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Active Multifunctional Microelectromechanical System Metadevices: Applications in Polarization Control, Wavefront Deflection, and Holograms

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Metasurfaces have provided a novel route to control the local phase of electromagnetic radiation through subwavelength scatterers where the properties of each element remain passive. A passive metasurface design can only achieve a specific functionality as it is extremely challenging to reconfigure each element that contributes toward the control of the radiation. In this work, the authors propose a different scheme based on microelectromechanical system (MEMS) to reconfigure the resonance and radiation phase via control of each dipolar element. The suspension angle of the individual bimorph cantilever in air can be precisely controlled through electrostatic actuation that determines the operative phase diagram of the metadevice. The dynamic polarization conversion is demonstrated through global control. In addition, it is proposed that a multifunctional operation such as dynamic wavefront deflection and rewritable holographic display can be accomplished by using 1D and 2D control of the cantilever array when each cantilever in the MEMS metadevice array is uniformly and accurately controlled in the large-area samples. Such a rewritable proposition can enable myriad of applications of MEMS-based metadevices in polarization-division multiplexing and dynamic flat lenses.

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1. Introduction

Terahertz (THz) radiation in the electromagnetic spectrum has attracted enormous attention in the recent years with its non-ionizing property and its ability to sense materials with fingerprint precision.^[1] THz devices have potential applications in diverse areas such as imaging, high resolution spectroscopy, and biomedical analytics.^[2] To manipulate electromagnetic waves at will, artificially designed metadevices^[3] with subwavelength sized unit cells have emerged as an important tool in the recent years, which forms the basis for many fascinating and exotic effects such as negative refraction,^[4] perfect lenses,^[5] and cloaking.^[6] Looking beyond the passive metamaterials, dynamic metadevices have recently been proposed via active media integration, such as liquid crystals, doped semiconductors, vanadium dioxide, chalcogenides

and graphene, to realize the global control of the metamaterial array.^[3,7-12] The dynamic properties of the integrated media enable many fascinating phenomena such as the active slow light effect,^[8] chirality switch, and polarization control.^[10,13] However, the applications are restricted due to the limitations in the response of materials to external stimuli and complex excitation methods. Additionally, there is a lack of local control in these hybrid systems where the dynamic effect only occurs globally across the entire array. Recently, the idea to realize the optically reconfigurable metasurfaces based on phase-change material was proposed for multifunctional rewritable metadevices through laser writing that would open up a new avenue for real application of metamaterials.^[14] However, it is still not possible to realize the real-time control with the optical writing approach. As an alternative, microelectromechanical system (MEMS) metamaterials have enabled the dynamic control of electromagnetic waves ranging from microwave to infrared through thermal bimorphs,[15] comb drives,[16,17] outof-plane deformable cantilevers,^[18] and electrostatically actuated beams.^[19,20] MEMS-based complex metamaterials enabled a series of applications such as a dynamic filter,^[21,22] chirality switch,^[23] programmable devices,^[24] giant nonlinearity,^[25] and thermochromic infrared metamaterials.^[26]

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2. Discussion of MEMS-Based Metal–Insulator–Metal (MIM) Metadevices

The MEMS technology has been extensively exploited in the metamaterial community to switch the resonances by controlling the cantilevers to be in the "ON" and "OFF" states in the transmission mode by applying external voltage (see Note S1, Supporting Information, for details of the MEMS cantilever operation). A slight disturbance of the cantilevers due to the external voltage would introduce the obvious modulation of the resonance according to the perturbation theory.^[27,28] The MIM configuration would further enhance its sensitivity and enable operation in the reflection mode.^[29] As depicted in Figure 1a, a MEMS-based MIM system is typically composed of structured metallic resonator designed as a suspended cantilever that could be reconfigured by applying electrostatic force, and a continuous metallic plane separated by a dielectric spacer on the substrate. Due to the existence of the metallic ground plane, there would not be any transmission of the electromagnetic wave. Therefore, only the reflected wave is considered for analysis in this work. The one-port single-mode resonator model can be used to describe the spectral behavior when the resonances are spectrally separated according to the coupledmode theory.^[30,31] The reflection coefficient \tilde{r} of the model can be described as

$$\tilde{r} = -1 + \frac{1/Q_r}{-i(\omega/\omega_0 - 1) + 1/2Q_a + 1/2Q_r}$$
(1)

The Equation (1) indicates that the reflection spectrum is determined by the two intrinsic parameters: absorptive (Q_a) and radiative (Q_r) quality factors where $Q = \omega_0 \tau/2$ with τ_a and τ_r being the lifetimes of the resonance with the damping due to intrinsic absorptive and radiative losses, respectively, and ω_0 represents the resonance frequency. The reflection spectrum has been well studied for perfect absorption that occurs for the condition of $Q_a = Q_r$ according to Equation (1). The absorbance in the system decreases significantly if any of these two quality factors deviates from the equality condition. As clearly indicated in Figure 1b, the resonance changes in both resonance strength and frequency from the state of near perfect absorption for the case of $\beta = 0.5^\circ$ when β is tailored, where β is the effective angle of the suspended cantilever in simulations. By tuning the external voltage, the effective angle



 β can be gradually altered and this would lead to the continuous modulation of the dipolar resonance frequency due to the change in its equivalent capacitance and inductance in the system. At the same time, the radiation phase spectrum shifts along with the amplitude spectra and the slope varies with the modulation of the amplitude spectrum as shown in Figure 1c. However, the phase spectrum undergoes an abrupt transition when perfect absorption $(Q_a = Q_r)$ condition is reached which eventually prevents the continuous modulation of the radiation phase response. Based on the mode-expansion theory (MET),^[32] the radiative quality factor Q_r scales inversely with the spacer thickness while Q_a reveals an almost linear dependence on the spacer thickness (see Note S2, Supporting Information). In the MEMS-based MIM metadevice, the tuning of effective angle (β) leads to the modulation of the effective spacer thickness and thus gives rise to a switchable operation state which shifts from underdamped region $(Q_a > Q_r)$ to overdamped region ($Q_a < Q_r$). The two states are characterized by the *phase span* ($\Delta \varphi$) as shown in Figure 1c where the phase span of the resonator undergoes a 360° coverage across the resonance operating in the underdamped state while it undergoes a less than 180° range in the overdamped state. This property provides us the theoretical basis for designing the MIM cavity for the continuous phase modulation in the underdamped region.

In this work, we propose a MEMS-based MIM metadevice to manipulate the local radiation properties of the electromagnetic wave and achieve functionalities such as polarization control, wavefront deflection, and real-time holographic display. We experimentally demonstrate the active modulation of the resonance frequency and the phase response for MEMS-based metadevice through global control of the MEMS device by applying external voltage. Based on this metadevice, we propose a much more complex scenario of individual element control through extensive simulations that shows complete polarization control, dynamic wavefront deflection, and rewritable hologram. All of these functionalities rely mainly on the two features that could be accomplished by the MEMSbased MIM metadevice: (a) constant 360° phase span in the entire gradual modulation range that requires the device operation in the underdamped region (requires a careful design of the MIM cavity) and (b) the large resonance frequency shift when the out of plane angle of suspended cantilevers is adjusted.



Figure 1. Model of MEMS-based metal–insulator–metal (MIM) unit cell with a cantilever as the reconfigurable resonator. a) Model of MEMS-based MIM metadevice in the one-port system with incidence (In) and reflection (\tilde{r}); b) simulated amplitude and c) radiation phase spectra at varied cantilever angles.



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3. Results and Applications

A MEMS-based MIM metadevice was fabricated as shown in Figure 2a,b, which represent "ON" and "OFF" states of the device, respectively (see the Experimental Section and Note S3, Supporting Information, for the fabrication steps and the performance details of the MEMS-based metadevice). After the device fabrication, a release process is carried out which results in the bimorph cantilevers to be bent up in the "OFF" state due to the residual stress. Once the external voltage is applied to the metadevice between the top metasurface and bottom ground plane, the attractive electrostatic force pulls the suspended cantilevers closer to the spacer layer depending on the applied bias voltage. The cantilevers physically touch the spacer layer at 30 V and this state is defined as the "ON" state. The intrinsic switching speed of cantilevers is restricted by the first order mechanical resonance frequency that is estimated to be in the sub-MHz level in our case and is also affected by the adhesion force of the interface between cantilevers and substrate.^[33]

Figure 2c,d show the measured amplitude and phase spectra of the fabricated MEMS-based metadevice in reflection mode. The metadevice reveals a dipolar resonance at 1.34 THz with

the linearly polarized (LP) incidence along y-axis in the "OFF" state and the resonance redshifts to 0.74 THz when the metadevice is switched to the "ON" state in Figure 2c. The suspension angle of cantilevers could be gradually altered by applying varied voltages and thus the reflective spectra could be modulated both in amplitude and resonance frequencies that are presented as the inset of Figure 2d. By observing the spectra of "ON" and "OFF" states in Figure 2d, the corresponding radiation phase spectra also shifts along with the amplitude spectra and undergoes a phase transition from the underdamped region to the overdamped region. The transition could be understood from the retrieved radiative and absorptive quality factors of the MIM cavity at different cantilever configurations (see Note S2, Supporting Information) that is consistent with the analysis based on the MET theory. The constant 360° phase span in the underdamped region together with the large resonance frequency shift enables the potential applications in planar optics with the phase encoding related effects including polarization control,^[34] wavefront deflection,^[35] hologram,^[36] flat lenses,^[14] and encoding metasurfaces.^[37-39] We would now discuss the application of such a MEMS-based scheme in realizing active polarization control.



Figure 2. Experimental verification of the reflection spectra for the MEMS-based MIM metadevice. The optical microscope and scanning electron microscope (SEM) images of the fabricated MEMS-based metadevice array in the a) "ON" state and b) "OFF" state corresponding to the cantilever angles of $\beta = 0^{\circ}$ and $\beta = 2^{\circ}$, respectively. The spacer is SiO₂ with thickness of $t = 5 \,\mu\text{m}$ and the metal is aluminum with thickness of 500 nm for the structured surface (reflector is 1 μ m thick). The detailed geometrical parameters are indicated in the inset image where g = 4, w = 6, d = 4, $l_1 = 100$, and $l_2 = 50$ (in μ m). The square period of unit cell is 104 μ m. The measured c) reflection amplitude and d) phase spectra in the "ON" and "OFF" states; Inset shows the gradual modulation of the reflection spectra at different voltages with both amplitude and phase information.



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In this section, we focus on the active polarization control using the MEMS-based metadevice configuration as polarization is one of the most fundamental properties of light and control of the polarization state is extremely important for several applications.^[40–44] The different optical responses along the orthogonal principal axes of the unit cell give rise to the varied amplitude and radiation phase responses of the scattered light. With the incident light of a certain polarization, the transmission or reflection can be mathematically described by

$$\hat{p} \begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} r_{xy}e^{i\delta} & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\theta \cdot e^{-i\delta'} \\ \sin\theta \end{bmatrix} = \begin{bmatrix} r_{xy}e^{-i(\delta'-\delta)}\cos\theta \\ \sin\theta \end{bmatrix}$$
(2)

where \hat{p} represents the Jones Matrix of the metamaterial, θ and δ' are the azimuth of polarization ellipse and *phase difference* between the orthogonal components for the incident light, and r_{xy} and δ are the amplitude ratio $(r_{xy} = |\tilde{t}_x| / |\tilde{t}_y|)$ and *phase difference* ($\delta = \varphi_y - \varphi_x$) induced by the metamaterial. Through tailoring r_{xy} and δ that originate from anisotropy of the metamaterial, it is possible to obtain any desired polarization state. Considering the frequently employed LP incidence, the *phase difference* (δ') of incident light is fixed at 0° (or 180°) and the azimuth θ can be controlled at any desired angle by a polarizer. Therefore, any polarization state is achievable as long as *phase*



difference (δ) induced by the metamaterial could attain the value ranging from 0° to 360°.

We have shown that the radiation phase span of MEMSbased metadevice operating in the underdamped region covers 360° range across the resonance frequency and the radiation phase value at a fixed frequency is tunable by adjusting the cantilevers. The *phase difference* (δ) is defined as the difference between the radiation phase values at two orthogonal polarizations. We note that it is the phase difference that we will focus on for polarization control in this section. Due to the anisotropic design of the unit cell, there is no resonance excited with linearly polarized incidence along *x*-axis in the frequency range of operation which is evidenced by the amplitude spectra as shown by the dashed lines in Figure 3a where the incident light is totally reflected. As we have discussed, the continuous modulation of the suspended cantilever configuration by tuning the external voltage would lead to the dipolar resonance frequency shift for both amplitude and phase spectra excited by y-polarized incidence as the solid lines shown in Figure 3a. This leads to a continuous modulation of the phase difference as shown in Figure 3b which arises from the modulation of phase radiated along the y-polarization (due to dipolar mode) and the unchanged phase radiated along the x-polarization (nonresonant) in the underdamped region (see Note S4, Supporting Information, for detail of the perturbation theory).^[45] In this way, we could obtain the desired phase difference value at a specific frequency of operation.



Figure 3. The performance of the metadevice for active polarization control. a) The reflection amplitude spectra with *y*-polarized excitation (solid lines) and *x*-polarized excitation (dash lines) at three different voltages ($V_1 = 13$ V, $V_2 = 8$ V, and $V_3 = 1$ V). b) The corresponding *phase difference* spectra at the three voltages. c) The continuously modulated *phase difference* response of the metadevice at varied voltages and d) the corresponding ellipticity of reflected light and the conversion efficiency of the metadevice as a polarization convertor at 1.15 THz. e) The input and output polarization states at the three different voltages.



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The phase difference can be continuously tuned from -75° to -340° at 1.15 THz as shown in Figure 3c and the range can be further enlarged by optimizing the design that would allow larger frequency shift in the underdamped region by increasing the initial height of the suspended cantilevers (see Notes 1 and 2, Supporting Information). The typical phase difference values of -90° , -270° , and -180° are available at the three specific voltages of $V_3 = 1$ V, $V_1 = 13$ V, and $V_2 = 8$ V, respectively. At 1.15 THz, the calculated ellipticity based on Stokes parameters (see the Experimental Section) is modulated from 45° (at V_1) to 0° (at V_2) and then to -45° (at V_3) as depicted in Figure 3d. These results indicate that the output polarization state is actively modulated from right-handed circularly polarized light (RCP) to LP and then to the left-handed circularly polarized light (LCP). Therefore, three typical output polarization states could be actively obtained by the MEMS-based metadevice whose incident and output polarization states are illustrated in Figure 3e. For a more general case of elliptically polarized light, it could also be obtained by continuously modulating the external voltage. With the dynamic polarization control, the metadevice could be employed for the encoding of binary data with the orthogonal circular polarization basis and for the multiplexer in polarization-division multiplexing technique in communication systems to enhance the information carrier capacity. Based on the concept of movable cantilever metadevice as described earlier, we now propose a scheme to achieve dynamic wavefront deflection by simulating the local response of a similar MEMS-based metadevice.

3.2. Dynamic Wavefront Deflection

The concept of metasurface utilizing the phase gradient has been proposed to arbitrarily manipulate the wavefront with applications including flat lenses,^[14,39] beam splitter,^[46] and hologram.^[47,48] However, the dynamic tuning^[49] of the deflection angle or focal length cannot be accessed by the conventional global control approaches. Therefore, we propose a more complex local control strategy using a MEMS-based metadevice to achieve the dynamic wavefront deflection. The voltage gated MEMS-based metadevice not only allows global control of the metasurface array but also offers the freedom of columnwise (1D) and unit cell level (2D) local control. Through the local control of column in the array (1D control), the dynamic wavefront steering could be achieved as described here. According to the generalized Snell's law, the deflected wavefront angle for the normal incidence in air is determined by

$$\alpha_r = \arcsin\left(\frac{\lambda_0}{2\pi} \frac{\mathrm{d}\varphi}{\mathrm{d}y}\right) \tag{3}$$

where α_r is the deflection angle, λ_0 is vacuum wavelength and $d\varphi/dy$ term describes the 1D phase gradient along the *y*-axis. Various deflection angles could be achieved by tailoring the gradient $d\varphi/dy$. Here, we define the local radiation phase change between the adjacent unit cells as *phase shift* ($d\varphi$). In a typical passive metasurface array where the unit cell period is fixed, i.e., *dy* is constant, the deflection angle only depends on the *phase shift* ($d\varphi$). In the MEMS-based metadevice, the radiation

phase value of each column is controlled by the corresponding external voltage and thus the *phase shift* is tunable which enables the dynamical deflection angle. As a proof of concept, a simple design of a dynamic wavefront deflector is numerically demonstrated here which could deflect light at angles of -70° , -39° , 39° , and 70° , respectively.

In simulations, the MEMS unit cell is optimized with a simpler resonator and a larger spacer thickness in order to enhance the modulation range in the underdamped region (refer to Note S2, Supporting Information). As shown in **Figure 4**a,b, the resonator is a single aluminum strip of length 60 μ m, width of 15 μ m, and thickness of 500 nm that is suspended in air as the "OFF" state and the SiO₂ spacer thickness is increased to 10 μ m. The anchor is also aluminum with width of 4 μ m and thickness of 500 nm. A dipolar resonance would be excited with linearly polarized excitation along *y*-axis and the resonance frequency is tuned as the external voltage is applied, thus gradually decreasing the angle β between the cantilever and the spacer.

As shown in Figure 4a, the radiation phase at 0.8 THz is continuously tuned from 310° to 0° when the angle β is gradually varied from 2° to 0°. This would enable a repetitive sixcolumn encoding with *phase shift* $(d\phi)$ of $\pm 60^{\circ}$ or four-column encoding with *phase shift* of $\pm 90^{\circ}$. A scheme for the dynamic deflector is illustrated in Figure 4b where 12 adjacent columns as one supercell in the array are encoded through the corresponding electrodes biased at different voltages. We would like to stress that in this proposal, only 12 external electrodes in total are required for the dynamic deflector which highly reduces the fabrication complexity. For the $\pm 60^{\circ}$ phase shift, a six-digit encoding sequence is enough for the deflection angles of $\pm 39^{\circ}$. The deflection angle can be simply tuned to $\pm 70^{\circ}$ with a 90° phase shift using a four-digit encoding sequence. The simulated reflection electric field distribution with normal plane wave incidence is shown in Figure 4b and the wavefronts are deflected to the designated angles with the corresponding encoded sequences at 0.8 THz. Here, we only consider the phase encoding and ignore the influence from the unevenly distributed local intensity which is coupled to the radiation phase modulation. However, according to the simulated electric field distribution, the uneven local intensity would have a weak influence on the performance of deflection angle and the wavefront quality. We further extend the idea of 1D control of the cantilever array to 2D array in order to achieve a real-time rewritable hologram using a similar MEMS-based metadevice as described in the following section.

3.3. Real-Time Control of Rewritable Hologram

In addition to the 1D control of column in the array, 2D control at unit cell level could also be potentially achieved with the MEMS-based metadevice configuration that could find many applications such as hologram.^[36,48,50] In this section, we predict this functionality through detailed calculations. A recently developed geometric metasurface provides an efficient approach to realize the high-efficiency multilevel holograms in the visible regime.^[48,50] The metasurfaces have been demonstrated to arbitrarily manipulate the phase and amplitude of the local radiation at the unit cell level which could function as a pixel for the



Figure 4. The schemes for a dynamic deflector and a real-time holographic display. a) The simulated radiation phase spectra of the MIM resonator at varied angles of cantilevers. b) The encoding scheme for the dynamic wavefront deflection. With six-digit control ($d\phi = \pm 60^{\circ}$), the wavefront is deflected by $\pm 39^{\circ}$ and with four-digit control ($d\phi = \pm 90^{\circ}$), the wavefront is deflected by $\pm 70^{\circ}$ with normal plane wave incidence. c) The scheme of real-time rewritable holographic display by individual control of each unit cell. d) The calculated six-digit phase distributions of the two images and the corresponding holographic images displayed by the encoded metadevice.

multilevel holography with both phase and amplitude information. However, the hologram is fixed for the lithography-based metasurfaces once the phase distribution is patterned. With the envisioned MEMS-based metadevice, the real-time rewritable multilevel phase-only holography could be possible with the dynamically controlled phase of the local radiation.

One of the possible schemes is illustrated in Figure 4c where each unit cell is separately controlled for the entire 2D array. With the calculated local phase distribution of the predesigned holographic images by Rayleigh-Sommerfeld diffraction theory, each unit cell is then encoded with the corresponding voltage and the holographic images would be displayed at the designated plane with the terahertz illumination (see Note S5, Supporting Information, for the detailed calculation of the phase distribution). Using an identical MEMS-based metadevice design as in the last section, we numerically verified the hologram quality with a six-digit phase encoding. As shown in Figure 4d, a series of holograms that shows the words "Nanyang Technological University" and "SPMS" (abbreviation for School of Physical and Mathematical Sciences) are exhibited by applying different six-bit encoding sequences. In the ideal case, we could clearly observe the holograms through the dynamic electrical encoding of the metadevice. The overall efficiency of the reflective hologram is larger than 25% and it could be further improved by reducing the losses. We can design the metadevice operating at a desired frequency which could be easily tuned as long as one can find the required encoding phase values of the metadevice at the specific frequency of interest. Here, we used phase-only method to retrieve the holograms and have ignored the effects induced by the randomly modulated local intensity which would certainly affect the contrast of the display. A more sophisticated supercell design may address this problem that can encode both phase and amplitude of the radiation. Therefore, such an encoding scheme with the MEMS-based metadevice has the potential to deliver a real-time holographic display. However, certain issues must be resolved before applying this idea into a real MEMS-based device. First, the separate encoding of each unit cell increases the complexity of the design and large number of external encoding electrodes are required which aggravates the difficulty level of encoding. Secondly, it would be a challenge to meet the uniformity and the precision required to control each individual pixel in the entire array of the large-area metadevices.

4. Conclusion

In summary, we have experimentally demonstrated the active control of the cantilever configuration using the MEMS-based metal–insulator–metal metamaterial that enables the dynamic tuning of the properties of the resonance. By employing a constant 360° *phase span* that is available in the underdamped region and the resonance frequency shift by active manipulation of the cantilever configuration, the anisotropic metadevice modulates the *phase difference* of the output light that enables an active control of polarization states. In addition to the global control of the



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array, the MEMS-based metadevice provides the possibility of local control in each unit cell which we have explored in this work with extensive simulations. The local control in MEMSbased metadevices offers an unprecedented avenue to realize more complicated functionalities such as dynamic wavefront deflection via 1D encoding of column and real-time rewritable holographic display via 2D encoding of each unit cell. The realistic applications that could be accessed by MEMS-based metadevices enable customized and rewritable functionalities through electrical encoding of the array. Experimental realization of all the proposed multifunctional electrically controllable metadevice in near future would certainly push the frontiers of existing photonics and MEMS technologies.

5. Experimental Section

Fabrication: The metadevice was fabricated using a complementary metal-oxide semiconductor (CMOS) compatible process as described below. First, an 8" silicon (Si) wafer as the substrate was deposited with 1 μ m thick aluminum (Al) reflector layer. After this, a 5 μ m thick silicon oxide (SiO₂) spacer was deposited using plasma enhanced chemical vapor deposition (PECVD) method. Then, a 100 nm aluminum oxide (Al₂O₃) layer was deposited using atomic layer deposition (ALD) process which prevents the etching of spacer SiO₂ during the release process. On top of this layer, a 100 nm thick SiO₂ sacrificial layer was deposited using PECVD method.

In the second step, patterns were required to form the anchors and cantilevers where conventional photolithography process was used. With the designed pattern, parts of sacrificial SiO₂ for anchor regions were dry etched. After this, a 50 nm thick Al₂O₃ layer was deposited using ALD process, followed by the sputter deposition process of 500 nm thick Al. Note that the bimorph layers (Al/Al₂O₃) were in physical contact with bottom Al₂O₃ layer at the anchor region, and in the remaining part of the wafer, it was on top of SiO₂ layer.

Third, the authors moved to the step of defining the metal lines of metadevice patterns by another photolithography process. After this, both Al and Al₂O₃ layer were dry etched to form the designed metadevice pattern. Finally, vapor hydrofluoric acid (VHF) was used to isotropically etch the SiO₂ sacrificial layer away, thereby suspending the cantilevers over the spacer with an air gap between them. At the anchor region, the bimorphs were in physical contact with spacer layer; hence the VHF release process was not time controlled, and this ensured higher yield of the devices. Due to the residual stress in the bimorph cantilevers, the released cantilevers were bent up, thereby increasing the initial tip displacement that was defined as "OFF" state.

Measurements: The terahertz time-domain spectroscopy system (TeraView, TPS Spectra 3000) in reflection mode was employed to measure the spectral response of the metadevice samples and the reference (aluminum plate) in dry air atmosphere and the time-domain waveform was obtained. Fourier transform was employed to obtain the frequency domain spectra with both amplitude and phase information. The reflection amplitude spectra $|\tilde{r}(\omega)|$ and phase spectra $\varphi(\omega)$ were obtained by $\tilde{r}(\omega) = \tilde{r}^{\text{Sam}}(\omega)/\tilde{r}^{\text{Ref}}(\omega)$ where $\tilde{r}^{\text{Sam}}(\omega)$ is the complex reflection signal of metadevices and $\tilde{r}^{\text{Ref}}(\omega)$ is the complex reflection signal of reference, respectively.

Simulations: The numerical simulations (reflection spectra, surface current, and electric field distributions) were carried out using a commercially available software (CST Microwave Studio) by a finiteelement frequency-domain solver with unit cell boundary conditions. Both normal-incident TE00 (polarization along the *x*-axis) and TM00 (polarization along the y-axis) modes were defined at the incident and receiving ports. The corresponding angles of the suspended cantilevers were designated in the model to simulate the responses, which depended on the voltage levels in real devices. At least eight mesh steps per wavelength were used to ensure the accuracy of the calculated results.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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