

针对不同形状和尺寸陶瓷材料的双频自适应微波介电传感器

王 宸¹, 刘小明¹, 刘志甫², 张 丹¹

(1. 安徽师范大学物理与电子信息学院, 安徽 芜湖 241002; 2. 中国科学院上海硅酸盐研究所, 上海 201899)

摘 要: 陶瓷材料作为在微波系统开发中的重要材料, 通常被加工成多种形状, 例如以厘米级别为尺寸的圆柱形和立方体。因此, 对此类样品进行介电常数的测量是一项具有挑战性的工作。针对该难点, 研制了 1 种基于互补开口环谐振器的双波段介电传感器, 并提出了一种表征不同形状和尺寸样品的介电测量方法。该传感器有 2 个工作频段, 2 个频段均为无线通信频段。在每个频段范围内, 进行了数值模拟并建立了每个样本的拟合模型, 对传感器进行加工并实际测量以验证数值模型和测量精度, 对比参考值, 测量精度高达 3.5%。结果表明: 提出的传感器及测量方法能够针对不同形状和尺寸的合成陶瓷进行精确的介电测量, 表明该传感器具有良好的样品自适应性。该传感器的新颖之处在于它能够在不改变传感器和被测物结构的情况下测量厘米级别的各种样品的介电常数。此外, 双频测量也是该传感器的优势, 2 个频段之间的差异小于 5%。

关键词: 微波陶瓷; 介电常数; 双频带; 谐振频率; 互补开口环谐振器

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A Dual-band Sample Adaptive Dielectric Sensor for Ceramics of Versatile Profile and Size in Microwave Range

WANG Chen¹, Liu Xiaoming¹, LIU Zhifu², ZHANG Dan¹

(1. School of Physics and Electronic Information, Anhui Normal University, Wuhu 241002, Anhui, China;

2. Shanghai Institute of Ceramics, Chinese Academy of Sciences, Shanghai 201899, China)

Abstract: Ceramic materials for microwave systems often show versatile profiles, such as cylindrical and cubic shapes with centimeter sizes. The measurement of such samples thus becomes a challenge. In this paper, a dual-band dielectric sensor based on the complementary split-ring resonators was developed, and a measurement method to characterize the samples with different shapes and sizes was proposed. The resonator creates two operation frequency ranges, which are in wireless communication bands. In each range, numerical simulation was conducted to build the fitting models for each sample. The measurement was conducted to verify the numerical models and the measurement accuracy. The results indicate that the measured accuracy can be as high as 3.5%. Such a measurement method in association with the proposed sensor is competent for dielectric measurement for ceramic of versatile profile, indicating a sample adaptive capability. The novelty of this work lies in its capability of measurement of various samples in a centimeter scale without modifying either the sensor or the material under test (MUT). In addition, a dual-band operation is also a feature of this work, and the discrepancy between the two bands is less than 5%.

Keywords: microwave ceramics; dielectric constant; dual band; resonate frequency; complementary split ring resonator

1 Introduction

Synthetic ceramics are critical materials in

fabrication of many electronic devices^[1-2]. They also play an important role in applications such as

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第一作者: 王 宸(1990—), 男, 博士研究生。

通信作者: 刘小明(1983—), 男, 博士, 教授。

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First author: WANG Chen (1990—), male, Ph.D., Doctoral candidate.

E-mail: wangchen@ahnu.edu.cn

Correspondent author: LIU Xiaoming (1983—), male, Ph.D., Professor.

E-mail: xiaoming.liu@ahnu.edu.cn

manufacturing, processing, antenna design and aerospace technology^[3-6], etc. With the rapid evolution of 5G and 6G communication, ceramic materials have increasing applications in resonate antenna and filter. In the design of these microwave components, the knowledge of the dielectric constant is a must^[7]. In this regard, it is fundamental to require the precision measurement of dielectric constant for synthetic ceramics.

Some dielectric measurement methods are developed, *i.e.*, free space method, transmission line method and resonant cavity method. The free space method uses a free space as a transmission medium and is suitable for dielectric measurements of large planar samples^[8-9]. However, this method is less convenient for small volume ceramic samples. The transmission line method requires that the material be tailored to fit the inner space of a transmission line^[10]. Clearly, this method is not preferred in the sample preparation. The transmission line method is only able to measure the samples of a fixed size^[11]. This method is not ideal for the measurement of low-loss materials^[12-13]. For the resonant cavity method, samples are usually customized to match the resonant cavity, which is less flexible for measuring ceramic materials of different sizes^[14-15].

For synthetic ceramics, several related issues are considered before choosing a proper method. The first issue is that they often have different profiles with a small volume^[16-18], the second issue is that they usually exhibit a low loss merit^[19-20], and the third issue is that they are not easy to be tailored precisely to fit the required space^[21-22]. It is thus difficult to measure such materials due to the issues above. The development of a sensor adaptive to the profile and size of the MUT becomes thus a necessity, and the sensor is referred to as sample adaptive.

In recent years, some planar resonant sensors based on microstrip lines have been developed^[23-25]. One of these resonators is called as a complementary split ring resonator (CSRR) sensor^[26]. These sensors can be used to measure the dielectric constant quickly and accurately. However, the related designs consider the methodology of using the same sensor to measure

the samples of different sizes or profiles. Usually, they require the MUT be fabricated to specific shape and size. However, these resonant sensors provide an approach to measure the low loss samples with a sufficiently high accuracy. This merit inspires to invest their potential of sample adaptive capability, reflecting that one sensor can be used to measure the sample of different profiles and sizes without modifying either the sensor or the MUT.

In this paper, a dual-band dielectric sensor based on the CSRR was proposed to address these issues mentioned above. Different theoretical models were established for ceramic samples of various shapes, and the extensive simulation was carried out to verify the adaptability of the sensor to synthetic ceramics. In addition, the measurements were also conducted without modifying either the sensor or the MUT.

2 Fundamental

Fig. 1 shows the structure and its equivalent circuit model of the CSRR sensor. The quasistatic electrically small resonators are usually designed with an open loop, being referred to as split ring. The CSRR structure is formed *via* placing two split rings concentrically. The change in the capacitance of CSRR is due to the permittivity variation of the MUT, whereas the inductance of the CSRR is assumed to be unchanged for dielectric materials.

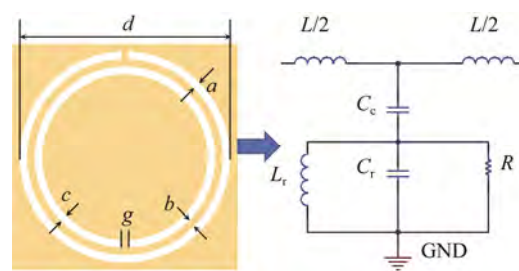


Fig. 1 Structure and its equivalent circuit model of the CSRR sensor

In the equivalent circuit, L_r and C_r represent the inductance and capacitance of the CSRR, respectively, L is the line inductance, and C_c is the coupling capacitance between microstrip line and the CSRR. To extract the exact values of these components, a full wave simulation in couple with circuit simulation has to be conducted^[27]. Their

relationship with the resonant frequency can be written as:

$$f_r = \frac{1}{2\pi\sqrt{L_r(C_c + C_r)}} \quad (1)$$

This is a quick way to estimate the resonant frequency and size. To achieve dual-band operation, two CSRR structures with different sizes are used, as shown in Fig. 2. The larger CSRR operates in a lower frequency band, while the smaller CSRR operates in a higher frequency band. The two structures are separated by a distance to reduce mutual coupling.

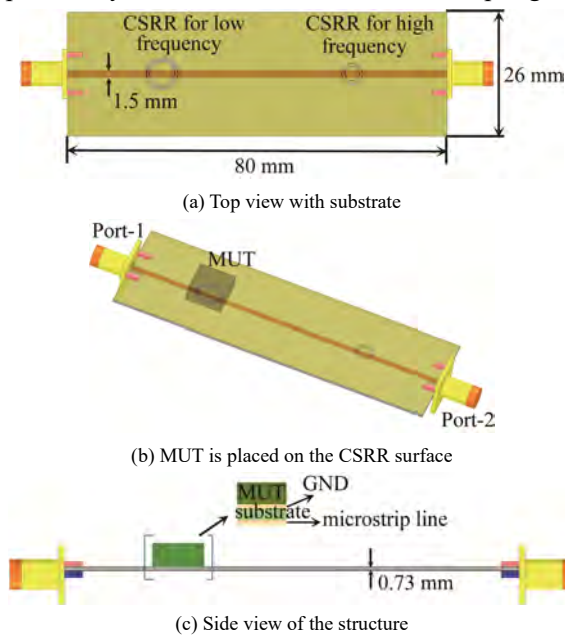


Fig. 2 Double circular CSRR structure

Two circular CSRR structures are etched out from the GND layer. The MUT is placed on top of the CSRR and covers the CSRR completely. Field will be coupled to the sample through the circular slots. Therefore, it is expected that such field-matter interaction could be reflected in the transmission coefficient of this structure.

Two operation bands are chosen (*i.e.*, 1.8–2.8 GHz and 3.5–5.0 GHz). Table 1 and Table 2 show the corresponding structure and circuit parameters. The substrate is FR4 with a dielectric constant of 4.9. Fig. 3 shows the transmission coefficients obtained by the full wave simulation and circuit simulation, respectively. The reason for using S_{21} as representative data is that S_{21} is closely related to the resonating frequency and the quality factor. Clearly, the simulated results obtained by the two simulation methods are in

reasonable agreement with each other at different frequencies. The discrepancy in the transmission coefficient outside the resonating frequencies is because the circuit theory only reflects the resonating frequency. More complicated modeling has to be built to fully simulate the structure. However, the circuit model is sufficiently accurate for a resonant frequency prediction. For the data extraction, the full wave simulation is a more suitable method used.

Table 1 Main parameters for the two operation bands

Parameters/mm	<i>a</i>	<i>b</i>	<i>c</i>	<i>g</i>	<i>d</i>
Band-1: 1.8–2.8 GHz	0.39	0.22	0.38	0.22	7.0
Band-2: 3.5–5 GHz	0.2	0.11	0.19	0.11	3.5

Table 2 Lumped parameters for the equivalent circuits

Lumped parameters	Band-1	Band-2
<i>L</i>	4.214 nH	1.214 nH
<i>C_c</i>	0.774 pF	0.474 pF
<i>C_r</i>	1.282 pF	0.722 pF
<i>L_r</i>	1.755 nH	0.863 nH

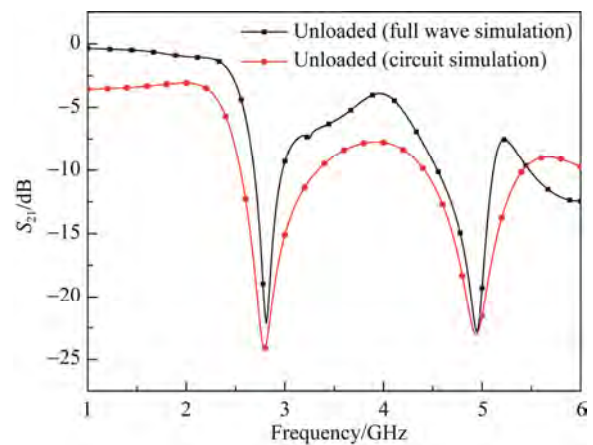


Fig. 3 Transmission coefficients on unloaded cases by the two simulation methods at different frequencies

3 Simulation

3.1 Sample preparation

Fig 4 shows six samples for the measurement. Sample 1 is polycarbonate, sample 2 and sample 3 are synthetic ceramics of known dielectric constant, prepared by the methods by Kim *et al.*^[28] and Yoon *et al.*^[29], respectively. The detailed parameters are shown in Table 3. Sample 1, sample 2 and sample 3 are measured as background benchmarks. These samples have different shapes and sizes, so that it is more convincing to use this measurement method for dielectric characterization.

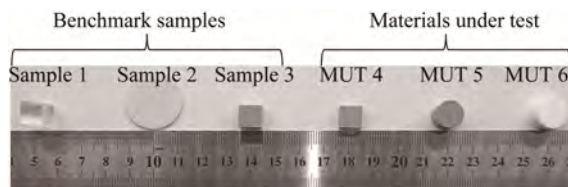


Fig. 4 Samples for measurement

Table 3 Parameters for samples 1, 2 and 3

Sample No.	Shape	Size/mm	Material	ϵ'_r
Sample 1	Cube	9×9×9	PC	2.8 ^[30]
Sample 2	Circular sheet	$\phi 19 \times 1$	Ceramics	8.7 ^[28]
Sample 3	Cuboid	9×9×6	Ceramics	5.7 ^[29]

Sample 1 is fabricated to be a cube, sample 2 is a circular sheet, and sample 3 is a cuboid (nearly a cube). For the circular sheet, the diameter is 19 mm ($\phi 19$ mm). The other three samples in Fig. 4 are materials to be determined. MUT 4 is actually the same material as sample 3, but its thickness is 4 mm, being different to that of sample 3. This is to cross validate the accuracy of this measurement method. MUT 5 and MUT 6 are

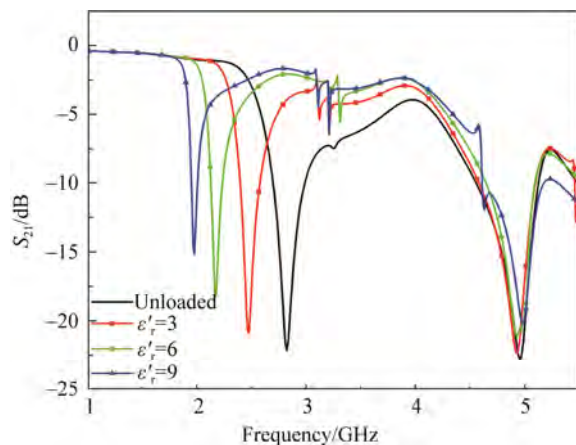
also synthetic ceramics, but their dielectric constants are unknown. Table 4 shows the sizes of these samples. MUT 4 is a cuboid, while MUT 4 and MUT 5 are cylinders. And their diameters are 11 mm ($\phi 11$ mm) and 13 mm ($\phi 13$ mm), respectively.

Table 4 Parameters for samples 4, 5 and sample 6

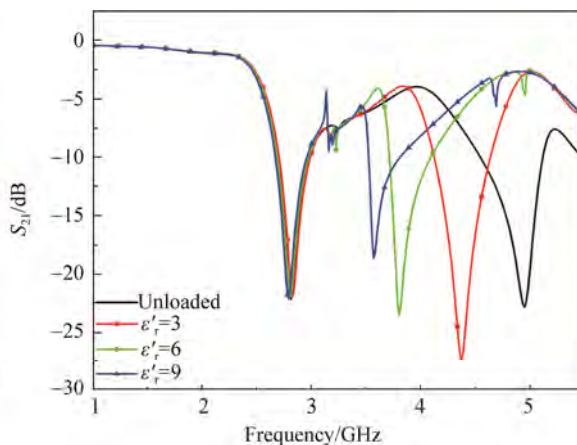
Sample No.	Shape	Size/mm	Material	ϵ'_r (Reference)
MUT 4	Cuboid	9×9×4	Ceramics	5.7 ^[29]
MUT 5	Cylinder	$\phi 11 \times 8$	Ceramics	Unknown
MUT 6	Cylinder	$\phi 13 \times 6.5$	Ceramics	Unknown

3.2 Extraction model for sample 1

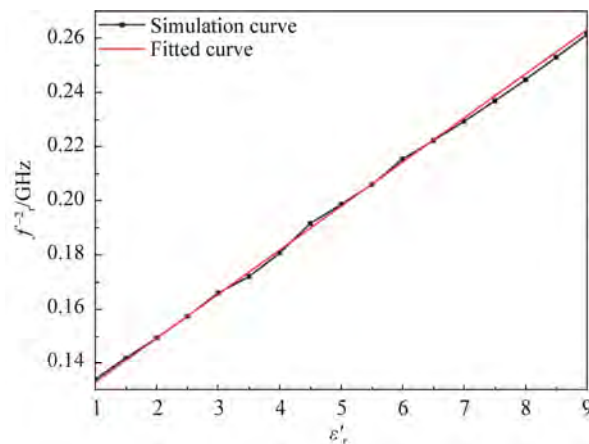
Fig. 5 shows the transmission coefficients of S_{21} for sample 1 in the designed frequency bands. Parametric sweep is performed in a step of 0.5 for the permittivity. In Fig. 5, only a few curves appear for simplicity. Fig. 6 shows the relation between the resonance frequency and the dielectric constant for different frequency ranges.



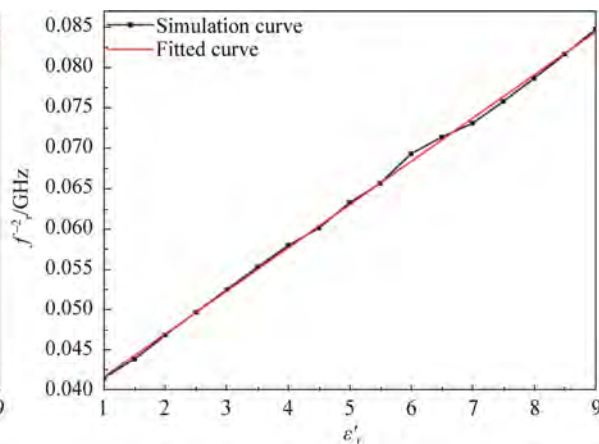
(a) For the frequency range of 1.8–2.8 GHz



(b) For the frequency range of 3.5–5 GHz

Fig. 5 S_{21} of sample 1 for different frequency ranges

(a) For the frequency range of 1.8–2.8 GHz

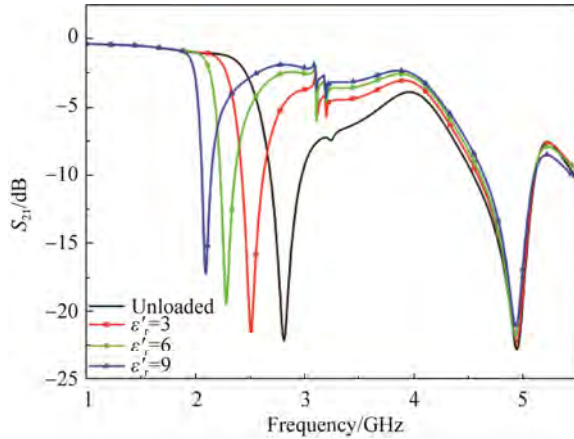


(b) For the frequency range of 3.5–5 GHz

Fig. 6 Relationship of sample 1 between ϵ'_r and Δf_r

By linear fitting, for the first band, and for the second band. Clearly, the goodness of fitting (R^2) for Eqs. (2) and Eqs. (3) are 0.999 2 and 0.998 8 respectively^[31].

$$\varepsilon'_r = \frac{f_r^{-2} - 0.116\ 64}{0.016\ 24} \quad (2)$$

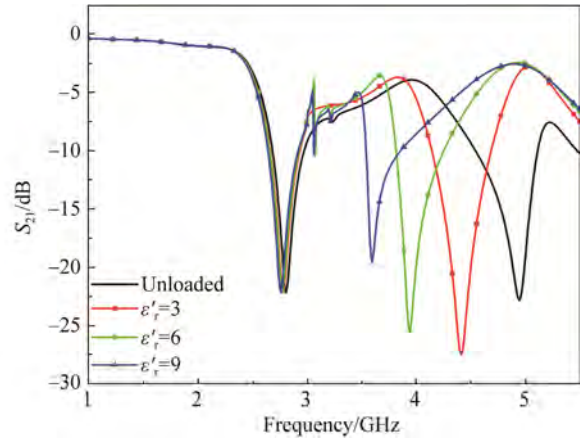


(a) For the frequency range of 1.8–2.8 GHz

$$\varepsilon'_r = \frac{f_r^{-2} - 0.036\ 29}{0.005\ 33} \quad (3)$$

3.3 Extraction model for sample 2

Table 3 also shows the dimensions of sample 2. Different from sample 1, the material of sample 2 is a synthetic ceramic.

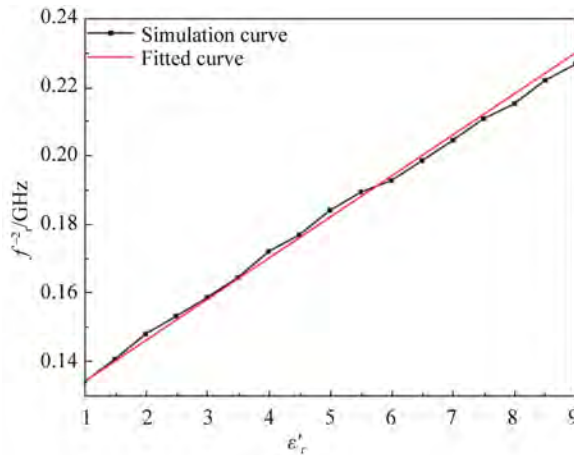


(b) For the frequency range of 3.5–5.0 GHz

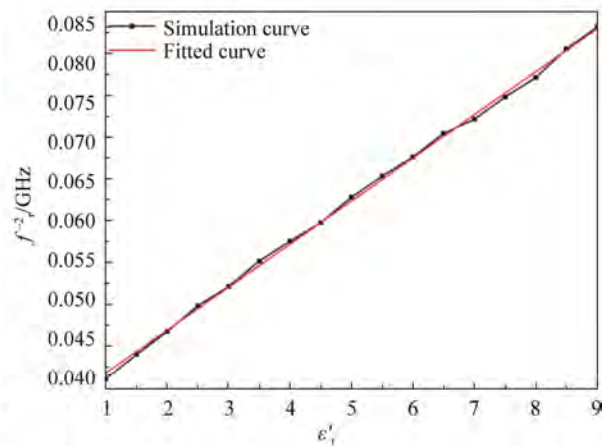
Fig. 7 S_{21} of sample 2 for different frequency ranges

Fig. 7 shows the simulation results for sample 2 obtained by the same method for sample 1. Fig. 8

shows the relation between the resonant frequency and the dielectric constant.



(a) For the frequency range of 1.8–2.8 GHz



(b) For the frequency range of 3.5–5.0 GHz

Fig. 8 Relationship of sample 2 between ε'_r and Δf_r

The following retrieval functions in the two designed frequency bands for sample 2 can be obtained via linear fitting:

$$\varepsilon'_r = \frac{f_r^{-2} - 0.121\ 99}{0.012\ 01} \quad (4)$$

$$\varepsilon'_r = \frac{f_r^{-2} - 0.036\ 64}{0.005\ 15} \quad (5)$$

where, the R^2 for Eqs. (4) and Eqs. (5) are 0.998 and

0.999, respectively.

3.4 Fitting equations of other samples

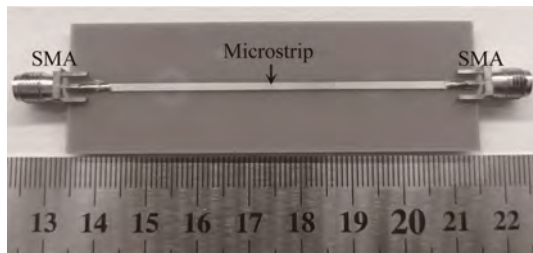
The same method can be repetitively used to obtain the fitting equations of sample 3 and MUT 4, MUT5, and MUT 6. The simulated results are not presented to save the space. Table 5 shows the final equations. The R^2 of all fitted equations are greater than 0.990.

Table 5 Fitted equations of samples and MUTs

Sample No.	ϵ_{rl} (1.8–2.8 GHz)	ϵ_{rh} (3.5–5.0 GHz)
Sample 1	$\epsilon'_r = \frac{f_r^{-2} - 0.116\ 64}{0.016\ 24}$	$\epsilon'_r = \frac{f_r^{-2} - 0.036\ 29}{0.005\ 33}$
Sample 2	$\epsilon'_r = \frac{f_r^{-2} - 0.121\ 99}{0.012\ 01}$	$\epsilon'_r = \frac{f_r^{-2} - 0.036\ 64}{0.005\ 15}$
Sample 3	$\epsilon'_r = \frac{f_r^{-2} - 0.114\ 22}{0.016\ 8}$	$\epsilon'_r = \frac{f_r^{-2} - 0.036\ 17}{0.005\ 28}$
MUT 4	$\epsilon'_r = \frac{f_r^{-2} - 0.116\ 49}{0.016\ 4}$	$\epsilon'_r = \frac{f_r^{-2} - 0.035\ 71}{0.005\ 1}$
MUT 5	$\epsilon'_r = \frac{f_r^{-2} - 0.115\ 99}{0.017\ 2}$	$\epsilon'_r = \frac{f_r^{-2} - 0.035\ 86}{0.005\ 48}$
MUT 6	$\epsilon'_r = \frac{f_r^{-2} - 0.116\ 42}{0.017\ 62}$	$\epsilon'_r = \frac{f_r^{-2} - 0.036\ 36}{0.005\ 42}$

4 Fabrication and Measurement

Fig. 9 shows the sensor manufactured by PCB technology. The substrate is an FR4 substrate with a dielectric constant of 4.9 and the thickness of 0.8 mm. The top view and bottom view of the sensor are shown in Fig. 9 (a) and Fig. 9 (b), respectively.



(a) Bottom view of the sensor



(b) Top view of the sensor

Fig. 9 Sensors and samples for measurement

A pair of 50 Ω SMA connectors were soldered onto the both ends of the sensor. The measurement was conducted using a vector network analyzer (VNA) Ceyear AV3672D. The VNA is calibrated using a standard short-load-open-thru (SLOT) method with the 3211.0–3.5 mm calibration kit. The measurement frequency was 1.0–5.5 GHz. Fig. 10 shows the experimental set up.

The S_{21} of unloaded situation was first measured after calibrating the system. In Fig. 11, the S_{21} of the

measured results are close to the simulated data. Some discrepancy appears for the second band, which is because a higher frequency is more affected by fabrication error. Several samples were measured by placing these samples at the two CSRRs consecutively. Fig. 12 and Fig. 13 show the transmission coefficients S_{21} of samples and MUTs. From the measured data, the resonating frequency and the quality factor can be deduced. The dielectric constant can be calculated by using the simulated results. Table 6 and Table 7 show the retrieved results and the data in the literature.

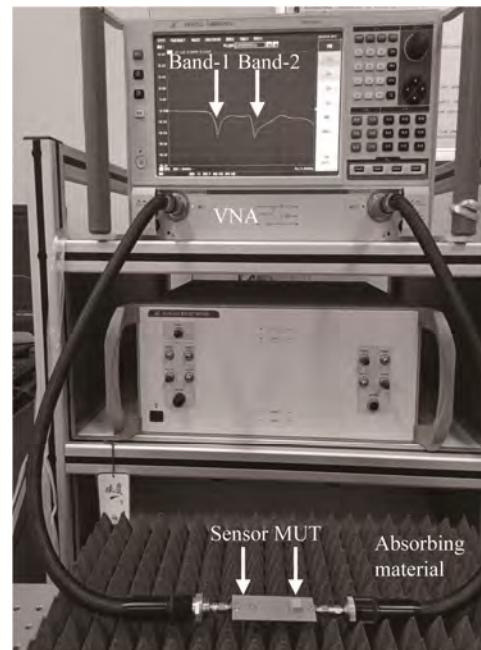


Fig. 10 Experimental set up

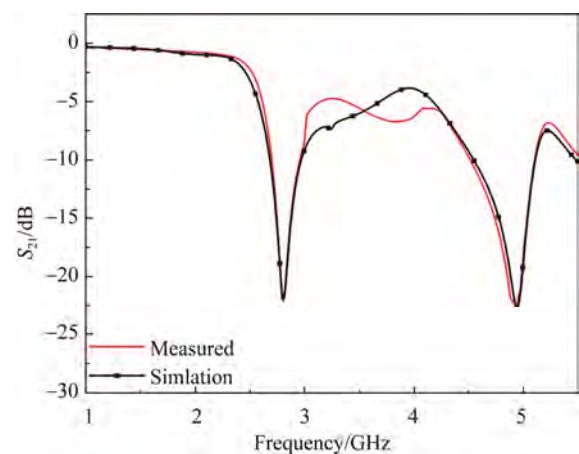
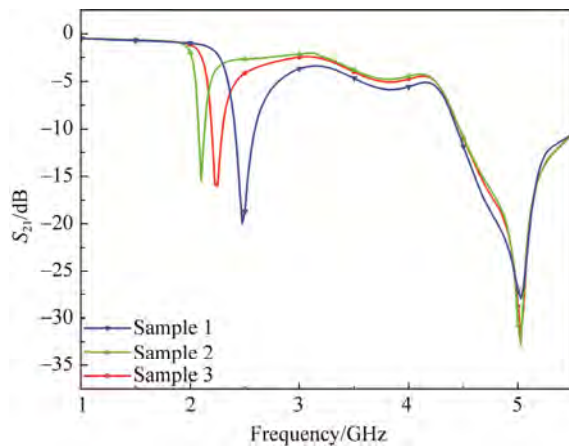


Fig. 11 Comparison between measurement and simulation

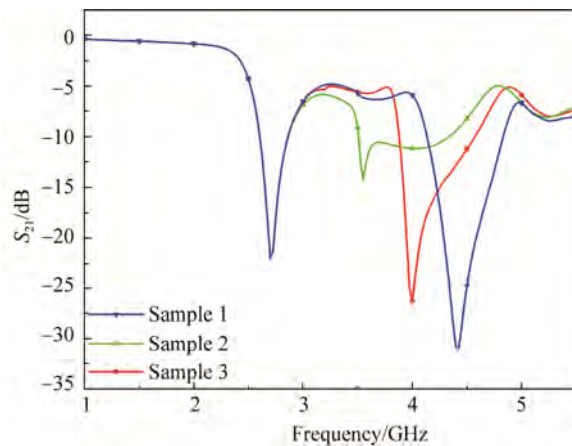
In Table 6, the results for different samples measured by the designed sensor are similar to the reference value^[28–30] in different frequencies. At

1.8–2.8 GHz, the accuracy is better than 3.5%. And at 3.5–5.0 GHz, the accuracy is better than 3.8%. Clearly, the sensor has a good measurement

adaptability to materials with different shapes and sizes. In addition, the discrepancy between the first band and the second band is also less than 5%.



(a) For the frequency range of 1.8–2.8 GHz



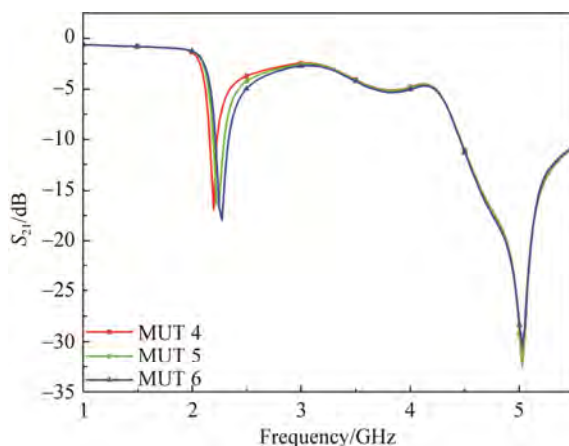
(b) For the frequency range of 3.5–5.0 GHz

Fig. 12 Measured S_{21} parameters of calibration samples for different frequency ranges

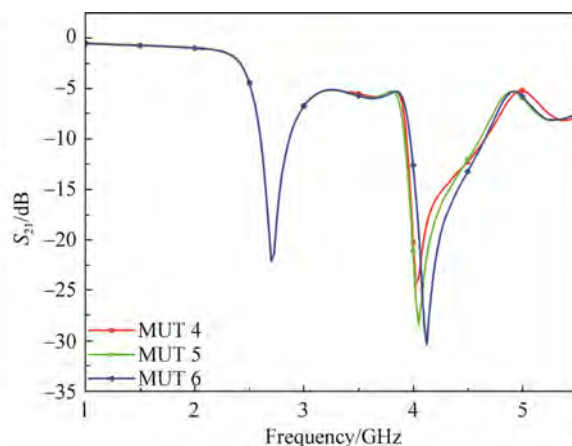
Table 6 Measured results for different samples

Sample No.	Lower frequency/GHz	ϵ'_r	Higher frequency/GHz	ϵ'_r	ϵ'_r (Reference)
Sample 1	2.475	2.87	4.425	2.77	2.82
Sample 2	2.100	8.72	3.550	8.49	8.70
Sample 3	2.200	5.50	3.950	5.39	5.60

The measurement of MUT 4–6 was also conducted, and Fig. 13 shows the curves for the parameter of S_{21} for MUT 4, MUT 5 and MUT 6. Table 7 shows their retrieved dielectric constants in different frequencies.



(a) For the frequency range of 1.8–2.8 GHz



(b) For the frequency range of 3.5–5 GHz

Fig. 13 Measured S_{21} parameters of MUT for different frequency ranges

Table 7 Measured results for different MUTs

Sample No.	Lower frequency/GHz	ϵ'_r	Higher frequency/GHz	ϵ'_r
MUT 4	2.200	5.50	4.000	5.25
MUT 5	2.250	4.74	4.050	4.58
MUT 6	2.275	4.36	4.125	4.13

In Table 6 and Table 7, the results of MUT 4 are similar to those of sample 3. At 1.8–2.8 GHz, the dielectric constant of MUT 4 is the same as that of sample 3. And at 3.5–5.0 GHz, a difference between

their dielectric constants is only 0.03. Therefore, it is evident that the measurement accuracy can be maintained even the sample size is changed.

For MUT 5, the measured dielectric constant is 4.74 in the first band, and 4.58 in the second band. The discrepancy is only 0.16 (<3.5%). For MUT 6, the measured dielectric constant is 4.36 in the first band, and 4.13 in the second band. The discrepancy is only 0.23 (<5%). In this connection, the

consistence between two frequency bands is within 5%. The dielectric constant of MUT 5 is 4.74, which may be similar to the synthetic ceramic in Ref [32]. The dielectric constant of MUT 6 is 4.36, which may be similar to the synthetic ceramic in Reference[33].

Clearly, this sensor is superior in flexibility in terms of size and profile of MUT. Also, its accuracy in dielectric constant is satisfactorily good. The dielectric constant of the MUT measured by the sensor is optimum in the range of 1–9 due to a higher mode effect in the sample. In addition, the quality factor of this sensor is yet examined. The reasons are that the quality factor is affected by both the microstrip line and the sample. To separate the unloaded and loaded quality factors, a further investigation is still needed. And it is envisaged that the investigation into quality factor deserves another round of systematic and extensive simulation and modelling.

The sensor is suitable for measuring ceramics of low to medium dielectric constant. Since the quality factor is not systematically analyzed, the precise range of the loss tangent of ceramics cannot be decisively determined. However, the design of this sensor as a resonant sensor is suitable for the measurement of low to medium loss samples.

5 Conclusion

A dual band CSRR sensor was designed, fabricated and verified with synthetic ceramics samples for the dielectric measurement. The sensor exhibited a good sample adaptability *via* measuring synthetic ceramics with different shapes. It was demonstrated that the samples could be measured with an accuracy of 3.5%. Several synthetic ceramics of unknown dielectrics were measured, obtaining the reliable results. In addition, a dual-band operation was also realized, and the discrepancy between the two designed bands could be well controlled within 5%. Considering these measured samples had different shapes and sizes, we used this sensor for the measurement of non-standard samples, thus establishing the sample adaptable measurement. The use of this sensor could overcome the difficulty of

precision fabrication of the sample to fit the conventional sample holder. The ceramic samples measured by this sensor could be those with low to medium-high dielectric constant. The quality factor characterization using this sensor could be further investigated.

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