Coupling loss minimization of slow light slotted photonic crystal waveguides using mode matching with continuous group index perturbation

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We experimentally demonstrate highly efficient coupling into a slow light slotted photonic crystal waveguide. With optical mode converters and group index tapers that provide good optical mode matching and impedance matching, a nearly flat transmission over the entire guided mode spectrum of 68.8 nm range with 2.4 dB minimum insertion loss is demonstrated. Measurements also show up to 20 dB baseline enhancement and 30 dB enhancement in the slow light region, indicating that it is possible to design highly efficient and compact devices that benefit from the slow light enhancement without increasing the coupling loss. © 2012 Optical Society of America

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Slotted photonic crystal waveguides (slotted PCWs) offer a unique platform that merges the best properties of slot waveguides and photonic crystal waveguides (PCW): strong optical confinement in slot waveguides [1] and slow light-enhanced light-matter interaction in PCWs [2]. In a W1 PCW, the optical mode profile spreads deeper into the photonic lattice with reduced group velocity [3]. This lateral spread reduces optical confinement and increases propagation loss for slow light modes, which can weaken some of the benefits derived from the slow light effect. By contrast, in slotted PCW, optical confinement does not decrease with increased group index, as a result of the high index contrast in silicon platform. In a high index contrast interface, a transverse electric guided mode is required to have much higher intensity in the low index region. Consequently, when approaching the edge of the photonic bandgap, the percentage of energy concentration in the low index slot will increase rather than decrease [4]. The increasing optical confinement with slower group velocity is a very advantageous property for compact optical communication [4–6] and sensor devices [7,8]. Despite these benefits, optical coupling between a strip waveguide and a slotted PCW is more challenging than conventional PCW due to the exotic mode profile and slow group velocity in the slotted PCW. Without a properly designed coupling interface, strongly confined guided mode profile with minimal overlap and large group index mismatch result in negligible coupling [9]. Efforts to improve the coupling efficiency include using a multimode interference (MMI) coupler [9], changing the termination of the slot [10], and resonant coupling [11]. However, MMI coupler only provides efficient coupling with limited bandwidth. Changing the slot termination position improves bandwidth [10], but with low overall transmission. Resonant coupler approach shows better coupling efficiency. However, the transmission dip below −10 dB in slow light region weakens the performance of slow light devices. By contrast, the theoretical study in [12] suggests that good coupling is achievable with good mode profile and group index matching. Based on a similar concept, we present a simpler design and experimentally demonstrate highly efficient coupling into slow light slotted PCW. We also study the effect of mode matching and group index matching experimentally, which offers more insights on the strip-slotted PCW coupling process.

The schematic of the slotted PCW is shown in Fig. 1. The slotted PCW devices are formed by etching air holes and slots on a 230 nm crystalline silicon nanomembrane sandwiched between a 3 μm thick silicon dioxide layer ($n = 1.46$) and a 2 μm thick polymer layer ($n = 1.63$), which serves as the bottom and top cladding layers, respectively. Air holes and slots are filled with the same material as the top cladding, which also prevents undesirable oxidation of the silicon layer. The lattice constant (a), air hole diameter (d), slot width (sw), silicon thickness (h), and line defect waveguide width (T_{12}) for the slow light waveguide are chosen to be $a = 425$ nm, $d = 297$ nm, $\mathrm{sw} = 320$ nm, $h = 230$ nm, and $T_{12} = 1.3\sqrt{3}a$ so that this waveguide supports a defect-guided mode that falls inside our experiment observation window of $1520 \sim 1610$ nm. The photonic band diagram

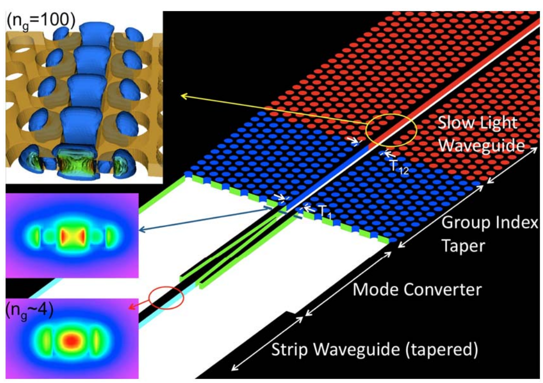

Fig. 1. (Color online) Schematic of the slow light slotted PCW, group index taper, mode converter, and strip waveguide (tapered). The insets show the mode profiles of a strip waveguide and a slow light slotted PCW at high group index ($n_g = 100$).

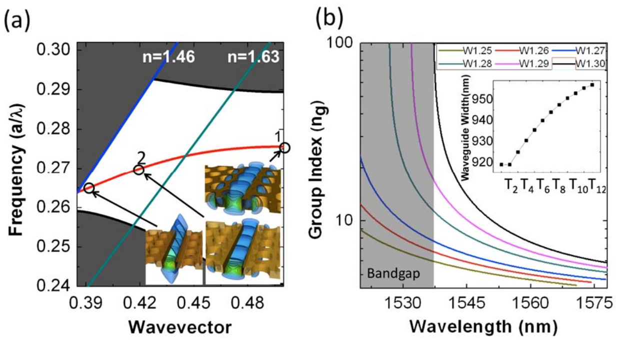

Fig. 2. (Color online) (a) Photonic band diagram. (b) Group index versus wavelength. The inset shows the waveguide width in the group index taper region.

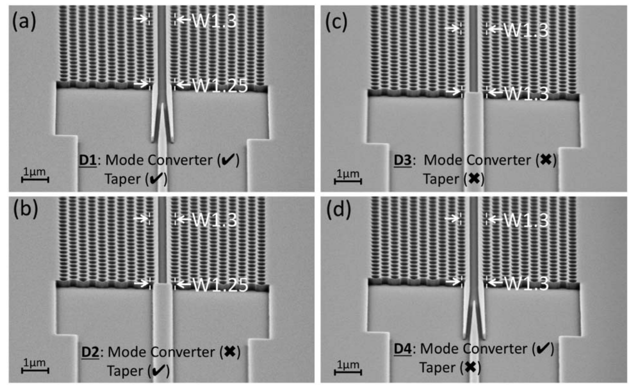

Fig. 3. Transmission spectra of D1, D2, D3, and D4. SWG represents strip waveguide.

for the slow light waveguide is shown in Fig. 2(a). The in-plane electric field distributions of the guided mode at wave vectors below and above polymer light line are also shown in the inset of Fig. 2(a). The radiation loss above polymer light line is small for the length of our devices. Therefore it is possible to have transmission between polymer light line ($n = 1.63$) and oxide light line ($n = 1.46$). This phenomenon was also verified experimentally as shown in Fig. 3. To minimize the modal mismatch, we use an optical mode converter that can convert a strip waveguide mode into a conventional slot waveguide mode [13], which has a mode profile similar to that of a slotted PCW [1,4]. To further improve mode profile matching with a strip waveguide, a wide slot width of 320 nm is intentionally chosen, a maximum width that supports a mode size similar to that of a 340 nm wide silicon strip waveguide. For a photonic crystal modulator operating in the slow light region, the increased slow light mode coupling efficiency and relaxed fabrication requirements compensate for the loss in optical confinement, leading to better overall performance with a wider slot [4,5].

The group index mismatch can be adiabatically tuned by using a photonic crystal group index taper [14] that provides a smooth transition in group index [15] as shown in Fig. 2(b). The taper is formed by parabolically reducing the width of a line defect waveguide from ($T_{12} = 1.3\sqrt{3}a$) towards the coupling interface ($T_1 = 1.25\sqrt{3}a$) as shown schematically in Fig. 1. The parabolic photonic crystal taper is designed by choosing a line defect waveguide width (T_1) that has lower group index than the slow light waveguide (T_{12}) over the entire guided mode spectrum followed by parabolic fitting to determine the waveguide widths (T_2~T_{11}) between them. The taper design uses unified hole size, which is much easier to realize than the taper in [12]. It is worth nothing that these design principles based on mode profile matching and parabolic group index taper should work for narrower slots as well. However, narrower slots are more sensitive to sidewall roughness due to higher field intensity.

Slotted PCW devices were fabricated on a silicon-on-insulator wafer with 230 nm top silicon layer and 3 μm buried oxide. Details on the fabrication and characterization methods were described elsewhere [4]. Four different designs were fabricated to experimentally study the effect of mode matching and group index matching in a strip waveguide-slotted PCW coupling. Scanning electron microscopy (SEM) pictures of the fabricated devices are shown in Fig. 4, which shows the differences of four designs.

Figure 3 shows the comparison of transmission spectra measured from the four different devices (D1–D4) in Fig. 4 and experimental n_g value calculated from the fringes in D4 using the method described in [16]. These results highlight the importance of mode matching and impedance matching for achieving wide bandwidth, low loss, and group velocity independent coupling. Several distinct differences are observed in the transmission spectra. First, the transmission spectrum of D1 shows the best coupling efficiency, featuring minimum insertion loss of 2.4 dB around 1546.5 nm in reference to a strip waveguide of equal length on the same chip. Second, low frequency fringes due to Fabry–Perot reflections at the strip-slotted PCW interface are suppressed. This results in a nearly flat and high transmission throughout the entire defect-guided mode spectrum. Third, comparing D1 to D4 demonstrates a 7 dB loss in coupling efficiency if group index matching is not achieved. Fourth, the comparison between D1 and D3 shows the loss in transmission can be as high as 13 dB if both mode matching and group index matching are not attempted. Fifth, the mode cutoff wavelengths of slotted PCW devices without mode converters (D2 and D3) happen at 1538.8 nm and 1538.4 nm, as opposed to 1537.3 nm and 1537.4 nm for devices that have mode converters

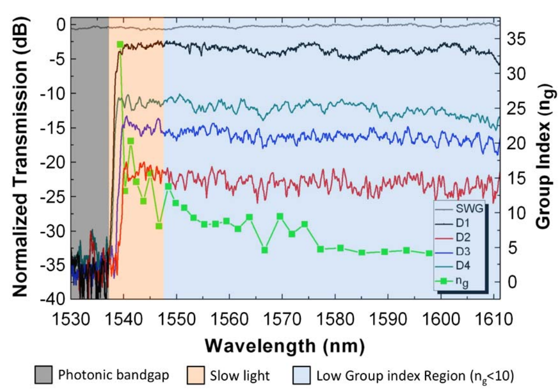

Fig. 4. (Color online) Scanning electron microscope (SEM) pictures of the fabricated slotted PCW devices.

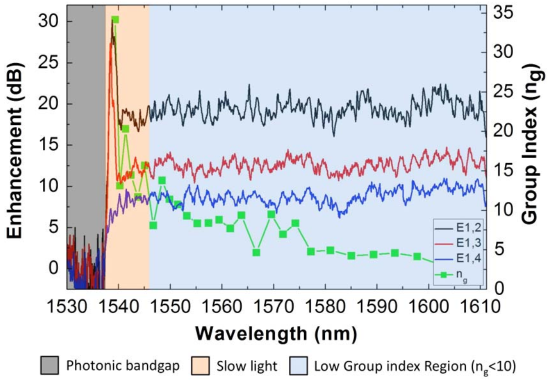

Fig. 5. (Color online) Enhancement spectrum defined as the transmission difference between device D1 and other devices.

(D1 and D4). It is known that cutoff wavelength is a unique property of the guiding region, which is identical for D1 ~ D4. This result illustrates that the coupling loss for slow light can be very high for nonoptimized structures. To make sure that this difference in cutoff wavelengths is not a result of fabrication error, careful SEM inspection was performed on three sets of samples to confirm that all devices are identical in the slow light waveguide region. The same measurement was also repeated multiple times on each set of samples. All measurements show identical trends with minor variations. Finally, D2 shows the lowest coupling efficiency despite having the group index taper design. This is mainly due to the gradually decreasing waveguide width in the photonic crystal taper region. Without a mode converter to achieve mode matching, the narrower width of slotted PCW at the taper region can deteriorate the modal mismatch and cause low coupling efficiency when compared with the scenario shown in D3.

In order to accurately depict the enhancement of coupling efficiency in the slow light region, we also show the difference in transmission between the best case of D1 and others (D2, D3, and D4) together with group index. From Fig. 5, one can see that the baseline in D1 is more than 17 dB (E1,2 curve), 10 dB (E1,3 curve), and 7 dB (E1,4 curve) higher than D2, D3, and D4. The transmission enhancement in the high group index region around 1537 nm~1541 nm is even more significant. Curves E1,2, and E1,3 show strong enhancements of 30 dB and 27 dB within a 3 nm and a 2 nm spectrum next to the photonic bandgap. These results highlight the coupling efficiency enhancement in the most important region for the operation of slow light devices.

In conclusion, the experimental demonstration of efficient coupling into a slow light slotted photonic crystal waveguide is reported. Measurement results show up to 20 dB enhancement in overall coupling efficiency and up to 30 dB enhancement in the high group index region near the band edge. Suppression of low frequency fringes confirms that Fabry–Perot reflection at a strip-slotted PCW interface is minimized. A flattop transmission spectrum and a 2.4 dB insertion loss for a 34 μm long slotted PCW represents the possibility to design devices that benefit from slow light enhancement without the classically high coupling loss associated with impedance or modal mismatch.

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