Studies on Filtering Characteristics of X-shaped Photonic Crystal Waveguide in Two-Dimensional Triangular Lattice by Microwave Model

Yuting Bao
Grad. School of Comm. and Info. Networking
Fukuoka Institute of Technology
Fukuoka 811-0295, Japan
Email: mgm14006@bene.fit.ac.jp

*Hiroshi Maeda, Norimasa Nakashima
Dept. of Info. and Comm. Eng.
Fukuoka Institute of Technology
Fukuoka 811-0295, Japan
*Email: hiroshi@fit.ac.jp

***Abstract*—For the application in wavelength division multiplexing (WDM) system, propagation and filtering characteristics of X-shaped photonic crystal waveguide composed of metallic pillars in two-dimensional triangular lattice were studied in this paper. First, symmetrical X-shaped waveguide and two types of asymmetric X-shaped waveguides were measured to compare their transmission characteristics. Next, three sets of dielectric pillars with different lengths were situated in each output waveguide as cavities. Filtering characteristics were compared to select the most applicable structure as a basic filter component in WDM system.**

Keywords—microwave; photonic crystal; scale model; X-shaped; cavity; filtering characteristics

I. Introduction

Photonic crystal (PC) or electromagnetic band gap structure[1]-[4] plays an important role not only in microwave communication but also in optical signal processing as it has unique and sensitive characteristics for wavelength based on photonic band gap theory. High density multiplexing can be expected in these systems due to its sensitiveness to optical wavelength. Especially in WDM system, the structure of cavity is an important component as a filtering device. There are also other applications of PC structures such as improvement of coherency in laser, compact optical circuits for signal processing and monolithic integration. Optical circuit using photonic crystal has the advantage of highly integration that various components like oscillator, transmission circuit and signal processing circuit can be integrated on one substrate shaped monolithic. Our research indicated that frequency separation function can be realized by simple resonator structure formed by placing a pair of pillars having any distance in two-dimensional photonic crystal waveguide with triangular lattice. Moreover, even without using large scale of arrayed waveguide grating (AWG) and in asymmetrical structure, the filtering function can be easily achieved in the desired part of optical circuit. Although AWG is an effective method for the wavelength division multiplexing in large scale (from hundreds to thousands of channels), element with the size that is several hundreds of wavelengths is required. For the separation of several kinds (4~8) of frequencies in the photonic crystal waveguide, the simple structure in small size of several wavelengths with sufficient separation capability is more expected. The structure proposed in this paper is available for this purpose.

In this paper, the characteristics of X-shaped photonic crystal waveguide [5], with one input port and three output ports were analyzed through the measurement results. And the paper is divided into the following sections. In Section II, the experimental set up for scale model in microwave frequency was introduced. In Section III, the transmission and reflection characteristics of three types of X-shaped waveguides were measured to confirm which type has the best symmetrical dividing characteristics among three output ports. In Section IV,

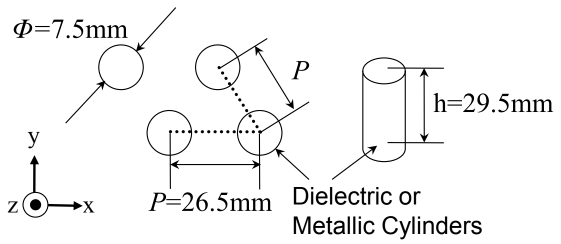

Fig. 1. Schematic of triangular periodic array

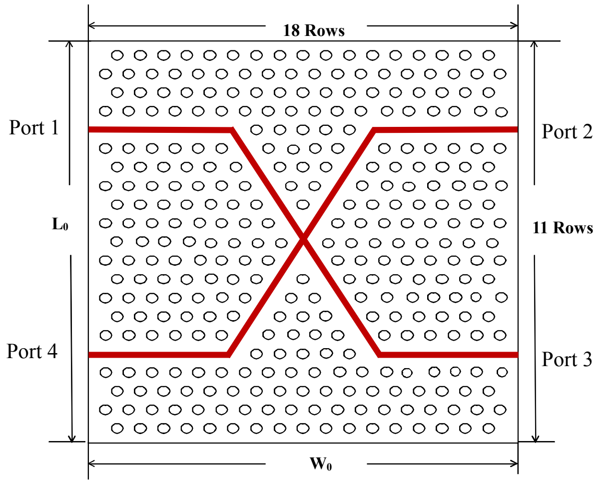

Fig. 2. Top view of two dimensional photonic crystal waveguide with symmetrical X-shaped branch, which is called Type-I.

the cavities were formed in the waveguide by putting three pairs of dielectric pillars in each branch. The filtering characteristics and extinction ratios at each output port of different types were compared. In Section V, the results of X-shaped photonic crystal waveguide composed of metallic pillars in this paper were compared with the waveguide composed of dielectric pillars in the same shape.

II. Experimental Setup of Scale Model

This research shows that in the asymmetrical X-shaped waveguide, signals of different frequencies in microwave domain can be separated. Generally, the same result can be obtained even when the period of lattice, the size of the waveguide, the material and the frequency change. This is because that the experiment is based on the confinement of electromagnetic wave according to photonic band gap theory and the resonator with the size which is similar to the wavelength of standing wave of the signal being transmitted. Especially in the optical signal processing based on photonic crystal waveguide of nano structure using semiconductor materials, this conclusion is also applicable.

Fundamental lattice and the structure of symmetrical X-shaped photonic crystal waveguide are illustrated in Fig. 1 and Fig. 2, respectively. The measurements were done by referring to [6]-[8]. The rods with diameter Φ of 7.5mm and height h of 29.5mm were situated as regular triangular lattice with period P of 26.5mm. Period P was determined by finite difference time domain (FDTD) method [9] for that under the restriction of material parameter and mechanical fabrication, the line defect in this structure is able to operate as a waveguide. Periodic array of rods were sandwiched between two aluminum plates and surrounded by aluminum walls to realize two dimensional structure based on principal of mirror image in electromagnetic theory. In this structure, the electromagnetic polarization is transverse electric (TE) mode, which the unique electric field is polarized parallel to axis of rods.

Measurements of S-parameters S_{11} and S_{21} were done by vector network analyzer *Agilent E5071C.* Waveguide to coaxial adapter were attached to input and output ports while the other two output ports which are not under measurement were terminated by anti-reflection adapters. As frequency range of input and output adapters is from 3.6GHz to 4.2GHz, all the measurements were done during this frequency band.

III. Measurement of X-shaped Waveguide

The symmetrical X-shaped waveguide which is defined as Type-I was depicted by red lines in Fig. 2. The structure is composed of 11 vertical and 18 horizontal rows of metallic rods with length L_0 of 485.5mm and width W_0 of 477.0mm. The reflection and transmission characteristics from port 1 to port 2, port 3 and port 4 described by dashed line, dash-dotted line, and solid line were shown in Fig. 3 and Fig. 4, respectively. According to the figures, three reflection curves almost coincide with each other. However, the transmission for port 3 and port 4 were lower than that for port 2 in an average value of 5dB, approximately. This means that although the structure was symmetrically fabricated, the input power was not divided into each output port equally.

In Fig. 5 and Fig. 6, the asymmetrical X-shaped waveguide called Type-II and Type-III were illustrated, respectively. The difference between these two types is the set in branch from port 2 to port 4, meanwhile, the set of branch from port 1 to port 3 is the same as in symmetrical waveguide. From the results of symmetrical X-shaped waveguide Type-I, it can be seen that the symmetrical dividing characteristic is confirmed by transmission characteristics for each port. Therefore, only the transmission results of these two types of asymmetrical X-shaped waveguides were given in the following as illustrated in Fig. 7 and Fig. 8. For the waveguide Type-II, the power transmitted into port 2 became closer to the power of port 3 and port 4 during the frequency range from 3.8GHz to 4.2GHz. For Type-III, the magnitude of transmission for port 3 was higher

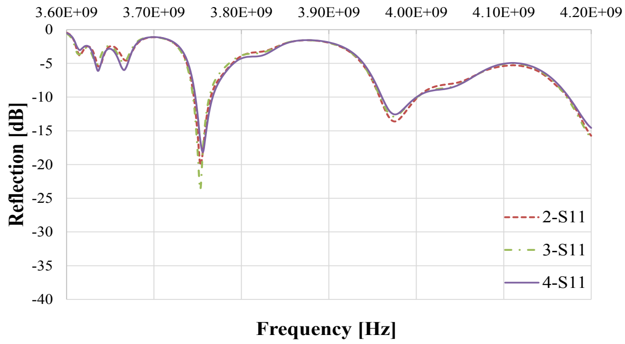

Fig. 3. Measured reflection of symmetrical X-shaped waveguide Type-I.

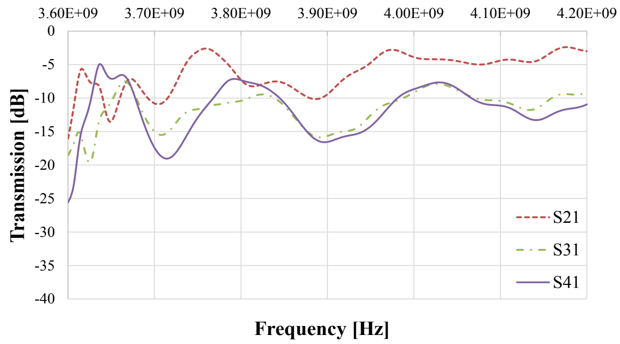

Fig. 4. Measured transmission of symmetrical X-shaped waveguide Type-I.

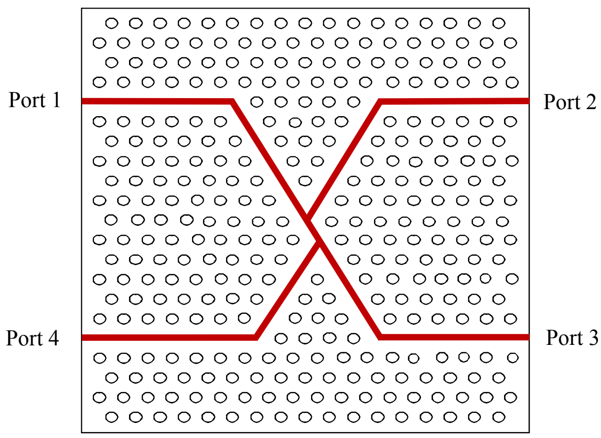

Fig. 5. Top view of two dimensional photonic crystal waveguide with asymmetrical X-shaped branch, which is called Type-II.

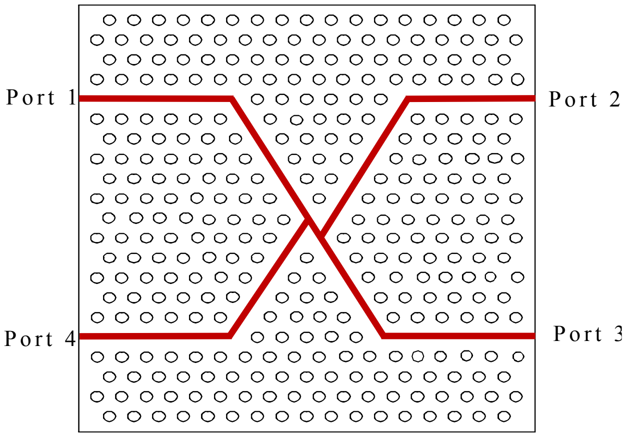

Fig. 6. Top view of two dimensional photonic crystal waveguide with asymmetrical X-shaped branch, which is called Type-III.

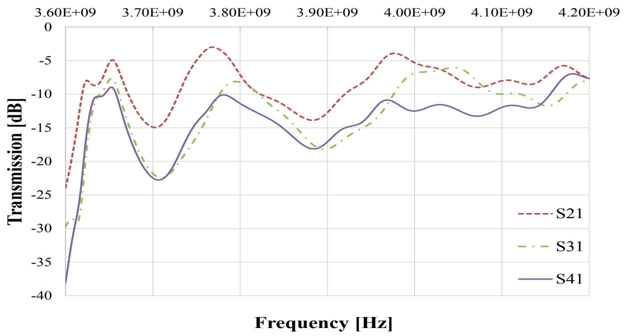

Fig. 7. Measured transmission of asymmetrical X-shaped waveguide Type-II.

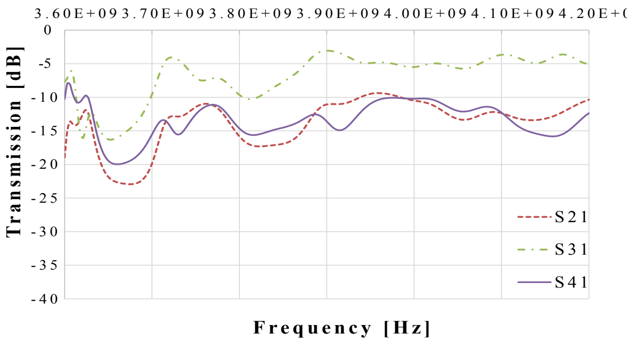

Fig. 8. Measured transmission of asymmetrical X-shaped waveguide Type-III.

than that of port 2 and port 4. To figure out which type of these three kinds of X-shaped waveguide has the best symmetrical dividing characteristic numerically, variance between the transmissions of each port for three types were calculated. The result was illustrated in Fig. 9. According to the figure, variance of Type-II was relatively the smallest and most stable during the frequency range from 3.8GHz to 4.2GHz. It also means that the power in asymmetrical X-shaped waveguide Type-II were divided more equally into three output ports than in other two types of waveguides.

IV. Measurement of X-Shaped Waveguide with Cavities

As in the symmetrical X-shaped waveguide shown in Fig.2, when we see from Port 1, before the branch point to Port 2, the periodicity of the structure has disappeared. It means that

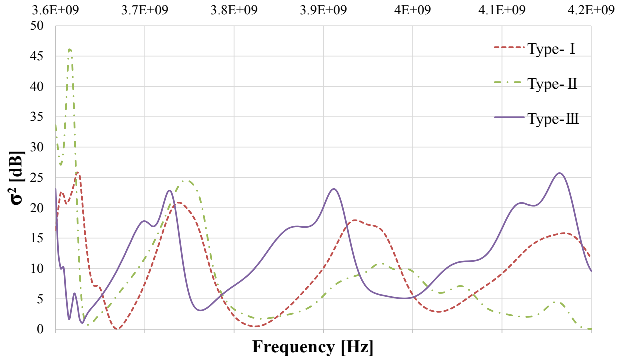

Fig. 9. Variance between the transmissions of three output ports for three types of X-shaped waveguides.

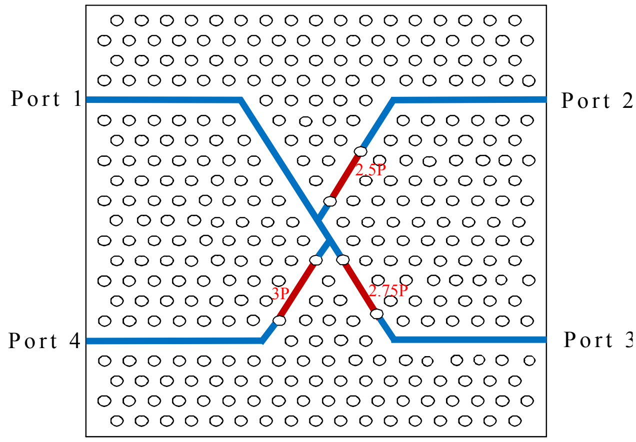

Fig. 10. Top view of asymmetrical X-shaped waveguide Type-II. with cavities of lengths 2.5P, 2.75P and 3P.

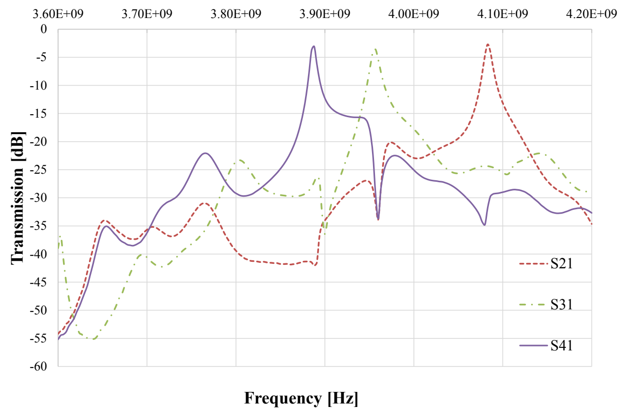

Fig. 11. Measured transmission of asymmetrical X-shaped waveguide Type-II with cavities.

before the power arrives at the branch, more than half of it leaks to Port 2 and the left power is almost equally divided to port 3 and port 4. As shown in Fig.4, the power to port 2 accounts for most of all which causes unequal division. Therefore the asymmetrical structure is considered as the equal filtering power can't be obtained from each port when we place the resonators in this symmetrical structure. According to the measurement results above, asymmetrical X-shaped waveguide

Type-II shows the best symmetrical dividing characteristic. Therefore, in this section, the filtering characteristics of this type of waveguide will be studied on by situating three sets of ceramic pillars in the waveguide. As shown in Fig. 10, cavities with lengths of 2.5P, 2.75P and 3P marked by red lines were situated in each output branch indicated by blue lines, where P is the lattice period. The transmissions of three output ports were shown in Fig. 11. It can be seen that by placing the resonator at the branch to port 2, the inflow of too much power to port 2 has been avoided. Then the branch to port 3 and port 4 are placed and the power to these two ports are equally divided. Finally the power is divided into three parts equally. In Fig. 11, three resonant peaks can be observed obviously and the decibel value at the center frequency of three peaks were almost the same. To study the filtering characteristic of this type of waveguide with cavities, Q factor and extinction ratio are introduced. Q factor is defined as in

$$Q = f_{\mathrm{Res}} / f_{3\mathrm{dB}}, \quad (1)$$

where, f_{Res} is center frequency of resonance and $f_{3\mathrm{dB}}$ is the 3dB full band width, respectively. Extinction ratio indicates the goodness of separation for desired frequency component at each output port. The evaluated results of these two parameters were shown in Table I. As shown in Table I, quite sharp resonant peaks were obtained in this type of asymmetrical X-shaped waveguide with the separation over 100MHz. Meanwhile, the extinction ratios of all three peaks were over 22dB.

TABLE I. SUMMARY OF PARAMETERS OF THREE PORTS IN WAVEGUIDE TYPE-II WITH CAVITIES.

Port No.	Cavity Length	Peak Freq.	Q factor	Ext. Ratio
Port 2	2.50P	4.083GHz	445.0	21.6dB
Port 3	2.75P	3.957GHz	377.6	25.8dB
Port4	3.00P	3.888GHz	598.8	24.1dB

V. CONCLUSION

In this paper, transmission and reflection characteristics of three types of X-shaped photonic crystal waveguides were measured around 4GHz in scale model. According to the comparision of the results, the asymmetrical X-shaped waveguide Type-II showed the best symmetrical dividing characteristic. In the following paper, the cavities with different lengths were set in this kind of waveguide to study its filtering characteristic. Through the analysis for two parameters of Q factor and extinction ratio, the qualities of three resonant peaks are quite good.

In our previous work [5], we proposed several types of X-shaped photonic crystal waveguide composed of ceramic pillars. The measurement result of the waveguide with the best symmetrical dividing characteristic shows higher Q factors.
For the application of WDM system, our future work is to improve the Q-factor and extinction ratio of the structure proposed in this paper.

VI. ACKNOWLEDGMENT

This work was financially supported by KAKENHI No.15K06043, Grant-in-Aid for Scientific Research (C) by Japan Society for the Promotion of Science (JSPS) in 2015.

REFERENCES

[1] K. Yasumoto, "Electromagnetic Theory and Applications for Photonic Crystals," CRC Press, New York, 2005.

[2] K. Inoue and K. Ohtaka, “Photonic Crystals: Physics, Fabrication and Applications,” Chap. 12, Eds. Heidelberg, Springer-Verlag, 2004.

[3] S. Noda and T. Baba, “Roadmap on Photonic Crystal,” Kluwer Academic Publisher, Boston, 2003.

[4] J. D. Joannopoulos, R. D. Meade and J. N. Winn, “Photonic Crystals,” Princeton University Press, New Jersey, 1995.

[5] H. Maeda, Y. Zhang, and H. Terashima, "Study on X-shaped Photonic Crystal Waveguide in 2D Triangular Lattice for WDM System.," Journal of Mobile Multimedia 8.2 (2012): 105-113.

[6] Y. Zhang, H. Terashima, D. Ogata and H. Maeda, “Some Trials to Suppress Unnecessary Resonance in Photonic Crystal Cavity Structure,” Proceedings of 6th International Conference on Broadband, Wireless Computing, Communication and Applications (BWCCA 2011), pp.482-486.

[7] B. Temelkuran and E. Ozbay, “Experimental Demonstration of Photonic Crystal based Waveguides,” Applied Physics Letters, vol.74, no.4, pp.486-488, 1999.

[8] M. Beaky et al., "Two-dimensional Photonic Crystal Fabry-Perot Resonators with Lossy Dielectrics." IEEE Transactions on Microwave Theory and Techniques, Vol. 47, No.11, pp.2085-2091, 1999.

[9] A. Taflove , “Advances in Computational Electrodynamics - The Finite-Difference Time-Domain Method,” Ed. Artech House, Boston, 1998.