NANO, MESO, MICRO : SCIENCES ET INNOVATIONS POUR LA RADIO ET LA PHOTONIQUE.

Cavité asymétrique 1D multifonctionnelle à base de graphène et de cristaux liquides pour les métasurfaces accordables.

Graphene and liquid crystal-based multifunctional 1D asymmetric cavity for tunable metasurfaces.

Giovanni Magno,* Marco Grande, and Antonella D'Orazio
Dipartimento di Ingegneria Elettrica e dell'Informazione (DEI), Politecnico di Bari, Via Re David 200, 70126 Bari, Italy
* *giovanni.magno@poliba.it*

Cristaux photoniques, Cristaux liquides, Graphène, Structures multifonctionnelle.
Photonic crystals, Liquid crystals, Graphene, Multifunctional structures

Résumé/Abstract

FR : Le besoin croissant de compacité des dispositifs optiques fait de leur multifonctionnalité et de leur reconfigurabilité des propriétés cruciales. Nous étudions numériquement une nouvelle structure présentant ces caractéristiques. La structure proposée se base sur une combinaison de cristaux photoniques 1D (PhC) et de matériaux reconfigurables (graphène et cristaux liquides). Cette structure compacte peut réaliser des fonctions optiques essentielles, reconfigurables et à bande étroite, telles que la modulation d'amplitude, le filtrage coupe-bande et le déphasage. La polarisation du graphène monocouche et des cristaux liquides génère des effets indépendants sur l'intensité d'absorption, l'action de déphasage et la position spectrale de la résonance et sont détaillés ici. Cette structure peut être utile pour l'ingénierie de métasurfaces reconfigurables pour les modulateurs optiques et les systèmes de contrôle de la direction des faisceaux.

ENG: The increasing need for compactness of optical devices makes multifunctionality and reconfigurability features crucial. We numerically investigate a novel design exhibiting these features. The proposed structure relies on the joint paradigm of 1D photonic crystals (PhC) and reconfigurable materials (graphene and liquid crystals). This compact structure can perform valuable reconfigurable optical narrowband functions such as amplitude modulation, notch filtering, and phase shifting. The independent effects of monolayer graphene and liquid crystal biasing on the absorbance intensity, phase shifting action, and the spectral position of the resonance are detailed. This structure can be valuable for engineering reconfigurable metasurfaces for optical modulators and beam-steering systems.

1 Introduction

Designing optical devices incorporating multifunctionality and reconfigurability is imperative to satisfy the increasing request for compact and smart solutions. Multi-functionality can be more easily found in structures having an abundance of degrees of freedom [1–3]. The use of tunable materials, on the other hand, paves the way for design reconfigurability. In particular, graphene [4] and liquid crystals [5] have proven to be of great interest for achieving reconfigurability in optical devices.

2 Method, results and discussion.

Here we numerically present a novel structure combining 1D photonic crystals (PhC), graphene, and liquid crystals to obtain both multifunctionality and reconfigurability. As sketched in Fig.1(a), the structure consists of an asymmetric cavity, whose mirrors are made of 1D Ta_2O_5 / SiO_2 photonic crystal terminating on two graphene monolayers. The thicknesses of the Ta_2O_5 and SiO_2 layers are 173 nm and 250 nm, respectively, so that the unitary cell is 423 nm thick. In reference to Fig.1(a), the upper and lower mirrors bounding the cavity consist of 15 and 7 periods, respectively. The cavity defect, bounded by two graphene monolayers on which a 50-nm thick polyimide ($n = 1.678 + j10^{-4}$ [6]) orientation layer is deposited, is filled with a nematic liquid crystal (E7 mixture), whose properties are modeled after [7,8]. Both the properties of monolayer graphene and liquid crystals can be tuned through electrostatic control. The two graphene monolayers are modeled as a surface current density. Graphene conductivity is modeled after [9–11] as the sum of an intraband and an interband term.

We have numerically observed, through simulations based on the finite element method, that the above-described structure allows for important reconfigurable optical functions such as amplitude modulation, notch filtering, and phase shifting. On the one hand, geometrical parameters and chemical potentials of graphene layers can be exploited to control the (i) intensity of a 1 nm-wide absorbance peak and (ii) the phase of the reflected wave. On the other hand, liquid crystal orientation can be exploited to spectrally tune features (i) and (ii) over about 200 nm around the working wavelength of 1550 nm.

By varying both chemical potentials of the two graphene monolayers, we can identify six different working regimes, with different absorbance and reflectance behavior of the structure. A single graphene layer will be in an ON (OFF) state if its chemical potential is less than or equal to (greater than or equal to) 0.35 eV (0.55 eV). In particular, when one of the two graphene layers is in the ON state while the other one is in the OFF state, we are in a working regime in which the absorbance is maximum and the reflectance minimum. Vice versa, when graphene layers are both in the OFF state the absorbance decreases, and the reflectance increases to values close to unity.

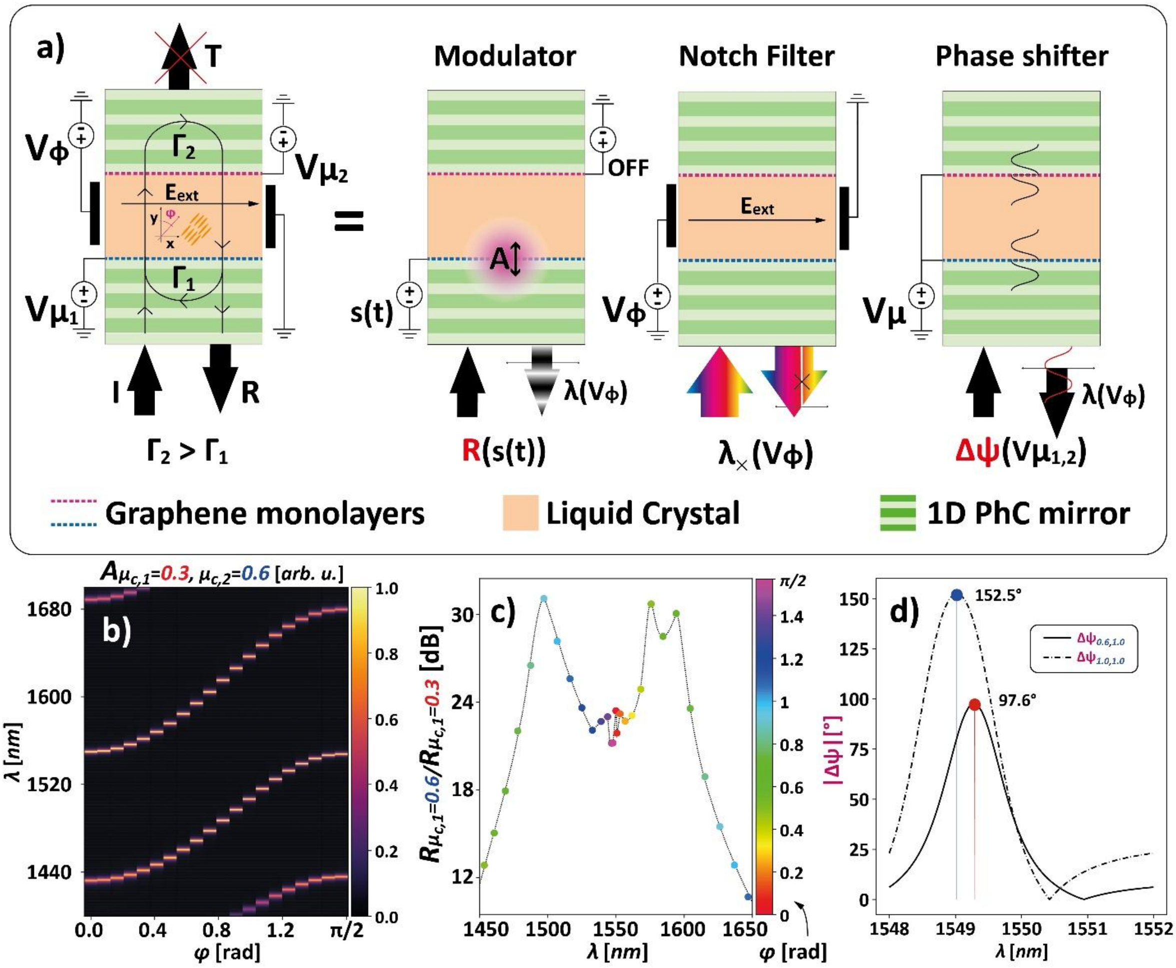

Fig. 1. (a) Sketch depicting the proposed structure, the optical functions it enables, and the degrees of freedom that can be adjusted to reconfigure these functions. (b) Map of absorbance as a function of the wavelength and of the liquid crystal optical axis angle ϕ, when one of the two graphene monolayers is in the ON state and the other in the OFF state. (c) Logarithm of the ratio between the reflectance calculated when the chemical potential of one of the two graphene monolayers is 0.6 eV and the reflectance calculated when the chemical potential of the same layer is varied to 0.3 eV, while the remaining graphene monolayer is in the OFF state. (d) Absolute value of phase shift difference calculated for different configurations of chemical potentials of graphene layers.

Fig. 1(b) shows that it is possible to tune the ϕ angle (corresponding to the liquid crystal elongated particles orientation to the y-axis) to spectrally reconfigure the cavity resonance. Fig. 1(b) shows the absorbance map as a function of wavelength and of the ϕ angle, when one graphene layer operates in the ON state and the other one in the OFF state, respectively. As the ϕ angle increases, the resonances redshift consistently with the increasing refractive index experienced by the extraordinary wave traveling along the y-direction. Fig.1(c) shows the extinction ratio, defined as the logarithm of the ratio between the reflectance calculated when the chemical potential of one of the two graphene monolayers is 0.6 eV and the reflectance calculated when the chemical potential of the same layer is varied to 0.3 eV, while the remaining graphene monolayer is instead kept in the OFF state. Within the spectral range of interest, the extinction ratio is greater than 21.8 *dB* and reaches maximum values of 31 and 30.7 *dB* for λ equal to about 1497 *nm* and 1576 *nm*, respectively.

Conversely, when both the graphene layers are in the OFF state, the reflectance is higher than 94.9%, and a full phase excursion of the reflected wave is observed. Fig.1(d) shows the phase shift difference (defined with respect to the phase of the reflected wave when both chemical potentials of the graphene layers are maintained at 0.6eV) as a function of wavelength for two different configurations of the graphene layer chemical potentials. When both chemical potentials are raised to 1 eV, the phase shift difference reaches its maximum achievable value of about 152.5°. Being in a non-absorbing regime, this phase shift is attained with low insertion losses, less than -0.23 *dB* in our observation domain.

Like the other functions, the phase shifting can also be spectrally reconfigured throughout a 200 nm spectral range centred around 1550 nm thanks to the action of the liquid crystal.

3 Conclusion

We numerically investigated the behavior of a novel multifunctional and reconfigurable 1D PhC asymmetric Fabry-Pérot cavity, whose defect is filled with nematic liquid crystal and bounded by two graphene monolayers. Many degrees of freedom, emerging thanks to the coexistence of two different reconfigurable materials, distinct optical spectrally tunable operations in reflection can be identified: a notch filter (with a linewidth of 1 *nm*), a narrowband modulator, a phase shifter (up to about 152° and with insertion losses lower than -0.23 *dB*). In all these operations, the liquid crystal is exploited to attain spectral reconfigurability in a window of about 200 *nm* around the working wavelength of 1550 *nm*. This powerful yet simple structure can pave the way for the realization of metasurfaces, optical modulators, and phased arrays. These may be at the basis of beamsteering systems for lidar and navigation applications.

GM is supported by a grant from Regione Puglia "Research for Innovation" (REFIN). REFIN is an intervention co-financed by the European Union under the POR Puglia 2014-2020, Priority Axis OT X "Investing in education, training and professional training for skills and lifelong learning - Action 10.4 - DGR 1991/2018 - Notice 2/FSE/2020 n. 57 of 13/05/2019 (BURP n. 52 of 16/06/2019)

References

[1] G. Magno, M. Grande, A. Monmayrant, F. Lozes-Dupuy, O. Gauthier-Lafaye, G. Calò, and V. Petruzzelli, "Controlled reflectivities in self-collimating mesoscopic photonic crystal," J. Opt. Soc. Am. B Opt. Phys. 31(2), (2014).

[2] G. Magno, A. Monmayrant, M. Grande, F. Lozes-Dupuy, O. Gauthier-Lafaye, G. Calò, and V. Petruzzelli, "Stable planar mesoscopic photonic crystal cavities," Opt. Lett. 39(14), (2014).

[3] A. Monmayrant, M. Grande, B. Ferrara, G. Calò, O. Gauthier-Lafaye, A. D'Orazio, B. Dagens, V. Petruzzelli, and G. Magno, "Full optical confinement in 1D mesoscopic photonic crystal-based microcavities: An experimental demonstration," Opt. Express 25(23), (2017).

[4] F. Bonaccorso, Z. Sun, T. Hasan, and A. C. Ferrari, "Graphene photonics and optoelectronics," Nat. Photonics 4(9), 611–622 (2010).

[5] S. P. Palto, L. M. Blinov, M. I. Barnik, V. V Lazarev, B. A. Umanskii, and N. M. Shtykov, "Photonics of liquid-crystal structures: A review," Crystallogr. Reports 56(4), 622 (2011).

[6] P. A. Kawka and R. O. Buckius, "Optical properties of polyimide films in the infrared," Int. J. Thermophys. 22(2), 517–534 (2001).

[7] V. Tkachenko, G. Abbate, A. Marino, F. Vita, M. Giocondo, A. Mazzulla, F. Ciuchi, and L. De Stefano, "Nematic liquid crystal optical dispersion in the visible-near infrared range," Mol. Cryst. Liq. Cryst. 454(1), 263/[665]-271/[673] (2006).

[8] S. T. Wu and K. C. Lim, "Absorption and Scattering Measurements of Nematic Liquid Crystals.," Appl. Opt. 26(9), 58 (1987).

[9] L. A. Falkovsky and A. A. Varlamov, "Space-time dispersion of graphene conductivity," Eur. Phys. J. B 56(4), 281–284 (2007).

[10] L. A. Falkovsky, "Optical properties of graphene," J. Phys. Conf. Ser. 129, (2008).

[11] G. W. Hanson, "Dyadic Green's functions and guided surface waves for a surface conductivity model of graphene," J. Appl. Phys. 103(6), 64302 (2008).