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Reconfigurable digital metamaterial for dynamic switching of terahertz anisotropy

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Terahertz (THz) regime of the electromagnetic (EM) spectrum lies between the microwave and infrared region ($f = 0.1 - 10$ THz). THz wave combines the merits of both neighboring spectral regions and potentially enables numerous impactful applications such as non-invasive medical inspection, non-destructive fault analysis, security surveillance and next-generation wireless communication networks.^[1-4] However, THz wave interacts minimally with natural materials and this has hindered the development of devices for THz wave manipulation.^[5] Metamaterials offer the possibility to realize EM properties for desired spectral range that has the potential to bridge the so-called “THz gap”. Metamaterials are array of subwavelength structures, whose properties can be engineered through the design of unit cell geometry. The diversity of the unit cell shape along with the scalability has led to the demonstration of even

exotic THz properties such as artificial magnetism,^[6] negative refractive index,^[7,8] unnaturally large refractive index,^[9] chirality,^[10] polarization control,^[11] wavelength selective absorption,^[12,13] electromagnetically induced transparency analogue,^[14,15] and slow light behavior^[16]. Furthermore, the THz properties realized through metamaterials can also be actively controlled through external stimuli. This tunability of active metamaterials adds in a new dimension for the manipulation of THz wave. Tunable metamaterials are reported for the active control of varied THz properties such as magnetic resonance,^[17-23] electrical resonance,^[23-28] polarization response,^[29-31] chirality,^[32] absorption,^[33-35] multiband and broadband modulation^[36-42], and near field coupled resonances^[43-45]. Recently, digital metamaterials, coding metamaterials, and programming metamaterials have been demonstrated,^[46-51] where discrete subwavelength unit cells with specific geometrical filling ratio act as the “digital bits”. The state of the meta-bits is defined by its reflection phase. The metamaterial then formed by placing these meta-bits in a coding sequence determines the phase gradient of the metamaterial and hence the reflection profile of incident EM waves. By changing the coding sequence, the reflection beam can be steered along specific direction with a desired reflection profile.^[49-51]

From an alternate perspective, the meta-bit states can also be defined based on the transmission intensity rather than the reflection phase. These metamaterials can be considered as a new class of coding metamaterials, which enable advanced resonance-based EM wave manipulation. More interestingly, a single meta-bit can be switched between ON and OFF states, i.e. transmission high (or no resonance) and transmission low (or presence of resonance), respectively through external stimulus at a given frequency. This allows for the dynamic selection of the functionality of the coding metamaterial based on the state of the meta-bits. The dynamically switchable meta-bit can be realized using various control mechanism such as optical,^[17,24] magnetic^[18] or thermal stimulus.^[19] However, above-mentioned control mechanisms only allow for global control of active elements in all the unit

cells and hence provides only single meta-bit system. In order to realize multibit resonance based metamaterial, independent control of active elements integrated into a single unit cell is highly desirable. Microelectromechanical system (MEMS) based metamaterials by integrating microactuators into the unit cell geometry are reported to achieve isolation of control at the unit cell level.^[52] Especially, the out-of-plane deformable microactuators based metamaterials are of great interest, owing to its simplicity in design and versatility in application. Multiple microcantilevers can be readily integrated to the unit cell geometry and upon electrical isolation will readily enable dynamically reconfigurable multi-bit digital metamaterial for advanced manipulation of THz waves. These multi-bit digital metamaterials pave way for the realization of disruptive THz functional devices such as multifunctional and programmable metamaterials. The multifunctional metamaterial will provide independent control of multiple THz properties by integrating various resonator designs into a single metamaterial. On the other hand, programmable metamaterial can be realized by controlling identical unit cells individually and then dynamically programmed to function as a tunable filter, switchable polarizers, spatial light modulator, gradient metamaterial or even a random metamaterial.

Active control of THz anisotropy is a critical EM parameter that will enable numerous THz polarimetric devices such as active wave plates, beam splitters and isolators for application in THz spectroscopy, ellipsometry, and imaging systems. Active metamaterials for dynamic switching of linear polarization response from either x - or y - polarization to polarization-insensitive state at a given frequency are reported before.^[17,29,30] In order to get complete control of anisotropy it is critical to achieve symmetry breaking of the metamaterial unit cell geometry independently along x - and y -directions. In this report, a digital metamaterial for independent control of orthogonal polarization response of the THz waves is experimentally demonstrated. Two orthogonally placed, out-of-plane deformable, electrically isolated microcantilevers allow for the independent switching of linear polarization responses in THz spectral region. The physical position of the microcantilevers defines the state of the

cantilevers and can be dynamically switched between OFF and ON states by applying voltage across the cantilevers and Si substrate. When the cantilever is suspended with an air gap the state is defined as “OFF” or “0” state and the state in which the cantilever is in physical contact with the substrate is defined as “ON” or “1” state. As the two cantilevers are electrically isolated, the state of the metamaterial is defined as S_{XY} , where ‘x’ represents the state of the MCX cantilever, which is placed along the x-direction, and ‘y’ represents the state of MCY cantilever. The MCX and MCY cantilevers dominantly influences the resonance features of the metamaterial for *x*-polarized (electric field along *x*-direction) and *y*-polarized (electric field along *y*-direction) THz incidence, respectively. Hence, for *x*-polarized incidence, the resonance at 0.8 THz can be controlled by reconfiguring the digital metamaterial between S_{0Y} and S_{1Y} and similarly for *y*-polarized incidence the reconfiguration of states between S_{X0} and S_{X1} provides the dynamic control of the resonance at 0.8 THz. The anisotropy of the proposed digital metamaterial can be actively switched from less than unity to 2.65 at 0.8 THz though selective reconfiguration of these microcantilevers. The proposed approach can be potentially scaled to integrate more number of independently controlled cantilevers for complex multibit coding metamaterials and higher degree of polarization control.

The unit cell of the proposed digital metamaterial consists of four geometrically identical microcantilevers placed with $\pi/2$ rotational symmetry. Length of each cantilever (*cl*) is 34 μm , length of tip (*tl*) is 20 μm and width (*cw*) is 3 μm . Two cantilevers, FCX and MCX are placed facing each other along the *x*-direction, while the other two cantilevers, FCY and MCY are placed along the *y*-direction as shown in **Figure 1(a)**. The FCX and FCY cantilevers are fixed to the Si substrate at all times, while the MCX and MCY cantilevers are released and are deformable. The microcantilevers are suspended bimorph structures made of 500 nm aluminum (Al) over 50 nm aluminum oxide (Al_2O_3) dielectric layer fabricated on lightly doped silicon (Si) substrate.^[28] Silicon dioxide is used as the sacrificial layer and the MCX and MCY cantilevers are released using vapor hydrofluoric acid. When released, the MCX

and MCY cantilevers curve up in the out-of-plane direction due to the residual stress gradient in the bimaterial layers. The optical image (OM) of the fabricated metamaterial after the release step is shown in **Figure 2(a)** and the scanning electron microscope (SEM) image of the metamaterial unit cell is shown in Figure 2(b), respectively. The digital holographic microscope (DHM) image shows a quantitative description of the release height as gradual change in phase from anchor to the tip position as shown in Figure 2(c). The initial tip displacement of the released MCX (red curve) and MCY cantilevers (blue curve) was measured to be $g \sim 3 \text{ } \mu\text{m}$ as shown in Figure 2(d). The small mismatch between the release height of MCX and MCY cantilevers is attributed to the fabrication imperfections in the devices.

To reconfigure the physical position of movable cantilevers, voltage is applied across the released cantilever and Si substrate. The applied voltage generates an attractive electrostatic force, which deforms the movable cantilever towards the fixed substrate. This physical deformation in cantilevers will bring in an opposing force called the spring restoring force. The balance between the electrostatic force and restoring force determines the final position of the cantilever for any given voltage. However, the electrostatic force increases sharply relative to the restoring force when the voltage is increased. After a critical value of applied voltage called the “pull-in voltage” ($\sim 30 \text{ V}$), electrostatic force will be higher than the restoring force and thereby completely closing the air gap between the cantilever and Si substrate.^[53-55] The cantilever acts as a mechanical switch that can be in one of the two states based on the physical position of the released cantilever and voltage applied. The “OFF” (or “0”) state is the state in which the cantilevers are released and no voltage is applied, while the “ON” (or “1”) state refers to the situation where the cantilever is physically in contact with Si substrate when the applied voltage is higher than the pull-in voltage of 30 V. Figure 2(d) shows the measured out-of-plane deformation profile for the MCX (orange curve) and MCY cantilevers (green curve) in ON state. The flat profile of the cantilevers confirms the physical

contact of cantilevers on the Si substrate. The negative 100 nm displacement measured in the ON state for both cantilevers represents the sacrificial layer thickness, which is removed during the release process. The MCX cantilevers in all the metamaterial unit cells are electrically connected to each other through metal interconnects, which is isolated from the metal line connecting all the MCY cantilevers in the metamaterial. Thus, this isolation allows for the independent actuation of MCX and MCY cantilevers. The MCX and MCY cantilevers forms the digital bits, which can be dynamically switched to achieve desired transmission response for x - and y -polarized incidence THz wave at a given frequency. Based on the physical position the digital metamaterial can be in one of four possible states – MCX-OFF/MCY-OFF (S_{00}), MCX-ON/MCY-OFF (S_{10}), MCX-OFF/MCY-ON (S_{10}) and MCX-ON/MCY-ON (S_{11}) as schematically shown in Figure 1(b), (c), (d) and (e), respectively.

The digital metamaterial is characterized using THz time domain spectroscopy in transmission mode for normally incident THz waves with predefined x -polarization (electric field is along the FCX-MCX cantilever direction or x -direction) or y -polarization (electric field is along the FCY-MCY cantilever direction or y -direction) as shown in Figure 1(a). The simulated transmission spectra of the digital metamaterial for x -polarization incidence with MCX cantilever in OFF and ON states, while the MCY cantilever is kept in ON state are shown in in **Figure 3(a)**. When the MCX cantilever is in OFF state, the simulated transmission spectrum (red-circle curve) of the metamaterial in S_{01} state shows two distinct resonances at 0.724 THz and 0.886 THz. The surface current distribution at 0.724 THz is shown in Figure 3(c) and it can be observed that there is a strong current induced in the FCX cantilever and a weaker current in the MCX-OFF cantilever. The reduction in current is caused due to the air gap beneath the MCX-OFF cantilevers compared to the FCX cantilever that is in direct contact with Si substrate. The FCX and MCX-OFF cantilevers effectively act as two separate single resonators. However, at 0.886 THz, there is only a weak current induced in the MCX-OFF cantilever as shown in Figure 3(d), which acts as an independent

resonator. This causes the resonance to be at a higher frequency owing to the reduced effective dimension of the resonator.^[28] It is important to note that the metal lines along with a small in-plane gap contributes to the resonances and the in-plane gap is unavoidable due to the desired electrical isolation between MCX and MCY cantilevers. When the MCX cantilever is switched to ON state, the simulated transmission spectrum (green-square curve) has a single resonance at 0.644 THz. As the MCX cantilever is switched ON, the air gap is drastically reduced, thereby causing the effective capacitance of the resonator to increase and lowering the resonant frequency. Strong and identical surface currents are induced in both FCX and MCX-ON cantilevers at 0.644 THz. The measured transmission spectra for metamaterial in S_{01} state (red-circle curve) and S_{11} state (green-square curve) shown in Figure 2(b) matches quite well with the simulated results. In S_{01} state there are two distinct resonances at 0.64 THz and 0.8 THz and for S_{11} state, a single resonance is observed at 0.675 THz. The small mismatch between the simulated and measured spectra can be attributed to the variation in the geometrical parameters and the deviation of the material properties used in simulation from the real case. The position of MCY cantilever has minimal influence on the resonance spectra of the digital metamaterial for x -polarization incidence (See supporting information for more details). Hence, for the x -polarization incidence, the resonance at 0.8 THz is selectively switched by controlling the state of MCX cantilever.

The rotational symmetry of the metamaterial allows for similar features for the y -polarization incidence (the electric field is along the FCY-MCY cantilever direction and perpendicular to FCX-MCX cantilevers). Now, the state of the MCY cantilever predominantly determines the resonance behavior of the digital metamaterial. The simulated transmission spectra of the metamaterial with MCY cantilever in OFF and ON states with MCX cantilever in ON state, for y -polarization incidence are shown in **Figure 4(a)**. When the MCY cantilevers are in OFF state, the simulated transmission spectrum (black-circle curve) show two distinct resonances at 0.736 THz and 0.84 THz. The current distribution at 0.736

THz and 0.84 THz are shown in Figure 4(c) and 4(d), respectively and is identical to the MCX case but rotated by 90° . Hence, the resonance mechanisms at the resonant frequencies are similar to the x -polarized incidence. When the MCY cantilever is switched to ON state, there is only a single resonance at 0.61 THz as shown in simulated spectra of the metamaterial in S_{11} state (blue-square curve) in Figure 4(a). The strong current induced in the FCY-MCY-ON cantilevers shown in Figure 4(e), confirms the excitation of a single dipole mode resonance across the entire length of MCY-FCY cantilever configuration. The measured transmission spectra for y -polarized incidence shows two resonance dips at 0.64 THz and 0.8 THz for S_{10} state (black-circle curve) and a single resonance at 0.65 THz for S_{11} state (blue-square curve), respectively as shown in Figure 4(b). Compared to the x -polarization excitation, the influence of the metal interconnects is highly reduced as there is no in-plane gap along the y -direction in the unit cell geometry. The slight mismatch in the resonant frequencies for x -polarization and y -polarization incidence at different configuration states is caused due to the lack of perfect rotational symmetry in the metamaterial unit cell, as the need for metal line is inevitable for providing the isolated control for MCX and MCY cantilevers.

The isolated control of MCX and MCY cantilevers allows for the breaking and recovery of the rotational symmetry in the metamaterial unit cell on demand and hence provides dynamic switching of THz anisotropy. The anisotropy (A) of the metamaterial is defined as the ratio of transmission response of the metamaterial for x -polarization and y -polarization of incident THz waves. i.e. $A = T_X/T_Y$, where T_X and T_Y are the transmission intensities of the digital metamaterial for x -polarization and y -polarization of THz waves, respectively and is shown in **Figure 5**. At 0.8 THz for MCX-OFF and MCY-ON state, resonance is observed for x -polarization incidence (low transmission T_X), but no resonance occurs for y -polarization incidence (high transmission, T_Y). Hence, the calculated anisotropy is 2.65 at 0.8 THz. When the MCX cantilever is switched to ON state, the resonance at 0.8 THz disappears and hence the anisotropy is almost unity due to the high transmission for x - and y - polarization incidence

as shown from the red-triangle curve in Figure 5. Similarly, when MCY is in OFF state, the resonance occurs for y-polarization incidence and hence the anisotropy is approximately 0.8 at 0.8 THz. Thus, the proposed approach of independent reconfiguration of MCX and MCY cantilevers has the power to dynamically switch the anisotropy of the metamaterial between less and more than unity values at any desired frequency. The non-unity value for measured anisotropy when both MCX and MCY cantilevers are in ON state and the mismatch between the values of anisotropy for MCX switching and MCY switching cases is primarily caused by the asymmetry due to the metal interconnects. This can be overcome by having bi-metallic layers, where in one metal layer the x-polarization responsive resonators can be formed, while the other metal layer houses the y-polarization responsive resonators. These two isolated metal layers can be designed to form a perfectly symmetric unit cell geometry. Furthermore, the proposed digital metamaterial can be scaled up to have more number of cantilevers that could be independently controlled to provide even more flexibility in manipulating the THz anisotropy.

In summary, a digital metamaterial with selectively reconfigurable microcantilevers integrated into a single unit cell for independent control of orthogonal THz polarization response is experimentally demonstrated. The switching of MCX cantilevers controls the x-polarization response, while MCY cantilevers provides selective resonance switching only for y-polarization incidence, respectively. Hence, the proposed metamaterial can be actively reconfigured to interact only with x-polarized or only y-polarized incidence or both x- and y-polarized incidence or neither x- nor y-polarization of incidence THz waves at 0.8 THz. This allows for dynamic switching of THz anisotropy between values less (0.8) and more (2.65) than unity at 0.8 THz. This advanced control over polarization response of metamaterial will enable the realization of numerous high performance polarimetric devices to be used in the next generation high-speed communication systems operating at sub-THz regime and THz spectroscopy. The proposed class of digital metamaterial with multibit configuration is a key

technological milestone for the realization of disruptive advanced THz materials such as multifunctional metamaterials and programmable metamaterials, which can be dynamically transformed to take up one of many functional forms such as tunable filter, spatial light modulator, gradient metamaterials or a random metamaterial.

Experimental Section

Electromechanical Characterization: The deflection profile of released microcantilevers were measured using Lyncee Tec. reflection digital holographic microscope (R-DHM). The released chips are wire bonded to a printed circuit board (PCB). Separate voltage supply is used for the actuation of MCX and MCY cantilevers. Si substrate is chose as the ground potential, and the microcantilevers are positively biased. The voltage is increased between the microcantilevers and Si substrate and when the applied voltage is higher than the pull in voltage (~ 30 V), the microcantilevers will come in physical contact with the Si substrate. The pull in can be clearly observed through the optical microscope fitted on the R-DHM. The Al_2O_3 layer beneath the Al layer, will ensure that there is no current flowing from Al layer to Si substrate, when pull in occurs. This is crucial because if the current flows through the Al/Si junction, then the temperature will raise up locally thereby melting the Al tips with the Si substrate, and will permanently damage the device.

Electromagnetic Characterization: THz time domain spectroscopy (THz-TDS) was used to characterize the transmission spectra of the metamaterial at different configuration states. THz wave was incident normally to the sample with predetermined polarization (x -polarization or y -polarization). The released metamaterial chip was bonded to a PCB with a hole of 1 cm x 1 cm in center. The bonded sample was then placed in the nitrogen-filled chamber. The MCX bondpad and MCY bondpad were connected to two different voltage sources. Si substrate was kept as ground, while positive potential was applied to MCX and MCY bondpads. The

transmission spectra was measured at different reconfiguration states for both x -polarization and y -polarization incidence. The measured data was then normalized with transmission through bare Si substrate of same thickness as the samples.

Supporting Information

(i) Microscope images of digital metamaterial in various reconfiguration states

The optical microscope (OM) images shows the metamaterial in various configuration states based on the physical position of the MCX and MCY cantilevers in the unit cell geometry. The out-of-plane curvature of the released microcantilevers can be seen from the out-of-focus in the cantilever tip, when the objective lens is focused on the Si substrate. In S_{00} , both MCX and MCY cantilevers are curved up as shown in Figure S1(a). To achieve S_{10} state, the MCX cantilever is switched to ON state by applying voltage across the MCX interconnect and Si substrate, the entire length of MCX cantilever is in focus, just like the FCX and FCY cantilevers as shown in Figure S1(b), thereby confirming the complete physical contact of MCX cantilever with Si substrate in the ON state. However, the MCY cantilever is still in OFF state. Similarly in S_{01} state, the MCY is selectively switched to ON state, while keeping the MCX in OFF state as shown in Figure S1(c). When both MCX and MCY cantilevers are switched to ON state, it can be seen that all four cantilevers are in focus as shown in Figure S1(d) and so qualitatively ensures that there is no airgap between the cantilevers and Si substrate.

(ii) Transmission Response of digital metamaterial for x -polarization incidence

The simulated and measured transmission spectra of the digital metamaterial in different reconfiguration states for x -polarization incidence are shown in **Figure S2(a)** and **3(b)**, respectively. For the MCX-OFF/MCY-OFF state, the simulated transmission spectrum (black-square curve) shows two distinct resonances at 0.726 THz and 0.88 THz. The surface

current distribution at 0.726 THz is shown in Figure S2(c) and it can be observed that there is a strong current induced in the FCX cantilever and a weaker current in the MCX-OFF cantilever. The reduction in current is caused due to the air gap beneath the MCX-OFF cantilevers compared to the FCX cantilever that is in direct contact with Si substrate. The FCX and MCX-OFF cantilevers effectively act as a single resonator. However, at 0.886 THz, there is only a weak current induced in the MCX-OFF cantilever, which acts as an independent resonator. This causes the resonance to be at a higher frequency owing to the reduced effective dimension of the resonator. It is important to note that the metal lines along with a small in-plane gap contribute to the resonances and the in-plane gap is unavoidable due to the desired electrical isolation between MCX and MCY cantilevers. When the metamaterial is reconfigured to MCX-ON/MCY-OFF state by selectively switching the MCX cantilever to ON state, the simulated transmission spectrum (red-circle curve) has a single resonance at 0.676 THz. Strong and identical surface currents are induced in both FCX and MCX-ON cantilevers at 0.676 THz. As the MCX cantilever is switched ON, the air gap is drastically reduced, thereby causing the effective capacitance of the resonator to increase and lowering the resonant frequency. As the MCX cantilever contributes to both the resonances in MCX-OFF/MCY-OFF states, the switching of MCX cantilever will cause a red shift in both the resonant frequencies. However, the amount by which the resonant frequency reduces depends on the effective dimensional change relative to the original dimension of the resonators. Hence, the resonance at 0.726 THz will have a smaller red shift compared to the 0.886 THz and here both these resonances merge to a single resonance at 0.676 THz. In the other reconfiguration state where the MCY cantilevers are switched to ON state, while retaining the MCX cantilevers at OFF state, two distinct resonances at 0.724 THz and 0.866 THz are observed in the simulated transmission spectrum (blue-triangle curve). The surface current distribution at 0.724 THz for MCX-OFF/MCY-ON state is shown in Figure S2(f) and is identical to the distribution of surface currents at 0.726 THz for MCX-OFF/MCY-OFF state.

shown in Figure S2(c). Similarly, the current distribution at 0.866 THz for MCX-OFF/MCY-ON state shown in Figure S2(g) is almost identical to that of MCX-OFF/MCY-OFF state at 0.88 THz shown in Figure S2(d). This is quite expected, since the orthogonal positioning of the FCY-MCY cantilevers with respect to incident electric field in x-polarization remains highly dormant and hence has relatively minimal contribution to the resonances. Finally, when both the MCX and MCY cantilevers are in ON state, the transmission spectrum of metamaterial shows a single resonance at 0.644 THz as shown in green-pentagon curve. The strong current distribution is seen along the FCX-MCX cantilevers as shown in Figure S2(h). The measured transmission spectra of the digital metamaterial are all four reconfiguration states that closely match with the simulation results. However, the small mismatch between the simulated and measured spectra can be attributed to the variation in the geometrical parameters and the deviation of the material properties used in simulation from the real case. Hence, for the x-polarization incidence, the measured resonance at 0.8 THz can be selectively switched by controlling the physical position of the MCX cantilever, while the position of MCY cantilever has no significant impact.

(iii) Transmission Response of digital metamaterial for y-polarization incidence

For the y-polarization incidence, the electric field is along the FCY-MCY cantilever direction and perpendicular to FCX-MCX cantilevers. The simulated and measured transmission spectra of the metamaterial in different states for y-polarization incidence are shown in **Figure S3(a) and 4(b)**, respectively. For the metamaterial in MCX-OFF/MCY-OFF states, the simulated transmission spectra (black-square curves) show two distinct resonances at 0.74 THz and 0.886 THz. The current distribution at 0.74 THz shown in Figure S3(c) indicates a stronger current in the FCY cantilever and weaker current in MCY-OFF cantilever. The lack of symmetry in the unit cell also allows the MCY cantilever to behave as an independent

cantilever with OFF state resonant frequency at 0.886 THz, which is seen from the weak current induced only in the MCY-OFF cantilever in Figure S3(d). Compared to the x-polarization excitation, the influence of the metal interconnects is highly reduced as there is not in-plane gap along the y-direction in the unit cell geometry. When the MCX cantilever is selectively switched to ON state, the transmission response of metamaterial in MCX-ON/MCY-OFF state (red-circle curve) shows two resonances at 0.736 THz and 0.84 THz. The current distribution at these resonant frequencies are shown in Figure S3(e) and S3(f), respectively and are identical to the current distribution at resonances for MCX-OFF/MCY-OFF case. Hence, for y-polarization incidence, the MCX-FCX cantilevers becomes dormant. When MCY cantilever is switched to ON state with MCX in OFF state, only a single resonance is observed at 0.65 THz as shown in blue-triangle curve. Similarly, when the metamaterial is switched to MCX-ON/MCY-ON configuration, there is only a single resonance at 0.61 THz as shown in green-pentagon curve. The current distribution in the metamaterial at 0.64 THz for MCX-OFF/MCY-ON configuration and 0.61 THz for MCX-ON/MCY-ON configuration are similar as shown in Figure S3(d) and S3(e), respectively. In both these cases, the FCY-MCY-ON cantilevers forms a single dipole mode resonator that is strongly excited. The slight mismatch in the resonant frequencies for x-polarization and y-polarization incidence at different configuration states is caused due to the lack of perfect rotational symmetry in the metamaterial unit cell, as the need for metal line is inevitable for providing the isolated control for MCX and MCY cantilevers. For y-polarization incidence, the measured resonance at 0.8 THz can be selectively switched by controlling the position of the MCY cantilever, while the position of MCX cantilever does not significantly influence the resonance at all reconfiguration states.

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Figure 1. Schematic drawing of the proposed digital metamaterial and various reconfiguration states. (a) Digital metamaterial formed by two independently reconfigurable cantilevers - MCX and MCY. The orthogonal placement allows for switching the linear polarization response of the metamaterial dynamically. The isolated electrical control of MCX and MCY cantilevers allows for four possible reconfiguration states. The schematics of the unit cell in each state is shown in (b) MCX-OFF/MCY-OFF, (c) MCX-ON/MCY-OFF, (d) MCX-OFF/MCY-ON and (e) MCX-ON/MCY-ON.

Figure 2. Fabricated digital metamaterial after release step. (a) Microscopic image of the metamaterial with MCX and MCY cantilevers in OFF state. The out-of-plane displacement of the released MCX and MCY cantilevers can be quantitatively observed from the out-of-focus, relative to the FCX and FCY cantilevers, which is completely in focus. (b) Scanning electron microscope image of the unit cell with MCX and MCY in OFF state and the air gap between the MCX, MCY cantilevers and Si substrate can be clearly observed. (c) R-DHM phase profile of the corresponding unit cell, (d) Measured out-of-plane deformation of the MCX cantilevers in OFF state (red-hollow square) and ON state (orange-solid square) and MCY cantilever in OFF state (blue-hollow circle) and ON state (green-solid circle), respectively.

Figure 3. *x*-polarization response of digital metamaterial. (a) Simulated and (b) Measured transmission spectra of the metamaterial for *x*-polarization incidence (electric field along FCX-MCX cantilever direction) with MCX cantilevers in OFF state (red-circle) and ON state (green-square), respectively. Simulated surface current distribution of the metamaterial with MCX in OFF state at (c) 0.724 THz and (d) 0.886 THz and (e) with MCX in ON state at 0.644 THz, respectively.

Figure 4. y-polarization response of digital metamaterial. a) Simulated and (b) Measured transmission spectra of the metamaterial for y-polarization incidence (electric field along FCY-MCY cantilever direction) with MCY cantilevers in OFF state (black-circle) and ON state (blue-square), respectively. Simulated surface current distribution of the metamaterial with MCY in OFF state at (c) 0.736 THz and (d) 0.84 THz and (e) with MCY in ON state at 0.623 THz, respectively.

Figure 5. Calculated anisotropy of the digital metamaterial when MCX cantilever is in OFF state (black-square), MCY cantilever is in OFF state (blue-circle) and both MCX and MCY cantilevers in ON state (red-triangle), respectively.

Figure S1: The schematics of the unit cell in each state is shown in (b) MCX-OFF/MCY-OFF, (c) MCX-ON/MCY-OFF, (d) MCX-OFF/MCY-ON and (e) MCX-ON/MCY-ON.

Figure S2. *x*-polarization response of dibit digital metamaterial. (a) Simulated and (b) Measured transmission spectra of the metamaterial for *x*-polarization incidence (electric field along FCX-MCX cantilever direction) in all four states: MCX-OFF/MCY-OFF (black-square), MCX-ON/MCY-OFF (red-circle), MCX-OFF/MCY-ON (blue-triangle) and MCX-ON/MCY-ON (green-pentagon). (c) – (h) simulated surface current distribution at each resonant frequencies at different reconfiguration states.

Figure S3. y-polarization response of dibit digital metamaterial. (a) Simulated and (b) Measured transmission spectra of the metamaterial for y-polarization incidence (electric field along FCY-MCY cantilever direction) in all four states: MCX-OFF/MCY-OFF (black-square), MCX-ON/MCY-OFF (red-circle), MCX-OFF/MCY-ON (blue-triangle) and MCX-ON/MCY-ON (green-pentagon). (c) – (h) simulated surface current distribution at each resonant frequencies at different reconfiguration states.