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Design, Fabrication and Characterization of Wide-Band Metamaterial Absorber for THz Imaging †

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Abstract: In this paper, designs and optimization of wideband THz metamaterial absorbers (MMA) is proposed. By simulation, we reached four structures with absorptions higher than 50%, 70%, 80%, and 90% with relative absorption bandwidths (RABW) of 1.43, 1.29, 0.93, and 0.72, respectively. Terahertz absorbers can be used in many potential applications such as in imaging, energy harvesting, scattering reduction, and thermal sensing. Our intended application is to use an optimal absorber on a thermal detector for the detectivity in a wide THz range. Since a broadband absorption in the range of 0.3 to 2 terahertz is considered for use in medical imaging, the MMA with more than 50% absorption in the range of 0.35-2.1 THz has been selected to be achieved. The designs are also intended to have the capability to be implemented on different devices such as bolometers. The cost of the fabrication of the proposed absorbers is also low, because of the implementation of single-layer MMA design, and utilization of affordable and more accessible materials and techniques. Our proposed structure has a minimum feature size of 3 μm making the fabrication process convenient using the standard photolithography method as well. We used thin layers of Nickel as a metal for both single-layer pattern and ground layer which are placed on the front and back sides of the structure respectively. The Nickel thin film layers are deposited using the sputtering technique and are separated by a dielectric layer. The material chosen for the dielectric layer is SU8 which has proper electromagnetic properties and also has good adhesion to Nickel. Characterization of the fabricated absorber has been performed using a terahertz spectroscopy system, and the experimental results verified the high absorption of the sample.

Keywords: Terahertz; Metamaterial absorber; THz Imaging; Detectivity; Wideband absorption

1. Introduction

The extraordinary electromagnetic properties of all materials, many of which are not found in nature, have been widely studied in recent years from the visible to the microwave [1,2]. They have been of research attention for characteristics like negative refraction[3], invisible cloak[4], energy harvesting[5], imaging lens[6], and wave absorption[7,8]. The latter has been widely used in applications like THz radiation detection, imaging, filters, and spectroscopy.

To absorb the incident wave in the detectors, we need an absorber of electromagnetic waves (EM) and we know that the detection rate is proportional to the amount of absorption[9]. Therefore, we need to design an absorber with significant absorption in a wide frequency range in the terahertz region, in other words, a broadband terahertz absorber. Most materials in nature have absorption at separate frequencies, which results in a small absorption bandwidth. This is where metamaterials come into play. Electromagnetic metamaterials are artificially engineered materials arranged in sub-wavelength dimensions and can be modeled as materials with negative effective electrical permittivity (ε(ω)) and negative magnetic permeability (μ(ω)) values. Therefore, they have a refractive index of less than zero[10,11]. Veselago was the first person who publish a theoretical analysis of materials with negative electric permittivity and magnetic permeability[12]. Metamaterials are an excellent choice for use in electromagnetic wave absorbers in order to increase the absorption bandwidth[13]. Landy and Tao designed and fabricated the first metamaterial absorber[14].

Early designed metamaterial absorbers were not broadband and did not absorb (eg absorption above 50%) over a significant frequency range and only had absorption peaks at some isolated frequencies. The need to increase the absorption bandwidth [in order to access a larger frequency range depending on their application] encouraged scientists to look for the design of broadband structures[15–22].

Here we have designed four different THz broadband absorbers for different purposes. In these designs, we have used nickel as an absorbent layer material, which causes high losses and increased absorption due to its high permeability coefficient. Also, for the dielectric, we used a low-cost and available photoresist material so that the fabrication process can be done easily and at a low cost, and these absorbers can be implemented on different devices. In addition to the appropriate selection of materials, we have used suitable designs for different structures, which by using combination of substructures with different dimensions and optimizing these dimensions, the absorption peaks caused by each substructure are brought closer to each other and finally we achieved the broadband structures. The proposed absorbers are designed and simulated using the numerical electromagnetic solver, the Computer Simulation Technology (CST). The absorption results of these structures have been compared with other similar works, and we realize the excellent performance of the presented structures. The fabrication process is easily done with the standard process of sputtering and photolithography. The structures and results are described in the following.

2. Materials and Methods

Generally, metamaterial absorbers are designed in three layers where the metamaterial being an array of periodic structures is separated from the ground plane (uniform metal plate) by a dielectric layer[23]. The existence of a metallic layer with high conductivity as the ground plane at the back of the structure is the reason that all the incident wave that reaches the ground plane will be reflected and all we have is absorption and reflection. In other words, because the transmission is zero (T=0); we have:

$$A=1-R\,, \qquad (1)$$

Where R and A are reflectivity and absorptivity of the structure respectively. For the reflectivity (R) of TE and TM polarization of the incident wave with the angle of incidence θ by modeling the absorber by a material with $\varepsilon(\omega) = \varepsilon_0\varepsilon_r(\omega)$ and $\mu(\omega) = \mu_0\mu_r(\omega)$ where $\varepsilon_0 = \frac{1}{36\pi} \times 10^{-9}\, Fm^{-1}$ and $\mu_0 = 4\pi \times 10^{-7} Hm^{-1}$ and $\varepsilon_r(\omega)$ and $\mu_r(\omega)$ are relative permittivity and relative permeability respectively, we have:

$$R_{TE} = |r_{TE}|^2 = \left|\frac{\cos\theta - \mu_r^{-1}\sqrt{n^2 - \sin^2\theta}}{\cos\theta + \mu_r^{-1}\sqrt{n^2 - \sin^2\theta}}\right|^2, R_{TM} = |r_{TM}|^2 = \left|\frac{\varepsilon_r \cos\theta - \sqrt{n^2 - \sin^2\theta}}{\varepsilon_r \cos\theta + \sqrt{n^2 - \sin^2\theta}}\right|^2 \qquad (2)$$

Where r is the reflection coefficient and n is the refractive index of the absorber ($n = \sqrt{\varepsilon_r(\omega)\mu_r(\omega)}$). So the absorptivity (A) of absorber can be easily calculated from reflectivity (R) of the incident wave.

To design our structure and choose the feature sizes to achieve broadband absorption, we took advantage of the fact that in MMAs, each part of the pattern induces resonance in the structure, and this resonance results in a peak in the absorption spectra, $\frac{\lambda_0}{4} \propto$

L, where λ_0 is the wavelength corresponding to the resonance frequency and L is the length of the resonator in the structure. The absorption has been maximized through independent engineering of the structural parameters. Due to different effective permittivity and permeability resulted by each material, all optimizations were carried out for each material to enhance the overall absorption. The size of metallic structures has the highest contribution in frequency tuning. Periodicity, fill factor and dielectric thickness can modify the frequency as well, while they mainly affect the peak absorption and the quality factor. The permeability coefficient of metallic components is also a key parameter to extend the bandwidth; higher permeability show a wider bandwidth, so we utilized nickel as metallic layer that is ferromagnetic material and has high permeability coefficient.

The designs reported in this paper combine different sizes of rings in a single layer to have a broadband absorption behavior. Another phenomenon in these structures is that when the size values become a bit closer, coupling between neighbors of different sizes takes place as well. This adds an extra component in frequency response of the absorber. We utilized this behavior to extend the absorption.

We designed and simulated four different structures in CST environment that is shown in Figure 1. Each structure unit cell consists of four rings that cause high absorption bandwidth. Nickel is utilized as ground and metamaterial metallic layer material with the relative permeability of 600.

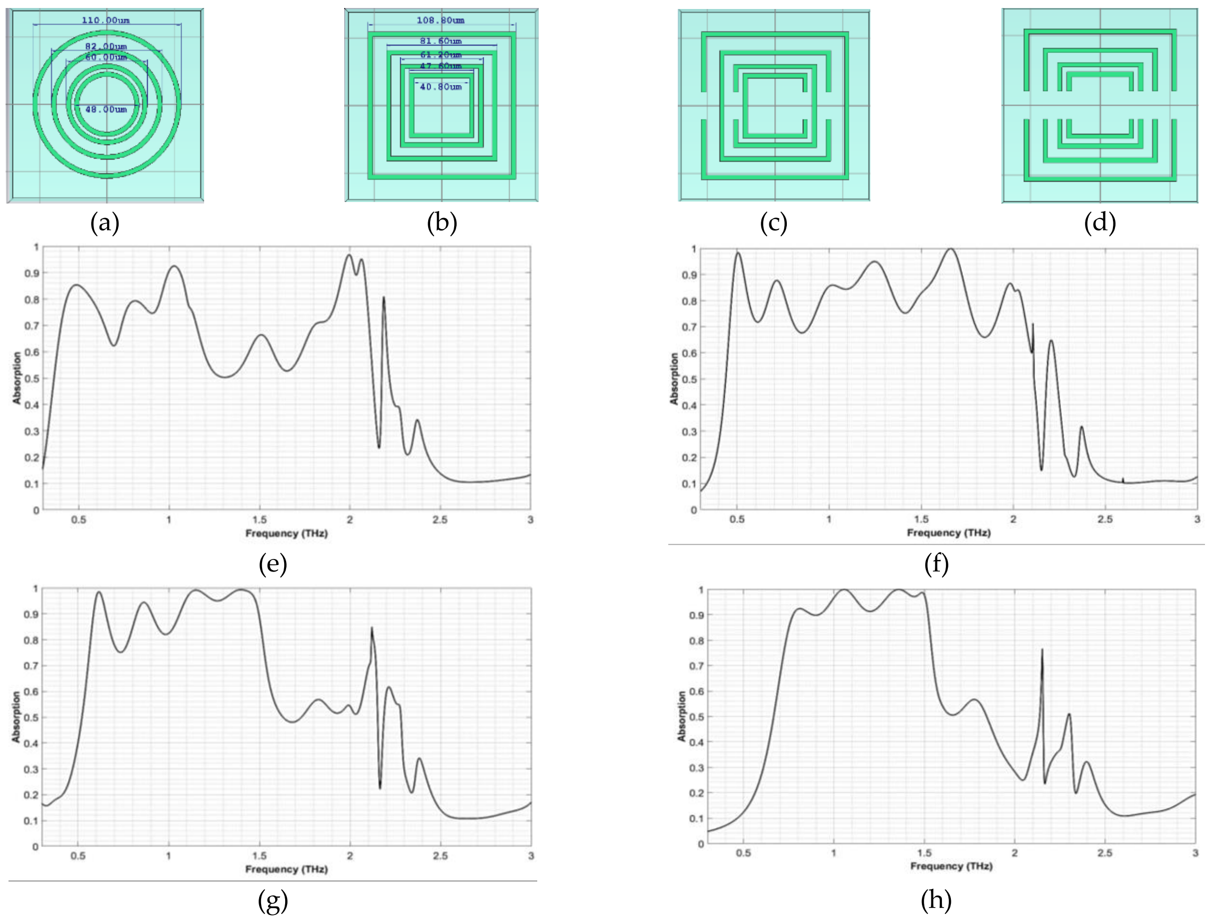

Figure 1. Unit cell structure and simulation result of designed metamaterial absorbers, (a) Structure #1 with a unit cell size of 142µm and dielectric thickness of 37µm, (b) Structure #2 with a unit cell size of 144µm and dielectric thickness of 36µm, (c) Structure #3 with a unit cell size of 143µm and dielectric thickness of 34µm, (d) Structure #4 with a unit cell size of 143µm and dielectric thickness of 34µm, (e) Absorption spectra of the structure #1, (f) Absorption spectra of the structure #2, (g) Absorption spectra of the structure #3, (h) Absorption spectra of the structure #4.

In Table 1, we compared some basic properties of our MMAs with some other recent MMAs designed for THz frequencies, which indicates that the bandwidth of our proposed metamaterial absorbers is higher than similar works.

Table 1. Comparison of different structures based on number of layers, absorption BW and absorption rate

Ref.	MM layer material	Number of layers	Absorption frequency range (THz)	Center frequency (THz)	RABW	% Absorption
[24]	Gold	3	1.24 – 2.86	2.05	0.79	>%50
[25]	Gold and Graphene	4	22.02 – 36.61	29.3	0.50	>%68
[26]	Gold	19	5 – 7.75	6.37	0.43	>%80
[27]	Black phosphorus	10	4.77– 6.49	5.63	0.30	>%90
This paper (#1)	Nickel	3	0.35-2.1	1.22	1.43	>%50
This paper (#2)	Nickel	3	0.45-2.07	1.25	1.29	>%70
This paper (#3)	Nickel	3	0.55-1.5	1.02	0.93	>%80
This paper (#4)	Nickel	3	0.7-1.5	1.1	0.72	>%90

Due to proper design and suitable selection of materials and parameters, fabrication of the absorber is easy, rapid, and low cost. We used standard photolithography for fabrication and the steps are given in Figure 2. Glass is chosen as a substrate that can be replaced by any other device surface. After the RPA cleaning process, Nickel is sputtered on the glass, as the ground layer. Then the SU8 negative photoresist is spin-coated as a dielectric layer. For the metamaterial layer, Nickel is sputtered again. For patterning, first, S1813 positive photoresist is spin-coated. After chromium mask alignment and UV exposure, the excess photoresist is removed using NaOH as a developer. $FeCl_3$ is chosen as Ni etchant. Finally, the photoresist is removed using acetone.

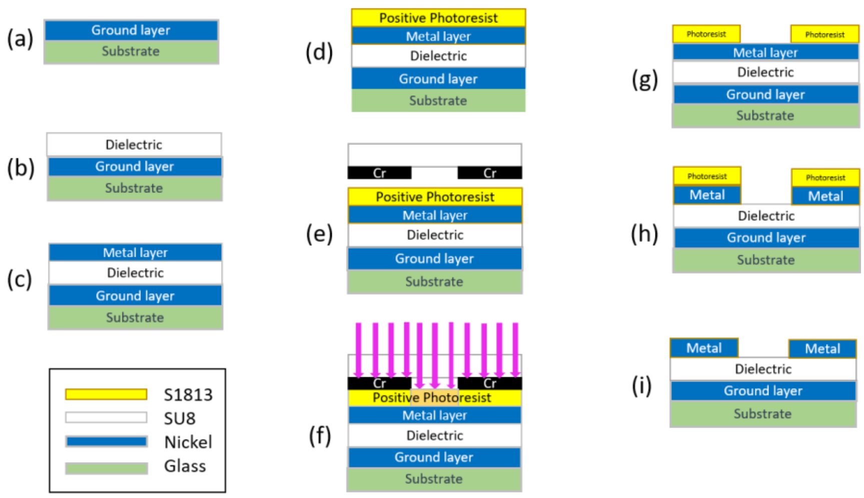

Figure 2. Fabrication process: (a) Sputtering Ni as ground layer, (b) Spin coating SU8 as dielectric layer, (c) Sputtering Ni as top metal layer, (d) Spin coating positive photoresist (s1813), (e) Aligning chrome lithography mask, (f) Exposing for 11s, (g) Removing exposed photoresist using NaOH developer, (h) Etching top metal layer to achieve the pattern, (i) Removing excess photoresist utilizing acetone

To evaluate the fabrication process and performance of the absorber, we used structure #2 with a slight difference that instead of 37µm, we coated a 30µm dielectric layer. This difference is made in order to investigate the effect of dielectric thickness on structure absorption. The final fabricated absorber is shown in Figure 3. We will see the simulation and measurement results of this absorber in the next part.

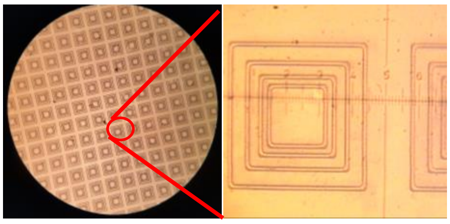

Figure 3. Fabricated MMA absorber

3. Results and Discussion

We used a time-domain THz spectroscopy system to evaluate the absorption of our designed and fabricated structure. As shown in Figure 4, the simulation and measurement results are consistent. The slight difference is because we used a 100 nm thick gold layer to calibrate and normalize the graph. But as we know, for this purpose we need a perfect reflective reference and the gold material itself has a fingerprint in this frequency range. Also, due to its symmetrical design, this structure is polarization-independent, which is an advantage in many applications.

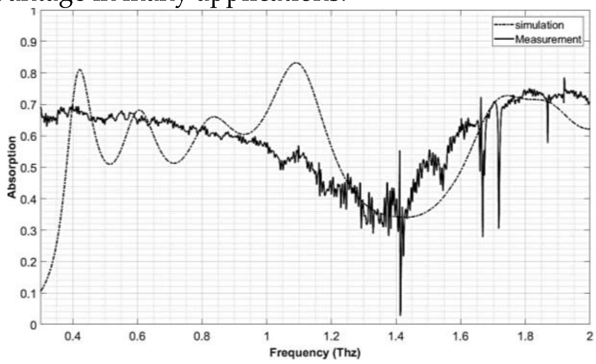

Figure 4. Measurement result of proposed MMA

4. Conclusions

We introduced four ultra-wideband metamaterial THz absorbers that can be implemented on various devices, such as bolometer detectors to increase the detectivity. Absorption of structures is more than 50%, 70%, 80%, and 90% with relative absorption bandwidth (RABW) of 1.43, 1.29, 0.93, and 0.72 respectively. Simulations in the CST Studio Suite environment confirm the correct operation of the designs. We used nickel as ground and metamaterial layer material, which due to its ferromagnetic nature and high permeability coefficient, causes more absorption of the structure. Also we utilized SU8 negative photoresist as a dielectric material that can be easily spin-coated on various surfaces. Also, the minimum feature size of designs is 3um. Using these available and low-cost materials and suitable designs, we successfully fabricated the absorber using rapid, standard, and low-cost method. On the other hand, we designed structures with only one patterned layer, and this is one of the outstanding advantages of our MMA over other broadband MMAs that employ more than one layer, which makes our fabrication process more cost-effective. Finally, we measured the absorption of the fabricated structure, using a time-domain THz spectroscopy system. This special design with broadband absorption allows us to use the structure in various applications such as bolometric imaging, scattering reduction, and thermal sensing.

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