1. INTRODUCTION

Topological insulators (TIs), that were first discovered in condensed matter physics [1–7], support conduction on their boundaries but behave as insulators in the interior. Importantly, the energy transport on the edges is topologically protected and robust against structural perturbations and disorder. Recent progress in engineered materials, such as metamaterials and artificially created crystals has laid the foundation for the development of optical [8–14] and acoustic [15] analogs of TIs. Topological photonic systems promise a new generation of compact-scale photonic devices and facilitate energy-efficient on-chip information routing and processing [16]. However, the demonstration of tunable topological photonic devices with on-demand control of light propagation remains a grand challenge.

Photonic TIs (PTIs) can be divided into two categories with broken or preserved time-reversal (TR) symmetry. The first experimental realization of anomalous-Hall PTI was performed in microwave frequencies using gyromagnetic material and magnetic fields to break the TR symmetry [17]. The gyromagnetic response of materials vanishes towards shorter wavelengths, necessitating alternative approaches for the realization of PTIs in the visible and near-infrared (NIR) ranges. Another method to realize the PTIs with broken TR symmetry in linear optical systems relies on temporal modulation of the structure with precise phase control [18]. In structures with preserved TR symmetry, the inversion symmetry can be broken to realize less robust but more feasible topological systems. Recently, the Floquet TI was proposed, where an array of evanescently coupled waveguides was modulated in the propagation direction, mimicking the temporal modulation of the structure [13]. In another approach, an artificial magnetic field was generated in an array of coupled ring resonators, where the phase accumulated by the electromagnetic wave during propagation around a unit cell was equivalent to that acquired by an electron moving in an external magnetic field [12].

The other realizations of the PTIs include metamaterial structures [10] and photonic-crystal-based (PC-based) systems [14,19–23]. As shown above, optics offers a unique platform for realizing many remarkable topological phenomena at room temperature and without strong magnetic fields. Moreover, optical analogs of TIs bring topological phenomena to the domain of practical applications, including robust energy transport in compact, integrated photonic devices, all-optical circuitry, and communication systems. For many of these applications, dynamically controlled scattering-free propagation of light is essential. However, nowadays, the majority of proposed PTIs operate in a fixed wavelength range, and their mode of operation cannot be dynamically tuned. Recently, the first steps toward the design and realization of tunable topological photonic structures have been made [24–29]. Dynamic tunability was proposed in one-dimensional (1D) and two-dimensional (2D) structures using mechanisms based on refractive index change due to Kerr-type nonlinearity [28], using thermal phase-changing material [25] and by liquid crystal reorientation [24]. Tunable TIs for elastic [26] and optical waves [27] based on mechanical control of geometric parameters of stretchable structures were reported.

Here, we design and demonstrate tunable, on-chip, integrated PTIs based on the valley-Hall effect in Si PCs operating at the telecommunication wavelength [20,30]. Non-trivial topology of the crystal ensures backscattering-free light propagation around the path with four sharp turns and allows the structure to be
immune against defects and imperfections. Tunability of the structure is enabled by the free-carrier (FC) excitation initiated by the pump beam, resulting in reduction of the real part of the refractive index and increase of the imaginary part of the refractive index. The refractive index change, in turn, leads to the shift of the bandgap and, correspondingly, to the change in the transmission-peak position.

Previously, several conventional (trivial) tunable photonic devices based on the FC injection in semiconductors were demonstrated, including microcavities, integrated waveguides, and optical modulators [31–36]. Free-carriers can be injected electrically by applying an electric current or optically by illuminating a semiconductor with light. The electrical method requires a complicated fabrication procedure due to the necessity of deposition of electrical contacts. Therefore, in this work, we focus on all-optical refractive index manipulation by means of PC illumination with ultra-violet (UV) radiation. This approach enables fast switching times of the order of nanoseconds corresponding to gigahertz (GHz) modulation frequency. Furthermore, such Si-based structures are compatible with contemporary semiconductor industry fabrication processes. Combining the concepts of topological protection and all-optical modulation may pave the way for future robust and dynamically controllable devices for optical communication.

2. RESULTS
A. Operation Principle
We study tunability of topological PCs fabricated on the standard Si-on-insulator platform shown schematically in Fig. 1(a). The sample characterization is enabled by diffraction gratings connected to the PC by Si-wire waveguides. The light is coupled to the chip by the input grating, and it is split in two parts. One part propagates through the topological PC and is out-coupled by the output grating. The second part is used as a reference. The refractive index of Si is controlled by the UV pump beam illuminating the PC.

We consider a PC slab supporting the valley-Hall effect described in detail in Ref. [23]. The unit cell of the PC contains two triangular holes in a Si slab surrounded by air on the top and bottom. The symmetry in the z direction allows us to consider solely transverse-electric-like (TE-like) modes in this work. We used a standard approach to design topologically non-trivial structures. First, a system exhibiting a Dirac cone in its band structure was found. Second, certain symmetries of the original structure were broken in order to open a topological bandgap. In our design, the Dirac cone exists when the triangular holes are of the same size. For the dissimilar triangles, the inversion symmetry is broken; the symmetry of the structure is reduced from C₆ to C₃ and a non-trivial bandgap opens, as illustrated in Fig. 1(c). The plane wave expansion method was used to calculate the band diagrams shown in Fig. 1. The similarity between electronic and PCs implies that many topological phenomena predicted for electronic systems should be observable in photonic structures with the same symmetry properties. The structure studied here is similar to the boron-nitride structure that is well-known to support the valley-Hall effect for electrons.

We used UV light in order to enable efficient FC excitation [32,33] and induce refractive index change in Si. Si has the bandgap size of around $E_g = 1.14$ eV, which is equal to photon energy at the wavelength of approximately 1.1 μm. There are two processes that contribute to the FC excitation shown schematically in Fig. 1(b). When the energy of the irradiation light exceeds the bandgap size of Si, electrons from the valence band can be directly excited to the conduction band, leading to a single-photon-absorption (SPA) process. The second mechanism, which

![Fig. 1. Principle of operation. Tuning of transmission of the topological PC is enabled by refractive index modulation (see panel c) due to optically induced FC excitation (see panel b).](image)

(a) NIR probe light was coupled to the chip by an input diffraction grating, then split in two parts, where half goes to the topological PC and another part is used as a reference. The transmitted light is out-coupled from the chip by a pair of diffraction gratings. The PC is illuminated by an ultra-violet (UV) pump beam to control the refractive index of Si. (b) Two mechanisms of the FC excitation: single-photon absorption (SPA) occurs when the photon energy exceeds the bandgap size, and electrons are excited directly from the valence band to the conduction band; two-photon absorption (TPA) happens when two photons are absorbed simultaneously, and the electron is excited to the conduction band. (c) Band diagram for the hexagonal PC slab with two triangular holes per unit cell. The inset shows the geometry of the unit cell. The parameters used are $d_1 = 425$ nm, $b = 270$ nm, $d_1 = 0.4a_0$, and $d_2 = 0.6a_0$, and the effective refractive index of Si is assumed to be $n_{e,eff} = 2.965$. Illumination of the sample with a UV pump beam induces a refractive index change in the semiconductor material. Assuming the index change of $\Delta n = -0.1$, the bandgap position is shifted towards higher frequencies (shorter wavelength). The inset shows the zoomed in picture of the band diagram in the vicinity of the bandgap. UV illumination can be used to control the spectral position of the bandgap and, correspondingly, the operation frequencies of the PC.
contributes to the FC excitation, is two-photon absorption (TPA), where electrons are excited to twice as high energy levels due to simultaneous absorption of two photons. The SPA dominates at low pump fluence, while the TPA prevails at high power levels [37]. It should be noted that other competing processes (in addition to the FC excitation) take place in semiconductors simultaneously, including the Kerr nonlinear index modulation and FC dispersion effect [31,34], whose contribution is negligible for the parameters used in our experiments. We used the Drude model to describe the dielectric permittivity variation under light illumination [37]:

$$\Delta \epsilon_{\text{FC}}(F_{\text{eff}}) = -\left[\frac{\omega_p(F_{\text{eff}})}{\omega}\right]^2 \frac{1}{1 + i \frac{\omega}{\omega_0}},$$  \hspace{1cm} (1)

where $\omega$ is the angular frequency of the incident light, $\tau_D$ denotes the Drude damping time, $F_{\text{eff}}$ is the effective pump fluence, $\omega_p(F_{\text{eff}}) = \sqrt{N_{\text{e-b}}(F_{\text{eff}}) e^2 / \epsilon_0 m^*_{\text{opt}}}$ is the plasma frequency, $e$ is the electron charge, $m^*_{\text{opt}} = (m^*_{\text{e}} + m^*_{\text{h}})^{-1}$ denotes the unitless optical effective mass of carriers, $m^*_{\text{e}}$ are the mobility effective masses of electrons and holes, $m^*_h$ is the electron mass, $N_{\text{e-b}}(F_{\text{eff}})$ is the electron–hole density depending on the pump fluence, and $\epsilon_0$ stands for the vacuum permittivity.

The electron–hole density is characterized by the equation [37]

$$N_{\text{e-b}}(F_{\text{eff}}) = \frac{2\pi F_{\text{eff}}}{\hbar \omega} \left(\alpha + \beta \frac{F_{\text{eff}}}{2 \sqrt{2} \pi \tau_0}\right),$$  \hspace{1cm} (2)

where $\alpha$ is the linear absorption coefficient, $\beta$ denotes the TPA coefficient, $\tau_0$ is the pump-pulse duration, and $\hbar$ denotes the Planck constant. The model described by Eqs. (1) and (2) allows us to estimate the Drude damping time and electron–hole density in Si, based on variation in the real and imaginary parts of the refractive index. The refractive index change at pump fluence of 18.1 mJ/cm$^2$ was found by comparison between the experimental and simulation results and allowed us to estimate the Drude damping time $\tau_D = 10^{-14}$ s and electron–hole density $N_{\text{e-b}} = 10^{19}$ cm$^{-3}$, which are typical values for Si [37,38].

The optical effective mass of carriers was assumed to be $m^*_{\text{opt}} = 0.15$ [37]. According to Eqs. (1) and (2), there are two parts contributing to the permittivity change: the first is associated with the SPA and linearly depends on pump fluence $F_{\text{eff}}$; the second is responsible for the TPA with quadratic dependence on the UV radiation fluence $F_{\text{eff}}$. The linear dependence of the permittivity change $\Delta \epsilon_{\text{FC}}$ on the pump fluence observed in our experiments is in agreement with the previous observations [33,37,38] and allows us to conclude that for low levels of the pump fluence used in our experiments, the SPA process prevails in the FC generation over the TPA.

**B. Transmittance Control**

Next, we study how the refractive index change $\Delta n$ induced by the FC excitation influences the light propagation in the PTI under investigation. According to Eqs. (1) and (2), the refractive index change $\Delta n$ linearly depends on the fluence of the beam $F_{\text{eff}}$, as for small refractive index perturbation, $\Delta n \approx \Delta \epsilon / (2 n_{\text{Si,eff}})$. Therefore, the index change profile in the sample plane is assumed to have the same Gaussian distribution as the UV pump beam used in the experiment. The transmittance, defined as a ratio of energy density after and before the four turns, as a function of the refractive index change and the wavelength is shown in Fig. 2(b). The region with high and nearly unitary transmittance corresponds to topologically protected light propagation with

---

**Fig. 2.** Bandgap position control by PC illumination. (b) Transmittance spectrum for the trapezoidal-shaped interface in topological PC as a function of the refractive index change in Si. For efficient guiding, two conditions have to be satisfied: (i) the edge state must exist, while (ii) no bulk states should be present at the guided frequency. (a), (c) Band diagrams for the super-cell periodic in the $x$ direction (see the inset) that contains two parts with different orientations of large and small triangles. The interface between the two parts is located in the middle of the structure (in the $y$ direction). The position of the high-transmittance region is shifted towards shorter wavelengths upon reduction of the refractive index. The width of the bandgap is also decreased due to the reduction of the index contrast. (d), (e) Energy-density distributions for pump illumination turned ON and OFF marked in panel (b) by the green and cyan dots, respectively. For the ON state, the transmittance is reduced at the wavelength $\lambda = 1642$ nm compared to the off state.
suppressed back-scattering. A typical energy density distribution for the edge state is shown in Fig. 2(d), where the light propagates around four turns without significant scattering, resulting in a nearly perfect transmittance. When the refractive index is decreased due to the FC excitation, the high-transmittance region shifts towards shorter wavelengths. This behavior can be qualitatively explained by considering the changes in the band structure of the super-cell upon reduction of the refractive index, see Figs. 2(a) and 2(c). For these simulations, the structure is periodic along the x direction and finite along the y axis with 20 unit cells in each region below and above the edge. We show only the band diagram for positive values of the wave vector $k_x$. The band diagram is symmetric with respect to $k_x = 0$, and another edge state can be found for $k_x < 0$ that propagates in the opposite direction. The scattering-free guiding occurs in the spectral region, where a single topological edge state exists for each of the $K$ and $K'$ valleys. This guiding region in shown in green in the super-cell band diagrams shown in Figs. 2(a) and 2(c). The edge states corresponding to $K$ and $K'$ valleys have electromagnetic field distributions with opposite helicity. The field profiles with opposite helicity do not overlap, preventing these states from coupling with each other. There are defects that may couple states with opposite helicity, but the probability of their appearance is lower compared with other arbitrary defects [23]. The refractive index is assumed to be uniform within the super-cell, and its value was chosen such that the spectral position of the guiding region matches the wavelength range of the high transmittance obtained in the simulations shown in Fig. 2(b).

Figures 2(d) and 2(e) show how the energy density distribution changes at a single wavelength when the pump is turned on, and the refractive index is reduced by $\Delta n = -0.02$. Under the UV-light illumination, the bandgap is blue shifted, and there are bulk states supported at the studied wavelength $\lambda = 1642$ nm. As a result, the light scatters from the edge state into the interior of the crystal and the transmittance is reduced. Finally, it should be mentioned that as the refractive index of Si decreases, the index contrast between Si and air is also reduced, resulting in a narrower bandgap. This effect becomes notable for larger refractive index changes.

C. Experimental Results

In order to confirm the theoretical predictions, samples with straight and trapezoidal-shaped interfaces were fabricated. The sample fabrication procedure is described in detail in the supplementary materials of our previous paper [23]. The samples were measured with the experimental setup schematically shown in Fig. 3(a). A Ti:sapphire laser with the repetition rate of 1 kHz and 100 fs output pulse width was used as a light source in the experiment. Pulsed laser radiation was separated in two parts by a beam-splitter (BS) and routed into two optical parametric amplifiers (OPA), where the UV pump beam (400 nm) and the NIR probe pulse (tunable near 1500 nm) were generated such that the pump and probe beams have orthogonal polarizations. We used a delay line to control relative arrival times of the NIR and UV pulses. The convex lens was employed to control the spot size of the pump beam in the sample plane.
The approximate size of the beam waist was \( \sigma = 37 \) nm. The pump and probe beams were combined together and directed onto the same propagation path by a dichroic mirror and were focused on the sample by an infinitely corrected objective lens. Another BS was used for routing light towards the sample. The objective and an achromatic lens form a 4f system that was used for sample imaging and transmission measurements.

Figure 3(b) shows the dependence of the transmission spectra on the fluence of the pump beam measured for two samples: with a trapezoidal-shaped propagation path (blue lines) and with a straight interface with no bends (red lines). Upon UV illumination, the refractive index decreases, and the transmission peak shifts towards the shorter wavelengths (blue shift). Wavelength shifts of up to 20 nm have been measured for the highest pump-beam fluence. Besides the reduction of the real part of the refractive index, UV pump illumination results in a significant rise of absorption in Si [34]. At the highest pump power, the peak transmission is reduced by approximately 85%.

In the numerical simulations, we used the crystal with the same parameters as in the experiments. COMSOL Multiphysics Software was used for super-cell simulations and for transmission and transmittance calculations. We assumed that the real and imaginary parts of the refractive index are linearly dependent on the pump-beam fluence, and the pump beam was assumed to have a Gaussian profile.

First, the real part of the refractive index was fitted to match the blue shift found in the experimental measurements. At the highest pump intensity, we obtain the refractive index change of \( \Delta n = -0.02 \). Second, the absorption coefficient was calculated, taking into account the group velocity in the medium found in edge-state simulations (see Fig. 2(c)) and the measured transmittance of around 15% of the value with the pump beam switched off. Then, the imaginary part of the refractive index was found to be \( \text{Im}(\Delta n) = 0.0013 \) at the highest pump-beam power. Thus, at the pump-beam fluence of 18.1 mJ/cm², the estimated refractive index change was \( \Delta n = -0.02 + 0.0013i \). Third, assuming the linear dependence of the refractive index change on the pump-beam power, the values of \( \Delta n \) were calculated for other fluences used in the experiments. The value of the index change was found to be comparable with the ones reported in the literature, although it should be noted that it depends on several factors, such as semiconductor doping, surrounding material, and patterning of the structure [31,34]. The results of the numerical simulations are shown in Fig. 3(c), and they are in a good agreement with the experimental data. As predicted, the transmissions for straight path and for the one with bends are similar, confirming that the energy transport stays robust even under strong UV illumination. We used the following definitions for transmittance and transmission of light. Transmittance is the amount of light propagated through four bends in the PC for the case of a continuous source. Transmission is measured in the experiments using a femtosecond pulsed laser. The spectrum of the pulse covers a wavelength range with the width of 40 nm around the central wavelength, and therefore the transmission is an average over this spectral region. For each point in the transmission spectrum, we set the input pulse central wavelength and measure the transmitted power. In order to match the numerical and experimental results, we computed the convolution of the CW transmittance with the spectral shape of the pulse. The simulations were performed in 2D approximation with the effective refractive index \( n_{\text{eff}} = 2.965 \) (for the switched off pump beam). The peaks for the simulated results are red shifted with respect to the experimental results due to the discrepancy coming from the effective index approximation. The refractive index model is assumed to have a Gaussian distribution given by \( 2\Delta n \exp[-(r/\sigma)^2] \).

In order to estimate the minimum switching times attainable for the proposed structure, we characterized the times of the refractive index recovery by measuring the FC lifetime. The dependence of transmission on the delay time between the pump and probe pulses was measured. The change of transmission due to the FC excitation can be characterized by the expression \( T = 1 - A \), where \( A \) denotes absorption, and, assuming exponential dependence of absorption, \( A = A_0 e^{-t/\tau} \) on pump–probe delay \( t \), where \( A_0 \) is the attenuation factor, and \( \tau \) is the FC lifetime. By fitting the results shown in Fig. 3(f), we found the attenuation factor \( A_0 = 0.794 \) and the FC lifetime \( \tau = 600 \) ps. It is worth noting that the FC lifetime decreases as the pump-beam width \( \sigma \) decreases [33]. The FC lifetime measured here allows for the structure switching time in the order of a nanosecond. In the case when a faster modulation rate is required, the semiconductors with a direct bandgap [39] instead of Si can be used. Alternatively, a control mechanism based on Kerr nonlinearity, allowing faster switching times [40,41], can be employed.

3. CONCLUSION

We studied the all-optical modulation of a Si topological PC slab supporting the valley-Hall effect. The non-trivial topology of the crystal ensures backscattering-free light propagation around the path with four sharp turns and allows the structure to be immune against defects and imperfections. Switching of the crystal is enabled by the FC excitation by the pump beam, causing the reduction of the real part of the refractive index and increase of absorption. Consequently, the transmission peaks are blue shifted by up to 20 nm, and the transmission is reduced by around 85%. The control mechanism used here allows for switching at a GHz frequency. Different methods of refractive index modulation can be explored, including phase-changing materials, electro-optical modulation and Kerr nonlinearity. For instance, if third-order nonlinearity is employed, only the real part of the index can be modulated at an even higher (femtosecond) rate, while the material absorption remains negligible. Chalcogenide glasses might be a suitable platform for tunable topological photonics due to their transparency in the NIR wavelength range, very low TPA, exceptionally high Kerr nonlinearity coefficients, and a high linear refractive index, allowing for strong light confinement on the nanoscale. The system studied here is fully compatible with contemporary semiconductor fabrication techniques and operates at technologically important telecommunication wavelengths. This research paves the way for efficient and tunable photonic devices for future classical and quantum communication systems.

Funding. Army Research Office (ARO) (W911NF-18-1-0348).
REFERENCES

1. C. L. Kane and E. J. Mele, “Z2 topological order and the quantum spin Hall effect,” Phys. Rev. Lett. 95, 146802 (2005).
2. C. L. Kane and E. J. Mele, “Quantum spin Hall effect in graphene,” Phys. Rev. Lett. 95, 226801 (2005).
3. J. E. Moore, “The birth of topological insulators,” Nature 464, 194–198 (2010).
4. A. B. Bernevig and T. L. Hughes, Topological Insulators and Topological Superconductors (Princeton University, 2013).
5. G. J. Ferreira and D. Loss, “Magnetically defined qubits on 3D topological insulators,” Phys. Rev. Lett. 111, 106802 (2013).
6. F. Katmis, V. Lauter, F. S. Nogueira, B. A. Assaf, M. E. Jamer, P. Wei, B. Satpati, J. W. Freeland, I. Eremin, D. Heiman, P. Jarillo-Herrero, and J. S. Moodera, “A high-temperature ferromagnetic topological insulating phase by proximity coupling,” Nature 533, 513–516 (2016).
7. G. Jotzu, M. Messer, R. Desbuquois, M. Lebrat, T. Uehlinger, D. Greif, and T. Esslinger, “Experimental realization of the topological Haldane model with ultracold fermions,” Nature 515, 237–240 (2014).
8. R. O. Umucalilar and I. Carusotto, “Artificial gauge field for photons in coupled cavity arrays,” Phys. Rev. A 84, 043804 (2011).
9. M. Hafezi, E. A. Demler, M. D. Lukin, and J. M. Taylor, “Robust optical delay lines with topological protection,” Nat. Phys. 7, 907–912 (2011).
10. A. B. Khanikaev, S. H. Mousavi, W.-K. Tse, M. Kargarian, A. H. MacDonald, and G. Shvets, “Photonic topological insulators,” Nat. Mater. 12, 233–239 (2013).
11. K. J. Fang, Z. F. Yu, and S. H. Fan, “Realizing effective magnetic field for photons by controlling the phase of dynamic modulation,” Nat. Photonics 6, 782–787 (2012).
12. M. Hafezi, S. Mittal, J. Fan, A. Migdall, and J. M. Taylor, “Imaging topological edge states in silicon photonicics,” Nat. Photonics 7, 1001–1005 (2013).
13. M. C. Rechtsman, J. M. Zeuner, Y. Plotnik, Y. Lumer, D. Podolsky, F. Dreisow, S. Nolte, M. Segev, and A. Szameit, “Photonic Floquet topological insulators,” Nature 496, 196–200 (2013).
14. S. Barik, A. Karasahin, C. Flower, T. Cai, H. Miyake, W. DeGottardi, M. Hafezi, and E. Waks, “A topological quantum optics interface,” Science 359, 666–668 (2018).
15. J. Lu, C. Qiu, L. Ye, X. Fan, M. Ke, F. Zhang, and Z. Liu, “Observation of topological valley transport of sound in sonic crystals,” Nat. Phys. 13, 369–374 (2017).
16. L. Lu, J. D. Joannopoulos, and M. Soljačić, “Topological photonics,” Nat. Photonics 8, 821–829 (2014).
17. Z. Wang, Y. Chong, J. D. Joannopoulos, and M. Soljačić, “Observation of unidirectional backscattering-immune topological electromagnetic states,” Nature 461, 772–775 (2009).
18. K. Fang, Z. Yu, and S. Fan, “Realizing effective magnetic field for photons by controlling the phase of dynamic modulation,” Nat. Photonics 6, 782–787 (2012).
19. L. H. Wu and X. Hu, “Scheme for achieving a topological photonic crystal by using dielectric material,” Phys. Rev. Lett. 114, 223901 (2015).
20. T. Ma and G. Shvets, “All-Si valley-Hall photonic topological insulator,” New J. Phys. 18, 025012 (2016).
21. X.-D. Chen, F.-L. Zhao, M. Chen, and J.-W. Dong, “Valley-contrasting physics in all-dielectric photonic crystals: orbital angular momentum and topological propagation,” Phys. Rev. B 96, 020202 (2017).
22. J.-W. Dong, X.-D. Chen, H. Zhu, Y. Wang, and X. Zhang, “Valley photonic crystals for control of spin and topology,” Nat. Mater. 16, 298–302 (2016).