LA-UR- 11-01275

Approved for public release; distribution is unlimited.

Title: Active Terahertz Metamaterials

Author(s): Hou-Tong Chen, Abul K. Azad, John F. O'Hara, Ranjan Singh, Jiangfeng Zhou, Matthew T. Reiten. Dibakar Chowdbury, Quanxi Jia, Stuart A. Trugman and Antoinette J. Taylor

Intended for: Invited Talk for IRMMW-THz Conference, 2011, Houston, USA

Los Alamos
NATIONAL LABORATORY
EST. 1943

Active Terahertz Metamaterials

Hou-Tong Chen, Abul K. Azad, John F. O'Hara, Ranjan Singh, Jiangfeng Zhou, Matthew T. Reiten.
Dibakar Roy Chowdhury, Quanxi Jia, Stuart A. Trugman and Antoinette J. Taylor*
Center for Integrated Nanotechnologies, Los Alamos National Laboratory, Los Alamos, NM 87544
*ttaylor@lanl.gov

***Abstract*—We present a series of novel THz metamaterials with designed active functionality, enabling dynamic tuning of the amplitude, frequency and polarization state of a THz wave.**

I. INTRODUCTION AND BACKGROUND

Electromagnetic metamaterials are structured composites with patterned metallic sub-wavelength inclusions. These mesoscopic systems are built from the "bottom up", at the unit cell level, to yield specific electromagnetic properties. Individual components respond resonantly to the electric, magnetic, or both components of the electromagnetic field. In this way electromagnetic metamaterials can be designed to yield a desired response at frequencies from the microwave through the visible. Importantly, additional design flexibility is afforded by the judicious incorporation of naturally occurring materials within the active region of the metamaterial elements. Specifically, hybrid metamaterial composites result when the properties of a natural material, e.g. semiconductors or complex oxides strongly couple with the resonance of a metamaterial element. The resulting hybrid metamaterials will still exhibit "passive" properties (e.g. negative electric response, negative index, gradient index, etc.), as determined by the patterning of the metamaterial elements. However, the aforementioned coupling engenders control of the passive metamaterial response via external stimulus of the natural material response (photoconductivity, nonlinearity, gain, etc.).

In recent years terahertz (1 THz = 10^{12} Hz) technology has become an optimistic candidate for numerous sensing, imaging, and diagnostic applications. Nevertheless, THz technology still suffers from a deficiency in high-power sources, efficient detectors, and other functional devices ubiquitous in neighboring microwave and infrared frequency bands, such as amplifiers, modulators, and switches. One of the greatest obstacles in this progress is the lack of materials that naturally respond well to THz radiation. The potential of metamaterials for THz applications originates from their resonant electromagnetic response, which significantly enhances their interaction with THz radiation. Thus, metamaterials offer a route towards helping to fill the so-called "THz gap".

In this work we present a series of novel planar THz metamaterials [1]. Importantly, the critical dependence of the resonant response on the supporting substrate and/or the fabricated structure enables the creation of active THz metamaterial devices. We show that the resonant response can be controlled using optical, electrical or thermal approaches, enabling efficient THz switches and modulators which will be of importance for advancing numerous real world THz applications.

II. RESULTS

In many THz and metamaterial applications it is desirable to develop electrically switchable THz metamaterials. We have demonstrated a unique design of hybrid THz metamaterial employing the Schottky diode structure [2]. When the all-connected metal metamaterial elements or split ring resonators (SRRs) are fabricated on a slightly doped semiconductor substrate (n-GaAs), a Schottky diode structure forms and the depletion regions can be actively controlled by applying a voltage bias between the metamaterial and substrate [Fig. 1(a) and (b)]. This leads to a modified conductivity of the substrate particularly near the split gaps, thereby actively switching the metamaterial resonant response and the THz transmission [Fig. 1(c)]. This device was fabricated by a standard semiconductor fabrication procedure, i.e., photolithography, e-beam deposition, rapid thermal annealing, and lift-off. THz time domain spectroscopy (THz-TDS) was used to characterize their performance at room temperature. The results show a switching/modulation depth of 50% for the transmitted THz intensity, which is one order of magnitude improvement over the existing electrically driving terahertz switch/modulator based on quantum well structures. Further, the switching speed of this device is ~100 kHz.

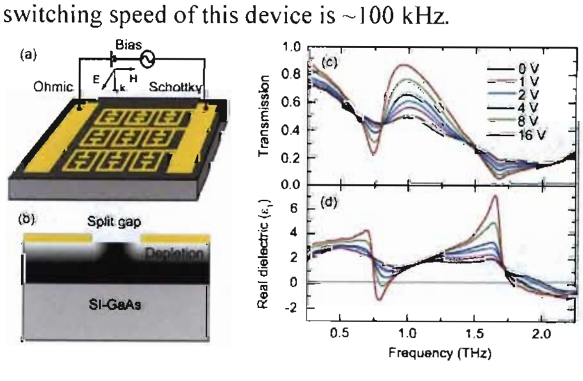

Figure 1: Electrically switchable THz metamaterials. (a) Schematic device design, (b) Schottky diode structure, (c) THz transmission spectra as a function of applied voltage, and (d) extracted real part of the complex dielectric function.

Improvement in this initial design of the split ring resonator such that the split gaps are directly connected to the ohmic contact, so that the full applied voltage can deplete charge carriers in the gap [3], rather than surrounded by the closed ring under which the substrate is also depleted in the design shown in Figure 1. In this design a power modulation depth of 80% has been demonstrated at a bias of 16 V and the amplitude modulation is shown to vary linearly with voltage.

Further, phase modulation of $\pi/6$ is demonstrated at 16 V, also with a linear voltage dependence. Broadband modulation (~1 THz), which combines phase and amplitude modulation, results between the two resonances. A 4x4 array of such modulators, operating around 0.35 THz has been integrated into a device which serves as a spatial light modulator for THz radiation [4].

The metamaterial resonant response inherently shows strong frequency dispersion and its consequent narrow bandwidth operation may severely restrict many applications. We have created a hybrid metamaterial whose THz resonance frequency can be optically tuned [5]. This metamaterial device is comprised of a two-dimensional array of split-ring resonators fabricated on a silicon-on-sapphire wafer, in which the silicon is selectively etched in such a way that we incorporate two silicon strips within each split-ring resonator element acting as variable capacitor plates [Fig. 2(a) and (b)]. This provides a new technique for 'designing' the optical response of a material. When the metamaterial is illuminated by near-infrared laser pulses, photoexcitation of free charge carriers in the silicon stripes causes the silicon to behave like a metal. This behavior changes the effective capacitance in the split-ring resonator elements thereby tuning the metamaterial's resonance frequency. We have experimentally demonstrated a tuning range of 20%, from 1.06 THz to 850 GHz [see Fig. 2(c)] in good agreement with numerical simulations [Fig. 2(d)]. Simulations based on two other split-ring resonator architectures has also been carried out suggesting that tuning to higher frequencies can be achieved by changing the inductance within the split-ring resonator elements.

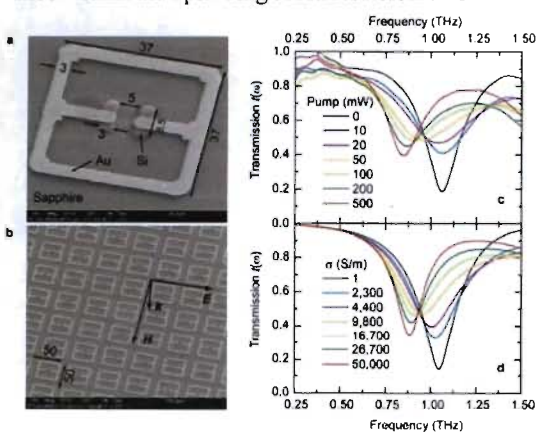

Figure 2: Frequency agile THz metamaterials. SEM graphs of (a) an individual unit cell and (b) periodically array with integrated silicon capacitor plates. (c) Experimental THz transmission spectra as a function of photo-excitation fluence, and (d) simulated results as a function of silicon conductivity.

We investigated the resonance properties and their tuning in superconducting THz metamaterials, where high temperature superconducting YBCO films replace metals to compose SRRs [6], as shown Fig. 3(a). By changing the temperature, we observed the resonance strength as well as frequency tuning in the superconducting metamaterials, as shown in Fig. 3(b) for a 50-nm-thick YBCO SRRs. More interestingly, we found that for thicker YBCO SRRs, increasing the temperature initially results in a lower resonance frequency but it shifts back to a higher resonance frequency after a temperature near Tc. We carried out numerical simulations and theoretical modeling of the metamaterial resonance by using the experimentally obtained temperature dependent complex conductivity of the YBCO film, in which the results agree very well with the experimental measurements. Theoretical investigation predicated that identical YBCO SRRs with smaller thickness should have a lower resonance frequency and higher tuning efficiency, which was experimentally verified. Additional experiments have shown that similar resonance tuning can also be accomplished by optical excitation, which excites the superconducting Cooper pairs back to their normal state. Note that such a tuning mechanism is by modifying the properties of materials composing the resonators rather than their surrounding environment.

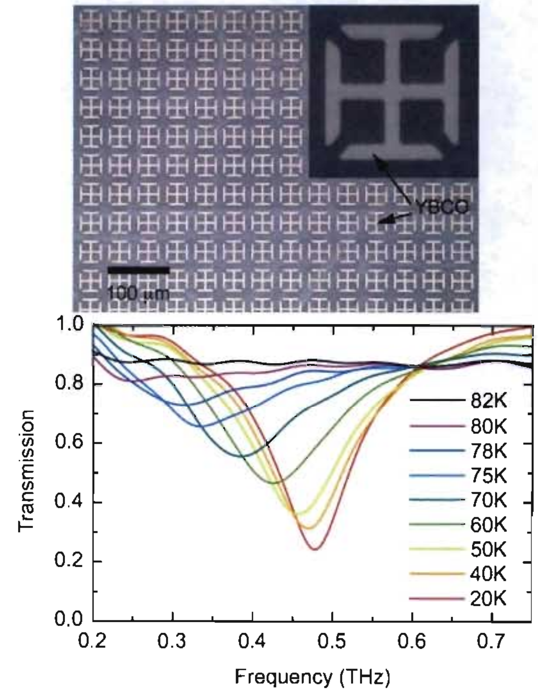

Figure 3: (a) Superconducting metamaterial where the superconducting YBCO forms the metal split ring resonator. **(b)** Amplitude spectra of THz transmission through a 50-nm-thick YBCO metamaterial at different temperatures.

Frequency tuning in metamaterials is very often accompanied with a large variation of resonance strength, which is undesirable and is caused by the varying losses after external excitations are applied. By fabricating the 200-nm-thick gold electric split ring resonator array on a single crystal strontium titanate ($SrTiO_3$ or STO) substrate, we demonstrated thermal tuning of the resonance frequency of ~43% when cooling the metamaterial from 409K to 150K, due to the temperature dependent dielectric constant of the STO substrate. There is very little variation in resonance strength, in contrast to other approaches employing semiconductors or superconductors.

The normalized THz transmission amplitude spectra are shown in Fig. 4(a) at the corresponding temperatures. At all these temperatures, the metamaterial exhibits a strong dip in transmission due to the resonant excitation of circulating currents by the incident THz electric field. The resonance experiences a gradual red shift from 0.223 THz at 409 K to 0.128 THz at 150 K. The total frequency shift in resonance is 95 GHz. This is due to the temperature dependent refractive index of the STO, which reveals an increasing refractive index with decreasing temperature. Since the fundamental resonance frequency of SRRs is approximately given by $\omega_0 = (LC)^{-1/2}$, where L is the loop inductance and C is the gap capacitance, the latter is directly proportional to the dielectric constant $\varepsilon = n^2$ (when the loss is negligible) of the STO, i.e. $\omega_0 \sim 1/n$. This is verified by the plots shown in Fig. 4(b), where excellent agreement is achieved in the temperature dependence of the resonance frequency ω_0 and the inverse of refractive index $1/n$ taken at the corresponding resonance frequencies.

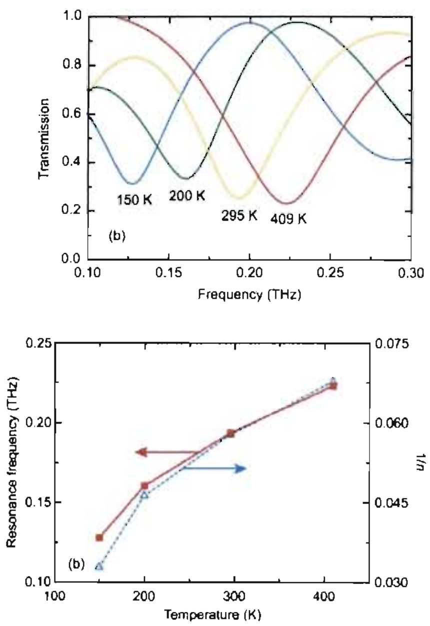

Figure 4: (a) Normalized transmission amplitude spectra through the STO metamaterial for a series of temperatures. (b) A comparison between the resonance frequency ω_0 and the inverse of refractive index indicating $\omega_0 \sim 1/n$.

III. CONCLUSION

In summary, we have demonstrated several novel planar THz metamaterial devices where the resonant response is actively controlled through external stimuli, using either electrical, optical or thermal approaches. Specifically we have demonstrated efficient amplitude switching and frequency tuning of THz radiation at room temperature, as well as thermal tuning of the frequency and amplitude. This enhanced interaction between THz radiation and metamaterials will enable the development of future THz functional devices with unprecedented performance, overcoming the materials issues associated with the "THz gap".

REFERENCES

1. H.-T. Chen, J. F. O'Hara, A. K. Azad and A. J. Taylor, "Manipulation of terahertz radiation using metamaterials," *Laser Photon. Rev.* **5**, 513 (2011).
2. 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 (2006).
3. H.-T. Chen, W. J. Padilla, M. J. Cich, A. K. Azad, R. D. Averitt, and A. J. Taylor, "A metamaterial solid-state terahertz phase modulator," *Nature Photon.* **3**, 148 (2009).
4. W. L. Chan, H.-T. Chen, A. J. Taylor, I. Brener, M. J. Cich, and D. M. Mittleman, "A spatial light modulator for terahertz beams," *Appl. Phys. Lett.* **94**, 213511 (2009).
5. 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," *Nature Photon.* **2**, 295 (2008).
6. H.-T. Chen, H. Yang, R. Singh, J. F. O'Hara, A. K. Azad, S. A. Trugman, Q. X. Jia and A. J. Taylor, "Tuning the resonance in high temperature superconducting metamaterials," *Phys. Rev. Lett.* **105**, 247402 (2010).
7. R. Singh, A. K. Azad, Q. X. Jia, A. J. Taylor and H.-T. Chen, "Thermal tunability in terahertz metamaterials fabricated on strontium titanate single-crystal substrates," *Opt. Lett.* **36**, 1230 (2011).