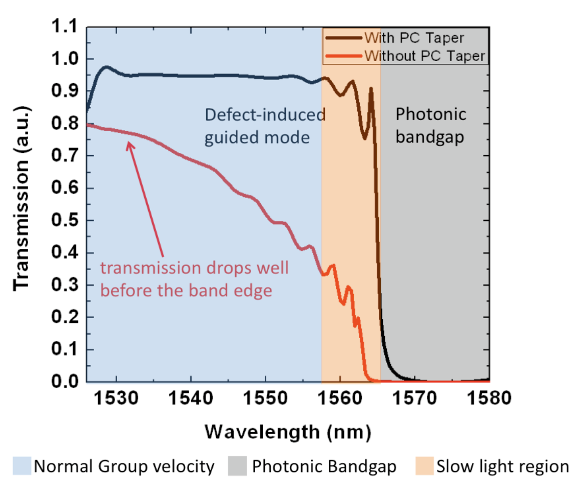

Fig. 3. Simulated transmission spectrum using two-dimensional (2D) finite difference time domain (FDTD) analysis, comparing the coupling performance of W1 photonic crystal waveguide with (black curve) and without (red curve) a photonic crystal taper.

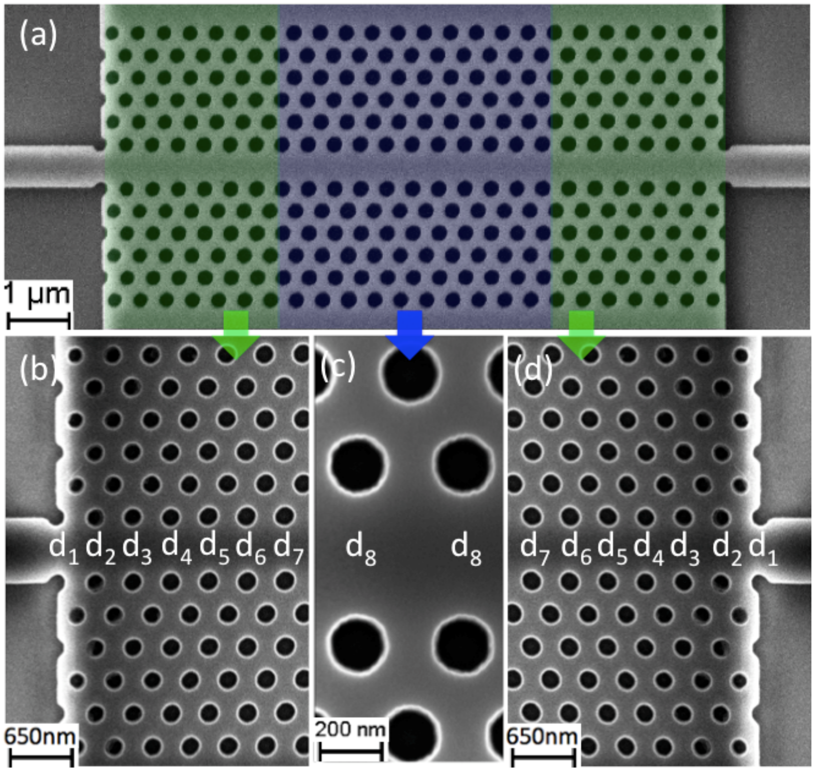

Fig. 4. Scanning electron micrograph (SEM) of the fabricated photonic crystal waveguide structure. (a) Global look of the photonic crystal waveguide device, which includes a strip waveguide, a photonic crystal taper (green), and a slow light photonic crystal waveguide (blue). (b), (d) Enlarged view of the eight periods of photonic crystal taper. (c) Enlarged view of the slow light photonic crystal waveguide region.

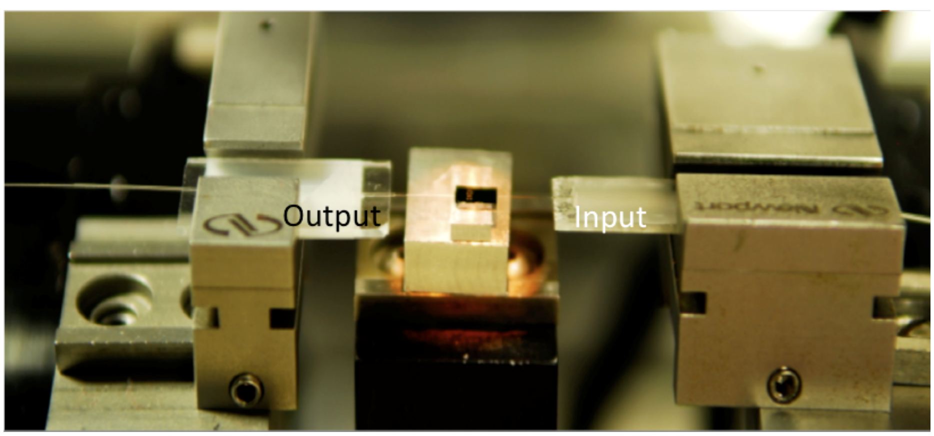

Fig. 5. Testing setup for the photonic crystal waveguide devices.

4. DEVICE CHARACTERIZATION

To characterize the coupling performance, photonic crystal waveguide devices were tested on a Newport six-axis auto-aligning station. Testing setup is shown in Fig. 5. Input light from a broadband ASE source (Thorlab ASE-FL7002) covering the 1520nm~1620nm wavelength range was TE-polarized with a 23dB TE/TM rejection ratio and butt-coupled to / from the device with a polarization maintaining single mode tapered lensed fiber with a mode field diameter of 3μm. Transmitted light was analyzed with an optical spectrum analyzer (ANDO AQ6317B) with 0.04nm resolution. The transmission spectra of photonic crystal waveguides with and without photonic crystal tapers were normalized to the transmission spectrum without the device as shown in Fig. 6.

5. EXPERIMENT RESULT & DISCUSSION

The transmission spectra show that the photonic crystal waveguide devices support defect-guided modes from 1523nm to 1568nm, which agrees well with both PWE and FDTD simulation. Compared with direct coupling from a strip waveguide, the W1 photonic crystal waveguide with group index taper shows several distinct improvements in the coupling efficiency. First, one can see significantly less Fabry-Perot noise when the group index tapers are added. The transmission fluctuation caused by the Fabry-Perot effect is suppressed by 5dB throughout the defect mode. As a result, photonic crystal waveguide with photonic crystal taper shows a nearly flat transmission. Secondly, the transmission is improved by more than 20dB over the entire guided mode bandwidth of 45nm. Third, the coupling efficiency remains very close to its peak value until 2 nm away from the photonic bandgap cut-off at 1568nm. This means that slow light modes near the band edge with very high group index can be coupled into the photonic crystal waveguide as low group index mode. Fourth, the photonic crystal taper offers even better coupling enhancement for the slow light mode near the bandedge. For the photonic crystal waveguide with photonic crystal taper, the normalized transmission at 1566 nm (2nm from the photonic bandgap) only drops 2dB from its peak transmission, whereas it drops 10dB without the photonic crystal taper. Under 20dB of baseline enhancement, this translates into 28dB improvement for the band edge slow light mode.

The limitation of this coupling approach can also be observed from the band edge cut off behavior. One may notice that the slope of the transmission dropping between 1566nm and 1568nm has two distinct regions. The first region from 1566nm to 1567.5nm shows a 25dB drop in transmission within 2.5nm, indicating this coupling mechanism starts to reach its limitation when group velocity slows rapidly as a function of wavelength. The second region from 1566.5nm to 1567nm shows a 10dB drop in transmission in just 0.5nm, which is likely due to the very high propagation loss associated with extremely high group index.

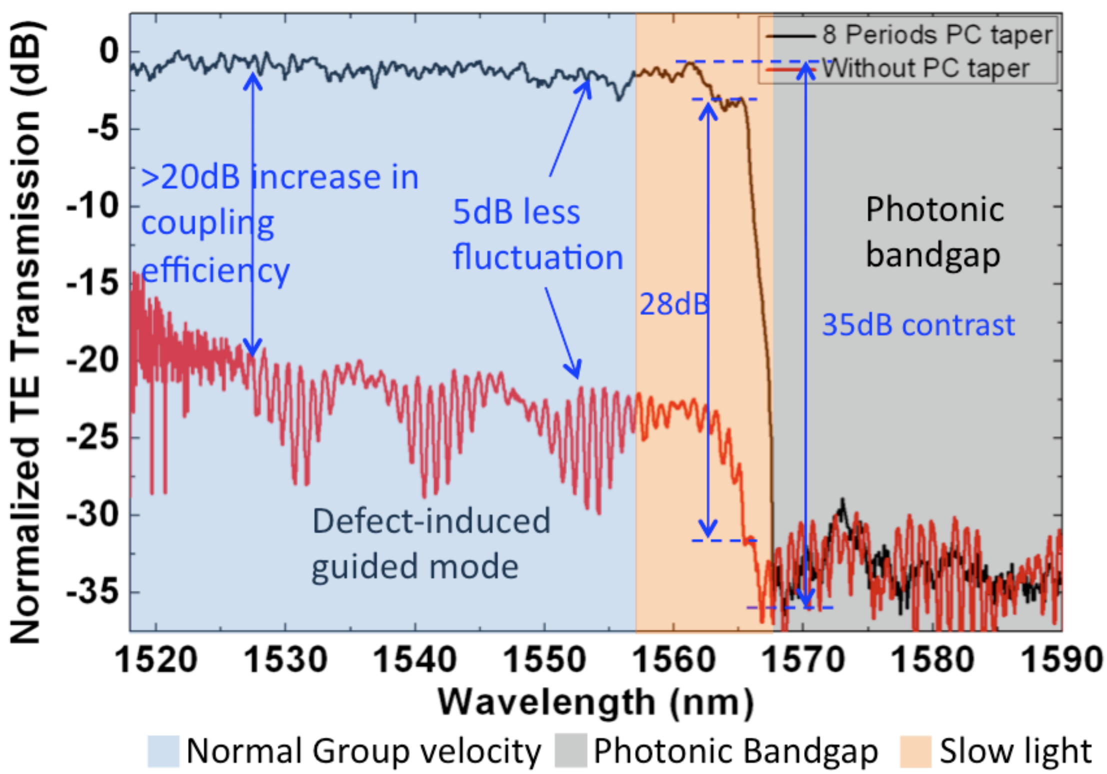

Fig. 7. Transmission spectrum comparison for photonic crystal waveguide with group index tapers (black curve) and the control group without taper (red curve).

To visualize the effect of the group velocity taper, we observe the light transmission behavior with infrared (IR) microscope above the photonic crystal waveguide. The waveguide testing setup is identical to the device characterization section, except that we replace the broadband light source with a tunable laser (Santec ECL-2000) for input source. The IR images are shown in Fig. 8. At the wavelength of the photonic bandgap (1568nm and longer), the input light from the strip waveguide is completely blocked by the photonic bandgap effect and no light is observed at the output of the photonic crystal waveguide as shown in Fig. 8 (b). Fig. 8 (c) and (d) show the transmission behavior at the slow light wavelength (1565nm) of defect mode for photonic crystal devices without and with group index taper. One can see in Fig. 8 (d) that the input light from strip waveguide is better transmitted when the group index taper is present, whereas it is mostly reflected for the control group without taper as shown in Fig. 8 (c).

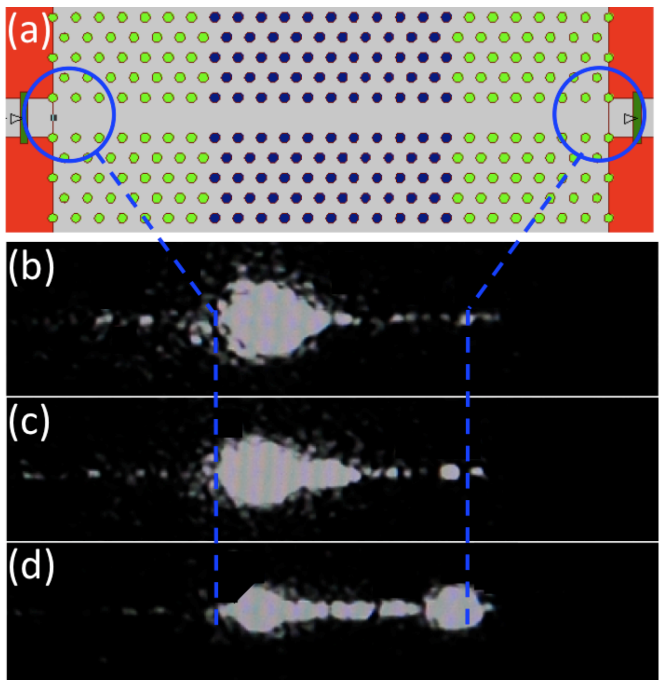

Fig. 8. (a) Schematic of the photonic crystal waveguide device. (b) IR image taken at the wavelength of the photonic bandgap. (c) IR image for the control group without group index taper. (d) IR image for the photonic crystal waveguide with group index taper.

6. CONCLUSION

In conclusion, we present the design and experimental results of efficient coupling into a photonic crystal waveguide using photonic crystal tapers based on matching the group velocity between a conventional strip waveguide and a slow-light photonic crystal waveguide. Experiments show good coupling efficiency that can be maintained at the photonic crystal band edge, regardless of the group velocity of the guided mode that uses only eight periods of photonic crystal taper. Compared to a photonic crystal waveguide without a photonic crystal taper, measurements show a 20dB baseline improvement in coupling efficiency, 5dB less fluctuation, and a 28dB enhancement for the slow light mode using only 3.24μm long of photonic crystal taper. The experimental result also shows that less than 10μm of photonic crystal waveguide is needed to create a 35dB contrast in transmission. Such a photonic crystal waveguide structure could serve as the stepping-stone toward building ultra-compact photonic devices for on-chip optical interconnects.

7. ACKNOWLEDGEMENT

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