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Topology Optimized Mode Conversion In a Photonic Crystal Waveguide

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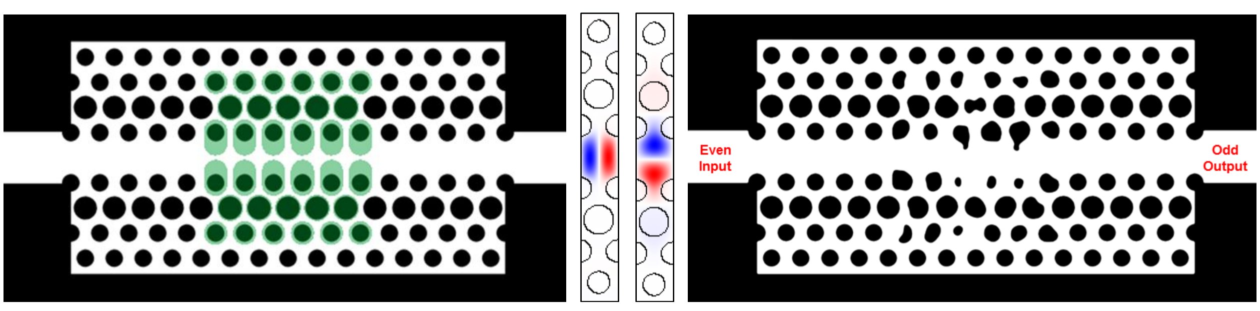
Abstract: We experimentally demonstrate an ultra-compact TE_0-TE_1 mode converter obtained in a photonic crystal waveguide by utilizing topology optimization and show a ~39 nm bandwidth around 1550 nm with an insertion loss lower than ~3 dB.

Mode conversion in ultra-compact photonic integrated circuits (PICs) has recently been investigated [1, 2, 3] to support on-chip processing of mode-division multiplexed data-signals. Typically, integrated mode converters rely on phase detuning between waveguides in an interferometric configuration [1] or scattering effects induced in single waveguides [2, 3]. The approach based on phase detuning gives a compact and efficient solution for conversion between the fundamental even and the first order odd modes, but requires a large size of the device for doing higher order conversions [4], which makes it a less attractive choice for dense PICs handling several mode orders. On the other hand, mode converters based on scattering effects topologically induced in the waveguide may have footprints of a few square vacuum wavelengths, but have problems of being realized in practice due to the delicacy of the scatters.

Topology optimization (TO) [5] has so far been proven to be a strong and robust inverse design tool for designing various compact nanophotonic components with broadband and low-loss performances [6]. Here, we present the first experimental results for low-loss TE_0-TE_1 mode conversion in a topology optimized photonic crystal waveguide (PhCW) fabricated in silicon-on-insulator (SOI) material and demonstrate the practical feasibility of using TO to realize ultra-compact mode conversion in PICs.

The initial PhCW design shown in Fig. 1(a) is formed by air holes (black) with diameter D=0.6Λ in silicon (white) where Λ=420 nm is the pitch of the triangular lattice. The diameter of the second row of holes has been increased to D_2=0.8Λ to make the first order transverse electric odd mode (TE_1) non-degenerate in the wavelength region of interest. The objective of the TO is to convert the fundamental transverse electric even (TE_0) mode (Fig. 1(b)) of the PhCW into the TE_1 mode (Fig. 1(c)) in a 40 nm wavelength region located in the index-guided regime of the PhCW around 1550 nm.



(a) **(b)** **(c)** **(d)**

Fig. 1. **(a)** Initial design of the PhCW defined by air holes (black) arranged in a triangular lattice in silicon (white). Also shown is the design domain (green) chosen in the TO. 2D mode plots for the **(b)** TE_0 and **(c)** TE_1 mode of the PhCW. **(d)** Topology optimized mode converter design obtained by utilizing 2D TO.

TO is performed utilizing 2D finite-difference time-domain (FDTD) modelling using a software package developed in-house. The optimization process is based on repeated solutions of the state and the adjoint equations and design updates [7]. The design domain (green areas in Fig. 1(a)) was intuitively specified as a set of regions around the 3 innermost rows of holes in order to prevent dramatic changes in the design and to avoid appearance of silicon islands. A converged topology optimized design with a TE_0/TE_1 extinction ratio better than -12 dB is obtained after ~100 optimization steps and the final design is shown in Fig. 1(d).

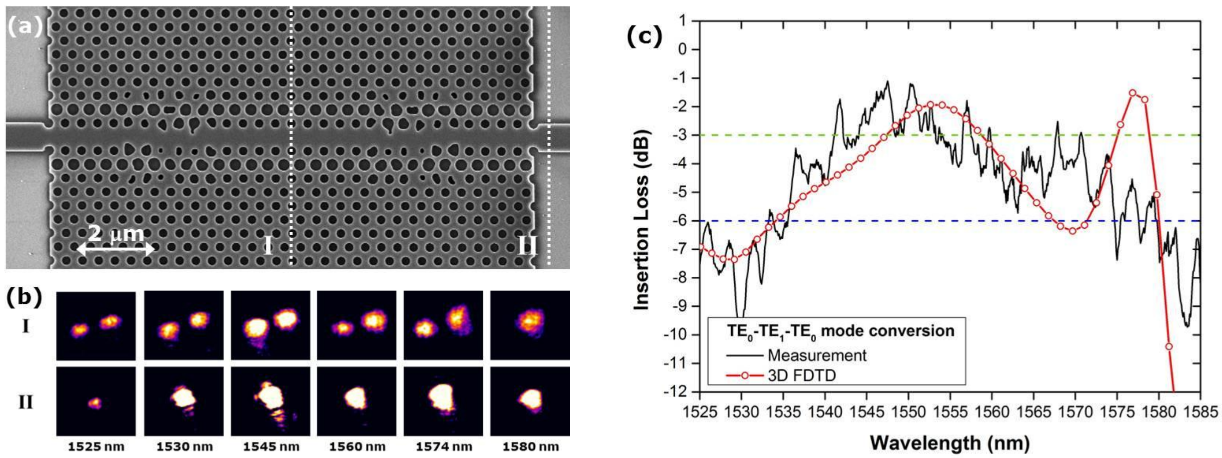


Fig. 2. **(a)** SEM image of the optimized TE_0-TE_1-TE_0 mode converter fabricated for characterization purpose in SOI material. **(b)** Mode profiles recorded for the TE_0-TE_1 (I) and TE_0-TE_1-TE_0 (II) mode converters at given wavelengths. **(c)** Measured (black) and 3D FDTD calculated (red) insertion loss for the device.

For characterization purposes, both a TE_0-TE_1 and a TE_0-TE_1-TE_0 mode converter were realized. The latter was done by mirroring the TE_0-TE_1 converter subsequently after the TE_0-TE_1 conversion. Figure 2(a) shows a scanning electron micrograph (SEM) image of the TE_0-TE_1-TE_0 mode converter fabricated in SOI material. Mode field profiles corresponding to positions I and II in Fig. 2(a) are recorded on an infrared camera by use of vertical grating couplers [8] placed after the TE_0-TE_1 and the TE_0-TE_1-TE_0 mode converters. Figure 2(b) shows the recorded output field profiles for the TE_0-TE_1 (I) and TE_0-TE_1-TE_0 (II) converters for TE_0 light input, clearly demonstrating that the TO design converts light from the TE_0 to the TE_1 mode and back in a ~49 nm wavelength region from ~1525 nm to ~1574 nm. Figure 2(c) shows the measured (black) and 3D FDTD calculated (red) insertion loss as a function of wavelength for the TE_0-TE_1-TE_0 mode converter. An insertion loss better than 6 dB is experimentally seen in the wavelength region from ~1535 nm to ~1574 nm with a minimum insertion loss of ~1.5 dB, which is in good agreement with 3D FDTD calculations. For the TE_0-TE_1 converter the insertion loss can be halved, experimentally demonstrating an efficient conversion of the TE_0 to the TE_1 mode with an insertion loss lower than 3 dB in a ~39 nm bandwidth. We believe that the TO method can easily be applied to realize low-loss conversions between higher order modes with complex mode fields in PhCWs or photonic wires.

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