Influence of magnetic field on the surface waves properties in the photonic crystal / graphene structure for terahertz frequency range

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Abstract. In this paper magneto-tunable photonic crystal with graphene layer was investigated for terahertz frequency range. The peaks of transmissivity in band-gaps of photonic crystal that caused by excitation of surface waves were obtained. The control of frequency peaks’ position by magnetic field was demonstrated.

1. Introduction
Today photonic crystals (PC) are one of the most promising metamaterials. PCs allow to manipulate electromagnetic waves and therefore they can be used for development of optical devices such as filters, superlenses, polarization changers, waveguides, superprisms, etc [1-3]. Also today graphene has considerable attention among scientists due to the specific properties such as high electric and thermal conductivity etc. [4]. The photonic crystal with graphene layers has periodic narrow stop bands in frequency spectrum and that may be used as spectral-selective mirror [5]. Surface waves may be excited in the photonic crystal structure using graphene layer as the boundary medium. In this paper the influence of magnetic field on the surface waves properties in the photonic crystal bounded by graphene layer for terahertz frequency range was investigated. Peaks of transmissivity in band-gaps of photonic crystal that caused by excitation of surface waves were obtained. The possibility of frequency peaks position tuning and amplitude by external magnetic field was shown.

2. Problem statement
In this paper three one-dimensional (1D) photonic crystal structures were considered (figure 1). The first analyzed PC structure has 5 bilayer cells and each cell consists of $\text{SiO}_2$ and Si layer (figure 1(a)). The second structure is 5-layered $\text{SiO}_2$/Si PC composite bounded by graphene layer on $\text{SiO}_2$ substrate (figure 1(b)). The third structure is PC - $\text{SiO}_2$ - graphene - PC composite (figure 1(c)). External magnetic field was applied perpendicularly to PC layers surface. The structures were excited by linearly polarized transverse electric wave (TE-wave). The wave vector $k$ is perpendicular to the layers of each PC.
3. Optical graphene conductivity

Graphene conductivity is a sum of two contributions: (i) a Drude term $\sigma_D$ describing intra-band processes, and (ii) a term $\sigma_I$ taking into account inter-band transitions [6]. The inter-band transitions term can be calculated as $\sigma_I = \sigma'_I + i\sigma''_I$:

$$\sigma'_I = \sigma_0 \left( 1 + \frac{1}{\pi} \arctan \frac{\hbar \omega - 2E_F}{\Gamma} - \frac{1}{\pi} \arctan \frac{\hbar \omega + 2E_F}{\Gamma} \right),$$

and

$$\sigma''_I = -\sigma_0 \frac{1}{2\pi} \ln \frac{(2E_F + \hbar \omega)^2 + \hbar^2 \omega^2}{(2E_F - \hbar \omega)^2 + \hbar^2 \omega^2},$$

where $\sigma_0 = \frac{e^2}{2\hbar}$, $e$ – electron charge, $E_F$ - Fermi energy, $\Gamma$ - relaxation rate.

The Drude contribution term is following:

$$\sigma_D = \sigma_0 \frac{4E_F}{\pi} \frac{1}{\Gamma - i\hbar \omega}.$$

As seen from figure 2, at the terahertz frequencies the Drude term significantly exceeds the inter-band term, therefore the total conductivity may be approximately defined by the Drude term ($\sigma_I = \sigma_D$).
Figure 2. (Color online). Dispersion of inter-band (a) and intra-band (b) terms of conductivity.

It should be noted, that the graphene conductivity varies under external magnetic field [6]. Figure 3 shows changing of the total conductivity at various magnetic fields (0-3.6 T).

Figure 3. (Color online). Influence of external magnetic field on graphene conductivity.
3. Analytical modeling

Simulation of PC bandgap structures was performed by Matlab program using the transfer matrix method [7]. The photonic crystal structure has 5 bilayer cells, which were composed by SiO$_2$ and Si layers with refractive index $n_{SiO_2}$ = 2.154, $n_{Si}$ = 3.418 and thickness $d_{SiO_2}$ = 500 µm, $d_{Si}$ = 525 µm and $d_{substrate}$ = 331 µm correspondingly for frequency range from 0.1 to 1 THz [8]. Therefore the transfer matrix of whole composite has the following form:

$$\hat{T} = K_{air}D_{Si} \star T^K_{Si, SiO_2} f_{sub} \star ( fJ_{air, SiO_2} + \alpha ) \cdot 4$$

where $N$ is number of times. $T$ matrix is repeated in the structure and has the following form:

$$T = T_{Si, SiO_2} f_{SiO_2, Si} \cdot 5$$

The matrix characterizing the free propagation through some material in the structure (with $j = Si, SiO_2, substrate$) is

$$\Phi_j = \begin{bmatrix} e^{-i\omega\sqrt{\varepsilon_i}d_{i,j}/c} & 0 \\ 0 & e^{i\omega\sqrt{\varepsilon_i}d_{i,j}/c} \end{bmatrix} \cdot 6$$

The matrix characterizing the transfer through the boundary of two dielectrics is:

$$K_{i,j} = \begin{bmatrix} (\sqrt{\varepsilon_j/\varepsilon_i} + 1)/2 & (1 - \sqrt{\varepsilon_j/\varepsilon_i})/2 \\ (1 - \sqrt{\varepsilon_j/\varepsilon_i})/2 & (\sqrt{\varepsilon_j/\varepsilon_i} + 1)/2 \end{bmatrix} \cdot 7$$

where $i, j = air, Si, SiO_2, substrate$.

The matrix $K_{SiO_2, air} + \alpha fJ$ characterizes the transfer through graphene to air, where

$$J = \begin{bmatrix} 1 & 1 \\ -1 & -1 \end{bmatrix} \cdot 8$$

$\alpha \approx 1/137$ is fine structure constant and $f$ is a dimensionless function, which characterizes graphene optical conductivity under magnetic field influence:

$$f = \sigma_D \frac{h}{e^2} \left( \frac{\Gamma}{h - i\alpha} \right)^2 + wB \cdot 9$$

where $E_F$ - Fermi energy (0.45 eV); $\Gamma = 2.6$ meV; $wb$ is the cyclotron frequency defined as:

$$wb = \frac{e\nu_F B}{E_F} \cdot 10$$

where $c$ - electron charge; $\nu_F$ - Fermi velocity in graphene ($\approx 10^6$ m/s); $B$ is external magnetic field.

The simulated transmission coefficients of the photonic crystal and photonic crystal bounded by graphene layer of various magnetic field were shown in fig.4. As seen from fig 4, the transmission tuning of PC-graphene structure is observed at the magnetic field range from 0 to 3.6 T.
Figure 4. (Color online). The bandgap structure of photonic crystal without graphene layer and bounded by graphene.

The bandgap structure of PC ($SiO_2/Si$) – graphene/$SiO_2$ substrate - PC ($SiO_2/Si$) at various magnetic fields is shown in figure 5.

Figure 5. (Color online). The bandgap PC-graphene-PC structure.

As seen from fig. 5 peak of transmissivity in band-gap in frequency range of 0.2-0.22 THz is excited by $SiO_2$ substrate, it is defect mode in PC structure. The peak of transmissivity in frequency range of
0.145-0.165 THz is generated by the external magnetic field. It is caused by excitation of surface wave at the graphene boundary.

4. Conclusion
In this paper the transmission properties of photonic crystal structures on basis of graphene were investigated for terahertz frequency range. The possibility of transmission control of photonic crystal bounded by graphene layer under magnetic field influence was shown. The surface wave in the PC-graphene-PC bandgap structure was excited. The tuning of frequency position of transmittivity peak caused by surface wave excitation under magnetic field impact was demonstrated.

This work was financially supported by Government of Russian Federation, Grant 074-U01.

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