Dielectric metamaterials with hexagonal lattice

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Abstract. We consider all-dielectric photonic structures with electric response consist of dielectric rods arranged in a hexagonal lattice. We construct gap map as a function of rod permittivity for a constant filling factor by analyzing photonic band diagrams. A near-boundary phase with a strong spatial dispersion is found, whereas in the case of a square lattice this phase does not exist. We observe ε-near zero modes in a metamaterial phase, which do not depend on a lattice orientation and a structure boundary.

1. Introduction
Photonic crystals (PhC) and metamaterials (MM) represent two fascinating classes of artificial structures, which bring new opportunities to photonics due to the original ways of manipulating the electromagnetic waves in various spectral ranges. In photonic crystals band gaps related to Bragg resonance, which is associated with the periodicity of the structure. In metamaterials,
Figure 2. Band diagrams for hexagonal lattice, $r/a = 0.06$: (a) PhC ($\varepsilon=12$), (b) a near-boundary phase ($\varepsilon=31$), (c) MM ($\varepsilon=40$). The thick solid curves show the second dispersion branch. The gray rectangle is area of band diagram where the isofrequency contours are plotted. (d-f) Isofrequency contours, which correspond to the band diagrams in (a-c). The thick solid curves show contours with the same frequency: (a,d) $a/\lambda = 0.580$, (b,e) $a/\lambda = 0.571$, (c,f) $a/\lambda = 0.515$; the dotted line (e) $a/\lambda = 0.569$. Insets: a structure scheme (a) and Brillouin zone (b).

Effects are associated with local resonances at each structural element [1]. This feature makes it possible to describe metamaterials by using the material parameters that are the dielectric permittivity $\varepsilon$ and magnetic permeability $\mu$. Since the effective parameters $\varepsilon$ and $\mu$ of metamaterials can take arbitrary values, there exist many opportunities to create novel optical devices. In this work we consider a structure consisting of dielectric cylinders in hexagonal lattice sites. We calculate band diagrams by using plane wave method. The band diagram of a photonic crystal contains a typical Bragg gap unlike the the band diagram of a metamaterial, which has a polariton-type feature [2]. We construct phase diagrams of structures with a hexagonal lattice for TE and TM polarizations by analyzing the band diagrams with parameter of structure in the intervals $\varepsilon$ in [1..100] and $r/a$ in [0.0..0.5] [3].
Figure 3. TM + TE photonic phase diagrams of dielectric rods arranged in a hexagonal lattice. The region of electric metamaterials in TM polarization are marked by blue. The region of magnetic metamaterials in TE polarization are marked by red. Circles are phase boundary obtained from the band diagram analysis. Solid curves are guides for the eyes only.

2. Results

The band diagrams allow us to build a gap map as a function of rod permittivity for the hexagonal structure with $r/a = 0.06$ in the TE polarization (Figure 1). The Mie band splits off the Bragg stop band with the dielectric permittivity $\varepsilon = 31$, which is marked by the black circle. However, we find that the point of the photonic crystal to metamaterial transition has a higher dielectric permittivity than $\varepsilon = 31$ because the polariton-type feature has yet formed in the band diagram.

We construct isofrequency contours to analyze the states inside the Brillouin zone. The isofrequency contours are calculated for three values of rod permittivity $\varepsilon$: 12, 31, and 40, which correspond to three states of structure with $r/a = 0.06$: photonic crystal, near-boundary phase, metamaterial.

The isofrequency contours of the photonic crystal are shown in Figure 2d. At the lower boundary of the second branch the states are observed near the $\Gamma M$ direction only (red lined in Figure 2a, d). When the frequency is increased the states appear for every direction of the wave vector. Thus, this case corresponds to a strong spatial dispersion condition. In a near-boundary phase (Figure 2e) the circle shape contours are observed at the lower boundary of the second branch, however there are another contour for the same frequency value and same direction, which makes the situation worse than for the photonic crystal phase. Thus, we cannot describe the structure in the near boundary phase by using effective material parameters. In the metamaterial (Figure 2f) the contours have a shape close to a circle and only one contour in the Brillouin zone per each frequency value exists. Therefore, in the metamaterial phase waves propagate under the condition of weak spatial dispersion around the Mie resonance frequency.

Figure 3 shows the phase diagrams ($\varepsilon - r/a$) of the electric and magnetic metamaterials for TM and TE polarizations, respectively. The diagram demonstrates that the metamaterials exist in a narrower range of dielectric permittivity and filling ratio in the TM polarization than TE polarization. The metamaterial phase for structures with the electric response appears in the left part of the TM diagram where the distance between the closest rods is long enough, i.e. the metamaterials with electric response are sparse structures, and the minimum of rod permittivity for the electric metamaterial is $\varepsilon = 22$.

A distribution of electromagnetic field in a structure is more significant for practical
applications than the band diagram. Thus, we calculated the field distribution in photonic crystals and metamaterials. The results reveal that in the metamaterial phase the distribution of fields is uniform over the entire volume and does not depend on the orientation of the lattice. In particular, this distribution confirms a possibility of the $\varepsilon$-near-zero regime in dielectric metamaterials. In a photonic crystal we observe a ‘striped’ distribution of the field in the $\Gamma K$ direction and the wave decay owing to the stop band in the $\Gamma M$ direction.

3. Conclusion

Thus, we have constructed the TM+TE photonic phase diagram for structures with a hexagonal lattice. A dielectric metamaterial with electric response are found to be sparse structures in contrast to the metamaterial with magnetic response. The near-boundary phase with a strong spatial dispersion has been uncovered in structures with a hexagonal lattice. We have shown that the metamaterial behavior by demonstration of the homogeneous $\varepsilon$-near zero modes, which are observed regardless of a lattice orientation and a structure boundary.

Acknowledgments

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References

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