Fast Measurements of Dielectric Properties with Small Size Microwave Transceiver

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Abstract—The dielectric properties of biological tissues are fundamental for the design of electromagnetic medical devices as well as in non-ionizing radiation dosimetry studies. In recent studies, dielectric data has been typically collected using the open-ended coaxial probe and the vector network analyzer (VNA) setup. In this work, we replace the traditional swept frequency VNA from this setup with a more compact microwave transceiver. The microwave transceiver uses a novel broadband, multi-tone source and broadband receivers to capture the instantaneous S-parameters at multiple tones simultaneously. We conducted dielectric properties measurements on standard liquids which have known dielectric properties using our modified setup and compared the results with the theoretical values. We also conducted the same measurements with the typical setup which includes the swept frequency VNA and compared the performances of the two measurement setups. We concluded that the microwave transceiver can provide faster measurement speeds than the conventional VNA without sacrificing measurement precision and accuracy.

Index Terms—dielectric properties, open-ended coaxial probe, microwave transceiver, N7081A, measurements.

I. INTRODUCTION

The open-ended coaxial probe technique is the most commonly used technique in measurements of dielectric properties of biological tissues [1]. The open-ended coaxial probe consists of a truncated section of a transmission line. The electromagnetic field propagates along the coaxial line and reflection occurs when the electromagnetic field encounters an impedance mismatch between the probe and the tissue sample. The open-ended coaxial probe measurement set-up and the probe cross-section are schematised in Fig. 1. The reflected signals at different frequencies are measured and then converted into dielectric properties [1].

The N7081A Microwave Transceiver is a compact vector network analyzer that uses a novel broadband, multi-tone source and broadband receivers to capture the instantaneous S-parameters at multiple tones simultaneously. Measurements can be made up to the full frequency range of the N7081A and are orders of magnitude faster than with the traditional swept frequency vector network analysers (VNA) [2]. With the ability to measure instantaneous S-parameters, fast measurement speed, small size and low cost, the N7081A Microwave Transceiver is the ideal measurement subsystem for Microwave Sensing and Imaging (MSI) solutions, high volume test solutions and built-in test in operational equipment [2].

II. MATERIALS AND METHODS

A. Data Acquisition

Measurements of reflection coefficient ($s_{22}$) were performed with the N7081A Microwave Transceiver from Keysight. The port two (therefore the measured values are $s_{22}$) of the
microwave transceiver was connected to the Keysight Slim Form probe, a commercially available open-ended coaxial probe. The open end of the probe was left open or terminated by either a short or one of the liquids with known dielectric properties. By knowing the dielectric properties of each of the mediums used to terminate the open end of the probe it was possible to use each of the measurements as a calibration standard in the one-port calibration procedure [4] or as a verification of measurement. Since we need three measurements of known dielectric properties to carry out the calibration procedure and one measurement of known dielectric properties to do the verification of the measurement setup after the calibration, each set of measurements consisted of four measurements (each one of a different material).

The total number of measurement is 3000 measurements, each consisting of 1260 complex $s_{22}$ values linearly spread over the frequency range from 1 GHz to 5 GHz. The total number of measurements can be divided in five different groups, each corresponding to either the measurements made on one of the calibration standards (i.e. open and short) or the measurements made on one of the liquids with known dielectric properties (i.e. deionised water, 0.1 mol/L saline solution and methanol). Each group of measurements contains 600 measurements. Since the dielectric properties of all three liquids are known each one of them can be used as the third calibration standard, while other two can then be used for verification of the measurements. In our case we used deionised water as a calibration standard and 0.1 mol/L saline solution and methanol for verification of the measurements.

In order to compare the performance of the microwave transceiver setup with the swept frequency VNA setup, one measurement on 0.1 mol/L saline solution and one measurement on methanol was made using the E5063A ENA Series Network Analyzer from Keysight. These two measurements were conducted in the same manner by first measuring the complex $s_{22}$ values for three calibration standards and then measuring the complex $s_{22}$ values for the 0.1 mol/L saline solution in the first case and methanol in the second case. The E5063A VNA was set up using the Keysight Technologies N1500A Materials Measurement Suite [5] with the following settings:

- start frequency: 500 MHz,
- stop frequency: 8.5 GHz,
- number of points: 201 MHz,
- linear sweep,
- power: -5 dBm,
- intermediate frequency bandwidth (IFBW): 30 Hz.

The temperature of the liquids at the time of the measurements was recorded for all of the measurements where the probe was in contact with liquids. The raw $s_{22}$ values acquired during the measurements were later processed and converted to dielectric properties values of the measured liquid.

### B. Data Processing

The model used to convert the raw values of $s_{22}$ to dielectric properties of the dielectric medium is the virtual line model from [6,7]. Results from a comparative study indicate that the use of the virtual line model for biological tissue characterization is adequate and it offers a relatively good confidence for measurement results [7]. The virtual line model uses an effective transmission line to model the fringing electric field in the dielectric medium at the extremity of the probe [7].

The equation used to compute the dielectric properties from the measured reflection coefficients in an iterative procedure is [7]

$$
\epsilon_d = \frac{-j c \sqrt{\epsilon_d}}{2\pi f L} \frac{1 - \Gamma_m^{2j\beta_t D}}{1 + \Gamma_m^{2j\beta_t D} \cdot \cot(X)},
$$

where

- $\epsilon_d$ dielectric properties of the medium,
- $X$ $(2\pi f L\sqrt{\epsilon_d})/c$,
- $\Gamma_m$ complex reflection coefficient at the $B \rightarrow B'$ plane,
- $\beta_t$ propagation constant in coaxial probe,
- $D$ physical length of the probe,
- $L$ length of the virtual line,
- $c$ speed of light,
- $f$ measurement frequency.

In order to correctly calculate the dielectric properties of the dielectric medium from the $s_{22}$ parameter we need the $s_{22}$ at the extremity of the probe which is the $A \rightarrow A'$ plane.
in Fig. 3. However the microwave transceiver measures the \( s_{22} \) parameter at its port which is the B - B’ plane. To obtain the \( s_{22} \) parameter at the A - A’ plane we need to do the de-embedding of the probe which is implemented in the virtual line model.

The measured \( s_{22} \) parameter also suffers from the instrument’s systematic (repeatable) errors which should be corrected in the error correction procedure. Both the de-embedding of the probe and the error correction are done by the one-port calibration procedure [4].

Since the one-port calibration procedure is done before implementing the virtual line model, the de-embedding part of the virtual line model is redundant in this case.

In Fig. 4, \( \Gamma_m \) represents the measured value of \( s_{22} \) while the true value of \( s_{22} \) is represented by \( \Gamma \). The four error coefficient are organized as \( s \) parameters of a fictitious network called the error matrix. The error matrix is represented by the error box which includes both the difference caused by measurements being made in the B - B’ plane instead of the A - A’ plane and the instrument’s systematic errors. The error coefficients can be written as [4]:

\[
\begin{bmatrix}
    b_{m1} \\
    a_1
\end{bmatrix} =
\begin{bmatrix}
    e_{11} & e_{12} \\
    e_{21} & e_{22}
\end{bmatrix}
\begin{bmatrix}
    a_{m1} \\
    b_1
\end{bmatrix},
\]

(2)

From (2) we calculate the error corrected reflection coefficient at the A - A’ plane as [4]:

\[
\Gamma = \frac{\Gamma_m - e_{11}}{e_{22}\Gamma_m - \Delta},
\]

(3)

where \( \Delta = e_{11}e_{22} - e_{12}e_{21} \).

The error coefficients \( e_{11} \), \( e_{22} \) and \( \Delta \) are calculated from [4]:

\[
\begin{bmatrix}
    1 & -\Gamma_1 \Gamma_m & -\Gamma_1 \\
    1 & -\Gamma_2 \Gamma_m & -\Gamma_2 \\
    1 & -\Gamma_3 \Gamma_m & -\Gamma_3
\end{bmatrix}
\begin{bmatrix}
    e_{11} \\
    e_{22} \\
    \Delta
\end{bmatrix} =
\begin{bmatrix}
    \Gamma_m \\
    \Gamma_m \\
    \Gamma_m
\end{bmatrix}.
\]

(4)

After error correction and implementation of the virtual line model to calculate the dielectric properties of the dielectric medium the results were fitted to find the parameters of a two-pole Debye model. The fitting method used was a weighted least squares method (W-LSM) [8,9].

The fitted results were compared with the results from the literature for 0.1 mol/L saline solution [10] and methanol [11].

C. Performance analysis and Comparison

The performance of the microwave transceiver measurement setup was characterized in two ways: the accuracy of the measurement was characterized by the percentage error between the mean of the values computed from the measured \( s_{22} \) parameters and the values obtained from the literature. The repeatability was characterized by standard deviation of the entire measurement set.

The accuracy of the swept frequency VNA setup was also characterized by the percentage error. It is worth noting that while in the case of the microwave transceiver setup the percentage error is calculated for the mean of 600 measurements while in the case of the swept frequency VNA setup the percentage error is calculated for one single measurement.

III. RESULTS AND DISCUSSION

In Fig. 5 and Fig. 6 we see a good agreement between the values of the relative permittivity and conductivity computed from the measurements made with microwave transceiver and the known properties from the literature for both 0.1 mol/L saline solution and methanol.

In Fig. 7 the percentage error is giving us a closer look into the difference between the computed values and the values from the literature. We can see that the measurement setup was performing better while measuring the dielectric properties of 0.1 mol/L saline solution than when measuring the dielectric properties of methanol. This could be due to the fact that the dielectric properties of 0.1 mol/L saline solution is closer to the value of the dielectric properties of deionised water than the dielectric properties of methanol are. The measurement setup is expected to perform better when measuring dielectric properties that are similar to dielectric properties of one of the calibration standards.

In Table I we have the same measurement errors as in the Fig. 7 averaged over the frequency range. The error values for the single measurement with the swept frequency VNA setup is also added to the table for comparison. The swept frequency VNA error is also averaged over the frequency range.

We can see that in the worst case for microwave transceiver which is the case when we measured the relative permittivity of methanol, the average value of measurement error is less than 4%. The average measurement error for measurements on 0.1 mol/L saline solution are close to 1% for the measurement of conductivity and 0.76% for the measurement of relative permittivity.

It is important to mention that even though it seems that the microwave transceiver performed better than the swept frequency VNA in the case of the measurements on both the 0.1 mol/L saline solution and methanol, this is not necessarily true as the error value that was calculated for the microwave transceiver is from the average of 600 measurements, while in the case of the swept frequency VNA there was only one measurement. However the error values for the microwave transceiver are generally very low and it can be concluded...
that this measurement setup performs measurements with good accuracy.

The total time it takes to make 600 measurements in 1260 points each with the microwave transceiver is 151.2 ms [2]. The time it takes to make one measurement in 201 points with the IFBW set to 30 Hz with the E5063A ENA Series Network Analyzer was measured to be over 3 s.

In Fig. 8 and Fig. 9 we can see that the standard deviation for all cases is about two to three orders of magnitude less than the measured values. This shows that the repeatability of the measurements is good.

IV. CONCLUSION

In this work we showed that it is possible to replace the traditional swept frequency VNA from the open-ended coaxial probe setup for measurements of dielectric properties with faster and more compact microwave transceiver. The results confirm that the N7081A Microwave Transceiver from Keysight can be used instead of the swept frequency VNA for frequencies up to 5 GHz without sacrificing precision or accuracy. It is also confirmed that the virtual line model performs well for the computation of dielectric properties that are in the range of dielectric properties of biological tissues.

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Fig. 8. Standard deviation of the measurements of the relative permittivity: 0.1 mol/L saline solution (blue) and methanol (red)

Fig. 9. Standard deviation of the measurements of the conductivity: 0.1 mol/L saline solution (blue) and methanol (red)

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