LA-UR- 08-7520

Title: Metamaterials for terahertz polarimetric devices

Author(s): John O'Hara, LANL; Antoinette J. Taylor, LANL; Evgenya Smirnova, LANL; Abul Azad, LANL

Intended for: Journal Optics Express

Los Alamos
NATIONAL LABORATORY
EST. 1943

Metamaterials for THz polarimetric devices

Xomalin G. Peralta,[1,*] Evgenya Smironova,[2] Abul K. Azad,[3] Hou-Tong Chen,[3]
Antoinette J. Taylor,[3] Igal Brener,[1,4] and John F. O'Hara[3]

[1]*Sandia National Laboratories, P. O. Box 5800, MS 1082, Albuquerque, NM 87185, USA*
[2]*ISR-6, Los Alamos National Laboratory, P. O. Box 1663, MS H851, Los Alamos, NM 87545, USA*
[3]*MPA-CINT, Los Alamos National Laboratory, P. O. Box 1663, MS K771, Los Alamos, NM 87545, USA*
[4]*CINT, Sandia National Laboratories, P. O. Box 5800, MS 1082, Albuquerque, NM 87185, USA*
[*]*Corresponding author: xgperal@sandia.gov*

Abstract: We present experimental and numerical investigations of planar terahertz metamaterial structures designed to interact with the state of polarization. The dependence of metamaterial resonances on polarization results in unique amplitude and phase characteristics of the terahertz transmission, providing the basis for polarimetric terahertz devices. We highlight some potential applications for polarimetric devices and present simulations of a terahertz quarter-wave plate and a polarizing terahertz beam splitter. Although this work was performed at terahertz frequencies, it may find applications in other frequency ranges as well.

OCIS codes: (230.5440) Polarization-selective devices; (160.3918) Metamaterials; (260.5740) Resonance.

References and links

1. B. Ferguson, and X. C. Zhang, "Materials for terahertz science and technology," Nat. Mater. **1**, 26-33 (2002).
2. R. Piesiewicz, T. Kleine-Ostmann, N. Krumbholz, D. Mittleman, M. Koeh, J. Sehoebel, and T. Kurner, "Short-range ultra-broadband terahertz communications: Concepts and perspectives," IEEE Antennas Propag. Mag. **49**, 24-39 (2007).
3. B. B. Hu, and M. C. Nuss, "Imaging with Terahertz Waves," Opt. Lett. **20**, 1716-1718 (1995).
4. S. Hunsche, D. M. Mittleman, M. Koeh, and M. C. Nuss, "New dimensions in T-ray imaging," IEEE Trans. Electron. **E81c**, 269-276 (1998).
5. B. M. Fischer, H. Helm, and P. U. Jepsen, "Chemical recognition with broadband THz spectroscopy," Proceedings of the IEEE **95**, 1592-1604 (2007).
6. R. H. Jacobsen, D. M. Mittleman, and M. C. Nuss, "Chemical recognition of gases and gas mixtures with terahertz waves," Opt. Lett. **21**, 2011-2013 (1996).
7. T. W. Crowe, T. Globus, D. L. Woolard, and J. L. Hesler, "Terahertz sources and detectors and their application to biological sensing," Philos. Trans. R. Soc. London Ser. A **362**, 365-374 (2004).
8. J. Xu, G. J. Ramian, J. F. Galan, P. G. Savvidis, A. M. Scopatz, R. R. Birge, J. Allen, and K. W. Plaxco, "Terahertz circular dichroism spectroscopy: A potential approach to the in situ detection of life's metabolic and genetic machinery," Astrobiology **3**, 489-504 (2003).
9. R. Shimano, H. Nishimura, and T. Sato, "Frequency tunable circular polarization control of terahertz radiation," Jpn. J. Appl. Phys. Part 2-Letters & Express Letters **44**, L676-L678 (2005).
10. N. Amer, W. C. Hurlbut, B. J. Norton, Y. S. Lee, and T. B. Norris, "Generation of terahertz pulses with arbitrary elliptical polarization," Appl. Phys. Lett. **87**, 221111 (2005).
11. N. Kanda, K. Konishi, and M. Kuwata-Gonokami, "Terahertz wave polarization rotation with double layered metal grating of complimentary chiral patterns," Opt. Express **15**, 11117-11125 (2007).
12. E. Castro-Camus, J. Lloyd-Hughes, M. B. Johnston, M. D. Fraser, H. H. Tan, and C. Jagadish, "Polarization-sensitive terahertz detection by multicontact photoconductive receivers," Appl. Phys. Lett. **86**, 254102 (2005).
13. J. C. Vardaxoglou, *Frequency Selective Surfaces: Analysis and Design* (Research Studies Press Ltd, Taunton, 1997).
14. B. A. Munk, *Frequency Selective Surfaces: Theory and Design* (Wiley Interscience, 2000).
15. J. S. Tharp, B. A. Lail, B. A. Munk, and G. D. Boreman, "Design and demonstration of an infrared meanderline phase retarder," IEEE Trans. Antennas Propag. **55**, 2983-2988 (2007).

16. C. Winnewisser, F. Lewen, J. Weinzierl, and H. Helm, "Transmission features of frequency-selective components in the far infrared determined by terahertz time-domain spectroscopy," Appl. Opt. **38**, 3961-3967 (1999).
17. J. B. Pendry, A. J. Holden, D. J. Robbins, and W. J. Stewart, "Magnetism from conductors and enhanced nonlinear phenomena," IEEE Trans. Microwave Theory Tech. **47**, 2075-2084 (1999).
18. D. R. Smith, W. J. Padilla, D. C. Vier, S. C. Nemat-Nasser, and S. Schultz, "Composite medium with simultaneously negative permeability and permittivity," Phys. Rev. Lett. **84**, 4184-4187 (2000).
19. D. Schurig, J. J. Mock, B. J. Justice, S. A. Cummer, J. B. Pendry, A. F. Starr, and D. R. Smith, "Metamaterial electromagnetic cloak at microwave frequencies," Science **314**, 977-980 (2006).
20. R. A. Shelby, D. R. Smith, and S. Schultz, "Experimental verification of a negative index of refraction," Science **292**, 77-79 (2001).
21. A. Degiron, J. J. Mock, and D. R. Smith, "Modulating and tuning the response of metamaterials at the unit cell level," Opt. Express **15**, 1115-1127 (2007).
22. E. Kim, Y. R. Shen, W. Wu, E. Ponizovskaya, Z. Yu, A. M. Bratkovsky, S. Y. Wang, and R. S. Williams, "Modulation of negative index metamaterials in the near-IR range," Appl. Phys. Lett. **91**, 173105 (2007).
23. W. J. Padilla, A. J. Taylor, C. Highstrete, M. Lee, and R. D. Averitt, "Dynamical electric and magnetic metamaterial response at terahertz frequencies," Phys. Rev. Lett. **96**, 107401 (2006).
24. H. T. Chen, W. J. Padilla, J. M. O. Zide, A. C. Gossard, A. J. Taylor, and R. D. Averitt, "Active terahertz metamaterial devices," Nature **444**, 597-600 (2006).
25. Q. Zhao, L. Kang, B. Du, B. Li, J. Zhou, H. Tang, X. Liang, and B. Z. Zhang, "Electrically tunable negative permeability metamaterials based on nematic liquid crystals," Appl. Phys. Lett. **90**, 011112 (2007).
26. F. Zhang, Q. Zhao, L. Kang, D. P. Gaillot, X. Zhao, J. Zhou, and D. Lippens, "Magnetic control of negative permeability metamaterials based on liquid crystals," Appl. Phys. Lett. **92**, 193104 (2008).
27. J. Han, and A. Lakhtakia, "Semiconductor split-ring resonators for thermally tunable, terahertz metamaterials," archived in http://arxiv.org/abs/0808.3183 (2008).
28. H.-T. Chen, J. F. O'Hara, A. K. Azad, A. J. Taylor, R. D. Averitt, D. B. Shrekenhamer, and W. J. Padilla, "Experimental demonstration of frequency-agile terahertz metamaterials," Nat. Photonics **2**, 295 (2008).
29. T. Driscoll, G. O. Andreev, D. N. Basov, S. Palit, S. Y. Cho, N. M. Jokerst, and D. R. Smith, "Tuned permeability in terahertz split-ring resonators for devices and sensors," Appl. Phys. Lett. **91**, 062511 (2007).
30. N. I. Landy, S. Sajuyigbe, J. J. Mock, D. R. Smith, and W. J. Padilla, "Perfect metamaterial absorber", Phys. Rev. Lett. **100**, 207402 (2008).
31. M. S. Boybay, and O. M. Ramahi, "Double Negative Metamaterials for Subsurface Detection," *Proceedings of the 29th Annual International Conference of the IEEE EMBS*, 3485-3488 (2007).
32. J. F. O'Hara, R. Singh, I. Brener, E. Smirnova, J. Han, A. J. Taylor, W. Zhang, "Thin-film sensing with planar terahertz metamaterials: sensitivity and limitations," Opt. Express **16**, 1786-1795 (2006).
33. A. K. Azad, J. M. Dai, and W. L. Zhang, "Transmission properties of terahertz pulses through subwavelength double split-ring resonators," Opt. Lett. **31**, 634-636 (2006).
34. X. Xu, B. Quan, C. Gu, and L. Wang, "Bianisotropic response of microfabricated metamaterials in the terahertz region," J. Opt. Soc. Am. B **23**, 1174-1180 (2006).
35. N. Wongkasem, A. Akyurtlu, K. A. Marx, Q. Dong, J. Li, and W. D. Goodhue, "Development of chiral negative refractive index metamaterials for the terahertz frequency regime," IEEE Trans. Antennas Propag. **55**, 3052-3062 (2007).
36. W. Zhang, A. Potts, A. Papakostas, and D. M. Bagnall, "Intensity modulation and polarization rotation of visible light by dielectric planar chiral metamaterials," Appl. Phys. Lett. **86**, 231905 (2005).
37. J. D. Baena, L. Jelinek, R. Marques, and J. Zehentner, "Electrically small isotropic three-dimensional magnetic resonators for metamaterial design," Appl. Phys. Lett. **88**, 134108 (2006).
38. R. Marques, J. Martel, F. Mesa, and F. Medina, "A new 2D isotropic left-handed metamaterial design: Theory and experiment," Microwave Opt. Tech. Lett. **35**, 405-408 (2002).
39. C. Imhof, and R. Zengerle, "Strong birefringence in left-handed metallic metamaterials," Opt. Commun. **280**, 213-216 (2007).
40. A. A. Zharov, N. A. Zharova, R. E. Noskov, I. V. Shadrivov, and Y. S. Kivshar, "Birefringent left-handed metamaterials and perfect lenses for vectorial fields," New J. Phys. 7, 220 1-9 (2005).
41. M. Iwanagaa, "Ultracompact waveplates: Approach from metamaterials," Appl. Phys. Lett. **92**, 153102 (2008).
42. W. J. Padilla, D. R. Smith, and D. N. Basov, "Spectroscopy of metamaterials from infrared to optical frequencies," J. Opt. Soc. Am. B **23**, 404-414 (2006).
43. S. O'Brien, and J. B. Pendry, "Magnetic activity at infrared frequencies in structured metallic photonic crystals," J. Phys.: Condens. Matter **14** 6383-6394 (2002).
44. J. F. O'Hara, J. M. O. Zide, A. C. Gossard, A. J. Taylor, and R. D. Averitt, "Enhanced terahertz detection via ErAs : GaAs nanoisland superlattices," Appl. Phys. Lett. **88**, 251119 (2006).
45. J. D. Jackson, *Classical Electrodynamics* (Wiley Academic Press, 1998).
46. CST Microwave Studio, © 2008 CST—Computer Simulation Technology, Wellesley Hills, MA, USA. www.cst.com.

47. J. F. O'Hara, E. Smirnova, A. K. Azad, H. T. Chen, and A. J. Taylor, "Effects of microstructure variations on macroscopic terahertz metafilm properties," Act. Passive Electron. Compon. 2007, 49691 (2007).
48. M. Born and E. Wolf, *Principles of Optics: Electromagnetic Theory of Propagation, Interference and Diffraction of Light*, (Cambridge University Press, 1989).
49. Y. Yuan, C. Bingham, T. Tyler, S. Palit, T. H. Hand, W. J. Padilla, D. R. Smith, N. M. Jokerst, and S. A. Cummer, "Dual-band planar electric metamaterial in the terahertz regime," Opt. Express **16**, 9746-9752 (2008).
50. N. C. J. van der Valk, W. A. M. van der Marel, and P. C. M. Planken, "Terahertz polarization imaging," Opt. Letters **30**, 2802-2804 (2005).
51. A. Agrawal, H. Cao, and A. Nahata, "Excitation and scattering of surface plasmon-polaritons on structured metal films and their application to pulse shaping and enhanced transmission, New J. Phys. **7**, 249 1-13 (2005).

---

1. Introduction

Technology in the terahertz (THz) region of the electromagnetic spectrum (0.1 – 4 THz = 3000 – 75 μm = 3.3 – 133.3 cm^{-1}) has remained relatively immature due to moderate progress in the development of passive and active devices operating at these frequencies [1]. In spite of this, numerous potential applications such as communications [2], imaging [3, 4], and chemical [5, 6] and biological sensing [7] have been identified and are being pursued. These applications may benefit greatly from materials that enhance our ability to manipulate, control, and detect THz radiation. One particular example of electromagnetic manipulation that is currently quite limited at THz frequencies is polarization control – besides wire grid polarizers there are no commercial devices that alter polarization. As a result of a recent interest in THz circular dichroism [8], there have been some advances in the generation [9-11] and detection [12] of arbitrarily polarized THz radiation. To fully exploit these recent advances and successfully develop the applications mentioned above, there is a pressing need for polarizing components such as wave plates, polarization splitters and combiners, and others. Frequency selective surfaces and metamaterials represent two technologies that have the potential to address this need.

Frequency selective surfaces (FSS) can be thought of as periodic arrangements of apertures on metallic films, or patches of metal on a substrate, that reflect or transmit certain electromagnetic frequencies depending on the geometry and thickness of the metal. Typically their periodicity is comparable to the wavelength of operation. They have been implemented at radio, microwave, THz, infrared (IR) and, recently, visible frequencies. FSSs have been used as filters, laser-cavity output couplers and interferometers to the extent that some of the most successful designs at radio and microwave frequencies have been incorporated into commercial products [13, 14]. They can be designed to be sensitive or insensitive to polarization and have already been proposed for IR phase retarders [15], THz dichroic filters and pulse-shaping devices [16].

Metamaterials can be broadly described as a class of composite materials designed to have specific effective electromagnetic properties often not found in naturally occurring materials [17-20]. One of the more common implementations utilizes the split ring resonator (SRR), a metallic resonant particle periodically distributed in an insulator matrix. Periodicity is not critical to operation, but is often employed, may extend into three dimensions, and is significantly smaller than a wavelength such that the effective medium approximation holds. Split-ring resonators can interact with either or both the electric and magnetic field, enabling tuning of a composite's permittivity and/or permeability. These properties distinguish metamaterials from FSS and provide numerous important performance capabilities. Metamaterials have been demonstrated at radio, microwave, THz, IR and visible frequencies but we chose to concentrate on developing polarization sensitive and insensitive metamaterials as building blocks for THz polarimetric devices.

SRR-based metamaterials have proven to be very versatile in the construction of devices enabling both static and dynamic responses, the latter being optically, electrically, magnetically or thermally controlled and tunable in both frequency and amplitude [21-28]. The aforementioned versatility in combination with their novel electromagnetic properties and sensitivity to the surrounding dielectric environment has also been the basis for diverse proposals of metamaterial based detectors [29-32]. Most metamaterial designs utilizing the SRR are anisotropic presenting a desirable resonant response to one state of linear polarization and a very different response, or none at all, to the other [33, 34]. However, this could be advantageous in polarization control. Only recently have there been efforts directly targeted at polarization control and detection using chiral [35, 36], isotropic [37, 38] and, to a lesser extent, birefringent [39, 40] and stratified metal-dielectric [41] metamaterials.

We present two planar metamaterials, one each designed to be insensitive or sensitive to the polarization of the normally incident electromagnetic wave by virtue of their isotropic or anisotropic design. Both designs show a spectrally selective behavior in the form of a decreased transmission at the resonant frequencies, and both maintain a response regardless of polarization orientation. However, for the anisotropic design the characteristics of the transmitted THz spectra strongly depend on the incident polarization, which is not the case for the isotropic design. We will present the advantages offered by these designs, and discuss their potential polarimetric applications, in particular at THz frequencies but with the view that they can be scaled to other frequency ranges [42, 43]. Last, we present simulations of a THz quarter-wave plate and a polarizing THz beam splitter, which utilize the polarization sensitive metamaterial.

2. Sample design and experimental setup

The isotropic (polarization insensitive) metamaterial unit, referred to as a circular split ring resonator (CSRR), was designed from two concentric circular rings joined by four linear spokes, where the inner ring has splits in each sector, as shown in Fig. 1(a). The anisotropic (polarization sensitive) metamaterial unit was obtained from the CSRR by breaking the circular symmetry; replacing the inner split ring with a split ellipse resulting in the elliptical split ring resonator (ESRR) shown in Fig. 1(b). The two metamaterials therefore share several geometrical parameters and have the same unit size. They were fabricated simultaneously into square arrays of 1 cm × 1 cm in extent on 550μm thick, semi-insulating GaAs substrates using standard photolithography techniques. Metallization consisted of 100 Å of titanium (adhesion layer) followed by 2000 Å of gold. Dimensions are indicated in the figure and figure legend.

We characterized the transmission response of both metamaterials with terahertz time-domain spectroscopy (THz-TDS) as a function of the angle between the major axis of the ellipse (see Fig. 1(b)), or one radial spoke in the case of the CSRR, and the linearly polarized electric field (see insets in Fig. 2(f)). The THz-TDS system is based on linearly polarized photoconductive antennas for both the source and the detector and has been presented elsewhere [44]. Samples were mounted on a rotating stage at the focus of the normally incident THz beam (~3 mm in diameter) and were rotated manually. The experiments were performed at room temperature in a dry air atmosphere (<1% relative humidity). The electric field of the THz radiation was coherently recorded after transmitting normally through the metamaterial samples at 10 polarization angles, and through a bare GaAs substrate serving as the reference. Numerical Fourier transforms were used to calculate the sample and reference spectra, by which we obtained the normalized frequency-dependent complex transmission spectra (*i.e.* amplitude and phase) as a function of the polarization angle.

3. Experimental results: THz transmission spectra

Figure 2(b) shows the experimentally measured transmission spectra of the isotropic CSRR metamaterial at five different angles. The transmission amplitude spectra present a resonant decrease down to 17% at 0.69 THz and 29% at 1.64 THz. Importantly, these spectra are completely independent of the polarization angle as is evident from their good overlap. The overlap is also evident in the corresponding phase change, Fig. 2(c), which has the shape of the derivative of the amplitude spectra, a result of the Kramers-Kronig relations [45]. Note that the maximum variation of phase is larger than 50°, illustrating the strong phase shifting effect that even a single metamaterial layer can have on the incident electromagnetic wave.

Figure 2(e) shows the experimentally measured transmission amplitude spectra of the anisotropic ESRR metamaterial at 0°, 30°, 45°, 66° and 90° orientations. When the incident polarization is horizontal (*i.e.* parallel to the major axis of the ellipse or 0° orientation) there are two minima occurring at 0.79 and 1.94 THz. As the angle increases, these minima gradually decrease while other resonances appear and gradually become prominent. When the incident polarization is vertical (*i.e.* perpendicular to the major axis of the ellipse or 90° orientation) there are again only two minima, now at 0.59 and 1.39 THz. At the polarization angle of 45° all four resonances at 0.59, 0.79, 1.39 and 1.94 THz are present though with relatively weak response. Figure 2(f) shows the corresponding phase data with its dispersive line shape characteristic of Lorentzian resonances..

John O'Hara 11/10/08 7:57 AM

Comment: We have to be careful about saying the resonance strength increases/decreases. It doesn't, but rather we access it more or less.

An interesting observation that provides the basis for building a quarter-wave plate or polarizing THz beam splitter using the anisotropic metamaterial is the fact that the amplitude and phase changes are interrelated. That is, at frequencies where the phase variation is maximized the amplitude is largely unchanged, and vice versa. Figures 3(a) and 3(b) show plots of the anisotropic metamaterial's measured transmission amplitude and phase at the resonance frequencies as a function of polarization angle. The amplitude variation is generally large and nonlinear while the phase variation is typically rather flat, on average varying about 20°. On the other hand, at three, non-resonant frequencies, 0.65, 1.06 and 1.83 THz, indicated by vertical lines in Figs. 2(e) and 2(f), the transmission amplitude for the different polarization angles varies by, at most, 11%, shown in Fig. 3(c), while the phase varies significantly and also reveals a nonlinear behavior, as plotted in Fig. 3(d). At 0.65 THz the phase varies by as much as 69° between the horizontal and vertical polarizations. A detailed discussion on how to take advantage of this observation to implement a THz quarter-wave plate and a polarizing THz beam splitter is presented in section 5.

In order to check the symmetry of the response, we performed THz transmission measurements at 45° and -45° on both samples. As expected, we found no observable difference between the two spectra for the CSRR. There was less than 10% difference in the transmission amplitudes of the ESRR. This difference may be attributable to slight angular misalignments in the sample mounting or a slight rotation of the THz polarization out of horizontal.

4. Modeling results and analysis

Figure 2(a) shows the simulated THz transmission amplitude spectra for the isotropic metamaterial using the commercially available finite-element software CST Microwave Studio [46]. Comparing them to the experimental results presented in Fig. 2(b), we note that there is a difference of, at most, ~3% when comparing the values reached at the transmission minima and a difference of less than 8% when comparing the resonance positions. Figure 2 also compares the simulated (d) and experimental (e) results for the THz transmission amplitude spectra of the anisotropic metamaterial at 0° and 90° orientations. Experiments and simulations show a difference of, at most, 10% when comparing the values of the transmission minima and less than 2% when comparing the resonance frequencies. The differences between modeling and experimental results can be attributed to slight variations in fabrication or material composition of the actual devices relative to their ideal, simulated counterparts.

By virtue of this accurate match to data, simulations can be extended to model much more complicated systems. Previous work [47] has shown that planar metamaterials can be modeled as relatively simple surface impedances. Full electromagnetic simulations determine these impedances relatively fast and are combined with the analytical formalism of stratified media [48] to integrate multi-layer effects. This approach allows us to quickly characterize and modify the overall response of an arbitrary stack of dielectric and metamaterial layers. These results supplement and are verified by the full simulations of the stacked systems, which are extremely time-consuming. This method is employed in Section 5 to design the THz quarter-wave plate and polarizing THz beam splitter.

In addition, the equation describing the normalized THz transmission response through the metamaterials is given by

$$\bar{\mathbf{E}}(\theta) = T_H \cos(\theta)\exp(i\phi_H)\hat{\mathbf{h}} + T_V \sin(\theta)\exp(i\phi_V)\hat{\mathbf{v}} \tag{1}$$

where θ is the polarization angle of the incident, linearly-polarized wave with respect to the metamaterial's horizontal axis $\hat{\mathbf{h}}$, T_H and T_V are the metamaterial's horizontal and vertical transmission amplitudes, and ϕ_H and ϕ_V are the phase shifts imparted by the metamaterial to the horizontal and vertical electric field components, respectively. The *measured* normalized THz transmission spectra is given by

$$\tilde{E}(\theta) = T_H \cos^2(\theta)\exp(i\phi_H) + T_V \sin^2(\theta)\exp(i\phi_V) \tag{2}$$

John O'Hara 1/16/08 8:20 AM

Comment: I changd the equation to get rid of x and y and make sure it's clear that our principal axes are those of the metamaterial itself.

The squared sine and cosine terms in Eq. (2) result from projecting the linearly polarized source and detector, which are aligned with each other, onto the metamaterial axes. The terms T_H, T_V, ϕ_H and ϕ_V are all determined by measuring the metamaterial response in the horizontal and vertical orientations with linearly polarized THz radiation. Using these values we can match the measured data at all intermediate polarization angles, as shown by the solid curves in Fig. 3. When $T_H = T_V = 1$ and $|\phi_V - \phi_H| = 90°$ this equation describes the measured response of an ideal quarter-wave plate. Similarly, when $T_H = 0$ and $T_V = 1$ (or vice versa) and $|\phi_V - \phi_H| = 0°$, it describes the response of an ideal beamsplitter. The match between Eq. (2) and the measured data indicates that our anisotropic metamaterial is an excellent candidate for creating real THz wave plates.

5. THz polarimetric devices: examples and discussion

From Fig. 3(c), at 1.06 THz the transmission amplitude between the horizontal and vertical polarizations varies by only ~0.5%, while from Fig. 3(b) the phase difference is about 45° - this is the difference between the phase of the horizontally and vertically polarized transmitted light. Therefore, at 1.06 THz the single anisotropic metamaterial layer acts like a wave plate imparting an equal amplitude change, but a different phase shift to the horizontal and vertical electric field components. Given the 45° phase variation per layer, two such metamaterial layers should impart an overall 90° shift, exactly producing the behavior of a quarter-wave plate.

To implement such a THz quarter-wave plate, we modeled two parallel anisotropic metamaterial layers one each on either side of a GaAs slab. For normally incident continuous wave THz radiation, the multiple reflections between the two air/slab interfaces significantly degrade the device performance modifying both the transmission amplitude and phase shift by introducing strong oscillatory behavior. To rectify this issue and develop a realistic quarter-wave plate design, we added a dielectric layer to both sides of the structure, see inset in Fig. 4(d). The dielectric layer has a dielectric constant of $(\varepsilon_{GaAs})^{1/2}$ and therefore may behave as a quarter-wave antireflection coating near the operating frequency. This modification removes much of the multi-reflection problem caused by the air/slab interfaces, but also shifts the ESRR resonance frequency by changing its dielectric environment. Working with these alterations we adjusted both the dielectric and substrate layer thicknesses until we found that at 0.865 THz the transmission amplitude for both polarizations is equivalently 0.89, shown in Figs. 4 (a) and (b), while the phase difference between them is 90° (see Figs. 4 (c) and (d)). Note that this is absolute transmission and is not normalized to a reference slab. The performance of this design is approaching that of mature optical technology and can be improved by further refinements. The remaining oscillatory behavior at other frequencies is caused by multiple reflections that are not eliminated by the antireflection layers. In practice, such a wave plate could be implemented using readily available materials, *e.g.*, fused quartz ($\varepsilon \sim 4$) as the substrate and polyethylene ($\varepsilon \sim 2$) as the antireflection coating.

We also used modeling to design a polarizing THz beam splitter based on the anisotropic metamaterial. Following the design of the quarter-wave plate, we included a dielectric layer in the front and back as an antireflection coating but had only one layer of the metamaterial on the incoming side of the GaAs substrate, see inset in Fig. 5(d). Figures 5(a) and (b) show the transmission amplitude spectra for the horizontally and vertically polarized waves. From Fig. 5(c) it is evident that at 0.70 THz the transmission amplitude is only 0.12 for the horizontal polarization but 0.98 for the vertical polarization with no relative phase difference, as indicated in Fig. 5(d). The absorption of these metamaterials is quite low, so that nearly all of the energy not transmitted in the horizontal polarization is reflected, therefore the reflected wave is horizontally polarized. While this design is somewhat impractical due to the restriction of normal wave incidence, minor adjustments should enable equal or better performance with oblique angles of incidence.

In general, both metamaterial designs introduced in this paper present, at least, a dual-band resonant response whose location and relative positions can be modified by changing the geometric parameters of the constituent resonator units. However, our approach offers numerous additional benefits. In contrast to other instances of dual-band planar metamaterials [49], both resonances come from the same metamaterial unit, therefore we can maintain a small size of the unit cell and maximize the metamaterial oscillator strength. Having a small unit cell also allows us to remain within the effective medium approximation and facilitates the design and implementation of most tuning schemes developed to date [21-29]. We also note that any anisotropic SRR design would create some polarization dependent effects, but our ESRR approach allows us to simultaneously tune these effects for *both* polarizations. For example, we can ideally tune the two interacting resonances in frequency space. Doing so allows us to maximize the phase difference while minimizing the amplitude difference for wave plate implementations, or conversely, minimize the phase difference while maximizing the amplitude difference for variable attenuators or beam splitters. Devices based on polarization sensitive or insensitive metamaterials have the advantage of being compact, fast, versatile and efficient, making them ideal for developing novel polarimetric devices.

6. Polarimetric applications

As mentioned previously, there remains a need to mature THz technology for applications like communications, spectroscopic imaging and sensing. Each of these applications, as well as basic THz research, could make use of the structures discussed in this paper as is highlighted in the following.

Polarization insensitive designs represent a step towards three-dimensionally isotropic metamaterials, and eliminate some of the difficulty in forming truly three-dimensional effective media. Polarization insensitive planar metamaterials will also find applications in imaging, detection and communications where the alignment or state of the polarization should not affect functionality. In particular, recently proposed free-space, short-range THz communication systems [2] rely on reflections off of surfaces within the room to maintain a signal connection when the direct-line-of-sight between emitter and detector is interrupted. In this case polarization insensitive devices would be very useful, eliminating the concern that multiple reflections have modified the polarization state of the wave. Similarly, if we consider spectroscopic imaging of concealed objects where filtering is required, filters based on polarization insensitive structures would be useful since any interaction that could modify the state of polarization would not affect the imaging scheme. For this particular application, the isotropic CSRR presented in this paper, or its complementary design, would be ideal for building a notch filter, or a narrow band pass filter respectively. Incoherent imaging systems on the other hand, would require polarization sensitive filters; imaging with different polarizations can provide complementary information about the objects [50] and in this case the ESRR would be useful. Another area that would greatly benefit from both polarization sensitive and insensitive metamaterials is that of chemical or biological sensing. Sensing with metamaterials relies on the sensitivity of the resonator's response to its dielectric environment. Having both polarization sensitive and insensitive detectors may enable distinction between simple absorption and optical activity.

For ultrafast time resolved studies, polarization sensitive metamaterials could be the foundation of pulse shaping devices as a simple rotation of the incident polarization provides a means of shaping the electric field of the THz pulse (Supplemental material Fig. 1). In contrast with other proposals for THz pulse shaping devices [16, 51], the proposed device does not make use of nonlinear processes or require a different design for each particular pulse shape. Polarization sensitive metamaterials allow us to control the transmission amplitude or phase based on polarization state, therefore enabling applications such as polarization isolation and analysis, amplitude and phase modulation, birefringence, and dichroism.

7. Summary

We have developed both isotropic and anisotropic THz metamaterials that respond to the polarization of the incident electromagnetic wave in predesigned ways. We characterized their transmission as a function of frequency and incident polarization using THz time-domain spectroscopy and have shown that their amplitude and phase response enables unique and high-performance polarimetric devices. By electromagnetic simulations and analytical modeling we have created realistic designs of a THz quarter-wave plate and a polarizing THz beam splitter based on the anisotropic metamaterial. Finally, we have discussed how this improvement in our ability to control THz radiation with planar metamaterials may find use in applications. Although this work was performed at THz frequencies, it is also applicable to other frequency ranges where planar polarization sensitive devices may be required.

Acknowledgments

We gratefully acknowledge support from the CINT, the IC Postdoctoral Research Fellowship Program (XGP) and the US DOE through the LANL/LDRD program. Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by Los Alamos National Security, LLC, for the NNSA of the US DOE under contract DE-AC52-06NA25396. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the US DOE's NNSA under Contract DE-AC04-94AL85000.

Fig. 1. Geometry of (a) the circular split ring and (b) the elliptical split ring resonators showing some of the dimensions. The splits and metal line widths are all 2μm while the periodicity is 60μm. The measurement of the angle between the incident THz electric field relative to the major (horizontal) axis of the ellipse or circle is indicated in (b).

Fig. 2. Electromagnetic modeling and experimental results of terahertz transmission spectra as a function of polarization angle. Modeling results for: (a) CSRR independent of angle, (d) ESRR at 0° (solid) and 90° (dashed). Normalized transmission amplitude and phase spectra at various angles for (b, c) CSRR and (e, f) ESRR respectively. (b, c) 0°, 24°, 45°, 72° and 90° and (e, f) 0° (■), 30° (⊛), 45° (▲), 66° (▼) and 90° (○). The polarization of the THz radiation for 0° and 90° is as indicated in (f). Vertical lines in (e, f) indicate the frequencies at which the vertical and horizontal metamaterial transmission amplitudes are equal.

Comment: These shapes are not visible in the figure (too small). Is there something else that would allow them to be seen in black and white?

Fig. 3. (a) Transmission amplitude and (b) phase of the anisotropic metamaterial as a function of polarization angle for resonances at 0.79 THz (■), 1.94 THz (□), 0.59 THz (⊛) and 1.39 THz (○). (c) Transmission amplitude and (d) phase of the anisotropic metamaterial as a function of polarization angle at 0.65 THz (■), 1.06 THz (⊛) and 1.83 (▲) THz. Symbols indicate measured data and curves show results from Eq. 2.

Fig. 4. Multilayer electromagnetic transmission modeling of a THz quarter-wave plate based on the ESRR. (a) Amplitude spectra for a dielectric/metamaterial/GaAs/metamaterial/dielectric structure for 0° -horizontal (solid) and 90° - vertical (dashed) polarized waves. (b) Zoom in on the region enclosed by the dashed line in (a). (c) Phase difference spectra. (d) Zoom in on the region enclosed by the dashed line in (c). Inset: schematic diagram of the layered structure where the dielectric layer thickness is 36μm, GaAs thickness is 121μm and the dashed lines represents the location of the metamaterial layers.

Fig. 5. Multilayer electromagnetic transmission modeling of a polarizing beamsplitter based on the ESRR. (a) Amplitude spectra for a dielectric/metamaterial/GaAs/dielectric structure for 0° - horizontal (solid) and 90° - vertical

(dashed) polarized waves. (b) Zoom in on the region enclosed by the dashed line in (a). (c) Phase difference spectra. (d) Zoom in on the region enclosed by the dashed line in (c). Inset: schematic diagram of the layered structure where the dielectric layer thickness is 56μm, GaAs thickness is 50μm and the dashed line represents the location of the metamaterial layer.