TELKOMNIKA Telecommunication Computing Electronics and Control
Vol. 20, No. 2, April 2022, pp. 447~454
ISSN: 1693-6930, DOI: 10.12928/TELKOMNIKA.v20i2.23158

Design of resonator cavity for liquid material characterization

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Article Info

Article history:

Received Jun 26, 2021
Revised Feb 25, 2022
Accepted Mar 05, 2022

Keywords:

Complex permittivity
Dielectric properties
Distilled water
Material characterization
Resonator cavity

ABSTRACT

Dielectric characterization is very essential before the material can be utilized in designing microwave networks. Circular cylindrical resonators have been widely used for material characterization, but it is not a preferable design during the measurement of liquid samples as the sample placement requires repetitive process of opening and closing the lid of the cavity. This repetition procedure easily affects the accuracy of measurement and may lead to a measurement error. In this study, a rapid and less measurement procedure of liquid material characterization is proposed. The proposed rectangular resonator design is far more convenient and easier to handle as it does not require complex sample preparation. Considering electric field leakage, a hole is designed at the top of the cavity to ease the inserting process of sample. A 5-GHz prototype of a rectangular resonator is designed and fabricated to measure a liquid sample. Complex scattering parameters are measured using a vector network analyzer before the dielectric properties are estimated using an inverse technique. The dielectric properties of distilled water are measured to demonstrate the practicality of the proposed measurement technique. As a result, the measured dielectric properties of distilled water show a reasonable agreement with the values from other literature.

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1. INTRODUCTION

The rapid expansion of wireless networking, communication [1], radar, and medical systems [2], [3] necessitated the development of novel materials in radio frequency (RF) and microwave engineering. Apart from the geometry and design of devices, microwave design is heavily influenced by the dielectric characteristics of materials. Consequently, accurate measurement in material characterization is critical for RF/microwave engineering as well as for low frequency applications such as insulator development.

Many researchers have developed microwave sensors and measurement techniques for material characterization that are based on free-space, transmission line and resonant methods. The free-space method is grouped under the non-destructive and non-contact dielectric measurement methods that are applicable in material characterization [4]-[6]. A sample is placed between the transmitting and receiving antennas, which are typically horn antennas. Scattering parameters can be measured using a vector network analyzer (VNA). This method does not require sample machining but is easily affected by the noise due to the open system. Another closed system technique used in material characterization is the transmission line. The benefit of this technique is that it allows the analysis of the fluctuation of electrical characteristics of substrate samples against temperature. The disadvantage of this technique is that even a tiny air gap could affect the accuracy of the measurement. Transmission lines could be classified into four types, which are coaxial, microstrip, waveguide and stripline. Waveguide is a commonly used technique [7]-[9] in the transmission line method since the sample preparation is less complicated compared to coaxial, microstrip and stripline. In the waveguide technique, the sample is placed in the waveguide to fill the corresponded band's height where either complex transmission or reflection parameters or both are needed for complex permittivity extraction. Meanwhile, the resonant method [10]-[13] outperforms the free-space and transmission line methods in measuring low-loss materials, while the other methods provide high accuracy in measuring moderate-loss materials [14], [15]. This is because the cavity of the resonator is filled with the sample, and the difference in resonance frequency and quality factor is measured [16], [17]. The disadvantage of using a cavity resonator is that it is only applicable in a narrow band and the sample to be tested must be machined precisely [18]-[20], where the cavity of a circular cylindrical must be filled by the sample so that there is no air gap. Air gaps may cause errors in the evaluation of material, so it is important to make sure the sample is fitted into the cavity. In addition, the sample under test is inserted into the cavity by opening the lid of the cavity. The sample insertion may lead to uncertainty in the placement of material when preparing the measurement setup. This is because the material might move and not exactly be at the center, which may cause a tiring measurement procedure in the evaluation of the material and lead to systematic error. For liquid material, dielectric probes have been commonly used for determining permittivity, but this open system technique is not free of errors since there is a lot of noise between the end of the coaxial probe and the sample [21]. Therefore, the purpose of this paper is to design a rectangular waveguide resonator capable of measuring the complex dielectric permittivity of liquid materials with a sample slot for easier measurement. This design will be validated by analysing distilled water, a widely used material.

The remaining of this work is structured as follows. The overall architecture of the rectangular resonator cavity is highlighted in section 2. The section 3 presents analyses of sample placement, dimensions, and range of sample characterization. Then, in section 4, the method of material characterization is described. Section 5 then shows the measurement setup and material characterization results. Finally, in section 6, we brought our work to a conclusion.

2. DESIGN OF RESONATOR

2.1. Design of rectangular cavity

The basic concept of the rectangular waveguide and the rectangular resonator cavity are similar. The design in this work is extended from [11], where the resonant frequency for this work is 5 GHz and the material under test (MUT) is in liquid form. The odd mode is preferable for measurement so that expressions of the resonant frequencies of a rectangular cavity and the unloaded Q of the TE_{mnl} mode are derived. The transverse modes used in the cavity resonators will provide the different dimensions, resonant frequencies, and Q values. In order to fabricate the real design of a cavity resonator, it is important to first define the dimension of the cavity. There are several methods implemented for defining the dimension of the cavity. The resonant frequencies for the general TE_{m0l} modes, f_r of a cavity can be derived from the equation in [22].

$$f_r = \frac{c}{2\pi\sqrt{\mu\varepsilon}}\sqrt{(\frac{3\pi}{a})^2 + (\frac{4\pi}{d})^2} \tag{1}$$

Where, a is the width and d is the length of the cavity while c, ε and μ are speed of light, permittivity, and permeability of air, respectively. The equation is derived in order to create a mode chart. The x-axis and y-axis parameters of the mode chart are obtained from the derivation equation (1).

$$(2af_r)^2 = (3k)^2 + (4k)^2(\frac{a}{d})^2 \tag{2}$$

$(2af_r)^2$ is the y-axis and $(a/d)^2$ is the x-axis for the mode chart. The mode chart for the design is plotted by considering the cavity without the input and output waveguides. A mode chart is generated and reduced to show certain modes, as shown in Figure 1. In this method, a mode is chosen in order to obtain the values of a and d. The ratio of the dimensions a to d is chosen from the horizontal axis and the value d can be obtained by using simultaneous calculation. A mode is chosen from the uncrowded region of the graph in order to avoid overlapping with other unwanted modes. If a mode is chosen from the crowded region, a slight change in the dimension values will cause the mode to change to another nearby mode.

2.2. Design of resonator with input and output waveguide

The resonator cavity is connected to the input and output waveguides through the windows or irises. Figure 2 illustrates the sample with a rectangular cross-section which is placed in a rectangular resonator cavity. The sample may be a high or low-loss dielectric material and will affect the resonant frequency and *Q*-factor. When the permittivity sample is loaded into the cavity, the resonant frequency will shift to a lower frequency. Due to the geometrical design and sample placement restrictions, the samples may require very specific machining to fit the conventional cavity. In this work, to ease the sample inserting process during measurement, a hole with a diameter of less than $\lambda/4$ is designed at the top of the cavity to avoid leakage of the electric field.

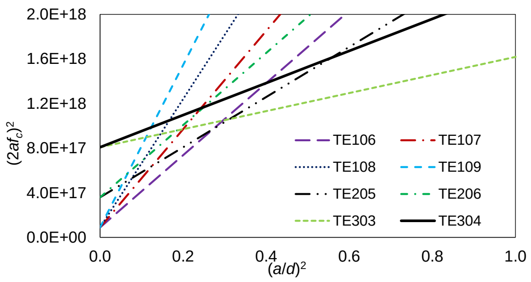

Figure 1. Mode chart

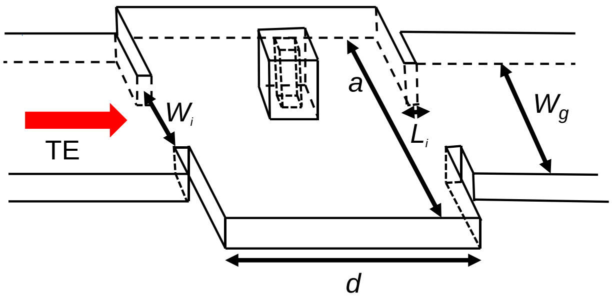

Figure 2. MUT placed in rectangular resonator cavity and dimension of cavity with waveguide attached

The dimensions of the cavity resonator are shown in Table 1. To avoid the problems of insufficient *Q*-factor and too small transmission wave, a rectangular resonator cavity with adjustable windows, W_i, is used. The narrower window is used to get a higher value of external *Q*. Wide windows have a lower *Q*-factor than narrower windows, implying that a high *Q*-factor might result in a low rate of energy loss. Analyses of sample placement and dimension are presented in section 3.

Table 1. Optimized parameters for the rectangular resonator cavity

Parameter	Optimized values (mm)
Length of cavity, *d*	200.07
Width of cavity, *a*	112.11
Length of iris, L_i	0.10
Width of waveguide, W_g	47.55

3. PARAMETRIC ANALYSIS OF SAMPLE POSITION, DIMENSION AND PROPERTIES

The MUT will be inserted into the sample container as shown in Figure 3. This position of the MUT with the sample container is analyzed in this section to identify the best position for minimizing the electric field leakage. Meanwhile, analysis of MUT dimension is necessary to find an optimum size of sample since a large sample of high-loss material will absorb the signal, which will cause too low a transmission level. Then, the range of sample properties that could be characterized by this model is determined by analyzing the effect of complex permittivity changes toward resonant frequency and *Q*-factor. As a material container, polylactic acid (PLA) with a relative permittivity, ε'_{PLA} = 2.615 and loss tangent, tan δ = 0.025 is utilized. The height of the material is set at the same height as the G-band waveguide. For analysis purposes, the material is set to have the same complex permittivity as distilled water, whose permittivity, ε' is equal to 76.7 and tan δ is 0.157 [22]. The analysis model used is the same as shown in Figure 2.

3.1. Effect of MUT position

In the scenario of measuring high-loss materials, the sample is preferable to be placed between four electric field distributions to get the weakest point of the electric field [7]. Figure 4 shows the changes in S_{21} when the position of MUT is changed around the weakest point of electric field distributions. For the TE_{304} mode, the weakest point of the electric field is not at the center of the cavity, but it is located between four centered electric field distributions, which is 28.03 mm from the center of the cavity. Based on Figure 4, the resonant frequency is larger than 5 GHz when the MUT is located at 16.02 mm, 18.69 mm, and 22.42 mm from the weakest point of electric field distribution, which will lead to difficulty in determining the complex permittivity since the resonant frequency for an unloaded cavity is 4.99 GHz. Thus, we choose the position when MUT is placed at 28.03 mm from the weakest point of the electric field distribution since the level of transmission is still acceptable for measurement purposes and does not drop to noise level.

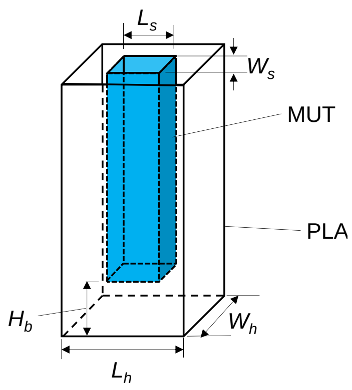

Figure 3. Sample container

3.2. Effect of MUT dimension

The dimension of the MUT is critical, and an analysis must be performed because S_{21} may drop into the noise level if the energy absorption rate of the material is high. The result plotted in Figure 5 shows the changes in the resonant frequency of S_{21} for different values of the length and width of the MUT. Length and width are set to be same (L_s = W_s). As can be observed, the changes in frequency compared to the resonant frequency of the unloaded cavity (4.99 GHz) are more significant when the dimension is 4×4 mm, while the others show inconsistent changes that may be due to the overlapping of the TE_{304} mode with other modes.

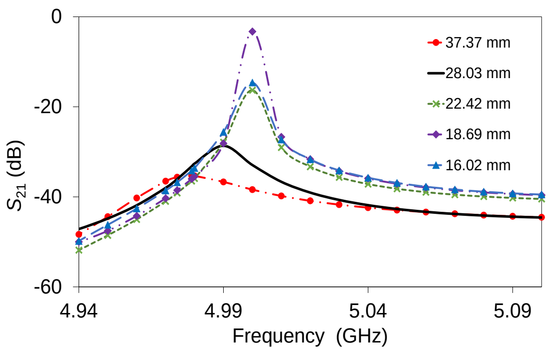

Figure 4. Changes of S_{21} parameters due to sample position

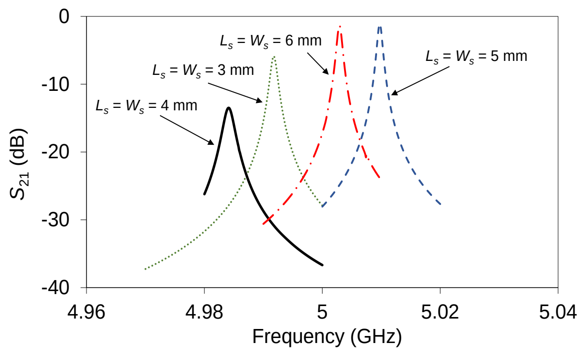

Figure 5. Changes of S_{21} parameters due to sample dimension

3.3. Robustness of the purpose design toward variety of sample characteristic

An inverse technique is implied in this work to determine the complex permittivity from the changes in resonant frequency, $\Delta f/f$, and Q-factor, $\Delta(1/Q)$ [10]. $\Delta f/f$ will mainly influence the value of the dielectric constant, ε', while dielectric loss, tan δ is influenced by $\Delta(1/Q)$. Thus, the changes in resonant frequency and Q-factor are very vital during the inverse technique. Insignificant changes will lead to inaccuracy of complex permittivity estimation. The characteristic of $\Delta f/f$ and $\Delta(1/Q)$ towards the relative permittivity and loss tangent changes are shown in Figure 6 and Figure 7, respectively. The analyses have been done at the resonant frequency of TE_{304} mode by using computer simulation technology (CST) Studio Suite software. It can be observed in Figure 6 that the values of $\Delta f/f$ and $\Delta(1/Q)$ for relative permittivity from 50 to 80 are changed significantly which indicates a high permittivity material characterization is affordable using this design. Meanwhile, the loss tangent shows significant changes in $\Delta f/f$ and $\Delta(1/Q)$ from 0.01 to 1.0 which are in the range of high-loss material.

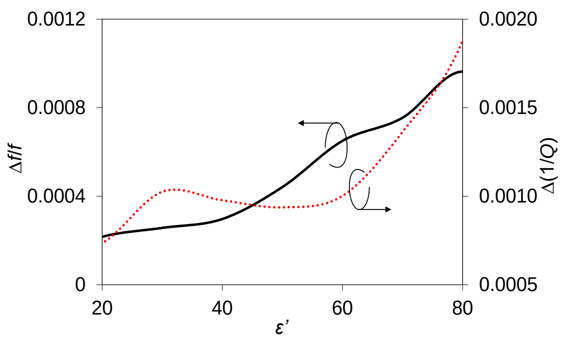

Figure 6. Changes of resonant frequency and *Q*-factor due dielectric constant

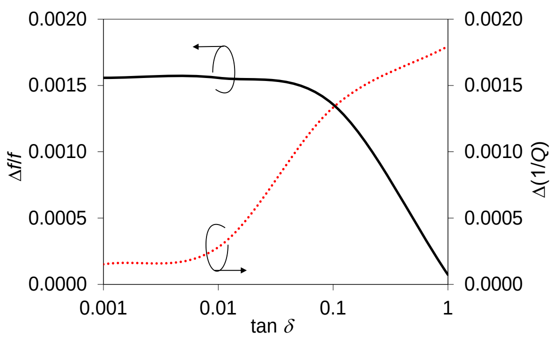

Figure 7. Changes of resonant frequency and *Q*-factor due loss tangent

4. MATERIAL CHARACTERIZATION TECHNIQUE

The prototype cavity is used for material characterization. The unknown material parameters are determined by solving the inverse problem of the scattering analysis based on CST software. This method is conducted by doing measurement and simulation to investigate the accuracy of the estimated complex permittivity. Unknown material parameters can be characterized using the prototype cavity by placing them inside the cavity where the resonant frequency and *Q*-factor are extracted from the measured scattering parameters. In the simulation, the permittivity of the sample is pre-assigned where the resonant frequency and *Q*-factor are then obtained. The complex permittivity is varied to minimize the difference between the resonant frequency and the *Q*-factor of simulation and measurement. Once the difference is below tolerance, the final varied complex permittivity is adopted as the characteristic for the MUT. The full illustration of the material characterization technique is shown in Figure 8.

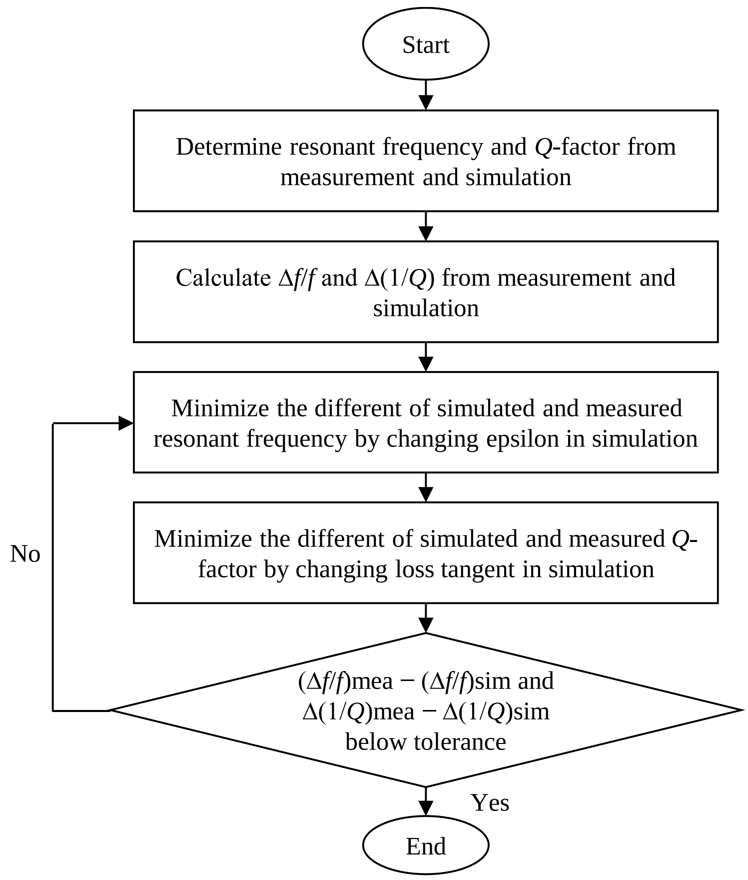

Figure 8. Flow of material characterization

5. MEASUREMENT SETUP AND MATERIAL CHARACTERIZATION RESULT
5.1. Measurement setup
An experimental setup is assembled to measure the transmission coefficient, S_{21}, as shown in Figure 9. In this work, G-band waveguides which support frequencies between 4 and 6 GHz are used to connect rectangular cavity. The resonator cavity is then connected to a VNA using coaxial cable and waveguide-to-coax adapters. Before measurement, the VNA is first calibrated using a full two-port short-open-load-thru (SOLT) calibration. This step is not really necessary since the measurement technique is calibration-independent [7]. In this study, distilled water is used as MUT with room temperature set at 25 °C. For each sample, 201 frequency points at around the resonant frequency were recorded to determine the accurate resonant frequency and Q-factor of the TE_{304} mode. From the measured value, the complex permittivity value is estimated using an inverse technique as mentioned in section 4.

5.2. Measurement result
Figure 10 depicts the measured S_{21} characteristics across the G-band frequency range. The simulation result is also presented in the figure as a comparison. Then, further detailed measurement of mode TE_{304} is done at its resonant frequency, 5 GHz, to extract the Q-factor. Material characterization is done at this frequency. The measurements of complex permittivity of distilled water from other researchers who are using the open-ended coaxial probe technique are compared and tabulated in Table 2. It can be seen that the measured value from the proposed method is in range with the value from Zhadobov *et al*. [23]. Meanwhile, the measurement values of complex permittivity from Xing *et al*. [24] and Hu *et al*. [25] are slightly higher than the proposed method. This might be due to the drawback of the open-ended coaxial probe technique, which is easily affected by the surrounding environment during the measurement.

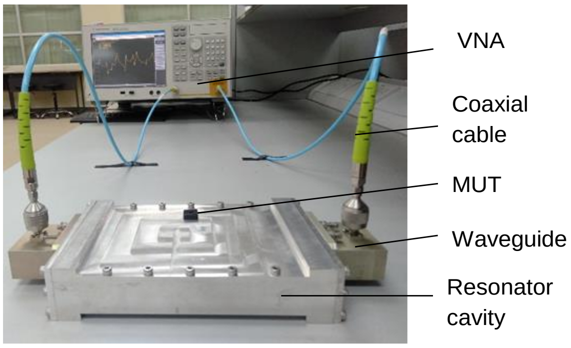

Figure 9. Measurement setup

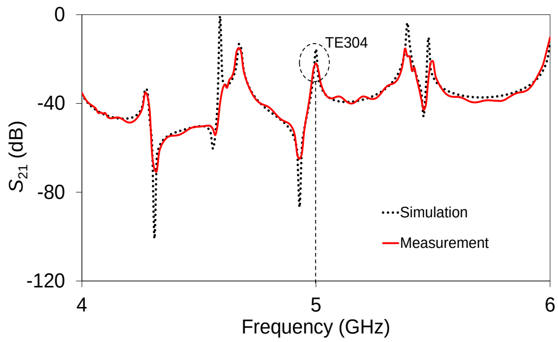

Figure 10. Comparison between simulation and measurement

Table 2. Comparison of complex permittivity of distilled water

Method	Temperature (°C)	Frequency (GHz)	Permittivity, ε'	Loss tangent, tan δ
Present method	25	4.996	71.1	0.141
Open-ended coaxial probe [23]	24	2 to 10	63.00 to 74.0	0.108 to 0.492
Open-ended coaxial probe [24]	25	2 to 6	73.00 to 79.0	0.100 to 0.600
Open-ended coaxial probe [25]	20	2 to 10	62.76 to 77.5	0.065 to 0.478

6. CONCLUSION
In this paper, a fast and easy measurement procedure was proposed to characterize liquid sample materials. The measurement setup used the rectangular resonator cavity with a hole at the top of the cavity to ease the sample placement during the measurement. Liquid material was filled into the sample container before it could be placed in the hole. A complex permittivity value was estimated from the measured resonant frequency and Q-factor using an inverse technique. The 5 GHz resonator cavity prototype was designed, and its practicality was validated by measuring the dielectric properties of distilled water. According to the experimental results, the dielectric property of distilled water was 71.1–j10.03, which confirmed the practicality of the proposed measurement technique.

ACKNOWLEDGEMENTS

This work was supported in part by the Universiti Malaysia Pahang and the ministry of education (MOE) Malaysia under the fundamental research grant scheme (FRGS) with reference no. FRGS/1/2018/STG02/UMP/02/1 or RDU190140. This work was also partially funded by the research and innovation department with research grants RDU210305 and PGRS200315.

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