Optically Tunable THz Frequency Metamaterial Absorber

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***Abstract*—In this paper, we propose a metamaterial-based terahertz (THz) absorber with optically tunable absorbance. The unit cell of the structure consists of a cross-shaped resonator, a dielectric spacing layer for wave impedance matching and a high-resistivity silicon (HRS) substrate. Without illumination, the structure acts as a capacitive metal mesh filter that has minimum transmittance and maximum reflectance at its resonance frequency. When the HRS substrate is optically illuminated, its conductivity increases, effectively blocking transmission through the structure. Therefore, this device will have a low reflectance if the impedance is matched. The optimized structure shows a high absorbance of 98% at 0.25 THz in simulations. This concept can be used for the realization of dynamic control of absorbance and emissivity for applications in the THz and infrared (IR) range.**

I. INTRODUCTION

Terahertz (THz) technologies have received increasing interest over the past few decades [1]. Metamaterial-based devices, which include modulators [2], filters/resonators [3, 4] and absorbers [5], provide a powerful way for the effective control and manipulation of THz signals. Existing research on THz absorbers has its main focus on the static property of the absorbance. In [6], an optically modulated THz absorber was reported, requiring fairly complex fabrication processing of a silicon-on-sapphire substrate. In this paper, we report a simple approach for the dynamic absorbance control of a metamaterial-based THz absorber. Instead of using a continuous metal ground plane, normally used to minimise transmittance, we employ a high resistivity silicon (HRS) substrate with optical illumination. Numerical studies show that by modulating the photoconductivity within the HRS, it is possible to tune the absorbance of a metamaterial-based structure. The principle of changing the electromagnetic tansmission properties of a photo-conductive medium (e.g. photo-induced carriers in HRS) was previously reported by the authors for implementing *'virtual'* waveguides [7, 8] and switches/variable attenuators [9].

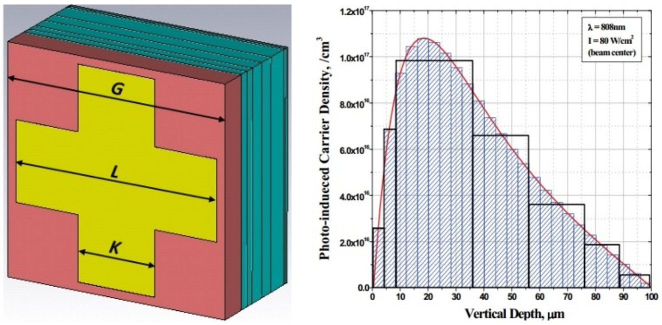
II. DESIGN AND RESULTS

The proposed optically tunable THz absorber consists of a 100 μm thick HRS substrate having a resistivity of 10 kΩ·cm, a 35 μm benzocyclobutene (BCB) impedance matching layer and a 100 nm thick gold cross-shaped metal-mesh filter layer, as illustrated in Fig. 1(a). The structure was designed to achieve the peak absorbance at 0.25 THz, with the following optimized parameters: $G = 270$ μm, $K = 95$ μm and $L = 250$ μm.

To tune the level of absorbance, the HRS substrate is back-side illuminated. As a result, the conductivity of the HRS substrate increases due to photo-induced carrier generation. This region acts as a '*virtual*' ground plane to absorb the incident electromagnetic wave. The optical source was simulated as an 808 nm laser having a uniform power density of 80 W/cm^2. The photo-induced carrier density profile has previously been simulated using *Silvaco™ Luminous,* with the results shown in Fig. 1(b) [7]. This profile was discretized into 7 layers, in order to calculate the corresponding conductivity of different HRS layers using [7, 8]

$$\sigma = \frac{\omega_p^2 \varepsilon_0 \tau}{1 + j\omega\tau} \tag{1}$$

where $\omega_p = \sqrt{Ne^2/\varepsilon_0 m^*}$ is the angular plasma frequency, N is the photo-induced carrier density, e is the elementary charge, ε_0 is the free-space permittivity, m^* is the effective carrier mass, τ is the phenomenological relaxation time and ω is the angular frequency.



(a) (b)

Fig. 1. (a) Illustration of the THz absorber; and (b) simulated photo-induced carrier density for a 100 μm HRS substrate (with back-sided illumination) and its discretization [7].

The structure in Fig. 1 (a) was simulated within CST Microwave Studio®, with and without optical illumination, using the Floquet mode solver to simulate an infinite array. Scattering-parameters were obtained and absorbance A was calculated using $A(\omega) = 1 - T(\omega) - R(\omega)$, where $T(\omega) = |S_{21}(\omega)|^2$ and $R(\omega) = |S_{11}(\omega)|^2$, are the power transmittance and reflectance, respectively. It is shown in Fig. 2 that without optical excitation there is minimal absorption at resonance, which is expected as the structure is a conventional cross-shaped filter [3]. It is seen that absorption due to losses in the metal and dielectric layers is negligible. When the structure is illuminated, a high absorbance is achieved at 0.25 THz, with a change in power absorbance of ΔA = 98% observed for this device when compared to a non-illuminated structure.

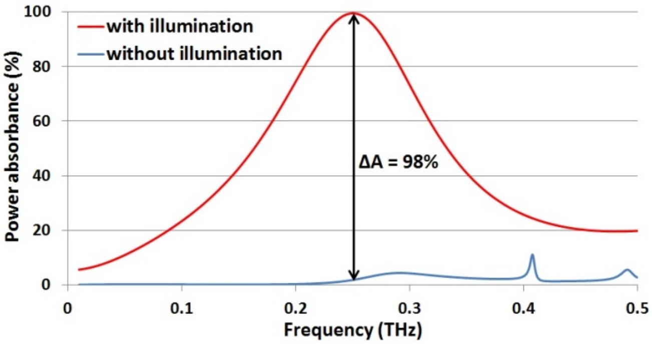
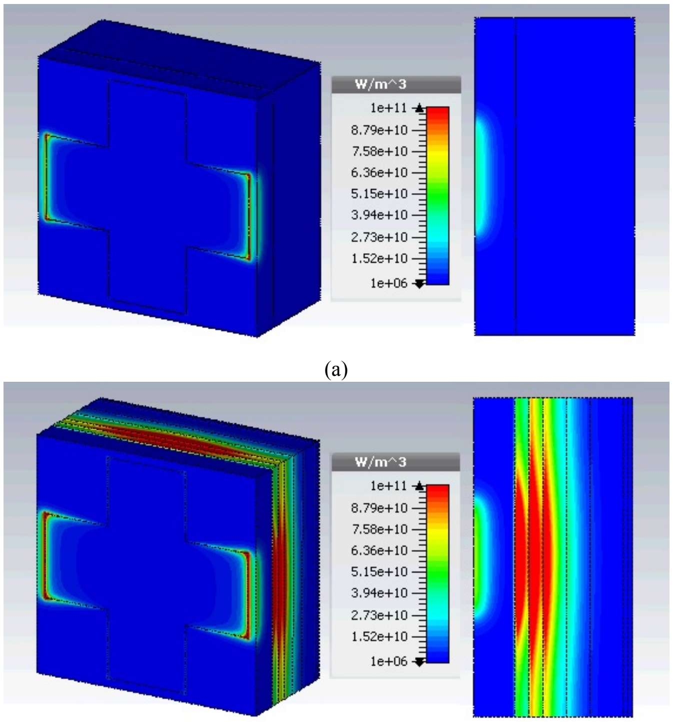


Fig. 2. Simulated power absorbance with and without optical illumination.

To further investigate the underlying absorption mechanism, power dissipation within this multilayer structure is plotted at 0.25 THz, with and without external optical excitation. Fig. 3(a) shows the power dissipation in the non-illuminated device, where the majority of the energy is dissipated as dielectric loss within the BCB layer. When external illumination is applied, power dissipation in both the metal cross and BCB layers are of the same order of magnitude to those of the non-illuminated device. However, the illuminated HRS substrate, where the photo-induced conductivity is gradually increasing towards its backside, acts as an absorbing medium; blocking the incident electromagnetic wave transmitting through the structure.



(a)

(b)

Fig. 3. Power dissipation within the device (a) without illumination; and (b) with illumination.

III. CONCLUSION

In this paper, we have shown a simple approach to dynamically control the absorbance of a THz metamaterial structure using an external optical source. When illuminated, the HRS layer is able to block the incident THz electromagnetic wave to minimize transmittance. By monitoring the power dissipation, it can be seen that the majority of the power is absorbed within the HRS substrate. With the ease of scalability for this structure [10], the proposed concept has potential to be used to create tunable absorbers, high-speed thermal emitters and spatial light modulators in the THz and IR frequency range.

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