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Graphene-Based 2D Photonic Crystal Demultiplexer Design

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***Abstract*—This work presents the simulation of a 2D photonic crystal demultiplexer based on graphene, whose main objective is to evaluate the contrast between the transmission parameters of the device with and without the use of the two-dimensional material. The simulation was performed using the commercial software COMSOL Multiphysics. And the results obtained were promising, evidencing that graphene presented significant improvements on the characteristics of the output signal.**

***Keywords*— Demultiplexer; Photonic crystal; Graphene**

I. INTRODUCTION (*HEADING 1*)

In the current telecommunications era, where the search for systems with high data transmission and processing capacity is rampant, compact photonic crystal (PC) systems have stood out as a promising research domain for application in integrated circuits [1]. Intrinsically designed to operate at the nanoscale, these systems offer extraordinary possibilities in the precise manipulation of light [2], bringing with them the promise of significant transformations in communication technologies.

The search for more efficient optical transmission and information processing systems is an imperative that permeates optical communications research. In this context, graphene, a two-dimensional material with unique electrical and optical properties[3], emerges as a promising alternative to optimize the performance of compact photonic crystal systems.

Thus, this work presents the study of a graphene-based photonic crystal demultiplexer model, with the aim of evaluating the improvements in the device's transmission parameters. Furthermore, the remainder of the work is organized into the following parts: section II - Theoretical Analysis Numerical Methods; section III - Design of eight-channel demultiplexer; section IV - Simulation Results and Discussion and finally the conclusions about the work.

II. Theoretical Analysis Numerical Methods

A. *PWE and FEM Methods*

To carry out the study of the proposed demultiplexer, we employ the Finite Element (FEM) and Plane Wave Expansion (PWE) methods. Each of these methods played a crucial role in the analysis and design of the photonic device.

The Finite Element method is a numerical technique widely adopted in computer engineering simulations due to its versatility and effectiveness in a wide variety of applications. In this study, we apply FEM to analyze the demultiplexer transmission parameters such as resonant wavelength, spectral width, and quality factor (Q). This allowed us to understand how the device interacts with light at different wavelengths and optimize its performance.

On the other hand, Plane Wave Expansion was used to calculate the Photonic Forbidden Bands (PBGs) of the TE (Electric Transverse) and TM (Magnetic Transverse) modes of the photonic crystal used in the construction of the demultiplexer. PBGs are frequency bands in which light propagation is not allowed in the crystal. Through this analysis, we were able to accurately determine the frequencies at which the crystal blocks the propagation of light, a critical aspect for the function of the demultiplexer.

Combining the information obtained through FEM and PBG analysis, we were able to design and adjust the demultiplexer in order to optimize its performance and ensure better transmission efficiency.

B. *Graphene Conductivity*

To model graphene, the classical form of the Drude model of the graphene conductivity tensor parameters was used, as discussed in [5][6] and presented below:

$$\sigma_{xx} = \frac{2D}{\pi} \frac{1/\tau - i\omega}{\omega_c^2 - (\omega + i/\tau)^2}, \qquad (1)$$

$$\sigma_{xy} = -\frac{2D}{\pi} \frac{\omega_c}{\omega_c^2 - (\omega + i/\tau)^2}, \qquad (2)$$

where $D = 2\sigma_0\epsilon_F / h2\pi$ is the Drude weight, $\sigma_0 = e^2/(4h2\pi)$ is the universal optical conductivity of graphene, ϵ_F is the Fermi energy of graphene, $\omega_c = e\mathbf{B}_0\mathbf{v}_F^2/\epsilon_F$ is the cyclotron frequency, $h2\pi$ is the reduced Planck constant, e is the charge of the electron, ω is the frequency of the incident wave, $\mathbf{v}_F$ is the Fermi speed, $\mathbf{B}_0$ is the external DC magnetic field, $i = \sqrt{-1}$ e $\tau = 0.9$ ps is the relaxation time of graphene.

III. Design of eight-channel demultiplexer

To develop the demultiplexer, a square network of silicon dielectric rods immersed in air was used, with an array size of 40 x 60, radius **r** of the Si rods of 100 nm and network constant **a** of 560 nm [7]. Based on the radius of the rods and the network constant, the analysis of the Photonic Bands (PBGs) for PC2D was carried out, as shown in Fig. 1.

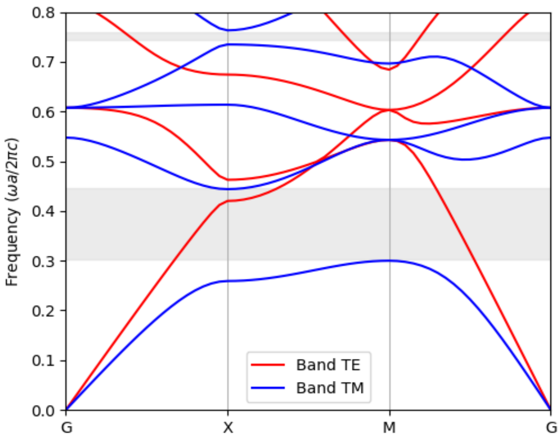

Figure 1 - Band Diagram for the proposed structure

As can be seen from the figure above, the photonic crystal has two TM band gaps in its band diagram, the first around $0.30233 < \mathbf{a} / \lambda < 0.44593$ and the second around $0.74448 < \mathbf{a} / \lambda < 0.75959$. Due to the fact that the first has a wider frequency range, it was considered for analysis of the device, which in terms of wavelength varies from 1255 nm to 1852 nm [7].

By introducing defects in the crystalline arrangement and varying the parameters that directly affect the 2D photonic crystal, that is, the radius of the rods and their lattice constant, we obtained the device shown in Fig. 2:

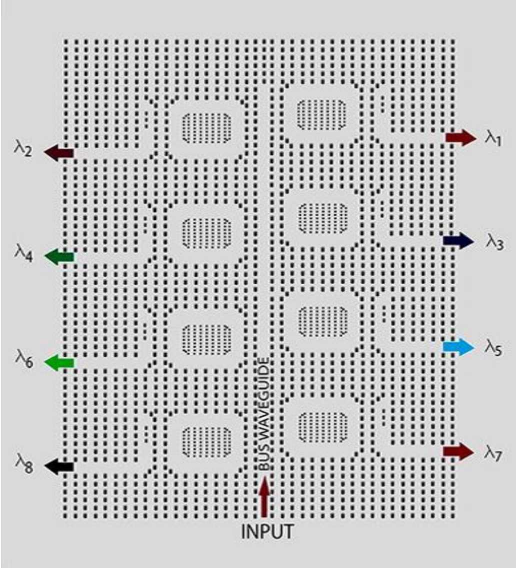

Figure 2 - 2D view of the proposed eight-channel demultiplexer

As can be seen in figure 2, the demultiplexer has a linear waveguide (Signal input) and eight transmission channels (Signal output), identified by λ_1, λ_2, λ_3, λ_4, λ_5, λ_6, λ_7 and λ_8. For a more detailed view, Fig. 3 highlights the main parts that make up each channel of the device.

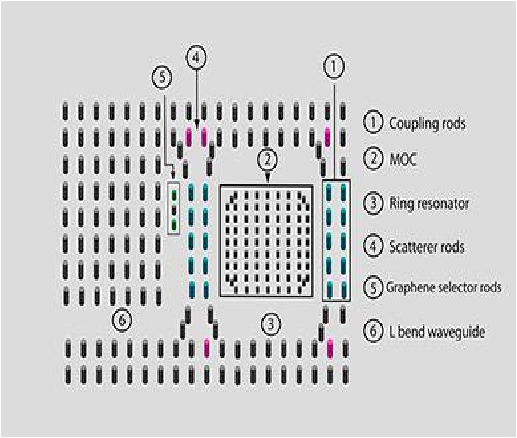

Figure 3 - Structure of the proposed demultiplexer output channels

From the figure and legend above, we see that each channel is made up of six main parts, namely: coupling rods; MOC;

Resonator ring, dispersion rods, graphene selector rods and L-shaped waveguide. However, the only parts that change in relation to one channel and another are the MOC and the graphene selector rods; such changes occur in terms of the rod radius and lattice constant, as presented in [7].

IV. Simulation Results and Discussion

After finishing the design process of the graphene-based PC2D demultiplexer, the optical behavior of the device was investigated. For this purpose, the COMSOL software was used to model and simulate the proposed structure. In order to achieve an accurate modeling of the device, it is necessary to perform 3D simulations. However, due to the requirement of an extensive execution period and the need for a high-capacity computer for this type of simulation, it was decided to use 2D simulations.

Since the purpose of this work is to evaluate the influence of graphene on the demultiplexer transmission parameters, our analysis will be restricted to the first transmission channel of the proposed device.

The transmittance spectrum of the PC2D demultiplexer for the case without graphene selector rods is shown in Fig. 4(a). Fig. 4(b) shows that the device operates selecting only the wavelength of 1503.3 nm, a bandwidth of 3.69 nm and Q factor = 407.4. The optical waves of wavelength λ = 1503.3 nm that propagate inside the device are illustrated in Fig 4(b). As evidenced from this wavelength, the input waves are coupled to the output guide (L-bend waveguide) through the resonator ring that is located between the input waveguide and the respective output waveguide.

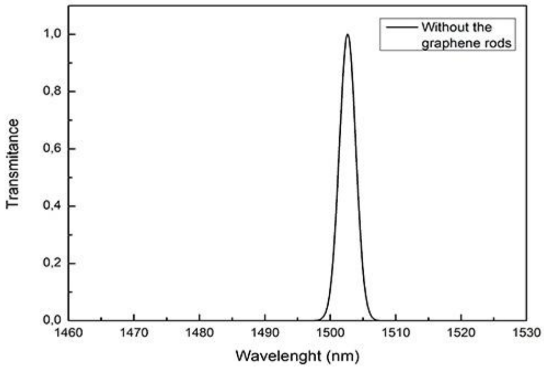

Figure 4 (a) - Output spectrum for the device without the graphene

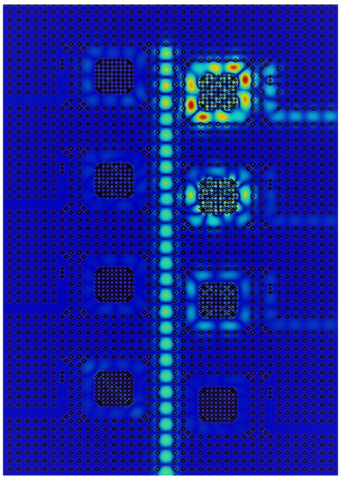

Figure 4 (b) - field distribution for the device without the graphene

Inserting the graphene rods, for a chemical potential equal to 0.5 eV, the results shown in Fig 5(a) and Fig 5(b) are obtained. For this case, the device works by selecting the wavelength 1502.0, a bandwidth of 1.56 nm and quality factor Q = 962.8.

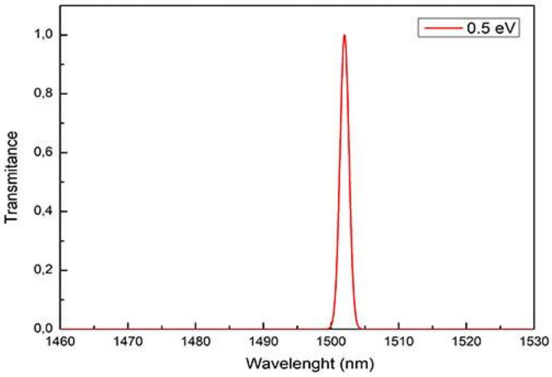

Figure 5 - Output spectrum for the graphene device

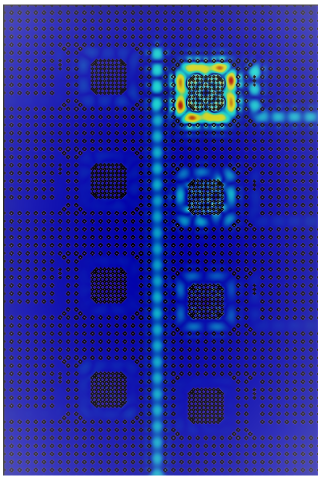

Figure 5 (b) - field distribution for the device with graphene

As can be seen from the data presented in figures 4(a) - (b) and figures 5(a) - (b), the introduction of graphene rods in the device provides a significant improvement in the transmission parameters of the signal that comes out through the channel λ_1. Next, the effect of varying the chemical potential of graphene on the transmission parameters of the proposed demultiplexer is investigated.

Table 1 below presents the results obtained for 3 different graphene chemical potential values, namely: 0.5 eV; 0.8 eV and 1.5 eV.

TABLE I. - TRANSMISSION PARAMETERS FOR DIFFERENT VALUES OF THE GRAPHENE CHEMICAL POTENTIAL

Chemical potential	**0.5 eV**	**0.8 eV**	**1.5 eV**
Wavelength (nm)	1502.0	1502.0	1502.0
Spectral width $\Delta\lambda$ (nm)	1.56	1.62	1.75
Quality factor Q	962.8	927.7	858.3

a.

As summarized in the table above, the variation of the chemical potential of graphene has no effect on the resonant length that comes out through channel λ1, however it provides changes in the spectral width which consequently influences the quality factor of the signal that is injected by the channel considered . In addition, among the 3 simulated chemical potential values, the one that presents a significant improvement regarding the output parameters is the chemical potential equal to 0.5 eV.

V. CONCLUSIONS

This work presents the results of a 2D photonic crystal demultiplexer based on graphene modeled and simulated using COMSOL software. With the objective of evaluating the effect of graphene on the transmission parameters of the device, we show with our results that there is a significant improvement in them, mainly for the case in which the chemical potential of the two-dimensional material is equal to 0.5 eV.

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