Numerical Analysis of Two-Dimensional Photonic Crystal Waveguide Devices Using Periodic Boundary Conditions

Y. Nakatake and K. Watanabe
Fukuoka Inst. of Tech., Fukuoka 811-0295

Introduction
Photonic crystal is a periodic structure consisting of high contrast dielectrics, in which the electromagnetic wave cannot transmit in a specific wavelength range. It is therefore known that, if localized defects are introduced in the photonic crystal, the electromagnetic fields are strongly confined around the defects. For example, point defects in the photonic crystal work as resonance cavities and line defects work as waveguides. Also, appropriate arrangements of the defects function as photonic crystal waveguide devices, such as branching filter, resonator filter. Since any energy cannot escape through the surrounding photonic crystal, the leakage loss is suppressed. This feature may contribute to miniaturize the integrated circuit in millimeter wave, sub-millimeter wave, and optical regions. For the straight waveguides, the structure maintains the periodicity in the propagation direction, and the Floquet theorem asserts that the electromagnetic fields in the structure can be expressed by superposition of the Floquet-modes[1]. General structures of the photonic crystal waveguide devices are considered as cascade connections of the straight waveguides. Yasumoto and Watanabe[2,3] presented a numerical method to analyze discontinuities in photonic crystal waveguides. This method is based on the Fourier series expansion method (FSEM), and the fields are expressed in the Fourier series expansions by introducing artificial boundaries with periodic condition. The amplitudes of the Floquet-modes are related by a scattering-matrix (S-matrix) for each waveguide section, and S-matrix for cascade connection of waveguides is derived by a recursive calculation for each waveguide section. On FSEM, the Floquet-modes of photonic crystal waveguides are obtained by an eigenvalue analysis of the transfer matrix for the periodicity cell in the propagation direction.

Outline of the Formulation
This paper deals with the analysis of photonic crystal waveguide devices formed by circular cylinders. The device structures are considered as cascade connections of straight waveguides. Decomposing the structure into layers of the cylinder arrays, the input/output properties of the devices are obtained using an analysis method of multilayer structure. We introduce periodic boundary conditions in the direction perpendicular to the wave propagation, and the Floquet-modes of each layer are calculated by FSEM with the help of the recursive transition-matrix algorithm (RTMA) [4]. RTMA treats the boundary conditions on the cylinder surface in an adequate manner and accelerates the convergence of the Floquet-mode analyses. Then, the input/output properties of the devices are obtained by recursive calculation of scattering matrix with each layer.
Numerical Experiments
We choose the parameters for the surrounding photonic crystal as follows: permittivity of the surrounding medium $\varepsilon_s = \varepsilon_0$; lattice constants $d = h = 340\text{nm}$; permittivity and radius of the arrayed cylinders $\varepsilon_c = 12.25\varepsilon_0$ and $a = 0.2$; permeability of the surrounding medium and the arrayed cylinders $\mu_s = \mu_c = \varepsilon_0$. Using these values, a waveguide formed by a single straight line defect supports only one guided Floquet-mode and the fields are confined near the defects. Here, we use $w = 17d$ for the periodic boundary conditions. Fig.1(a) are plotted in Fig.1(b) as functions of the wavelength $\lambda_0$. It is seen that the transmission spectra has sharp resonance peak at around $\lambda_0 = 0.91\mu\text{m}$.

Conclusion
This paper has provided a formulation of two-dimensional photonic crystal waveguide devices formed by circular cylinders based on FSEM. The formulation decomposes the device structure into straight waveguide sections, and the input/output properties are derived by the recursive calculation for each straight waveguide section. This approach requires the Floquet-mode analyses involving both guided and evanescent modes. Introduction of periodic boundary conditions makes us possible to obtain the Floquet-modes by eigenvalue calculations of the transfer matrices for the straight waveguides sections. To improve the convergence, the present formulation applied an accurate Floquet-mode analysis technique with the help of RTMA.

References

Fig.1 Photonic crystal waveguide filter consists of a resonance cavity strongly coupled with straight waveguides: (a)structure under consideration and (b) power reflection and transmission spectra.