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Development of directional coupler switch with ultra-short switching length based on flat-band photonic crystal structure

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Abstract

We have proposed a directional coupler (DC) switch with short switching length and wide bandwidth, which have a flat-band in even mode. We fabricated the DC and demonstrated that the DC had a flat-band.

1 Design of DC for short switching length and wide bandwidth

The DC switch we proposed is composed of a two-dimensional photonic crystal slab of air bridge type. This consists of GaAs substrate (thickness of 190nm) and air cylinders (circular holes). The lattice constant (a) is 390 nm, and the circular holes whose radii are $0.29a$ are arranged in the triangular lattice.

The coupled waveguide, which is a pair of parallel waveguides (shown in Fig. 1), is separated into two region A and B. The switching operation is realized by changing the refractive index of region A (the length of region A in the direction of waveguide is called "switching length").

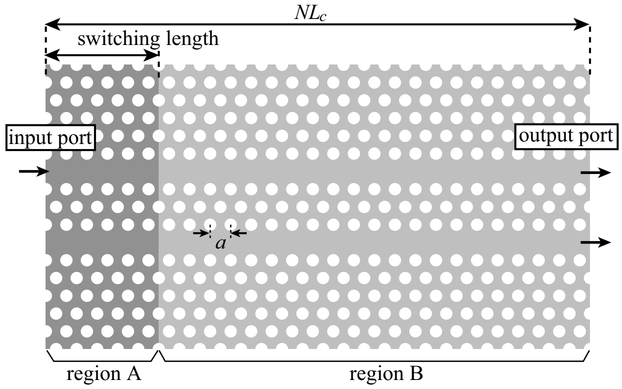

Fig. 1: The structure (top view) of coupled waveguide. The entire length is set to integral multiple of coupling length (L_c). Switching operation is realized by changing the refractive index of region A.

A DC switch requires short switching length and wide bandwidth. However they are a relation of trade-off for conventional DC. This relation can be dissolved using a DC which have a flat-band in even mode[1,2].

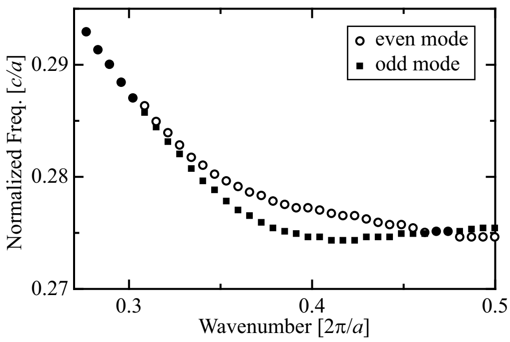

Fig. 2: Dispersion curves for conventional DC. The open circles denote the dispersion relation for even mode, and the rectangles denote that for odd mode.

The dispersion curves of conventional DC switch are shown in Fig. 2. Although conventional DC has no flat-band, dispersion curves can be generally transformed by structural modulation of photonic crystal. We designed the structure of DC so that the DC has a flat-band in even mode. The structure and dispersion curves of structure-modulated DC switch are shown in Fig. 3. By numerical analysis with two-dimensional (2D) FDTD method, it was found that the switching length was $11a$ (a is a lattice constant), which is 2.86% of conventional one. The bandwidth is 5.01nm, which is 35.0% of conventional one. The bandwidth becomes narrower than that of conventional DC, however, considering the shortening rate of the switching length, it is very wide.

2 Fabrication of DC

Next, the designed DC was lithographically fabricated with electron beam. The SEM images are shown in Fig. 4. In order to eliminate the reflection at bent waveguides, adiabatic bent waveguides (Fig. 4(c)) were introduced to all bent points. In addition, in order to inhibit the reflection at the edge of the coupled waveguide, and to improve the coupling efficiency of propagation mode between single waveguide and coupled waveguide, adiabatic branch waveguides (Fig. 4(a))

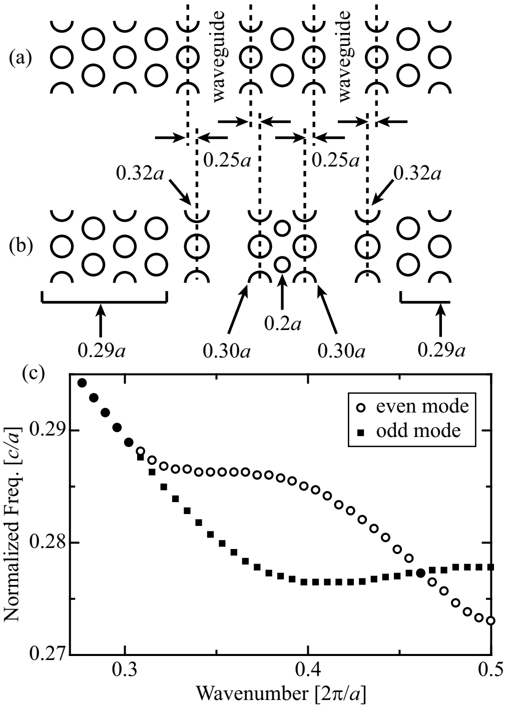

Fig. 3: The structure of conventional DC (a) and structure-modulated DC (b). (c):dispersion curves of structure-modulated coupled waveguide.

were introduced at both ends of the coupled waveguide.

3 Measurement of wavenumber difference between even and odd modes

In order to confirm whether the fabricated DC has a flat-band in even mode, the difference of wavenumbers ($\Delta k \equiv k_e - k_o$) between even and odd mode were measured with the following method. The Δk cannot be measured directly, then the coupling length (L_c) for every frequency was measured, and Δk was calculated by the following equation

$$\Delta k = \pi / L_c. \quad (1)$$

The coupling length is obtained by measuring the power spectra of DCs for different length of coupled waveguide, then the difference of length of the coupled waveguide between bar condition and cross condition is equal to coupling length.

By using the measured power spectra, we obtained the Δk, which are shown in Fig. 5 with open circles. Figure 5(a) is the result for conventional DC and (b) is that for structure-modulated DC. The solid lines in Fig. 5 are theoretical values obtained by band calculation with 2D-FDTD method. Experimental values well agree with theoretical one. The Δk for conventional DC gently changes for the frequency of incident light, this corresponds to the band diagram in Fig. 2.

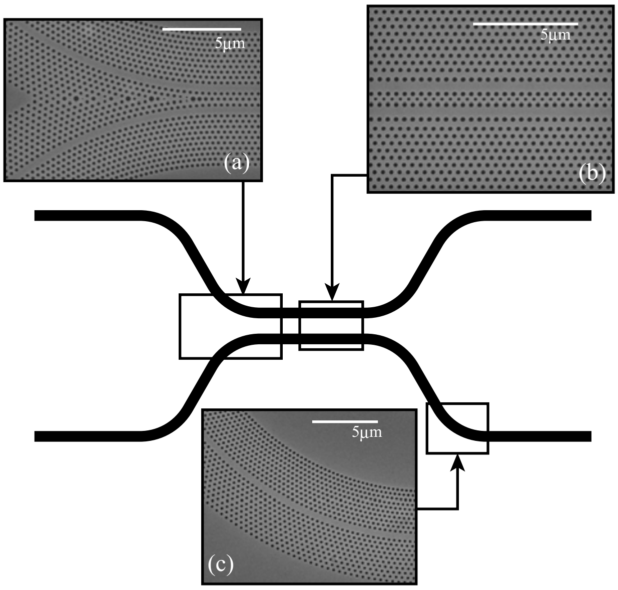

Fig. 4: SEM images of (a): adiabatic branch waveguide, (b): coupled waveguide (structure-modulated), and (c): adiabatic bent waveguide.

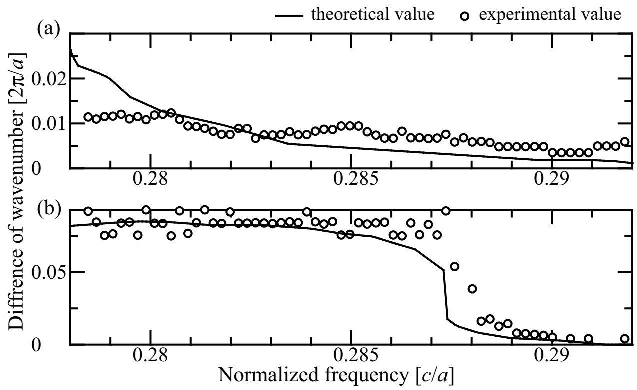

Fig. 5: The difference of wavenumber between even and odd mode for (a): conventional DC and (b): structure-modulated DC.

On the other hand, The Δk for structure-modulated DC changes rapidly at $0.288[c/a]$. This results show that the fabricated DC has a flat-band in even mode.

4 Conclusion

A novel structure of DC switch was designed and fabricated. The power spectra were measured correctly by introducing adiabatic structures. Next the difference of wavenumbers between even and odd modes were calculated from the measuring result of power spectra. From the result, it was shown that the fabricated DC has a flat-band in even mode by structural modulation.

Reference

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