# DIELECTRIC MEASUREMENT BASED ON MICROSTRIP TRANSMISSION LINE

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*For my beloved mother and father;*

*Fadzilah Binti Omar and Ikhsan Bin Omar*

*Siblings;*

*Irna Farhana Binti Ikhsan and Anis Sofea Binti Ikhsan*

*Supervisor;*

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# ABSTRACT

The measurement of complex dielectric properties of materials at radio frequency is very important especially in the research fields, such as material science, microwave circuit design, absorber development, biological research, etc. Dielectric measurement is important because it can provide the electrical and magnetic characteristics of the materials, which proved useful in many research and development fields.The proposed technique present a simple microstrip transmission line method for the broadband radio frequency characterization of dielectric constant of non-dispersive materials. A microstrip line having impedance other than 50 Ω is designed and material under test is used as the substrate. The impedance mismatch between a non-50 Ω characteristic impedance of the microstrip line and 50 Ω coaxial to microstrip connectors generates significant reflection/transmission at the input ports. The mismatch between the input impedance and port is used to extract the dielectric constant of the substrate. For experimental validation, the microstrip trace is sticked on the test substrate which are FR4, Teflon and Roger 5880. During the measurement, the microstrip line is connected to vector network analyser through SMA connectors. It is found that this technique introduce error of 10.83%, 7.53% and 21.32% for FR4, Teflon and Roger 5880 respectively. On the other hand, the comparison with the experimental measurement shows 13.5%, 52.95% and 31.40% of error for FR4, Teflon and Roger 5880 respectively. The future research, can focus on measuring the dielectric properties of dispersive material including its loss factor material based on Kramers-kronig relationship.

.

# ABSTRAK

Pengukuran sifat-sifat dielektrik kompleks bahan-bahan pada frekuensi radio sangat penting terutamanya dalam bidang penyelidikan, seperti sains bahan, reka bentuk litar gelombang mikro, pembangunan penyerap, penyelidikan biologi, dan sebagainya. Pengukuran dielektrik adalah penting kerana ia dapat memberikan ciri-ciri elektrik atau magnetik bahan yang terbukti berguna dalam banyak bidang penyelidikan dan pembangunan. Teknik yang dicadangkan menyediakan kaedah talian penghantaran mikrostrip mudah untuk pencirian kekerapan radio jalur lebar bagi pemalar dielektrik bahan bukan penyebaran. Garis mikrostrip yang mempunyai impedans selain 50 Ω direka bentuk dan bahan di bawah testis digunakan sebagai substrat. Keserasian impedans antara impedans bukan 50 Ω ciri garis mikrostrip dan 50 koordinat coaxial kepada penyambung microstrip menjana reaksi / penghantaran yang penting pada pelabuhan input. Ketidaksamaan antara impedans input dan port digunakan untuk mengekstrak pemalar dielektrik substrat. Untuk pengesahan percubaan, struktur mikrostrip dibuat di substrat ujian yang FR4, Teflon dan Roger 5880. Semasa pengukuran, garis mikrostrip disambungkan ke penganalisis rangkaian vektor melalui SMA. Berdasarkan perbandingan keputusan simulasi dengan teoretikal pemalar dielektrik, didapati teknik ini memperkenalkan kesilapan 10.82%, 7.53% dan 21.32% untuk FR4, Teflon dan Roger 5880 masing-masing. Sebaliknya, perbandingan dengan pengukuran eksperimen menunjukkan 13.5%, 52.95% dan 31.40% kesilapan untuk FR4, Teflon dan Roger 5880 masing-masing. Pada masa akan datang, penyelidikan dalam tajuk kajian ini boleh memberi tumpuan kepada mengukur sifat dielektrik bahan dispersif termasuk bahan kehilangan faktor berdasarkan Kramers-kronig.

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## LIST OF SYMBOLS AND ABBREVIATIONS

| | | |
|---|---|---|
| $\Omega$ | - | Ohm |
| RF | - | Radio Frequency |
| NRW | - | Nicolson- Ross Weir |
| CST | - | Computer Simulation Technology |
| $\mathcal{E}_r$ | - | Dielectric Constant |
| $\delta$ | - | Loss tangent |
| $t$ | - | Sample of thickness |
| $r$ | - | Reflection coefficient |
| $k_c$ | - | Waveguide cut off |
| $C_o$ | - | Free space of capacitance |
| $t$ | - | Sample thickness |
| $Z_o$ | - | Characteristic impedance |
| $\epsilon$ | - | Complex relative permittivity |
| $\varepsilon_o$ | - | Free space permittivity |
| $\mu_r$ | - | Complex permeability |
| VSWR | - | Voltage standing wave ratio |
| PCB | - | Printed circuit board |
| TRL | - | Thru, reflect line |
| $l$ | - | Length |
| SMA | - | SubMiniature version A |
| $h$ | - | Substrate height |
| $w$ | - | Substrate width |
| $wd$ | - | Trace width |
| $E_t$ | - | Transmitted electric field (V/m) |
| $H_t$ | - | Transmitted magnetic field (A/m) |
| $Z_{in}$ | - | Port impedance |

| | | |
|---|---|---|
| $\beta$ | - | Propagation constant |
| $\varepsilon_{real}$ | - | Real part of complex permittivity |
| $f_m$ | - | Minima frequency |
| $f_n$ | - | Maxima frequency |
| VNA | - | Vector network analyzer |
| $\varepsilon_{r\ eff}$ | - | Effective dielectric constant |
| q | - | Filling factor |

# CHAPTER 1

# INTRODUCTION

## 1.1. Project Background

Dielectric characterization in the radio frequency (RF) and microwave frequency region is significance in industrial applications to improve the design, process, and quality of product [1]. One of the dielectric properties is complex permittivity, it describes the ability of a material to store energy when an external electric field is applied on it. It is important in defence and aerospace industry, when developing stealth technology, radomes and material that absorb radiation. Besides, dielectric characterization is also important for composite and ceramic used in car parts, plastics and polymer for insulation, films and fibers and hydrogels used in contact lens [1]. In food sector, dielectric properties measurement technique is important in the creation of microwaveable food when packaging [1]. In forestry, dielectric measurements are used to identify the moisture content in wood and paper [2], while in mining, they help analyze the contents of oil [2]. While in the pharmaceutical industries, the dielectric properties is used for drug research and manufacturing [2]. Dielectric properties are important for human tissue characterization, fermentation and biomass system design and bio-implant research [2].

There are various type of techniques for dielectric measurement based on coaxial probe, transmission line, free space, resonant cavity, parallel plate and planar transmission. These technique can be divided into two main categories which are resonant and non-resonant.

The resonant methods characterize the dielectric properties at discrete frequency point. One of its limitation is rigorous sample preparation, especially for conventional metallic cavity [1]. Hence split cylinder technique are used to overcome this limitation. In this technique, a sample is placed in the gap between the two halves of the cavity sections. The advantage of the split cylinder method is only planar sample are required which extend sufficiently far beyond the walls of the two cylindrical waveguide sections [10]. In other words, no sample machining is needed, and this is making this method more accurate. In perturbation method, the sample is placed into a resonant cavity that will causes the perturbation and resulting resonant frequency shift [1]. This method is suitable for lower and moderate-loss samples.

The characterization of sample for non-resonant method is over a wider band of radio frequency. The non-resonant method are based on the measurement of reflections and transmission coefficient of the test sample over the specified frequency range [11]. Hence, rectangular dielectric waveguide is used. Usually this technique is used to determine the dielectric constant of material from effective refractive index measurement [36]. To measure the sample, the material under test is placed between two dielectric waveguide. The material under test can be in arbitrary shape, but the transverse dimension must greater than or same size with the transverse dimension of the dielectric waveguide [5]. In this technique, the dielectric constant is calculated from the refractive index measurement by using S-paramater, which is the effective complex permittivity is calculated from the Nicolson-Ross and Weir(NRW) method. The NRW method has some difficulty such as phase uncertainty, reflection minima and accurate knowledge of the reference plane, but this approach has a good effect to characterize the metamaterial elements used in many antennas [13]. The researcher has been use NRW method to establish a relationship between the S-parameters of a measured system, and the properties of the permittivity and permeability extracted from the S-parameters. The advantages of using this method are non-destructive, quick and simple. Besides, issues of sensitivity and measurement error also has been solved. In addition, open ended transmission line technique is also one of method in non-resonant [38]. Usually this technique is to determine the dielectric properties of materials. In this technique, the material is placed against the cut-off section of the transmission line. But this technique has limitation, which are only can be used to measure high dielectric constant and loss sample and require the calibration references plane to obtain probe aperture.

## 1.2. Problem Statement

There are several factors that must be considered when choosing the suitable dielectric measurement such as operating frequency range, required accuracy, temperature, material nature, sample size, thickness, contacting, non-contacting, destructive, non-destructive and cost. Beside planar transmission line, there are other dielectric measurement technique such as coaxial probe, transmission line (waveguide), free space method, resonant cavity method and parallel plate method [1]. The main drawbacks regarding coaxial probe method is the air gaps between the probe and the liquid to be tested [5]. Besides, the sample must be thick, semi-infinite and much larger than diameter of the aperture of coaxial probe [14]. While, the drawbacks of transmission line (waveguide or coaxial line) are measurement accuracy is limited by the air-gap effects and limited to low accuracy. When the sample length is the multiple of one-half wavelength of the material [6]. For resonant cavity method, the drawbacks are the measurement is conducted at single frequency which is suitable for small sizes sample [2]. Besides that, the sample preparation process is complicated. The drawbacks of free space method is it needs large and flat sample under test. Other than this, the multiple reflections between antenna and surface of sample and diffraction effects at the edge of sample can cause measurement inaccuracy [4].

Therefore, in order to overcome these limitations in the dielectric measurement, in this work, a dielectric measurement method base on microstrip transmission line is presented. In this technique, a conducting tape is pasted on the surface of material under test. The mismatch between the input impedance and port is used to extract the dielectric constant of material under test. The sample that involve in this experiment are FR4, Teflon and Roger 5880. The advantages of this technique is it free from the phase uncertainty problem, which is the main concern in conventional broadband microwave characterization techniques. Besides, this technique is simple and easy to prepare material under test. It is suitable for industrial application because of compactness of the structure and. This proposed method does not required any extra calibration and no special sample handling with low manufacturing cost.

### 1.3. Project Objectives

This study embarks on the following objectives:

1. To stimulate S-parameter of microstrip line with different substrate in Computer Simulation Technology (CST) microwave studio.
2. To propose a dielectric measurement technique based on microstrip transmission line from 0.1 GHz to 10 GHz.
3. To measure the dielectric constant of FR4, Teflon and Roger 5880 based on the proposed technique.

### 1.4. Project Scopes

1. This project only focus on non-dispersive material such as FR4, Teflon and Roger 5880.



### 1.5. Organization of the Thesis

This thesis is organized in five individual chapter. Chapter 1 presents the project background of the study, problem statement, objective of the study and project scope. Chapter 2 introduce the literature review related to this research and some basic understanding about dielectric measurement techniques. Next in chapter 3, it describes the flow of the research including process of the sample preparation, effective permittivity calculation, mathematical formulation, simulation, fabrication and measurement setup. Chapter 4 focused on result based on the simulations with CST and experimental measurement. The findings of the result are discussed. Finally chapter 5 concludes the research and proposes future works for this research.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1. General

There are various technique of dielectric measurement of microwave dielectric properties (relative complex permittivity also known as dielectric constant, real part and loss tangent. It is very important to choose the correct choice of microwave measurement technique as there are various techniques are available and restriction exist in the techniques. The chosen measurement technique would depend on the values of real and imaginary part of permittivity and the dimension of the measured sample [15]. Some significant factor to choose the microwave measurement technique:

1) Have a good accuracy for complex permittivity and tangent loss.
2) Measurement procedure is simple and easy.
3) The required sample dimension is small and non-destructive measurement.
4) The measured frequency range is wide and has capability of swept frequency.

There are two type of microwave measurement techniques which are non-resonant and resonant technique. Non-resonant technique can be used to obtain the real part of permittivity of a high and low loss specimen but have limitation to measure low loss tangents [15]. Besides, non-resonant has swept frequency ability for the frequency range. The non-resonant technique can be divide into two categories which are distributed impedance method and lumped impedance method. While for resonant techniques, it also divided into two categories which are dielectric resonance technique and cavity resonant techniques [5] – [15]. This resonant method have their own advantages which is have higher accuracy of measurement and also several limitation in this method. The disadvantages of the dielectric resonance technique are do not have capability of frequency sweep and calculation of dielectric properties is complicated [15].

## 2.2. Non-resonant Method

There are various non-resonant techniques for measuring the dielectric properties of dielectric samples. In non-resonant methods, from the impedance and velocity of material, dielectric properties, permittivity and permeability can be derived from the partial reflection of an incident wave from the interface between two materials. In such a method a transmission line is needed to direct the wave to the material under test and then collect the reflected and/or the transmitted energy [16]. This transmission line can be coaxial, metallic waveguide, dielectric waveguide, planar transmission line and free space. As mentioned, the advantage of the non-resonant techniques is the swept frequency capability and non-resonant techniques can be further divided into two categories which are the distributed impedance technique and the lumped impedance technique [15].

For distributed impedance method, S11 and S21 parameters are measured for the calculation of dielectric properties [15] – [18].

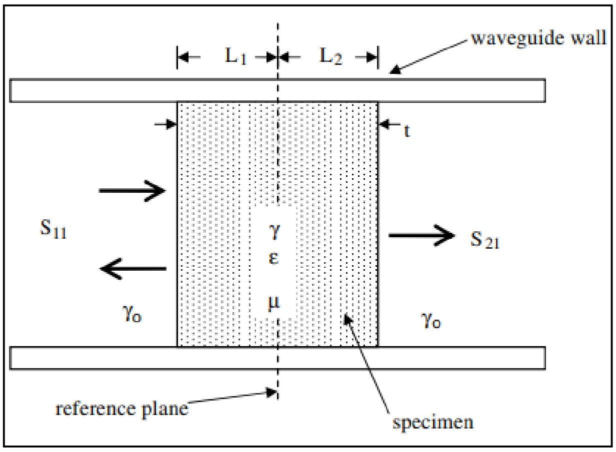


Figure 2.1: Distributed transmission technique [15].

Figure 2.1 shows that rectangular waveguide is as holder so dielectric sample can be bounder by the holder while the arrow is indicate as the direction of signal flows and measurement parameter for transmission signal, $S_{21}$ and reflection signal, $S_{11}$. These signal can be expressed as [15], [21]

$$S_{11} = R_1^2 r \frac{1-z^2}{1-r^2z^2} \tag{2.1}$$

$$S_{22} = R_2^2 r \frac{1-z^2}{1-r^2z^2} \tag{2.2}$$

$$S_{21} = R_1 R_2 z \frac{1-r^2}{1-r^2z^2} \tag{2.3}$$

$$R_1 = e^{\gamma_o L_1} \tag{2.4}$$

$$R_2 = e^{\gamma_o L_2} \tag{2.5}$$

$$z = e^{-\gamma t} \tag{2.6}$$

$$r = \frac{\gamma_o/\gamma - 1}{\gamma_o/\gamma + 1} \tag{2.7}$$

$$\gamma = \sqrt{k_c^2 - \varepsilon k_0^2} \tag{2.8}$$

$$\gamma_0 = \sqrt{k_c^2 - k_0^2} \tag{2.9}$$

$$k_0 = \omega\sqrt{\mu\varepsilon_0} \tag{2.10}$$

These equation can be used to calculate $\varepsilon_r$ and $\delta$ where, $t$ is the sample thickness, $\gamma$ is the propagation constant in the sample, $r$ is the reflection coefficient on air of dielectric boundary and $k_c$ is the waveguide cut off wavenumber [3], [15], [19] – [21].

Another category is lumped impedance method which are the calculation of dielectric properties are based on the circuit theory and the electric field in the measured sample is assumed to be uniform. Figure 2.2 shows that a small disk shaped and electrode is place at the end of the shorted coaxial line [19], [20].

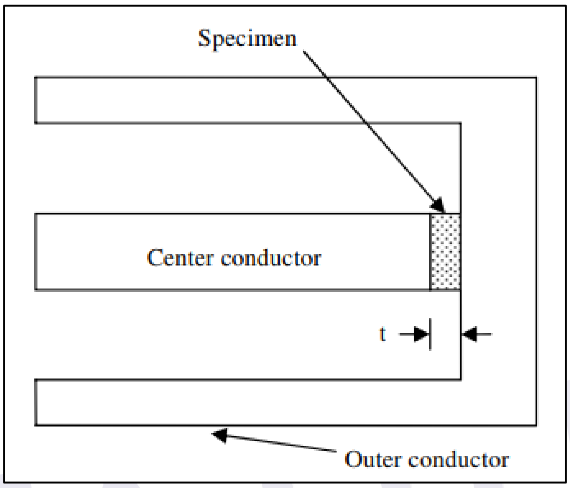


Figure 2.2: Lumped impedance technique [15]

In this method, the complex reflection coefficients are measured by network analyzer. The value of $\varepsilon_r$ and $\gamma$ can be obtained by using 2.11 [19], [20]

$$r = |r|e^{-j\theta} = \frac{1-j\omega C_o Z_o \varepsilon}{1+j\omega C_o Z_o \varepsilon} \tag{2.11}$$

where $C_o = A\varepsilon_o/t$ is the free space of capacitance, $A$ is the sample area, $t$ is sample thickness, $Z_o$ is the characteristic impedance of coaxial line, $\epsilon$ is the complex relative permittivity, $\varepsilon_o$ is the free space permittivity value and r is the complex reflection coefficient with amplitude |r| and phase θ. Calculations of dielectric properties are based on the circuit theory and the calculation of the loss tangent is same as distribution transmission technique [15]. In Table 1, comparison of techniques used in non-resonant method is presented.

Table 2.1. Comparison of Dielectric Measuring Techniques in non-resonant [15], [16], [22] – [28]

| Method | Advantages | Drawbacks |
|---|---|---|
| Waveguide and coaxial transmission line techniques. | • Waveguides are suitable for measuring larger samples and n be suitable for the measurements of biological fluids.<br>• Waveguide transmission cells can be constructed from either rectangular or circular waveguides and the mode of transmission depends on the structure. | • At frequencies below 2.45 GHz, the use of waveguides is not well suited due to the large volume of the test sample required<br>• Have a problems with air gaps when the size of the cell becomes too small.<br>• Sample preparation relatively difficult thus more time consuming because sample must cover entire cross-section area of a line, therefore it must be in slab or annular geometry form. |

| | | |
|---|---|---|
| Free space transmission techniques | • Do not require any special sample preparation, and are particularly suitable for measuring materials at high temperatures and for inhomogeneous dielectrics.<br>• Accurate measurement of the permittivity over a wide range of frequencies can be achieved.<br>• Non-destructive and contactless measuring methods.<br>• Do not require any special sample preparation, and are particularly suitable for measuring materials at high temperatures and for inhomogeneous dielectrics. | • Multiple reflections, mismatches, and diffraction effects at the edges of the sample are generally considered to be the main sources of errors.<br>• The measurements are difficult and time consuming to make because the open-circuited sample has to be established at each measurement frequency.<br>• For materials with dielectric (or magnetic) loss tangent less than 0.1, the loss factor measurements are found to be inaccurate because of errors in reflection and transmission coefficient measurements. |

| | | |
|---|---|---|
| Open ended transmission line techniques | • Suitable to measuring high dielectric constant and high loss samples, and is ideal for characterize lossy materials.<br>• This method is simple and sample handling is minimal and non-destructive.<br>• Both ex vivo and in vivo measurements can be over a broad frequency range. | • It requires calibration reference planes to be obtained at the probe aperture.<br>• Air bubbles and uneven sample surfaces can result in inaccurate measurements. |
| Planar transmission line techniques | • Ease of fabrication, low cost of manufacture, and compactness.<br>• The dielectric sample can serve both as the substrate or the superstrate. | • Low quality factor<br>• Air gap causes error |



## 2.3. Resonant Method

As mentioned, resonant methods characterize the material properties at a single frequency or a discrete set of frequencies with high accuracy in comparison to broadband methods. Waveguide cavity resonators, coaxial cavity resonators, waveguide cavity resonators and coaxial cavity resonators can be classified as resonant method [16]. Resonant method can be further divided into two categories which are the dielectric resonance techniques and cavity resonance technique [15].

### 2.3.1. Dielectric Resonance Techniques

For dielectric resonance technique resonance is basically supported by the dielectric sample itself and the sample acts as a dielectric resonator. While metal shields with different geometries, are always introduced to prevent radiation loss [15]. In this technique, the measured technique can be in transmission and reflection. For transmission measurement, usually made with weak coupling to minimize uncertainties Q-factor and vice versa for reflection measurement. Hakki-Coleman is one of the popular dielectric resonance method that has been used. Another dielectric resonance method are cylindrical cavity resonance, reflection resonance and split-post resonance [15].

In Hakki-Coleman resonant method, cylindrical dielectric rod is placed between two parallel metal plates as shown in figure 2.3. Two coupling antennas are used to couple the power in and out. In this technique, $S_{21}$ is measured. While the $TE_{011}$ mode is adopted for measurements. The real part of permittivity is calculated by the relationship between the resonant frequency and sample dimensions.

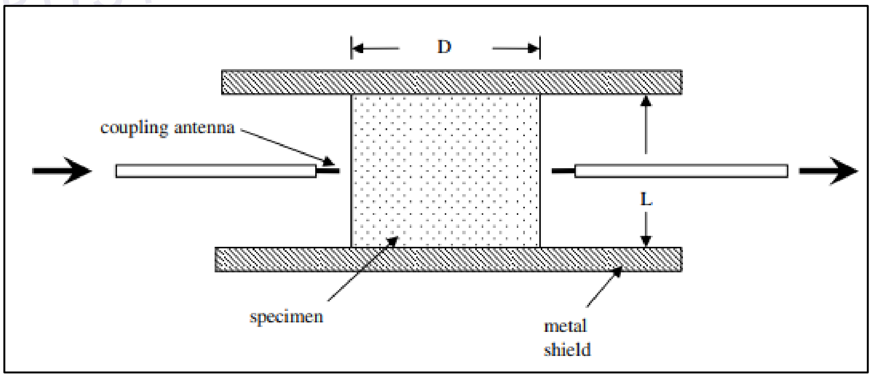


Figure 2.3: Hakki-Coleman resonant method [15]

The other measurement technique is cylindrical cavity resonance technique. As shown in the figure 2.4, the material under test is put inside a cylindrical metal cavity

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