A Novel Tunable Broadband Absorber based on Graphene

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Abstract——A tunable wideband absorber is presented in this paper. It is based on periodic resistive patterned graphene operating in microwave regime. The proposed absorber not only has wide absorption band but also can be tuned by changing the conductivity of graphene. At chemical potential of 0.3 eV, 90% absorption can be achieved from 10.2GHz to 43.5GHz with 124% fractional bandwidth. Furthermore, the absorber shows relatively stable performance with respect to the incident angle of plane waves.

1. Introduction

Electromagnetic absorbers have been of great interest over the last decades. The main aim of such absorbers is to reduce the unwanted reflections significantly in certain frequency range. Since the classical Salisbury screen[1] and Jaumann absorber[2] are introduced, there have been numerous absorbing structures put forward[3][4]. However, these absorbers have shortcomings of narrow bands and heavy thickness. In order to improve the performance of absorbers, periodic resistive patterns called frequency selective surfaces (FSSs) are applied to absorbers[5]. Without the limitation of one quarter-wavelength thickness, it can achieve a wideband in terms of 90% absorption. However, the aforementioned absorbers remain fixed structures, which makes bandwidth invariant. The solution to achieve a tunable absorber is to combine pin diodes or new materials such as graphene into the FSS structure.

Graphene has appealed a great attention in absorbing owing to its excellent and unique electrical, optical and mechanical properties, since it is first acquired by using micromechanical cleavage by Geim and Novoselov in 2004[6]. In recent years, a large number of graphene-based absorbers have been discussed in [7]-[12]. A transparent graphene absorber with 28% fractional bandwidth at 140GHz has been experimentally demonstrated in[7]. In[8], graphene-based high impedance surface is proposed as an absorbing structure at microwave frequencies. Graphene periodic resistive patterns called frequency selective surfaces are applied to absorber[9].In[10] and[11], by changing chemical potentials, the absorption energy of transparent graphene broadband absorber is controlled over a relatively large interval in the frequency band. A transparent absorber based on patterned graphene film is theoretically illustrated, practically fabricated and experimentally demonstrated[12].

In this paper, a novel, thin and graphene-based absorber is designed by placing Jerusalem-shaped graphene patch between dielectric layers. Graphene’s tunability and frequency-independent surface impedance in microwave band is utilized for broadband matching and high absorption. Consequently, the proposed absorber can obtain wideband characteristic and be tunable. Moreover, the absorption stays large when the incident angle is smaller than 60°. The design and performance of the absorber will be discussed in details in the following parts.
2. Graphene Conductivity Model

Graphene is a two-dimensional crystalline material consisted of an atomic thick layer of carbon atoms bonded in a hexagonal structure. Due to its unique electromagnetic, thermal and mechanical properties, graphene has attracted numerous researches for potential applications at microwave and terahertz frequency. It is well known that the surface conductivity $\sigma$ can be tuned by chemical potential $\mu_c$ through electrostatic bias or chemical doping. Therefore, graphene can be described with isotropic complex surface conductivity $\sigma(\omega, \mu_c)$ based on Kubo formula:

$$
\sigma(\omega, \mu_c) = \frac{-i\omega^2(\omega+2\Gamma)}{\pi\hbar^2} \left[ \int_0^\infty \xi \left( \frac{\partial f_d(\xi)}{\partial \xi} - \frac{\partial f_d(-\xi)}{\partial \xi} \right) d\xi - \int_0^\infty \xi \left( \frac{f_d(-\xi)-f_d(\xi)}{(\omega+2\Gamma)^2+\xi^2} \right) d\xi \right]
$$  \hspace{1cm} (1)

$$
f_d(\xi) = \left( \exp((\xi-\mu_c)/(k_B T)) + 1 \right)^{-1}
$$  \hspace{1cm} (2)

where $\omega$ is radian frequency, $-e$ is the charge of an electron, $\Gamma$ is the phenomenological scattering rate that is assumed to be independent of energy, $\hbar$ is the reduced Planck’s constant, $k_B$ is Boltzmann’s constant, $T$ is the temperature, $\mu_c$ is the chemical potential, and $f_d(\xi)$ is the Fermi-Dirac distributions. In this paper, temperature is $T = 300K$, phenomenological scattering rate is $\Gamma = 1 \times 10^{12}Hz$. The chemical potential is set from 0 eV to 0.5 eV as the scope for discussion.

Figure.1. Real parts (dashed lines) and imaginary parts (solid lines) of the graphene surface conductivity in terms of frequency for various chemical potentials.

The figure 1 shows that the surface impedance ($Z = 1/\sigma$) and the conductivity of the graphene are much more frequency-sensitive in THz as this Kubo formula describes. While in microwave band, the surface conductivity is almost frequency-independent and strongly dependent on the chemical potentials. Graphene remains the surface impedance tunable property, but the inductance characteristic can be negligible.

3. Description of Absorber Structure and Parametric Studies

In order to achieve wideband absorption, impedance matching is a primary requirement to eliminate the reflection in a wide band of frequencies. A unit cell of the absorber structure is depicted in figure 2. The proposed structure is composed of four layers: graphene resistive pattern, two dielectric slabs, and ground plane. The graphene layer is between the two dielectric layers. The details of the graphene pattern are $p_x = p_y = 4mm, d = 2.8mm, w = t = 0.2mm, g = 0.1mm$. The dielectric layers are of same relative permittivity $\varepsilon_r$. In this paper, the design and simulation of graphene absorber are performed with the aid of 3-D full-wave simulator CST. The absorption $A(\omega)$ can be calculated by:

$$
A(\omega) = 1 - |S_{11}(\omega)|^2
$$  \hspace{1cm} (3)
Figure 2. (a) Top view of a unit cell of absorber structure. (b) Three-dimensional sketch of the absorber structure.

In the following sections, we investigate the effects of thickness and relative permittivity of dielectric substrates on absorption properties of the graphene-based absorber. The results presented here only concern the normal incident and the chemical potential is 0.3eV.

3.1. The dielectric constant $\varepsilon_r$ of the substrate
Here we assume the thicknesses of the dielectric layers are the same $h_1=h=2\text{mm}$. The dielectric constants $\varepsilon_r$ of the substrate are 2, 3, 4, respectively. The simulated absorption results of the absorber using these substrates are shown in figure 3 as a function of the operating frequency. From table 1, it is clearly seen that fractional bandwidth hardly changes but bandwidth decreases with the increase of relative permittivity of dielectric layers.

Table 1. Bandwidth and fractional bandwidth of the absorber.

| $\varepsilon_r$ | $f_L$(GHz) | $f_H$(GHz) | Bandwidth(GHz) | Fractional Bandwidth |
|----------------|------------|------------|----------------|---------------------|
| 2              | 10.2       | 43.5       | 33.3           | 124%                |
| 3              | 8.2        | 35.2       | 27.0           | 124%                |
| 4              | 7.3        | 30.2       | 22.9           | 122%                |

Figure 3. Absorption of the proposed absorber with different relative permittivity $\varepsilon_r$ of dielectric substrate.

3.2. The thickness $h$ and $h_1$ of the substrate
The dielectric constant of the substrate is $\varepsilon_r=2$. Firstly, we assume dielectric layers are the same thickness and change the value of the thickness. The variation of the absorption is shown in figure 4(a). The variations of bandwidth and fractional bandwidth are summarized in table 2(a). Bandwidth and fractional bandwidth both decrease with the increase of the thickness. Figure 4(b) shows the results for different thicknesses of upper dielectric layer. From table 2(b), it is clearly that the bandwidth and fractional bandwidth both decrease with the increase of $h_1$. 
Table 2. Bandwidth and fractional bandwidth of the absorber.

| h (mm) | \( f_L \) (GHz) | \( f_H \) (GHz) | Bandwidth (GHz) | Fractional Bandwidth |
|--------|-----------------|-----------------|-----------------|----------------------|
| 2.0    | 10.2            | 43.5            | 33.3            | 124%                 |
| 2.5    | 8.4             | 33.8            | 25.4            | 120%                 |
| 3.0    | 7.2             | 26.7            | 19.5            | 115%                 |

Table 2 (a)

| h1 (mm) | \( f_L \) (GHz) | \( f_H \) (GHz) | Bandwidth (GHz) | Fractional Bandwidth |
|---------|-----------------|-----------------|-----------------|----------------------|
| 1       | 11.5            | 42              | 30.5            | 114%                 |
| 2       | 10.2            | 43.5            | 33.3            | 124%                 |
| 3       | 9.8             | 25.7            | 15.9            | 89%                  |

Table 2 (b)

Figure 4. Reflection of the proposed absorber with (a) different thickness \( h \). (b) different thickness \( h_1 \).

4. Design and simulation

For a normal impinging plane wave, the simulated results for the absorber’s performance when the chemical potential is of 0.3eV, are displayed in figure 5. It can be seen that the bandwidth for reflection less than -10dB is from 10.2GHz to 43.5GHz with 124% fractional bandwidth.

Figure 5. Reflection and absorption of the proposed absorber at chemical potential of 0.3eV.

The results of absorption properties with different chemical potentials(0.2~0.5eV) are depicted in figure 6. The real parts of the surface impedance of graphene monolayer for different chemical potentials(eV) are summarized in table 3. As shown in figure 6, the structure can be tuned to obtain a maximum of absorption and bandwidth by adjusting the chemical potential. According to this figure, the reflection of the absorber is controlled by the chemical potential over a relative large interval. Bandwidth increases but the magnitude of absorption decreases with the increase of chemical potentials.
Table 3. Surface Impedance of Graphene Monolayer

| $\mu_c$/eV | 0.2  | 0.3  | 0.4  | 0.5  |
|------------|------|------|------|------|
| $R_e(Z_g)/\Omega$ | 42.47 | 28.32 | 21.24 | 16.99 |

Finally, we demonstrate that the absorption properties of the absorber is insensitive to incident angles. As shown in figure 7, the absorber has a relatively stable performance with different oblique incident angles $\theta$. As the incident angle increases from 0° to 45°, the amplitude of the reflection peak decreases slightly and it still keeps above 90% absorption in a sufficiently broad frequency band. When $\theta$ is up to 60°, the absorption remains 80%. The insensitivity to incident angles can be ascribed to the high symmetry of graphene patterns.

5. Conclusion
In this paper, we have introduced a graphene-based broadband absorber. The proposed absorber realizes excellent absorption from 10.2GHz to 43.5GHz with 124% fractional bandwidth. The maximum absorption can be realized by tuning the surface impedance of graphene. Furthermore, the insensitivity to incident angle has been proved.

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