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A design of the photonic crystal directional coupler with a high extinction ratio and a short complete coupling length

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1. Introduction

Photonic crystals are new optical materials which have periodic dielectric constant and attract a grate deal of attention because of potential of realizing ultra small optical integrated circuits, low threshold laser, high Q cavity, add-drop filter and so on.

We are developing a photonic crystal directional coupler optical switch as an element of optical integrated circuit [1]. In order to make use of a merit of photonic crystal optical circuit, it is necessary to realize the directional coupler switch which have short coupling length and good extinction ratio. However, it is very difficult to satisfy both features by utilizing ordinary photonic crystal directional coupler.

In this paper, we show the reason of the difficulty and novel directional coupler structure which satisfy both features.

2. Theory and calculation

In ordinary, the behavior of the directional coupler is explained by utilizing the mode coupled theory. However, it is explained by utilizing eigenmodes of a pair of parallel waveguides here. The eigenmodes of a symmetric pair of waveguides of which dimension is Fig. 1 are even and odd modes as follows because of the symmetry

$$\psi_\pm(x,y,z) = \phi_\pm(x,y,z)e^{\mathrm{i}k_\pm z}e^{-\mathrm{i}\omega t}. \quad (1)$$

Here, + and - marks mean even and odd modes respectively. The functions $\phi_\pm(x,y,z)$ satisfy the condition

$$\phi_\pm(x,y,z) = \pm\phi_\pm(-x,y,z). \quad (2)$$

When the pair of waveguides consists of normal index contrast waveguides, the functions are constant for variable z. When it consists of photonic crystal waveguides, the functions are periodic for variable z. $k_\pm$ are the wavenumber of even and odd modes towards the z direction, and ω is the angular frequency of eigen modes.

We examine the overlap of the even and odd modes. When we assume the condition $\phi_+(x,y,z) = \phi_-(x,y,z)$ at $x > 0$, the overlap at $z = 0$ is

$$\begin{aligned}&\psi_+(x,y,0) + \psi_-(x,y,0)\\ &= \{\phi_+(x,y,0) + \phi_-(x,y,0)\}\, e^{-\mathrm{i}\omega t}\\ &= \begin{cases}2\phi_+(x,y,0)e^{-\mathrm{i}\omega t} & (x \geq 0)\\ 0 & (x < 0)\end{cases}. \end{aligned} \quad (3)$$

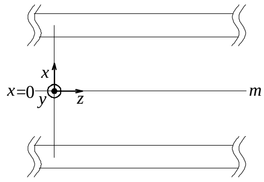

Fig. 1: Schematic of the geometry of a pair of waveguides.

It means that the distribution of EM wave exists into $x \geq 0$ region only at $z = 0$. The overlap at the position $z = L$, which satisfies the condition $L(k_- - k_+) = (2m+1)\pi$ ($^\exists m \in \mathbb{Z}$), is

$$\begin{aligned}&\psi_+(x,y,L) + \psi_-(x,y,L)\\ &= \left\{\phi_+(x,y,L)e^{\mathrm{i}k_+L} + \phi_-(x,y,L)e^{\mathrm{i}k_-L}\right\} e^{-\mathrm{i}\omega t}\\ &= \{\phi_+(x,y,L) - \phi_-(x,y,L)\}\, e^{\mathrm{i}k_+L}e^{-\mathrm{i}\omega t}\\ &= \begin{cases}0 & (x \geq 0)\\ 2\phi_+(x,y,L)e^{\mathrm{i}k_+L}e^{-\mathrm{i}\omega t} & (x < 0)\end{cases}. \end{aligned} \quad (4)$$

At this position, the EM wave exists $x < 0$ region only. The EM wave which is localized $x \geq 0$ region is transfered into the $x < 0$ region after the length of L propagation. Thus the pair of waveguides works as directional coupler of which coupling length L.

Now, we should note that there are important assumption $\phi_+(x,y,z) = \phi_-(x,y,z)$. If the condition is not satisfied, the localized EM wave in $x < 0$ or $x \geq 0$ region cannot be expressed by linear summention of the eigen modes. It means low extinction ratio from the viewpoint of a directional copler. To reduce the coupling length of DC, it is necessary to enlarge the difference between k_+ and k_-. The difference of the wavenumber of even and odd modes is caused by the difference of the equivalent dielectric constants of which origin is the difference of the field distribution of the modes. Therefore, it is necessary to enlarge the difference of the field distribution for shorting the coupling length. However, it collapses the condition $\phi_+(x,y,z) = \phi_-(x,y,z)$, and the extinction ratio becomes low.

As stated above, the transition of EM field becomes incomplete as the coupling length is shorter. However, the difference between phases of even and odd mode becomes $2(m+1)\pi$ at complete coupling length. If the phase difference can be converted to the field distribution localized in one side, the directional coupler with short coupling length and high extinction ratio can be

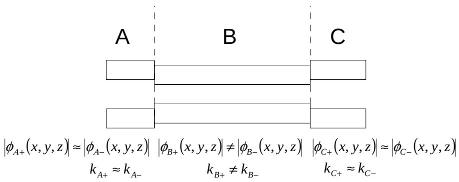

Fig. 2: Schematics of directional coupler utilizing hetero or chirp structure.

realized. For this purpose, we propose utilizing hetero or chirp structures shown in Fig. 2. For input (A) and output (C) region, we utilize the pair of waveguides in which the absolute value of field distribution of even and odd modes are very close. The pair of waveguides in which the difference between wavenumber of even and odd modes is large (B) is between those waveguides . Because of the symmetry, even mode cannot be excited by odd mode beyond the hetero or chirp junction, and odd mode cannot be also excited by even mode. Thus, the light localized the one side in the region A is transfered to the another side in the region C by changing the difference of phase of even and odd modes while the light propagate in the region B.

As a specific example, we calculated a directional coupler shown in Fig. 3 by 2D-FDTD method. The structure consists of triangular lattice air holes with lattice constant of a in a dielectric with the constant of 6.74×10^{-11}, which is assumed semiconductor material such as GaAs. The radius of air hole corresponding to the area A and C in Fig. 2 is $0.3a$, and the radius corresponding to the area B is $0.33a$. The radius is gradually changed at junctions between each areas, and the length of changing areas is $5a$. The reason why we utilize the chirp structure is that the transmittance of even and odd modes at junction becomes nearly equal. The total length of directional coupler is $18a$. At first, we show the band diagram of pair waveguide with $r = 0.3a$ ($\circ$) and $r = 0.33a$ ($\bullet$) in Fig. 4. The broken line shows the position at normalized frequency $f_n = 0.274$. The wavenumber of the even mode differs much from one of the odd mode for $r = 0.33a$ structure. In contrast, the wavenumbers of even and odd modes nearly equal for $r = 0.3a$ structure. Next, Fig. 5 shows the extinction ratio of port 3 to port 2 shown in Fig. 3. The ab-

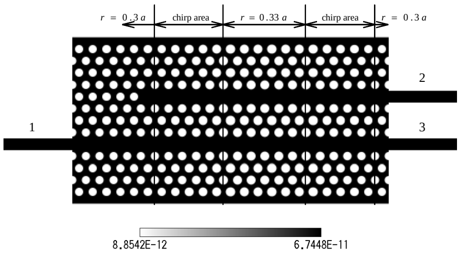

Fig. 3: Distribution of dielectric constant of the directional coupler with chirp structure. The radius of holes at input and output position is $0.3a$,

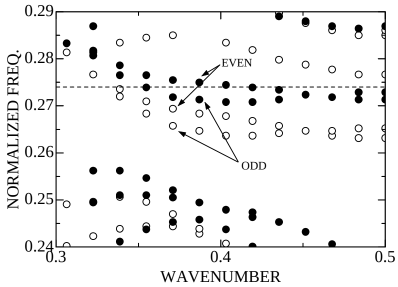

Fig. 4: Band structures of the pair waveguide with $r = 0.3a$ ($\circ$) and $r = 0.33a$ ($\bullet$). The dashed line shows that the normalized frequency (f_{n}) is 0.274.

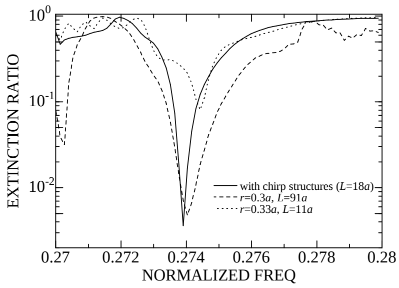

Fig. 5: Extinction ratios of DC with chirp structure (solid line), DC with $r = 0.3a$ (broken line) and DC with $r = 0.33a$ (dotted line).

scissa is normalized frequency. It is shown that the ratio is -24.4dB near $f_n = 0.274$. In the figure, the ratios of the structure with $r = 0.3a$ and length of $91a$ and the structure with $r = 0.33a$ and length of $11a$ are also shown as dashed and dotted lines. For the structure with $r = 0.3a$, the ratio is very good (-23.2dB), but its coupling length is too long. On the other hand, the coupling length is very short, but the ratio is worse (-10.9dB). In comparison those structure, our proposed structure has good extinction ratio and short coupling length simultaneously.

3. Conclusion

To realize the directional coupler with short coupling length and high extinction ratio, we have shown a noval design of directional coupler. It has been shown that he reason of low extinction ratio in short directional coupler is difference of absolute value of field distribution. To realize high extinction ratio and short coupling length, we proposed to utilzie hetero or chirp structure. By numerical calculation of an example, we have successfully achieved to design the directional coupler with extinction ratio of -24.4dB and coupling length of $18a$. The result shows that our design method is very useful for designing photonic crystal directional coupler.

References

[1] K. Furuya, Y. Watanabe, N. Yamamoto and K. Komori, PECS-V, Kyoto, March 2004.