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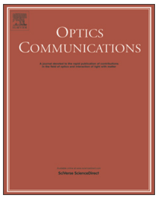

Graphene metamaterial for multiband and broadband terahertz absorber

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ABSTRACT

In this paper, we present the efficient design of functional graphene thin film metamaterial on a metal-plane separated by a thick dielectric layer. Perfect absorption is characterized by the complete suppression of incident and reflected light and complete dissipation of incident energy. We investigate the properties of graphene metamaterials and demonstrate multiband absorbers that have five absorption bands, using silicon interlayers, in the 0–2.2 THz range. The absorption rate reached up to 99.9% at a frequency of 1.08 THz, and the quality factor was 6.98 for a 0.14 THz bandwidth. We present a novel theoretical interpretation based on standing wave field theory, which shows that coherent superposition of the incident and reflection rays produce stationary waves, and the field energy localized inside the thick spacers and dissipated through the metal-planes. Thus, light was effectively trapped in the metamaterial absorbers with negligible near-field interactions, causing high absorption. The theory developed here explains all features observed in multiband metamaterial absorbers and therefore provides a profound understanding of the underlying physical mechanisms.

1. Introduction

Graphene is a two-dimensional (2D) carbon material with extensive applications due to its unique properties, such as optical transparency, flexibility, high electronic mobility and conductivity. These extraordinary electronic properties make graphene a serious candidate for ultrafast, low loss electronic devices [1–6]. As its intraband transition frequencies are in the Terahertz (THz) range, graphene is promising for use in THz photo-electronic devices. In compare with other Thz materials, such as ferroelectric materials, subwavelength metal structures and high-resistivity silicon, graphene's unique linear electronic band and electron transport characteristics naturally suggest graphene could also form the basis for a new generation of high-performance devices operating in the terahertz (THz) range of the electromagnetic spectrum. Owing to its high carrier mobility, gapless spectrum, frequency-independent absorption, and the possibility to deeply alter its dielectric constant through electrical gating, graphene is a very promising material for the development of modulators, sources, and detectors operating across the far-infrared. Additionally, graphene supports surface plasmon polaritons (SPP) in the THz and infrared ranges [7–10] and can be integrated into metamaterials, which provide a wider range of electromagnetic properties than conventional graphene. The SPP is a collective oscillation of charge density and light at the interface between a graphene sheet and its surroundings [11–14]. At THz frequencies, the optical properties of graphene resemble those of a Drude-type material. graphene and graphene-like two-dimensional (2D) materials have highlighted a new family of nano-materials with outstanding physical and chemical properties, and even opened up a new playground with unprecedented chances for testing and realizing conceptually new electronic and optoelectronic devices. Current research in 2D materials primarily focuses on graphene, the insulating hexagonal boron nitride, the topological insulator (Bi_2Te_3, Bi_2Se_3, etc.), and members from the wide-bandgap transition metal dichalcogenides such as molybdenum disulfide and narrow band-gap material as black phosphorous [15–17]. Each type of 2D materials possesses some intrinsic advantages for particular applications. Among these 2D materials, graphene with zero-band nature have attracted the interest of the metamaterial and plasmonic community [18–22]. Recently, a metamaterial with perfect absorption based on graphene was theoretically and experimentally investigated [23–27], demonstrating graphene micro-ribbons and structured graphene metamaterials by the effective surface conductivity approach. However, little attention has been paid to

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metamaterial multiband absorbers.

In this paper, we designed a multiband absorber. Perfect absorption was achieved by patterning graphene in an open micro-ring array and micro-column on top of a reflecting metal substrate separated by a thick spacer. Furthermore, we showed that complete THz wave absorption was due to a standing wave effect that formed a local energy field. This perfect absorber differed from those made of metallic nanoparticles brought in close proximity to a metallic ground plate. Such devices are characterized by a thick dielectric intermediate layer that prohibits any near-field interaction between the structured graphene and the ground plate.

Thus, perfect absorption is achieved by exploiting a perfect destructive interference of the reflected light [28–33]. Transmission through our structure was totally suppressed because the thickness of the ground plate was much larger than the typical skin depth at THz frequency. Therefore, the complete electromagnetic energy was absorbed by the graphene metamaterial absorber. We explained our results using stationary wave theory, in which the reflected and incident light form a standing wave, allowing us to calculate the absorption in the device. Predictions from such simple model were in excellent agreement with CST simulations and strongly indicated that the perfect absorption was a standing wave effect.

2. Graphene perfect absorber

The structure of the graphene metamaterial absorber is plotted in Fig. 1(a). It consists of two graphene open micro-ring arrays and a micro-column on top of a metallic ground plate separated by a thick dielectric spacer. It is radially periodic in r with periodicity $p=16$ μm, structured graphene layer thickness $t_3=1$ nm and the center of all circles at (0,0). We assume the refractive index of $n=\sqrt{\varepsilon_d}=3.42$ for the dielectric silicon deposited on the metal, with thickness $t_2=99$ μm. The ground plate is made of copper with conductivity $\sigma=5.9\times10^7 \text{S/m}$, which is perfectly reflecting in the THz frequency region, and thickness $t_1=1$ μm. The graphene was numerically modeled as a thin layer (with thickness $t_3=0.5$ nm) of permittivity $\varepsilon_{\text{eff}}=1+i\cdot\sigma_s/\varepsilon_0\omega\Delta$ $(\Delta=t_3)$, where σ_s is the surface conductivity of the graphene sheet, which can be derived using the well-known Kubo formula. The conductivity of graphene is described with interband and intraband contributions as

$$\sigma_s=\sigma_s^{\text{int ra}}+\sigma_s^{\text{int er}} \tag{1}$$

$$\sigma_s^{\text{int ra}}=\frac{2k_BTe^2}{\pi\hbar^2}\ln\left(2\cosh\frac{E_F}{2k_BT}\right)\frac{i}{\omega+i\tau^{-1}} \tag{2}$$

$$\sigma_s^{\text{int er}}=\frac{e^2}{4\hbar}\left[H\left(\frac{\omega}{2}\right)+i\frac{4\omega}{\pi}\int_0^{\infty}\frac{H(\Omega)-H(\frac{\omega}{2})}{\omega^2-4\Omega^2}d\Omega\right], \tag{3}$$

where $H(\Omega)=\sinh(\frac{\hbar\Omega}{k_BT})/[\cosh(\frac{\hbar\Omega}{k_BT})+\cosh(\frac{E_F}{k_BT})]$, T is the temperature, E_F is Fermi energy, ω is frequency of the electromagnetic wave and $\tau=10^{-13}$ s is the relaxation time. For THz frequencies, where the photon energy $\hbar\omega<<E_F$, $E_F>>k_BT$, the interband contribution (Eq. (3)) is negligible compared to the intraband. Therefore, in the THz range, graphene is well described by the Drude-like surface conductivity (Eq. (2)). The conductivity depends linearly on the Fermi energy

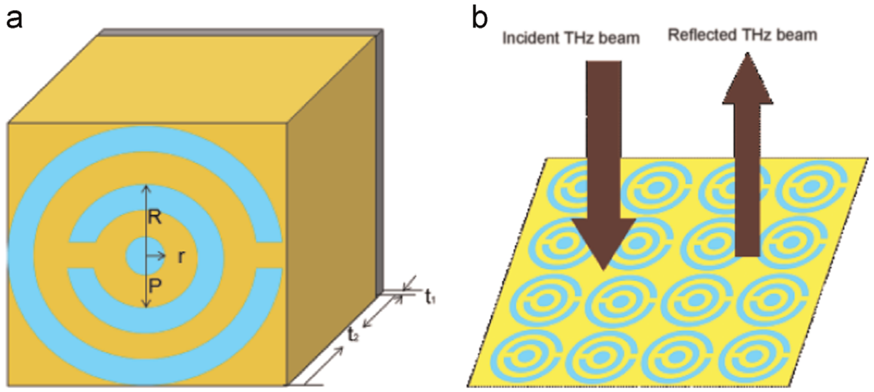

Fig. 1. (a) The unit cell of the graphene metermaterial absorber structure. (b) Perspective drawing of a planer cell array with a normally incident THz wave at the air–graphene–spacer interface.

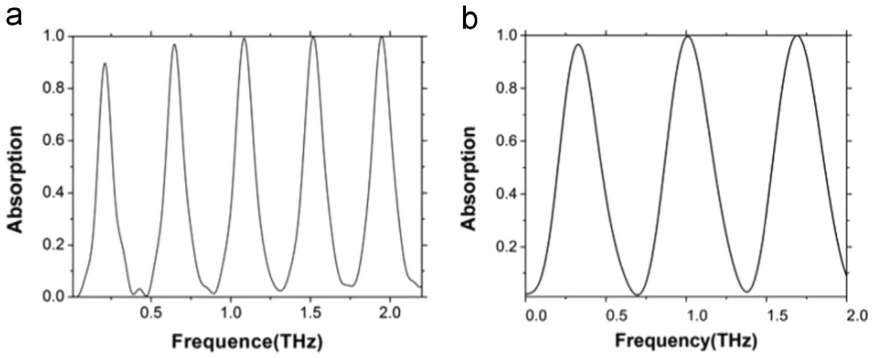

Fig. 2. Absorption spectra of the graphene metamaterial absorber, with copper ground plane 1 μm thick, dielectric spacer layer 99 μm thick, and graphene metamaterial 1 nm thick, for a (a) silicon spacer and a (b) glass spacer.