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Highly polarization and wide-angle insensitive metamaterial absorber for terahertz applications

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A B S T R A C T

Metamaterial absorbers, due to their potential applications in the field of photonics, are vastly studied in the last decade. Herein, we present a novel design of a resonant metamaterial absorber in the terahertz (THz) region based on numerical simulations. This perfect THz absorber, due to its symmetry, is highly independent on the polarization state of an incident plane wave. Moreover, the absorber is insensitive to a wide range of incident angle from 0 to 70°. The absorbance approaches unity at a resonance frequency of 3.74 THz. The absorber shows remarkable results even at the two extreme incident angles, e.g. a minimum absorbance value of ∼80% was recorded at an incident angle of 70°. With this promising performance, the proposed THz absorber can serve as a possible sensing device for transparent analytes adsorbed on it. For this structure, aluminum and TiO_2 are used. Both materials are commonly available for manufacturing photonic devices.

1. Introduction

Metamaterials have gained a tremendous amount of importance during the last decade due to their peculiar electromagnetic (EM) behavior [1]. These sub-wavelength structures can produce remarkable and interesting properties due to their negative index of refraction that is impossible to observe in naturally existing materials [2]. The negative values of the permittivity and permeability are the key catching points of the metamaterials that make their use possible for manufacturing superlenses, cloacks and spoof plasmons just to name a few [3–5].

In recent years, various resonant metamaterial structures with high absorbance properties are introduced. The principle of resonant metamaterial absorber (RMA) is to make the values of transmission and reflection equal to zero at a frequency of interest. The reflectivity is minimized if the impedance of a free space Z_0 becomes equal to the impedance Z of the metamaterial structures. Impedance is a ratio of permeability (μ) to permittivity (ε). The transmission can be made equal to zero by enhancing the absorption of the structured material [6]. Both conditions are achievable by designing a metamaterial with resonant at a certain frequency. From a designing or manufacturing point of view, the most efficient metamaterial absorbers are the ones that generate a maximum absorption for a wide range of incidence angles irrespective of the polarization state of an incidence EM wave [7]. Recently, numerous highly polarization insensitive absorbers containing different shapes or designs have been studied. Typical examples of these structures are bilayer structure at 1.3 THz [8], crossed-shaped for bio sensing [9], thin wire-crossed [10], dual-band [11], circular-sectors [12], Via arrays [13], modified electric rings resonators [14], metal groove features [15], symmetric slotted sectors [16] and ultrathin absorbers [17] etc. Moreover, THz-based metamaterial absorbers with tunable absorbance [18], varying thickness of dielectric layers [19,20] and tunable frequency [21] have been reported in the literature. High performance absorbers in the infrared [22], visible [23] and microwave [24] regions have also been investigated. However, the resonant frequency region of interest for RMAs is usually within the terahertz gap since it is difficult to find naturally occurring resonant absorbers in this part of the spectrum [25,26]. Furthermore, the relative long wavelength of the terahertz waves requires micrometer-size metamaterials, which is an advantage from the fabrication point of view. These resonant absorbers have potential applications in both civilian and military products. For examples, a THz absorber can serve as a thermal detector or as a coating layer to prevent light reflections [8,27–30] in order to reveal or conceal military items.

Herein, we present a novel design of a THz metamaterial absorber based on a numerical simulation performed using the finite element method (Comsol Multiphysics). The ability to design a perfect absorber to perform at maximum efficiency (a unity absorbance) irrespective of

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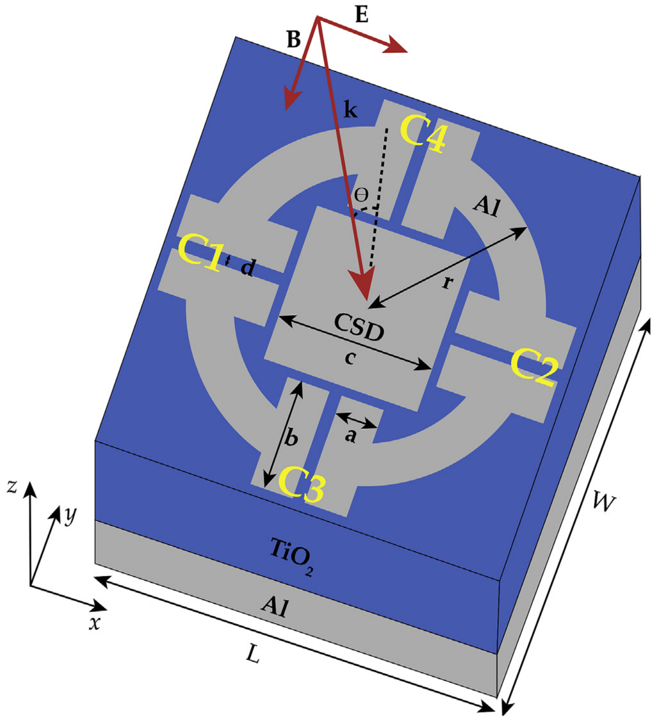

Fig. 1. A schematic diagram of a metamaterial absorber (split ring resonator). The optimized parameters of the structure are the following: L = 38 µm, W = 38 µm, a = 4 µm, b = 10 µm, c = 13 µm, r = 15 µm and d = 1 µm. The structure is made of aluminum with a layer thickness of 50 nm. C1 and C2 represent the two pairs of capacitor plates along the x-axis while C3 and C4 are the two pairs along the y-axis. CSD is a centered-square disc of Al. An incident plane wave in the xz-plane is demonstrated wherein **E** and **B** represent electric and magnetic fields, respectively, which are perpendicular to the wave vector **k**. The plane wave is incident with an angle θ with respect to the normal (black dotted line) of the surface. The thickness of the TiO$_2$ and Al layers are 2 µm and 200 nm, respectively.

the polarization state of the incidence wave is quite challenging. However, the designed THz absorber of this study gives approximately a unity absorbance for any polarization state of an incidence EM-wave compared to previously reported works [24,30–32]. Moreover, the absorbance remains ~80% for a wide incident range (0–70°) of a plane THz wave for both transverse electric (TE) and transverse magnetic (TM) modes. To the best of our knowledge, this design is one of the most efficient THz absorbers with an incredible performance at a wide range of incident angle. With this structure, the absorption approaches unity at a resonance frequency of 3.74 THz. The absorber consists of two metallic layers of aluminum (Al), a split ring resonator (SRR) structure [33–35] on top and a metallic layer at the bottom. The metallic parts are separated by a layer of a dielectric TiO$_2$. The thickness of the device is only ~2 µm. The Al and TiO$_2$ are commonly used materials in nanofabrication processes and therefore provide an easy route of fabrication for the designed structure.

2. Concept and design

The schematic diagram of the structure (SRR) with its optimized parameters is shown in Fig. 1. In the figure, the SRR (circular as well as square parts at the top) is made of an Al with thickness of 50 nm. The symmetric nature of the designed metamaterial makes it polarization insensitive since its absorption efficiency is not affected by the polarization state of an incident THz field. For instance, when the field is polarized in an y-direction the two pairs of capacitor plates, C1 and C2, along x-axis direction and sides of a centered-square disc (CSD) facing C3 and C4 contain high-energy region in-between. Based on a similar analogy, the two pairs of plates in the y-direction, C3 and C4, and the sides of the CSD facing C1 and C2 are only activated when interacted with a polarized electric field in the x-direction. The dimension (length, L × width, W) of the device in Fig. 1 is ~38 × 38 µm. The thickness of the TiO$_2$ layer is 2 µm. The bottom layer of the Al is added to eliminate the possible transmission of the incident signal through the device. The thickness of the Al layer, 200 nm, is thicker than the skin depth (~35 nm) of the incident THz radiation. The thickness values for the various layers are wisely chosen to ensure optimum performance as well as ease of fabrication of the device.

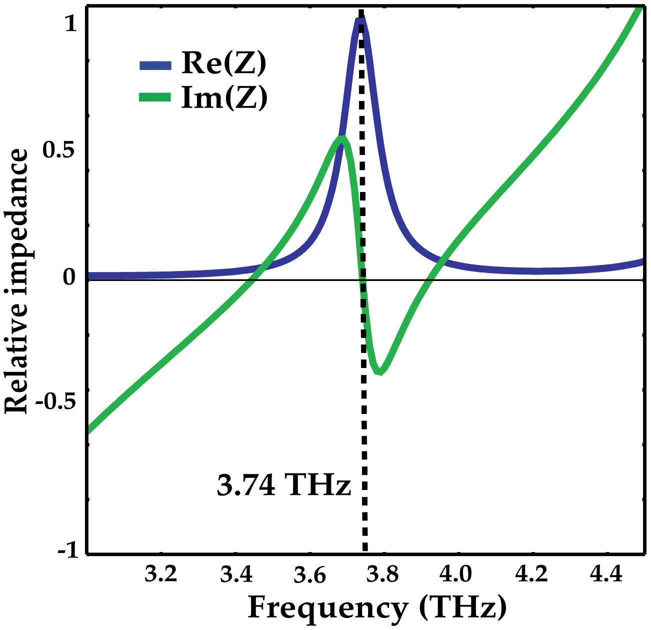

Fig. 2. Relative impedance of the proposed metamaterial structure as a function of frequency. Re(Z) and Im(Z) are the respective real and imaginary parts of the impedance. The dotted black line represents the resonant frequency of 3.74 [THz].

In principle, to maximize the absorption of the structure, the transmission and the reflection should be minimized according to the relationship A = 1 − T − R, where A, T and R respectively represent absorption, transmission and reflection. The metamaterial structure is designed in such a way that it achieves a near perfect impedance that matches with the free space impedance. The impedance of the structure is determinable from the calculated scattering parameters as demonstrated in Ref. [36]. In Fig. 2, a relative impedance of the structure is plotted as a function of frequency. At the resonant frequency 3.74 THz (a black dotted line), the real Re(Z) and the imaginary Im(Z) parts of the impedance approach unity and zero, respectively. This indicates the perfect match between the impedance of the medium Z and that of the free space Z_0 at 3.74 THz. At this impedance matching condition, the value of reflection R approaches zero whilst that of the imaginary part of the complex refractive index (ñ) becomes large. The large values of ñ at the impedance matching condition increases the wave attenuation within the medium [37] and hence, maximum absorption is achieved. Also, the transmission T is set to zero due to the presence of the bottom metallic layer of the structure, therefore all energy is absorbed by the structure. The imaginary part of the refractive index can be deduced from ε(ω) and μ(ω) where ω is an angular frequency. Thus, by optimizing ε and μ, and achieving the impedance matching condition, the value of ñ can be made as large as possible to ultimately enhance the absorption [6]. Herein, for the metamaterial absorber, we calculate the S-parameters S_{11} and S_{21}, which are reflection and transmission coefficients, respectively [38].

Aside being commercially available and low cost, TiO$_2$ and Al are used as the major materials of the proposed structure due to the