Switchable Terahertz Metamaterials in Resonance Amplitude

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***Abstract*—Through integrating materials susceptible to optical intensity and electric field, the self-resonance and coupling of individual meta-atoms have been tailored with different excitations, achieving the dynamical modulation of broadband plasmon induced transparency, adjacent coupling and Schottky effect in terahertz metamaterials.**

I. INTRODUCTION

Recently, the concept of artificially engineered materials, known as metamaterials, has provided access to an even broader range of novel functionalities. In particular, active control of meta-atoms induced resonances attracts much interest in realistic applications, such as sensing, ultrafast switching and slow light propagation, and various active schemes have been exploited to manipulate the properties of electromagnetic waves in metamaterial-based devices. Here, we experimentally and theoretically demonstrate three types of active metamaterials in the terahertz regime, two of which can be optically manipulated through integrating photosensitive silicon islands into the metamaterial building blocks and the third with high-doped GaAs ingredient can be electrically controlled. These particular schemes enable an in-depth understanding of fundamental resonances and coupling mechanism, which can enable functionalities and applications for designing on-demand reconfigurable metamaterial and plasmonic devices.

The unit cell of the first meta-device is comprised of two pairs of identical and gap opposite-directed U-shape split-ring resonators (SRRs), symmetrically placed on both sides of a central metallic bar resonator, in which the silicon islands connect the arms of the opposite U-shape SRRs. Attributed to the modification of the damping rate in one of the resonance modes under optical excitation, the broadband transparency transmission window resulted from the mode coupling is dynamically modulated. The second active metamaterial sample with coaxial rectangle microstructures is also presented. Due to the coupling mechanism between adjacent meta-atoms, two pronounced transparent windows are produced. By carefully designing the position of silicon islands in the metamaterial unit cell, one or more transmission peaks can be dynamically modulated in amplitude individually or simultaneously under optical excitation. The unit cell of the third metamaterial consists of eight complementary C-shape split-ring resonators (SRR) with an equal phase increment of $\pi/4$ and identical transmission amplitude, fabricated on a doped semiconductor substrate. This metasurface device enables the generation of the outgoing orthogonally polarized wave for the frequency range from 0.48 to 0.93 THz. Meanwhile, the metamaterial arrays and the substrate together effectively form a Schottky diode, enabling the modulation of the cross-polarization diffraction through controlling the applied external voltage. The schemes suggested here are promising to construct active terahertz devices and to realize on-to-off switching response of the terahertz radiation at room temperature.

II. RESULTS

The amplitude of the broadband transparency window over a broad spectral range extending from 0.54 to 0.82 THz was dynamically modulated at room temperature, decreasing from 91% to 55% with optical excitation scaling from 0 to 1200 mW. The widely used coupled Lorentz model is adopted to reveal the coupling characteristics with varied optical excitations, showing the good agreement with the measurement, as indicated in Fig. 1. The analytical fit to the measured transmission amplitudes in the experiments demonstrates that the increasing of the pump power enhances the losses of the four U-shape resonators, namely suppressing the dark mode resonance, which hampers the destructive interference between the bright and dark modes. As a result, the broadband PIT transmission amplitude is actively tuned.

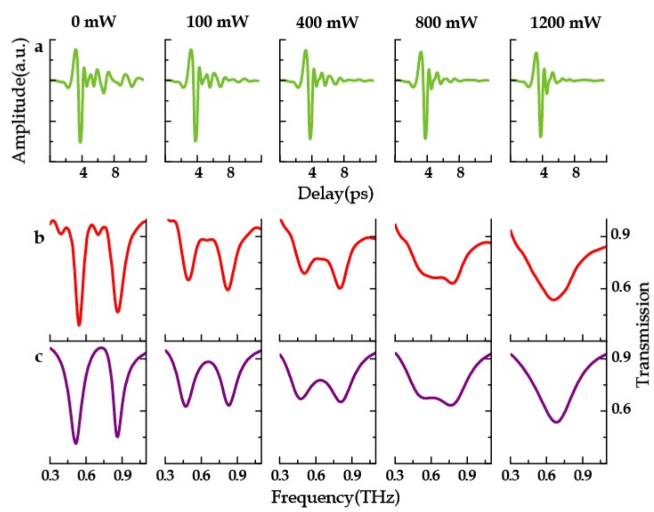

Fig. 1. (a) Experimentally measured temporal pulses. (b) Normalized transmission of the sample as a function of photoexcitation power. (c) Theoretical fitting results with various damping rates.

In the metallic concentric squares metamaterials, dynamic modulations of the transmission properties were observed by varying the optical pump power, as shown in Fig. 2. For the sample M123-12 with the Si islands connecting the outermost two rings, as the optical pump power was increased from 0 to 800 mW, the low frequency transmission window decreased gradually until it disappeared. Additionally, the transmission spectra of M123-23 with the Si islands bridging the innermost two rings were also measured under different photoexcitations. When increasing the pump power, the high frequency transparency window was dynamically controlled. Interestingly, both the cases possess a remarkable feature that has no impact on adjacent transparency window during the amplitude modulation. As the Si islands connected all the three rings (sample M123-123), the two transmission windows were simultaneously reduced in magnitude with increased optical excitation. At the maximum excitation of 1500 mW, the two transmission windows nearly disappeared. It is found that the active modulation arises from the enhanced loss of the resonances in the rings connected by the photoexcited Si islands and the reduced coupling between the two bridged rings.

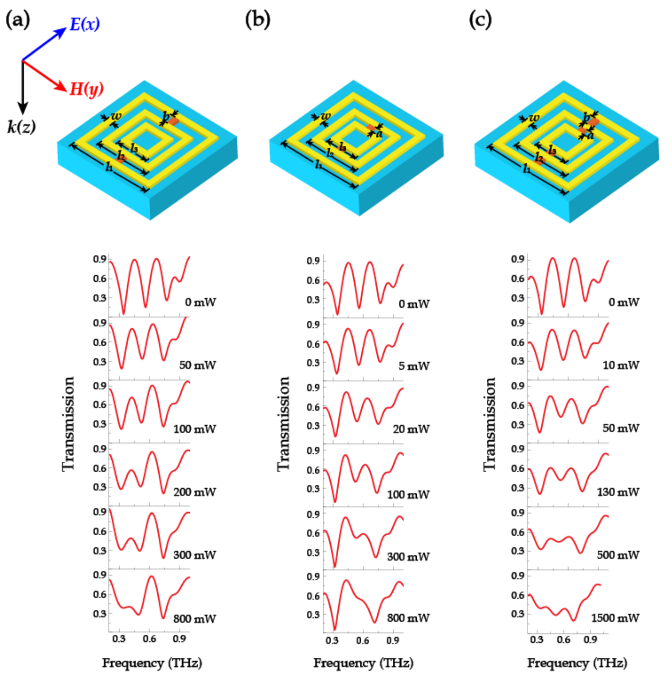

Fig. 2. (a)-(c) Schematic diagram of M123-12, M123-23 and M123-123 metamaterial unit cells, and Corresponding normalized transmission spectra as a function of photoexcitation power, respectively.

For the third case, without the applied external voltage, the deflected waves with orthogonal polarization propagated from the measurface reveal a broad frequency response from 0.48 to 0.93 THz in a broad angular range from 26^{o} to 81^{o}, but a relatively weak amplitude, as shown in Fig. 3. With the increase of the reverse voltage bias, the anomalous diffraction amplitude distinctly enhances, while the frequency range and deflected angle range remain unchanged. This is because the increasing reverse voltage bias depletes the free charge carriers of the n-GaAs layer under the metal structures and therefore, significantly reduces the dissipation near the C-shape SRR gaps, which strengthens the resonant behavior. At the reverse voltage bias, the intensity modulation depth as high as 46% is achieved, however, the obverse biases have negligible influence on it. The modulation speed can reach 3 kHz, which can be further improved through increasing the doped density of the n-GaAs layer and optimizing the contact form between the metal structure and substrate.

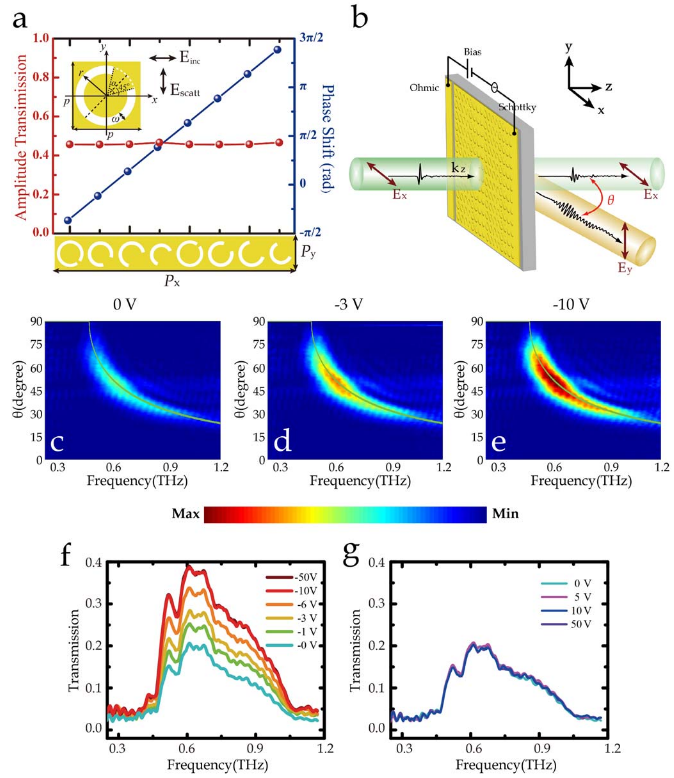

Fig. 3. (a) Calculated transmission amplitudes and phases of the cross-polarized radiation from eight complementary C-shaped SRRs in a unit cell. (b) Experimental diagram of the angular resolved terahertz time-domain spectroscopy system. (c)-(e) The measurement results with respect to the scan angles (y-axis) and frequency (x-axis) at three reverse voltage biases 0 V, -3 V and -10 V, with the x-polarized wave incidence and y-polarized wave detection. The color represents the relative anomalous diffraction amplitude, and the green lines are calculated result using the generalized Snell's law. (f) and (g) are the transmitted spectra of the deflected waves as a function of reverse and obverse voltage biases, respectively.

III. Summary

The theoretical and numerical analyses revealed that the modulation of these three active metamaterials is attributed to the suppression of the self-resonance or the coupling between adjacent resonance modes under external stimuli. The proposed design schemes open up a novel avenue to construct active metamaterial devices, broadening the potential applications greatly.

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