การศึกษาตัวแปรของสายอากาศแบบไมโครสตริป รูปสี่เหลี่ยมผืนผ้าแบบมีช่องว่างอากาศ

นิรันดร์ คำประเสริฐ [1] เฉลิมพล น้ำค้าง [2] และ ทัศพงศ์ ทัศศรี [3]
มหาวิทยาลัยเทคโนโลยีพระจอมเกล้าธนบุรี บางมด ทุ่งครุ กรุงเทพฯ 10140

บทคัดย่อ

งานวิจัยนี้เสนอการศึกษาตัวแปรของสายอากาศแบบไมโครสตริปรูปสี่เหลี่ยมผืนผ้าแบบมีช่องว่างอากาศ โดยช่องว่างอากาศจะถูกแทรกระหว่างฐานรองไดอิเล็กตริกและระนาบสร้างเงาซึ่งทำให้ได้สายอากาศที่มีความกว้างแถบสูงกว่าสายอากาศแบบที่ใช้งานกันอยู่ทั่วไป อีกทั้งได้นำเสนอสมการรูปแบบปิดเพื่อที่จะใช้ในการคำนวณความถี่เรโซแนนซ์ อินพุทอิมพีแดนซ์ และความกว้างแถบ ซึ่งผลลัพธ์ที่ได้จากการคำนวณจากสมการรูปแบบปิดนี้เมื่อเปรียบเทียบกับผลการวัดจะให้ค่าที่ใกล้เคียงกัน และจากผลการทดลองพบว่าความถี่เรโซแนนซ์และความกว้างแถบจะแปรผันตามความกว้างของช่องว่างอากาศ และความกว้างแถบจะแปรผันตามอัตราส่วนของความหนารวมของฐานรองไดอิเล็กตริกกับความยาวคลื่นในอวกาศว่าง

[1] *รองศาสตราจารย์ (มรณะแล้ว) ภาควิชาวิศวกรรมอิเล็กทรอนิกส์และโทรคมนาคม*

[2] *รองศาสตราจารย์ ภาควิชาวิศวกรรมอิเล็กทรอนิกส์และโทรคมนาคม*

[3] *นักศึกษาปริญญาโท ภาควิชาวิศวกรรมอิเล็กทรอนิกส์และโทรคมนาคม*

Parametric Study of the Rectangular Microstrip Antenna with an Air Gap

Nirun Kumprasert [1] Chalermpol Namkang [2] and Taspong Tassri [3]
King Mongkut's University of Technology Thonburi, Bangmod, Toongkru, Bangkok 10140

Abstract

This paper presents parametric study of the rectangular microstrip antenna with an air gap. The air gap is inserted between the dielectric substrate and the ground plane for obtaining a larger bandwidth than a conventional antenna. The closed form expressions are proposed to calculate the resonant frequency, input impedance, and bandwidth of the antenna. The calculated results based on the closed forms are compared with experimental results and very good agreements are achieved. From experiments, it is found that the resonant frequency and the bandwidth increase while the air gap thickness is increased. In addition, the bandwidth increases while the ratio between the total thickness and the free space wavelength is increased.

[1] *Associate Professor (Deceased), Department of Electronics and Telecommunication Engineering*
[2] *Associate Professor, Department of Electronics and Telecommunication Engineering*
[3] *Graduate Student, Department of Electronics and Telecommunication Engineering*

1. Introduction

The use of microstrip antennas has become increasingly popular because of various inherent advantages such as light weight, simplicity of fabrication, ease of mass production, etc. The main inherent disadvantages of these antennas are their very narrow bandwidth (0.5-1%) [1]. A number of techniques have appeared in technical literature on bandwidth enhancement of microstrip antennas [2-6]. However these techniques create many problems for the designer (e.g., complicated configuration and numerical analysis). A simple antenna configuration with enhanced bandwidth and fewer problems has been reported by Abbound et al.[7].

In this paper, simple construction of microstrip antenna with an air gap between the dielectric substrate and the ground plane [7] is studied. It is well known that using a thick low permittivity substrate can increase the bandwidth of the microstrip antenna. A thick low permittivity substrate can be obtained by adding an air gap between the dielectric substrate and the ground plane. By adding an air gap, the thickness of the microstrip antenna substrate will be increased and the average relative permittivity of the dielectric substrate will be lowered. Another advantage is the resonant frequency can be tuned by adjusting the air gap thickness without needing a new design. The theoretical and experimental parameters of the rectangular microstrip antennas with an air gap are described in detail. The calculated results from the theory agree with the experiment excellently.

The rectangular microstrip antenna with an air gap between the dielectric substrate and ground plane is shown in Fig. 1. Analytic characteristics (or parameters) of the antenna in Fig. 1 are described in the following sections.

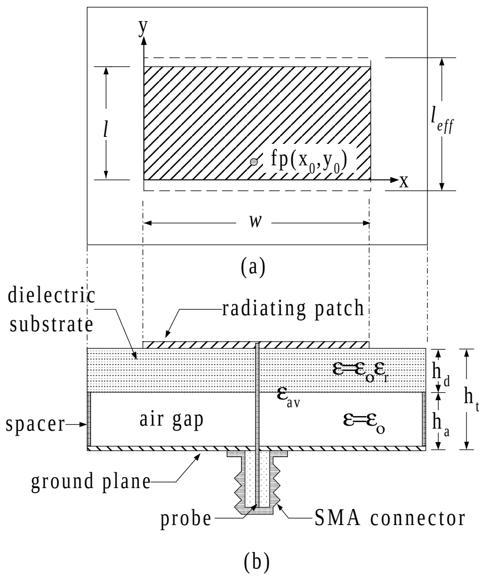

Fig. 1 The rectangular microstrip antenna with an air gap: (a) physical and effective dimension (b) structure

2. Theory

The theory is described in three subsections. There are expressions for the resonant frequency, input impedance, and the bandwidth of the rectangular microstrip antenna with an air gap, which are explained in the following subsections.

A. Resonant Frequency

A closed form for the resonant frequency of the rectangular microstrip antenna can be obtained from (2) of [7] as:

$$f_r = f_{mn} = \frac{C_0}{2\sqrt{\varepsilon_{dyn}}}\sqrt{\left[\left(\frac{m}{w_{eff}}\right)^2 + \left(\frac{n}{l_{eff}}\right)^2\right]} \tag{1}$$

Where f_{mn} is the resonant frequency (f_r) in GHz, subscript mn refers TM_{mn} modes, ε_{dyn} is the dynamic permittivity with an average relative permittivity (ε_{av}), and is the effective (electrical) length of the rectangular microstrip antenna with physical length and width in cm. respectively, and is the velocity of light in free space (300×10^6 m/s). This formula takes into account for the edge extension (fringing effect).

To compute the resonant frequency of the dominant mode (TM_{01}), we make use of (1) by set $m = 0$ and $n=1$, thus

$$f_{mn} = f_{01} = \frac{15}{l_{eff}\sqrt{\varepsilon_{dyn}}} \tag{2}$$

An average relative permittivity (ε_{av}) is used to average the permittivity of the two-layer dielectric. The formula of an average relative permittivity is as (1) of [7] as:

$$\varepsilon_{av} = \frac{\varepsilon_r h_d + \varepsilon_r h_a}{h_d + \varepsilon_r h_a} \tag{3}$$

Where ε_r is relative permittivity of the dielectric substrate, h_a is the air gap thickness, and h_d is the dielectric substrate thickness as the structure shown in Fig 1.

The dynamic permittivity (ε_{dyn}) in (2) is a function of the dimensions, the relative permittivity (ε_r), and the different modes field distribution. In this paper, we can determine it by using an expression from [8]:

$$\varepsilon_{dyn} = \frac{C_{dyn}(\varepsilon = \varepsilon_{av}\varepsilon_0)}{C_{dyn}(\varepsilon_0)} \quad (4)$$

Where $C_{dyn}(\varepsilon_{av}\varepsilon_0)$ and $C_{dyn}(\varepsilon_0)$ in (4) are the total dynamic capacitance of the rectangular microstrip antenna with dielectric substrate and without dielectric substrate (ε_r =1), respectively. These total capacitances can be obtained from [8], which we can simplify it without loss of accuracy for TM_{01}

$$C_{dyn}(\varepsilon_r\varepsilon_0) = \frac{\varepsilon_0\varepsilon_{av}wl}{2h_t} + 2\left[\frac{l}{4}\left(\frac{\sqrt{\varepsilon_{eff}(w)}}{c_0 Z(w,h_t,\varepsilon_r)} - \frac{\varepsilon_0\varepsilon_{av}w}{h_t}\right) + \frac{w}{2}\left(\frac{\sqrt{\varepsilon_{eff}(l)}}{c_0 Z(l,h_t,\varepsilon_r)} - \frac{\varepsilon_0\varepsilon_{av}l}{h_t}\right)\right] \quad (5)$$

The total dynamic capacitance in (4) can be used for determining $C_{dyn}(\varepsilon_0)$, by substituting ε_{av} =1 into (4).

To compute the effective length of a rectangular patch in (2), the effect of the edge extension is taken into account because of the influence of fringing field at the edge of the radiating patch. The effective length can be obtained from [7] as:

$$l_{eff} = l + 0.5\left(\frac{\varepsilon_{eff}(w)+0.3}{\varepsilon_{eff}(w)-0.258}\right)\left(\frac{120\pi h_t}{Z(w,h_t,\varepsilon_{av})\sqrt{\varepsilon_{eff}(w)}} - w\right) \quad (6)$$

Where $\varepsilon_{eff}(w)$ is the effective permittivity of the microstrip line and $Z(w,h_t,\varepsilon_{av})$ is the characteristic impedance of the microstrip line, which can be obtained from [9] and [10] as (7) and (8) respectively.

$$\varepsilon_{eff}(w) = \frac{\varepsilon_{av}+1}{2} + \frac{\varepsilon_{av}-1}{2}\left(1+\frac{10}{w/h_t}\right)^{-1} \quad (7)$$

$$Z(w,h_t,\varepsilon_r) = \frac{377}{\sqrt{\varepsilon_{eff}(w)}}\left[\frac{w}{h_t} + 1.393 + 0.667\ln\left(\frac{w}{h_t}+1.444\right)\right]^{-1} \quad (8)$$

$\varepsilon_{eff}(l)$ and $Z(l,h_t,\varepsilon_r)$ can be determined by using l instead of w in (7) and (8) respectively.

B. Input Impedance

Simple and valid closed form of the input impedance of the rectangular microstrip antenna with an air gap excited by a coaxial line can be determined from the cavity model analysis [7]:

$$Z_{in} = \frac{R}{1+Q_t^2\left(\frac{f}{f_{01}}-\frac{f_{01}}{f}\right)^2} + j\left[X_l - \frac{RQ_t\left(\frac{f}{f_{01}}-\frac{f_{01}}{f}\right)}{1+Q_t^2\left(\frac{f}{f_{01}}-\frac{f_{01}}{f}\right)^2}\right] \tag{9}$$

Where R is the input resistance at the resonance and X_l is the inductive reactance due to the probe [11]. This formula is valid on condition that the feed position (y_0) is located along l side and x_0 is at $\frac{w}{2}$.

$$R = \frac{Q_t h_t}{\pi\ f_r\ \varepsilon_{dyn}\varepsilon_0 l w}\cos^2\left(\frac{\pi\ y_0}{l}\right) \tag{10}$$

$$X_l = -\mu_0\ f_r h_t\left[\ln\left(\frac{\pi\ d\ f_r\sqrt{\varepsilon_{dyn}}}{2C_0}\right)+0.577\right] \tag{11}$$

and Q_t is the total quality factor.

C. Bandwidth

Inserting an air gap between the dielectric substrate and the ground plane causes the average relative permittivity of the substrate become smaller and the thickness is larger. The consequence is the enlarged bandwidth.

The bandwidth formula of the microstrip antenna can be obtained from various formulae such as those from [2] and [12]. In this paper, we adopt (15) of [12] but the formulae in [12] is used for single-layer microstrip antenna, so we modified it by using the average relative permittivity instead of the relative permittivity and the modified formulae is:

$$BW = \frac{\sqrt{2}p}{45\pi}\left(1-\frac{1}{\varepsilon_{av}}+\frac{2}{5\varepsilon_{av}^2}\right)\left(\frac{1}{\varepsilon_{av}}\right)\left(\frac{h_t}{\lambda_0}\right)\left(\frac{w}{l}\right) \tag{12}$$

Where p is the ratio of the patch-radiated power to the dipole-radiated power [12]

3. Calculated and Experimental Result

The top views and the side view of the constructed antennas are shown in Fig. 2 and Fig. 3 respectively.

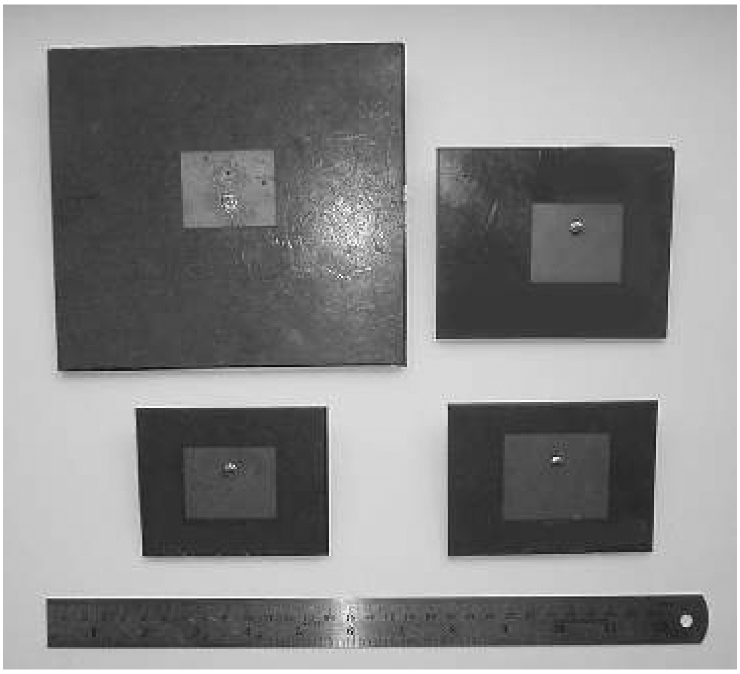

Fig. 2 The top view of the rectangular microstrip antennas with an air gap.

Fig. 3 The side view of the rectangular microstrip antennas with an air gap.

In this section, we present comparisons of the calculated and measured input impedance, resonant frequency, and bandwidth of the rectangular microstrip antenna with various air gap thicknesses. The calculation of the resonant frequencies can be obtained by using equation (2), the input impedance can be obtained by using equation (9) and the bandwidth can be obtained by using equation (12). The comparisons of these results are shown in Fig. 4- Fig. 10.

Fig. 5 and Fig. 6 show comparisons of the measured and calculated input impedances from [7] and input impedances of the present method of the rectangular microstrip antenna with w=2.65 *cm*, l=2 *cm*, h_d=0.156 *cm*, ε_r=4.55, $\tan\delta$=0.02, and y_0=0.54 *cm*.

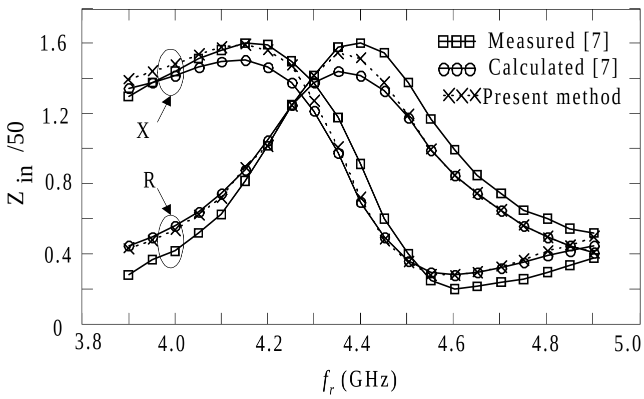

Fig. 4 Comparison of the calculated and measured input impedance of the antennas with an air gap of 0.5 mm.

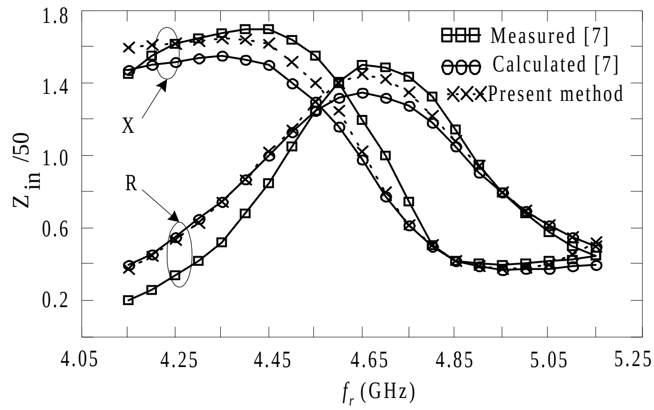

Fig. 5 Comparison of the calculated and measured input impedance of the antennas with an air gap of 1 mm.

In the study of the relation between the resonant frequency, the bandwidth and the air gap thickness, the antennas were constructed from RT/duroid 5880 with ε_r=2.2, $\tan\delta$=0.0004, and h_d=0.159 *cm*. All antennas were designed to match the transmission line having the characteristic impedance of 50 Ω. The instruments used in our experiments are the Advantest Network Analyzer model R3762A and the S-parameter test set model R3961A. Before measuring, instrumentation calibration has to be performed. Then the antenna will be connected to the S-parameter test set at Channel 1 to measure S11, and then the resonant frequency at the minimum SWR. The bandwidths of the antennas are measured as the frequency range, which the SWR is less than or equal to 2. The best SWR achieved with this type antenna is 1.017 with h_t/λ_0= 0.0216 and bandwidth = 2.99%.

The calculated and measured bandwidths of the rectangular microstrip antennas with different air gap thicknesses (h_a) are shown in Fig. 6 and Fig. 7. Both figures show that the bandwidths vary increasingly with air gap thicknesses when such antennas are designed at the same resonant frequency.

However, as the bandwidth is being increased by this technique, the lower efficiency and the degradation of radiation pattern will be obtained because of excited surface wave as reported in [11]. Therefore, in designing the rectangular microstrip antenna by adding an air gap, it should be compromised between the tolerated bandwidth, the radiation pattern and efficiency.

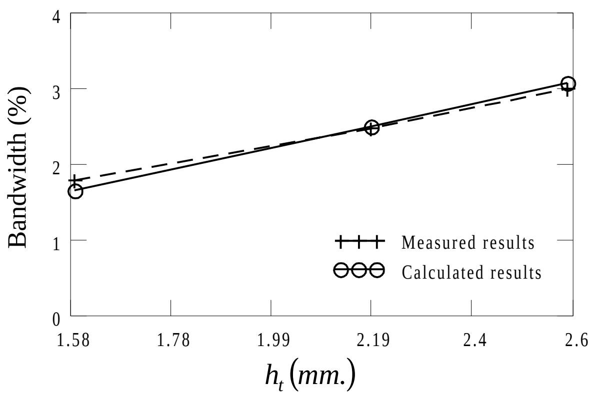

Fig. 6 Comparison of the calculated and measured bandwidth of the antennas with = 2.5 GHz.

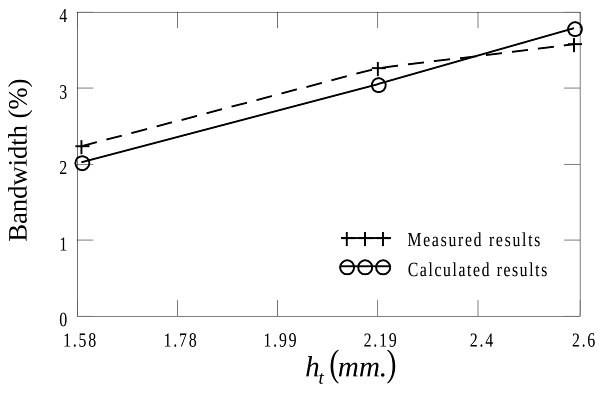

Fig. 7 Comparison of the calculated and measured bandwidth of the antennas with = 3 GHz.

The calculated and measured resonant frequency of the rectangular microstrip antennas with different air gap thicknesses (h_a) are shown in Fig. 8 and Fig. 9. Both figures show that the resonant frequency varies increasingly with air gap thicknesses when such antennas have the same width and length. Also, the differences between the calculated and the measured resonant frequencies toward higher while air gap thicknesses are increasing.

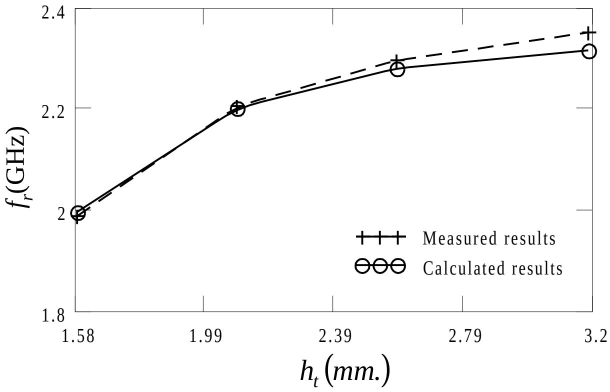

Fig. 8 Comparison of the calculated and measured resonant frequencies of the antennas.

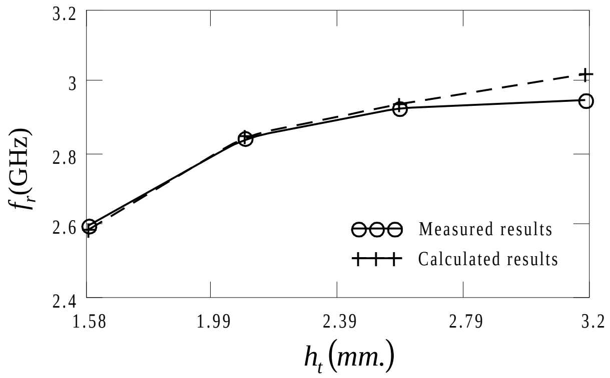

Fig. 9 Comparison of the calculated and measured resonant frequencies of the antennas.

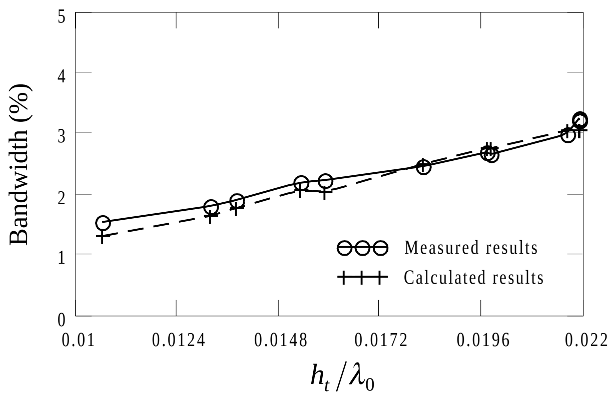

Fig. 10 Comparison of the calculated and measured bandwidth of the antennas with different air gap thicknesses (h_a).

The calculated and measured bandwidths of the rectangular microstrip antennas by increasing the thicknesses of air gap are shown in Fig. 10. It shows that bandwidths vary directly with the ratio of h_t and λ_0.

4. Conclusions

This paper is the study of parameters and the closed form expressions of rectangular microstrip antenna with an air gap. The average errors between the calculated and measured results of the resonant frequencies and the bandwidths are 0.83% and 8.82% respectively. The resonant frequencies of the rectangular microstrip antenna with an air gap vary increasingly with the air gap thickness as the patch size is fixed. The bandwidths vary increasingly with the air gap thickness as the antennas are resonant at the same frequency. The bandwidth increases while the ratio between the total thickness and the free space wavelength ($0.011 \leq h_t/\lambda_0 \leq 0.022$) is increased. This antenna configuration gives a bandwidth more than the microstrip antenna without an air gap by about 1.5-2 times.

References

1. Hansen, R. C., 1981, "Fundamental Limitation in Antennas," *Proc. IEEE*, Vol. 69, pp. 170-182.

2. Pues, H. F. and Van De Capelle, A. R., 1989, "An Impedance-matching Technique for Increasing the Bandwidth of Microstrip Antenna," *IEEE Trans. Antennas Propagat.*, Vol. 37, No. 11, pp. 1345-1354.

3. Croq, F. and Pozar, D. M., 1991, "Millimeter-wave Design of Wide-band Aperture-coupled Stacked Microstrip Antennas," *IEEE Trans. Antennas Propagat.*, Vol.39, pp.1770-1776.

4. Fong, F. S., Pues, H. F., and Withers, M. J., 1985, "Wideband Multilayer Coaxial-fed Microstrip Antenna Element," *Electron. Lett.*, Vol. 21, pp. 497-499.

5. Pozar, D. M. and Kaufman, B., 1987, "Increasing the Bandwidth of a Microstrip Antenna by Proximity Coupling," *Electron. Lett.*, Vol. 23, No. 8, pp. 368-369.

6. Wood, C., 1980, "Improved Bandwidth of Microstrip Antennas using Parasitic Elements," *IEE Proceedings*, Vol. 127, Part H, pp. 231-234.

7. Abboud, F., Damiano, J. P., and Papiernik, A., 1989, "Accurate Model for the Input Impedance of Coax-fed Rectangular Microstrip Antenna with and without Air Gaps," *IEEE Trans. Antennas Propagat.*, Vol. 1, pp. 102-106.

8. Wolf, I. and Knoppik, N., 1974, "Rectangular and Circular Microstrip Disk Capacitors and Resonators," *IEEE Trans. Microwave Theory Tech.*, Vol. 22, pp. 857-864.

9. Schneider, M. V., N., 1964, "Microstrip Line for Microwave Integrated Circuits," *Bell. Syst. Tech.J.*, Vol. 48, pp. 1422-1444.

10. Hammerstad, E. O., 1975, "Equations for Microstrip Circuit Design," *Proc. 5th European Micro. Conf.*, Hamburg, pp. 268-272.

11. Sainati, R. A., 1996, *CAD of Microstrip Antennas for Wireless Applications*, Artech House Inc., Norwood, MA.

12. Jackson, D. R. and Alexopoulus, N. G., 1991, "Simple Approximate Formulas for Input Resistance, Bandwidth, and Efficiency of a Resonant Rectangular Patch," *IEEE Trans. Antennas Propagat.*, Vol. 39, No. 3, pp. 407-410.