Near field distribution for the infrared characterization of nano-metamaterials.

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Abstract

In this paper, metamaterials made of gold on silicon are considered. We demonstrate experimentally and numerically how the near field distribution in infrared metal-dielectric metamaterials can lead to a better understanding and classification of the resonances through a geometric modification of SRR (Split Ring Resonators). The result of numerical simulations and experiment are compared and show very good agreement. To the best of our knowledge, the structures considered here have not been studied in the infrared domain yet. Our experimental results show that higher order excitation modes are more difficult to excite experimentally.

1. Introduction

The field of metamaterials is growing very rapidly since their theoretical description and fabrication [1-3]. However the fabrication and characterization in infrared and optical regime is still very challenging. In this paper a metamaterial made of gold on silicon are considered. We show experimentally and numerically how the spectral response and the resonances are altered by the modification of the geometry of the elements it is made of. The near field distribution of the resonances leads to a plasmonic interpretation of the resonant mode. We show how these modes can influence the electric and magnetic parameters of our metamaterials.

2. Design, simulation and fabrication of the infrared metamaterials

The structure is composed from split-ring resonators (SRR) and wires, made of gold on silicon. The wires are parallel to the bottom of the SRR (fig.1). This figure shows a picture of the four realized structures with a detailed cell of the lattice in each case. The nano-wires are arranged periodically at a pitch of 600 nm so that the plasma frequency associated to this wire array is above the expected infrared resonances of the SRR. The dimension of the rectangular shaped SRR is 260nm*360nm. The conducting elements are made of gold with a width of 40 nm and assumed to be on a silicon substrate with a relative permittivity of 11.9. The wires are parallel to the gap of the SRR. The distance between the wires and the side of the SRR parallel to the gap is 80 nm. The fabrication is performed by e-beam lithography on a 280 µm thick silicon substrate followed by high vacuum electron beam evaporation of 5 nm thick titanium, 40 nm thick gold and a lift off procedure. The different samples are fabricated during a single lithography and have the same treatment allowing a meaningful comparison. A SEM (Scanning Electron Microscope) picture of the four samples and the overall dimensions can be seen on figure 1. The four structures are fabricated and numerically simulated. The 1st is composed of continuous wires and of rectangular SRR, the 2nd of wires and rectangular U-shaped SRR, the 3rd of wires and shorted U-SRR and the 4th of wires and discontinuous wires. In the fourth structures the distance between the continuous wires and the discontinuous one (the side of the SRR parallel to the wires) remains identical (80 nm). The size of the discontinuous wire (357 nm) is also the same as the size of the side of the SRR parallel to the wires. The size of the legs of the SRR is 284 nm in the 1st structure, 190 nm in the 2nd structures. These legs are reduced to 114 nm in the 3rd one. The gap has a width of 124 nm in the 1st structure. All those dimensions are gathered in figure 1.

As in our preceding paper, the structures are simulated using a finite element method [9, 10]. The spectral response of the proposed structures is carefully studied for two polarizations, the horizontal polarization with the electric field parallel to the gap of the SRR (parallel to the continuous wires) and the perpendicular polarization with the electric field perpendicular to the gap of the SRR. In simulation, a Drude model is used for gold conducting elements since they do not behave as perfect reflector in the infrared. The Drude model is the following:

$$\varepsilon(\omega) = 1 - \frac{\omega^2{}_p}{\omega(\omega + i\omega_c)}$$

ω_p and ω_c are respectively the plasma and collision frequency of gold film [5]. The values used here are the following: $\omega_p = 1.367.10^{16}\ s^{-1}$ (f_p =2176 THz) and $\omega_c = 6.478\ 10^{13}\ s^{-1}$ (f_c = 10.3 THz).

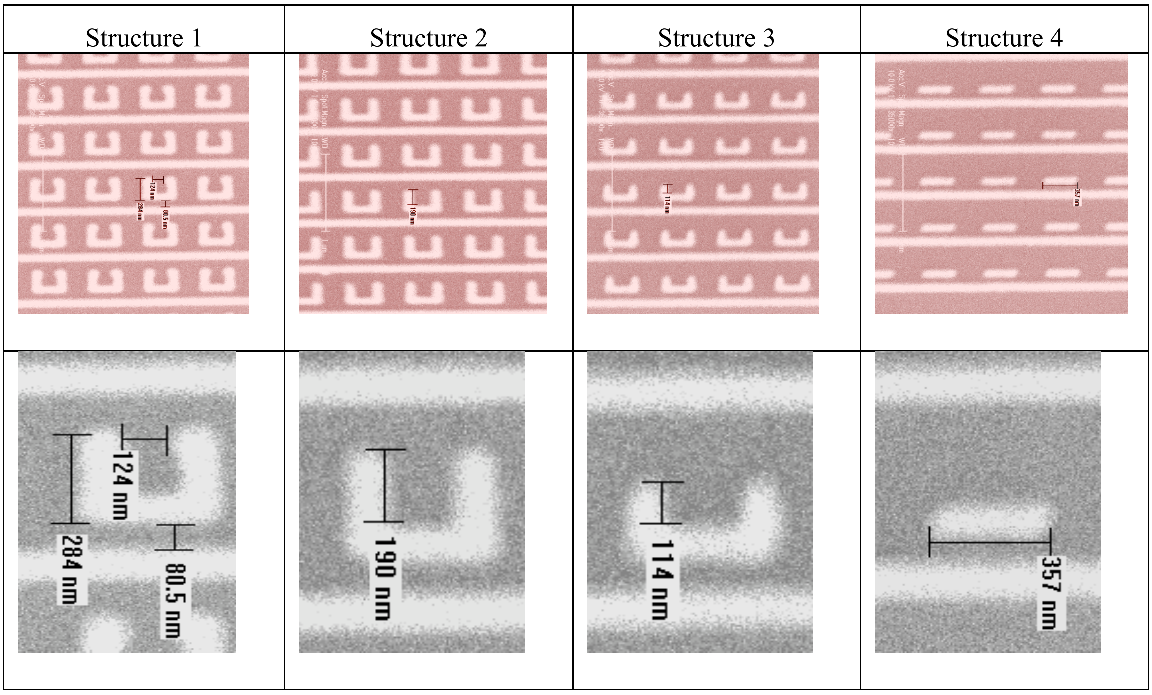


Fig. 1. SEM (Scanning electron Microscope) picture of the different samples showing the geometric transformation, from the SRR to the discontinuous wires by progressively removing the side of the SRR perpendicular to the gap.

In order to improve the agreement between simulation and experiment, the collision frequency can be fitted. Increasing the collision frequencies results in higher losses in the structures and has the physical meaning of supplementary collision due to the film nature of the deposited gold but do not change the spectral position of the resonances. We are interested in the modification of the spectra due to the geometrical transformation presented on fig. 1. Geometrical transformation of the SRR when progressively diminishing till completely removing the length of the “legs” of the U shaped resonator has an impact on the spectral position of the resonances and the excitable plasmon modes in the structure. At the end the structure is reduced to an array of continuous and discontinuous wires stripes far simple to fabricate with smaller size than the original structure due the proximity effect in e-beam lithography. In a previous paper we have presented results on a metamaterial made of continuous and discontinuous wires in the microwave range and phase inversion at the first resonance has suggest a left handed behaviour [9]. The experimental measurement are performed with a FTIR (Fourier transformed Infrared spectrometer) BioRad FTS 60A combined with a microscope. Since each array is 100 µ*100µm, a diaphragm is needed to focus the signal on the sample. The light is polarized between 20 THz (15µm) and 200 THz (1.5µm). The transmission spectra of the structures are normalized over the transmission of the silicon substrate and the reflectance are normalized over the reflectance of a gold film of 40 nm.

3. Measurements and simulations results

The numerical spectra as well as experimental results of the successive structures are shown for both the parallel and perpendicular polarization on figure 2. The transmission and reflection curves as well as resonances positions are compared with simulation results and show a very good agreement as it can be seen from figure 2. Calculations are performed using an elementary cell with periodic boundaries conditions corresponding to the polarization of the incident wave.

In measurements, when the electric field is parallel to the gap of the SRR, the first resonance moves from 60 THz in structure 1 to 120 THz in the structure 4. A stop band due to the continuous wires is observed at low frequencies. For the perpendicular polarization the minimum pick in transmission is shifted from 120 THz in structure 1 to 160 THz in structure 3. For the structure 4 the resonance is out of the range of our experimental setup. The simulations give the same results with two plasmonic resonances for the 1st structure at 60 and 140THz. The first resonance shifts toward higher frequencies when the legs of the SRR are progressively reduced in the structures 2, 3 and 4. The second resonance follows the same behaviour for the structures 1 to 3. For the 4th structure however this resonance does not appear in our frequency range of calculation. It should be noticed that the differences between the structures 1 and 2 are weak. The transformation of the first square SRR structure to a U-structure does not change significantly the frequency behaviour of the material. The changes are more important for the structures 3 and 4 with a strong reduction of the length of the whole structure. Higher order modes are more difficult to excite due to both fabrication imperfection and the higher energy required. Measurements between 200 THz and 300 THz (not shown here) do not show any other resonance.

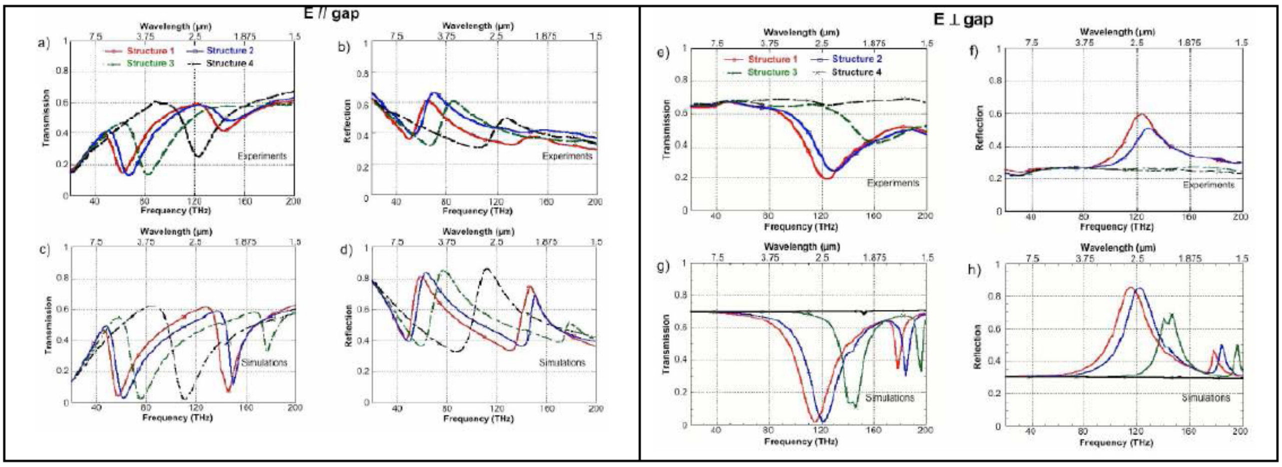


Figure 2: Measured and simulated transmission and reflection spectra for the four structures and for the two polarizations. Electric field parallel to the gap (a to d) and electric field perpendicular to the gap (e to h).

4. Near field distribution of the resonances

The figure 2 below shows the near field distribution at the top surface of our four structures. These results are in agreement with the results presented by C. Rockstuhl *et al.* in [8]. When the electric filed is parallel to the gap, modes with odd number of nodes can be excited while modes with even numbers of nodes are excited for the perpendicular polarization. Its can also be shown that only odd numbers of node can lead to artificial magnetism.

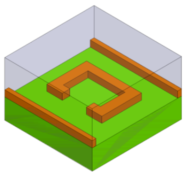
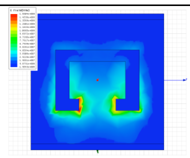
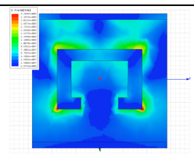
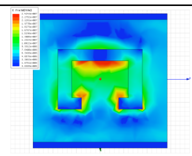
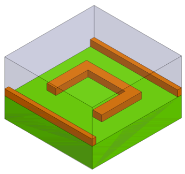
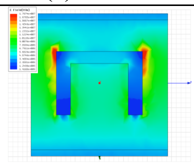
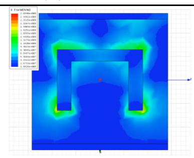
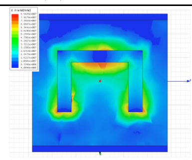
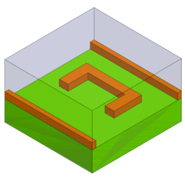
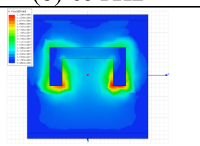
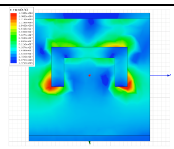
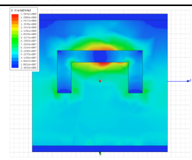
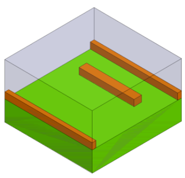
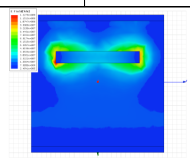
	E // Gap		E ⊥ Gap
Structure 1 through 4	Resonance 1	Resonance 2	Resonance1
	 (a) 60THz	 (e) 140THz	 (h) 120THz
	 (b) 65THz	 (f) 145THz	 (i) 130THz
	 (c) 80THz	 (g) 180THz	 (j) 160THz
	 (d) 120THz		Not observed

Figure 2: Near field distribution at the resonances observed in experiment for the four structures.

5. Conclusion

We have studied the impact of geometrical transformation of the SRR (split ring resonators) on both the spectra and the near field distribution of the resonances. We have experimentally confirmed that all the resonances can be understand and explained in term of plasmonic resonances. The first and second resonances have been the only observed experimentally. The geometrical transformation studied here is for great interest in application such as cloaking where a suitable metamaterial is spatially adjusted. The application of our structures to cloaking will be presented in a very next future. The structure 4, derived from the previous one is far simple to fabricate at optical frequencies. However, in order to consider the effective parameters, the structures considered here need to be stack in a bulk manner even if this approach is at present time limited by the aspect ratio in e-beam lithography.

7. References

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