Metamaterial analogue of the Mössbauer effect

V. A. Fedotov[1], N. Papasimakis[1], A. Bitzer[2], M. Walther[2] and N. I. Zheludev[1]
1. Optoelectronics Research Centre, University of Southampton, SO17 1BJ, UK
2. Department of Molecular and Optical Physics, University of Freiburg, D-79104, Germany

We report on intriguing behavior of an electromagnetic metamaterial that presents a phenomenological analogue of the Mossbauer effect, where the metamaterial resonance becomes narrower and stronger with increasing number of meta-molecules in the array structure, similarly to how the broad gamma-emission line collapses in crystalline media Such behavior was observed in both the microwave and THz parts of the spectrum in the so-called trapped-mode metamaterial, a high-Q metamaterial that has recently been introduced by the authors [1] and shown to have a range of interesting applications characteristic to essentially quantum systems, such as lasing spaser [2] and metamaterial analogue of the electromagnetically induced transparency and the Fano resonances [3].

Our metamaterial is formed by a regular planar array of sub-wavelength asymmetrically-split copper rings (ASRs) placed on a dielectric substrate (see inset to Fig. 1a). Such periodic structures exhibit a very strong resonant response for horizontal polarization, which can be seen as a narrow dip in reflection (see Fig. 1b). The resonance is due excitation of the so-called trapped mode, an anti-symmetric high-Q current mode of the split ring (see inset to Fig. 1b) that is normally inaccessible, but becomes weakly coupled to free-space if small asymmetry is introduced in the shape of each ring [1]. What we found is that Q-factor of the metamaterial, which is naturally limited by the asymmetry of its ASR-resonators, is also strongly controlled by the lateral size of the array, i.e. depends on the total number of its unit cells engaged in the interaction with the incident EM-wave. The dependence experimentally observed for the microwave version of the metamaterial is presented in Fig. 1a. The number of unit cells exposed to microwaves was controlled by placing diaphragms on the metamaterial array (as illustrated in the inset to Fig. 1a). Our data shows that Q-factor of the trapped-mode resonance, which measures

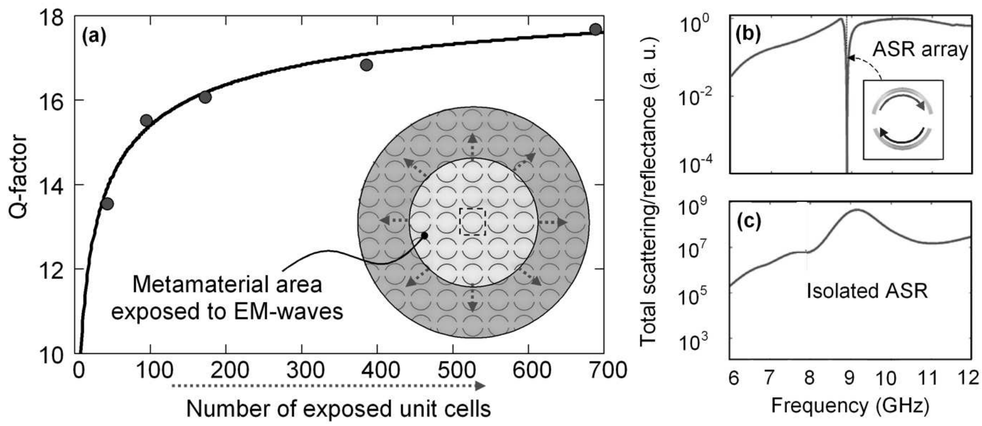

Fig. 1. (a) Q-factor of the metamaterial fragments containing different number of unit cells (red dots – experiment, solid line – theory). Inset shows a fragment of the metamaterial array observed through a diaphragm. Unit cell is indicated by dashed frame. (b) Reflectance spectrum of the microwave metamaterial array. Inset shows resonant anti-symmetric current mode. (c) Total scattering cross-section spectrum of an isolated ASR.

about 13.5 for a small non-diffracting array of 7×7 unit cells, increases by almost 40% for the full-sized array containing about 700 unit cells. The data is in a very good agreement with the theoretically predicted behavior, which also suggests that the quality factor is extremely sensitive to the number of unit cells in the metamaterial arrays less then 10×10 (see Fig. 1a). Furthermore, our near-field measurements of the THz-version of the metamaterial revealed that in the limiting case of a single isolated ASR-resonator excitation of the trapped mode is virtually impossible (i.e. $Q = 0$) and this is fully supported by our numerical FEM simulations (see Fig. 1c). Finally, we attribute such unusual size-dependant electromagnetic behavior to the existence of strong interactions mediated by magneto-inductive surface waves, which render sharp trapped-mode resonance in the ASR-metamaterial a truly collective phenomenon.

[1] V. A. Fedotov, M. Rose, S. L. Prosvirnin, N. Papasimakis and N. I. Zheludev, "Sharp trapped-mode resonances in planar metamaterials with a broken structural symmetry", Phys. Rev. Lett. **99**, 147401 (2007).
[2] N. I. Zheludev, S. L. Prosvirnin, N. Papasimakis and V. A. Fedotov, "Lasing spaser", Nature Photonics **2**, 351 (2008).
[3] N. Papasimakis, V. A. Fedotov, N. I. Zheludev and S. L. Prosvirnin, "Metamaterial analog of electromagnetically induced transparency", Phys. Rev. Lett. **101**, 253903 (2008).