

Freeform Direct-Written Nonreciprocal Metasurfaces on Ferrite Film for Terahertz Bidirectional Beam Modulation

Qindong Xie^{1,2}, Weihao Yang¹, Zechuan Bin³, Xiaowei Wang¹,
Xiuli Yue¹, Tang Fu³, Lei Bi¹, Baile Zhang^{2,4,*}, and Peiheng Zhou^{1,*}

¹National Engineering Research Center of Electromagnetic Radiation Control Materials
Key Laboratory of Multi-Spectral Absorbing Materials and Structures of Ministry of Education
University of Electronic Science and Technology of China, Chengdu 611731, China

²Division of Physics and Applied Physics, School of Physical and Mathematical Sciences
Nanyang Technological University, Singapore 637371, Singapore

³Terahertz Research Center, Key Laboratory of Terahertz Technology of Ministry of Education
School of Electronic Science and Engineering, University of Electronic Science and Technology of China, Chengdu 611731, China

⁴Centre for Disruptive Photonic Technologies, The Photonics Institute
Nanyang Technological University, Singapore 637371, Singapore

ABSTRACT: Bidirectional wavefront control requires metasurfaces that encode distinct responses in opposite propagation directions. Ferrite films possessing nonreciprocity at terahertz frequencies are crucial for bidirectional control; however, they are difficult to pattern. We address this materials-fabrication mismatch by one-step, resist-free femtosecond direct laser writing (DLW), which directly transforms continuous low-loss lanthanum-doped yttrium iron garnet (La:YIG) films into freeform nonreciprocal metasurfaces. This approach sculpts complete nonreciprocal metasurfaces (NRMs) with meta-atoms in a wide variety of prism geometries, including hexagonal, oval, rectangular, and pentagonal forms, directly in the film. By reconfiguring gyrotropic resonances of each element, we demonstrate precise nonreciprocal control of THz beams through unidirectional transmission, bidirectional beam focusing, and holographic imaging. This streamlined fabrication strategy dramatically lowers the barrier to NRM research and broadens its applicability across several scientific fields.

1. INTRODUCTION

Terahertz (THz) waves occupy the spectral region between microwaves and infrared light, typically spanning 0.1–10 THz. Their ability to penetrate non-conductive materials while retaining submillimeter spatial resolution has enabled high-resolution imaging [1–4], molecular spectroscopy [5, 6], and emerging high-capacity wireless links [7, 8]. Continued progress in these areas increasingly depends on components that do more than tailor wavefronts, and they must also distinguish forward from backward propagation. Such nonreciprocal responses are essential for isolators, circulators, gyrators, and other circuit elements that protect sources, suppress back-reflections, or route energy asymmetrically [9, 10]. A metasurface capable of assigning one wavefront to forward propagation and another to backward propagation would therefore add a valuable degree of freedom to compact THz systems.

Nonreciprocity generally demands breaking time-reversal symmetry, a condition rarely satisfied in natural materials at THz frequencies [11]. Feasible approaches include time-modulated systems [12–14], nonlinear media [15, 16], and magnetically biased gyrotropic materials [17, 18]. Among them, gyrotropic ferrites offer the most practical path: under an external magnetic bias, and they develop off-diagonal

permeability tensor components that induce asymmetric propagation via magneto-optical effects (e.g., the Faraday rotation). Rare-earth-doped yttrium iron garnet (YIG), in particular, Lanthanum-doped YIG (La:YIG), shows pronounced nonreciprocal behavior in the THz range [19–21].

Nevertheless, integrating these magneto-optical materials into compact metasurfaces has been hindered by their mechanical harness, chemical resistance, and susceptibility to thermal-stress cracking — limitations that are exacerbated at sub-millimeter feature scales. Conventional lithography often proves incompatible with garnet-based compounds. Recent developments in resist-free direct laser writing (DLW), however, enable maskless microstructuring of La:YIG films, overcoming these fabrication barriers [22–24].

In this work, we use one-step femtosecond DLW to transform continuous La:YIG films on silicon into nonreciprocal metasurfaces (NRMs) with meta-atoms. We first verify the direction-dependent resonance using a one-way-transmission metasurface. Then, a digital library with each element indexed by a forward-backward transmission phase pair is constructed and selected using a figure of merit that accounts for both phase error and throughput. Finally, using this library, we realize a nonreciprocal metalens and nonreciprocal holographic imaging at ~ 0.3 THz (wavelength = 1 mm). The resulting platform links material response, maskless fabrication, and bidirectional

* Corresponding authors: Baile Zhang (blzhang@ntu.edu.sg); Peiheng Zhou (phzhou@uestc.edu.cn).

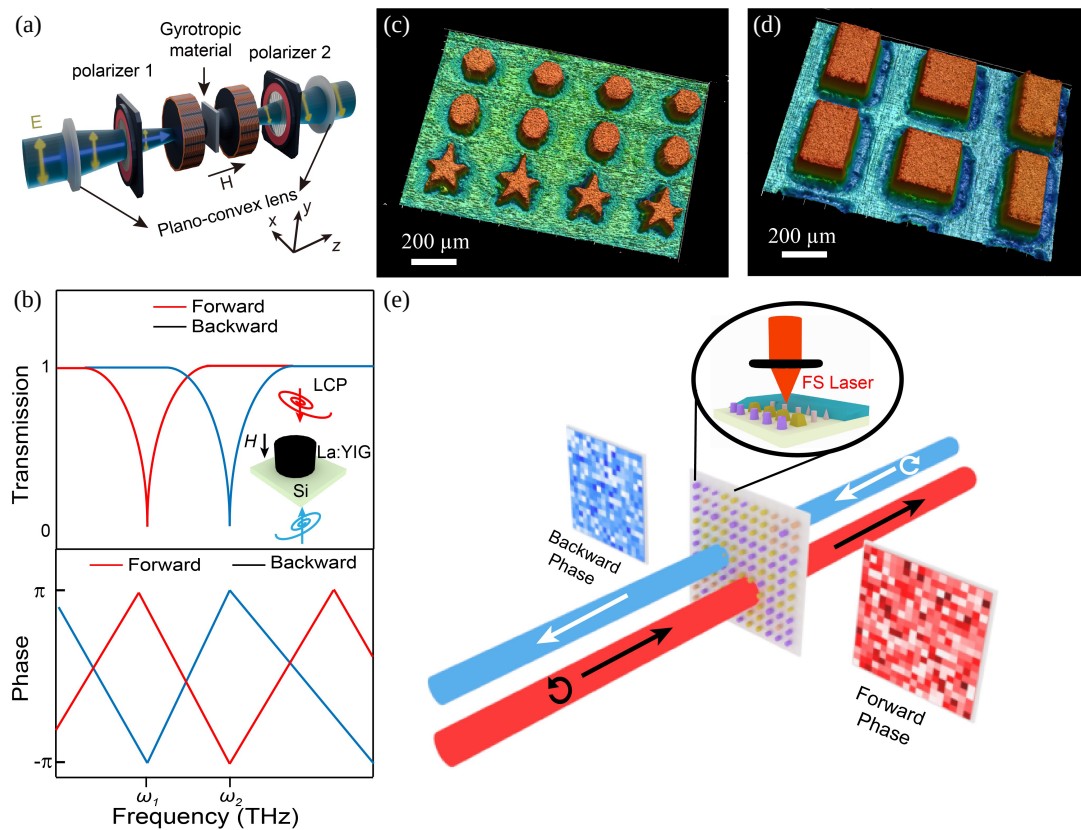


FIGURE 1. Freeform direct-written nonreciprocal metasurfaces (NRMs). (a) Schematic of Faraday effect measurement. (b) Nonreciprocal transmission near a Mie resonance of NRM, showing (top) amplitude and (bottom) phase difference between forward and backward transmission. Inset: operation mechanism of a single La:YIG meta-atom under magnetic field H along z axis. (c) 3D optical microscopy of DLW-fabricated La:YIG meta-atoms with hexagonal, oval, and pentagonal cross-section (lateral dimensions of several hundred micrometers). (d) 3D optical micrographs of rectangular La:YIG pillar with varying length-to-width aspect ratio, all produced in one resist-free DLW step. (e) Schematic of a phase-gradient NRM by reconfiguring gyrotropic resonances across the metasurface. The device imparts independent phase and amplitude profiles to forward (red) and backward (black) left-circularly polarized (LCP) THz beam.

tional wavefront manipulation in a single workflow, and can be adapted to integrated THz photonics, full-duplex antennas, and intelligent manufacturing platforms [25–32].

2. RESULTS

2.1. Operation Principles, Direct-Written Meta-Atoms and Device Structures

Figure 1 summarizes the operating concept of the proposed nonreciprocal metasurfaces. When an electromagnetic wave propagates along the magnetic-bias direction H in a gyrotropic medium, its right-circularly polarized (RCP) and left-circularly polarized (LCP) eigenstates experience different refractive indices. The propagation direction reverses the relationship between the forward and backward wavevectors. Consequently, a given circular polarization state samples a different effective constitutive response upon propagation reversal (inset, Fig. 1(b)). We embedded this directional asymmetry in Mie resonators. Near resonance, even a change in the effective magnetic response produces a shift in both transmission amplitude and phase. Consequently, a periodic array of identical resonators can exhibit distinct forward and backward spectral

features, whereas a spatially varying array can encode two different phase profiles on the same surface.

Our fabrication employs a single-step, resist-free DLW process on continuous La:YIG films (Supplementary Note 1), obviating conventional lithography and etching. We directly wrote a full library of meta-atoms, including hexagonal, oval, pentagonal, and rectangular pillars with lateral dimensions ranging from $\sim 10\ \mu\text{m}$ to several hundred micrometers (Figs. 1(c) and 1(d)). This approach enables the rapid, shape-agnostic prototyping and local reconfiguration of NRMs. Fig. 1(e) schematically depicts a phase-gradient NRM that shows both circular birefringence and circular dichroism [17, 19, 20] to generate independently tailored phase and amplitude profiles in the forward and backward directions.

2.2. THz One-Way-Transmission NRM

We first used a simple periodic structure to verify nonreciprocal resonance. The device consists of cylindrical La:YIG pillars written on a $15\ \text{mm} \times 15\ \text{mm} \times 0.2\ \text{mm}$ silicon substrate (Supplementary Note 3) and is biased by a magnetic field of $H = 0.178\ \text{T}$. It is designed to operate near $0.333\ \text{THz}$ and has

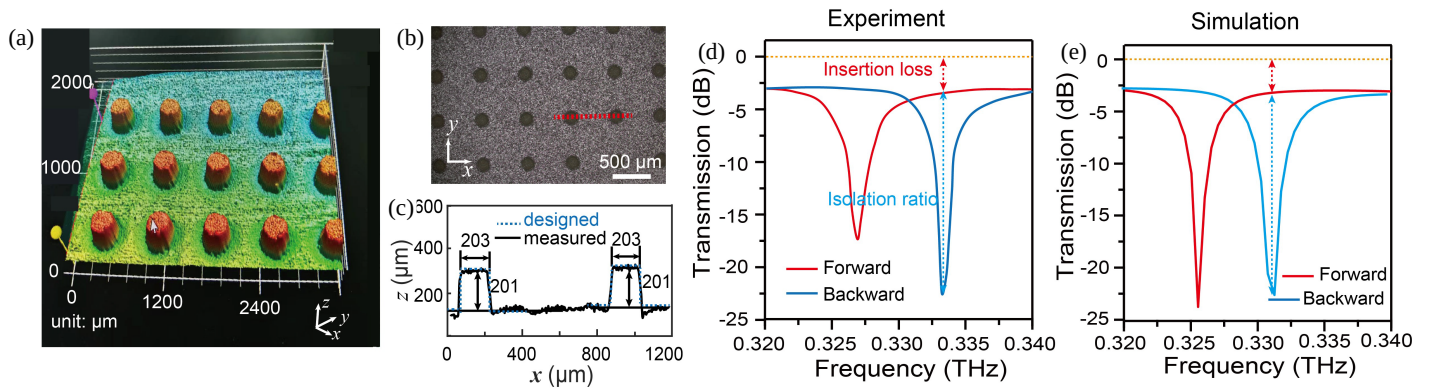


FIGURE 2. One-way transmission nonreciprocal metasurface (NRM). (a) 3D optical microscopy of the DLW-fabricated sample. (b) 2D image of the sample. (c) Height profile along the red trace in (b). The blue dotted line marks the designed pillar diameter. (d) Measured and (e) simulated transmission spectra for a left-circularly polarized (LCP) THz beam in the forward (red) and backward (blue) directions.

TABLE 1. Comparison between one-way-transmission on-chip NRMs/isolators.

No.	Type	Frequency (THz)	Isolation ratio (dB)	Active control	Insertion loss (dB)	Platform	Magnetic field (T)
[25]	isolator	0.47	52	Thermal	7.5	Si	0.68
[26]	isolator	3	2	Electric	~7.5	Graphene	7
[27]	NRM	0.2–1	20	Optical	~10	Si	0.15
[28]	isolator	3.4	64.3	Optical	17.8	Si	0.632
[29]	NRM	0.2–1	35	magnetic	6.2	InSb	0.2
[30]	isolator	0.2–1	2	magnetic	4	Insb	0.23
[31]	isolator	0.5–0.9	23	magnetic	/	LaYIG/Si	0.26
[32]	NRM	0.5	32.6	magnetic	/	YIG/Si	0.26
[21]	NRM	0.1–1.2	23	magnetic	< 10	La:YIG	0.26
This work	NRM	0.333	20.1	magnetic	3.1	La:YIG	0.178

an 800 μm square lattice. The fabricated pillars have a diameter of 203 μm and a height of 201 μm (Figs. 2(a)–(c)), closely matching the design values of 200 μm for both diameter and height. This agreement confirms that the DLW process can accurately reproduce required dimensions at submillimeter scale.

Forward and backward transmissions were measured under LCP illumination using a THz time-domain spectroscopy (THz-TDS) system (Supplementary Note 2; Fig. 2(d)). The two directions show distinct minima: the forward dip occurs at 0.327 THz, whereas the backward dip appears at 0.333 THz. Experimentally, we achieve a one-way isolation ratio of 20.1 dB (forward-to-backward power ratio) with only 3.1 dB insertion loss (forward input-to-output power ratio). Full-wave simulations yield 20.3 dB isolation and 2.9 dB insertion loss (Fig. 2(e)), with the small discrepancy mainly attributed to fabrication tolerances and experimental imperfections. Multipole decomposition indicates that the one resonance corresponds to a magnetic dipole resonance mode (Supplementary Note 3, Fig. S3). To the best of our knowledge, this insertion loss of 3.1 dB is the lowest reported for THz NRMs and related isolators (Table 1).

2.3. Bidirectional Transmission Library

Phase-gradient NRMs provide on-demand, bidirectional wave-front control by encoding distinct phase profiles for forward and backward illumination. We implement this using nonreciprocal digital-coding metasurface elements, each defined by a forward-backward phase pair, denoted as $(\phi_f(\omega), \phi_b(\omega))$. For fabrication simplicity, we choose rectangular and oval pillar meta-atoms (Fig. 3(a)), parametrized by their major and minor axes, i.e., a , b , and h , respectively. We then simulate the LCP transmission amplitude and phase across a dense grid of (a, b, h) values and apply an arbitrary $(\phi_f(\omega), \phi_b(\omega))$ target criterion, seeking to minimize phase error while maximizing transmission efficiency. To balance this trade-off, we introduce a single figure of merit (FOM) [33] that simultaneously penalizes phase deviation and low throughput. Optimizing for the highest FOM yields viable meta-atom designs at $\omega = 0.3$ THz (Fig. 3(b); Supplementary Note 5), forming a comprehensive database for assembling functional phase gradient NRM. This parametric study explicitly reveals the resonance splitting effect: for the same geometric dimensions, the forward and backward phases diverge due to the distinct effec-

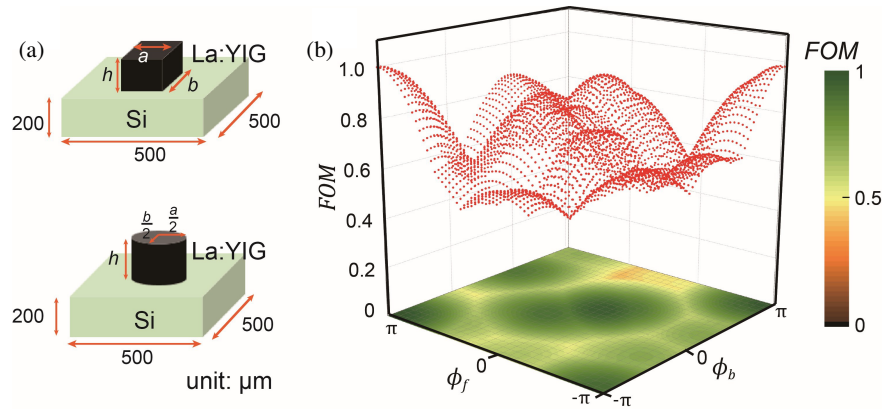


FIGURE 3. Meta-atom selection for nonreciprocal metasurface (NRM). (a) Schematic of the two pillar geometries — rectangular (top) and oval (bottom) — fabricated on a 200 μm thick Si substrate. All pillars share the height ($\leq 500 \mu\text{m}$) and are arranged in a 2D square lattice with 500 μm lattice constant. The geometrical parameters (a , b , h) are independently varied. (b) Bidirectional transmission-phase library at 0.3 THz obtained from the parameter sweep over $((a, b, h))$. The horizontal and vertical axes denote the forward and backward transmission phases, (ϕ_f) and (ϕ_b) , respectively. Each red point represents the maximum of the figure of merit (FOM) satisfying the forward and backward phases corresponding to the color 2D grid, which balances phase-error minimization against transmission efficiency.

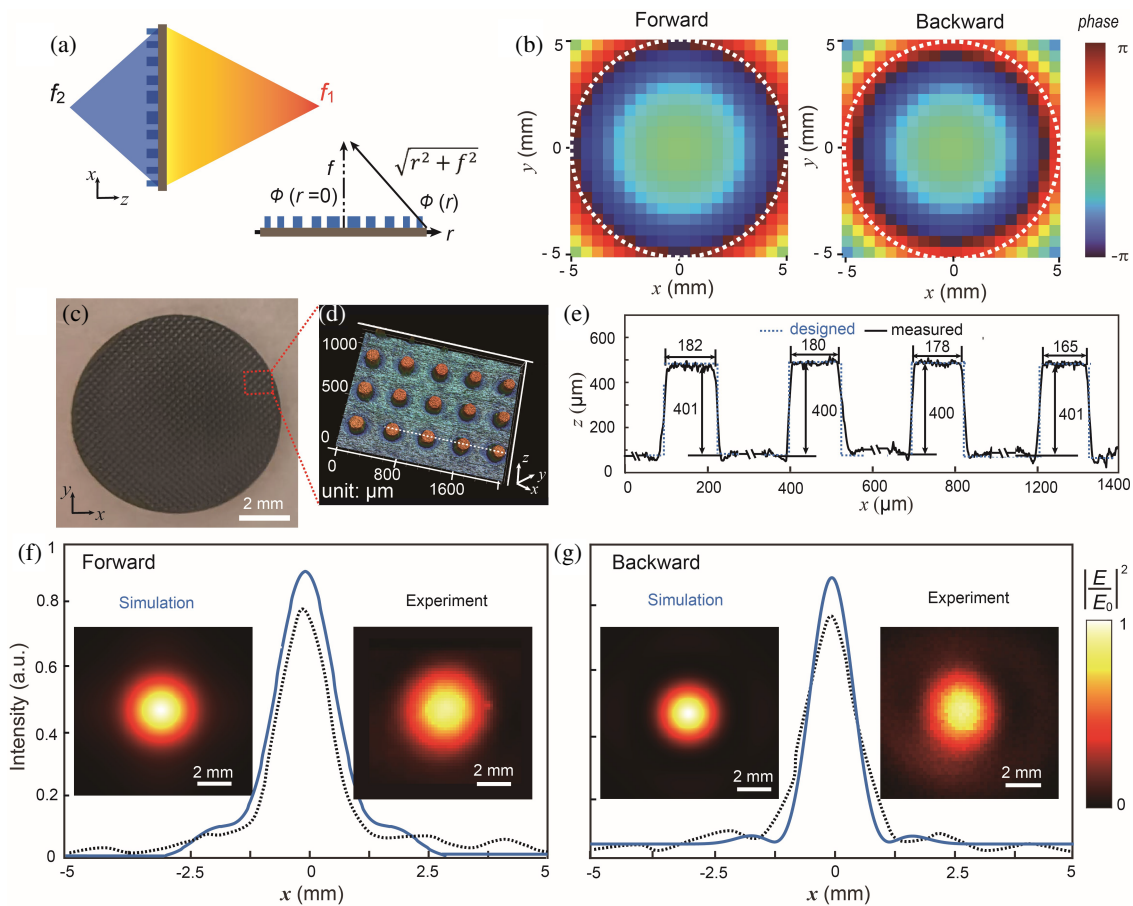


FIGURE 4. THz nonreciprocal metalens. (a) Schematic of the phase-gradient nonreciprocal metalens under magnetic bias. (b) Designed phase profiles of the metalens for forward and backward incidence (The actually fabricated sample is framed by a white dashed circle). (c) Photograph of the DLW-fabricated metalens on a silicon substrate. (d) 3D optical microscopy of the region outlined by the red dashed box in (c), showing individual meta-atoms. (e) Height profile along the white dashed line in (d), with the blue dashed line indicating the target pillar diameter. (f), (g) Normalized focal-spot energy distributions along the x axis in the focal plane ($y = 0$) for (f) forward incidence and (g) backward incidence at 0.3 THz. Dots: experimental data; solid line: full-wave simulations. Insets show 2D energy maps at the focal plane for each direction.

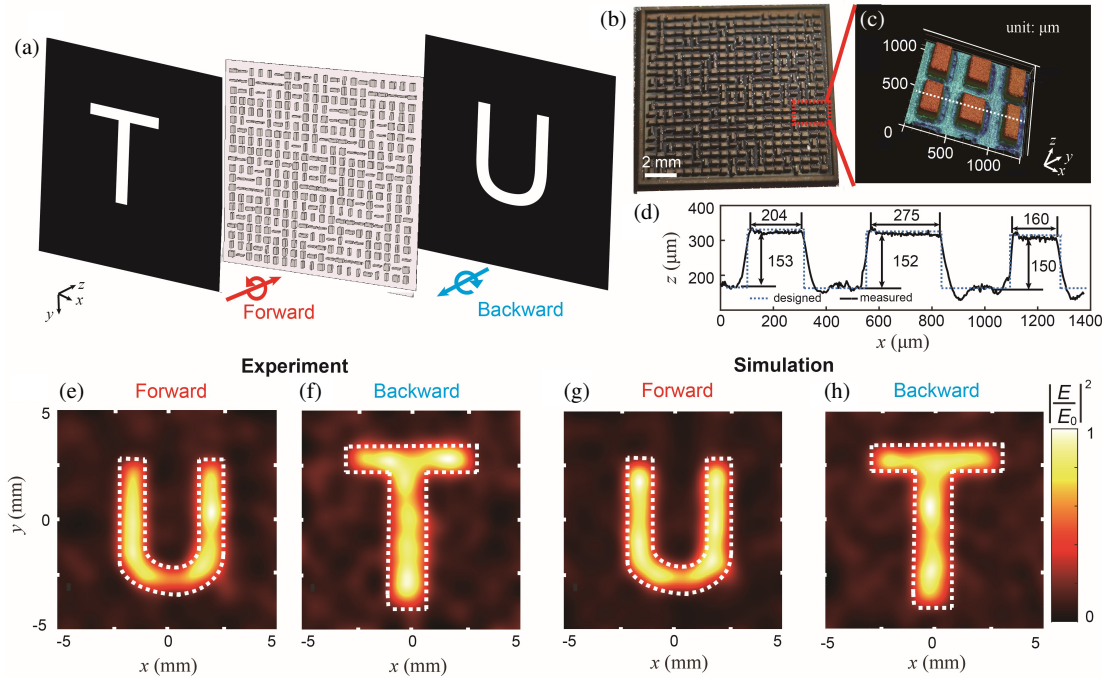


FIGURE 5. Nonreciprocal hologram NRM. (a) Schematic of the phase-only nonreciprocal hologram metasurface. (b) Overview photograph of the DLW-fabricated hologram sample on the silicon substrate. (c) 3D optical microscopy of the region outlined by the red dotted line in (b). (d) Height profile along the white dotted line in (c), with the blue dotted line marking the designed pillar sizes. (e), (f) Measured holographic images at the image plane for (e) forward and (f) backward illumination, showing distinct ‘U’ and ‘T’ patterns. (g), (h) Simulated THz energy intensity maps at the image plane under (g) forward and (f) backward illumination, in excellent agreement with the experimental results.

tive refractive indices of La:YIG. This database allows designers to select meta-atoms that maximize the phase difference at specific operational frequencies, providing a clear pathway for adapting this non-reciprocal platform to other frequency bands. The design process is target-phase-specific: for each required bidirectional phase pair $(\phi_f(\omega), \phi_b(\omega))$, the meta-atom with the highest FOM (balancing phase accuracy and transmission) is selected from this database.

2.4. THz Nonreciprocal Metalens

A terahertz lens is one of the most critical components for enabling high-resolution THz imaging [3, 4]. The nonreciprocal metalens exhibits different focal lengths for forward and backward illumination. For a radial coordinate r , the required phase delay for each propagation direction is determined by the corresponding focal length [17, 33, 34]:

$$\phi_{1/2}(r) = -\frac{2\pi}{\lambda} \left(\sqrt{r^2 + f_{1/2}^2} - f_{1/2} \right) \quad (1)$$

where λ is the design wavelength, and f_1 and f_2 are prescribed focal lengths for forward and backward incidences, respectively (Fig. 4(a)).

In our prototype, we set $f_1 = 25$ mm and $f_2 = 20$ mm. To simplify fabrication, cylindrical pillars ($a = b$) with $h = 400$ μ m were selected from the FOM-optimized library and assigned to the two target phase profiles. The resulting pattern covered a 10 mm $\times$ 10 mm area (Fig. 4(b)). Subsequently, the sample was diced into a 10 mm-diameter disk to fit the standard

silicon wafer format (Fig. 4(c)). Three-dimensional optical microscopy of a representative region (Fig. 4(d)) revealed well-defined pillars across the patterned aperture. Measurements taken at four different positions confirm that both heights and diameters closely followed their design values (Fig. 4(e)), indicating that the spatially varying phase mask can be transferred with high dimensional fidelity.

Focusing response was characterized using a custom-built near-field THz scanning system. Field distribution was sampled with a step size of 0.2 mm over a 10 mm $\times$ 10 mm area at various z positions (Supplementary Note 6), and the measured results were compared with full-wave simulations of the complete lens. The simulated focal distances were 23.5 mm in the forward direction and 19.3 mm in the backward direction (Fig. S9), which are slightly shorter than the design values of 25 and 20 mm, respectively. This shift is attributed to coupling effects between adjacent meta-atoms (Supplementary Note 7). At corresponding focal planes, both experiment and simulation showed a single, well-confined intensity maximum (Figs. 4(f) and (g)). We define the focusing efficiency as the fraction of incident power contained within a circular region of radius three times the full width at half maximum (FWHM) of the focal spot, normalized to the total incident power [17, 35]. Measured efficiencies were 41.5% for forward incidence and 49.8% for backward incidence, compared with simulated values of 46.1% and 55.6% , respectively. Experimental-system loss and calibration uncertainty contributed to the discrepancy between measured and simulated focusing efficiencies. The oscillatory side-lobe observed in the x -directed line profiles arises from the interference between the incident field and weakly reflected waves.

2.5. Nonreciprocal Holography

Holography underpins a wide range of applications, ranging from three-dimensional displays [35, 36], data encryption [37], to dynamical beam control [36, 37], and artificial-intelligence-enhanced imaging [38]. Here, we extend our NRM platform to nonreciprocal holography, generating two distinct holograms for forward and backward THz illuminations. We position image planes 10 mm from the metasurface on each side and encode the uppercase letters ‘U’ and ‘T’ as our target patterns (Fig. 5(a)). Using the Gerchberg-Saxton algorithm [17, 35], we compute the discrete phase profiles required to reconstruct these holograms at 0.3 THz. Phase-gradient elements were drawn from a rectangular-pillar library ($h = 150\ \mu\text{m}$) in Fig. 3(b) and then mapped onto 20×20 units over a $10\ \text{mm} \times 10\ \text{mm}$ area, completing the design of our nonreciprocal holographic NRM.

After DLW fabrication, the overview micrograph in Fig. 5(b) reveals meta-atoms of varying dimensions, each tailored to a specific nonreciprocal phase requirement. We then selected a representative sampling zone and acquired a 3D micrograph of the prisms in that zone (Fig. 5(c)). The measured height and width of three rectangular pillars along the indicated line agree closely with the design specifications (Fig. 5(d)).

We evaluated the nonreciprocal hologram using the same near-field scanning system as for the metalens. Figs. 5(e) and 5(f) show the experimentally measured ‘U’ and ‘T’ reconstructions at their respective image planes, in excellent agreement with the simulated intensity maps (Figs. 5(g) and 5(h)). The diffraction efficiencies [39, 40], defined as the power concentrated in the holographic image referenced to the total power transmitted by the hologram, reached 73% for forward incidence and 82% for backward incidence. The transmission efficiencies [39, 41], defined as the energy on the holographic plane normalized by the total incident energy, are 44% (forward) and 41% (backward). Compared to the simulated transmission efficiencies of 59% and 57%, the shortfall arises from an average 7% reduction in the transmission of meta-atoms, approximately 5% fabrication tolerance, and about 3% phase deviation from the ideal design. Holographic performance could be further enhanced by employing low-loss magnetic materials, integrating an impedance-matching layer, and increasing the number of discrete phase-sampling levels in the meta-atoms library.

3. CONCLUSION

This study demonstrates that freeform fabrication and nonreciprocal wavefront synthesis can be integrated within a single La:YIG metasurface platform. The femtosecond DLW process directly patterns hard gyrotropic films without resists, masks, or multi-step etching sequence, while retaining the geometric versatility required to engineer local resonances. Starting from the directional splitting of a Mie resonance, we constructed a bidirectional transmission library and used it to realize three progressively complex functions near 0.3 THz: one-way transmission, bifocal metalens, and nonreciprocal hologram. Across these devices, the measured responses were in good agreement with the full-wave simulations.

Future extensions of this platform include multilevel (grayscale) structuring for enhanced phase resolution [36–38], custom substrate integration (e.g., silicon-on-insulator incorporating magnetically tunable films), and hybrid magneto-/electro-optical architectures for programmable THz circuits [42]. By offering a low-cost, accessible DLW workflow that democratizes NRM prototyping, our work paves the way for rapid innovation in nonreciprocal photonics across a broad range of scientific and engineering disciplines.

METHODS

Metasurface Characterization. All experimental results were measured using terahertz time-domain spectroscopy at room temperature (21°C) and a relative humidity of 8%. The beam diameter of the terahertz signal passing through the sample was 10 mm, and a terahertz receiving antenna collected the transmitted beam. Time-domain signals were converted to the frequency domain using the Fourier transform and normalized to the reference air signals to obtain the transmission amplitude and phase information at certain frequencies. In the case of metalens and hologram metasurfaces, a field-scanning imaging system was used to map the E -field distribution. The receiving antenna (field resolution: $10\ \mu\text{m}$) was fixed on a linear stage with a maximum travel range of 20 mm, driven by stepper motors in the horizontal and vertical directions. In our experiments, the moving speed of the receiving antenna was 2 mm/s. The custom-built motor-scanning program communicated with THz time-domain spectroscopy to execute point-by-point measurements, yielding the amplitude/phase distribution of the E -field on a specific plane.

Metasurface Simulation. Simulations were performed using the commercial COMSOL Multiphysics software based on the finite element method. For one-way transmission and transmission library simulations, periodic boundary conditions were applied in both transverse directions for each unit cell, and the polarization and incident angle of the THz wave were defined at the incident port along the z (longitudinal) axis. A perfectly matched layer was imposed at the incident port to absorb the scattered waves. The transmission phase and amplitude spectra were obtained from the S -parameter in COMSOL Multiphysics. The metalens’ electromagnetic analysis was simulated using wave optics modules of the same software. Home-made Python codes based on the Gerchberg-Saxton algorithm were used to calculate the non-reciprocal focusing characterization and holographic patterns, respectively.

Fabrication Section. A commercial, direct-writing lithography tool (LR-Femto, Shengzi LaserRush Co. Ltd) was employed to write ferrite films (Fig. S4). The tool uses a femtosecond laser (wavelength 343 nm, pulse width ≤ 500 fs, modulation frequency 1 MHz), and laser source parameter (20 μW , 200 kHz, pulse duration: 400 fs, focus spot: $8\ \mu\text{m}$).

ACKNOWLEDGEMENT

We are grateful for the support from the National Natural Science Foundation of China (Grants Nos. 52425205

and 52021001). Q. X. thanks for the support from the Chinese Scholarship Council (CSC).

REFERENCES

- [1] Zhang, X.-C. and J. Xu, *Introduction to THz Wave Photonics*, Springer, 2010.
- [2] Ferguson, B. and X.-C. Zhang, "Materials for terahertz science and technology," *Nature Materials*, Vol. 1, 26–33, September 2002.
- [3] Zhang, X.-C., "Terahertz wave imaging: Horizons and hurdles," *Physics in Medicine and Biology*, Vol. 47, No. 21, 3667–3677, October 2002.
- [4] Lyu, N., J. Zuo, Y. Zhao, and C. Zhang, "Terahertz synthetic aperture imaging with a light field imaging system," *Electronics*, Vol. 9, No. 5, 830, 2020.
- [5] Liu, B., Y. Peng, Y. Hao, Y. Zhu, S. Chang, and S. Zhuang, "Ultra-wideband terahertz fingerprint enhancement sensing and inversion model supported by single-pixel reconfigurable graphene metasurface," *Photonix*, Vol. 5, 435–465, April 2024.
- [6] Cai, B., L. Yang, L. Wu, Y. Cheng, and X. Li, "Dual-narrowband terahertz metamaterial absorber based on all-metal vertical ring array for enhanced sensing application," *Physica Scripta*, Vol. 99, No. 9, 095503, August 2024.
- [7] Yang, Y., Y. Yamagami, X. Yu, P. Pitchappa, J. Webber, B. Zhang, M. Fujita, T. Nagatsuma, and R. Singh, "Terahertz topological photonics for on-chip communication," *Nature Photonics*, Vol. 14, No. 7, 446–451, April 2020.
- [8] Wang, W., Y. J. Tan, T. C. Tan, A. Kumar, P. Pitchappa, P. Szriftgiser, G. Ducournau, and R. Singh, "On-chip topological beam-former for multi-link terahertz 6G to XG wireless," *Nature*, Vol. 632, No. 8025, 522–527, August 2024.
- [9] Zhao, D., F. Fan, J. Liu, Z. Tan, H. Wang, Q. Yang, Q. Wen, and S. Chang, "Terahertz magneto-optical metadvice for active spin-selective beam steering and energy distribution with nonreciprocal isolation," *Optica*, Vol. 10, No. 10, 1295–1301, September 2023.
- [10] Zhao, D., F. Fan, Q. Xue, H. Wang, Y. Ji, Q. Yang, Q. Wen, and S. Chang, "Terahertz magnetic moiré grating for enhanced chirality manipulation and nonreciprocal spin isolation," *Advanced Functional Materials*, Vol. 34, No. 42, 2404881, April 2024.
- [11] Caloz, C., A. Alù, S. Tretyakov, D. Sounas, K. Achouri, and Z.-L. Deck-Léger, "Electromagnetic nonreciprocity," *Physical Review Applied*, Vol. 10, 047001, 2018.
- [12] Yu, Z. and S. Fan, "Complete optical isolation created by indirect interband photonic transitions," *Nature Photonics*, Vol. 3, 91–94, 2009.
- [13] Yu, L. and B. Zhang, "Energy variation in stochastically driven light walks [Invited]," *Optical Materials Express*, Vol. 15, No. 3, 555, February 2025.
- [14] Long, Y., L. Zou, L. Yu, H. Hu, J. Xiong, and B. Zhang, "Inverse design of topological photonic time crystals via deep learning," *Optical Materials Express*, Vol. 14, No. 8, 2032, July 2024.
- [15] Tripathi, A., C. F. Ugwu, V. S. Asadchy, I. Faniayeu, I. Kravchenko, S. Fan, Y. Kivshar, J. Valentine, and S. S. Kruk, "Nanoscale optical nonreciprocity with nonlinear metasurfaces," *Nature Communications*, Vol. 15, No. 1, 5077, June 2024.
- [16] Cotrufo, M., A. Cordaro, D. L. Sounas, A. Polman, and A. Alù, "Passive bias-free non-reciprocal metasurfaces based on thermally nonlinear quasi-bound states in the continuum," *Nature Photonics*, Vol. 18, No. 1, 81–90, November 2023.
- [17] Yang, W., J. Qin, J. Long, W. Yan, Y. Yang, C. Li, E. Li, J. Hu, L. Deng, Q. Du, and L. Bi, "A self-biased non-reciprocal magnetic metasurface for bidirectional phase modulation," *Nature Electronics*, Vol. 6, No. 3, 225–234, March 2023.
- [18] Liu, G.-G., S. Mandal, X. Xi, Q. Wang, C. Devescovi, A. Morales-Pérez, Z. Wang, L. Yang, R. Banerjee, Y. Long, Y. Meng, P. Zhou, Z. Gao, Y. Chong, A. García-Etxarri, M. G. Vergniory, and B. Zhang, "Photonic axion insulator," *Science*, Vol. 387, No. 6730, 162–166, January 2025.
- [19] Li, Y.-L., T.-F. Li, Q.-Y. Wen, F. Fan, Q.-H. Yang, and S.-J. Chang, "Terahertz magneto-optical effect of wafer-scale La: Yttrium iron garnet single-crystal film with low loss and high permittivity," *Optics Express*, Vol. 28, No. 14, 21062, July 2020.
- [20] Li, Y.-L., D. Zhang, M. Luo, Q.-H. Yang, F. Fan, S.-J. Chang, and Q.-Y. Wen, "Terahertz magneto-optical response of bismuth-gadolinium-substituted rare-earth garnet film," *Optics Express*, Vol. 29, No. 15, 23540, July 2021.
- [21] Zhang, X., D. Zhao, D. Zhang, Q. Xue, F. Fan, Y. Liao, Q. Yang, and Q. Wen, "Wafer-level substrate-free YIG single crystal film for a broadband tunable terahertz isolator," *Photonics Research*, Vol. 12, No. 3, 505, March 2024.
- [22] Li, Z.-Z., H. Fan, L. Wang, X. Zhang, X.-J. Zhao, Y.-H. Yu, Y.-S. Xu, Y. Wang, X.-J. Wang, S. Juodkazis, Q.-D. Chen, and H.-B. Sun, "Super-stealth dicing of transparent solids with nanometric precision," *Nature Photonics*, Vol. 18, No. 8, 799–808, May 2024.
- [23] Jiang, L., A.-D. Wang, B. Li, T.-H. Cui, and Y.-F. Lu, "Electrons dynamics control by shaping femtosecond laser pulses in micro/nanofabrication: Modeling, method, measurement and application," *Light: Science & Applications*, Vol. 7, No. 2, 17134, August 2017.
- [24] Meza, L. R., S. Das, and J. R. Greer, "Strong, lightweight, and recoverable three-dimensional ceramic nanolattices," *Science*, Vol. 345, No. 6202, 1322–1326, September 2014.
- [25] Yuan, S., L. Chen, Z. Wang, W. Deng, Z. Hou, C. Zhang, Y. Yu, X. Wu, and X. Zhang, "On-chip terahertz isolator with ultrahigh isolation ratios," *Nature Communications*, Vol. 12, No. 1, 5570, September 2021.
- [26] Tamagnone, M., C. Moldovan, J.-M. Pouirol, A. B. Kuzmenko, A. M. Ionescu, J. R. Mosig, and J. Perruisseau-Carrier, "Near optimal graphene terahertz non-reciprocal isolator," *Nature Communications*, Vol. 7, No. 1, 11216, April 2016.
- [27] Mu, Q., F. Fan, S. Chen, S. Xu, C. Xiong, X. Zhang, X. Wang, and S. Chang, "Tunable magneto-optical polarization device for terahertz waves based on InSb and its plasmonic structure," *Photonics Research*, Vol. 7, No. 3, 325–331, February 2019.
- [28] Jia, R., T. C. Tan, S. S. Mishra, W. Wang, Y. J. Tan, and R. Singh, "On-chip active non-reciprocal topological photonics," *Advanced Materials*, Vol. 37, No. 26, 2501711, April 2025.
- [29] Lin, S., S. Silva, J. Zhou, and D. Talbayev, "A one-way mirror: High-performance terahertz optical isolator based on magnetoplasmonics," *Advanced Optical Materials*, Vol. 6, No. 19, 1800572, July 2018.
- [30] Zhao, D., F. Fan, Z. Tan, H. Wang, and S. Chang, "Tunable on-chip terahertz isolator based on nonreciprocal transverse edge spin state of asymmetric magneto-plasmonic waveguide," *Laser & Photonics Reviews*, Vol. 17, No. 2, 2200509, November 2022.
- [31] Zhang, J. C., G.-B. Wu, M. K. Chen, X. Che, Y. Liang, D. P. Tsai, and C. H. Chan, "Electromagnetic wave tailoring: From one dimension to multiple dimensions," *Electromagnetic Science*, Vol. 1, No. 3, 1–21, September 2023.
- [32] Liu, C., F. Yang, S. Xu, and M. Li, "Reconfigurable metasurface: A systematic categorization and recent advances," *Electromagnetic Science*, Vol. 1, No. 4, 1–23, December 2023.

- [33] Shalaginov, M. Y., S. An, Y. Zhang, F. Yang, P. Su, V. Liberman, J. B. Chou, C. M. Roberts, M. Kang, C. Rios, Q. Du, C. Fowler, A. Agarwal, K. A. Richardson, C. Rivero-Baleine, H. Zhang, J. Hu, and T. Gu, “Reconfigurable all-dielectric met-alens with diffraction-limited performance,” *Nature Communi-cations*, Vol. 12, No. 1, 1225, February 2021.
- [34] Shalaginov, M. Y., S. D. Campbell, S. An, Y. Zhang, C. Rios, E. B. Whiting, Y. Wu, L. Kang, B. Zheng, C. Fowler, H. Zhang, D. H. Werner, J. Hu, and T. Gu, “Design for quality: Reconfig-urable flat optics based on active metasurfaces,” *Nanophotonics*, Vol. 9, No. 11, 3505–3534, June 2018.
- [35] Pi, D., J. Liu, and Y. Wang, “Review of computer-generated hologram algorithms for color dynamic holographic three-dimensional display,” *Light: Science & Applications*, Vol. 11, No. 1, 231, July 2022.
- [36] Wu, J., K. Liu, X. Sui, and L. Cao, “High-speed computer-generated holography using an autoencoder-based deep neural network,” *Optics Letters*, Vol. 46, No. 12, 2908–2911, June 2021.
- [37] Georgi, P., Q. Wei, B. Sain, C. Schlickriede, Y. Wang, L. Huang, and T. Zentgraf, “Optical secret sharing with cascaded metasur-face holography,” *Science Advances*, Vol. 7, No. 16, eabf9718, April 2021.
- [38] Shi, L., B. Li, C. Kim, P. Kellnhofer, and W. Matusik, “To-wards real-time photorealistic 3D holography with deep neural networks,” *Nature*, Vol. 591, No. 7849, 234–239, March 2021.
- [39] Ni, X., A. V. Kildishev, and V. M. Shalaev, “Metasurface holo-grams for visible light,” *Nature Communications*, Vol. 4, 2807, 2013.
- [40] Wang, L., S. Kruk, H. Tang, T. Li, I. Kravchenko, D. N. Neshev, and Y. Kivshar, “Grayscale transparent metasurface holograms,” *Optica*, Vol. 3, No. 12, 1504–1505, 2016.
- [41] Wu, J. W., Z. X. Wang, L. Zhang, Q. Cheng, S. Liu, S. Zhang, J. M. Song, and T. J. Cui, “Anisotropic metasurface holography in 3-D space with high resolution and efficiency,” *IEEE Trans-actions on Antennas and Propagation*, Vol. 69, No. 1, 302–316, January 2021.
- [42] Nath, U., S. Banerjee, C. Santini, R. Citroni, F. Mangini, and F. Frezza, “Simple and cost-effective design of a THz-metamaterial-based hybrid sensor on a single substrate,” *Sen-sors*, Vol. 25, No. 12, 3660, 2025.