Fast Tunable Terahertz Absorber Based on a MEMS-driven Metamaterial

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Abstract: We present an experimental study of ultra-thin tunable THz absorbers based on MEMS-driven metamaterials. Using the high mechanical sensitivity of thin subwavelength metamaterial absorbers, we proposed a paradigm to combine meta-atoms and suspended flat membranes to simultaneously maximize the near-field coupling and avoid resonance broadening. We employed a MEMS technology and successfully fabricated THz absorbers based on integration of meta-atoms and MEMS, demonstrating giant tuning of resonant absorption. The devices presented in this paper are among the best-performing tunable THz absorbers achieved to date, particularly in device thickness and tunability characteristics.

OCIS codes: (160.3918) Metamaterials; (310.3915) Metallic, opaque, and absorbing coatings

High-performance tunable absorbers for terahertz frequencies are crucial for advancing applications such as terahertz detection and imaging. Among the numerous solutions for reconfigurable THz metamaterials and meta-devices (see [1][2] and the references therein), the hybridization of micro-electro-mechanical-systems (MEMS) and THz metamaterials is one of the most promising paradigms. Using the strong sensitivity of the electromagnetic response of metamaterials to the mutual position of its elements, we place meta-atoms supporting strongly localized modes on microscopic suspended flat membranes of micro-electro-mechanical systems. We demonstrate prototype devices that are among the best-performing tunable THz absorbers to date with ultra-thin device thickness (~1/50 of the working wavelength), strong absorption (up to 80%), giant mechanical tunability (resonance shifts by more than 200% of the resonance linewidth), large modulation (up to 65% of absolute change in absorption), and fast switching speed (~27 micro-seconds). The demonstrated approach can be further extended in order to modulate transmission, phase and polarization of the terahertz radiation.

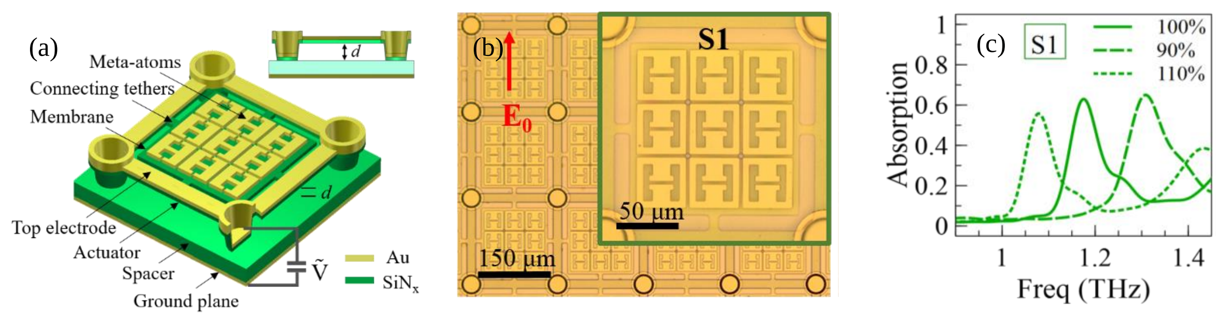

Figure 1. (a) Schematic of the unit cell of the THz absorber. (b) Microscope photograph and (c) the measured THz absorption spectra of the fabricated MEMS arrays. Spectra are also shown for devices with geometry scaled by 90% and 110%.

We designed and fabricated a series of MEMS tunable metamaterial absorbers using standard surface micromachining techniques compatible with most MEMS foundries (schematic of the unit cell of the device is shown in Fig. 1 (a), and microscope photograph of one of the devices is shown in Fig. 1 (b)). It includes a 200 nm thick metallic ground plane, a 2 μm thick silicon nitride spacer, and a matrix of meta-atoms suspended above the silicon nitride layer by an adjustable distance d. The size of each unit cell is 180 μm

×180 µm, and each unit cell contains 9 metallic meta-atoms supported by a suspended silicon nitride membrane (140 µm × 140 µm × 200 nm). The introduction of the silicon nitride membrane and spacer is crucial in reducing the footprint and thickness of the absorber due to its relatively high permittivity ($\varepsilon_{SiNx} \approx 7$). The movable membrane is tethered to four actuation arms suspended from four posts in a square arrangement. The separation between the membrane and the spacer is d = 3 µm at rest and can be tuned electrostatically by attracting the silicon nitride micro-beam actuators (covered by gold top electrode layer) to the gold ground plane, which also serves as the bottom.

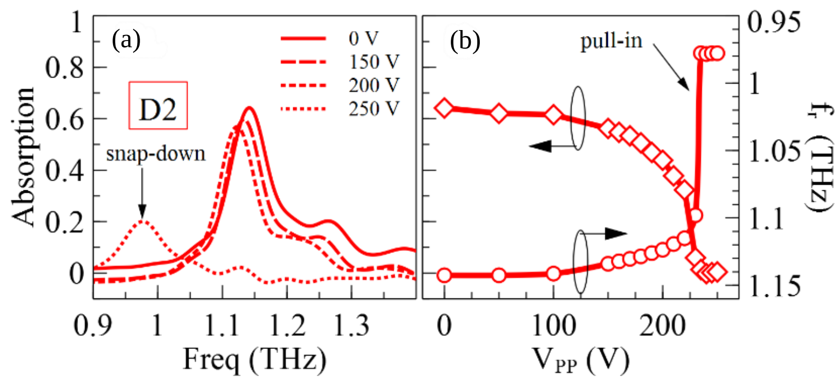

Figure 2. (a) Measured absorption spectra for different applied peak-to-peak voltage V_{pp} for one of fabricated devices. (b) Absorption change measured at the initial resonant frequency of maximum absorption for unactuated device, and the change of resonant frequencies with actuation voltage

We experimentally characterized the dynamic mechanical response, including the response time of our devices by monitoring the displacement of the meta-atoms using an optical vibrometer. The time dependent displacement shows that the device is over-damped at ambient air pressure, and the response time, measured from 10% to 90% displacement, is $\tau \approx 27\ \mu$s.

We further measured the THz absorption using time-domain spectrometer, and observed the modulation of the absorption (see Fig. 2(a,b)). The absorption maximum at resonance in some of our devices reaches 80%, sufficient for imaging applications, and this can be further improved by optimizing fabrication process in order to achieve the theoretically predicted 98% absorption. To test the maximum modulation, we drove one pf the devices to irreversible snap-down state, when membrane moves all the way to the dielectric spacer layer and sticks to it. The resonance shifts by 165 GHz (~ 206% of the resonance linewidth, 14.4% of initial resonance wavelength) and a modulation of absolute absorption of up to 65% is achieved. Compared to the results predicted by our simulation, the measured resonance shift at snap-down state is smaller. One possibility is the incomplete snap-down, i.e. a small gap forms between the membrane and the top of spacer, due to imperfection of fabrication.

In summary, we proposed, designed and experimental studied thin tunable THz absorbers based on MEMS-driven metamaterials. We characterized our devices and demonstrated large modulation of absorption. Simulations suggest that further optimization of the fabrication process can enhance of maximum absorption, reduction of operation voltage, introduction of anti-stiction layer, etc. The current design facilitates integration with addressable circuits to realize individual pixel control in the array, which is particularly attractive for sophisticated applications relying on full spatial control of THz waves11

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