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RESEARCH ARTICLE

Dielectric Characterization Using Reflected Group Delay of a Partially-Filled Coaxial Resonator

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ABSTRACT This paper features an effective and novel method to characterize dielectric materials using the reflected group delay of an over-coupled partially-filled coaxial resonator. The method employs a simple and cost-effective approach by utilizing one-port measurements from a Vector Network Analyzer to determine the dielectric constant and loss tangent of a dielectric material filled inside a coaxial resonator. Simulations using Advanced Design System by PathWave and ANSYS Electronics Desktop are done to test the mathematical model under different scenarios. Based on the results obtained from simulations, the proposed method can determine the dielectric constant and loss tangent with an error of less than 2% and 30% respectively, when operated to have a coupling coefficient in the range of 2.5 to 10. A region of confidence is derived by taking into account the effect of systematic errors to determine the maximum expected error in the calculated values of dielectric constant and loss tangent. The region of confidence describes that the resonator when filled to more than 50% of its capacity to have coupling coefficient greater than 2.5 can determine the dielectric constant and loss tangent of a material with an error of less than 5% and 80% respectively. However, by limiting the value of coupling coefficient the error in the loss tangent can be restricted under 30%. A coaxial resonator is designed and fabricated, and Teflon is tested in order to validate the proposed method. A hollow Teflon rod is tested twice for different values of coupling capacitance to confirm the repeatability of the method. Soil samples with different moisture contents are tested to confirm the capacity of the method in testing different types of materials. Each of the soil sample is tested three times and standard deviation in the calculated values of the dielectric properties re-confirmed the repeatability of the method. The proposed method is considered appropriate to test the dielectric properties of solid materials which can be machined to fit inside the hollow cavity of the resonator and other materials like soils, fine particle solids, grains and liquids.

INDEX TERMS Coaxial resonator, dielectric materials, dielectric measurements, microwave filters, one-port measurement, reflected group delay, soil measurement.

I. INTRODUCTION

The knowledge of dielectric constant and loss tangent of a material has evolved as a solution to a variety of industries that include microwave engineering, telecommunications, biomedical, food, agriculture, environment and aerospace [1], [2], [3], [4], [5], [6], [7], [8], [9], [10]. The emerging need of dielectric characterization has led to the development of several methods over a period of time and their performance is regulated mainly by factors such as frequency range, level of accuracy, physical form of the material under test, size of sample, destructive and non-destructive, and cost [11].

In [4], [6], [11], [12], [13], and [14] methods employing coaxial probes have been presented and are a good choice for a variety of materials including biological tissues but lack accuracy in testing the non-homogeneous solids and low loss materials. The free space methods in [3], [5], [11], and [15] have the ability to work under hostile environments

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and are good for materials with medium to high dielectric loss but are bulky. The parallel plate methods in [3], [11], [16], and [17] offer high accuracy, however, they are fit to test thin and flat materials. The resonant cavity methods in [3], [11], [18], [19], [20], [21], and [22] can do accurate measurements either for the dielectric constant or for the loss tangent based on the choice of the resonance technique. These methods make use of nearly critically-coupled resonator for the dielectric characterization and makes them limited to measurements at a single frequency or a limited bandwidth. Resonant cavity methods like split cylinder resonator method can do accurate measurements for the dielectric properties for low loss materials. However, they are considered fit to test only thin sheets of the sample having low dielectric loss [23], [24]. [25] uses an under-coupled coaxial resonator to perform dielectric characterization using curve fitting on a reflection response. The material under test is injected in a container placed inside the resonator and parametric extraction is done using the reflection response at one of the longitudinal modes. The methods described in [26], [27], and [28] make use of graphical analysis on the response obtained from a resonator coupled anywhere between the under-coupled to over-coupled state but they lack precision when solved manually using a graph. The review of these techniques opens up a wide area of research to develop a method of dielectric characterization which is fast, accurate, simple to use, cost effective, non-destructive and can test a wide range of materials.

This paper presents a method to determine the dielectric constant and loss tangent of an unknown material using the reflected group delay of an over-coupled partially-filled coaxial resonator. Reflected group delay has been used as an effective tool in developing new methods and improving the existing methods of filter design and tuning [29], [30], [31], [32], [33], [34], [35], [36]. The research presented in [30] and [31] explains the use of reflected group delay in designing high-order superconducting filters. So far, the methods of filter design and tuning employing the reflected group delay either does not include the effect of loss or are based on high quality factor (Q-factor) where loss can be neglected. In actual practice, losses are an integral part of a filter or a resonator and the research presented in this paper is significant in understanding the nature of the reflected group delay in a lossy resonator. It is found that for a given gap capacitance if the loss in the resonator goes above a certain limit it becomes under-coupled. The research in this paper also advances the understanding of reflected group delay of lossy resonators for the purposes of designing low-Q, high-loss filters, as the reflected group delay method of designing filters has been limited to high-Q resonators only.

A set of one-port measurements using a Vector Network Analyzer (VNA) connected to a coaxial resonator are done and applied in the mathematical model to extract the dielectric properties of the material partially filling the resonator cavity. The work presented in this paper is an improved version of the method in [37]. For the method proposed in this paper, the resonator is kept partially-filled with the dielectric material unlike the method in [37] where the resonator is considered completely filled. A comparative analysis is done to validate the improvement in the method proposed in this paper. In addition to that, the proposed method is also used to determine the dielectric constant and loss tangent of different soil samples to present the application in the field of environmental engineering. The proposed method has the following merits:

- The method makes use of only one-port measurements using a VNA and makes the system cost effective as – compared to the two port set ups [38], [39].

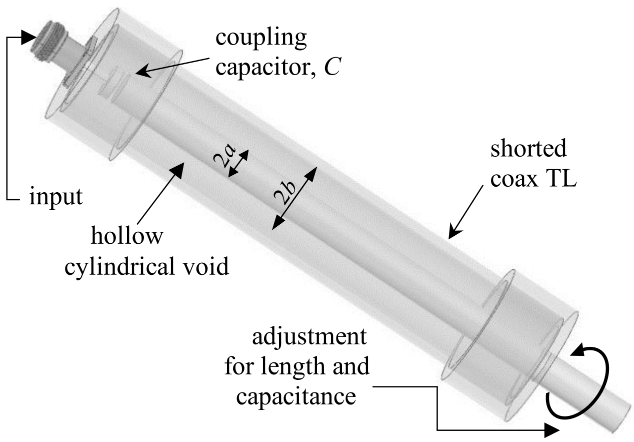


FIGURE 1. A rendering of the resonator to show the input coupling capacitor and other important details.

- As compared to the methods employing coaxial probes and free space techniques, this method provides a suitable solution in determining loss tangent of low loss materials.
- As compared to some of the resonant cavity methods, this method is able to determine both the dielectric constant and loss tangent in a single test.
- The method allows to operate over a wider range of frequency as compared to resonant cavity methods which makes use of critically coupled resonators and restrict the use of the method to only one frequency.
- In comparison to parametric extraction of dielectric properties through circuit modeling and curve fitting the proposed method is faster and simple to apply [3].
- The method is suitable for repeatable measurements as demonstrated through the testing of Teflon and sandy soils presented in this paper.
- The design of the resonator is ideal for measuring the dielectric properties of a wide range of materials which can be filled inside the hollow cylindrical void of the coaxial transmission line and can include soils, fine particle solids, grains, and liquids.

The initial research using the reflected group delay of a completely-filled coaxial resonator is presented in Section II of this paper. This section also describes the limitations and scope of improvement in the method using the completely filled resonator. Section III explains the mathematical model based on the reflected group delay of a partially-filled lossy resonator. Section IV illustrates the region of confidence derived using circuit simulations in Advanced Design System (ADS) and EM simulations in ANSYS Electronics Desktop. The validation of the proposed method by performing the dielectric characterization of a hollow Teflon cylinder is explained in Section V. Section VI has a detailed discussion on the results obtained from the testing of sandy soils with different moisture contents using the proposed method, and conclusion is presented in Section VII.

II. COMPLETELY FILLED COAXIAL RESONATOR

A mathematical model using the reflected group delay of an over-coupled coaxial transmission line (TL) to determine the dielectric constant and the loss tangent has been presented in [37]. The coaxial resonator shown in Figure 1 has been fabricated using an aluminum alloy with the inner radius, $a = 6.35$ mm and the outer radius, $b = 16.0875$ mm. The top lid on the resonator has a small piece of inner conductor inside it which is soldered to the pin of an N-type connector [40]. The piece of inner-conductor inside the top lid acts as a plate for the input coupling capacitor. The bottom lid has a threaded through hole for adjusting the length of the inner conductor and is used for controlling the coupling capacitance. There is a locking nut on the inner conductor outside the resonator to ensure a good electrical contact between the inner and the outer conductor. The error in the determined values of dielectric constant and loss tangent of Teflon in [37] as compared to the reported values in [41] are considered to have come from two main reasons as listed below:

- There is a clearance of about 1mm present between the top surfaces of the inner conductor and the Teflon hollow cylinder to prevent the fringing fields enter in the dielectric material inside the resonator. However, the mathematical model considers that the resonator is filled completely with the material.
- The procedure of dielectric characterization makes use of two one-port measurements. First, the resonator is kept air-filled and the measurement is done to extract the coupling capacitance and metal conductivity. Second, the resonator is filled with the dielectric material without changing the gap between the plates of the capacitor and measurement is done to extract the dielectric constant and loss tangent. It is considered in the mathematical model that the coupling capacitance is same when the resonator is air- filled and when it is filled with the dielectric material. However, the fringing fields are likely to go beyond the clearance of approximately 1mm in [37] and penetrate into the dielectric. This can result in a difference in the coupling capacitance and result in error while determining the dielectric properties using the method in [37].

In order to limit the error due to the above-mentioned reasons a new model is derived using the reflected group delay of a partially-filled over-coupled lossy coaxial resonator. This method also allows the dielectric characterization under the following conditions:

- the sample available is not sufficient to fill the resonator completely, and/or
- the dielectric material is very lossy, for example, sandy soils with higher moisture contents.

When a resonator is filled with a lossy dielectric material the requirement of coupling capacitance to keep the resonator in an over-coupled state goes up and due to the limitations of the design, it is not possible in some cases to meet the demand of that high capacitance. In such a case, reducing the amount of dielectric inside the resonator is helpful to a very large extent to achieve an over-coupled state. Therefore, the proposed method allows the dielectric characterization of the lossy dielectrics in case the resonator is not able to produce enough capacitance.

III. MATHEMATICAL MODEL OF A PARTIALLY FILLED OVER-COUPLED LOSSY COAXIAL RESONATOR

The coaxial resonator filled partially with the dielectric material can be modeled as a combination of two ideal coaxial transmission lines. One of the transmission lines is considered filled with the dielectric material, while the other is considered air-filled. The resonator is coupled to the input by means of a capacitor as shown in Figure 2.

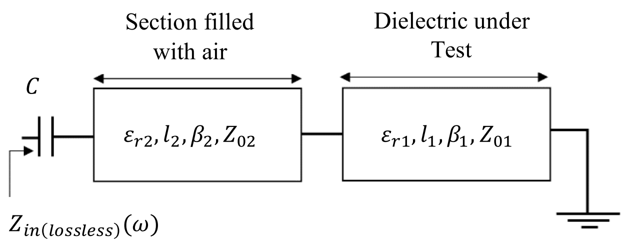


FIGURE 2. Diagram explaining the basic circuit for the lossless partially-filled coaxial resonator.

The air-filled section is characterized by length (l_2) , phase constant (β_2), characteristic impedance (Z_{02}) and dielectric constant (ε_{r2}). Similarly, the portion of the resonator filled with dielectric sample is characterized by length (l_1), phase constant (β_1), characteristic impedance (Z_{01}), and dielectric constant (ε_{r1}). Assuming $\varepsilon_{r1} = \varepsilon_r \ and \ \varepsilon_{r2} = 1$, the impedance at the input of the lossless coaxial resonator can be derived as follows:

$$Z_{in(lossless)}(\omega) = j\left[\frac{-1}{\omega C} + Z_{02}\left(\frac{tan\beta_1 l_1 + \sqrt{\varepsilon}_r tan\beta_2 l_2}{\sqrt{\varepsilon}_r - tan\beta_1 l_1 tan\beta_2 l_2}\right)\right], \tag{1}$$

where ω, is the angular frequency and C is the coupling capacitance.

The Taylor series approximation in (2) can be used to reduce the input impedance of the lossless coaxial resonator to a simpler form in (3) as follows:

$$Z_{in(lossless)}(\omega) = Z_{in(lossless)}(\omega_0) + (\omega-\omega_0)\frac{d}{d\omega}Z_{in(lossless)}(\omega)\Big|_{\omega=\omega_0}, \quad (2)$$

$$Z_{in(lossless)}(\omega) = jP(\omega-\omega_0), \quad (3)$$

where ω_0, is the centre angular frequency. The factor P, in (3) can be expressed as follows:

$$P = \left[\frac{1}{\omega_0^2 C} + Z_{02}\left\{\frac{l_1(1+x^2)+l_2(1+x^2+y^2+z^2) + \varepsilon_r l_1(y^2+z^2)}{c(z-1)^2}\right\}\right], \quad (4)$$

where c, is the speed of light in free space, $x = \tan\beta_2 l_2$, $y = \tan\beta_1 l_1/\sqrt{\varepsilon_r}$ and $z = xy$.

To account for the conductive and the dielectric losses in the resonator, replace $\omega_0 \longrightarrow \omega_0(1+j/2Q_u)$ in (3). Q_u is the unloaded quality factor of the resonator and it can be determined as explained later in (11-13). After applying the transformation, the input impedance is given as follows:

$$Z_{in_{lossy}}(\omega) = j(P(\omega-\omega_0)) + R, \quad (5)$$

where the loss in the resonator R, is represented by:

$$R = \frac{P\omega_0}{2Q_u}. \quad (6)$$

The reflection coefficient of the resonator can be expressed using (7) as follows:

$$S_{11} = \frac{Z_{in}-Z_0}{Z_{in}+Z_0} = \frac{j(P(\omega-\omega_0))+R-Z_0}{j(P(\omega-\omega_0))+R+Z_0}, \quad (7)$$

where Z_0 is the port impedance and is normally 50Ω.

The reflected group delay at the centre frequency $\Gamma_d(\omega_0)$, can be derived from the phase of the reflection coefficient, φ, as follows:

$$\Gamma_d(\omega) = -\frac{\partial\varphi}{\partial\omega}, \quad (8)$$

$$\Gamma_d(\omega_0) = \frac{2PZ_0}{Z_0^2 - R^2}. \quad (9)$$

The polynomial in P can be derived using (6) and (9) as shown in (10).

$$P^2\left(\frac{\omega_0}{2Q_u}\right)^2\Gamma_d(\omega_0) - 2PZ_0 + \Gamma_d(\omega_0)Z_0{}^2 = 0 \quad (10)$$

Coupling coefficient k for the over-coupled resonator can be determined as following [29], [42]:

$$k = \frac{1+|S_{11}|}{1-|S_{11}|}. \quad (11)$$

The loaded quality factor, Q_L, of the resonator can be expressed as [29]:

$$Q_L = \frac{2|S_{11}|}{1+|S_{11}|}\frac{\omega_0\Gamma_d(\omega_0)}{4}. \quad (12)$$

The unloaded quality factor, Q_u, can then be determined using the loaded quality factor, Q_L, and the coupling coefficient k in (11) as follows [27], [29], [42]:

$$Q_u = (1+k)Q_L = \left(\frac{1}{Q_c}+\frac{1}{Q_d}\right)^{-1}, \quad (13)$$

where Q_c and Q_d are the quality factors due to the conductive losses and dielectric losses, respectively.

The procedure of dielectric characterization is carried out with two different one-port measurements using the VNA connected to the coaxial resonator as follows:

- The capacitive gap is set to a level that the resonator becomes over-coupled.
- The first measurement is carried out using the air-filled (empty) resonator to record $|S_{11}|$ and Γ_d at the centre frequency ω_0. Then the unloaded quality factor Q_u for the empty resonator is calculated using (11)-(13). The polynomial in (10) is used to solve for P. In case the resonator is empty or air-filled, ε_r can be assumed to be 1, and (4) can be used to solve for the coupling capacitance, C.
- For the air-filled resonator, $Q_c = Q_u$, as $\tan\delta = Q_d^{-1} = 0$. The conductivity of the resonator conductor can be found as follows [27], [42]:

$$\sigma_C = Q_c^2\left(\frac{1}{a}+\frac{1}{b}\right)^2\frac{1}{4\pi f_0\mu}\frac{1}{\left(\ln^b/_a\right)^2}, \quad (14)$$

where μ is the permeability of the conductor and a and b are the outer radius of the inner conductor and the inner radius of the outer conductor, respectively.
- The second measurement is done using the resonator filled with the dielectric material to record $|S_{11}|$ and Γ_d at the centre frequency ω_0. Then, the unloaded quality factor, Q_u, for the partially filled resonator is calculated using (11)-(13) and the polynomial in (10) is used to solve for P. Using the derived value of C, (4) is used to solve for ε_r of the dielectric.
- Using the value of σ_C calculated using the measurement from the air-filled resonator, (14) can be solved for Q_u and substituted into (13) to determine the dielectric loss tangent using (15) as follows:

$$\tan\delta_{(measured)} = Q_d^{-1} = Q_u^{-1} - Q_c^{-1} \quad (15\text{-a})$$

$$\tan\delta_{(actual)} = \frac{l_1+l_2}{l_1}\tan\delta_{(measured)}, \quad (15\text{-b})$$

where loss tangent, $\tan\delta_{(measured)}$ in (15-a) describes the dielectric loss taking into account the total length of the resonator. However, (15-b) addresses the effect of partially filled resonator during measurements in finding the actual value of loss tangent, $\tan\delta_{(actual)}$.

A. CENTRE FREQUENCY

Centre frequency, f_0, in the proposed method is chosen as the frequency at which the imaginary part of the input impedance of the resonator becomes zero. However, in [37] the centre frequency has been the frequency at which the $|S_{11}|$ is minimum. The following are the reasons to pick the new centre frequency for this method:

- The center frequency in (12) is the center frequency of the loaded resonator and is the frequency at which the $|S_{11}|$ is minimum [27], [29]. However, in (12) even if the center frequency is chosen as the frequency at which the imaginary part of input impedance becomes zero, the change in the value of the quality factor has a negligible effect on the solution of P in (10). Hence, the choice of the frequency does not affect the calculated value of the dielectric constant.
- The expression for conductivity in (14) suggests that for a particular value of σ_C, the factor Q_c^2/f_0 has to be a constant. Simulations using the circuit shown in Figure 3 are carried out. For example, in order to attain $\sigma_C = 1.27 \times 10^7\text{S/m}$ for the values of inner radius and outer radius specified in the circuit the value Q_c^2/f_0 should be $2.6 \times 10^{-3}\text{Hz}^{-1}$. It is found in the simulations that for different values of capacitor in the circuit, the value of constant $Q_c^2/f_0 = 2.6\times10^{-3}\text{Hz}^{-1}$, is realized only at the frequency where the imaginary part of input impedance becomes zero.

In order to, reduce the error in the calculated value of conductivity the choice of new centre frequency is favorable. In addition to this, the use of the new centre frequency adds simplicity to the mathematical model without compromising with the accuracy. Hence, the new centre frequency is considered as an acceptable approximation for the proposed method.

IV. REGION OF CONFIDENCE FOR THE PROPOSED METHOD

Simulations are carried out using ADS and ANSYS Electronics Desktop to understand the behavior of the resonator under different scenarios and to determine the usable limits of the resonator before doing the actual measurements. The simulations are described in a set of three different scenarios and based on the results obtained from simulations, a region of confidence (ROC) is derived.

Scenario 1 (ROC): The circuit shown in Figure 3 is used to represent an air-filled resonator having a metal conductivity of $1.27 \times 10^7\text{S/m}$. The fabricated resonator is made up of an aluminum alloy having a conductivity anticipated to be lower than the bulk conductivity of aluminum. Also, the actual testing of Teflon and soil presented in the upcoming sections of this paper reveals that the extracted value of metal conductivity is close to $1.27\times10^7\text{S/m}$ and hence is chosen for the circuit simulations in deriving region of confidence. The resonator is capacitively coupled to the input and simulations are done by varying the value of capacitance C, in the circuit between 0.5pF to 7.5pF. The results presented in Figure 4, shows that the proposed method is very effective in extracting the coupling capacitance and the conductivity.

Scenario 2 (ROC): The circuit shown in Figure 5 is used to represent a capacitively coupled partially-filled coaxial resonator. The objective is to determine the accuracy in finding the dielectric constant and loss tangent under different conditions: by varying the percentage filled between 8% to 100%, with the change in coupling coefficient and testing materials with different dielectric constant and loss tangent. The effect of these conditions on the accuracy in characterizing the dielectric properties is presented in a one-by-one manner and is helpful in making a better understanding of region of confidence derived later. Circuit simulations are done with the dielectric constant as 2.1, 4.6 and 7.1, the coupling capacitance varying between 0.5pF to 7.5pF and the loss tangent values as 0.001, 0.005 and 0.01. The amount of dielectric filled inside the resonator is varied between 8% to 100% and is termed as percentage filled in this work. Percentage filled indicates the height of the cylindrical void around the inner conductor inside the resonator to which the dielectric material is filled as a percentage of the total height of the cylindrical void.

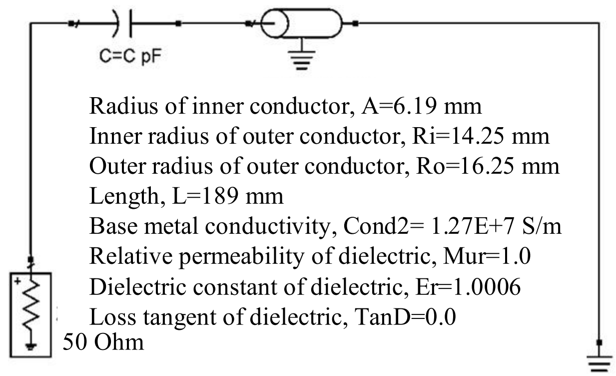


FIGURE 3. Circuit in ADS used to simulate scenario 1 (ROC).

The results obtained by varying percentage filled with $\varepsilon_r = 2.1$ and different values of coupling capacitance in the circuit are shown in Figure 6 and Figure 7. It can be inferred, that the error in determining the dielectric constant and loss tangent increases significantly as soon the percentage filled falls below 40%. Similar trends are found in simulations using dielectric constant of 4.6 and 7.1 in the circuit. Hence, percentage filled is considered as an important factor in characterizing the dielectric materials using the proposed method.

The results presented in Figure 7 shows that the error in loss tangent can be brought down to the range of 10-20% if the percentage filled is kept between 80-90% and the value of coupling capacitance is less than 1.75 pF. However, with the materials having higher dielectric constant and loss tangent this value of percentage filled and coupling capacitance might not work as this may result in under-coupled resonator. In that case, the percentage filled and the coupling capacitance can be varied so that the coupling coefficient lies in a specific range as described ahead.

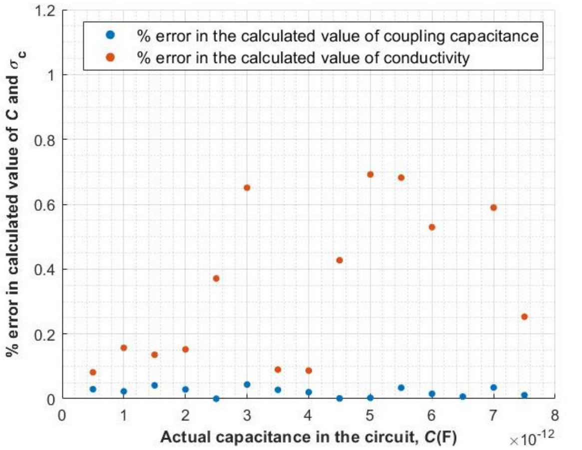


FIGURE 4. Error in the determined value of the capacitance and the conductivity vs actual value of capacitance C in the circuit for Scenario 1 (ROC).

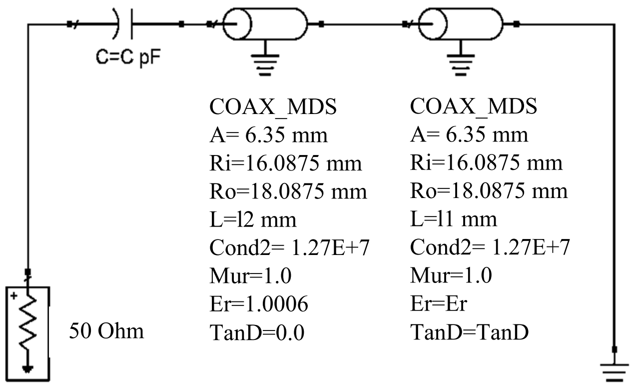


FIGURE 5. Circuit in ADS used to simulate Scenario 2 (ROC).

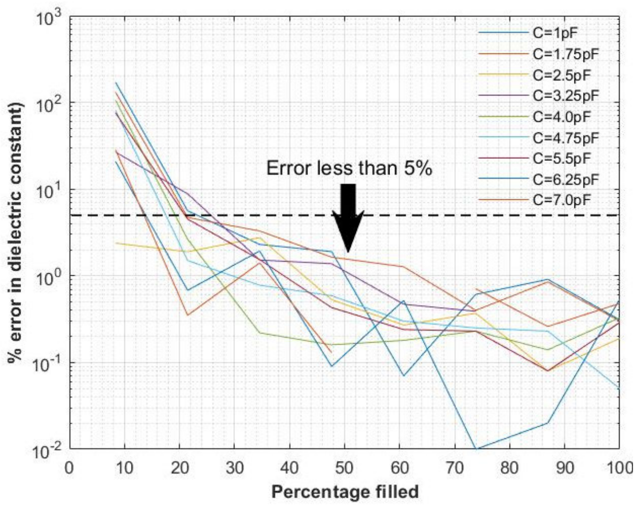


FIGURE 6. Error in dielectric constant vs percentage filled for $\varepsilon_r = 2.1$ and $\tan\delta = 0.001$ in the circuit.

The extraction of dielectric properties is also found affected by the strength of coupling, which is governed mainly by two factors in the resonator: the coupling capacitance and the percentage filled. The strength of coupling in the resonator can be characterized by means of coupling coefficient, k, and for an over-coupled resonator, k should always be greater than 1.

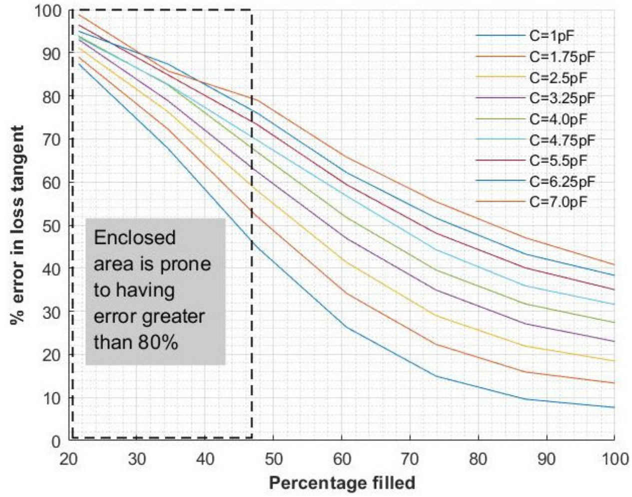


FIGURE 7. Error in loss tangent vs percentage filled for $\varepsilon_r = 2.1$ and $\tan\delta = 0.001$ in the circuit.

The simulation results obtained for percentage filled above 40% are used to obtain the plots in Figure 8 and Figure 9. It can be seen that the error in dielectric constant becomes significant as soon the coupling coefficient tends to go below 2.5. The error in the loss tangent shown in Figure 9, is found tolerant to the value of coupling coefficient, however, is found affected more by the dielectric constant of the material under test. A value of coupling coefficient in between 2.5-10 is preferrable to keep the error in loss tangent under 30%. This can be achieved by varying the percentage filled in between 50-90% and/or varying the coupling capacitance.

In order to include the effect of systematic errors in the simulations, an exercise is carried out by assuming an error of 1% in the calculated value of coupling capacitance and 10% in the calculated value of conductivity. Using the erroneous capacitance and conductivity in the mathematical model, the values of dielectric constant and loss tangent are extracted and the results are shown in Figure 10 and Figure 11. The results are shown for loss tangent of 0.01 in the circuit, however, simulations for loss tangent of 0.001 and 0.005 in the circuit are also performed, and similar trends have been found.

Scenario 3 (ROC): The simulations in this scenario are done to understand the behavior of the resonator when it is filled close to the maximum height of the cylindrical void inside the resonator. To carry out the simulations, a gap coupled coaxial resonator is designed using ANSYS Electronics Desktop as shown in Figure 12. The resonator in the design is specified by its inner radius of 6.35 mm, outer radius of 16.0875mm and conductivity of the metal as 1.27×10^7S/m. The length of the- inner conductor is kept at 192.2mm such that the capacitive gap can set the resonator to an over-coupled state.

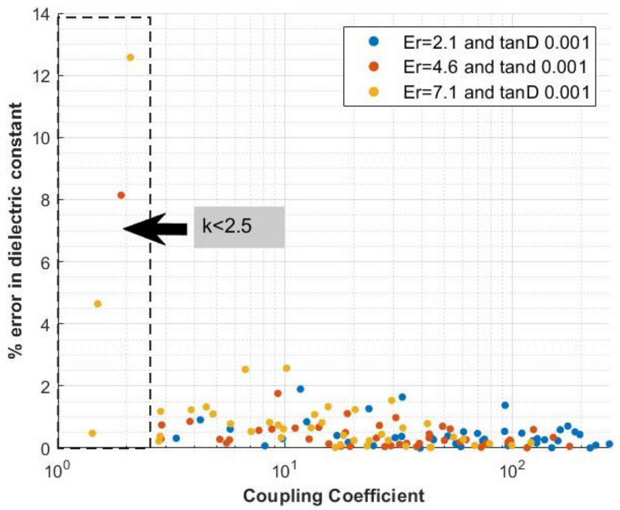


FIGURE 8. Error in dielectric constant vs coupling coefficient.

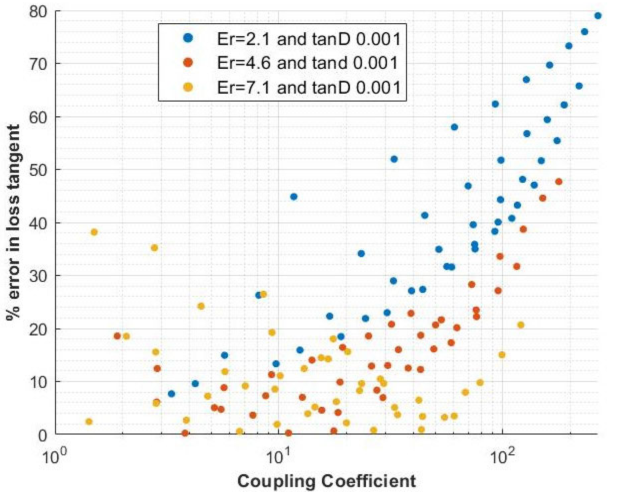


FIGURE 9. Error in loss tangent vs coupling coefficient.

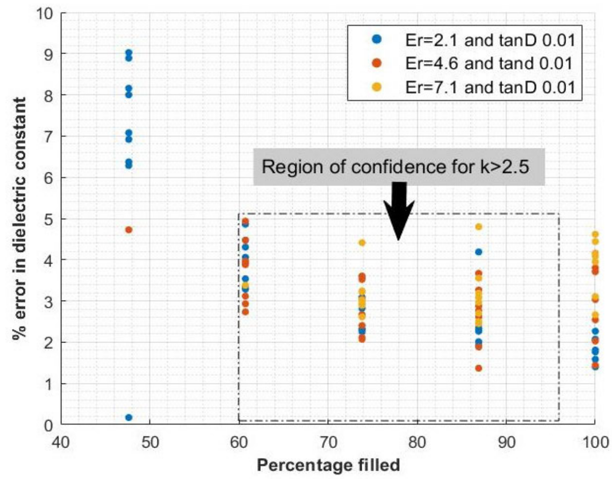


FIGURE 10. Error in dielectric constant vs percentage filled having coupling coefficient, $k > 2.5$ and an estimated systematic error in coupling capacitance and metal conductivity.

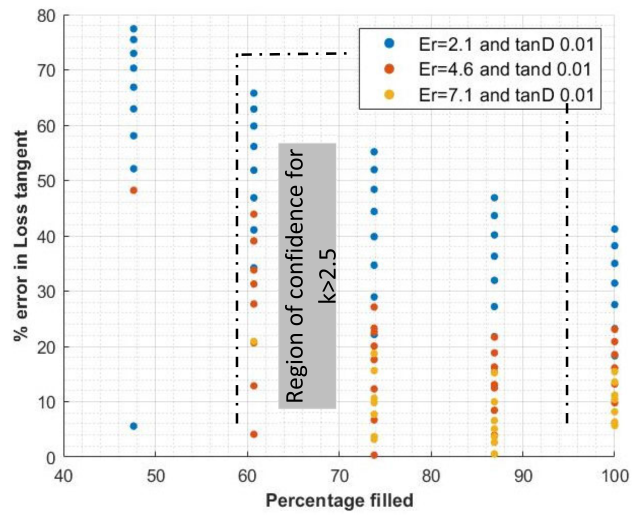


FIGURE 11. Error in loss tangent vs percentage filled having coupling coefficient, $k > 2.5$ and an estimated systematic error in coupling capacitance and metal conductivity.

First, the resonator is simulated as air-filled. The coupling capacitance ($C = 1.7$pF) is calculated using the $|S_{11}|$ and Γ_d at the center frequency. After that the resonator in Figure 12 is filled with dielectric of $\varepsilon_r = 2.1$ and $\tan\delta = 0.001$. The dielectric constant is calculated by varying the height of the dielectric between 191.2mm to 189.4mm. The difference in the total length of the inner conductor and the height of the dielectric sample is named as clearance. The results shown in Figure 13, indicate that the error in the extracted value of the dielectric constant decreases as the clearance increases. This shows that the resonator is prone to high error in case it is filled completely.

A circuit shown in Figure 5 is used to derive the coupling capacitance from the EM response using the parametric extraction. The results indicate that the value of capacitance changes and become more stable as the clearance increases. The clearance required in dielectric characterization could be different with different coupling capacitance and dielectric material, however, a clearance of 10mm should be sufficient to avoid the effect of fringing fields completely.

In order to restrict the error in dielectric constant under 5% and error in loss tangent under 80%, a region of confidence is derived as highlighted in Figure 10 and Figure 11 and dictates the following guidelines to perform dielectric characterization using the proposed method:

- The percentage filled should be more than 50%.
- The resonator should not be filled completely and there should be a clearance of about 10 mm.
- The value of coupling coefficient, k, should be greater than 2.5.

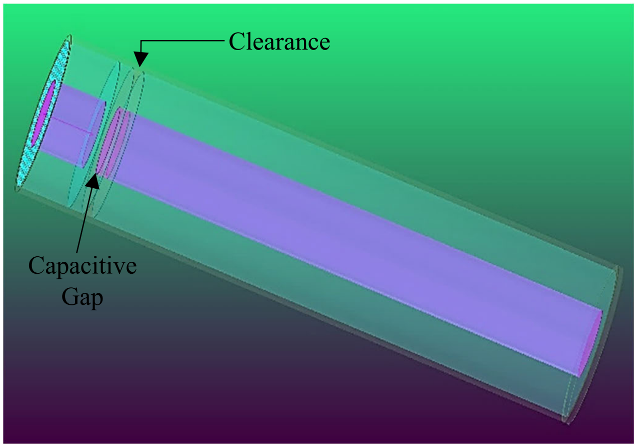


FIGURE 12. Resonator designed using ANSYS Electronic Desktop.

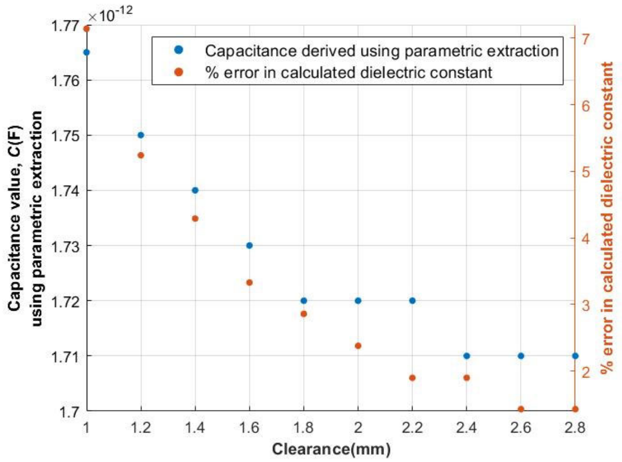


FIGURE 13. Effect of clearance on the error in the calculated value of dielectric constant and derived value of capacitance.

To an extent, the higher error in calculating the dielectric properties when the percentage filled of the resonator is less than 50% can be accounted to the Taylor series approximation used to represent input impedance of the resonator in the mathematical model. The higher order terms in the Taylor series approximation are neglected in this method, however they become significant as the percentage filled of the resonator is reduced.

The error in the extracted values of the dielectric properties at values of coupling coefficient, k, less than 2.5 can be related to the narrowband response of the resonator under the given conditions. This error can be accommodated by improving the resolution in the simulations. However, in general it is better to avoid running the resonator closer to the critically coupled region ($1 \leq k < 2.5$).

The error in the dielectric constant using a completely filled resonator is due to the change in capacitance. This change occurs because the fringing fields penetrate into the dielectric material and results in an error in the extracted value of dielectric constant.

It is important to note that the region of confidence describes the conditions to use the proposed method for determining loss tangent with an error of less than 80%. However, by varying the percentage filled in between 50-90% and/or the coupling capacitance to have a coupling coefficient in between 2.5-10, this error can be reduced to less than 30%.

V. VALIDATION OF THE PROPOSED METHOD BY THE TESTING OF HOLLOW TEFLON CYLINDER

In order to validate the proposed method, dielectric characterization of the hollow Teflon cylinder is carried out and described using the scenarios as follows:

1) Scenario 1 (validation): Hollow Teflon cylinder of three different lengths is tested.
2) Scenario 2 (validation): Hollow Teflon cylinder is tested with different gap capacitances in the resonator.

De-embedding of the lid: First of all, a full one-port calibration is performed on the VNA using the short, open and 50 Ω load standards. The VNA used in the measurements is the R60 1-Port 6 GHz Analyzer by Copper Mountain Technologies.

Then in order to remove the effect of the lid in the measurements, the reference plane is moved past the lid using the port-extension feature [43]. This can be achieved by matching the response of the VNA with lid as shown in Figure 14 (a) to the response of the VNA after calibration for the frequency range of 100500MHz. Port extension of approximately 113 ps is used to de-embed the lid. The amount of delay produced by the lid is not significant at higher values of the group delay. However, for smaller values of group delay the de-embedding is important to reduce the error in measurements.

Coupling Capacitance and Metal Conductivity in Scenario 1 (validation): 1-port VNA measurements are done using the air-filled coaxial resonator with the length of the inner conductor set to 188.6mm to obtain an over-coupled response. The values of $|S_{11}|$ and Γ_d are recorded at the centre frequency f_0 as shown in Figure 15. The recorded values are applied in the mathematical model according to the procedure described in Section III to determine the coupling capacitance and the conductivity of the resonator.

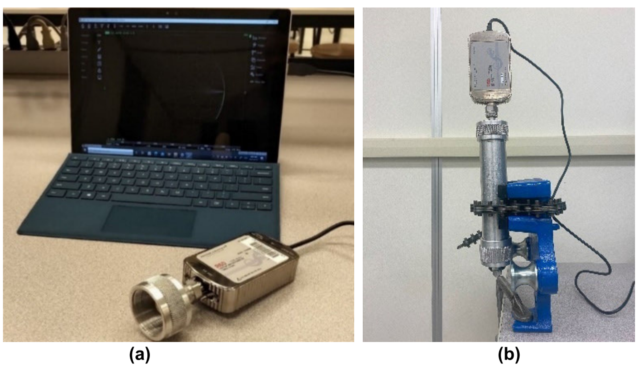
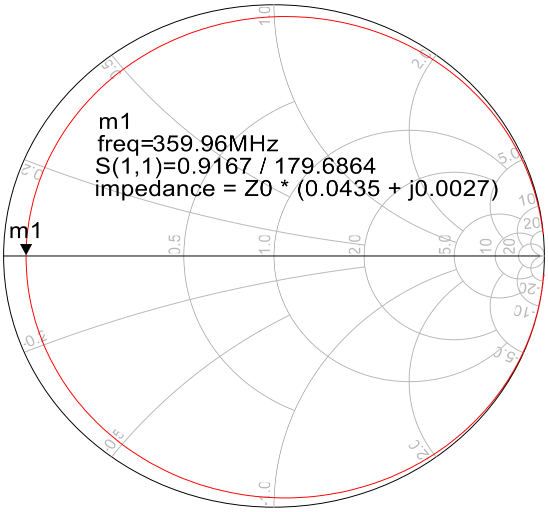
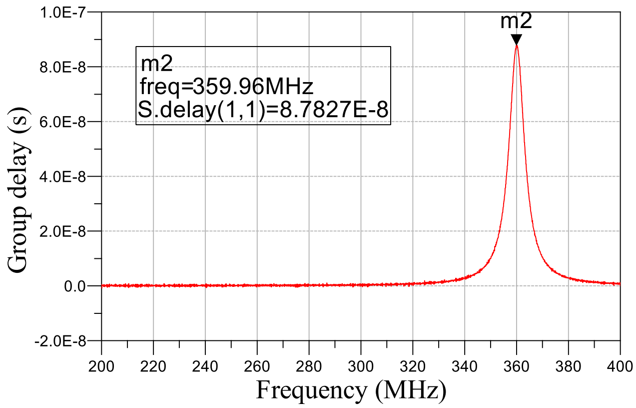


FIGURE 14. (a) VNA connected to the lid of the resonator. (b) VNA connected to the resonator for measurements.



(a)



(b)

FIGURE 15. **1-port response of the air-filled coaxial resonator in Scenario 1 (validation) (a) S_{11} circles on smith chart with marker on the center frequency (b) Group delay (s) vs Frequency.**

Table 1 summarizes the calculated results obtained from the measurements done using the air-filled resonator after the calibration and de-embedding of the lid. The conductivity in Table 1 represents the effective conductivity and takes into account the effects of metal losses, losses at connections and non-ideal short circuit.

Dielectric constant and loss tangent in Scenario 1 (validation): Three different lengths of the hollow Teflon cylinder as shown in Figure 16, are used for the testing. One- port VNA measurements are done by placing the hollow teflon cylinder of different lengths inside the resonator one at a time. The length of the inner conductor is kept unchanged to maintain the same coupling capacitance C. The values of $|S_{11}|$ and Γ_d are recorded at the centre frequency f_0 and applied according to the procedure explained in Section III to determine the dielectric constant and the loss tangent of the Teflon.

In order to ease the assembly, there is a small clearance around the inner conductor in Teflon hollow cylinder that adds about 5% of air in the dielectric sample. The effect of the air is taken into account using the equation as follows:

$$\varepsilon_{r(measured)} = 0.95\varepsilon_{r(actual)} + 0.05\varepsilon_{r(air)}. \tag{16}$$

TABLE 1. **Calculated results with the air-filled resonator for Scenario 1 (Validation).**

ε_r	tanδ	k	Q_u	C (pF)	$\sigma_{c(eff)}$ (S/m)
1.0	0.0	23.01	1140.5	**1.058**	$\mathbf{1.28 \times 10^7}$

TABLE 2. **Summary of measured and calculated results for the resonator filled with teflon hollow cylinder for Scenario 1(Validation).**

	Teflon I	**Teflon II**	**Teflon III**
f_0 **(MHz)**	359.52	354.36	290.72
$\|S_{11}(\omega_0)\|$	0.915	0.908	0.793
k	22.47	20.90	8.65
$\Gamma_d(\omega_0)(ns)$	90.42	95.34	228.73
Q_u	1145.3	1106.9	891.2
$\varepsilon_{r(actual)}$	**4.80**	**2.01**	**2.01**
% error (ε_r)	137.62	0.50	0.50
$\tan\delta_{(actual)} \times 10^{-4}$	**n/a**	**0.70**	**1.82**
% error ($tan\delta$)	n/a	65.5	9.0

Table 2 presents a comparative analysis with the results obtained using the three different lengths of the hollow Teflon. It can be seen that the resonator when filled using the Teflon with length of 160mm gives the minimum error and this also complies with the findings of the circuit simulations. Also, there is a considerable improvement in results obtained using the partially-filled model as compared to the model in [37]. The error in the calculated value of dielectric constant and loss tangent of Teflon is compared to the reported values of $\varepsilon_r = 2.02$ and tan$\delta = 0.0002$ in [41]. The dielectric properties of Teflon reported in [5], [39], and [44] also indicate a good agreement with the calculated values using the proposed method.

Scenario 2 (validation): The objective of testing this scenario is to validate the repeatability of the proposed method. The same piece of hollow Teflon cylinder measuring 160 mm is tested for different values of coupling capacitance in the resonator. Each time the length of the inner conductor is changed to achieve a new capacitance, the hollow Teflon cylinder of length 160mm is tested twice. For a particular length of the inner conductor, when the Teflon cylinder is tested a second time, the following steps are taken:

- The resonator is disconnected from the VNA to open the top lid.

- Teflon cylinder is taken out and then inserted back.
- The top lid is tightened back and then the resonator is connected back to the VNA.

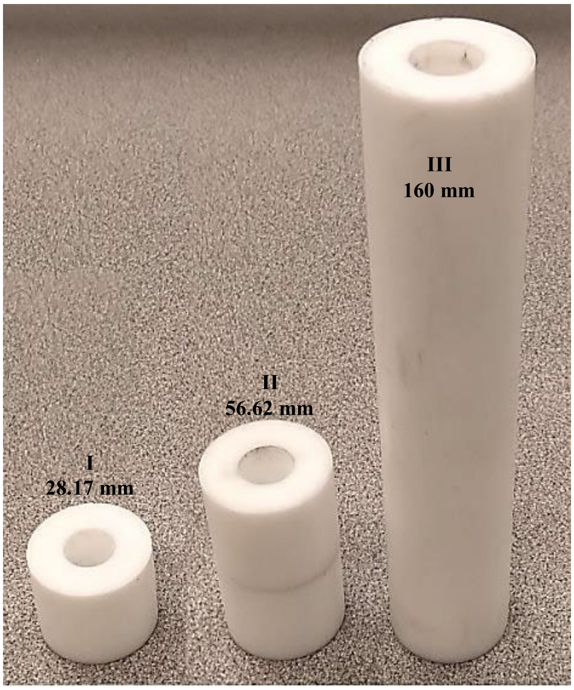


FIGURE 16. Different lengths of the hollow Teflon used in testing for Scenario1 (validation).

TABLE 3. Summary of measurements using the air-filled resonator in Scenario 2 (Validation) of testing.

Iteration No.	L_{inner} (mm)	f_0 (MHz)	$\lvert S_{11}\rvert$	Γ_d (ns)
1	189.96	209.68	0.997	5.05
2	189.73	283.28	0.991	10.81
3	189.71	323.44	0.980	22.92
4	189.29	350.64	0.948	55.50
5	188.56	361.28	0.915	93.44
6	188.12	374.08	0.822	218.20
7	186.73	379.76	0.733	357.06

The results obtained in this scenario of testing are summarized in Table 3 and 4. The error in the iterations from 2 to 6 has shown acceptable error in both the dielectric constant and the loss tangent. The higher error in iteration 1 corresponds to the limitation in the design of the resonator to produce very high values of the coupling capacitance. The air gap required to produce that high capacitance using the fabricated resonator is very small and hence is not repeatable. This can be seen from the difference in error for 1-1 and 1-2. The error in iteration 7 corresponds to the lower values of coupling coefficient ($k < 2.5$). The results obtained in this scenario of testing also corresponds to the region of confidence derived in Section IV.

VI. DIELECTRIC CHARACTERIZATION OF SANDY SOIL USING THE PROPOSED METHOD

The results obtained from the testing of Teflon confirms the accuracy of the mathematical model within the acceptable range of error. The sandy soil samples are tested using the fabricated coaxial resonator with an objective to expand on the capacity of the proposed method in testing different types of materials.

Sandy soil is collected from Regina outskirts in southern Saskatchewan, Canada. The grain size distribution (GSD) is determined using sieves in accordance with [45]. Based on the GSD, two sand samples are prepared by retaining the grains between various sieves (that is, between 4.75 mm and 2 mm for coarse sand and between 2 mm and 0.6 mm for fine sand), as shown in Figure 17. The grain size distribution of the tested soil samples is shown in Figure 18. The coarse sand and the fine sand are named as Sand 1 and Sand 2, respectively. Each soil sample is oven dried for 24 hrs at 105 ± 5 °C to remove soil-water [46]. To achieve various moisture content, *w* (percentage of water in sand), the predetermined mass of dry sample and deionized water were thoroughly mixed and allowed to equilibrate over 24 hrs in double plastic bags

Dry samples of Sand 1 and Sand 2 are tested first and the length of the inner conductor is changed slightly in every iteration to observe the effect of change in capacitance in the dielectric characterization of soils. The measurements with the air-filled resonator used in testing dry samples of Sand 1 and Sand 2 are shown in Table 5 and Table 6, respectively.

For each value of coupling capacitance and conductivity calculated using the measurements in Table 5 and Table 6, the corresponding results for dielectric constant and loss tangent for Sand 1 and Sand 2 are summarized in Table 7 and Table 8. It has been ensured in the testing that the percentage filled is above 50% and the coupling coefficient k is above 2.5. The dielectric constant and loss tangent for both Sand 1 and Sand 2 have shown fairly close results in all the three iterations and thus established the repeatabilty of the method in testing soil samples as well.

FIGURE 17. Prepared soil samples of coarse sand and fine sand used in testing.

TABLE 4. Summary of the measured and calculated results for the Scenario 2 of testing.

Iteration No.	C	$\left(\begin{matrix}\sigma_{c(eff)} \times 10^7 \\ \text{S/m}\end{matrix}\right)$	f_0 (MHz)	$\lvert S_{11}\rvert$	$\Gamma_d(\omega_0)$ (ns)	k	ε_r	% error ε_r	$\left(\begin{matrix}\tan\delta \\ \times 10^{-4}\end{matrix}\right)$	% error $\tan\delta$
1-1	**12.22**	**2.55**	193.68	0.996	7.12	539.5	**2.09**	3.6	**0.12**	94.0
1-2	**12.22**	**2.55**	196.08	0.996	7.25	525.3	**2.31**	14.2	**0.15**	92.5
2-1	**4.63**	**1.55**	249.04	0.984	19.72	125.6	**2.03**	0.7	**0.89**	55.6
2-2	**4.63**	**1.55**	247.84	0.985	19.40	128.0	**1.95**	3.5	**0.89**	55.8
3-1	**2.50**	**1.48**	271.68	0.956	50.06	43.9	**2.02**	0.0	**1.5**	23.8
3-2	**2.50**	**1.48**	271.84	0.955	50.19	43.6	**2.03**	0.5	**1.6**	21.2
4-1	**1.39**	**1.34**	286.08	0.872	137.39	14.6	**2.00**	0.8	**1.8**	10.1
4-2	**1.39**	**1.34**	286	0.873	136.01	14.8	**1.98**	2.1	**1.8**	10.1
5-1	**1.02**	**1.40**	291.44	0.779	249.43	8.1	**2.06**	2.0	**2.02**	1.2
5-2	**1.02**	**1.40**	291.36	0.781	246.15	8.1	**2.03**	0.3	**2.1**	4.4
6-1	**0.63**	**1.59**	297.68	0.547	643.60	3.4	**2.01**	0.6	**2.4**	18.3
6-2	**0.63**	**1.59**	297.68	0.550	646.36	3.5	**2.02**	0.2	**2.2**	7.6
7-1	**0.49**	**1.69**	300.48	0.361	1175.5	2.1	**1.88**	7.1	**2.9**	46.5
7-2	**0.49**	**1.69**	300.48	0.364	1151.1	2.1	**1.84**	9.0	**3.1**	54.1

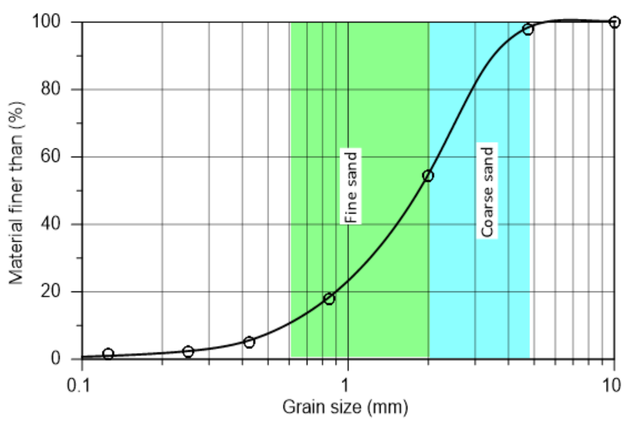


FIGURE 18. Grain size distribution of the tested soil samples.

TABLE 5. Summary of measurements with air-filled resonator for the testing of Sand 1 with 0 percent moisture.

Iteration No.	L (mm)	f_0 (MHz)	S_{11}	$\Gamma_d(ns)$
1	191.57	273.20	0.993	9.43
2	190.185	275.40	0.992	9.81
3	190.02	258.80	0.994	8.02

Sand 1 and Sand 2 with 2.5% and 5% moisture content are also tested. Each of the sand samples with a different moisture content is tested three times while maintaining the same capacitive gap. The purpose of not varying the capacitive gap during the testing of sand samples with same moisture content is to reduce the duration of the tests and preserve the moisture content to the extent possible.

TABLE 6. Summary of measurements with air-filled resonator for the testing of Sand 2 with 0 percent moisture.

Iteration No.	L (mm)	f_0 (MHz)	S_{11}	$\Gamma_d(ns)$
1	189.73	282.25	0.991	10.71
2	189.53	284.80	0.991	11.18
3	190.18	276.40	0.992	10.08

Table 9 summarizes the measurements of the air-filled resonator required for the testing of Sand 1 and Sand 2 with 2.5% and 5% moisture content. The extracted dielectric properties for Sand 1 and Sand 2 with different mositure contents are summarized in Table 10 and Table 11 respectively.

Mean and standard deviation (SD) are calculated using the three iterations done for each soil sample with different moisture contents. The procedure is slightly different for testing the soil samples with moisture and without moisture. The soil samples without moisture are tested in each iteration using a slightly different coupling capacitance. For example, while testing Sand 1 with 0 % moisture, the resonator is emptied after the first iteration and the coupling gap is varied

TABLE 7. Summary of measured and calculated results for the resonator filled with Sand 1 having 0 percent moisture.

Iteration No. →	1	2	3
$C\ (pF)$	**5.34**	**5.12**	**6.38**
$\sigma_{c(eff)} \times 10^7 (S/m)$	**1.62**	**1.43**	**1.78**
L_{inner} (mm)	144.52	157.92	156
$Density\ (g/cc)$	1.55	1.55	1.55
$f_0 (MHz)$	221.80	213.20	206.0
$\lvert S_{11} \rvert$	0.820	0.758	0.839
$\Gamma_d (ns)$	22.75	28.06	20.08
ε_r	**2.83**	**2.73**	**2.74**
$\tan\delta$	**0.012**	**0.014**	**0.013**

TABLE 8. Summary of measured and calculated results for the resonator filled with Sand 2 with 0 percent moisture.

Iteration No. →	1	2	3
$C\ (pF)$	**4.68**	**4.50**	**5.01**
$\sigma_{c(eff)} \times 10^7 (S/m)$	**1.35**	**1.49**	**1.48**
L_{inner} (mm)	159.48	161.25	161.28
$Density\ (g/cc)$	1.63	1.61	1.61
$f_0\ (MHz)$	215.35	215.65	213.10
$\lvert S_{11} \rvert$	0.655	0.647	0.694
$\Gamma_d (ns)$	39.16	41.03	35.33
ε_r	**3.38**	**3.21**	**3.38**
$\tan\delta$	**0.015**	**0.015**	**0.015**

TABLE 9. Measurements and calculated results using air-filled resonator for testing Sand 1 and Sand 2 with 2.5% and 5% moisture content.

	Sand 1		Sand 2	
w (%)	2.5	5	2.5	5
$L (mm)$	191.05	190.96	190.52	190.13
$f_0\ (MHz)$	247.00	248.80	241.60	252.85
$\lvert S_{11} \rvert$	0.9955	0.9955	0.9962	0.9956
$\Gamma_d (ns)$	7.25	7.26	6.90	7.53
$C (pF)$	**7.31**	**7.23**	**7.80**	**6.88**
$\sigma_{c(eff)} \times 10^7$ (S/m)	**2.23**	**2.25**	**2.70**	**2.57**

slightly and then filled with soil sample to find the values for the second iteration. The same procedure is repeated for the third iteration as well. However, the soil samples with moisture are tested using the same coupling capacitance in each of the three iterations. For example, while testing Sand 1 with 2.5 % moisture, the resonator is emptied after the first iteration and is filled with soil sample a second time without changing the coupling gap. The same procedure is repeated one more time to run a complete set of three iterations for Sand 1 with 2.5% moisture content. In addition to the above-mentioned steps, the soil samples are tapped with the hollow Teflon cylinder in every iteration. This is to produce a flatness on the top surface of the soil sample filled inside the resonator.

The calculated mean dielectric constant (2.76) for Sand 1 with 0% moisture is close to the reported value of 2.7 in [47] and [48]. The higher dielectric constant (3.32) of Sand 2 with 0 % moisture can be related to the increase in density. The dielectric constant for Sand 1 and Sand 2 has shown closely matching trends with moisture content and soil density, similar to the range of values reported in [47]. The data also indicate that there is a slight decrease in the loss tangent for both Sand 1 and Sand 2 at 5% moisture when compared with the corresponding samples at 2.5%. Again, this can be related to the higher density of the samples.

TABLE 10. Summary of results for Sand 1.

w (%)		0	2.5	5
ε_r	Mean	2.76	4.08	4.67
	SD	0.06	0.09	0.03
$\tan\delta$	Mean	0.013	0.052	0.050
	SD	0.001	0.002	0.01
Density (g/cc)	Mean	1.55	1.49	1.5
	SD	0	0.025	0.021

TABLE 11. Summary of results for Sand 2.

w (%)		0	2.5	5
ε_r	Mean	3.32	3.70	4.79
	SD	0.1	0.05	0.12
$\tan\delta$	Mean	0.015	0.055	0.051
	SD	0	0.005	0.005
Density (g/cc)	Mean	1.62	1.35	1.43
	SD	0.012	0.035	0.021

VII. CONCLUSION

A method is proposed to determine the dielectric constant and loss tangent of a material filled inside a coaxial resonator. The method is based on the reflected group delay of a capacitively coupled lossy coaxial resonator filled partially with the material under test. To extract the dielectric properties, one port measurements obtained using VNA are applied in a procedural manner to the mathematical model presented in the paper. The simulations carried out using different scenarios helped in identifying that the resonator when operated to have a coupling coefficient in the range of 2.5 to 10, can determine the dielectric constant and loss tangent of a material with an error of less than 2% and 30% respectively. However, region of confidence is also derived that takes into account the effect of systematic errors to calculate the maximum expected error in determining the dielectric properties when the resonator is filled to more than 50% of its capacity and operated for a value of coupling coefficient greater than 2.5. Hence provides a wide-ranging solution in terms of coupling coefficient and percentage filled that allows characterization with an expected error of less than 5% and 80% in the calculated value of dielectric constant and loss tangent respectively. The testing of Teflon validates the accuracy of the method and the limits prescribed in the region of confidence. The testing of soil samples with different moisture contents confirms the application of the proposed method in testing different types of materials.

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