Modified Smith-Chart Representation on the Basis of the Dynamic Permittivity of a Microstrip Structure

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Abstract: The dynamic permittivity of a microstrip structure leads to a convenient and modified Smith-chart representation that includes the frequency-dependent influence of the lossy characteristics of the line cohesively. The efficacy of the model is illustrated with an example concerning a microstrip patch antenna. Relevant simulations show that the input impedances calculated from the model are more accurate than those from the previous model in the literature by comparing to the measure results, as illustrated with an example of a patch antenna. This model is compatible for CAD efforts with MATLAB™ facilitating fast and user-friendly implementations.

1. Introduction

The microstrip line 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 line have been derived in the existing literature [1]-[7]. Although many computer-aided design (CAD) systems have been developed using such algorithms with built-in microstrip design capabilities, simple calculation methods for microstrip line 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 microstrip circuits on step-by-step basis. Therefore, many researchers are in search of simple methods, which are at the same time and sufficient to explain the physical aspects of microstrip circuits, precisely.

2. Frequency-dependent Smith-chart (Modified Smith-chart)

In this section, the frequency-dependent effective permittivity concept is applied to construct a frequency-dependent (lossy) Smith-chart to analyze microstrip line characteristics. Before deriving the frequency-dependent Smith-chart relations, the capacitance parameter in microstrip-line system can be considered. The classical parallel-plate capacitor is shown in Fig. 1. From the geometry shown in Fig. 1, the capacitance per unit length of the structure can be expressed as [8]:

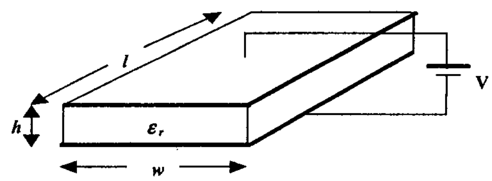

Fig. 1 A parallel-plate capacitor

$$C = \varepsilon \frac{w}{h} \tag{1}$$

A simple frequency-dependent capacitance of the parallel-plate capacitor can be modeled in terms of any frequency-dependent attributes of ε. That is,

$$C(\omega) = \varepsilon_o \varepsilon(\omega) \frac{w}{h} \tag{2}$$

where $\varepsilon(\omega)$ is a complex permittivity equal to

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

Therefore,

$$C(\omega) = \varepsilon_0\left(\varepsilon_r - \frac{\varepsilon_r - \varepsilon_{eff}(0)}{1+Q(\omega)}\right)\frac{w}{h} = \varepsilon_0\varepsilon_r\left(1 - \frac{1-\varepsilon_{eff}(0)/\varepsilon_r}{1+Q(\omega)}\right)\frac{w}{h} \tag{3}$$

$$C(\omega) = C\left(1 - \frac{1-\varepsilon_{eff}(0)/\varepsilon_r}{1+Q(\omega)}\right) \tag{4}$$

where $C = \varepsilon_0\varepsilon_r(w/h)$.

For simplicity, the coefficients of Eqn. (4) are defined as follows:

$$b=\left(1-\frac{1-\varepsilon_{eff}(0)/\varepsilon_r}{1+Q(\omega)}\right) \quad (5)$$

If G (conductance per unit length) and C (capacitance per unit length) are neglected, the characteristic impedance can be written as:

$$Z_0=\sqrt{\frac{L}{C}} \quad (6)$$

To obtain the frequency-dependent characteristic impedance ($Z_0'(\omega)$), the frequency-dependent capacitance ($C(\omega)$) of Eqn. (4) is substituted into the capacitance (C) in Eqn. (6). The resulting frequency-dependent characteristic impedance is then given by:

$$Z_0'(\omega)=\sqrt{\frac{L}{C(\omega)}}=\sqrt{\frac{L}{Cb}}=\frac{Z_0}{\sqrt{b}} \quad (7)$$

Now, the frequency-dependent (lossy) Smith-chart can be constructed by applying $Z_0'(\omega)$ in Eqn. (7) into the normalized terminal impedance expression following the procedure as that for a standard Smith-chart [9]. Hence, the resulting normalized terminal impedance z'_L is given by

$$z_L'=\frac{Z_L}{Z_0'(\omega)}=br+jbx \quad \text{(Dimensionless)} \quad (8)$$

where r and x are the normalized resistance and normalized reactance, respectively.

Corresponding, the voltage reflection coefficient of present Smith chart can be expressed as:

$$\Gamma'=\Gamma_r'+j\Gamma_i'=\frac{z_L'-1}{z_L'+1} \quad (9)$$

or

$$z_L'=\frac{Z_L}{Z_0'(\omega)}=br+jbx=\frac{(1+\Gamma_r')+j\Gamma_i'}{(1-\Gamma_r')-j\Gamma_i'} \quad (10)$$

Now, the desired set of equations depicting the modified Smith-chart are:

$$\left(\Gamma_r'-\frac{br}{1+br}\right)^2+\Gamma_i'^2=\frac{1}{(1+br)^2} \quad (11)$$

and

$$(\Gamma_r'-1)^2+\left(\Gamma_i'-\frac{1}{bx}\right)^2=\left(\frac{1}{bx}\right)^2 \quad (12)$$

3. Application of the Frequency-dependent Smith-chart Constructed on the Basis of the Frequency-dependent Effective Permittivity Concept

This section is devoted to illustrate the use of frequency-dependent Smith-chart considerations deduced (on the basis of the frequency-dependent effective permittivity concept) in characterizing microstrip lines. A microstrip patch antenna is considered as a test structure for analysis.

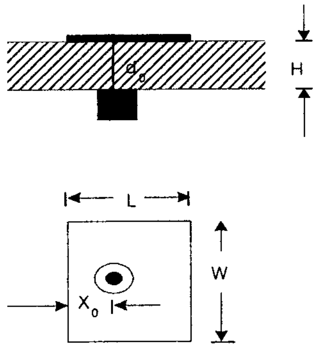

Fig. 2 Geometry of a coax-fed rectangular microstrip patch antenna

A microstrip antenna may be excited or 'fed' by different types of transmission lines, for example coaxial (Fig. 2), microstrip, or coplanar. The radiating elements may be fed directly, with electrical continuity between the conductor of the transmission line and the conducting patch. On the other hand, the microstrip patch antenna fed by a transmission line behaves as a complex impedance $Z_{in} = (R + jX)$, which depends mainly on the geometry of the coupling between the transmission line and the antenna. The input impedance expressions of the microstrip patch antenna used are from Abboud's model [10].

The input impedance of the structure shown in Fig. 2 is given by [10]

$$z(f)=\frac{R}{1+Q_T^2\left[f/f_R-f_R/f\right]^2}+j\left[X_L-\frac{RQ_T\left[f/f_R-f_R/f\right]}{1+Q_T^2\left[f/f_R-f_R/f\right]^2}\right] \quad (13)$$

where R is the resonant resistance including the influence of the fringing field at the edges of the patch; Q_T is the quality factor associated with system losses; f is the operating frequency; and f_R is the resonant frequency. It can be written as [10]:

$$R=\frac{Q_T H}{\pi f_R \varepsilon_{dyn}\varepsilon_0 LW}\cos^2\left(\frac{\pi X_0}{L}\right) \quad (14)$$

where ε_{dyn} is the dynamic permittivity.

To take the effect of coax-feed probe (Fig. 2) into account, it is necessary to modify the input impedance by an inductive reactance term [11], given by

$$X_L = \frac{377 fH}{c_0} Ln\left(\frac{c_0}{\pi f d_0 \sqrt{\varepsilon_r}}\right) \quad (15)$$

where c_o is the velocity of light in vacuum and d_o is the diameter of the probe. The detail in Eqn. (13) can be found in [10].

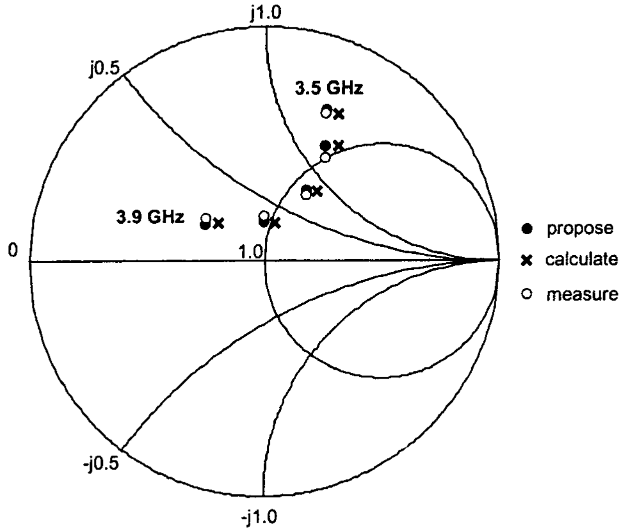

Fig. 3 Input impedance of coax-fed rectangular microstrip patch antenna

ε_r=4.53, $Tg\sigma$=0.025, H=0.300cm, d_0=0.065cm, Z_0=50 Ω, mode (m=0,n=1), L=1.74cm, W=2.31cm, X_0=0.55cm.

Fig. 3 shows the input impedance for a patch antenna operating at about 3.5GHz – 3.9GHz. The proposed model results are compared with the computed results in [10] and measured data of [12]. The results indicate that the proposed model gives results close to the experimental data. It can also be observed that the present results are better than those predicted in [10] especially at the higher frequency range. Also, at 3.5GHz – 3.9GHz, the result from the proposed model is closer to the measured result [10] than that calculated by [10]. The reason is that, in the proposed model, the frequency-dependent characteristic impedance is more comprehensively addressed included in the algorithm so that possible errors in the high frequency are reduced.

4. Concluding Remarks

The use of modified Smith-chart is proved to be a method representing the frequency-dependent characteristics of microstrip structures. The present study demonstrates the feasibility of a cohesive presentation of the dispersion (lossy and lossless) characteristics of a microstrip line via Cole-Cole diagram format, which is compatible for CAD efforts. Relevant simulations show that the input impedances calculated from the model are more accurate than those from the Abboud's model by comparing to the measure, as illustrated with an example of a patch antenna.

In summary, the technique described in this paper offers a strategy for portraying the frequency-dependent characteristics of microstrip structures via a modified Smith-chart representation.

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