Realization of band-pass and low-pass filters on a single chip in terahertz regime*

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In this paper, we present the design, simulation, fabrication and characterization of a terahertz (THz) filter based on metamaterial consisting of the periodical double symmetric splits ring resonator (DS-SRR) array. We can observe that the metamaterial-based filter possesses a band-pass transmission when the electrical field is along *y* direction, and it possesses a low-pass transmission when the electrical field is along *x* direction. Our results demonstrate that the proposed filter can realize the switching between band-pass effect and low-pass effect by only changing the polarization direction of the incident electromagnetic wave. Moreover, the calculated surface current distributions are also used to analyze the switchable mechanism of the THz metamatrial filter. Therefore, the proposed THz wave filter has a potential application in THz wave communication systems.

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Metamaterials are a kind of artificially engineered materials, which consist of periodically patterned sub-wavelength scale unit cell arrays, such as split ring resonators (SRRs), cut wire pairs, fishnet structures and other stereostructures. By proper designs of the unit cell geometry and crystal lattice, metamaterials can lead to unique electromagnetic responses which are unavailable in nature, such as negative refractive index, perfect absorption and imaging with sub-wavelength resolution[1]. Because of their unique and distinct reversed electromagnetic properties, the metamaterials have received increasing attention and obtained significant progress in development during the last decade[2,3].

Recently, the diversified metamaterial-based devices, including phase modulator[4], perfect absorber, ultrafast switching device[5], invisibility cloaks[6] and filters[7], have been developed by conventional photolithography and micro-electromechanical system (MEMS) techniques[8]. With these devices, particularly, the terahertz (THz) metamaterial filters are of great key elements to realize THz communication and attract great interest[9]. So far, the extensive efforts have been devoted in developing various types of THz filters, such as band-pass[10], band-stop[11], high-pass[12], low-pass[13] and tunable filters[14]. However, these metamaterial-based filters realize only single function in THz range, which seriously affects and restricts their applications. Therefore, the THz metamaterial filter whose function can be dynamically controlled is of great interest and importance, and the application range will be further expanded.

In this paper, we demonstrate a THz metamaterial filter consisting of double symmetric splits ring resonators (DS-SRRs), which can be used as the band-pass and low-pass filters with improved transmission performance and reduced mechanical risks on a single chip. Moreover, the band-pass and low-pass effects can be switched by only changing the polarization direction of the incident wave. Therefore, the proposed THz wave filter has a potential application in THz wave communication systems.

Based on the most commonly used U-shaped resonators, we propose a switchable THz metamaterial filter, which consists of DS-SRRs as shown in Fig.1. The unit cell size of the metamaterial-based filter is optimized and obtained with CST simulation solver. In simulation process, we input the unit cell of the metamaterial filter with the periodical boundary conditions along *x* and *y* directions, respectively, to ensure a normally incident electromagnetic wave, as shown in Fig.1(b). As a result, the dimensions of the resonator unit cell of the proposed filter are l=70 μm, l_1=44 μm, g=6 μm and w=8 μm. Moreover, the proposed filter structure can realize

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switching between band-pass and low-pass filters by adjusting the polarization direction of incident electromagnetic wave.

To demonstrate the performance of the filter, the designed filter structure is fabricated on a 10.16 cm silicon wafer with thickness of 1 mm and high resistivity of more than 5 000 Ω·cm by MEMS technology to get a high transmittance. As shown in Fig.2, the main fabrication processes include standard lithography, deposition and lift-off process. The detailed information of the fabrication processes is as follows. Firstly, the photoresist is coated on the silicon substrate by the spinning method, and then it is exposed and patterned. Secondly, a 200 nm-thick gold film is deposited by radio frequency magnetron sputtering method. Finally, the metallic layer on the photoresist is removed by the lift-off technology. The wafer is sawed to 1 cm×1 cm samples by the automatic precision dicing saw. The fabricated sample is evaluated by the optical microscope, as shown in Fig.1.

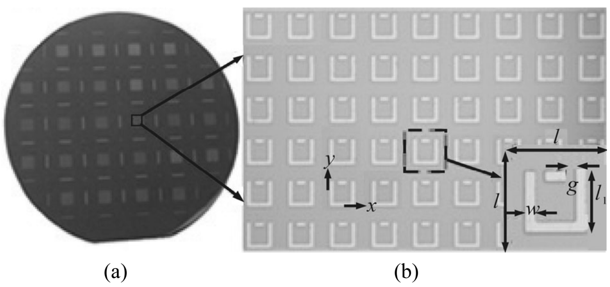

Fig.1 (a) The photo of THz filter metamaterials on 10.16 cm silicon wafer; (b) Optical microscope image of DS-SRR metamaterial structure

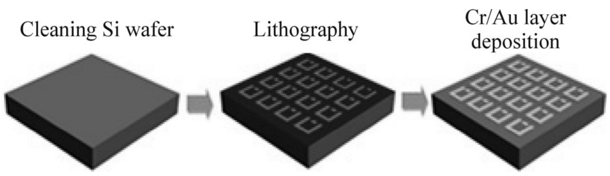

Fig.2 Fabrication processes of the THz metamaterial filter on silicon substrate

To verify the performance of the fabricated samples, the metamaterial filter samples are characterized by a THz time domain spectroscopy (THz-TDS) system in transmission mode. A bare silicon wafer identical to the sample substrate serves as reference, and the measured transmission spectra are normalized against the reference spectrum measured with the silicon wafer with high resistivity in the same nitrogen environment. Moreover, all measurements are taken under the pure nitrogen environment (humidity of 0 and ambient temperature) to avoid noises from water absorption. Here, transmission spectra at two orthogonal polarization states corresponding to x axis and y axis shown in Fig.1(b) are measured.

Fig.3(a) shows the measured transmission spectra of the DS-SRR metamaterial filter on the silicon wafer with high resistivity in two polarization directions. As shown in Fig.3(a), when the electrical field direction of THz wave coincides to the y axis of the DS-SRR THz filters, there is a transmission window above 80% from 0.559 THz to 1.241 THz, which can serve as a band-pass filter. When the direction of electrical field is rotated by 90°, which means that the electrical field direction of THz wave coincides to the x axis of the DS-SRR THz filters, the measured transmission with more than 80% is obtained from 0.2 THz to 1.19 THz, which can be used as a low-pass filter. Meanwhile, the transmission spectra are also calculated using software package CST. We notice that there is a little deviation between the simulation and measurement results arising from the imperfect fabrication process. Therefore, the band-pass and low-pass filters in THz regime can be realized on a single metamaterial chip by changing the polarization direction of the incident wave.

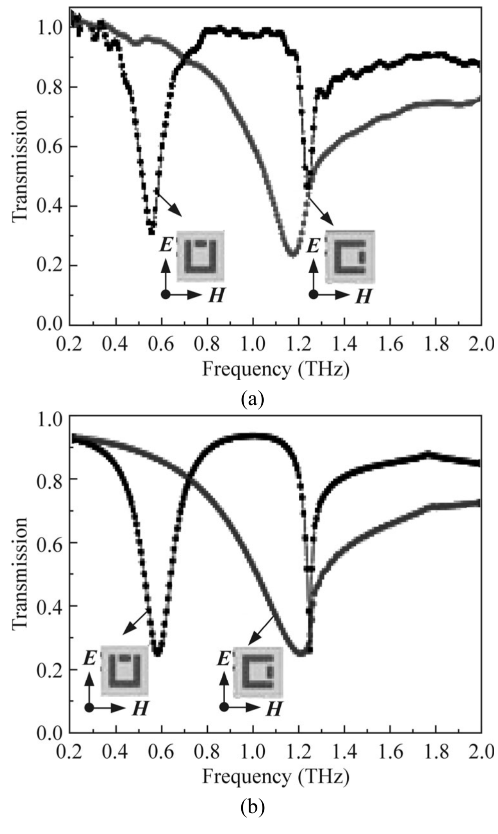

Fig.3 (a) Measured and (b) simulated transmission spectra of THz metamaterial filter based on the silicon wafer with high resistivity

To understand the nature of the designed filter device, we calculate the surface current density distributions on the metallic layer at the corresponding resonance frequencies, which are shown in Fig.4. As the electrical field direction of incident wave is along the y axis, the circular surface currents on the DS-SRR structure at 0.565 THz are excited as shown in Fig.4(a), turning out to be an LC resonance (as shown in Fig.3). While at 1.245 THz, since the THz wave is normally incident on the DS-SRR structure plane, the excited DS-SRR structure is expected to have different dipole phases and make the plasmon hybridization coupling, as shown in Fig.4(b). As a result, such a coupling mode inherently has very weak resonance due to the destructive coupling (as shown in Fig.3). Therefore, a transmission band between two resonances can be obtained. As the electrical field direction of incident wave is along the x axis, the symmetric surface currents on the DS-SRR structure at 1.2 THz are excited due to the same dipole phase, showing the different resonance properties from above resonances, as shown in Fig.4(c). Here the DS-SRR structure has only one resonance at 1.2 THz, which forms a low-pass filter (as shown in Fig.3).

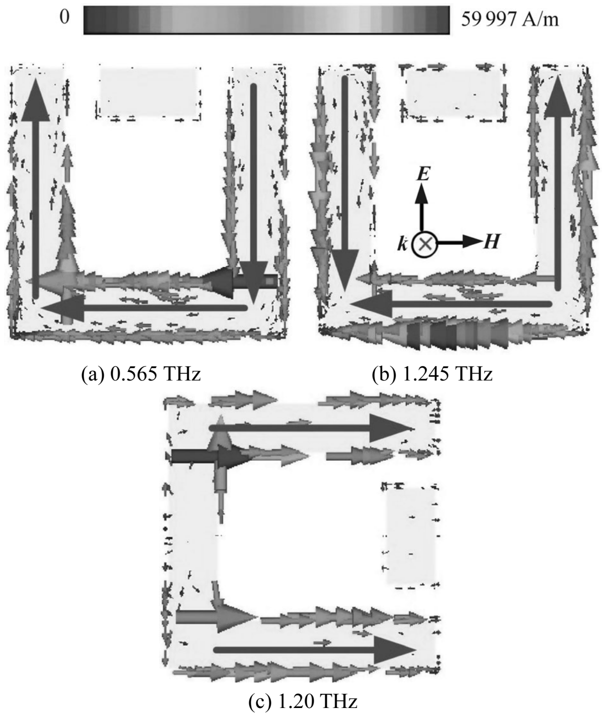

Fig.4 Simulated surface current distributions of high resistivity silicon substrate metamaterials at resonant frequencies of 0.565 THz, 1.245 THz and 1.20 THz

In this paper, we fabricate a switchable THz metamaterial filter consisting of the DS-SRR array. The measured results show that as the electrical field is along y direction, the metamaterial-based filter possesses a band-pass transmission above 80% between 0.559 THz and 1.241 THz, and as the electrical field is along x direction, a low-pass transmission with more than 80% between 0.2 THz and 1.19 THz is obtained. These results demonstrate that the fabricated filter can realize the switching between band-pass and low-pass effects by only changing the polarization direction of the incident electromagnetic wave. Moreover, the surface current distributions can explain the switchable mechanism of the THz metamaterial filter. Therefore, the proposed THz wave filter has a potential application in THz wave communication systems.

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