Extended Abstracts of the 2004 International Conference on Solid State Devices and Materials, Tokyo, 2004, pp. 296-297

F-5-2 (Invited)

PBG Resonators and Waveguides in SOI Photonic Crystal Slabs

M. Notomi, A. Shinya, E. Kuramochi, S. Mitsugi

NTT Basic Research Laboratories, Nippon Telegraph and Telephone Corporation,
3-1 Morinosato-Wakamiya, Atsugi, 243-0198 JAPAN
TEL: +81-46 240 3553, FAX: +81-46-240 4305
E-mail: notomi@nttbrl.jp, URL: http://www.brl.ntt.co.jp/people/notomi

1. Introduction:

Photonic crystals (PhCs) having photonic band gaps (PBGs) are expected to be key platforms for future large-scale optical integrated circuits.[1] At a first look, in order to get high performance, 3D PhCs having 3D PBGs are essentially required, but recent studies show that fairy good performance can be obtained for so-called 2D *PhC slab* structures. PhC slabs are 2D PhCs located within high-index-contrast slab waveguides. In this presentation, we will show our recent progress in terms of both design and fabrication of PBG waveguides, PBG resonators, and multi-port devices consisting of waveguide-resonator coupled elements. Our basic structure is a Si PhC slab on a silicon-on-insulator (SOI) substrate (SOI PhC slab) [2,3,4,5,6,7]. The SOI PhC slab is formed by electron-beam lithography and electron-cyclotron-resonance ion-stream dry etching in the top Si layer whose thickness is approximately half a wavelength in Si.[8]

2. PBG waveguides:

Loss is a critical issue for PBG waveguides. As regards this issue, there has been significant progress. Figure 1(a) shows our recent result of the propagation loss measurement. The obtained loss (1.5 dB/mm for the SiO_2-clad PhC and 0.6 dB/mm for the air-clad PhC) [9] is significantly better than that of our previous reports (~6 dB/mm) for SiO_2-clad PhCs.[3,4] Besides the propagation loss, the connection loss to single-mode fibers has been also considered as a fatal problem. To solve this problem we had proposed an adiabatic mode connector shown in Fig. 1(b). [10] It consists of a spot-size converter [11] between a polymer waveguide and Si-wire waveguide, and a mode-profile converter between a Si-wire waveguide and a PBG waveguide. The fabricated device showed approximately 3dB conversion efficiency. Detail of this device can be found in ref. [11]. Thanks to the progress in the loss problem, we recently observed a large group delay of 100-200 ps in a 1-mm long PBG waveguide by a time-domain measurement, as shown in Fig. 1(c). [12]

3. PBG resonators coupled with PBG waveguides

PBG resonators can be effectively coupled to PBG waveguides in various ways. This is one of the most important advantages of PBG resonators compared with other micro-resonators. Resonator-waveguide coupled systems are starting points for various applications, and will be key components in future PhC-based optical circuits. Here we discuss how we implement resonators in functional coupled systems.

To realize effective coupled components, the first thing we have to design is to increase Q of PBG resonators while keeping their mode volume small enough. We have used two methods to significantly increase Q. One is utilizing short Fabry-Perot cavities

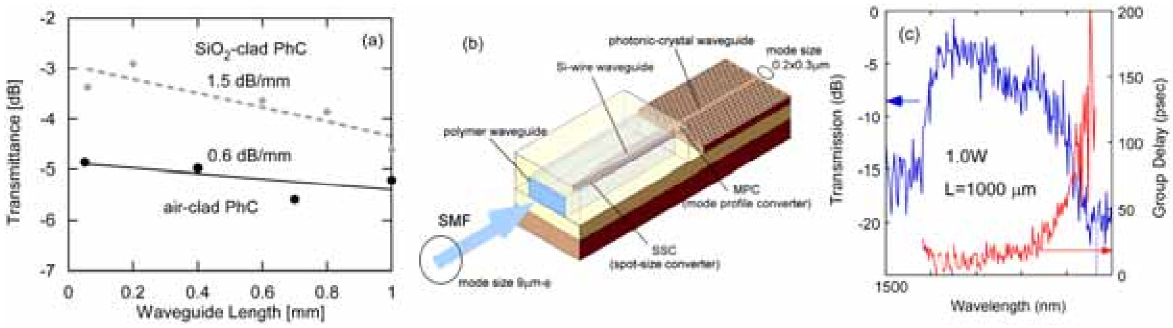

Fig. 1. (a) Propagation loss measurement for single-mode PBG waveguides in SiO_2-clad and air-clad PhCs. (b) Schematic diagram of an adiabatic mode connector, which consists of a spot-size converter and a mode-profile converter. (c) Time-domain measurement of group delay dispersion in PBG waveguides in SOI PhC slab.

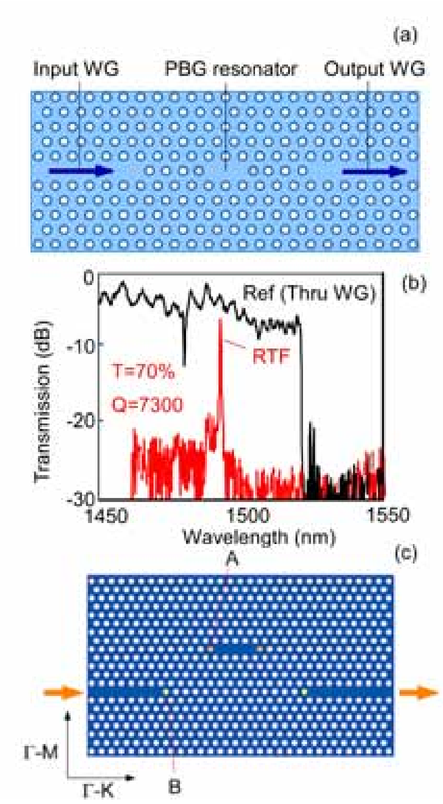

Fig. 2. Two-port resonant tunneling transmission filter: (a) Structural design. Shaded holes are shifted in the outward direction to increase Q. (b) Measured transmission spectra for a resonant tunneling filter and a reference PhC waveguide without a cavity.

(as shown in Fig. 2(a)) [13] and the other is utilizing hexapole cavities.[14] In both cases, we numerically confirmed that both cavities have very large Q (far larger than 10^5). The largest Q estimated is $>2x10^6$ in hexapole cavities. [14]

Next, we investigate a simple two-port design in which there are only single input and output waveguides, as shown in Fig. 2(a). Using this design, we have realized high-Q and high-transmission ultrasmall resonant-tunneling transmission filters using a short Fabry-Perot-type resonator having $Q=10^4 \sim 10^5$ (Fig. 2(b)). The observed total transmission Qs are 5000~24000. We achieved the transmittance larger than 70% with the total transmission Q of 7000. [13] Furthermore, we will show four-port and three-port designs in which there are two (or one) input and two output waveguides., A channel-drop filter [15] can be implemented with this design. Figure 4 shows a novel 3-port channel-drop filter using resonant tunneling process that we propose [16] We have recently fabricated similar devices and confirmed the operation.

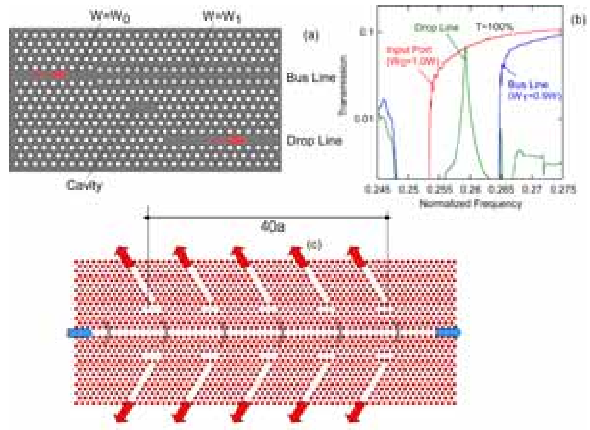

Fig. 3. Three-port resonant-tunneling channel drop filter: (a) basic configuration to explain the operation principle. (b) Simulated transmission of (a). (c) Structural design of the cascaded multi-channel drop filter using the resonant tunneling process.

Related references:

[1] J.D. Joannopoulos *et al. Photonic Crystals*, Princeton University Press (1995).

[2] I. Yokohama, M. Notomi, A. Shinya, C. Takahashi, T. Tamamura, *OECC 2000*, 42 (2000).

[3] M. Notomi, A. Shinya, K. Yamada, J. Takahashi, C. Takahashi, I. Yokohama, Electron. Lett. **37**, 243 (2001).

[4] M. Notomi, A. Shinya, K. Yamada, J. Takahashi, C. Takahashi, and I. Yokohama, IEEE J. Quantum Electron. **38**, 736(2002).

[5] M. Notomi, K. Yamada, A. Shinya, J. Takahashi, C. Takahashi, I. Yokohama, Phys. Rev. Lett. **87**, 253902 (2001).

[6] M. Notomi, A. Shinya, K. Yamada, J. Takahashi, C. Takahashi, I. Yokohama, Proc. SPIE, 4655, 92 (2003).

[7] M. Notomi, A. Shinya, E. Kuramochi, S. Mitsugi, H-Y. Ryu, T. Kawabata, T. Tsuchizawa, T. Watanabe, T. Shoji, and K. Yamada, IEICE Trans. Electron. March issue, (2004).

[8] C. Takahashi, J. Takahashi, M. Notomi, and I. Yokohama, *2000 Fall Meeting of Materials Research Society* (MRS Proceedings, vol. 637, E1.8, 2000).

[9] E. Kuramochi et al., PECS-V, Kyoto, 2004.

[10] A. Shinya, M. Notomi, E. Kuramochi, T. Shoji, T. Watanabe, T. Tsuchizawa, K. Yamada, and H. Morita, Proc. SPIE, **5000**, 21, 104-117 (2003).

[11] T. Shoji, T. Tsuchizawa, T. Watanabe, K. Yamada and H. Morita, ", Electron. Lett. **38**, 1669-1670 (2002).

[12] M. Notomi, A. Shinya, S. Mitsugi, E. Kuramochi, H-Y. Ryu, Opt. Exp. 12, 1551-1561 (2004).

[13] S. Mitsugi, A. Shinya, E. Kuramochi, M. Notomi, T. Tsuchizawa, and T. Watanabe, *LEOS 2003*, 214 (2003).

[14] H-Y. Ryu, M. Notomi, and Y-H. Lee, Appl. Phys. Lett. **83**, 4294-4296 (2003).

[15] S. Fan, P. R. Villeneuve, J. D. Joannopoulos, and H. A. Haus, Phys. Rev. Lett. **80**, 960-963 (1998).

[16] A. Shinya et al., *PECS-V*, Kyoto, 2004.