A COMB-DRIVE ACTUATOR ENABLED DYNAMICALLY TUNABLE TERAHERTZ METAMATERIAL

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ABSTRACT

This paper reports our recent progress on a dynamically tunable terahertz metamaterial based on broadside-coupled split ring resonators (BC-SRRs) and a comb-drive actuator. In the structure, the coupling between two arrays of SRR is modulated with the lateral displacement exerted by the comb-drive actuator. In the spectrum of BC-SRRs, two resonant modes can be observed, i.e. symmetric mode and anti-symmetric mode, due to the strong inductive and capacitive coupling. Over 20 μm lateral displacement, the symmetric mode blueshifts ~ 60 GHz and the anti-symmetric mode redshifts ~ 50 GHz. The amplitude of the transmission at 1.03 THz is modulated by 69%. We can realize a large tuning range with structure optimization, thereby enabling the applications including THz modulators and chemical sensing.

INTRODUCTION

Over the past decade, metamaterials (MMs) have been proved to be a scheme to engineer the electromagnetic response of materials through resonance excitations [1]. They have many remarkable applications, such as negative refractive index [2], super lensing [3], perfect absorption [4], and cloaking [5], in information processing [6], chemical and biology sensing [7], and security [8, 9].

In order to enhance the functionalities of MMs, a number of approaches have been employed to make the MMs reconfigurable. These include electrical gating [10], photo-excitation [11], thermal tuning [12], modulation of near-field coupling [13] and structural and mechanical reconfiguration [14]. Among these methods, tuning the near field coupling is of interest because of its high efficiency, stability and ease of controlling [15]. One coupled MM structures is broadside-coupled split ring resonator (BC-SRR), including two split ring resonators (SRRs) arrays are stacked vertically and rotated 180° to each other. Recent study shows that the lateral displacement between the two SRR layers will tune the MM resonance frequency [13].

Micromachined electrostatic actuators provide an intuitive path to realize the functional broadside-coupled tunable devices. We demonstrated implantation of the real-time tunable metamaterial based on the BC-SRRs and comb-drive actuators in [16].

In this paper, we report our recent process of the BC-SRRs based metamaterial at THz frequencies. The coupling between the SRRs is optimized with new geometry design and the fabrication process is improved to achieve good alignment in the flip-chip bonding. With the new mechanical structure design, the yield of the functional device is increased as well. With this improvement, the tunability is improved significantly compare to our previous work [16]. The first resonant mode redshifts 60 GHz and the second mode redshifts 50 GHz with 20 μm lateral displacement achieved by the comb-drive actuator. Meanwhile, the amplitude at 1.03 THz is modulated by 69%.

DESIGN AND FABRICATION

The illustration of the designed tunable MMs is shown in Figure 1. The MMs are composed with two layers of SRRs separated by 20 μm air gap. One layer is on 10 μm thick silicon with

electrostatic comb-drive actuators, while the other is fixed on 500 nm thick SiN_x thin film. The unit-cell of the MMs with different x-axis displacement is shown in Figure 1 (b). The rings are rotated 180° to each other, forming a broadside coupled configuration. Since the two layers of MMs are closed to each other, the near-field inductive and capacitive interactions between them are strong. The relative shift along x-axis between the arrays, controlled by the applied voltage, can change the coupling between the SRRs. Thus, it modulated the frequency response of the MM.

In this device, the geometries of the two SRRs in each coupled pair are not identical to compensate for the effect of the different substrates. We determine the parameters, as listed in Table 1, using numerical simulation in order to match the resonant frequency of the uncoupled SRRs. The frequency match can improve the coupling efficiency between the SRRs and tunability comparing to the unmatched condition [16]. The simulated transmission spectrum of SRR1 and SRR2 are shown in Figure 2. The dip in the each spectrum corresponds to the LC resonant frequency of the SRR, which is determined by the self-inductance and capacitance of each ring. When the two rings are stacked together, the mutual inductance and capacitance will show up and lead to the frequency split in the spectrum [17], as shown with the red curve in Figure 2.

Figure 1: Illustration of the broad-side coupled tunable metamaterials: (a) the exploded diagram of the tunable metamaterials, in which two chips were bonded together with polyimide spacer; (b) and (c) the unit-cell of the metamaterials with different x-axis shift.

Table 1: The dimensions of SRRs (unit in μm)

	Periodicity (P)	Side-width (l)	Linewidth (w)	Gap (g)
SRR1	58	40	11	16
SRR2	58	40	11	2

The tunable metamaterial was fabricated with micromachining processes as shown in Figure 3, which include two wafer processes and flip chip bonding. An SOI wafer with a 10 μm thick device layer and 2 μm buried oxide layer was used as the first wafer. Both sides of the wafer were coated by 400nm thick low-stress SiN_x films grown by LPCVD. With subsequent photolithography and reactive ion etching (RIE), the SiN_x film on the top side was patterned [Figure 3 (a)]. Then, the electrodes were deposited on the exposed silicon using e-beam evaporation of 400 nm Al. The ohmic contact was achieved by annealing at 450 $^\circ\text{C}$ in H_2/N_2 ambient. The electrodes were coated with a 150 nm gold thin film after annealing [Figure 3 (b)]. Subsequently, 150 nm thick gold SRRs were patterned via a lift-off process and the device layer was etched using deep reactive ion etching (DRIE) to form the comb-drive actuators and supporting beams [Figure 3 (c) and (d)]. A 600 nm thick SiO_2 passivation layer was deposited on the front side with PECVD in order to protect the patterned device layer in the following steps [Figure 3 (e)]. Next, backside alignment and photolithography using AZ9260 (MicroChemicals, Inc.) was performed and the SiN_x film was etched with RIE, followed by etching through the Si substrate using DRIE [Figure 3 (f) and (g)]. The last step [Figure 3 (h)] was to etch the passivation layer and buried oxide layer with Silox Vapoxxy III etchant (Transene, Inc.) to release the movable structure. The second wafer, a single crystal $\langle 100 \rangle$ silicon wafer, was coated with low-stress SiN_x film on both sides using LPCVD. Then, 150 nm thick gold SRRs were patterned on the top side with lift-off process [Figure 3 (i)]. Then, the silicon wafer was etched through with KOH wet etching from the window opened on the backside SiN_x film [Figure 3 (j)]. After the wafer-level fabrication, the two wafers were diced into chips. For clarity and conciseness, we name the chips from the SOI wafer as chip 1 and the chips from the silicon wafer as

Figure 2: The simulated response of the SRR1, SRR2 and BC-SRRs with the geometries listed in Table 1. The resonant frequencies of the SRR1 and SRR2 are matched. The vertical distance between the SRRs is 20 μm in the BC-SRRs. Frequency splitting shows up in the BC-SRRs.

chip 2. Polyimide bonding pads were patterned on chip 2 via photolithography of the photosensitive polyimide (HD8820, HD Microsystems). Finally, chip 1 and chip 2 were bonded together using a flip chip bonder (FC150, Suss MicroTec AG) under 200 g force and 175 $^\circ\text{C}$ temperature. The bonded chips were connected with a printed circuit board via bonding wire to apply the voltage.

The fabricated device is shown in Figure 4 (a). Details of the chip 1 are shown in Figure 4 (b) and (c). The microscope images of the bonded device [Figure 4 (d) and (e)] show that the SRRs are well-aligned in y direction and the misalignment in the x direction can be controlled with the comb-drive actuated lateral displacement.

Figure 3: Fabrication process of the broad-side coupled tunable metamaterials: (a)-(h) the first (SOI) wafer process; (i)-(j) the second (silicon) wafer process; (k) the flip-chip bonding. The bonded chips were connected with a printed circuit board via bonding wire to apply the voltage

Figure 4: Fabricated device. (a) The flip-chip bonded tunable metamaterial; (b) and (c) SEM images of the comb-drive chip; (d) the SRRs with 0 μm lateral displacement, where the SRRs are aligned; (e) the SRRs with 20 μm relative lateral displacement, where the SRRs are misaligned.

EXPERIMENT AND RESULTS

The electromagnetic response of the real-time tunable metamaterial was characterized by THz time domain spectroscopy

(THz-TDS), as shown in Figure 5. A 1 kHz Ti:sapphire femtosecond laser producing 1.55 eV near-infrared pulse (800 nm, 3 mJ, 35 fs) was utilized to pump the ZnTe crystal to generate THz pulses. The THz pulses were focused on the sample or reference with a parabolic mirror. The electric field of the THz pulses was polarized perpendicular with the gaps of the SRRs. The transmitted THz pulses were collimated and focused in the detection ZnTe crystal, with which the electro optical (EO) sampling based on Pockels effect can detect the electric field strength of the THz pulses. We can obtain the time domain signal of the sample and reference individually with this scheme. Then, a Fourier transform was performed on the time domain signal to obtain the frequency spectrum of the reference and metamaterial samples. The transmission spectrum of the sample was calculated by normalize the spectrum of metamaterial sample to the reference. A DC voltage power supply was used to drive the comb-drive actuator. By sweeping the applied voltage, the spectra of the metamaterial were measured at different lateral displacements.

The measured transmission spectra of the metamaterial with different lateral displacements are shown in Figure 6 (a). When the lateral displacement is 0 μm , there are two resonant modes with resonant frequencies of 1.03 THz and 1.23 THz. With the increasing lateral shift, the first resonant mode shifts higher frequency (blueshift) while the second mode shifts to lower frequency (redshift). With the lateral displacement up to 20 μm , the first mode blueshifts by 60 GHz and the second mode redshifts by 50 GHz. At the same time, the transmission amplitude at 1.03 THz is tuned from 0.2 to 0.65, as shown in Figure 6 (b).

DISCUSSION

The behavior of the BC-SRRs can be described with different theories [18], including coupled mode theory and mutual capacitance and inductance model [19]. We will use the third method to interpret the presented tunable metamaterial.

We simulated the transmission spectra and surface current distributions of the BC-SRRs with different lateral displacements using CST Microwave Studio. In the simulation, unit-cell boundary condition was applied. The spectra agree [Figure 7 (a)] well with the experimental results [Figure 6 (a)]. When the lateral shift is 0 μm , the surface currents are in the same direction at the first mode and in the opposite direction at the second mode, as shown in Figure 7 (b) and (c). We define the first mode as symmetric mode and the second mode as the anti-symmetric mode. The mutual inductance and capacitance are positive for the symmetric mode but negative for the

anti-symmetric mode due to the surface current and charge distribution. With increasing lateral displacement, the absolute value of the mutual inductance and capacitance decrease. As a result, the total inductance and capacitance of the symmetric mode decrease, leading to a blueshift in the resonant frequency; at the same time, the total lumped L and C increase, resulting in the redshift of the second mode. When the lateral displacement is about 20 μm , the two resonators oscillate individually without any coupling as shown in Figure 7 (d) and (e). The simulated transmission spectra agree well with the experimental data and support our qualitative analysis.

CONCLUSION

We presented our recent process on the dynamically tunable terahertz metamaterial based on broadside-coupled split ring resonators (BC-SRRs). The BC-SRRs are with a symmetric mode and an anti-symmetric mode. With the optimization of the structural design, we achieved 60 GHz redshift of the symmetric mode and 50 GHz blueshift of the anti-symmetric mode. At the same time, 69% modulation depth was demonstrated at 1.03 THz. The tunable metamaterial has potential applications for dynamic modulation of the THz radiation and spectral sensing of chemicals.

Figure 5: Terahertz time domain spectroscopy for the tunable metamaterial characterization.

Figure 6: (a) The experimental transmission spectra of the real-time tunable metamaterial. With the increase of the lateral displacement, the two resonance modes merge together due to the decrease of the coupling. (b) The magnitude of transmission at 1.03THz with different lateral displacement. The transmission is tuned by 69%.

Figure 7: (a) The simulated transmission spectrum at different lateral displacement. (b) – (e) the surface current at the corresponding resonance frequency as shown in (a). Strong coupling exists between the broadside coupled SRRs in (b) and (c), while little coupling in (d) and (e).

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REFERENCES

- [1] N.I. Zheludev and Y.S. Kivshar, "From Metamaterials to Metadevices", *Nature Materials*, 11, 917 (2012).
- [2] D.R. Smith, J.B. Pendry, and M.C. Wiltshire, "Metamaterials and negative refractive index", *Science*, 305, 788 (2004).
- [3] X. Zhang and Z. Liu, "Superlenses to Overcome the Diffraction Limit", *Nature Materials*, 7, 435 (2008).
- [4] N.I. Landy, S. Sajuyigbe, J.J. Mock, D.R. Smith, and W.J. Padilla, "Perfect Metamaterial Absorber", *Physical Review Letters*, 100, 207402 (2006).
- [5] N. Engheta, "Circuits with Light at Nanoscales: Optical Nanocircuits Inspired by Metamaterials", *Science*, 317, 1698 (2007).

- [6] X. Xu, B. Deng, D. Li, J. Zhang, L. Wong, Q. Zhang, S. Wang, and Q. Xiong, "Flexible Visible-Infrared Metamaterials and Their Applications in Highly Sensitive Chemical and Biological Sensing", *Nano Letters*, 11, 3232 (2011).
- [7] L. Feng, Y. Xu, W.S. Fegadolli, M. Lu, J.E. Oliveira, V.R. Almeida, Y. Chen, and A. Scherer, "Experimental Demonstration of a Unidirectional Reflectionless Parity-time Metamaterial at Optical Frequencies", *Nature Materials*, 12, 108 (2012).
- [8] D. Shrekenhamer, C.M. Watts, J. Montoya, S. Krishna, and W.J. Padilla, "Metamaterial-based Imaging for Potential Security Applications", *Proceeding of SPIE*, 8632, 863321 (2013).
- [10] H.-T. Chen, W.J. Padilla, M.J. Cich, A.K. Azad, R.D. Averitt, and A.J. Taylor, "A metamaterials solid-state terahertz phase modulator", *Nature Photon*, 3, 148 (2009).
- [11] K. Fan, X. Zhao, J. Zhang, K. Geng, G.R. Keiser, H.R. Seren, G.D. Metcalfe, M. Wraback, X. Zhang, and R.D. Averitt, "Optically Tunable Terahertz Metamaterials on Highly Flexible Substrates", *IEEE Transaction on Terahertz Science and Technology*, 3, 702 (2013).
- [12] H. Tao, A.C. Strikwerda, K. Fan, W.J. Padilla, X. Zhang, and R.D. Averitt, "MEMS Based Structurally Tunable Metamaterials at Terahertz Frequencies", *Journal of Infrared, Millimeter and Terahertz Waves*, 32, 580 (2011).
- [13] E. Ekmekci, A.C. Strikwerda, K. Fan, G.R. Keiser, X. Zhang, G. Turhan-Sayan, and R.D. Averitt, "Frequency Tunable Terahertz Metamaterials Using Broadside Coupled Split-ring Resonators", *Physical Review B*, 83, 193103 (2011).
- [14] A.Q. Liu, W.M. Zhu, D.P. Tsai, and N.I. Zheludev, "Micromachined Tunable Metamaterials: A Review", *Journal of Optics*, 14, 114009 (2011).
- [15] A.D. Boardman, V.V. Grimalsky, Y.S. Kivshar, M. Lapine, and N. Litchinister, "Active and Tunable Metamaterials", *Laser Photonics Review*, 5, 287 (2011).
- [16] X. Zhao, K. Fan, G.R. Keiser, H.R. Seren, R.D. Averitt, and X. Zhang, "A Real-Time Tunable Terahertz Metamaterial Based on Broadside-Coupled Split Ring Resonators", *Proceeding of the 18th International Conference on Solid-State Sensors, Actuators, and Microsystems*, Anchorage, AK, June 21-25, 2015, pp. 315-318.
- [17] G.R. Keiser, A.C. Strikwerda, K. Fan, V. Young, X. Zhang, and R.D. Averitt, "Decoupling Crossover in Asymmetric Broadside Coupled Split-Ring Resonators at Terahertz Frequencies", *Physical Review B*, 88, 023101 (2013).
- [18] H. Haus and W.P. Huang, "Couple-Mode Theory", *Proceedings of the IEEE*, 79, 10 (1991).
- [19] G.R. Keiser, K. Fan, X. Zhang, and R.D. Averitt, "Towards Dynamic, Tunable, and Nonlinear Metamaterials via Near Field Interactions: A Review", *Journal of Infrared, Millimeter and Terahertz Waves*, 34, 709 (2013).

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