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# Coupled Waveguide Devices Based on Autocloned Photonic Crystals

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## 1. Introduction

Photonic crystals (PCs), which are periodic structures of the refractive indices of materials, have attracted much attention because their unique properties--such as strong optical confinement due to photonic bandgap, dispersion, and anisotropy--make it possible to fabricate micro lightwave circuits [1-3]. A simple process is essential to produce these circuits. We developed a technique called autocloning to fabricate two-dimensional (2D) or three-dimensional (3D) PCs [4]. It enables monolithic integration of various optical device functions such as channel waveguides, superprisms, filters, and dispersion compensators [1]. Coupled waveguides are important elements in PC-based micro lightwave circuits because they can be applied to various devices such as optical directional couplers and optical add/drop multiplexers.

In this paper, we describe coupled waveguide devices based on lattice-modulated photonic crystals fabricated by autocloning. We observed their fundamental operations as optical directional couplers at a wavelength of 1.55 μm. Furthermore, by adding optical resonators to the directional couplers, we also observed fundamental operations as optical add/drop multiplexers.

## 2. Optical Directional Coupler

The channel waveguide structures were formed by modulating the lattice of autocloned PCs. The PCs consisted of $Ta_2O_5$ and $SiO_2$ layers alternately stacked on a Si substrate with periodic grooves using an appropriate combination of sputter deposition and sputter etching [4]. The lattice constants were modulated both parallel and perpendicular to the substrate surface. These modulations caused differences in the effective refractive indices. Figure 1 shows a cross-sectional scanning electron microscope (SEM) photograph of the fabricated coupled waveguide structure. The thicknesses of the $Ta_2O_5$ and $SiO_2$ layers were the same. The calculated difference in the effective refractive indices between the core and cladding regions was 0.8 %. In this case, an electric field is parallel to the substrate surface. The cross-sectional area of each core was 3 x 3 μm, and two adjacent cores were separated by 1.0 μm. We prepared some optical directional couplers with different coupling lengths ($L$), from 200 to 600 μm. The total length of each sample was 2 mm including the s-shape waveguides and two input ports on one end and two output ports on the other.

Figure 2(a) shows the experimental setup to measure

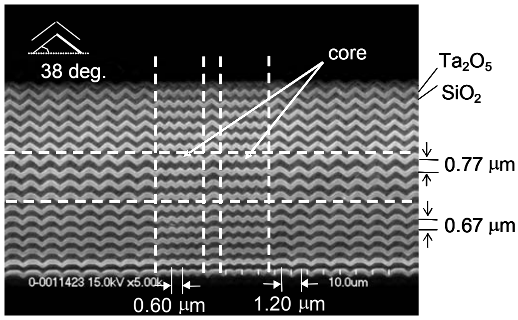


Fig. 1. Cross-sectional SEM photograph of fabricated coupled waveguide

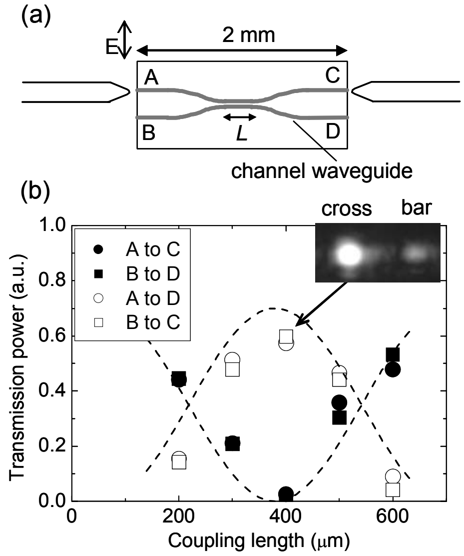


Fig. 2. (a) Experimental setup to measure power splitting ratio. (b) Measured transmission power for various coupling lengths. Near-field pattern of output with 400-μm coupling length inserted

the optical power splitting ratio. A light beam with a wavelength of 1.55 μm was introduced into one of the input ports (A or B) through a tapered optical fiber, and transmitted optical power was detected at both output ports (C and D) through another fiber. First, we measured the propagation loss for straight waveguides. We estimated it to be 1.5 dB/mm, which was almost comparable with the previously reported value [5].

Figure 2(b) shows the measured transmission power from both output ports for devices with various coupling

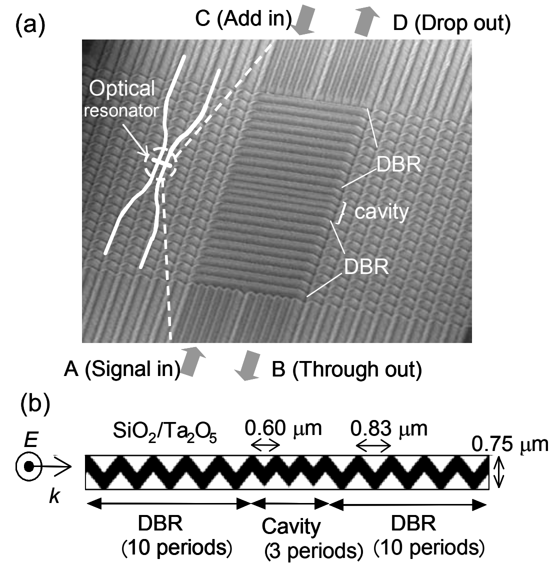


Fig. 3. (a) Top-view SEM photograph of optical add/drop multiplexer, (b) Illustration of cross section of optical resonator.

lengths. The closed circles and squares represent the measured output power from the bar ports (A to C and B to D), and the open circles and squares represent the measured output power from the cross ports (A to D and B to C). A near field pattern of light output from a device with a coupling length of 400 μm is inserted in Fig. 2(b). The power splitting ratios of the two output ports varied according to the length of the coupled section, indicating basic operation as a directional coupler. The dashed lines in Fig. 2(b) indicate fitting curves, and the estimated coupling length was 350 μm [6]. This value agrees well with the calculated one of 400 μm acquired by the beam propagation method (BPM) with effective refractive indices. This value is one order of magnitude smaller than that of the conventional silica-based directional couplers. Theoretical analysis also revealed that the length could be shortened to less than 200 μm, when the distance between two coupled core areas is reduced to 0.5 μm.

## 3. Optical Add/Drop Multiplexer

In the previous section, we observed an almost complete energy transfer to the cross port with a coupling length of 400 μm. If an optical resonator is added at the center of the directional coupler, the device can operate as an optical add/drop multiplexer. Figure 3(a) shows the top view of the fabricated optical add/drop multiplexer. The optical resonator consisted of a cavity embedded between two distributed Bragg reflectors (DBRs) [1]. Figure 3(b) illustrates the cross section of the optical resonator. The stop band for each DBR calculated by a finite difference time domain (FDTD) method was 1520-1610 nm. The calculated transmission spectrum of the optical resonator has a peak around a wavelength of 1.56 μm. The calculated bandwidth of the transmission peak was 3 nm, which corresponded to a quality (Q) factor of 500.

Figure 4 shows the measured optical spectra from the through-out (B) and drop-out (D) ports. A light beam from

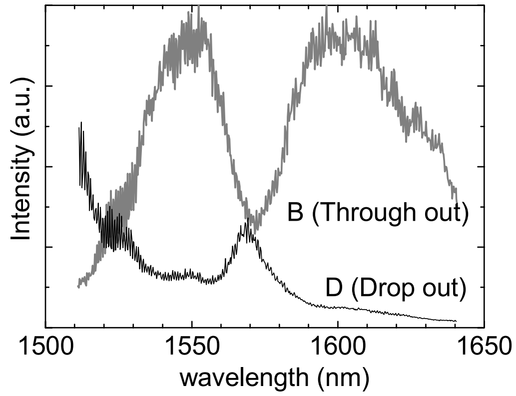


Fig. 4. Measured optical spectrum from the through-out and the drop-out ports.

a wavelength-tunable light source was introduced into the signal-in port (A). A peak for the drop-out port and a dip for the through-out port were observed around a wavelength of 1.57 μm. The measured bandwidth of an optical drop filter was about 20 nm, which corresponded to a Q factor of 80. This value was smaller than the calculated value, however, it could be improved by structurally optimizing the optical resonator.

## 4. Conclusions

We demonstrated the operation of coupled waveguides based on lattice-modulated PCs, which we fabricated using autocloning technology, for the first time. The measured complete coupling length was 350 μm at a wavelength of 1.55 μm, which is one order of magnitude smaller than that for a conventional silica-based waveguide. The fundamental operation for an optical drop filter was also achieved by adding the optical resonator at the center of the directional coupler. These results indicate that it is possible to produce various devices with coupled waveguides in micro lightwave circuits.

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