The impact of nearest neighbor interaction on the resonances in terahertz metamaterials

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By using terahertz time-domain spectroscopy and rigorous simulations, we investigate the impact of gap orientation of neighboring split rings on the three lowest order eigenmodes for a metamaterial based on split ring resonators. We distinct scenarios where neighboring split rings have their gap either on the same or on opposite sides. The two lowest order eigenmodes are marginally affected, whereas the higher order eigenmode experiences a significant spectral reshaping. By modifying the period it is shown that due to a coherent interaction a huge resonance sharpening is observed. Hence potential application can be anticipated by using such materials, e.g., in sensing devices. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3063051]

The major fascination of metamaterials (MMs) is that the rational design strategies for the unit cells permit to tailor the effective properties.[1] Such ability is particularly important in the terahertz regime since many materials do not respond to such frequencies.[2] The unique properties of MMs could offer a possible solution for building up subwavelength imaging devices relying on a negative index lens at terahertz frequencies. Free control over the effective material parameters is a prerequisite to steer light in such devices.

For such a purpose MMs containing split ring resonators (SRRs) were proposed to obtain an effective negative permeability.[3] Continuous metallic wires were suggested to mimic a diluted metal. If it is in the same spectral domain where the SRR has its negative permeability, a negative index is encountered. Due to such a simplistic concept, the realization of negative index materials often relies on SRRs and wires. Although such an envisioned operation requires erected SRRs relative to a substrate, for probing the basic properties of SRRs it is common sense to fabricate those using planar technologies. When the illumination direction is normal to the SRR the same eigenmodes can be excited as in the case of an in-plane illumination.[4] The eigenmodes are at the heart of obtaining control over the effective material parameters. However, the impact of each eigenmode on altering the effective properties is different for different illumination scenarios.

For normal incidence, dispersion is solely induced in the effective permittivity. Depending on the polarization of the incident *E*-field the eigenmodes can be discriminated into odd and even modes.[5] For odd modes the *E*-field has to be parallel to the gap, whereas for even modes it has to be perpendicular. The lowest order odd mode, also called the *LC*-mode, is potentially the most fascinating one, as it is usually at the focus of interest in the design of MMs. Nevertheless, higher order modes attracted likewise a significant interest as they are potential candidates for applications in, e.g., biosensing or surface enhanced Raman spectroscopy.[6] For an in-plane illumination the odd modes allow modifying the effective permeability, whereas the even modes allow modifying the effective permittivity. Tuning the resonance position of all modes is usually at the focus of interest,[7] but also the impact of disorder was investigated.[8] Nevertheless, a systematic investigation of how the orientation of the SRR in the unit cell affects the spectral response is missing.

To bridge this gap, we analyze here the impact of the SRR orientation in the unit cell on the spectral position and the width of the resonance at normal incidence. To this end we investigate MMs composed of three different supercells containing four SRRs. The geometrical arrangement of the SRRs in each supercell is shown in Fig. 1. In the first sample, all SRRs have their gap on the same side. In the second sample, the SRRs are arranged with vertical mirror symmetry. In the third sample the SRRs have the same orientation of their gaps along the diagonal directions of the supercell. In this work the effect of the orientation on the spectral position and the width of each resonance are investigated. It will be shown that the two lowest order modes are only marginally affected, whereas the higher order eigenmode suffers a severe spectral reshaping that depends strongly on the period. Much larger quality factors than those usually encountered for terahertz MMs can be observed.[9] As a consequence, it is shown that control over the orientation of the SRRs and the periodicity allows to observe extremely sharp features in the spectrum that are promising candidates for various practical applications such as sensing devices.

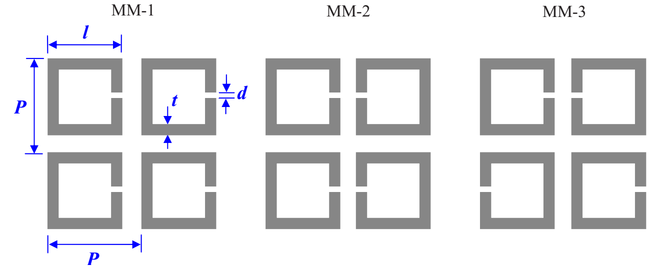

FIG. 1. (Color online) Arrangement of supercells MM1–MM3 with lattice constant $P=50$ μm.

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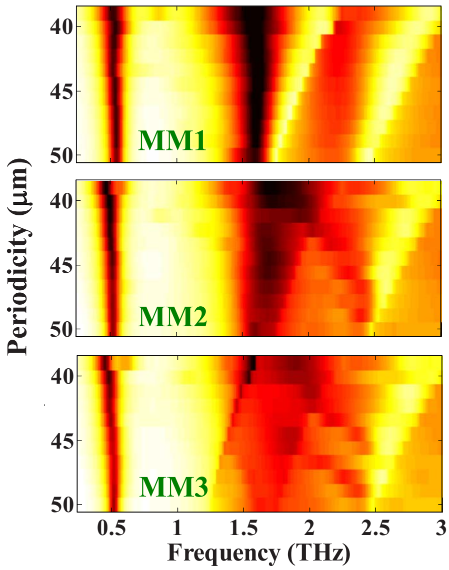

FIG. 2. (Color online) Simulated transmission of samples MM1, MM2, and MM3 as a function of the periodicity for an incident E-field perpendicularly polarized to the gap-bearing sides of the SRRs.

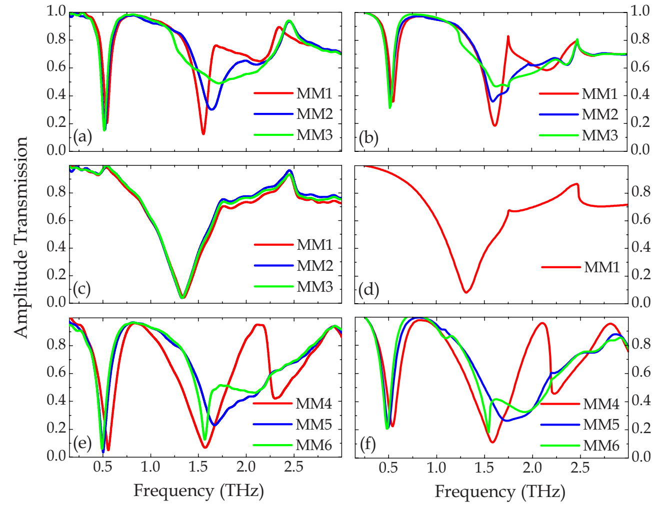

FIG. 3. (Color online) (a) Measured and (b) simulated transmission spectra of samples MM1–MM3; the incident E-field is polarized perpendicular to the gap-bearing sides of the SRRs. (c) Measured spectra of MM1–MM3 and (d) simulated spectrum of MM1 with the incident E-field polarized parallel to the gap-bearing sides. (e) Measured and (f) simulated spectra of MM4–MM6.

Six samples of planar SRRs (denoted in the following as MM1–MM6) of 200 nm thick Al metal rings were fabricated by conventional photolithography on a silicon substrate (0.64-mm-thick, n-type resistivity 12 Ω cm). As shown in Fig. 1, MM1–MM3 are single ring SRRs with lattice constant $P=50$ μm. The distribution of the gaps can be deduced from the figure and corresponds to the scenarios as described before. MM4–MM6 are single ring SRRs with the same symmetry as MM1–MM3 but with reduced periodicity of $P=39$ μm. The dimensions of all SRRs are $t=6$ μm, $l=36$ μm, and $d=2$ μm.

The exact parameters of the fabricated samples were motivated from numerical simulations of the optical response of the devices. Simulations were done with the Fourier modal method.[10] All geometrical parameters of the system were taken into account. Figure 2 shows the transmission for the three configurations as a function of the period and the frequency. In all cases the incident E-field is polarized perpendicular to the gaps. The main peculiarities we can elucidate and which we will discuss in depth once the experimental results are shown as the following: (1) the impact of the configuration, (2) the impact of the period for each configuration on the spectral positions and the widths of the resonance, and (3) the occurrence of coherent phenomena once SRRs are closely spaced. In the physical interpretation we subsequently provide we rely mainly on the selected experimental configurations. The transition between the different scenarios can be inferred from this simulation.

A broadband terahertz time-domain spectrometer is employed to characterize the transmission properties of the fabricated SRR arrays. The terahertz beam illuminates the samples at normal incidence.[11] The reference is a blank silicon slab identical to the substrate. The transmission is extracted from the ratio of the amplitude spectra of the samples.[12] The measured amplitude transmission of MM1–MM3 is shown in Fig. 3(a). The two significant dips in transmission are traces from the two lowest order odd eigenmodes. Significant differences in the spectra are observed depending on the orientation of the gap of neighboring SRRs.

When comparing the resonances of MM2 with those of MM1, it can be seen that the LC resonance at 0.5 THz is redshifted by 20 GHz and the transmission is reduced by 4%. Contrary, the next higher order odd resonance at 1.5 THz broadens significantly, blueshifts by 84 GHz, and the transmission increases from 12.5% for MM1 to 30.1% in MM2. Furthermore, the orientation of the SRRs in the supercell for MM3 causes only a marginal additional redshift of the lowest order eigenmode by 8 GHz and nearly no change on transmission. On the contrary, the next higher order resonance suffers from a severe broadening and a significant increase in transmission up to 49%. The simulated spectrum in Fig. 3(b) is in perfect agreement with the measurement.

For an incident E-field parallel to the gap-bearing sides the response of MM1–MM3 is shown in Fig. 3(c). Independent of the arrangement all spectra show a strong resonance at 1.33 THz and have nearly the same spectral dependency. Exactly the same observation is made in the simulation. As the spectra are indiscernible, Fig. 3(d) shows only the simulated spectra for MM1. This resonance is the lowest order even eigenmode.

The transmission spectra for MM4–MM6 are shown in Fig. 3(e). The incident E-field is polarized perpendicular to the gap. Due to reduced periodicity and high density of SRRs we observe a different spectral behavior in comparison with the samples MM1–MM3. In MM4 there are three distinct resonances, the LC resonance at 0.556 THz with a linewidth of 167 GHz, the next higher order odd eigenmode at 1.57 THz with a linewidth of 494 GHz, and a third strong resonance at 2.3 THz. This resonance, however, is a Wood anomaly in the substrate. This resonance is of no particular interest for the present study and will not be discussed further. In MM5 the lowest order odd eigenmode appears redshifted by 54 GHz and has a reduced linewidth of 125 GHz when compared to MM4. The next higher order odd eigenmodes is broadened and blueshifted by 100 GHz. In MM6 the lowest order odd eigenmode is again only marginally further redshifted by 11 GHz. The linewidth is reduced to 115.5 GHz. Finally and potentially most interesting, the next higher order odd eigenmode appears as an extremely sharp feature with a linewidth of only 69.5 GHz; resonating approximately at the same frequency as the higher order odd eigenmode of MM4. The resonance has a high Q-factor of 18.5. This is essential to achieve high sensitivity in planar terahertz MM sensors as sensitivity increases with the sharpness of the spectral resonance feature. In Fig. 3(f) the simulation of the experimental situation agrees nearly perfectly with the measurements. Upon illuminating the samples with an E-field polarized parallel to the gap, again no influence of the SRR arrangement on the spectral response was observed.

To explain the influence of the arrangement on the spectral properties of the lowest order eigenmode one may evoke analogies to transmission line theory. Placing SRRs like in MM2 and MM4 will cause an increase in the effective capacitance as the next neighbor in such situation provides a parasitic capacitance in parallel. The increase in effective capacitance causes a reduction in the eigenfrequency and a decrease in radiation losses, hence decreasing the linewidth. If furthermore, as in the transition from MM2 to MM3 or MM5 to MM6, the SRRs in the direction parallel to the gap have an alternating orientation, the parasitic capacitance in parallel is reduced, hence increasing furthermore slightly the effective capacity of the SRR. Nevertheless, the impact of this rearrangement is not as pronounced, as only a marginal further reduction in the resonance frequency and the linewidth for this second transition can be seen.

Seemingly, for the second resonance the placing of the gap on either side of the SRR has no influence. This is perfectly explainable as this mode is dominantly characterized by oscillating currents in the side arms of the SRR that have no gap. Therefore, no modification of the resonance conditions for the SRR is neither observed nor expected.

For the third resonance, being the second order odd eigenmode, the situation is more involved, as seemingly the resonance shape and position depend on the chosen period and consequently on the absolute distance between neighboring SRRs. By taking into account that the resonance wavelength is comparable to the chosen interparticle distance, we presume that the coherent superposition of the scattered field by neighboring SRRs causes the strong modification of the transmission in this spectral domain. The formation of a subradiant and a superradiant type mode, depending on the interparticle distance and the gap orientation, causes a blueshift or a redshift of the resonance.[13] The superradiant (subradiant) mode also increases (decreases) the radiation losses in the excited eigenmode which leads to a broadening (narrowing) of the spectral resonance as encountered. The resulting strong dependence of the transmission spectrum on the periodicity was already seen in Fig. 2 where these effects are particularly pronounced for the structures described as MM2 and MM3.

To summarize, we have investigated the impact of gap orientation of neighboring SRRs on the spectral properties of the resonances that are excitable in such systems. It was shown that by choosing an appropriate orientation the lowest order eigenmode is shifted toward lower frequencies and suffers from a decrease in radiation losses, causing the linewidth to be much narrower. The effect was explained in terms of an increase in the effective capacitance of the SRR. As this resonance is usually used to evoke a strong dispersion in the effective permeability, the approach might open an avenue toward MMs with an even stronger material dispersion at a better ratio of resonance wavelength over a period by fabricating SRRs with nominally the same size. It was furthermore shown that potentially due to a strong coherent coupling between the fields scattered by neighboring SRRs at the next higher order odd eigenmode, the resonance experiences a significant reshaping depending on the distance, and sharp spectral features do occur. Such sharp resonant features, obtained due to coupling in MMs, can open up possibilities for the use of MMs as highly efficient sensing devices and also provide a better understanding of SRR arrays with different symmetry layouts.[14] Overall, resonance coupling reveals a method to engineer the MM spectrum in a controlled and predictable way across the entire electromagnetic spectrum. Manipulation of spectral properties of MMs in terahertz domain would ensure the rapid development of terahertz photonics and would lead to design of terahertz devices.

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