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Geometrical tuning of nanoscale split-ring resonators

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Abstract: We investigate the capacitance tuning of nanoscale split-ring resonators. An *LC*-model predicts a simple dependence of resonance frequency on slit aspect ratio. Experimental and numerical data follow the predictions of the *LC*-model.

OCIS codes: (160.3918) Metamaterials, (250.5403) Plasmonics

1. Introduction

Metamaterials are artificially structured materials with exceptional optical properties inherited from the structure of the sub-wavelength, mesoscopic unit-cell. Designing negative index materials with simultaneously negative permittivity ε as well as a negative permeability μ is one of the promising aspects of metamaterials. Since a negative electric response is common in metals at e.g. optical frequencies, the search has primarily focused on designing structures with a negative magnetic response. Different types of split-ring resonator (SRR) geometries [1–3] are particularly central in this context and have been realized at Terahertz [1, 4] to visible frequencies [3, 5].
The analogy with inductor-capacitor (*LC*) circuits have motivated considerable efforts in establishing simple circuit models, allowing for an estimate of the resonance frequency $\omega_0 = 1/\sqrt{LC}$ in terms of geometrical parameters of the split-ring resonator structure, see. e.g. Refs. [6–7] and references therein. The *LC*-model has proven to be a good approximation as long as the coupling response of the SRR array is small compared to the response of a single SRR, hence the period Λ has to be sufficiently large [8]. Tuning of the resonance has been accomplished by scaling of a single geometrical dimension [9], linear scaling of all SRR dimensions [5], and finally by altering the cladding [10].

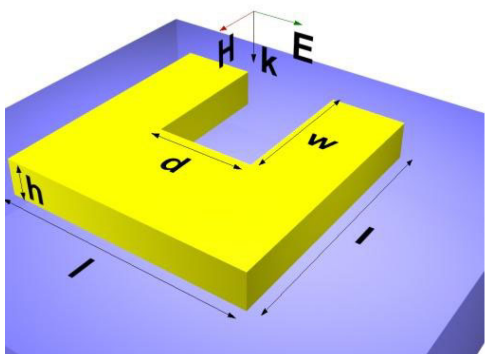

Figure 1. Schematic drawing of the split-ring resonator design, indicating central geometrical parameters as well as the polarization configuration of the excitation.

In this paper, the influence on resonance frequency of geometrical scaling of split-ring resonators is studied experimentally and by means of full-wave numerical simulations. The SRRs are placed in a periodic array keeping the period constant and large, Λ=500 nm, to minimize coupling effects. The system is described by an *LC*-model [7]. The model predicts a data collapse, which is experimentally verified.

$$(k_0 l)^2 \sim d/w \qquad (1)$$

where k_0 is the free-space wave number, l is the side length, d is the slit width, w is the slit length, see Fig. 1.

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2. Results

The LC-model is compared to experimental and numerical simulation data. Full-wave simulations were performed in CST Microwave Studios. The numerical data in Fig. 2(b) are calculated for a structure with l=200 nm, d=80 nm, h=30 nm, Λ=440 nm. The numerical data support the predicted linear scaling of the *LC*-model.

For the experimental investigations, 8 samples with 2 mm by 2 mm arrays of gold SRRs were fabricated on glass substrates by electron beam lithography and lift-off [7], see Fig. 2(a). The geometrical parameters of the samples covered: d=80 nm, w=90-110 nm, l=200 nm, h=35 nm.

The transmission was measured using a 1 mm diameter laser spot, thus effectively probing an ensemble of 10^8-10^9 SRRs. The experimental data are fitted to the *LC*-model in Fig. 2(b), using $k = 2\pi/\lambda$, where λ is the measured resonance wavelength λ, and the split ring dimensions d, l, w are measured by SEM inspections.

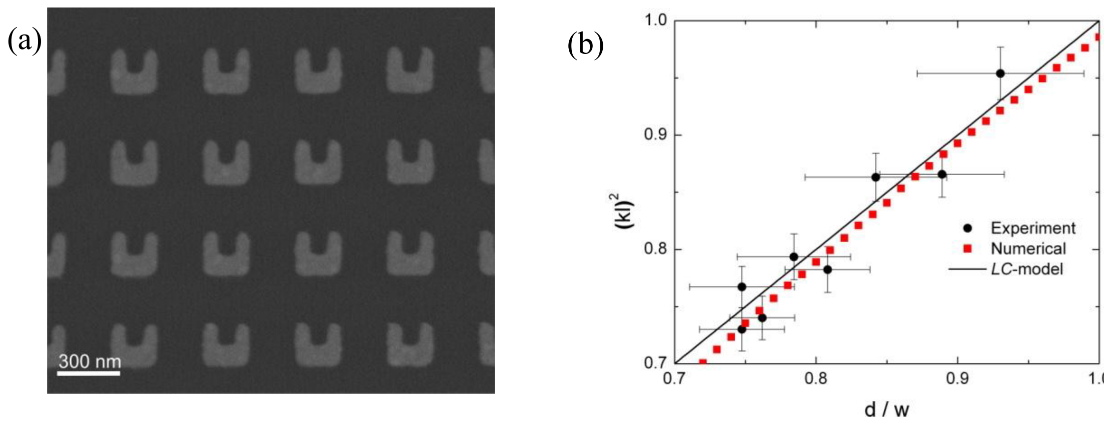

Figure 2. (a) Micrograph of a SRR array with pitch Λ = 440 nm. This sample has l = 200 nm, w = 95 nm, d = 80 nm, and h = 35 nm. (b) Plot of $(k_0 l)^2$ versus d/w where experimental and numerical data are plotted together with the *LC*-model. The x-error bars on the experimental data represent the standard deviation (SD) of ten individual measurements of w, and d added together. The y-error bars are the 1 nm spectral resolution of the Ando AQ-6315E Optical Spectrum Analyzer added to the SD of ten measurements of the length.

In conclusion, we have fabricated periodic arrays of subwavelength, nanoscale split-ring resonators to investigate geometrical tuning. Our key observation is that the experimental and numerical data follow the predictions of the *LC*-model.

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