High-purity transmission of a slow light odd mode in a photonic crystal waveguide

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We demonstrate a novel scheme to control the excitation symmetry for an odd mode in a photonic crystal waveguide and investigate the spectral signature of this slow light mode. An odd-mode Mach–Zehnder coupler is introduced to transform mode symmetry and excite a high-purity odd mode with 20 dB signal contrast over the background. Assisted by a mixed-mode Mach–Zehnder coupler, slow light mode beating can be observed and is utilized to determine the group index of this odd mode. With slow light enhancement, this odd mode can help enable novel miniaturized devices such as one-way waveguides. © 2012 Optical Society of America

OCIS codes: 130.5296, 230.5208.

Photonic crystal waveguides (PCWs) [1–5] can modify light propagation and dispersion characteristics through their periodic structures and thus have important applications in communications and sensing. Particularly, the slow light effect in a PCW can significantly enhance light–matter interaction [6–8], as demonstrated in significant reduction of interaction lengths for PCW-based modulators and switches [9–11]. To date, most of the PCW research has been focused on the TE-like mode with even symmetry. However, a PCW often has an odd TE-like mode inside the photonic bandgap exhibiting the slow light effect as well. This odd mode can potentially open up the opportunities for mode-symmetry-based novel devices, such as one-way waveguides that exploit indirect interband photonic transitions between even and odd modes [12]. The slow light effect in PCWs can help reduce the interaction length for such transitions, enabling ultracompact devices. To utilize this odd mode in any device, it is crucial to control its excitation symmetry and understand its slow light spectral characteristics. Normally, this odd mode does not exhibit itself evidently in the PCW transmission spectrum because its odd symmetry prohibits its excitation by the fundamental even mode of a conventional waveguide typically used at input. Symmetry-breaking structure imperfections sometimes may induce some coupling to this odd mode, causing a decrease of PCW transmission in the odd mode band [13,14]. Here we demonstrate a novel scheme to control the excitation symmetry for high-purity transmission of this odd mode and investigate the spectral signatures under various excitation symmetries.

Consider a W1 PCW formed on a silicon-on-insulator (SOI) wafer by removing a row of air holes in a hexagonal lattice with lattice constant a = 400 nm, hole radius r = 0.325a, and Si slab thickness t = 260 nm. The band diagram in Fig. 1(a) is calculated by three-dimensional (3D) plane wave expansion [15] (with >1 μm top/bottom claddings and six rows of holes per side). Below the lightline (for the oxide bottom cladding), the even TE-like mode has a flat dispersion relation with group index n_g > 50 and a narrow bandwidth (<1 nm). In contrast, below the lightline, the odd TE-like mode has a much wider bandwidth, ~20 nm, with n_g down to ~15. Such a mod-
1. REPORT DATE  
25 JUL 2012

2. REPORT TYPE

3. DATES COVERED
00-00-2012 to 00-00-2012

4. TITLE AND SUBTITLE
High-purity transmission of a slow light odd mode in a photonic crystal waveguide

5a. CONTRACT NUMBER
5b. GRANT NUMBER
5c. PROGRAM ELEMENT NUMBER
5d. PROJECT NUMBER
5e. TASK NUMBER
5f. WORK UNIT NUMBER

6. AUTHOR(S)

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Rutgers University, Department of Electrical and Computer Engineering, Piscataway, NJ, 08854

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:
   a. REPORT
      unclassified
   b. ABSTRACT
      unclassified
   c. THIS PAGE
      unclassified

17. LIMITATION OF ABSTRACT
   Same as Report (SAR)

18. NUMBER OF PAGES
   3

19a. NAME OF RESPONSIBLE PERSON
two-step approach. First, a Mach–Zehnder coupler (MZC) whose two arms have a phase difference of $\pi$ is utilized to transform mode symmetry and excite an odd mode in a wide (multimode) Si wire waveguide; then this odd mode is coupled to the odd mode of the PCW. To create a phase difference in this odd-mode MZC, its two arms can be designed to have a length difference of $(\Delta l)_x = \lambda/2n_{\text{eff}}$, where $n_{\text{eff}}$ is the effective index of the Si waveguide. Finite difference time-domain (FDTD) simulation has been performed to confirm that such a MZC produces an odd mode in a wide output waveguide, as shown in Fig. 2(a). The input and output waveguide widths are 400 and 700 nm, respectively. The coupling between the odd mode of a Si wire waveguide (700 nm wide) and that of the PCW is also simulated. Simulation results in Fig. 2(b) show coupling efficiencies up to $\sim$84% ($\sim$0.75 dB) for the odd mode. The field pattern in Fig. 2(b), left inset, confirms that the coupled PCW mode is an odd mode. The fundamental even mode of a Si wire waveguide couples into the PCW with inconsequential loss. The right arm has two extra waveguide segments (in orange) with a combined length of $\Delta l$, where $n_{\text{eff}}$ is the effective index of the Si layer. The transmission is due to the leaky even TE-like mode as simulated in Fig. 2(b). Figure 2 also shows the PCW transmission with MZCs whose two arms have a length difference $\Delta l$ deliberately designed to be $50\%$ greater than $(\Delta l)_x$. Such a mixed-mode MZC offers a symmetry configuration that can excite a mixture of even and odd modes according to $I_\pm \propto \cos(2\pi n_{\text{eff}}(\Delta l/\lambda))$. As such, the background transmission due to the even mode rises. In the odd-mode band, the mixed-mode spectrum oscillates strongly due to the beating of two modes. Figures 4(a) and 4(b) illustrate that distinctive spectral signatures can be observed with controlled excitation symmetries.

The mode-beating pattern of the mixed-mode spectrum contains important information of the odd mode. The beating period is related to the group indices of even and odd modes through $\Delta l = \lambda/(n_{g,\text{odd}} - n_{g,\text{even}})L$, where $L$ is the PCW length. Simulation indicates that $n_{g,\text{even}}$ is virtually a constant ($\sim$5) in the odd-mode band. Thus the chirped beating periods are due to the dispersion of $n_{g,\text{odd}}$. We have calculated $\Delta n_g = n_{g,\text{odd}} - n_{g,\text{even}}$ from the mixed-mode spectrum and plotted it in Fig. 4(c). The peak spacing and valley spacing of the spectrum give two sets of $\Delta n_g$ data, plotted by circles and crosses.
respectively. They agree with each other, as expected. Note that the $\Delta n_g$ value obtained from two adjacent peaks (valleys) is assigned to the mid-point wavelength in between. Further, $n_{g,even} = 4.9$ is obtained in Fig. 4(d) through the Fourier transform of the transmission spectrum of another directly coupled PCW with more obvious spectral ripples. Note that the Fourier frequency $f_\lambda$ is just the inverse of the spectral oscillation period $\delta \lambda$, thus $n_{g,even} = f_\lambda \times \lambda^2 /2L$. Based on Figs. 4(c) and 4(d), we find $n_{g,odd} = \Delta n_g + n_{g,even}$ in the range of 14 to 29. Note that the Fabry–Perot (F-P) oscillation amplitude in Fig. 4(a) is relatively weak. In contrast, the mode-beating amplitude of the mixed-mode spectrum in Fig. 4(b) is much higher and more robust against noise, which facilitates the evaluation of $n_{g,odd}$. Also note that in Fig. 4(a), the background transmission increases discernibly beyond 1430 nm due to the dispersive effect in the odd-mode MZC, which modifies the phase shift difference between the two arms as $\lambda$ deviates far from the designed value (1390 nm). The TM-like mode (guided for $\lambda > 1.45 \mu m$) may also contribute to the background at long wavelengths. However, these effects are much weaker for 1380–1415 nm.

Although this work focuses on PCWs on a SOI chip, the MZC and the mode-beating-based $n_{g,odd}$ measurement method can be adapted to the cases of air-bridge or oxide-covered PCWs and coupled-cavity PCWs, where interesting anomalous propagation related to an odd mode has been observed [19]. It would be interesting also to explore a refined design to optimize the bandwidth and the slow-down of light together for this odd mode. Detailed discussion of these possibilities is beyond the scope of this work. The odd-mode wavelength can also be shifted to ~1550 nm or other values (depending on specific applications) by changing the lattice constant. In a SOI PCW, there is some coupling between the TE-like guided modes and the TM-like photonic crystal bulk modes due to asymmetric top/bottom claddings. Prior work on the even mode has demonstrated that reducing $n_g$ can reduce the loss due to such coupling [3]. This odd mode has a much lower $n_g$, ~14, than the normal even mode ($n_g \sim 50$) below the lightline. This helps to reduce the coupling to the TM-like bulk modes. For many PCW devices operating at a short length $<80 \mu m$ [9,10], the propagation loss of the odd mode is expected to be reasonable. Lastly, the understanding of the slow light and mode-beating characteristics of this odd mode, as well as the controlled excitation and $n_{g,odd}$ characterization schemes developed here, can facilitate the development of mode-symmetry-based novel devices, such as one-way waveguides that involve active transition and passive conversion between even and odd modes [12]. Slow light can help reduce device interaction length. Note that previously demonstrated conventional waveguide mode converters employed branching waveguides [20,21] or multimode interference couplers [22]. Photonic-crystal-based mode converters have also been designed [23]. Here, the odd-mode MZC is focused on transforming mode symmetry to attain a high-purity odd mode, and the mixed-mode MZC offers a symmetry configuration for coherent mixing of even and odd modes, which enables $n_{g,odd}$ measurement through slow-light mode beating.

As a side note, beating between two degenerate modes in a periodically patterned microring resonator has recently been observed, but the resonant wavelength spacing is not affected by beating [24].

In summary, we have experimentally demonstrated the control of excitation symmetry for an odd TE-like mode in a PCW. An odd-mode MZC is utilized to selectively excite the odd mode with a contrast $>20$ dB over the background. Assisted by a mixed-mode MZC, slow light mode beating is observed and is utilized to measure the group index of this odd mode.

This work is supported in part by AFSOR Grant No. FA9550-10-C-0049. This research is carried out in part at the Center for Functional Nanomaterials, Brookhaven National Laboratory, which is supported by the U.S. Department of Energy, Office of Basic Energy Sciences, under Contract No. DE-AC02-98CH10886.

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