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Topological photonics
(Mini-review)

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Topological photonics has recently emerged as a novel approach to robust waveguiding and routing of light [1, 2]. It exploits engineered photonic structures with the properties analogous to electronic topological insulators (TIs) [3], which are insulating in their bulk but exhibit conducting states at the surfaces. Unusual manifestations inherent to topologically nontrivial states, including the ability of edge modes to overcome structural imperfections without back reflection, drive general interest in topological effects within photonics and optical communications.

Intriguing properties of TIs are rooted in the wavevector-space topology and the existence of abstract "holes" in the modes of the media in momentum space, similar to how a sphere is topologically distinct from a torus. Whenever a system can be characterised by a topological invariant with nonzero value, one can expect physical features that remain insensitive to a range of perturbations, giving rise to resilience in operation and disorder resistance.

Figure 1 shows the actual representative demonstrations of two-dimensional topological photonic systems in their historical sequence. Following a theoretical proposal by Raghu and Haldane [4], Wang et al. were first to implement the photonic counterpart of the quantum Hall effect, the seminal example of the topologically nontrivial phase, at microwave frequencies [5]. In their experiment, time-reversal (TR) symmetry was broken by the magnetic field applied in a square-lattice photonic crystal of gyromagnetic ferrite rods (Figs. 1a, b). The resultant band structure hosts a gapless chiral edge state that propagates around defects with back scattering significantly suppressed within the band gap frequency range shaded yellow in Fig. 1c. However, the path with preserved TR symmetry appears preferential in optics because magneto-optical response is weak at optical frequencies. TR-invariant topological phases were realised in lattices of coupled silicon ring resonators [6] (Figs. 1d, e), waveguide arrays [7] (Figs. 1f, g), and bianisotropic metamaterials [8]. Motivated by optical on-chip applications, the most recent realisations of topological phases in photonics have advanced to the nanoscale. For example, spin-polarized nanophotonic topological edge states were imaged via third-harmonic generation (Figs. 1h, i) in topological arrays of silicon nanopillars [9]. The high-quality-factor topological modes, including strongly confined corner states, can also be employed for nanolasing with improved stability and nontrivial radiation characteristics [10, 11].

Topological photonics is likely to continue to be a highly active and flourishing area of research for the next decade. It proves itself not only useful for classical light control but also promising for a variety of quantum optical applications [12]. Links are being established between topological photonics and other frontier topics, including bound states in the continuum [13], structured light, transformation optics, and leaky mode theory [14]. We anticipate harnessing topological photonic phases in nonlinear and quantum optics [2] will drive the cutting-edge developments in quantum computing and on-chip neuromorphic signal processing with ultrafast operation speed and low energy consumption.

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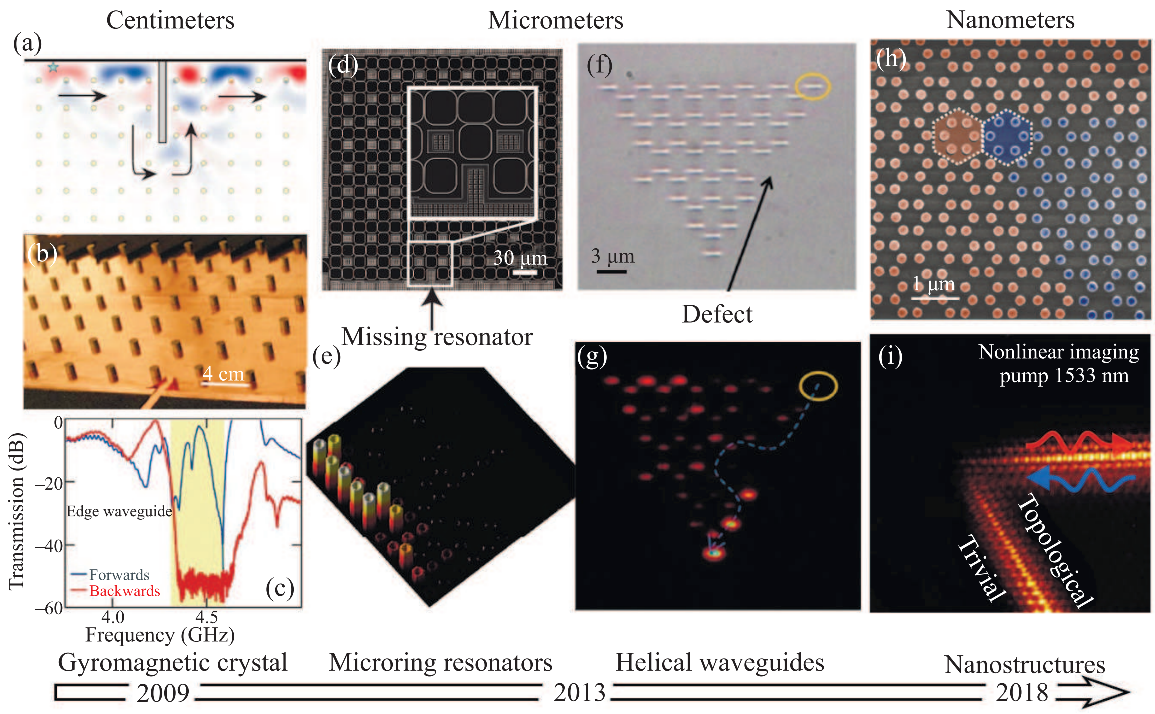

Fig. 1. (Color online) (a), (b) – Demonstration of back and side scattering suppression of the edge wave when a large obstacle is inserted in the array of magnetised ferrite rods emulating the quantum Hall topological phase; (c) – Measured spectra confirm unidirectional propagation in the edge waveguide at mid-gap frequencies. Blue and red curves represent forward and backward transmission, respectively. (d) – A fragment of the topological array of silicon ring resonators with one site-resonator deliberately removed; (e) – Topological protection is experimentally demonstrated as light traverses around the defect. (f), (g) – A triangle-shaped array of helical waveguides acts as a photonic topological insulator so that light excited at the corner (yellow circle) is guided along its surface and bypasses a defect, created by a missing waveguide (blue arrow). (h) – A top view of a sample and (i) experimental image of the third-harmonic generation from topological edge states in a metasurface composed of expanded (bluish) and shrunken (reddish) hexamers of silicon pillars on a glass substrate. Timeline with the milestone years is shown on the bottom. Adapted from [5–7, 9]

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