Ultrafast optical switching of terahertz metamaterials fabricated on ErAs/GaAs nanoisland superlattices

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We demonstrate optical switching of electrically resonant terahertz planar metamaterials fabricated on ErAs/GaAs nanoisland superlattice substrates. Photoexcited charge carriers in the superlattice shunt the capacitive regions of the constituent elements, thereby modulating the resonant response of the metamaterials. A switching recovery time of 20 ps results from fast carrier recombination in the ErAs/GaAs superlattice substrates. © 2007 Optical Society of America

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Metamaterials consisting of periodically patterned split ring resonators (SRRs) display a strong resonant electromagnetic response [1]. Importantly, the resonant frequency scales with the SRR dimensions. This is of particular importance for the terahertz ($1\ \mathrm{THz}=10^{12}\ \mathrm{Hz}$) regime, where naturally occurring materials rarely have a useful electronic or photonic response [2,3]. Recently, it has been shown that the resonance strength, and hence the transmission, can be controlled via external stimuli for planar metamaterials fabricated on semiconducting substrates [4,5]. This has resulted in efficient switching and modulation of freely propagating THz radiation, which is essential for many potential applications such as secure short-range communication.

Switching/modulation of THz radiation with an applied voltage was recently demonstrated using a hybrid structure consisting of a Schottky diode and a planar metamaterial array [5]. An external voltage controlled the conductivity of the semiconducting substrate at the capacitive split gaps, thereby modulating the metamaterial resonance strength. Owing to the large capacitance and series resistance, the device operates at a low switching/modulation rate (up to $\sim$10 kHz). An optically based approach has also been demonstrated where photoexcitation of free charge carriers in the semiconducting substrate shunts the metamaterial resonance [4]. The advantage of the optical approach is the possibility of extremely fast switching using femtosecond optical pulses. In this case, although the switching rise time can be very fast, the recovery time must also be minimized to achieve high bit rate modulation. For intrinsic GaAs this recovery time is of the order of nanoseconds due to carrier recombination. In this Letter, we demonstrate ultrafast switching of THz metamaterial with recovery time as short as 20 ps through engineering the substrate carrier lifetime using molecular beam epitaxy grown ErAs/GaAs superlattices. We note the recent progress in THz switching/modulation based on one-dimensional photonic crystals using GaAs as a defect layer [6]. Switching is achieved through photogeneration of carriers in GaAs, with a demonstrated switching time of $\sim$100 ps limited by the carrier recombination time.

Various methods to shorten the carrier lifetime in semiconductors have been employed including radiation damage and low-temperature growth to introduce defects. We use an ErAs/GaAs superlattice structure grown by molecular beam epitaxy on an intrinsic GaAs wafer. In the ErAs/GaAs superlattice structure, the carrier lifetime is strongly correlated with the period L [7]. In this work 20 periods with $L=100$ nm ErAs/GaAs superlattice results in a carrier lifetime of approximately 10 ps shown in Fig. 1, as determined using optical-pump THz-probe spectroscopy. Such a carrier lifetime is ideal to demonstrate ultrafast switching of THz metamaterials due

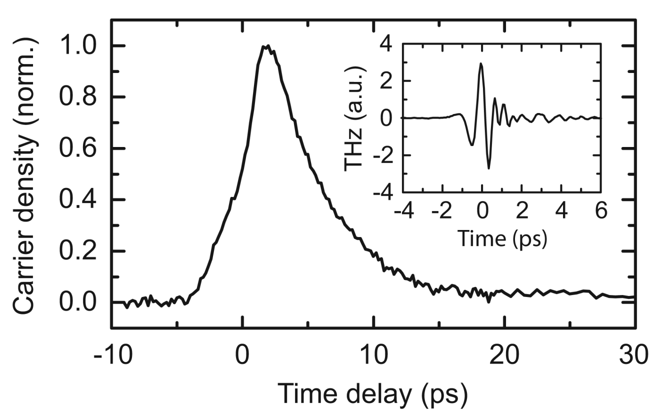

Fig. 1. Time dependence of the normalized carrier density following photoexcitation of the ErAs/GaAs superlattice, as measured by optical-pump THz-probe experiments. The inset shows the impulsive THz electric field time-domain waveform that probes the pump-induced changes in the metamaterial response.

to the picosecond duration of the THz pulses (see the inset of Fig. 1).

Electric metamaterials characterized in this work have previously been introduced, and we follow the notations and dimensions used therein [8,9]. The unit cells are illustrated in the insets to Figs. 2 and 3 for the original (OE2) and complementary (CE2) electric split ring resonators (eSRRs), respectively. They are periodically patterned on the ErAs/GaAs superlattice substrates using conventional photolithography with an electron-beam deposition of 10 nm of titanium for adhesion followed by 200 nm of gold. These metamaterials, in accordance with Babinet's principle, have shown complementary transmission properties, meaning that the transmission minimum in the OE2 sample corresponds to a transmission maximum in the CE2 sample, both characterized by a frequency-dependent permittivity $\epsilon(\omega)$ [9].

The optical-pump THz-probe experimental system has been described elsewhere [10]. The linearly polarized impulsive THz radiation is focused to an $\sim$3 mm diameter spot onto the metamaterials at normal incidence, with the field polarization indicated in the insets of Figs. 2 and 3. Synchronized femtosecond optical pulses with 100 fs pulse duration, 1 kHz repetition rate, and 800 nm center wavelength are expanded to $\sim$8 mm diameter, larger than the THz focal spot, to excite free charge carriers in the ErAs/GaAs superlattice substrates. At various time delays between the arrival of THz pulses and optical excitation, the transmitted THz electric field transient is measured. A second measurement of the transmitted THz pulse through an ErAs/GaAs superlattice without the photoexcitation and the metamaterial serves as a reference. The frequency-dependent transmission of the metamaterial structure is obtained by dividing the Fourier transform of the sample scan by the Fourier transform of the reference scan. This is performed at each delay such that the temporal evolution of the frequency-domain metamaterial response can be determined. We purposely engineered the ErAs/GaAs superlattices to have a lifetime of $\sim$10 ps to minimize artifacts that arise in the analysis when the sample response varies quickly in comparison with the THz pulse duration. However, ErAs/GaAs nanoisland superlattices can be engineered to have subpicosecond response times, making it possible, in principle, to have even faster switching and recovery times than what is demonstrated below.

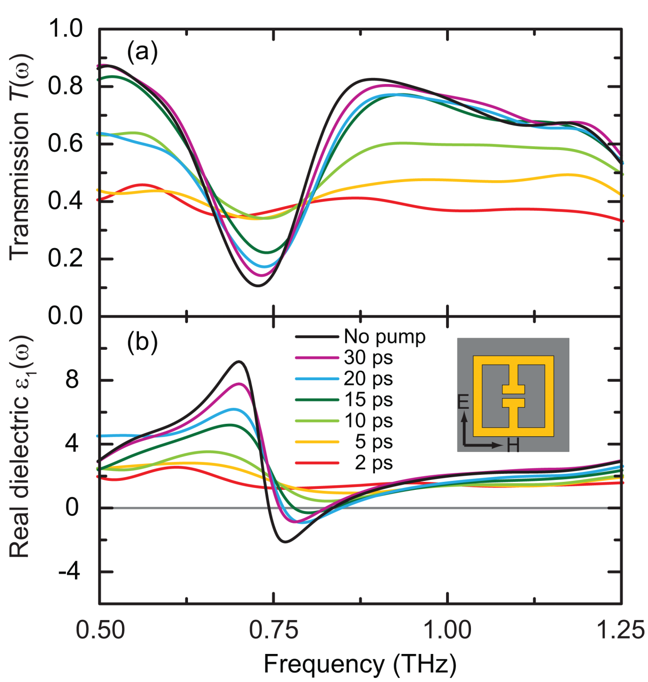

Fig. 2. (a) Frequency-dependent transmission of the eSRR array at various times following photoexcitation and (b) corresponding real part of the effective dielectric function. Inset, metamaterial eSRR unit cell; arrows, polarization of the normally incident THz radiation.

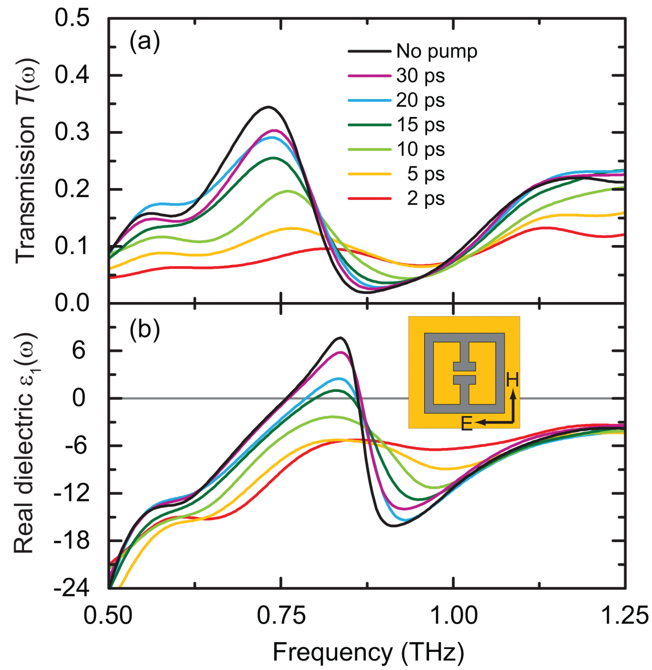

Fig. 3. Frequency-dependent transmission of the complementary eSRR array at various times following photoexcitation, and (b) corresponding real part of the effective dielectric function. Inset, complementary metamaterial eSRR unit cell; arrows, polarization of the normally incident THz radiation.

It has been shown that a substrate carrier density of 10^{16} cm^{-3} (corresponding to fluence of $\sim$1 μJ/cm^2) is sufficient to shunt the resonant metamaterial response [4,5]. The transmission changes of THz intensity in the composite metamaterial ErAs/GaAs structures are displayed in Figs. 2(a) and 3(a) for the original and complementary metamaterials, respectively. For OE2 (CE2), a strong resonant decrease (increase) occurs at 0.7 THz without photoexcitation. This pure electric resonant response (i.e., deriving from the effective permittivity $\epsilon(\omega)$) critically depends on the capacitive split gaps. Photoexcitation of carriers in the substrates shunts this capacitance, thereby decreasing the resonant strength. The resonant transmission for both OE2 and CE2 is turned off within 2 ps. As the substrate carriers are trapped and recombine, the resonant transmission characteristics reappear. For the present devices, nearly complete recovery is achieved within 20 ps following photoexcitation. Importantly, the magnitude of the transmission changes are much larger in comparison with the bare superlattice substrates, which have a 10% decrease in the THz transmission from the Drude response of the photoexcited carriers, indicating the importance of the planar metamaterials that dominate the electromagnetic response.

Following a procedure described elsewhere [9], we determine the effective frequency-dependent complex dielectric function of the metamaterials assuming a cubic unit cell. The real portion of the dielectric function is shown in Figs. 2(b) and 3(b) for the OE2 and CE2 metamaterials, respectively. Without photoexcitation, both display a Lorentz-like resonant response. For CE2 this is superimposed on a Drude-like response due to the interconnected topology of the metallization. Over a narrow frequency range the permittivity obtains negative (positive) values for the original (complementary) metamaterial. Photoexcitation shunts the Lorentz-like resonant response, thus switching the permittivity from negative (positive) values to positive (negative) values in the original (complementary) metamaterial.

The present approach is different from previously demonstrated THz waveform synthesis, in which the switching is accomplished during the THz pulse generation [11]. We switch and modulate the freely propagating THz waves by modifying the resonance strength of the planar metamaterials. The engineered carrier lifetime in the ErAs/GaAs superlattice substrates provides an advantageous ultrafast switching recovery time. This would also be very useful in THz pulse shaping. In contrast, many other resonant switches have slow recovery time due to unavoidable thermal effects. For instance, a similar phenomenon arises in the ultrafast switching of the mid-infrared surface-plasmon resonance through photoinduction of an insulator-to-metal phase transition. However, it takes tens of nanoseconds to recover to the insulating phase [12]. In the present approach metamaterials may simply be scaled to operate at other target frequency ranges, though to obtain a usable response the carrier density in the substrate must also be carefully considered. For applications such as short-range THz communication, the bit rate will, of course, be determined by the repetition rate of the optical pulses.

In summary, optical modification of the resonant response of metamaterials and appropriate engineering design of the supporting substrates enables construction of efficient THz functional devices such as THz switches and modulators. We have demonstrated ultrafast optical switching of the resonant response of THz metamaterials. A switching recovery of $\sim$20 ps was demonstrated by engineering design of the carrier lifetime of the ErAs/GaAs superlattice substrates upon which the planar metamaterial arrays were constructed.

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