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Nanophotonic graphene-based racetrack-resonator add/drop filter

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ABSTRACT

We are presenting and analyzing a graphene-based nanophotonic device to operate as a resonator-add/drop filter, whose control is obtained by varying the graphene chemical potential. That device consists of graphene-based waveguides, two directional couplers and a racetrack resonator with 90° bends. Since the graphene chemical potential provides the achievement of the necessary parameters, the resonance and filtering of the signals are obtained by applying the correct value of the graphene chemical potential in the graphene nanoribbons.

The results of this study should help in the development of new graphene-based nanophotonic devices operating in the terahertz and infrared range (including in the C-band of the International Telecommunication Union – ITU), for use in future communications networks.

1. Introduction

Due to the electrical and optical parameters of graphene, researchers worldwide are increasingly devoting to the study of graphene, so that various nanodevices have been obtained. It is noteworthy that graphene plasmon technology provides the design of new nanophotonic devices, which can be used in Photonic Integrated Circuits (PICs). Hence, graphene can contribute significantly to the development of the communications networks.

We are presenting and analyzing a graphene-based nanophotonic device to operate as an add/drop filter, which consists of graphene-based waveguides, two directional couplers and a racetrack resonator filter with 90° bends, where the filtering control is obtained by varying the graphene chemical potential.

We believe that the results of this study should help in the development of new graphene-based nanophotonic devices operating in the terahertz and infrared range (including in the C-band of the International Telecommunication Union – ITU), for use in future communications networks.

This paper is organized as follows. In Section 2, we present the detailing of the graphene-based waveguides. The graphene-based directional couplers is shown in Section 3. Section 4 is devoted to the detailing of the nanophotonic graphene-based racetrack resonator add/drop filter. In Section 5 we show the results and discussion related to the nanophotonic graphene-based racetrack-resonator add/drop filter and in Section 6 we present our conclusions.

2. Graphene-based waveguides

Graphene is a quasi-two-dimensional material (effective thickness $t=0.34$ nm) consisting of carbon atoms positioned in a honeycomb lattice. Unlike what occurs in standard semiconductors, whose dispersion relation spectrum is parabolic near the Fermi level (Dirac point), graphene has a linear energy spectrum near the Fermi level.

The graphene chemical potential (μ_g) (or the Fermi energy (E_F)) value at the Dirac points is null. However, we can shift the Fermi energy to the upper or lower energy band applying a DC voltage (gate voltage) between a graphene layer and a semiconductor substrate, so that the carrier (electron or hole) density (n_s) can reach values up to $\approx 10^{13}\ \mathrm{cm}^{-2}$.

Hexagonal Boron Nitride (h-BN), also known as “white graphite”, is a graphite isomorphic insulating in which atoms of boron and nitrogen occupy A and B positions in the Bernal structure of graphene. Therefore, the atomic structure of h-BN is similar (hexagonal) to the graphene structure. Graphene on a h-BN layer

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possesses homogeneity and mobility of charge carriers almost an order of magnitude better than on SiO_2. Moreover, the dielectric properties of the h-BN are similar to the dielectric properties of SiO_2. Taking into account the above mentioned, we realized that graphene can be embedded in a h-BN layer, which in turn should be above the SiO_2 substrate. It is worth noting that previous studies have defined the value of the charge mobility in graphene on h-BN; $\mu = 60{,}000\ cm^2/V\ s$ [1].

In this study the electrical and optical properties of graphene were determined by the following equations:

Charge carrier density (n_s): in graphene is given by [2]:

$$n_s = \frac{\mu_g^2}{\hbar^2}\cdot\frac{1}{\pi V_F^2}, \tag{1}$$

where μ_g is the chemical potential applied to the graphene, $V_F = 10^6$ m/s is the Fermi velocity in graphene and $\hbar$ is the reduced Planck constant.

Relaxation time [3]:

$$\tau = \frac{\mu_g \mu}{e V_F^2}, \tag{2}$$

e being the elementary charge.

Chemical potential [4]:

$$\mu_g = \hbar V_F \sqrt{n_s \pi} \tag{3}$$

Local conductivity ($\sigma = \sigma_{intra} + \sigma_{inter}$):

$$\sigma_{\text{intra}}\left(w,\mu_g\right) = \frac{ie^2\mu_g}{\left(\omega + i\tau^{-1}\right)\pi\hbar^2}, \tag{4}$$

Where σ_{intra} is the intraband conductivity (due to electron–photon scattering), ω is the light angular frequency in the air and τ is the phenomenological scattering rate [5].

$$\sigma_{\text{inter}}\left(w,\mu_g\right) = \frac{e^2}{4\hbar}\left[1 + \frac{i}{\pi}\ln\frac{\hbar\left(\omega + i\tau^{-1}\right) - 2\mu_g}{\hbar\left(\omega + i\tau^{-1}\right) + 2\mu_g}\right]. \tag{5}$$

It is worth noting that for $\mu_g = 0$ graphene has a conductivity value $\mu_{g0} = 4 \times e/h \times \pi$ [5], where h is the Planck Constant [4].

Electric permittivity [3, 6, 7]:

$$\epsilon = \epsilon_0 + i\frac{\sigma}{wt};\ \epsilon_r = 1 + i\frac{\sigma}{w\epsilon_0 t}, \tag{6}$$

where ε_0 is the permittivity of free space and t the graphene layer effective thickness.

It was proved that unlike what happens in a free electron gas, where only TM polarization modes can be supported, graphene can support TM modes (s polarization) and TE (p polarization). The imaginary part of the conductivity determines the type of mode that can be supported on graphene. While TE modes can be supported for $\sigma'' < 0$, TM modes can be supported for $\sigma'' > 0$ [8].

In the collision limit ($\tau^{-1} = 0$) at absolute zero temperature, we have that $K_B/\mu_g = 0$, so that TE and TM modes are supported by graphene, for $0 < \hbar\omega/\mu_g < 1667$ $\left(\lambda > \frac{2\hbar\pi c}{1.667\mu_g}\right)$ and $1667 < \hbar\omega/\mu_g < 2$, $\left(\frac{\hbar\pi c}{\mu_g} < \lambda < \frac{2\hbar\pi c}{1.667\mu_g}\right)$, respectively [8, 9]. On the other hand, as the real part of the graphene conductivity is positive (in fact, when the real part of the graphene conductivity in the interband regime is positive, because in this case the real part of the graphene conductivity in the intraband regime is null) the energy of a graphene mode is absorbed or dissipated when $\frac{\hbar w}{\mu_g} > 2$ $\left(\lambda > \frac{\hbar\pi c}{\mu_g}\right)$. However, at room temperature occurs a little attenuation in the region where $\frac{1.5 \approx < \hbar w}{\mu_g} \approx < 2$. It is noteworthy that TE modes are more attenuated than TM modes [8].

At the top of Fig. 1 we show the possible photon wavelengths in air (before they have been coupled to the graphene surface plasmon – GSPs) related to the graphene surface plasmon polaritons (GSPPs) TM modes, versus graphene chemical potential and at the bottom of Fig. 1 the possible photon wavelengths in air, (before they have been coupled to the GSPs) related to the GSPP TE modes versus graphene chemical potential.

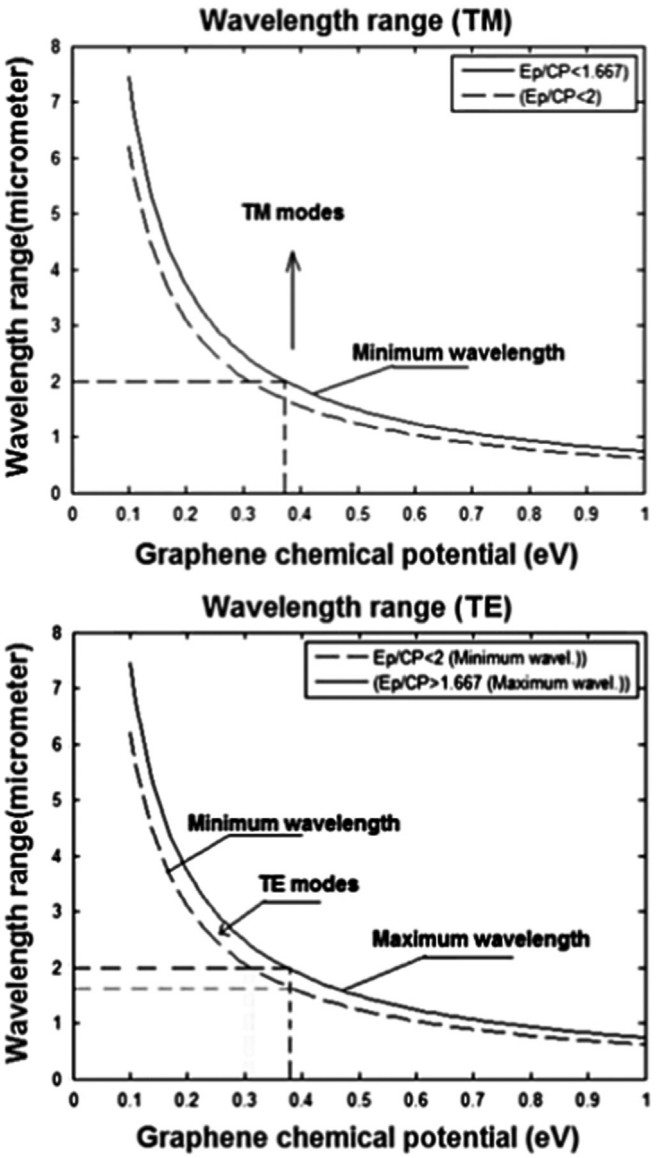

Fig. 1. Top – Air photon wavelength versus graphene chemical potential for TM modes. Battom – Air photon wavelength versus graphene chemical potential for TE modes.

Considering the charge carrier density between 10^{11} and $10^{14}\ cm^{-2}$, we can show that TM modes are found in the region between the far-infrared and terahertz and TE modes in the region between the far-infrared and the near-infrared. The wavelength range referring to the near-infrared, mid-infrared and far-infrared regions are summarized in Table 1.

The dispersion relation of graphene embedded between two dielectrics for TM modes is given by [9,10]:

$$\beta^2 = K_0^2\left[\epsilon_d - \left(\frac{2\epsilon_d}{\eta_0\sigma_g}\right)^2\right], \tag{7}$$

Moreover, the dispersion relation for TE modes is given by: [9]