Novel optical XOR/OR logic gates based on topologically protected valley photonic crystals edges

Ming-Hao Chao\textsuperscript{1,2,3}, Bo Cheng\textsuperscript{1,2,3}, Qing-Song Liu\textsuperscript{1,2,3}, Wen-Jing Zhang\textsuperscript{1,2,3}, Yun Xu\textsuperscript{1,2,3,∗} and Guo-Feng Song\textsuperscript{1,2,3,∗}

\textsuperscript{1} Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, People’s Republic of China
\textsuperscript{2} College of Materials Science and Opto-Electronic Technology, University of Chinese Academy of Sciences, Beijing 100049, People’s Republic of China
\textsuperscript{3} Beijing Key Laboratory of Inorganic Stretchable and Flexible Information Technology, Beijing 100083, People’s Republic of China

E-mail: sgf@semi.ac.cn

Received 27 April 2021, revised 18 June 2021
Accepted for publication 5 July 2021
Published 5 October 2021

Abstract

Valley photonic crystals (VPCs) have provided a novel topological photonic platform to manipulate light. In this work, we construct zigzag and armchair domain walls using two-dimensional silicon VPCs, the edges between domains of opposite valley indices link to the corresponding topological invariant. We study the light transmission of these edges with defects and sharp bent corners. We design all-optical logic gates at telecommunication wavelength with both XOR and OR functions based on the valley-contrasting edges. Topologically protected waveguides own high transmission and backscattering-immune features, and the coupling process of different edge modes results in interference for logic functions. Compared with traditional photonic crystal logic gates, our device shows outstanding properties, including robust transmission, higher contrast ratio and more compact footprint. Furthermore, our work also shows the potential of topological photonics to be applied in optical logic circuits.

Supplementary material for this article is available online

Keywords: valley photonic crystals, topological photonics, logic gates, integrated optics

(Some figures may appear in color only in the online journal)

1. Introduction

With the limitation of the transit time of electrons and the accuracy of nanofabrication, people are pursuing the alternatives of basic logic devices. Optical integrated circuits are a possible solution owing to the intrinsic properties of photons: like lower-power consumption and faster response rate. The essential elements for manipulating light include the waveguides to control the flow of light, and the logic gates to achieve the logic operation.

As an analogy of crystals with the periodic arrangement of atoms, artificial metamaterials with periodic dielectric constants were named photonic crystals (PhCs) \cite{1}. The specific linear defects (like an array of shrunk rods or holes) in PhCs could serve as waveguides to trap and guide light. Due to the low losses in manipulating photons, PhCs were regarded as potential platforms to build integrated optics. Utilizing multimode interference \cite{2–5}, self-collimated beams with phase shifter \cite{6,7}, nonlinear effects \cite{8,9}, almost all major logic
gates based on traditional PhCs have been designed [10]. However, in these methods, the phase difference relied on optical path differences or external phase shifters, which led to larger footprints and longer response time. Besides, the inevitable backscattering at corners and fabrication defects limited the properties of PhCs waveguides [11], which was critical for subsequent error rates.

Meanwhile, recent advances in the field of topological effects opened up new opportunities to control the behavior of light. The theory of quantum mechanics in condensed-matter systems has inspired people to transform electromagnetism in PhCs as an eigenvalue problem. Similarly, the topological phase of matter in solid-state physics, like the quantum Hall effect, was transformed into PhCs too, now known as topological photonics [12]. A series of topological insulators were realized in various optical platforms: analogs of quantum Hall effects were performed via gyromagnetic photonic crystals in theory [13, 14] and experiments [15], quantum spin Hall effects have been implemented by using pseudospin strategies like clockwise/counterclockwise modes and so on [16–19]. In particular, valleytronics originating from two-dimensional (2D) transition metal dichalcogenides [20] provided a novel degree of freedom to build topological systems with protected time-reversal symmetry. Valley photonic crystals (VPCs) were optical analogs of valleytronics. In common half-integers of valley Chern numbers systems, there would be a single topological valley edge state at the interface between valley topological bulk domains [21], this is so-called bulk-edge correspondence. The topologically protected edge states have displayed robust propagating properties along the sharp-bent edge inside the photonic bandgap [22–24], while the band range could be finely tuned by changing the structural parameters. Besides, the chirality of photonic valley pseudospin and related beam splitting has been demonstrated in previous researches [25–27].

In this work, we demonstrate four kinds of edge states by changing the stack approach of VPC bulk domains. The robust transmission and backscattering-immunity of edge modes are verified by numerical simulations under sharp bent paths and defects. And we report a novel design of all-optical logic gates operating at telecommunication wavelength based on cross-link of valley-contrasting edges. The logic gates, including OR and XOR functions, are achieved using the phase difference between modes. Besides, we simulate the pulse propagation, the response time agrees well with group velocity obtained from the dispersion curve, and the theoretical response frequency of the logic gates achieves 4.39 THz.

2. Valley photonic crystals structure and robust topological transport

Our design consists of a triangular lattice with holes drilled on the 2D Si (with relative permittivity $\varepsilon = 12$), as shown in figures 1(a) and (b). The honeycomb domain with six sectors is regarded as the unit cell, where lattice constant $a = 340$ nm and the radius of sectorial holes at interposition are assigned to be $r_A$ and $r_B$. In order to obtain the band diagram of 2D PhCs, the eigenfrequencies of the unit cell in figures 1(a) and (b) were calculated under the Floquet periodicity conditions. Only transverse electric (TE) field polarization modes were discussed. All the simulations were performed using commercial finite element method simulation software (COM-SOL Multiphysics, Wave Optics module, all of the following simulations are the same). When $r_A = r_B = 0.24 \cdot a$, the VPCs could be regarded as the photonic graphene containing the so-called Dirac points at $K$ and $K'$ point as gray plots in figure 1(d) shown. When $r_A = 0.24 \cdot a, r_B = 0.12 \cdot a$, by breaking the inversion symmetry of the structure, the doubly degenerated eigenfrequencies split in momentum space. The phase distribution of $H_r (\phi (H_r))$ at non-equivalent $K$ and $K'$ valley centers indicates the pseudospin effects, shown as insert graph in figure 1(d). According the definition [21], the $K$ valley state carries the right-handed circular polarized (RCP) spin angular momentum (SAM) owing to clockwise decreasing $\phi (H_r)$. Likewise, the $K'$ valley state carries left-handed circular polarized (LCP) SAM, further details are given in supplementary materials, appendix A (available online at stacks.iop.org/JOPT/23/115002/mmedia). As the gray region in figure 1(d) depicts, the normalized bandgap ranges from 0.212 to 0.233, corresponding to 1449.2–1603.8 nm, covering the telecommunication C band.

Considering the symmetry in free space, the difference of hole diameter results in two sorts of cell arrangements: zone $(\uparrow)$ and zone $(\downarrow)$, where the arrows represent direction from hole A to hole B in the single triangular lattice cell. Two arrangements of zones are depicted as pink and cyan in figure 1(e). The horizontal interface between zone $(\downarrow)$ and zone $(\uparrow)$ (zone $(\uparrow)$ and zone $(\downarrow)$) are defined as armchair A (and zigzag B), it is shown in figure 1(a) that their arrowheads (or arrow tails) face each other. Similarly, when zone’s arrows are arranged side by side, the vertical interface between zone $(\uparrow)$ and zone $(\downarrow)$ (zone $(\downarrow)$ and zone $(\uparrow)$) are defined as armchair A (and armchair B). The type’s names derive from the boundary shape, as shown in figure 1(e).

The orientation of cell arrangement also leads to the non-trivial topology. The topological indices of $K$ and $K'$ valley is $+1/2$ and $-1/2$ respectively. According to bulk-edge correspondence, the valley Chern number $\Delta C_v = C_K - C_K' = 1$ or $\Delta C_v' = C_K' - C_K = -1$ indicates there exist only one edge state per valley between bulk domains with opposite sign of valley topological indices [23].

Detailed deductions through $k \cdot p$ approximation can be seen in supplemental materials, appendix A.

In order to observe the edge states, we demonstrate four sorts of supercells, each one of these supercells contains interfaces and ten units at each side. The projected band structures of edges were obtained by calculating the eigenfrequencies of the supercells, as depicted in figures 2(a) and (b). In the case of the zigzag interface shown in figure 2(a), the gray plots represent the bulk modes, and the bandgap exists between envelop lines of these bulk modes. The irrelevant modes caused by the upper and lower boundary of the entire device are ignored.
Figure 1. VPC structure. (a), (b) are schematics of VPCs with the hexagonal lattice of air holes (shown as pink and blue region) embedded in a silicon background (shown as gray region). Where $r_A = r_B = 0.24 \cdot a$ in (a) and $r_A = 0.24 \cdot a, r_B = 0.12 \cdot a$ in (b). (c) shows the arrangement of the structure, the white arrow direction in the triangular lattice cell (red dash line) represents different bulk domains, there exists zigzag-type and armchair-type interface in orthogonal orientation, which is depicted as the red line and the dark green line respectively. (d) is the band diagram of bulk VPCs, where VPCs structures transform from $C_6$ symmetry ($r_A = r_B$) to $C_3$ symmetry ($r_A \neq r_B$), the band diagram of $C_6$ symmetry is shown as gray dots, the band diagram of $C_3$ symmetry is shown as red dots, and the bandgap is depicted as the gray region. The insert diagrams show phase vortex of $H_z$ at $K$ and $K'$ points.

Figure 2. Schematics of VPCs supercells containing four types of interfaces. (a) is projected band structure by calculating eigenfrequencies of zigzag-type interface supercell. The envelop curve of the dark gray line represents the bulk band. The zigzag A (red plots) modes and zigzag B (blue plots) modes occupy the bandgap. The operation frequency (1550 nm) is shown as dash green line. Similarly, the projected band structure of armchair-type interface supercell is shown in (b). The averaged $H_z$ field distribution of different modes shown in (c) and (d), and the black arrows represent energy flux.
The edge modes are shown as red (zigzag A) and blue (zigzag B) plots in figure 2(a), these dispersion curves span across the entire bandgap. The horizontal dash line indicates the normalized operating frequency ($\sim \omega a/2\pi$). For zigzag A type interface, there exist two states $Z_A^+$ and $Z_A^-$ locating at positive and negative momentum space respectively. The same naming method is applied for the other three types of interfaces’ operating modes, which correspond to $Z_B^+, Z_B^-, A_A^+, A_A^-$ and $A_B^+, A_B^-$. The $H$ field distribution of operating modes shown in figures 2(c) and (d) confirms the wave confined effect. In contrast, the distribution of bulk modes is shown in supplementary materials figure S1. The black arrows in figures 2(c) and (d) represent energy flux, which indicates that the $Z_A^+$ and $Z_A^-$ modes exhibit opposite transport direction due to positive and negative group velocity. Besides, the circular polarization of the state link to waveguides too, the unidirectional excitation of pseudospin state was proved in previous work [28].

The features mentioned above features indicate that the edge states in VPCs have the potential to construct waveguides [29]. In order to characterize the robust transport properties of the topologically protected waveguide, we construct paths with a sharp angle corner (bent paths), with the cavity, and with the defect. The scattering boundary conditions were used to terminate the scattering light in simulation. Figure 3(a) shows the field distribution in different paths at 1550 nm. The transmission shown in figure 3(a) indicates that the waveguide keeps outstanding robustness, the backscatter caused by sharp bends and defects is suppressed. The range of high transmission above $-5$ dB (shown in the gray region of figure 3(a)) is consistent with the band of edge states. The transmission declines abruptly outside the bandgap region because the incident beam is scattered to the bulk domain and exterior environment. Besides, the high-pass band mismatches the gap slightly at the short-wavelength side, and the bandgap in bulk VPCs (shown in figure 1(d)) is a little larger than the bandgap in VPCs edges (shown in figure 2(a)). The mismatch and the difference in bandgap could be attributed to the incomplete periodicity of supercells and waveguides. At the long-wavelength side, the high-pass range of straight waveguides is beyond bandgap, and this extended band vanishes in bent waveguides because of the increasing backscattering, the peaks among this extended range belong to corner states [30]. In addition, we notice the slight noise of the transmission spectrum in the range 1485–1535 nm. There exist more than one mode among this range in half Brillouin zone, which confirms the multi-modes scattering caused noisy behaviors. Transmission simulation of other waveguides is shown in supplemental materials appendix C.

3. XOR and OR logic function

In this section, we construct a crossroad containing four types of interfaces to achieve the logic function as the analogy in acoustic valley crystals [31]. The region with the opposite sign of valley Chern number form the zigzag-type waveguide in a horizontal orientation and the armchair-type waveguide in a vertical orientation. As shown in figure 4(a), we regard the left port 1 ($I_1$) and right port 2 ($O_2$) as Output ports, connecting to zigzag B and zigzag A receptively. The upper port 3 ($I_3$) and lower port 4 ($I_4$) are set as input ports connecting to armchair A and armchair B, receptively. In simulation, we applied the incident beam on $I_1$, as depicted in figure 5(a), the incident light was set as the plane wave with optimized incident angle ($a_1 = a_2 = 23^\circ$, details in supplemental materials, appendix C). The mode $A_A^+$ in armchair A waveguide was excited. When the mode propagated into the center of crossroad, neither mode in another vertical waveguide armchair B matched $A_B^+$, but $A_A^+$ could be coupled into $Z_B^+$ and $Z_A^-$. The field maps from simulations (figure 5(a)) show the distribution of the magnetic field clearly. The high-intensity signals received at output ports $O_1$, $O_2$ are noted as 1’ (on state), while the low-intensity signals at output ports are recorded as 0’ (off state). A similar phenomenon would be more obvious when applying the incidental beam at port 1, which is discussed in supplemental appendix D. The $Z_B^+$ and $Z_A^-$ modes.
Figure 4. (a) shows the logic device structure, the red region represents zone (↑) and blue region represents zone (↓). There are four ports link to four types of the domain wall, the I₁, I₂ serve as input ports, and O₁, O₂ serve as output ports. The dash arrows represent the light with optimized incident angle. (b) shows phase distribution of Hₓ in the waveguide, the upper path corresponds to excited I₁, and the lower path correspond to excited I₂. The π phase difference confirms the destructive interference in zigzag B waveguide.

Figure 5. (a)–(c) are normalized H filed distribution of different incident ports, where (a), (b) represent situation applying excite source at I₁ and I₂ respectively. (c) is the interference when applying excite source at I₁ and I₂ simultaneously. (d)–(f) represent corresponding transmission of the receiver at output ports, the black plots represent O₁, red plots represent O₂.

share similar transport directions in free space, but they and their corresponding valley (K’ and K) are separated by half Brillouin zone in momentum space. In this work, both modes Z⁻ₓ, Z⁻ₓ link to valley K’ and both modes Z⁺ₓ, Z⁺ₓ link to valley K, this mismatch of valley suppresses the scatter between contrasting modes. The absence of intervalley scattering is also the key reason to explain the backscattering-immune in the bent waveguide, which is shown in section 2. However, the light block between armchair B and armchair A waveguide is more complicated. Theoretically, both armchair modes belong to mixed valley modes, a portion of the mode A⁺ₓ could couple into A⁻ₓ in perfect topological VPCs. A⁺ₓ and A⁻ₓ modes locate equally in kₓ, but there is still a certain space in kₓ, which is hidden in figure 2(b) [32]. The dim field in the armchair B waveguide (figure 5(a)) indicates this weak coupling effect between A⁺ₓ and A⁻ₓ. However, the mixed valley modes consist of equal constituents of K’ and K, the majority of light would couple into horizontal zigzag waveguide firstly.
Table 1. Truth table for XOR and OR logic gate at 1550 nm.

| Input ports | Output ports |
|-------------|--------------|
| Port 3      | Port 4       |
| 0           | 0            | 0           | 0            |
| $p_0$       | 0            | 0.298$p_0$  | 0.180$p_0$   |
| 0           | $p_0$        | 0.299$p_0$  | 0.180$p_0$   |
| $p_0$       | $p_0$        | 0.00000202$p_0$ | 0.738$p_0$   |

Table 2. Comparison table of main reported XOR logic gates based on PhCs.

| Reference | Footprint ($\mu$m$^2$) | Response time (fs) | Contrast ratio (dB) | Platform | Mechanism          |
|-----------|------------------------|--------------------|---------------------|----------|--------------------|
| [8]       | 236.7                  | Order of picoseconds | 16.8                | Nonlinear PhCs defects | Resonant cavity |
| [7]       | 72                     | —                  | 17                  | PhCs defects splitter | Self-collimated beams |
| [10]      | 145                    | —                  | 14.7                | PhCs defects        | Optical path difference |
| [3]       | 106.9                  | —                  | 13.3                | PhCs defects        | Multimode interference |
| [4]       | 54                     | —                  | 21                  | PhCs defects        | Multimode interference |
| [5]       | 43                     | 324                | 5                   | PhCs defects        | Multimode interference |
| [2]       | 46                     | —                  | 28.6                | PhCs defects        | Multimode interference |
| [11]      | 1260                   | —                  | 54.4                | Topological PhCs    | Multimode interference and resonant cavity |
| [33]      | 340                    | —                  | 35                  | VPCs edges          | Multimode interference and edge states |
| This work | 66                     | 227.63             | 49.5                | VPCs edges          | Multimode interference and edge states |

Analogous signal could be obtained under incident light at $I_4$ due to the structural symmetry of the device, mode $A_R$ couple with $Z_{27}$ and $Z_{13}$. Nearly the same transmission of receivers is shown in figures 5(d) and (e). When ports $I_3$ and $I_4$ were applied incident beams simultaneously, the probe at $O_1$ would receive a near-zero signal. Additionally, the power intensity in table 1 shows that the output intensity of $O_2$ increase to nearly four times than intensity under single incident port. Furthermore, the phase distribution of $H_z$ confirms the constructive interference in zigzag A waveguide and destructive interference in zigzag B waveguide, as depicted in figure 4(b). Different from the external modulation of incident light phase, this phase difference originates from different valley mode coupling process. In the discussion of section 2, we regard the phase vortex of $\phi(H_z)$ as the pseudospin, the LCP/RCP pseudospin state link to unidirectional excitation of zigzag type waveguides. Since we set the excited source as linearly polarized light, the LCP/RCP pseudospin degenerate to linearly polarized state $E_x/E_y$ [27]. The evidence is the phase diagram in figure 4(b), the difference of pattern indicates the waveguide zigzag B support $E_x$ state and zigzag A support $E_y$ state. The incident light with angle could be divided into the $E_y$ component and the $E_x$ component. The $E_x$ component is in-phase while the $E_y$ component is out-of-phase because of the opposite transport direction. In other words, the coupling process between results in $\pi$ phase difference at port $O_1$.

In conclusion, output 1 will form the XOR logic function while output 2 form the OR logic function simultaneously. It should be noted that the transmission in figure 5 exhibits high contrast ratio across the whole telecommunication C band. The contrast ratio of output probes is up to 49.5 dB at 1550 nm, which is higher than most traditional logic devices based on PhCs (shown in table 2). Compared with previous logic devices based on VPCs [33], the fundamental difference of our work is the topological edges formed by two nontrivial domains, while edges in previous work are the interfaces between topologically trivial and nontrivial domains.

4. Response time and group velocity

Response time is a significant characteristic in electrical logic devices, and the slow light modes in topological waveguide might limit this characteristic in our optical logic gates [34]. In order to obtain the response time of the VPCs logic gates, we calculate the group velocity of a single waveguide firstly. The pulse transport was studied in the time domain with transient nodes. Four independent point probes were set along the zigzag B waveguide (which is shown in figure 6(b)) and the excitation source at the left port was modulated by amplitude function. The amplitude function of excitation source is $E_x(t) = E_0 \cdot \cos(\delta \omega (t - T_c)) \cos(\omega (t - T_c))$, where center frequency $\omega$ is operating frequency $2\pi c/\lambda_{\text{operation}}$, broadening range $\delta \omega$ is $\omega/20$, the delay time $T_c = \lambda_{\text{operation}}/c$. The waveforms of different probes in the time domain are shown in figure 6(a). And the distance–time relationship of pulse transmission was recorded according to enveloping peaks. The averaged group velocity $v_g = 0.68 \times 10^8$ m s$^{-1}$ was obtained from the linear fitting result of the distance–time relationship (shown in figure S5(a)). On the other hand, the dispersion curve was fitted by a polynomial function and the...
Figure 6. The pulse transmission in the waveguide. (a) measured pulse ($E_y$ amplitude) by point probes set along waveguide with different space. (b) shows the four point probes are placed along the zigzag B waveguide. (c) shows the step pulse received at logic gates $O_1$. The input signal is a step Gaussian pulse starting at $t = 40$ fs.

theoretical group velocity $v^t_g(Z_B) = \frac{d\omega}{dk} |_{\lambda=1550\text{ nm}} = 0.235 \cdot c = 0.70 \times 10^8 \text{ m s}^{-1}$, which agreed well with the averaged group velocity. The comparison shows it is reasonable to evaluate the response time according to the tangent slope value of the dispersion relationship.

The entire device footprint is $10 \mu m \times 6.6 \mu m$, and theoretical group velocity of different waveguide is $v^t_g(Z_A) = 0.149 \cdot c = 0.447 \times 10^8 \text{ m s}^{-1}$, $v^t_g(A_A) = v^t_g(A_B) = 0.095 \cdot c = 0.285 \times 10^8 \text{ m s}^{-1}$. The calculated dwell time is $187.18 \text{ fs} (O_1)$ and $227.63 \text{ fs} (O_2)$, corresponding to the step pulse signal results at $O_2$ (shown in figure 6(c)), where the step pulse source start exciting at $t = 40$ fs. The logic gate could flip at 4.39 THz theoretically, which is better than logic gates based on PhCs defects.

5. Conclusion

In summary, we have designed a topologically nontrivial 2D VPC structure with 2D hexagonal drilled silicon and studied the valley contrasting TE-like band structure. Based on this structure, we constructed four kinds of topologically protected domain walls. We revealed the backscattering-immune features by simulating the transmission of waveguides with different defects. Besides, we designed the logic gates using crossroad with horizontal zigzag-type waveguides and vertical armchair-type waveguides. The interference caused by the phase difference between modes resulted in contrasting output light intensity. The OR/XOR function was achieved at two ports simultaneously, with a contrast ratio up to 49.5 dB. The entire device footprint was reduced to $66 \mu m^2$ due to the topologically confined effect. The pulse transmission simulation and group velocity calculation showed the response frequency is up to 4.39 THz. The proposed logic devices perform the potential of topological photonics applying in optical logic circuits.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

We thank the associate editor and the reviewers for their useful feedback that improved this paper. This work was supported by the Strategic Priority Research Program of Chinese Academy of Sciences (Grant No. XDB43010000), National Natural Science Foundation of China (Grant Nos. 61835011 and 12075244), and Key Research Projects of the Frontier Science of the Chinese Academy of sciences (Grant No. QYZDY-SSW-JSC004).

ORCID iDs

Ming-Hao Chao https://orcid.org/0000-0002-0246-041X
Yun Xu https://orcid.org/0000-0002-6143-9282
References

[1] Joannopoulos J D, Johnson S G, Winn J N and Meade R D 2008 Photonic Crystals: Molding the Flow of Light (Princeton, NJ: Princeton University Press)

[2] Liu W, Yang D, Shen G, Tian H and Ji Y 2013 Design of ultra compact all-optical XOR, XNOR, NAND and OR gates using photonic crystal multi-mode interference waveguides Opt. Laser Technol. 50 55–64

[3] Ishizaka Y, Kawaguchi Y, Saitoh K and Koshiba M 2011 Design of ultra compact all-optical XOR and AND logic gates with low power consumption Opt. Commun. 284 3528–33

[4] Tang C, Dou X, Lin Y, Yin H, Wu B and Zhao Q 2014 Design of all-optical logic gates avoiding external phase shifters in a two-dimensional photonic crystal based on multi-mode interference for BPSK signals Opt. Commun. 316 49–55

[5] Rani P, Kalra Y and Sinha R K 2016 Design and analysis of polarization independent all-optical logic gates in silicon-on-insulator photonic crystal Opt. Express 374 148–55

[6] Sousa J R R, Filho A E F G, Ferreira A C, Batista G S, Sobrinho C S, Bastos A M, Lyra M L and Sombra A S B 2014 Generation of logic gates based on photonic crystal fiber Michelson interferometer Opt. Commun. 322 143–9

[7] Zhang Y, Zhang Y and Li B 2007 Optical switches and logic gates based on self-collimated beams in two-dimensional photonic crystals Opt. Express 15 9287

[8] Liu Y, Qin F, Meng Z-M, Zhou F, Mao Q-H and Li Z-Y 2011 All-optical logic gates based on two-dimensional low-refractive-index nonlinear photonic crystal slabs Opt. Express 19 1945

[9] Jandieri V, Khomeriki R and Erni D 2018 Realization of true all-optical AND logic gate based on nonlinear coupled air-hole type photonic crystal waveguides Opt. Express 26 19845

[10] Hussein H M E, Ali T A and Rafat N H 2018 New designs of a complete set of photonic crystals logic gates Opt. Commun. 411 175–81

[11] He L, Zhang W X and Zhang X D 2019 Topological all-optical logic gates based on two-dimensional photonic crystal Opt. Express 27 25841

[12] Ozawa T et al 2019 Topological photonics Rev. Mod. Phys. 91 015006

[13] Raghu S and Haldane F D M 2008 Analogs of quantum-Hall-effect fields in photonic crystals Phys. Rev. A 78 033834

[14] Haldane F D M and Raghu S 2008 Possible realization of directional optical edge states in photonic crystals with broken time-reversal symmetry Phys. Rev. Lett. 100 013904

[15] Wang Z, Chong Y, Joannopoulos J D and Soljačič M 2009 Observation of unidirectional backscattering-immune topological electromagnetic states Nature 461 772–5

[16] Hafezi M, Mittal S, Fan J, Migdall A and Taylor J M 2013 Imaging topological edge states in silicon photonic Nat. Photon. 7 1001–5

[17] He C, Sun X C, Liu X P, Lu M H, Chen Y, Feng L and Chen Y F 2016 Photonic topological insulator with broken time-reversal symmetry Proc. Natl Acad. Sci. USA 113 4924–8

[18] Khanikaev A B, Hossein Mousavi S, Tse W K, Kargarian M, MacDonald A H and Shvets G 2013 Photonic topological insulators Nat. Mater. 12 233–9

[19] Yves S, Fleury R, Berthelot T, Fink M, Lemoult F and Lerosey G 2017 Crystalline metamaterials for topological properties at subwavelength scales Nat. Commun. 8 1–10

[20] Xiao D, Yao W and Niu Q 2007 Valley-contrast physics in graphene: magnetic moment and topological transport Phys. Rev. Lett. 99 236809

[21] Chen X D, Zhao F L, Chen M and Dong J W 2017 Valley-contrast physics in all-dielectric photonic crystals: orbital angular momentum and topological propagation Phys. Rev. B 96 020202(R)

[22] Ma T and Shvets G 2016 All-Si valley-Hall photonic topological insulator New J. Phys. 18 025012

[23] Gao Z, Yang Z, Gao F, Xue H, Yang Y, Dong J and Zhang B 2017 Valley surface-wave photonic crystal and its bulk.edge transport Phys. Rev. B 96 201402(R)

[24] Yang Y, Jiang H and Hang Z H 2018 Topological valley transport in two-dimensional honeycomb photonic crystals Sci. Rep. 8 1–7

[25] Bahari B, Ndao A, Vallini F, El Amili A, Fainman Y and Kanté B 2017 Nonreciprocal lasing in topological cavities of arbitrary geometries Science 358 636–40

[26] Zhao H, Qiao X, Wu T, Midya B, Longhi S and Feng L 2019 Non-Hermitian topological light steering Science 365 1163–6

[27] Gao F, Xue H, Yang Z, Lai K, Yu Y, Lin X, Chong Y, Shvets G and Zhang B 2018 Topologically protected refraction of robust kink states in valley photonic crystals Nat. Phys. 14 140–4

[28] Wu X, Meng Y, Tian J, Huang Y, Xiang H, Han D and Wen W 2017 Direct observation of valley-polarized topological edge states in designer surface plasmon crystals Nat. Commun. 8 1304

[29] Yang Y, Yamagami Y, Yu X, Pitchappa P, Webber J, Zhang B, Fujita M, Nagatsuma T and Singh R 2020 Terahertz topological photonics for on-chip communication Nat. Photon. 14 446–51

[30] Shi A, Yan B, Ge R, Xie J, Peng Y, Li H, Sha W E I and Liu J 2021 Coupled cavity-waveguide based on topological corner state and edge state Opt. Lett. 46 1089

[31] Wang Z et al 2021 Multichannel topological transport in an acoustic valley Hall insulator Phys. Rev. Appl. 10 024019

[32] Noah J, Huang S, Chen K P and Rechtsman M C 2018 Observation of phononic topological valley Hall edge states Phys. Rev. Lett. 120 063902

[33] He L, Ji H Y, Wang Y J and Zhang X D 2020 Topologically protected beam splitters and logic gates based on two-dimensional silicon photonic crystal slabs Opt. Express 28 34015

[34] Yoshimi H, Yamaguchi T, Ota Y, Arakawa Y and Iwamoto S 2021 Experimental demonstration of topological slow light waveguides in valley photonic crystals Opt. Express 29 422962