Compact and Multi-Resonant Plasmonic Metamaterials Based on Nano-Apertures

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Abstract

We investigate a nano-aperture based plasmonic metamaterial by integrating the U- and T-shaped nano-aperture antennas in a compact geometry. We experimentally and numerically demonstrate the physical origin of the multi-resonant behavior of the UT-shaped nano-aperture based metamaterials. We also determine the parameter dependence of the proposed nano-aperture antennas. Due to its compact geometry, multi-spectral response, and enhanced near field distributions, our design offers greater flexibility in applications of subwavelength lithography, wavelength-tunable filters, optical modulators, ultrafast switching devices, and biosensing.

1. Introduction

Metamaterials have gained tremendous interest over the past few years due to their unusual electromagnetic properties, which can be useful for negative refractive index materials, perfect lensing, bio-sensing, and invisibility cloaking [1-4]. The electromagnetic properties of metamaterials are derived mainly from the resonating elements rather than atoms or molecules as in conventional materials [5]. Engineering metamaterials with multiple resonances that can be tuned from mid- to near-IR wavelengths could have indepth consequences for chip based optical devices, active filters, optical modulators, and bio-sensors [1-5]. A microwave dual-band negative-index metamaterial was fabricated [6] and experimentally confirmed as a multi-frequency resonator [7]. Recently, near-IR metamaterials with dual-band negative-index characteristics were also reported [8,9]. Obtaining such unique electromagnetic responses require investigation of novel metamaterial designs. As a result, many researchers have focused on subwavelength apertures, resulting in unusual high transmissions, in the optical [10], infrared [11], terahertz (THz) [12], and microwave [13] frequency ranges. The optical characteristics of the apertures are highly dependent on the refractive index of the adjacent medium [14], the shape and orientation of the apertures [15], aperture diameter [16], film thickness [17], and lattice geometry [18].

In this study, we propose a compact metamaterial composed of integrated U- and T-shaped nano-apertures supporting multi-spectral resonances as shown in Fig. 1. We investigate the spectral response of the nano-aperture based metamaterial antenna both numerically and experimentally. In order to understand the physical origin of the multi-resonant behavior, we analyze the structure by using finite difference time domain (FDTD) method. For further confirmation, we experimentally investigate the spectral responses of the individual U- and T-shaped nano-aperture antennas and compare the experimental results with the numerical analysis. We also determine the parameters that can enable fine control of the resonance features. Due to the multi-spectral response and enhanced near field distributions,

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the proposed metamaterial structure can be useful for wide range of applications, such as wavelength-tunable active filters, optical modulators, ultrafast switching devices, and biosensing.

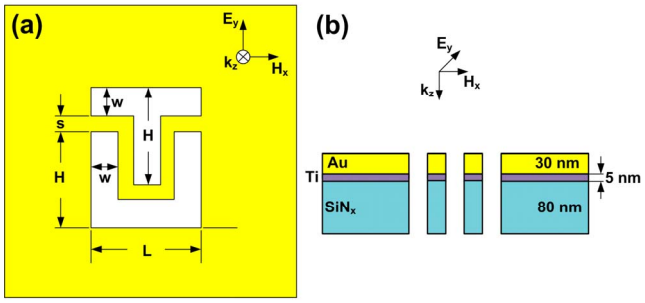


Fig. 1. The schematic view of the proposed UT-shaped metamaterial antenna design (a) Top (b) Side view.

2. Numerical analysis and fabrication process

Fig. 1 shows the schematic view of the proposed UT-shaped metamaterial antenna design. In this figure, L indicates the length of the structure, H indicates the height, w indicates the gap width, and s shows the distance between the individual U- and T-shaped apertures. We investigate the spectral response of the proposed antenna both numerically and experimentally. For the numerical analysis, the UT-shaped nano-aperture antennas are modeled by FDTD method [19]. During the simulations, the dielectric constants of Ti and Au are taken from Ref. [20]. In the unit cell, consist of the two individual elements, periodic boundary conditions is used along x and y axes and perfectly matched layers are used along +z, the direction of the illumination source.

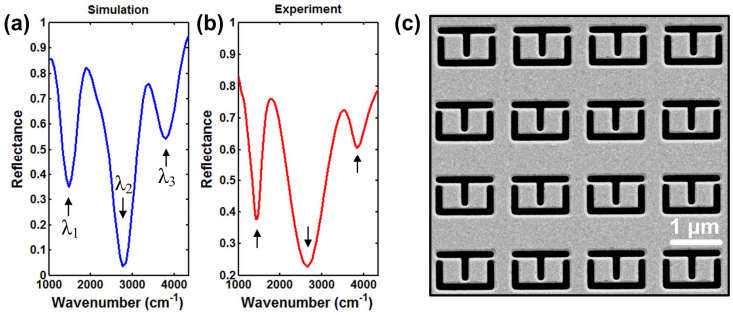


Fig. 2. Calculated and measured reflection spectra and SEM image of the proposed UT-shaped metamaterial antenna. (a) Numerical and (b) Experimental results (s = 180 nm, w = 120 nm, H = 720 nm, and L = 1200 nm) (c) SEM image of the fabricated structures.

The scanning electron microscope (SEM) image and the optical responses of the fabricated nanostructures are shown in Fig. 2. Calculated and measured reflection spectra, given in Fig. 2(a) and 2(b), clearly show that the proposed nano-aperture antenna have multiple resonances at the mid-IR wavelengths. For the experimental demonstration of the calculated multi-resonant characteristic, the proposed UT-shaped nano-aperture antennas are fabricated on a free standing 80 nm thick silicon nitride (SiNx) membrane. Fabricated structures are characterized optically by a Fourier transform infrared (FTIR) microscope. Our experimental set-up consists of an IR microscope coupled to a BrukerTM FTIR spectrometer with a KBr splitter [21]. Electromagnetic radiation, normally incident to the array (along the

z-direction shown in Fig. 1) with the incident E-field polarized parallel to the aperture arms, is used to efficiently couple the light to the resonators. Polarized light source is normally incident on the nanopatterned surface. Reflected infrared signal is collected by a Cassagrian reflection optics (NA = 0.4) and coupled into a liquid N_2-cooled mercury cadmium telluride detector. Reflection data are normalized using an optically thin gold standard.

3. Experimental results

We fabricated different UT-shaped nano-aperture antenna arrays for the experimental investigation of the parameter dependence. The results of these experiments are illustrated in Fig. 3(a), 3(b), and 3(c), for L, H, and w, respectively. Increasing w slightly changes the resonance wavelengths while increasing H and L result in a strong red-shift in the reflection spectrum. Fig. 3(d) shows that there is a linear relation between the resonance wavelength and the aperture length. According to the H dependence shown in Fig. 3(b), second order mode shows much weaker variations than the first and third modes. Therefore, changing height (H) which increases the tail of the T-aperture does not strongly effect the overall spectral position of the second mode. This is not the case for the first and third order modes as they are localized in the U-shaped apertures. Although our proposed structure operate in mid-IR frequency range, by scaling the geometry of the compact structure, the resonance locations can be tuned over a wide range, from mid-IR to visible wavelengths.

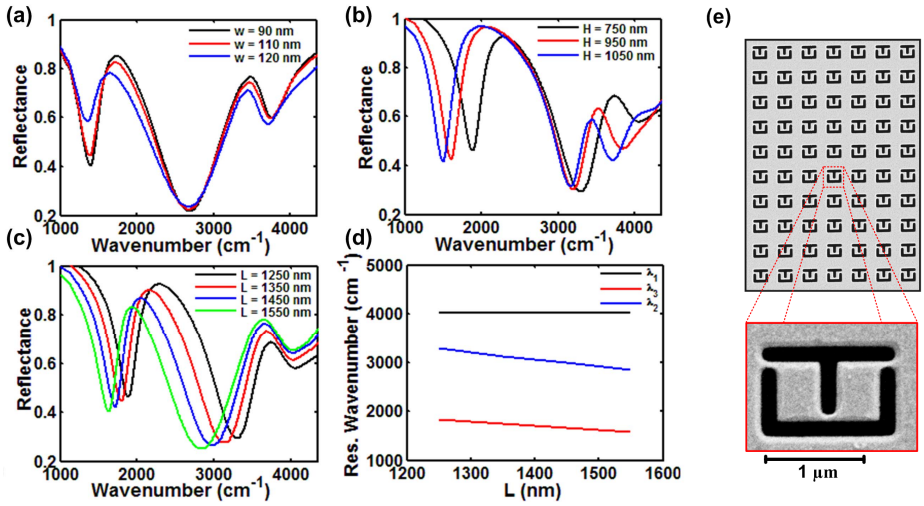


Fig. 3. Measured results (a) s, L and H are fixed while w is varied (L = 1250 nm, s = 140 nm, and H = 750 nm) (b) s, w and L are fixed while H is varied (L = 1250 nm, s = 140 nm, and w = 230 nm) and (c) s, w, and H are fixed while L is varied (H = 750 nm, s = 140 nm, and w = 230 nm) (d) The three resonance dips (cm^{-1}), λ_1, λ_2, λ_3 as a function of length (nm) (e) SEM images of the UT-shaped nano-aperture array with a zoomed single unit cell.

4. Conclusion

In conclusion, we introduce a novel nano-aperture based metamaterial design based on coupled U- and T-shaped nano-apertures. By using nanostructured resonators, we show that light can be manipulated on a chip and multi resonant behavior can be obtained with compact antenna geometry. The proposed nano-aperture antenna can support multi-band of operations and act as a highly frequency selective device. Metamaterials with tunable

resonances from mid-IR to visible wavelengths could have far-reaching consequences for chip based optical devices, active filters, optical modulators, and bio-sensors. Finally, our design shows high near-field resolution, which can be useful for near field imaging and surface enhanced spectroscopy.

5. Acknowledgments

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