# ANALYSIS OF TRANSMISSION CHARACTERISTICS OF TWO-DIMENSIONAL PHOTONIC CRYSTAL L-SHAPED OPTICAL BEND WAVEGUIDES

Yoshihiro NAKA and Hiroyoshi IKUNO
Department of Electrical and Computer Engineering, Kumamoto University
Kurokami 2-39-1, Kumamoto-shi, 860-8555 Japan
TEL:+81-96-342-3850 FAX:+81-96-342-3630
E-mail: naka@eecs.kumamoto-u.ac.jp

## 1 Introduction

Great interest has been given to the photonic crystals [1–3]. By using the strong confinement of the light by the photonic band gap, it is expected that waveguide devices whose size is on the order of the wavelength of light can be realized [2, 3].

We analyze the characteristics of several kinds of optical waveguides constructed by two-dimensional photonic crystal of circular dielectric rods in air on a square array numerically. To do so, we need a highly accurate numerical solution since we have to consider change of polarization, reflected waves and radiated waves in time domain and that in the complicated structures and media [3]. One of the effective numerical analysis method is the finite-difference time-domain (FD-TD) method based on the principles of multidimensional wave digital filters (MD-WDFs) [4, 5]; this method can easily be implemented and is more accurate than the conventional one, the Yee algorithm [6]. In order to design high density integrated optical waveguide devices it is important to establish fundamental properties of photonic crystal waveguides such as dispersion relation. We have confirmed the eigen mode propagation in the photonic crystal optical waveguide and check the dispersion relation of this waveguide [7].

In this paper, we analyze the transmission characteristics of two-dimensional L-shaped bend waveguide with additional dielectric rods in the corner region. These rods act as potential barriers used for resonant tunneling in a quantum wire [8]. We show that reflected waves from the right-angle corner can be completely eliminated by adding additional rods due to resonant tunneling. Next we design the directional coupler with right-angle bend waveguide and demonstrate that it can work as low-insertion-loss wavelength demultiplexer whose size is on the order of the wavelength of light.

## 2 Formulation of problems and numerical results

We consider a optical waveguide constructed by two-dimensional photonic crystal of circular dielectric rods on a square array with lattice constant $a$ as shown in Fig.1. The relative permittivity of the rods and background are $\varepsilon_a = 11.56$ and $\varepsilon_b = 1.0$, respectively and the radii of rods are $r_a/a = 0.175$. The photonic crystal has photonic band gap for only the $E$ polarized field $(E_y, H_x, H_z)$ which extends from frequency $\omega a/2\pi c = 0.320$ to $\omega a/2\pi c = 0.462$ where $c$ is the speed of light in a vacuum. The incident pulse is taken as

$$\psi(x, z = 0, t) = \psi_0(x) \exp\left(\frac{t - t_0}{T}\right)^2 \sin\{\omega_c(t - t_0)\}, \tag{1}$$

where $\psi_0(x)$ denotes a transverse profile which is a half-waveform of cosine, $T$ is pulse duration, $t_0$ is center point of the incident pulse, and $\omega_c$ is center angular frequency. In this paper we analyze single mode waveguide whose waveguide width is $W/a = 1.65$. Considering cut-off frequency of fundamental mode in this waveguide [7] and photonic band gap, we choose the incident parameters as $\omega_c a/2\pi c = 0.40$ and $cT/a = 11.0$.

First we analyze the right-angle bend waveguide with additional dielectric rods in the corner region as shown in Fig.1. In the corner region two additional dielectric rods whose radii and relative permittivity are $r_{a2}$ and $\varepsilon_{a2}$, respectively are placed. Fig.2 shows transmission characteristics of optical power when radii and relative permittivity of additional rods are changed. By adding additional rods we can completely eliminate reflected waves from the right-angle corner at the resonant frequency. From Fig.2(a) with an increase in radii $r_{a2}$ the resonant frequency shifts to lower and its quality factor increases. We can see from Fig.2(b) that increasing relative permittivity $\varepsilon_{a2}$ made same effect which arise when radii $r_{a2}$ are changed. Fig.3 shows Poynting vector and electric intensity of L-shaped bend waveguide. The radii and relative permittivity are $r_{a2}/a = 0.175$ and $\varepsilon_{a2} = 11.56$, respectively and the frequency of incident waves is $\omega a/2\pi c = 0.388$. We can see that optical power flow efficiency through right-angle bend and electric field concentrate at corner region due to resonant tunneling.

Next we design the directional coupler with L-shaped bend constructed by single mode waveguide whose width is $W/a = 1.65$ as shown in Fig.4. In the corner region additional rods are placed at position denoted black circles in this figure. The radii and relative permittivity of additional rods are $r_{a2}/a = 0.175$ and $\varepsilon_{a2} = 2.25$, respectively and the length of coupling region is $L/a = 19.0$. Fig.5 shows propagation characteristics of the directional coupler. We can see from this figure that there is little influence of right-angle bend by adding additional rods and realize high extinction ratio which is almost 19dB at the frequency $\omega a/2\pi c = 0.413$ when optical power is transmitted at port II. Fig.6 shows electric intensity of the directional coupler for frequency $\omega a/2\pi c = 0.383$ and $\omega a/2\pi c = 0.413$. We can see that low-insertion-loss and high-extinction radio coupler can be realized in both incident frequencies.

## 3 Conclusion

We have analyzed the characteristics of two-dimensional photonic crystal optical waveguides using the FD-TD method based on the principles of MD-WDFs. First we have analyzed the transmission characteristics of a L-shaped bend waveguide with additional dielectric rods in the corner region and shown that reflected waves from the right-angle corner can be completely eliminated due to resonant tunneling. Next we have designed the directional coupler with right-angle bend waveguide and demonstrate that it can work as low-insertion-loss and high-extinction radio wavelength demultiplexer. From these results we can conclude that the photonic crystal optical waveguide is a candidate of basic elements for constructing high density integrated optical circuits whose size is on the order of the wavelength of light.

## References


[1] E.Yablonovitch, "Inhibited Spontaneous Emission in Solid-State Physics and Electronics", Physical Review Lett., **vol.58**, pp. 2059–2062 (1987).

[2] A.Mekis, J.C.Chen, I.Kurland, S.Fan, P.R.Villeneuve and J.D.Joannopoulos, "High Transmission through Sharp Bends in Photonic Crystal Waveguides", Physical Review Lett., **vol.77**, pp. 3787–3790 (1996).

[3] J.S.Foresi, P.R.Villeneuve, J.Ferrera, E.R.Thoen, G.Steinmeyer, S.Fan, J.D.Joannopoulos, L.C.Kimerling, H. I.Smith and E.P.Ippen, "Photonic-bandgap microcavities in optical waveguides", Nature, **vol.390**, pp. 143–145 (1997).

[4] A.Fettweis, "Wave Digital Filters: Theory and Practice", Proc. IEEE, **vol.74**, pp. 270–327 (1986).

[5] A.Fettweis, "Multidimensional Wave Digital Filters for Discrete-Time Modelling of Maxwell's Equations", Int. J. Numerical Modelling, **vol.5**, pp. 183–201 (1992).

[6] Y.Naka, H.Ikuno, M.Nishimoto and A.Yata, "FD-TD Method with PMLs ABC Based on the Principles of Multidimensional Wave Digital Filters for Discrete-Time Modelling of Maxwell's Equations", IEICE Trans. Electron., **vol.E81-C**, pp. 305–314 (1998).

[7] H.Ikuno and Y.Naka, "Analysis of fundamental properties of guided mode on photonic crystal optical waveguides", PIERS2000 to be presented.

[8] J. Wang and H. Guo, "Resonant tunneling through a bend in a quantum wire", Appl. Phys. Lett., **vol.60**, pp. 654–656 (1992).

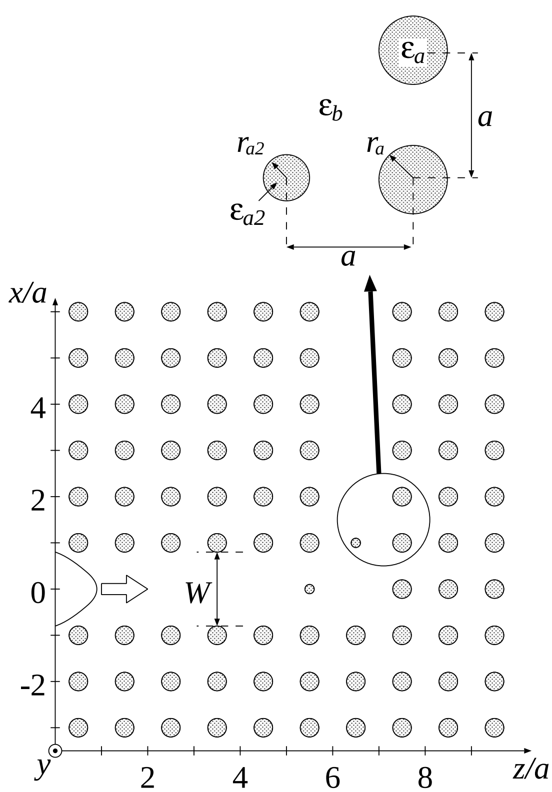



Fig. 1 Photonic crystal optical L-shaped bend waveguide with additional rods in the corner region.

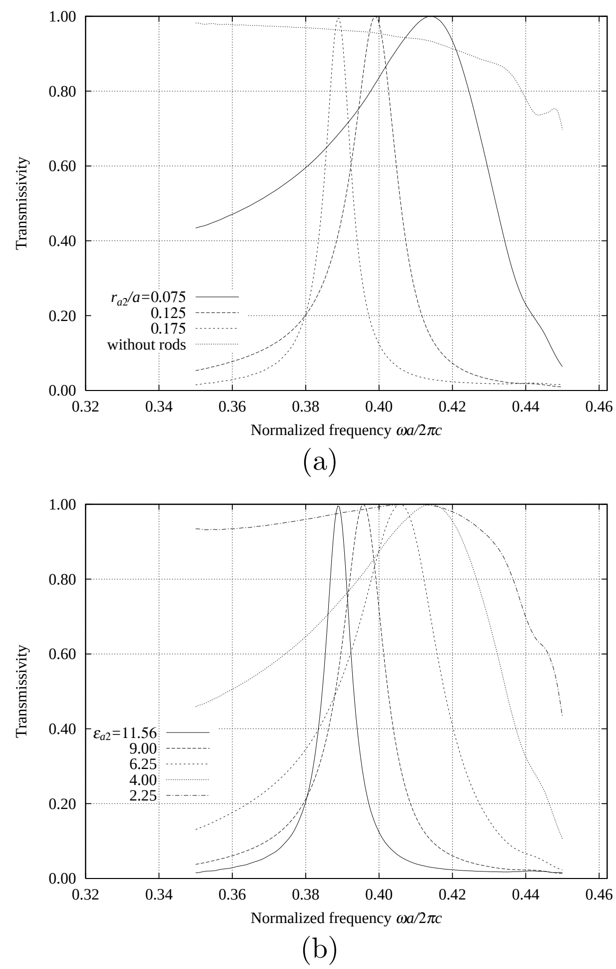
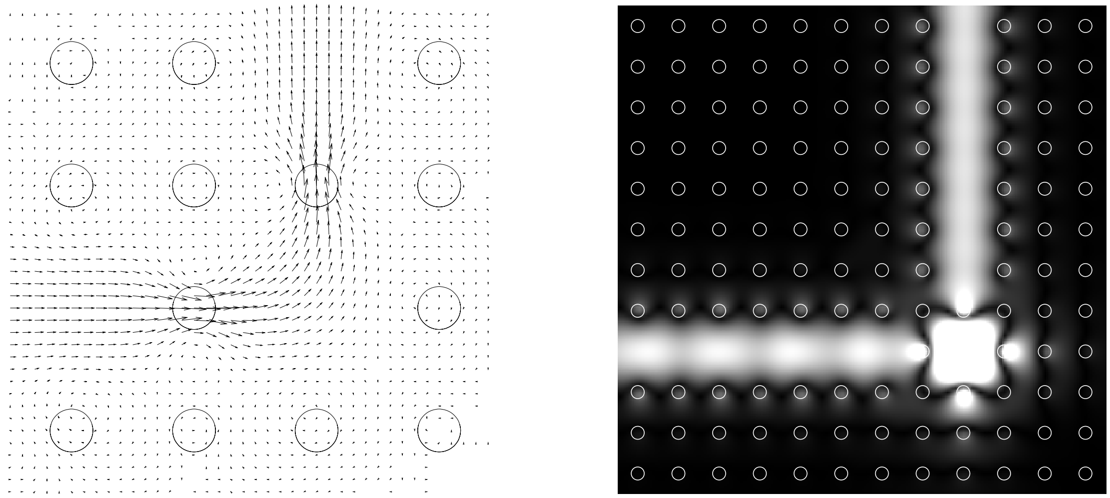



Fig. 2 Optical power transmission characteristics of L-shaped bend waveguide. (a) Radii $r_{a2}$ are changed. ($\varepsilon_{a2} = 11.56$) (b) Relative permittivity $\varepsilon_{a2}$ are changed.($r_{a2}/a = 0.175$)



(a) (b)

Fig. 3 Poynting vector and electric intensity of L-shaped bend waveguide. The frequency of incident waves is $\omega a/2\pi c = 0.388$, and the radii and relative permittivity of additional rods are $r_{a2}/a = 0.175$ and $\varepsilon_{a2} = 11.56$, respectively. (a) Poynting vector. (b) Electric intensity.

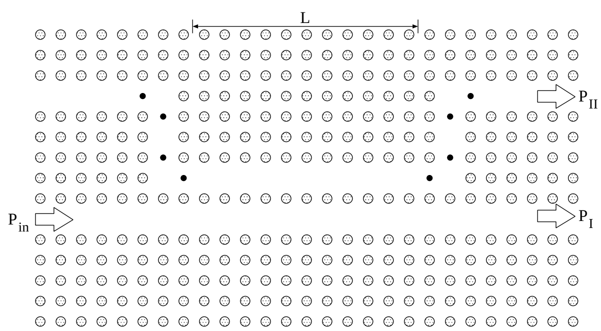



Fig. 4 Directional coupler with bend waveguide. Black circles denote additional rods whose radii and relative permittivity are $r_{a2}/a = 0.175$ and $\varepsilon_{a2} = 2.25$, respectively. Length of coupling region is $L/a = 19.0$.

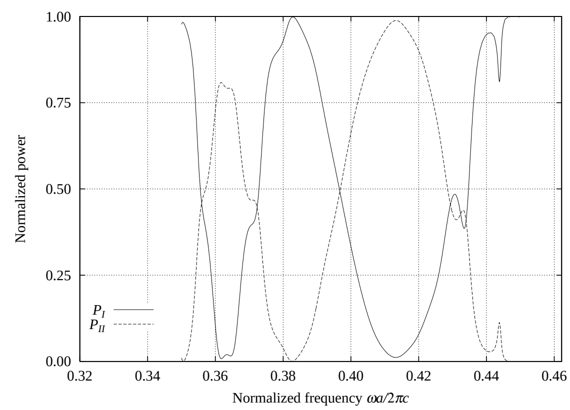
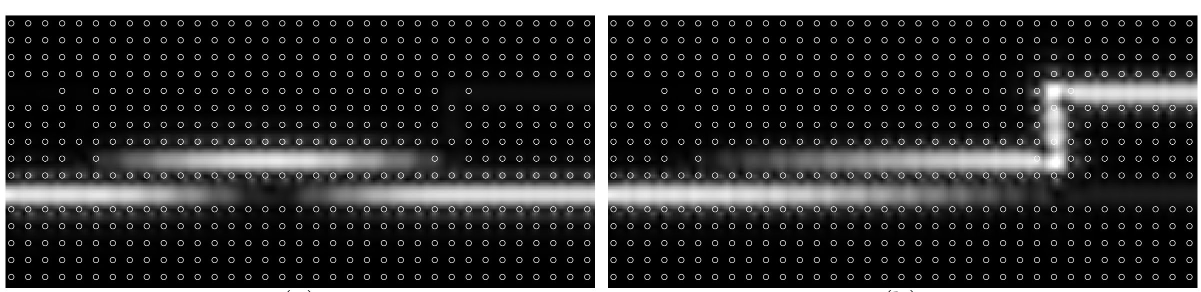



Fig. 5 Propagation characteristics of the directional coupler.



(a) (b)

Fig. 6 Electric intensity of the directional coupler. (a) $\omega a/2\pi c = 0.383$. (b) $\omega a/2\pi c = 0.413$.