Engineering the Meta-Resonances toward Functional Terahertz Devices

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***Abstract*—We present unique terahertz response of metasurfaces and proof-of-concept elements and components with an ultimate goal of developing next generation integrated photonic terahertz devices.**

I. INTRODUCTION

METAMATERIALS are a new class of composite media that may be designed to interact with the electric or magnetic field, or both, of a propagating wave in ways not observed in natural materials. Numerous exciting phenomena including negative index of refraction, invisibility cloaking, and giant optical activities have been observed in metamaterials, showing potentials in developing subwavelength devices functioning in the terahertz regime. By use of the state-of-the-art terahertz spectroscopy and microelectronic processing, we study unique terahertz resonance properties of metasurfaces and proof-of-concept terahertz elements and components with an ultimate goal of developing next generation integrated photonic terahertz devices.

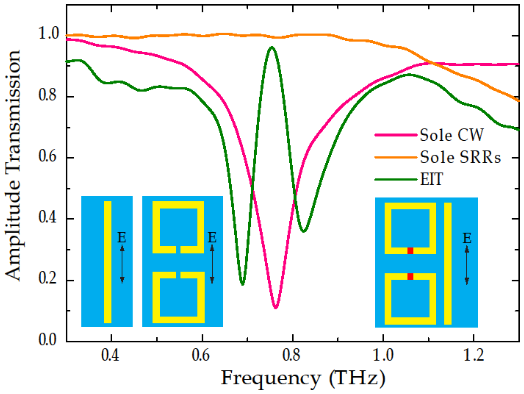

Fig. 1 Active controlled EIT analogues. Measured amplitude transmission spectra of the sole-cut wire (pink), SRR-pair (orange) and the EIT metasurface unit cell (olive) [1]. Insets: structural geometries of the sole-cut wire, SRR-pair and the EIT unit cell from left to right, respectively.

Metasurface analogues of electromagnetically induced transparency (EIT) and electromagnetically induced absorption (EIA) in near-field coupled subwavelength terahertz systems are experimentally demonstrated [1]. By use of optical photodoping and superconducting media, active switching of the EIT analogue is presented. Plasmonic metamaterials have recently allowed the observation of the quantum phenomenon of EIT as a result of the near-field coupling effect between a bright and a dark resonator, where the destructive interference of the resonance modes delivers a sharp window of nearly perfect transmission within a broad absorption band, as illustrated in Fig. 1. The EIT effect drastically modifies the dispersive properties of an otherwise opaque medium. In contrast to the destructive interference of the coupled EIT resonators, a constructive interference of different excitation pathways would lead to a new interesting phenomenon known as EIA. Instead of a pronounced transparency window, a sharp absorption resonance is induced in the EIA system [2].

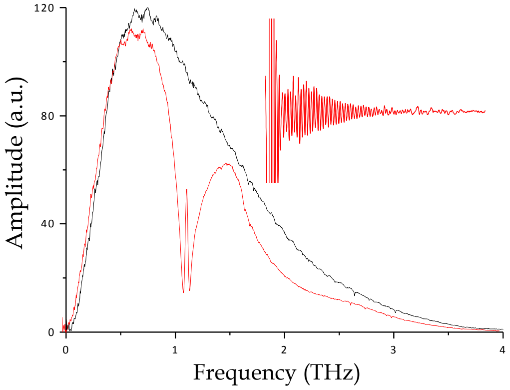

Fig. 2 Fourier transformed spectrum (red) achieved from the measured time-domain pulses of the dark quadrupole resonance in the asymmetric metasurface [3]. The black curve is the reference spectrum of a silicon wafer identical to the metasurface substrate. Inset: ringing feature in the time-domain signal following the main pulse of the metasurface.

Excitation of high-quality factor (Q) resonances in an asymmetric terahertz metasurface was observed. By introducing a weak asymmetry in a two-gap split-ring resonator, the radiative losses were tremendously suppressed through the excitation of dark quadrupole, showing much higher quality factors than that known from the single gap split-ring resonators. Interestingly, the quality factor decreases exponentially with an increasing degree of asymmetry. As shown in Fig. 2, a quality factor of 65 was achieved around 1.1 THz in the terahertz Fano resonators with a highest value of 227 [3]. The design was engineered where extremely sharp quadrupole as well as Fano resonances were excited at normal incidence for two different polarizations of the incident electric field.

Quasi-three-dimensional terahertz invisibility cloaks, comprised of either homogeneous or inhomogeneous media are experimentally realized [4,5]. Both the geometrical and spectroscopic signatures of a rectangular absorber placed under such a cloak were completely concealed. The inhomogeneous cloak which was lithographically fabricated using a scalable

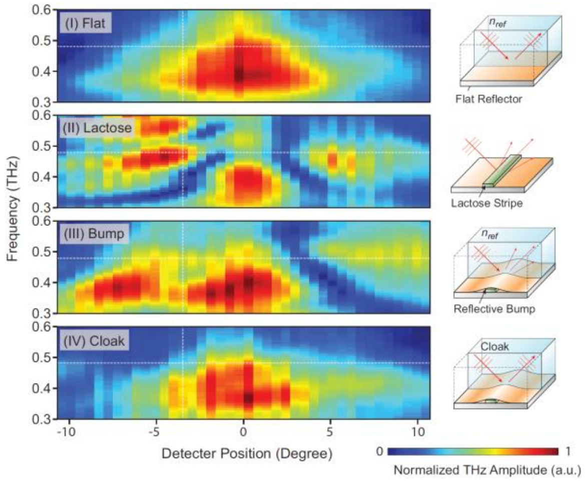

Fig. 3 Measured spectra of four different devices [4]. (I) Reflective flat reference, (II) exposed α-lactose monohydrate, (III) reflective bump, and (IV) cloak, are measured using reflection terahertz time-domain spectroscopy. The lactose (II) shows both a scattering effect and absorption. The reflective bump (III) avoids the absorption effect, but is still split into three peaks. The measured spot position of the cloak (IV) and the reflective flat (I) match reasonably well with each other.

Projection Microstereolithography process is characterized using angular-resolved reflection terahertz time-domain spectroscopy. The invisibility device has successfully concealed both the geometrical and spectroscopic signatures of the absorber, as shown in Fig. 3, making it undetectable to the observer [4]. The homogeneous cloaking device made from birefringent crystalline sapphire features a large concealed volume, low loss, and broad bandwidth [5]. Figure 4 shows measured results that compare between the cloaking effect for the TM incidence wave and the uncloaking case with the TE incidence. It is capable of hiding objects with a dimension nearly an order of magnitude larger than that of its lithographic counterpart, but without involving complex and time-consuming cleanroom processing. The cloak device was made from two 20-mm-thick high-purity sapphire prisms. The cloaking region has a maximum height 1.75 mm with a volume of approximately 5% of the whole sample. The reflected TM beam from the cloak shows nearly the same profile as that reflected by a flat mirror.

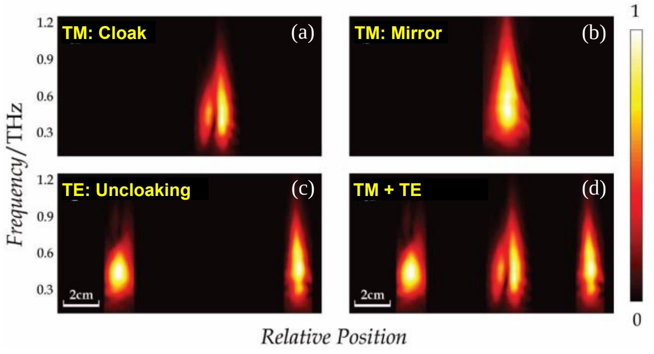

Fig. 4 Experimental results of the large-dimension homogenous cloak made from birefringent crystalline sapphire [5]: (a) the cloaking effect with the TM incidence; (b) the mirror reference with the TM incidence; (c) the uncloaking effect with split beam under the TE incidence; (d) the combined beam pattern with both the TE and TM incidences.

Near-field responses of metasurface devices are experimentally characterized using a near-filed scanning terahertz microscopic (NSTM) system [6]. Electromagnetic behaviors of subwavelength geometries in the near field is essential in in-depth understanding of their resonant responses and interactions with the incident waves. Such near-field information was normally acquired only through numerical simulations due primarily to lacking of functioning systems in the terahertz regime. Here, we experimentally implement the near-field mapping of electromagnetic responses of metasurface devices using a home-made fiber-coupled NSTM system, which was developed based on a photoconductive-switched time-domain spectrometer. Figure 6 shows the measured near-field results of a broadband metasurface flat-lens. The NSTM will also be used to explore plasmonic and graphene devices functioning in the terahertz regime [7].

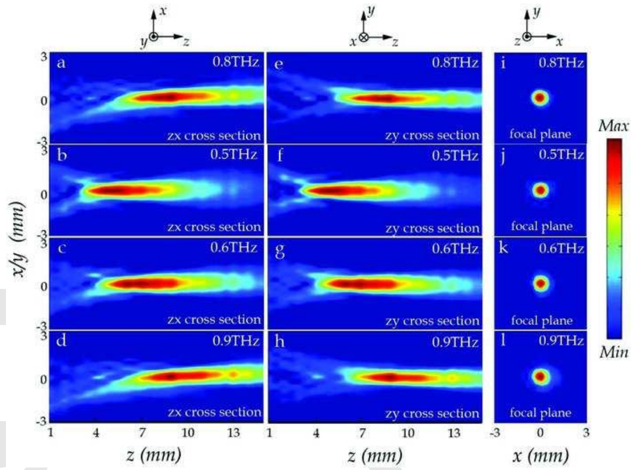

Fig. 5 NSTM characterized electric field distributions of the flat-lens made from a metasurface with phase discontinuities [6]. a-h) *y*-polarized electric field amplitude distributions in the *zx* and *zy* cross section at 0.8, 0.5, 0.6 and 0.9 THz, respectively. i-l) *y*-polarized electric field amplitude distributions on respective focal planes corresponding to 0.8, 0.5, 0.6 and 0.9 THz. The normal incidence is *x*-polarized.

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