CAD OF RECTANGULAR MICROSTRIP ANTENNAS

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Abstract

New simple computer-aided design formulas for the rectangular microstrip patch antennas have been developed. The cavity model is used but the more accurate models for open-end effect of microstrip lines and the effective permittivity are used. That allows increasing the calculation resonant frequency accuracy. Calculations of several cases have been compared with the conventional cavity calculations, expressions generated by curve fitting to full wave solutions and experimental values.

Keywords

CAD formulas, rectangular microstrip antennas, microwave antennas

1. Introduction

During the past twenty years, microstrip patch antennas experienced a great gain in popularity and have become a major research topic in both theoretical and applied electromagnetic fields. They are well known for their highly desirable physical characteristics such as low profile, light weight, low cost, ruggedness, and conformability. Numerous researchers have investigated their basic characteristics and extensive efforts have also been devoted to the design of "frequency agile," "polarization agile," or dual-band microstrip antennas.

Although patch antennas appear simple and are easy to fabricate, obtaining electromagnetic fields, which satisfy all the boundary conditions, is a complicated task. For this reason, simplified approaches such as the transmission line model and the cavity model have been developed. The cavity model is particularly popular [1] - [4]. The basic idea of the cavity model is to treat the region between the patch and ground plane as a resonant leaky cavity. The simplified approaches allow the analysis as well as the design of rectangular microstrip patch antennas but the accuracy of those formulas is rather low.

On the other hand, the more accurate full-wave analysis [4] cannot be used for design because it is very time consuming. Therefore, new simple computer-aided design formulas for the rectangular microstrip patch antennas have been developed. The cavity model is used but the more accurate models for open-end effect of microstrip lines and the effective permittivity are used.

One of the common method of feeding a microstrip antenna is by means of a coaxial probe. The basic configuration is shown in Fig. 1, where a single metallic rectangular patch is printed on a grounded substrate.

2. Computer-aided design formulas for rectangular patch antennas

Consider the basic form of microstrip antenna with the rectangular patch fed by a coaxial probe shown in Fig. 1. The patch is of length a, width b, and is at a height h above the ground plane (i.e., h is the substrate thickness). The dielectric substrate has a relative permittivity ε_r. The feed-point coordinates of coaxial probe are x_o and y_o. The value of $y_o = b/2$ is chosen. In this case, the linear polarization is radiated and the dominant mode is TM_{10}.

The cavity model [1], [2], and [3] uses the following assumptions:

1. The fields in the cavity are TM (transverse magnetic).
2. The cavity is bounded by magnetic walls ($H_{tangential} = 0$) on the sides.
3. Surface wave excitation is negligible.
4. The current in the coaxial probe is independent of z.

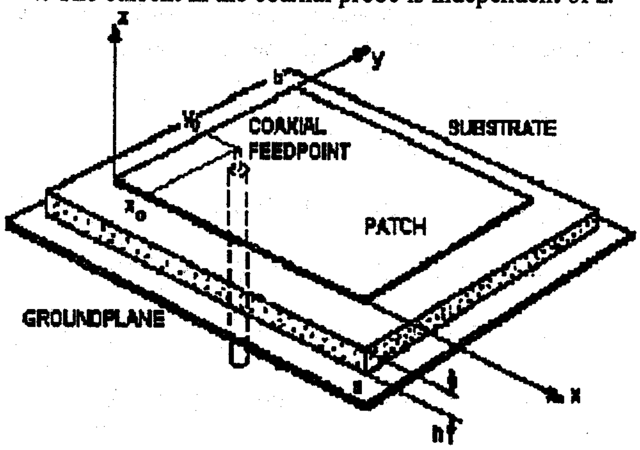

Fig. 1. Rectangular patch antenna fed by a coaxial probe

The resonant frequency f_r is given by

$$f_r = k_x c/(2\pi\sqrt{\varepsilon_r}) \qquad (1)$$

where c is the speed of light. The value of $k_x = k_x' + k_x''$ is given by

$$\tan k_x a = \frac{2\alpha_x k_x}{k_x^2 - \alpha_x^2}, \qquad (2)$$

where $\alpha_x = jk_oZ_oY'_{wx}F_x$, $k_o = 2\pi/\lambda_o$, $\lambda_o = c/f$, $Z_o = 376.73$. The value of F_x can be calculated by

$$F_x = 0.7747 - 0.5977(1-b/a) - 0.1638(1-b/a)^2 \qquad (3)$$

The wall admittance Y'_{wx} is given by

$$Y'_{wx} = 0.00834\, h/\lambda_o + j\, 0.01668\, \Delta a\, \varepsilon_{eff}/\lambda \qquad (4)$$

Usually, the Hammerstad's formula [5] is used for calculation of fringing length Δa and the Schneider's formula [6] for effective permittivity ε_{eff}. An iterative algorithm is used for finding the solution of equation (2).

To increase the cavity model accuracy, the calculation of fringing length Δa uses the model [7] and effective permittivity ε_{eff} is calculated combining the model [8] and model [9]. The model [9] uses the following formula to calculate the frequency dependence of ε_{eff}

$$\varepsilon_{eff} = \varepsilon_r - \frac{\varepsilon_r - \varepsilon_{eff}(f=0)}{1+P(f)} \qquad (5)$$

A mathematical structure of expression (5) is identical to Getsinger's formula describing microstrip dispersion. However, the term $\varepsilon_{eff}(f=0)$ is calculated using [8] and the term $P(f)$ is calculated using the following formulas

$$P(f) = P_1 P_2 [(0.1844 + P_3 P_4) 10 f_h]^{1.5763} \qquad (5a)$$

where f_h is the normalized frequency in GHz cm (note: $f_h = fh \sim h/\lambda_o$) and $u = b/h$ denotes the microstrip width b normalized with respect to the substrate thickness h

$$P_1 = 0.27488 + [0.6315 + 0.525/(1+0.157 f_h)^{20}]u - 0.065683 \exp(-8.7513u)$$

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

$$P_3 = 0.0363 \exp(-4.6u)\, \{1 - \exp[-(f_h/3.87)^{4.97}]\}$$

$$P_4 = 1 + 2.751\{1 - \exp[-(\varepsilon_r/15.916)^8]\}$$

The input impedance Z_a is given by the following equation [2]

$$Z_a = \frac{j\omega\mu_0 h}{2\upsilon} \ln\sqrt{\frac{ab}{\pi r_0^2}} - \frac{2jZ_0 h \cos^2(\pi x_0 / a)}{\varepsilon_r k_0 ab} \frac{\omega^2}{\omega^2 - \omega_{10}^2 (1 + j/2Q_T)^2} \qquad (6)$$

where $\omega = 2\pi f$, $\mu_o = 4x10^{-7}$ H/m, r_o is the radius of the probe, and Q_T is the total quality factor, which can be calculated by

$$Q_T = (1/Q_m + 1/Q_d + 1/Q_r)^{-1} \qquad (7)$$

$$Q_m = \frac{\omega^3 \varepsilon_r h \sigma\, \mu_o\, \varepsilon_o a^2}{2\pi^2 \sqrt{\pi\, f \sigma \mu_o}} \qquad (7a)$$

$$Q_d = \varepsilon_r / \tan\delta \qquad (7b)$$

$$Q_r = k_x' / 2\, k_x'' \qquad (7c)$$

where σ is the conductivity of the metal, $\tan\delta$ is loss tangent of the substrate, ε_o is free space permittivity, and $\varepsilon = \varepsilon_r \varepsilon_o$.

The bandwidth B of the patch for the standing-wave ratio S is given by

$$B = (S-1)/(Q_T\sqrt{S}) \qquad (8)$$

This bandwidth is unitless. To obtain the percentage result, multiply B by 100.

Usually, the standing-wave ratio $S = 2.0$ is chosen. In this case, the Eq. (7) can be written as

$$B = 1/(Q_T\sqrt{2}) \qquad (8a)$$

The far-field radiation pattern of a rectangular microstrip patch operating in the TM_{10} mode is broad in both the E and H planes. The pattern of a patch over a large ground plane may be calculated using electric-current model [4]. For non-magnetic material, the E-plane radiation pattern is given by Eq. (9) and the H-plane radiation pattern is given by Eq. (10).

$$E_\theta = C_\theta \left[\frac{\cos\left(\frac{k_0 a \sin\theta}{2}\right)}{\left(\frac{\pi}{2}\right)^2 - \left(\frac{k_0 a \sin\theta}{2}\right)^2} \right] \cdot \frac{\tan(k_0 h N(\theta))\cos\theta}{\tan(k_0 h N(\theta)) - j\frac{\varepsilon_r}{N(\theta)}\cos\theta} \qquad (9)$$

$$E_\phi = C_\phi \left[\frac{\sin\left(\frac{k_o b \sin\theta}{2}\right)}{\left(\frac{k_o b \sin\theta}{2}\right)} \right] \cdot \frac{\tan(k_0 h N(\theta))}{\tan(k_0 h N(\theta)) - jN(\theta)\sec\theta} \qquad (10)$$

where C_θ and C_ϕ are constants and $N(\theta) = \sqrt{(\varepsilon_r - \sin^2\theta)}$.

The program has been written for the analysis or the design of the patch antennas using the above formulas. It is possible to analyze the patch of length a and width b with the substrate thickness h, substrate relative permittivity ε_r, substrate loss tangent, patch thickness t, feed-point coordinates of coaxial probe x_o and $y_o = b/2$, probe radius r_o, and characteristic impedance Z of the incoming coaxial cable. The resonant frequency f_r and the normalized frequencies f/f_o are calculated where

$$f_0 = c / (2a\sqrt{\varepsilon_r}) \qquad (11)$$

is the zero-order resonant frequency. Moreover, the fringing length Δa, effective permittivity ε_{eff}, the ratio of h/a, the bandwidth B of the patch for the standing-wave ratio $S = 2.0$, antenna efficiency Q_T/Q_r, the E and H-plane radiation patterns, and the input impedance Z_a in the extended frequency range $<f_r(1\text{-}1/Q_T); f_r(1+1/Q_T)>$ for 21 various frequencies can be calculated.

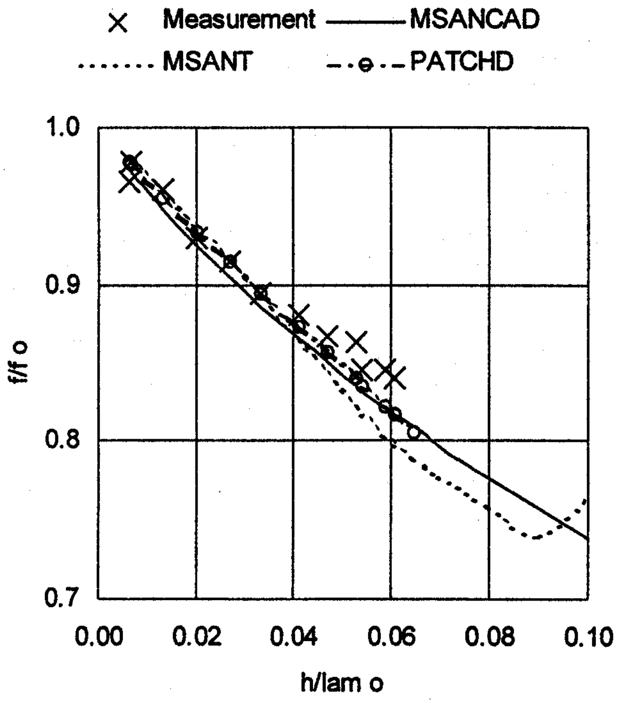

Fig. 2. Normalized resonance frequency versus the electrical thickness of the substrate

When the design is chosen, the patch width b with the substrate thickness h, substrate relative permittivity ε_r, substrate loss tangent, patch thickness t, characteristic impedance Z of the incoming coaxial cable, and the resonant frequency f_r are entered. The length a, normalized frequencies f/f_o, feed-point coordinates of coaxial probe x_o and $y_o = b/2$, the fringing length Δa, effective permittivity ε_{eff}, the ratio of h/a, the bandwidth B of the patch for the standing-wave ratio $S = 2.0$, and antenna efficiency Q_T/Q_r are calculated.

The results are stored into output data files both for the analysis and design.

The various rectangular patches have been investigated. The calculations using the above described program (MSANCAD) with $b/a = 1.5$ and $x_o = a/4$ are shown with the solid line. The measurement results [4], which were obtained by using a variety of different substrate thickness and patch sizes (with $b/a = 1.5$), are shown with crosses. The conventional cavity method using program MSANT [10] and the program PATCHD [11] have been used for comparison.

The basis for the program PATCHD is a series of closed form expressions, which were generated by curve fitting to full wave solutions. As such the program PATCHD results include surface wave effects and are rigorous except for the fact that no feed model is included. However, there are some limitations on certain parameters ($0 \le \sqrt{(\varepsilon_r\text{-}1)}\, h/\lambda_o \le 0.2$, $1 \le \varepsilon_r \le 10$ and for rectangular patches $0.9 \le b/a \le 2$ and $0 \le h/a \le 0.2$).

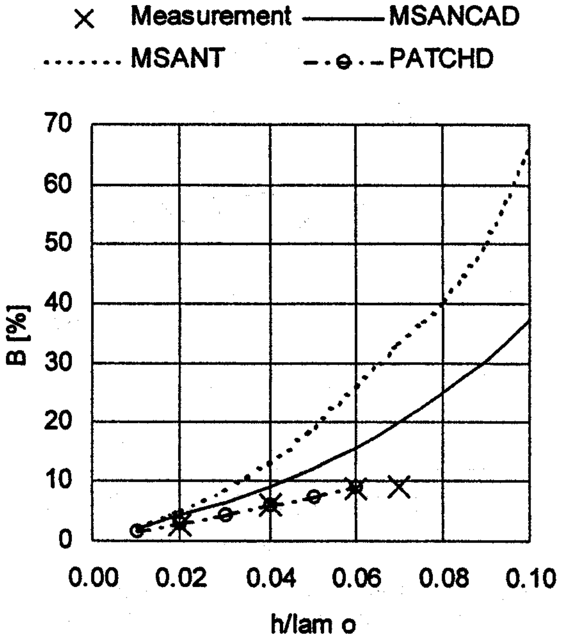

Fig. 3. The percentage bandwidth of a rectangular patch versus the electrical thickness of the substrate

The normalized resonance frequency versus the electrical thickness of the substrate h/λ_o is shown in Fig. 2. It can be seen that the results are in agreement both with experimental and published calculation results. When the electrical thickness of the substrate h/λ_o increases, the differences between MSANCAD and MSANT results are greater and the program PATCHD cannot be used due to above given limitations.

The percentage bandwidth of a rectangular patch versus the electrical thickness of the substrate h/λ_o is shown in Fig. 3. It can be seen that the results of experimental and published calculations are different. When the electrical thickness of the substrate h/λ_o increases, the differences between MSANCAD, MSANT, PATCHD and measurement results are greater and the program PATCHD cannot be used. However, the MSANCAD results are better than the MSANT results.

The resonant input resistance of probe-fed rectangular patch versus the electrical thickness of the substrate h/λ_o is shown in Fig. 4. It can be seen that the results of both experimental and published calculations are different. When the electrical thickness of the substrate h/λ_o increases, the differences between MSANCAD, MSANT, PATCHD and measurement results are greater and the program PATCHD cannot be used. However, the MSANCAD results are better than the MSANT and PATCHD results.

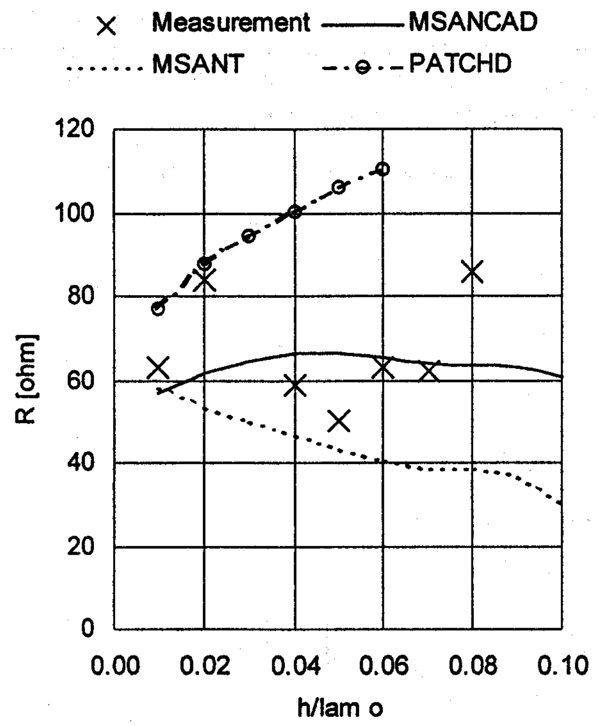

Fig. 4. The resonant input resistance of probe-fed rectangular patch versus the electrical thickness of the substrate

Another patches have been investigated as well. The conclusions of comparison are similar. However, the comparisons will be published later.

3. Conclusions

New simple CAD formulas for a rectangular patch antenna have been presented. The cavity model has been used but the more accurate models for open-end effect of microstrip lines and the effective permittivity have been used. That allows increasing the calculation resonant frequency accuracy. Moreover, the reliability of calculation considering the frequency range and the ratio h/a is higher than for the usual cavity model MSANT [10]. Because of the relative simplicity of the new model, the analysis as well as the design of rectangular microstrip patch antennas can be performed.

It can be concluded that the normalized resonance calculations are in agreement both with experimental and published calculation results. The experimental and published calculations of bandwidth and resonant input resistance are different. However, the MSANCAD results are better than the MSANT results. Considering the resonant input resistance the MSANCAD results are better than the PATCHD [11] results.

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