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Topological interface modes in graphene multilayer arrays

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ABSTRACT

We investigate the topological interface modes of surface plasmon polaritons in a multilayer system composed of graphene waveguide arrays. The topological interface modes emerge when two topologically distinct graphene multilayer arrays are connected. In such multilayer system, the non-trivial topological interface modes and trivial modes coexist. By tuning the configuration of the graphene multilayer arrays, the associated non-trivial interface modes present robust against structural disorder. The total number of topological modes is related to that of graphene layers in a unit cell of the graphene multilayer array. The results provide a new paradigm for topologically protected plasmonics in the graphene multilayer arrays. The study suggests a promising approach to realize light transport and optical switching on a deep-subwavelength scale.

1. Introduction

As many recent prominent discoveries in physics such as quantum Hall effect [1–3], topological superconductors [4], and topological insulators [5–7], the nontrivial topological properties of matter play the crucial role and have attracted intense attention. So far similar concepts have been analogized to the field of optics [8,9] and acoustics [10]. The nontrivial topological effects have been demonstrated across a variety of optical systems including metallic-dielectric waveguides [11] and photonic crystals [12]. A paradigm of topological structure is the famous Su-Schrieffer-Heeger (SSH) model [13,14], in which the topological interface modes emerge at the interface between topological trivial and non-trivial structures with distinct topological invariants [8]. Generally, the winding number can be regard as the topological invariant and is used to characterize the topological properties of the SSH model and the other one-dimensional structures [15]. According to the ratio between intra- and inter-cell couplings, the winding number is either zero or unity separated by the Dirac point. Such SSH model can be realized in many optical systems, including dimerized dielectric waveguides [16], nanoparticles [17], and metallic nanodisks [18].

Recently, the topological nontrivial modes associated with the SSH model have been investigated in graphene waveguide system [19,20]. Graphene can support surface plasmon polaritons (SPPs) in a wide range of spectrum from terahertz to infrared frequencies [21–23]. The SPPs in graphene can be flexibly tuned by gate voltage and chemical doping [24–27], which also exhibit relatively low propagation loss and strong field confinement [28–30]. These properties enable graphene a promising platform to study topologically nontrivial SPP modes.

In this work, we generalize the traditional SSH model from dimerized waveguide array to graphene multilayer arrays (GMAs), which can also constitute a hyperbolic metamaterial for application in negative refraction and transformation optics [31,32]. Here the topologically nontrivial modes may emerge at the interface between two GMAs with distinct topological invariants, which is characterized by the binary winding number of the bulk bands. Meanwhile, the trivial interface modes coexist at the interface, leading to beat between the trivial and nontrivial modes. The topological interface modes of SPPs are also found to be robust against the perturbations of the structure. The dependence of the total number of topological modes on that of graphene layers in each unit cell of GMAs is also discussed in detail.

2. Concept and theory

We start by investing the Bloch modes in the period GMAs. As shown in Fig. 1, each graphene sheet can support TM polarized SPP mode that propagates along z direction. By applying the tight-binding approximation [33], we can obtain the coupled-mode equation for the mode amplitude

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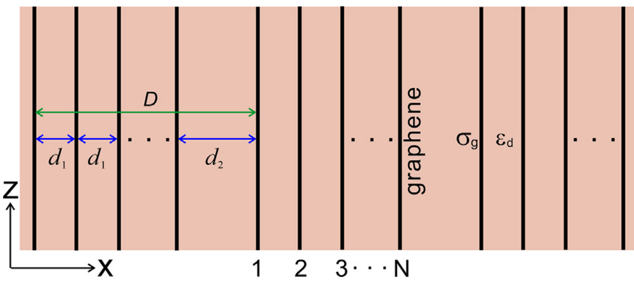

Fig. 1. Schematic of the periodic GMAs. In each unit cell, there are N graphene sheets. The spatial period is $D = (N-1)d_1 + d_2$ with d_1 and d_2 being the spacing of the intra-cell within a unit and the inter-cell between adjacent unit, respectively. σ_g is the surface conductivity of graphene, and ε_d is the relative permittivity of the dielectric medium between graphene.

$$\frac{\partial a_n(z)}{\partial z} = i\beta_g a_n(z) + iC_{n-1,n}a_{n-1}(z) + iC_{n,n+1}a_{n+1}(z), \tag{1}$$

where β_g is the propagation constant of SPPs in a single layer graphene. $C_{n,n+1}$ is the coupling coefficient between the nth and $(n+1)$th graphene sheets. According to Bloch theorem [34,35], the mode amplitude in the nth graphene at the position x_n is

$$a_n(z) = u_n \exp(ik_x x_n)\exp(i\beta z), \tag{2}$$

where β and k_x are the propagation constant and Bloch wave vector. $u_n = u_{n+N}$ is the period-in-cell part of the Bloch mode. The band structure $\beta(k_x)$ can thus be obtained from the Eqs. (1) and (2). Since there exists N layers of graphene in each period, the GMAs can support N Bloch bands [25]. For each Bloch band m, the topological invariant is the winding number, which is defined as [36,37]

$$W_m = \frac{i}{\pi}\int_{-\pi/D}^{\pi/D}\left[\int_{cell} u^*_{m,k_x}(x)\frac{\partial u_{m,k_x}(x)}{\partial k_x}dx\right]dk_x, \tag{3}$$

with the period function given by

$$u_{m,k_x}(x) = \sum_{n=1}^{N}\mathrm{sgn}(x-x_n)u_n\exp(-\kappa|x-x_n|). \tag{4}$$

where $\kappa = (\beta_g - \varepsilon_d k_0^2)^{1/2}$ and $\beta_g = k_0[\varepsilon_d - (2\varepsilon_d/\eta_0\sigma_g)^2]^{1/2}$ are the decay constant and propagation constant of SPPs in a single layer graphene. σ_g is the surface conductivity of graphene, which can be modeled by the Kubo formula [38,39]. $k_0 = 2\pi/\lambda$ is the wave number in air with η_0 being the corresponding air impedance. The coupling coefficient can be derived as $C_{n,n+1} = (\beta_0 - \beta_\pi)/4$ with β_0 and β_π being the propagation constants of Bloch modes in monolayer graphene array as $k_x = 0$ and π/D, respectively. It should be mentioned that the coupling coefficient $C_{n,n+1}$ can be tuned by the intra-cell spacing of d_1 and inter-cell spacing of d_2, which will basically determine the topological property of the GMAs.

Fig. 2(a) and (b) show the band structures of the Bloch modes for different inter-cell spacing d_2 as the fixed intra-cell spacing of $d_1 = 40$ nm. We choose $N = 3$, thus there are three Bloch bands. As d_2 increases from $d_2 < d_1$ to $d_2 > d_1$, the band gaps close and then reopen, indicating the emergence of a band inversion. Specially as $d_2 = d_1$ shown in Fig. 2(c), the band gaps vanish with the Dirac points emerging at Brillouin zone center between band 2 and 3 and Brillouin zone edge between band 1 and 2, respectively [40,41]. The GMAs thus experience a topological phase transition at the Dirac points.

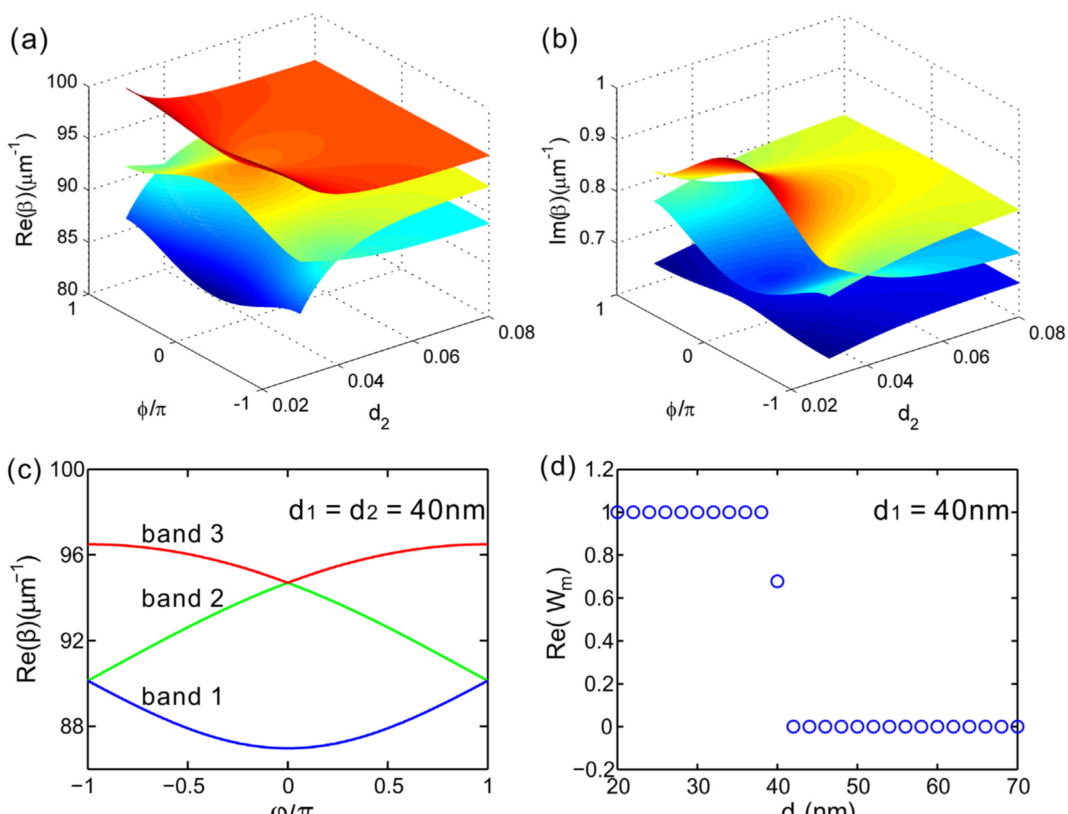

Fig. 2. Diffraction relation of SPPs and topological invariant in the GMAs with parameters given by $N = 3$, $d_1 = 40$ nm, $\varepsilon_d = 2.13$, $\lambda = 10$ μm, $\mu_c = 0.15$ eV, and $\tau = 0.5$ ps at room temperature. (a) Real and (b) imaginary parts of diffraction relation as the inter-cell spacing d_2 is varying. (c) Band structures of Bloch modes as $d_2 = d_1 = 40$ nm. (d) Real part of winding numbers for band $m = 3$ as the inter-cell spacing d_2 is varying.