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Kerr Effect of Valley-Hall Topological Edge Plasmons on Graphene Nanohole Plasmonic Crystal Waveguide

Yupei Wang[1], **J. W. You**[1,2] **and Nicolae C. Panoiu**[1]

[1]University College London, Department of Electronic and Electrical Engineering, Torrington Place, WC1E 7JE, London, United Kingdom
[2]Southeast University, State Key Laboratory of Millimeter Waves, No. 2 Southeast University Road, Nanjing, 211189, China
yupei.wang.18@ucl.ac.uk

Abstract – **We present and study the Kerr effect of valley topological plasmonic edge modes based on graphene nanohole plasmonic crystal waveguide. By adding an extra small holes on graphene nanohole crystal, the spatial-inversion symmetry of whole structure is changed from C_{6v} to C_{3v}. As a result, the spatial symmetry breaking leads to a gapless Dirac cone and topologically protected edge mode appears inside the nontrivial frequency bandgap which shows unidirectional properties. As a nonlinear material with strong nonlinearity enhancement, graphene processes a giant second-order nonlinear refractive index $n_2 = 6.28 \times 10^{-6}\text{cm}^2/\text{W}$, which is more than 9 orders of magnitude larger than other bulk dielectrics. With a pump bulk mode changing the refractive index of the whole system, we observe a remarkable variation of the transmission of topological signal mode with respect to the applied pump power. This work may develop graphene-based robust plasmonic integrated nonlinear applications.**

I. Introduction

In our work, we show the vally-Hall topologically protected edge mode in a graphene nanohole plasmonic crystal waveguide with the spatial-inversion symmetry breaking, by an extra air hole etched on graphene crystal waveguide. As a result, the changed spatial-inversion symmetry opens the symmetry-protected Dirac cone and unidirectional topological edge mode is formed inside the nontrivial bandgap. Employing the unidirectional topological property and giant nonlinear refractive index of graphene, we demonstrate the Kerr effect on graphene nanohole plasmonic crystal waveguide. Under pump bulk modes with different group velocities approaching to slow light region, the variation of transmission of signal topological light is quantitatively characterized. All the simulations are calculated by the optic module of COMSOL Multiphysics 5.6.

Research in topological plasmonic egde states has been attracting increasing attention, especially due to the novel and unique properties, like unidirectional propagation without back-scattering and robustness against induced disorder [1]. By breaking the time-reversal symmetry under an external static magnetic field [1], or spatial-inversion symmetry via spatially asymmetric perturbations [2], symmetry-protected Dirac cones are gapped out and topological edge mode appears inside the nontrivial bandgap. Most of the topological photonics studies have focused on linear systems, but graphene-based topological system with a giant nonlinear interaction shows great potential on applications of nonlinear regime [3].

II. Kerr Effect on Graphene Nanohole Plasmonic Crystal Waveguide

In this section we present the main results of our work. We first discuss the structure and band diagram of the designed graphene nanohole plasmonic crystal waveguide, then show the transmission of unidirectional topological signal mode by applied uniform pump power changing the refractive index of the whole system.

A. Topological Bands of Graphene Nanohole Plasmonic Crystal Waveguide

The schematic of the proposed topological graphene nanohole plasmonic crystal waveguide is presented in Fig. 1(a). It consists of one graphene layer etched by air holes with two different radius. The graphene waveguide contains a domain-wall interface formed by left- and right-domains with horizontal mirror symmetry. Each domain is composed by a hexagonal lattice with two air holes of different sizes in the unit cell. The nanohole unit cell structure and First Brillouin zone (FBZ) of nanohole lattice are shown in Fig. 1(b) and Fig. 1(c), respectively. We fix the lattice constant $a = 400\sqrt{3}\text{nm}$ and radius of big hole $R = 140\,\text{nm}$.

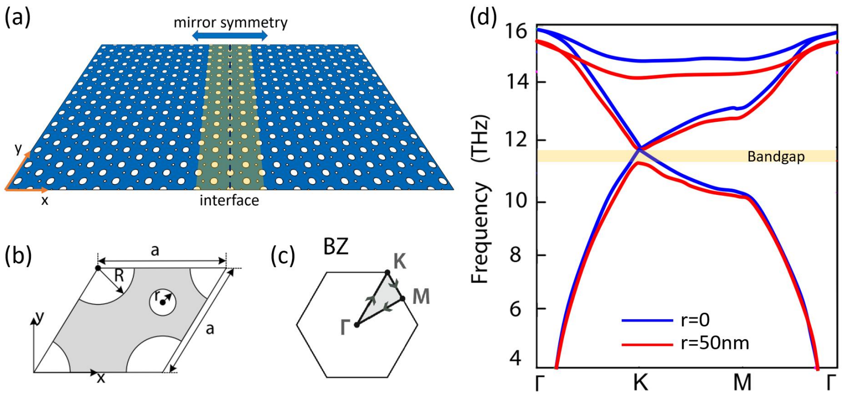

Fig. 1: (a) Schematic of graphene plasmonic nanohole crystal with a mirror symmetric domain-wall interface along y-axis. (b) Unit cell of graphene lattice composed of two air holes with radius R and r. (c) First Brillouin zone (FBZ) of a hexagonal graphene lattice, consisting there high symmetric points Γ, K and M. (d) Band diagram of the graphene nanohole plasmonic crystal with and without small air hole r. Since the spatial inversion symmetry is broken in the case with small hole $r = 50\,\text{nm}$, a nontrivial frequency bandgap emerges.

The plasmonic band structure of graphene nanohole crystal is calculated through the high symmetric points Γ, K and M of the FBZ. In the graphene nanohole crystal without small air hole $r = 0$, the spatial symmetry of the periodic system is C_{6v}, which protects the Dirac cone at K point, as shown in blue curves of Fig. 1(d). When the small hole $r = 50\,\text{nm}$ is etched on the graphene crystal, the C_{3v} spatial symmetry opens the Dirac cone and a nontrivial bandgap emerges at the location of Dirac point (red curves in Fig. 1(d)).

The projected band diagram of a finite graphene nanohole waveguide consisting a domain-wall interface is computed, and the graphene nanohole structure and projected band are presented in Fig. 2(a) and Fig. 2(b), respectively. The red line represents topological mode inside the bandgap whereas blue regions represent the bulk mode. Moreover, the corresponding field distribution of topological edge mode and bulk mode are discussed. Under a left-circularly polarized (LCP) source, the field distribution of topological mode (Fig. 2(c)) at $11.4\,\text{THz}$, corresponding to E_s in Fig. 2(b), shows highly-confined and unidirectional properties at the domain-wall interface. Besides, the field distribution of bulk mode is uniform and extended around the whole graphene waveguide, which is shown in Fig. 2(d).

B. Kerr Effect of Topological Valley Edge Mode

The unidirectional propagation feature of topological interfacial mode and graphene nonlinearity can be applied on graphene-based nonlinear nanodevices. In this work, we studies the Kerr effect on graphene nanohole plasmonic waveguide pumped by bulk modes with different group velocities. As seen in Fig. 3(a), bulk mode E_b with high power uniformly pumps the whole system whereas the topological signal mode E_s is excited by a low power LCP source at $11.4\,\text{THz}$. The length and height of graphene nanohole waveguide are $L = 35a$ and $W = 19a$, respectively. As a nonlinear material with large nonlinear refractive index $n_2 = 6.28 \times 10^{-6}\text{cm}^2/\text{W}$ [3], graphene waveguide shows tunable refractive index excited by the power of pump mode, which can also shift the frequency of bandgap. Consequently, the topological signal mode can be switched to a leaky and scattered bulk mode, which can sharply decrease the transmission $\eta = P_{s_{out}}/P_{s_{in}}$ (the ratio between the output and input power) of the signal mode.

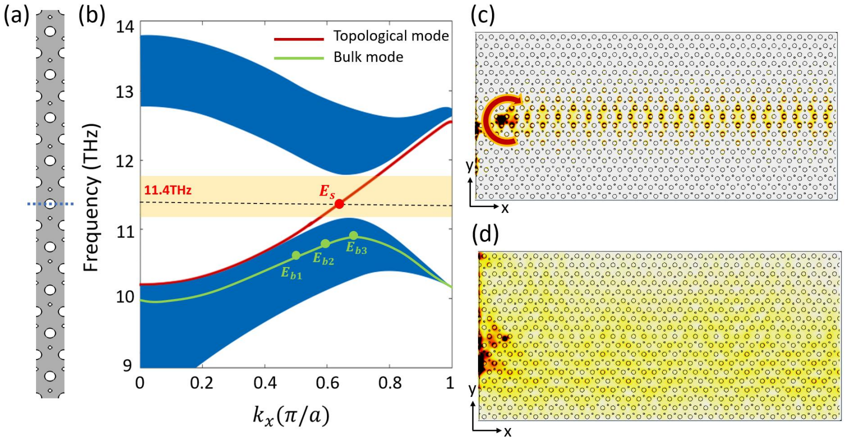

Fig. 2: (a) Domain-wall interface with a vertical mirror symmetry of the graphene nanohole crystal supercell. (b) Projected band diagram of graphene nanohole crystal waveguide with $r = 50\,\mathrm{nm}$, topological protected interfacial mode (red) appears inside the nontrivial bandgap. (c) Unidirectional propagation along the domain-wall interface, when the finite graphene nanohole waveguide excited by a left-circularly polarized (LCP) source at $11.4\,\mathrm{THz}$, corresponding to the topological mode E_s in Fig. 2(b). (d) Field distribution of uniform bulk along the whole graphene nanohole waveguide, corresponding to the bulk mode E_b in Fig. 2(b).

The variation of signal transmission with respect to the pump power is shown in Fig. 3(b). Under there pump bulk mode (E_{b1}, E_{b2} and E_{b3} in Fig. 2(b)) with different group velocities approaching to slow light region, the transmission of signal mode shows sharply decreases to 0.1 when the power of pump mode increases, however, the required power of bulk mode E_{b3} at slow light region is lowest compared with other two bulk modes. The closer pump mode is to the slow light region, the lower required pump power is to achieve the same transmission of signal mode.

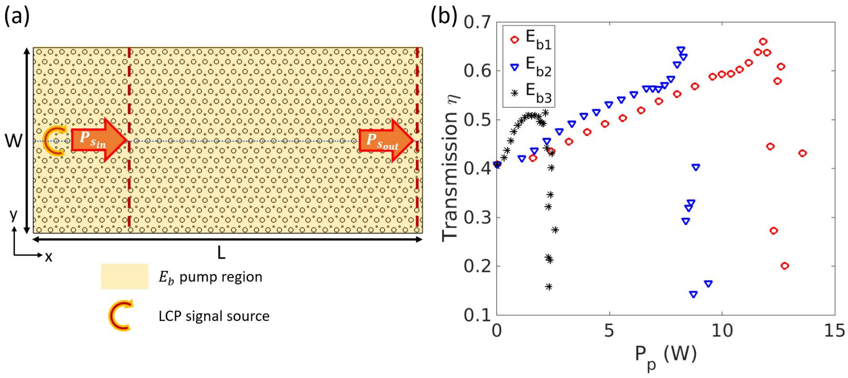

Fig. 3: (a) Schematic of the Kerr effect based on the graphene nanohole plasmonic crystal waveguide. Light of uniform bulk mode E_b (yellow) pumps the whole waveguide. The unidirectional signal mode E_s at $11.4\,\mathrm{THz}$ carries an input power $P_{s_{in}}$ and output power $P_{s_{out}}$. (b)Transmission of signal light with respect to the variation of pump power under the cases pumped by there electric fields of bulk modes in Fig. 2(b).

III. Conclusion

We proposed valley-Hall topological plasmons on graphene nanohole plasmonic crystal waveguide. The change of spatial-inversion symmetry realizes a gapless Dirac cone and topological interfacial mode with unidirectional property. Kerr effect on the designed graphene nanohole waveguide is studied based on the large nonlinear refractive index of graphene. Our results shows the transmission of signal mode sharply decreases with the increasing pump power and the less pump power is required when the pump mode is closed to slow light region.

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