Design of Microstrip Antenna for WPAN Applicationsby Applying Modified Smith-Chart Representation

Settapong Malisuwan and Jesada Sivaraks

***Abstract*—The use of frequency-dependent (lossy) Smith-chart representation is proved to be an effective method for rectangular microstrip antenna design. This research manifests the feasibility of a well-integrated presentation of the dispersion (lossy and lossless) characteristics of a microstrip line by adopting modified Smith-chart format. The effectiveness of this model is demonstrated via a model of microstrip patch antenna for Wireless Personal Area Network (WPAN) applications. The outcome of proposed algorithm within this research is scrutinized and compared with the experimental results in past literatures. The proposed model within this study is suitable for use in computer-aided microstrip design and is pertinent since it conforms to the modern day requirements and trends of modern computer-aided microstrip antenna design and RF integrated circuit (RFIC) design.**

***Index Terms*—Microstripantenna, WPAN, modified smith-chart , and CAD.**

I. Introduction

"Smith-chart is an effective visualization tool adopted in high frequency engineering for designing impedance matching circuits, amplifiers, filter and to assess the transmission line characteristics" [1]. Regardless of the fact that there is variety of impedance and coefficient charts that can be adopted in this case, the Smith Chart is most notable and widely employed tool. The concept of Smith Chart was invented by P.Smith at the Bell Telephone Laboratories in 1939. In the modern day, it has become a vital tool in current computer-aided design (CAD) software specifically for high-frequency designs. Numerous computer-aided design (CAD) systems have been developed by using this type of algorithm with built in microstrip design capabilities. However, it is essential that a simple calculation method for microstrip line parameters in the preliminary design stage is achieved by manual calculation through hand-calculators or personal computer. Designers of microstrip are required to scrutinize the physical considerations of microstrip circuits on a step-by-step basis. As a result, researchers require simpler methods that are adequate to clarify precisely the physical aspects of microstrip circuits.

In this study, the proposed algorithm illustrating the dynamic permittivity of the microstrip structure results in an efficient and modified Smith-chart representation accommodating the frequency-dependent influence of fringing field and the lossy characteristics cohesively. The outcome of the proposed model is assessed against data in past literatures on microstrip patch antenna in the frequency range of WPAN applications[1]. "This model is compatible for CAD efforts with MATLAB facilitating fast and user-friendly implementations"[1].

Manuscript received March 9, 2013; revised July 3, 2013. This work is fully supported by National Broadcasting and Telecommunications Commission in Thailand.

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II. Frequency Dependent Smith-Chart (Modified Smith-Chart)

"The Smith-chart is an impedance representation in a complex plane depicting a set of circles of constant resistance and partial circles of constant reactance" [1]. The Smith-chart is formulated from the statistic characteristic impedance (Z_0) but excluding the frequency dependent characteristic of Z_0. Logically, it is crucial to include frequency-dependent factor in the calculations in order to add to the accurateness of the models.

The application of the frequency-dependent permittivity is used to create the frequency-dependent (lossy) smith-chart which is then used to scrutinize the characteristics of the microstrip line. Prior to developing the frequency-dependent smith-chart relations, the capacitance parameter in microstrip line system has to be studied. The standard parallel-plate capacitor is illustrated in Fig. 1. The figure also illustrates the capacitance per unit length of the structure which is expressed as [2]:

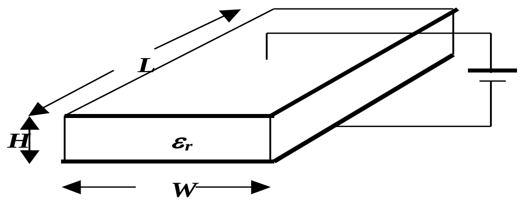

Fig. 1. A parallel-plate capacitor.

$$C = \varepsilon \frac{W}{H} \tag{1}$$

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

$$C(\omega) = \varepsilon_0 \varepsilon(\omega) \frac{W}{H} \tag{2}$$

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

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

$Q(\overline{\omega})$is the frequency-dependent term given:

$$Q(\overline{\omega}) = P_1 P_2 [(0.1844 + P_3 P_4) f_n]^{1.5763} \tag{4}$$

DOI: 10.7763/IJMO.2013.V3.303

$$P_1 = 0.27488 + u\left[0.6315 + \frac{0.525}{(1+0.0157f_n)^{20}}\right] - 0.065683exp(-8.7513u) \quad (5)$$

$$P_2 = 0.33622[1 - exp(-0.03442\varepsilon_r)] \quad (6)$$

$$P_3 = 0.0363exp(-4.6u)\left\{1 - exp\left[-\left(\frac{f_n}{38.7}\right)^{4.97}\right]\right\} \quad (7)$$

$$P_4 = 1 + 2.751\left\{1 - exp\left[-\left(\frac{\varepsilon_r}{15.916}\right)^{8}\right]\right\} \quad (8)$$

where u is the microstrip width and substrate thickness ratio and f_n GHz.mm is the frequency normalized with respect to the substrate height,

$$f_n = \frac{fH}{10^6} \quad (9)$$

Hence,

$$C(\omega) = \varepsilon_0\left(\varepsilon_r - \frac{\varepsilon_r - \varepsilon_{eff}(0)}{1+Q(\omega)}\right)\frac{W}{H} = \varepsilon_0\varepsilon_r\left(1 - \frac{1-\varepsilon_{eff}(0)/\varepsilon_r}{1+Q(\omega)}\right)\frac{W}{H} \quad (10)$$

$$C(\omega) = C\left(1 - \frac{1-\varepsilon_{eff}(0)/\varepsilon_r}{1+Q(\omega)}\right) \quad (11)$$

So, $C = \varepsilon o \varepsilon r(w/h)$.

In simple terms, the coefficients of equation (11) is as follows:

$$b = \left(1 - \frac{1-\varepsilon_{eff}(0)/\varepsilon_r}{1+Q(\omega)}\right) \quad (12)$$

If G (conductance per unit length) and R (resistance per unit length) are excluded, the characteristic impedance is defined as:

$$Z_0 = \sqrt{\frac{L}{C}} \quad (13)$$

Therefore, L is defined as "inductance per unit length and C is the capacitance per unit length" [3]

To achieve the frequency-dependent characteristic impedance ($Z0'(\omega)$), the frequency-dependent capacitance ($C(\omega)$) of Eqn. (11) is put as a substitute into the capacitance equation (C) in Eqn. (13). The outcome is frequency-dependent characteristic impedance which is as follows:

$$Z_0'(\omega) = \sqrt{\frac{L}{C(\omega)}} = \sqrt{\frac{L}{Cb}} = \frac{Z_0}{\sqrt{b}} \quad (14)$$

Now, the frequency-dependent (lossy) Smith-chart is constructed through application of $Z0'(\omega)$ into Eqn. (14) into the normalized terminal impedance expression after the standard Smith-chart is derived [4]. Hence, outcome which is the normalized terminal impedance $z'L$ is given as:

$$Z_L' = \frac{Z_L}{Z_0'(\omega)} = br + jbx \quad (Dimensionless) \quad (15)$$

where r and x are the normalized resistance and normalized reactance, respectively [1].

Consequently, voltage reflection coefficient of the derived Smith chart is expressed in Equation (16) and (17) as:

$$\Gamma' = \Gamma_L' + j\Gamma_i' = \frac{Z_L' - 1}{Z_L' + 1} \quad (16)$$

or

$$Z_L' = \frac{Z_L}{Z_0'(\omega)} = br + jbx = \frac{(1+\Gamma_r') + j\Gamma_i'}{(1-\Gamma_r') - j\Gamma_i'} \quad (17)$$

Therefore, the equations describing the modified Smith-chart are:

$$\left(\Gamma_r' - \frac{br}{1+br}\right)^2 + \Gamma_i'^2 = \frac{1}{(1+br)^2} \quad (18)$$

and

$$(\Gamma_r' - 1)^2 + \left(\Gamma_i' - \frac{1}{bx}\right)^2 = \left(\frac{1}{bx}\right)^2 \quad (19)$$

III. Input Impedance of the Microstrip Patch Antenna

"A microstrip antenna may be excited or 'fed' by different types of transmission lines, for example coaxial, microstrip, or coplanar. Two different types of feed are shown in Figures 2 (a) and (b)" [5]. The radiating elements are fed directly with electrical continuity to excite the microstrip antenna. It is fed between the conductor of the transmission line and the conducting patch [5]. However, the microstrip patch antenna fed by a transmission line acts as a complex impedance Zin = (R + jX), which is dependent on the physical aspect or geometry of the cohesion between transmission line and antenna.

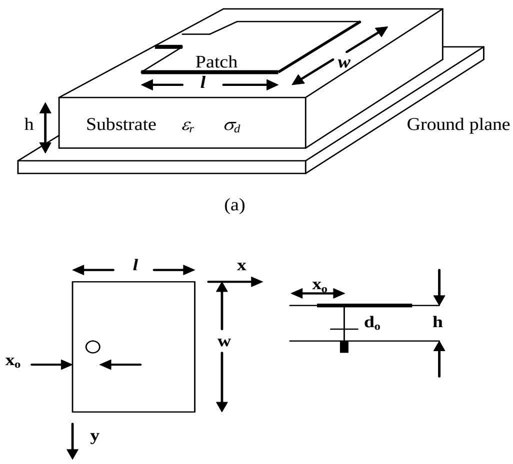

Fig. 2. Rectangular microstrip patch antenna.
(a) Direct feed
(b) Coax-feed

The input impedance of the model illustrated in Fig. 2 is given by [6]:

$$Z(f) = \frac{R}{1 + Q_T^2[f/f_R - f_R/f]^2} + j\left[X_L - \frac{RQ_T[f/f_R - f_R/f]}{1 + Q_T^2[f/f_R - f_R/f]^2}\right] \quad (20)$$

where "R is the resonant resistance with influence of the fringing field at edges of the patch; f is the operating frequency; and f_R is the resonant frequency". These are expressed as [6]:

$$R = \frac{Q_T H}{\pi f_R \varepsilon_{dyn}\, \varepsilon_0 L W} cos^2\left(\frac{\pi X_0}{L}\right) \quad (21)$$

where ε_{dyn} is the dynamic permittivity.

Q_T is quality aspect in regards to system losses, which comprises of radiation from the wall (Q_R), losses in the dielectric (Q_D) and losses in the conductor (Q_C). Q_T expressed as [6]:

$$Q_T = \left[\frac{1}{Q_R} + \frac{1}{Q_C} + \frac{1}{Q_D}\right]^{-1} \quad (22)$$

where Q_R,Q_D and Q_C are given below

$$Q_R = \frac{C_0\sqrt{\varepsilon_{dyn}}}{4 f_R H} \quad (23)$$

$$Q_D = \frac{1}{Tg\delta} \quad (24)$$

$$Q_C = \frac{0.786\sqrt{f_R Z_{ao}(W) H}}{P_a} \quad (25)$$

for copper; f_R in GHz

where $Z_{ao}(W)$ is the impedance of an air filled microstrip line of width (W) and thickness (H). $Z_{ao}(W)$is assessed by $\varepsilon_r = 1$. The impedance of a dielectric filled line can be expressed as Equation 26 and 27 [6]:

$$Z_a(W) = \frac{60\pi}{\sqrt{\varepsilon_r}}\left\{\frac{W}{2H} + 0.441 + 0.082\left[\frac{\varepsilon_r - 1}{{\varepsilon_r}^2}\right]\right\} + \frac{(\varepsilon_r + 1)}{2\pi\varepsilon_r}\left[1.451 + Ln\left(\frac{W}{2H} + 0.94\right)\right]^{-1}, W/H > 1 \quad (26)$$

$$P_a = \frac{2\pi\left[\frac{W}{H} + \frac{W/(\pi H)}{W/(2H) + 0.94}\right]\left[1 + \frac{H}{W}\right]}{\left\{\frac{W}{H} + \frac{2}{\pi} Ln\left[2\pi exp\left(\frac{W}{2H} + 0.94\right)\right]\right\}^2}, W/H \geq 2 \quad (27)$$

To include the effect of coax-feed probe (Fig. 2), it is essential to adapt the input impedance by an inductive reactance term [7], which is

$$X_L = \frac{377 f H}{C_0} Ln\left(\frac{C_0}{\pi f d_0 \sqrt{\varepsilon_r}}\right) \quad (28)$$

where "c_0 is the velocity of light in vacuum and d_0 is the diameter of the probe." [5]

$$f_R = f_{mn} = \frac{C_0}{2\sqrt{\varepsilon_{dyn}}}\sqrt{\left[\left(\frac{m}{W_{eff}}\right)^2 + \left(\frac{n}{L_{eff}}\right)^2\right]} \quad (29)$$

where W_{eff} is the optimal width, L_{eff} is the optimal length and ε_{dyn} is the dynamic permittivity, that is the function of dimension (W, L, H) [6]:

$$\varepsilon_{dyn} = \frac{C_{dyn}(\varepsilon)}{C_{dyn}(\varepsilon_0)} \quad (30)$$

where $C_{dyn}(\varepsilon)$ depicts the sum of dynamic capacitance of the patch in the presence of a dielectric of relative permittivity and $C_{dyn}(\varepsilon_0)$ depicts the sum of dynamic capacitance of the patch in the presence of air, $C_{dyn}(\varepsilon)$ is expressed as

$$C_{dyn}(\varepsilon) = C_{0,dyn}(\varepsilon) + 2C_{el,dyn}(\varepsilon) + 2C_{e2,dyn}(\varepsilon) \quad (31)$$

Therefore, $C_{0,dyn}(\varepsilon)$ is the dynamic main field of the patch capacitance in exclusion of the fringing field. $C_{e,dyn}(\varepsilon)$ is the dynamic edge field of the patch capacitance when including the fringing field on each side of the patch thus written as [6]:

$$C_{0,dyn}(\varepsilon) = \frac{\varepsilon_0 \varepsilon_r W L}{H \gamma_n \gamma_m} = \frac{C_{0,stat}(\varepsilon)}{\gamma_n \gamma_m} \quad (32)$$

where$C_{0,stat}(\varepsilon)$is the static main capacitance of the patch when excluding the the fringing field and γ_n and γ_m are:

$$\gamma_i = \begin{cases} 1\ for\ i=0 \\ 2\ for\ i\neq 0 \end{cases} \quad (33)$$

An assumption is made that the edge-field of the resonator has an x- and y- dependent field distribution in this case, therefore the dynamic fringing capacitances is expressed in general as [6]:

$$C_{e1,dyn}(\varepsilon) = \frac{1}{\gamma_n}\left\{\frac{1}{2}\left[\frac{Z(W,H,\varepsilon_r=1)}{C_0 Z^2(W,H,\varepsilon_r)} - \frac{\varepsilon_0\varepsilon_r W}{H}\right] L\right\} \quad (34)$$

$$C_{e2,dyn}(\varepsilon) = \frac{1}{\gamma_m}\left\{\frac{1}{2}\left[\frac{Z(L,H,\varepsilon_r=1)}{C_0 Z^2(L,H,\varepsilon_r)} - \frac{\varepsilon_0\varepsilon_r L}{H}\right] W\right\} \quad (35)$$

where $Z(W,H,\varepsilon_r)$ is the characteristic impedance of the microstrip line [8], [9]. If the outcome of the strip thickness is excluded,

$$Z(W,H,\varepsilon_r) = \frac{377}{\sqrt{\varepsilon_{eff}(W)}}\left[\frac{W}{H} + 1.393 + 0.667 Ln\left(\frac{W}{H} + 1.444\right)\right]^{-1} \quad (36)$$

Consequently, in this proposed model, a more accurate expression for the characteristic impedance [3] is as follows:

$$Z(W,H,\varepsilon_r = 1) = \frac{377}{2\pi} Ln\left(\frac{f(W/H)}{(W/H)} + \sqrt{1 + \left(\frac{2}{(W/H)}\right)^2}\right) \quad (37)$$

$$f(W/H) = 6 + (2\pi - 6) exp\left[-\left(\frac{30.666}{(W/H)}\right)^{0.7528}\right] \quad (38)$$

o evaluate ε_{eff} ,the equation from [10] is applied [6]:

$$\varepsilon_{eff}(W) = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + \frac{10}{W/H}\right)^{-1/2} \quad (39)$$

To obtain $C_{dyn}(\varepsilon 0)$, ε can be substituted by $\varepsilon 0$ in all of the previous equations derived in this study. To take into consideration the effect of the fringing field at each side and the dielectric in homogeneity [6] of the rectangular microstrip patch antenna, the W_{eff} and L_{eff}, is calculated following:

$$L_{eff} = L + \left(\frac{W_{eq} - W}{2}\right)\frac{\varepsilon_{eff}(W) + 0.3}{\varepsilon_{eff}(W) - 0.258} \quad (40)$$

whereW_{eq} is the equivalent width

$$W_{eq} = \frac{120\pi H}{Z_a(W)\sqrt{\varepsilon_{eff}(W)}} \quad (41)$$

Similarly, "we can calculate W_{eff} from equation (40) and (41) by replacing L_{eff}, L, W_{eq}, W with W_{eff}, W, L_{eq}, L respectively" [1].

IV. Antenna System in Wireless Communication Applications (ISM band): Design Considerations

In this part, the appliance of modified Smith-chart on the rectangular microstrip patch antenna design is described. The outcome of the modified Smith-chart model is assessed with the results by using the method in [6]. It is also scrutinized and assessed with measured values from [10] concerning the fundamental mode (m = 0, n = 1). It is apparent that the outcome of the proposed model in this study is more effectual and accurate than the equations derived in [6] and [11] and it complies with the experiment.

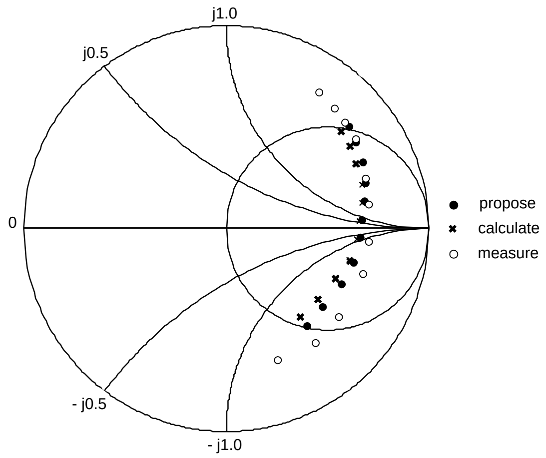

Fig. 3. Input impedances of coax-fed rectangular microstrip patch antenna $\varepsilon_r = 2.55, Tg\sigma(dielectric\ loss\ tangent) = 0.002, H = 0.159cm, d_0 = 0.127cm, Z_0 = 50\Omega, mode(m = 0, n = 1),\ L = 2.01cm, W = 2.01cm, X_0 = 0.13cm.$

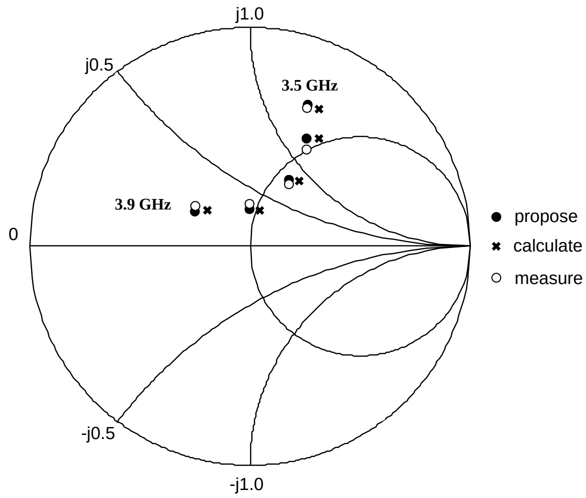

Fig. 4. Input impedances of coax-fed rectangular microstrip patch antenna $\varepsilon_r = 4.53, Tg\sigma = 0.025, H = 0.300cm, d_0 = 0.065cm, Z_0 = 50\Omega,$ $L = 1.74cm, W = 2.31cm, X_0 = 0.55cm, mode(m = 0, n = 1).$

Fig. 3 and Fig. 4 illustrate the input impedance for a patch antenna operating at 4.5 GHz and 3.7 GHz. The proposed model's outcome is scrutinized and assessed against the computed results derived in [6] and measured data in [8]. The outcome shows that the proposed model gives results which are similar to that of experimental data. It is also apparent that the results within this study are improved than those predicted in [6]. This is because in this proposed model, the frequency-dependent characteristic impedance comprehensively scrutinized and adopted in the algorithm so that avoidable errors in the high frequency is mitigated to a high degree.

V. Design of Microstrip Antenna for a WPAN Application by Using Modified Smith-Chart Representation

To devise a microstrip antenna for WPAN devices, it is essential that engineers consider operating frequency of WPAN systems. FCC in US regulates broadcast, telecommunications and gives permission for use of spectrum including those employed in WPANs.Other countries corresponding regulatory policies to that of FCC. WPANs are designed to operate in such a way that FCC does not make it compulsory for end-user to acquire license to utilize the airwaves. For WPANs to be available for sale in any nation, WPANs manufacturers must make certain thatthe certification is approved by the respective agency within that nation.

The proposed Smith-chart is adopted to create a rectangular microstrip antenna for WPAN applications. The current design is such that the rectangular microstrip antenna has a substrate with dielectric constant (εr) of 4.53 and the antenna is a coax-fed type. As illustrated in Fig. 5, the size of the patch is 2.85 cm (w) × 2.78 cm (l) (at f = 2.45 GHz) and a thickness of h = 0.3 cm.

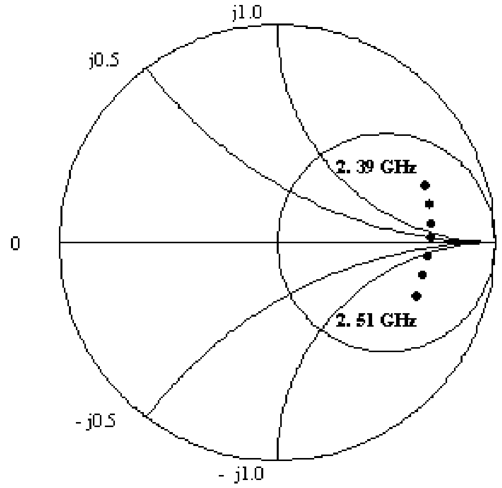

Fig. 5. Input impedances of coax-fed rectangular microstrip patch antenna operating at 2.45 GHz, $\varepsilon_r = 4.53, Tg\sigma = 0.002, H = 0.300cm, d_0 = 0.5573cm, Z_0 = 50\Omega, L = 2.78cm, W = 2.85cm,\ X_0 = 0cm, mode(m = 0, n=1.$

VI. Concluding Remarks

The use of modified Smith-chart is a proven and an effectual method in depicting the frequency-dependent characteristics of microstrip antennas for WPAN applications. This research determines the practicability of a cohesive presentation of the dispersion (lossy and lossless) characteristics of a microstrip line, that complies with the computer aided software or CAD efforts. Pertinent simulations in this research illustrates that the input impedances calculated within this study has higher accuracy than that of Abboud's as evidenced in this research with an example of a patch antenna.

To sum, the method adopted in this study proposes a new way for designing rectangular microstrip patch antenna with higher precision.

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