Experimental Demonstration of the Saturation and Weakening of the Resonant Response of the SRR and the CSRR

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In 1999, J. B. Pendry and co-workers proposed the Split Ring Resonator (SRR) for designing magnetic materials at high frequencies from non magnetic metal (J. B. Pendry et al., IEEE Trans. MTT 47, 2075, 1999). This possibility was experimentally demonstrated in microwaves (D. R. Smith et al., Phys. Rev. Lett. 84, 4184, 2000) and millimeter waves (T. J. Yen et al., Science 303, 1494, 2004). However, when the particle is scaled down enough to resonate in the optical range, the resonance frequency achieves a saturation level and the magnetic response becomes very weak (J. Zhou et al., Phys. Rev. Lett. 95, 223902, 2005). This phenomenon was only demonstrated through numerical simulations, but there has not been yet an experimental probe. Separately, Zentgraf et al. experimentally demonstrated that the Babinet's principle is almost valid for the SRR and its complementary screen, the so called Complementary-SRR (CSRR), in spite of bad conductivity of metals and big thickness of the screens (T. Zentgraf et al., Phys. Rev. B 76, 033407, 2007). Now, in this paper, we experimentally study the saturation and weakening phenomenon for both SRR and CSRR. Figure 1 shows the unit cell of a 2D array of square SRRs, being yellow for silver and blue for the substrate. The CSRR looks the same but with yellow and blue colors interchanged. The samples were manufactured by ion milling over silver lying on an Infrasil substrate. The geometry was checked by SEM microscopy. Transmission and reflection coefficients were obtained by FTIR. Table 1 shows the resonance frequencies for geometries gradually scaling from period $a = 2000$ nm down to $a = 500$ nm. For instance, the fundamental resonance of the SRR was found at 38.3 THz for $a = 2000$ and 73.9 THz for $a = 500$ nm. Thus, the resonance frequency grew up by a factor of 1.9, while the geometry was reduced by a bigger factor of 4. It is clearly evidencing that the beginning of the saturation. Also we observed the weakening of the resonant response for smaller particles. This phenomenon will be critical for application of metamaterials in optics.

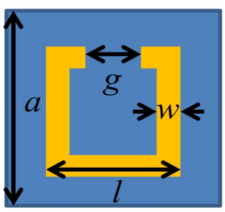

Fig. 1 Split Ring Resonator. The biggest geometry was (all in nm): periodicity $a = 2000$, $l = 1400$, $w = 200$, $g = 733$, and thickness of metal $h = 50$. The rest of geometries were scaled down from this one.

Table 1 Resonance frequencies for SRR and CSRR. Arrows represent the polarization of the electric field.

	SRR (THz)		CSRR (THz)	
a (nm)	↕	↔	↔	↕
2000	66.76	38.3(77.76)	63.99	38.36(76.77)
1000	97.72	46.8(124)	99.97	49.06(125)
900	128.7	60.52(155.2)	120.2	57.68(151.1)
600	117.2	53.17(140)	163	74.2(180)
500	158	73.94(206)	174	77.5(192)