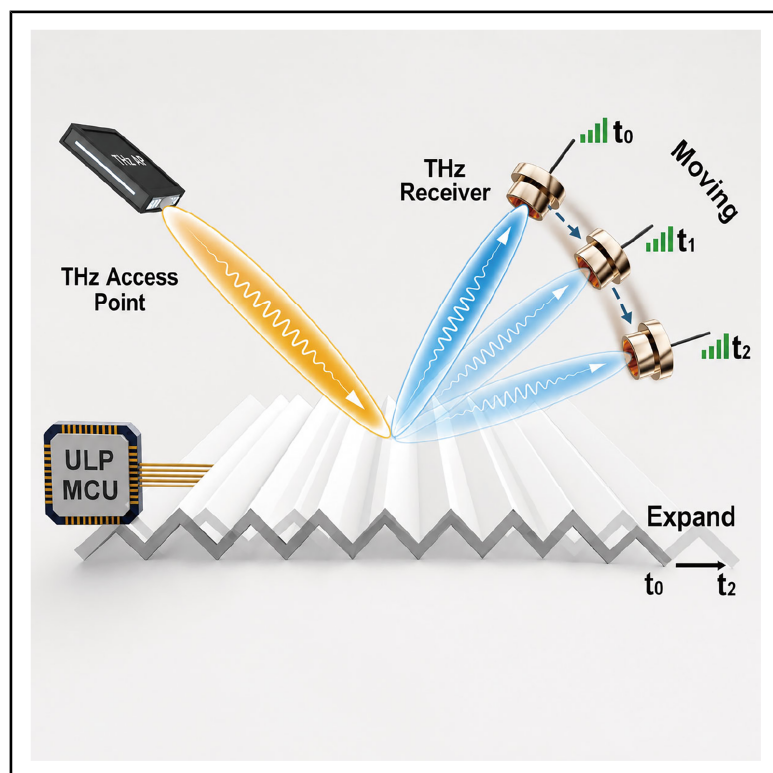


Mechanically programmable metasurface for ultralow-power subterahertz beam steering

Graphical abstract



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In brief

Tan et al. show that a mechanically latched metasurface can steer subterahertz beams by changing its surface shape rather than maintaining electrical bias. The low-cost platform holds beam states without holding power, supports multiple beams and beam tracking, and offers an energy-efficient route to directional wireless links.

Highlights

- Mechanical latching steers subterahertz beams without holding power
- Millimeter-scale tuning enables continuous and multi-beam steering
- A prototype offers low-cost beamforming for dense mobile links



Article

Mechanically programmable metasurface for ultralow-power subterahertz beam steering

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SUMMARY

Metasurfaces are promising for shaping terahertz wavefronts, but reconfigurable platforms remain constrained by trade-offs among programmability, energy consumption, and cost. Many active metasurfaces require continuous electrical bias to hold states, whereas low-cost passive designs are static. Here, we report a mechanically latched programmable metasurface that steers subterahertz beams by tuning the period of periodic wavy metal elements, thereby reconfiguring the diffraction-induced phase distribution. A lead-screw-driven scissor-telescopic mechanism provides repeatable millimeter-scale geometric tuning under microcontroller control and retains states without holding power. Experiments over 110–170 GHz demonstrate continuous beam steering with a 1.2° average pointing error, simultaneous steering of up to five beams, and real-time tracking up to 25°/s. In a 150-GHz 16-quadrature amplitude modulation (16-QAM) link, it supports multi-direction reception with symbol error rates below 10^{−6} in target beam directions. With a US\$21.12 prototype cost and microwatt-level standby electronics power, this metasurface offers a low-cost route to energy-efficient beamforming for dense, mobile subterahertz links.

INTRODUCTION

Terahertz wireless links are being actively explored to meet the growing demand for high data rates and device density in beyond 5G and 6G networks.¹ Operating at wavelengths of only a few millimeters to submillimeters, these bands offer large contiguous bandwidth^{2–6} but also impose stringent requirements on directional transmission because free-space path loss and blockage sensitivity increase rapidly with frequency.^{7,8} Maintaining reliable links in non-line-of-sight (NLOS), high-concurrency, and mobile scenarios therefore hinges on fast and energy-efficient beam steering and beam management.

Conventional electronic beamforming solutions, such as phased arrays, provide flexible steering but typically rely on many radio frequency (RF) chains, phase shifters, and tightly integrated antenna elements, which increase cost, complexity, and power consumption—challenges that become more pronounced as the operating frequency approaches the subterahertz regimen.^{9–12} Frequency-scanned architectures such as leaky-wave antennas can reduce hardware overhead,^{13,14} but their steering characteristics are strongly coupled to frequency and often constrained to predetermined bands and scan trajectories, limiting their usefulness for agile beam management in dynamic networks.¹⁵

In recent years, terahertz beam steering and wavefront shaping have been driven by the rapid development of metadevices. Emerging studies have enabled diverse functionalities in

the terahertz regimen, including spin-selective beam steering, energy redistribution, vortex-vector beam conversion, chiral field manipulation, unidirectional focusing of surface plasmons, and programmable vortex interference.^{16–19} Metasurfaces offer an alternative route to wavefront control by engineering spatial phase discontinuities across a thin surface.²⁰ Passive metasurfaces are inexpensive and compact, but their beam patterns are fixed after fabrication.^{21–25} Reconfigurable metasurfaces have been demonstrated using tunable materials and electronic biasing schemes, including liquid crystals,^{26–28} phase-change materials,^{29,30} mechanical devices,^{31,32} and two-dimensional materials.^{33,34} However, many of these approaches require a continuous holding bias to maintain a programmed state, leading to non-negligible standby power and added system overhead. For infrastructure-grade deployments, where beam states may be held for long durations and only updated intermittently, holding power can dominate the long-term energy cost, motivating reconfigurable architectures that decouple state retention from energy consumption.

Here we introduce a mechanically latched, programmable subterahertz metasurface that steers one beam or multiple beams by physically tuning the surface profile of periodic wavy metallic elements, as shown in Figure 1. Our approach leverages diffraction from a periodic undulating reflector: an incident wave is scattered into multiple diffraction orders, and constructive interference among the reflected fields forms directive beams whose angles are governed by a grating-type phase-matching



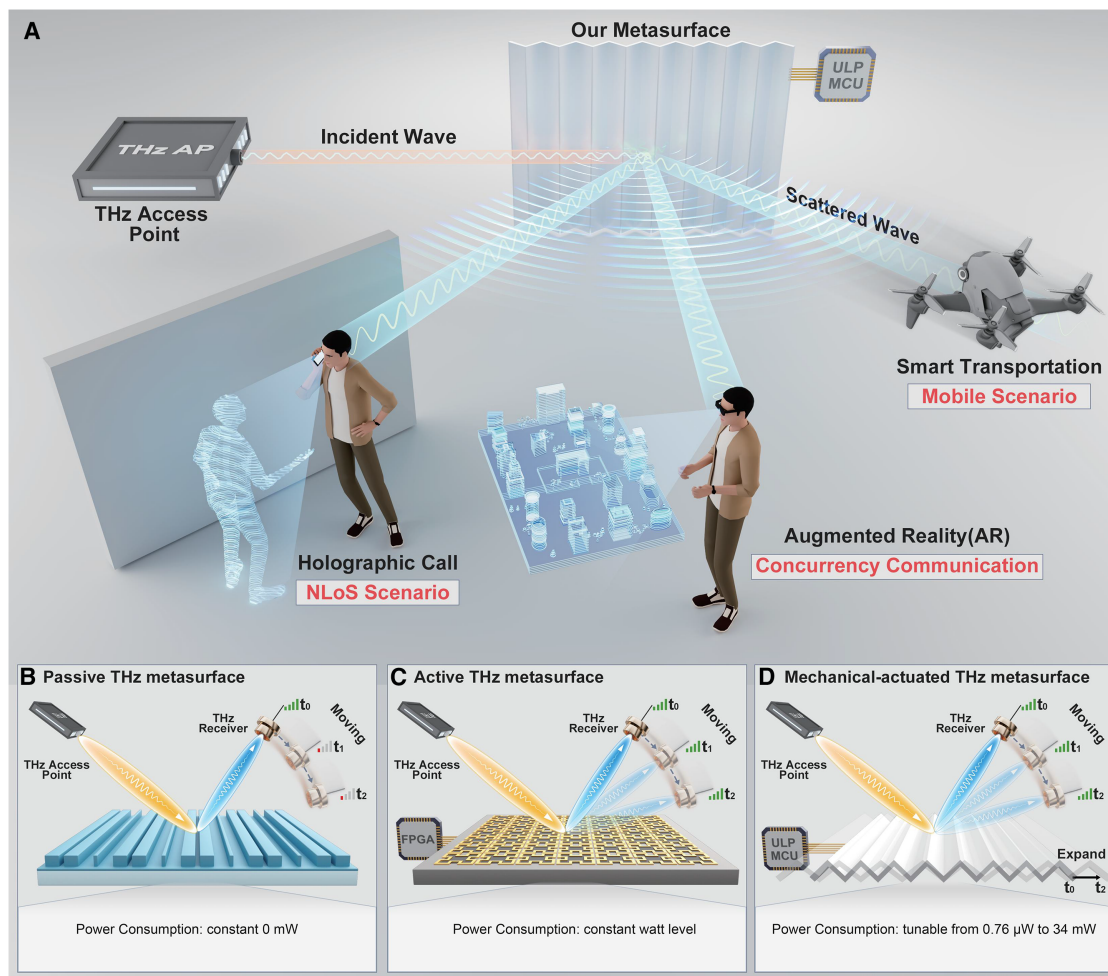


Figure 1. Overview of the mechanically programmable terahertz metasurface

(A) Conceptual schematic illustrating use of the proposed metasurface to support terahertz communication links in non-line-of-sight (NLoS) propagation, concurrent connections, and mobile scenarios.

(B) Passive terahertz metasurface: low cost and low system complexity but without programmability for dynamic beam steering.

(C) Active terahertz metasurface: enables agile beam control but typically incurs higher cost and increased power consumption.

(D) Mechanically programmable terahertz metasurface: achieves reconfigurable beam steering controlled by an ultra-low-power microcontroller (ULP MCU) while retaining low cost and low power consumption.

condition. By changing the effective period of the wavy elements, the metasurface reconfigures the diffraction-induced phase distribution and thus the beam directions. Importantly, once the geometry is set, the programmed state is retained mechanically without electrical holding power.

To enable precise and repeatable geometric programming, we implement a lead screw-driven scissor-telescopic mechanism that tunes the element period with millimeter-scale resolution under microcontroller control. We further formulate a beam optimization routine that selects the incident angle and element periods to enhance power in the desired directions while suppressing undesired orders. Using a prototype operating from 110 to 170 GHz, we experimentally demonstrate continuous beam steering with an average pointing error of 1.2° , simultaneous steering of up to five beams, and real-time beam tracking for a moving receiver at angular velocities up to $25^\circ/\text{s}$. In a 150 GHz link

demonstration with 16-quadrature amplitude modulation (16-QAM), the metasurface enables multi-direction reception with symbol error rates below 10^{-6} in the target beam directions. With a prototype hardware cost of US\$21.12 and microwatt-level standby electronics (Note S1; Table S1), our mechanically reconfigurable metasurface provides an energy-efficient and low-cost beamforming primitive for dense, concurrent, and mobile subterahertz links.

RESULTS

Principle of beam generation by a wavy element metasurface

The key idea of a mechanically actuated programmable terahertz metasurface is illustrated schematically in Figure 2. We investigate the beam generation capability of our metasurface

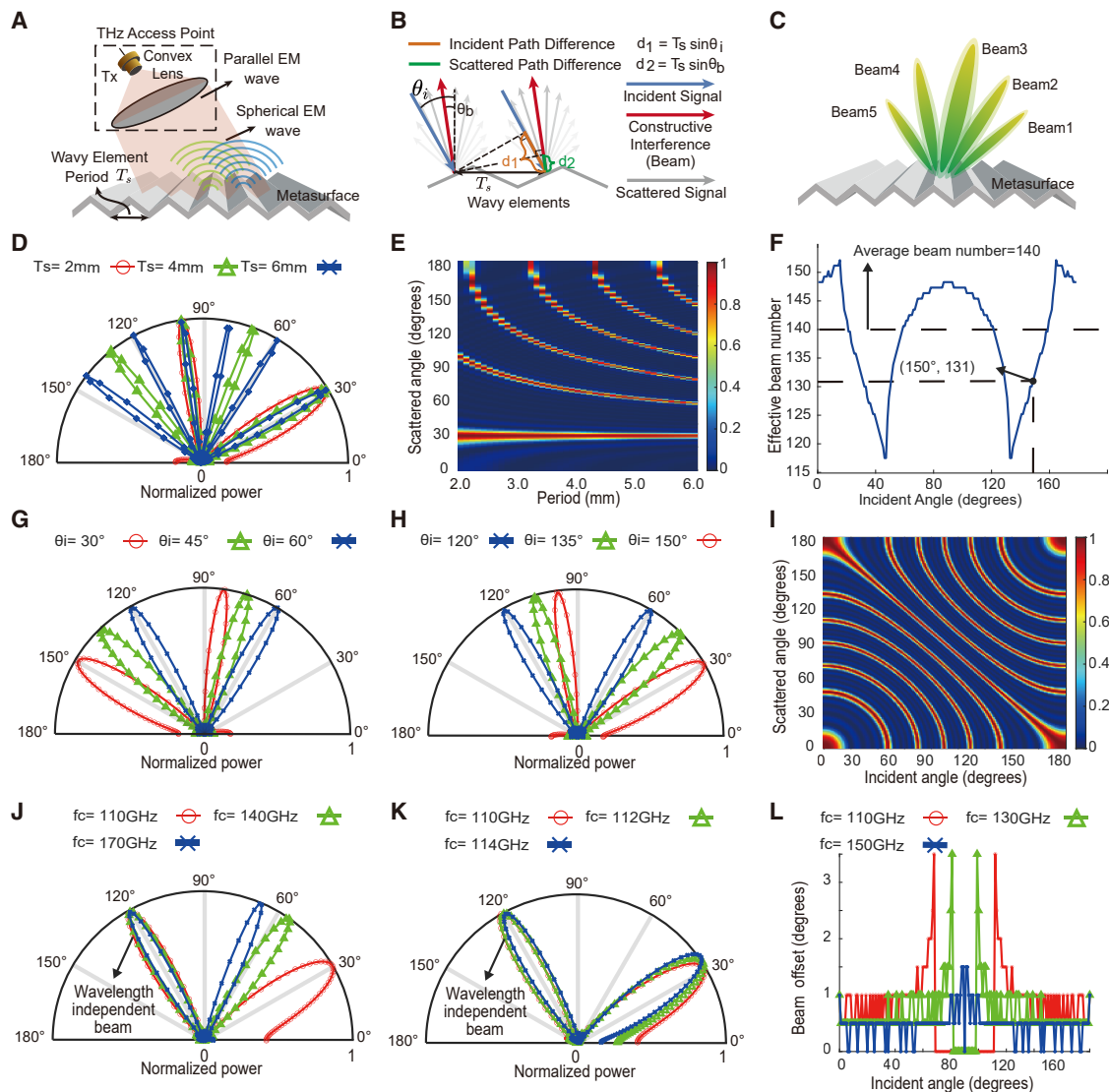


Figure 2. Operating principle and beam-steering characteristics of the mechanically actuated metasurface

(A) Schematic of the metasurface comprising a periodic array of triangular wavy elements; incident subterahertz waves are reflected and diffracted.
 (B) Diffraction-induced phase differences among waves reflected from adjacent elements produce constructive interference at discrete angles, yielding directional beams.
 (C) Mechanical tuning of the wavy element period modulates the inter-element phase difference and thereby steers the beam.
 (D) Calculated beam directions as a function of the wavy element period.
 (E) Angular intensity distribution of scattered beams for different wavy element periods at a fixed incident angle of 150°; color indicates normalized beam intensity.
 (F) Number of accessible steering angle states versus incident angle.
 (G and H) Beam directions for six representative incident angles, highlighting reciprocity between incident and reflected directions.
 (I) Beam direction distribution across incident angles.
 (J) Beam directions at incident frequencies of 110, 140, and 170 GHz, demonstrating frequency-dependent steering.
 (K) Beam shift versus frequency spacing.
 (L) Maximum beam shift within a 2 GHz bandwidth for different carrier frequencies.

with wavy elements. The main principle is that, when an external parallel electromagnetic (EM) wave is incident on the metasurface, the uneven surface causes the signal to scatter in different directions (Figure 2A). According to Bragg's law, the scattered beams undergo diffraction, forming spherical waves that radiate outward through the aper-

tures. During this process, the spherical waves diffracted from different wavy elements and interfered with each other, further forming beams. The key to analyzing the beam direction is understanding the phase difference between the spherical waves radiating from different apertures (Figure 2B). For two adjacent wavy elements, their phase difference

primarily arises from the differences in the incident path and the scattered path.

Note that the direction of the scattering angle is outwardly divergent, since diffraction generates spherical waves. Moreover, only directions where the path difference is an integer multiple of the wavelength form a beam (Figure 2C). Therefore, we can obtain the beam mapping model to represent the relation between beam direction and wavy element parameters as

$$T_s(\sin \theta_i + \sin \theta_r) = n\lambda_i, \quad (\text{Equation 1})$$

where T_s denotes the period of the wavy element, θ_i is the incident angle of the terahertz transmitter, θ_r is the scattering angle from the spherical waves, $\lambda_i = \frac{c}{f_c}$ denotes the wavelength of the incident wave, $n = 0, \pm 1, \pm 2, \dots$, is the interference series, c is speed of light in a vacuum, and f_c is the incident frequency. Notably, when $n = 0$, Equation 1 reduces to the specular reflection condition, indicating that the zeroth-order reflected beam is an intrinsic diffraction order of the platform. Rather than targeting its elimination, our metasurface operates by redistributing the reflected energy among the accessible diffraction orders through mechanical programming of the element period (see Note S2 and Figure S1 for quantitative comparisons of the target and specular beams).

From the beam steering principle of our metasurface in Equation 1, we observe that the period of the wavy elements (T_s), the incident angle (θ_i), and wavelength (λ_i) together determine the beam direction, and the following relationships exist. First, when the incident wavelength (λ_i) is fixed, the beam directions are primarily determined by the period of the wavy elements (T_s) and the incident angle (θ_i). Therefore, we can adjust these two parameters to achieve beam steering. Second, incident and scattered angles exhibit angle reciprocity. Specifically, when the incident angle is θ_i , the corresponding beam angles include θ_r . Conversely, when the incident angle is θ_r , the beam angles include θ_i . This indicates that our metasurface supports bidirectional communication for both uplink and downlink. Third, the wavelength of the incident wave (λ_i) determines that the period of our wavy element (T_s) should be within the same order of magnitude to satisfy the diffraction condition. Thus, EM waves undergo diffraction on the surface of the wavy element, and variations in the wavy element period lead to significant phase changes in the scattered spherical waves, resulting in altering the beam directions.

Experimental validation of beam generation

To validate the beam generation capabilities of our metasurface, we conduct a scale-model test bed (see experimental methodology and setup under methods). A dual-station subterahertz device is used to transmit and receive subterahertz signals from 110 to 170 GHz. We choose the triangular wavy element to balance the trade-off between the controllability and the beam quality (see Note S3 and Figure S2 for the comparison among different wavy element shapes). The wavy element period (T_s), incident angle (θ_i), and incident wavelength (λ_i) are exploited for the beam direction of our metasurface.

- (1) Impact of wavy element period. First, we intuitively observe the impact of different wavy element periods on

the beam. The incident frequency is 150 GHz, the incident angle is set at 150° , and the period of the wavy element is varied from 2 to 6 mm. As shown in Figure 2D, the beam directions are related to the period of the wavy elements. Besides, the number of beams increases as T_s increases. Specifically, when T_s values of 2, 4, and 6 mm correspond to 2, 4, and 6 beams, respectively. This is because, within the scattering angle range of 0° – 180° , the solutions in Equation 1 are non-unique, and a larger T_s simultaneously satisfies the conditions for other interference series. Next, we quantitatively analyze the impact of the wavy element period on the beam direction by finely varying the wavy element period from 2 to 6 mm. As shown in Figure 2E, the relationship between beam direction and wavy period is continuous, and our method achieves an adjustable beam range of up to 131° . The effective beam number under different incident angles is shown in Figure 2F; our method demonstrates an average of 140 effective steerable angular states. Additional analysis further shows that larger target angles do not necessarily lead to lower target-beam intensity (Note S2; Figure S3).

- (2) Impact of incident angle. First, we intuitively observe the impact of different incident angles on the beam. Figures 2G and 2H show the beam directions corresponding to an incident frequency of 150 GHz, the wavy element period of 2 mm, and incident angles of 30° , 45° , 60° , 120° , 135° , and 150° . We find that the beam direction can be effectively controlled by adjusting the incident angle, and the number of beams is not unique. Moreover, the incident angle and beam direction are paired, which also verifies the reciprocity of our metasurface. The overall relationship between the incident angle and the beam direction is shown in Figure 2I. The wavy element period is set to 6 mm. It can be observed that the beam can scan within 180° by adjusting the incident angle.
- (3) Impact of incident wavelength. We first intuitively investigate the impact of different wavelengths on the beam direction of our metasurface across the 110–170 GHz subterahertz band. The incident angle is set to 60° , the period of the wavy elements is set to 2 mm, and the incident frequency varied from 110 and 140 to 170 GHz. As shown in Figure 2J, a significant variation in the input frequency can lead to a shift in the beam direction. However, there is a wavelength-independent beam in a specific direction. This phenomenon arises because the scattered path compensates for the phase difference caused by the incident path according to Equation 1. Then, we reduce the input signal bandwidth to 2 GHz to meet the commercial communication requirements, and the beam direction difference decreases to 2.5° , as shown in Figure 2K. Next, a limited analysis is conducted to evaluate the maximum impact of wavelength on our metasurface. As shown in Figure 2L, we compare the beam steering offsets for carrier frequencies of 110, 130, and 150 GHz with the bandwidth of 2 GHz, and the average beam steering offsets are 0.75° , 0.64° , and 0.49° , respectively. Note that, when the incident angle is within the range of 70° – 110° , the beam offset reaches 0° . This can

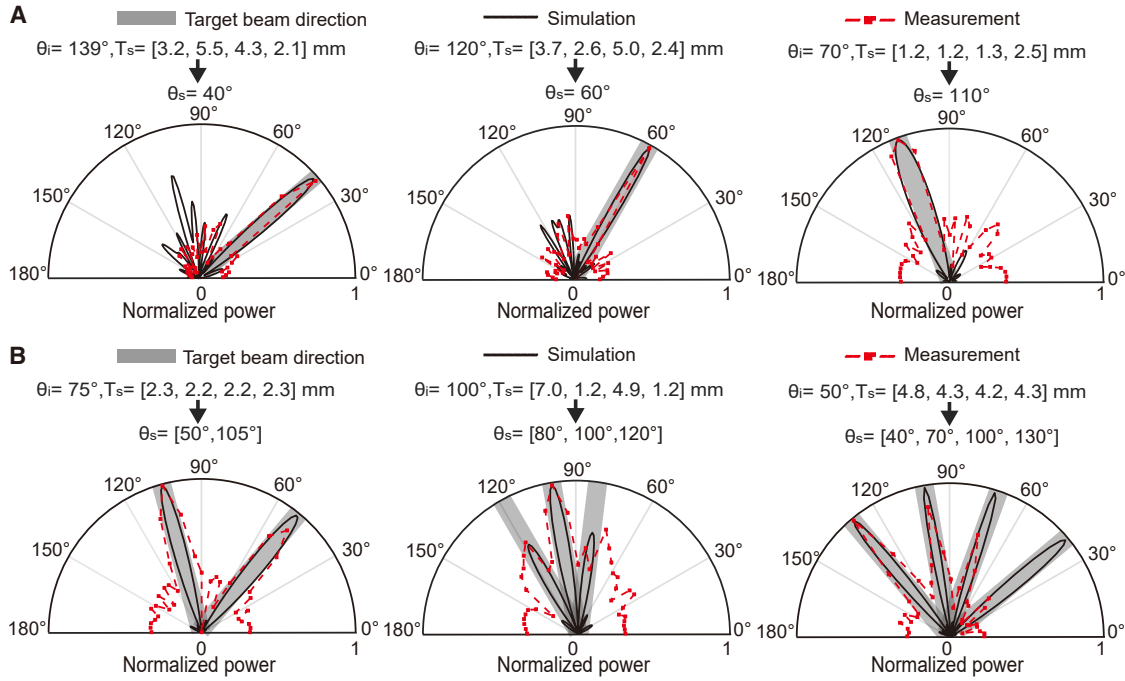


Figure 3. Illustration of the target beam generation

By tuning the metasurface parameters, the device can generate either a single beam or multiple beams at prescribed directions. The metasurface comprises four wavy elements, and the output beam directions are controlled by the period of each element (T_s) and the incidence angle (θ_i).

(A) Single-beam operation with steering to three representative directions.

(B) Multi-beam operation producing beams in two, three, and four directions.

be attributed to the increase in beam width, which mitigates the effect of wavelength on beam steering. The results demonstrate that our metasurface has the potential to support broadband data transmission (see [Note S2](#) and [Figure S4](#) for the broader-frequency adaptability analysis).

Mechanically programmable beam steering

As demonstrated above, our metasurface can generate scattered beams. However, the direction and number of beams are jointly influenced by parameters such as the wavy element period, incident angle, and wavelength. Therefore, determining the optimal parameters to meet the beam requirements for various scenarios remains a significant challenge. To address this issue, we propose a beam optimization method based on sequential quadratic programming (SQP). Our basic idea is to adjust the period of the wavy elements and the incident angle to maximize the beam power in the target directions while suppressing the beam power in non-target directions. To be specific, based on [Equation 1](#), the objective function is formulated as

$$\min J(\theta_i, \mathbf{T}_s) = -a \sum_{\alpha_r \in \theta_s} |A(\theta_i, \alpha_r, \mathbf{T}_s)|^2 + b \sum_{\beta_r \in \theta_u} |A(\theta_i, \beta_r, \mathbf{T}_s)|^2, \quad (\text{Equation 2})$$

where θ_i is the incident angle, $\mathbf{T}_s$ is the vector of different wavy element periods, θ_s is the set of target beam directions, and θ_u

is the set of non-target beam directions. a and b are the weight factors. $A(\theta_i, \alpha_r, \mathbf{T}_s)$ is the array factor field amplitude,

$$A(\theta_i, \alpha_r, \mathbf{T}_s) = \sum_{T \in \mathbf{T}_s} \exp \left(j \frac{2\pi}{\lambda_i} x_m(T) (\sin \theta_i + \sin \alpha_r) \right), \quad (\text{Equation 3})$$

where λ_i is the incident wavelength, and $x_m(T)$ denotes the lateral position of the m -th effective scattering element, obtained from the cumulative programmed periods. Then, we transform this nonlinear optimization problem into a series of quadratic programming (QP) subproblems for iterative solving. Finally, the optimal control parameters can be determined by incorporating constraints on the incident angle and the period of the wavy elements (see [Method S1](#), algorithm 1; [Figure S5](#); and [Table S2](#) for the detailed optimization workflow, convergence behavior, and ablation comparison).

Here, we evaluate the beam-steering performance of our metasurface. The number of wavy elements is set to 4 to ensure that the terahertz signal emitted by the transmitter completely covers the entire wavy elements. Subsequently, the period of these four wavy elements and the incident angles are precisely adjusted according to the optimal parameters. We establish a spatial correlation between radiation direction and signal strength distribution through angle-dependent measurements of received signal strength. As illustrated in [Figure 3](#), our method optimizes the parameters to maximize beam energy in the

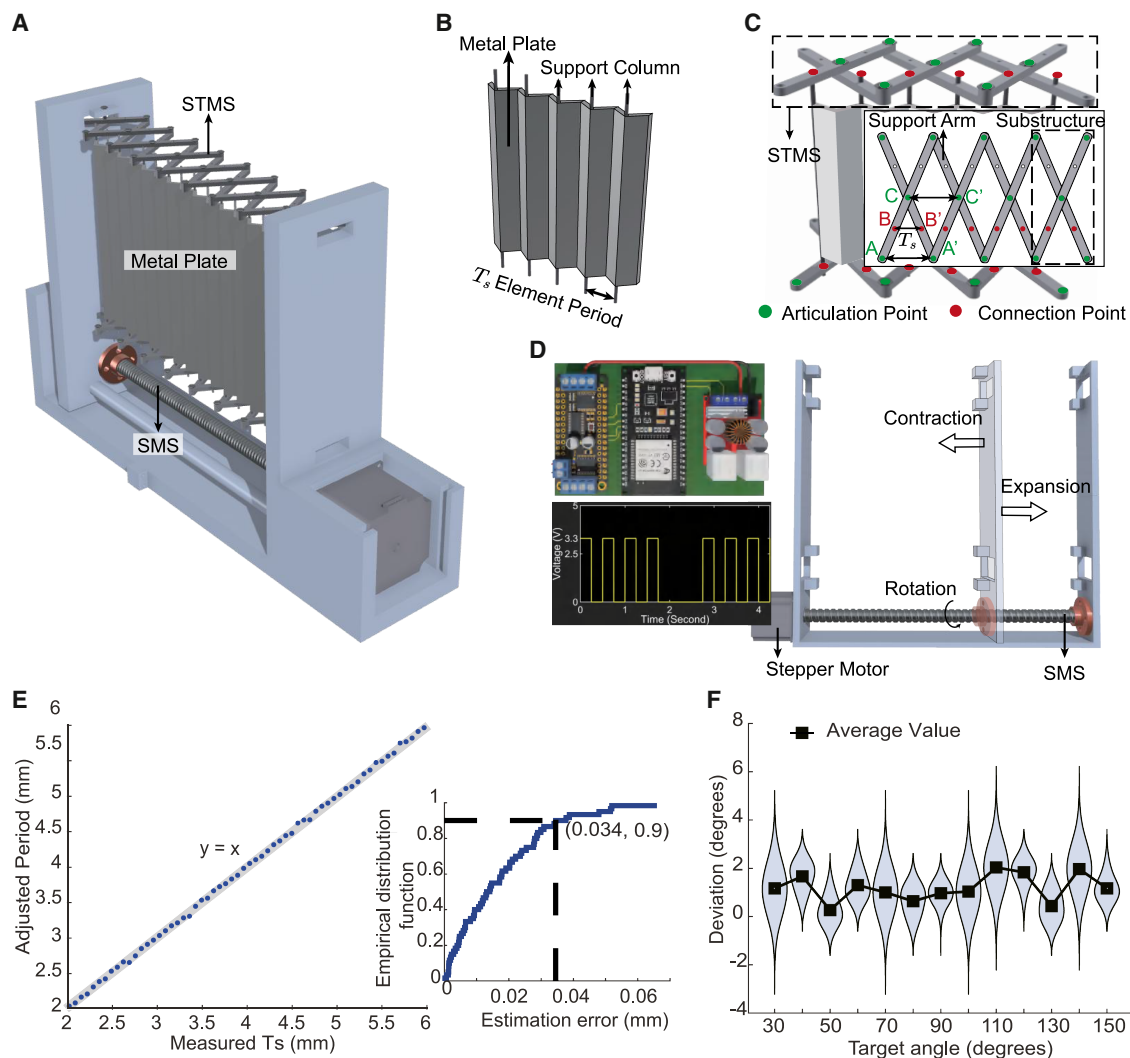


Figure 4. Hardware architecture overview

(A) Mechanical assembly comprising a metal plate, a scissor telescopic mechanical structure (STMS), and a screw mechanical structure (SMS). The metal plate is mounted on the STMS to form triangular wavy elements; SMS expansion/contraction tunes the wavy element period.

(B) Metal plate design. The plate is segmented and supported by columns that constrain each wavy element, forming a periodic undulating surface.

(C) STMS design. The STMS consists of multiple scissor-telescopic substructures; perforations (A–C) define the inter-substructure links and the support-arm connections, and the support columns mount through perforation (B).

(D) Control circuitry and SMS actuation principle. A microcontroller generates drive pulses for the stepper motor, which actuates the SMS and, in turn, expands/contracts the STMS to adjust the period.

(E) Target versus measured wavy element period, showing a linear relationship with 90% of measurements exhibiting an error below 0.034 mm.

(F) Target versus measured beam direction across orientations. The mean angular deviation is 1.2° , attributable to residual period-setting errors.

desired direction while effectively suppressing side lobe energy. For single-beam scenarios (Figure 3A), we alter the orientation of the target beam and compute the optimal metasurface parameters utilizing the SQP algorithm. Through simulation and empirical measurement, the results show that our metasurface is capable of effectively generating the single target beam. In multiple-beam scenarios, our metasurface generates beams in two, three, and four directions. Figure 3B demonstrates that our method efficiently allocates and steers beams to meet specific multi-beam requirements. Under fixed-incidence conditions, the achievable beam steering scan remains effective but

bounded by diffraction-order accessibility and structural degrees of freedom (Note S2 and Figure S6).

Next, we exploit fine-grained period control for our wavy elements. We design a mechanical control structure with millimeter-level control accuracy, consisting of a scissor telescopic mechanical structure (STMS) and a screw mechanical structure (SMS), as shown in Figure 4. During the beam steering process, STMS establishes a global baseline displacement, which further alters the period of the wavy element (Figure 4C). We analyze the impact of STMS on the variation in the period of wavy elements and determine the optimal coupling position of wavy elements

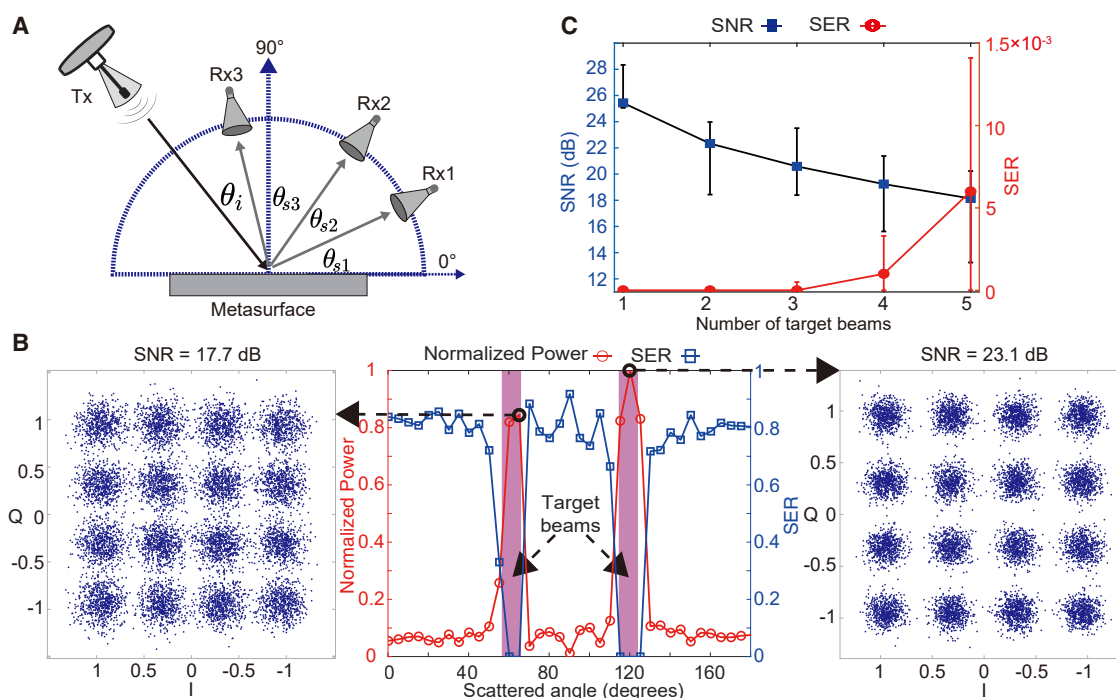


Figure 5. Concurrent communication performance

(A) Experimental configuration for concurrent communication. The receive antenna is scanned along a semicircle to sample subterahertz signals reflected by the metasurface; 1–5 simultaneous beams are evaluated.

(B) Two-beam example showing received power and symbol error rate (SER) versus angle. Constellations indicate SNRs of 17.7 and 23.1 dB at the two target directions.

(C) SNR and SER as a function of the number of target beams, revealing an SNR decrease and SER increase with beam count (SER = 1.4×10^{-3} for five beams). The error bars refer to standard deviation.

with STMS (see [STMS](#) under [methods](#)). Then, the SMS powered by a stepper motor is leveraged to control the deformation of the STMS, which converts the stepper motor's rotational power into linear driving force, thus enabling STMS to achieve millimeter-level precision in movement (see [millimeter-scale period control](#) under [methods](#)).

We evaluate the beam control capability of our method. The microcontroller generates pulse signals to drive the stepper motor, advancing the linear displacement in 0.1 mm increments. The period of the wavy element is measured using a caliper.

Figure 4E illustrates the linear relationship between the measured and control periods. The results indicate a strong linear correlation. Compared to the measured period, the adjustment error has a mean of $-1.2 \mu\text{m}$ and a standard deviation of $22.6 \mu\text{m}$. Next, we control the period of the wavy elements to generate beams in the target direction. We then measure the deviation between the target beam direction and the measured beam direction. As illustrated in Figure 4F, our method achieves an average beam steering accuracy of 1.2° by conducting repeated experiments to meet the beam requirements in different directions. This highlights the system's capability for accurate and fine-grained beam steering (see [Note S2](#) and [Figure S7](#) for the sensitivity analysis of fabrication and alignment errors, and see [Note S4](#) and [Figure S8](#) for the repeated-cycle repeatability and reliability evaluation).

Concurrent and mobile communication performance

Here, we build a prototype (see [fabrication](#) under [methods](#)) to evaluate our method's overall performance in the concurrency and mobile scenarios ([Video S1](#)).

Concurrent communication

To demonstrate the ability of concurrent data backscattering in a multi-user scenario, we receive the modulated signal at different angles (Figure 5A). The concurrent communication capability is evaluated based on the received signal power and symbol error rate (SER). We first evaluate the decoding capability of the received signal in the direction of the target beam. The period of every wavy element is set to 2.1 mm, with an incident angle of 60° , and the carrier frequency is configured at 150 GHz. Figure 5B presents the decoding results for beam signals received at different angles. The results demonstrate that the beam effectively assists communication, achieving an average SER below 10^{-6} . Furthermore, error-free decoding can be achieved by increasing the transmitted signal power and incorporating error correction schemes.³⁵ We randomly generate beams with varying numbers of beams and measure the signal-to-noise ratio (SNR) and SER, as shown in Figure 5C. Note that increasing the number of beams reduces the average gain of each beam because the reflected energy is redistributed among more accessible diffraction orders. This energy-splitting effect is the physical trade-off associated with wider angular

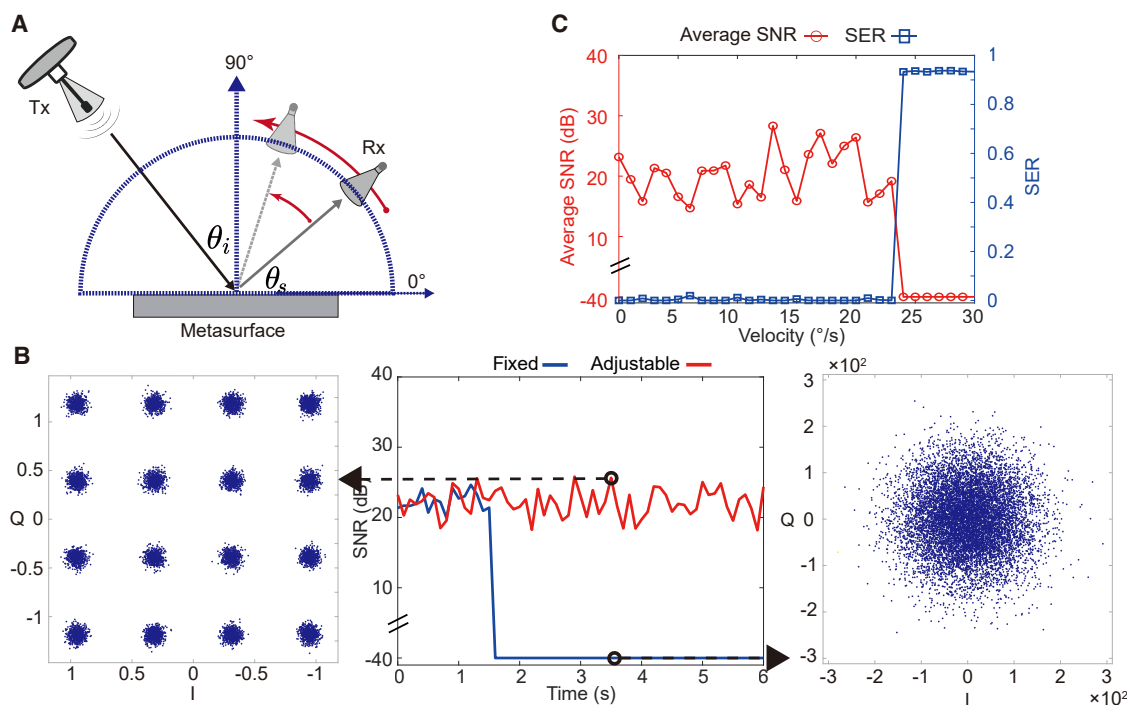


Figure 6. Mobile communication performance

(A) Mobile link schematic. The receive antenna moves anticlockwise at different angular velocities along a constant-radius trajectory, while the metasurface steers the beam to track the receiver.

(B) Mobile performance with fixed versus adaptive beam assistance. Adaptive steering maintains a stable SNR and sustained low SER, whereas a fixed beam exhibits rapid SNR degradation as the receiver moves off-boresight.

(C) Average received SNR versus angular velocity, showing stable operation up to 25°/s.

coverage and multi-beam generation. As the beam count increases, the weakest-user quality also degrades first, because the weakest target direction is the most sensitive to limited aperture resources and inter-beam leakage. However, our method still supports low-error-rate communication under different beam-concurrency levels (see Note S2 and Figure S9 for a more detailed analysis of inter-beam interference and adaptive mitigation). From an application perspective, this capability is particularly relevant to concurrent multi-user coverage, parallel link establishment, and fair directional service (see Note S2 and Figure S10 for additional communication-oriented metrics).

Mobile communication

We evaluate the SNR and SER in the real-time reconfiguration of our metasurface under receiver mobility, as shown in Figure 6A. We first compare the performance of mobile communication assisted by fixed-beam and adaptively steered-beam configurations. The receiver is moved with an angular velocity of 10°/s along a circular arc, and the received SNR is measured. As shown in Figure 6B, the result indicates that the received SNR remains relatively stable with the assistance of the adaptively steered beam. However, fluctuations in beam strength cause some variation in the SNR. In contrast, the received SNR significantly decreases when the receiving direction deviates from the transmission direction of the fixed beam. We then measure the mobile communication performance at different angular velocities. As shown in Figure 6C, when the velocity is below

25°/s, our metasurface can stably adjust the beam direction to support node communication, which is determined by the speed of change in the motor drive cycle (see Note S1 for potential routes toward higher trackable angular velocities).

DISCUSSION

We demonstrated a mechanically latched, programmable subterahertz metasurface that steers one or multiple beams by physically tuning the period of periodic wavy metallic elements. Unlike electronically biased active metasurfaces that require continuous electrical bias to maintain a programmed state, our platform retains its geometry mechanically and therefore requires no electrical holding power to preserve the configured beam directions, although the standby control electronics still operate at the microwatt level. In our prototype, we validate the approach over 110–170 GHz, demonstrating continuous beam steering, simultaneous steering of five beams, and real-time beam tracking for a moving receiver at angular velocities up to 25°/s. These results indicate that mechanically latched programmability can support not only static steering but also concurrent and mobile scenarios that are central to emerging subterahertz networks.

From a system perspective, the proposed architecture targets the practical operating mode of beam management in infrastructure-grade links; beam states are typically held for

long durations and updated intermittently. In this regimen, eliminating holding power can materially reduce long-term energy consumption compared with bias-maintained tunable metasurfaces while avoiding the cost and complexity of subterahertz phased arrays that rely on many RF chains and phase-control components. Our prototype also highlights manufacturability and deployment potential; it uses simple metallic elements and low-cost actuation/control hardware with a total prototype hardware cost of US\$21.12. A broader comparison of the prototype cost and reconfiguration power overhead against representative active metasurfaces is provided in [Note S5](#) and [Table S3](#). This low-cost, low-complexity terahertz metasurface is an attractive candidate for next-generation reconfigurable communication, connectivity, and terahertz systems.

METHODS

STMS

As illustrated in [Figure 4C](#), the STMS is composed of multiple scissor-telescopic substructures. Each substructure is connected by perforated C between two support arms, and adjacent substructures are linked via perforated A.^{36,37} By manipulating the movement of the structure's endpoints, the displacement is effectively transmitted to the substructures while maintaining a constant distance between the articulation points. This displacement transmission property enables precise period control of wavy elements. In our method, the STMS is positioned horizontally to ensure that it is perpendicular to the metal plate. The metal plate is connected to the STMS via support columns to form triangular wavy elements. The support columns are supported through perforated B. When the STMS expands or contracts, the support columns move accordingly, thereby adjusting the period of the wavy elements. Note that the control accuracy of the wavy element period is influenced by two key factors: the choice of connection points and the number of scissor units.

First, the choice of connection points affects the uniformity and control accuracy of the wavy element period. Only articulation points (A) and midpoints of articulation points (B) are present to ensure equal spacing of each cycle during expansion and contraction. Note that, when the stepper motor controls the screw to produce displacement, it causes a change in CC', which, in turn, leads to variations in BB' and AA'. These variations satisfy the relationship $AA' = 2BB' = CC'$. In this case, point B can effectively reduce the displacement caused by the motor control, thereby improving the precision of the motor control. Therefore, we connect the support columns to the midpoints of the articulation points to give more precise control over the element's wave period.

Second, the number of scissor-telescopic substructures also determines the control accuracy. We establish a relationship between the length of STMS and the variety of wavy element periods as

$$\Delta S = 2(n_s - 1) \cdot \Delta T_s, \quad (\text{Equation 4})$$

where ΔS is the control displacement, ΔT_s is the variety of the wavy element period, and n_s is the number of substructures. This equation indicates that an increase in the number of substructures (n_s) allows for more precise control of the period.

However, since the maximum rotational speed of the stepper motor is fixed, an excessively large number of substructures can lead to a decrease in the system's response speed. In our case, we set n_s to 5.

Millimeter-scale period control

We achieve precise control of the stepper motor through the control circuit, as illustrated in [Figure 4D](#). We utilize a millimeter-pitch lead screw mechanism driven by a stepper motor to achieve precise position control. The screw pitch, denoted K, implies that, for each full rotation of the screw with a 1 mm pitch, the control displacement (ΔS) increases by 1 mm. Additionally, the angular resolution of the stepper motor is improved through micro-stepping control. Specifically, the two-phase four-wire stepper motor typically has a step angle (θ_s) of 1.8°, meaning the motor rotates 1.8° per pulse signal received. Micro-stepping control improves motor precision by accurately modulating the current in the motor coils, which, in turn, generates finely tuned driving magnetic fields. Using these control methods, we establish a relationship between the wavy element period and the control parameters as follows:

$$T_s = T_0 + \frac{\theta_s n_p K}{360 \cdot N} \frac{1}{2(n_s - 1)}, \quad (\text{Equation 5})$$

where T_0 is the initial wavy element period, n_p is the number of control pulses, K is the screw pitch, θ_s is the rated step angle, N is the micro-stepping parameter, and n_s is the number of substructures. When non-uniform local tuning is required, independently addressable local stepper motor branches can be attached to the SMS-supported wavy elements to introduce small differential corrections on top of this shared baseline. Each local branch converts stepper motor rotation into a local period change for its corresponding element, so the final local period can be represented as the sum of the baseline value set by the STMS/SMS chain and an element-specific correction term (see [Method S2](#) and [Figure S11](#) for details).

Fabrication

The fabrication of our metasurface primarily consists of two key components: the programmable mechanical structure and the low-standby-power control circuit. The programmable mechanical structure comprises the metal plate, STMS, and SMS ([Figure 7A](#)). For the metal plate, we utilize a smooth aluminum foil material with the support structure, which is comprised of support arms with a diameter of 1 mm to provide mechanical stability. The support arms are made of aluminum metal, with dimensions of 2 mm in width and 1 mm in thickness, and are connected through holes to form the STMS. The SMS is driven by a stepper motor with a 1.8° step angle, coupled with a lead screw that has a 1 mm pitch, enabling precise rotational control. The entire mechanical structure is enclosed within a custom-designed 3D-printed shell, which has dimensions of 265 × 60 × 180 mm³. This enclosure provides protection and mechanical integrity to the metasurface system. The control circuit consists of an ultra-low power microcontroller, digital stepper driver for micro-stepping control, and power management module ([Method S3](#); [Figure S12](#)).

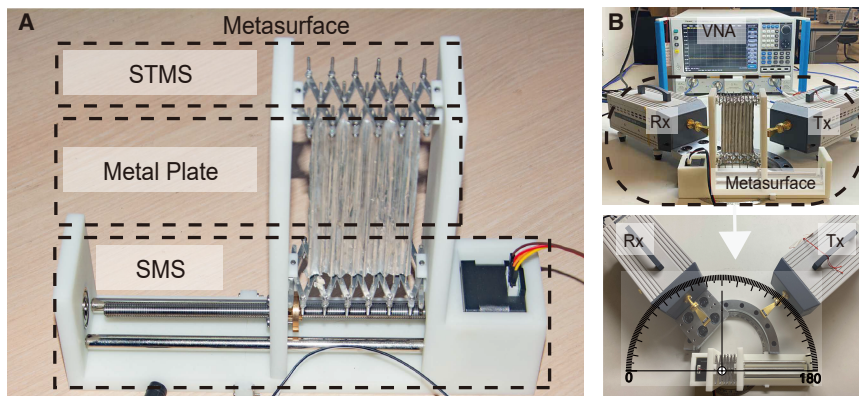


Figure 7. Beam-steering experiment using the metasurface prototype

(A) Photograph of the fabricated metasurface prototype.

(B) Experimental setup. The metasurface is placed between the transmit and receive antennas, and a vector network analyzer (VNA) provides the sub-terahertz excitation and readout. The received signal is recorded as a function of angle by rotating/translating the receiver.

Experimental methodology and setup

The test bed is illustrated in Figure 7B. We utilize a dual-port Ce-year 3672D vector network analyzer (VNA) combined with mixers to transmit and receive subterahertz signals spanning 110–170 GHz to evaluate the received signal strength. For the decoding evaluation, a 16-QAM modulated signal is generated using the Xilinx Zynq UltraScale + RFSoc ZCU111 Evaluation Kit and up-converted to a 1 GHz intermediate frequency (IF) signal. This IF signal is then further upconverted to the 150 GHz subterahertz band using a subharmonic mixer and transmitted via a horn antenna. Our metasurface is placed in front of the transmitter. At the receiver, a horn antenna and a low-noise amplifier (LNA) capture and amplify the subterahertz signal, which is then downconverted and demodulated. In the experiments, the angles of the incident and scattered waves are determined by using a 10 cm radius guide rail and a protractor.

RESOURCE AVAILABILITY

Lead contact

Requests for further information and resources should be directed to and will be fulfilled by the lead contact, Xiuzhen Guo (guoxz@zju.edu.cn).

Materials availability

This study did not generate new unique materials.

Data and code availability

- All data reported in this paper are available within the article and its [supplemental information](#).
- All original code is available at the Zenodo repository: <https://doi.org/10.5281/zenodo.20094145>.
- Any additional information required to reanalyze the data reported in this paper is available from the [lead contact](#) upon reasonable request.

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AUTHOR CONTRIBUTIONS

L.T., investigation, methodology, experimental design, formal analysis, and writing – original draft; X.C., investigation, experiments, formal analysis, and

writing – original draft; X.G., conceptualization, supervision, methodology, project administration, and writing – review and editing; S.H., investigation and experimental support; C.G., investigation and technical support; P.C., resources and funding acquisition; Y.S., supervision, conceptual input, and writing – review and editing; J.C., supervision, resources, and funding acquisition. All authors discussed the results, revised the manuscript, approved the final version, and agreed to be accountable for all aspects of the work.

DECLARATION OF INTERESTS

The authors declare no competing interests.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work, the authors used ChatGPT-5 in order to polish the article and check for syntax errors. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

SUPPLEMENTAL INFORMATION

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