CAD Model of Cole Cole Representation for Analyzing Performance of Microstrip Moisture Sensing Applications

Settapong Malisuwan, Jesada Sivaraks, Wasan Jaiwong and Veerapat Sanpanich

***Abstract*—**In the past decade, the development of microstrip sensor application has evolved tremendously. Although cut and trial method was adopted to develop microstrip sensing applications in the past, Computer-Aided-Design (CAD) is a more effective as it ensures less time is consumed and cost saving is achieved in developing microstrip sensing applications. Therefore microstrip sensing applications has gained popularity as an effective tool adopted in continuous sensing of moisture content particularly in products that is administered mainly by liquid content. In this research, the Cole-Cole representation of reactive relaxation is applied to assess the performance of the microstrip sensor devices. The microstrip sensor application is an effective tool suitable for sensing the moisture content of dielectric material. Analogous to dielectric relaxation consideration of Cole-Cole diagrams as applied to dielectric materials, a "reactive relaxation concept" concept is introduced to represent the frequency-dependent and moisture content characteristics of microstrip sensor devices.

***Keywords*—**Microstrip, Sensor, Cole-Cole Representation, Moisture content.

I. INTRODUCTION

MOISTURE content is an indicator to assess the quality of a product or required processing conditions of a product [1]. Microstrip sensor has been introduced as an effective real-time and durable device suitable for continuous sensing of moisture content in various materials including soil, food, building structures and particularly any product that is mainly administered by the presence of liquid water. The microstrip antenna is a tool that is small in size, light weight, has low profile, low manufacturing costs and has increasingly gained popularity in the commercial sector.

Microstrip structure is one of the most popular types of planar transmission lines, primarily because it is easily integrated with other passive and active microwave devices. Relevant design equations in closed-form using semi-empirical strategies specifying the frequency-dependent, effective dielectric permittivity concept and dispersion characteristics of a microstrip structure have been derived in the existing literature as elaborated [1], [2].

In the past, the cost to manufacture the microstrip sensor was extremely high as the cut and try method adopted to create the microstrip sensor is time consuming. In the modern day, as technology has evolved, the time and cost in manufacturing the antenna has reduced tremendously because of the maturity of creating microstrip antennas and also due to adoption of a simplified process using the Computer-Aided-Design (CAD).

Although many computer-aided design (CAD) systems have been developed using such algorithms with built-in microstrip design capabilities, simple calculation methods for microstrip structure parameters by hand-calculator and/or by personal computer are needed for preliminary design purposes, and/or for quick circuit evaluation purposes. Moreover, designers may need to observe the physical considerations of microstip circuits on a step-by-step basis. Therefore the CAD is a sufficient and simplified process in designing the physical aspects of microstrip circuits, precisely. Researchers are keen in identifying and creating antenna technologies that obtain better performance at a reduced cost hence, suitable for future applications.

The main contribution of this paper is to analyze the microstrip structure performance based on the Cole-Cole diagram representation for microstrip moisture sensing applications. To achieve this goal, an approach that uses the Debye relation [3] is introduced to portray such frequency-dependent characterization of a microstrip structure. Hence, "a reactive relaxation diagram" (analogous to the Cole-Cole diagram) is proposed to represent the frequency-dependent capacitive effects as well as the associated losses in a microstrip structure. Therefore, the analysis and design of microstrip sensor for measuring water content of dielectric material is described. Further impact of various levels of moisture content on performance of microstrip sensor is also observed. The proposed model is conducive for computer-aided microstrip circuit designs.

II. MICROSTRIP TEST STRUCTURE AND CHARACTERISTICS

A microstrip is a two-conductor transmission line consisting of a thin conducting strip and wider ground plane, separated by a dielectric sheetas show in Fig 1. The primary mode of propagation of microstrip is quasi-Transverse Electromagnetic (quasi-TEM). The presence of the dielectric material ($\varepsilon_r > 1$),

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is what leads to the quasi-TEM mode of propagation [4]. As the wave propagates through the microstrip, a portion of the field lines is traveling in the air above the conductor, while most of the signal propagates through the dielectric material below the conductor. The phase velocity and propagation constant in these two regions differ, resulting in the quasi-TEM mode of propagation.

In general, the number of modes that a transmission line can support is equal to the number of conductors minus one [5]. Therefore, for amicrostrip line, the number of modes that can propagate is one. For the quasi-static analysis to be valid, quasi-TEM propagation is assumed. By definition, quasi-TEM propagation means the magnetic and electric field components, in the direction of propagation, are small enough to be considered non-existent.

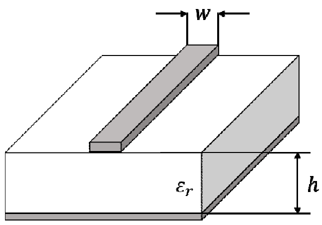


Fig. 1 Microstrip Transmission Line

Of interest in the study and analysis of planar transmission lines are the effective dielectric constant, characteristic impedance, and propagation constant. The propagation constant is a complex parameter that describes the attenuation and phase shift the transmitted signal experiences while propagating in the transmission line.

The effective dielectric constant of a microstrip line is a function of the dielectric constant of the substrate material, the height of the substrate, and the width of the top conducting strip. Equation (1) shows the dependence of the effective dielectric constant on the parameters mentioned above [6].

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + 10\frac{h}{w}\right)^{-B} \quad (1)$$

where B is given by:

$$B = 0.564\left\{1 + \frac{1}{49}\ln\left(\frac{\left(^{w}/_{h}\right)^4 + \left(^{w}/_{52h}\right)^2}{\left(^{w}/_{h}\right)^4 + .432}\right) + \frac{1}{18.7}\ln\left[1 + \left(\frac{w}{18.1h}\right)^3\right]\right\}\left(\frac{\varepsilon_r - 0.9}{\varepsilon_r + 3}\right)^{0.053} \quad (2)$$

In (1), w is the width of the top conductor, h is the height of the substrate, and ε_r is the dielectric constant of the substrate.

The effective permittivity of the microstrip structure is expected to change with frequency due to dispersion effects. The effective permittivity increases with frequency and asymptotically approaches ε_r. The effects due to dispersion become significant for high frequencies (above 4 GHz).

The frequency-dependence of the effective dielectric constant is specified by the following empirical relation [7]:

$$\varepsilon_{eff}(\omega) = \varepsilon_r + \frac{\varepsilon_{eff}(0) - \varepsilon_r}{1 + Q(\omega)} \quad (3)$$

where $Q(\omega)$ can be found in [6] and $\omega_n^* = 2\pi f_n^*$ (f_n^* in GHz.mm) is the frequency ratio. That is,

$$f_n^* = k\left(\frac{f}{f_0}\right)\left(\frac{h}{\lambda_0}\right) = k\left(\frac{l}{\lambda_0}\right)\left(\frac{h/\lambda_0}{l/\lambda_0}\right) \quad (4)$$

where $k = 300$ and l is the line-length.

The reported accuracy for Eqn. (1) is better than 0.2% for $\varepsilon_2 \leq 128$ and $0.01 \leq w/h \leq 100$[2]. The accuracy of the characteristic impedance calculation is better than .01% for $w/h \leq 1$ and .03% for $w/h \leq 1000$[2].

III. Dielectric Loss in Microstrip

The propagation of the electromagnetic wave in a dielectric material with a complex relative permittivity $\varepsilon_r = \varepsilon' - j\varepsilon''$ is usually characterized by attenuation and phase shift as seen in the following relationship [8].

$$\gamma = \alpha + j\beta = \frac{2\pi}{\lambda_0}(\varepsilon' - j\varepsilon'')^{\frac{1}{2}} \quad (5)$$

where ε' is the dielectric constant and ε'' is the loss factor, α is the attenuation constant, β is the phase constant and $\lambda_0$is the free space wavelength. Equating the real parts of (5) gives the general expression for the dielectric loss α_d in dB/m

$$\alpha_d = \frac{8.686\pi}{\lambda_0}\sqrt{\varepsilon_{eff}}\tan\delta_{eff} \quad (6)$$

Alternatively, (6) can be written as

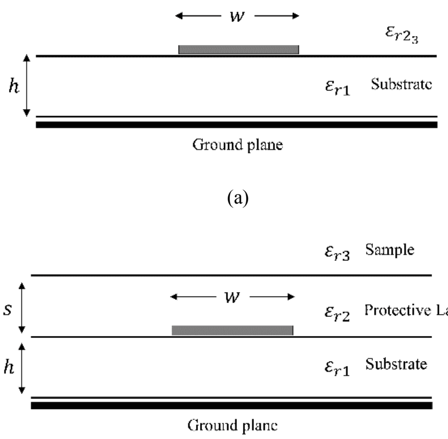
$$\alpha_d = \frac{27.3\delta_{eff}}{\lambda_0\omega\varepsilon_0\sqrt{\delta_{eff}}} \quad (7)$$

Returning to the case of propagation along the double-covered microstrip with semi-infinite layer, the effective conductivity and permittivity can be written in terms of filling fraction q occupied by each dielectric as

$$\delta_{eff} = q_1\delta_1 + q_2\delta_2 + (1 - q_1 - q_2)\delta_2 \quad (8)$$

$$\varepsilon_{eff} = q_1\varepsilon_{r1} + q_2\varepsilon_{r2} + (1 - q_1 - q_2)\varepsilon_{r2} \quad (9)$$

where δ_1,δ_2 and δ_3 are the conductivity of the substrate, protective layer respectively and q_1, q_2 are the dielectric filling fractions. These filling fractions maybe calculated by transforming the three layers of the microstrip structure of Fig. 2 (a) to two layers structure shown in Fig. 2 (b). Both structures have the same effective dielectric constant ε_{eff}. The effective dielectric constant of the upper layer of the two layers structure may be obtained by using 'regular Falsie' root seeking method



(a)

(b)

Fig. 2 Semi-infinite (a) Double-Covered microstrip (b) Covered microstrip with an effective dielectric Constant of the Upper Layer ε_{2_3}

Knowing the values of ε_{2_3}, it is expressed as

$$\varepsilon_{eff} = q_1\varepsilon_{r1} + (1 - q_2)\varepsilon_{r2_3} \quad (10)$$

and

$$q_1 = \frac{\varepsilon_{eff} - \varepsilon_{r2_3}}{\varepsilon_{r1} - \varepsilon_{r2_3}} \quad (11)$$

From (7), (8) and (9), q_2 may be obtained.

$$q_2 = \frac{(\varepsilon_{r3} - \varepsilon_{eff})(\varepsilon_{r3} - \varepsilon_{r1})}{\varepsilon_{r32}} \quad (12)$$

Substituting (7), (8) and (9) in (5) replacing $\lambda_0 = c/f_0$ we have dielectric loss in the semi-infinite double-covered microstrip structure in db/m as:

$$\alpha_d = \frac{27.3f}{c\sqrt{\varepsilon_{eff}}}[q_1\varepsilon_{r1}\tan\delta_1 + q_2\varepsilon_{r2}\tan\delta_2 + (1 - q_1 - q_2)\varepsilon_{r3}\tan\delta 3] \quad (13)$$

Equation (13) gives constructive information on the loss that can be expected for a particular geometrical configuration.

IV. Microstrip-Based Equivalent Relaxation Process

The method for analyzing the performance of a microstrip structure using the concept of Cole-Cole diagram is proposed in [9]. This paper is an extended study on the double-layered microstrip structure.

The concept of dielectric relaxation can be used to characterize the frequency-dependent microstrip structure performance. For this purpose, the real part of the Debye relation can be equated to the equivalent frequency-dependent permittivity deduced for a microstrip. That is,

$$\varepsilon'_u(\omega) = \varepsilon_{eff}(\omega) = \left[\varepsilon_r + \frac{\varepsilon_{eff}(0) - \varepsilon_r}{1 + Q(\omega)}\right] \quad (14)$$

From Kirschning and Jansen' frequency-dependent effective permittivity in Eqn. (14), it can be equated to the real part of the complex permittivity of the dielectric material as follows [3]:

$$\text{Re}\,[\varepsilon_m^*(\omega)] = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + 4\pi^2(\omega/\omega_r)}$$

and finally we get :

$$\varepsilon_r + \frac{\varepsilon_{eff}(0) - \varepsilon_r}{1 + Q(\omega)} = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + 4\pi^2(\omega/\omega_r)^2} \quad (15)$$

This gives,

$$\varepsilon_r = \varepsilon_\infty \quad (16)$$

$$\varepsilon_{eff}(0) = \varepsilon_s \quad (17)$$

$$\tau_0 = \frac{\sqrt{Q(\omega)}}{\omega} \quad (18)$$

Now, an "imaginary part" of the equivalent permittivity of a microstrip system can be obtained by applying (16)-(18) into the imaginary part of $\varepsilon''_m(\omega)$[3]. Hence, the imaginary part of Cole-Cole expression for a microstrip system can be written as

$$\varepsilon''_u(\omega) = \left[\frac{(\varepsilon_{eff}(0) - \varepsilon_r)\sqrt{Q(\omega)}}{1 + Q(\omega)}\right] \quad (19)$$

Hence, the complex permittivity of microstrip system in compact form can be written as:

$$\varepsilon''_u(\omega) = \varepsilon_r + \frac{\varepsilon_{eff}(0) - \varepsilon_r}{1 + j(1/2\pi)(\omega_0/\omega)} \quad (20)$$

In theory, the maximum points of semi-circles in the Cole-Cole patterns correspond to maximum Debye loss in a dielectric material [8] but, in respect to the microstrip system, these points can be used to depict the maximum reactive (capacitive) energy confined within the microstrip structure that is pertinent to the maximum value point (A) in Fig 3. Therefore, it can be considered that the microstrip geometry holds the field within itself, rather than letting it fringe out.

That is, pertinent to these maximum value points (A) in Fig 3 (a), it can be considered that the microstrip geometry holds the field within itself, rather than letting it fringe out.

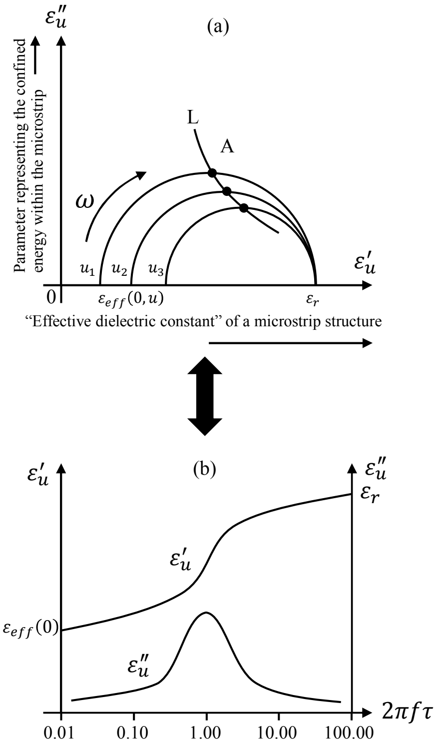


Fig. 3 (a) Cole-Cole representation of reactive relaxation of a microstrip structure with $u = (w/\lambda)(h/\lambda)$ and u1<u2<u3
(b) Equivalent Debye relation: microstrip-based

V. Cole-Cole Representation of Microstrip Sensor with Moisture Content Effects

Based on the research in [10], the variation of ε′ and ε″ with moisture content can be found and will be used in this paper. The results from [10] is illustrated where the relationship between ε′ and ε″ versus moisture content at a specific frequency (GHz) is shown in Fig 4.

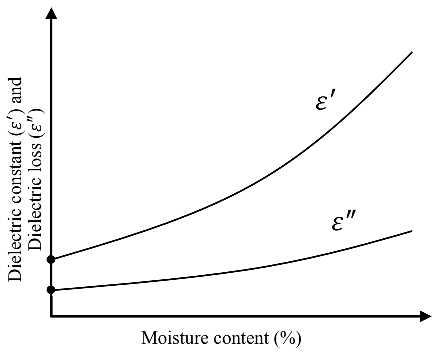


Fig. 4 Relationship between dielectric constant (ε′) and dielectric loss (ε″) versus moisture content (%) at a specific frequency in GHz

For the next step, we will use the relationship betweenε′and ε″for the Cole-Cole representation in section IV to demonstrate the effects of moisture content on the performance of the microstrip structure. After applying the effects of moisture content in the model in section IV, the Cole-Cole representation is as shown in Fig 5.

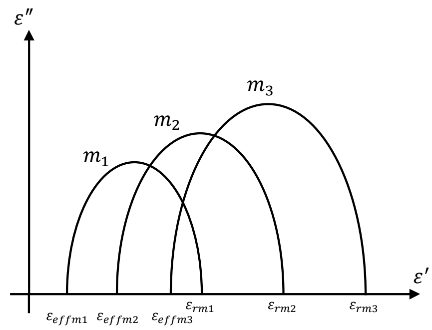


Fig. 5 Cole-Cole representation of reactive relaxation of a microstrip versus moisture content (moisture content (%) : m1 < m2 < m3)

VI. Simulations and Results

In this section, the variation of ε′ andε″ with moisture content is illustrated by cole-cole diagram concept.

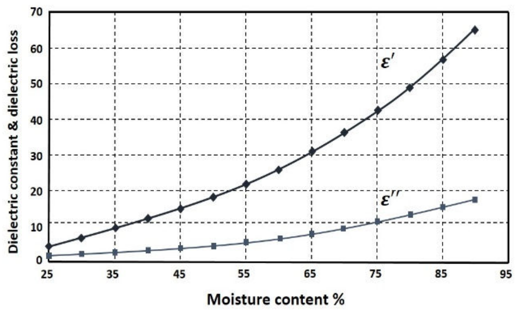


Fig. 6 Relationship between dielectric contant ε′and Dielectric Loss ε″ in employing rubber latex as an alternative to moisture content % at 27°C at frequency 2.4 GHz

Fig. 6 illustrates the relationship between dielectric constant ε′ and dielectric loss ε″ in using rubber latex as alternative to moisture content (%) at 27°C at frequency 2.4 GHz [10]. As seen in Fig. 7, the simulation results depicts that the increase in moisture content is proportional to the increase in ε′and ε″; hence, when the sensor detects the change in ε′and ε″, it is detecting the increase in moisture content i. After applying the result from Fig. 6, the simulation results reveal that the non-fringing part of the reactive energy in the microstrip increases when the moisture content increases. In Fig. 7, the maximum points of semi-circles in various moisture content levels represent the performance of microstrip moisture sensing applications. The results therefore indicate that the microstrip sensor adopted in this research is effective in sensing moisture content.

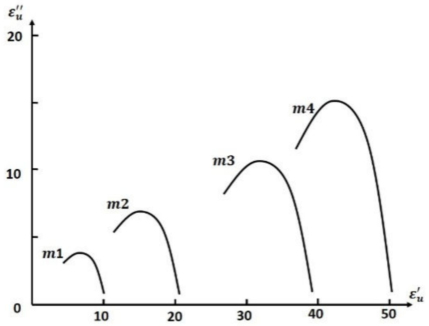


Fig. 7 Cole-Cole diagram for the test microstrip structure
Curve 1 : moisture content = 35%
Curve 2 : moisture content = 50%
Curve 3 : moisture content = 70%
Curve 4 : moisture content = 80%

VII. Concluding Remark

The contribution of this research is the use of Cole-Cole representation of reactive relaxation in assessing the performance of microstrip moisture sensing applications. It is observed in this study that the performance of microstrip structure is significantly impacted by various levels of moisture content. The concept proposed in this paper is fully compatible with computer-aided microstrip design and microwave circuit design. Therefore, this research also seeks to contribute that cole-cole reactive relaxation concept is practical in assessing the performance of microstrip moisture sensing applications and the results achieved in this study is suitable as an input into CAD systems to complete the development of the microstrip moisture sensing application.

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