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Lattice induced modulators at terahertz frequencies

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Abstract

We measured the transmission spectra of an array of split-ring resonators up to 10 terahertz for parallel and perpendicular polarizations. Calculations of the lattice and plasmon mode dispersion relations in combination with electromagnetic simulations confirm the presence of multiple higher order lattice and plasmon modes. We modify the quality factor of higher-order plasmon resonances by modulating the lattice-plasmon mode coupling via changes in the period of the array. We also propose single frequency switches and a broadband dual-state amplitude modulator based on structured illumination that actively modifies the period of the splitting resonator array.

Keywords

(240.6680) Surface Plasmons; (160.3918) Metamaterials; (260.5740) Resonance; (040.2235) Far Infrared or Terahertz; (300.6495) Spectroscopy, terahertz

Metamaterials are man-made composite materials designed to have specific electromagnetic (EM) properties that go beyond those found in naturally occurring materials, allowing them to manipulate EM waves in novel ways [1–5]. Metasurfaces, two dimensional metamaterials, have been identified as a promising technology to develop components to control and manipulate light at terahertz (THz) frequencies (0.1 – 10 THz; 3000 – 30 μm) [6–8]. Although multiple applications have been identified for this frequency range, the lack of THz components has limited their development [9–12].

The most common implementation of a metasurface utilizes a periodic array of metallic square split-ring resonators (SRRs) distributed on the surface of an insulator matrix, where the periodicity is smaller than the wavelength of operation. When illuminated at normal incidence, the transmission through the metasurface exhibits a series of resonant peaks which may be interpreted as resulting from collective excitations of the electrons in the metallic resonator units, i.e. standing-wave plasmon modes [13–16]. The plasmon resonant frequencies are found from

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$$v_m = \frac{c}{n} \left[\frac{m}{2L} \right] \quad (1)$$

where c is the speed of light in vacuum, n is the index of refraction, m is an integer that describes the plasmon mode, and L is the length of the resonator. Electric fields (E-fields) polarized perpendicular or parallel to the gaps in the SRRs excite odd or even modes.

When the wavelength of light illuminating a periodic array is longer than a certain wavelength, known as the Rayleigh cutoff wavelength, the diffracted beams propagate along the surface of the substrate, interacting with many resonators and giving origin to a lattice mode [17, 18]. There are two types of Rayleigh cutoff wavelengths; one corresponds to the air to substrate mode (air mode) and the other is the substrate to air mode (substrate mode). For a rectangular array with periodicities given by p_x and p_y the lattice mode frequencies are given by

$$v_{ij} = \frac{c}{n} \sqrt{i^2 \left(\frac{1}{p_x} \right)^2 + j^2 \left(\frac{1}{p_y} \right)^2} \quad (2)$$

where (i,j) is a pair of integers identifying the diffraction order, and n is 1 for the air mode or the index of refraction of the medium for the substrate mode. When the resonant frequency of the lattice mode is close to that of a plasmon resonance, the two modes can interact resulting in an increase in the quality (Q) factor of the plasmon resonance; $Q = \omega_0 / \text{ff}$ where ω_0 is the resonant frequency and ω is the full width at half maximum [19–21].

Most passive and active THz devices based on metasurfaces demonstrated to date, make use of the lowest order plasmon modes and/or their interaction with the first-order lattice mode [22–28]. In this letter, we present a procedure to identify higher order plasmon and lattice modes of a SRR array over a 10 THz range by utilizing experimental data in combination with eqs. (1) and (2), the S-parameters and the E-field distributions obtained from EM simulations. In simulations we modify the Q-factor of higher-order plasmon resonances by modulating the lattice-plasmon mode coupling strength via changes in the lattice period. Finally, we demonstrate switches and a broadband dual-state amplitude modulator by actively modifying the period of the array.

We fabricated a SRR array out of 200 Å Ti/500 Å Au on a low-stress, free-standing, thin silicon nitride (Si_3N_4) membrane as detailed in [29, 30]. In brief, standard photolithography and reactive ion etching were used to open four Si_3N_4 -free windows on the back side of a 4'' silicon wafer fully coated with Si_3N_4 . Metasurfaces were fabricated on the front side using standard photolithography. The wafer was mounted in a wafer holder designed to protect the front while a KOH bath was used to selectively remove the silicon substrate within the Si_3N_4 -free windows on the back. This results in metasurfaces patterned onto four large-area, 1 µm thick free-standing Si_3N_4 windows. The thin membrane allows us to extend the

characterization spectral range to 10 THz without having Fabry-Perot effects modulating the baseline transmission value.

The transmission spectra of the SRR array was measured using terahertz time domain spectroscopy (THz-TDS) and a Fourier transform infrared (FTIR) spectrometer equipped with THz optics [29]. The top (bottom) panel in Fig. 1 shows the transmission spectra when the E-field was polarized along x , i.e. perpendicular to the gap (along y , i.e. parallel to the gap). Below 4 THz the transmission spectra for both polarizations is notably different presumably because the resonances originate from plasmon modes of the SRR. Between 4 and 6 THz there are some features that occur at the same frequency locations for both spectra while others do not, indicating that they have different origins. Above 6 THz the features observed appear in both spectra, leading us to speculate that they originate from the periodicity of the array. Note that, as the frequency increases above 4 THz, the wavelength decreases becoming smaller than the period and, eventually, smaller than the size of the SRRs. In this situation the array starts to behave as a collection of individual scattering elements and can no longer be described by the effective medium approximation.

In order to identify the physical phenomena responsible for the resonances observed, we performed EM simulations and obtained the S-parameters and E-field distributions of the SRR. We used a commercial-grade simulator based on the finite-difference time-domain (FDTD) method [31]. The simulated SRR had the same dimensions as in Fig. 1 and was assumed to be made of 50 nm of gold on a $1\text{ }\mu\text{m}$ Si_3N_4 substrate. The dielectric parameters for gold were taken from [32] while constant values of 7 and 0 were used for the dielectric permittivity and loss tangent of the Si_3N_4 membrane [30, 33]. The incident THz pulse was normal to the plane containing the SRR, covered a spectral range of 0.1 – 10 THz, and was linearly polarized perpendicular or parallel to the gap. The boundary conditions used were periodic in the plane of the resonator and a Perfectly Matched Layer in the propagation direction to reduce reflections from the THz source.

Results for the magnitude of the near-field E-field in the propagation direction for the resonances indicated in Fig. 2 are presented in Fig. 3. Fig. 3(a) shows that the E-field distribution is localized along the metallic resonator, indicating that they correspond to collective excitations of the electrons. The number of nodes in the E-field distribution are correlated to the order of the plasmon mode. By counting the number of nodes in the E-field distribution, we assign the mode order to the corresponding resonances in the S21 parameter, Fig. 2.

The lower two rightmost images in Fig. 3(a) correspond to the plasmon excitation of the wires that form the sides of the SRR parallel to the direction of the polarization vector - labeled wires in Fig 2. They have slightly different resonant frequencies because when the E-field is perpendicular to the gap one of the wires has a gap that shifts the resonant frequency to higher values relative to the opposite orientation where there is no gap. We confirmed this assignment by simulating the E-field distributions for two parallel wires with the same dimensions and period (data not shown).

We used the S_{21} plasmon mode assignments and resonant frequencies as a guide to assign the plasmon mode order to the experimental resonances, Fig. 1. By substituting the mode order and the corresponding experimental resonant frequencies into eq. (1), we obtained the effective index of refraction of the membrane-SRR combination. And by using eq. (1) we identified the experimental resonance at 4.17 THz as the 8th plasmon mode. Therefore, we have identified up to 8 plasmon modes in the experimental transmission spectra of a SRR array - more than previously reported [28].

The wire resonances are also evident in the experimental results. However, the difference between the resonant frequencies for the two polarizations was larger than expected. This difference can be explained by an x - y asymmetry in the fabricated sample that was confirmed by visual inspection. We speculate that this asymmetry may also be responsible for being able to observe the 8th plasmon resonance in the transmission spectra but not in the simulations, which utilize perfectly symmetric devices.

The E-field distributions for the ~ 4 , 7.5 and 8.5 THz resonances for both polarizations show a different picture, Fig. 3(b) top to bottom. The E-fields are found in the non-metallic regions of the resonator and extend outside to the neighboring resonators in the direction parallel to the polarization vector. Therefore, the corresponding resonances involve the whole array allowing us to identify them as lattice modes.

Using eq. (2) with $n = 1$ for air and $p_x = p_y = 75 \mu\text{m}$, we calculated the lattice mode resonant frequencies for various index combinations. The resonance positions are in close agreement with the simulation results for the (1, 0) and (0, 1) modes. The slight difference between the corresponding experimental resonant frequencies can be explained by the asymmetry in the fabricated devices. There is a more significant difference between the frequency location of the resonances above 5 THz obtained from eq. (2), those observed in the simulations and the experiments, resulting in an ambiguity in the index assignments. The differences between the S_{21} parameter and the transmission spectra could be due to differences between the ideal, simulated devices and the imperfect, fabricated ones, the values used for the dielectric permittivity of the membrane and limited resolution in the modeling of thin membranes.

We performed a range of simulations in which we varied the period from 65 to 150 μm with the goal of confirming the mode assignments and the potential to modify the Q-factor of higher-order plasmon resonances by modulating the lattice-plasmon mode coupling strength. The resulting set of S_{21} spectra show that the location of the lowest order plasmon modes (< 3) does not change significantly as the period changes but the location of the lattice mode resonance does (data not shown). However, modifying the period resulted in a narrowing of some of the plasmon resonances, Figs. 4(a) and 4(b). For the 65 μm period (dashed lines), the frequency location of the first order air lattice mode is more than 0.5 THz higher than that of the plasmon mode. As the period increases, the separation between the two resonances decreases, resulting in an increase of the Q-factor (solid lines) due to an increase in the lattice-plasmon mode coupling. As the period increases further, the first order air lattice mode moves below the plasmons' resonant frequency and the Q-factor of the resonance decreases (dotted lines). For plasmon modes 6 and 7, the Q-factor increased $>70\%$ in going from a 65 to a 75 μm period, Fig. 4(c). This provides an avenue to control the

Q-factor of a higher order plasmon resonance by incorporating the effect of the lattice-plasmon mode coupling into the metasurfaces' design.

The observation that varying the period modifies the spectra can be the basis for active amplitude modulation devices. Consider a square array of SRRs with a periodicity of 75 μm fabricated on a photoconductive substrate. Using structured illumination with visible light, we can illuminate every other column and every other row of the array exciting the free carriers in the photoconductive substrate [34–37]. The carriers modify the local conductivity and effectively short out the gaps in the SRRs. This translates into generating an array with a unit cell consisting of a square of 3 continuous rings and one SRR spaced 150 μm , see inset in Fig. 5(c).

The S_{21} spectra of the unilluminated SRR array for the E-field polarized perpendicular to the gap shows a featureless transmission in the 3.1 to 3.5 THz range, dark blue line in Fig. 5(a). However, the S_{21} spectra of the structurally illuminated array shows a resonant response centered at 3.29 THz, light blue line. Therefore, by illuminating every other row and every other column we can go from 97% to 25% transmission at 3.29 THz, effectively producing a switch with an ON/OFF ratio of ~ 4 , Fig. 5(a). Similarly, we can produce a switch at 3.71 THz with an ON/OFF ratio of ~ 3 , Fig. 5(b). The S_{21} spectra of the unilluminated SRR array shows a featureless transmission in the 4.1 to 4.8 THz range with an average of $(62 \pm 0.2) \% = (\text{mean} \pm \text{S.D.}) \times 100$, Fig. 5(c). Within that same frequency range, the spectra of the structurally illuminated array is similarly featureless but with an average transmission of $(90 \pm 0.3) \%$. Therefore, we can increase the transmission amplitude of all frequencies within that frequency range by about 45% by using structured illumination, effectively producing a dual-state broadband amplitude modulator with a 0.7 THz bandwidth.

In summary, by reducing the substrate thickness we measured, analyzed and characterized higher order plasmon and lattice modes than previously reported. In simulations, we varied the period to alter the lattice-plasmon mode coupling strength and modify the Q-factor of the higher-order plasmon resonances, providing an avenue to extend the range of application of THz metasurfaces that require narrow resonances to higher frequencies. We proposed a scheme to actively modify the period of an array to implement switches and a dual-state broadband amplitude modulator. This proposal highlights the possibility of actively modulating the metasurfaces' response by modifying the period using structured illumination. The results presented in this letter can be applied to other periodic systems and can be extended to other frequency ranges.

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References

1. Smith DR, Padilla WJ, Vier DC, Nemat-Nasser SC, and Schultz S, *Physical Review Letters* 84, 4184–4187 (2000). [PubMed: 10990641]
2. Pendry JB, Holden AJ, Robbins DJ, and Stewart WJ, *IEEE Transactions on Microwave Theory and Techniques* 47, 2075–2084 (1999).
3. Pendry JB, and Smith DR, *Scientific American* 295, 60–67 (2006).
4. Shelby RA, Smith DR, and Schultz S, *Science* 292, 77–79 (2001). [PubMed: 11292865]
5. Schurig D, Mock JJ, Justice BJ, Cummer SA, Pendry JB, Starr AF, and Smith DR, *Science* 314, 977–980 (2006). [PubMed: 17053110]
6. Siegel PH, *IEEE Transactions on Microwave Theory and Techniques* 50, 910–928 (2002).
7. Hosako I, Sekine N, Patrashin M, Saito S, Fukunaga K, Kasai Y, Baron P, Seta T, Mendrok J, Ochiai S, and Yasuda H, *Proceedings of the IEEE* 95, 1611–1623 (2007).
8. Tonouchi M, *Nat Photonics* 1, 97–105 (2007).
9. Piesiewicz R, Kleine-Ostmann T, Krumbholz N, Mittleman D, Koch M, Schoebel J, and Kurner T, *Ieee Antenn Propag M* 49, 24–39 (2007).
10. Hu BB, and Nuss MC, *Opt Lett* 20, 1716–& (1995). [PubMed: 19862134]
11. Hunsche S, Mittleman DM, Koch M, and Nuss MC, *Ieice T Electron E81c*, 269–276 (1998).
12. Crowe TW, Globus T, Woolard DL, and Hesler JL, *Philos T Roy Soc A* 362, 365–374 (2004).
13. Chen CY, Wu SC, and Yen TJ, *Applied Physics Letters* 93 (2008).
14. Chen WY, and Lin CH, *Opt Express* 18, 14280–14292 (2010). [PubMed: 20588563]
15. Rockstuhl C, Lederer F, Etrich C, Zentgraf T, Kuhl J, and Giessen H, *Opt Express* 14, 8827–8836 (2006). [PubMed: 19529264]
16. Acuna G, Heucke SF, Kuchler F, Chen HT, Taylor AJ, and Kersting R, *Opt Express* 16, 18745–18751 (2008). [PubMed: 19581961]
17. Wood RW, *Philos Mag* 4, 396–402 (1902).
18. Rayleigh P R Soc Lond a-Conta 79, 399–416 (1907).
19. Xu NN, Singh R, and Zhang WL, *Applied Physics Letters* 109 (2016).
20. Kravets VG, Schedin F, and Grigorenko AN, *Physical Review Letters* 101 (2008).
21. Bitzer A, Wallauer J, Helm H, Merbold H, Feurer T, and Walther M, *Opt Express* 17, 22108–22113 (2009). [PubMed: 19997457]
22. Xu NN, Singh R, and Zhang WL, *J Applied Physics* 118, 163102 (2015).
23. Fan K, and Padilla WJ, *Mater Today* 18 (2015).
24. Peralta XG, Brener I, Padilla WJ, Young EW, Hoffman AJ, Cich MJ, Averitt RD, Wanke MC, Wright JB, Chen H-T, O'Hara JF, Taylor AJ, Waldman J, Goodhue WD, Li J, Reno J, *Metamaterials* 4, 83–88 (2010).
25. Lin YS, Huang CY, and Lee C, *Ieee J Sel Top Quant* 21 (2015).
26. Chen HT, O'Hara JF, Azad AK, Taylor AJ, Averitt RD, Shrekenhamer DB, and Padilla WJ, *Nat Photonics* 2, 295–298 (2008).
27. Manjappa M, Srivastava YK, and Singh R, *Phys Rev B* 94 (2016).
28. Jeyaram Y, Verellen N, Zheng X, Silhanek AV, Hojeij M, Terhalle B, Ekinci Y, Valev VK, Vandenbosch GAE, and Moshchalkov VV, *Opt Express* 21, 15464–15474 (2013). [PubMed: 23842334]
29. Peralta XG, Wanke MC, Arrington CL, Williams JD, Brener I, Strikwerda A, Averitt RD, Padilla WJ, Smirnova E, Taylor AJ, and O'Hara JF, *Applied Physics Letters* 94 (2009).
30. Peralta XG, Arrington CL, Williams JD, Strikwerda A, Averitt RD, Padilla WJ, O'Hara JF, and Brener I, *Mater Res Soc Symp P* 1182, 145151 (2009).
31. Lumerical Solutions, Inc. <http://www.lumerical.com/tcad-products/fdtd/>.
32. Garet F, Duvillaret L, and Coutaz JL, "Thz time-domain spectroscopy of nanometric-thick gold layers," in *Infrared and Millimeter Waves, Conference Digest of the 2004 Joint 29th International*

Conference on 2004 and 12th International Conference on Terahertz Electronics, 2004(2004), pp. 467–468.

33. Cataldo G, Beall JA, Cho HM, McAndrew B, Niemark MD, and Wollack EJ, Opt Lett 37, 4200–4202 (2012). [PubMed: 23073410]
34. Smaali R, Taliercio T, and Centeno E, Opt Lett 41, 3900–3903 (2016). [PubMed: 27519118]
35. Okada T, and Tanaka K, Sci Rep-Uk 1 (2011).
36. Kamaraju N, Rubano A, Jian L, Saha S, Venkatesan T, Notzold J, Kramer Campen R, Wolf M, and Kampfrath T, Light Sci Appl 3, e155 (2014).
37. Busch S, Scherger B, Scheller M, and Koch M, Opt Lett 37, 13911393 (2012). [PubMed: 22513696]

Fig. 1.

Transmission spectra of a 75 μm period array of SRRs with E-field polarized perpendicular (top) and parallel (bottom) to the 2 μm gap. Solid (open) dots correspond to THz-TDS (FTIR) measurements. Single numbers indicate the plasmon mode order, pairs of numbers indicate the air-lattice mode indices, and gray lines indicate the plasmon mode originating from the horizontal (top) or vertical (bottom) sections of the SRR. Insets: optical images of the SRR showing the dimensions and orientation of the THz E-field. x -axis is horizontal.

Fig. 2.

S_{21} spectra of a 75 μm period array of SRRs with E-field polarized perpendicular (top) and parallel (bottom) to the gap. Symbols are the same as in Fig. 1. Insets show the orientation of the THz E-field.

Fig. 3.

E-field distributions at resonance for the orientations indicated on top. (a) Plasmon modes. Numerals within the image correspond to the plasmon mode index. V wires and H wires correspond to plasmon modes excited in the vertical and horizontal sections of the resonator. (b) Lattice modes. Pairs of numbers identify the lattice mode indices. Color scales have been modified for clarity.

Fig. 4.

S_{21} parameters for three different periods: 65 μm (dashed), 75 μm (solid), and 85 μm (dotted) for E-field polarized (a) parallel and (b) perpendicular to the gap. Single digits indicate the plasmon mode. Asterisks locate the first order air lattice mode. Spectra have been vertically offset for clarity. (c) Q-factor for plasmon mode 6 (black) and 7 (blue) as a function of array period.

Fig. 5.

S_{21} parameters for E-field polarized perpendicular to the gap for an array of SRRs (dark blue) and an array of SRRs and rings (light blue). ON/OFF switch at (a) 3.3 THz and (b) 3.7 THz. (c) Dual-state broadband amplitude modulator. Inset: the equivalent structurally illuminated array and relative orientation of the THz E-field.