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Perspective

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Quantum topological photonics with special focus on waveguide systems

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In the burgeoning field of quantum topological photonics, waveguide systems play a crucial role. This perspective delves into the intricate interplay between photonic waveguides and topological phenomena, underscoring the theoretical underpinnings of topological insulators and their photonic manifestations. We highlight key milestones and breakthroughs in topological photonics using waveguide systems, alongside an in-depth analysis of their fabrication techniques and tunability. The discussion includes the technological advancements and challenges, limitations of current methods, and potential strategies for improvement. This perspective also examines the quantum states of light in topological waveguides, where the confluence of topology and quantum optics promises robust avenues for quantum communication and computing. Concluding with a forward-looking view, we aim to inspire new research and innovation in quantum topological photonics, highlighting its potential for the next generation of photonic technologies.

Timeline of topological photonics in waveguide systems

Originating from solid-state physics, the concept of topology is increasingly being applied in the field of photonics, garnering widespread attention and giving rise to numerous novel applications. A seminal contribution in this domain involves the theoretical prediction of topological insulators. The concept of topological insulators originated with the discovery of the quantum Hall effect[1–5]. Although this effect was originally demonstrated in electronic systems, it could also be realized in bosonic systems (such as photonics). Through the manipulation of system parameters, the creation of an artificial magnetic field is achievable, resulting in the observation of the quantum Hall effect (QHE) and quantum spin Hall effect (QSHE) within two-dimensional photonic systems[6–10].

Throughout the evolutionary trajectory of topological photonics, the waveguide platform has assumed a pivotal role (Box 1). Based on photonic platforms, the unidirectional backscattering-immune topological electromagnetic states have been realized by implementing the chiral edge states in a gyromagnetic photonic-crystal slab, as shown in Fig. 1[8]. In another context, photonic crystals consisting of gyromagnetic materials, such as yttrium iron garnet (YIG) were applied[11]. Under an additional uniform magnetic field **B**, the gyromagnetic response of the material will induce an effective magnetic field for photons in the microwave frequency range, which can be mapped to the Haldane model. Concurrently, in the year of 2009, the first experimental realization of Su–Schrieffer–Heeger (SSH) model[12] in the photonic context was performed in a photonic superlattice[13]. Subsequently, a two-dimensional topological insulator was realized in a Floquet helical waveguide array through the utilization of the femtosecond laser direct writing method, as shown in Fig. 1[9]. This progress culminated in numerous milestones in topological insulators such as the Anderson insulator[14], fractal photonic topological insulator[15,16], and bimorphic Floquet topological insulator[17]. Most recently, a significant advancement was made by introducing the periodic gain/loss into a two-dimensional system comprising 48 waveguides, the evidence of the existence of a non-Hermitian topological insulator with a real-valued energy spectrum has been presented in a Floquet regime, as shown in Fig. 1[18].

In the meanwhile, coupled resonator optical waveguide (CROW) system also offers a great platform to study topological insulator phases, where the direction of propagation of light in each resonator functions as a spin. A resilient optical delay line featuring topological protection has been successfully implemented in a silicon photonics platform leveraging the QHE and QSHE principles[10,19]. In 2013, an important model of quantum anomalous Floquet Hall model was proposed[20] and realized in the CROW system to demonstrate topologically protected entanglement emitters[21]. Most recently, a fully programmable topological photonic chip was realized using tunable microring resonators, and the platform showcased the capability to implement multifunctional topological models[22]. Another key model is a topological crystalline insulator[23], which could introduce a topological quantum optics interface[24].

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Box 1 | Formation of photonic lattices and fabrication techniques

Photorefractive crystal

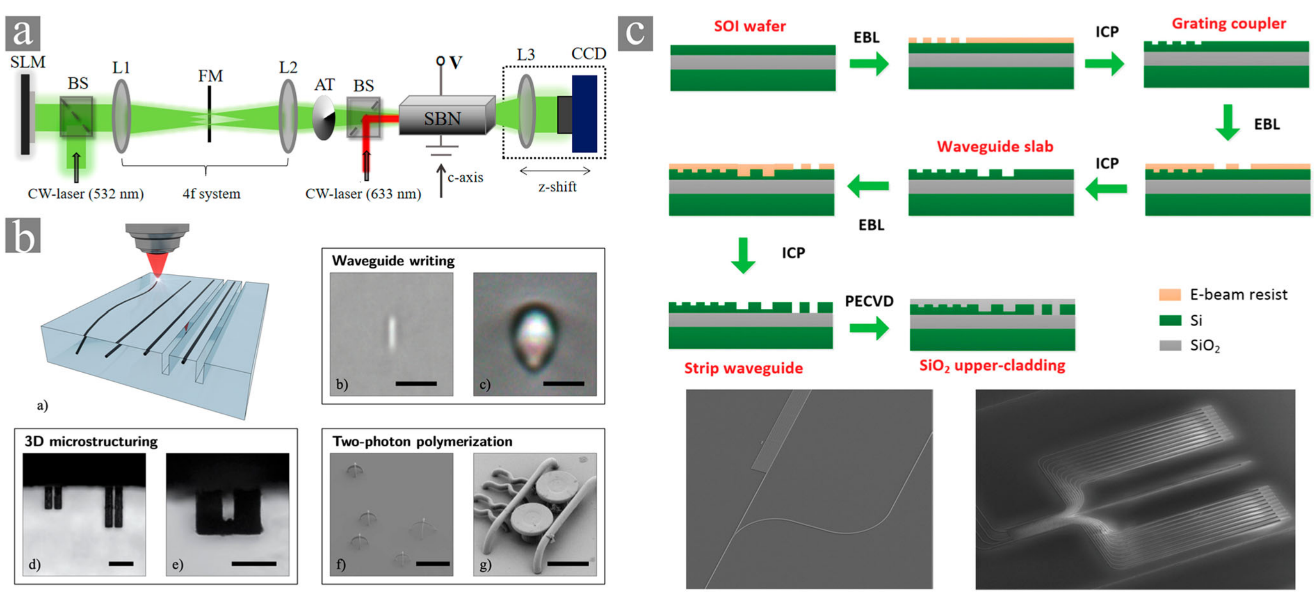
Topological photonic lattices can be intricately created using optical induction[135]. This process starts with encoding the desired lattice's phase information, based on the interference patterns of counterpropagating plane waves, onto a high-resolution spatial light modulator (SLM). When a continuous-wave laser, typically with a wavelength of 532 nm, illuminates this encoded SLM, it reconstructs the intended interference wave field. However, directly using this wave field is challenging due to its diffraction properties. To address this, the wave field is transformed into the wavevector domain and filtered to remove undesired components, ensuring only the first-order diffraction pattern is retained. This filtered wave field is then converted back, resulting in a smooth, non-diffracting beam perfect for creating the lattice in a physical sample. The light is then coupled to a photorefractive crystal to form the lattice, and a signal light at a longer wavelength is used to probe the propagation dynamics of light in the photonic lattice. The experimental setup is illustrated in (a), adapted from ref. 136.

Femtosecond laser direct writing technique

Femtosecond laser machining (FLM) utilizes femtosecond laser pulses focused through high-precision optics, such as aspheric lenses or microscope objectives, onto or into the material. The intense peak power of the laser triggers nonlinear absorption processes, resulting in localized, permanent modifications within the material. By moving the material relative to the laser's focus using high-precision stages, intricate three-dimensional structures can be realized. The applications of FLM span various domains, from waveguide writing to 3D microstructuring and even two-photon polymerization, showcasing the technique's flexibility. For waveguide fabrication, FLM enables the creation of optical channels within glasses and crystals by inducing positive refractive index changes. This has been extensively explored for producing single-mode waveguides across a wide spectral range, with properties finely tunable through the adjustment of laser parameters like pulse energy, scan speed, and repetition rate. Materials commonly used include pure fused silica and commercial borosilicate glasses, with fabricated waveguides demonstrating low propagation and bending losses, making them well-suited for integrated photonics applications. In 3D microstructuring, FLM allows for the precise excavation of microtrenches and the creation of hollow microstructures by focusing the laser on the material's surface or by water-assisted laser ablation. Two-photon polymerization represents another facet of FLM's versatility, allowing for additive manufacturing of three-dimensional polymeric structures with sub-micrometer precision. This process involves the localized polymerization of a photosensitive resin through nonlinear two-photon absorption, enabling the creation of complex photonic elements such as waveguides, couplers, and microdisc resonators.

Top-down CMOS-compatible process

The fabrication process begins with the patterning of the wafer to define various optical components, such as grating couplers and photonic waveguides. This step can be achieved through electron beam lithography or optical lithography, depending on the required precision and the scale of the circuits. Electron beam lithography offers high resolution, suitable for intricate patterns, while optical lithography provides a more cost-effective solution for large-scale applications. Once the layout is patterned on the wafer, an etch mask protects certain areas during the etching process. Reactive ion etching (RIE) can then be used to carve out the optical elements from the silicon substrate. This etching process is highly controllable, allowing for the precise definition of waveguide dimensions and the realization of complex optical structures. To enhance the functionality and efficiency of the devices, certain components, like grating couplers, may undergo partial etching to improve the coupling efficiency between the integrated waveguides and external optical fibers. After the primary structure of the photonic circuits is established, a top cladding layer, such as silicon dioxide (SiO_2), can be deposited over the devices. This top oxide layer serves multiple purposes: it provides a symmetric environment for the optical modes, and it also protects the underlying components from physical damage and contamination. By leveraging established CMOS processes, this method offers a scalable and economically viable route to the mass production of integrated photonic circuits. The process is depicted in the figure with two SEM images showcasing a 1D lattice with grating couplers, all adapted from refs. 38,137,138.



(a) Experimental setup for creating photonic lattices using computer-generated holography. (b) Femtosecond laser writing process for realizing optical lattices through photorefractive effect, 3D micro-structuring, and two-photon polymerization. (c) Top shows a top-down CMOS-compatible process to realize nanophotonic lattices. Bottom shows an SEM image of a 1D photonic lattice with grating couplers to probe the dynamics in each lattice site. Panels adapted with permission from (a), ref. 136; (b), ref. 139; (c), refs. 38,137,138.

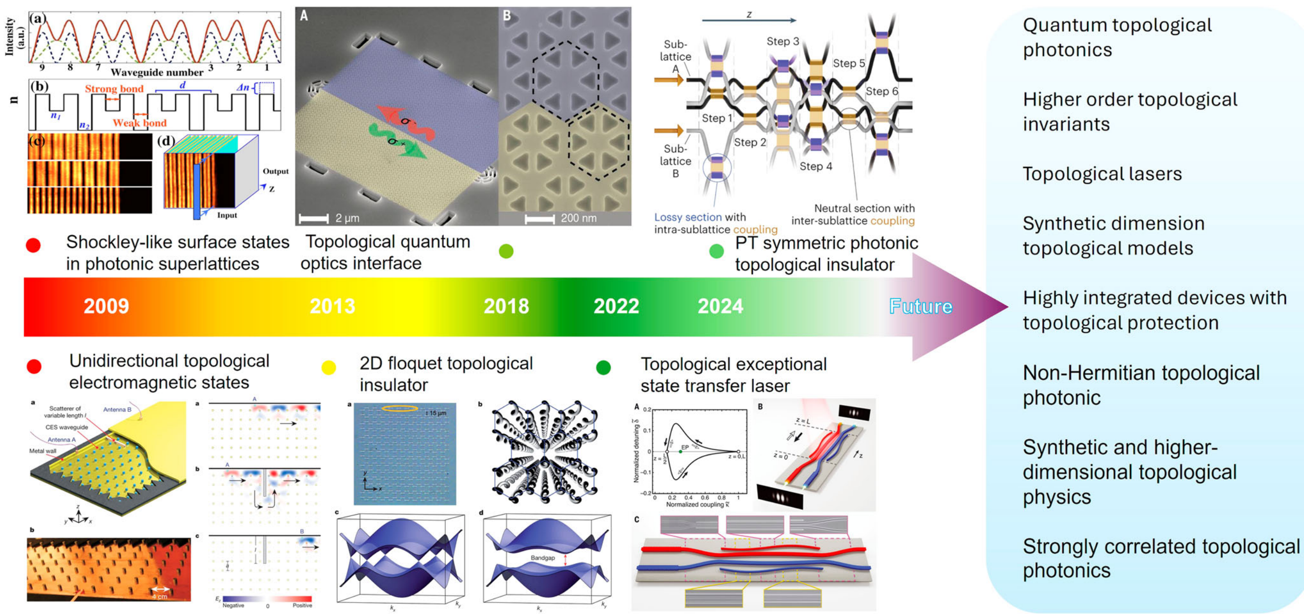


Fig. 1 | Timeline showing key experimental milestones in waveguide-based topological photonic lattices. Shockley-like surface states in photonic superlattices[13]. Unidirectional topological electromagnetic states[8]. Floquet topological insulator[9]. Topological quantum optics interface assisted quantum emitter[24]. Topological exceptional state transfer laser[55]. PT-symmetric photonic topological insulator realized in a 2-dimensional waveguides array[18]. Panels adapted with permission from refs. 8,9,13,18,24,55.

Another platform worth mentioning is based on meta-waveguides. In 2013, a photonic analog of a topological insulator was theoretically proposed using metacrystals, demonstrating the potential for one-way photon transport without the need for external magnetic fields or breaking time-reversal symmetry[25]. Subsequently, in 2015, a simple yet insightful photonic structure based on a periodic array of metallic cylinders was developed to emulate spin–orbit interaction through bianisotropy[26]. This meta-waveguide platform does not suffer from high Ohmic losses and could potentially be scaled to infrared optical frequencies. This approach has proven fruitful for topological photonics, as evidenced by numerous experimental demonstrations[27–29].

These insulators maintain insulation within their bulk while permitting the propagation of waves on their surfaces. They exhibit notable robustness to disorder and effectively impede back-scattering. The robust demonstration of the QHE and quantum anomalous Hall effect[5,30] in terms of edge conductivity across various parameters serves as a compelling illustration of the predictions within this domain. The topological invariant known as the Chern number[31] plays a crucial role in elucidating the aforementioned effects. It is the adept application of the winding number (one-dimensional systems) and the Chern number (even-dimensional systems) that establishes a profound theoretical foundation for topological photonics

$$\begin{aligned} W &= \frac{1}{2\pi}\int_{BZ} A(\mathbf{k})d\mathbf{k} \\ C &= \frac{1}{2\pi i}\int_{BZ} \mathrm{Tr}\left(P\left[\partial_{k_x}P, \partial_{k_y}P\right]\right)\mathrm{d}^2\mathbf{k} \end{aligned} \tag{1}$$

where $A(\mathbf{k}) = i\langle u_{\mathbf{k}}|\nabla_{\mathbf{k}}|u_{\mathbf{k}}\rangle$ represents the Berry connection[32] in the momentum–space and P denotes the projector operator $P(\mathbf{k}) = \sum_{i=1}^{n}|u_i(\mathbf{k})\rangle\langle u_i(\mathbf{k})|$. These topological invariants keep the nature of the integer and only undergo a change when there is a closure of the band gap. Despite the myriad differences in properties such as dimensions, the number of waveguides, and shapes, photonic systems sharing the same topological invariants can often be categorized into a unified class, exhibiting consistent characteristics in key properties. Consequently, these integers serve as a manifestation of the robust attributes inherent in topological photonics systems against small continuous perturbations, for example, the defects in photonic device processing, or small changes in the refractive index of the material. Building upon this foundation, the exploration of methods to enhance the nonlinear effects in materials and the quest for novel invariants that could potentially confer topological protection to devices have increasingly become noteworthy endeavors within the realm of topological photonics based on photonics waveguide systems (Table 1).

In one-dimensional topological photonics systems, the emergence of topological phases is inevitably associated with the presence of symmetries[33,34]. A paramount one-dimensional model is the SSH model with a Hamiltonian denoted as

$$\hat{H} = \kappa_1\sum_{i=1}^{n}\hat{a}_{i,A}^{\dagger}\hat{a}_{i,B} + \kappa_2\sum_{i=1}^{n-1}\hat{a}_{i,B}^{\dagger}\hat{a}_{i+1,A} + h.c., \tag{2}$$

characterized by chiral symmetry. κ_1 and κ_2 denote the intra/inter-cell hopping amplitudes in this dimerized system. Further exploration has been undertaken in the photonic waveguide system regarding the topology associated with the winding number (or the Zak phase), including the interface between two dimer chains with different Zak phases[35–37], localization behavior in SSH model with defects[38], superlattice model with more sites (>2) in a cell[39,40] and direct detection of topological invariant[41–43].

Originating from the embodiment of topology in two-dimensional materials, chiral topological photonics also shows its potential rich application prospects[44]. Barik et al. achieved the realization of a chiral quantum emitter using InAs quantum dots, as shown in Fig. 1, thanks to the exploration of interface edge modes connecting two topologically distinct regions. This implementation involved the selective coupling of 900–980 nm white light to the grating coupler, while photons outside the bandgap dissipated to the bulk[24]. Additionally, a series of investigations in chiral topological photonics have been systematically conducted, building upon photonic waveguide systems[45–48].

Another emerging area based on waveguide systems that have garnered widespread attention is PT-symmetric topological photonics, which provides a new perspective by considering gain and loss in optical systems. This emerging field has attracted considerable attention and the readers could find many nice review articles on related topics[49–54]. Leveraging the novel design motivated by exceptional points, a

Table 1 | Summary of different topological photonics platforms, and their key characteristics

Photonic platform	Optical confinement and birefringence	Photon generation	Dimensionality of the models	Tunability	Transparency	Qubit coding possibilities
Glass (borosilicate, fused silica)[62–64,68–71]	Low, $\Delta n \approx 5 \times 10^{-3}$–$1 \times 10^{-2}$[100], low birefringence	Probabilistic, four-wave mixing[70,101]	1D and 2D[9,102]	Slow, thermo-optic[103]	0.18–3 μm[104]	Polarization, time-bin, frequency-bin, path and OAM[105,106]
III–V[24,44,107]	Can be high, in suspended membranes $\Delta n > 2.5$[108], with high birefringence	Probabilistic through SPDC, on-demand using QDs[109]	1D and 2D[110–112]	Fast EO modulation, MEMS[113]	GaAs 1–16 μm, check ref. 114 for GaP, InP, InAs, and InSb	Time-bin, frequency-bin, path
Silicon-based (Si, SiN, SiC)[10,43,115,116]	High, $\Delta n \approx 2$[10], high birefringence	Probabilistic four-wave mixing, on-demand defects[65,117],	1D and 2D[10,35,65,67,115]	Thermo-optic, carrier-induced dispersion (Si), MEMS, phase change materials[118–122]	Si 1.1–8 μm, SiN 0.40–2.235 μm and SiC 0.37–5.6 μm[123–126]	Time-bin, frequency-bin, path, and transverse mode[127,128]
Lithium niobate[129]	High in thin-film LNOI (high birefringence), low in diffusion-based waveguides (low birefringence)[130]	Probabilistic SPDC, on-demand through hybrid integration[131,132]	1D and 2D[129]	Fast EO modulation[133]	0.4–5.2 μm[134]	Time-bin, frequency-bin, path

topological laser emitting in two different but topologically linked transverse profiles is realized through exceptional state transfer within two waveguides, as shown in Fig. 1[55]. Inspired by the ongoing non-Hermitian physics in condensed matter, the non-Hermitian photonics, such as non-Hermitian skin effect incorporating non-Bloch band theory, will follow further[56,57], apart from the PT topological insulator and PT-symmetric lasing[58]. Finally, we would like to point out another direction, that is, the interplay between topology and quantum optics (for instance, see ref. 59), and this is also the focus of this perspective.

Physics of photonic waveguide arrays

Photonic waveguides represent a cornerstone in the field of photonics, facilitating the controlled propagation of light (Box 2). These structures are capable of guiding light waves through the modulation of refractive indices, creating pathways that allow for the efficient transmission of optical signals. The underlying physics of photonic waveguide arrays is governed by the interplay between the wave nature of light and the geometrical/material properties of the waveguides themselves.

The behavior of light within these waveguides is described by Maxwell's equations, which, under the approximation of a slowly varying envelope and assuming linear, isotropic, and non-dispersive media, can be reduced to the Helmholtz equation:

$$\nabla^2_{x,y}\varphi(x,y,z) + 2ik_z\frac{\partial}{\partial z}\varphi(x,y,z) - k_z^2\varphi(x,y,z) + k_0^2n^2(x,y)\varphi(x,y,z) = 0 \quad (3)$$

where $\nabla^2_{x,y}$ is the transverse Laplacian, $\varphi(x, y, z)$ is the electric field envelope, k_z is the propagation constant along the z-direction, k_0 is the free space wave number, and $n(x, y)$ is the refractive index distribution.

The coupling of light between adjacent waveguides in an array is described by the coupled-mode theory, which can be simplified under the tight-binding approximation to yield a set of discrete equations modeling the evolution of light amplitude in each waveguide:

$$-i\frac{\partial}{\partial z}\varphi_i = \beta_i\varphi_i + \kappa_{i,i-1}\varphi_{i-1} + \kappa_{i,i+1}\varphi_{i+1} \quad (4)$$

where φ_i is the wave amplitude in the ith waveguide, β_i is the propagation constant, and $\kappa_{i,j}$ represents the coupling coefficient between the ith and jth waveguides.

Adjusting the on-site potential (β_i) and the hopping terms ($\kappa_{i,j}$) allows for the meticulous control of light propagation. Variations in the on-site potential can lead to phase shifts within the waveguides, affecting interference patterns. Similarly, modifying the hopping terms influences the extent of light spread across the array, effectively controlling the bandwidth of the photonic band structure. By engineering the geometry and refractive index distribution of the waveguide array, it is possible to tailor the propagation characteristics of light. This framework allows for the exploration of various phenomena unique to waveguide arrays, such as bandgap formation, localization effects, and the emergence of topological edge states.

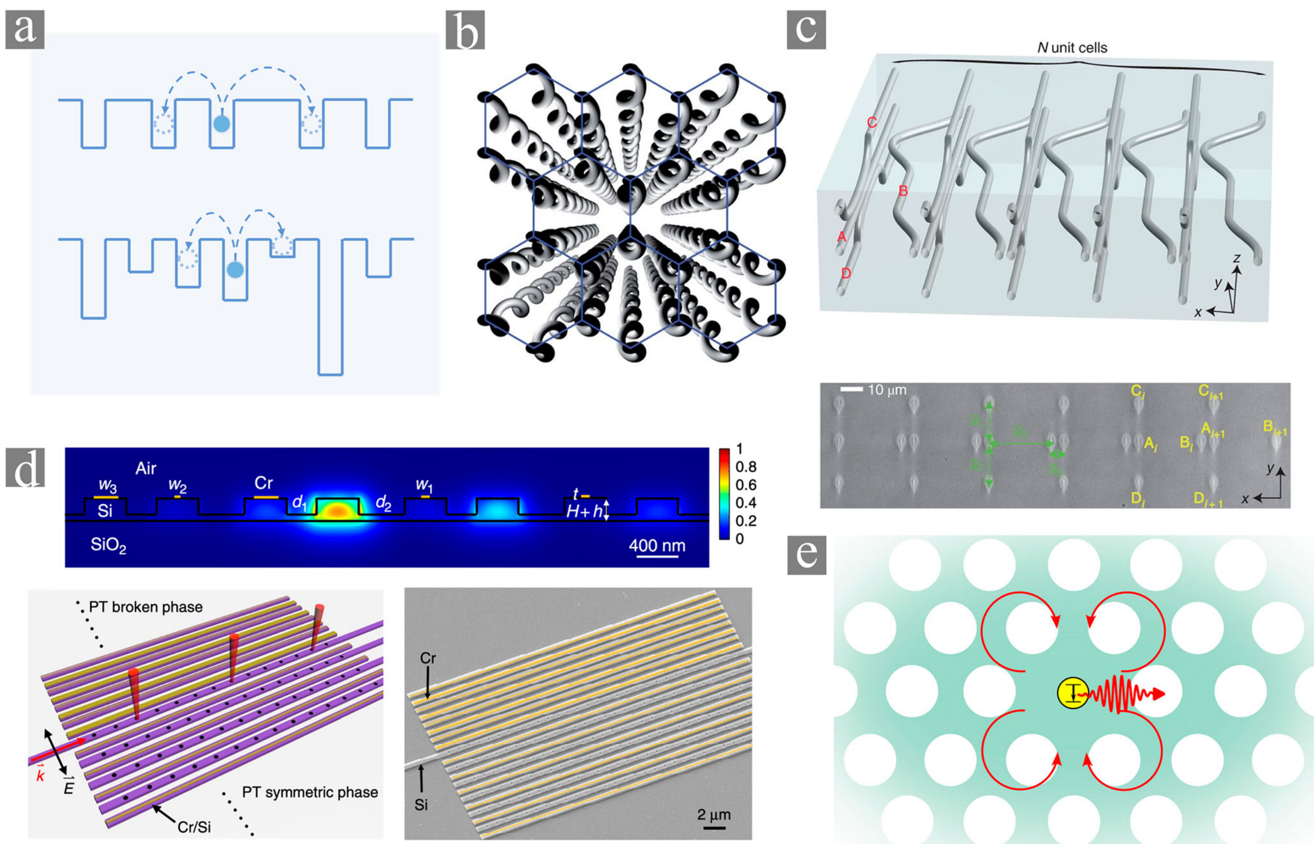
In addition to linear propagation, photonic waveguide arrays can exhibit complex dynamics due to nonlinear effects. When the intensity of light within the waveguides reaches a certain threshold, nonlinear phenomena such as self-phase modulation and soliton formation can occur. These effects can be described by introducing nonlinear terms into the coupled-mode equations, providing a rich avenue for the study of nonlinear optics in discretized systems. For a comprehensive exploration of the principles governing light propagation within photonic waveguide arrays, we kindly refer the readers to refs. 60,61.

Quantum states of light in topological waveguides

To maintain a focused perspective in this discussion, we will limit our exploration to systems that involve single or arrayed waveguides. This approach allows us to delve deeply into the specifics of these systems, examining their unique properties and applications without extending into

Box 2 | Tunability and control of photonic lattices

Photonic waveguide systems present considerable tunability across various parameters. Serving as the fundamental unit, a waveguide embodies two inherent characteristics: the hopping term and on-site potential, as depicted in (a). The modulation of the gaps between neighboring waveguides enables the adjustment of the hopping rate via evanescent coupling fields. Conversely, manipulation of the physical dimensions of the waveguide facilitates control over the on-site potential. By incorporating the propagation direction (*z*-axis) of photonic lattices, a helical structured waveguide is introduced to break *z*-reversal symmetry. This temporal modulation, as depicted in (b), facilitates the realization of one-way edge states propagating in photonic Floquet topological insulators[9], which has spurred experimental investigations into Floquet systems[140–142]. By leveraging the flexibility of 3D laser fabrication, waveguides can be arranged in a specialized geometry, which allows evanescent coupling to occur exclusively in a designated direction, see one example in (c) ref. 143. This operation is in line with non-Abelian wave physics and greatly enriches the classification of topological physics[144,145]. Another emerging research field to broaden topological photonics is to introduce the loss of Hermiticity, which describes energy exchanges with an open system. A crucial aspect of non-Hermitian Hamiltonians is the simultaneous presence of on-site gain and loss. However, certain quasi-PT-symmetric systems can be realized using passive photonic lattices with partly lossless and partly lossy structures, as depicted in (d)[146]. On-site losses are introduced by depositing chromium on top of waveguides, and it has been proved that this system exhibits identical evolution dynamics to that of a system with gain and loss, albeit with a global exponential damping factor.[147]. Last but not least, it is possible to interface a quantum emitter with nano-scale waveguide systems, opening up new possibilities to tailor light–matter interaction and enable novel quantum-electrodynamics experiments, for which the readers can refer to ref. 148.



(a) Schematic diagram of photonic waveguide systems with hopping terms and on-site modulation. (b) 2D honeycomb photonic lattice made of helical waveguides. (c) Schematic and microscope photograph of a two-dimensional photonic lattice to realize non-Abelian Thouless pumping. (d) Schematic of a waveguide array with Cr deposited on top to introduce loss and study non-Hermitian systems. (e) Single photon emitter interfaced with nanophotonic structures. Panels adapted with permission from (b), ref. 9; (c), ref. 143; (d), ref. 146; (e), ref. 148.

the broader and more complex landscape of other optical systems. The generation of single and entangled photon pairs are cornerstones for quantum communication and computing. Entangled photon pairs emerge primarily from non-linear optical phenomena like spontaneous four-wave mixing and spontaneous parametric down-conversion. On the other hand, on-demand single photons are generated from atomic-like transitions in quantum dots, color centers, and 2-D emitters. As the exploration in quantum photonics forges ahead, it becomes increasingly clear that addressing the efficiency and quality of entangled photon-pair sources, and the uniformity and purity of single-photon sources are pivotal challenges.

Surmounting these obstacles will not only enhance our understanding of the quantum world but also open avenues for more practical and scalable applications in quantum technologies.

Early theoretical studies highlighted the potential of photonic topological insulators to maintain the integrity of fragile multiphoton states in quantum walks[62], which is vital for applications like Boson sampling, a process known for its potential exponential speedup in certain algorithms. In waveguide systems, topological protection of the two-photon state against decoherence was demonstrated[63]. The study reveals that in the topologically nontrivial boundary state of a photonic chip, two-photon quantum-correlated states are effectively preserved, exhibiting high cross-correlation and a strong violation of the Cauchy–Schwarz inequality by up to 30 standard deviations. These findings highlight the robustness of topological protection against factors like photon wavelength difference and distinguishability. Moreover, the study in ref. 64 reports high-visibility quantum interference of single-photon topological states within an integrated photonic circuit, where two topological boundary states at the edges of a coupled waveguide array are brought together to interfere and undergo a beamsplitter operation. This process results in the observation of Hong–Ou–Mandel interference with a visibility of 93.1 ± 2.8%, demonstrating the nonclassical behavior of topological states. This significant achievement illustrates the practical feasibility of generating and controlling highly indistinguishable single-photon topological states. To confirm the resilience of topological biphoton states against disorder, the work in ref. 65 fabricated structures with varying levels of introduced disorder. The measured Schmidt number remains close to 1, underlined by the topology's assurance of a single localized mode. These results not only underscore the importance of quantum correlation robustness but also spotlight the potential advantages of topological methods in quantum information systems. Entanglement protection was also demonstrated in refs. 66,67. In the latter, the team demonstrates topological protection of spatially entangled biphoton states. Utilizing the SSH model, the system exhibits strong localization of topological modes and spatial entanglement between them under varying levels of disorder, underscores the topological nature of these entangled states. The topological protection was extended to systems with quasi-crystal structures and sawtooth lattice, the non-classical features are safeguarded against decoherence caused by diffusion in interconnected waveguides and from the environment noise disturbances[68,69]. Similar ideas were extended to the generation of squeezed light[70], a key component in quantum sensing and information processing. Due to the weak optical nonlinearity and limited interaction volume in bulk crystals, the study uses waveguide arrays to increase nonlinearity. The topologically protected pump light enables the waveguide lattice to operate effectively as a high-quality quantum squeezing device. In addition to path-entanglement, topological protection was realized for polarization-entangled photon pairs in a waveguide array lattice[71]. Additionally, in another waveguide-based system that utilizes valley photonic crystals (VPCs), topological protection of frequency entangled photons was realized[72]. The photon pairs were generated by four-wave mixing (FWM) interactions in topological valley states, propagating along interfaces between VPCs. Furthermore, theoretical studies showed that topological protection can be extended to dual degrees of freedom, specifically time and energy[73]. Such a demonstration highlights the potential of topologically protected quantum states in photonic systems, particularly for applications operating at telecommunication wavelengths.

In addition to photon pairs based on non-linear interactions, significant progress has been made in engineering the topological properties of photonic circuits hosting on-demand single photon sources and potentially solid-state optical memories. In a recent study[24], the authors successfully demonstrate a powerful interface between single quantum emitters and topologically robust photonic edge states, a significant achievement at the intersection of quantum optics and topological photonics. Utilizing a device composed of a thin GaAs membrane with epitaxially grown InAs quantum dots acting as quantum emitters, the team creates robust counter-propagating edge states at the boundary of two distinct topological photonic crystals. A key result of their experiment is the demonstration of chiral emission of a quantum emitter into these modes, confirming their robustness against sharp bends in the photonic structure. This research not only exemplifies the successful coupling of single quantum emitters with topological photonic states but also highlights the potential of these systems in developing quantum optical devices that inherently possess built-in protection. Moreover, the work in ref. 74 developed a chiral quantum optical interface by integrating semiconductor quantum dots into a valley-Hall topological photonic crystal waveguide, showcasing the interface's capability to support both topologically trivial and non-trivial modes. The convergence of nanophotonics with quantum optics has led to the emergence of chiral light–matter interactions, a phenomenon not addressed in conventional quantum optics frameworks. This interaction, stemming from the strong confinement of light within these nanostructures, results in a unique relationship where the local polarization of light is intricately linked to its propagation direction. This leads to direction-dependent emission, scattering, and absorption of photons by quantum emitters, forming the basis of chiral quantum optics. Such advancements promise novel functionalities and applications, including non-reciprocal single-photon devices with deterministic spin–photon interfaces[44]. The study showcases the potential of chiral quantum photonics in ref. 75. It successfully demonstrates that the helicity of a quantum emitter's optical transition determines the direction of single-photon emission in a glide-plane photonic-crystal waveguide. The implications of this research are vast, including the construction of non-reciprocal photonic elements like single-photon diodes and circulators.

Topological protection of quantum resources

The field of topological photonics, inspired by groundbreaking concepts in quantum mechanics and solid-state physics, promised a revolution in controlling light propagation in photonic systems. The notion of harnessing topological properties to create backscattering-immune waveguides presented a paradigm shift, particularly in developing efficient quantum resources and enhancing photonic system performances. In nanophotonic waveguides, the precision of fabrication is challenged by the occurrence nanometer-level imperfections along the etched sidewalls. These imperfections, significantly smaller than the fabricated unit-cell, for example, in photonic crystal waveguide systems, cast doubt on the efficacy of employing topological protection strategies for quantum resources[76]. The backscattering mean free path (ξ) is essential for assessing photonic waveguides against nanostructural imperfections. It marks the threshold between efficient transmission with minimal scattering and significant backscattering when waveguide length (L) exceeds ξ. Such a figure of merit is imperative for substantiating the advantages of topological over conventional transport at the nanoscale[77]. Recent experimental evidence in ref. 76, showed significant backscattering in valley-Hall topological waveguides despite record low-loss waveguides. The persistence of backscattering raises fundamental questions about our understanding of light–matter interaction in topologically structured photonic environments. This necessitates rethinking the materials and designs used in photonic quantum technologies, potentially shifting focus towards alternative mechanisms for achieving topological protection. Addressing these challenges requires exploring beyond conventional topological paradigms. This might involve investigating new classes of materials, such as magneto-optic systems, to break time-reversal symmetry at optical frequencies. Despite these challenges, topologically non-trivial systems with non-broken time-reversal symmetry have been shown to outperform topologically trivial ones for certain disorder strength[77]. Such structures can offer a viable foundation for novel quantum logic architectures, resource robustness, non-reciprocal photonic elements, and efficient spin–photon coupling[44,78,79] (Fig. 2).

Quantum topological photonics: Looking ahead

What next for topological quantum photonics? As the field of quantum topological photonics continues to mature, the journey ahead is lined with both challenges and opportunities[34,80–83]. Building on the foundation laid by pioneering research in this field, the future direction is poised to explore

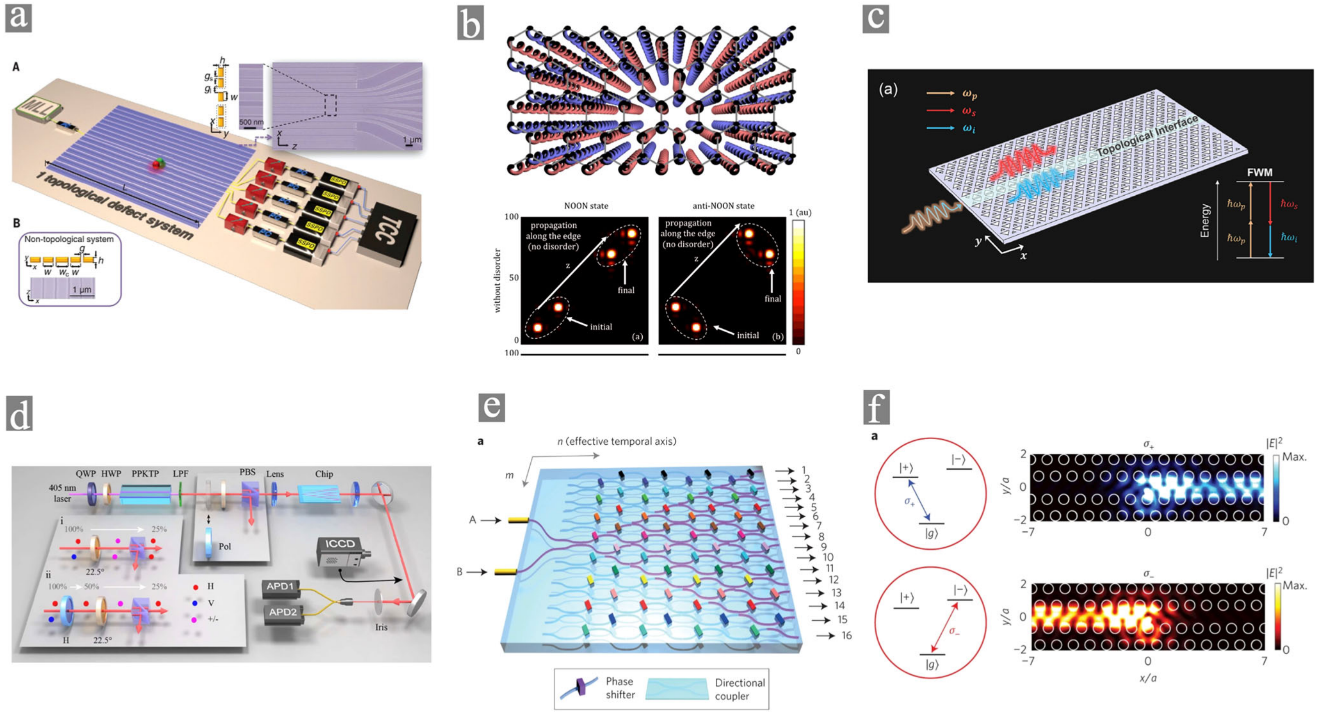


Fig. 2 | Topological protection of quantum resources. **a** Topological protection of biphoton states[65]. **b** Topological protection of path entanglement[62]. **c** Topological protection of continuous frequency entangled biphoton states[72]. **d** Topological protection of two-photon states against the decoherence in diffusion[63]. **e** Anderson localization of entangled photons in an integrated quantum walk[66]. **f** Topological light–matter interface[75]. Panels adapted with permission from refs. 62,63,65,66,72,75.

novel paradigms and technologies that could further revolutionize photonics and quantum information processing. One of the most promising frontiers is the development of active tuning and dynamic control mechanisms within topological photonic structures[84]. Current research has predominantly focused on passive systems, where the topological properties are fixed once fabricated. However, the integration of active materials or mechanisms that allow for real-time control of topological features can dramatically enhance the versatility of photonic devices, and create synthetic dimensions[85]. Such advancements could enable reconfigurable photonic circuits, adaptable computing architectures, and dynamic communication networks. For instance, integrating electro-optic or thermo-optic materials into topological waveguides could provide a means to dynamically tune the band structure, thus controlling the propagation and interaction of photons in these systems[86]. Additionally, incorporating magneto-optic materials into topological photonics offers a powerful approach to breaking time-reversal symmetry[87]. Hybrid integration could pave the way for devices that exploit magnetic fields to control photonic states[88]. The exploration of materials with strong magneto-optical responses at room temperature and their seamless integration into photonic chips will be crucial in this endeavor[89]. With regard to quantum sources, the challenge that remains is enhancing the efficiency and uniformity of quantum sources, such as single-photon emitters and entangled photon pairs. Efforts should be directed toward improving the coupling efficiency between quantum emitters and photonic structures, minimizing losses, and increasing the purity of quantum states[90]. Research in developing more efficient non-linear materials for photon pair generation, along with better fabrication techniques for quantum dots and other emitters, will be vital[91–94]. The integration of topological photonics with quantum optics and information processing has already demonstrated significant potential. The next step is to develop complex quantum photonic systems that leverage topological protection for enhanced performance and new functionalities, with careful investigation of the figures of merits, and to benchmark their superior performance to topologically trivial devices. On a more fundamental level, future research should also focus on discovering new topological phases and experimenting with a wider range of materials. The exploration of 2D materials, such as graphene and transition metal dichalcogenides, offers exciting prospects for hosting topologically protected states with unique properties and building systems that rely on the interplay between electronic and photonic states[78,95]. Lastly, it is crucial to address fundamental questions raised by recent experimental observations, such as the persistence of coherent backscattering in topologically protected systems. This will require a deeper theoretical understanding of light–matter interactions in topologically structured environments and might lead to the development of new theoretical models and simulation tools. Moreover, the fusion of non-Hermitian physics with topological insulators reveals a plethora of novel phenomena and offers more approaches to optical device design. By harnessing the intricate balance of gain and loss within photonic systems, non-Hermitian topological photonics paves the way for manipulating topological states in unprecedented manners. Recent advancements and applications include the manipulation of topological phase transitions and the skin effect[96]. Additionally, quantum topological time crystals represent a transformative advancement in the manipulation of temporal properties for photonic applications. It leverages the periodic modulation of material properties, which gives rise to dispersion relations characterized by bands separated by momentum gaps, resulting in a class of non-conservation energy states due to broken time-translation symmetry. Quantum topological time crystals are poised to enable exciting new devices, including detectors of entangled states and generation of cluster states[97].

Additionally, the concept of gain and time crystals can be combined, leading to amplified emission and lasing with narrowing radiation linewidth over time[98]. The research into such crystals, with loss/gain and temporal modulation, not only revisits the classical understanding of light–matter interaction but also proposes the intriguing concept of non-resonant, tunable lasers. These lasers, devoid of the traditional resonance requirements, can draw operational energy from the external modulation of the medium, presenting a versatile approach to laser design. Moreover, the study of strongly correlated photonic systems introduces a novel dimension to our understanding of quantum topological states. A standout achievement in this domain is the experimental realization of Laughlin states using light[99].

The control over light-matter interactions can have implications for different quantum technologies ranging from quantum computing to novel topological quantum devices.

In the rapidly advancing field of quantum topological photonics, the intersection of theoretical innovation and practical application paints a promising yet challenging future. This domain, rich with potential, stands at the forefront of revolutionizing information processing, communication technologies, and quantum computing, thanks to its predicted robustness against disturbances and its ability to manipulate light in novel ways. However, the path forward is not without its hurdles. Fabrication imperfections, scalability of systems, and the integration of quantum sources with topological structures remain significant challenges that demand meticulous attention and creative solutions. Additionally, the complexities of non-Hermitian dynamics, the realization of time crystals in practical settings, and harnessing the full potential of strongly correlated photonic systems require a deeper understanding and more sophisticated experimental techniques. Despite these challenges, the field of quantum topological photonics holds significant promise for advancing technology and science. As we continue to navigate its complexities, the potential for transformative breakthroughs remains vast, paving the way for a new era of photonic applications and discoveries.

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Competing interests
The authors declare no competing interests.

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