Adjusting the functionality of terahertz split-ring resonators through geometry

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ABSTRACT

We examine planar double split-ring resonators (SRRs) consisting of two concentric rings with either opposite, similar, or asymmetric gap orientation. Depending on the geometry we observe resonance hybridization, metamaterial induced transparency, or the excitation of dark resonances. These properties can be used for SRR based sensing applications, to realize strongly dispersive behavior, or for determining the optical properties of metals. We further find that THz SRRs featuring very narrow gaps on the micro- or nanoscale can provide in-gap enhancement factors of several 10,000, a property particularly useful for the realization of nonlinear THz experiments.

Keywords: THz radiation, metamaterials, split-ring resonators

1. INTRODUCTION

In recent years significant research has been stimulated towards the development of a novel class of materials which may exhibit intriguing optical properties such as negative refractive indices\textsuperscript{,1} perfect lensing\textsuperscript{,2} or invisibility cloaking\textsuperscript{,3} These metamaterials are artificial structures that consist of arrays of subwavelength electromagnetic resonators. One of the most prominent examples is a metallic ring with a gap, the so called split-ring resonator (SRR).\textsuperscript{4} Using an incident electromagnetic wave for excitation, SRRs can exhibit several resonant responses where a combination of charge accumulation and current flow of increasing order are excited on the structure.\textsuperscript{5}

Due to the great number of potential applications, it is of considerable interest to tailor metamaterials and gain control over the spectral position and line width, as well as the type of the resonance. In this work we investigate the response of planar double split-ring resonators (DSRRs) consisting of two concentric rings with either opposite, similar, or asymmetric gap orientation. Our results show that depending on the relative gap orientation completely different response characteristics are obtained so that the metamaterial functionality can simply be adjusted through the DSRR geometry. In addition we show that THz SRRs featuring very narrow gaps on the micro- or nanoscale can be used as field enhancing devices providing huge in-gap field enhancement factors.

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Figure 1. (a) Geometry of the oppositely oriented DSSR structure under study. Total energy density integrated over the outer and inner ring for (b) \( s = 70 \mu m \), (c) \( s = 32.5 \mu m \), and (d) \( s = 5 \mu m \). The dashed vertical lines mark the resonance frequencies of single rings with corresponding dimensions. Out of plane electric field component in a plane 15 \( \mu m \) above the SRR at the (e, g) lower and (f, h) higher resonances of the \( s = 70 \mu m \) (top row) and \( s = 5 \mu m \) (bottom row) structures.

2. RESULTS

2.1 DSRRs with 180° relative ring orientation

In order to tailor the metamaterial response different concepts have been suggested. These include simple size scaling of the SRR’s dimensions,\(^6\) using photo- or electro-active substrates for actively controllable elements,\(^7, 8\) or introducing a coupling between the individual eigenmodes of neighboring SRRs.\(^9, 10\) The latter is based on resonance hybridization, a concept originally observed in closely spaced metallic nanostructures where the coupling between the plasmon eigenmodes results in a new set of hybrid resonances characterized by symmetric or antisymmetric distributions of the induced surface charges.\(^11\) Using this concept Li and coworkers\(^12\) have shown that very narrow resonances may be realized in bilayered double SRR systems with 180° relative ring orientation. Since bilayered systems are rather difficult to fabricate it is of great interest to investigate whether a similar behavior may be obtained using a corresponding DSRR structure with a planar geometry. We therefore start by numerically investigating the response of DSRRs as shown in Fig. 1(a) using finite element method (FEM) modeling.\(^13\) Whereas the outer side length is kept constant at \( l_o = 500 \mu m \) the inner side length is increased in steps from \( l_i = 300 \mu m \) to \( l_i = 430 \mu m \). The other dimensions are \( d = 100 \mu m \), \( w = 30 \mu m \), and \( t = 9 \mu m \). The \( k, E \), and \( H \) triad of the incoming light field is oriented relative to the structure as indicated in Fig. 1(a). In Fig. 1(b) we plot the total energy densities integrated over the volumes of the outer ring (black line) and inner ring (red line) obtained for a structure with large ring separation (\( s = 70 \mu m \)). Two resonances at frequencies of 78 GHz and 165 GHz are observed where the lower resonance is mainly located on the outer and the higher resonance on the inner ring.\(^14\) A slight coupling is introduced between the two rings so that the energy density in the inner ring is increased at the outer ring’s resonance and vice versa. When the ring separation is decreased, as shown in Fig. 1(b)–(d), the coupling becomes stronger such that, for the smallest ring separation (\( s = 5 \mu m \)), the energy densities in the inner and outer ring show an almost complete overlap. Guo and coworkers\(^15\) have already shown that for the structures under study mode hybridization is exhibited where the resonances at the lower and higher energies are assigned to symmetric and antisymmetric current flows on the two rings. These results are reproduced by our simulations as can be seen from Fig. 1(e)–(h). The plots show the out-of-plane electric field component \( E_z \) above the SRR at the two resonances for the structures shown in Fig. 1(b) and (d). At the fundamental resonance circulating currents are excited that lead to a build up of charge across the gap.\(^16\) These charge accumulations are directly reflected in the field distribution of the \( E_z \) component. Whereas at the lower resonance the circulating currents in the two rings both oscillate in same rotational direction they oscillate in opposite directions at the higher resonance as indicated by the arrows. One of the main consequences of mode hybridization is that the new set of eigenmodes is frequency shifted from the resonance positions of the uncoupled elements.\(^15\) This behavior can be seen in Fig. 1(b)–(d) where the dashed vertical lines mark the resonance frequencies of single rings with...
corresponding dimensions which were obtained from separate simulations. For increasing coupling, the lower (symmetric) resonance is redshifted whereas the higher (antisymmetric) resonance is blueshifted as indicated by the blue arrows. In analogy to the bilayered DSSR system we additionally observe a significant sharpening of the symmetric resonance peak which is explained by a mutual cancelation of the electric dipole moments associated with the two rings.\(^{12,17}\) Such sharp resonances are of particular interest for the realization of low loss metamaterials since for frequencies shifted away from the resonance position the imaginary part of the material parameters decays faster than the real part.\(^{18}\) In addition high quality resonances are also very beneficial for increasing the obtainable sensitivity in SRR-based sensing applications.\(^{19}\)

### 2.2 DSRRs with 0° relative ring orientation

We continue by investigating the response of DSRR samples with similarly oriented rings. Figure 2(a) shows a microscope image of a corresponding complimentary structure which was fabricated by laser machining into a 10\(\mu\)m thick copper foil. A simulated transmission spectrum for a corresponding positive sample is shown as the black line in Fig. 2(b). The dashed red and blue lines are the transmission curves of single SRRs with corresponding dimensions. It has been shown previously that for single SRRs under the given excitation scheme, only those resonances can be excited that feature an odd number \(j = 1, 3, \ldots\) of nodes between the charge accumulations induced on the ring.\(^{5}\) Here, the \(j = 1\) and \(j = 3\) resonances located on the outer (\(O\)) and inner (\(I\)) ring fall within the frequency range considered. The single ring resonances are correspondingly denoted by \(O_j\) and \(I_j\). Evidently, the spectral positions of the resonances exhibited by the DSRR and the single rings overlap. Thus, the spectral splitting associated with mode hybridization that was exhibited by oppositely oriented DSRRs is not observed for the 0° relative ring orientation case. However, another interesting observation can be made. At frequency positions in between the resonance pairs, the green arrows mark the intersection of the outer and inner ring’s transmission curves, whereas the black arrows mark the transmission maxima of the DSRR structure. Significantly higher transmission values are obtained for the DSRR than for the combined transmission of the single rings. This behavior has previously been observed in other metamaterial geometries\(^{20}\) and can be considered as an analogue to the quantum phenomenon of electromagnetically induced transparency (EIT).\(^{21}\) The concept involves Fano resonances where destructive interference between the radiation scattered from neighboring subunits oscillating in antiphase leads to very sharp transmission peaks. The transmission maxima marked by the black arrows can therefore be understood as induced transmission resonances sandwiched between two absorption peaks and are denoted \(T_1\) and \(T_3\), respectively. In Fig. 2(c), we show the transmission spectrum of the fabricated DSRR sample as recorded using THz time-domain spectroscopy (THz TDS).\(^{22}\) For the measurement, a complementary sample was chosen because it allows for easier fabrication and higher structure-fidelity, an important requirement for array samples. According to Babinet’s principle, original and complementary structures exhibit the same response, only that transmission and reflection are interchanged and that the incident field needs to be rotated by 90° around the wavevector axis.\(^{23}\) At low frequencies, the \(O_1\) and \(I_1\) modes could not be resolved separately, which is explained through the limited frequency resolution of our spectrometer (\(\Delta\nu = 12\) GHz). For \(j = 3\), however, the resonances are wider so that the double resonance character could clearly be resolved. Though not shown here, we have also employed an electrooptic THz near-field imaging approach\(^{24}\) which allowed us to directly resolve the antisymmetric mode profile with the subunits oscillating in antiphase which gives rise to the induced transparency window.\(^{25}\) The closely spaced sequence of absorption and transmission peaks can be
used for filtering or sensing applications, whereas the strongly dispersive behavior accompanying the induced transparency can lead to unusual optical properties such as slow light propagation.

### 2.3 DSRRs with 90° relative ring orientation

Since both the 180° and the 0° ring orientation cases have yielded intriguing and differing optical behaviors it is also of interest to investigate the remaining asymmetric (90°) case. Figure 3(a) shows a microscope image of an asymmetric DSRR structure which was fabricated through laser machining of a 10 µm thick copper foil. The red curve in Fig. 3(b) shows the transmission spectrum simulated for a corresponding but slightly smaller structure. Various absorption peaks are observed which again correspond to the different order resonances excited on the structure. The two low frequency peaks are of particular interest since they exhibit very narrow line widths. This behavior is in analogy to the results obtained for oppositely oriented DSRR structures in the strong coupling regime. However, a few differences should be pointed out. The ring separation of the asymmetric DSRR sample under study is still rather large and the second resonance is seen to be even sharper than the first. From the simulation we find that mode hybridization is not observed and that the two peaks correspond to the fundamental resonances located on either the outer or the inner ring. This is illustrated in Fig. 3(c) and (d) which show the out-of plane electric field component at the two resonance frequencies. With the given excitation scheme the lowest order resonance can in principle only be excited on the outer ring. This resonance can therefore be considered bright and is labeled B-mode, whereas the resonance associated with the inner ring is dark and is correspondingly labeled D-mode. In the asymmetric DSRR, however, the presence of the outer ring breaks the symmetry so that the fundamental resonance can also be excited on the inner ring. The solid black line in Fig. 3(e) shows the experimentally recorded transmission of the fabricated sample in the frequency range of interest. The data was recorded using a vector network analyzer (VNA) based setup which is able to provide a very fine frequency resolution (\(\Delta \nu = 0.05\) GHz). The dashed red line represents a corresponding simulation. Evidently, the sharp dark resonance is resolved in both the measurement and the simulation. We have additionally fabricated such asymmetric DSRR structures as complementary samples and a corresponding measurement is included in Fig. 3(b) as the black squares. These data points were recorded using a THz TDS approach (\(\Delta \nu = 4\) GHz). Interestingly all spectral features except for the D-mode could be reproduced by the measurement. The transmission was also analyzed using the VNA setup which verified that the absence of the D-mode is not linked to the limited spectral resolution. Employing additional simulations where we varied the metallic properties, we found that for positive samples the transmission is nearly independent of the conductivity whereas for complementary samples, the presence and amplitude of the D-peak depends strongly on the conductive properties. Babinet’s principle, which is valid only for perfectly conducting structures, can therefore not be applied. In the THz frequency range metals are often considered as ideal conductors. Our results, however, suggest that for copper this might not be the case. The low frequency optical conductivity of metals is usually obtained through ellipsometry or Kramers-Kronig analysis of the normal incidence reflectivity. In a very good metal like copper, however, it is tremendously difficult, if not impossible, to obtain the correct absolute value of the reflectivity at THz frequencies because the sample itself behaves as an almost ideal mirror. This prevents the analysis of very subtle deviations from the ideal metal description of these systems. The spectral width of SRR resonances generally depends on ohmic as well as radiation damping. In the THz range,
Figure 4. (a) Geometry of the micro- and nanogap SRR structure under study. Field enhancement in mid-gap versus frequency for SRRs with (b) 100 µm, (c) 10 µm, and (d) 1 µm gap width. (e) Mid-gap field enhancement at resonance as a function of resonance wavelength divided by gap width. (f) Mid-gap field enhancement of \(d=1\) µm SRR under combined \(E\)- and \(H\)-field excitation and only \(E\)-field excitation.

due to the large conductivity, the ohmic contribution is very small so that the line width is determined almost exclusively through radiation damping. For the very sharp dark resonances observed in the asymmetric DSRR geometry, however, radiation damping is suppressed. Thus, ohmic damping is the only remaining loss channel so that asymmetric DSRRs may be used to investigate the optical properties of metals. This is of particular interest in respect of recent results where a significant contribution of electron-electron interactions to the optical scattering rate have been reported.\(^{27}\) We note that even in noble metals such as gold deviations from the ideal conductor description have been observed.\(^{28}\)

2.4 THz SRRs with micro- or nanogaps

Whereas in the previous sections we have investigated coupling effects between the subunits in DSRRs we are considering single SRRs in this section. One of the major and yet unmet limitations of THz technologies is that, compared to the optical regime, the pulse energies supplied by current THz sources are still rather limited. This is particularly problematic for the realization of nonlinear THz experiments which have been a topic of considerable interest in recent years and where the quantity of interest is essentially the electric field strength \(E\). It was recently suggested that metallic nanoslit structures may act as field enhancing devices that collect the incident radiation and focus it in subwavelength volumes.\(^{29,30}\) THz radiation being incident onto the structure can induce a current flow on the metal surface that leads to an accumulation of charge carriers in the gap region. This capacitive charging in turn results in an in-gap enhancement of the electric field by orders of magnitude. For a 70 nm wide slit and a frequency of 0.1 THz, field enhancement factors on the order of 1,000 were reported.\(^{29}\) In order to increase the obtainable field enhancement even further we suggest to use THz SRRs which, compared to their side length, feature extremely small gaps on the micro- or nanoscale as schematically illustrated in Fig. 4(a). The response of such structures is investigated numerically and the structure dimensions were set to \(L=300\) µm, \(w=5\) µm, \(t=1\) µm, and the gap width \(d\) was varied from 100 µm down to 100 nm. We start by considering \(E\)-field excitation where the \(E\), \(H\), and \(k\) triad of the incoming field is oriented along the \(x\), \(y\), and \(z\) axes. In Fig. 4(b)–(d) we exemplarily show the in-gap field enhancement obtained for three SRRs with decreasing gap width. Within the considered frequency range the curves exhibit a single peak corresponding to the fundamental SRR resonance. For decreasing \(d\) the in-gap field strength is significantly enhanced and the field enhancement is found to scale linearly with the ratio \(\lambda_r/d\) where \(\lambda_r\) denotes the wavelength at resonance. This is shown in Fig. 4(e) where the red line is a linear fit to the data points. For the smallest considered gap width of \(d=100\) nm giant enhancement factors approaching 40,000 are obtained which is more than an order of magnitude larger than the maximum field enhancement obtained for the nanoslits. This is explained by the resonant behavior where the oscillating currents excited in the SRR are much stronger than the non-resonant current flow induced on the metallic surface of the slit structures. It has been shown previously\(^{31}\) that the fundamental SRR resonance may be excited more strongly using a combined \(E\)- and \(H\)-field excitation where the \(E\), \(H\), and \(k\) triad is oriented...
along the $x$, $-z$, and $y$ axes. For this excitation scheme the in-gap field enhancement can be increased even further. This is exemplarily shown in Fig. 4(f) for a SRR with $1\mu m$ gap width. By simply rotating the structure the peak values of the in-gap fields can approximately be increased by another factor of 1.3. Though not shown here, we have also investigated the obtainable nonlinearity from such structures by exemplarily considering a second harmonic generation process.

3. CONCLUSION

We have investigated the response of double split-ring resonators with $180^\circ$, $0^\circ$, and $90^\circ$ relative ring orientation. For the different geometries, completely different functionalities were obtained. For oppositely oriented DSRRs, we observed the emergence of hybridized modes featuring very narrow line widths, a property particularly beneficial for SRR based sensing applications. Similarly oriented DSRRs yielded a behavior reminiscent of electromagnetically induced transparency. A closely spaced sequence of absorption and transmission peaks was obtained which is associated with a strongly dispersive behavior and may be used to realize unusual optical properties such as slow light propagation. For asymmetric DSRRs, on the other hand the excitation of very sharp dark resonances was observed which are characterized by a suppression of radiation damping. The shape of the resonance peak is therefore mainly determined by ohmic damping which in turn allows for sensing of the metal’s optical properties. For complementary DSRRs made from copper, a deviation from the predictions of the Drude model is observed indicating that the often employed assumption of infinite conductivity does not hold. These structures hold great promise as sensitive tools for investigating the optical properties of metals at THz frequencies. The response of single SRRs featuring very narrow gaps on the micro- or nanoscale were also analyzed and it was shown that these structures may act as field enhancing devices providing in-gap enhancement factors of several 10,000. This property is particularly useful for the realization of nonlinear THz experiments.

ACKNOWLEDGMENTS

This work was funded by the Swiss National Science Foundation project 200020-119934

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