6-4-2009

Metamaterial Devices for the Terahertz Band

Gabriel Paul Kniffin
Portland State University, gabekniffin@gmail.com

Citation Details
Kniffin, Gabriel Paul, "Metamaterial Devices for the Terahertz Band" (2009). *Center for Electron Microscopy and Nanofabrication Publications and Presentations*. 3.
https://pdxscholar.library.pdx.edu/cemn_pub/3

Metamaterial Devices for the Terahertz Band

Gabriel Kniffin

June 4, 2009

Abstract

Terahertz (THz) and metamaterials are both hot topics in electromagnetics research. The THz band (0.1-10 THz) lies in the ‘gap’ between microwave and far infrared regions. Research is currently underway to characterize how these waves interact with matter, with potential applications including security screening, medical imaging, and non-destructive evaluation. Metamaterials are artificial materials containing sub-wavelength structures whose material properties, μ and ϵ can be ‘tuned’ to desired specifications, including simultaneously negative values, resulting in exotic properties such as a negative refractive index. Current metamaterials research includes the design of devices that operate at THz frequencies, filling a niche left wide open by the relative lack of naturally occurring materials with significant THz response. In this work, a background on both THz and metamaterials is given followed by a summary of a recently published paper in which metamaterial devices are used for switching and modulation of THz waves [1].

Motivation

While the focus of my research in the NEAR-Lab is the modeling and measurement of THz scattering from random media, I’m also interested in the unusual properties of metamaterials. The NEAR-Lab will soon be collaborating with Dr. Jun Jiao’s Center for Electron Microscopy and Nanofabrication, so my work may soon include investigating the interaction of THz waves with nanostructures, including metamaterials. I saw this project as an opportunity to familiarize myself with the direction that overlapping research in THz and metamaterials has taken so far.

1 Introduction to THz

The terahertz (THz) region of the electromagnetic spectrum lies between the upper end of the microwave band and the lower end of the far infrared band, ($100\mu m \leq \lambda \leq 3mm$, see Figure 1).

Since the THz gap lies between the upper extreme of conventional electronics and the lower end of conventional photonics, the technology to transmit

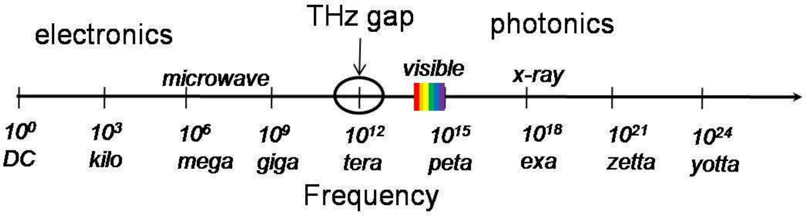


Figure 1: The electromagnetic spectrum [4]

and receive THz radiation has lagged far behind that of lower frequency microwaves and higher frequency optics. Sufficiently powerful transmitters and sensitive receivers for THz frequencies have not been developed until fairly recently. Commercial THz systems are now available and are currently being used to explore the scattering and propagation physics in this 'new frontier' of electromagnetics research.

THz waves have several advantages over existing technologies. Many explosives and drugs have characteristic absorption peaks in the THz spectrum. In addition, clothing and many other common packaging and concealment materials are transparent to THz waves. These properties combined with the fact that THz radiation is non-ionizing make it nearly ideal for screening passengers and luggage at airports or mail or standoff detection of explosive materials on the battlefield. Additional applications for THz technology include medical imaging, nondestructive evaluation, and wireless communications systems.

2 Introduction to Metamaterials

Optical wavelengths are much greater than the size of the constituent atoms or molecules of a naturally occurring substance. This large difference in scale allows the effect of the interaction of the electric and magnetic field components of the wave with the substance to be quantified in terms of two values, the electric permittivity, ϵ, and magnetic permeability, μ. However, atoms are not the only sub-wavelength structures that can affect a material's macroscopic electromagnetic response. In fact, any structures that are sufficiently small compared a wavelength of interest that exhibit an electromagnetic response will have an effective permittivity and permeability different from the constituent materials of the structures. Such materials embedded with such sub-wavelength structures are referred to as metamaterials.

For practical reasons, most research in metamaterials has been carried out in the microwave to millimeter wave regimes. However, nanofabrication techniques are allowing researchers to scale these structures, extending their responses into the higher frequency THz and optical bands. As of 2007, [8] reports metamaterial structures had been constructed exhibiting responses from the gigahertz band up to 1 THz [11], 60 THz [12], 85 THz [3], and all the way up to 780 nm [2].

2.1 Negative n

In his 1968 paper, Veselago [10] hypothesized on the physics of materials whose permittivity ϵ and permeability μ had simultaneously negative real parts. Electromagnetic waves propagating in a natural material are right handed in nature, since

$$\mathbf{H} = \frac{c}{\omega|\mu|}\mathbf{k} \times \mathbf{E}, \qquad \mathbf{E} = -\frac{c}{\omega|\epsilon|}\mathbf{k} \times \mathbf{H}. \tag{1}$$

The absolute value signs around μ and ϵ are shown to emphasize that both parameters are positive. In contrast, if both parameters are negative,

$$\mathbf{H} = -\frac{c}{\omega|\mu|}\mathbf{k} \times \mathbf{E}, \qquad \mathbf{E} = \frac{c}{\omega|\epsilon|}\mathbf{k} \times \mathbf{H}. \tag{2}$$

Notice that (1) forms a right-handed system of vectors and (2) forms a left-handed system. For this reason, Veselago referred to materials with a simultaneously positive ϵ and μ as 'right handed' materials (RHMs) and to those with simultaneously negative ϵ and μ as 'left-handed' materials (LHMs) [10].

Veselago also predicted that LHMs would have several interesting properties, including a negative refractive index, allowing for the realization of a superlens [10]. In addition, he showed that light propagating in a negative index medium would have it's magnetic field vector opposite in direction to that of light propagating in a positive index medium, that Doppler shift and Cerenkov radiation would be reversed, and that the light's Poynting flux would flow opposite to the direction of the phase velocity, resulting in radiation tension [10]. As no such materials exist in nature, his theories would have to wait three decades to be tested.

2.2 Negative ϵ

The electrons of a nonmagnetic conductor, when placed in an electric field, will migrate in the direction opposite to that of the field. If the field is switched off instantaneously, the restoring force caused by the initial charge imbalance will result in oscillatory motion at the plasma frequency,

$$\omega_p^2 = \frac{ne^2}{\epsilon_0 m_e}, \tag{3}$$

where n is the electron density and m_e and e are the electronic mass and charge, respectively. These plasmonic effects result in a permittivity,

$$\epsilon(\omega) = \frac{\omega_p^2}{\omega(\omega + i\gamma)}, \tag{4}$$

where ω is the incident radiation frequency and γ is a term used to quantify the damping of the electronic density oscillations due to electrical resistance. For frequencies lower than the plasma frequency, the permittivity will be negative and the wave will be evanescent if the magnetic permeability is simultaneously positive.

In 1996, Pendry et al. devised a metallic mesostructure with a plasma frequency in the microwave region [6]. The structure consisted of a 3-dimensional grid of thin, metal, nonmagnetic wires as in Figure 2.2. Inductive coupling between wires effectively increases the momentum of electrons traveling through them, causing them to behave as though they had increased in mass by 4 orders of magnitude - to the mass of nitrogen atoms [6]. This enormous increase in effective electron mass results in a reduced plasma frequency.

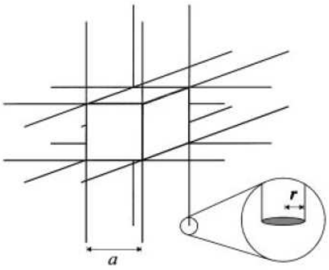
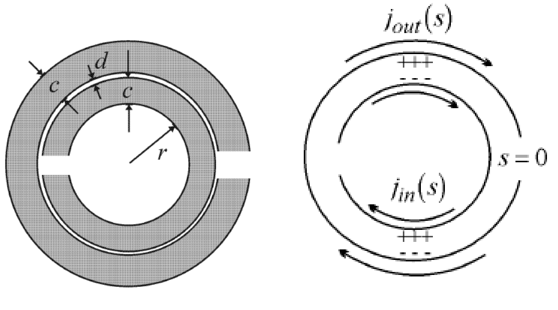


Figure 2: Cubic lattice proposed by Pendry et al. [6]. Wires have radius r and unit cell dimension a.

2.3 Negative μ

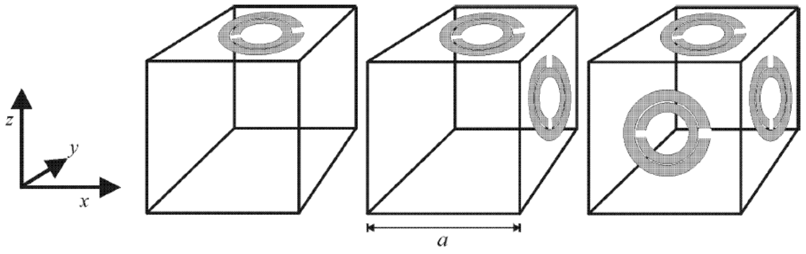
In 1999, Pendry et al. proposed several additional mesostructures that would give rise to a negative magnetic permeability [5]. Among these microstructures was a pair of concentric split rings, often referred to as a split ring resonator (SRR), shown in Figure 3(a). An incident wave whose magnetic field vector is parallel to the axis of an SRR will result in an emf in the rings. Current flows in each ring ring due to the large amount of capacitance between the inner and outer rings as in Figure 3(b). The SRRs would be placed on the faces of each unit cell of an artificial lattice structure (Figure 3(c)), to create an isotropic metamaterial. This 3-dimensional arrangement's magnetic response is described by an effective magnetic permeability which is complex and has a resonant frequency.

As can be seen in Figure 4, the real part of the effective permeability increases to a high peak slightly below resonance before dropping dramatically to a low minimum slightly above resonance. It is in this minimum that the real permeability can drop below 0.



(a) Single SRR

(b) Current flow in SRR due to capacitance between rings



(c) 3-dimensional SRR array for isotropic response

Figure 3: Split Ring Resonator (SRR) Configurations from Pendry et al. [5]

3 Metamaterials applied to THz gap

3.1 Metamaterial Switching and Modulation

Using variations on Pendry's split ring resonator, Chen et al. in 2008 introduced two novel metamaterial devices that operate at THz frequencies (see Figure 5) [1]. Both operate by manipulating the properties of the semiconductor substrate upon which the metamaterial structures are embedded.

One device used a single rectangular split ring resonator, in contrast to Pendry's dual concentric circular ring design. An array of these modified SRRs was embedded onto a SI-GaAs or ErAs/GaAs superlattice substrate. The metamaterials were analyzed using a femptosecond pump beam and a THz probe beam as in Figure 6. Incident linearly polarized THz waves couple into the structure when their electric field vectors are normal to the split gaps of the SRRs while the femptosecond pump beam generates electron-hole pairs in the substrate. The photoexcited carriers short out the gaps in the SRRs, thereby dampening their LC resonance. Experimental results are shown in Figure 7. Carrier lifetime in the bare SI-GaAs substrate much longer than the incident THz pulse, allowing characterization of the metamaterial's quasi-steady state

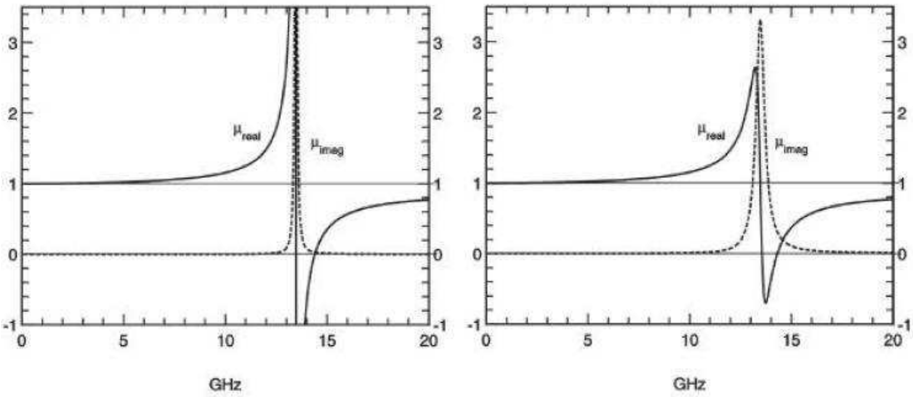


Figure 4: Frequency response of real and imaginary parts of μ_{eff} from [5]. Left: Ring resistivity = 200 Ω, Right: Ring resistivity = 2 kΩ.

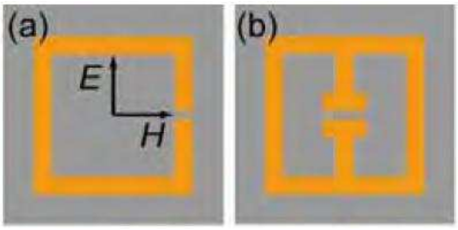


Figure 5: (a) Single split ring resonator (SRR). (b) Electronic split ring resonator (eSRR) [1].

response. The 0.5 THz absorption peak was due to metamaterial LC response while the 1.6 THz peak was due to $\lambda/2$ resonance of unsplit SRR sides [1]. This demonstrates that the metamaterial response was effectively switched off by the pump beam.

Switching recovery time was measured using the same metamaterial structures embedded in the ErAs/GaAs superlattice substrate, which has a much shorter carrier lifetime. Results are shown in 8. By varying the delay time between pump beam photoexcitation and THz probe beam arrival, it was found that the metamaterial's resonant response had almost fully recovered after approximately 30 ps.

The other device used another variation on the SRR, referred to as the eSRR for electronic split ring resonator. Structurally, the eSRR is composed of two single rectangular rings joined at the split gap as in Figure 5. These eSRRs were fabricated on an n-type GaAs substrate in a Schottky diode configuration (see Figure 9). A DC bias is introduced between the substrate and the eSRR array to manipulate the depletion region around the split gaps in the eSRRs. With no bias the gaps are shorted by the conductive doped substrate and the resonant

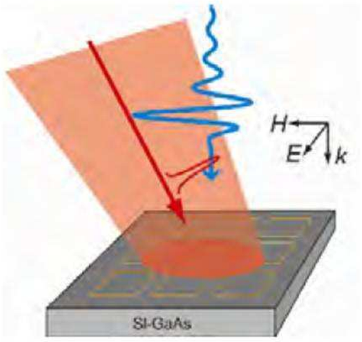


Figure 6: THz probe beam (blue) and femptosecond pump beam (red) incident on the SI-GaAs embedded metamaterial structure [1].

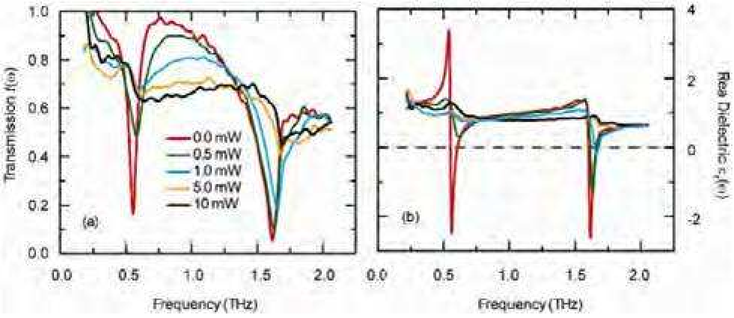


Figure 7: Quasi-steady state metamaterial response at varying pump beam intensities [1].

behavior of the eSRRs is damped. As the bias voltage is increased, the depletion region forms, decreasing the conductivity in the gap and increasing the resonant response of the eSRR array. Figure 10 shows the increase in resonant response as the voltage bias is increased from 0 to 16 V.

3.2 Additional THz Metamaterial Devices

Many additional groups are also working on novel THz metamaterial devices, including Peralta et al. [7], who designed a metamaterial structure that interacts with the polarization THz waves. Tao et al. [9] have also developed a flexible polyimide substrate embedded with SRR structures, paving the way for a flexible THz cloak.

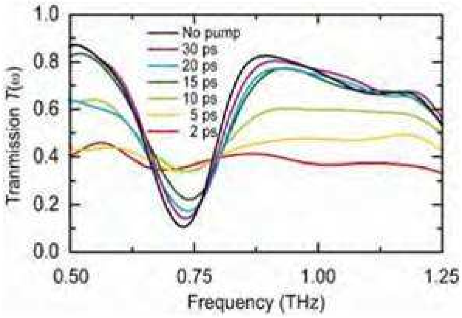


Figure 8: Metamaterial response with varying delay times between pump beam and probe beam [1].

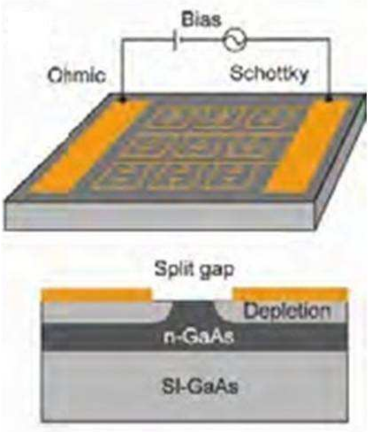


Figure 9: THz modulating material structure. eSSRs embedded in a conductive n-type GaAs substrate [1].

Conclusions

Even before I began working toward my MS, I found the exotic properties of metamaterials intriguing. While I went into the project with some basic understanding of metamaterials and their properties, I didn't know how much overlap there was between THz and metamaterial research. My goal in this project was to find out. I was able to use the project to explore how research in metamaterials is being coupled to the current field of THz research - the focus of my work at the NEAR-Lab. While the scope of this paper is somewhat limited compared to the steadily increasing number of publications on the subject, I now have an idea of where the current research stands and where it is going. The NEAR-Lab will soon be collaborating with Dr. Jun Jiao's Center for Electron Microscopy and Nanofabrication and I may yet conduct my thesis research on

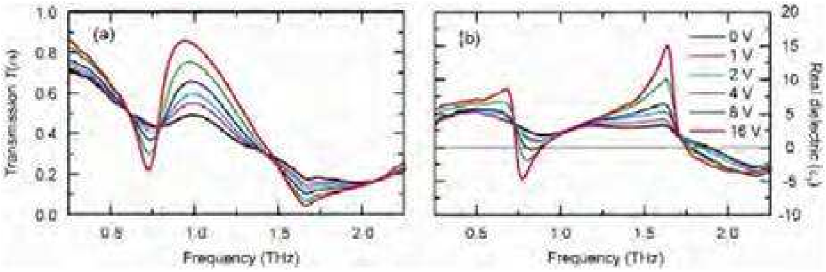


Figure 10: Modulation of THz resonant response by increasing voltage bias [1].

a topic relating to nanostructures and/or metamaterials. This project has laid the groundwork for that effort.

This project also provided me with much needed practice generating documents using LaTeX.

References

[1] Hou-Tong Chen, Willie J. Padilla, Richard D. Averitt, Arthur C. Gossard, Clark Highstrete, Mark Lee, John F. OHara, and Antoinette J. Taylor. Electromagnetic metamaterials for terahertz applications. *Terahertz Science and Technology*, 1(1):42–50, March 2008.

[2] G. Dolling, M. Wegener, C.M. Soukoulis, and S. Linden. Negative-index metamaterial at 780 nm wavelength. *Optics Letters*, 32(1):53 – 55, 2007. Metamaterial design;Negative-index metamaterial;Time-of-flight experiments;.

[3] Stefan Linden, Christian Enkrich, Martin Wegener, Jiangfeng Zhou, Thomas Koschny, and Costas M. Soukoulis. Magnetic response of metamaterials at 100 terahertz. *Science*, 306(5700):1351 – 1353, 2004. Metallic split rings;Negative permittivity;Optical spectra;.

[4] S.P. Mickan and X.-C. Zhang. T-ray sensing and imaging. *International Journal of High Speed Electronics and Systems*, 13(2):601 – 676, 2003. Sensing;T-rays;Terahertz (THz);.

[5] J.B. Pendry, A.J. Holden, D.J. Robbins, and W.J. Stewart. Magnetism from conductors and enhanced nonlinear phenomena. *IEEE Transactions on Microwave Theory and Techniques*, 47(11):2075 – 2084, 1999. Photonic crystals;.

[6] J.B. Pendry, A.J. Holden, W.J. Stewart, and I. Youngs. Extremely low frequency plasmons in metallic mesostructures. *Physical Review Letters*, 76(25):4773 – 4773, 1996.

[7] Xomalin G. Peralta, Evgenya I. Smirnova, Abul K. Azad, Hou-Tong Chen, Antoinette J. Taylor, Igal Brener, and John F. O'Hara. Metamaterials for thz polarimetric devices. *Optics Express*, 17(2):773 – 783, 2009. Beam splitters;Frequency ranging;Metamaterial (MM);Metamaterial structures;Metamaterials (MTM);Phase characteristics;Potential applications;Terahertz (THz) frequencies;Terahertz devices;Terahertz transmission;Wave plates;.

[8] V.M. Shalaev. Optical negative-index metamaterials. *Nature Photonics*, 1:41–48, January 2007.

[9] Hu Tao, N.I. Landy, Kebin Fan, A.C. Strikwerda, W.J. Padilla, R.D. Averitt, and Xin Zhang. Flexible terahertz metamaterials: Towards a terahertz metamaterial invisible cloak. *Technical Digest - International Electron Devices Meeting, IEDM*, 2008. Cylindrical shells;Invisible cloaks;Metamaterial;Multi layers;Polyimide substrates;Terahertz;Terahertz frequencies;.

[10] V. G. Veselago. The electrodynamics of substances with simultaneously negative values of epsilon and mu. *Soviet Physics USPEKHI*, 10(4):509–514, January-February 1968.

[11] T.J. Yen, W.J. Padilla, N. Fang, D.C. Vier, D.R. Smith, J.B. Pendry, D.N. Basov, and X. Zhang. Terahertz magnetic response from artificial materials. *Science*, 303(5663):1494 – 1496, 2004. Artificial materials;Terahertz devices;.

[12] Shuang Zhang, Wenjun Fan, B.K. Minhas, Andrew Frauenglass, K.J. Malloy, and S.R.J. Brueck. Midinfrared resonant magnetic nanostructures exhibiting a negative permeability. *Physical Review Letters*, 94(3):1 – 4, 2005. Left-handed material (LHM);Negative permeability;Optical frequencies;Split ring structure (SRS);.