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RESEARCH ARTICLE

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An ultrathin and flexible terahertz electromagnetically induced transparency-like metasurface based on asymmetric resonators

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Abstract. Terahertz (THz) electromagnetically induced transparency-like (EIT-like) metasurfaces have been extensively explored and frequently used for sensing, switching, slow light, and enhanced nonlinear effects. Reducing radiation and non-radiation losses in EIT-like systems contributes to increased electromagnetic (EM) field confinement, higher transmission peak magnitude, and Q-factor. This can be accomplished by the use of proper dielectric properties and engineering novel designs. Therefore, we fabricated a THz EIT-like metasurface based on asymmetric metallic resonators on an ultra-thin and flexible dielectric substrate. Because the quadruple mode is stimulated in a closed loop, an anti-parallel surface current forms, producing a transparency window with a transmission peak magnitude of 0.8 at 1.96 THz. To control the growing trend of EIT-like resonance, the structure was designed with four asymmetry levels. The effect of the substrate on the resonance response was also explored, and we demonstrated experimentally how the ultra-thin substrate and the metasurface asymmetric novel pattern contributed to higher transmission and lower loss.

Keywords: Terahertz / metasurface / EIT-like resonance

1 Introduction

Surface plasmons (SPs) are electronic oscillations that occur at the interface of materials with opposing permittivity, notably metals and dielectrics. At optical and infrared frequencies, EM waves can link to surface plasmons to form a propagating wave at metal-dielectric contacts, known as surface plasmon polariton (SPP). SPP waves can be excited in a variety of ways, including prism-coupled, grating-coupled, waveguide-coupled, and optical fiber [1]. Surface plasmon resonance (SPR) is the phenomenon of EM wave coupling to an SPP wave. Regardless of technique, SPRs amplify and confine EM field and have been widely used in photonic devices for a variety of purposes, most notably biosensing [2–7].

Metals are good conductors at THz frequencies (below plasma frequency) and may often be treated as simply perfect conductors; this prevents them from sustaining SPPs. To take advantage of SPPs' capacity in the THz regime, one feasible option is to use metals with textured surfaces that enable SPP-like modes, known as spoof surface plasmon. It is now possible to build a wide range of spoof surface plasmons [8] under the metamaterial paradigm.

Many metasurface applications rely on the creation of high Q-factor metasurfaces. We are primarily concerned with radiation losses in THz resonant-based metasurfaces, which should be decreased to increase the Q-factor. There are higher-order plasmonic modes, such as Fano and EIT-like resonance-based metasurfaces, that can satisfy this criterion.

Fano resonances were first found in quantum physics to explain asymmetrically structured atom and molecule ionisation [9]. The theory of Fano resonance was recently applied to the fields of photonics and metamaterials [10]. Exciting Fano and EIT-like resonances by breaking the symmetry of coupled resonators was first demonstrated in the microwave regime [10] and later in THz [11,12]. After that many research works studied these structures in THz metasurfaces [13–15]. By using an oblique incidence, they can also be induced in symmetric resonators [16,17].

Fano and EIT-like resonance-based metasurfaces give a substantial amplification of EM fields in their vicinity, as well as a greater Q-factor. Because they are caused by the interference of oscillators, they are naturally sensitive to changes in geometry or the immediate environment. As a

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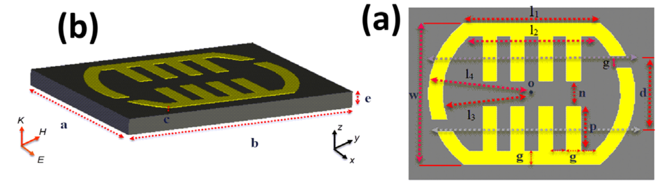

Fig. 1. Schematic representation of the designed metasurface's unit cells (a) top view of the unit cell with the circle center of O and the following parameters: $l_1 = 39$ μm, $l_2 = 36$ μm, $l_3 = 25.45$ μm, $l_4 = 29.45$ μm, $g = 4$ μm, $n = 8$ μm, $p = 14$ μm, $d = 20$ μm, $w = 44$ μm, (b) side view of the unit cell with following parameters: $a = b = 70$ μm, $c = 0.2$ μm, $e = 5$ μm.

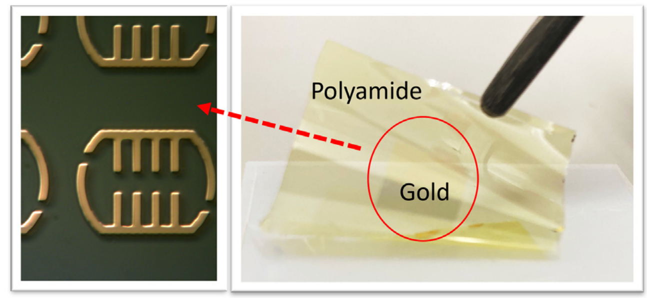

Fig. 2. Display of the metasurface's flexibility and image under an optical microscope.

result, even small perturbations can cause significant variations in their resonance spectra. This feature makes Fano and EIT-like resonances extremely appealing for a wide range of applications. They have been widely used for biological sensing where changes in the refractive index of biological samples can be manifested in the resonance frequency shift and transmission magnitude [18,19]. In the same manner, the sensitivity to local displacement or deformation of Fano and EIT-like structures can also be used to detect physical quantities such as displacement, temperature, or pressure by affecting their coupled oscillator properties [20]. The combination of Fano and EIT-like structures with nonlinear and phase-changing media opens up new possibilities for switching and electro-optics applications as well [7,21].

In order to develop THz Fano and EIT-like metasurfaces that properly meet the requirement in mentioned applications, we need to reduce the radiation and non-radiation losses in the system. This can be achieved by correct dielectric characteristics and engineering novel design to increase the EM field confinement and obtain a higher transmission window. Thus, we created a flexible EIT-like metasurface based on asymmetric SRRs on an ultra-thin polyimide. Because the quadruple mode is stimulated in a closed loop, an anti-parallel surface current develops, and by reducing radiation losses, a transparency window with a transmission peak magnitude of 0.8 develops at 1.96 THz. The structure was built with four asymmetry levels to tune the intensifying trend of EIT-like resonance, as well as the analysis of surface current, transmission peak magnitude, and FWHM parameters.

2 Simulation and experimental methods

The unit cell of the designed metasurface is made of asymmetric gold split ring resonators (SRRs) on a dielectric substrate, displayed in Figure 1. The material of the dielectric layer is polyimide with a thickness of 5 μm, a permittivity of 2.9, and a loss tangent of 0.05 at 1 THz.

THz waves are incident and interact with the gold metallic pattern before passing through the dielectric layer. The caption of Figure 1 shows the precise dimensions of the unit cell geometries. The asymmetry value between the coupled resonators, *d*, will be employed to tune the EIT-like resonance. The CST microwave studio software, which is based on a finite difference time domain (FDTD) solver, is used to simulate and optimise the metasurface resonance response. Along the *x*, *y*, and *z* axes, the electric, magnetic, and open (add space) boundary conditions are used.

Several processing procedures were used to create the metasurface sensor. A polyimide layer was spin-coated and baked on a silicon wafer and then a bilayer of photoresist was spin-coated onto the polyimide. Metasurface was patterned and built using maskless laser lithography and conventional developing process, respectively. A Ti and Au adhesion layer was deposited using a sputter coater. Finally, the wafer was submerged in hydrofluoric acid to remove the SiO_2 layer from the polyimide. Figure 2 depicts the fabricated metasurface with 6.3 × 6.3 mm in size and an array of 90 × 90 unit cells.

For the measurements, THz-TDS in transmission mode was used to analyze the transmission spectra. It has a coherent synchronized source and detector that provides instant amplitude measurement of the THz waves. The measurments performed in a setup using four F/2 parabolic mirrors in a conventional optical arrangement. To eliminate absorption from atmospheric water vapour, the THz beam path was purged with dry air. Samples were placed at the focal plane of the beam, normal to the beam axis, with a beam diameter of 3 mm. The frequency resolution was 10 GHz. The operating frequency is kept below 3 THz which is in adaption with THz-TDS and also for avoidance of the higher noise and water absorption in upper frequency ranges.

A mechanical delay stage provides a time delay between two split laser beams. A pump beam illuminates the low-temperature grown GaAs (LT-GaAs) photoconductive antenna to produce picoseconds THz waves which are then collimated and focused into the metasurface. The transmitted THz pulses are detected using electro-optic (EO) sampling technique by measuring THz-field induced birefringence of EO crystal with one of the split laser beams called probe beam. Time-domain THz response of the metasurface can be recorded using lock-in detection technique and then analysed in frequency-domain by performing fast Fourier transform (FFT).

3 Results and discussion

The transmission spectra of the structure in two cases of symmetric and asymmetric SRRs with asymmetry degree of 24 μm is presented in Figure 3a. While the symmetric

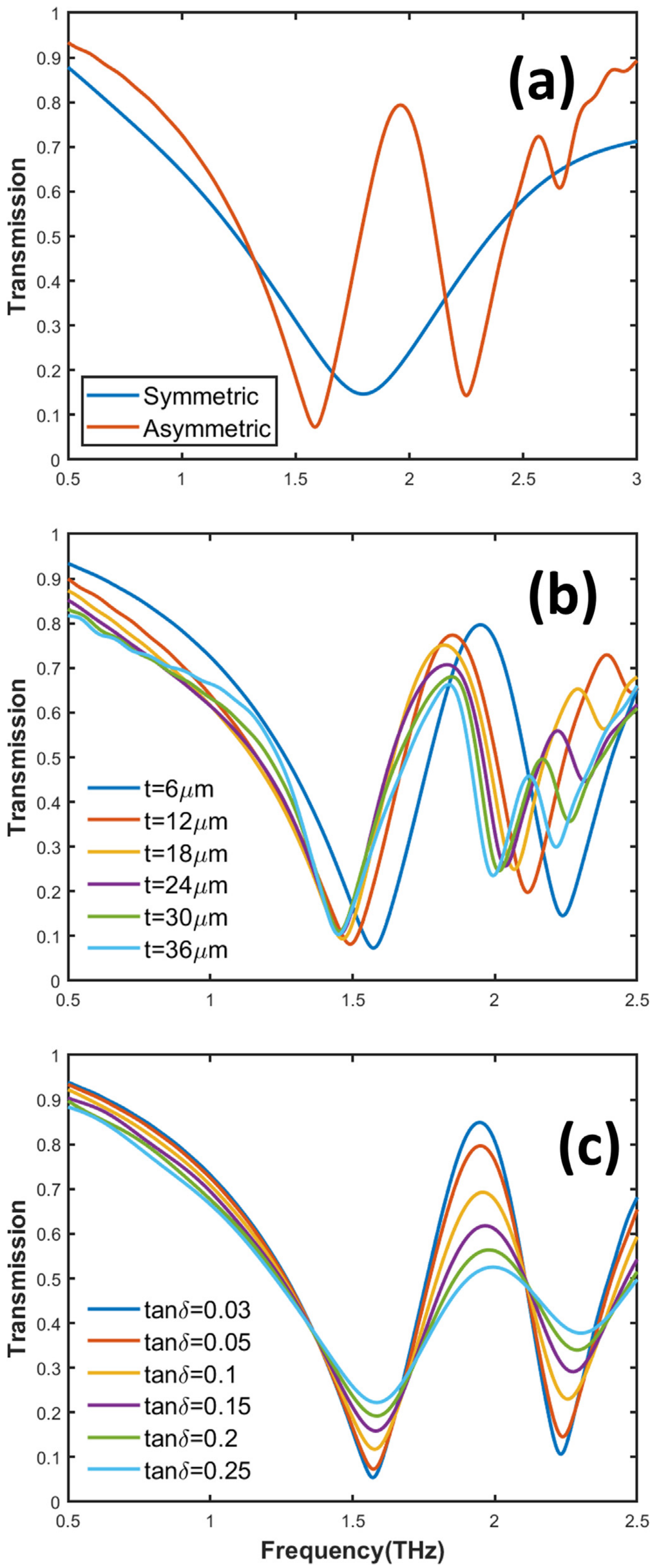

Fig. 3. (a) Transmission spectra of the designed EIT-like metasurfaces without and with asymmetry degree of 24 μm. (b) Transmission spectra of the metasurface simulated with various dielectric substrate thickness with fixed loss tangent of 0.05. (c) Transmission spectra of the metasurface simulated with various dielectric substrate loss tangent with fixed thickness of 6 μm.

structure shows a non-EIT-like resonance behaviour, the asymmetry structure with asymmetry degree of 24 μm causes an EIT-like resonance at 1.96 THz with a transmission peak magnitude of 0.8. The concept of forming the EIT-like resonance can be understood based on the characteristics of the atomic system. In the same manner, the photonic structure must consist of two resonance elements: "bright," which is strongly coupled to the input light and has a short radiative lifespan, and "dark," which is weakly coupled to the incident wave and has a long lifetime. When the resonance frequency of the bright mode equals the resonance frequency of the dark mode and their Q-factor contrasts significantly, the Fano resonance is referred to as EIT-like resonance. In the absence of coupling, the incident wave's energy is scattered into free space by the bright resonator. When the bright and dark resonators are coupled, the system's EM response improves dramatically, and the energy received through the bright mode is transmitted to the dark mode at the resonance frequency of 1.96 THz. As a result, absorption and scattering losses are considerably reduced, and a transparency window forms which with increasing asymmetry rises more upward.

Because of the short interaction length (radiation with metal) in THz resonant-based metasurfaces, an ohmic loss is frequently overlooked, and in the case of a dielectric substrate, related losses can be decreased by selecting a low-loss material. Therefore, we investigated the effect of substrate dielectric thickness and loss tangent on the THz spectrum of the designed metasurface. According to Figure 3b, narrower thickness results in better transmission and narrower linewidth, which is consistent with predictions. Furthermore, the effect of the dielectric loss tangent, as shown in Figure 3c, displays a direct relationship with the magnitude of the transmission peak and the full width at half maximum (FWHM).

As a result, selecting a dielectric substrate with the correct characteristics aids in providing a stronger transmission window peak. Then, for the final fabrication, we used an ultrathin 6 μm polyimide with permittivity as low as 2.9 and a loss tangent of 0.05. This ultra-thin substrate provides mechanical support as well as lower loss. Another advantage of using this substrate is its flexibility, which eliminates several barriers in practical applications [22].

When the asymmetry degree d is applied, the coupling between the bright and dark resonators occurs, breaking the resonance equilibrium in the nearby arms. Figures 4a–4d depict the EM simulation and experimental transmission spectra of the structures with four asymmetry values of 16, 20, 24, and 28 μm. Except for a minor discrepancy due to fabrication error, the simulations and observations of both the transmission magnitude and phase are in good agreement. Due to the coupling of the bright and dark modes, the peak of the EIT-like resonance occurs at 1.96 THz. As can be seen in Figures 4a–4d, as the asymmetry degree d grows from 16 to 28 μm, the coupling strength between the resonators steadily increases and the peak transmission intensifies, resulting in a quadruple EIT-like mode with narrower linewidth and stronger transmission window [10].

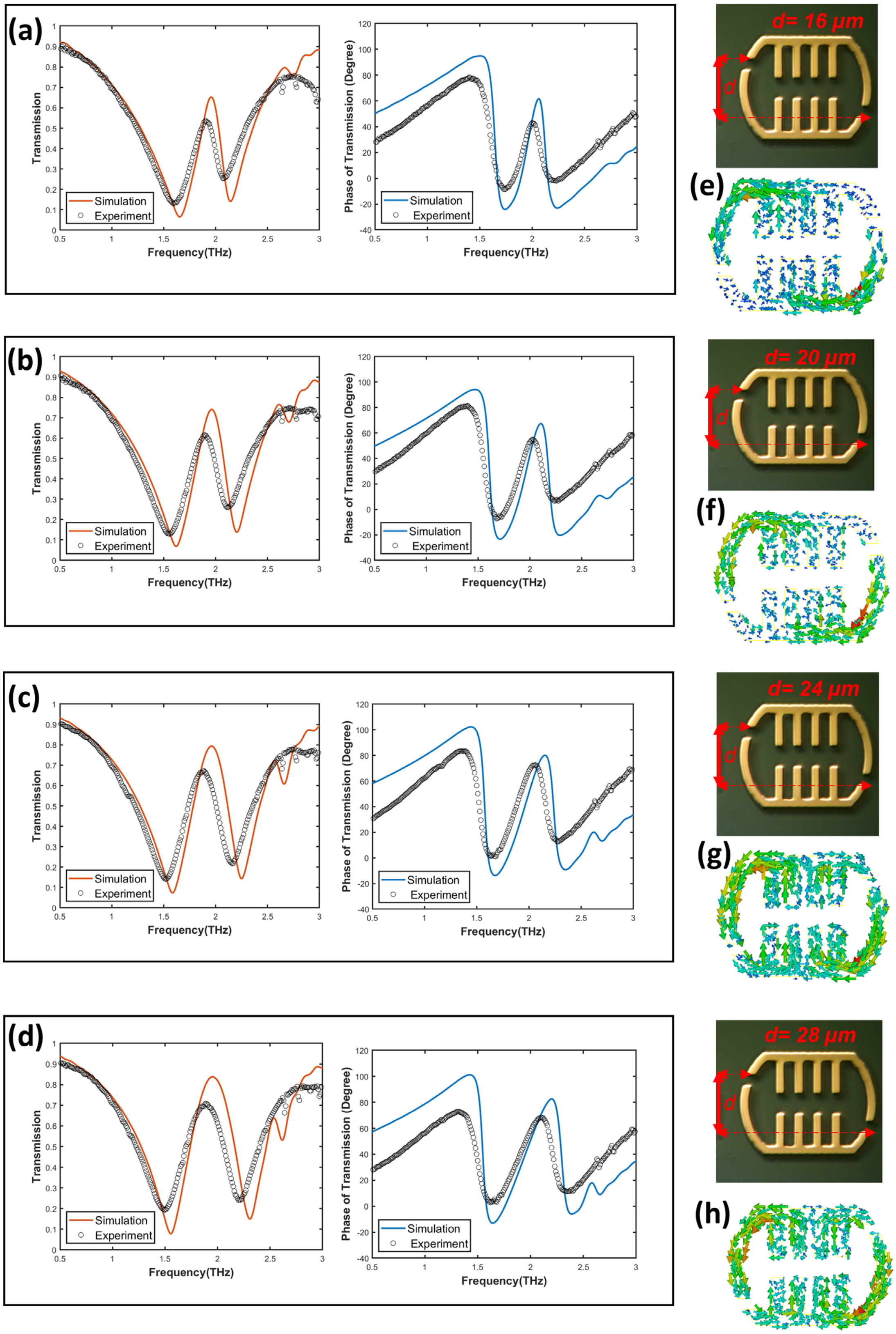

Fig. 4. The magnitude and phase of transmission spectra for the designed THz metasurface as measured (black circle) and simulated (brown line) for (a) $d = 16$ μm, (b) $d = 20$ μm, (c) $d = 24$ μm and (d) $d = 28$ μm along with their corresponding physical asymmetry degree and surface current distribution represented in (e–h).

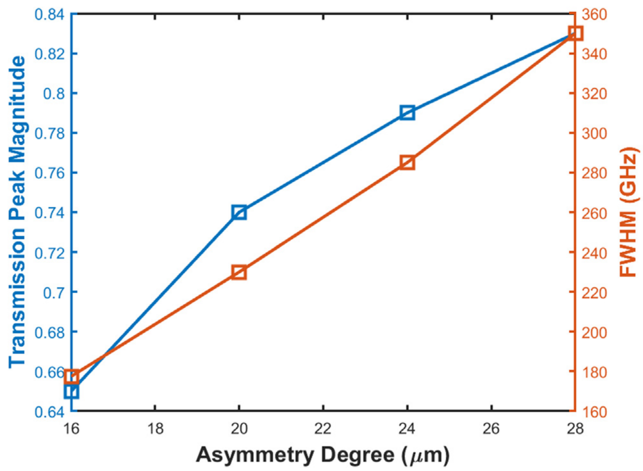

Fig. 5. Variation in FWHM and transmission peak magnitudes of designed metasurfaces with four degrees of asymmetry.

In order to analyze the EIT-like effect, the current distribution of the structure is depicted at the transmission peak of 1.96 THz in Figures 4a–4d. In response to the activation of the quadrupole mode, a magnetic dipole arises between coupled resonators, resulting in anti-parallel surface currents in a closed loop for $d = 16\,\mu\text{m}$. At this frequency, a transparency window forms, and radiation losses are inhibited. The magnetic dipole and surface current becomes stronger when the asymmetry degree increases gradually to 20 and 24 μm and finally at 28 μm, we observed the strongest surface circulation current.

We have calculated the transmission peak magnitude and FWHM of the transmission spectra of the four structures and the results are shown in Figure 5. It shows that with increasing the asymmetry degree, the transmission peak rises and the linewidth gets wider. Then, although the design with an asymmetry value of 28 μm has a higher transmission peak magnitude than 24 μm, it suffers from a lower FWHM, and with considering a tradeoff, the metasurface with an asymmetry degree of 24 μm finalized. In comparison with the literature, the measured transmission peak magnitude is higher and FWHM is narrower [23], [24]. Reference [25] uses the etching technique combined with Fano resonance in a THz metasurface to suppress more losses and increasing the performance in liquid sensing application in which measured maximum 0.5 in transmission peak magnitude with wider line width for the bare structure. Another THz EIT-like metasurface introduced by [26] for polymer sensing reported transmission peak magnitude of less than 0.6 with wider line width.

4 Conclusion

In conclusion, we demonstrated a flexible THz metasurface biosensor made up of asymmetric resonators on an ultra-thin and flexible dielectric polyimide that induces EIT-like resonance. For four asymmetry levels, we reported experimental proof of bright-dark mode coupling at 1.96 THz and transmission peak magnitude higher than 0.8. The novel design and ultra-thin dielectric helped to reduce radiation losses, resulting in a higher transparent window peak magnitude with a narrower line width.

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