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Propagation and transmission of a light beam in a graphene-like metallic photonic lattice

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Abstract: We study theoretically light beam propagation in a graphene-like metallic photonic lattice, associated to distorted Dirac cones, and discuss the beam transmission in terms of the coupling between the local resonance modes and incident fields.

1. Introduction

Graphene-like photonic structures create Dirac cones in their frequency spectra and provide opportunities for optically probing Dirac cone related physical properties. Potential applications, such as valley photonics exploring optically the valley degree of freedom associated to Dirac cones [1], have been proposed for information processing [2]. Studies on K -valley dependent light beam propagation, associated to the lower Dirac cones in dielectric photonic crystals [1, 3] and the upper cones in analogous situations of electron beams in atomic graphene [4, 5], are both carried out. Beam splitting and self-collimation are obtained for the zigzag and armchair edge incidences. We have shown previously that a light beam propagating in a metallic graphene-like photonic lattice displays drastically different behaviors as compared to the above results. Namely, at the armchair edge, the incident beam associated to the lower Dirac cone is collimated to one central beam, and that associated to the upper cone is split into two beams with a $2\pi/3$ angle. The other expected beams are all strongly inhibited [6]. Here we report a study of the propagation of narrow incident beams, of the widths of the crystal period sizes, allowing to probe the coupling between the incident field and the local resonance modes at elementary structure scales, as well as the consequence on the beam transmission, for different local structure configurations.

2. Light beam propagation

The metallic structure is constructed by infinite cylinders, with radius $r = 0.25a$ and dielectric constant set to negative infinity, placed at the triangular lattice [Fig. 1(a)] nodes in an air background. The frequency band diagram for TM polarization [Fig. 1(b)] is obtained by solving Maxwell's equations using the finite-difference time-domain (FDTD) method. Dirac cones are formed by the first two bands. The iso-frequency contours of the upper and lower cones are depicted in the same figure [1(d) and 1(e)].

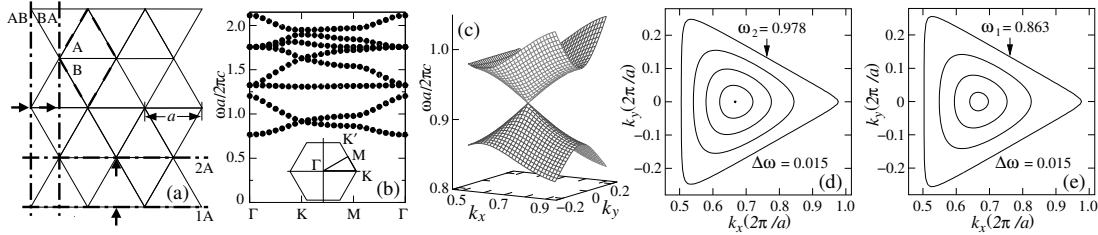


Fig. 1. Triangular photonic lattice (a) and the frequency band diagram (b), as well as a 3D view of the Dirac cone at K ($4\pi/3a, 0$) [(c)] and the iso-frequency contours of the upper [(d)] and lower part [(e)]. The frequency level (ω_1 and ω_2) and interval ($\Delta\omega$) values are normalized to $\omega a/2\pi c$.

We can show that, in a tight-binding (TB) model, for wave vectors close to the edges of the quasi-triangular contours, the crystal frequency ω_k can be expressed as

$$\omega_k^2 \approx \left(\omega_0^2 - \frac{\beta \mp \gamma}{1 \mp \alpha}\right) - \frac{\mp 2[\cos(\frac{\sqrt{3}k_y a}{2})\cos(\frac{k_x a}{2}) + \cos^2(\frac{k_x a}{2})]\gamma}{1 \mp \alpha} \quad (1)$$

with ω_0 representing the frequency of a resonance mode in an individual triangular tile, α , β and γ the classical first neighbor TB parameters [6], and \mp corresponding respectively to the upper and lower Dirac cone.

The first term in Eq. 1 corresponds to the energy levels of two coupled modes in a unit cell, with \mp corresponding, respectively, to the anti-bonding and bonding state. The band structure along a Γ - K direction close to the quasi-triangular contours can then be viewed as arising from a series of bonding or anti-bonding states on one-dimensional chains, with the band frequencies derived from that of these states, adjusted by the second term in Eq. 1, and the wave propagation can be considered as being based on a series of such states formed in the unit cells.

Transmission of narrow beams, associated to both the upper and lower Dirac cones, is investigated for armchair and zigzag edges for different local configurations [AB, BA, A1 and A2 cases, see Fig. 1(a)] using the FDTD method. Strong excitation difference in the first unit cells, following their positions and orientations with respect to the incident fields, is observed. This in turn determines the beam transmission associated to the upper and lower Dirac cones for different K valleys. Large transmission is obtained for incident conditions allowing strong coupling between the incident fields and the resonance modes in the first unit cells at the incident edges, and leading to field distributions corresponding or close to bonding or anti-bonding states for these modes. As an example, the A_1 beam (associated to the lower Dirac cone) transmission in the AB and BA cases is shown in Fig. 2, that illustrates well that a strong field coupling in the impact zone leads to strong beam transmission, and confirms, besides, that the beam propagation is based on a series of resonance states in the unit cells.

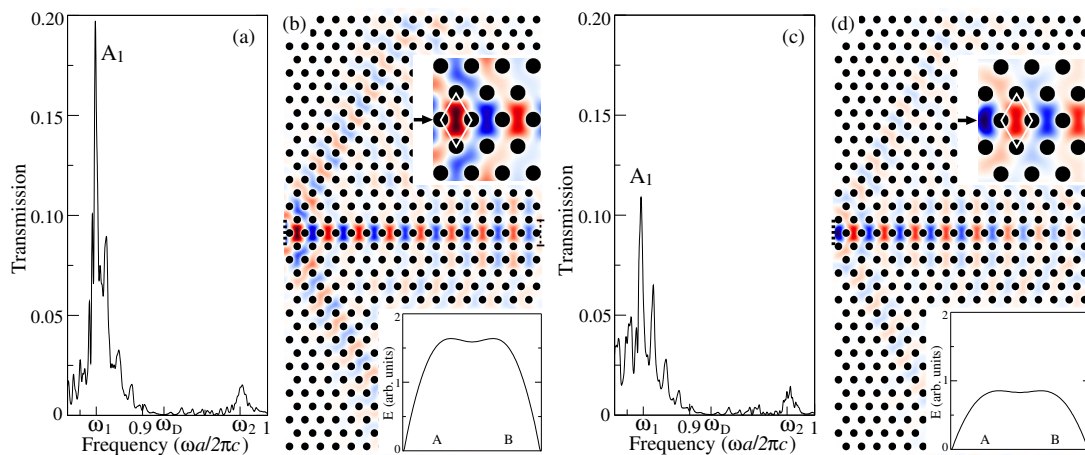


Fig. 2. Transmission spectra for the armchair edge incidence for the AB [(a)] and BA [(c)] cases in the center direction. The electric field distributions of the A_1 beams are shown in (b) and (d), with the thick dashed lines at the sample left side symbolizing the line sources, and the thin dashed lines at the right side the outgoing regions. The upper part insets show a magnified region in the vicinity of the impact zone, with the arrows indicating the incident beam axes. The lower part insets show the electric field magnitude along the long diagonal of the first unit cell, passing by the A and B tiles, in the upper insets.

3. Conclusion

This work allows understanding of the particularity of a metallic graphene-like photonic lattice in its interaction with the light waves at scales down to the size of local resonance states. It may find application in valley photonics in the designs of beam collimation and splitting devices for information processing, by providing information for tuning and optimizing the beam transmission in various incident conditions.

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