Fano Resonance and Light Localization in Disordered Metamaterials

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Abstract

We present the first experimental study of light localization in disordered planar metamaterials. The statistics of the near field intensity are investigated and and the role of subradiant and superradiant modes is discussed.

1. Introduction

Disordered electromagnetic systems are attracting growing interest due to their potential to confine electromagnetic energy and enhance light-matter interactions with substantial implications for sensing, non-linear optics, light emission, even cavity quantum electrodynamics. Here we extend the study of light localization to planar metamaterials consisting of asymmetrically-split ring (ASR) resonators that support subradiant, magnetic, collective excitations [1, 2]. These modes correspond to magnetic dipoles oriented normal to the plane of the array and are uncoupled to the magnetic field of the incident wave. Such a system is weakly coupled to free-space and hence ideal for localization studies.

2. Samples and experimental setup

Metamaterial ASR arrays were manufactured from 1.6 mm thick FR4 PCB laminates using standard photolithography techniques. The radius of the asymmetrically split ring structure is 6 mm, while the length of the arcs correspond to angles of 160 and 140 degrees. The width of the wire is 0.8 mm. The unit cells of the regular structure have the size of 15x15 mm^2, ensuring no diffraction at frequencies below 20 GHz. Disorder was introduced by displacing the centre of each unit cell according to a random uniform distribution defined over a square with side 2.25 mm. The overall size of the metamaterial arrays is 15x18 unit cells.

All the experiments were performed in an anechoic chamber using a microwave SNOM system built in-house. The near field intensity was measured by scanning a small monopole antenna probe positioned perpendicularly to the sample under normal incidence illumination by a linearly polarized wave from a broadband horn antenna. The probe position was controlled using a motorized x-y stage with a step size of 2 mm. The polarization of the incident electromagnetic wave was set parallel to the arcs.

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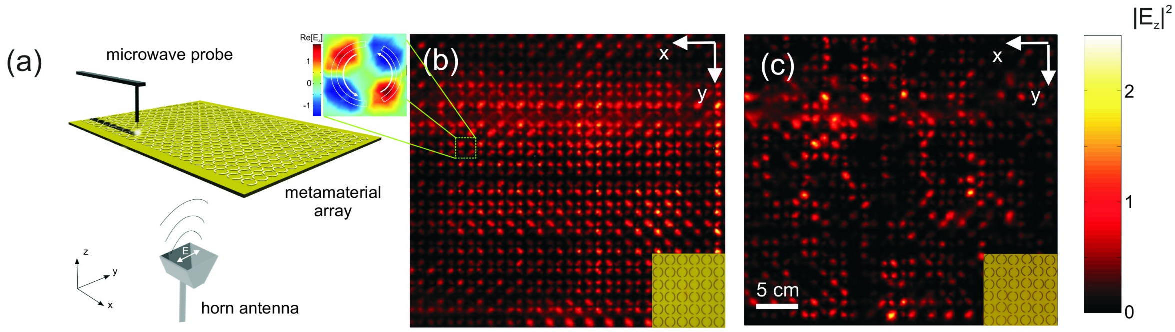

Fig. 1: (a) Drawing of the experimental setup. (b-c) Maps of the electric field intensity at the vicinity of the regular (b) and disordered (c) asymmetrically split-ring array. The inset in (b) shows the real part of the electric field for a single unit cell, where the arrows indicate the direction of the currents flowing on the arcs.

3. Results and discussion

Experimentally obtained characteristic maps of the near field intensity are shown in Fig. 1 for ordered and disordered metamaterial arrays. The periodic array exhibits a regular field pattern throughout with the exception of a small modulation that is attributed to finite size effects (panel (b)). Looking closer to the near field map of a unit cell, four foci can be identified near the edges of the two arcs comprising the ASR, indicating the excitation of the antisymmetric current configuration (trapped-mode). This is more evident in the inset, where it is shown that the two arcs are excited with opposite phases. On the other hand, the disordered array reveals a distinctly different picture (see panel (b)): although the displacement of the unit cells is small (less than 15% of the unit cell side), the periodic pattern present in the regular case is much less pronounced, and a speckle pattern develops, where only certain ASRs are strongly excited.

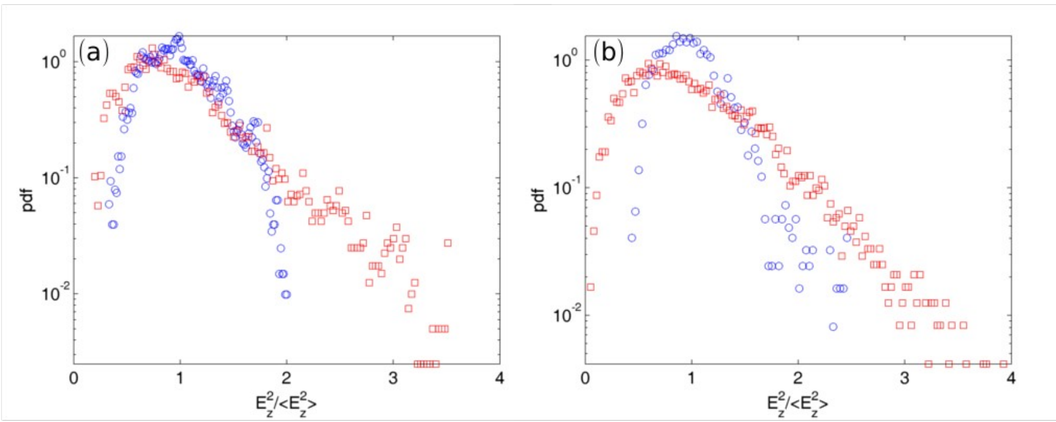

Fig. 2: Experimentally measured (a) and numerically calculated probability density function (b) for regular (blue) and disordered (red) asymmetrically split-ring arrays.

This difference in the behaviour of ordered and disordered ASR arrays was corroborated by studying the statistics of the near field intensity over a narrow band in the vicinity of the subradiant collective excitation. Marked differences are seen in the probability density function (pdf) of the intensity in regular and disordered arrays, with long tails at high intensities emerging in the latter case (see Fig. 2). To facilitate comparison, each distribution is normalized to its average value. Counter-intuitively even the distribution of the regular arrays exhibits a finite width as a consequence of the finite size of the sample. Nevertheless, the pdf of the disordered array is much broader and a long tail develops at high intensities, reaching values muchs higher than those attained with the regular array. The slow decay of the pdf at high field values, is representative of a regime where rare, but bright regions begin to appear. This behaviour is corroborated by finite element simulation results (see Fig. 2b), where the pdf for the random metamaterial case is calculated over 20 different realizations of disordered arrays, indicating that the behaviour of the experimentally measured array is typical for the given degree of disorder.

4. Conclusion

In conclusion, we study experimentally localization in planar metamaterial systems that support subradiant collective modes of excitation. The role of such collective modes and possible applications will be discussed. In conclusion, we report on near-field experimental investigations of metamaterials that support high-Q collective modes and demonstrate that disorder modifies statistics of the metamaterial response leading to intense localized excitations. Our results draw attention to the design control over the nature of the interactions available with metamaterials and are expected to ignite research interest in further demonstrations of multiple scattering phenomena and related applications.

References

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