Low-loss Mode Converter for Silicon-Polymer Hybrid Slot Photonic Crystal Waveguide

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Abstract: We demonstrate an efficient adiabatic mode converter for coupling light into a silicon slot photonic crystal waveguide with slot width as large as 320nm. The loss of the mode converter is measured to be 0.08dB.

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In slot photonic crystal waveguides (SPCWs), the strong optical confinement in the slot filled with air or dielectric cladding is combined with enhanced light-matter interaction provided by a slow-light structure. Specifically, silicon SPCWs infiltrated with electro-optic (EO) polymers have shown to enable high performance optical interconnects [1], modulators [2], and sensors [3]. It has been demonstrated that a slot width (S_w) as large as 320nm can significantly suppress the leakage current in poling process and achieve an EO coefficient which is over two orders of magnitude larger than that in a narrow slot (S_w~75nm), while still achieving high optical confinement [4]. However, efficient coupling from a strip waveguide into a wide slot waveguide is challenging due to the large mode mismatch [bottom insets of Fig. 1 (a)]. To address this problem, in this paper, we explore an efficient adiabatic mode converter to couple light into a 320-wide slot PCW, as shown in Figs. 1 (a) and (b). Although this type of mode converter has been used for narrow slot waveguides (S_w<130nm) [5], it has not been reported for larger slot widths (e.g. S_w~320nm). In addition, contrary to conventional design rules, wherein the outer edge of slot waveguide rails terminate at the center of holes in the first adjacent rows of the SPCW [4] as shown in Fig. 1 (c), we find that if the termination is not at the center of the holes, very good coupling efficiency can still be achieved. The measured loss of this mode converter for S_w=320nm is below 0.08dB, which is 0.1dB lower than that of a V-shape mode converter. Furthermore, we demonstrate the use of this mode converter for efficiently coupling light into a 300 μm-long 320nm-wide slot PCW with an improvement of 3.5dB in coupling efficiency within the slow-light wavelength region compared to the V-shape mode converter.

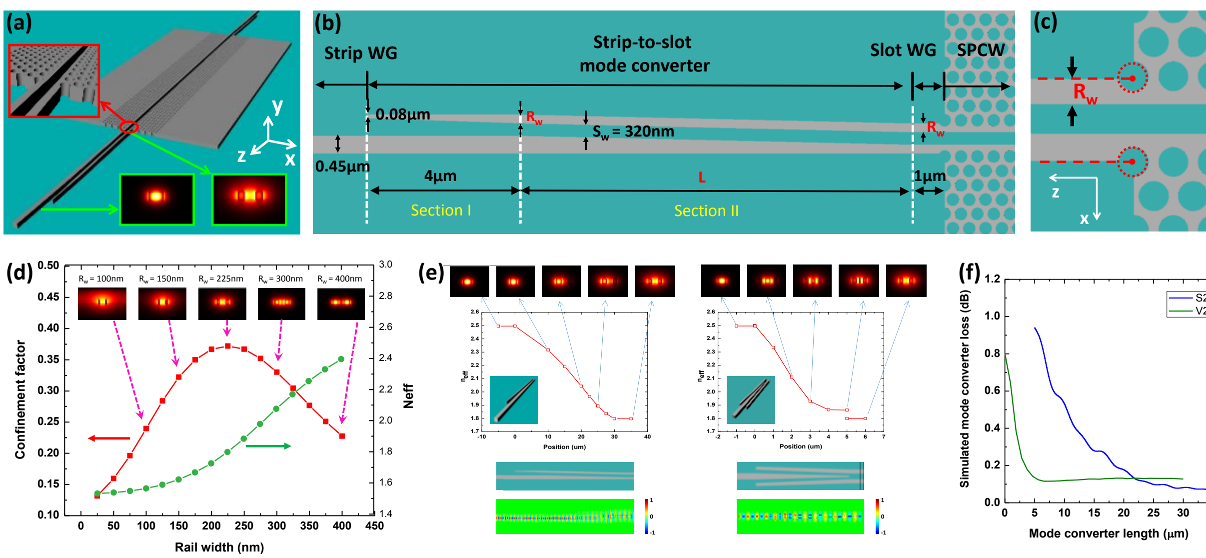

Fig. 1. (a) Schematic of our mode converter. (b) Top view of the mode converter between the strip waveguide and the SPCW, consisting of two linearly tapered sections. (c) c) Top view of magnified image of the coupling interface between the slot waveguide and the SPCW. (d) Confinement factor within the slot and n_{eff} as a function of rail width (R_w). (e) n_{eff} transition along our mode converter and conventional V-shape mode converters, respectively, overlaid with mode profiles and propagation modes (FDTD top view simulation). (f) Simulated loss of mode converter S2 and V2, as a function of mode converter length at the wavelength of 1550nm.

As shown in Fig. 1 (a), a slot waveguide is designed and used as an input for a designed SPCW with the same S_w [Fig. 1 (b)]. The SPCW and mode converter are filled with EO polymer (n=1.63). Good optical mode confinement in the slot waveguide plays an important role in increasing the coupling efficiency into the SPCW; therefore, our work starts with the optimization of this slot waveguide section. The S_w is fixed at 32nm, and the rail width (R_w) of the slot waveguide is optimized for maximum mode confinement. Fig. 1 (d) shows the simulated TE mode profile, confinement factor and the effective refractive index (n_{eff}) plotted as a function of R_w, indicating the largest confinement factor of 38% is achieved at R_w=225nm. In comparison, the conventional design with slot waveguide rails terminating at the center of holes in the SPCW interface, e.g. R_w=300nm, has a smaller confinement factor of 33%.

Fig 1. (e) shows a comparison of our mode converter and a 5 µm-long conventional V-shape mode converter. Our mode converter results in a smooth transformation of mode profiles and an adiabatic transition of n_{eff}. In comparison, the V-shape mode converter has a non-zero tip width (~80nm) due to practical lithography limitations. This discontinuity in the mode field distribution causes an abrupt change of n_{eff} and thus additional optical scattering loss. In addition, as shown in Fig. 1 (f), the loss of V-shape mode converter cannot be reduced by increasing its length, since the sudden discontinuity still causes a high insertion loss, while the loss of adiabatic mode converter can be improved by increasing the length of Section II in Fig. 1 (b), due to a smoother transition.

Next, utilizing the optimized slot waveguide (S_w=225nm), next we verify the length-dependent mode converter loss by fabricating and characterizing mode converter pairs with L varied from 5 µm to 30 µm. Test structures with different numbers of mode converters (2, 4 and 8) of varying lengths (L) connected in series are fabricated using e-beam lithography and RIE on an SOI substrate, and then are covered by EO polymer. Next, the total insertion loss is measured for different L as a function of mode converter number, as shown in Fig. 2 (a). The measured loss per mode converter, indicated by the slope of the linear regression lines of the measured data, is extracted and plotted in Fig. 2 (b), agreeing well with the simulation results. The optical loss is <0.1dB for L>25 µm. Therefore, the mode converter length is finally chosen to be 30 µm. Additionally, the simulated and measured optical loss of a single adiabatic mode converter over a wavelength range from 1520 to 1580 are shown in Fig. 2 (c), indicating a wide low-dispersion optical bandwidth.

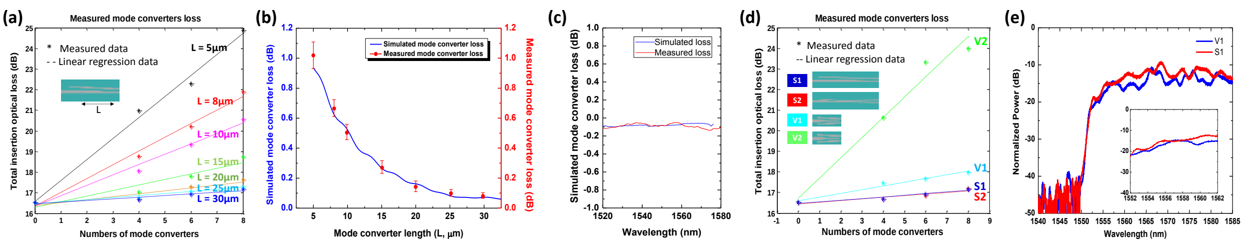

Fig. 2. (a) Measured insertion loss as a function of number of mode converters. (b) Measured mode converter loss v.s. length overlaid with simulated mode converter loss. (c) Simulated and measured normalized transmission spectrum of one adiabatic mode converter. (d) Comparison of measured loss of our mode converter and conventional V-shape mode converter. S1: mode converter in this paper, loss: 0.080dB; S2: mode converter in [8], loss: 0.075dB; V2: V-shape mode converter with R_w=225nm, loss: 0.182 dB; V1: V-shape mode converter with R_w=300nm, loss：0.981dB. (e) Normalized transmission spectrum of SPCW with our mode converter (S1).

Next, our adiabatic mode converters (L=30 µm, S1: R_w=225nm) together with the conventional V-shape mode converters (5 µm-long, V1: R_w=225nm, V2: R_w=300nm) are fabricated on the same chip, and the insertion losses are measured and compared in Fig. 2 (d). It can be clearly seen that our optimized adiabatic mode converter (S1) has a loss of 0.080dB, which is at least 0.1dB smaller than V-shape mode converters (V1: 0.182dB; V2: 0.981dB). Furthermore, by comparing V1 and V2, one can tell that an improvement of about 0.8dB is achieved using the optimized R_w (225nm) compared to un-optimized R_w (300nm). Additionally, another mode converter (S2) used in [3] is also fabricated and measured with loss=0.075dB.

Finally, in order to demonstrate that our optimized adiabatic mode converter can enable efficient light coupling between a strip waveguide and a SPCW, a 300 µm-long EO polymer infiltrated SPCW with S_w=320nm [2] with our mode converter (S1) is fabricated and characterized. As a comparison, the same SPCW with the V-shape mode converter (V1) is also fabricated on the same chip and measured. The measured normalized transmission spectrum is shown in Fig. 2 (e), and a clear band gap with more than 25dB contrast is observed, indicating that our optimized mode converter enables efficient coupling into the slow-light SPCW. In comparison, using the V-shape mode converter, the band gap has a ~2dB lower contrast in the normalized transmission spectrum. The inset of Fig. 3 (e) shows a magnified portion of the transmission spectrum in the slow-light wavelength region. The total insertion loss in the slow-light wavelength region is lower using our adiabatic mode converter compared to that using the V-shape mode converter, with a maximum loss difference of up to 3.5dB at 1560nm.

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