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Achieving sharp spectral resonances in metamaterials via engaging "closed-modes"

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Abstract: We report the first experiential results on a new type of planar metallic metamaterials, which shows very narrow transmission and reflection resonances. The spectrally narrow responses are achieved by reducing the coupling between resonant inclusions and free-space via excitation of so-called "closed modes".

The idea of frequency selective planar structures (metamaterials) has been investigated in the microwave part of the spectrum for some time using arrays of *separated* holes in a metal screen or metallic particles such as crosses, snowflakes, tapers and split-rings or recently introduced *continuous* metallic fish-scale pattern. Wavelength sensitive transmission and reflection of such planar structures result from patterning the surface on a sub-wavelength scale in a special way, which makes coupling of electromagnetic excitation to the structure resonant. Planar metamaterials are now widely exploited in microwave antenna applications and very recently have attracted a lot of attention as a new paradigm for photonics, paving the way to achieve and improve functionality of the existing bulk optical devices such as spectral filters, polarizers, wave plates, polarization rotators etc. Unfortunately, in the optical domain losses in metals become very strong, which makes resonant properties of the appropriately scaled metamaterial structures less pronounced (the resonant band increases while the strength of the resonant effect decreases). Therefore developing a structure with a large resonance quality factor and significantly reduced resonant spectral band is crucially important for potential photonic applications.

Here we report the first experiential results on a new type of planar metallic metamaterials, which shows exceptionally narrow transmission and reflection stop-bands. The metamaterials is formed by a periodic array of identical sub-wavelength asymmetrically structured planar metallic "particles" placed on a dielectric substrate (see inset to Fig. 1). Such planar metamaterials exhibit a very sharp resonant response with the quality factor at least one order of magnitude large than that typically encountered in conventional frequency selective structures/surfaces. We show that the nature of such a strong and narrow spectral response can be traced to so-called closed modes, i.e. electromagnetic modes that are weakly coupled to free-space [1]. These modes are usually forbidden but can be excited if, for example, particles have a certain structural asymmetry. Manifestation of the resonant properties depends on the type of the asymmetry. For the case of particles shown in Fig. 1a (a metallic ring split into 2 unequal arcs) the metamaterial exhibits an ultra-narrow resonant reflection stop-band near 5.5 GHz (see Fig. 1b). At this resonance, as shown in the inset to Fig. 1b, two parts of the particle are excited in anti-phase, which dramatically reduces coupling to free-space. "Closed mode" resonance is accompanied by two "conventional" resonances, where excitation of one part of the particle dominates the other (see Fig. 1b). We also found that if the ring is divided into two equal arcs but the sizes of the splits are different, an ultra-narrow stop-band is seen in transmission near the same frequency. Correspondingly in symmetrical case, i.e. when the arcs as well as splits are equal, no high quality factor resonance can be observed (see Fig. 1b).

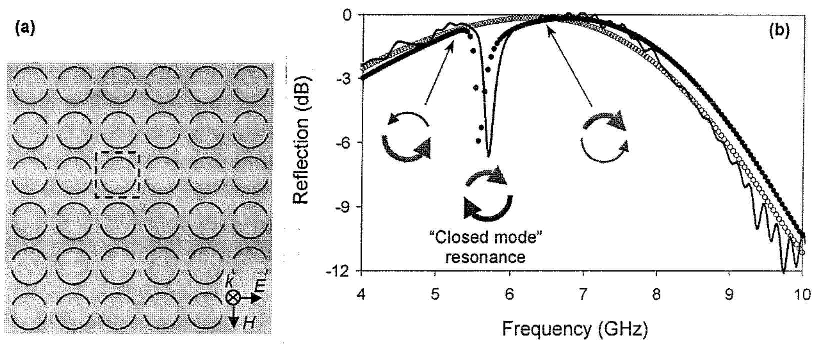

Fig. 1. (a) A fragment of metamaterial with asymmetrically structured particles, where dashed line box indicates a 15x15 mm elementary translational cell of the structure. (b) Intensity of electromagnetic wave reflected from planar metamaterial: solid line – experiment, filled circles – theory, empty circles – theory (reference structure with no particles asymmetry). Insets present resonant current distributions in the asymmetric particles: where arrows show the directions (phases) and relative intensities of the induced currents.

[1] S. Zouhdi, S. Prosvirnin, *Advances in Electromagnetics of Complex Media and Metamaterials* (Kluwer Academic Publishers, Netherlands, 2003), pp. 281-290