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Graphene-photonic crystal switch

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ABSTRACT

We have designed and analyzed a graphene-based photonic crystal directional coupler working as a switch, which is embedded in a SOI photonic crystal slab with triangular lattice of dielectric rods. The directional coupler has two W_1 (one missing row of dielectric rods) waveguides and the coupling region is coated with a graphene nanoribbon with width $W = 50$ nm.

We use an electric gate to modify the graphene chemical potential to obtain the desired change of the graphene equivalent permittivity. Thus, we can drive the directional coupler to get its transition from the bar state to the cross state and vice-versa.

1. Introduction

Photonic crystal structures are composed of dielectric constant basic block (unit cell), periodically repeated in space, so that the unit cell is a lattice with discrete translational symmetry. In a photonic crystal there is a dielectric constant lattice in one, two or three dimensions. That periodicity is defined by the lattice vectors, which have magnitudes on the order of a few hundred nanometers, working with modes usually (but not necessarily) in the infrared region. Indeed, even the physics of 3D photonic crystal slabs is based upon the 2D triangular lattice, where the Bloch modes are the eigenmodes, whose propagation direction is defined by the group velocity direction, so that the resulting electromagnetic energy distribution of the Bloch waves matches the periodicity of the lattice. In analogy to the atomic lattice, a bandgap in the dispersion diagram can be created, which does not allow light with a frequency in this bandgap to propagate.

To allow the light confinement in the third direction in a 2D photonic crystal, we utilize the concept of total internal reflection at the interface of the photonic crystal slab and the cladding material. Photonic crystal slab platform is used in most photonic crystal (PhC) devices because its fabrication process is easier than that of the 3D PhC slab platform.

Generally, the so-called slab structure consists of a thin 2D photonic crystal in a high-index membrane surrounded by air. However, this type of structure is not easily integrable into a chip. Hence, we used a SOI-based hybrid structure, where the lower cladding consists of a structured oxide layer, whose effective refractive index is close to 1 [1]. Thus, the device with this structure is easier to integrate into a chip than a membrane and is almost symmetrical.

The PhC structure we choose is a silicon on insulator (SOI) slab with triangular lattice of dielectric rods. Given that this device will operate in the C-band of the ITU, which covers the wavelength range from 1528.77 nm to 1560.61 nm [2], we adopted the refractive index of the silicon dielectric rods, $n = 3.481$ (at a wavelength equal to 1.55052 μm). The dielectric rods are embedded in a substrate (SiO_2), whose refractive index is $n_s = 1.528$ (at a wavelength equal to 1.55052 μm).

In a purely 2D PhC, the transverse magnetic (TM) modes (odd modes) have no electric field in the horizontal middle plane (x–y plane) of the PhC and have magnetic field in the x–y plane. Moreover, the TM modes have an electrical field in the z direction, and no magnetic field in the z direction. TE modes (even modes) present the reverse of what occurs in TM modes. On the other hand, the finite height of the photonic crystal slabs leads polarization mixing and the modes are not purely TM (or TE)-polarized anymore. However, if the (x, y)-plane in the middle of the slab is a mirror plane of the structure, the first-order modes are very similar to the corresponding modes existing in infinite 2D photonic crystals. Furthermore, in the (x, y)-mirror plane itself, these modes are a purely TM (or TE) polarized. In other words, in this case the polarization mixing is quite small and the approximation TE for even modes (TE-like) and TM for odd modes (TM-like) can be assumed.

While the effective vertical wavelength of the TE-like modes is more dependent on the high dielectric material, this effective vertical wavelength of the TM-like modes is more dependent on

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low dielectric material. For this reason, the gap in the hole slabs opens up at a smaller thickness than for the rod slabs.

The light cone consists of optical power radiating vertically (region outside of the slab). The boundary between guided and radiation modes is called the light line. In a PhC slab consisting of a uniform material above and below the slab core, the light line is constituted by the modulus of the wave vectors divided by the cladding refractive index. The cladding refractive index must be lower than the average index of the slab core in order to confine light in the vertical direction.

A defect in the PhC structure can enable modes within the bandgap. For example, by removing a line of rods, light can be guided in a PhC. Given the peculiar diffraction phenomena of the photonic crystals, the dimensions of the photonic crystal-based devices range from a few to tens of micrometers.

Photonic crystal enabled the achievement of new optical devices, for example, waveguides [3], lasers [4], splitters [5], antennas [6], optical switches [7,8], etc.

On the other hand, graphene is a two-dimensional (2D) allotropic form of carbon comprising of atoms periodically arranged in an infinite hexagonal structure. Taking into account that the lattice vectors of graphene are based on the distance between two neighboring carbon atoms (0.192 nm), graphene technology is embedded in the field of nanophotonics.

The physics involving the two-dimensional graphene is based on the fact that electrons in this structure have a tiny rest mass and respond quickly to electric fields. On the other hand, plasmons in a graphene microribbon are collective oscillation of electrons, whose frequency depends on how rapidly waves in this electron sea travel back and forth between its edges. Light of the same frequency applied in the graphene microribbon gives rise to a “resonant excitation,” (a large increase in the strength of the oscillation). The strength of the light-plasmon coupling can be affected by the concentration of charge carriers (electrons and holes). We can modify the concentration of charge carriers in graphene, which can easily be increased or decreased simply by applying a strong electric field (electrostatic doping).

It is noteworthy that when the chemical potential of graphene is greater than half the photon energy, intraband transitions at the conduction band dominate, so that graphene behaves like a metal. Hence, graphene can support transverse magnetic (TM) polarized surface plasmon polaritons (SPPs).

Due to the graphene surface plasmons (GSPPs), graphene ribbons of micrometric widths can operate as a waveguide into photonic integrated circuits (PICs) [9–11]. However, the propagation length, where the field amplitude of the SPP falls to $1/e$ of the initial value is $L=V_F\tau$, where $V_F=10^6$ m/s is the Fermi velocity and τ is the momentum relaxation time.

Graphene enables the propagation of modes in the terahertz frequency range between 300 GHz and 1.87^{14} Hz $=187$ THz ($\lambda=1600$ nm), which had never been explored for telecommunications, due to the lack of a technology that would provide devices and transmission media with the appropriate parameters for operation in this range of frequencies.

We designed and analyzed a switch based on a directional coupler embedded in a photonic crystal structure with coupling length compatible with the propagation length allowed in a graphene waveguide. The coupling region of the directional coupler is coated with a graphene nanoribbon, thus yielding a graphene based waveguide. Even though we implanted a graphene based waveguide in the coupling region of the directional coupler described above, we use the graphene nanoribbon only to modify the coupling region dielectric constant. Thus, we can control the directional coupler to leave the cross state and to go to the bar state (and vice versa), via alteration of the graphene chemical potential.

We believe that this graphene-photonic crystal switch is one of the most compact switch achieved up to this present moment, so that it could be the basis for future communication networks operating in the range of terahertz and infrared. Moreover, the use of an electric gate in a graphene nanoribbon to control the medium permittivity may be useful in other types of compact devices, which can be used in photonic integrated circuits (PICs).

This paper is organized as follows. In Section 2, we present the graphene_photonic crystal directional coupler working as a switch. The switch control is presented in Section 3. Finally, in Section 4 we show our conclusions.

2. Graphene_photonic crystal directional coupler

The coupler is embedded in the silicon on insulator (SOI) slab as shown in Section 1. As the photonic band gap (PBG) and the gap–midgap ratio of a SOI slab is a function of the silicon rods radius we used the Plane Wave Expansion (PWE) to find the silicon rods radius that provides the highest gap–midgap ratio ($r_r=0.23$, gap–midgap ratio$=$28.83%). On the other hand, the PBG width of a PhC slab depends on the height of the slab. However, by PWE we can observe that the slab height (h) between 1.5a and 2.2a, where “a” is the lattice constant, provides the highest PBG. Hence, we adopted $h=2a$.

The directional coupler has two W_1 (one missing row of dielectric rods) waveguides and the coupling region is coated with a graphene nanoribbon with width $W=50$ nm. The reason for the insertion of graphene nanoribbon is that we can easily control its refractive index by use of the electric field effect, since the work function of graphene can be adjusted as the gate voltage tunes the Fermi level across the charge neutrality point [12].

Hence, we can use the electrical gate as a command signal working in the coupling region. The increase of the refractive index graphene nanoribbon (due to the action of the electric gate) causes the decrease of the coupling coefficient value (and vice-versa. See details below). Based on the above details if we consider that the coupler was designed to operate in the bar state, the decrease of the coupling coefficient should be sufficient to bring the coupler to work in the cross state.

The substrate on which graphene is embedded must be carefully chosen to prevent deterioration of quality of the system. For example, graphene on SiO_2 is highly disordered, exhibiting characteristics that are far inferior to the expected intrinsic properties of graphene [13–15]. Thus, we inserted a hexagonal boron nitride (h-BN) layer between SiO_2 and the graphene nanoribbon, because graphene on h-BN substrates has mobilities and carrier inhomogeneities that are almost an order of magnitude better than devices on SiO_2. h-BN is an insulating isomorph of graphite with boron and nitrogen atoms occupying the inequivalent A and B sublattices in the Bernal structure. Hexagonal boron nitride (h-BN) is also known as “white graphite” and has similar (hexagonal) crystal structure as of graphite. In this case, the density-independent mobility due to charged-impurity Coulomb (long-range) scattering is $\mu=60{,}000\ \mathrm{cm^2/V\,s}$ [16].

According to the super mode method, we know that the minimal coupling length (LC) of a symmetrical directional coupler is given by

$$L_c=\frac{\pi}{|\beta_{odd}-\beta_{even}|}=\frac{\pi}{|\Delta\beta|}\ \text{(cross state)};\ L_c=\frac{2\pi}{|\Delta\beta|}\ \text{(bar state)} \tag{1}$$

By means of the Equations (2) and (3), if it is considered a low-intensity continuous-wave (CW) beam, we can get the amplitude (A) and intensity (I) of the traveling signal as follows [17]:

$$A_a(z)=A_0\ \cos(kx)\ and\ I_a(z)=A_0^2(\cos(kx))^2 \tag{2}$$