第33卷第1期
2004年1月

光 子 学 报
ACTA PHOTONICA SINICA

Vol.33 No.1
January 2004

Promoting the Coupling Efficiency of Waves by a 2D Photonic Crystal*

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Abstract Numerical simulations adopting the multiple-scattering method and experimental measurements demonstrate that it is practical to promote the coupling efficiency with the help of a 2D photonic crystal. It is found that higher coupling efficiency of waves generally appears at the edge of the photonic bandgaps. And resonance coupling of waves with relatively high coupling efficiency is likely to occur for the optical lattice constant of the photonic crystals approaching to the wavelength of the waves transmitted. Besides, there also exist many other frequencies that high coupling efficiency may be obtained. The maximum coupling efficiency may be as high as 1.89 times of that without introducing the 2D photonic crystal. Such an effect is especially useful for wave-coupling in optical integrated devices.

Keywords Photonic crystal; Coupling efficiency; Resonance coupling; Photonic bandgap

CLCN **Document Code** A

0 Introduction

Interest in promoting the coupling efficiency of waves in various electromagnetic and optical devices is ever lasting for theorists and engineers because high coupling efficiency of waves means low insertion loss. We here explore the way of promoting the coupling efficiency of waves through 2D photonic crystals. In normal situations, photonic crystals[1~3] are used for reflection of waves rather than for transmission and coupling purposes because photonic crystals are known for their photonic band gaps, and thus almost all attentions are paid to the application of the photonic band gaps[1~7]. Through investigations, It is found that photonic crystals are also useful for promoting the coupling efficiency of waves outside the photonic bandgap regions. Theoretical calculation and experimental measurements show that the coupling efficiency of waves can be promoted remarkably for certain operating frequencies through introducing a simple square lattice photonic crystal in the wave coupling region. The maximum coupling efficiency is as high as 1.89 times of that without introducing the 2D photonic crystal. The effect of high coupling efficiency through 2-D photonic crystals investigated is especially useful for wave-coupling in optical integrated devices where bulk coupling components are not allowed.

1 Theoretical model

Fig. 1 shows the system we investigated. The waves are coupled from the slit (1) to waveguide (2). We may view the slit as a power source for the waveguide. The length of a slit is supposed to be infinite in the two-dimensional system. Different from that in Fig. 1(a), a 2D photonic crystal is introduced in the wave-coupling region in Fig. 2(b). The 2D photonic crystal is a square lattice of dielectric poles with radius r and lattice constant d.

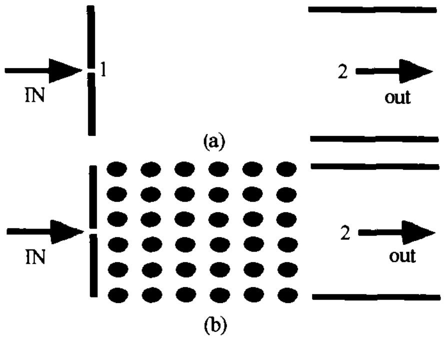

Fig. 1 Wave coupling from one slit to another, where the coupling region is free space for (a) and a 2D photonic crystal (PC) for (b)

The coupling efficiency is defined as the ratio of the power coupled to the waveguide and the total of that from the slit source. We define a parameter called relative coupling efficiency as follows

$$\eta = \eta_2 / \eta_1 \qquad (1)$$

where η_1 and η_2 are the coupling efficiency for Fig. 1(a) and that for Fig. 1(b), respectively. To eliminate the reflection of waves, wave-absorbing materials are applied where is necessary.

Theoretically, we adopt the multiple-scattering method[8] to investigate the coupling properties of the structures shown in Fig. 1; experimentally, we employ a

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*Supported by the Natural Science Foundation of China under the contract No. 60177030 and by the Shenzhen Bureau of Science and Technology

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Received date: 2002-12-03

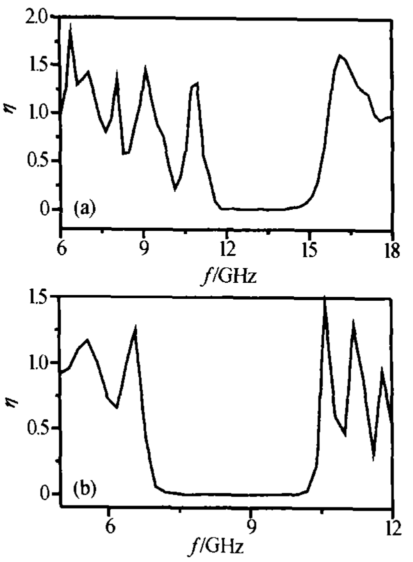

Fig. 2 Typical results of simulated T with frequency for two crystals with different lattice periods, where the radius and the relative dielectric constant of the pole in the 2D photonic crystal are 2 mm and 8.9, respectively, and the 2D photonic crystal is of 15 × 8 rows

vector microwave analyzer for measurements.

Our investigations are performed in the microwave frequency region, but the results are of general usage because if we replace (x,y,z) and with $(\alpha x,\alpha y,\alpha z)$ and $\alpha^{-1}\omega$ respectively, the following Maxwell's equation

$$\nabla \times \nabla \times A - \frac{\varepsilon(x,y)\omega^2}{C^2}A = 0 \tag{2}$$

keeps exactly the same form. This is called the scaleable property of Maxwell's equations. With the scaleable property, we may scale the results into any frequency bands desired.

2 Results and discussions

Typical simulation results are shown in Fig. 2, from which we may see that the relative coupling efficiencies are greater than 1 at some places outside the photonic bandgap region. This means that the coupling efficiency can be greater than that without adding a 2-D photonic crystal in the coupling region. The maximum relative coupling efficiency is greater than 1 . 8 in Fig. 2(a) and is approaching 1.5 in Fig. 2(b).

Fig. 3 gives a comparison of our theoretical and experimental results. From Fig. 3 we see that the measurements and calculations are in good agreement, the maximum relative coupling efficiencies of the measured and calculated are approximately the same and are greater than 1.5. In calculations, no reflection from any of the boundaries is supposed to exist. In experiments, however, a certain kind of reflections in the forward and backward directions are unavoidable, this may cause some kind of differences between the measured and calculated results, as shown in Fig. 3.

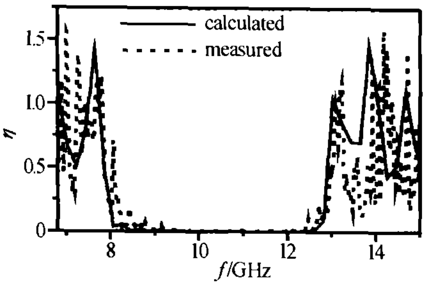

Fig. 3 The measured and calculated T with frequency, where the radius and the lattice period of the 2D photonic crystal are 2 mm and 11 mm, respectively, and other parameters ae the same as that in Fig. 2

From Figs. 2 ~ 3 we see that at some points, the relative coupling efficiency arrives a maximum. We call the coupling at these points " resonance coupling". Through simulations we find that resonance coupling is likely to occur for the optical lattice constant OL of the photonic crystals approaching to the wavelength λ, i. e.

$$OL \approx \lambda \tag{3}$$

where λ is the wavelength of the waves transmitted. The optical lattice length is defined as

$$OL = n_{\mathrm{ave}} d \tag{4}$$

where d is the lattice constant of the photonic crystal, and n_{ave} is the average refractive index defined as follows for TE waves

$$n_{\mathrm{ave}} = \frac{S + (n_2 - 1)\pi r^2}{S} \tag{5}$$

Here r and n_2 are respectively the radius and the refractive index of the dielectric poles, and S is the area of one lattice cell in the photonic crystal. For a square lattice photonic crystal, we have

$$S = d^2 \tag{6}$$

Table 1 shows some of the results of simulations. From Table 1 we see that the relation given by Eq. (3) is true. To see the effect of resonance coupling we show one example in Fig. 4. From Fig. 4 we can see that the maximum relative coupling efficiency is as high as 1.89.

Table 1 The optical lattice length and the resonance coupling wavelength in different photonic crystals, parameters not shown are the same as that in Fig. 2

d/mm	r/mm	OL/mm	λ/mm	OL/λ
9.0	2.5	13.33	13.27	1.00
10.0	3.5	17.63	17.65	1.00
10.0	4.0	19.97	19.74	1.01
12.0	4.0	20.31	20.27	1.00
14.0	5.5	27.46	26.39	1.04

From the point of view of electromagnetism we may understand the mechanism of the promotion of the coupling efficiency through a photonic crystal as follows . Simulations indicate that the electric field in

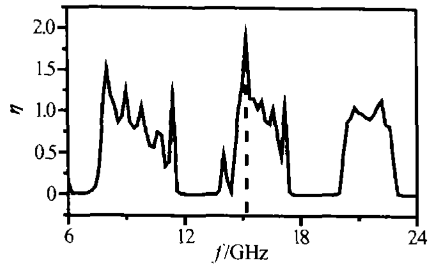

Fig. 4 Resonance coupling through a photonic crystal at $f=15.2$GHz with $T=1.89$, the radius and the lattice period of the 2D photonic crystal are 4 mm and 10 mm, respectively, other parameters are the same as that in Fig. 2

the photonic crystal is generally confined in the dielectric poles with high dielectric constant, as shown in Fig. 5. This means that the photonic crystal guides the waves forward and thus higher coupling efficiency can be obtained. In this way we may also understand the mechanism of resonance coupling. At certain frequencies for a given photonic crystal, the scattered waves from two lattices in the photonic crystal have a phase difference of $2m\pi$, so that the waves going sideways are greatly decreased and the waves transferred to the waveguide are strongly enhanced, leading to resonance coupling. Here m is an integer.

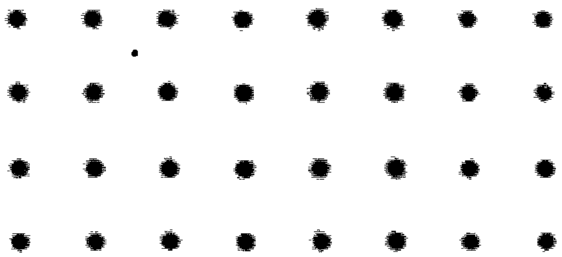

Fig. 5 The typical filed pattern in a photonic crystal, in which the field becomes stronger as the pattern color becomes darker

Through simulations we also find that higher relative coupling efficiency generally appears at the edge of the photonic bandgaps, as can be seen from Figs. 2 ~ 4. This adds a new interesting point to the property of the edge of the photonic bandgaps. From the point of quantum electrodynamics, we may understand that the waves reflected by the photonic crystal in the photonic bandgap region have a negative momentum, so that the waves transmitted forward should gain a positive momentum. This momentum is more likely transferred to waves at the edge of the photonic bandgap , so that the relative coupling efficiencies of these waves become higher than 1.

Besides the two cases stated above, there exist many other frequencies that high relative coupling efficiencies appear. The physics under them remains to be explored.

3 Conclusions

The coupling efficiency of waves can be promoted remarkably by adding a two-dimensional photonic crystal in the wave-coupling region for certain operating wavelengths. Generally, higher coupling efficiency of waves appears at the edge of the photonic bandgaps. Resonance coupling of waves with relatively high coupling efficiency is likely to occur for the optical lattice constant OL of the photonic crystals approaching to the wavelength λ of the waves transmitted. There also exist many other frequencies that high coupling efficiency may be obtained. The effect of high coupling efficiency through 2-D photonic crystals investigated in this paper is especially useful for wave-coupling in optical integrated devices where bulk coupling components are not allowed.

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利用二维光子晶体提高波的耦合效率

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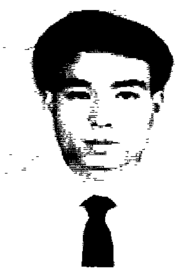
收稿日期:2002-12-03

摘 要 通过多重散射方法数值模拟研究和实验测量表明利用二维光子晶体可以提高波的耦合效率．研究发现,高的波耦合效率通常发生在光子禁带的边沿和其它非禁带区的某些频率处．当光子晶体的晶格常数接近于所传输的波的波长时,会出现很高耦合效率的共振耦合现象．利用二维光子晶体的情况下的波耦合效率最高可以达到不利用二维光子晶体时的 1.89 倍．这种现象在光集成器件中尤其有用．

关键词 光子晶体;耦合效率;共振耦合;光子禁带



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