International Journal of Engineering &Technology, 7 (4) (2018) 6171-6174

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET
doi: 10.14419/ijet.v7i4.23127
Research paper

Design, construction and validation of a planar probe for measuring complex relative permittivity of materials

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Abstract

A planar probe for inspecting the complex relative permittivity of materials was redesigned and constructed in this research. The proposed planar probe was made of the Arlon AD260A PCB with the coaxial and microstrip structure. Experiments were conducted in the frequency range of 0.5-6 GHz. Ethanol and methanol were used as samples to validate the probe. It was found that the complex relative permittivity of the samples had a good tendency to the references in the frequency range of 0.5-2 GHz. Moreover, this redesigned probe provided improved accuracy on the measurement compared to the conventional planar probe.

Keywords: *Planar Probe; Complex Relative Permittivity; Microstrip; Coaxial.*

1. Introduction

Complex relative permittivity is an important dielectric property of materials which describes the interaction or polarization of materials with an electric field. This parameter is necessary for modeling and studying the behavior of materials. Moreover, it can be used for classifying materials [1]-[2].

Therefore, many researchers have studied and invented methods and tools to inspect the complex relative permittivity of materials, i.e., free space [3]-[4], waveguide [5]-[6] and open-ended coaxial [7]-[8], etc. However, the open-ended coaxial technique is widely used because a commercial open-ended coaxial probe exists. Although using a coaxial probe to investigate complex relative permittivity is attractive and has many advantages, the size of the commercial probe is small and it is expensive. Moreover, the fabrication of the probe is complicated and the cost of production increases with decreasing dimension of the probe. Therefore, a new probe is developed by applying a microstrip transmission line with a coaxial feature, called a planar probe. The novel probe provides real time and reliable measurement, low cost of production and easy fabrication. Many researchers [9]-[12], have used this new probe to measure the dielectric properties of solutions but the size of the probe is still small and difficult for handmade fabrication. In 2016, a planar and large-sized probe was developed that could be fabricated more easily, in order to measure complex relative permittivity of concrete specimens. For probe design, researchers used a dielectric constant of air (ε_r=1) to calculate the parameters of coaxial feature. The measured frequency range of this research was 0.5-3.5 GHz. Although, the complex relative permittivity of solutions in probe calibration had a tendency to the references, the accuracy of the obtained complex relative permittivity was low [13]-[14].

In this paper, the planar probe was redesigned using a dielectric constant (ε_r) of 2.6 to calculate the parameters of the coaxial feature. The complex relative permittivity of ethanol and methanol was investigated using the redesigned probe. The frequency range obtained experimentally was 0.5-6 GHz. The obtained complex relative permittivities of the samples were compared with the results from the previous study [13] and the literature.

2. Materials and methods

2.1. Planar probe design

The proposed probe was made of the Arlon's AD260A printed circuit board (PCB). The structure of the AD260A includes top and bottom conductors and a substrate placed between the conductors as illustrated in Figure 1. The dielectric constant and thickness of a substrate were 2.6 and 1 mm, respectively. The thickness of both conductors was 0.0175 mm. The proposed probe had the same shape and size as the probe used in the previous study [13]; a square shape of 10×10 cm. The structure of the proposed probe consisted of a microstrip transmission line and coaxial features as shown in Figure 1.

A microstrip of this probe was designed same as the previous probe [13] with a characteristic impedance of 50 Ω. The structure of microstrip line consisted of strip, substrate and ground plane as illustrated in Figure 1 (A). The strip width (W) of the microstrip was designed by using the equation (1) and (2) [13].

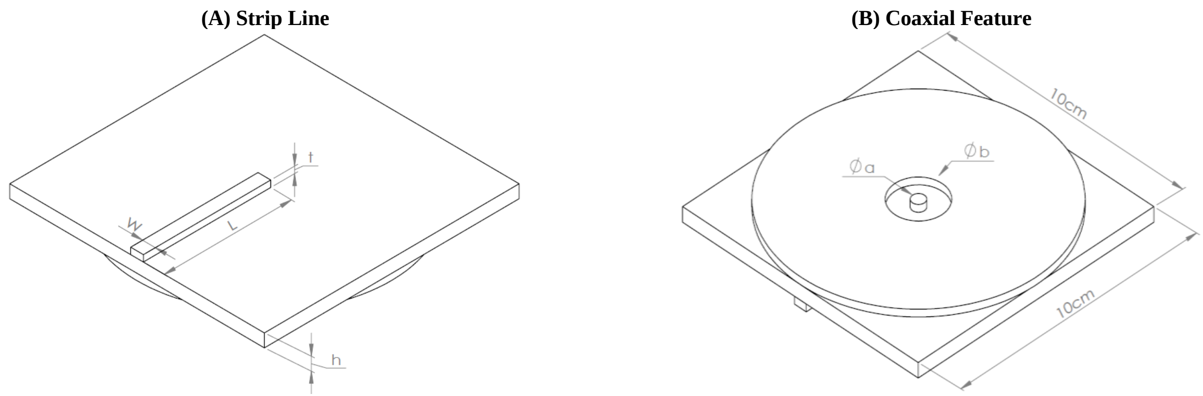

Fig. 1: Structure of Proposed Probe.

For the $\frac{W}{h}$ ratio is greater than or equal to 1 ($\frac{W}{h} \geq 1$);

$$\varepsilon_{eff} = \frac{\varepsilon_{r1}+1}{2} + \frac{\varepsilon_{r1}-1}{2}\left(1+12\frac{h}{W}\right)^{-0.5}$$
(1)

$$Z_0 = \frac{120\pi}{\sqrt{\varepsilon_{eff}}}\left[\frac{W}{h} + 1.393 + 0.667\ln\left(\frac{W}{h}+1.444\right)\right]^{-1}$$
(2)

where ε_{r1} is the dielectric constant of a substrate, W is the strip width, h is a substrate thickness, ε_{eff} is the effective dielectric permittivity and Z_0 is the characteristic impedance of the microstrip.
The coaxial structure, shown in Figure 1 (B), consisted of inner conductor, dielectric material and outer conductor and was designed with a characteristic impedance of 50 Ω calculated from (3) [13].

$$Z_c = \frac{60}{\sqrt{\varepsilon_{r2}}}\ln\left(\frac{b}{a}\right)$$
(3)

where Z_c is the characteristic impedance of the coaxial structure, a is the diameter of an inner conductor, b is the internal diameter of an outer conductor, and ε_{r2} is the dielectric constant of a dielectric material between two conductors.
In the previous study [13], the dielectric constant (ε_{r2}) of the coaxial was 1 because copper in this section was removed and there remained only air between the inner and outer conductors with the same thickness. However, the thickness of the air part or dielectric material of the coaxial was only 0.0175 mm which was thin. This meant that a dielectric constant (ε_{r2}) of the coaxial should be a dielectric constant of a substrate rather than a dielectric constant of air. Therefore, this study used a dielectric constant (ε_{r2}) of 2.6 to find diameters of the coaxial.
The 2.8 mm via-hole filled with lead was used to connect a microwave signal from the microstrip to an inner conductor of the coaxial. All parameters used in and obtained from the calculations are presented in Table 1.

Table 1: Parameters of the Proposed Probe

Feature	Parameters
Microstrip	Z_0 = 50Ω, ε_{r1} = 2.6, h = 1 mm, t = 0.0175 mm, ε_{eff} = 2.148, W = 2.8 mm, L = 51.4 mm
Coaxial	Z_C = 50Ω, ε_{r2} = 2.6, a = 3 mm, b = 11.49 mm

2.2. Experimental setup

The fabricated probe is shown in Figure 2. The proposed probe connected to the Keysight E5071C ENA series network analyzer via a SMA connector and coaxial cable which had characteristic impedance of 50 Ω as illustrated in Figure 3. The experimental setup used to validate the probe is shown in Figure 4. The experiment was conducted at the frequency range of 0.5 - 6 GHz. The samples were ethanol and methanol. Air, methanol and distilled water were used as the reference materials if the sample was ethanol. Air, ethanol and distilled water were used as the reference, when the sample was methanol. The temperature of the samples and references was 25°C. The reflection coefficients (Γ) reflected from samples and reference materials to the network analyzer were used for determining the complex relative permittivity of the samples as indicated in (4), [13].

$$\frac{(\varepsilon_s-\varepsilon_A)(\varepsilon_B-\varepsilon_C)}{(\varepsilon_s-\varepsilon_B)(\varepsilon_C-\varepsilon_A)} = \frac{(\Gamma_s-\Gamma_A)(\Gamma_B-\Gamma_C)}{(\Gamma_s-\Gamma_B)(\Gamma_C-\Gamma_A)}$$
(4)

where, ε_A, ε_B, and ε_C are the complex relative permittivity of the reference materials, ε_s is the complex relative permittivity of the sample and Γ_A, Γ_B, Γ_C and Γ_S are the reflection coefficients of the references and sample, respectively.
The complex relative permittivities of the references were defined from parameters in Table 2 and the Cole-Cole equation as pointed in (5) [13].

$$\varepsilon_r = \varepsilon_\infty + \frac{\varepsilon_s-\varepsilon_\infty}{1+(j\omega\tau)^{1-\alpha}}$$
(5)

where ε_∞ is the relative permittivity at an infinite frequency, ε_s is the relative permittivity at a static frequency, ω is the angular frequency (rad/s), τ is the relaxation time and α is the distribution parameter of the relaxation time.
The obtained complex relative permittivities of the samples were compared to the results from the previous study and the references [13].

Table 2: Parameters of the Reference Materials at 25°C [13]

Parameters	Reference materials			
	Distilled water	Ethanol	Methanol	Air
ε_∞	4.22	3.91	4.45	ε_r = 1
ε_s	78.6	21.4	33.7	
τ (ps)	8.8	980.39	49.5	
α	0.013	0.03	0.036	

(A) Coaxial Feature **(B) Strip Line**

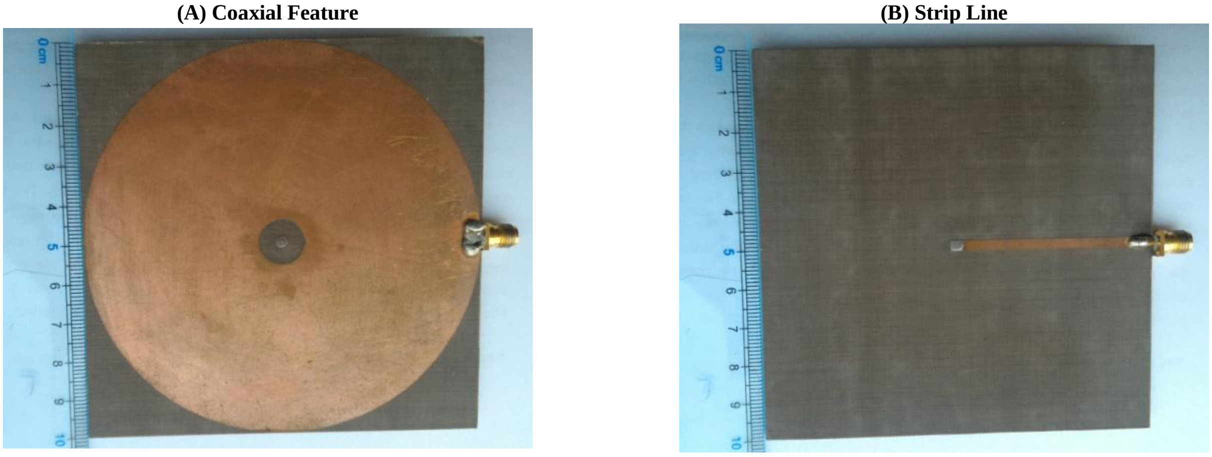

Fig. 2: Fabricated Probe.

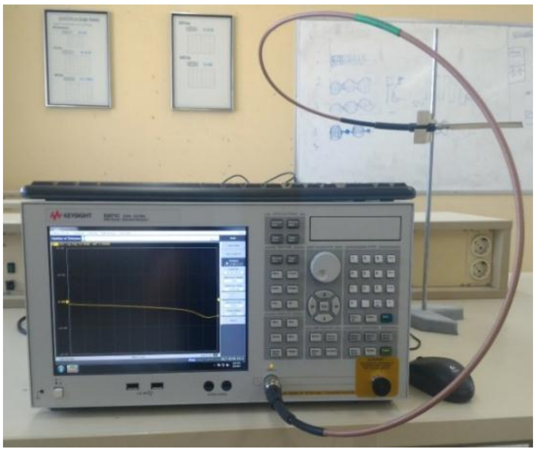

Fig. 3: Connection of the Vector Network Analyzer, SMA Connector and Coaxial Cable.

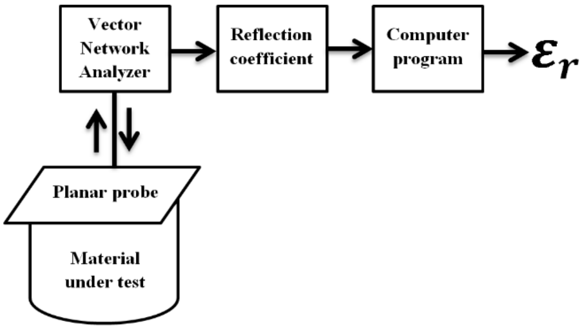

Fig. 4: Experimental Setup for Determining the Complex Relative Permittivity of the Samples.

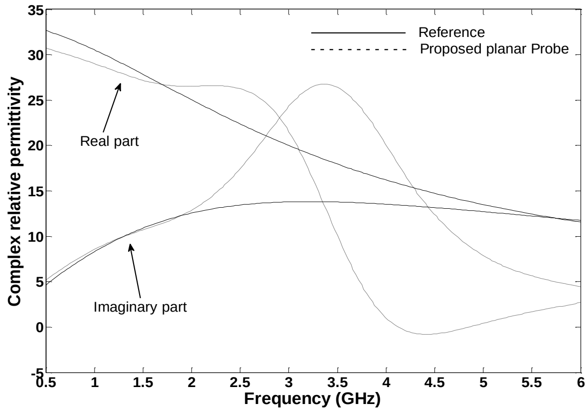

Fig. 5: Comparison of the Complex Relative Permittivity of Methanol from the Experiment and Reference.

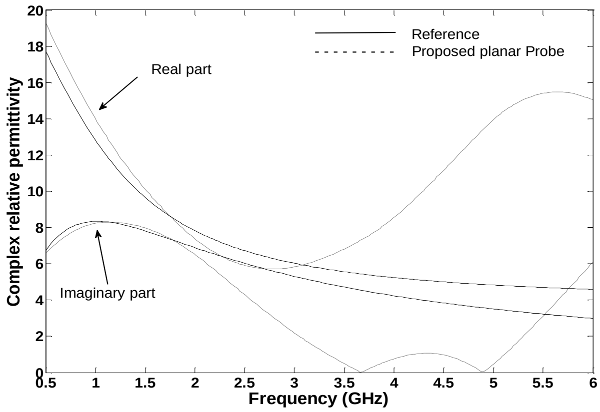

Fig. 6: Comparison of the Complex Relative Permittivity of Ethanol from the Experiment and Reference.

3. Results and discussions

The experiment was conducted in the frequency range of 0.5 - 6 GHz following the experimental setup in the previous section. The results are illustrated in Figure 5 – 8.

Figure 5 presents the comparison of the complex relative permittivity of methanol from the experiment and reference. Figure 6 shows the comparison of the complex relative permittivity of ethanol from the experiment and reference. The results indicated that the obtained complex relative permittivity of methanol and ethanol agrees closely with the references in the frequency range of 0.5 - 2 GHz.

Figure 7 presents the comparison of the complex relative permittivity of methanol from the experiment, previous study and reference. Figure 8 shows the comparison of the complex relative permittivity of ethanol from the experiment, previous study and reference. The results indicated that the complex relative permittivity of methanol and ethanol from this experiment and previous study yielded results consistent with the references. The conventional planar probe [13] can perform in the frequency range of 0.5 – 3.5 GHz which is wider than the frequency range of the novel probe. However, the accuracy of measurement with the conventional planar probe is less than that of the proposed probe in the frequency range of 0.5 – 2 GHz.

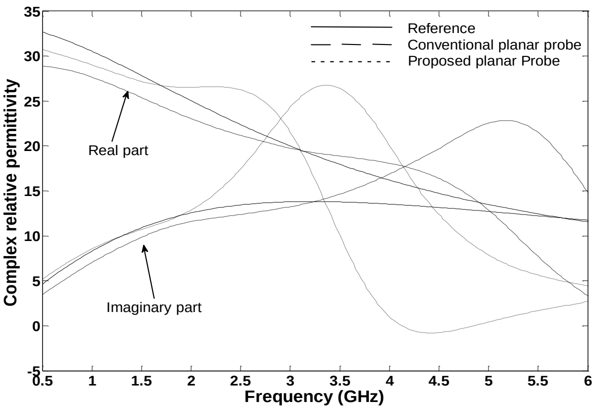

Fig. 7: Comparison of the Complex Relative Permittivity of Methanol from the Experiment, Previous Study and Reference.

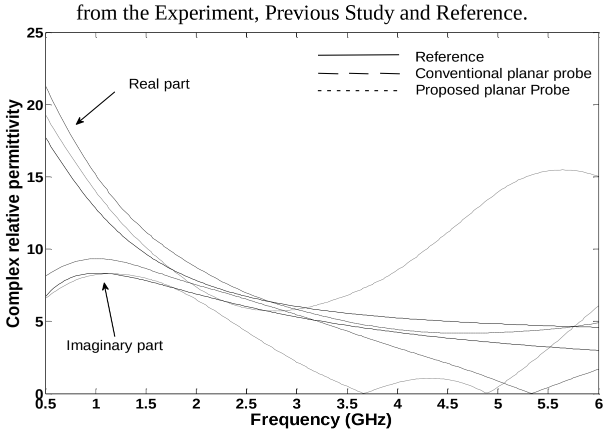

Fig. 8: Comparison of the Complex Relative Permittivity of Ethanol from the Experiment, Previous Study and Reference.

4. Conclusion

In this paper, a measurement of the complex relative permittivity of materials using a planar probe has been reported. The planar probe was redesigned from a previous study by changing a dielectric constant of dielectric material in the calculation of the coaxial. The proposed planar probe can work properly in the frequency range of 0.5 – 2 GHz and the measured values are in good agreement with the references. The results also indicate that the proposed planar probe provided more accuracy of measurement than the conventional planar probe in the frequency range of 0.5 – 2 GHz. Therefore, the planar probe in this study is suitable for measuring the complex relative permittivity of materials in the frequency range of 0.5 – 2 GHz.

Acknowledgement

This research was financially support by Mahasarakham University grant year 2018. The authors would like to thank you for the equipment and tools support from the Research Unit for Computational Electromagnetics and Optical Systems (CEMOS), the Faculty of Engineering, Mahasarakham University, Thailand. The authors would like to express our appreciation to Dr. Adrian Roderick Plant for language editing and suggestions to improve the manuscript.

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