# Active THz Metamaterials

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***Abstract*— In this work, we demonstrate THz metamaterials exhibiting either amplitude control, via carrier injection or depletion in the active semiconductor substrate or frequency control, via photoexcitation of carriers into active semiconducting materials incorporated into the sub-wavelength metamaterial structure**.

## I. Introduction And Background

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" [1]. In this work we present a series of novel planar THz metamaterials. 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 or electrical approaches, enabling efficient THz switches and modulators which will be of importance for advancing numerous real world THz applications.

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, 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.). We describe here metamaterials operating at THz frequencies which exhibit either amplitude achieved by carrier injection or depletion in a semiconductor substrate which shunts the capacitive region of the metamaterial elements, as well as frequency control, achieved via the photoexcitation of carriers into active semiconducting materials incorporated into the sub-wavelength metamaterial inclusions.

## II. Results

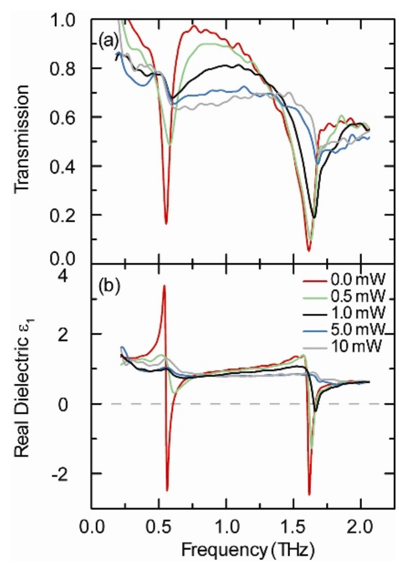


**Figure 1:** Dynamically switchable THz metamaterials via ultrafast photo-excitation of semiconductor substrate.

When planar THz metamaterials are fabricated on a high resistivity semiconductor substrate, their resonant response can be dynamically switched upon photoexcitation of substrate free charge carriers, which short-circuits the split gaps of the metamaterial elements and turn off the THz metamaterial resonance. In such a way, the metamaterial effective permittivity is switched between negative and positive values, and the THz transmission intensity is effectively modulated with very high modulation depth under relatively low photoexcitation fluence (~ $4 \times 10^{16}$ cm$^{-3}$ charge

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carrier density) (see Fig. 1). In GaAs, the resonance is extinguished on an ultrafast timescale (<1 ps); however, due to the long carrier lifetimes in crystalline semiconductors (GaAs, ~ 1 ns), the switching recovery time is relatively slow [2]. We overcome this problem by the use of MBE-grown ErAs/GaAs nanoisland superlattice substrates, where the carrier lifetimes can be designed to have desired values from sub-picosecond to tens of picoseconds [3]. With a designed carrier lifetime of ~10 ps, we demonstrate, using optical pump, THz probe spectroscopy, a switching recovery time of ~20 ps [4].

In many THz and metamaterial applications it is also desirable to develop electrically switchable THz metamaterials. We have demonstrated a unique design of hybrid THz metamaterial employing the Schottky diode structure [5]. When the all-connected metal metamaterial elements 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. 2(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. 2(c)]. This device was fabricated by a standard semiconductor fabrication procedure, i.e., photolithography, e-beam deposition, 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.

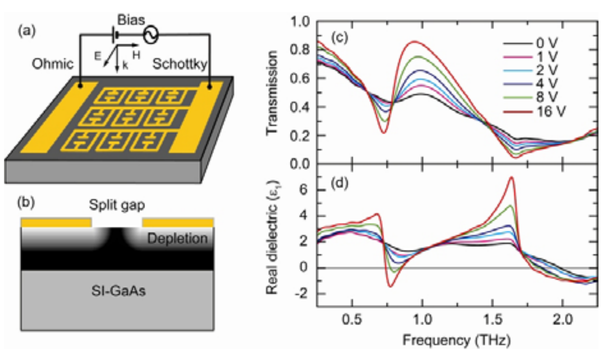


**Figure 2:** Electrically switchable THz metamaterials. (a) Schematic device design, (b) Schottky diode structure, (c) THz transmission spectra as a function of applied voltage, and (d) extracted real part of the complex dielectric function.

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. 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. 3(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. In the first attempt, we have experimentally demonstrated a tuning range of 20%, from 1.06 THz to 850 GHz [see Fig. 3(c)] in good agreement with numerical simulations [Fig. 3(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.

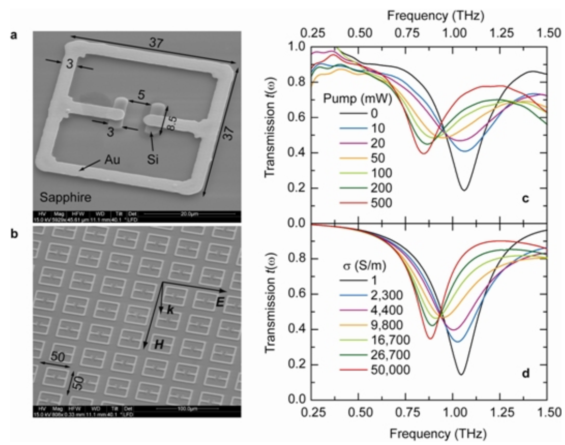


**Figure 3:** Frequency agile THz metamaterials. SEM graphs of (a) an individual unit cell and (b) periodically array with integrated silicon capacitor plates. (c) Experimental THz transmission spectra as a function of photo-excitation fluence, and (d) simulated results as a function of silicon conductivity.

In summary, we have demonstrated several novel planar THz metamaterial devices where the resonant response is actively controlled through external stimuli, using either electrical or optical approaches. Specifically we have demonstrated efficient amplitude switching and frequency tuning of THz radiation at room temperature. 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".

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