Performance Evaluation of Microstrip Patch Antenna by Applying Cole-Cole Representation for X-Band Satellite Communications System

Settapong Malisuwan, Noppadol Tiamnara, and Nattakit Suriyakrai
National Broadcasting and Telecommunications Commission, Thailand
Email: {settapong.m, noppadol.t, nattakit.s}@nbtc.go.th

Abstract—In this research we analyze the performance of a rectangular patch antenna for X-band applications for satellite communications based on the Cole-Cole diagram representation. The Debye relation is introduced to represent frequency-dependent performance characterization of a microstrip patch. The Cole-Cole representation model can be used to design a single and multilayer microstrip patch antenna. However, this research focuses on constructing a single layer microstrip patch antenna and aims to provide a valuable contribution on literature of computer-aided microwave circuit designs.

Index Terms—performance, Cole-Cole, patch antenna, x-band, satellite

I. INTRODUCTION

Rectangular patch antennas are widely discussed by researchers [1]-[6]. Microstrip patch is one of the most preferred types of antenna because it is low cost and has a compact design making it easily integrate with in passive or active microwave devices. Antenna is a necessity for many wireless communications including radar, microwave and space communications. Although patch antennas appears to be simple and easy to fabricate, most computer aided design systems used these algorithms with built in microstrip design capabilities but simple hand calculations are required for preliminary design and for quick circuit evaluation purposes. It is also necessary to observe physical considerations of microstrip circuits on a step by step basis. Hence, researchers put emphasis on a simple method yet one sufficient to explain the physical characteristics of the patch antenna.

Different types of configurations on the antenna will give different outcomes such as high gain, wide bandwidth and better efficiency. The distribution of the voltage depends on the array of the feeding network. An optimal feeding network collects all of the imposed voltage into one feeding point [7].

Ensuring there is proper impedance matching all through corporate and series feeding array configuration will result in a highly efficient microstrip antenna [8]. Whereas, power distribution of elements within the antenna can be altered by the corporate feed network. The corporate network can then introduce a phase [9].

The choice of design parameters for dielectric material, height and frequency is fundamental to good antenna performance. For instance, radiation release can be mitigated by using proper design [10] and most importantly, use of permittivity substrates enables a smaller size of microstrip antenna that is equally effective to a large size antenna [11]. Further, using thick substrates ensures lower range of dielectric offer, higher efficiency, wide bandwidth and larger element size [12].

X-band is popular with military communication satellites, as ITU has advised the use of X-band uplink frequency from 7.9 to 8.4GHz to be optimal for this purpose. While, ITU assigned downlink frequency band is from 7.25 to 7.75GHz.

In telecommunication engineering, X-band uplink and downlink frequency pair is also called 8/7GHz X-band satellite communications system. [13]

The main contribution of this paper is to analyze the performance of a rectangular patch antenna for X-band applications based on the Cole-Cole diagram representation.

In this paper, an approach that uses the Debye relation [14] is presented to portray such frequency-dependent performance characterization of a microstrip structure.

II. THEORETICAL FORMULATIONS OF THE RECTANGULAR PATCH ANTENNA

For ease in analysis of performance of the antenna, the microstrip patch is structure choice is square, rectangular, circular or some other common shapes. In this research, the for rectangular microstrip, the Length is denoted as \( L \) and is most commonly between range \( 0.333\lambda_0 \leq L \leq 0.5\lambda_0 \), where \( \lambda_0 \) is the free space wavelength. The patch must thin, where the thickness denoted as \( t \) is such that \( t \ll \lambda_0 \). The height or \( h \) of the substrate is \( 0.003\lambda_0 \leq h \leq 0.05\lambda_0 \). The dielectric constant of the substrate \( \epsilon_r \) is between \( 2.2 \leq \epsilon_r \leq 12 \) [15]. For efficient radiation emanation, best width used in case of rectangular shape is [16].

\[
w = \frac{1}{2f} \sqrt{\frac{\mu_0 \epsilon_0}{\epsilon_r + 1}} \left( \sqrt{2} \right)
\]
And the length of the antenna becomes:
\[
L = \frac{1}{2f\sqrt{\varepsilon_{\sigma}\sqrt{\varepsilon_{\sigma}\mu_0}}} - 2\Delta L
\]  
(2)

where:
\[
\Delta L = 0.41h \frac{\varepsilon_{\sigma} + 0.3}{\varepsilon_{\sigma} - 0.258} \left( \frac{w}{h} + 0.264 \right)
\]  
(3)

And [17]:
\[
\varepsilon_{\sigma} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left( 1 + \frac{10}{h} \right)^{-s}
\]  
(4)

where \( B \) is given by:
\[
B = 0.564 \left\{ 1 + \frac{1}{49} \ln \left( \frac{w}{h} \right)^{4} \left( \frac{w}{h} \right)^{4} \right\} + \frac{1}{18.7} \ln \left[ 1 + \left( \frac{w}{18.1h} \right)^{2} \right] \left( \frac{\varepsilon_r - 0.9}{\varepsilon_r + 3} \right)^{0.053}
\]  
(5)

Further, “\( \lambda \) is denoted for wavelength, \( f_r \) (in Hz) is the resonant frequency, \( L \) and \( W \) are the length and width of the patch element, in cm, respectively and \( \varepsilon_r \) is the relative dielectric constant” [16].

To include the effect of high frequency in the procedure, the concept of microstrip-based Cole-Cole diagram is adopted to create frequency-dependent (lossy) characteristic impedance.

Before analysis of frequency-dependent variables, the capacitance parameter within the microstrip line should be calculated. The capacitance per unit length of the classical parallel-plate capacitor is [18]:
\[
C = \varepsilon \frac{w}{h}
\]  
(6)

“A simple frequency-dependent capacitance of the parallel-plate capacitor can be expressed in any frequency-dependent attributes of \( \varepsilon \) which is” [16]:
\[
C(\omega) = \varepsilon \varepsilon_r(\omega) \frac{w}{h}
\]  
(7)

where \( \varepsilon_r(\omega) \) is a complex permittivity is expressed as \( \varepsilon_r(\omega) = j \varepsilon_r^*(\omega) \). Therefore:
\[
C(\omega) = \varepsilon \varepsilon_r(\omega) \frac{w}{h} - j \varepsilon \varepsilon_r^*(\omega) \frac{w}{h}
\]  
(8)

Further referring to Cole-Cole diagram deduced for a parallel-plate microstrip line in [19] the equation is substituted into (8) which is represented as:
\[
C(\omega) = C \left[ \frac{1}{1 + Q(\omega) \left[ \frac{Q(\omega) + \varepsilon_{\sigma}}{\varepsilon_r} \right]} - j C \frac{\varepsilon_r(\omega) + \varepsilon_r^*(\omega) + \varepsilon_r^*(\omega)}{\varepsilon_r} \right]
\]  
(9)

where \( C = \varepsilon \varepsilon_r \left( w/h \right) \).

For ease of calculation, the coefficients of (9) are as:
\[
A(\omega) = \frac{1}{1 + Q(\omega) \left[ \frac{Q(\omega) + \varepsilon_{\sigma}}{\varepsilon_r} \right]}
\]  
(10)

\[
B(\omega) = \frac{1}{\varepsilon_r} \left[ \varepsilon_r(\omega) + \varepsilon_r^*(\omega) + \varepsilon_r^*(\omega) \right]
\]  
(11)

In general, the characteristic impedance of a transmission line is given by:
\[
Z_0 = \sqrt{\frac{R + j\omega L}{G + j\omega C}}
\]  
(12)

where \( R \), \( L \), \( G \), \( C \) are per unit length quantities defined as follows:
- \( R \) = resistance per unit length in Ohm/m.
- \( L \) = inductance per unit length in H/m.
- \( G \) = conductance per unit length in S/m.
- \( C \) = capacitance per unit length in F/m. [20]

If \( G \) and \( C \) are neglected, the characteristic impedance can be written as:
\[
Z_0 = \sqrt{\frac{L}{C}}
\]  
(13)

Microstrip patch antenna can be fed by two approaches which are contacting and non-contacting [21]. In the case of contacting, the RF power is fedded using microstrip line as a connecting element, and the RF power is fed directly into the radiating patch through the microstrip line. Contrarily, the non contacting approach uses electromagnetic field coupling to transfer power from microstrip line to the radiating patch.

The four widely used techniques are through microstrip line and coaxial probe which are both contacting schemes, or, aperture coupling and proximity coupling which are both non contacting techniques.

We propose microstrip line feed technique in this research. The technique adopted is such that conducting strip is connected to the edge of the microstrip patch.

III. THE FREQUENCY-DEPENDENT SMITH-CARTH MODEL (FDSC)

The microstrip-based Cole-Cole diagram is used to create frequency-dependent (lossy) Smith-chart which we use to analyze the microstrip line characteristics [17], [22] and [23]. This is to evaluate efficiency of the microstrip.

Referring to the equivalent Cole-Cole diagram deduced for a parallel-plate microstrip line in is derived [22] and then we can obtain the frequency-dependent characteristic impedance \( Z_0(\omega) \) given by:
\[
Z_0(\omega) = \sqrt{L \left[ A(\omega) - jB(\omega) \right] Z_0} = \frac{Z_0}{\sqrt{A(\omega) - jB(\omega)}}
\]  
(14)

where \( A(\omega) \) and \( B(\omega) \) can be found in [22].

Now, the frequency-dependent (lossy) Smith-chart can be constructed by applying \( Z_0(\omega) \) into normalized terminal impedance expression after the procedure is done for the Smith-chart. Therefore, the normalized terminal impedance \( Z_t \) is:
where \( r \) and \( x \) are the normalized resistance and normalized reactance, respectively, and 
\[
b = \sqrt{A(\omega) - jB(\omega)}.
\]

Corresponding, the voltage reflection coefficient of present Smith chart can be expressed as:
\[
\Gamma' = \frac{Z_t - 1}{Z_t + 1}
\]
or
\[
Z'_t = \frac{Z_t}{Z_0(\omega)} = br + jbx = \frac{(1 + \Gamma') + j\Gamma'}{(1 - \Gamma') - j\Gamma'}
\]

Now, the desired sets of equations depicting the modified Smith-chart are:
\[
\left(\Gamma' - \frac{br}{1 + br}\right)^2 + \Gamma'^2 = \frac{1}{(1 + br)^2}
\]
and
\[
\left(\Gamma' - \frac{1}{rx}\right)^2 + \Gamma'^2 = \left(\frac{1}{bx}\right)^2
\]

When loss characteristics such as substrate loss, conductor loss, frequency dependent characteristic impedance of the microstrip line and lossy transmission line theory are all included in the analysis or calculation, then the attenuation function of line-length plotted on the Smith chart, is represented in the form of a spiral [22].

IV. THE COLE-COLE REPRESENTATION: THE PERFORMANCE MODEL

A. Theory of Dielectric Behavior

The quantity of dielectric constant and dissipation factor is essential in designing a device especially for microelectronic equipments.

Debye [15] illustrates the relaxation of polarization with a single relaxation time. It showed that non-interacting dipoles are free to rotate in opposition to much resistance in a fluid like medium. The equation for complex permittivity is:
\[
e' = \varepsilon_0 + \frac{\varepsilon_0 - \varepsilon_\infty}{1 + i\omega\tau}
\]

where:
- \( \varepsilon_0 \) = Dielectric constant at low frequency
- \( \varepsilon_\infty \) = Dielectric constant at high frequency
- \( \omega \) = Angular frequency
- \( \tau \) = Relaxation time

By taking out the parameter \( \omega \tau \) between the two equations and rearrange parameters \( (\varepsilon' \text{ and } \varepsilon'') \), the equation becomes:

\[
[\varepsilon' - \frac{\varepsilon_0 + \varepsilon_\infty}{2} + \varepsilon'' = \left[\frac{\varepsilon_0 - \varepsilon_\infty}{2}\right]^2
\]

The above equation is of a circle of radius \( \frac{\varepsilon_0 - \varepsilon_\infty}{2} \). Only the semicircle over which \( \varepsilon'' \) is positive has physical significance. Materials with single relaxation time yield a semicircle in \( \varepsilon' \text{ and } \varepsilon'' \) plane.

B. Microstrip-Based Equivalent Relaxation Process: Cole-Cole Representation

The analysis approach for performance of the antenna in this research is the Cole-Cole diagram discussed in detail in [22].

The dielectric relaxation is adopted to illustrate the performance of frequency-dependent microstrip structure. Therefore, the Debye relation is equivalent to frequency-dependent permittivity deduced for a microstrip. That is:
\[
e'(\omega) = \varepsilon_{eff}(\omega) = \left[\varepsilon(1 + \varepsilon_{eff}(0) - \varepsilon)\frac{1}{1 + Q(\omega)}\right]
\]

From Kirschning and Jansen’ frequency-dependent effective permittivity in (22):
\[
e'(\omega) = \frac{\varepsilon_{eff}(0) - \varepsilon}{1 + Q(\omega)} = \varepsilon(1 + \varepsilon_{eff}(0) - \varepsilon)\frac{1}{1 + 4\pi^2(\omega_l \omega)^2}
\]

This gives:
\[
\varepsilon_0 = \varepsilon_\infty = \varepsilon_0
\]
\[
\varepsilon_{eff}(0) = \varepsilon
\]
\[
\tau_0 = \frac{\sqrt{Q(\omega)}}{\omega}
\]

The imaginary part of Cole-Cole expression for a microstrip system is written as:
\[
e''(\omega) = \left[\frac{(\varepsilon_{eff}(0) - \varepsilon)\sqrt{Q(\omega)}}{1 + Q(\omega)}\right]
\]

Therefore, the complex permittivity of microstrip system in compact form is:
\[
e'(\omega) = \varepsilon_0 + \frac{\varepsilon_{eff}(0) - \varepsilon}{1 + j(1/2\pi)(\omega_l \omega)}
\]

According to [24], "the maximum points of semi-circles in the Cole-Cole patterns correspond to maximum Debye loss in a dielectric material but, 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. 1(a). Therefore, it can be considered that the microstrip geometry holds the field within itself, rather than letting it fringe out." This is important as the maximum value points (A) shown in Fig. 1(a), is such that microstrip geometry holds the field within itself, rather than letting it fringe out. [24]
Figure 1. (a) Cole-Cole representation of the microstrip structure. (b) Cole-Cole arc is symmetrical about a line through the center, parallel to the \( \varepsilon'' \) axis [27]. However, simulation results do have this symmetry. As shown in Fig. 3, the plots presented show skewed arcs in Cole Cole diagram representation, and the skewed is called Davison-Cole diagram [27]. Furthermore, the skewed arcs or Cole Cole representation of microstrip antenna is due to additional terms that represent dielectric and conductor losses.

VI. CONCLUDING REMARKS

This research paper uses Cole Cole representation model to design microstrip patch antenna used for X-band satellite communication applications. The proposed method in this research provides an additional method to design a computationally tractable approach via Cole Cole concept to study frequency-dependent aspects of microstrip structure for X-band.

TABLE I. MICROSTRIP PATCH ANTENNA PARAMETERS

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>4.7</td>
</tr>
<tr>
<td>b</td>
<td>1.4</td>
</tr>
<tr>
<td>c</td>
<td>5.2</td>
</tr>
<tr>
<td>L</td>
<td>8.9</td>
</tr>
<tr>
<td>W</td>
<td>10.8</td>
</tr>
<tr>
<td>h (thickness)</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Performance of the microstrip antenna depends on the used dielectric patch material, operating frequency and height of the substrate. Since antenna dimension is dependent on these parameters, the efficiency in radiation emanation and directivity also depends on such parameters. To ensure excellent performance of the microstrip antenna, the value of parameters need to be within a desired threshold level. [25]

There are many substrates that can be used for the design of microstrip antennas and their dielectric constants are usually in the range of \( 2.2 \leq \varepsilon_r \leq 12 \). To implement the microstrip antennas [15], [25] and [26], the shown in Table II are different types of substrates for microstrip antenna design.

TABLE II. SUBSTRATES FOR MICROSTRIP ANTENNA DESIGN

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fr-4</td>
<td>( \varepsilon_r = 4.9 )</td>
</tr>
<tr>
<td>Rogers TMM</td>
<td>( \varepsilon_r = 4.5 )</td>
</tr>
<tr>
<td>Taconic TLY-5</td>
<td>( \varepsilon_r = 2.2 )</td>
</tr>
<tr>
<td>Alumina (96%)</td>
<td>( \varepsilon_r = 9.4 )</td>
</tr>
<tr>
<td>Teflon (PTFE)</td>
<td>( \varepsilon_r = 2.08 )</td>
</tr>
<tr>
<td>Arlon AD 5</td>
<td>( \varepsilon_r = 5.1 )</td>
</tr>
</tbody>
</table>

Considering the performance of the proposed antenna in Table I, the simulation results in Fig. 3, indicate that the nonfringing part of the reactive energy in the antenna increases when the dielectric constant increases.

Figure 3. Cole-Cole representation of the microstrip antenna.

As illustrated in Fig. 2, the antenna constructed is designed to work on 7.5GHz and the quarter wavelength transformer method is used to match the impedance of the patch element with the transmission line. The essential parameters for the antenna are in Table I.
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REFERENCES


Settapong Malisuwan was born on March 24th, 1966 in Bangkok, Thailand. He received his PhD in electrical engineering (telecommunications), specializing in mobile communication systems from Florida Atlantic University (State University System of Florida), Boca Raton in 2000. He received his MSc in electrical engineering in mobile communications system, from George Washington University in 1996, and MSc in electrical engineering in telecommunication engineering from Georgia Institute of Technology in 1992. He served in the Royal Thai Armed Forces for more than 25 years and is currently the Vice Chairman of National Broadcasting and Telecommunications and the chairman of Telecommunication Commission Bangkok, Thailand. His research interests are in electromagnetics, efficient spectrum management and Telecommunications policy and management.

Noppadol Tiammana was born on November 12th, 1968 in Pah Na Korn Sri Ayuttaya, Thailand. He received his BSc in Electrical engineering from Saint John’s University, Thailand, 2002. He received his MSc in Technology Management from Thammasat University, Thailand, 2012. Since 2006, he has been working in National Broadcasting and Telecommunications Commission as Assistant to Secretary of Vice Chairman of National Telecommunication Commission (NBTC). His research interests include LTE design, wireless systems, microstrip antenna and applied electromagnetism.

Nattakit Suriyakrai was born in Khonkhaen, Thailand on March 22nd, 1987. He received his Bachelor of Liberal Arts in Japanese Language from Thammasat University in 2010. He has been working as an Assistant to Vice Chairman in National Broadcasting and Telecommunications, Bangkok, Thailand since November 2012. His research interests are in technology management and spectrum management.