One-way optical tunneling induced by nonreciprocal dispersion of Tamm states in magnetophotonic crystals

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We show that optical Tamm states (OTSs) with nonreciprocal dispersion can be formed at the boundary separating two different magnetophotonic crystals magnetized in the Voigt geometry. At the frequencies of the Tamm states, one-way optical tunneling can be achieved. The nonreciprocity features of OTSs originate from the simultaneous violation of reciprocity, time-reversal, and all related spatial symmetries in the system. Our predictions are confirmed by the nonreciprocal dispersion of interface modes, unidirectional transmission spectra, and field distributions for our system. Such theoretical results may provide a mechanism to create compact optical isolators.

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Recently, considerable attention has been focused on the investigation of surface electromagnetic (EM) waves [1], which is primarily due to their unique properties as well as the prospects for important applications, e.g., in imaging, sensing, and trapping. Surface waves (SWs) are a specific type of waves that are localized at the interface between two different media. One of the most familiar types of SWs is surface plasmon polaritons (SPPs) [2], which exist at the boundary of a metal. In dielectric structures, lossless localized photonic states, so-called Dyakonov SWs [3,4], are supported at the interface between dielectric homogenous medium and birefringent medium under certain conditions.

Another form of lossless interface modes, referred to as optical Tamm states (OTSs) [5,6], could be possibly supported at the interface of two photonic structures having overlapping band gaps. In contrast to conventional TM-polarized SPPs and hybrid (TE-dominant) polarized Dyakonov SWs, OTSs can be formed in both TE and TM polarizations. The splitting between TE and TM polarized OTSs increases quadratically with the in-plane wave vector. Furthermore, OTSs remain localized for any value of the in-plane wave vector inside the light cone for free space, and thus it is possible for us to excite OTSs directly in planar structures, without the use of prism, grating coupling or other alternative surface structuring approach. In 2008, Goto *et al.* [7] first reported the experimental observation of OTSs on the interface of magnetophotonic crystals (MPCs) magnetized in the Faraday geometry and pointed out such surface state is associated with a transmission peak through the structure and the enhancement of the Faraday rotation.

It is well known that SWs may show nonreciprocal properties in the presence of a magnetic field. In two-dimensional (2D) electron systems, chiral edge states could be realized by applying a strong magnetic field perpendicular to electron systems [8]. Such one-way states can carry current only along a single direction and the transport is robust against scattering from disorder. Recently, Raghu and co-workers [9,10] theoretically predicted that EM analogues of such electronic edge states could be observed in a 2D photonic crystals. Under a static magnetic field, the breaking of time-reversal symmetry opens a photonic band gap at the Dirac points, giving rise to photonic edge states. Subsequently, experimental realizations and observations of such EM one-way edge states in different MPCs were reported by Wang *et al.* [11] and Poo *et al.* [12], respectively. Many other studies on nonreciprocal SWs [13–19], i.e., the existence of one-way SPP modes formed at the interface between a metal and a PC (or vacuum) [13], or nonreciprocal spoof SPPs supported by a structured conductor embedded in an asymmetric magneto-optical medium [14], are also demonstrated by several groups.

In the present work, we aim to demonstrate the existence and a possible application of nonreciprocal OTSs formed at the interface between two different 1D MPCs (as shown in Fig. 1). It is found that the splitting between the forward and backward OTSs increases with the in-plane wave vector and vanishes at the zero wave-vector corresponding to the normal incidence case. Calculations on field patterns and nonreciprocal

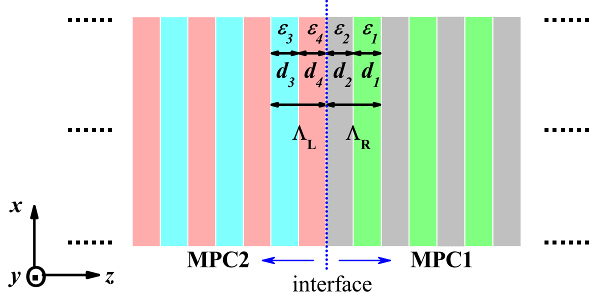

Fig. 1. Geometry of an interface separating two different semi-infinite MPCs formed by alternating magneto-optical and isotropic dielectric layers.

transmission spectra through the whole structure are employed to support the spectral splitting in the dispersion of OTSs propagating in the opposite directions.

Let us consider the interface between two periodical layered media MPC1, MPC2 shown in Fig. 1, composed by the pairs of one magneto-optical layer and one isotropic dielectric, with thicknesses d_2, d_1 (the period $\Lambda_R = d_2 + d_1$) and permittivities ϵ_2, ϵ_1 on the right-hand side of the interface and thicknesses d_3, d_4 (the period $\Lambda_L = d_3 + d_4$) and permittivities ϵ_3, ϵ_4 on the left-hand side of the interface. To accomplish the required symmetry breaking, we use a gyrotropic material for the magneto-optical layer in both of the MPCs. It is homogeneously magnetized in the Voigt geometry, with magnetization in the plane of the MPCs interface and perpendicular to the wave vector of OTSs and characterized by a dielectric tensor $\hat{\epsilon}_g$, with $\epsilon_{g,xx} = \epsilon_{g,yy} = \epsilon_{g,zz} = \epsilon_g$ and $\epsilon_{g,xz} = -\epsilon_{g,zx} = i\Delta_g$. For initial calculations, we employed isotropic and non-light-absorbing materials as samples. At the end of this paper, we discuss the influence of the absorption of the material by introducing an imaginary part ϵ_g' to the diagonal elements. The isotropic dielectric layer (with diagonal and off-diagonal elements ϵ_d and Δ_d, respectively), provides good index contrast with mangetooptical layer to create the band gap. Although both TE and TM modes exist in this geometry, the TE modes still possess time-reversal symmetry and, thus, we focus only on the TM modes in the following.

By using the standard transfer matrix approach [20–22], we obtain the exact solutions for the OTSs in our system. First, we define the transfer matrix in the right media MPC1, $\hat{T}_R = \hat{M}_{21}\hat{P}_2\hat{M}_{12}\hat{P}_1$, where $\hat{P}_i = \mathrm{diag}[\exp(ik_{zi}d_i), (-ik_{zi}d_i)]$ are the usual propagation matrices, with $k_{zi} = \sqrt{((2\pi/\lambda_0)n_i)^2 - k_x^2}$, λ_0 the wavelength in vacuum, k_x the component of the wave vector in the plane of surface, and $n_i = \sqrt{(\epsilon_i^2 - \Delta_i^2)/\epsilon_i}$ the refractive index. The $\hat{M}_{ij}$ are the interface matrices

$$\hat{M}_{ij} = \frac{\epsilon_j^2 - \Delta_j^2}{2\epsilon_j k_{zj}} \begin{pmatrix} F_j^* + F_i & F_j^* - F_i^* \\ F_j - F_i & F_j + F_i^* \end{pmatrix}, \quad (1)$$

where $F_m = (\epsilon_m k_{zm} + i\Delta_m k_x)/(\epsilon_m^2 - \Delta_m^2)$, $m = i, j$.

There exist two Bloch wavevectors for the transfer matrix $\hat{T}_R$,

$$e^{iK_R\Lambda_R} = \frac{1}{2}\left[(T_R^{11} + T_R^{22}) \pm \sqrt{(T_R^{22} - T_R^{11})^2 + 4T_R^{12}T_R^{21}}\right], \quad (2)$$

where K_R is a Bloch vector for MPC1.

The transfer matrix $\hat{T}_L$ and Bloch wavevectors K_L for the left media MPC2 are easily obtain from the matrix $\hat{T}_R$ and Eq. (2) by replacing ϵ_1 and ϵ_2 with ϵ_4 and ϵ_3, respectively, and also by replacing d_1 and d_2 with d_4 and d_3, respectively.

To form guided waves at the interface between MPC1 and MPC2, the constant K_L and K_R must be complex, and the sign of their imaginary part, i.e., in our case $\mathrm{Im}[K_L] > 0$ and $\mathrm{Im}[K_R] < 0$, has to be properly chosen to guarantee the field exponential decay in the both sides. This could be possible when the forbidden bands of both layered media have some overlap and the propagation constant falls into these overlap regions. Another condition is that the electric field and its tangential derivative be continuous at the interface. This gives us the dispersion relation for interface modes [23]

$$ik_{z4}\frac{e^{iK_L\Lambda_L} - T_L^{11} - T_L^{12}}{e^{iK_L\Lambda_L} - T_L^{11} + T_L^{12}} = ik_{z1}\frac{e^{iK_R\Lambda_R} - T_R^{11} - T_R^{12}}{e^{iK_R\Lambda_R} - T_R^{11} + T_R^{12}}, \quad (3)$$

which is identical with the obtained result in [5] and [24].

To demonstrate the nonreciprocity of OTSs, we solve Eq. (3) numerically for two specific semi-infinite MPCs having overlapping band gaps. The kind of overlap can be realized between the first stop band of MPC1, with a set of parameters $d_2 = 69.3$ nm, $d_1 = 152.5$ nm, $\epsilon_2 = 1.96$, $\Delta_2 = 0.4$, and $\epsilon_1 = 4$, $\Delta_1 = 0$, and the second stop band of MPC2, with parameters $d_3 = 291.8$ nm, $d_4 = 218.5$ nm, $\epsilon_3 = 1.96$, $\Delta_3 = -0.4$, and $\epsilon_4 = 4$, $\Delta_4 = 0$. The chosen values of dielectric layers can be easily achieved, for instance, in porous silicon structure, and as for the magneto-optical layer, the value of the off-diagonal element is one order of magnitude larger than that of Bismuth iron garnet (0.06) [25,26]. By reducing the parameter to realistic levels, there can be some overlaps between the tunneling peaks for the two opposite directions of incident light for some small angles of incidence. In the following simulations, we have used $\Delta = 0.4$ so as to highlight the effect of asymmetric OTSs.

Here we should emphasize that broken time-reversal symmetry alone is not sufficient to support a one-way propagation, all related spatial symmetries that can protect the symmetry in Green's function should be removed simultaneously. Our proposed MPCs geometry has broken reflection, inversion, and 180-degree rotation symmetry simultaneously. Therefore, it is expected the nonreciprocity of surface modes could appear in the interface geometry in the presence of magneto-optical active materials.

Figure 2 shows the dispersion of the forward ($k_x > 0$, red lines) and backward ($k_x < 0$, blue lines) OTSs inside the overlapping photonic bandgaps of MPC1 and MPC2, respectively. Apparently, the interface modes have asymmetric dispersion solutions, $\omega(k_x) \neq \omega(-k_x)$, giving rise to one-way propagation characteristics. It is found that OTSs show stronger nonreciprocity as k_x increases, whereas reciprocal transmission at $k_x = 0$ corresponding to the normal incidence case. At $k_x = 0$, the wave propagating problem in MPCs simplifies as a scalar 1D wave problem; thus the nonreciprocal response vanishes. For the results shown below, the dispersion curves for OTSs lie within the light line for free space. Therefore, the associated modes could be accessible to direct excitation by incident radiation without the need of prism or grating coupling.

As a direct visualization of the one-way property, we use a finite element solver (COMSOL Multiphysics) to plot the out-of-plane magnetic field profile in Fig. 3 for a finite structure having eight pairs of layers in MPC1 and 33 pairs of layers in MPC2, under the light illumination of a plane wave. We take an example as the in-plane

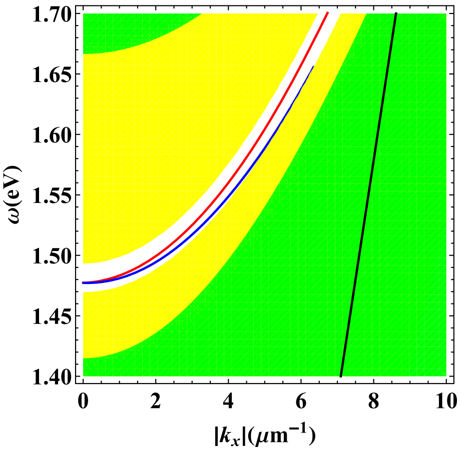

Fig. 2. Dispersion of OTSs at the interface between two semi-infinite MPCs. Red and blue lines correspond to $k_x > 0$ and $k_x < 0$ propagating OTSs, respectively. The white region depicts the overlapping stop-band of MPC1 and MPC2, while green and yellow regions correspond to pass-bands of an infinite MPC1 and MPC2, respectively. The light line for free space (black line) is also shown.

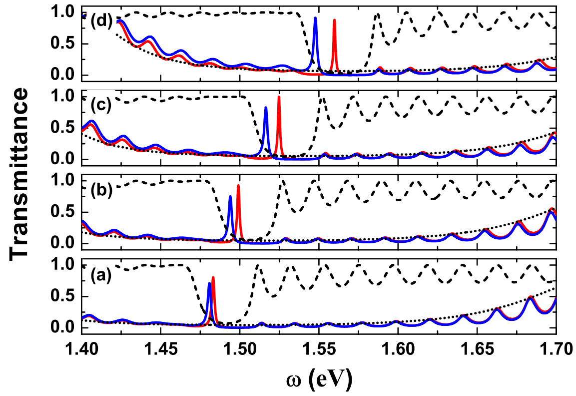

Fig. 4. Transmission spectra of our model structure calculated with different in-plane components of wave vector, (a)–(d) $|k_x| = 1, 2, 3, 4\ \mu\text{m}^{-1}$. Red and blue lines show the forward and backward illumination of light beams, respectively. The dotted and dashed lines correspond to the transmission spectrum of single MPC1 or MPC2 in vacuum. One can observe the sharp peaks within the stop band of the structure, which are associated with nonreciprocal OTSs, occurs at different energies.

wave vector $k_{x+} = 3\ \mu\text{m}^{-1}$ for forward illumination and $k_{x-} = -3\ \mu\text{m}^{-1}$ for backward illumination. The corresponding energies for nonreciprocal OTSs at k_{x+}, k_{x-} obtained from Fig. 2, are $E_+ = \hbar\omega_+ = 1.525$ eV and $E_- = \hbar\omega_- = 1.517$ eV, respectively. Figure 3 shows the steady-state field patterns at the energy E_+ where one-way behavior is most pronounced. For the case of forward incidence seen in Fig. 3(a), full transmission is obtained, due to the strong field enhancement at the interface of MPC1 and MPC2 associated with the excitation of OTSs. In contrast, complete reflection is observed for backward incidence, resulted from the suppression of the excitation of OTSs. Therefore, such joined MPCs demonstrate one-way total transmission.

Moreover, at the energy of OTSs, the transmittance spectrum of the whole structure exhibits a sharp peak inside the overlapping stop-band. In order to verify the above results, we then plot the transmittance in Fig. 4 for the same finite-size structure as Fig. 3. Counterpropagating plane waves are incident from air upon either side of MPC1 (red lines) or MPC2 (blue lines) through the joined crystals. Transmission spectra for single MPC1 (dotted lines) or MPC2 (dashed lines) in vacuum are also depicted for reference. It is observed that, under front or back illumination of plane waves, there exists a sharp transmission peak inside the overlapping stop-band, but with two different energies. Strong nonreciprocity effect for transmission at such two points could then be achieved. Changing the incidence angle pushes the OTSs toward higher energies and improves the nonreciprocity effect, as one can see from the spectra in Fig. 4. These results for finite-size MPCs are very consistent with those shown in Fig. 2 for the joined semi-infinite MPC1 and MPC2.

When the material loss is introduced, particularly in the case of high loss, transmission may become negligible and significant absorption can be observed in the structure. To take into account the inevitable resistive losses in the magneto-optical layer, we show in Fig. 5 the nonreciprocity in transmission (absorption) spectra defined by the absolute differences between forward

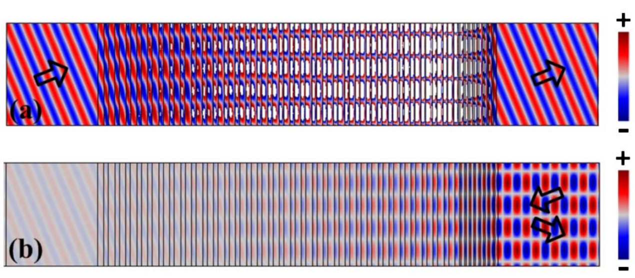

Fig. 3. Out-of-plane magnetic field patterns at the energy $E_+ = 1.525$ eV for the finite-size structure having eight pairs of layers in MPC1 and 33 pairs of layers in MPC2, under front illumination (a) and back illumination (b), when the in-plane component of wave vector $|k_x| = 3\ \mu\text{m}^{-1}$.

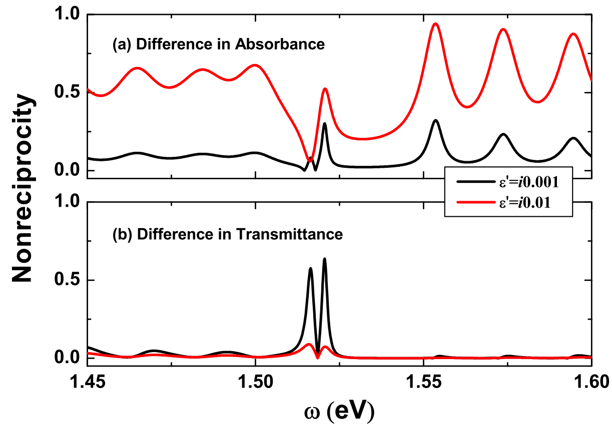

Fig. 5. Nonreciprocity in absorption (a) and transmission (b) for the same structure as Fig. 4, except that the loss effect is considered for the magneto-optical layer in MPCs. Here we assume the magneto-optical layers with the same loss, $\epsilon_2' = \epsilon_3' = \epsilon'$. Black and red lines show the cases for $\epsilon' = i0.001$ and $\epsilon' = i0.01$, respectively.

and backward transmittances (absorbances) through the structure. As the loss ϵ' in magneto-optical layers is increased from $i0.001$ to $i0.01$, the original transmission peak is suppressed gradually, broadens, and shifts to lower energy, which is due to the insufficient ability to confine the interface mode. Nevertheless, in the absorption spectra, absorption peaks occur at different energies for the front-illuminated or back-illuminated structure. This is the consequence of the presence of the excitation of nonreciprocal OTSs. Note that some other absorption peaks could be obtained under front illumination, while disappears under back illumination. This could be explained by the asymmetric resonant reflection at either side of MPC1 or MPC2. Therefore, when material loss is present, we could still achieve large nonreciprocity in the absorption or reflection for the proposed structure.

It should be noted that, in contrast to using the one-way bulk Bloch modes of an infinite periodic photonic crystals [26–28], our design can switch the one-way transmission direction by application of nonreciprocal surface modes at the interface between two different MPCs. Moreover, such kinds of surface states could be closely related to the topologically protected edge states, which cannot be destroyed by a small roughness. Meanwhile, the operation frequency can be fine-tuned by adjusting the angle between the device and the incident light.

In summary, we have shown that the nonreciprocal dispersion of OTSs located at the interface between different two MPCs can give one-way resonant optical tunneling with a strong nonreciprocity. The key condition is that the dispersion curve of OTSs falls into the overlapping photonic band gap of MPCs and simultaneously removes the reciprocity, time-reversal, and all related spatial symmetries. The results can be extended to more general systems provided that the required conditions are satisfied.

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