Effects of Sample Thickness for Dielectric Measurements Using Transmission Phase-Shift Method

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Abstract. This paper re-studies the simple transmission phase-shift method for dielectric measurement of low-loss material. This method is explicit and material position-invariant. However, the sensitivity of transmission phase-shift is dependent on the material thickness. In this study, the effect of material thickness to the predicted relative permittivity of the material has been analyzed quantitatively. The sensitivity measurement was tested using customized X-band rectangular waveguide and three well-known materials, which are acrylic, FR-4 and RT/duroid 5880 substrate. Finally, appropriate thickness of the material in order to provide accurate predicted values of permittivity was determined.

Keywords: Transmission phase-shift, sample thickness, rectangular waveguide, dielectric measurements, sensitivity

1. Introduction

Recently, there has been an increased interest in the determination of dielectric properties of materials at microwave frequencies range. These properties are used in the construction of high-frequency electronic components, the superconducting material, the quality of printed circuit board (PCB) substrate, the efficiency of microwave absorption materials, metamaterial characterizations, food-chemical processing, and the performance of dielectric antenna design appeared to be the main reason that lead to increasing interest.

The complex permittivity ($\varepsilon_r = \varepsilon_r' - j\varepsilon_r''$) and the permeability ($\mu_r = \mu_r' - j\mu_r''$) of the sample filled in the coaxial or rectangular waveguide are obtained by converting the calibrated reflection (S_{11}) and transmission (S_{21}) coefficients by using conventional or improved Nicholson-Ross-Weir (NRW) routines [1-5]. However, by using NRW, the phase of the measured S_{11} and S_{21} is required to be on the position of the calibration reference plane and on consistent position of the sample in the waveguide. Since no calibration kit is available particular for the aperture coaxial waveguide therefore, inconvenience caused in the laboratory evaluations, especially for the measurement using coaxial waveguide.

Recently, a lot of researchers have studied the above material position-invariant issues. Yet, most of these proposed methods require complex mathematical calculations [3-4] or further measurements, such as group delay treatment [5]. In this paper, another alternative method, namely transmission phase-shift (TPS) method [6] is reviewed. The TPS method is a calibration-independent and material position-invariant technique, which can reduce the complexity of the de-embedding procedures without any iterative algorithm. Unlike NRW, the TPS can be applied for the thickness of the material which is exceeded $\lambda/4$. The literature [6] has mentioned that the uncertainty of the predicted relative permittivity is high for the low-loss thin sample by using TPS method due to the decrease of the sensitivity for the transmitted wave through the sample. However, in [6] the samples only with a thickness of 5 mm were considered for measurement and did not discuss the thickness of the thin sample which may affect the uncertainty of measurement using TPS technique which is based on actual measurements and numerical simulation. In accordance with this reason, the TPS method is re-examined in this paper. Various thicknesses of acrylic, FR-4, and RT/duroid 5880 substrate samples are placed in the X-band WR 90 type rectangular waveguide and measured for validation. In this work, the variation in the transmission phaseshift, reflection coefficient, and transmission coefficient with the thickness of the sample are illustrated and analyzed in detail.

2. Review of theory

A TE_{10} mode wave propagates through a homogeneous and isotropic sample slab (material) in which the sample with thickness d is partly placed in a rectangular waveguide. The relative permittivity, ε_r of the sample in the waveguide can be expressed explicitly as [6]:

$$\varepsilon_r' = \frac{1}{k_o^2}\left\{\left(\gamma_o + \frac{\phi_{21\_air} - \phi_{21\_sample}}{d}\right)^2 + \left(\frac{\pi}{b}\right)^2 - \alpha^2\right\} \qquad (1a)$$

$$\varepsilon_r'' = \frac{2\alpha}{k_o^2}\left(\gamma_o + \frac{\phi_{21\_air} - \phi_{21\_sample}}{d}\right) \qquad (1b)$$

where $k_o = 2\pi f/c$ is the propagation constant of free space (c = 2.99792458 ms^{-1}); b (in meter) are the width of the aperture of the waveguide, respectively; d (in meter) is the thickness of the filled sample. The ϕ_{21_air} and ϕ_{21_sample} in (1a) and (1b) are the measured phaseshift of the transmission coefficient in the air (without sample) and the sample, respectively. The phase constant, γ_o for TE_{10} mode propagates in the rectangular waveguide is given as:

$$\gamma_o = \sqrt{k_o^2 - \left(\frac{\pi}{b}\right)^2} \qquad (2)$$

On the other hand, symbol α (in nepers/meter) is the dielectric attenuation constant for the sample as:

$$\alpha \approx -1.15129254 \left[\begin{array}{l} \frac{1}{d}\log_{10}\left(\left|S_{11\_sample}\right|^2+\left|S_{21\_sample}\right|^2\right) \\ -\frac{1}{d_w}\log_{10}\left(\left|S_{11\_air}\right|^2+\left|S_{21\_air}\right|^2\right) \end{array} \right] \quad (3)$$

where $|S_{11\_air}|$, $|S_{21\_air}|$, $|S_{11\_sample}|$, and $|S_{21\_sample}|$ are the measured linear magnitudes of the reflection coefficient and the transmission coefficient for the air (without sample) and sample, respectively. Symbol d_w (= 0.05 m) is the total length of the X-band waveguide.

3. Experimental-setup and measurements

3.1. Rectangular waveguide

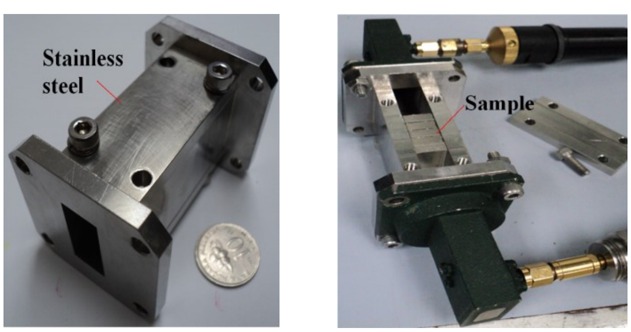
The linear magnitude $|S_{21}|$ and the phase shift ϕ_{21} for air and the sample are measured with an Agilent E5071C vector network analyzer (VNA) from 8.2 GHz to 12.4 GHz using two Flann make 16094-SF40 Model waveguide adaptors and a customized waveguide with length of 5 cm as shown in Figure 1 (a). The customized waveguide is made of steel and one side of the waveguide's wall is allowed to open to insert a sample into the waveguide (Figure 1(b)).

3.2. Thru-reflect-line (TRL) calibration

The thru-reflect-line (TRL) calibration is done on the surface of *AA'* and *BB'* as shown in Figure 2 (a) and (b). Since, the position of the sample in the waveguide is independent on the calibration plane (plane-*AA'* and plane-*BB'*) therefore, the sample of thickness d is placed in any arbitrary position in the rectangular waveguide which does not affect the accuracy of the measurement (in Figure 2 (b)). During the measurement, the sample thickness is increased by adding piece by piece of the sample.

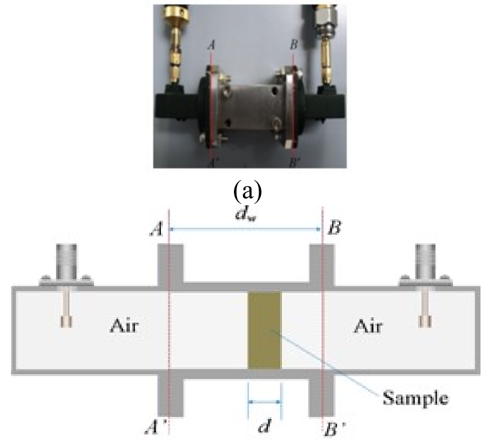
3.3. Slab sample preparation

The acrylic (ε_r' = 2.6, tan δ =0.019 at 10 GHz), FR-4 (ε_r' = 4, tan δ =0.02 at 10 GHz) and RT/duroid 5880 (ε_r' = 2.2, tan δ =0.0009 at 10 GHz) samples (in Figure 3), respectively, are placed in the waveguides and perform the measurement. The dimensions (width: 22.86 mm, height: 10.16 mm) of the samples are precisely machined by using a computer numerical control (CNC) cutter.



(a) (b)

Fig. 1. (a) 5 cm length of customized waveguide. (b) Experimental-setup.



(b)

Fig. 2. (a) Experimental setup. (b) Cross-section of a filled sample of d thickness at arbitrary position in the waveguide.

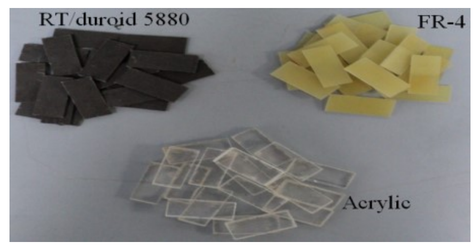
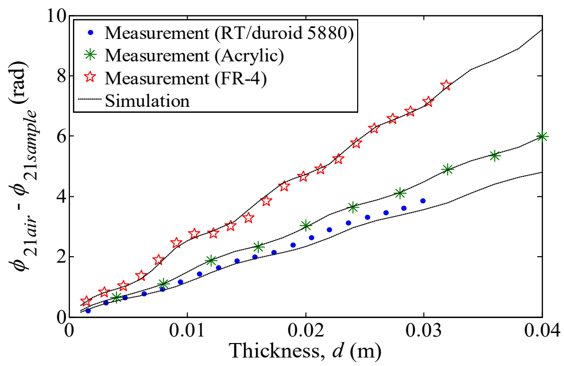


Fig. 3. RT/duroid 5880 substrate, Acrylic, and FR-4 samples.

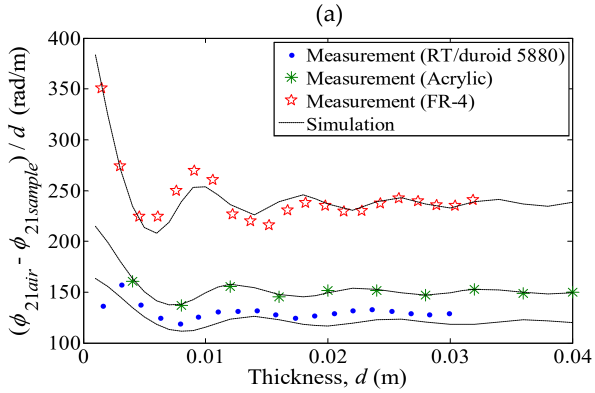
4. Results and analysis

The variation of differential transmission phase shift ϕ_{21_air} - ϕ_{21_sample} (in radians) between air and the sample with the sample thickness d at 10 GHz is shown in Figure 4 (a). The measured ϕ_{21_air} - ϕ_{21_sample} is compared to the simulated results using COMSOL Multiphysics for validation. It is found that the ϕ_{21_air} - ϕ_{21_sample} is less pronounced between different samples when the thickness of the samples is thin (d < 0.005 m). Nevertheless, the ϕ_{21_air} - ϕ_{21_sample} increases linearly with the thickness d of the samples which is due to the phase delay of the TE_{10} mode wave in the sample becomes larger in comparison to the air-filled waveguide. Besides thickness factor, the differential phase is more significant for the sample with high permittivity.

On the other hand, in Figure 4 (b), the differential phase shift divided by corresponding sample thickness d is presented. Clearly, the values of (ϕ_{21_air} - ϕ_{21_sample})/d for the three different samples show the instability at the beginning and become constant when the thickness increased. For a thin sample, coupling fringing field between the front and back of the surface sample is likely to occur, and the TE_{10} mode wave propagates in the thin sample are disturbed by this effect. Thus, the TE_{10} wave characteristics in the thin sample are not stable and inaccurate to predict the dielectric properties of the sample. In addition, for a very thin sample, the uncertainty of the small value of d is high. Hence, indirectly, the uncertainty in the determination of the ε_r for the thin sample based on transmission phase-shift is significantly increased.



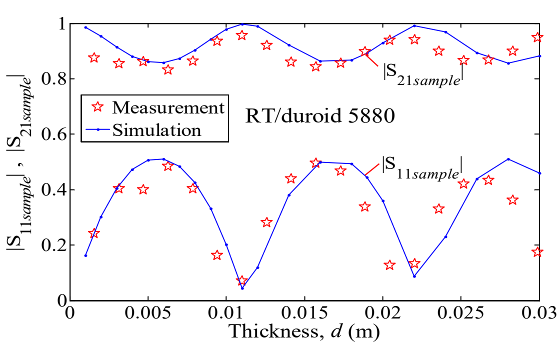
(a)



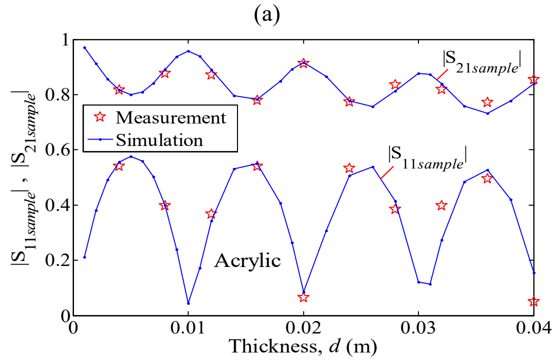
(b)

Fig. 4. The measured transmission phase-shift for RT/duroid 5880, Acrylic, and FR-4 at 10 GHz.

Figure 5 (a), (b) and (c) shows the measured $|S_{11\_sample}|$, $|S_{21\_sample}|$ and COMSOL simulation results at plane-*AA'* and -*BB'* for the three different samples at 10 GHz. The overall measured $|S_{11\_sample}|$ and $|S_{21\_sample}|$ indicate a good agreement to the simulated results.



(a)



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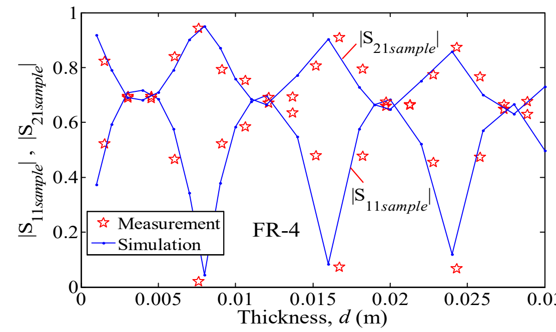
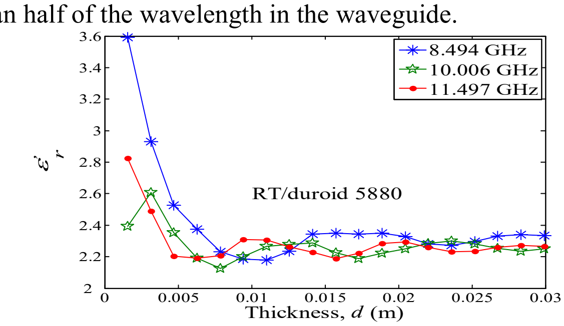


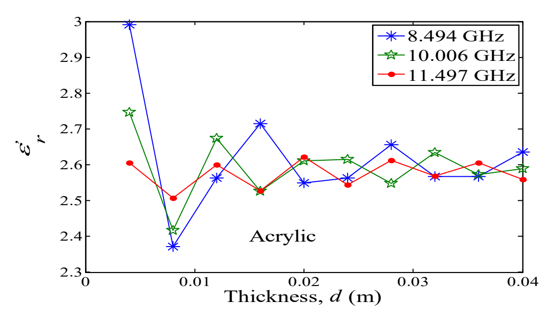
(c)

Fig. 5. The measured $|S_{11\_sample}|$ and $|S_{21\_sample}|$ for RT/duroid 5880, Acrylic, and FR-4 at 10 GHz.

Figure 6 (a), (b) and (c) show the predicted dielectric constant, ε_r' of the three samples using equation (1a) at 8.494 GHz, 10.006 GHz and 11.497 GHz, respectively. Clearly, the TPS method is capable of providing a stable and accurate measurement of operating frequency in X-band range when the thicknesses of the samples have exceeded 2 cm or more than half of the wavelength in the waveguide.



(a)



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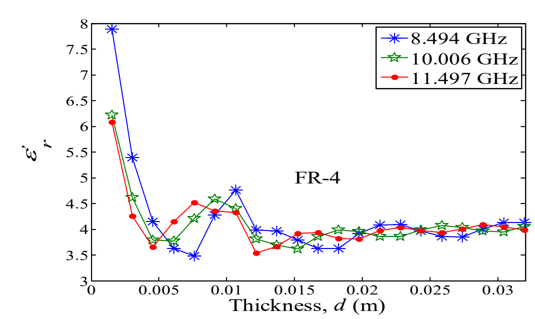
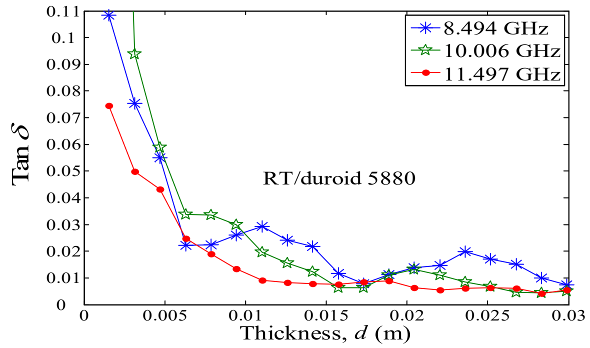


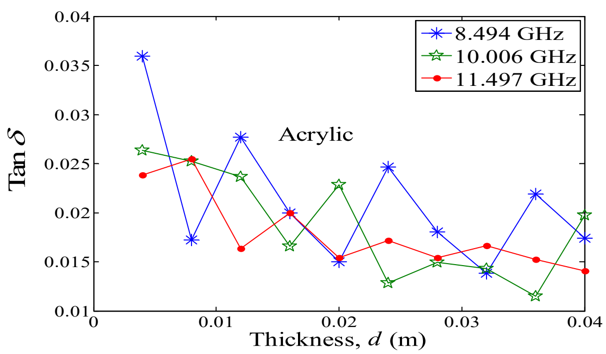
(c)

Fig. 6. Variations in relative dielectric constant, ε_r' with the thickness layer of (a) RT/duroid 5880 substrate, (b) acrylic, and (c) FR-4, respectively.

Figure 7 (a), (b) and (c) show the predicted loss tangent, tan δ (= $\varepsilon_r''/\varepsilon_r'$) of the three samples using equation (1b). Based on the results, the resolution of the measured tan δ can only achieve up to 5×10^{-3}.



(a)



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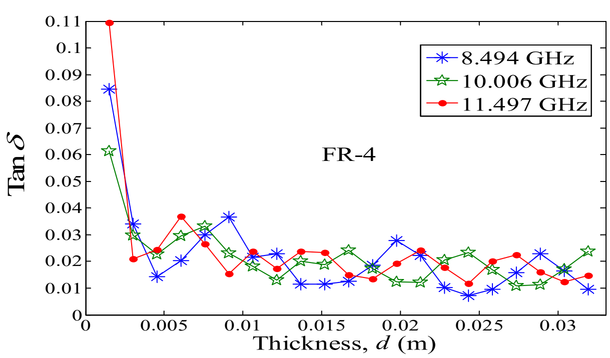

(c)

Fig. 7. Variations in loss tangent, tan δ with the thickness layer of (a) RT/duroid 5880 substrate, (b) acrylic, and (c) FR-4, respectively.

5. Conclusion

The equations (1a) and (1b) can provide wideband calibration-independent and material position-insensitive techniques for measuring the dielectric properties of materials. The stability and accuracy of the dielectric measurement can be achieved for the thick sample.

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Biography of the authors

Kok Yeow You was born in 1977. He obtained his B.Sc. Physics (Honours) degree in Universiti Kebangsaan Malaysia (UKM) in 2001. He pursued his M.Sc. in Microwave at the Faculty of Science in 2003 and his Ph.D. in Wave Propagation at the Institute for Mathematical Research in 2006 at Universiti Putra Malaysia (UPM). Recently, he is a Senior Lecturer at Communication Engineering Department, Faculty of Electrical Engineering, Universiti Teknologi Malaysia (UTM). His main personal research interest is in the theory, simulation, and instrumentation of electromagnetic wave propagation at microwave frequencies focusing on the development of microwave sensors for material characteristics, medical and agricultural processing.