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Research Article

Open-Ended Coaxial Cable Selection for Measurement of Liquid Dielectric Properties via the Reflection Method

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An open-ended coaxial cable is used to measure the dielectric properties of lossy liquid. The method which is based on the measurement of the reflection coefficient of the open-ended cable makes it easy to operate and postprocess. To meet the accuracy requirements, the dimensions of the coaxial cable need to be taken into consideration; therefore, it is necessary to select an appropriate coaxial cable for the measurement. This paper investigates the influence of cable dimensions on dielectric measurement accuracy. With careful choice of the coaxial cable, the relative error of calculated results can be less than 0.1%.

1. Introduction

Obtaining information regarding material dielectric properties is an important part of material analysis. Multiple approaches are available to acquire this information as discussed in [1]. In medical dosimetry, biological tissue properties such as dielectric constant, conductivity, and loss factor are of significance [2, 3]. Considering the increasing interest in dielectric properties of biomedical tissues due to advances in medical applications and for research, it is necessary to find an effective solution for the measurement of these dielectric properties. A commonly used method to determine the complex permittivity of materials at radio and microwave frequencies [4–7] is based on the open-ended coaxial cable due to its relative simplicity and accuracy [8]. The calibration of an open-ended coaxial probe for dielectric measurements is proposed in [9, 10].

Open-ended coaxial lines are particularly attractive for in vivo or in vitro measurements of biological material [11] as they offer merits including accuracy, the foundation of a simplified equivalent circuit with the form of capacitive impedance [12], and negligible radiation losses [5].

The capacitive nature of the cable changes with cable size; thus, there is an optimum cable size at a given frequency and permittivity, which offers the minimum measurement uncertainty [13]. Using a reference liquid, with well-known dielectric properties, the cable can be optimized to provide high measurement accuracy. Measurements are made of an unknown liquid using a comparison technique to a known reference liquid. In this work, liquid properties relating to the human body are of primary interest, though the technique could be extended to measure the dielectric properties of any liquid over a wide frequency range. In the literature, the complex dielectric structure of the body is represented by one set of properties: relative permittivity $\varepsilon_r = 56$ and conductivity $\sigma = 0.8\,\mathrm{S/m}$ at 403 MHz. Being able to reproduce liquids with the same properties is a common problem, for which the process described here could provide a reliable, rapid, and cost-effective solution.

In Section 2, the equivalent circuit for the measurement is illustrated. From the circuit, the complex permittivity of the object under test is analysed. In Section 3, investigations into the properties of the coaxial cable are performed. With the knowledge that the cable radius and length are related to the reflection coefficient and conductivity, analyses of how the accuracy of the measurements is influenced by the coaxial cable's dimensions are provided. Finally, conclusions are drawn in Section 4.

2. Equivalent Circuit

Several conventional methods are applied in permittivity measurements, such as the lumped capacitance method [13], short monopole antenna [7], and quasi-static analysis [14]. The method used in this paper is the open-ended coaxial cable reflection method.

The open-ended coaxial cable reflection method is based on the measurement of the complex reflection coefficient at a single network port. From this measurement, the complex dielectric constant of the object under test can be calculated. The conductivity of the object under test can also be found based on the relationship between the measured reflection parameters and the dielectric properties [15]. The coaxial cable has an inner conductor surrounded by a dielectric material (Teflon) and an outer conductor [16]. The configuration of the coaxial cable and the measurement system is shown in Figure 1.

An equivalent circuit for the measurement system is shown in Figure 2. The capacitance C_f represents the electric field concentration, which is inside the filled dielectric material part of the coaxial cable. The capacitance $C(\varepsilon)$ is the fringing field concentration in the dielectric, and the conductance $G(\varepsilon)$ is radiation into the dielectric surrounding the cable. The value of the conductance (G) is frequency (f) dependent. The equivalent admittance of the open-ended coaxial cable Y can be written as [18]

$$Y = j\omega C_f + j\omega C(\varepsilon) + G = j\omega C_f + j\omega C_0\varepsilon + G_0\varepsilon^{5/2}, \quad (1)$$

where C_0 represents the capacitance of the air-filled parallel plate capacitance, ε represents the permittivity of the object under test, and G_0 represents the external radiation conductance of a coaxial cable. From transmission line theory [7], terminal admittance Y based on the reflection coefficient Γ can be defined as follows:

$$Y = \frac{1-\Gamma}{1+\Gamma}\frac{1}{Z_0}, \quad (2)$$

where Z_0 represents the characteristic impedance of the coaxial line (50 Ω). The external radiation conductance of a coaxial cable is very small. As a result, it can be ignored ($G_0 \approx 0$). Hence, the relationship between the measured complex permittivity of the object under test and the reflection coefficient Γ is as follows:

$$Y = \frac{1-\Gamma}{1+\Gamma}\frac{1}{Z_0} = j\omega C_f + j\omega C_0\varepsilon. \quad (3)$$

The relative dielectric constant ε' and the loss factor ε'' are calculated using (4) and (5):

$$\varepsilon' = \frac{1}{2\pi f Z_0 C_0} \times \frac{-2|\Gamma|\sin(\varphi)}{1 + 2|\Gamma|\cos(\varphi) + |\Gamma|^2} - \frac{C_f}{C_0}, \quad (4)$$

$$\varepsilon'' = \frac{1}{2\pi f Z_0 C_0} \times \frac{1 - |\Gamma|^2}{1 + 2|\Gamma|\cos(\varphi) + |\Gamma|^2}, \quad (5)$$

where Γ and φ are the modulus and phase of the input reflection coefficient, respectively. The complex permittivity ε of the object under test and the relationship between loss factor ε'' and conductivity σ can be expressed as follows:

$$\varepsilon = \varepsilon' - j\varepsilon'', \quad (6)$$

$$\sigma = \omega\varepsilon_0\varepsilon'', \quad \varepsilon_0 = 8.548 \times 10^{-12}\ \text{F/m}. \quad (7)$$

The relationship between the sample capacitance measured by this method and the dielectric constant is linear, which can be found in [19]. In equations (4) and (5), the values of C_f and C_0 are calculated using equations (8) and (9) and the dielectric properties of the reference materials used, such as the deionized water or methanol.

$$C_f = \frac{1}{2\pi f Z_0}\frac{-2|\Gamma|\sin(\varphi)}{1 + 2|\Gamma|\cos(\varphi) + |\Gamma|^2} - \varepsilon' C_0, \quad (8)$$

$$C_0 = \frac{1}{2\pi f Z_0\varepsilon''}\frac{1 - |\Gamma|^2}{1 + 2|\Gamma|\cos(\varphi) + |\Gamma|^2}. \quad (9)$$

The complex permittivity of the object under test can be obtained using (4) and (5) and the measured reflection coefficient from the object under test. Finally, the dielectric constant and conductivity of the object under test can be calculated from the complex permittivity.

3. Permittivity Measurements

3.1. The Influence of Coaxial Cable Radius. A previous work has shown that the use of a reference liquid with similar dielectric properties to that of the test subject significantly improves measurement accuracy [18]. The dielectric properties of a body-equivalent phantom liquid (used to represent the average dielectric properties of the entire human body) are $\varepsilon_r = 56$ and $\sigma = 0.8$ S/m at 403 MHz. To measure the body-equivalent phantom liquid, for the purposes of simulation and investigation, a reference liquid with dielectric properties of $\varepsilon_r = 54$ and $\sigma = 0.6$ S/m is selected (close to the desired values). To observe the effect of the various cable radii, three radius (R) sizes of the cable are used. Each of the cables has an impedance of 50 Ω and a dielectric constant of 2.17, and they all have a fixed length of 100 mm.

The cable is located within the reference liquid, as shown in Figure 3. Commercial software (CST Studio Suite) has been used to simulate the measurement procedure and calculate the complex permittivity. For each radius of the coaxial cable, the modulus and phase of the reflection coefficient against frequency are shown in Figure 4. The modulus of the reflection coefficient shows a gentle increase with frequency for each cable. The phase of the reflection coefficient covers more than one cycle over the frequency range.

From these results, values of C_f and C_0 can be calculated using equations (6) and (7), and they are shown in Figure 5. It can be seen that the values of capacitance are different for each cable. Furthermore, the capacitances have a peak value within the frequency range. The peak value occurs at the frequency where the phase of the reflection coefficient is equal to −180° and can be seen from Figure 5.

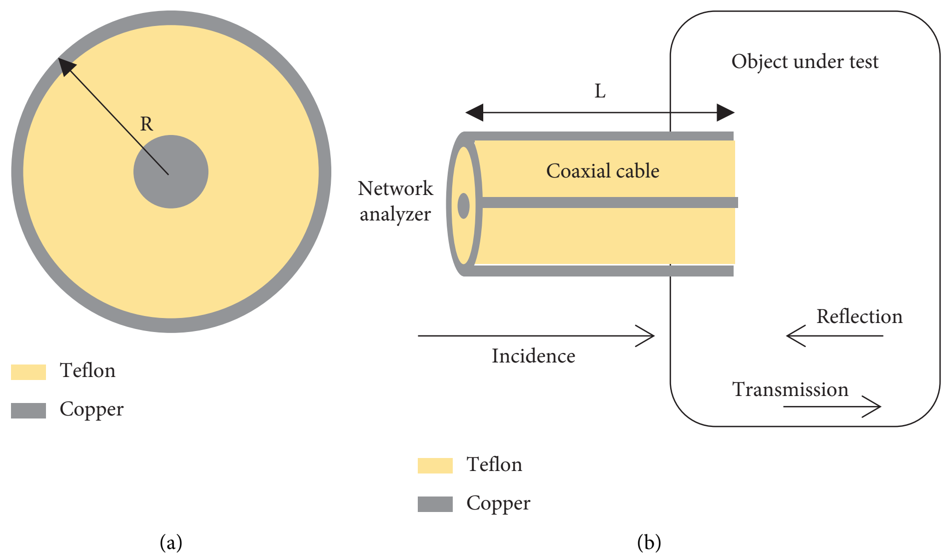


FIGURE 1: (a) The configuration of a coaxial cable. (b) Configuration of a permittivity measurement system using reflection methods [17].

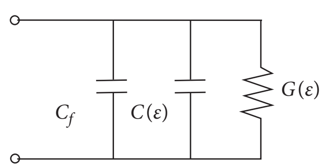


FIGURE 2: Cable equivalent circuit.

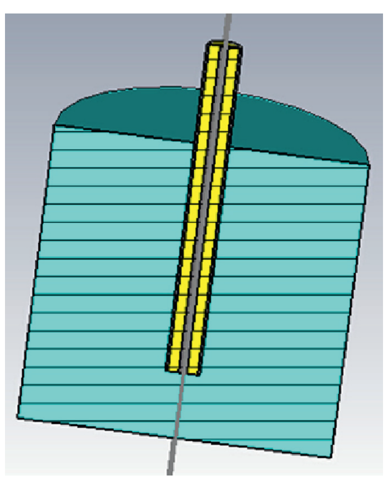


FIGURE 3: Cross section of the measurement model.

The same process is then followed using the liquid under test. The modulus and phase of the reflection coefficient against frequency obtained from the new simulation for each of the coaxial cables are shown in Figure 6.

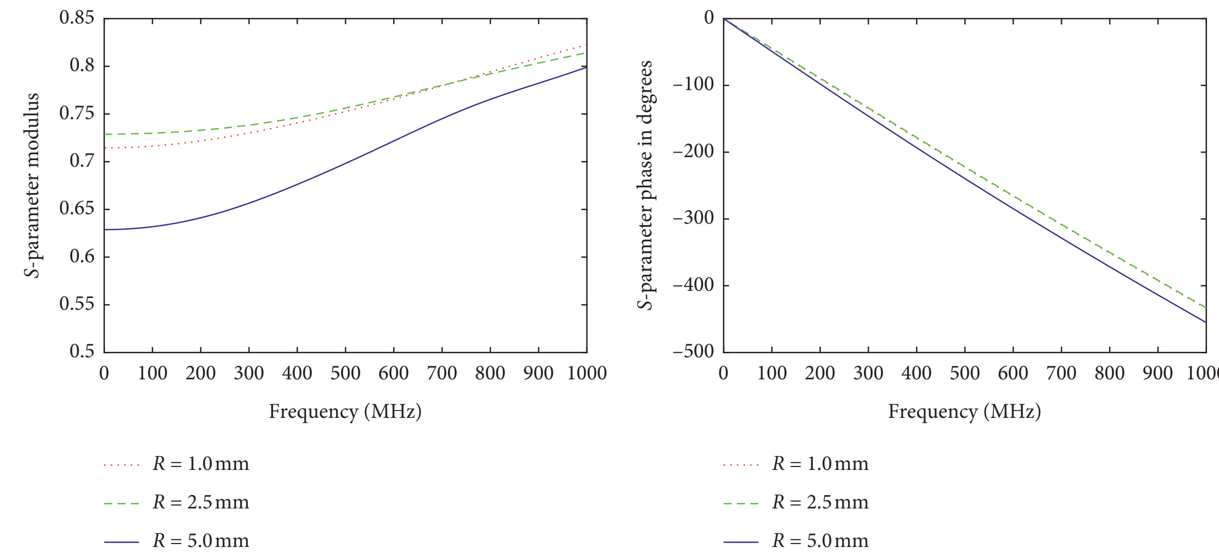
As would be expected, the modulus of the reflection coefficient decreases with respect to the results obtained for the reference liquid due to the increase in liquid permittivity and conductivity. The dielectric constant and conductivity of the liquid under test can be predicted from the reflection coefficient using the calculated complex permittivity, as shown in Figure 7.

From Figure 7, it can be seen that cable B with a radius of 2.5 mm offers the best accuracy in comparison with the actual values ($\varepsilon_r = 56$, $\sigma = 0.8$ S/m). The cable with a radius of 1 mm does not function suitably; therefore, it could not be used as a dielectric probe. It is clear from the results that the radius of the cable has a significant influence on the accuracy of the measurement. There is significant variation in the simulation for all 3 cables over the frequency range 200–600 MHz; this is caused by reaching the resonant frequency of the probe in the liquid. This cannot be predicted without knowing the dielectric properties of the liquid in advance; hence, measurements are made over a wide band of frequencies, and the dielectric characteristics are calculated at frequencies between resonances in the region where the calculated dielectric properties appear approximately linear.

3.2. Influence of Coaxial Cable Length. The influence of the cable length (L) on measurement accuracy is now investigated using the cable with 2.5 mm radius from the first investigation with lengths of 100 mm, 50 mm, and 15 mm. The modulus and phase of the reflection coefficient obtained from the simulation for each cable length in the reference liquid are shown in Figure 8.

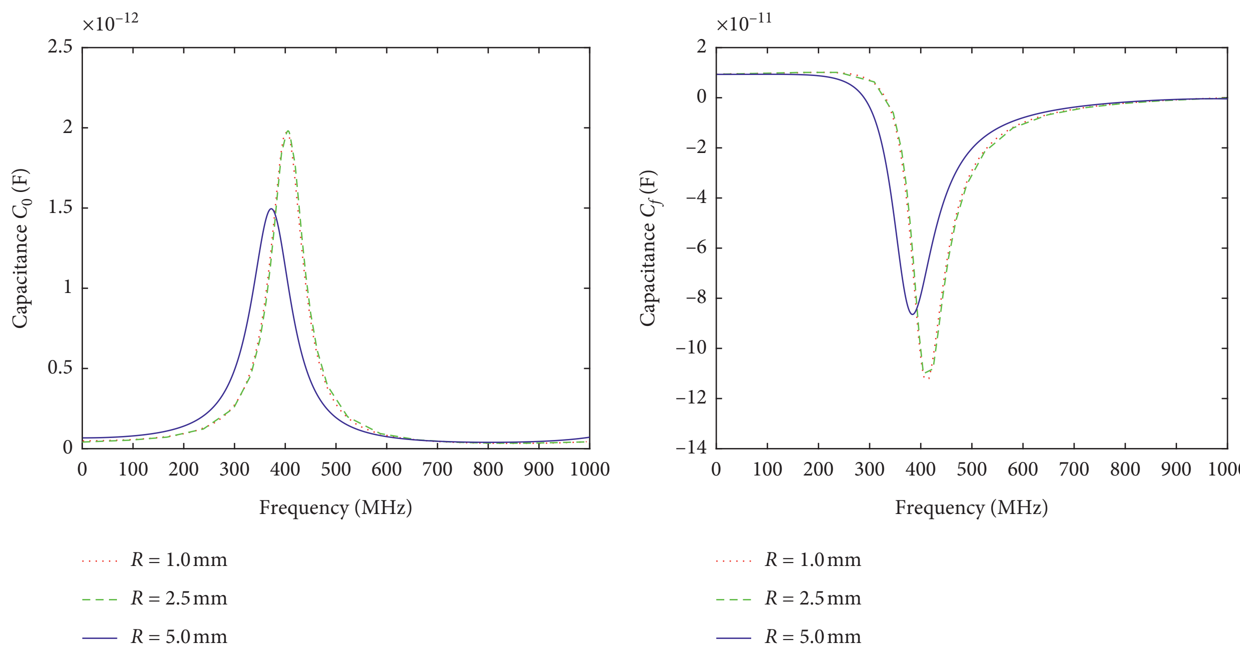
It can be seen from Figure 8 that the length of the cable has little influence on the modulus of the reflection coefficient; however, it has a significant influence on its phase. The shorter cable has a smaller phase range, whereas the longer cable has a larger phase range.

The values of C_f and C_0 are again calculated using equations (6) and (7), as shown in Figure 9. It is seen that the cables with lengths of 100 mm and 50 mm have a peak value of capacitance at the frequency where the phase is equal to −180°. The 15 mm long cable has a stable value of capacitance over the whole simulation frequency range. This results from the phase range being smaller than 180°.



(a) (b)

Figure 4: (a) The modulus and (b) phase of the reflection coefficient in the reference liquid for coaxial cables with different radii.



(a) (b)

Figure 5: (a) Calculated value of C_0 and (b) calculated value of C_f for coaxial cables with different radii when cables are located in the reference liquid.

Similarly, the simulated modulus and phase of the reflection coefficient for the liquid under test for each cable length are shown in Figure 10. Similar trends in the modulus and phase of the reflection coefficient are observed as that in the simulation using the reference liquid. The reflection coefficient modulus increases from 0.64 to 0.77 for each of the cables over the simulation frequency range. However, the change in phase is affected dramatically by cable length. The 15 mm cable has less than 180° of reflection coefficient phase variation, whereas the 50 mm and 100 mm extend far beyond that.

The complex permittivity is again used to find the dielectric constant and conductivity of the liquid under test, as shown in Figure 11. It can be seen that when the length of the coaxial cable is 15 mm, the average of the calculated results ($\varepsilon_r = 56.55$, $\sigma = 0.83$ S/m) are the closest to the true dielectric

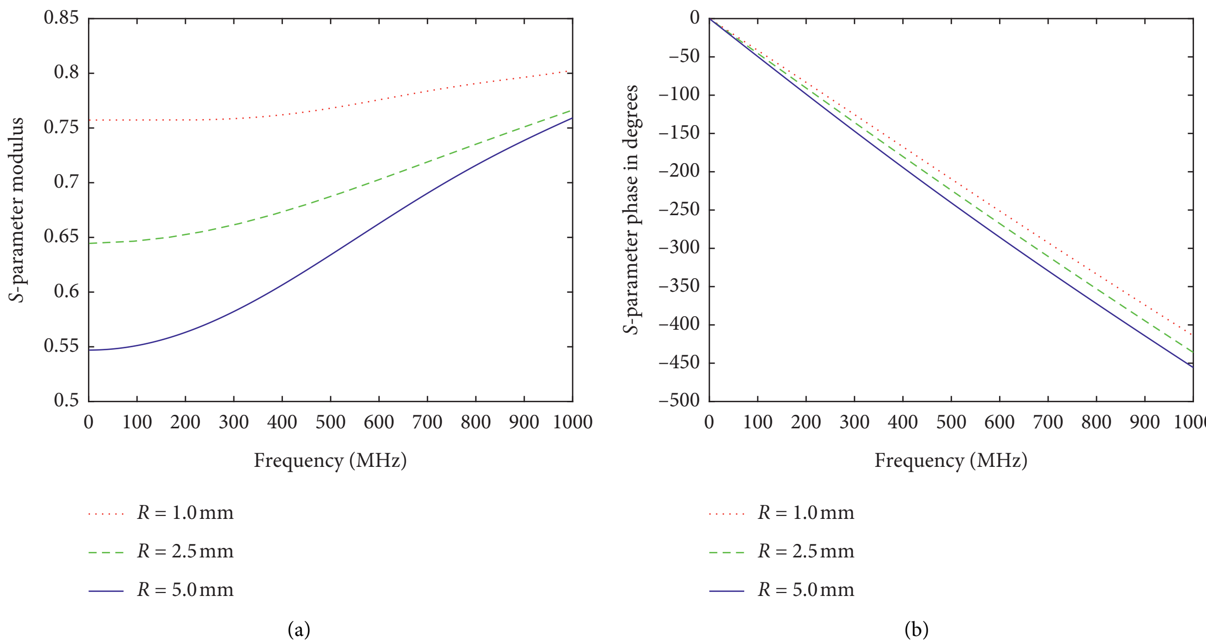


Figure 6: (a) The modulus and (b) phase of the reflection coefficient for the liquid under test with different cable radii.

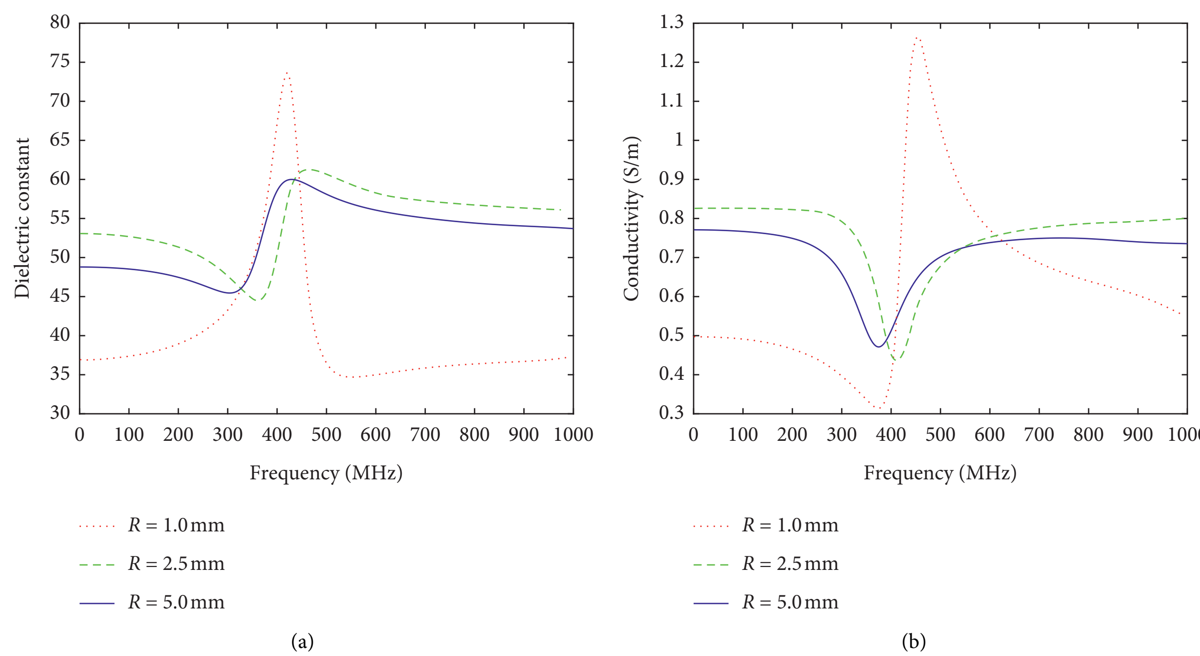


Figure 7: (a) Calculated dielectric constant ε_r and (b) calculated conductivity σ for the liquid under test for each coaxial cable.

constant and conductivity of the liquid under test ($\varepsilon_r = 56$, $\sigma = 0.8$ S/m). Over the simulation frequency range, the predicted values of dielectric constant and conductivity for the liquid under test are generally constant when using the 15 mm cable. Conversely, there is a big change in both the dielectric constant and the conductivity when using the cables with lengths of 50 mm and 100 mm. Therefore, cable length has a significant impact on measurement accuracy.

3.3. Analysis and Discussion. Through simulation, the relationships between the coaxial cable radius and length with conductivity and reflection coefficient prediction accuracy have been investigated and the importance of radius/length is emphasized in this regard.

The radius of the probe is related to the equivalent capacitance C_f and C_0, so the optimum cable radius can guarantee the accuracy of the calculated results. The most

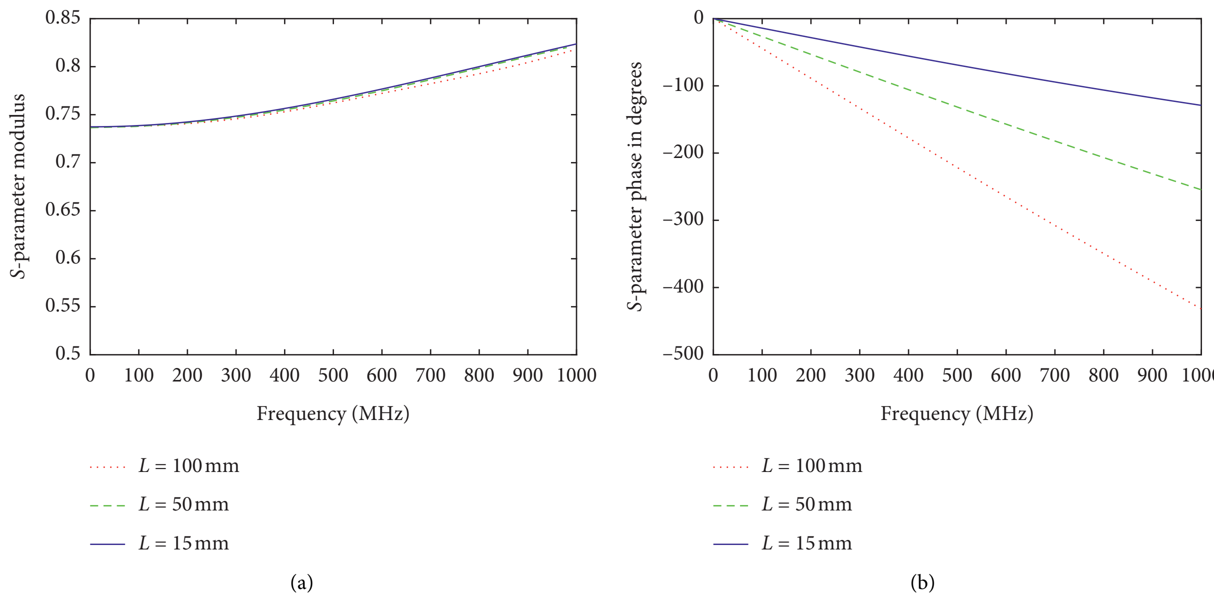


Figure 8: (a) The modulus and (b) phase of the reflection coefficient for the reference liquid with varying cable length.

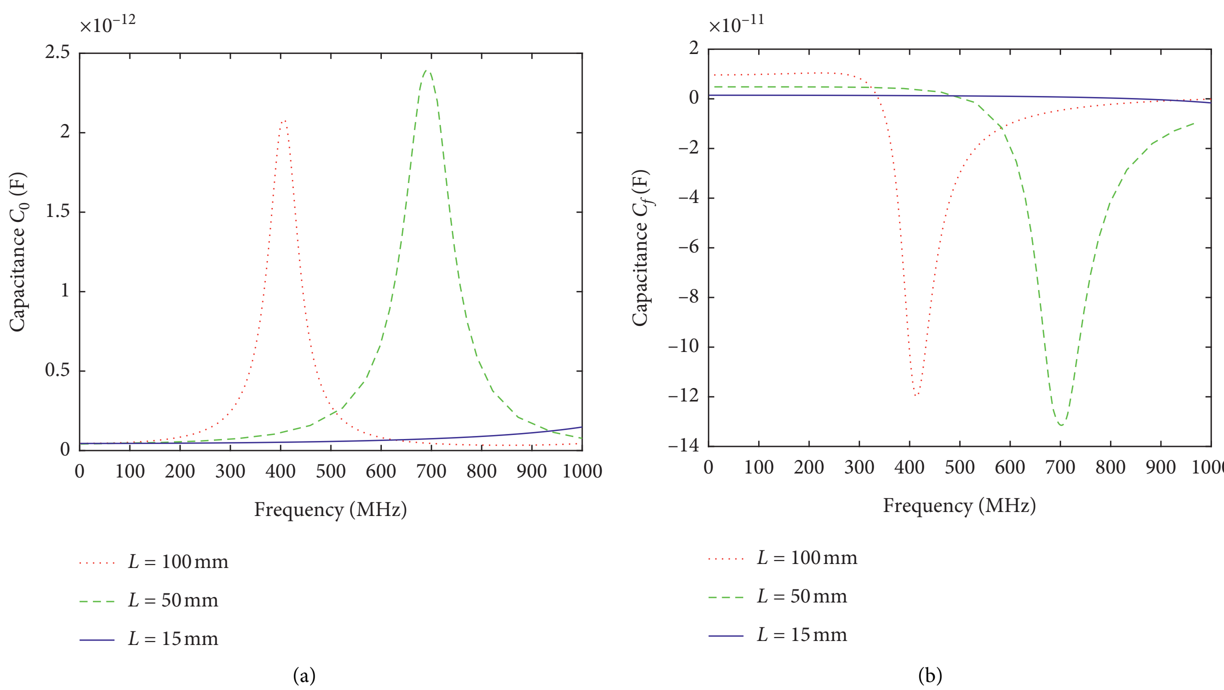


Figure 9: Calculated values of (a) C_0 and (b) C_f with varying cable length.

effective choice of cable radius was found to be 2.5 mm in this case. The length of the probe is related to the equivalent length of the coaxial cavity in the equivalent circuit model and is also related to frequency. A shorter probe has a longer period, which can lead to more stable results over a restricted frequency range. The optimal value of the cable length in this work was found to be 15 mm.

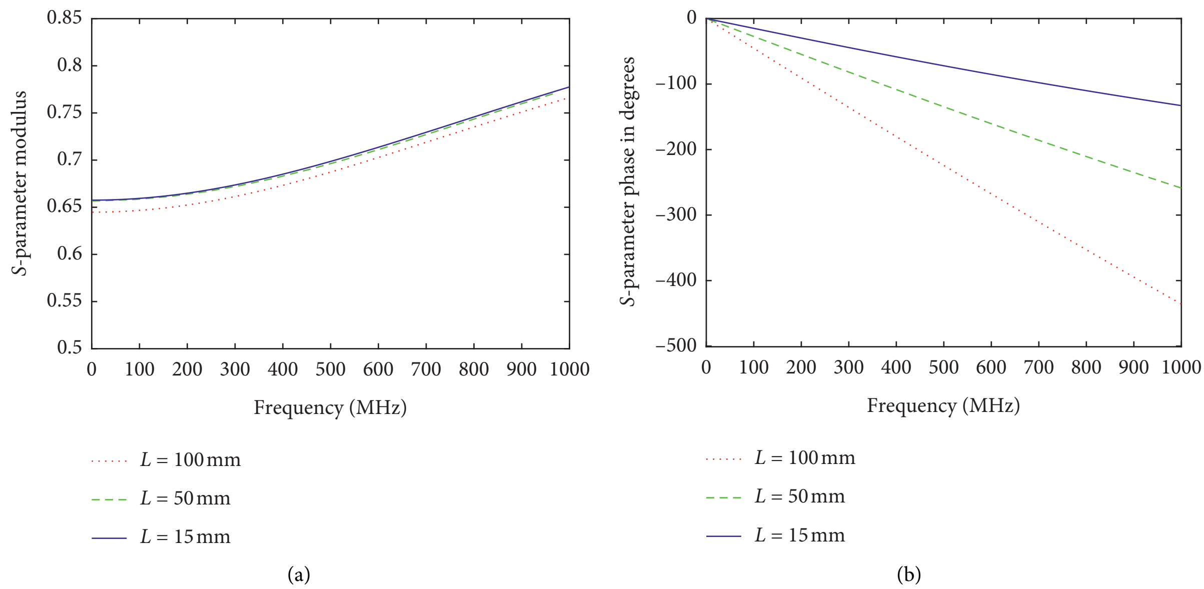


FIGURE 10: (a) Modulus and (b) phase of the reflection coefficient for the liquid under test with varying cable length.

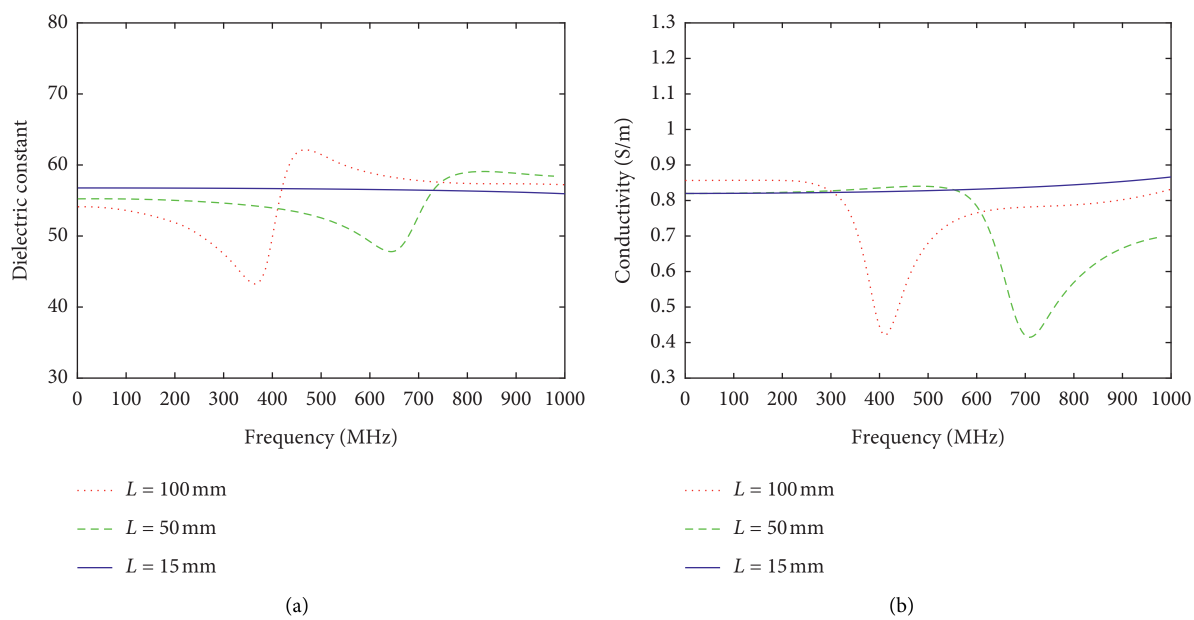


FIGURE 11: (a) Dielectric constant ε_r and (b) conductivity σ of object under test with varying cable length.

4. Conclusion

This paper investigates the influence of the dimensions of a coaxial cable on the accuracy of measured liquid dielectric properties from two aspects: radius and length. It was found that the accuracy of the cable has a strong dependence on the radius, with very small radii offering no accuracy. It was also found that decreasing cable length improved accuracy. The measured results can be close to the actual value over a restricted frequency range after the dimensions of cables are appropriately selected. It can be seen that, for the coaxial cable, selection of cable size and measurement frequency range are important factors when measuring the dielectric properties of a liquid using the return loss method.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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