Reconfigurable topological photonic crystal

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Abstract

Topological insulators are materials that conduct on the surface and insulate in their interior due to non-trivial topology of the band structure. The edge states on the interface between topological (non-trivial) and conventional (trivial) insulators are topologically protected from scattering due to structural defects and disorders. Recently, it was shown that photonic crystals (PCs) can serve as a platform for realizing a scatter-free propagation of light waves. In conventional PCs, imperfections, structural disorders, and surface roughness lead to significant losses. The breakthrough in overcoming these problems is likely to come from the synergy of the topological PCs and silicon-based photonics technology that enables high integration density, lossless propagation, and immunity to fabrication imperfections. For many applications, reconfigurability and capability to control the propagation of these non-trivial photonic edge states is essential. One way to facilitate such dynamic control is to use liquid crystals (LCs), which allow to modify the refractive index with external electric field. Here, we demonstrate dynamic control of topological edge states by modifying the refractive index of a LC background medium. Background index is changed depending on the orientation of a LC, while preserving the topology of the system. This results in a change of the spectral position of the photonic bandgap and the topological edge states. The proposed concept might be implemented using conventional semiconductor technology, and can be used for robust energy transport in integrated photonic devices, all-optical circuity, and optical communication systems.

Introduction

Topological insulators (TIs) build a class of materials that act as insulators in their interior and conduct on the surface, while having a non-trivial topology of the band structure [1–5]. The insulating properties result from the absence of conducting bulk states in a certain energy range, known as the bandgap. The interface between materials with different topology supports strongly confined topologically protected edge states. For these states, the energy transport is robust against structural disorders and imperfections that do not change the system’s topology. Until now, many theoretical and experimental demonstrations of TIs have been reported for fermionic (electronic) systems, but most of them work at low temperatures and require strong external magnetic fields which impedes their practical applications [1, 5–9]. Alternatively, systems preserving the time-reversal symmetry that support spin- and valley-Hall effects have been implemented [10, 11].

Recent studies have shown the existence of one-way protected topological edge states in bosonic (photonic) systems. With the use of time-reversal symmetry breaking, an analog of the quantum–Hall effect was achieved [12–16]. Later, analogs for spin–Hall and valley–Hall effects that do not require breaking of the time-reversal symmetry were realized using photonic TIs (PTIs) [17–20]. Comprehensive reviews of the advances in topological photonics can be found in [21, 22]. A considerable interest has been shown in manipulating photons by the use of an artificial gauge field, which acts as an effective magnetic field for photons [23, 24]. Several approaches to engineer synthetic gauge potential emulating an effective magnetic field have been realized [23–26] by dynamic modulation of the system parameters. Examples include temporal [23, 27–29] and spatial...
modulation using an array of helical waveguides that imitate a breaking of the time-reversal symmetry by breaking the mirror symmetry along the propagation direction [30]. Some of the other proposed realizations include use of meta-crystals [31–38]. Although these approaches demonstrate the possibility to realize PTIs, most of the designs either operate in the microwave regime [39] or are bulky. Implementation of TIs in photonic systems can pave the way for robust light propagation unhindered by the influence of back-scattering losses.

The breakthrough is likely to come from the synergy of the PTI concept and silicon-based photonics technology that enables high integration density, reconfigurability, and immunity to fabrication imperfections. In particular, silicon-based photonic crystals (PCs) offer a promising solution to integration of the fields of silicon photonics and topological photonics [18–20]. Indeed, PCs enable implementation of topological effects. Nowadays, the majority of proposed PTIs operate in a fixed wavelength range and their mode of operation cannot be dynamically reconfigured at a high speed. Recently, mechanically reconfigurable TI were reported in microwave regime [34, 40]. Here, we propose a reconfigurable PTI structure based on a PC designed to realize the photonic analog of the spin-Hall effect. The tunability of transmission properties for the system is facilitated by the liquid crystal (LC) environment surrounding the PC. This structure offers compatibility with CMOS integrated systems, allows for switching at MHz frequencies, and can be designed to operate at infrared wavelengths.

**Results**

Photonic crystals offer an excellent platform to control the flow of light by virtue of the periodicity of the dielectric constants of its constitutive materials [41]. The backbone of the proposed structure is the PC built of silicon pillars immersed in LC environment and enclosed between conducting electrodes; as shown schematically in figure 1(a). The design of the PC providing topological protection is based on the work of Wu and Hu [18]. The structure consists of two regions: one with trivial topology, and another with non-trivial topology. At the interface between crystals with different topological properties (shown in cyan), edge states are supported. Here, only edge states at the interfaces with the graphene-zigzag edge type are considered [42]. Each region is built of a triangular lattice containing six pillars per unit cell that build a meta-molecule. Depending on the spacing between the pillars (and therefore the hopping energy), the structure features a non-trivial or a trivial band-structure topology. Recently, one-dimensional edge states [42, 43] and zero-dimensional defect (corner) states [44] in such photonic lattices with hopping-energy textures were studied in detail. Topological edge states for this type of PC emerge due to the optical analog of the spin-Hall effect, and were analyzed in [18] where the PC was surrounded by air.

The PC in our design is immersed in a LC environment, which offers a possibility of refractive index tuning with unprecedented amplitude, reaching 10% at MHz switching speed [45–47]. This tuning is enabled by an external electric field supplied by the electrodes bounding the PC from top and bottom [48, 49]. Here, we restrict ourselves to considering transverse-magnetic-polarized (TM-polarized) waves for near- and mid-infrared frequency ranges where the high-refractive-index materials are available and transparent. The typical LCs have
refractive indices around 1.5 and the birefringence close to 0.2 [48, 50, 51]. Here, we assume the use of the E7 nematic LC with the following parameters: ordinary refractive index \( n_o = 1.51 \) and the extraordinary refractive index \( n_e = 1.69 \) [52]. When voltage is applied, corresponding to ON-state, the LC molecules align along the silicon pillars, resulting in a background refractive index \( n_{bg} = n_1 \) (figure 1(b)). In this case, light is efficiently guided along a rhombus-shaped path as an edge state located in the bulk bandgap, as shown in figure 1(c). If there is no voltage applied, corresponding to the OFF-state, the LC molecules orient perpendicular to the pillars due to the anchoring forces at the electrodes, and light experiences the background refractive index \( n_{bg} = n_{nr} \), as shown figure 1(d). The change of the background index does not modify the topological properties of the structure, but shifts the location of the bandgap, and bulk states are present at the wavelength of interest, enabling light scattering into the bulk of the PC. For this case, the structure does not support light propagation and energy penetrates into the PC interior resulting in low transmittance along the interface, as shown in figure 1(e).

The proposed tuning mechanism is applicable in the mid-infrared regime where the typical size of a PC cell size is of the order of a few micrometers. Reorientation of the LC molecules infiltrating the structures on this scale have been shown to be feasible [53–57]. In the near-infrared regime, effective tuning of the LC might be challenging due to the tight confinement inside of the PC structure [51, 58–62]. In the structures with high surface to volume ratio, the surface anchoring prevents uniform alignment of the LC director [51]. This might be facilitated by using surface chemistry [63] to weaken the anchoring surface energy and to obtain the required alignment [64].

The influence of the anchoring forces on the electrodes can be also reduced by use of a dual-band LC as a tunable-background-refractive-index material [65]. In this case, the AC electric field is applied to the LC cell all the time, and switching between the LC orientations parallel and perpendicular to the pillars is triggered by changing the modulation frequency of the applied electric field. Alternatively, tuning of the refractive index of a LC can be achieved thermally. This mechanism allows for switching between the nematic and isotropic phases resulting in different background refractive index experienced by TM-polarized light [48, 66, 67].

**Tunable topological edge states**

Topologically protected edge states offer unprecedented possibilities for designing robust guided-wave photonic structures and components, due to their feasibility for supporting light propagation along arbitrary-shaped interfaces between trivial and topological regions. In this paper, we consider a structure exhibiting an optical equivalent of the spin-Hall effect. For this case, there is always a pair of essentially decoupled states that propagate in opposite directions and have different spins. In sharp contrast to edge states in standard (trivial) PCs, the pair of topological states do not couple to each other even in presence of disorders and sharp turns along the propagation path.

The edge states in our system emerge at the interfaces between the topological and trivial PCs. Both PC lattices considered separately possess the \( C_6 \) symmetry. At the interface between the two PCs, the \( C_6 \) symmetry is broken. This symmetry breaking lifts the degeneracy between the spin states and allows for the interaction of the these states in the vicinity of the ` I point. As a result of this interaction, a small gap is open. The edge states are not gap-less and are not strictly speaking topologically protected. Despite that, these edge states support scatter-free propagation along interfaces with sharp turns, as it will be shown in figure 4. In the following, we will refer to the edges states in our structure as ‘topological edge states’ as they owe their existence to different topology of the two surrounding bulks [18, 20, 68–70].

Let us consider scattering of light in standard PCs by obstacles on the light’s path, such as rapid turns, crystal imperfections, or defects. When light propagating in the forward direction impinges on an obstacle, the wavevectors matching backward-propagating state may be introduced. For standard PC, the field distributions of forward- and backward-propagating states possess inversion symmetry along the propagation path, resulting in significant scattering of light from the forward state to the backward one [17, 18, 20, 68], degrading the PC performance and resulting in scattering losses. On the contrary, for topologically protected states, the field shows vortex-like distribution for forward- and backward-propagating states (opposite spins), breaking the inversion symmetry. In this case, the field distributions of opposite spins do not overlap, and therefore the states do not scatter one to another, resulting in the suppression of backward scattering for the photonic analog of spin-Hall effect.

Here, we define the conditions required for achieving such scatter-free propagation. Firstly, at the desired frequency, a non-trivial edge state should exist. To confirm the presence of an edge state, we considered a ribbon-shaped PCs shown schematically in the insets in figure 2. The band structure of this system reveals the presence of the bulk and edge states. However, the existence of an edge state is not sufficient to have loss-free propagation. Indeed, if besides the non-trivial edge state there is at least one bulk state at the frequency of interest, any obstacle on the light propagation path will cause undesired scattering of light into the PC interior,
resulting in losses of energy, as shown in figures 2 and 3. Hence, the second necessary condition is the absence of any bulk states at the frequency where topologically protected propagation is desired.

Light can be confined along the z-direction using two alternative mechanisms. The use of metal electrodes allows for strong light confinement inside the PC slab, however, this approach introduces an additional source of loss in the system at optical frequencies. Alternatively, the electrodes can be located at a distance from the PC slab. The space between electrodes and the slab can be filled with the LC which has much lower index than the PC itself. In this case, the light confinement stems from the total internal reflection between the high-index silicon slab and the low-index cladding. In both cases, these three-dimensional systems can be well approximated using 2D analysis.

Figures 2(d) and (g) present the band diagrams for the interface between the trivial and topological regions for uniform background refractive indices $n_{tr} = n_{to} = 1.51$ and $n_{tr} = n_{to} = 1.69$, respectively. In both cases, two edge states—one corresponding to a pseudo-spin-up (denoted by a minus sign and simply referred to as spin-up in the following text) and one corresponding to a pseudo-spin-down (denoted by a plus sign and
referred to as spin-down—are present in the bandgap separating the bulk bands, showing that the change of the background refractive index does not change the topological properties of the system. There is a small frequency range where neither the edge states nor the bulk states exist. This global gap is a result of the avoided crossing of the edge states caused by their interaction due to the broken $C_6$ symmetry at the conducting interface [18, 20, 68–70]. The position and size of the bandgap is affected by variations of the background refractive index. For the case of background index of 1.51, shown in figure 2(c), the bandgap spans the normalized frequency range $\omega a_0/(2\pi c) \in [0.441, 0.462]$, whereas for the background index of 1.69 shown in figure 2(g), the bandgap extends from 0.433 to 0.447. The shrinking and red-shifting of the bandgap observed here is consistent with the results presented in [71]. The effective working wavelength in the medium stays the same, but as a result of an increase in the effective index, the corresponding frequency (free space wavelength) becomes lower (higher) [41].

We choose to analyze the behavior of the structure at a normalized frequency of 0.433 that is located outside of the bandgap for $n_{bg} = 1.51$, and inside of the bandgap for $n_{bg} = 1.69$. Figures 3(a) and (d) show the propagation of light along an interface with a rhombus-shaped defect at $\omega a_0/(2\pi c) = 0.433$ for background refractive indices of 1.51 and 1.69, respectively. When the background index has the value of 1.51, the edge state

![Figure 3. Light propagation along the interface between trivial and topological photonic crystals for different values of background refractive indices. (a)–(d) Energy density distributions of the spin-down states at normalized frequency $\omega a_0/(2\pi c) = 0.433$, indicated by the dash-dot line in figure 2, for the four different configurations of background index values described in figure 2. The color maps show that propagation of the topological edge states is supported only for the case (d) where there is no bulk state allowed for both topological and trivial regions at the considered frequency, as shown in the right panel of figure 2(g). For the cases shown in (b) and (c), light penetrates inside the topological and trivial parts, respectively, due to the presence of bulk states for these regions, as shown in the right and left panels in figures 2(e) and (f), respectively. Bulk states are allowed in non-trivial and trivial regions for the case (a) resulting in light penetration to both regions (see figure 2(d)). (e) Energy density (color map) and the Poynting vector (white arrows) for a spin-down mode in the structure with $n_{tr} = n_{to} = 1.69$ at the normalized frequency $\omega a_0/(2\pi c) = 0.436$, corresponding to the mode indicated by the green point in figure 2(g).]
does not exist and the light couples to the bulk modes of both the trivial region located on the top of the structure, as well as the topological region on the bottom. This behavior can be understood by looking at the band structures for infinitely periodic triangular PCs shown in the left and right panels in figures 2(d) and (g), respectively. For \( n_{bg} = 1.51 \) (see solid curves), the normalized frequency 0.433 is located below the bandgap for both trivial (red curve) and topological (green curve) PC geometry. On the contrary, this frequency is located inside the bandgap of both trivial (red curve) and topological (green curve) structures for \( n_{bg} = 1.69 \) (dashed curves in the right panel of figure 2(g)). Therefore, as seen in figure 3(d), the light propagates along the rhombus-like shaped interface between trivial and topical material without scattering to the bulk. The electric field and the Poynting vector distributions in the vicinity of the waveguiding interface for the spin-down eigen-mode \( \omega/\pi = 1.69 \) at the normalized frequency \( \omega a_0/(2\pi c) = 0.436 \) is shown in figure 3(e), indicating a strong light localization at the interface between the trivial and topological PC configurations. Moreover, the Poynting vector shows the vortex-like character of energy propagation along the interface associated with the spin-Hall-effect nature of the TI.

We have also analyzed the behavior of mixed configurations where the background refractive indices of the trivial and topical regions have different values. This can be achieved by independent control of the voltages on the electrodes sandwiching the trivial and topological regions. To this end, the top electrodes should be separated by a thin insulating layer. The band diagrams for these systems are presented in figures 2(e), (f) and the corresponding light propagations through the rhombus-like defect is shown in figures 3(b), (c). The band diagrams presented in figure 2 show that the normalized frequency of interest, \( \omega a_0/(2\pi c) = 0.433 \), is located below the bandgap both for the configuration with \( n_{tr} = 1.51, n_{tr} = 1.69 \) and the inverse configuration with \( n_{tr} = 1.69, n_{tr} = 1.51 \). Therefore, in both cases, the light scatters into the bulk, and it penetrates the region with the lower background refractive index, as can be seen in figures 3(b) and (c). This behavior again can be explained using the right and left panels in figures 2(e) and (f), respectively, by analyzing whether the studied frequency lays inside or outside of the bandgap for the bulk trivial and topical PCs. The examples described above show that the transmission of light in the edge states at the interface between the trivial and topological PCs can have drastically different character depending on the background refractive index. Therefore, the control scheme over the background index presented above enables us to modify the transmission properties of the system.

**Transmission properties of the reconfigurable topological structure**

Let us consider light propagation along an interface between the trivial and topological regions with a rhombus-shaped path. Transmission calculation through the rhombus allowed us to identify spectral positions of the topological guided modes for different configurations of background refractive indices in trivial (\( n_{tr} \)) and topological regions (\( n_{bg} \)). The transmission spectrum is calculated according to the following expression:

\[
T(\omega) = \frac{\int_{out} P_x(\omega) \, dx \, dy}{\int_{in} P_x(\omega) \, dx \, dy},
\]

where \( P_x \) denotes the x-component of the Poynting vector and the surface integrations are performed over the input and output regions shown in figure 4(a). From the typical distribution of \( P_x \) when the transmission is close to unity, as depicted in figure 4(a), we observe that the energy is well localized near the edge.

Here, we consider the dependence of the transmission spectrum on the background refractive index variation for three cases: (i) background index is simultaneously changed in the topological and trivial regions (figure 4(b)); (ii) background index is modified in the topological region and fixed in the trivial region, \( n_{tr} = 1.51 \) (figure 4(c)); (iii) background index is kept constant in the topological region, \( n_{tr} = 1.51 \), and varied in the trivial region (figure 4(d)). Spectral position of the topological modes is defined by the top and bottom frequencies of the bulk bandgaps in both topological and trivial regions. These frequencies are dependent on the background refractive index, as shown in figure 2.

Figures 4(b)–(d) show that when the topologically protected guiding conditions (existence of edge state and lack of bulk states at given frequency) are satisfied, the transmission is high and close to unity. All three of the plots show the red-shift of the guided region with an increase in refractive index, due to the higher average index values. The width of the guided region is decreased for higher background indices as a result of reduced refractive index contrast between the silicon pillars and the background.

Choosing an appropriate operation frequency allows for switching between high and low transmission modes. For instance, propagation at the normalized frequency \( \omega a_0/(2\pi c) = 0.436 \) results in low transmission for \( n_{to} = n_{tr} = 1.51 \), and quasi-unitary transmission for \( n_{to} = n_{tr} = 1.69 \). Alternatively, one could operate at \( \omega a_0/(2\pi c) = 0.457 \) where the high and low transmission modes are reversed.
Conclusion

In this paper, we have proposed a dynamically tunable topological PC enabled by the photonic analog of the spin-Hall effect. The structure supports edge states at the interface between the trivial and topological parts of the crystal. These topological edge states are robust against structural disorders and imperfections. Their propagation is supported along arbitrarily shaped paths provided that the crystal lattices are connected with the zigzag edges. The reconfigurability is facilitated by immersing the PC into a nematic LC background. With the help of an external field applied to the LC, its molecules can be reoriented, causing variation in background refractive index and shifting the spectral position of edge states. We have shown that with rise of background permittivity, edge states exhibit red-shift due to rise in average refractive index of the crystal. The transmission characteristics through the structure can be dynamically tuned by modifying the spectral position of the non-trivial bandgap. Moreover, the topologically protected bandwidth decreases with an increase of the background refractive index because of the reduction in the index contrast between the background and high-index material. We have defined the conditions that are necessary for supporting topologically protected propagation to be: the presence of non-trivial edge states, along with an absence of bulk state(s) at desired guided frequencies. When these conditions are satisfied, the structure supports topological modes with transmittance close to 100%. Shifting the bandgap position results in scattering of light into the crystal interior, and a decrease in the transmittance through the structure. The reconfigurable photonic topological insulator proposed here is silicon-based, and supports operation at telecommunication frequencies, making it attractive for practical applications. An alternative mechanism for transmission control could be achieved by dynamical switching between trivial and topological states of the structure. This concept is outside of the scope of this paper and requires further investigation.

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Appendix A. Band structure calculations

The band diagrams for bulk PCs with different background refractive indices shown in figure 2(c) were obtained using a plane-wave-expansion method. The band diagrams for the edge states shown in figures 2(d)–(g) and the energy distributions shown in figure 3 were calculated using COMSOL Multiphysics. In order to compute the band diagrams for the edge states, we have analyzed a ribbon-shaped PC infinitely periodic along the x-direction with a finite size of 30 unit cells of both trivial and topological regions along the y-direction.

Appendix B. Transmission calculations

For transmission calculations, we used commercially available Lumerical FDTD Solutions software. The time domain calculations were carried in the simulation domain shown in figure 4(a), and the spectral response was obtained by Fourier transform method. The simulation domain is 50 × 20 unit cells large, and is surrounded by perfectly matched layers (PMLs). The size of the rhombus–shape path modification is 3 × 3 unit cells.

The system was excited with a spin–down (right circularly polarized light rotating counter–clockwise) dipole point source \( H_x = H_y + iH_z \), placed near the interface between trivial and topological parts of the crystal, matching well the profile of the mode propagating in the positive direction of x-axis. The dipole position is shown with the star in figure 4(a). Injection of a short (full–width half–maximum of 7 electromagnetic wave periods at frequency \( \omega_{0}/(2\pi) = 0.417 \)) broadband pulse covering the frequency range \( \omega_{0}/(2\pi) \in [0.417, 0.484] \) guaranteed excitation of all potentially guided states for any considered background refractive index combinations. For accurate calculation of transmission, we used the simulation time equal to 1250 electromagnetic wave periods ensuring that all the energy coupled into the crystal is absorbed by the PML domains.

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