博士論文（要約）

A Study on MEMS Reconfigurable Metamaterial for Terahertz Filter Applications
（ＭＥＭＳ可変メタマテリアルのテラヘルツフィルタ応用に関する研究）

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This work deals with a study on MEMS reconfigurable metamaterial for terahertz filter applications. A novel MEMS reconfigurable metamaterial have been proposed and demonstrated on a low loss quartz substrate for tunable terahertz band stop filter applications. The designed structure implements a reconfiguring RF-MEMS (radio frequency – micro electro mechanical systems) capacitor embedded within each split ring resonator (SRR). By electrostatically controlling the height of suspension structures, meanwhile the capacitance within the SRR, the tunable ability for the SRR resonance and thus the terahertz transmission of metamaterial device was controlled. Since a high transmission and low loss material of quartz was used as substrate, the device further shows a terahertz switch with high contrast ratio at the frequencies of the SRR resonance, which presents a potential prospect for high efficiency transmission terahertz device, such as Fresnel zone plate.

Chapter 1 reports the introduction of this work from the tunable terahertz metamaterial view. During the last 15 years, metamaterial has raised lots of interests. The main benefit of metamaterial is in the ability to tailor electromagnetic wave propagation from the designed micro- and nano-structures shorter than the wavelength of interests. Since the first experimental demonstration of metamaterial device with both negative permittivity and permeability in 2000, several unconventional properties have been found, such as the negative index, sub-wavelength imaging, artificial magnetism, and manipulating polarization.

Most natural materials inherently have very small electromagnetic interaction with terahertz light in the frequency range between 100 GHz and 10 THz, resulting in the lack of functional device, where metamaterial as a promise candidate shows the ability to control terahertz wave propagation. Recent studies on the tunable terahertz metamterial have reported the realization of terahertz wavelength modulator and filter. Tuning capability of metamaterial has been demonstrated based on the mechanisms of tuning the effective inductance or capacitance of the SRR, for instance, using voltage to control the built-in capacitors through the depletion layer in semiconductor substrate, using photo excitation to control the conductivity of local material within SRR gap, using temperature to control the effective permittivity of the substrate, using magnetic field to control the conductivity of SRR pattern.

On the other hand, geometry reconfiguration of SRR pattern by using micro electro mechanical system (MEMS) technique shows dramatic changing in the transmission performance of metamateiral devices. For instance, research have been conducted on reconfiguring the column layer of split ring resonators (SRRs) in plane, controlling the geometry orientation of SRR to the incident terahertz wave, and tuning the capacitance within SRR through a curved cantilever beam. However, the above works were based on a semiconductor substrate with the risk of loss. To have an efficiency terahertz device, a low loss substrate is necessary to combine with the tunability of SRR. In this work, we demonstrate a novel MEMS reconfigurable metamaterial on a low loss quartz substrate for terahertz filter applications.

Chapter 2 deals with the device design and simulation with a commercial software package, High

Frequency Structure Simulator (HFSS). The square SRR pattern (100 μm × 100 μm) is formed on a fused quartz wafer (thickness 300 μm). In the center of SRR lattice, a cantilever together with a disk made of gold and silicon oxide layered structure is suspended over an air gap above the bottom disk with bilayer composition of gold and silicon oxide, thereby forming the MEMS capacitor within the SRR. The metallic patterns at the outer ring of SRR are cut into two 8-μm-wide braces, such that it enables the entire SRR to be divided into two electrodes that can also be used as the electrical interconnection to supply MEMS drive voltage to the parallel disk. Meanwhile, the cut braces working as capacitance still maintain the electromagnetic coupling within the SRR, and SRR works as a resonator under external terahertz wave excitation.

The resonance tunability of the SRR can be achieved by controlling the cantilever suspension height above the bottom disk, associated with changing the capacitance within SRR. When applying voltage to the two electrodes beyond the pull-in voltage, due to the electrostatic force, the suspended disk will be brought down into contact with the bottom disk, where insulator layers of SiO2 with both the top disk and the bottom disk become laminated between the two metal electrodes, avoiding the electrical short circuit. Consequently, the closed air gap increases the capacitance of the SRR compared with the original OFF-state, resulting in a lower resonant frequency for the ON-state. Therefore a tunable terahertz band stop filter for particular frequencies is obtained from the tuning transmission spectrum.

For a functional metamaterial, the individual SRR unit cells are arranged into an array, where the chained line through SRR are electrically connected in the lateral direction, enabling MEMS drive voltage to feed to each cantilever and thereby actuating the cantilever array simultaneously.

HFSS was used on an SRR unit cell under periodic boundary condition to calculate the electromagnetic response. Under normal incidence with polarization perpendicular to the chained line, terahertz wave excite SRR to behave as an inductance-capacitance (LC) resonator. When modelling the cantilever down contacting with the bottom disk to reconfigure the SRR pattern from OFF-state to ON-state, the fundamental resonant frequency shift from 696 GHz (OFF-state) to 459GHz (ON-state), which indicates that the MEMS reconfigurable SRR has the ability to tune its resonant frequency.

Calculation on the field distribution at the resonant frequency of SRR OFF-state show that the electric field is mainly confined and enhanced in the center RF-MEMS capacitor and that the surface current distributed along the metallic pattern is close to form two loops, suggesting the capacitance and inductance resonate within the SRR. In this design, since the chained line is perpendicular to the polarization of the incident terahertz wave, it has little contribution from the chained lines to the electromagnetic resonance at the side edge corner neighboring to the next SRR, which are also deduced by the small value of the distributed eclectic field and the surface current. Hence, the DC/RF decoupling design has been achieved for the MEMS reconfigurable SRR and the design methodology simplifies the MEMS and metamaterial structures.

Another case has also been investigated by HFSS, where the polarization of incident electromagnetic wave is parallel with the chained line. The structure construction of SRR does not contribute to the resonance, but the metallic chained line behaves in a Drude-like response. Therefore, the RF-MEMS capacitor does not tune the electromagnetic performance of SRR with this polarization status. Consequently, our tunable metamaterial design by using RF-MEMS capacitor within each SRR pattern has polarization sensitivity, which is useful in the application where polarization selecting is mandatory.

Chapter 3 deals with the manufacture process of the MEMS reconfigurable SRRs by the surface micromachining technique. The entire processing utilizes three photo masks. The fabrication procedure begins with sputtering 10-nm-chromium (Cr) / 220-nm-gold (Au) / 10-nm-chromium three stacked layers on quartz wafer. After the bottom electrode patterning by normal photolithography and wet etching, a thin layer silicon oxide (SiO2 200nm) is sputtered on the wafer for the purpose of avoiding electrical short circuit during MEMS actuation. After that, a 2 μm photoresist as sacrificial layer is spin coated and patterned by photolithography. Next, the top structure layers of SiO2 / Cr / Au (240 nm / 10 nm / 230 nm) are sputtered sequentially on the device and followed by wet patterning. Finally, the sacrificial photoresist was removed by oxygen (O2) ashing to finish the fabrication of SRR device.

The scanning electron microscope (SEM) images of the developed device showed that the SRR cantilever tilted up a little after releasing, which we thought it was due to the residual strain. The tilting up structure does not intrinsically change the electromagnetic performance but the reduced capacitance due to the increasing of air gap between the top and bottom disks shifts the resonant frequency of SRR OFF-state to a higher value compared with the case of cantilever in flat status.

Chapter 4 reports the mechanical and terahertz characteristic of the developed MEMS SRR array.

Laser Doppler Vibrometer (LDV) was used to quantitively investigate the SRR cantilever's mechanical performance. The MEMS drive voltage with triangle wave at a frequency of 1 kHz and a peak of±40 V was applied through the lateral connections to each parallel disk of a test element group (TEG) of 4 × 4 MEMS-SRR array, via a pair of tungsten needles manually controlled by the micromanipulators under the microscope objective lens. Due to the relatively large angular motion of the cantilever tip, which was out of the LDV measurement range, we measured the motion in the middle part of the MEMS cantilever. Electrostatic pull-in motion of the cantilever was found at a voltage of ±33.5 V. The cantilever remained in contact with the bottom electrode until the voltage was lowered to ±1 V, after which the cantilever was released to the damped oscillation.

Terahertz transmission performance was characterized by terahertz time domain spectroscopy (THz-TDS). The two common electrodes of SRR array were bonded onto a printed circuit board (PCB) by wire bonding for the MEMS drive voltage. A metal holder was used to mount the PCB into insert to the optical path of the THz-TDS system with normal incidence to the substrate side. The SRRs have an array of 60×60, in an area of 6mm×6mm covering the punching hole (5mm in diameter) in the metal holder. Therefore, the terahertz wave with a beam waist smaller than 5mm through the punching hole will encounter the device area within the entire SRR array.

For the ON-sate, we used a symmetric square wave voltage with a frequency of 1 kHz and amplitude of ±35 V to pull the SRR cantilever array down to contact with the bottom disk. Since the cantilevers have nonuniform pull-in voltages, a voltage level of 35 V was intentionally set to be higher than the typical pull-in voltage of 33.5 V. The advantage of using a 1 kHz square wave to actuate the SRR cantilevers is that the bipolar voltages avoids the electrostatic charge-up to the cantilever with a SiO2 layer. After the ON-state measuring, on the other hand, no voltage was applied to the MEMS-SRR array during the TDS measurement for the OFF-state. Both transmission spectra of the ON-state and OFF-state were normalized with the air reference. The HFSS simulation results matched well with the measurement results. Therefore a tunable terahertz band-stop filter was demonstrated.

It is worthy to point out that the MEMS SRR device also worked as a high contrast ratio terahertz switch at the resonant frequencies both for SRR ON-state and OFF-state, which is an advantage compared with the conventional tunable terahertz metamaterial devices. A further optimization on substrate thickness and SRR pattern size will improve the performance of the demonstrated terahertz switch.

Chapter 5 discusses the key points during experiments and the originality and contribution of this work. The developed SRR cantilevers have issues of stiction, charge up, etc., which were solved by the optimization from the comparison of several cantilevers designed in different structure and size, together with drive voltage actuation by using a shaped waveform. The DC/RF decoupled structure was discussed from the SRR working principle with the fundamental electromagnetic coupling to a metallic pattern. Based on the independent properties of SRR, the influence of the device yield on the terahertz performance was also discussed.

Chapter 6 summarizes this work and proposes the related future research on terahertz optic components. In conclusion, we proposed and demonstrated a novel MEMS reconfigurable metamaterial on a low loss quartz substrate for tunable terahertz band stop filter and terahertz switch applications. Based on the high contrast ratio terahertz switch at SRR resonant frequencies, it presents a potential prospect for high performance transmission terahertz device, such as Fresnel zone plate.