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Localization of Photons in Two-Dimensional Triangular Lattices with Periodic Defects

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We propose and discuss a simple way for making defects in two-dimensional photonic crystals by radius-modification. It is demonstrated theoretically that localization of photons by the defects is much enhanced in a triangular semiconductor-rods-in-air structure compared to its complementary structure of air-rods-in-semiconductor. In the former structure, both a single acceptor level and a single donor level can be achieved with a defect band width of less than 5% of the band gap width for E-polarized in-plane waves.

1. INTRODUCTION

Two-dimensional (2D) photonic crystals have attracted increasing attention for their easy fabrication compared to three dimensional (3D) ones[1,2]. For the application of photonic crystals to semiconductor lasers, investigation of defect modes which provides an isolated energy level inside the band gap is necessary. So far, defects in 2D photonic crystals were made by either removing a rod or changing the dielectric constant of one of the rods[4-7]. In this paper, we propose and discuss a simple way for making defects by radius-modification, which is suitable for fabrication with electron beam patterning and semiconductor etching technology[1,2]. Analyses of defect modes are carried out with a supercell method for 2D triangular lattice. It is found that localization of photons is much enhanced in a semiconductor-rods-in-air structure compared to air-rods-in semiconductor structures.

2. BAND STRUCTURES

We consider triangular lattices of either semiconductor-rods-in-air structures or air-rods-in-semiconductor structures. The former can give a wide band gap for E-polarized waves and the latter can give a wide band gap for H-polarized waves[1,2]. Periodic defects are made by changing the radius of one rod (defect rod) in each supercell composed of nine original rods (one-in-nine structure). All the analyses were carried out by solving eigen value equations containing 2269 plane waves expanded for the supercell lattice.

(a) No-Defect Crystals

In Fig.1, such calculated supercell band structures for no-defect crystals (solid lines along J'-X'-Γ'-J') are compared to those for the original lattices (discrete points along J-X-Γ-J) expanded with 271 plane waves. Fig.1(a) shows the band structure of E-polarization for a semiconductor-rods-in-air structure with a radius of R = $0.2a$; and Fig.1(b) shows the band structure of H-polarization for an air-rods-in-semiconductor structure with a radius of R = $0.43a$, where a is the crystal constant. Here, each band of the original lattice creates nine bands for the corresponding supercell lattice due to the band folding effect. Therefore a band gap opening between the first and the second bands of the original lattice corresponds to a band gap between the 9th and the 10th bands of the supercell lattice. It can be seen that the band gap of the supercell lattice is in good agreement with that of the original lattice in both (a) and (b). The former crystal in (a) gives a wide band-gap with a gap width of about 50% of the mid-gap frequency (for E-polarized waves), and the latter one of (b) gives also a wide band-gap of 50% (for H-polarized waves). Here, GaAs of dielectric constant $\varepsilon = 13$ is assumed for the semiconductor material.

(b) Defect Modes of Semiconductor-Rods-in-Air Structures

Fig.2 shows the calculated dispersion curves of acceptor and donor modes of E-polarized waves for the same semiconductor-rods-in-air structure as in Fig.1(a) (R = $0.2a$), where the same 2269 plane waves were used in the calculation.

In Fig.2(a), acceptors are made by reducing the radius of the defect rods by $\Delta R = -0.1a$. In comparison to Fig.1(a), the 9th band rises up into the band gap and forms a well isolated acceptor level, while the band gap between the 8th and the 10th bands remains almost the same as the original no-defect crystal.

In Fig.2(b), donors are made by increasing the radius of the defect rods by $\Delta R = 0.1a$. Here in comparison to Fig.1(a), the 10th and the 11th bands drop down into the band gap and forms a degenerated donor level which is also well isolated. The band gap between the 9th and the 12th bands is again almost the same as the original no-defect crystal in Fig.1(a).

The above acceptor level and the donor level are both formed at about the middle of the wide band gaps (~50%

of the mid-gap frequency), and their band widths are both as small as less than 5% of the band gap widths. This indicates that the field is well localized in this one-in-nine periodic defect structure and there is almost no interaction between neighbouring defects.

(c) Defect Modes of Air-Rods-in-Semiconductor Structures

On the other hand, Fig.3 shows band structures of H-polarized acceptor and donor modes for the same air-rods-in-semiconductor structure as in Fig.1(b) (R = 0.43a).

In Fig.3(a) for acceptors, although the 9th band forms a single acceptor level, the dispersive 8th band is also pulled up into the band gap and tends to approach to the acceptor level. Here, the acceptors are made by increasing the radius of the defect rods of air by $\Delta R = 0.1a$, which leaves a very thin semiconductor wall of $0.04a$ ($= a - 2R - \Delta R$) in thickness between neighbouring air rods. It will be more difficult to further increase the radius of the defect rods of air to get more isolated acceptor level.

In Fig.3(b) for donors, multiple levels are formed inside the band gap. We also tested for larger defect sizes of ΔR. Although it can increase the frequency intervals between the multiple donor levels, the lowest donor level will become too closed to the bottom of the band gap.

The above results indicate that the field can not be well localized in this air-rods-in-semiconductor structure with one-in-nine periodic defects and there exists interaction between neighbouring defects. We notice that localization of the field is formed around the air-defect with a "ring" shape in this structure and is very closed to other "rings" of localized field formed in the neighbouring supercells. As the result, interaction between the "rings" of the field brings about multiple donor levels. Therefore, a larger inter-defect distance (or a larger supercell) is needed in order to obtain a better localized field.

3. EFFECTS of ABSORPTION LOSSES on BAND GAPS

We also calculated band structures taking into account of absorption losses through an imaginary part of the dielectric constant $Im(\varepsilon)$ for the semiconductor. It shows that at a typical absorption rate of $Im(\varepsilon) \approx -1$ for GaAs the band gap of the crystal in Fig.1(a) is narrowed by 10% in comparison to the original lossless band gap. Here, complex frequencies were obtained for the photonic bands and their real parts were in good agreement with the original lossless band structure. The imaginary parts were treated as to cause broadening of the photonic bands which in turn causes narrowing of the band gap. Therefore, the defect level needs to be designed away from also the broadened regions of the band edges.

4. CONCLUSION

In summary, we have analyzed defect modes in two-dimensional triangular lattices with the supercell method and a radius-modification defect model. It has been found that localization of photons in the one-in-nine periodic defects is much enhanced in the semiconductor-rods-in-air structure compared to the air-rods-in-semiconductor structure. In the semiconductor-rods-in-air structure, both a single sharp acceptor level and a single sharp donor level can be made at the middle of a wide band gap for E-polarized waves. The defect band widths are both less than 5% of the band-gap width. These results indicate a great possibility of applying 2D photonic crystals to semiconductor lasers especially for active media with well designed polarization characteristics.

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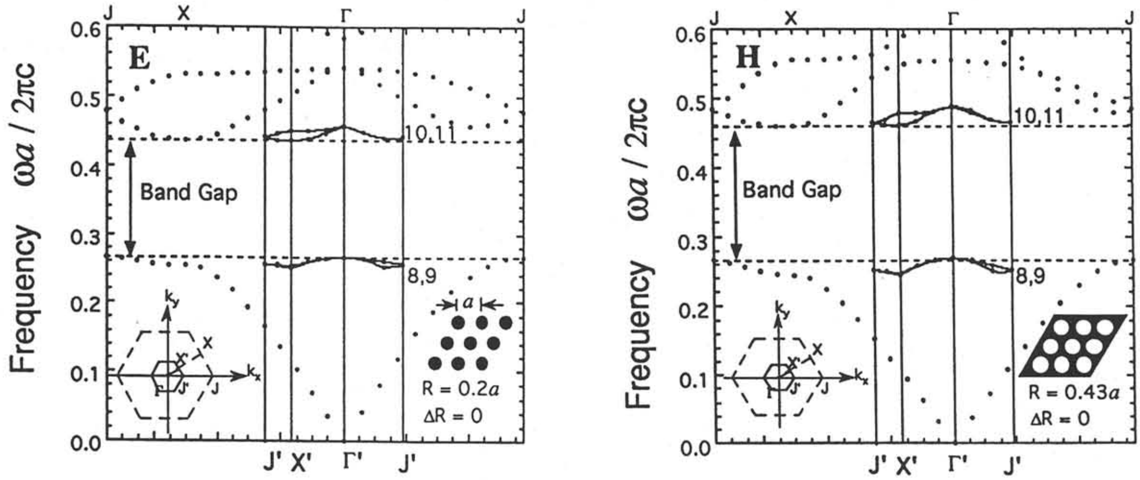
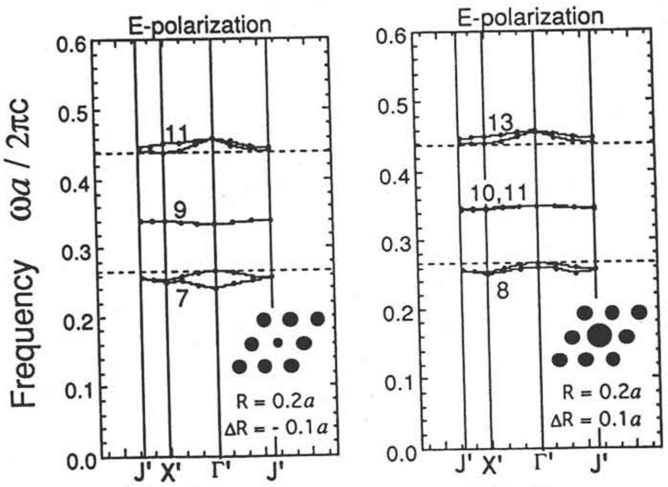


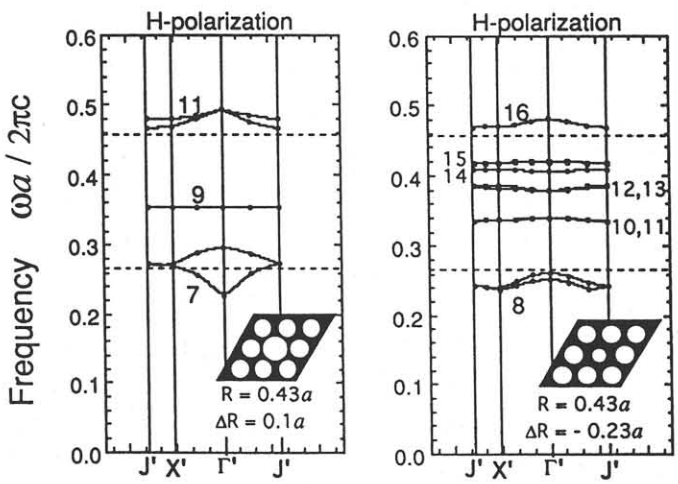
(a) Semiconductor-rods-in-air structure (b) Air-rods-in-semiconductor structure

Fig.1 Comparison of supercell band structures with those of the original band structures for no-defect cyrstals.



(a) Acceptor (b) Donor

Fig.2 Defect modes for the crystal in Fig.1(a).



(a) Acceptor (b) Donor

Fig. 3 Defect modes for the crystal in Fig.1(b).