Disorder-Robust Nonlinear Light Generation in Topological Nanostructures

Sergey Kruk[1,*], Alexander Poddubny[1,2,3], Daria Smirnova[1], Ivan Kravchenko[4], Barry Luther-Davies[5], and Yuri Kivshar[1,2]

[1]*Nonlinear Physics Centre, Australian National University, Canberra ACT 2601, Australia,*
[2]*ITMO University, St Petersburg 197101, Russia,*
[3]*Ioffe Institute, St Petersburg 194021, Russia,*
[4]*Center for Nanophase Materials Sciences, Oak Ridge National Laboratory, Oak Ridge, TN, USA,*
[5]*Laser Physics Centre, Australian National University, Canberra ACT 2601, Australia*
E-mail address: sergey.kruk@anu.edu.au

Abstract: We observe topologically nontrivial nonlinear edge states of light in zigzag arrays of silicon nanoparticles. We image the edge states via the third-harmonic generation and demonstrate their robustness against disorder and structural perturbations.
OCIS codes: (160.4236) Nanomaterials; (310.6628) Subwavelength structures, nanostructures (190.0190) Nonlinear optics

1. Introduction

Topological photonics has emerged as a route to robust optical circuitry protected against disorder [1] and now includes demonstrations of topologically protected lasing [2] and single-photon transport [3]. Most of the topological photonic systems explored so far have been based on waveguide geometries, and the size of their building blocks is therefore larger than the wavelength of light. A zigzag array of coupled nanoresonators has emerged as the first nanoscale system with non-trivial topological states of light [4], as has been observed experimentally in the regimes of linear scattering [5] and lasing from excitonic–polaritonic nanocavities [2].

Recently nonlinear optical topological structures have attracted special theoretical interest as they enable tuning of topological properties by a change in the light intensity and can break optical reciprocity to realize full topological protection. In our system, we use the intrinsic nonlinearity of silicon to generate a third-harmonic signal from such an array. The presence and interplay of Mie resonances of both electric and magnetic origin lead to an enhancement of the nonlinear light generation. In addition, topological localization of the electric field at the edge of the array provides multifold enhancement of the nonlinear generation efficiency, which is also robust against perturbations.

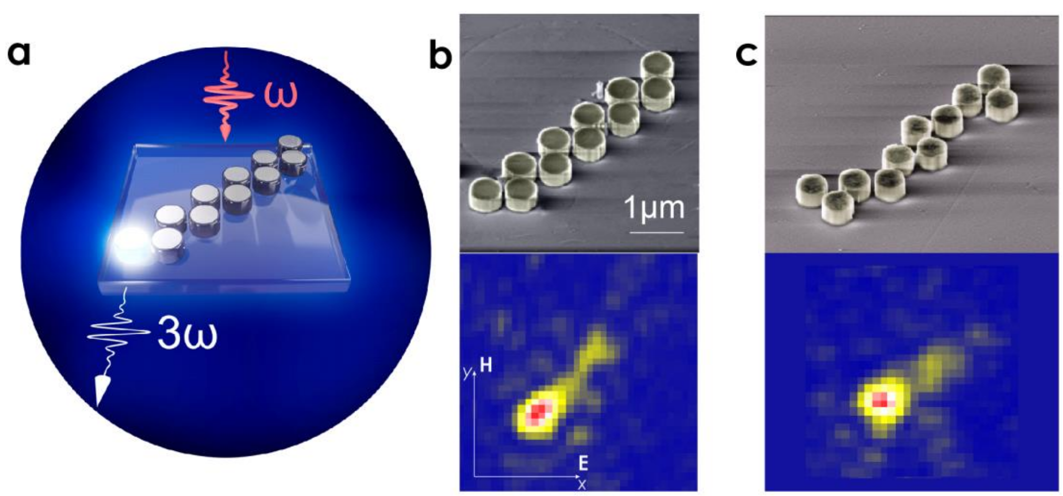

Fig. 1. Nonlinear parametric generation of light from topological zigzag arrays. (a) Concept of THG in a zigzag array of nanoresonators. A beam of light with the frequency ω illuminates the array, and the nonlinear signal at the 3ω frequency is generated from its edge. (b,c) SEM images (top) and measured distribution of the third-harmonic field (bottom) of 11-nanodisk zigzag arrays of Mie-resonant dielectric nanodisks with and without introduced disorder.

2. Results and Discussions

Figure 1a presents the concept of nonlinear parametric generation of light driven by topological edge states. The formation of the edge states is described by a polarization-enriched generalized Su–Schrieffer–Heeger (SSH)-type model with a gauge-independent Z_2 topological invariant [4].

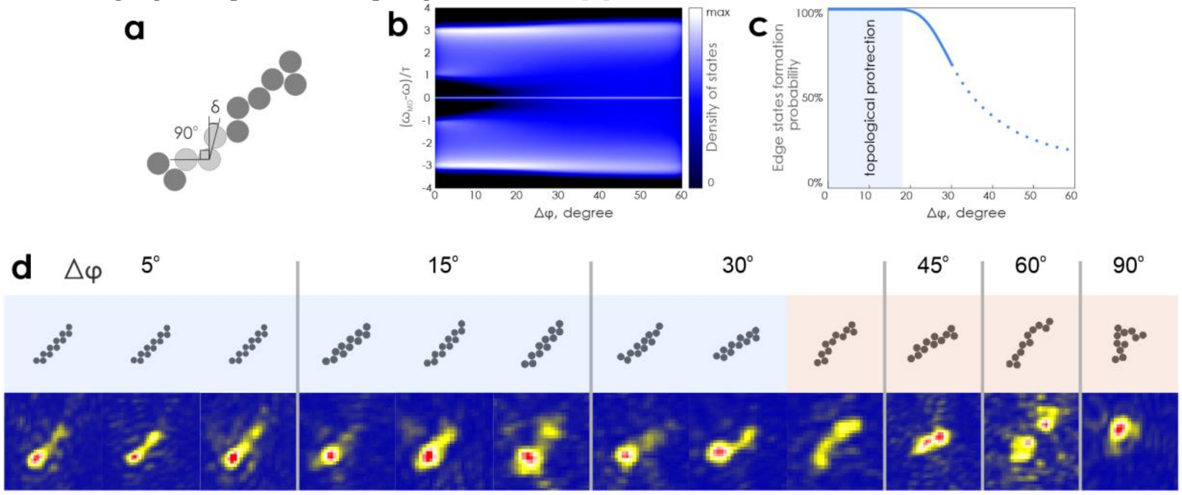

Fig. 2. Topological protection of the edge states against disorder. (a) A random distortion to the zigzag angles $-\Delta\varphi \leq \delta \leq \Delta\varphi$. (b) Photon DOS versus disorder parameter $\Delta\varphi$. (c) Analytically calculated probability of edge states formation versus $\Delta\varphi$. The dashed part corresponds to larger $\Delta\varphi$ where the accuracy of the analytical model decreases. (d) A representative set of experimentally observed distributions of THG in disordered zigzag chains. The edge states were observed for all cases where $\Delta\varphi < 20°$.

Example of the experimentally studied disorder-robust topological zigzag array of nanodisks are shown in Figs. 1b,c. The nanodisks are 510 nm in diameter and 300 nm in height and are spaced with a gap of 20 nm. The samples were fabricated using electron beam lithography. We excited them at 1590 nm using femtosecond pulses from an optical parametric amplifier pumped by a mode-locked laser. A spatial map of the third harmonic field in the 11-nanodisk-long zigzags array are shown in Fig. 1c.

We proceed with a systematic study of the robustness of the topology-driven THG against disorder. We fabricate a number of arrays with randomly generated bond angles between the disks as illustrated in Fig. 2a. The robustness of the edge states can be clearly seen in the calculated disorder-averaged spectra of the photon density of states (DOS) versus the disorder parameter $\Delta\varphi$ (Fig. 2b). The edge states are topologically protected up to the point when the spectral gap collapses. We next calculated the field distributions excited in 10^4 random cases of disordered zigzags and confirmed that, while the spectral gap is open, the hot spots at the edges are always present. Once the gap is quenched, the edge states are no longer topologically protected, and the probability that they form drops rapidly (Fig. 2c). We verified these predictions experimentally by fabricating and measuring a number of disordered zigzags with $\Delta\varphi$ ranging from 5° to 90°. Representative cases are shown in Fig. 2d. In our experiments, for $\Delta\varphi < 20°$, the edge states were observed in all cases. For $\Delta\varphi > 20°$, the number of arrays supporting edge states drops rapidly as $\Delta\varphi$ increases.

3. Conclusion

We have suggested novel opportunities for active and nonlinear topological photonics with dielectric nanoparticles by demonstrating enhanced and robust light generation at topological edge states. Our findings open the way to nonlinearity-induced topological effects.

Acknowledgements. We acknowledge a support from the Air Force Office of Scientific Research (project FA2386-16-1-0002) and the Strategic Fund of the Australian National University. A part of this research was conducted at the Center for Nanophase Materials Sciences, which is a DOE Office of Science User Facility.

4. References

[1] L. Lu, J.D. Joannopoulos, and M. Soljačić, "Topological states in photonic systems," Nature Physics **12**, 626–629 (2016).
[2] P. St-Jean et al. "Lasing in topological edge states of a one-dimensional lattice", Nature Photonics **11**, 651–656 (2017)
[3] S. Barik et al. "A topological quantum optics interface", Science **359**, 666 (2018)
[4] A. Poddubny et al., "Topological Majorana states in zigzag chains of plasmonic nanoparticles", ACS Photonics **1**, 101 (2014).
[5] S. Kruk et al. "Edge states and topological phase transitions in chains of dielectric nanoparticles", Small. **13**, 1603190 (2017).