01 Jan 2023

Sample Considerations For Short-Circuited Filled Transmission Line Measurements

Jared Sinkey

Alexander Hook

Kristen M. Donnell
Missouri University of Science and Technology, kmdgfd@mst.edu

Recommended Citation

J. Sinkey et al., "Sample Considerations For Short-Circuited Filled Transmission Line Measurements," *Conference Record - IEEE Instrumentation and Measurement Technology Conference*, Institute of Electrical and Electronics Engineers, Jan 2023.
The definitive version is available at https://doi.org/10.1109/I2MTC53148.2023.10175977

2023 IEEE International Instrumentation and Measurement Technology Conference (I2MTC) | 978-1-6654-5383-7/23/$31.00 ©2023 IEEE | DOI: 10.1109/I2MTC53148.2023.10175977

Sample Considerations for Short-Circuited Filled Transmission Line Measurements

Jared Sinkey, Alexander Hook, and Kristen M. Donnell
Microwave Sensing (μSense) Laboratory
Department of Electrical and Computer Engineering
Missouri University of Science and Technology
Rolla, Missouri, USA
<jdsdgt, ach6z9, kmdgfd> @mst.edu

***Abstract*— Microwave materials characterization can be performed using a number of well-established measurement approaches. One such approach, the short-circuited rectangular waveguide (SC-RWG) filled transmission line approach, is known to have sample placement restrictions related to measurement reliability. This work focuses on this approach as a viable solution for microwave materials characterization of liquid materials and addresses the measurement restrictions within the context of sample length and dielectric properties. It is shown via simulation and measurement that samples of length greater than $\lambda_g/6$ (where λ_g is the wavelength in the RWG) do not have the reported measurement restrictions, nor do materials with high dielectric permittivity and/or loss factor (of any length).**

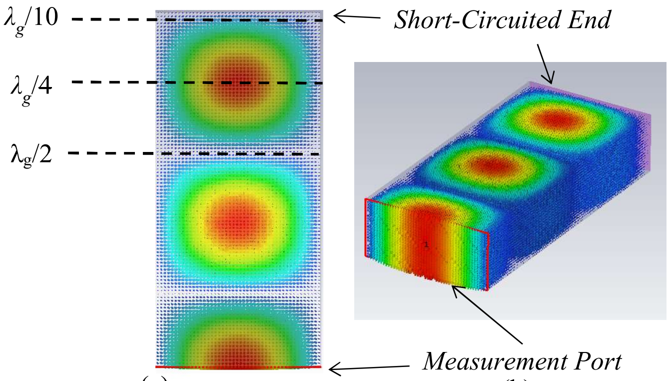
Keywords—materials characterization, microwave nondestructive testing, short-circuited rectangular waveguide, liquid measurements, filled transmission line

I. INTRODUCTION AND BACKGROUND

Microwave materials characterization is an important nondestructive evaluation approach that can be used to measure dielectric properties of a material. Such a measurement is done by irradiating a dielectric (i.e., nonconducting) material with high frequency energy. This causes dielectric polarization to take place within the material. This interaction of the material with high frequency energy is macroscopically described by the material's dielectric properties. Dielectric properties are complex and, when referenced to freespace, are denoted as $\varepsilon_r = \varepsilon_r' - j\,\varepsilon_r''$. The real part, or permittivity, represents the ability of a material to store electromagnetic energy, and the imaginary part, or loss factor, represents how a material absorbs electromagnetic energy. Dielectric properties can be related to many physical or chemical properties including compressive strength [1], chloride content [2], and alkali-silica reaction [3], amongst others.

As mentioned, at the heart of microwave materials characterization are measurements of complex dielectric properties. Dielectric properties are intrinsic, meaning they can be measured in many ways and are independent of the measurement approach. Typical measurement approaches include filled transmission line [4], freespace [5], and resonant cavity [4], amongst others. Each of these techniques come with their own advantages and disadvantages. For example, a resonant cavity is a very accurate measurement technique, but sample placement is critical, and the technique is not suitable for liquids. The freespace approach comes with similar limitations. The filled transmission line approach is traditionally applied in conjunction with a two-port calibrated S-parameter measurement. However, this setup does not lend itself well to liquid materials, as placing the sample is difficult. To this end, a one-port filled transmission line approach realized using a short-circuited rectangular waveguide (SC-RWG) sample holder (including a sealed SC-end) is considered as a viable alternative for liquid material measurements.

Aside from any specialized sample holder requirements that may arise specifically for liquid material measurements (such as the sealed SC termination), a SC-RWG measurement approach for materials characterization is already well known [7]. However, this approach includes a measurement limitation related to placement of the sample within the sample holder. In other words, due to the boundary conditions imposed by the presence of the short circuit termination, the electric field at the terminated end of the SC-RWG is zero. Therefore, should a relatively thin material be placed for characterization flush with the SC-end (a natural placement for ease of measurement preparation), very little signal will interact with the sample under test (SUT). Such a thin sample may arise in practice in cases of limited liquid sample quantity, or for solid materials such as coatings that may be prepared for measurement with a thickness on the order of a few mm or less. Hence, the measured signal may be marginally affected by the material and a low-accuracy measurement may result. In fact, for the SC-RWG approach, the literature states that placement of the sample within the RWG is critical, and that measurements are most effective when the sample is placed (centered) at a point of electromagnetic maxima, which occurs in the waveguide at multiples of $\lambda_g/4$ (where λ_g is the wavelength in the waveguide) from the short-circuited end [7]. In this way, the material to be characterized will with the greatest magnitude of electric field within the SC-RWG sample holder. This scenario is illustrated below in Fig. 1, where the electric field magnitude is shown within an air-filled SC-RWG of length $1.25\lambda_g$ (simulated in CST Microwave Studio™), with relevant locations within the RWG also noted. As seen, the maxima begin a distance of $\lambda_g/4$ from the short-circuited end and repeat every $\lambda_g/2$ along the length of the RWG. It is also evident that the electric field strength goes to zero at the short-circuited end and along the side walls. This is due to the fact that the electric field polarization is tangential to the conducting side walls and SC termination and hence boundary conditions dictate the electric field must be null at these locations [8].



(a) (b)

Fig. 1. Top (a) and 3D (b) views of electric field maxima and minima in a SC-RWG.

As it relates to materials characterization measurements, it is clear from Fig. 1 that the electric field null imposed by the presence of the SC termination suggests that samples with a length of $\lambda_g/4$ or less may require an offset from the end of the SC-RWG [7]. This limitation may be less restrictive for samples that are multiple wavelengths in length. This is because longer SUTs will experience multiple electric field maxima and minima when placed within the SC-RWG, and therefore placement within it is less critical. To this end, this paper presents a simulation- and measurement-based study of the effect length, placement, and dielectric properties of a sample placed within a SC-RWG on the resulting complex reflection properties. The magnitude of the reflection properties (|S11|) will be studied and compared to an empty (air-filled) SC-RWG to illustrate which types of samples must be offset (as mentioned in [7]) and which do not have this measurement restriction. For this work, a sample center-point offset of $\lambda_g/4$ is the only center-point offset considered, and it should be noted that this distance has not been optimized and may not be optimal for cases where an offset is needed.

II. SIMULATIONS

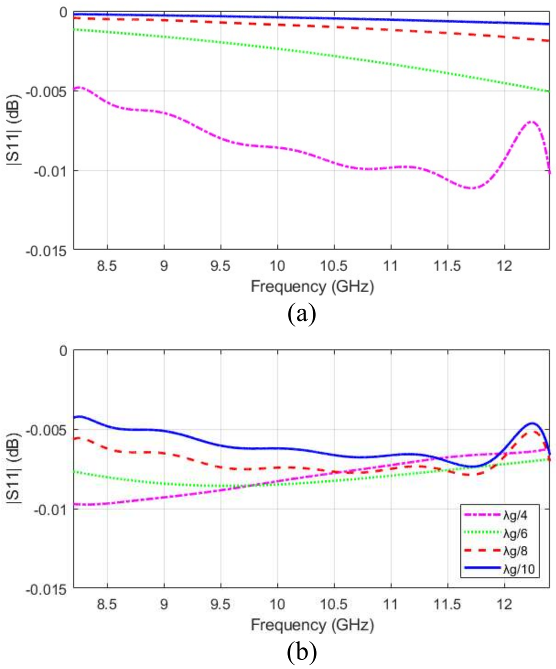
To investigate the effect of length, placement, and dielectric properties on the detected reflection properties of a sample placed within a SC-RWG, full wave electromagnetic simulations were conducted using CST Microwave Studio™. The samples were assumed to be placed inside a SC-RWG operating in the X-band (8.2 – 12.4 GHz) of length $1.25\lambda_g$, with all results reported for a frequency of 10 GHz (λ_g = 4 cm). However, the conclusions stated here are comprehensive and relevant to other frequencies as well since sample length and placement is considered relative to wavelength.

A. Short Samples

To begin, the effect of sample length for short samples (defined as length < $\lambda_g/4$), is studied, with samples of both high (e.g., water) and low (e.g., acrylic) dielectric properties considered. To this end and referring to Fig. 1, it is easy to see that very little signal will interact with a short material since the electric field is approaching a null at the short-circuited end. In such cases, in order to ensure that the material interacts with the electric field in a measurable way, the material center-point should be shifted to a location of maximum electric field [7] (i.e., $\lambda_g/4$ as defined in an empty SC-RWG and shown in Fig. 1). It is important to note that when a sample of relative permittivity greater than 1 is placed inside the sample holder (at any location), the electric field distribution will change per the dielectric boundary conditions that must be enforced at the air-dielectric boundary [8], [9]. This means that the distribution shown in Fig. 1 represents the scenario of an empty SC-RWG, and not what will occur when a dielectric SUT is placed within the RWG. However, it is representative of the field distribution and therefore can be used to illustrate the concept of appropriate and problematic sample placement.

Beginning with a low permittivity and low loss material, a simulation was conducted assuming an acrylic sample ($\varepsilon_r = 2.6 - j0.001$) with lengths of $\lambda_g/10$ to $\lambda_g/4$ (i.e., lengths that will fall within the field region of null-to-max, as starting from the SC-end). Simulations were conducted for sample placement flush with the SC-end and centered at $\lambda_g/4$ from the SC-end. The magnitude of S11 (i.e., |S11|) for these simulations is shown in Fig. 2 (phase is not included as the purpose of this simulation is to determine if the reflected signal is affected by the presence of the sample, which is evident in |S11|). Note that the response from an empty SC-RWG will be a magnitude of 0 dB across the frequency band, or full reflection. As such, signal deviations from 0 dB are attributed to the presence of the sample. As seen in Fig. 2a, deviation in |S11| from an empty SC-RWG (i.e., 0 dB) is minimal (maximum of ~0.01 dB) for the short acrylic samples placed flush with the SC-end. However, this is as expected, as the samples themselves are short and also of low permittivity and loss factor. As such, this indicates that this material is interacting minimally with the interrogating signal and hence is effectively invisible (when placed at the SC-end) from a reflection property point-of-view. Therefore, materials characterization measurements are not possible for these thin sample lengths.

The results of Fig. 2b, however, portray a different scenario. In this case, the same acrylic sample is centered about the electric field maximum (i.e., $\lambda_g/4$ from the SC-end). Here, while the deviation in |S11| is still on the order of a maximum of 0.01 dB from an empty SC-RWG, the signal throughout most of the band (aside from > 12 GHz) for all sample lengths is measurably different than 0 dB. In this way, materials characterization measurements can be more reliably performed for short, low permittivity and loss factor samples. In addition, it is also obvious that the results of Fig. 2a are different than those of Fig. 2b. This is expected, as when the SC-RWG is viewed from a transmission line point-of-view, the input impedance for the scenario of Fig. 2a is different than that of Fig. 2b and hence the reflection properties will also differ [9]. Moreover, when comparing the results of these two scenarios, an important measurement-related point can be seen. That is to say, once a low permittivity and loss factor sample reaches a length of $\lambda_g/6$ or greater, a detectable signal is possible regardless of sample placement and hence materials characterization measurements may be made without concern of sample placement. This is important practically, as it removes the difficult measurement limitation of a required sample offset inside the SC-RWG.

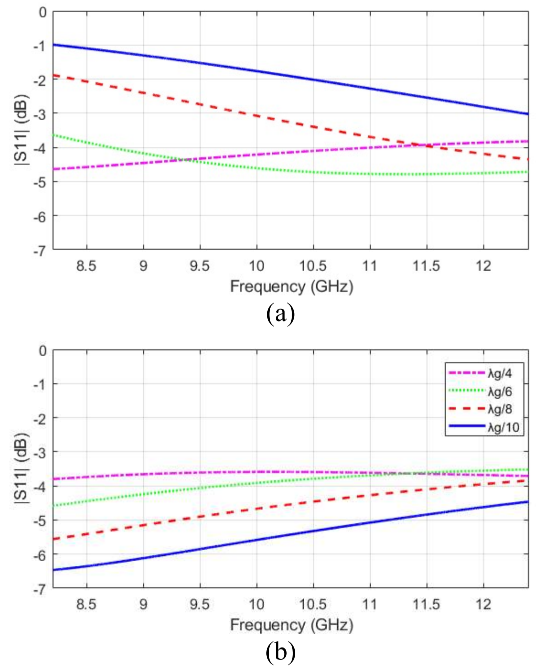


(a)

(b)

Fig. 2. |S11| for short acrylic samples placed at the SC-end (a), and offset by $\lambda_g/4$ (b).

It is also important to understand the effect of dielectric properties on this measurement issue. To this end, simulations were conducted on samples of the same electrical length as those of Fig. 2 but with different dielectric properties (i.e., tap water with measured $\varepsilon_r = 5.11 - j13$ as per [10]). The results of these simulations are shown in Fig. 3. Here, while sample placement clearly has an effect on the reflection properties, both placements result in measurable reflection properties that differ from that of an empty SC-RWG (0 dB). This apparent placement independence is due to the greater permittivity and loss factor of water vs. acrylic and has important practical ramifications. That is to say, when a material is of higher permittivity and loss factor, the restriction of placement offset from the SC-end is removed and the sample can easily be placed flush with the SC-end, even for very thin samples. This is extremely important as it relates to liquid measurements, where placement offset is very difficult to achieve in practice.



(a)

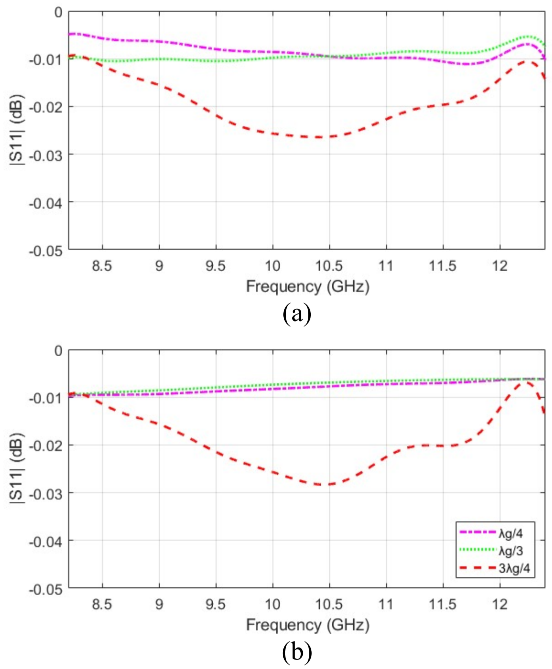
(b)

Fig. 3. |S11| for short water samples placed at the SC-end (a), and offset by $\lambda_g/4$ (b).

B. Long Samples

The case of longer samples, herein considered as a length of $\lambda_g/4$ or greater, must also be studied. In this case, due to the repetitive nature of the electric field (every $\lambda_g/2$ as is evident in Fig. 1), it is expected that shifting the sample by an offset of $\lambda_g/4$ will change the reflection properties, but not improve signal interaction. In other words, since the electric field repeats every $\lambda_g/2$, a sample that is half of that length or longer will experience the same electric field every $\lambda_g/4$. To this end, simulations were conducted using the same samples considered above but for sample lengths of $\lambda_g/4$ (as above and included for comparison), $\lambda_g/3$, and $3\lambda_g/4$. These lengths were chosen in order to capture the remaining relevant range of sample lengths up to λ_g and avoid multiples of $\lambda_g/2$. This particular length is suggested to be avoided due to the direct impedance transfer that takes place at this length (i.e., half wave impedance transformer [8], [9]). In other words, it is possible to effectively measure the SC-end for such cases, should the sample be placed flush with the SC-end and the sample holder be of equal length.

To begin, the simulated results for long acrylic samples are shown in Fig. 4. As can be seen, the reflection properties for when the sample is flush and shifted with respect to the SC-end are similar in all cases. The reason for this is clear when the electric field within the SC-RWG is studied directly, as seen in Fig. 5, where a top view of the electric field in the SC-RWG is shown for all cases of Fig. 4, with the placement of the sample shaded in purple.



(a)

(b)

Fig. 4. |S11| for long acrylic samples placed at the SC-end (a), and offset by $\lambda_g/4$ (b).

As seen, for the $\lambda_g/4$ case (Fig. 5a), the field distribution along the length of SC-RWG is affected by the presence of the sample due to the dielectric boundary conditions that must be met [9]. However, the sample still interacts with a field magnitude ranging from a null to a (near) maximum. As such, a detectable |S11| is evident in Fig. 4a. The shifted results for the $\lambda_g/4$ case (Fig. 4b and Fig. 5d) are similar to those when placed flush with the SC-end/ albeit with a reduced maximum field magnitude within the sample.

When the field distribution is considered for the flush $\lambda_g/3$ case (Fig. 5b), a different scenario is seen. Here, due to the same dielectric boundary conditions that must be enforced due to the presence of the sample, the field strength throughout the sample is reduced as compared to that of the other two cases (Fig. 5a and Fig. 5c). However, as per Fig. 4a, the results are still measurable.

Regarding the results for the $3\lambda_g/4$ case, |S11| (Fig. 4) in both cases is similar. This result is supported by the field distributions of Fig. 5. Here, the effect of the sample on the electric field distribution is evident, as is the multiple peak-to-null distributions with which the sample interacts. To this end, an important measurement conclusion can be made. That is to say, in order to avoid unreliable measurements for low permittivity/loss materials and maintain independence with sample placement, a sample length of greater than $\lambda_g/2$ (avoiding multiples of the same) must be used.

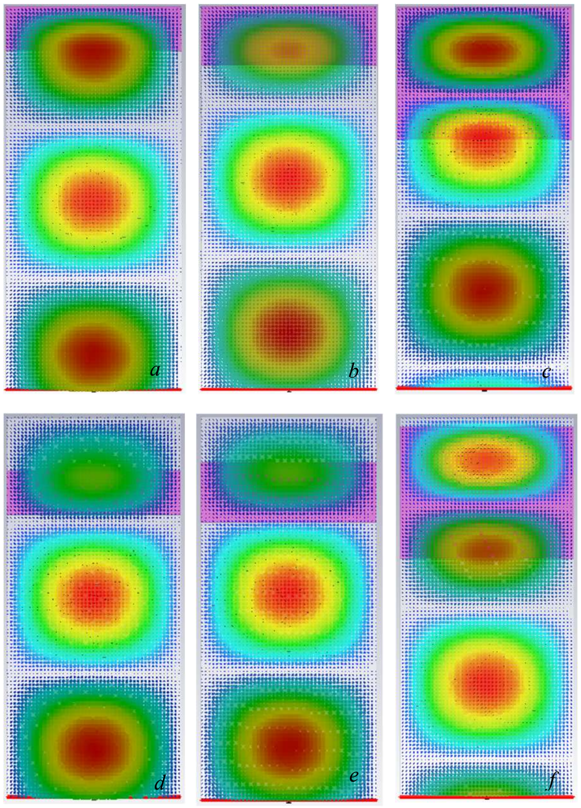
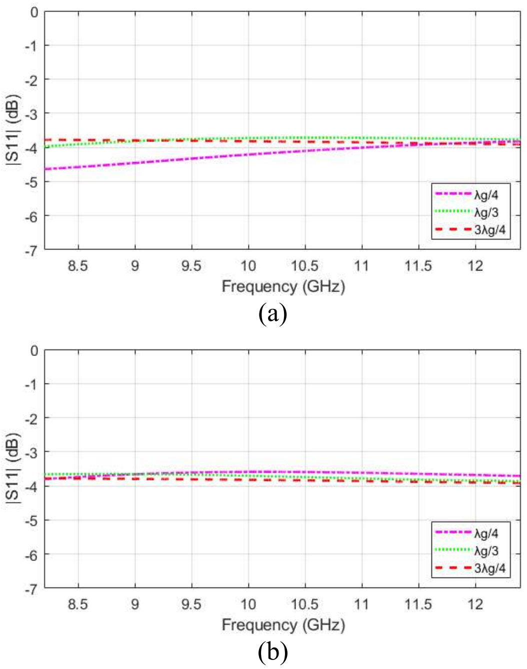


Fig. 5. Simulated electric field distribution in the SC-RWG for acrylic samples of lengths $\lambda_g/4$, $\lambda_g/3$, and $3\lambda_g/4$ flush with the SC-end (*a*, *b*, *c*, respectively) and shifted by $\lambda_g/4$ (*d*, *e*, *f*, respectively).

Simulations were also conducted for a short high permittivity/loss factor sample (water, as above), with |S11| shown in Fig. 6. As seen in Fig. 6, |S11|, regardless of placement within the SC-RWG, indicates substantial interaction of the material with the electric field (as evidenced by the deviation from 0 dB). This is as expected, as the material is high permittivity/loss and as such, less interaction is needed in order to see a change manifest in |S11|.

To support the results of Fig. 6, the associated electric field distributions of both placements for all 3 sample lengths are shown in Fig. 7. Here, it is immediately noticeable that the absolute length of these samples (shaded purple area) is shorter than the corresponding cases for the long acrylic samples. This occurs since the samples are specified in electrical length, and the wavelength in water is smaller than the wavelength in acrylic due to the respective permittivities [8]. It is also interesting to note the effect on the electric field distribution within the SC-RWG in these cases. In both cases (flush and shifted), the sample interacts with a similar electric field magnitude and distribution, further supporting the similarity in |S11| of Fig. 6. The reason for this is again the high permittivity/loss factor of water. These values create a substantial impedance change from an empty RWG to a filled section, meaning that most of the electric field will be reflected at that location. This is clearly seen in Fig. 7 and also supports the measurement conclusion above for high permittivity/loss materials: placement within a SC-RWG sample holder is not critical, regardless of sample length.



(a)

(b)

Fig. 6. |S11| for long water samples placed at the SC-end (a), and offset by $\lambda_g/4$ (b).

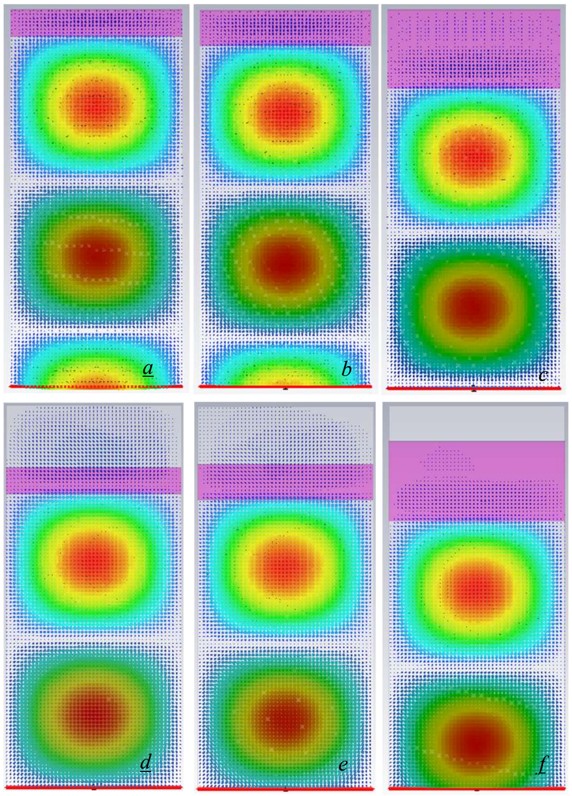


Fig. 7. Simulated electric field distribution in the SC-RWG for water samples of lengths $\lambda_g/4$, $\lambda_g/3$, and $3\lambda_g/4$ flush with the SC-end (*a*, *b*, *c*, respectively) and shifted by $\lambda_g/4$ (*d*, *e*, *f*, respectively).

III. MEASUREMENTS

To further support the measurement conclusions noted above and deduced via simulation, measurements were performed for acrylic and water samples placed in a SC-RWG sample holder of length $1.25\lambda_g$ (empty RWG) For measurement, the sample holder was connected to a calibrated port of an Anritsu MS4644A Vector Network Analyzer (VNA). The VNA was used to measure the complex reflection properties at X-band for sample placement flush with and shifted from the SC-end. To create the shifting, a 10 mm ($\sim\lambda_g/4$ at 10 GHz in an empty RWG) piece of insulating foam was placed flush with the SC-end. Foam was chosen as its dielectric properties are similar to that of air (1 – j0.07 as measured per [10]) and therefore will effectively not perturb the measurement scenario as an additional dielectric.

The complex measured reflection properties (S11) for the acrylic samples are shown in Fig. 8, along with the corresponding simulations for comparison. Specifically, samples of length 2 mm ($\sim\lambda_g/10$ in acrylic) and 2 cm ($\sim\lambda_g$ in acrylic) were measured. As can be seen, similar trends are evident in |S11|between the measured (Fig. 8, top) and simulated (Fig. 8, bottom) results. The measured results indicate more signal loss (more negative |S11|) than the simulations. This is attributed to error in the dielectric properties of acrylic used for simulation along with the presence of foam used for sample placement. There is also more variation in phase across the frequency band for the measured results. This indicates a longer (electrically) sample than that of simulation (also attributed to errors in dielectric properties). It is also evident that, overall, placement affects the short sample results more than those of the long samples, as is expected per the above.

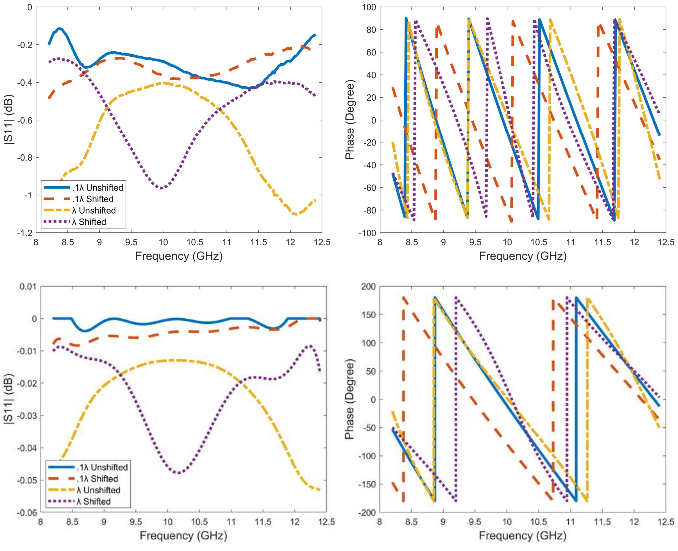


Fig. 8. Magnitude and phase of S11 for acrylic samples: measured (top) and simulated (bottom).

It is also worth noting that while the longer sample is an even multiple of $\lambda_g/2$ (traditionally a length to be avoided as discussed above), the measured result does not indicate any issue (i.e., is not the expected 0 dB of an empty SC-RWG). This indicates that in practice, the concern of sample lengths on the order of multiples of $\lambda_g/2$ is not substantial, so long as the material includes loss. This is evident in this case by the range of |S11| for both simulation and measurement (a range of ~-0.2 dB to nearly -1.2 dB for measurement).

The measured and simulated results for a water sample are provided in Fig. 9. The shifting was created in the same fashion as above for the acrylic (foam section of length $\lambda_g/4$). In this case, a short water sample was not able to be reliably created for measurement. Therefore, only the measured results for a long sample are shown in Fig. 9.

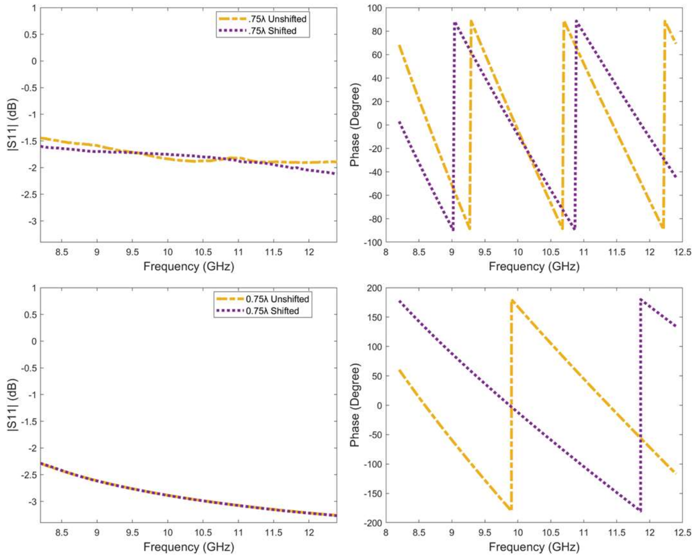


Fig. 9. Magnitude and phase of S11 for water samples: measured (top) and simulated (bottom).

As can be seen, similar trends are evident between the measured and simulated results. In this case, there is more signal attenuation in the simulated results, indicating that the dielectric properties used for simulation (measured using [10]) are not precise for the tap water used. In fact, this precisely illustrates the motivation for this paper; that two-port measurements of liquid materials are challenging, as evidenced here by the unusual value measured for permittivity of tap water (5). Moreover, the variation in phase for the measurements (also seen in Fig. 8) is greater than that of the simulation. This indicates that the sample length used for measurement is (electrically) longer than that assumed for simulation. This can be due to a physical mismatch, or due to an error in permittivity used in simulation for the material (thereby affecting the electrical length). Regardless, these measurements support the above conclusion that, for longer samples and/or samples with greater permittivity/loss factor, sample placement is not critical and therefore a straightforward measurement with a sample placed flush against the SC-end may be performed.

IV. CONCLUSION

The short-circuited rectangular waveguide (SC-RWG) filled transmission line approach is proposed for microwave materials characterization of liquid materials. This approach is well known to have material placement limitations related to the SC-termination. This work considers the effect of sample placement, length, and dielectric properties in the context of the reported measurement restrictions. It is shown that samples of length greater than $\lambda_g/6$ do not have the reported restrictions, nor do materials of any length with high dielectric permittivity and/or loss factor.

ACKNOWLEDGMENT

This work was partially supported by the National Science Foundation Civil, Mechanical and Manufacturing Innovation Division (CMMI) Award No. 1662897 and a Graduate Assistance in Areas of National Need (GAANN) national fellowship.

REFERENCES

[1] R. Zoughi, S. D. Gray, and P. S. Nowak, “Microwave nondestructive estimation of cement paste compressive strength,” *ACI Materials Journal*, vol. 92, no. 1, 1995.

[2] S. Peer, T. Case, K. Donnell, D. Hughes, R. Zoughi, and K. Kurtis. “Investigation of microwave reflection properties of mortar exposed to wet-dry cycles of tap water and chloride bath,” *Quantitative Nondestructive Evaluation*, vol. 615, no. 1, pp. 1269-1276, 2002.

[3] A. Hashemi., M. Horst, K. E. Kurtis, K. M. Donnell, and R. Zoughi, “Comparison of alkali–silica reaction gel behavior in mortar at microwave frequencies,” *IEEE Trans. on Instrumentation and Measurement*, vol. 64, no 7, pp. 1907-1915, 2015.

[4] X. Lin and B. -C. Seet, "Dielectric Characterization at Millimeter Waves With Hybrid Microstrip-Line Method," in *IEEE Transactions on Instrumentation and Measurement,* vol. 66, no. 11, pp. 3100-3102, Nov. 2017, doi: 10.1109/TIM.2017.2746362.

[5] S. Julrat and S. Trabelsi, "Free-Space Transmission Dielectric Properties Measurement Based on Six-Port Technology," in *IEEE Transactions on Instrumentation and Measurement*, vol. 70, pp. 1-7, 2021, Art no. 6007907, doi: 10.1109/TIM.2021.3084292.

[6] A. K. Jha and M. J. Akhtar, "A Generalized Rectangular Cavity Approach for Determination of Complex Permittivity of Materials," in *IEEE Transactions on Instrumentation and Measurement*, vol. 63, no. 11, pp. 2632-2641, Nov. 2014, doi: 10.1109/TIM.2014.2313415.

[7] J. Baker-Jarvis, M. D. Janezic, J. H. Grosvenor, and R. G. Geyer, *Transmission/reflection and short-circuit line methods for measuring permittivity and permeability*. Boulder, CO: U.S. Dept. of Commerce, Technology Administration, National Institute of Standards and Technology, 1993.

[8] D. M. Pozar, *Microwave Engineering*. Hoboken, New Jersey: Wiley, 2012.

[9] U. S. Inan, A. S. Inan, and R. Said, *Electromagnetic Engineering and Waves*. Upper Saddle River, New Jersey: Prentice Hall, 2013.

[10] K. J. Bois., et al. "Dielectric plug-loaded two-port transmission line measurement technique for dielectric property characterization of granular and liquid materials.*" IEEE Transactions on Instrumentation and Measurement* 48.6 (1999): 1141-1148.