

Low-loss terahertz topological transmission in a silicon based ridge waveguide platform

Jiayang Qi (齐佳扬)¹, Entao Wang (王恩涛)¹, Jingya Xie (谢静雅)¹, Liang Qiu (邱亮)¹, Alexander P. Shkurinov³, Yiming Zhu (朱亦鸣)¹, Songlin Zhuang (庄松林)¹, and Lin Chen (陈麟)^{1,2*}

¹Shanghai Key Lab of Modern Optical System, University of Shanghai for Science and Technology, Shanghai 200093, China

²Shanghai Institute of Intelligent Science and Technology, Tongji University, Shanghai 200092, China

³Faculty of Physics and International Laser Center, Lomonosov Moscow State University, Moscow 119991, Russia

*Corresponding author: linchen@usst.edu.cn

Received July 4, 2025 | Accepted September 24, 2025

Extending the terahertz (THz) silicon based ridge waveguide platform to THz asymmetric topological pumping remains unexplored due to theoretical deficiency and severe coupling inefficiency, which hinder practical deployment for potential THz on-chip 6G applications. Here we experimentally demonstrate asymmetric topological pumping in a silicon based terahertz ridge waveguide array operating over 159–171 GHz. A four-channel Rice-Mele (RM) configuration with modulated waveguide widths and spacings enables robust unidirectional transport with over 15 dB contrast across 12 GHz. The device established a CMOS-compatible, broadband, and robust platform for integrated THz photonic circuits.

Keywords: terahertz photonics; topological pumping; silicon ridge waveguide; nonreciprocal transport; integrated photonic circuits.

DOI: [10.3788/COL202624.021303](https://doi.org/10.3788/COL202624.021303)

1. Introduction

Terahertz (THz) technology, spanning 100 GHz to 10 THz, bridges the microwave-infrared gap and offers unique features such as deep penetration, high spatial resolution, and ultra-wide bandwidth, enabling emerging applications like high-speed wireless communications, nondestructive sensing, security imaging, and biomedical diagnostics^[1–4]. However, practical THz deployment is hindered by bulky, discrete optical and electronic components, e.g., couplers, lenses, and splitters, which restrict system scalability and integration. Silicon based THz integrated circuits (THz ICs) offer a compelling solution. High-resistivity silicon (HR-Si) exhibits low THz propagation loss and is fully compatible with CMOS fabrication, enabling monolithic integration of complex photonic-electronic systems^[5–13]. Among THz photonic components, silicon ridge waveguides are notable for their low-loss confinement, small footprint, and CMOS compatibility. Demonstrated applications include on-chip THz ridge resonators with Q factors up to 2839 at 218 GHz^[14], differentiators for signal processing^[15,16], sensors for particle distance estimation^[17], vortex beam emitters for radar detection^[18], and isolators^[19]. Yet, achieving broadband, fabrication-tolerant THz power coupling remains a major challenge. Conventional evanescent and adiabatic couplers are highly sensitive to dimensional variations, which is problematic at THz frequencies where tolerances exceed tens of micrometers.

Topological photonics, leveraging invariants such as Chern numbers and Zak phases, provides a promising path to robust light transport immune to disorder^[5–7]. In particular, Thouless pumping supports quantized adiabatic edge-state transport via dynamic modulation^[20–22]. Microwave experiments recently showed that nonparaxiality can induce asymmetric pumping via next-nearest-neighbor coupling^[20], a mechanism beyond standard coupled-mode theory. However, extending this approach to THz frequencies on CMOS-compatible silicon platforms remains unexplored due to theoretical deficiency, severe coupling inefficiency, and fabrication sensitivity, which hinder practical deployment for potential THz on-chip 6G applications.

In this work, we demonstrate asymmetric topological pumping in a silicon THz ridge waveguide array and experimentally verified this effect. A four-waveguide structure based on the RM model with periodic modulation of widths and spacings introduces controlled asymmetry. Coupled-mode theory and full-vector Helmholtz modeling reveal that nonreciprocity originates from nonparaxial CW coupling. Experimental results from 159–171 GHz show > 15 dB directionality, < −2 dB insertion loss, ~12 GHz bandwidth, and tolerance to ±50 μm fabrication deviations. We note that the existing topological transmission in THz range suffers from large ohmic loss induced by metals (spoof SPPs platform)^[23] and sensitive transmission and manipulation due to defects^[24] (silicon photonic crystals

platform). The advantage of this work is that we demonstrate low-loss, scalable, robust asymmetric topological pumping in a silicon THz ridge waveguide array. The Thouless pump mechanism can further be used in the design of a power splitting and splitting device in THz IC Systems, offering a path toward scalable, robust, and functionally diverse integrated THz photonic circuits.

2. Methods

2.1. Model

To capture the topological pumping mechanism, we adopt a multi-scale approach bridging effective Hamiltonian theory. The RM model offers a canonical framework for realizing one-dimensional Thouless pumping. To model the system, we start from the Helmholtz equation

$$i \frac{\partial \varphi}{\partial z} - \frac{1}{2kn_0} \frac{\partial^2 \varphi}{\partial z^2} = H\varphi, \quad (1)$$

where H is the Helmholtz Hamiltonian, $n_0 = 1$ (air), $k = \omega/c$, and φ is the electric field amplitude. This leads to the effective Hamiltonian form

$$H_{\text{eff}} \approx H - \frac{1}{2\kappa n_0} H^2, \quad (2)$$

where the second term accounts for nonparaxial effects and introduces the cross waveguide (CW) coupling. For a width-modulated ridge waveguide array, the effective Hamiltonian reads^[25]

$$H_{\text{eff}} = \left[\sum_{i=1}^N \beta_i \cdot a_i^\dagger a_i + \sum_{i=1}^{N-1} \kappa_{i,i+1} \cdot a_i^\dagger a_{i+1} \right] + \sum_{i=1}^{N-2} \kappa_{i,i+2} \cdot a_i^\dagger a_{i+2} + \text{H.C.}, \quad (3)$$

where β and $\kappa_{i,j}$ are modulated sinusoidally along x . This creates a closed loop in parameter space, whose winding number characterizes the topological pumping behavior.

For a constant-width array, the CW coupling is negligible, and the Hamiltonian simplifies to the near waveguide (NW) coupling only:

$$H = \sum_{i=1}^N \beta_i \cdot a_i^\dagger a_i + \sum_{i=1}^{N-1} \kappa_{i,i+1} \cdot a_i^\dagger a_{i+1} + \text{H.C.} \quad (4)$$

This simplified model serves as a control to isolate the role of nonparaxial effects and CW coupling in enabling asymmetric topological transport. Detailed derivation can be found in Supplement 1 Section 1.

2.2. Device designs

Based on the RM model, we designed and fabricated a silicon ridge waveguide array with periodic modulation of waveguide width along the propagation direction, as illustrated in Fig. 1(a). The four-waveguide configuration represents the minimal lattice capable of supporting a topologically nontrivial edge mode, while allowing clear spatial separation between input and output channels. This compact design facilitates direct observation of asymmetric edge-to-edge transport, minimizes fabrication complexity, and enhances simulation accuracy in the THz regime. The modulation was implemented by varying both waveguide width W_n and inter-waveguide gap G_n , enabling investigation of their impact on light propagation. A reference array with constant waveguide width and identical geometric layout (except for the width modulation) was also fabricated, as shown in Fig. 1(b), to isolate the influence of width variation. Both arrays share the same waveguide height (420 μm), base thickness (80 μm), array

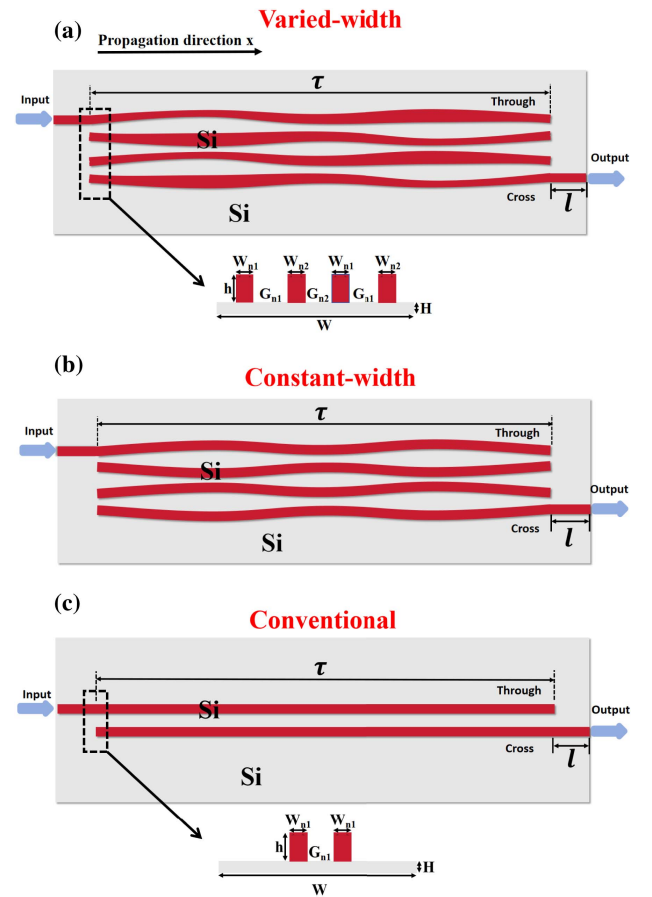


Fig. 1. Schematic diagrams of silicon ridge waveguide structures, with waveguides labeled 1 to 4 from top to bottom. (a) A four-channel waveguide array with periodically varied widths and spacings based on the RM model. (b) A constant-width waveguide array with identical bending trajectories as in (a), serving as a control configuration. (c) A conventional straight waveguide array with two uniform-width channels and fixed spacing. Insets depict the corresponding cross-sectional geometries and dimensional parameters for each configuration.

width (6.6 mm), and total length (50 mm), with input/output ports defined at waveguides 1 and 4. Each port connects to a 5 mm straight section to ensure efficient coupling. In addition, a conventional waveguide pair with straight channels, uniform width, and fixed spacing, shown in Fig. 1(c), was implemented as a baseline without curvature or modulation.

In both arrays, the first and third waveguides follow a cosine trajectory along the x -direction, with their y -position defined as $y = A_0 \cos(2\pi x/\tau)$, where $A_0 = 120 \mu\text{m}$ is the amplitude. The second and fourth waveguides are phase-shifted by π : $y = A_0 \cos(2\pi x/\tau + \pi)$. In the modulated-width array [Fig. 1(a)], the widths of waveguides 1 and 3 vary as $W_{n1} = W_0 - a \cdot \sin(2\pi x/\tau)$, and waveguides 2 and 4 follow $W_{n2} = W_0 + a \cdot \sin(2\pi x/\tau)$, where $W_0 = 300 \mu\text{m}$, and $a = 100 \mu\text{m}$. This modulation results in periodic variation of the inter-waveguide gaps: $G_{n1} = G + 2A_0 \cos(2\pi x/\tau)$, $G_{n2} = G - 2A_0 \cos(2\pi x/\tau)$, where $G = 300 \mu\text{m}$ and $G_{n3} = G_{n1}$, as shown in Fig. 1(a). These variations enable controlled study of spatial modulation effects on coupling and propagation. In the constant-width array [Fig. 1(b)], all waveguides retain fixed width W_0 , while the gap modulations G_{n1} and G_{n2} follow the same expressions. This serves as a reference for isolating the impact of width modulation.

The propagation constant (β) is sensitive to the waveguide width (w), with the propagation constant increasing as the waveguide width grows. Detailed discussion can be found in Supplement 1 Section 2. By introducing a sinusoidal modulation to the waveguide width, we can load the potential energy term onto the propagation constant β , allowing for an explicit control of light transport within these waveguides. We model this relationship as $\beta_i(x) \approx \beta_0 + (-1)^i \delta_\beta \sin(2\pi x/\tau)$, where $\beta_0 \approx 0.0078 \mu\text{m}^{-1}$ represents the base propagation constant, and $\delta_\beta = 0.001 \mu\text{m}^{-1}$ accounts for the variations due to structural changes. We also compare two silicon ridge waveguides: one with constant width and one with spatially varying width along a curved trajectory. Both waveguides exhibit high transmission efficiency. The coupling coefficient κ between two ridge waveguides of width $W_0 = 300 \mu\text{m}$ is also analyzed. Increasing G reduces κ due to weaker evanescent field overlap. Both waveguides maintain transmission losses around 0.001 dB/mm . The curved waveguide's gradual width variation does not degrade performance and can be utilized to control mode evolution, reduce backscattering, and suppress higher-order modes. Detailed discussion can be found in Supplement 1 Section 3.

Figure 2(a) (left) shows a four-waveguide array with spatially varied widths along the propagation direction, while the right panel presents the calculated coupling coefficients: $k_{1/2, \text{CW}}(x)$ for center waveguides and $k_{1,2}(x)$ for neighboring waveguides. The CW coupling is consistently weaker due to reduced mode overlap caused by the width modulation. For comparison, Fig. 2(b) depicts a uniform-width array and the corresponding $k_{1,2}(x)$, which follows a similar trend in both cases, indicating that NW coupling is mainly determined by waveguide spacing. In contrast, the spatially modulated CW coupling introduces a tunable asymmetry, acting as a synthetic gauge potential. This

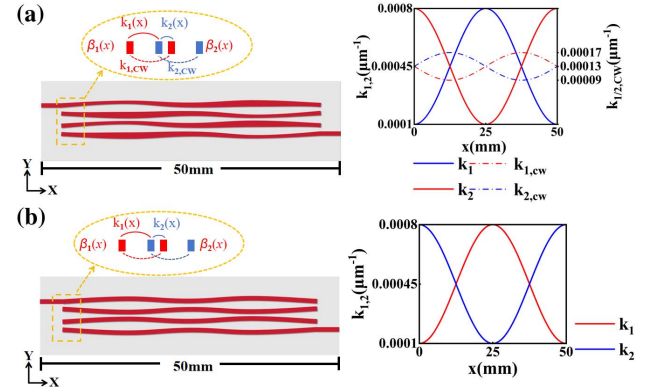


Fig. 2. (a) [left] Ridge waveguide array with varying width, showing propagation constants $\beta_1, \beta_2(x)$, NW coupling coefficients $k_1, k_2(x)$, and CW coupling coefficient $k_{1/2, \text{CW}}(x)$. [right] Variation of $k_1, k_2(x)$ and $k_{1/2, \text{CW}}(x)$ with respect to the waveguide position x . (b) [left] Ridge waveguide array with constant width, showing propagation constants $\beta_1, \beta_2(x)$, and NW coupling coefficients $k_1, k_2(x)$. [right] Variation of $k_1, k_2(x)$ with respect to the waveguide position x .

enables directional coupling and supports nontrivial transport phenomena such as adiabatic mode steering and topological pumping via engineered variations in waveguide width or index.

The band structure analysis reveals distinct spectral differences between the constant-width Hamiltonian H and the effective Hamiltonian H_{eff} for the varied-width configuration. As shown in Fig. 3(a), H exhibits a symmetric eigenvalue spectrum with two boundary bands embedded in the central bandgap, corresponding to edge-localized states. In contrast, Fig. 3(b) shows that H_{eff} yields an asymmetric spectrum: the conduction band expands, the valence band compresses, and the red boundary band merges with the valence band. This indicates a breakdown of the adiabatic separation between edge and bulk states, leading to asymmetric topological transport. The spatial modulation of waveguide width alters band coupling and overlap, causing the originally localized boundary states to hybridize with bulk modes and disrupting the spectral symmetry essential for ideal topological pumping.

3. Simulation Result

To evaluate the transmission characteristics of the periodically modulated four-waveguide array, we conducted a comparative

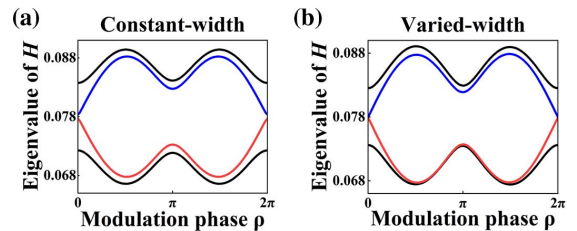


Fig. 3. Energy spectrum of RM model for (a) constant-width and (b) varied-width waveguides as a function of spatial modulation phase ρ ($\rho = 2\pi x/\tau$). The parameters used are $N = 4$, $\beta_0 \approx 0.0078 \mu\text{m}^{-1}$, $\delta_\beta = 0.001 \mu\text{m}^{-1}$, $k_0 \approx 0.00045 \mu\text{m}^{-1}$, $\delta_k \approx 0.00035 \mu\text{m}^{-1}$, $\tau = 50 \text{ mm}$.

study with two baselines: a constant-width array and a conventional straight waveguide pair. All three structures share identical geometries to ensure consistency. Simulations were done by using COMSOL. THz waves were injected from either cross1 (waveguide 1, topologically favored) or cross2 (waveguide 4, topologically suppressed). At 164 GHz, simulations reveal distinct field distributions in the varied-width array. Excitation at cross1 leads to directed transport toward waveguide 4, while excitation at cross2 results in localization within waveguides 2–4, without reaching waveguide 1. This asymmetry indicates clear nonreciprocal behavior. The transmission spectra [Fig. 4(a)] show directional contrast over 159–171 GHz, absent in the constant-width and conventional arrays [Figs. 4(b) and 4(c)], which display symmetric field patterns and reciprocal transmission. As shown in Fig. 4(d), the varied-width array maintains a stable insertion loss around -1 dB (min -0.22 dB), outperforming the other configurations that show higher loss and greater

variation. Robustness under fabrication perturbations was evaluated by varying the gap (250–350 μm) and waveguide width (± 50 μm). The modulated array retains performance under both, as shown in Figs. 4(e) and 4(f), unlike the controls. To further demonstrate scalability, we have extended frequency range to 350–390 GHz. Detailed results are presented in Supplement 1 Section 4.

4. Experiment

To experimentally verify unidirectional transport induced by asymmetric topological pumping, we fabricated two types of silicon ridge waveguide arrays: one with periodic width modulation and one with constant width as a reference. Both were patterned on 4 inch, 0.5 mm thick high-resistivity silicon wafers using standard photolithography and DRIE, achieving submicron accuracy and smooth sidewalls for low-loss THz propagation. As shown in Figs. 5(a) and 5(b), input and output tapers (3.635 mm, 6°) enable adiabatic mode conversion. Each array is 67.25 mm long and housed in a custom copper enclosure (90 mm $\times$ 20 mm $\times$ 4 mm) with an internal height of 820 μm . Each device includes four waveguides with two input/output ports (cross1 and cross2). Transmission was measured using an R&S ZNA26 vector network analyzer with WR-5 frequency extenders. During measurement, one input and one output were connected, while the other ports were isolated using THz

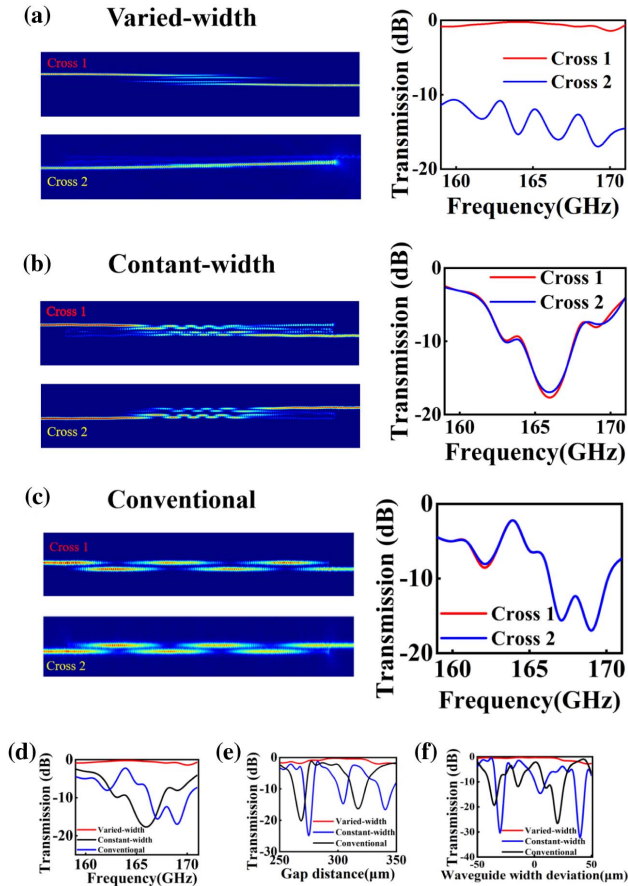


Fig. 4. Normalized electric field distributions at 164 GHz (left) and corresponding transmission spectra (right) for two observation points cross1: input to waveguide 1 [topologically favored injection site] and cross2: input to waveguide 4 [topologically suppressed site] in waveguide arrays comprising (a) varied-width curved waveguides, (b) constant-width curved waveguides, and (c) conventional straight waveguides. (d) Transmission spectra of cross1 for all three structures across 159–171 GHz. (e) Transmission of cross1 versus initial gap distance G . (f) Transmission of cross1 as a function of waveguide width tolerance, demonstrating robustness against fabrication tolerance.

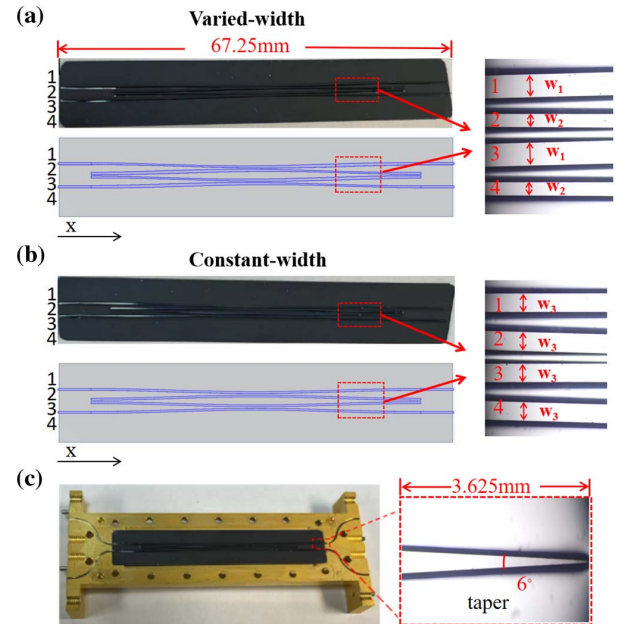


Fig. 5. Photographs of silicon ridge waveguide arrays with (a) varied width and (b) constant width. Insets on the right show corresponding microscope images highlighting the structural details of the waveguide channels. (c) Photograph of the fabricated metal-coupled packaging structure integrating the silicon ridge waveguide array. The magnified inset shows the tapered waveguide facet with a 6° angle and a width of 3.625 mm, as observed under an optical microscope.

absorptive materials to prevent reflection. Control experiments confirmed minimal influence from the open ports.

Due to the unavailability of WR-2.2 extension modules, experimental validation was conducted in the WR-5 band (159–171 GHz). The underlying physics of nonparaxial CW coupling and topological pumping depends on normalized waveguide dimensions relative to the operational wavelength. In our design, waveguide widths (300 μm), gaps (250–350 μm), and modulation amplitude (100 μm) are significantly larger than the wavelength ($\lambda \approx 1.8$ mm at 165 GHz), ensuring strong nonparaxial effects. The normalized parameters (δ_β , δ_κ) are comparable to those at higher THz frequencies on the same platform. Furthermore, high-resistivity silicon exhibits negligible dispersion across the sub-THz range^[20], making the 159–171 GHz band a valid regime for demonstrating the proposed mechanism. The measurement setup [Fig. 6(a)] used an R&S ZNA26 vector network analyzer with WR-5 extension modules (140–220 GHz) and precision WR-5 waveguide adaptors. Efficient coupling between the metallic WR-5 and silicon ridge waveguides was achieved using a two-stage mode converter: a metallic funnel taper (6°) followed by a dielectric taper etched into the silicon chip (3.6 mm length, 3.625 mm width). While simulations predict < -1 dB loss, measured loss reaches 5 dB [Fig. 6(b)], which includes both transmission loss (~ 0.15 dB) and insertion losses [~ 4.85 dB, originates mainly from (i) coupling inefficiency at the metal–silicon taper, (ii) packaging and alignment errors, (iii) scattering induced by sidewall roughness]. A detailed breakdown of the measured loss components is provided in Supplement 1 Section 5. Despite

these factors, the measured results validate the simulated topological behavior, with preserved directionality and bandwidth. Optimizing taper design and fabrication could further reduce total insertion loss. Frequency-domain transmission measurements were performed with 0.01 GHz step size. As shown in Fig. 6(b), the constant-width reference device exhibits fluctuating output (-8 to -25 dB) at both ports, with no clear directionality. In contrast, the width-modulated array shows robust asymmetric transport: -5 dB at cross1 and -20 to -30 dB at cross2 across the band. This confirms adiabatic pumping from one edge to the opposite side while suppressing backward flow—consistent with RM-type lattice dynamics and a photonic analogue of the Thouless pump. Unlike traditional directional couplers sensitive to fabrication tolerance, the modulated array shows stable broadband response and clear directionality. Despite system-level losses not captured in simulation—e.g., coupling inefficiencies, sidewall roughness, and packaging misalignment—the experimental results validate the topological transport mechanism under practical conditions. In addition, the reflection coefficients for both varied-width and constant-width structures under excitation from ports cross1 and cross2 were also measured, indicating efficient forward transport and minimal backscattering—characteristic of topological protection. Detailed derivation can be found in Supplement 1 Section 6. Additional experiments with intentionally introduced tolerances (waveguide width is 250 μm) were performed in Supplement 1 Section 7. The device still maintains > 10 dB directionality, consistent with the robustness predicted by simulations.

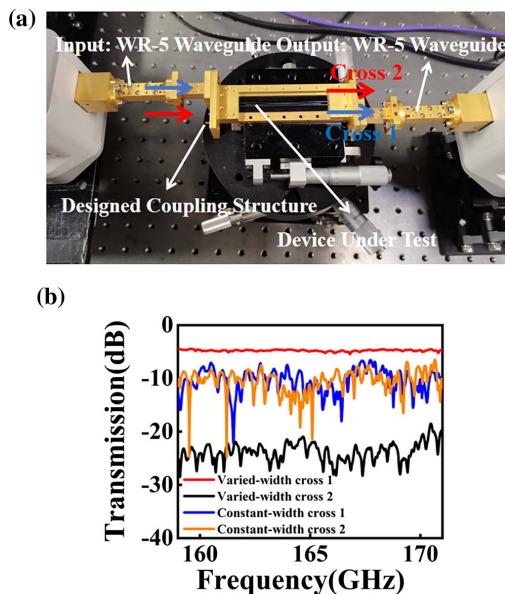


Fig. 6. (a) Experimental setup for transmission measurements using a WR-5 waveguide and a VNA. The device under test is coupled via a designed metal waveguide structure, with observation points labeled as cross1 and cross2. (b) Measured transmission spectra at cross1 and cross2 for both varied-width and constant-width waveguide arrays over the frequency range of 159–171 GHz.

5. Conclusion

In conclusion, we demonstrated the first experimental realization of asymmetric topological pumping in a CMOS-compatible silicon platform at THz frequencies (159–171 GHz). By spatially modulating a four-ridge waveguide array based on the RM model and leveraging nonparaxiality-induced CW coupling—a vectorial effect beyond conventional theory—we achieved robust, nonreciprocal signal transport. The device exhibits > 15 dB directionality contrast, < -2 dB insertion loss, backscattering suppression below -15 dB, and a 10 GHz operational bandwidth. Crucially, it tolerates waveguide width variations (50 μm). This work translates nonparaxial topological pumping into a practical, scalable, and fabrication-resilient silicon THz platform, addressing a key bottleneck in integrated THz photonics. Our design is essential in integrated THz devices for power coupling and splitting by introducing the Thouless pump mechanism into the coupling process, that is to say, the power coupling device that employs the waveguide array configuration of the Thouless pump system can accomplish a complete power transfer from the input port to the cross port. In the future, increasing the number of channels in a THz topological Thouless pump system can enable massive single-input multiple-output and multiple-input and multiple-output systems for multi-link terahertz 6G communications^[5]. On the

other hand, the introduction of phase-change material in a THz topological Thouless pump system will enable dynamic modulation for stable, nonvolatile, and programmable terahertz topological integrated chips^[12,26].

Acknowledgements

This work was supported in part by the Basic Science Center Project of the National Natural Science Foundation of China (Grant No. 62588201), National Natural Science Foundation of China (Grant No. 62275157), the National Key Research and Development Program of China (Project Number 2023YFF0717900), the Shanghai Shuguang Program, China (Grant No. 18SG44), 111 Project (Grant No. D18014), and the Science and Technology Commission of Shanghai Municipality (Grant No. 21S31907400).

References

1. A. Ren, A. Zahid, D. Fan, *et al.*, "State-of-the-art in terahertz sensing for food and water security—a comprehensive review," *Trends Food Sci. Technol.* **85**, 241 (2019).
2. J. Lyu, S. Shen, L. Chen, *et al.*, "Frequency selective fingerprint sensor: the Terahertz unity platform for broadband chiral enantiomers multiplexed signals and narrowband molecular AIT enhancement," *Photonix* **4**, 28 (2023).
3. L. Chen, Y. Song, D. C. Y. Lim, *et al.*, "Biochemical sensing with terahertz microfluidics: recent progress and future prospects," *Trends Anal. Chem.* **193**, 118416 (2025).
4. J. Lyu, L. Huang, L. Chen, *et al.*, "Review on the terahertz metasensor: from featureless refractive index sensing to molecular identification," *Photonics Res.* **12**, 194 (2024).
5. W. Wang, Y. J. Tan, T. C. W. Tan, *et al.*, "On-chip topological beamformer for multi-link terahertz 6G to XG wireless," *Nature* **632**, 522 (2024).
6. M. Gupta, A. Kumar, and R. Singh, "Electrically tunable topological notch filter for THz integrated photonics," *Adv. Opt. Mater.* **11**, 2301051 (2023).
7. M. Gupta, A. Kumar, P. Pitchappa, *et al.*, "150 Gbps THz chip-scale topological photonic diplexer," *Adv. Mater.* **36**, 2309497 (2024).
8. A. Kumar, Y. J. Tan, N. Navaratna, *et al.*, "Slow light topological photonics with counter-propagating waves and its active control on a chip," *Nat. Commun.* **15**, 926 (2024).
9. N. Navaratna, Y. J. Tan, A. Kumar, *et al.*, "On-chip topological THz biosensors," *Appl. Phys. Lett.* **123**, 033705 (2023).
10. A. Kumar, M. Gupta, P. Pitchappa, *et al.*, "Phototunable chip-scale topological photonics: 160 Gbps waveguide and demultiplexer for THz 6G communication," *Nat. Commun.* **13**, 5404 (2022).
11. P. Dechwechprasit, R. Tanyi Ako, S. Sriram, *et al.*, "Terahertz disk resonator on a substrateless dielectric waveguide platform," *Opt. Lett.* **48**, 4685 (2023).
12. S. Zhang, W. Wang, Z. Shen, *et al.*, "On-chip non-volatile reconfigurable phase change topological photonics," *Adv. Mater.* **37**, 2418510 (2025).
13. T. Sagisaka, R. Kaname, M. Kikuchi, *et al.*, "Integrated terahertz optics with effective medium for 600-GHz-band imaging," in *MWP* (2020), p. 62.
14. J. Xie, X. Zhu, X. Zang, *et al.*, "Terahertz integrated device: high-Q silicon dielectric resonators," *Opt. Mater. Express* **8**, 50 (2017).
15. J. Xie, X. Zhu, H. Zhang, *et al.*, "Terahertz-frequency temporal differentiator enabled by a high-Q resonator," *Opt. Express* **28**, 7898 (2020).
16. Y. Rui, S. Zhou, X. Tu, *et al.*, "All-silicon low-loss THz temporal differentiator based on microring waveguide resonator platform," *Light Adv. Manuf.* **5**, 13 (2024).
17. Z. Wang, S. Yuan, G. Dong, *et al.*, "On-chip single-mode high-Q terahertz whispering gallery mode resonator," *Opt. Lett.* **44**, 2835 (2019).
18. J. Xie, J. Qian, T. Wang, *et al.*, "Integrated terahertz vortex beam emitter for rotating target detection," *Adv. Photonics* **5**, 066002 (2023).
19. S. Yuan, L. Chen, Z. Wang, *et al.*, "On-chip terahertz isolator with ultrahigh isolation ratios," *Nat. Commun.* **12**, 5570 (2021).
20. Q. Cheng, H. Wang, Y. Ke, *et al.*, "Asymmetric topological pumping in non-paraxial photonics," *Nat. Commun.* **13**, 249 (2022).
21. W. Song, W. Sun, C. Chen, *et al.*, "Robust and broadband optical coupling by topological waveguide arrays," *Laser Photonics Rev.* **14**, 1900193 (2020).
22. L. Sun, H. Wang, Y. He, *et al.*, "Broadband and fabrication tolerant power coupling and mode-order conversion using Thouless pumping mechanism," *Laser Photonics Rev.* **16**, 2200354 (2022).
23. P. Hu, L. Chen, A. P. Shkurinov, *et al.*, "Observation of topological transmission in terahertz domino waveguide array," *IEEE Trans. Terahertz Sci. Technol.* **13**, 337 (2023).
24. Y. Yang, Y. Yamagami, X. Yu, *et al.*, "Terahertz topological photonics for on-chip communication," *Nat. Photonics* **14**, 446 (2020).
25. M. Rice and E. Mele, "Elementary excitations of a linearly conjugated diatomic polymer," *Phys. Rev. Lett.* **49**, 1455 (1982).
26. S. Ma, Y. Fan, L. Chen, *et al.*, "Electrically controlled real-time terahertz 'microladder' integrated with VO₂ patches for broadband holographic encryption," *Adv. Photonics* **7**, 066003 (2025).