The 28th Iranian Conference on Optics and Photonics (ICOP 2022), and the 14th Iranian Conference on Photonics Engineering and Technology (ICPET 2022).
Shahid Chamran University of Ahvaz, Khuzestan, Iran,
Feb. 1-3, 2022

طراحی و شبیه‌سازی جاذب امواج تراهرتز مبتنی بر گرافن

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در این مقاله، چهار ساختار جاذب فراماده در محدوده فرکانس تراهرتز که متشکل از دو نوع الگوی گرافن تک لایه بر روی سطح دی‌الکتریک با ضریب شکست ۳/۵ و زیرلایه طلا می‌باشد، طراحی و شبیه سازی شده است. در این شبیه‌سازی شدت طیف جذبی با تغییر سطح فرمی گرافن افزایش یافته است. همچنین تاثیر پارامترهای هندسی ساختار جاذب‌ها با الگوی متفاوت مورد بررسی قرار گرفته شده است. پیک جذبی ۹۹٪ درطول موج ۷۰ میکرومتر در دو نوع ساختار قابل توجه است. توزیع میدان الکتریکی در ساختارها نشان از تحریک و تقویت پلاسمون‌های سطحی گرافن در این طول موج را دارند که عامل اصلی در جذب حداکثری است. جاذب‌های پیشنهای قابل کاربرد حسگرها و آشکارسازهای در محدوده تراهرتز هستند.

کلید واژه: امواج تراهرتز، پلاسمون سطحی، جاذب فراماده، گرافن

Design and Simulation of Graphene-based Terahertz Waves Absorbers

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In this paper, four metamaterial absorbent structures in terahertz frequency range are designed and simulated consisting of two types of monolayer graphene pattern on the dielectric surface with a refractive index of 3.5 and a gold substrate. In this simulation, the intensity of the absorption spectrum is increased by changing the Fermi level of graphene. Also, the influence of geometric parameters on the structure of attractions with different patterns has been investigated. The 99% absorption peak at 70 µm is significant in two types of structures. The distribution of electric field in the structures indicates the stimulation and amplification of graphene surface plasmons at this wavelength, which is the main factor in maximum absorption. Suggested absorbents can be used in sensors and detectors in the terahertz range.

Keywords: Terahertz waves, Surface plasmon, Metamaterial absorber, Graphene

1. Introduction

In recent years, terahertz (THz) technology has become one of the most attractive research topics, because of its promising applications in the fields of imaging, spectroscopy, security and communications. The THz absorber is an important branch of THz technology, which can find practical applications in the above fields [1]. In the past decade, metallic metamaterials and metasurfaces have been used to develop THz absorbers. Electromagnetic metamaterials are artificially engineered materials that are designed to interact and control electromagnetic waves in novel ways. Photonic metamaterials are periodic optical nanostructures often composed of metallic elements on a dielectric or semiconducting substrate, where the period is shorter than the wavelength of light. More recently, graphene has been demonstrated as a good complementary material in realizing THz absorbers, because it can support surface plasmon polariton (SPP) in THz and far-infrared regions [2]. Graphene, as a material of single-layered carbon atoms arranged in a plane with honeycomb lattice, has excellent mechanical, chemical, and electrically tenable properties, which offer many interesting possibilities for terahertz and optical technologies [3]. The electromagnetic properties of graphene approach those of a conductor at low frequencies and those of a dielectric at optical frequencies. Between the two limits, particularly in the terahertz frequency region, graphene has sophisticated electromagnetic properties that can be tuned through varying its chemical potential [4]. For this reason, graphene has very interesting plasmonic properties that lead to many useful applications in the terahertz region. Surface Plasmon Polariton or SPPs are electromagnetic excitations that propagate at the junction of metal and insulation and propagate vertically on the damping surface. The simplest structure for SPP excitation is a uniform boundary between conductive and insulating. Graphene-based SPPs have unique properties over metal SPPs, one of the most important of which is the high concentration of SPP on the graphene surface. SPP is visible due to the metallic behaviour of graphene in the terahertz or lower frequency range, but is not achievable at optical frequencies due to the insulating behaviour of graphene. In this paper, using graphene monolayer, a double-band tenable plasmonic ideal absorber in the terahertz frequency range is designed and simulated. Also, the effect of geometric parameters and chemical potential on the absorption spectrum of the structure is investigated and analysed [5]. Due to the geometric structure of graphene in this paper, compared to similar works [6], the construction of such an adsorbent is possible in practice using chemical vapor deposition (CVD) and surface lithography.

2. Design and analysis of structure

The designed absorber consists of a monolayer graphene, a dielectric with refractive index 3.5, and a gold reflective layer with conductivity $\sigma = 4.5 \times 10^7$ S/m (Fig. 1). The thickness of graphene is 0.3 nm, the dielectric thickness is 20 μm and the thickness of gold is 1 μm.

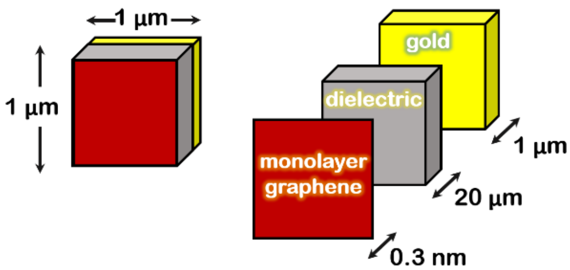

Fig. 1: Schematic of the terahertz absorbent structure consists of a monolayer graphene layer, a dielectric layer, and a gold reflecting layer.

We use for Graphene surface pattern of concentric square structure to achieve broadband absorption. The surface dimensions of these patterns are shown in Fig. 2. In four different modes, the pattern consisting of graphene and dielectric was investigated. In the calculation, our method mainly focuses on the material effect of the two-dimensional flat surface while ignoring that in the out-of-plane direction. At room temperature and low THz frequency ($E_f >> k_B T$, $E_f >> \hbar\omega$), the in-plane conductivity of the graphene can be represented by a Drude model [7]:

$$\sigma(\omega) = \frac{e^2 E_f}{\pi \hbar^2} \frac{i}{\omega + i\tau^{-1}}$$

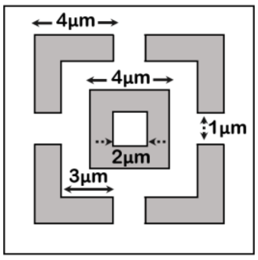

Fig. 2: Dimensions of the proposed absorbent surface pattern.

The intrinsic relaxation time is expressed as $\tau = \mu E_f / e v_F^2$, where μ is the measured carrier mobility, and $v_F = 10^6$ m/s is the Fermi velocity. The adsorption of graphene monolayers in the visible or near-infrared region is extremely low. But, in the far infrared and terahertz regions, light absorption can be increased due to the intensification of surface plasmon. When the chemical potential (Fermi level) of graphene is more than half the photon energy, the intra-band transmission dominates the conduction band and the graphene behaves as a metal. One way to change the absorption frequency of the structure is to change the geometry of the structure. However, the dynamic adjustment of such structures to very small dimensions is very difficult. By controlling the chemical potential via electrostatic doping of the graphene sheet, the peak absorption can be continuously tuned from 0.0 eV to 0.5eV. Here we simulated the graphene Fermi surface in the values of 0, 0.1, 0.2 and 0.5 eV. The proposed structures and their absorption performance have been investigated with Lumerical FDTD Solutions software based on finite element method. In the simulation environment, symmetric boundary conditions are applied in the x direction and anti-symmetric boundary conditions in the y direction. In the z direction, the boundary conditions of the absorption layer (PML) are completely adapted. The applied electromagnetic field was of plane wave kind with a wavelength of 25 to 110 µm, which collided perpendicular to the absorbent surface.

3. Results and discussions

In this section, four different structures for graphene absorbents are investigated. The first two structures (G_1 and G_2) are graphene-coated absorbents on which dielectric square patterns are engraved. The second two structures (D_1 and D_2) are placed on the dielectric surface of the graphene strips absorber in a square pattern. The absorption spectrum of

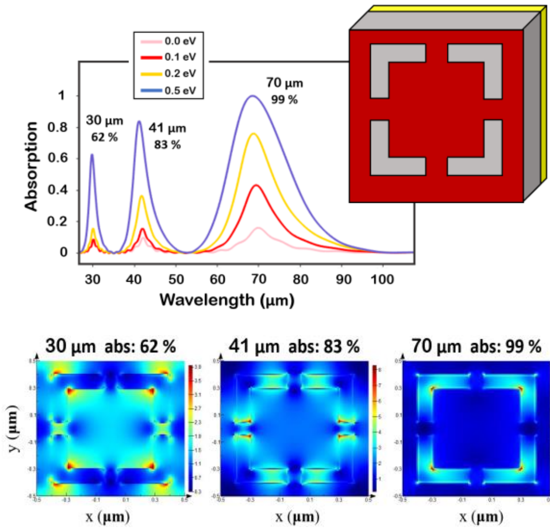

Fig. 3: Absorption spectra and distribution of electric fields in the absorbent structure G_1

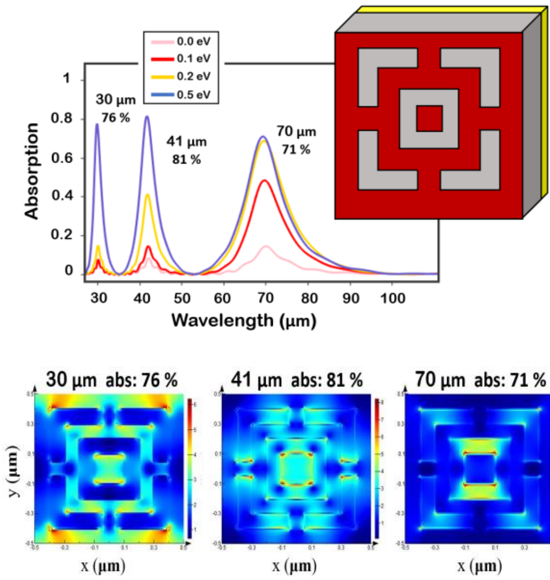

Fig. 4: Absorption spectra and distribution of electric fields in the absorbent structure G_2

absorption peaks at wavelengths of 30, 41 and 70 µm with E_f = 0.5 eV and τ = 10 ps. The results of changing the Fermi level of graphene can be seen on the absorption spectrum. With an increase of E_f, due to the increase in the density of carriers, the intensity of the absorption peak has increased. To fully determine the physical origin of the three band THz absorber, the normalized electric field distribution. Due to the size distribution of the electric field of the structure, 99% absorption occurred at a wavelength of 70 µm in the dielectric pattern. The main reason for adsorption is the amplification of the surface plasmon due to the presence of patterns on the absorbent surface. Then, by adding a square pattern in the center of the absorbent structure G_2 (Fig.4), we see a decrease in the absorption peak at a wavelength of 70 μm. The absorbent structure D_2 consistsof L-like graphene patterns on dielectric surfaces (Fig.5).

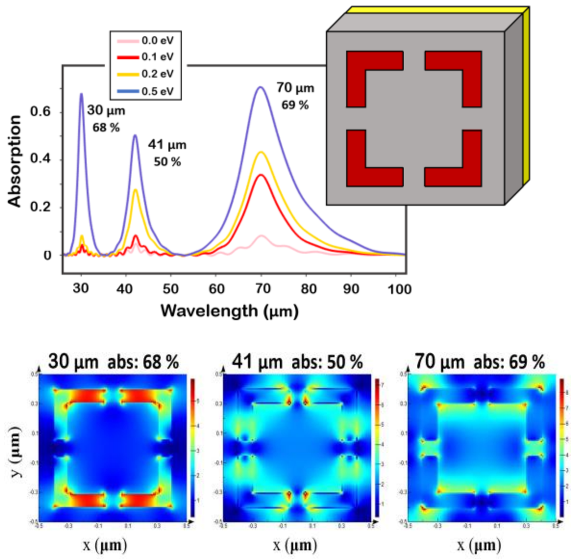

Fig. 5: Absorption spectra and distribution of electric fields in the absorbent structure D_1

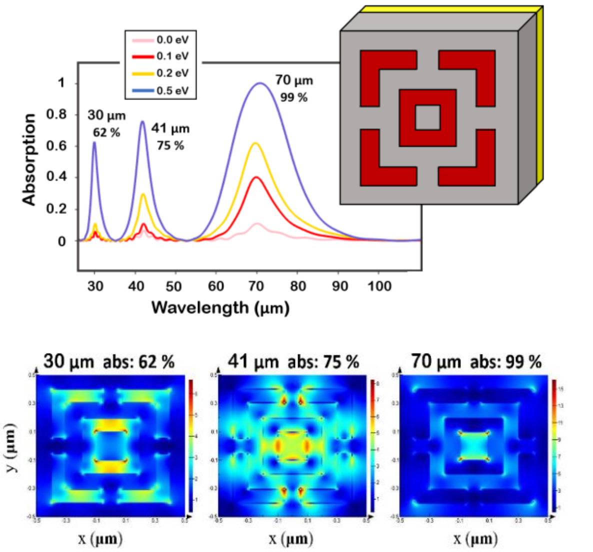

Fig. 6: Absorption spectra and distribution of electric fields in the absorbent structure D_2

The absorption spectrum of this structure indicates low absorption at three terahertz peaks. But in the center of structure D_2, with the addition of a square pattern made of graphene, we see a 99% absorption peak at 70 μm (Fig.6). At the same wavelength, the distribution of the electric field in the center of the structure intensifies, which causes the maximum absorption in the terahertz absorber.

3. Conclusions

In summary, we propose four terahertz absorbent structures consisting of gold, dielectric, and monolayer graphene patterns. Numerical simulations indicate that three absorption peaks at wavelengths 30 μm, 41 μm, and 70 μm can be realized. In two structures G_1 and D_2, we see 99% absorption at a wavelength of 70 micrometers in the terahertz region, which is related to the stimulation and amplification of graphene surface plasmons in the structure.

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تصحیحات انجام شده برای داور A-2444-19 :

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Due to the geometric structure of graphene in this paper, compared to similar works [6], the construction of such an adsorbent is possible in practice using chemical vapor deposition (CVD) and surface lithography.

[6] Yang, Huiping, et al. "Tunable Broadband THz Waveband Absorbers Based on Graphene for Digital Coding." *Nanomaterials* 10.9 (2020): 1844.

۲-

۳- کلمه **absorbent** جایگذین کلمه **adsorbent** گردید

۴- کلمه Absorbance در نمودارها به کلمه Absorption تغییر داده شد.

۵- مشخصات هندسه برهم کنش موج

The applied electromagnetic field was of plane wave kind with a wavelength of 25 to 110 μm, which collided perpendicular to the absorbent surface.

تصحیحات انجام شده برای داور A-2444-18 :

۱- در نرم افزار شبیه سازی Lumerical FDTD فقط ضریب شکست مواد مهم است. از خواص نوری مواد دیگر استفاده نمی‌شود.

۲- پتانسیل شمیایی تک لایه گرافن را می‌توان با اعمال میدان الکتریکی جزئی تغییر داد.

By controlling the chemical potential via electrostatic doping of the graphene sheet, the peak absorption can be continuously tuned from 0.0 eV to 0.5Ev.

۳-SPP

۴- این مقاله صرفاً یک شبیه سازی جاذب است. اما با توجه به تجربه نویسنده در بحث لایه نشانی گرافن به روش CVD بر روی زیرلایه دی الکتریک امکان ساخت این نوع جاذب‌ها با استفاده از روش CVD و لیتوگرافی امکان پذیر است.

Due to the geometric structure of graphene in this paper, compared to similar works [6], the construction of such an adsorbent is possible in practice using chemical vapor deposition (CVD) and surface lithography.

۵- رفرنس جدید

[2] Pan, Jialiang, et al. "Recent progress in two-dimensional materials for terahertz protection." *Nanoscale Advances* 3.6 (2021): 1515-1531.