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Accurate characterizations of material using microwave T-resonator for solid sensing applications

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ABSTRACT

The topic of microwave sensors in enclosures is one of the most active areas in material characterization research today due to its wide applications in various industries. Surprisingly, a microwave sensor technology has been comprehensively investigated and there is an industry demand for an accurate instrument of material characterization such as food industry, quality control, chemical composition analysis and bio-sensing. These accurate instruments have the ability to understand the properties of materials composition based on chemical, physical, magnetic, and electric characteristics. Therefore, a design of the T-resonator has been introduced and investigated for an accurate measurement of material properties characterizations. This sensor is designed and fabricated on a 0.787 mm-thickness Roger 5880 substrate for the first resonant frequency to resonate at 2.4 GHz under unloaded conditions. Various standard dielectric of the sample under test (SUT) are tested to validate the sensitivity which making it a promising low-cost, compact in size, ease of fabrication and small SUT preparation for applications requiring novel sensing techniques in quality and control industries.

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1. INTRODUCTION

A large and growing body of literature has investigated microwave resonator sensor for materials characterization. The most important of characterizing the materials is to know the composition and properties of the materials in relation to physical, chemical, magnetic, and electric characterization. Several types of sensors have been used for materials characterization such as waveguide resonator [1, 2], dielectric [3, 4], and coaxial probe sensor [5-7] due to their advantages of having high-Q factor and sensitivity. However, approaches of this kind carry with them various well-known limitations, including high cost to fabricate due to the design structure complexity and having a a large size. These limitations relating to the conventional devices were subjective and were therefore led to propose planar resonator sensors because of its advantages and drawbacks of having a compact in size, simplicity, ease of fabrication, and minimizing the manufacturing cost which makes them suitable for bio-sensing and chemical detection applications [8-10]. Therefore, well-established microwave resonator sensors with high accuracy and sensitivity measurements are required for producing important information from the sample under test of any materials, liquid, solid, and gases [11-20].

A common method is demonstrated in [21] and [22] where the authors used a half-wave line transmission resonator to find the quality factor. In general, as observed from the prior studies, the half-wave resonator was used to determine the transmission line attenuation that can be simply measured at high frequencies and it is difficult to obtain high accuracy measurement for high frequencies due to the radiation losses caused by coupling gap as demonstrated in Figure 1. Therefore, author motivation for this study is to develop a quarter-half wave resonator to reduce the radiation losses caused by coupling gaps and improve the measurement accuracy with minimizing the circuit size. The aim of the present work is to develop a quarter-wave T-resonator for characterizing solid material properties. Analysis of mathematical and theoretical calculations has been demonstrated in order to design the T-resonator. The paper also attempts to provide a more detailed investigation regarding the effects of testing a complete or partial sample under test (SUT). The T-resonator sensor can be used to demonstrate the potential of this approach and its suitability for the sensing applications such as quality control of the food industry and bio-sensing.

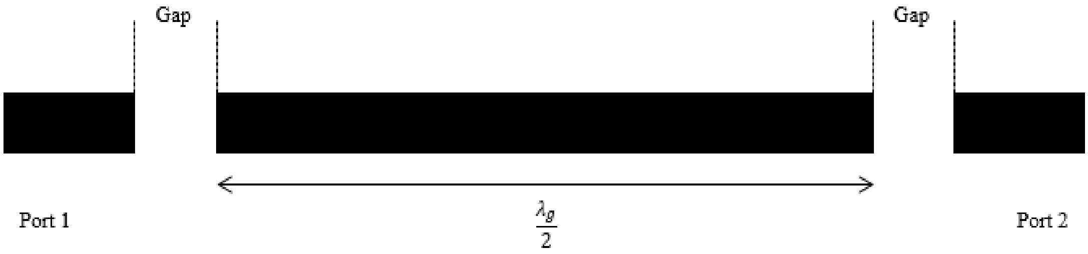

Figure 1. Half-wave line resonator structure for measuring attenuation

2. RESEARCH METHOD

Figure 2 demonstrates the design of the T-resonator on a dielectric substrate. In this paper, a Roger RT/Duroid 5880 is used as substrate materials with a dielectric constant of 2.2, a loss tangent of 0.0009, copper thickness of 0.07 mm and thickness of 0.787 mm. The cross dimension of the proposed T-resonator is 34.38x24.19 mm as width and length respectively. The width of the microstrip line is set at 2.5 mm to provide a characteristic impedance of 50 Ω at operating frequency of 2.4 GHz. Table 1 demonstrates the parameter specification for the T-resonator sensor design.

Table 1. The parametric specifications for the design of the T-resonator

Parameters	Value
Wg	34.38 mm
Lg	24.19 mm
w	2.50 mm
Lfeed	17.19 mm
Lstub	13.69 mm
Lh	7.00 mm
ws	0.75 mm

The microstrip line width can be formulated using the following equation from [23]:

$$Z_o = \frac{120\pi}{\sqrt{\varepsilon_{eff}}\left[\frac{w}{d}+1.393+0.667\ ln\left(\frac{w}{d}+1.444\right)\right]} \tag{1}$$

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\frac{1}{\sqrt{1+\frac{12d}{w}}} \tag{2}$$

where εr is the substrate permittivity, W is the width of the microstrip conductor line, h is the thickness of substrate, εeff is the dielectric effective permittivity for the medium of a homogenous that replaces the air region and the dielectric of the microstrip. The copper trace of the microstrip line width W is matched with an input and output 50 Ω SMA connectors and Vector Network Analyzer. The open-ended stub length is selected as a quarter wavelength at 2.4 GHz operating frequency. The stub length can be approximately modeled by the fundamental equation for a resonator of quarter-wave [24]:

$$L = \frac{nc}{4f\sqrt{\varepsilon_{eff}}} \tag{3}$$

where: n is the resonance order (n = 1, 3, 5, …), c is the light speed, f is the resonance frequency, and εeff is the dielectric effective constant. The Q-factor of resonant frequency can be found by using the following equation:

$$Q = \frac{f_o}{B.W} \tag{4}$$

where Q is the measurement of quality-factor, fo is the resonant frequency (MHz), and B.W is the bandwidth at 3dB (MHz).

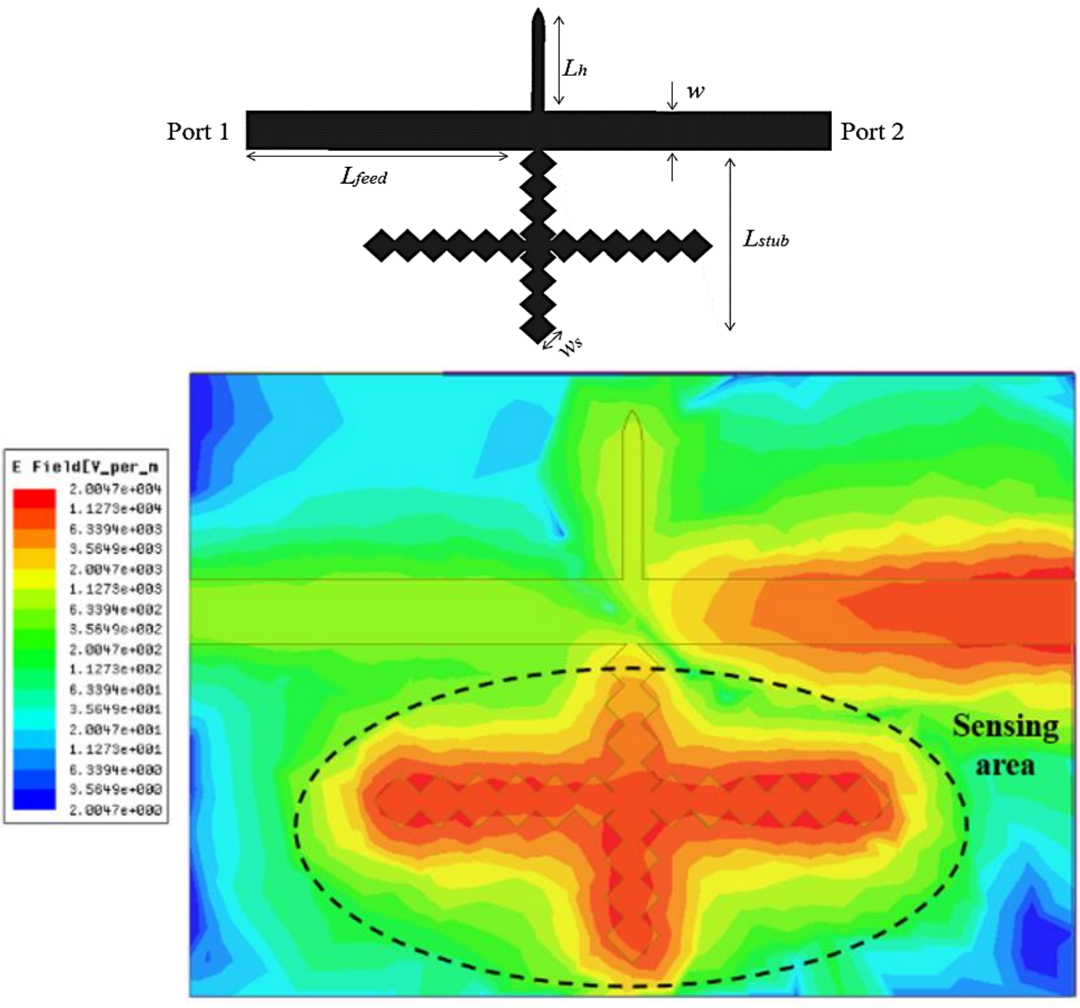

Figure 2. Configuration of T-resonator sensor and the sensing area where the maximum electric field location (red color shows the maximum) which indicates the possible location of tested SUT for measurements

The interaction of the permittivity of the tested material SUT and the electric field of the T-resonator leads to change the behavior of the resonant frequency. Thus, it is principally significant to determine the location of the SUT for sensitivity and accuracy of the measurements where in this case a location of maximum electric field for the T-resonator is illustrated in Figure 2. (The most electric field is represented by the red color). The SUT size is divided to three parts (namely: SUT A, SUT B, and SUT C) from partially to completely covered the T-resonator or overlays on the top of the T-resonator which cover the copper track. Figure 3 (a, b and c) illustrates the three different size of covered SUT for the T-resonator sensor respectively. The response of the resonant frequency variation is based on the MUT that has different permittivity and properties. The perturbation theory between the SUT and electric field of T-ring resonator where the perturbation to the sensor can be determined by the location and the size of the tested material. The tested SUT materials with their specifications are indicated in Table 2; where in this case, Rogers 5880, Rogers 4350, and FR4 [25].

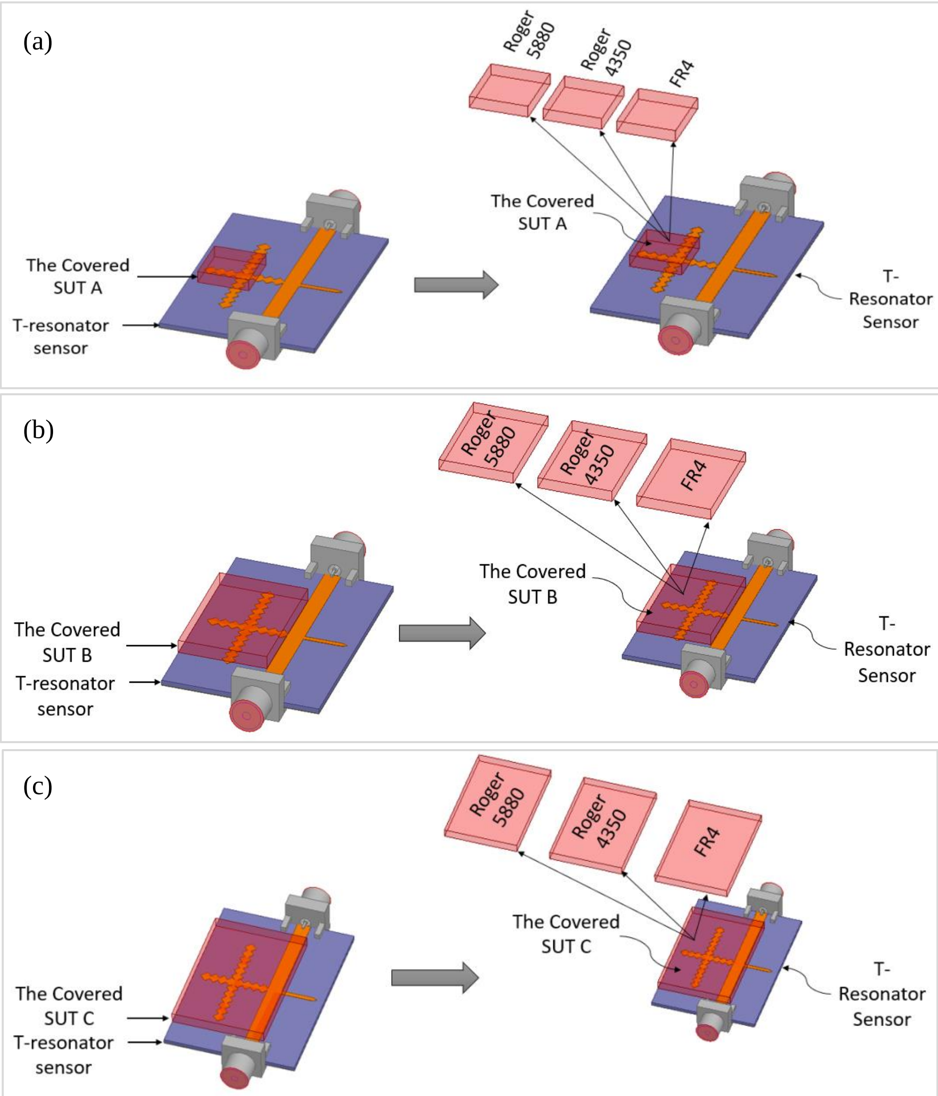

Figure 3. (a) T-resonator sensor covered by the SUT A for testing, (b) T-resonator sensor covered by SUT B for testing, and (c) T-resonator covered by SUT B for testing

Table 2. The specifications of used SUT materials for sensing

SUT Materials	Permittivity
Roger 5880	2.2
Roger 4350	3.48
FR4	4.4

3. RESULTS AND ANALYSIS

The simulation result for the design of the T-resonator is demonstrated in Figure 4 with unloaded conditions. The achieved resonant frequency is occurring at 2.4418 GHz with a shifting frequency of

41.8 MHz from the theoretical result of the calculation. The range of the simulated frequency is between 1 GHz to 5 GHz. It can be clearly seen from the result of Figure 4 that it has a narrower bandwidth and sharp dip which make it achieve a high Q-factor with high sensitivity for measuring the properties of the materials.

The discussion of the results begins with the sensitivity of the T-resonator which is dependent on the relative change of frequency shifting corresponding to the relative change of the tested material permittivity. A possible explanation for this is that a higher frequency shift is occurred when the permittivity of tested SUT materials is increased. Another possible explanation for this is that the size of tested sample under test materials effects the resonant frequency and increased the shifting. The size of covered SUT A, B, and C have been tested and investigated to validate the T-resonator sensor where several standard SUT materials with well-known permittivity have been considered. Those materials are as follows: Air with a permittivity value of 1, Roger 5880 with a permittivity value of 2.2, Roger 4350 with a permittivity value of 3.48, and FR-4 with a permittivity value of 4.4. Figure 5 illustrates the response behavior in term of transmission coefficients (S21, dB) for those standard materials when testing a partially covered SUT A. What is interesting in this Figure is that the resonant frequency of those standard tested SUT materials are gradually shifted to lower frequencies where the FR-4 SUT materials has the higher frequency shifting (172.4 MHz) compare to other partially tested SUT materials. This inconsistency is because the interaction between the SUT permittivity and the electric field of the T-resonator where the tested SUT absorbs the E-field and causes a change in resonant frequency.

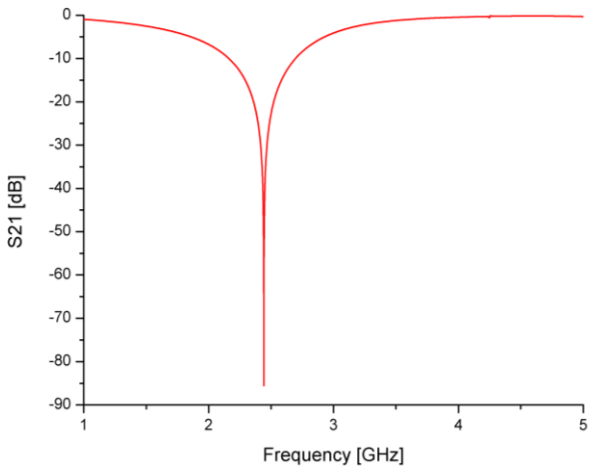

Figure 4. Simulated result of the transmission coefficients for T-resonator

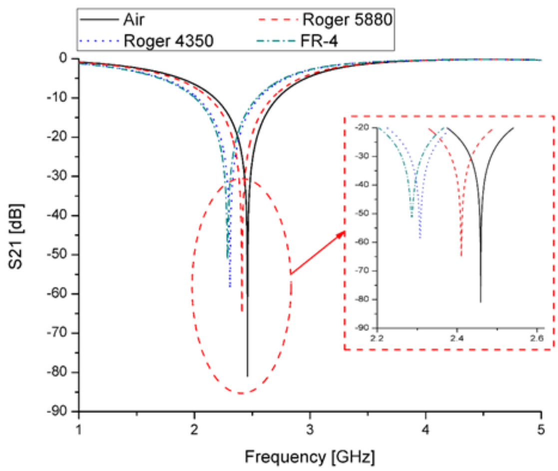

Figure 5. Change in transmission coefficients when changing SUT with standard permittivity materials for partially covered SUT A

Figure 6 demonstrates the result of the standard SUT materials when testing a covered SUT B. Similarly, with testing partially covered SUT A, the resonant frequency is shifted to lower frequency, however, it can be seen that the covered SUT B has a higher resonant frequency shifting with 315 MHz when testing FR-4 standard SUT materials. The results of the standard SUT materials for testing a covered SUT C are illustrated in Figure 7. It appears from this Figure 7 that the resonant frequency has the highest shifting to lower frequencies for all tested standard SUT materials. These differences can be explained in part by the interaction of the electric field of the T-resonator and the permittivity of the tested SUT materials. The large sample of material absorbs the whole electric field caused by the T-resonator which leads to higher frequency shifting. Table 3 provides a comparison of the frequency shifting between testing the covered SUT A, B and C materials for the T-resonator. There is a significant difference between the three tested SUT materials of covered overlay SUT A, B and C where it can be observed that by using partial covered overlay SUT A, it has a low relative change of shifting the resonant frequency compared to the covered overlay SUT B and C. Where in the case of testing FR-4 standard SUT material with known-permittivity of 4.4, a resonant frequency shifting of 172.4 MHz has been achieved by using partial covered SUT A materials compared to use the covered SUT B, and C material which achieved a 315 MHZ, and 363.4 MHz frequency shifting, respectively.

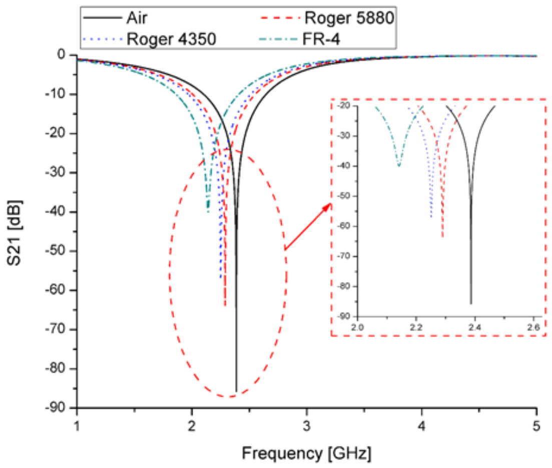

Figure 6. Change in transmission coefficients when changing SUT with standard permittivity materials for the covered SUT B

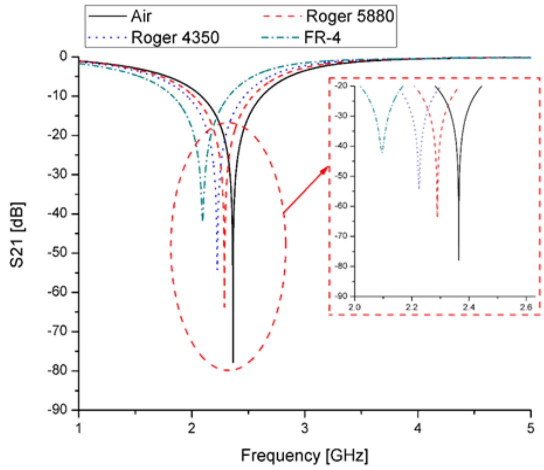

Figure 7. Change in transmission coefficients when changing SUT with standard permittivity materials for the covered SUT C

Table 3. Comparison of resonant frequency shifting for testing the covered standard SUT A, B, and C materials

SUT	SUT Permittivity	SUT Thickness [mm]	The Covered SUT A		The Covered SUT B		The Covered SUT C	
			Freq [GHz]	Δf [MHz]	Freq [GHz]	Δf [MHz]	Freq [GHz]	Δf [MHz]
Air	1	0	2.4590	0	2.4590	0	2.4590	0
Roger 5880	2.2	0.787	2.4104	48.6	2.2896	169.4	2.2886	170.4
Roger 4350	3.48	0.508	2.3074	151.6	2.2510	208.0	2.2252	233.8
FR-4	4.4	1.6	2.2866	172.4	2.1440	315.0	2.0956	363.4

4. CONCLUSION

The project was designed to determine and characterize the properties of materials based on T-resonator which operates at 2.4 GHz resonant frequency. Several standard SUT materials with well-known properties and permittivity have been used to validate the T-resonator sensor. A comparison is discussed and drawn for testing the covered SUT A, B, and C materials. A low relative change of resonant frequency shifting is achieved when using partially covered overlay SUT A compare to use the covered SUT B, and C overlay materials. The T-resonator was found to miniaturize the circuit size with low cost, to be reliable, and ease of design fabrication with using a small size of tested sample which makes it a suitable candidate for measuring low materials permittivity at normal case under room temperature. For future investigation, it can be extended for testing various chemical materials applications such as Ethanol, Methanol, Acetone, and Water or a mixture between them.

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