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The analysis on the parameters sensitivity of the microstrip line-typed metamaterials under two polarization

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ABSTRACT

The microstrip line-typed metamaterials (MTM) would exhibit different response to the external dielectric. Confirming the bandgap characteristics and parameters sensitivity is benificial to the proposal of the new device and the optimization of the corresponding device or sensor. Based on the considerations above, the bandgap characteristics and responsing sensitivity to the external thin film with different parameters of microstrip line-based CSSRR (Complementary single split ring resonator) are researched. The bandgap characteristics and sensing characteristics to the external dielectric with different thickness or permittivity of CSSRR under two polarization excitations are analyzed and compared. The sensitivity of the different sub-region of MTM responsing to the external small-sized square dielectric is analyzed respectively. The sensitivity distribution of each region of CSSRR under two polarization excitations is obtained. According to the simulation and experiment, the bandgap characteristics and sensitivity of the microstrip line-typed MTM are tested and verified.

1. INTRODUCTION

Due to its low profile, high integration, strong interference resistance, and the extraordinary EM (electromagnetic) characteristics, the planar MTM (metamaterials) has been widely used in the design on EM devices, such as antenna (Ziokowski R. W., 2009), perfect lens (Pendry J. B., 2000), cloak (Smith D. R., 2013), and so on. In the amounts of MTM forms, the microstrip line-typed planar MTM plays an important role in many MTM application fields. The MTM structure (such as complementary split single ring resonator, CSSRR) etched on the ground plate of microstrip line would be excited by the vertical electric field, so its electromagnetic characteristics would be inspired in

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certain frequency band. New methods for the resonance, impedance adjustment or sensing related to its configuration are brought in the design of the planar EM device. Lots of potential applications, such as filter (Liu Z., 2016), sensor (Ebrahimi A., 2014, and Yadav R., 2016), coupler (Menachem Z., 2012), are implemented.

In the application of microstrip line-typed MTM, the change of external environment or media would impact its intrinsic property. In one hand, the EM devices need a stable intrinsic property. The influence from the external interrupt would degrade the performance of the device, so it's necessary to choose a stable MTM form owning strong immunity to the external interrupt for the corresponding EM devices design. In another hand, due to MTM's high integration, strong interference resistance, low profile and fabrication cost, the unstability of the microstrip line-typed MTM shows a huge potential application prospect in the sensor area. The proposed sensors based on it contain crack detector (Albishi A., 2014), dielectric distinguishing or density detection sensor (Ebrahimi A., 2014, and Yadav R., 2016), rotation sensor (Ebrahimi A., 2014), aircraft envelope thickness detector (Boybay M. S., 2013), and so on. The microstrip line-typed MTM can also provide some feasible way for the medical testing, which contains DNA testing (Lee H. J., 2013), biofilm structure detection, and so on. In the design of the MTM-based sensor, the sensor needs a high sensitivity to the external detected objects. In view of these two aspects, mastering and controlling the sensitivity to the external media of microstrip line-typed MTM is necessary, and is also important for the optimization or improvement of the device performance.

The adjustment on the sensitivity of the microstrip line-typed MTM is mainly to change its shape or size parameters in the existing work, but the influence of the excitation polarization is ignored by most researchers. Because of the inhomogeneous electric field distribution on the microstrip line, the MTM on the microstrip line under different polarization would shows a different intrinsic band gap or response to the variation of the external media. The analysis on the sensitivity of the microstrip line-typed MTM under different polarizations is necessary.

In this paper, the band gap and sensing characteristics of the microstrip line-typed CSSRR under two polarizations are analyzed. The response of CSSRR under two polarization excitations to the detected media with different thickness or permittivity are discussed, compared and tested. The sensitivity distribution of each region of CSSRR under two polarization excitations is obtained.

2. THE BAND GAP CHARACTERISTICS OF MICROSTRIP LINE-TYPED CSSRR

Under the applied electric field excitation, the classical SSRR (split single ring resonator) can be equal to a LC series circuit, if vertical magnetic field passes through ring-shaped structure. According to Babinet principle, the CSSRR (complementary split single ring resonator) would response to the vertical electric field, and engender electric resonance and stop band (Falcone F., 2004). In order to get the vertical electric field and excitation, CSSRR can be etched on the ground plate of microstrip line. As shown in Fig.1, the blue part in the middle is FR4 substrate, copper signal line and ground plate at front and back of the substrate. CSSRR is the slot part at the center of the ground plate under signal line. Placing the etching area at this part is benefit for getting a strong exciting electric field and coupling.

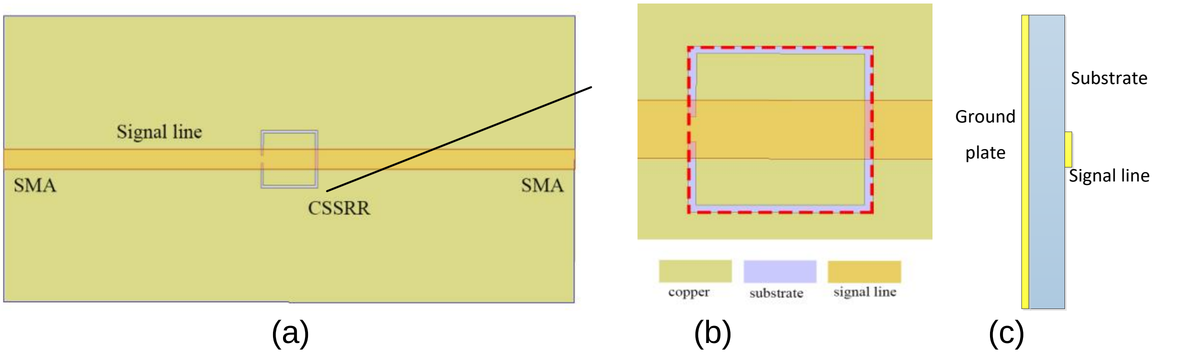


Fig. 1 The mirostructure coupled with microstrip line. (a) The front view, (b) the enlarged view of the microstructure, and (c) the side view of the microstrip line-typed CSSRR

The band gap characteristics of the CSSRR can be explained as an equivalent series LC resonant circuit. The size of CSSRR is small enough compared with wavelength, and CSSRR can be equal to a capacitance C_{equ} and inductance L_{equ}. The equivalent circuit is shown in Fig.2(a). Without considering the loss, the resonant frequency of CSSRR can be expressed as

$$f_{CSSRR} = \frac{1}{2\pi\omega_0} = \frac{1}{2\pi\sqrt{L_{equ}C_{equ}}} \tag{1}$$

CSSRR regarded as a series branch is coupled with microstrip line through a parallel capacitance C_{par}. When the frequency satisfy $f_{whole} = 1/2\pi\sqrt{(C_{seri}+C_{par})/L_{seri}C_{seri}C_{par}}$, the admittance of the branch is

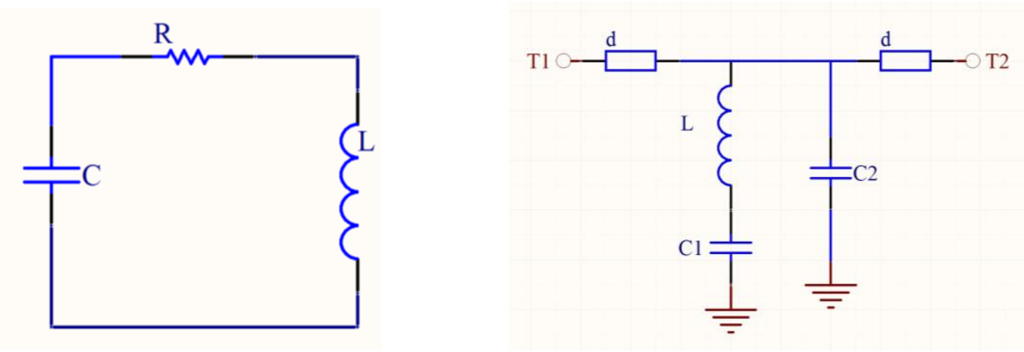
$$Y_{in} = j\omega C_{par} + \frac{1}{R + j(\omega L_{ser} - \frac{1}{\omega C_{ser}})} \approx j\omega C_{par} - j\frac{1}{\omega L_{ser} - \frac{1}{\omega C_{ser}}} = 0 \tag{2}$$

The minimum point of S11 is engendered at f_{whole}, and maximum is at f_{CSSRR}. The frequency at -3dB insert loss is set as f_{3dB},. Each lumped element is (Li F. 2007):

$$C_{\mathrm{par}} = \frac{Y_0(f_{whole}^2 - f_{3dB}^2)}{\pi f_{3dB}(f_{CSSRR}^2 - f_{3dB}^2)} \tag{3}$$

$$C_{\mathrm{ser}} = (\frac{f_{whole}^2}{f_{CSSRR}^2} - 1)C_{par} \tag{4}$$

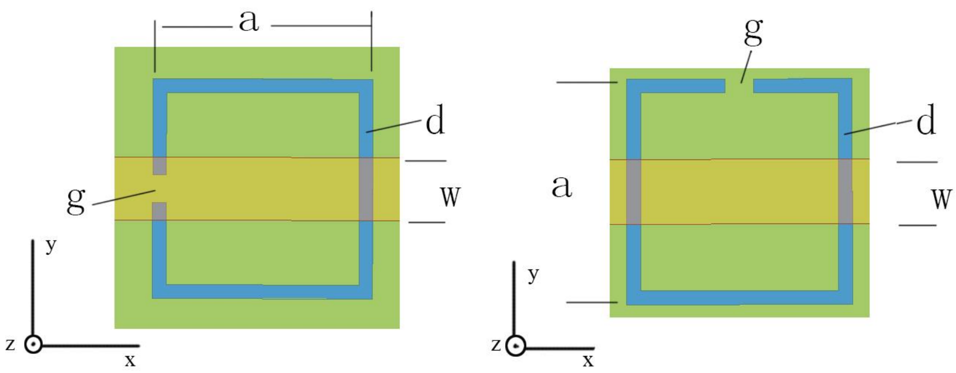
$$L_{ser} = \frac{1}{4\pi^2 f_{whole}^2 C_{\mathrm{par}}} \tag{5}$$



(a) (b)

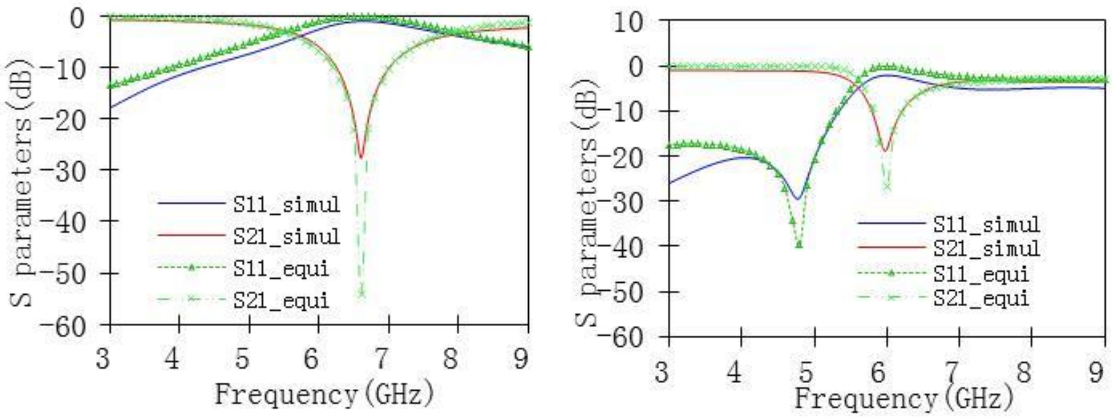
Fig.2 The equivalent circuit of the metamaterials. The equivalent circuit of (a) CSSRR, and (b) CSSRR under microstrip line excitation

Equation (1) indicates that the resonant frequency is related to the equivalent capacitance and inductance. Due to inhomogeneity of the electric field distribution perpendicular to the ground plate, the 1/4 asymmetric CSSRR under different polarization may engender different equivalent circuit element and response to the excitation. CSSRR is designed in a square area whose side length is 4mm, and the size parameters of each part is a=4mm, d=0.2mm, w=1.4mm, g=0.4mm, as shown in Fig.3. The S parameters under two polarizations are calculated. The S parameters from finite element simulation and ADS calculation are same, as shown in Fig.4. The minimum of S21 is at about 6GHz and 6.5GHz under two polarizations respectively. Meanwhile, CSSRR under vertical polarization engendered a minimum of S11 uniquely, which is caused by the parallel resonance at about 4.77GHz.



(a) (b)

Fig.3 The displacement of CSSRR under the two different polarization excitation, (a) horizontal polarization, and (b) vertical polarization



(a) (b)

Fig.4 The S parameters under different polarization excitations from finite element simulation and equivalent circuit calculation, (a) horizontal polarization, and (b) vertical polarization

3.THE PARAMETER SENSITIVITY OF THE MICROSTRIP LINE-TYPED CSSRR UNDER DIFFERENT POLARIZATION

CSSRR is the slot without any filler and is similar to a slotted line radiating electromagnetic wave. There exists an equivalent capacitance C_{res} at the slot of CSSRR, and the resonant frequency of the resonator f_0 is proportional to C_{res}, i.e. $f_0\ \mu\ (C_{res})^{-1}$. The induction field is engendered at the near field. If MUT (material under test) is placed at the CSSRR region, the near field would be interrupted, and a new equivalent capacitance C_{MUT} would be engendered in the MUT, as shown in Fig.5. The resonant frequency would shift, and the relation can be presented as $f_{MUT}\ \mu\ (C_{res}+C_{MUT})^{-1}$. The frequency shift from f_0 to f_{MUT} represents the variable quantity, which contains the change of thickness or permittivity. The sensing principle can be used in the biosensor area, such as the biofilm thickness detection or cell denaturalization testing.

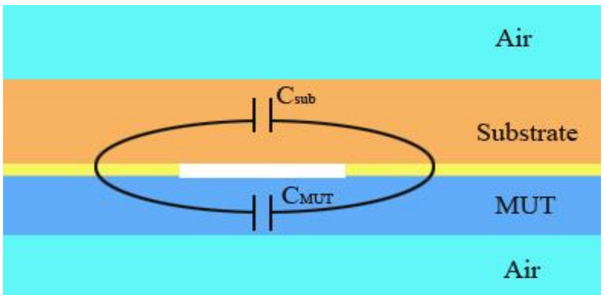


Fig.5 The displacement of MUT and the microstrip line-typed CSSRR

The thickness of MUT is set as 25µm, 50µm, 100µm and 500µm successively, and permittivity changes from 1 to 8. The S parameter of microstrip line-typed CSSRR under two different polarizations from simulation is shown in Fig.6. The resonant frequency of CSSRR is decreased with the increasing of the thickness or permittivity of MUT. The relationship between frequency shift and permittivity exhibits a good linearity when MUT is thin. The linearity becomes worse as MUT becomes thicker. CSSRR owns a little higher sensitivity, but owns almost the same relative sensitivity. Take the 25µm thick MUT as an example, the frequency shift is 63.9MHz and relative frequency shift is 9.59×10^{-3} under horizontal polarization. While the frequency shift is 54.6MHz and relative frequency shift is 9.32×10^{-3} under horizontal polarization.

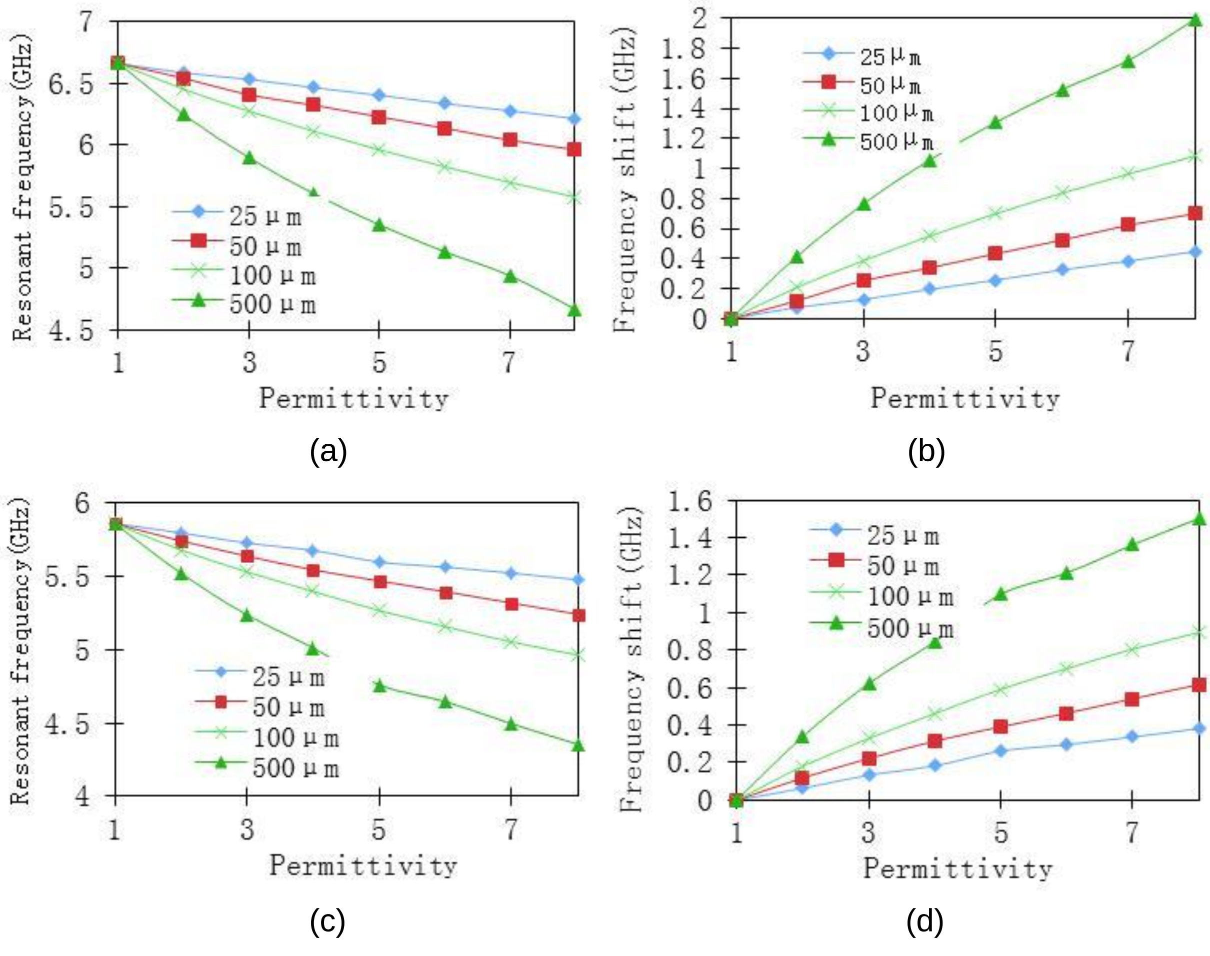


Fig.6 The relationship between the resonant frequency and external dielectric. When the permittivity of MUT increases from 1 to 8, (a) the resonant frequency, (b) frequency shift under horizontal polarization excitation, and (c) the resonant frequency, (d) frequency shift under vertical polarization excitation

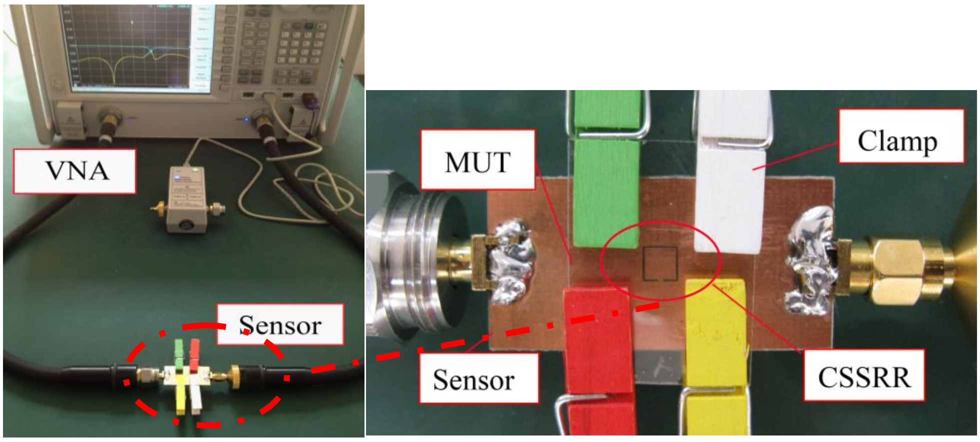
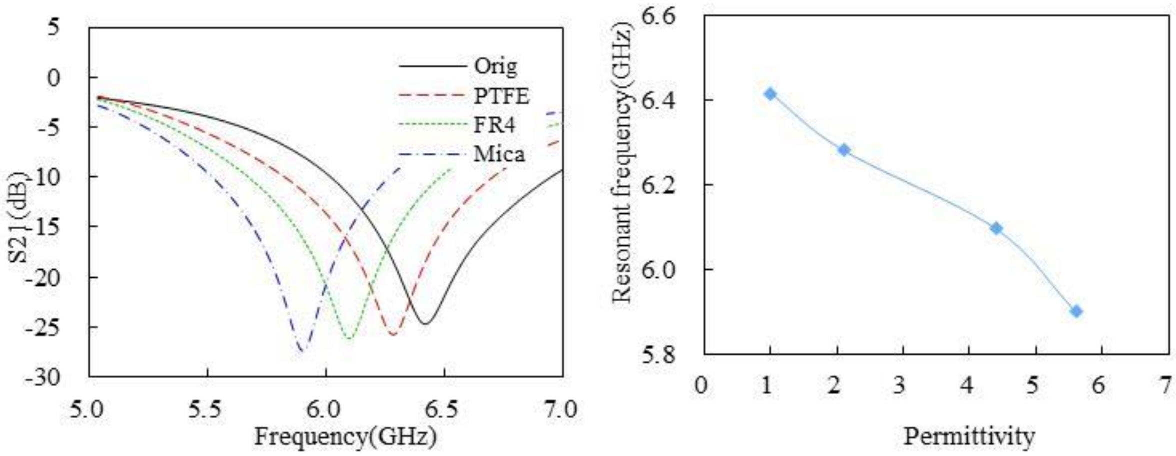
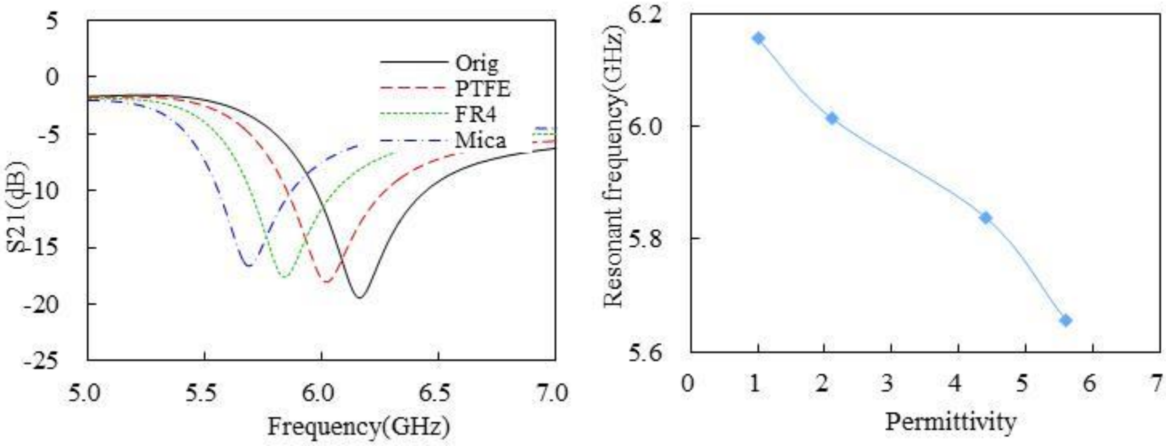


Fig.7 The experimental platform and the testing specimen



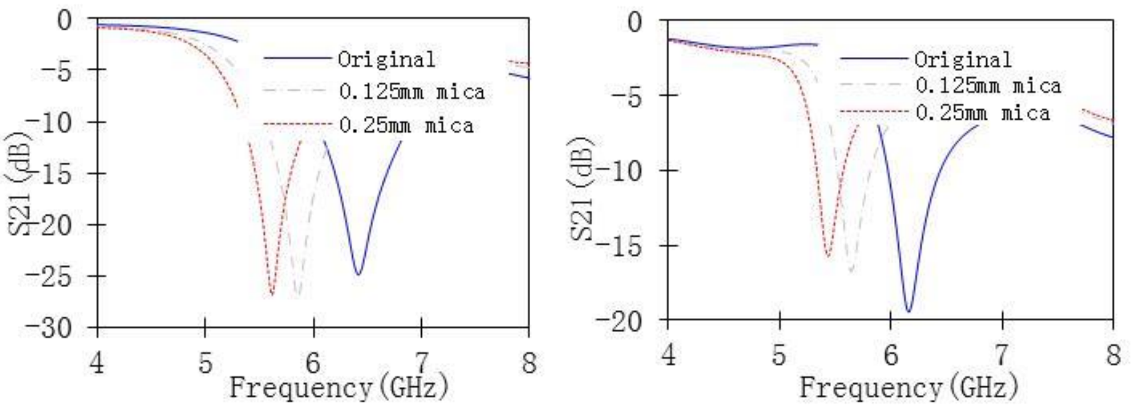
(a)



(b)

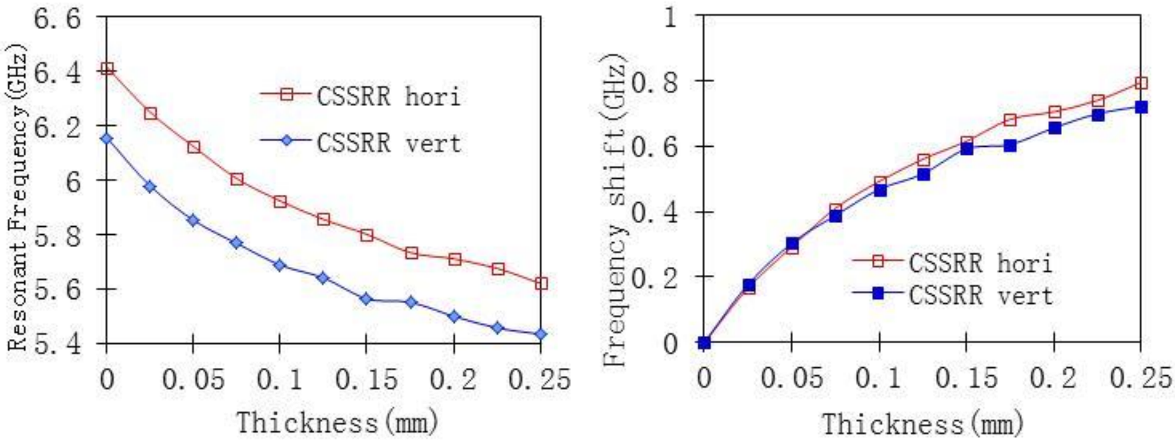
Fig.8 The tested S21 parameters and resonant frequency with different permittivity from experiment, (a) under horizontal polarization excitation, and (b) under vertical polarization excitation

The microstrip line-typed CSSRR specimens are fabricated and tested. Firstly, its sensitivity to the permittivity of MUT under two polarizations is tested. 100μm thick mica (ε_{MUT}=5.6), FR4 (ε_{MUT} =4.4) and PTFE (ε_{MUT} =2.1) films are chosen as MUT. The experimental platform is shown in Fig.7. The tested S parameters are in Fig.8. Following ε_{MUT} increasing from 2.1 to 5.6, CSSRR under two polarizations exhibits similar frequency shift. For PTFE the frequency shift of CSSRR under horizontal polarization is about 0.135GHz (from 6.416GHz to 6.281GHz), and 0.141GHz (from 6.156GHz to 6.015GHz) under vertical polarization. For mica the frequency shift of CSSRR under horizontal polarization is 0.516GHz (from 6.416GHz to 5.864GHz), and 0.500GHz (from 6.156GHz to 5.656GHz) under vertical polarization.



(a) (b)

Fig.9 The S21 shifting with thickness of mica increasing from experimental testing, (a) under horizontal polarization excitation, and (b) under vertical polarization excitation



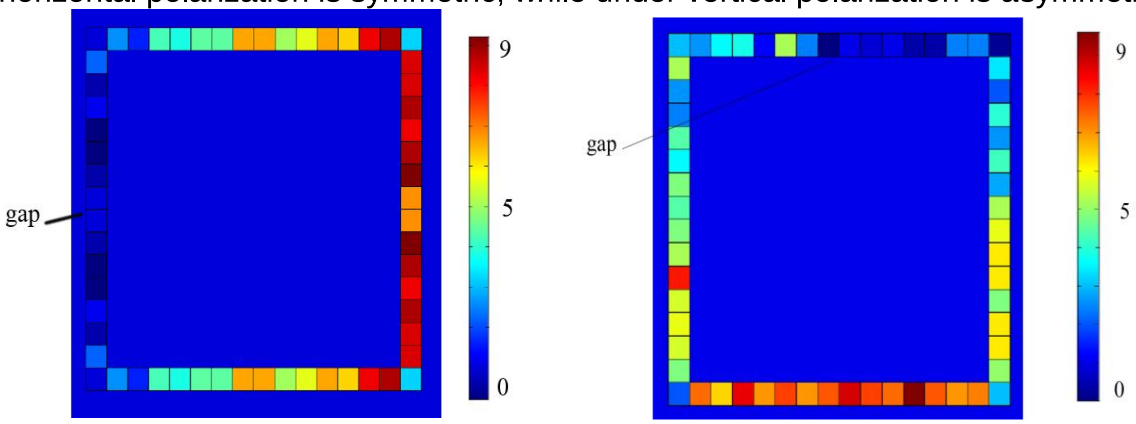
(a) (b)

Fig.10 The peak frequency and frequency shift with different thickness of mica from experiment under two different polarization excitations. (a) The peak frequency, and (b) frequency shift

Then, the sensitivity of CSSRR under two different polarizations to the thickness of MUT is tested. The 25μm thick mica film is chosen as MUT. The thickness of MUT is adjusted by regulating the amount of films. The clamp is used to cling MUT to the sensing region. The S parameters and resonant frequency shift is plotted in Fig.9 and Fig.10. Following the thickness of MUT increases from 0 to 250μm, the resonant frequency shifts to lower frequency. The shift under two polarizations is close at low thickness part. The CSSRR under horizontal polarization exhibits higher sensitivity as the thickness increasing. Such as the thickness is 250μm, the shift is 795MHz under horizontal polarization, while 722MHz under vertical polarization.

4. SENSITIVITY DISTRIBUTION

CSSRR under two different polarizations would exhibit different sensitivity distribution which is represented by the resonant frequency shift. A square MUT film is placed in each sub mesh of CSSRR successively to get the ergodic resonant frequency shift. The CSSRR region is discrete into 16×16 meshes, and each sub-mesh is $250\mu m\times250\mu m$, which is also the size of the square MUT film. The thickness of MUT film is 25μm. The sensitivity distribution is shown in Fig.11. The sensitivity raises from the gap part to the allpass part of CSSRR gradually. The highest shift is 9.2MHz, which is represented by the red square. The high sensitivity region under horizontal polarization is bigger than the one under vertical polarization. The sensitivity distribution under horizontal polarization is symmetric, while under vertical polarization is asymmetric.



(a) (b)

Fig.11 The sensitivity distribution for different defect areas of CSSRR under (a)horizontal polarization. and (b) vertical polarization

5. CONCLUSIONS

In this paper, the resonant and sensing characteristics of the microstrip line-typed CSSRR under two polarizations are analyzed. The resonant characteristics is analyzed through equivalent circuit of the microstrip line-typed CSSRR. It’s verified that the microstrip line-typed CSSRR under vertical polarization owns a parallel capacitance and exhibits a parallel resonance. The simulated and tested results provide with a detailed sensing characteristics of microstrip line-typed CSSRR under two different polarizations. From the results it’s found that the increasing of thickness and permittivity of the external media would decrease the resonant frequency. CSSRR under horizontal polarization exhibits a slightly higher sensitivity for the same external sensing media. The sensitivity distribution of each region of CSSRR under two polarization excitations is analyzed. CSSRR under horizontal polarization exhibits bigger high sensitivity region and a higher symmetry

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