RESEARCH ARTICLE

Frequency dependent complex dielectric permittivity of rubber and magnolia leaves and leaf water content relation

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ABSTRACT

A mathematical model based on both frequency and relative water content of two tropical crops ‘rubber and magnolia’ leaves derived from \(S_{21}\) measurements has been proposed in the frequency range of 3—7 GHz. Leaf samples sandwiched with Plexiglas side holders are inserted within waveguide sections, and the dielectric constants are calculated from the complex transmission coefficient \(S_{21}\). In general, complex dielectric constant of materials (leaves in this case) is a function of frequency and water content. A model obtained from the data of rubber based on both frequency and relative water content is compared with the models in the literature and verified by measurements of control samples (magnolia in this case). From the comparisons, it is observed that proposed model has been found to show more promise in prediction of the dielectric constants, and model has, at most, \(\pm 10\%\) error in relative dielectric constant \((\varepsilon_r)\) in broad band measurements. Relative dielectric constant is decaying by \(\sim 1/f^2\) and shifts down by relative moisture constant by \(\sim M_r\).

KEYWORDS

Dielectric measurements; parametric modelling; reflection measurement; remote sensing

1. Introduction

There are different microwave applications based on the knowledge of the dielectric properties of materials that electromagnetic waves are interacting with them. There are many technologies for processing biomass materials that the knowledge of dielectric properties of vegetative is an essential for system design. In addition to these commercial applications, there are lots of military-based technologies using this knowledge.

Remote sensing (RS) is one of the fundamental techniques used for the study of land surface for environmental and military purposes. Advantages are that RS techniques provide data on a large scale and they are non-destructive methods. Most RS techniques are based on the fact that all materials having a temperature higher than the absolute zero (\(0\)K) emit radiation depending as a function of their temperature, and those radiations can be picked up by different types of sensors such as optics and infrared. Alternatively, microwaves have three main advantages over other types of RS such that: first, microwaves have the ability to penetrate canopies and soils, providing volumetric information that is not available with visible frequencies. Second, microwave signals are strongly
sensitive to water content in soil and vegetation and can therefore be used as indicators of water stress. Finally, microwaves can continue to travel through the cloud cover and at night (Jackson et al. 1996; van Emmerik 2013).

The success of RS applications is based on understanding the dependence of reflecting, refracting and absorbing (briefly scattering) coefficients of vegetation canopies, since the scattering mechanisms elucidated greatly enhance one’s understanding of the physics of the problem, leading to better insight and applications of RS techniques for monitoring and management of vegetation and forest resources (Chuah et al. 1997). Leaves are significant features and predominant parts of any vegetation canopy affecting scattering phenomena. Modelling of the vegetative medium inevitably requires dielectric properties of the scatter in the medium, which represent a linkage between electromagnetic properties and physical properties of the component. Scattering models developed to study the electromagnetic wave interactions with vegetative media (Lang & Sidhu 1983; Richards et al. 1987; Karam et al. 1992) and empirical relationships proposed to investigate electromagnetic response of plant leaves depending on water content, leaf internal structure and its surface properties can be found in the literature (Ulaby & Jedlicka 1984; Hsieh 2003; de Jong & Herben 2004; Helhel et al. 2009; Kurnaz et al. 2012; Yoruk et al. 2012).

Designing and developing any microwave technology (rather than RS technologies) for processing biomass materials require the knowledge of the dielectric properties as an essential (Sait & Salema 2015). Sait and Salema have focused on the measurement of dielectric properties of three different Saudi Arabian’s date palm biomass by using a cavity perturbation method. Trabelsi et al. (2016) presented a dielectric properties-based method for rapid and non-destructive determination of moisture content in almonds independent of bulk density. Their method relies on the measurement of the dielectric properties at microwave frequencies that the properties of almonds were measured between 5 and 15 GHz at 1 GHz increments.

Ulaby and Jedlicka proposed a model valid for corn and wheat leaves at same frequency band of this study (Ulaby & Jedlicka 1984). Various dielectric models have also been developed as a tool for prediction (Carlson 1967; Ulaby & El-Rayes 1987; Matzler 1994). Zhen et al. (2014) focused mainly on the corn leaves, and they proposed an empirical model between the gravimetric water and the real/imaginary parts of complex permittivity at most commonly used RS frequencies of microwave sensors. They concluded that the real parts of complex permittivity of selected vegetation are relatively same, and they do not show major differences when the water content is less than 60%. Corn, lettuce and potato leaves represent the short vegetation having close water content (i.e. >60%) that they have similar dielectric values. In similar manner, real part of dielectric constant of the apple-pear leaves, winter apple leaves and green poplar leaves are close to each other because of their similar structures. These are mostly based on measurements of vegetation components from temperate regions at selected frequency bands.

By the way, there is a lack of data on microwave dielectric properties of tropical vegetative materials in the literature, and RS applications need valuable mathematical expressions for the components of complex dielectric constant and relative dielectric constant in terms of water content and frequency for tropical leaves.

There are four fundamental methods used to measure the complex permittivity. Lumped circuit method (Huang & Zhang 2008) is valid for low frequencies up to 100 MHz and it is the first one; resonant cavity method (Li et al. 2007, 2009) uses frequency
shifts as well as quality factor of resonators is the second method, but measuring frequency shifts in a good manner is quite hard (has more precision for dielectric measurement of low loss materials and cannot be applicable at a certain frequency); waveguide transmission/reflection method (Venkatesh & Raghavan 2005) is the third one and it is quite useful in the frequency range of 2–20 GHz; last one is the free space method which is quite open to outer interferers and need to be used in a controlled environment. The waveguide transmission/reflection method preferred in this study measures the reflection characteristics of filling medium called as S-parameters, both $s_{11}$ (reflection from port one) and $s_{21}$ (transmission through port one to two), and they are used for complex dielectric permittivity calculation (Agilent Technologies 2005). A frequency range of 3.0–7.0 GHz has been selected to be investigated for analysis, since different types of RS radars such as surveillance, marine control and long-range radars, as well as commercial and air control communication systems are present in this frequency range.

In this paper, authors aim to express a mathematical model for dielectric permittivity of rubber leaves based on both frequency and relative water content, and validate this model with measurements of magnolia leaves. Validation of proposed model with different leaves’ samples is because those two samples are in the same taxonomy. During the expression of mathematical model, phase and amplitude components of $s_{21}$ are used.

2. Measurement campaign

Measurements were held in June and July 2016, and long-term average outdoor reported humidity in our location is about 57% (temperatureweather.com). During measurements, dry bulb temperature was kept in the range of 22–24 °C and dew point was measured as 11 °C. Estimated relative humidity was calculated as 44.01%.

Akdeniz University, Industrial and Microwave Based Microwave Research Center (EMU-MAM) has different capabilities in the field of electromagnetic metrology, radio propagation and electro magnetic compatibility (EMC) and one of them is related to dielectric permittivity measurements. Test facility includes a vector network analyser (9 kHz–9 GHz), waveguides and related adaptors in the frequency range of 3–12 GHz, sample holders and broadband low loss coaxial cables (look at Figure 1). A control and analysing software installed in PC is connected to the measurement facility through general purpose interface bus (GPIB).

Figure 1. Measurement set up.
Figure 2 represents the three-dimensional model of sample holder made up of aluminium frames and Plexiglas sides. Plexiglas sides and sample between them make sandwich-like (three layers) structures as seen in the figure. Different sample holders in related frequency band were designed and integrated to the system. First holder is used in the frequency range of 3.30–4.90 GHz (compatible with WR229 type wave guides), second holder is in 4.90–7.05 GHz range (compatible with WR159 type wave guides) and third one is in 7.05–8.0 GHz range (compatible with WR137 type wave guides). Figure 3 is a picture of holder used in the frequency range of 3.30–4.90 GHz compatible with WR229 type waveguide. There are randomly distributed pores on both of those two Plexiglas sides to guarantee sample leaves to dry homogeneously. Otherwise, randomly drying leaves will twist, and this will make measurements almost impossible, or at least measurement will bring additional errors.

Figure 3. Leaves in the sample holder at S band.
Since rubber and magnolia leaves’ sizes are big enough to fulfill the cross section of any of the waveguides used in the study, it was used 1 single rectangular trimmed leaf as sample. That is why there is no need to use a bunch of leaves or a conglomerate of chopped leaves. To link the dielectric measurements to vegetation water content, samples were taken, cut in holder dimensions and kept in distilled water to be saturated for 24 hours. Data presented in Table 1 are for one of those five rubber samples fit with WR229 type waveguide and one of those five magnolia samples fit with WR159 type waveguide, as an example. It is observed in Table 1 that the weight gain due to water saturation ends at the end of 24 hours for rubber samples and at the end of 18 hours for magnolia samples, since weight deviation (increase) is less than $\pm 0.5\%$ of its previous value beyond these time duration. That is why 24 hours saturated samples are assumed as the one whose water content is 100%.

Finally, a sample is weighted with Plexiglas sides as a starting point. One measurement campaign takes about 5–7 days depending on leaves’ water content, and each campaign ends when final weight deviation (decrease) in dry sample is less than $\pm 0.5\%$ of its previous value. Data presented in Table 2 are for one of those five rubber samples fit with WR229 type waveguide and one of those five magnolia samples fit with WR159 type waveguide, as an example. That is why seven days for rubber and five days for magnolia are assumed as the one whose water content is 0%.

Each day, 2–3 measurement campaigns were held including weight check (current water content), reflection and transmission measurements. Weight of %100 water content called as absolute fresh ($m_{\text{fresh}}$) and dry leaves ($m_{\text{dry}}$) is used to calculate allowable maximum leaf water content (WaC) as in (van Emmerik 2013)

$$\text{WaC} = m_{\text{fresh}} - m_{\text{dry}}$$ (1)

With the help of Equation (1), relative moisture content of leaves ($M_r$) at current situation under investigation can be expressed as in Equation (2) where $m_{\text{measure}}$ is current mass of sample during measurements.

$$M_r = \frac{m_{\text{measure}} - m_{\text{dry}}}{\text{WaC}}$$ (2)

<table>
<thead>
<tr>
<th>Time (hours)</th>
<th>Weight (g)</th>
<th>Deviation (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rubber for WR229 waveguide</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>1,039</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1,207</td>
<td>0,17</td>
</tr>
<tr>
<td>4</td>
<td>1,283</td>
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</tr>
<tr>
<td>6</td>
<td>1,350</td>
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<td>12</td>
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<td>0,00</td>
</tr>
<tr>
<td>36</td>
<td>1,604</td>
<td>0,00</td>
</tr>
</tbody>
</table>

| Magnolia for WR159 waveguide | | |
| 0 | 0,215 | |
| 2 | 0,315 | 0,10 |
| 4 | 0,351 | 0,04 |
| 6 | 0,373 | 0,02 |
| 12 | 0,390 | 0,02 |
| 18 | 0,392 | 0,00 |
| 24 | 0,393 | 0,00 |
| 36 | 0,393 | 0,00 |
Total current density in an environment is defined as the sum of conduction and displacement current densities by Ampere’s law, and electrical conductivity and electric field intensity control the conduction current in a non-magnetic material. The complex dielectric permittivity of a material as a composition of a real part (which quantifies the material capability in storing electromagnetic energy through a polarization in response to their electric susceptibility) and an imaginary part known as the dielectric loss factor (which quantifies the material capability of dissipating electromagnetic energy) is described as in

\[ \varepsilon = \varepsilon' + j\varepsilon'' \]  

Well-known principle formula that uses phase and attenuation in \( S_{21} \) as expressed in Equations (4) and (5) (Trabelsi et al. 2000; Kraszewski & Nelson 2004). Equation (4) is for calculating the real part \([\varepsilon']\) and Equation (5) is for calculating imaginary part \([\varepsilon'']\) of dielectric constant.

\[ \varepsilon' \approx \left(1 + \frac{\Delta\phi \lambda_g}{360d}\right)^2 \]  

\[ \varepsilon'' \approx \frac{\Delta A \lambda_g \sqrt{\varepsilon'}}{8.686\pi d} \]  

Where \( d, \lambda_g, \Delta\phi \) and \( \Delta A \) are the thickness of sample, wave length in waveguide, phase in \( S_{21} \) and amplitude in dB, respectively. Note that, in the equations, both \( \Delta\phi \) and \( \Delta A \) are to be positive (Kraszewski & Nelson 2004). Note that \( \lambda_g \) in Equations (4) and (5) need to be replaced with free space wave length \( \lambda_0 \) in case of free space measurements. Guided wavelength can be calculated by Equation (6), where \( \lambda_c \)is the wavelength at cut-off frequency of selected waveguide.

\[ \frac{1}{\lambda_g^2} = \frac{1}{\lambda_0^2} - \frac{1}{\lambda_c^2} \]
2.1. Removing systematic error

There are two basic approaches to get rid of the systematic error; they are LRM – line reflection method and de-embedding method. De-embedding method uses a model of the test fixture and mathematically removes the fixture characteristics from the overall measurement. This fixture ‘de-embedding’ procedure can produce very accurate results for the non-coaxial device under test (DUT) without complex non-coaxial calibration standards (Agilent Technologies 2004). The process of de-embedding a test fixture from the DUT measurement can be performed using scattering transfer parameters (T-parameter) matrices (Agilent Technologies 1999). For this case, the de-embedded measurements can be post-processed from the measurements made on the test fixture and DUT together. The identical Plexiglas holders (behaves like DUT) need to be measured at related frequency bands for determining its own S-parameters. Meanwhile, both distilled water tag and thin sample hold by holder are needed to be measured as a reference. Finally, de-embedding method is harmonized and interpreted with methods presented in Helhel and Kurnaz (2016).

The line-reflect-match (LRM) calibration method is a technique developed to reduce the size of the calibration set without sacrificing measurement accuracy and subsequently demonstrated in coplanar waveguide. The method uses a compact thru reflect-line calibration set consisting of a short line, a line of moderately longer length and a symmetric reflect to determine the transmission-line characteristic impedance and propagation constant, and also to measure the impedance of an embedded resistor. This information corrects the inherent reference impedance error of an LRM calibration based on the short line, symmetric reflect and embedded resistor, and translates its reference plane accurately (Williams & Schappacher 1995). In this study, LRM has been selected since it is more applicable than the other method.

3. Experimental results

Measurement campaign took about two months, and 160,000 measurements data were collected and analysed. During the analysis, 0.2% of those data (320 of 160,000) were eliminated, since they had been diverging unexpectedly. Five different samples for rubber and five different samples for magnolia leaves for each frequency band were under investigation.

There is no way to guarantee that those samples will lose same weight in same manner and they will have same total weight at the same time. These different WaC values are needed to be averaged for making ease of model generation. This requirement forces us to classify samples having close WaC values. It is because of that, in figures, 68% WaC is classified as 70% WaC, 32% WaC is classified as 30% WaC, and so on. Classifying WaC in groups brings an error tabulated in Table 3 that it is observed as 8.7% at

<table>
<thead>
<tr>
<th>WaC (%)</th>
<th>Rubber</th>
<th>Magnolia</th>
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<tbody>
<tr>
<td>0</td>
<td>0.046</td>
<td>0.042</td>
</tr>
<tr>
<td>30</td>
<td>0.031</td>
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</tr>
<tr>
<td>50</td>
<td>0.033</td>
<td>0.038</td>
</tr>
<tr>
<td>70</td>
<td>0.087</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>0.039</td>
<td>0.041</td>
</tr>
</tbody>
</table>
most for one group. It is assumed that lost information is not valuable for result. Rubber leaves’ data and magnolia leaves’ data within an approximated WaC (like 68%–70%) are averaged in their own group. Standard deviation obtained for each measurement group is tabulated in Table 3.

Figures 4 and 5 indicate the leaf water content (WaC) dependent dielectric constants of rubber leaves (in both real and imaginary parts) with respect to frequency in between 3.3 and 7 GHz. In Figure 5, one may observe that decreasing moisture content results in shifting down an imaginary part of dielectric constant, and there is an inconsistency for absolute dry leaves below 4 GHz from down shifting point of view. For absolute dry leaves, there seems to be phase change in this frequency interval due to the change of physical state of the material. Real part of any sample having a certain WaC drops by

Figure 4. Real part of dielectric constant for rubber leaves.

Figure 5. Imaginary part of dielectric constant for rubber leaves.
~80% of its initial value at 3.3 GHz, and it becomes ~2.0 at 7.0 GHz. This is quite appropriate with literature findings. Observations bring out that imaginary part of samples having different WaC has divergent values at lower frequencies, and they meet around +i0.5 at 7.0 GHz. Beyond 7.0 GHz, it is expected that imaginary part is almost independent of its WaC value.

Figures 6 and 7 indicate the leaf water content (WaC) dependent dielectric constants of magnolia leaves (in both real and imaginary parts) with respect to frequency in between

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**Figure 6.** Real part of dielectric constant for magnolia leaves.

**Figure 7.** Imaginary part of dielectric constant for magnolia leaves.
3.3 and 7 GHz. In Figure 7, one may observe that decreasing moisture content results in shifting down an imaginary part of dielectric constant, and there is an inconsistency for absolute dry leaves below 4 GHz from down shifting point of view. Similar to rubber leaves, there seems to be phase change in this frequency interval. Real part of any sample having a certain WaC drops by \(~75\%\) of its initial value at 3.3 GHz, and it becomes \(~2.0\) at 7.0 GHz. This is also quite appropriate with literature findings as rubber leaves. Observations bring out that imaginary part of samples having different WaC has different values at lower frequencies, and they meet around \(\Im \varepsilon\) at 7.0 GHz. Beyond 7.0 GHz, it is expected that imaginary part is almost independent of its WaC value.

To be in parallel and compared with literature, we have focused on relative dielectric constant. By using the well-known formula \(\varepsilon_r = \sqrt{(\varepsilon')^2 + (\varepsilon'')^2}\), relative dielectric constants of each sample were calculated based on the phase shift and amplitude variation in \(S_{21}\) data. These calculated values are demonstrated in Figures 8 and 9. Plots on the figures show that relative dielectric constant \(\varepsilon_r\) is proportional to \(\approx 1/f^a\), and one may also observe from Figures 8 and 9 that the relative dielectric constant of drying leaves shifts and diverges to smaller values with respect to fresh leaves. Second observation requires adding \(\varepsilon = + k\left(\varepsilon - M_r\right)^3\) parameter into the model, where \(k\) and \(a\) are constants to be determined later. Finally, combining those two observation forces us to write a mathematical expression for a relative dielectric constant as in Equation (7). Rubber data were used for generating and tuning a mathematical expression, and magnolia data were used for validation of our proposed model.

\[
\varepsilon_r = a f^{-\alpha} - k \left(1 - M_r\right)
\] (7)
\( \varepsilon_r, f, M_r, a, \alpha \) and \( k \) are relative dielectric constant, frequency in GHz, relative water content of sample leaf, and parameters to be determined from data analysis, respectively. From the model tuning analysis, \( a = 100.52, \alpha = 1.875 \) and \( k = 4.38 \) were obtained, and Equation (7) has been re-written as in Equation (8). Parameter \( k \) was determined by averaging whole-band difference between 100% WaC and 0% WaC samples, and standard deviation of this averaging is about 0.427.

\[
\varepsilon_r = 100.52 f^{-1.875} - 4.38(1 - M_r)
\] (8)

Figure 9 shows validation measurements, proposed model and models given in the literature, together. Proposed model has 20% deviation through control measurements at most, and it has 10% error in the average of whole-band control data. Red stars are belonging to the corn model #1 of Zhen and colleagues (Trabelsi et al. 2016) at given frequency and certain moisture content. Their proposed model deviates by \( \sim 100\% \) (as observed from Figure 9), since they expressed a model for corn leaves and not for tropical leaves. In the same manner, Ulaby’s model expressed for corn leaves was also applied to same samples investigated in this study, and very big violation is observed, which is figured out as corn model #2.

4. Conclusion

A measurement campaign including Plexiglas sides and sample holders to make sandwich-like (three layers) structures in addition to vector network analyser was designed and set up. Measurements were conducted based on \( s_{21} \) in order to calculate dielectric constant based on phase shift and attenuation.

A mathematical model has been expressed for two tropical plants that they are in the same taxonomy in water content point of view and their origin. Relative dielectric constant expression depending on both water content and frequency was obtained from rubber leaves and verified by magnolia leaves. There is 10% error in the average, and %20
error at most between offered model and control data. Some part of observed error can be expected due to classifying WaC in close groups, and its contribution to total error cannot be more than 8.7%.

Finally, proposed model has been compared with the models proposed for short vegetative (well-known models in the literature), and it results in quite better achievements. One may also conclude that the relative dielectric constant is decaying by $\approx 1/f^2$ and shifts by relative moisture constant $M_r$.

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*Selcuk Helhel* started his carrier with Goltas Cement Factory as a control engineer developing PLC codes in AEG Modicon S5 platform for factory Line-2 modernization project. By January 1994, he joined to Space Technologies Department (to UEKAE in 1996) at TUBITAK as a researcher and spent 5 years of experience on radio telescope design, EMC platforms and facilities, military and civil based EMC Tests including MIL-STD 461-462 and some industrial projects between 1993 and 1998. He got trainee about EMC measurement techniques and EMC perspectives in circuit design at University of Missouri Rolla (USA, 1997). Between 1998 and 2002, he got industrial
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