Stop light and electrical control of the carbon nanotube-graphene structure

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Abstract

In this paper we propose a mechanism of a light control in a combined graphene-carbon nanotube (CNT) array structure. A finite-thickness slab consisting of carbon nanotubes, arranged perpendicularly to interfaces, supports low-loss backward waves in the far and mid infrared. Then we combine this slab with a layer of a usual dielectric, inserting graphene sheet between them. The energy flows will propagate in opposite directions in the dielectric and carbon nanotube slabs and the Poynting vector at the plane of graphene sheet is perpendicular to interfaces. A chemical potential of graphene and, therefore, its conductivity, can be changed by an electric bias field. Particularly efficient controllability can be achieved if energy flows in the forward-wave and backward-wave slabs are equal that corresponds to the stop light regime.

1. Introduction

The structure under study is shown in Fig. 1. It consists of the layer of vertically standing CNTs, which is two-dimensional periodic in the x and y (the orthogonal plane) directions. The thickness of the layer $h_1 = 600\,\text{nm}$. The bottom interface is the PEC plane. The upper layer is the isotropic dielectric with the permittivity $\varepsilon = 11.6$ and thickness $h_2 = 750\,\text{nm}$. Infinitely thin graphene sheet is placed between the CNT and dielectric layers. The upper interface of the dielectric layer is bounded with free space. For eigenwaves, propagating in the structure, we take the space-time dependence of fields as $\exp[j(\omega t - k_x x)]$. We consider mid and far infrared ranges since in these ranges electromagnetic waves in CNTs posses lowest attenuation.

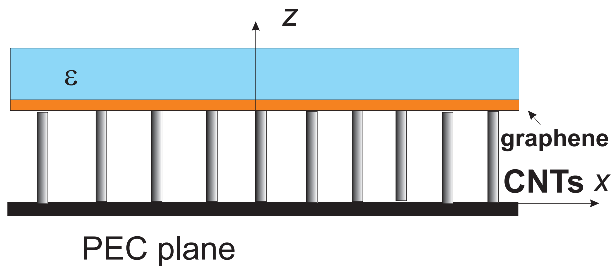

Fig. 1: Schematic view of the CNT-graphene-dielectric structure.

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2. Description of the model

Recently it was shown that slow waves, which are characterized by a conic-like dispersion, can propagate in arrays of metallic carbon nanotubes [1], so arrays of CNTs can be considered as indefinite media [2]. As a result, a finite-thickness slab of CNTs supports propagation of backward waves in a very wide frequency range [3]. Electromagnetic properties of individual carbon nanptubes are described in terms of a surface conductivity and effective boundary conditions [4]. Electromagnetic interaction between carbon nanotubes is taken into account using periodic Green's function [1]. For thin CNTs azimuthal currents can be neglected compared to axial ones that causes separation of Maxwell's equations into two subsystems, describing ordinary and extraordinary waves in CMT arrays (we are interested in extraordinary waves because their fields only effectively interact with carbon nanotubes). As a result, 2×2 transfer matrix method can be applied for analysis of electromagnetic waves, prppagating in multilayered media, containing CNT layers.

Electromagnetic properties of graphene are described in terms of the surface conductivity σ. Since our study relates to the mid and far infrared ranges, the intraband contribution only can be taken into account. The following expression, obtained from the Kubo formula, is used [5]:

$$\sigma_{\text{intra}}(\omega,\mu_c) = -j\frac{e^2 k_B T}{\pi\hbar^2(\omega - j2\Gamma)}\left(\frac{\mu_c}{k_B T} + 2\ln(e^{-\mu_c/k_B T}+1)\right), \tag{1}$$

where ω is radian frequency, e is the charge of an electron, $\hbar$ is the reduced Planck's constant, k_B is Boltzmann's constant, T is temperature, Γ is a phenomenological scattering rate, and μ_c is chemical potential.

Transfer matrices of the CNT layer $[\mathrm{M}_{\text{cnt}}]$ and graphene sheet $[\mathrm{M}_{\text{gr}}]$ have forms:

$$[\mathrm{M}_{\text{cnt}}] = \begin{bmatrix} \cos k_{1z}h_1 & jZ_1\sin k_{1z}h_1 \\ j/Z_1\sin k_{1z}h_1 & \cos k_{1z}h_1 \end{bmatrix}, \quad [\mathrm{M}_{\text{gr}}] = \begin{bmatrix} 1 & 0 \\ \sigma_{\text{intra}} & 1 \end{bmatrix}. \tag{2}$$

Wave number k_{1z} is calculated numerically using the model [1], $Z_1 = \eta k_{1z}/k$, where η and k are the wave impedance and wavenumber in free space, respectively. Transfer matrix for the dielectric layer $[\mathrm{M}_d]$ is similar to $[\mathrm{M}_{\text{cnt}}]$, where $k_{2z} = \sqrt{k^2\varepsilon - k_x^2}$, $Z_2 = \eta\sqrt{k^2\varepsilon - k_x^2}/(k\varepsilon)$. Dispersion relation looks as

$$-B_{12} + B_{22}Z_0 = 0, \tag{3}$$

where $[\mathrm{B}] = [\mathrm{M}_d]\times[\mathrm{M}_{\text{gr}}]\times[\mathrm{M}_{\text{cnt}}]$, and $Z_0 = \eta\sqrt{k^2 - k_x^2}/k$.

3. Results and discussion

Dispersion diagram, calculated for different chemical potentials, is shown in Fig. 2. The chemical potential μ_c can be changed in limits 0-0.5 eV applying electric bias field to graphene sheet that causes a considerable modification of the dispersion. Namely, a guiding regime can be changed by a cutoff regime. Change of a sign of dispersion is of a special interest because at the frequency point, where the group velocity equals to zero, but the phase velocity is not zero (so-called stop light regime), all processes of interaction of a wave and matter are enhanced. Such a regime seems to be promising for stimulation of nonlinear effects in graphene. Energy flows, calculated integrating the Poynting vector over cross-sections of layers 1 and 2, propagate in opposite directions. At the interface between these layers, i.e. in plane of graphene, the x-component of the Poynting vector equals to zero because the Poynting vector field forms vortices in the cross-section plane if adjacent layers separately support propagation of waves characterized by opposite signs of dispersion [6]. Note also that a possibility of a strong slowdown of electromagnetic waves and even "stopping light" becomes now one of the distinctive features inherent in layered structures with metamaterials [7, 8].

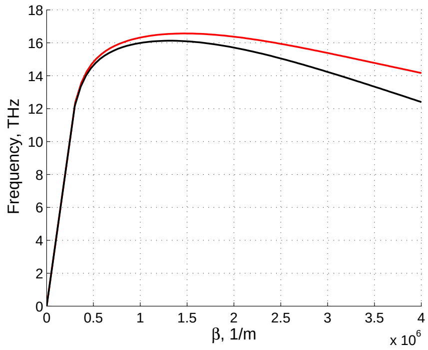

Fig. 2: Dispersion diagram, calculated at chemical potential $\mu_c = 0$ (red) and $\mu_c = 0.5\,\mathrm{eV}$ (black).

4. Conclusion

Characteristics of guiding waves in "isotropic dielectric-carbon nanotubes-graphene" layered structure are considered. The transfer matrix approach is used. Conditions for very interesting regime, when the energy concentration increases, the total energy flow in a layered structure decreases and large slowdown of waves, even including zero group velocity, are found. An effective control of wave characteristics of such structures is provided by an external bias electric field which tunes the Fermi level in graphene layer. "Stop light" regime seems to be promising for stimulation of nonlinear effects in graphene, such as a very effective harmonic generation etc. From the other hand, extra possibilities of a control of conductivity using spatial modulation of graphene films (using bias electric or magnetic field), spin-orbital interaction etc. may create new very effective ways of tunability for corresponding layered structures and devices.

References

[1] I.S. Nefedov, Electromagnetic waves propagating in a periodic array of parallel metallic carbon nanotubes, *Phys. Rev. B*, vol. 82, p. 155423, 2010.

[2] D. R. Smith and D. Schurig, Electromagnetic wave propagation in media with indefinite permittivity and permeability tensors, *Phys. Rev. Lett.*, vol. 90, p. 077405, 2003.

[3] I. Nefedov, Periodic array of finite-length carbon nanotubes as a planar metamaterial, in Proceedings of *ETOPIM 8*, Crete, Greece, 7-12 June 2009, p. Sess9.3Nefedov.pdf.

[4] G.Y. Slepyan, S.A. Maksimenko, A. Lakhtakia, O. Yevtushenko, A.V. Gusakov, Electrodynamics of carbon nanotubes: Dynamic conductivity, impedance boundary conditions, and surface wave propagation, *Phys. Rev. B*, vol. 60, p. 17136, 1999.

[5] G.W. Hanson, Dyadic Green's functions and guided surface waves for a surface conductivity model of graphene, *J. of Appl. Phys.*, vol. 103, p. 064302, 2008.

[6] V.N. Ivanov, N.P. Demchenko, I.S Nefedov, R.A. Silin, A.G. Schuchinsky, Waves in tangentially magnetized ferrite slab (numerical electrodynamic analysis and regular asymptotic expansions), *Izvestiya Vysshikh Uchebnykh Zavedenii. Seriya Radiofizika*, vol. 32, pp. 764-779, 1989, (in Russian). (English translation: *Radiophysics and Quantum Electronics*).

[7] K. L. Tsakmakidis, A. D. Boardman, and O. Hess, Trapped rainbow' storage of light in metamaterials, Nature, vol. 450, pp. 397-401, 2007.

[8] A. D. Boardman, N. King, Yu. Rapoport and L. Velasco, Gyrotropic impact upon negatively refracting surfaces, New Journal of Physics, vol. 7, pp.1-23, 2005.

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