Transition from photonic crystals to all-dielectric metamaterials

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Abstract

We bridge photonic crystals and all-dielectric metamaterials by analyzing a two-dimensional square lattice of dielectric rods with varying rod permittivity from low to high values. We analyze an interplay between the Bragg and Mie resonances in such periodic structures and suggest a general phase diagram marking a transition from photonic crystal to metamaterial through the splitting of the lowest TE$_{01}$ Mie band from the lowest Bragg band.

1. Introduction

Photonic crystals (PhC) are regular arrays of materials with different permittivity typically in the range $1 < \varepsilon < 10$ at optical frequencies (Fig. 1a) [1]. In contrast, all-dielectric metamaterials (AdMM) are composed of high-permittivity dielectric or semiconductor particles (Fig. 1b) [2]. If the optical diameter of the dielectric scatterer (sphere or cylinder) is comparable to the wavelength of incident light $2r\sqrt{\varepsilon} \approx 1$, the scattering from a single particle is in the so-called Mie regime and Mie resonances can be observed. In particular, ordered structure of dielectric rods in p-polarization (magnetic field parallel to the rods axis) have been shown to possess negative effective magnetic permeability [3]. In both PhC and AdMM, Bragg scattering from the lattice lead to the formation of band gaps, where destructive wave interference prevents light propagation in specific directions over specific frequency ranges. Here we investigate an interplay between Mie and Bragg resonances and demonstrate how such interplay can be used for creating of the phase diagram PhC-AdMM.

2. Numerical results and discussions

To investigate PhC-AdMM transition, we consider as an example 2D square lattices, i.e. periodic in $x$ and $y$ directions arrays of infinitely long in $z$ direction parallel dielectric rods with the radius $r$ and a real permittivity $\varepsilon$. The arrays can be characterized by the filling ratio $r/a$, where $a$ is the lattice constant. The host medium is air ($\varepsilon_{\text{air}} = 1$). Here the TE-polarization is considered, at which the magnetic field of incident waves is directed along the rod axis $z$, while the electric field is normal to this axis. We calculated three key sets of spectroscopic data, namely (Fig. 2): (i) Spectra of the Mie scattering by an isolated circular rod that are described by cylindrical Lorenz-Mie resonant coefficients [4]. (ii) Photonic band structure of a 2D square lattice composed of circular rods was calculated by using the plane wave expansion method. We restrict here our discussion by the case, for which the wave vector $k$ of the eigenmodes is oriented in the $\Gamma \rightarrow X$ direction of the first Brillouin zone. (iii) Transmittance spectra of a 2D square lattice were simulated by using the CST Microwave Studio software for the TE polarization and the wave vector of the incident beam parallel to the $\Gamma \rightarrow X$ direction. We considered the 2D square lattice finite along $x$ axis with thicknesses of 5 lattice layers that was found to be sufficient for providing the photonic band gap formation. All data sets have been calculated for a wide range of the rod permittivity $1 < \varepsilon < 100$.

We investigated theoretically a transition from PhC to AdMM depending on the dielectric contrast between cylindrical rods and homogeneous surrounding medium, filling ratio $r/a$ and polarization (TM and TE). Mie scattering creates flat bands for which the transport velocity of electromagnetic waves becomes strongly reduced at and a huge enhanced density of states is induced. In low-contrast PhC, Mie resonances are located at higher fre-
Quency range in comparison with the low Miller indices Bragg gaps. In particular, at \( \varepsilon = 10 \) and \( r/a = 0.2 \) the lowest \( \text{TE}_{01} \) Mie resonance has the normalized frequency of \( f = \omega a/(2\pi c) = 0.57 \) while the lowest Bragg gap is located at about \( f = 0.43 \). The calculations reveal strong decreasing of the \( n_k \) Mie eigenfrequencies and narrowing of the resonant bands with \( \varepsilon \) increasing. At certain region of \( \varepsilon_{nk} \) Mie band crosses the lowest Bragg gap (Fig. 2). Note that at \( \varepsilon \approx 24 \) the Mie band width is extinct and the band is extremely flat (Fig. 2e). At \( \varepsilon > 24 \), an anti-crossing effect with the involvement of the flat \( \text{TE}_{nk} \) Mie band causes a bands splitting and opening of the low-energy Mie gap.

The point of the splitting of the lowest \( \text{TE}_{01} \) Mie band from the lowest Bragg band was considered as transition from PhC to AdMM. At small \( r/a < 0.1 \), the AdMM-phase do not appear because the \( \text{TE}_{01} \) Mie resonance has the frequency higher then the Bragg gap. At large \( r/a > 0.45 \), the lowest Bragg gap strongly decreases and prevents creation of the low-energy \( \text{TE}_{01} \) Mie gap. Note that the strong increasing in \( \varepsilon \) leads to the narrowing of the Mie resonances and correspondingly to the decreasing of the Mie gap size, that is, the AdMM region has a maximum size at intermediate values of \( r/a \).

![Figure 2](image_url)

Figure 2: (a, d, g, j): Computed Mie scattering efficiency \( Q_{sca,0} \) for an isolated dielectric cylindrical rod for \( \alpha \) modes. (b, e, h, k): The band structure for 2D square lattice of rods with \( r = 0.2a \) in air for the TE polarization and different permittivity \( \varepsilon = 10, 24, 27, 35 \). The band structure is shown between the \( \Gamma \) point (wave vector \( k = 0 \)) and the X point (\( |k| = \pi/a \) along the \( x \) direction). (c, f, i, l): The transmittance \( (T) \) calculated for 5 lattice layers of the 2D square structure of rods in air for the TE polarization. The new \( \text{TE}_{01} \) Mie gaps are indicated by red circles in panels (i, l). The frequency \( \omega a/(2\pi c) \) and wave vector \( |k|a/2\pi \) are plotted in dimensionless units, where \( a \) denotes the lattice constant and \( c \) denotes the light velocity in free space.

Acknowledgement

This work was supported by the Ministry of Education and Science of the Russian Federation (project no. 13-02-00186), Russian Foundation for Basic Research (13-02-00186), and the Australian National University.

References


