DESIGN AND ANALYSIS OF GRAPHENE-BASED MULTILAYER STRUCTURES FOR ELECTROMAGNETIC COMPATIBILITY (EMC) APPLICATIONS

G. S. Kliros and M. I. Skontranis

Hellenic Air-Force Academy, Department of Aeronautical Sciences Division of Electronics,
Electric Power & Telecommunications
Dekeleia Air-Force Base, Attica GR-1010, Greece

georgios.kliros@hafa.haf.gr; gskliros@ieee.org

Abstract

We calculate the electromagnetic absorption in a thin dielectric/graphene multilayer structure on a quartz substrate and investigate its performance as absorber for electromagnetic compatibility (EMC) applications up to 250 GHz, employing a modified transfer matrix method (TMM). Our results indicate that, high broadband absorbance greater than 80% can be achieved for both TE and TM-wave polarizations of the impinging plane wave when the number of stacked layers is increased up to 5-layers with spacer thickness equal to a quarter wavelength. The absorbance magnitude can be strongly modulated by changing the Fermi level of the graphene sheets via dc-voltages. The sensitivity of the absorbing structure to oblique incidence for both TE and TM-wave polarizations are studied. Moreover, by increasing the permittivity of the dielectric spacers, both the absorption magnitude and bandwidth are reduced.

1. INTRODUCTION

The increasing density of radiation emitters in the environment has made the electromagnetic compatibility (EMC) an important issue in avionics, nanoelectronics and medical electronic equipment design. Thus, there is a real demand for high performance, thin and flexible structures as electromagnetic shields. Graphene offers a potential unique material for designing such structures especially because of its high electrical conductivity that can be controlled electrically via a gate voltage that tunes the Fermi energy of the material. Recently, graphene based multilayer structures have been proposed for efficient absorption of electromagnetic radiation in the GHz and low THz range. Wu et al. [1] have proposed a multilayer absorber with 28% bandwidth at 140 GHz which is based on graphene/ quartz stacks backed by a metal ground plate. Batrakov et al. [2] have demonstrated that there is an optimum number of graphene/polymer layers for maximum absorption of millimeter waves. It has been also demonstrated that localized or extended defects in the graphene sheet have no effect on the optimum absorbance [3].

In this work, we study theoretically a dielectric/ graphene multilayer structure deposited over a quartz substrate, avoiding the use of a metal ground plate as shown in Figure 1. Such a structure is of particular relevance for EMC applications [4]. A transfer matrix method (TMM) is employed in order to investigate the performance of the structure as absorber in a broadband frequency range up to 250 GHz.

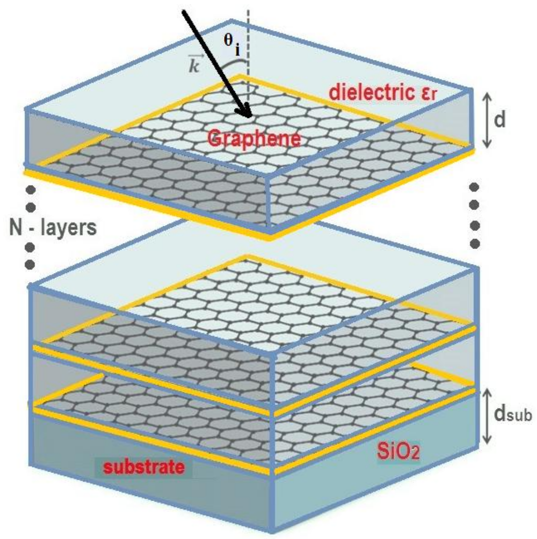


Figure 1. Schematic of N-layer graphene/dielectric multilayer structure backed by a quartz substrate and illuminated by a plane wave at oblique incidence.

2. DESIGN AND MODELING

2.1. Absorber Configuration

The basic configuration of the multilayer absorber under study is illustrated in Figure 1. It consists of N dielectric/graphene units deposited on a SiO_2 substrate of relative permittivity $\varepsilon_{r,sub}$ = 3.7 and thickness d_{sub}=0.5 mm. The dielectric spacers are flexible polymers with permittivity ε_r=2.6 and thickness d. Following the well-known configuration of the Jaumann absorber [5], the dielectric thickness d has been set equal to a quarter effective wavelength d=λ/(4$\sqrt{\varepsilon_r}$). The graphene layers can be assumed electronically decoupled from each other due to the significant thickness of the dielectric spacers. The frequency-dependent conductivity of graphene is controlled by applying dc biasing voltages between the graphene layers. In contrast to common absorbers, the absorber proposed in this work does not involves a metallic backing plate which can be an advantage for some EMC applications.

2.2. Transfer Matrix Method (TMM)

The absorbance of the structure can be simulated by a variety of methods. The technique used in this work is the TMM for oblique incidence of a plane wave impinging on a planar multilayer structure composed of M layers with complex refractive indices $\tilde{n}_j$ and (M+1) interfaces [6] as shown in Fig. 2.

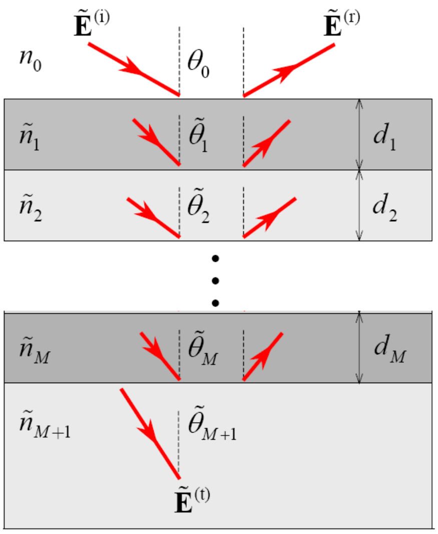


Figure 2. Propagation in a multilayer structure of M layers with complex refractive indices $\tilde{n}_j$ and (M+1) interfaces.

The total transfer matrix T of the system can be obtained by means of the transmission matrices D_{ij} across different interfaces i and j and the propagation matrices P_j through layer j.

$$T=\begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix}=\left(\prod_{j=1}^{M} D_{(j-1)j}P_j\right)D_{M(M+1)} \quad (1)$$

where

$$D_{ij}=\frac{1}{t_{ij}}\begin{bmatrix} 1 & r_{ij} \\ r_{ij} & 1 \end{bmatrix},\ P_j=\begin{bmatrix} e^{-i\delta_j} & 0 \\ 0 & e^{i\delta_j} \end{bmatrix} \quad (2)$$

with t_{ij} and r_{ij} are the complex transmission and reflection Fresnel coefficients, $\delta_j=(2\pi/\lambda)\tilde{n}_j d_j\cos\tilde{\theta}_j$ is the phase shift acquired by the wave passing through the layer j and $\tilde{\theta}_j$ is the complex propagation angles that follow the Snell's law. The reflection and transmission coefficients are then $r=T_{21}/T_{11}$ and $t=1/T_{11}$ respectively. The absorption of the multilayer structure is a function of angular frequency ω and can be calculated as

$$A(\omega)=1-|t(\omega)|^2\,\tilde{n}_{M+1}/\tilde{n}_0-|r(\omega)|^2 \quad (3)$$

As a result, maximum absorption can be achieved by minimizing both transmission and reflection.

2.3. Graphene Permittivity Model

Under the assumption that the electronic band structure of a graphene layer is not affected by neighbouring graphene layers, the complex relative permittivity of graphene ε_g is given by

$$\varepsilon_g=1-j\frac{\sigma_g}{\omega\varepsilon_0 t_g} \quad (4)$$

where σ_g is its surface conductivity and t_g=0.35 nm, its thickness. The isotropic surface conductivity σ_g of graphene can be written as a sum of the intra-band and inter-band terms resulting from Kubo's formula [7].

$$\sigma_g(\omega)=\sigma_{intra}(\omega)+\sigma_{inter}(\omega) \quad (5)$$

with

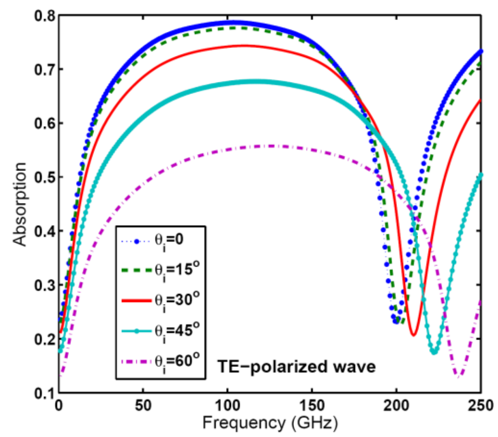
$$\sigma_{g,intra}=\frac{je^2}{\pi\hbar^2(\omega-j2G)}\int_0^{\infty}\varepsilon\left(\frac{\partial f_d(\varepsilon)}{\partial\varepsilon}-\frac{\partial f_d(-\varepsilon)}{\partial\varepsilon}\right)d\varepsilon$$

$$\sigma_{g,inter}=-\frac{je^2(\omega-j2G)}{\pi\hbar^2}\int_0^{\infty}\frac{f_d(-\varepsilon)-f_d(\varepsilon)}{(\omega-j2G)^2-4(\varepsilon/\hbar)^2}d\varepsilon$$

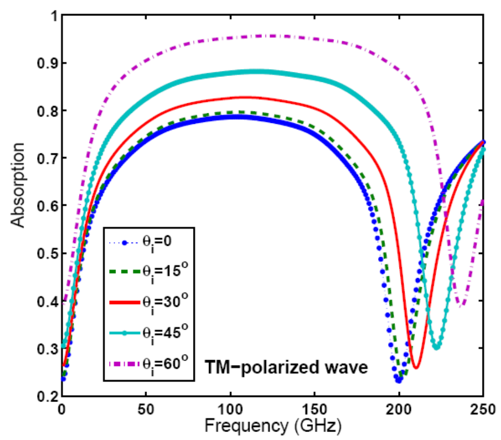
where $f_d(\varepsilon)$ is the Fermi-Dirac distribution and G is the scattering rate given by $G=\hbar e\upsilon_f^2/\mu E_f$ where υ_f =10^6 m/sec is the Fermi velocity in graphene and μ=2x10^4 $cm^2/(Vs)$ is the electron mobility at room temperature T=300 K.

3. RESULTS AND DISCUSSION

The absorption of the multilayer structure as function of the number of layers N has been simulated for both TE and TM-wave polarizations for a frequency range up to 250 GHz. High broadband absorbance is observed for both wave polarizations of impinging wave when the number of layers N is increased up to 5-layers. As shown in Figure 3, assuming a Fermi energy E_f =0.15 eV, the TE-wave absorption decreases as the angle of incidence increases, whereas the TM-polarized absorption has the opposite trend. However, the absorption is greater than 50% for a wide angle range up to 60° for both polarizations.



(a)



(b)

Figure 3. Absorption of 5-layer structure illuminated by (a) TE and (b) TM polarized wave at oblique incidence. The Fermi energy is set equal to 0.15 eV.

Figure 4 displays the sensitivity of absorption to the Fermi level changes. As is shown, strong modulation of the absorption, in all frequency range, can be achieved by increasing the Fermi energy. Moreover, as revealed by Fig.5, increasing the permittivity of the dielectric spacer, both the absorption magnitude and bandwidth are reduced.

To get insight into the dependence of absorption on the number of layers N, an example for TM-waves is given in Fig. 6. As shown, an almost perfect absorbance is obtained for N=5, at angle ~72° ('Brewster's angle') due to a minimum in the reflectance. However, such 'Brewster's angle' doesn't exists for TE-polarized waves.

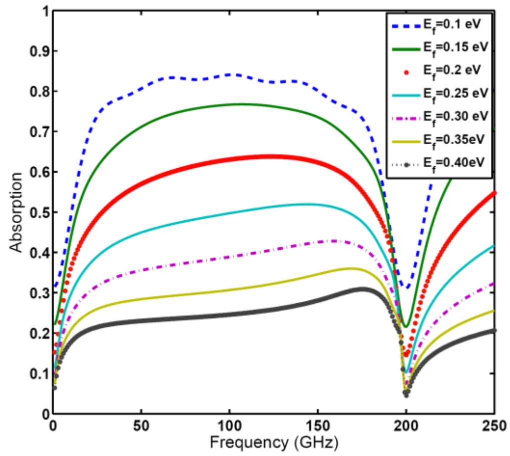


Figure 4. Absorption of 5-layer graphene/dielectric structure illuminated by a plane wave at normal incidence.

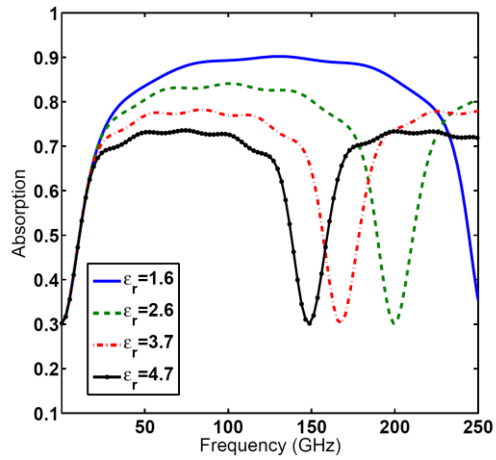
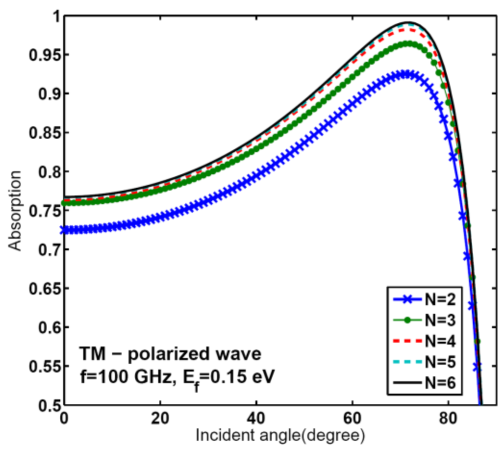
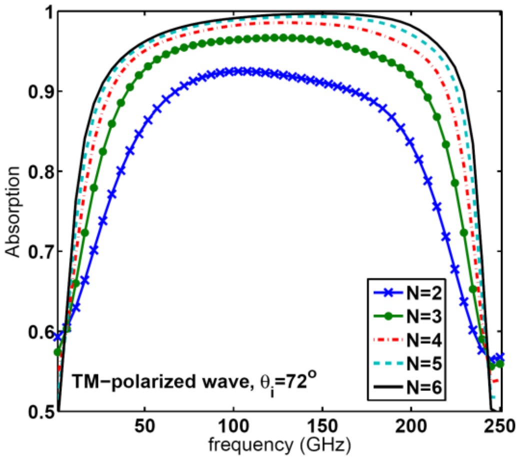


Figure 5. Absorption of 5-layer grapheme dielectric structure excited by a plane wave at normal incidence. The Fermi energy is set equal to 0.15 eV.



(a)



(b)

Figure 6. Absorption as function of (a) angle of incidence and (b) frequency when the structure is illuminated by TM-polarized waves for different number N of layers.

4. CONCLUSION

We have designed and simulated a broadband absorber composed of graphene sheets spaced by dielectric layers with thickness equal to a quarter wavelength at the central frequency.

Broadband and wide-angle high absorbance can be achieved for both polarizations when the number of stacked layers is increased up to 5-layers. The total thickness of the structure does not exceed 3 mm. The absorbance is strongly modulated by changing the Fermi energy of the graphene via a dc-voltage. We also found out that, increasing the spacer's relative permittivity, both absorption magnitude and bandwidth are reduced.

Interestingly, when the structure is illuminated by a TM-polarized wave, an almost perfect absorbance is obtained at angle of incidence around θ=72°.

References

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