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Design of a tunable multiband terahertz waves absorber

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A B S T R A C T

A thermally tunable multiband terahertz metamaterial absorber comprising a periodic array of closed metallic square ring resonators and four metal bars parallel to the four side of the square ring, fabricated on the low-temperature co-fired ceramic (LTCC) strontium titanate (STO) dielectric layer dielectric substrate has been proposed. The resonance frequencies of the absorber are demonstrated to be continuously tuned in the terahertz regime by increasing the temperature. It is found that in the window between 0.05 and 0.35 THz the absorber has three distinctive absorption peaks at frequencies 0.129 THz, 0.198 THz and 0.316 THz (at the room temperature), whose peaks are attained 99.3%, 99.1% and 94.6% respectively. The tunability is attributed to the temperature-dependent permittivity of the substrate and attained to 67.3% frequency tuning depth at the room temperature, when the temperature varied from 400 K to 200 K. The proposed designs ensure broadband thermally tunable terahertz devices.

1. Introduction

Metamaterials have exotic properties such as backward propagation, reverse Doppler effect and reverse Vavilov-Cerenkov effect, which are not possessed by natural materials [1]. And what's more, fabrication of metamaterials can be easily achieved by the lithographic techniques. Recently, there have been several studies in the design and experiment of metamaterial absorber, the frequency ranging from radio frequencies to terahertz and near infrared frequencies [2–7]. And in order to reducing the size and weight of terahertz communication component, several technologies has been suggested. Among these miniaturizing and packaging technologies, low-temperature co-fired ceramic (LTCC) seems to be the most efficient method because it has the capability to integrate passive components in a module, and to achieve the miniaturization and the exceptional function [8].

Terahertz electromagnetic waves have been less explored than those in the contiguous spectral regimes. The numerous applications for these waves in their generation and detection have triggered the interest in THz signal routing systems [9]. In which, the terahertz devices was complicated and important, because comparative lack of electromagnetic responses from natural materials. Metamaterials are one potential solution to construct THz components, so some efforts have been made to design the perfect THz metamaterial absorbers. Metamaterial absorbers have received considerable attention and many absorbers have been proposed [10–15]. Unfortunately, most metamaterials absorbers because of geometrically fixed and electromagnetic resonances provide only within a single frequency or a fixed spectral range absorption, which greatly limits their practical applications to spectroscopic detection and phase imaging. Multiband and tunable absorbers are urgently desired.

In order to attain the multiband absorbers, some researchers stacked the metamaterials. Recent progress in the passive tuning by the incorporation of naturally occurring materials within or as part of the metamaterial elements has recently been reported. For example, metamaterials have been tuned by loading dielectrics onto their surface and also by integrating semiconductors or carbon nanotubes within the structure to provide electronic or optical control of the resonance frequency [16–20]. Some designers used the methods of using the thermal control to realize the tunability, some were based on a variation of temperature altering the intrinsic carrier density in a semiconductor (InSb) [21,22]. Others

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used the photoexcited carrier by integrating semiconductors into metamaterial designs [19,20,23] and also someone used the property of ferrimagnetic/paramagnetic transition of the ferrites [24]. In addition to the magnetically tunable metamaterial is also a more effective way, some of them used the ferromagnetic precession of ferrite [25], and others used the ferromagnetic resonance (FMR) frequency which can be influenced by the dimension of the ferrites [26]. Most used the magnetically tuning the inductance via the active ambient effective permeability [27–30]. In these previous works, most of the resonant elements can be represented by an effective inductor–capacitor (LC) resonator, and the resonance frequency is dependent on the effective capacitance C and inductance L. So the method of tunability is introducing another component made from an electro-optic material [31–33], liquid crystal [34–36], ferrite [37,38], semiconductor [19,20,23] and superconductors [39], liquid metals [40], chemical control [41]to alter L, C or both of them.

Associated with metamaterial investigations and applications, it is necessary for enabling metamaterial structures to be of utmost flexible properties. In this paper, we present a design for blue shift tunability with the metamaterial fabricated on the temperature controlled LTCC STO substrate. Our approach takes advantage of a novel variant of the nested closed square rings with the outer ring cutting off the four corners resonator, where changing the external temperature or precise size of cutting corner permits frequency tuning of the metamaterial resonance. Our studies have shown that a large blue shift of resonance frequency in the proposed structures, and it can be implemented within quite a broad frequency range of as much as 67.3% (mode 1) in the THz regime with increasing temperature. We also present an absorber of this resonator which shows three strong resonances simultaneously in the window between 0.05 and 0.35 THz, with 99.3% absorption at 0.129 THz, 99.1% absorption at 0.198 THz and 94.6% absorption at 0.316 THz, respectively. Basing on the simulation of the LTCC, and the investigations to the field distribution of metamaterial absorbers are also proposed. And a metamaterial device based on it can be utilized as a good multiband switch. The results presented here thus may offer a desirable and flexible design for frequency-agile metamaterials and possess potential applications as tunable notch filters and multiband switches especially in THz regime.

2. Tunable multiband absorber design

In previous works, the essential resonant elements can be represented by an effective inductor–capacitor (LC) resonator, where the resonance frequency ω_0 is strongly dependent on the effective capacitance C and inductance L, i.e., $\omega_0 \propto (LC)^{-1/2} \propto (\varepsilon_r)^{-1/2}$. Tunability in our job is introduced by ensuring that another component is made from an ferrite, in the designs to alter ε_r.

The unit cell of the proposed absorber is illustrated in Fig. 2; it consists of two nested square metallic rings and with the outer ring cutting off the four corners and a thin strontium titanate (STO) dielectric layer on top of a metallic ground plane. In the terahertz regime, the complex-valued relative permittivity of STO is given by the damped harmonic oscillator model [42]:

$$\varepsilon(\omega) = \varepsilon_\infty + \frac{f}{\omega_0^2 - \omega^2 - i\omega\gamma} \tag{1}$$

where the ω is the angular frequency of the incident terahertz wave, the ε_∞ represents the high-frequency permittivity value, in which the $\varepsilon_\infty = 9.6$,as reported in the Ref. [43], the f is a temperature independent oscillator strength and the numerical constants resulting from the fits can be successfully used in the 70–300 K temperature range and they also yield an excellent fit of others' measured data [42] if a temperature independent oscillator strength of $f = 2.3 \times 10^6$ cm^{-2} used in the model. γ is the damping constant; and the ω_0 is the temperature dependent soft mode frequency. The soft mode frequency ω_0 can be fitted using the Cochran law$\omega_0^2 = \frac{f}{C}(T - T_0)$, which is closely related to the Curie–Weiss behavior of the static permittivity:

$$\omega_0(T)\left[cm^{-1}\right] = \sqrt{31.2(T - 42.5)} \tag{2}$$

The soft mode damping γ then can be fitted by an empirical linear dependence:

$$\gamma(T)\left[cm^{-1}\right] = -3.3 + 0.094T \tag{3}$$

where the T is the temperature (K).

From the above equations, we could get the Fig. 1(a) and (b), which show the dependence of the dielectric permittivity on the change of the temperature T. As can be seen from Fig. 1, the real part (Re(ε)) of the STO varies of with the temperature T. The real part of the permittivity gradually decreases with temperature increasing, particularly, the dispersion of the STO is very weak. The change of the Re(ε) is very small at every specific temperature. The Re(ε) is extremely sensitive to the change of the temperature, which suggests the potential using in tunable metamaterials and metadevices [38]. The loss tangent is defined as the imaginary part divided by the real part, as can be seen from the Fig. 1(b), tan δ is

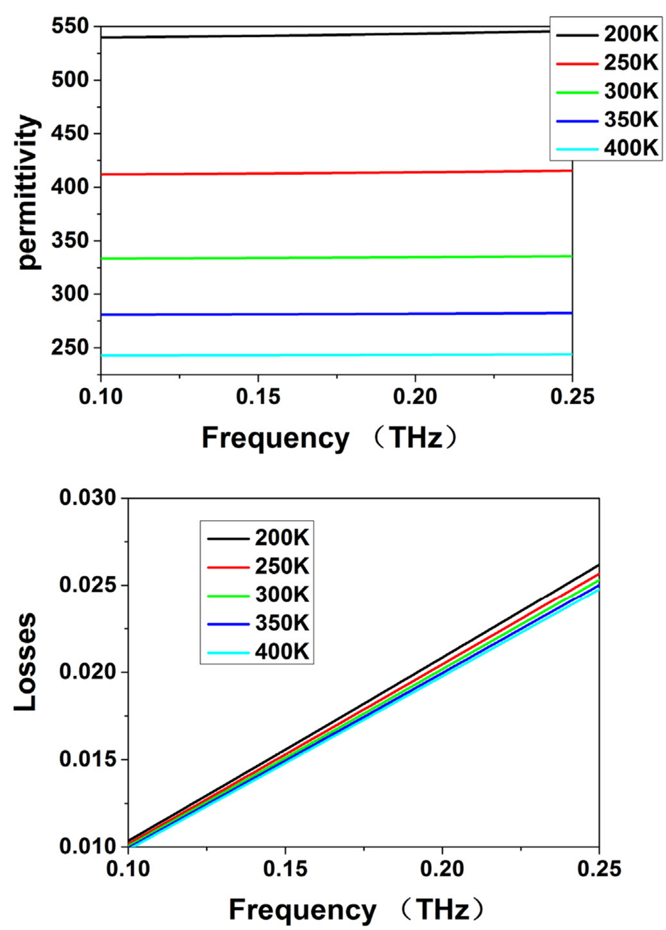

Fig. 1. Temperature dependence of the permittivity (Re(ε)) and the loss tangent (tan δ) of the STO dielectric layer of damped harmonic oscillator mode in the frequency of terahertz.