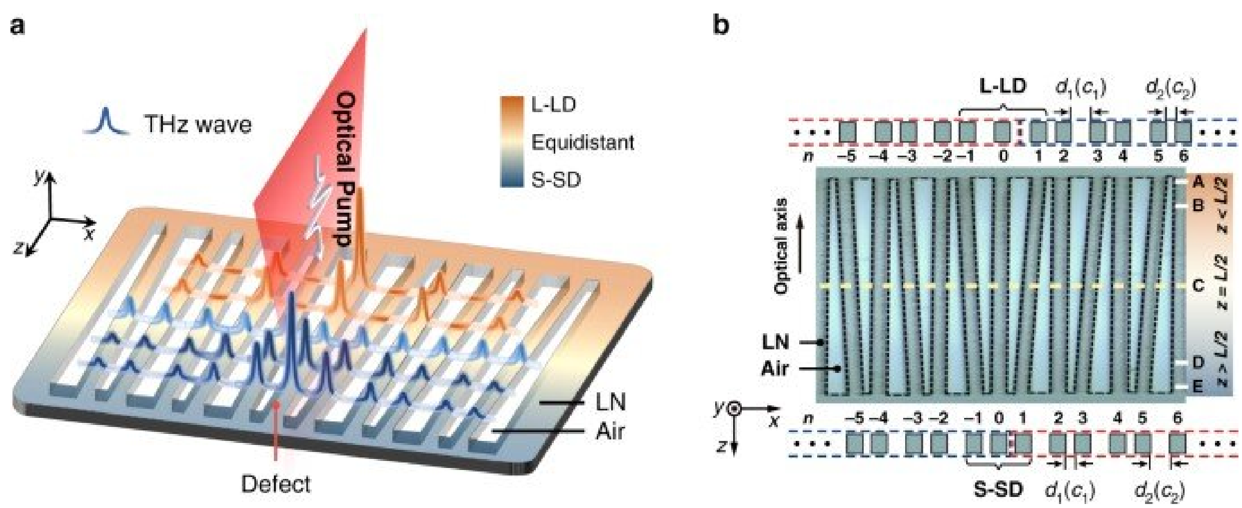
Topologically tuned terahertz on a nonlinear photonic chip

June 1 2022, by Thamarasee Jeewandara



Experimental realization of topologically controlled THz localization. (a) Illustration of nonlinear generation and confinement of THz-waves in an SSH-type microstructure. The LN structure undergoes a transition from L-LD, through equidistant, to S-SD regions along the +z-axis, illustrated by colors shaded from orange into blue. The polarization of the THz electric field and that of the optical pump beam are all along the direction of the LN crystalline axis (z-axis). (b) Microscope image of the LN array structure fabricated by fs-laser writing. The thickness of the LN chip is 50 μm in the y-direction. The total length of the microstructure along the z-direction is L=6mm. d1 and d2 are the spacings between neighboring LN stripes corresponding to the coupling coefficients c1 and c2, respectively. At the dashed yellow line, z = L/2 and d1 = d2 = 55 μm, which leads to an equidistant structure. Credit: *Light: Science & Applications* (2022). DOI: 10.1038/s41377-022-00823-7

Compact terahertz functional devices are highly useful for high-speed wireless communication, biochemical sensing and non-destructive inspection. However, controlled terahertz generation, alongside transport and detection is challenging for chip-scale devices, due to low coupling efficiency and absorption losses. In a new report now published in *Nature: Light Science & Applications*, Jiayi Wang, Shiai Xia and Ride Wang and a team of researchers in physics, biophysics, and nonlinear photonics, at the Nankai University, China and INRS-ENT, Canada, generated nonlinear and topologically tuned confinement of terahertz waves in an engineered lithium niobate chip. The team experimentally measured the band structures to provide direct visualization of the terahertz localization in the momentum space. The outcomes provide new possibilities to realize terahertz integrated circuits for advanced photonic applications.

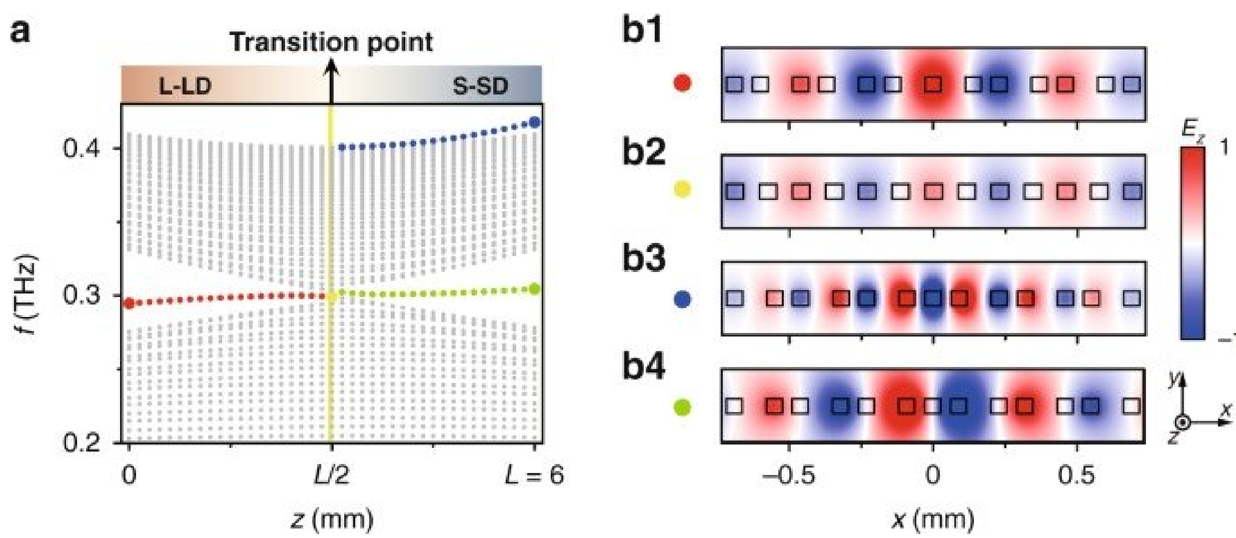
Tuning terahertz on a lithium niobate photonic chip

The development of reliable terahertz technology is primarily driven by a high demand for applications including wireless communications

signal processing and biosensing, as well as non-destructive evaluation. The lack of integrated functional devices in the terahertz range have, however, limited their applications, and it is challenging to guide terahertz wavelengths due to losses arising from critical features of the spectrum. Researchers have led tremendous efforts to explore diverse designs and approaches for terahertz sources via a variety of platforms, including metamaterials, nonlinear metasurfaces, plasmonic waves and wave mixing in ionic crystals and time-domain integration of terahertz pulses.

In this work, Wang et al proposed and developed a scheme for nonlinear generation and topologically tuned confinement of terahertz waves to fully realize the phenomenon on a single lithium niobate photonic chip.

The process relied on a photonic microstructure containing lithium niobate waveguide stripes that could undergo topologically trivial and nontrivial transitions. The team used [femtosecond-laser writing technology](#) to develop the construct with a topological defect at the central interface. They measured the terahertz field via pump-probe experiment to show tunable confinement along the chip, relative to the variation of the geometry of the photonic structure. The results provided a clear indication to terahertz-wave confinement as a result of topological protection.

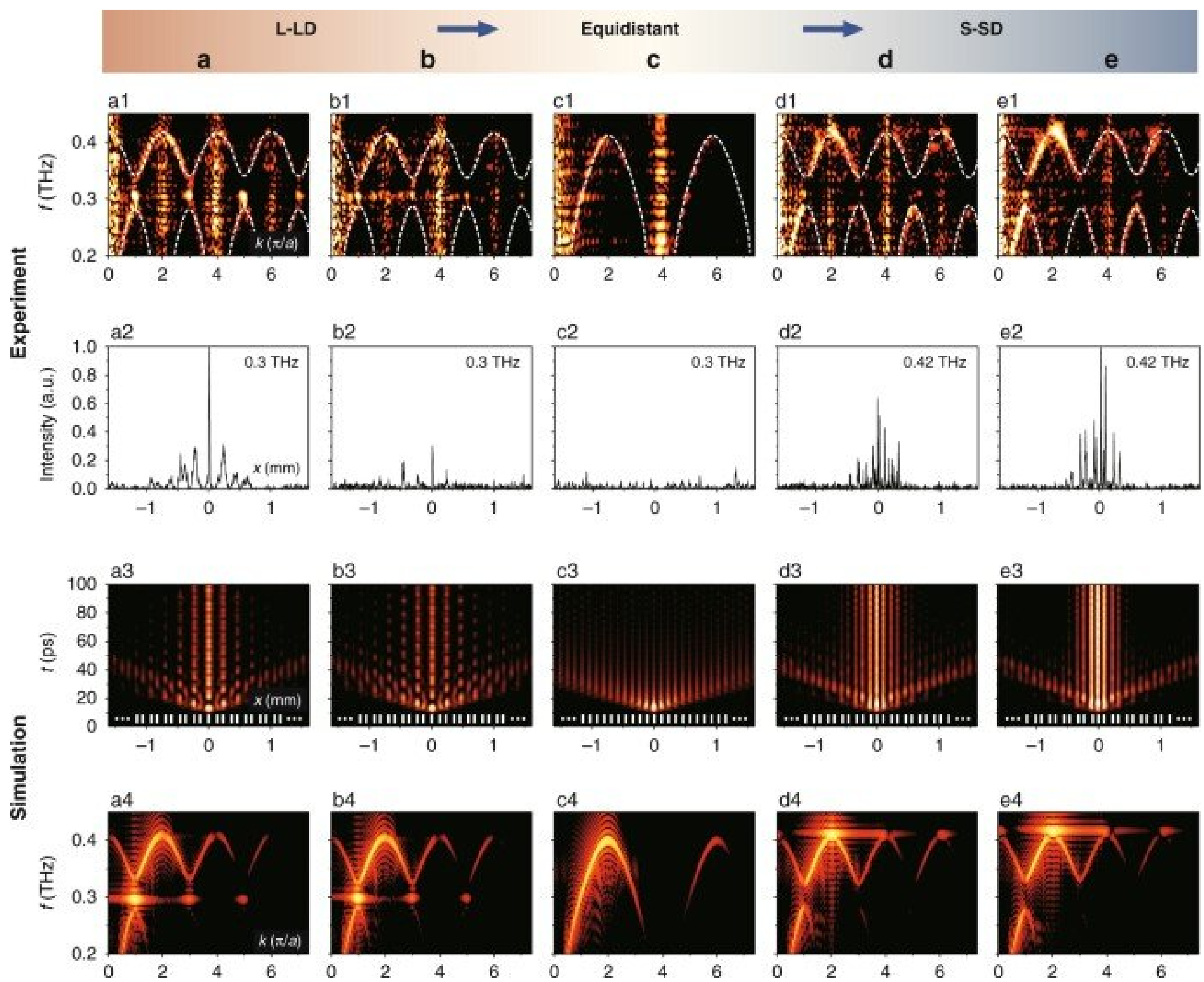


Eigenvalues and representative eigenmode distributions in the SSH-type LN topological structure. (a) Calculated eigenvalue distribution of the microstructure along the z-axis. The yellow line represents the equidistant structure at z = L/2 (d1 = d2 = 55 µm), which marks the phase transition point. The left side of the yellow line (z L/2) indicates the S-SD region, where topologically nontrivial and trivial defect modes are marked by green and blue dots, respectively. Gray dots represent the bulk modes. b1 Topological defect mode around 0.3 THz in the L-LD structure at z = 0. b2 The mode around 0.3 THz in the equidistant structure at z = L/2. b3, b4 Topological trivial mode around 0.42 THz (b3) and nontrivial mode around 0.3 THz (b4) in the S-SD structure at z = L. Credit: *Light: Science & Applications* (2022). DOI: 10.1038/s41377-022-00823-7

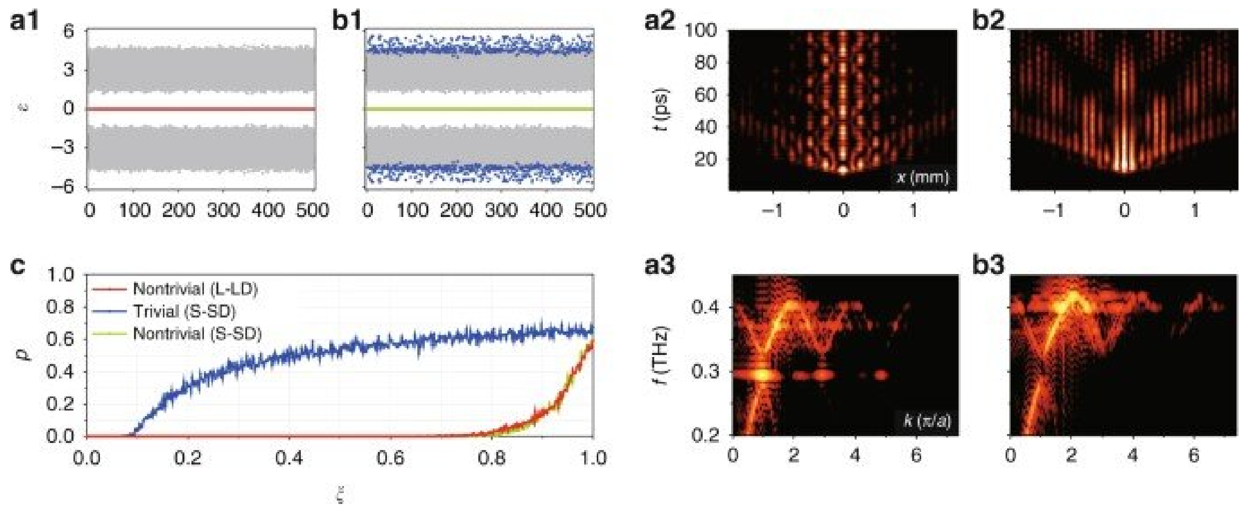
Terahertz generation on a chip

In physics, a standard technique for terahertz wave generation is based on optical rectification that can be induced via femtosecond laser pulses in second-order non-linear crystals. In the past four decades, scientists had developed a range of methods to improve terahertz generation efficiency, to activate a narrow terahertz bandwidth, and decrease the frequency decay in lithium niobate crystals. Researchers had also generated tunable terahertz pulses in nonlinear lithium niobate crystals via ultrashort laser pulses. Rapid enhancements in the field have led to new methods for THZ-wave localization and confinements. Wang et al employed a Su–Schrieffer–Heeger lattice-type photonic lattice on a lithium niobate chip to achieve tunable topological terahertz wave localization. The lattice provided a prototypical topological model with widespread demonstrations in photonics and plasmonics. Such models were previously applicable to generate robust, entangled photon pairs, to enhance nonlinear harmonic generation, realize topological lasing, and non-Hermitian topological states, aside from the terahertz wavelength regime.

To realize the proposed terahertz field manipulation, Wang et al performed a series of experiments, with a typical pump-probe setup. During the experiments, the team used a femtosecond pump beam to generate terahertz waves confined the evolving waves within the chip instead of free space. The team extended the scheme to include integrated topological circuits in compact terahertz devices. They detected the waves by using a time-resolved imaging method, based on a phase contrast imaging method to monitor the refractive index change induced by terahertz waves. The outcomes indicated a topological defect, which was in good agreement with the calculations. The results clearly showed how the generated terahertz waves can be strongly confined near the center defect of the construct, away from the transition point. Wang et al corroborated the outcomes with numerical simulations, which were in good agreement.



Experimental (top two rows) and numerical (bottom two rows) demonstrations of topologically controlled THz confinement in the LN chip from L-LD, through equidistant, to S-SD regions of the wedge-shaped SSH photonic lattice. (a–e) correspond to locations (A–E) marked in Fig. 1b. a1–e1 Measured spectra at the corresponding positions. a2–e2 Energy distribution of the modes showing different confinement of the generated THz waves in the LN chip. a3–e3 Simulated x−t diagrams showing the THz waves evolution in different regions, where a4–e4 are the corresponding spectra. The lattice sites are illustrated by white tick marks in a3–e3, and a in (a1, a4) is the lattice constant for the corresponding L-LD structure. Credit: *Light: Science & Applications* (2022). DOI: 10.1038/s41377-022-00823-7



Distinction between topologically nontrivial and trivial defect modes under chiral perturbations. (a1) Calculation of the eigenvalue distribution ε under 500 sets of off-diagonal perturbations in the L-LD structure. The red dots (forming a line) represent the eigenvalues associated to the topological mode and the gray dots show the distribution of the bulk modes. (a2) Simulation of the x−t diagram for the central defect excitation under perturbations. (a3) The corresponding spectrum of (a2). b1–b3 have the same layout as (a1–a3) but for the S-SD structure, where green and blue dots denote nontrivial and trivial defect modes, respectively. c Plot of p versus perturbation strength ξ, where p=nbulk/nall, with nbulk defined as the number of perturbation sets that result in coupling of the trivial defect mode with the bulk modes and nall as the total number of perturbation sets (in this case nall=500). Red and green lines illustrate the nontrivial modes in the L-LD and S-SD structures, respectively, while the blue line is for the trivial defect mode in the S-SD structure. Credit: *Light: Science & Applications* (2022). DOI: 10.1038/s41377-022-00823-7

Outlook

In this way, Jiayi Wang, Shiai Xia and Ride Wang developed a scheme for nonlinear generation of topologically tuned terahertz wave confinement on a single photonic chip. The theory was in good agreement with the experimental observations to substantiate the distinctive features of terahertz topological states. The work provides a flexible and convenient platform to tune the confinement and topological properties of terahertz waves on demand, to open new avenues to implement versatile, stable and compact terahertz photonic integrated circuits, for a variety of applications, including future topology-driven photonic technology.

More information: Jiayi Wang et al, Topologically tuned terahertz confinement in a nonlinear photonic chip, *Light: Science & Applications* (2022). DOI: 10.1038/s41377-022-00823-7

Tadao Nagatsuma et al, Advances in terahertz communications accelerated by photonics, *Nature Photonics* (2016). DOI: 10.1038/nphoton.2016.65