Quadrupole - driven metamaterials

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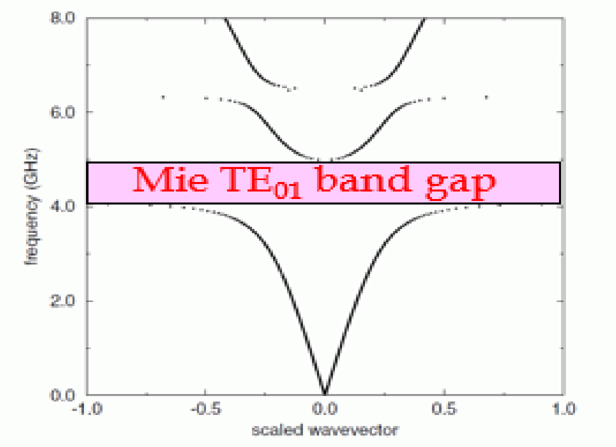
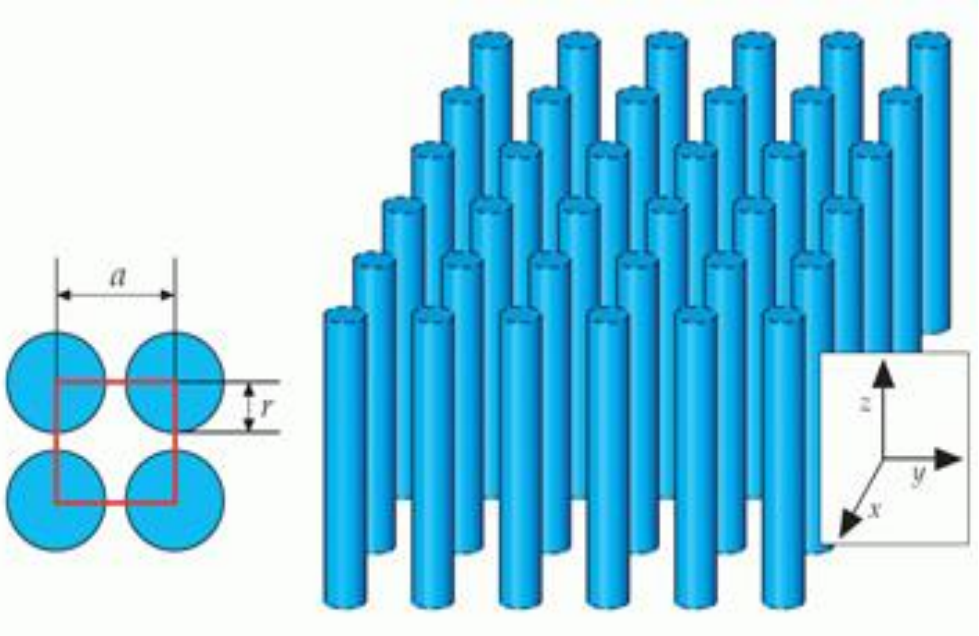
Introduction | Theory 1 | Theory 2 | Simulation | Results | Conclusion

Periodic photonic structures are one of the most important components in modern photonics since they form the basis of optical elements and devices. Such structures can be photonic crystals [1] and metamaterials [2].

In the periodic structure, Bragg and Mi resonances can occur, and if any of the Mi resonances are lower in photon energy than the Bragg resonance, then we are dealing with a metamaterial.





References

[1] J. D. Joannopoulos, S.G. Johnson, J.N. Winn, R.D. Meade. “Photonic Crystals” (2008).
[2] S. O’Brien and J. B. Pendry, J.Phys: Cond. Matt. 2002

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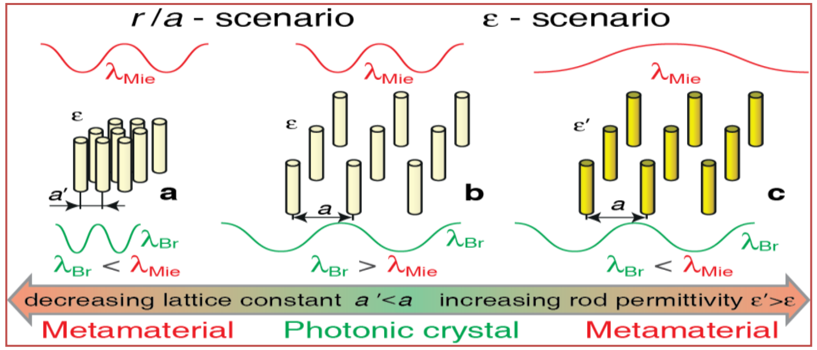
Increase of dielectric constant

As the dielectric constant increases, the frequency of the Mie resonance decreases, thus, the Mie resonance will be lower in energy than the Bragg resonance. Then, at large values of the dielectric constant, we will observe the Mie quadrupole resonance with a lower energy than the Bragg resonance

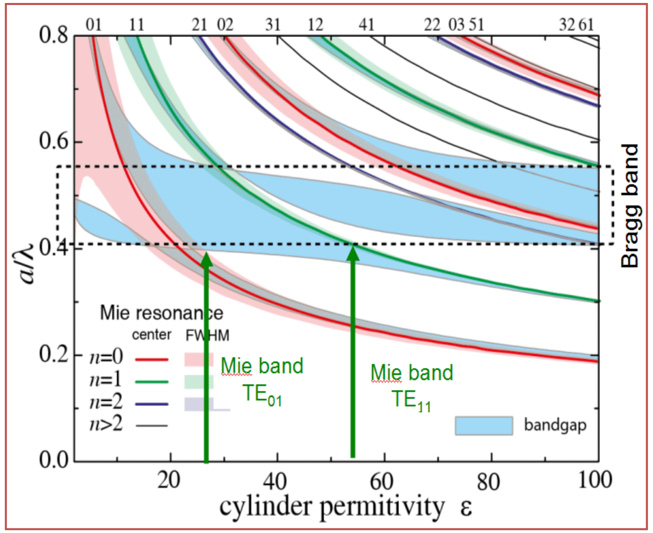


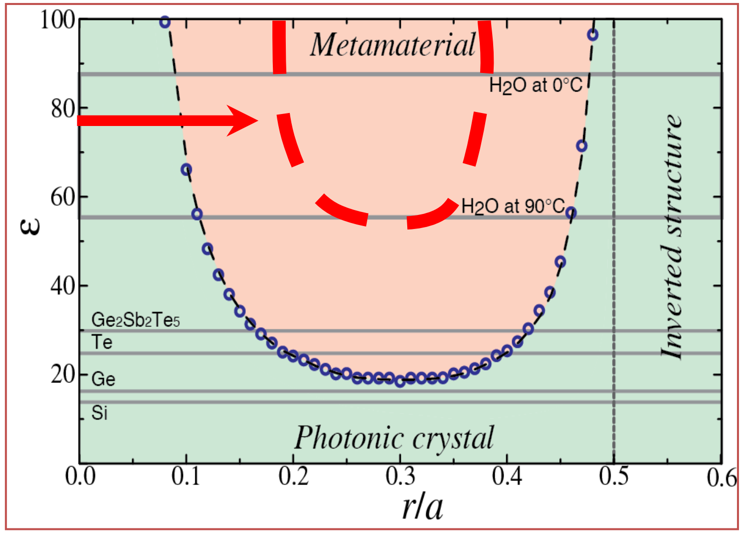
References

[3] M. V. Rybin, D. S. Filonov, K. B. Samusev, P. A. Belov, Y. S. Kivshar & M. F. Limonov, Nat. Com., **6**,10102 (2015)

Goal of theoretical work

At a large dielectric constant, the TE 11 resonance is observed lower in photon energy than the Bragg resonance, which means that there is a quadrupole-driven metamaterial in a certain frequency range. Thus, the **aim of this work is to describe the quadrupole-driven metamaterial**





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TE ^{01} materials

Dipole metamaterials have been studied for a long time, and works have been written that describe these materials in various ways: Rigorous coupled-wave analysis (RCWA) + discrete dipole approximation (DDA) [4] (“coins”) or, for example, metamaterials composed of sparse high-index dielectric rods allow a homogenization procedure by using the approach proposed in work [5]

References
[4] I. M. Fradkin, S. A. Dyakov & N. A. Gippius, arXiv:1812.11359v3, (2019)
[5] O’Brien, S., Pendry, J. B., J. Phys. Condens. Matter 14, 4035 (2002)

TE ^{11} materials

Let's choose a frequency range where quadrupoles will make the greatest contribution to the scattered field. The field created by the quadrupole can be calculated as:

$$\mathbf{E} = \hat{G}^{eq}\hat{\mathbf{Q}}$$

where $\hat{G}^{eq}$ is the quadrupole Green's function, the tensor of the third rank, and $\hat{\mathbf{Q}}$ is the quadrupole tensor, which is defined as:

$$Q^e_{ij} = \alpha^{eq}\left(\partial_i E_j + \partial_j E_i\right)$$

where α^{eq} is the quadrupole polarizability of a single cylinder

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Effective polarizability

since all quadrupoles create a field that acts on others

$$\mathbf{E}_k^{bg} = \mathbf{E}_k^0 + \sum_{l \neq k} \hat{G}^{eq}(\mathbf{r}_k, \mathbf{r}_l)\hat{\mathbf{Q}}_k e^{i\mathbf{k}_\parallel(\mathbf{r}_l - \mathbf{r}_k)}$$

using the Bloch theorem and introducing the notation

$$\mathbf{E}_k^{bg} = \mathbf{E}_k^0 + \hat{C}^q(\mathbf{k}_\parallel)\alpha^{eq}\left(\partial_i E^{bg}_{j,\,k} + \partial_j E^{bg}_{i,\,k}\right)$$

introducing the effective polarizability in the form

$$Q^e_{ij,k} = \alpha^{eq}_{eff}\left(\partial_i E^0_{j,k} + \partial_j E^0_{i,k}\right)$$

we can finally express it

$$\alpha^{eq}_{eff} = \alpha^{eq}\left(\hat{I} - \hat{C}^q(\mathbf{k}_\parallel)\alpha^{eq}\left(\partial_i\delta_j + \partial_j\delta_i\right)\right)^{-1}$$

Polarizability calculation

Quadrupole polarizability on a single particle is proposed to be calculated using the software package COMSOL Multiphysics.

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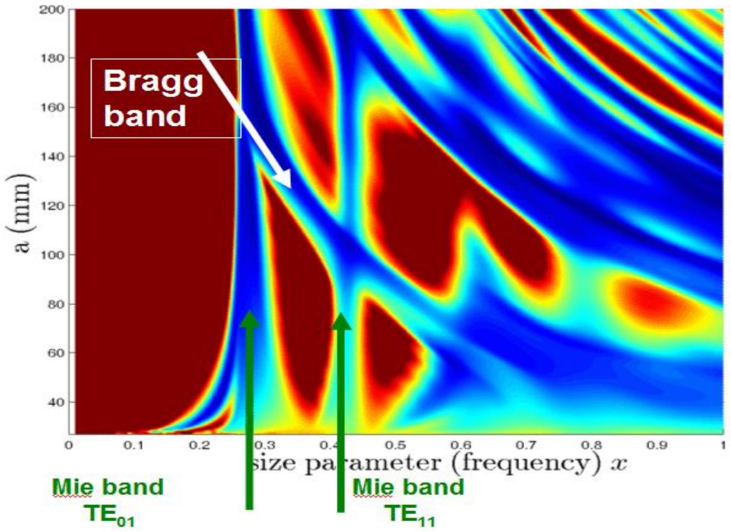
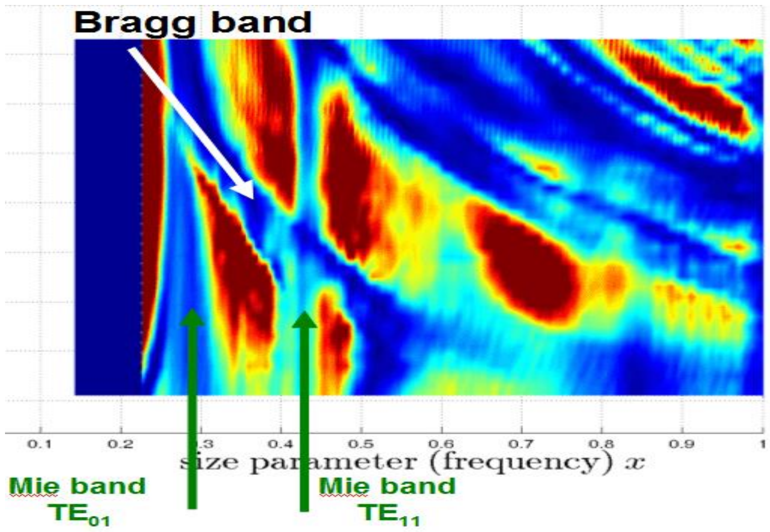
Results

Calculations $\varepsilon = 80$ Experiment





Work in progress

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1. The basis for the construction of the theory of quadrupole-driven metamaterials has been prepared;

2. It is necessary to numerically find the value of the polarizability of a single cylinder, find the effective polarizability;

3. And finally, compare the results that we will get in the future with the experiment.

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