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Experimental Characterization of Photonic Crystal Delay Lines Based on Coupled Defects

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1. Introduction

Optical delay lines are one of the key components for high-speed optical time-division-multiplexed (OTDM) telecommunication systems in the future [1,2]. Photonic crystals in which light waves experience multiple reflections are one of the promising candidates for realizing a low group velocity for optical pulses [3]. Previously, we have proposed the use of coupled cavity waveguides (CCWs) to achieve efficient delay with negligible distortion for short pulses and theoretically analyzed the transmission of ultrashort pulses through CCWs with various impurity bands [4,5].

In this paper, we report on the fabrication and characterization of optical delay lines based on CCWs for ultrashort pulses. The effect of structure parameters on the transmission properties of impurity bands will be examined and discussed.

2. Fabrication

Figure 1 shows the schematic structure of our proposed optical delay line and the SEM image of a fabricated sample. The basic structure is a 1D CCW composed of cylindrical air hole array with a lattice constant a made in a Si/SiO_2 ridge waveguide[6]. Defects are created by periodically increasing (x1.5) the separation between two neighboring air holes. Basically, we can describe the configuration of delay lines using three parameters (N, n, m), as schematically shown in Fig. 1. We deduced from a theoretical investigation that one of the basic conditions for obtaining quasiflat impurity bands is that n is an even number and $m = n/2$. Obviously, the coupling strength, hence the bandwidth, is determined by n.

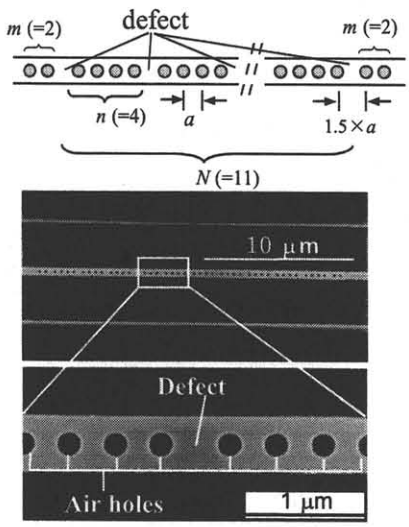

Fig. 1 Schematic structure and the SEM image of the fabricated PC delay line.

The patterning was realized using an electron beam (EB) lithography followed by a reactive ion beam etching [7]. Transmission spectra were measured using a tunable laser diode or an erbium doped fiber light source in combination with a spectrum analyzer. Pulse delay was measured by using a heterodyne interference method.

3. Characterization and Discussion

The transmission spectra for the fabricated delay lines with structure parameters of (N = 11, n = 4, m = 2) for different lattice constants are shown in Fig. 2. Impurity bands of ~20 nm wide have been observed. In addition, the tunable feature of the impurity bands is clearly demonstrated. By changing the lattice constant from 410 nm to 440 nm, the central wavelength of the impurity bands can be tuned from 1520 nm to 1590 nm.

A comparison of measured and calculated spectra for a sample is given in Fig. 3. The calculated spectrum was obtained by performing 3D finite-difference time-domain (FDTD) simulation on a real structure with diameter and

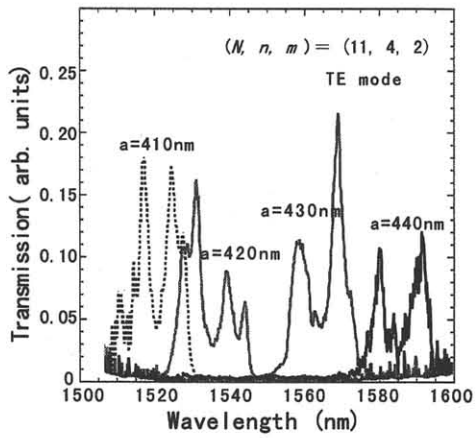

Fig. 2 Transmission spectra for fabricated PC delay lines.

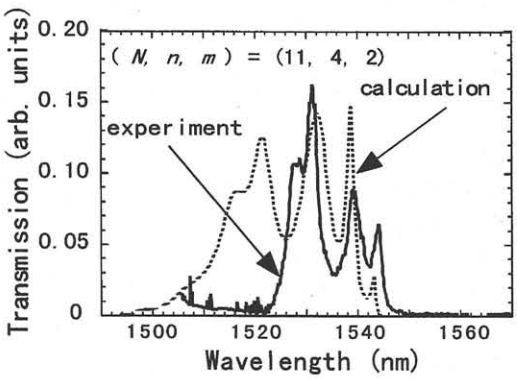

Fig. 3 Comparison between measured and calculated transmission spectra for PC delay line.

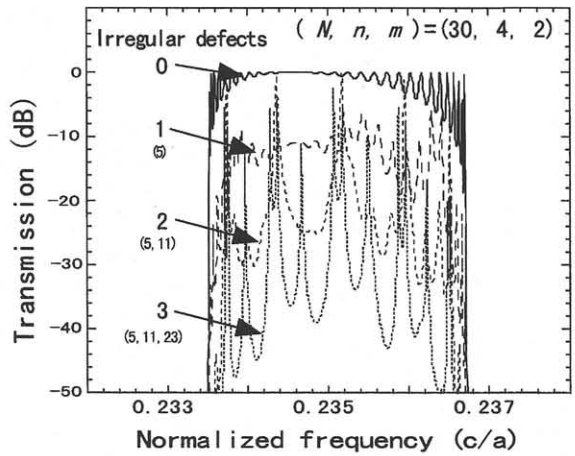

Fig. 5 Transmission spectra calculated for 1D coupled cavity waveguide with irregular defects.

position of each air hole measured by SEM. A good agreement on the location of impurity bands and the number of peaks can be seen between the two spectra.

The influence of the structure parameters (N, n, m) on the transmission properties of impurity bands are presented in Fig. 4. It can be seen that the bandwidth is reduced from ~50 nm to ~20 nm when n is increased from 2 to 4. Also, we can see that the absolute transmittance decreases with increasing N. Obviously, the achievable delay time is proportional to N. Therefore, it is important to clarify the origin of this decrease.

We have theoretically studied the effect of irregular defects with large deviation in size ($\pm 3\%$) on the transmission properties of impurity bands. For simplicity, we have used 1D CCWs composed of GaAs and air layers as an example [4]. In Fig. 5, we show the change of impurity bands after introducing 1-3 irregular defects at different positions. In the absence of irregular defects, the impurity band is quasi-flat with a unit transmittance. If we introduce an irregular defect, the absolute transmittance is reduced to -10 dB. However, the introduction of the second defect results in several resonant peaks with unit transmittance in the spectrum. When the third one is included, we can see a

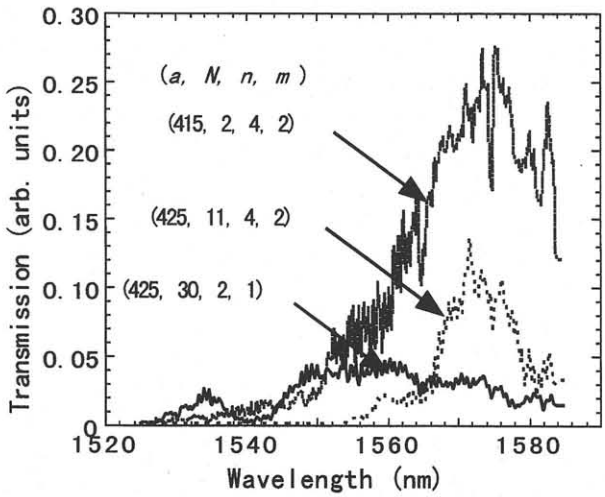

Fig. 4 Transmission spectra for fabricated PC delay lines.

significant reduction in the transmittance. Based on SEM measurements, we found that the largest deviation in the size of air holes can reach ± 6 % and it generally occurs at the field junction in the EB lithography (in our case, the periodicity is 5 μm). The decrease of transmittance in the samples with large N may be explained by the increase of irregular defects.

Finally, the transmission of ultrashort pulses and the delay effect were examined for the delay line ($N = 11$, $n = 4$, $m = 2$) using a 110 fs pulse. The delay time achieved in a sample of ~20 μm was found to be ~600 fs, which is in a good agreement with the calculated results. It implies that the group velocity in the delay line has been reduced to be 1/4 of that in the normal waveguide.

4. Conclusion

Optical delay lines based on CCWs have been successfully fabricated and characterized. Impurity bands with bandwidth of ~20 nm and transmittance >15 % have been observed. Their tunability was clearly demonstrated by changing the lattice constant. A good agreement was found between the measured and calculated spectra. The decrease of transmittance with increasing N was explained by the irregularity in the defects. Delay time of ~600 fs has been achieved for 110 fs pulse in a fabricated delay line of ~20 μm. These results confirmed that this kind of delay lines can be a promising element for future OTDM systems.

Acknowledgment

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References

[1] F. Saito, IEICE Trans. Electron., **E85, 1** (2002) 106.
[2] Y. Ueno et al., Jpn. J. Appl. Phys., **39** (1994)91.
[3] E. Yablonovitch et al., Phys. Rev. Lett., **67** (1991)3380.
[4] S. Lan et al., J. Appl. Phys., **90** (2001)4321.
[5] S. Lan et al., IEICE Trans. Electron., **E85, 1** (2002) 181.
[6] J. S. Foresi et al., Nature., **390** (1997) 143.
[7] Y. Sugimoto et al., *Mat. Res. Soc. Symp. 2001 Proc.,* (2001) E5.10.1.