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Optical properties for topological insulators with metamaterials

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ABSTRACT

The two fields of topological insulators and metamaterials are independent. In this Letter, we firstly investigate the Fresnel coefficients for the reflected and refracted electromagnetic waves across the interface between topological insulators and left-handed metamaterials. Then, we derive the exact analytic expressions for Kerr and Faraday rotations. By way of multiple reflections method, we demonstrate that perfect lens with left-handed metamaterials slab and topological insulators can be designed. On the other hand, the processes of reflection and refraction are investigated in the case of topological insulator and chiral metamaterial. Then, we give the reflection and transmission coefficients of topological insulator with a chiral medium slab. Lastly, the potential applications of these results are discussed.

1. Introduction

Because of the existence of topologically protected edge or surface states, topological insulator [1,2] (TI) has been investigated extensively. For the three-dimensional TI, a quantized magnetoelectric response, i.e., the topological magnetoelectric effect [3] (TME) can be induced, when a surface time-reversal-breaking perturbation is applied. The TME is a topological quantization phenomenon that an electric field can induce magnetization in the same direction with a universal constant of proportionality the fine-structure constant $\alpha = e^2/\hbar c$, while a magnetic field can induce polarization. Therefore, TIs provide a solid-states realization of the axion electrodynamics [4]. The magnetoelectric coupling can be described by the effective Lagrangian $S_\theta = (\theta/2\pi)(\alpha/2\pi)\int d^3x\,dt\,\mathbf{E}\cdot\mathbf{B}$, where $\mathbf{E}$ and $\mathbf{B}$ are the electric and magnetic fields, θ plays the role of the axion field. The TME has many interesting consequences such as: image magnetic monopole [5,6], topological Kerr and Faraday rotations [3,7–14], Witten effect [15], and tunable Casimir repulsion force [16]. Usually, Kerr and Faraday angles depends on the material parameters. However, Wang-Kong Tse et al. [9] and J. Maciejko et al. [10] independently proposed an new optical experiment to avoid the dependence on material details. When electron correlation is considered, new interesting phenomena such as topological magnetic insulators [17] and topological exciton condensate [18] can occur. Besides, there are some experiments [19–21] measuring these phenomena. All these demonstrate the potential applications of topological insulators in spintronic devices.

Left-handed metamaterials [22,23] or negative index metamaterials are electromagnetic medium with a negative refractive index value over some frequency range. The theoretical concept of negative refraction dates back to the mid-twentieth century [24–27]. For the historical details, see the recent review of Agranovich and Gartstein [28] and the references therein. Left-handed metamaterials (LHMs) have several interesting effects for example modified Snell's law, reversed Doppler shift, reversed Vavilov–Cerenkov radiation and flat lens. In the last decade years, theoretical proposals [29–31] and developed experiments [32,33] have sparked considerable interest in the study of electromagnetic metamaterials. One of the most fascinating devices that utilizing the striking optical properties of LHMs is the perfect lens [31]. It turns out that the perfect lens not only focuses the propagating waves, but also focuses the evanescent components of waves. So, both propagating and evanescent waves contribute to the resolution of the image. The evanescent components are associated with the spatial features of the source at a sub-wavelength length-scale. Resolution below the diffraction limit becomes possible.

Chiral metamaterial [34,35] is a new type of metamaterials that favors the realization of negative refraction and the propagation of backward wave with chiral medium (CM). In CM, there is cross-coupling between the electric and magnetic field [36,37]. The right circularly polarized (RCP) and left circularly polarized (LCP) wave propagate at different phase velocities in homogeneous CM. When the

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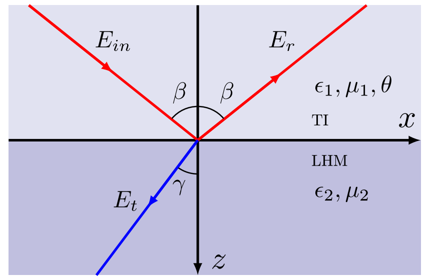

Fig. 1. Reflection and refraction of electromagnetic waves across the interface between TI and LHM.

optical activity is strong enough, negative refraction [38–40] and negative reflection [41] occur at one of the two circularly polarized waves. More and more experiments demonstrate the existence of chiral metamaterial [42–44]. Using the chiral medium (bi-anisotropic) and arranging judiciously designed metamaterials, A.B. Khanikaev et al. [45] theoretically demonstrate the existence of photonic topological insulators, which support helical edge states at the interfaces that exhibit spin-polarized one-way propagation of photons, robust against disorder.

Topological insulator, left-handed metamaterial, and chiral metamaterial appear intriguing and exotic electromagnetic properties, respectively. On the other hand, reflection and refraction of electromagnetic waves at a plane between two media are familiar phenomena. So it is necessary to investigate the electrodynamics of topological insulator with left-handed metamaterial and chiral metamaterial. The outline of our Letter is organized as follows: In Section 2.1, we investigate the reflection and refraction of electromagnetic waves across a plane interface between topological insulator and left-handed metamaterial. The Fresnel reflection and refraction formula, Kerr and Faraday rotations are given. Then, we consider the possibility of perfect lens with left-handed metamaterial slab and topological insulator. In Section 2.2, we firstly deduce the reflection and refraction of topological insulator and chiral metamaterial. According to the Fresnel coefficients, we can investigate the optical activity, circular dichroism, differential linear reflectance, and differential circular reflectance. Last, we derive the reflection and transmission coefficients of chiral medium slab and topological insulator. In Section 3, we make some concluding remarks.

2. Theory and discussion

2.1. Topological insulator with left-handed metamaterial

For three-dimensional topological insulators, the existence of nontrivial θ ($\theta = (2n+1)\pi$, n is integer) axion angle requires the surface time-reversal-breaking perturbation, which is realized by a thin magnetic coating on surface of the TI or by an applied perpendicular magnetic field. In the presence of nontrivial θ axion angle, the electromagnetic equations still take the usual Maxwellian forms. However, the constitutive relations are modified to [3,7,8,13]

$$\mathbf{D} = \varepsilon\mathbf{E} + \frac{\theta}{2\pi}(2\alpha\mathbf{B}) \tag{1}$$

$$\mathbf{H} = \frac{\mathbf{B}}{\mu} - \frac{\theta}{2\pi}(2\alpha\mathbf{E}) \tag{2}$$

Consider a TI with dielectric permittivity ε_1, magnetic permeability μ_1, and axion angle θ deposited on a LHM substrate with dielectric permittivity ε_2 and magnetic permeability μ_2 (see Fig. 1). In this Letter, we assume TI and LHM are lossless and transparent. Time dependence of $e^{i\omega t}$ is suppressed. To begin with, we derive the Fresnel coefficients for the reflected and refracted radiation across the interface. The $\mathbf{E}_{in}$, $\mathbf{E}_r$, and $\mathbf{E}_t$ are incidence, reflection, and refraction electric fields, respectively. Because of the negative refraction index, there is a negative refraction angle. As shown in Fig. 1, the incident and refraction waves locate on the same side of the surface normal line.

The wave vectors of incidence, reflection, and refraction are expressed as

$$\mathbf{k}_{in} = k_{in}(\sin\beta, 0, \cos\beta), \qquad \mathbf{k}_r = k_r(\sin\beta, 0, -\cos\beta), \qquad \mathbf{k}_t = k_t(\sin\gamma, 0, -\cos\gamma) \tag{3}$$

The Snell's law remains valid, even if θ is not zero on either or both sides. On the other hand, the tangential components of **E** and **H**, as well as the normal components of **D** and **B** require be continuous across the interface as usual. As usual, the electric field can be decomposed into their perpendicular (s-polarized wave with superscript $\perp$) and parallel (p-polarized wave with superscript $\parallel$) components to the plane of incidence. Applying the boundary conditions at the interface, we can calculate the components of reflected and refracted electric fields. The Fresnel coefficient for the reflected wave can be expressed in a matrix form

$$\begin{pmatrix} E_r^{\perp} \\ E_r^{\parallel} \end{pmatrix} = \frac{1}{\Delta}\begin{pmatrix} [\frac{\varepsilon_1}{\mu_1} - \frac{\varepsilon_2}{\mu_2} + \sqrt{\frac{\varepsilon_1\varepsilon_2}{\mu_1\mu_2}}\chi - (\frac{\alpha\theta}{\pi})^2] & -\frac{2\alpha\theta}{\pi}\sqrt{\frac{\varepsilon_1}{\mu_1}} \\ -\frac{2\alpha\theta}{\pi}\sqrt{\frac{\varepsilon_1}{\mu_1}} & -[\frac{\varepsilon_1}{\mu_1} - \frac{\varepsilon_2}{\mu_2} - \sqrt{\frac{\varepsilon_1\varepsilon_2}{\mu_1\mu_2}}\chi - (\frac{\alpha\theta}{\pi})^2] \end{pmatrix}\begin{pmatrix} E_{in}^{\perp} \\ E_{in}^{\parallel} \end{pmatrix} \tag{4}$$

where $\chi = \frac{\cos\beta}{\cos\gamma} - \frac{\cos\gamma}{\cos\beta}$, $\Delta = \frac{\varepsilon_1}{\mu_1} + \frac{\varepsilon_2}{\mu_2} + \sqrt{\frac{\varepsilon_1\varepsilon_2}{\mu_1\mu_2}}(\frac{\cos\beta}{\cos\gamma} + \frac{\cos\gamma}{\cos\beta}) + (\frac{\alpha\theta}{\pi})^2$.