A TUNABLE TERAHERTZ METAMATERIAL BASED ON A MICRO-CANTILEVER ARRAY

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ABSTRACT

This paper reports a mechanically tunable terahertz metamaterial based on microscale electrostatic actuators. The device consists of an array of suspended cantilevers, forming LC resonators with underlying capacitive pads. The applied voltage can pull the cantilever downwards to increase the capacitance value in the resonator, and thus, redshift the resonant frequency. In our preliminary experiments, the resonant frequency can be tuned from 1.105 THz to 1.06 THz under a 40 V voltage; at the same time, the transmission amplitude can be modulated by approximately 15 dB at the resonant frequencies. The results enables the implementation of tunable terahertz devices, including modulators, polarizers and waveplates, employing conventional micro-electromechanical structures.

INTRODUCTION

Electromagnetic metamaterials are artificial materials including subwavelength unit-cell structures, which allow engineering of the effective permittivity and permeability [1]. The ability to manipulate the constitutive parameters at the unit-cell level enables realization of unprecedented properties, including negative refractive index [2], super lensing [3], invisibility cloaking [4], and perfect absorption [5].

While most metamaterials have static properties, dynamic control of the metamaterials can improve their functionalities to create metamaterial devices [1], especially for terahertz (THz) regimes [6]. Different approaches, including optical excitation [7-9], electrical gating [10,11], mechanical actuation [12-15], and incorporation of nonlinear materials [16], have been demonstrated to modulate and reconfigure the response of the metamaterials.

In this paper, we will present a mechanically tunable THz metamaterial based on a micro-cantilever array, which is a typical microelectromechanical actuator. The preliminary experimental results reveal that 50 GHz resonant frequency modulation can be achieved with a 40 V driving voltage. Along with the resonant frequency tuning, up to 15 dB amplitude modulation and 80° phase modulation have been demonstrated. Further optimization on the metamaterial structure can create functional THz devices, including spatial light modulators, phase modulators, and tunable waveplates.

DESIGN AND FABRICATION

The metamaterial consists of an array of cantilevers that are fabricated on a silicon substrate covered by an insulation layer, such as silicon dioxide (SiO_2), as shown in Fig.1 (a). The unit cell of the array is a suspended cantilever over a capacitive pad. Both of the cantilever and capacitive pad are made of metal. At the THz regimes, the suspended cantilever can be considered as an inductor, forming a LC resonator with the capacitance arisen from the gap between the cantilever and the bottom capacitive pad, as shown in Fig. 1 (b). The geometries can determine the resonance frequency. When a voltage is applied across cantilevers and the ground electrode (GND electrode), which is in ohmic contact with silicon substrate as a ground plane, the cantilevers are pulled downward. The capacitance increases and redshifts the resonant frequency.

To verify the electromagnetic response of the cantilever metamaterial, we numerically study a metamaterial with structural parameters shown in Table. 1. In this design, the substrate is 500-µm-thick silicon and insulation layer is 400-nm-thick silicon dioxide. The simulation reveals that the resonance frequency of the metamaterial is approximately 1.0 THz.

The micro-cantilever array was fabricated using surface micromachining technique. At first, 400-nm-thick SiO_2 layers were grown using dry thermal oxidation on both sides of the silicon substrate. On the top side, photolithography was performed to define the GND electrode areas, followed by RIE to etch out opening areas.

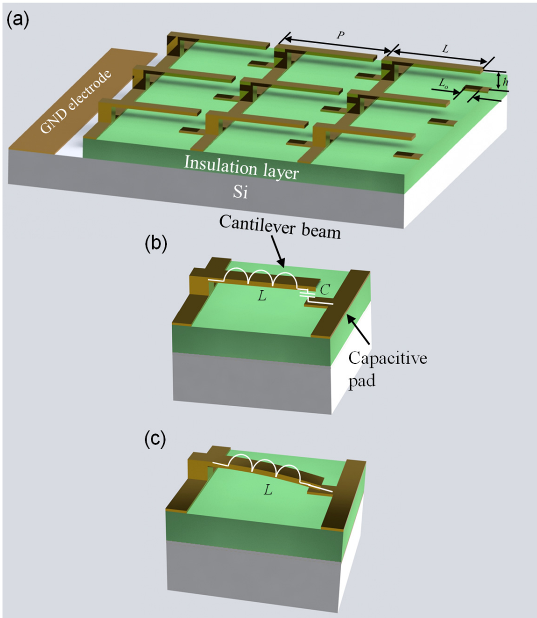

Figure 1: (a) The schematic of the cantilever based tunable metamaterial. All of the cantilever beams, which are suspended over the capacitive pads, are electrically connected with the interconnection wires. (b) The initial state of a unit-cell that is equivalent to an LC resonator. (c) The actuated state of the cantilever, in which the capacitance is increased due to decreased beam height.

Then, 600-nm-thick Al patterns were deposited on the top surface using the lift-off process (Fig.2 (b)). The wafer was annealed at 400 °C in N_2 ambient environment for 30 mins to form ohmic contact between the metal and silicon substrate. After that, the 150 nm gold thin film structures were patterned for GND electrodes and capacitive pads on the SiO_2 layer. Next, a layer of polyimide (PI2610) with 1 µm thickness was spin coated and cured at 275 °C in H_2/N_2 mixing gas for 1 hr as a sacrificial layer. Holes were opened for the anchors of the cantilevers using RIE with Ti film as the mask layer, as shown in Fig.2 (d). Afterward, copper cantilevers with thickness of 1 µm, covered by 20-nm-thick chrome layer, were patterned using e-beam evaporation and lift-off. The final step was to release the cantilever structure by isotopically etching the polyimide sacrificial layer. The ground electrode and the micro-cantilever array were connected to a printed circuit board using wire bonding to apply the driving voltage.

Table 1. Key structural parameters of the cantilever metamaterial.

Symbol	Value (*µm*)	Description
L	50	Length of the cantilever
P	60	Periodicity of the unit cell
W	10	Width of the cantilever beam
L_o	2.5	Overlapped length of the cantilever and the bottom pad
h	1.0	The vertical distance between the tip and the capacitive pad

The scanning electron microscope images of the released micro-cantilever array are shown in Fig. 3. Due to the residual stress generated in the fabrication process, the cantilevers were bent upward, leading to an initial ~2-µm vertical distance between the tip of the beam and the underlying pads. The curvature of the beam was measured using white light interferometer, as shown in Fig. 4 (a). The

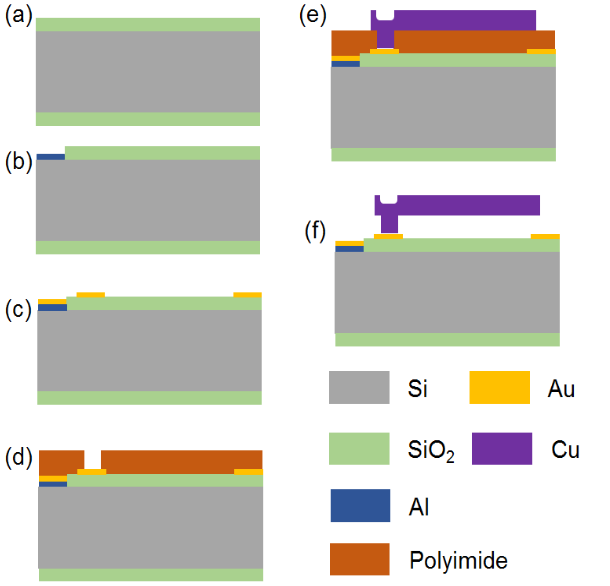

Figure 2: Fabrication process of the tunable meta-material.

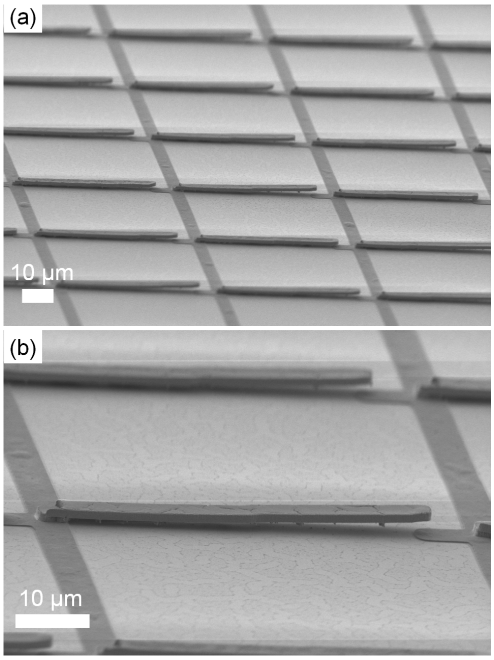

Figure 3: Scanning electron microscope images of the released micro-cantilever array.

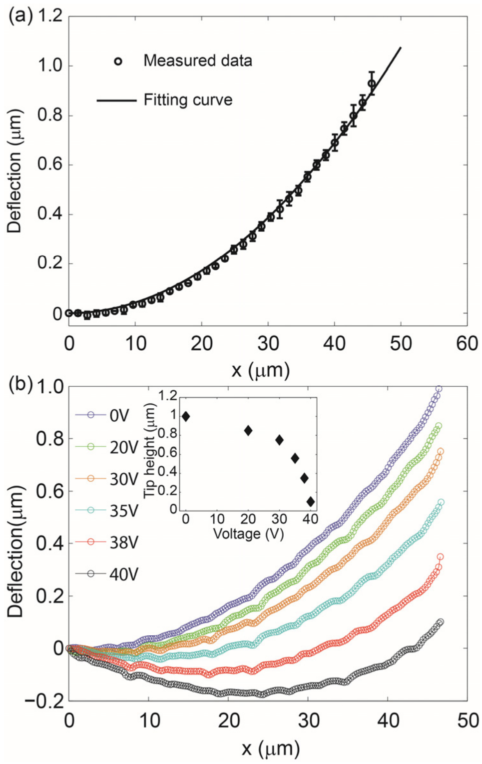

Figure 4: (a) The initial curvature of the released cantilever beam. (b) The cantilever deflection curvatures at different voltages. Inset: the height of the cantilever tip versus the applied voltage.

stress difference between the top and bottom surface was approximated 110 MPa by fitting the measured curvature with the deflection equation of the pre-stressed cantilever beam. The deflection of the cantilever was measured at varied driving voltages. The beam moved downward as the driving voltage increased and snapped down the to the ground plane when the voltage was exceeding 40 V, corresponding to the pull-in voltage of the structure.

Experiments and Results

The transmission response of the fabricated tunable metamaterial was characterized using the THz time domain spectroscopy (TDS) based on photoconductive antennas, as shown in Fig. 5. The incident THz pulses were polarized parallel to the cantilever beam. The time domain transmission signals through the metamaterial and air, which is used as reference, were measured separately. Fourier transform was performed on the temporal signals to get their frequency responses, i.e. $E_{MM}(\omega)$ and $E_{ref}(\omega)$. The transmission spectral response of the metamaterial can be calculated by $T(\omega) = E_{MM}(\omega)/E_{ref}(\omega)$. We measured the transmission spectrum for each applied voltage, as shown in Fig. 6.

When the applied voltage is 0 V, the transmission spectrum exhibits a strong resonance at 1.105 THz with the transmission amplitude of -23 dB, as shown in Fig. 6 (a). The resonant frequency corresponds to the LC resonant mode of the micro-cantilever, in which the cantilever serves as an inductor and forms a capacitor along with the underlying pad. As the applied voltage increases, the resonant frequency redshifts gradually as expected due to the decrease in the distance between the capacitive surfaces resulting increase in capacitance. When the voltage exceeds 40 V, i.e. the pull-in voltage of the micro-cantilever, the transmission spectrum cannot be tuned with further increase of the applied voltage since the capacitance cannot be increased. We can shift the resonant frequency from 1.105 THz to 1.06 THz with a 40 V DC voltage. Due to the modulation in the resonant frequency, we can control the transmission amplitude for some frequencies. For example, -15 dB and 10 dB amplitude modulation can be achieved at 1.062 THz and 1.106 THz, respectively, as shown in Fig. 6 (d). Besides amplitude modulation, we can modulate the phase of the transmission response as shown in Fig. 6 (b), in which ~80^{o} phase modulation is exhibited at 1.106 THz.

To understand the mechanism of the tunable response, finite element simulation was performed using CST Microwave Studio. In the model, unit-cell boundary was applied. We utilized the real curvature of the cantilever [as

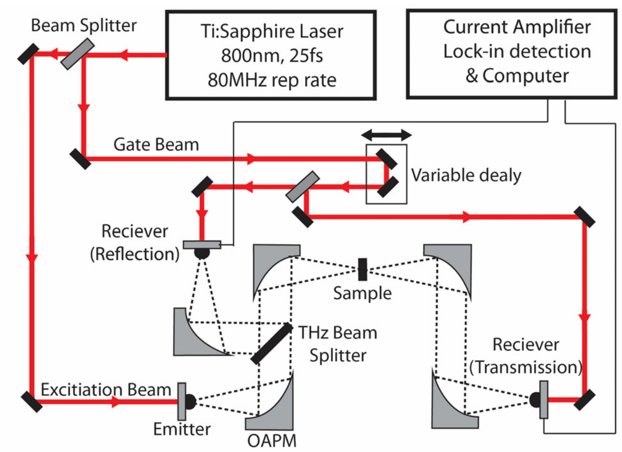

Figure 5: The schematic of the THz time domain spectroscopy (TDS) based on photoconductive antennas. The transmission channel is used to measure the response of the metamaterial sample.

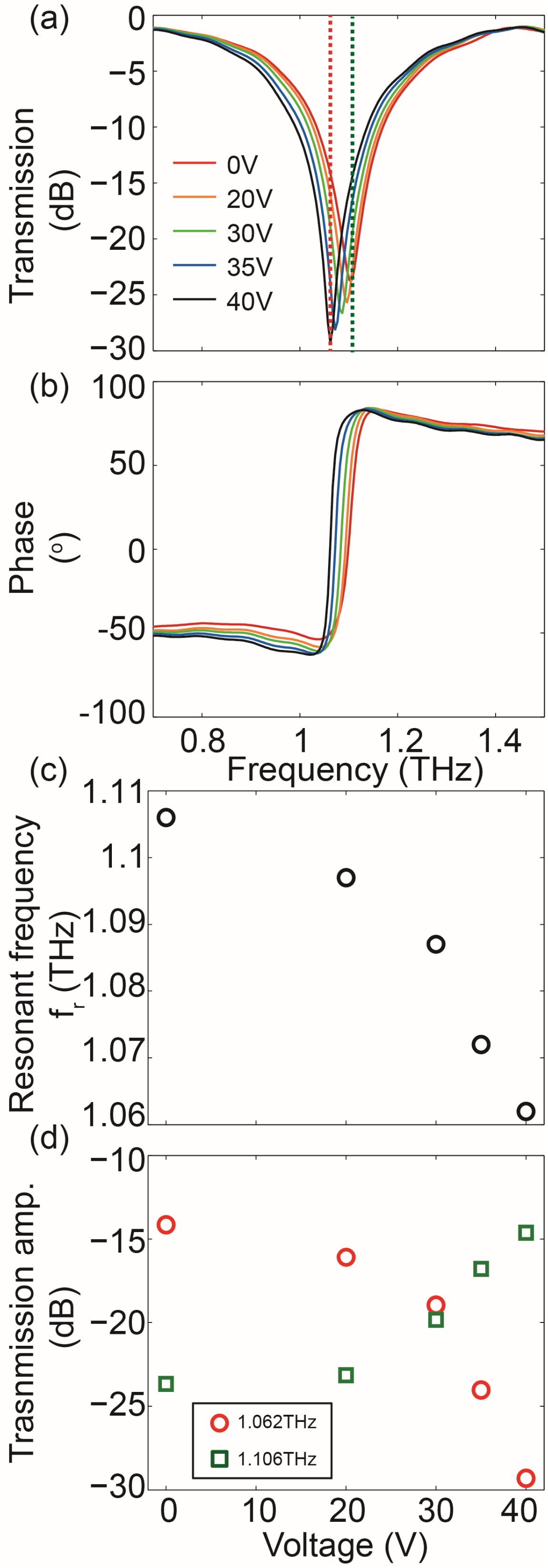

Figure 6: The experimental transmission spectra of a cantilever tunable metamaterial at different driving voltages: (a) amplitude and (b) phase. (c) The resonant frequency versus driving voltage. (d) Amplitude modulation for 1.106 THz and 1.062 THz at different driving voltages.

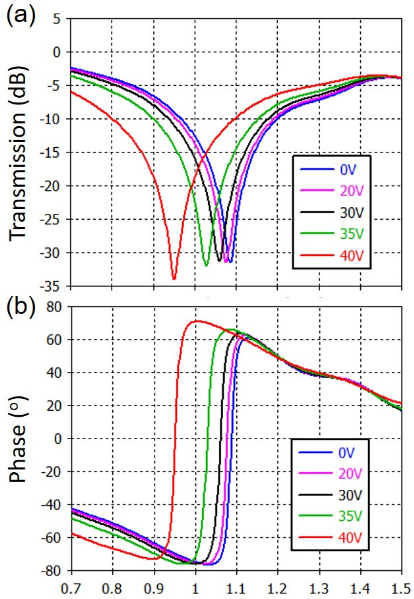

Figure 7: Numerically simulated transmission spectra of the tunable metamaterial: (a) amplitude and (b) phase. The curvature of the cantilever used in the simulation is from the experimental results as shown in Fig. 4 (b)

shown in Fig. 4(b)] to simulate the effect of the applied voltage. The simulation results (Fig. 7) exhibits a decent agreement with the experimental results, indicating that the mechanical movement of the cantilever is main reason of the tunable response. However, the shift of the resonant frequency shifting in the simulation results is larger than the experiment. This is possibly due to the imperfections in the fabrication.

CONCLUSION

In this paper, a tunable terahertz metamaterial based on a micro-cantilever array was designed and fabricated. The resonant frequency can be shift from 1.105 THz to 1.06 THz with a 40 V driving voltage. At the same time, ~80° phase modulation and ~15 dB amplitude modulation have been demonstrated for some frequencies. The structure can be optimized to create THz devices, including spatial light modulators, phase modulators, and tunable waveplates.

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