A Method for Designing Broad-Band Microstrip Antennas in Multilayered Planar Structures

Zhang-Fa Liu, Pang-Shyan Kooi, *Member, IEEE*, Le-Wei Li, *Senior Member, IEEE*, Mook-Seng Leong, *Senior Member, IEEE*, and Tat-Soon Yeo, *Senior Member, IEEE*

***Abstract*— The narrow bandwidth of a microstrip antenna is one of the important features that restrict its wide usage. A simple and practical method for the design of broad-band microstrip antennas is presented in this paper. Utilizing this design technique, several two-layer microstrip antennas have been proposed. To confirm the applicability of the method for the designs of antennas at L-band, experiments have been carried out. The measured results show that the proposed antennas have a bandwidth of up to 25.7%. Also, the method proposed in this paper is applicable to the design of other types of multilayered planar antennas.**

***Index Terms*—Broad-band antennas, nonhomogeneous media, patch antennas.**

I. Introduction

A MICROSTRIP antenna possesses many advantages such as low profile, light weight, small volume, and mass-production. It has attracted increasing attention of many researchers to investigate this type of antenna or arrays of various configurations to meet various practical applications. The analysis and design of various-shaped microstrip antennas mounted on different structures have been extensively reviewed in a book by Pozar and Schaubert [1]. However, the narrow bandwidth of these antennas is the major obstacle that restricts wide applications. In general, the impedance bandwidth of a traditional microstrip antenna is only a few percent, e.g., about 5% [2], [3]. Therefore, it becomes very important for the microstrip antenna designers to develop broad-band techniques so as to enhance the bandwidths of the microstrip antennas.

Recently, much progress has been made to broaden the bandwidths of microstrip antennas [1], [4]–[8]. Pozar [1] listed the bandwidths for microstrip antennas with several shapes such as narrow rectangular, square, wide rectangular, and circular. The ways to enhance the bandwidth of microstrip antenna can be used: parasitic elements [3], [9], aperture-coupled [10]–[12], and impedance matching network [13], etc. However, the research work is focused mainly on experimental investigations and the design is sensitive to fabrication tolerance [14]; there is a general lack of information that provides a systematic design method.

Manuscript received May 22, 1998; revised February 17, 1999. This work was supported in part under research Grant RP950646 and in part under Grant ARF950646 of the Academic Research Fund.

The authors are with Communications and Microwave Division, Department of Electrical Engineering, National University of Singapore, Singapore 119260.

Publisher Item Identifier S 0018-926X(99)04829-2.

In this paper, a practical, conceptually simple, very efficient method for designing wide-band microstrip antennas is proposed. The design theory and its relevant formulations are given in Section II. Section III shows both design and experimental results from which the bandwidth of the antenna is seen to have been increased up to 25.7% $(\mathrm{VSWR} \leq 2.0)$; the gain of this antenna is larger than 8 dB in the operating frequncy band. The measurement data shown for comparison are in very good agreement with the design results presented in this paper. Although the method in this paper is applied to a two-layered microstrip antenna where if the capacitance flat is not countered, the formulas provided can also be utilized to design other multilayered microstrip antenna structures.

II. Method for Designing Wide-Band Microstrip Antenna

One of the potential advantages of microstrip antenna is its simple physical architecture. Therefore, it is important to preserve the attractive features in the design of microstrip antennas. Generally, when the dimensions of the patches and the operating frequency are selected, the Q factor of the antenna can be decreased and its bandwidth broadened by either thickening the dielectric slab or reducing the permittivity of the substrate or by combining the above two approaches. However, increasing the thickness of the substrate will unfortunately result in surface wave generation and ensuing loss. For the microstrip antenna fed by a coaxial probe, the inductance produced by the probe will be quite significant when the substrate thickness is increased. Therefore, it is necessary to compensate the inductance to overcome the aforementioned problems.

The architecture of the microstrip antenna proposed in this paper is shown in Fig. 1. Fig. 1(b) shows the construction of the offset microstrip antenna where the excitation is by means of a small planar plate mounted on the top of the coaxial probe whose parameters are given in Fig. 1(a). It is assumed that the thickness h_2 is very small compared with the thickness h_1. The capacitance can be determined by its diameter and the characteristics of the dielectric substrate.

The design procedure is given subsequently. The input impedance and inductance of the microstrip antenna fed by a coaxial probe is [15]–[17]

$$Z_{\text{in}} = Z_R + jX_L \tag{1a}$$

$$X_L = \frac{\eta}{\pi} \tan(0.5kh_1) \ln(2.25/kd) \tag{1b}$$

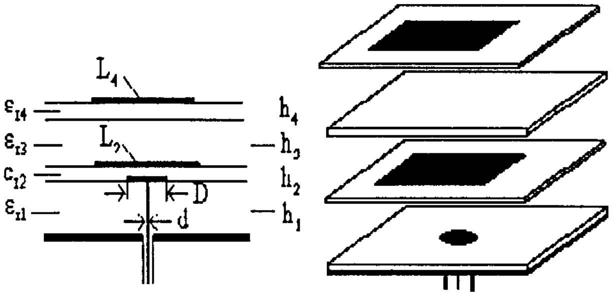


Fig. 1. A two-layer microstrip patch antenna geometry.

where η and k are the intinsic resistance and wave number in the substrate, respectively. In order to compensate the probes inductance, a series capacitor should be mounted on top of the probe to match the resonant condition given by

$$\omega_r C X_L = 1 \tag{2}$$

where ω_r is the angular frequency, C is the capacitance, and X_L is given by (1b).

In order to formulate the resonant frequency, the voltage from the top to the bottom of the antenna is assumed as V_0. Then, we can obtain

$$V_0 = V_{01} + V_{02} + V_{03} + V_{04} \tag{3a}$$
$$V_0 = (h_1 + h_2 + h_3 + h_4)E_z \tag{3b}$$
$$D_z = \varepsilon_0 \varepsilon_{rc} E_z \tag{3c}$$

where D_z and ε_{rc} are the effective electric flux density and relative permittivity, respectively; V_{0i} $(i = 1, 2, 3, 4)$ are voltages between two neighboring layers.

On the basis of electromagnetic boundary conditions on interfaces, we readily have

$$D_z = D_{z1} = D_{z2} = D_{z3} = D_{z4} \tag{4a}$$
$$D_{zi} = \varepsilon_0 \varepsilon_{ri} E_{zi} \tag{4b}$$
$$V_{0i} = h_i E_{zi}. \tag{4c}$$

Substituting (4c) into (3a), we can further obtain

$$V_0 = \sum_{i=1}^{4} h_i E_{zi}. \tag{5}$$

After the substitution of (4b) into (5), we can rewrite the (5) as

$$V_0 = \frac{D_z}{\varepsilon_0} \sum_{i=1}^{4} \frac{h_i}{\varepsilon_{ri}}. \tag{6}$$

At the same time, from (3b) and (3c), we can express the voltage V_0 as follows:

$$V_0 = \frac{D_z}{\varepsilon_0 \varepsilon_{rc}} \sum_{i=1}^{4} h_i. \tag{7}$$

So, equating (6) and (7) for the same voltage V_0 results in the effective permittivity expressed by

$$\varepsilon_{rc} = \frac{\sum_{i=1}^{4} h_i}{\sum_{i=1}^{4} \frac{h_i}{\varepsilon_{ri}}}. \tag{8}$$

TABLE I
RESONANT FREQUENCIES OF LOWER AND TOPPER LAYERS VERSUS DIFFERENT PERMITTIVITES

ε_{r1}	ε_{r2}	ε_{r3}	ε_{r4}	F_{r2} (GHz)	F_{r4} (GHz)	$F_{r2} - F_{r4}$ (MHz)
2.2	2.2	2.2	2.2	1.525	1.348	176.584
2.2	2.6	2.2	2.2	1.518	1.342	175.930
2.2	2.6	2.2	2.6	1.511	1.336	175.272
2.2	2.6	2.4	2.6	1.491	1.318	173.337
2.2	2.6	2.6	2.6	1.473	1.301	171.660
2.4	2.6	2.2	2.6	1.491	1.318	173.337
2.6	2.6	2.2	2.6	1.473	1.301	171.660
2.6	2.6	2.2	2.2	1.480	1.308	172.350

As for the second substrate, its effective permittivity is

$$\varepsilon_{e2} = \frac{\varepsilon_{rc}+1}{2} + \frac{\varepsilon_{rc}-1}{2}\left[1 + \frac{10.0\sum_{i=1}^{2} h_i}{L_2}\right]^{-\frac{1}{2}}. \tag{9}$$

Now, we can use the improved transmission line model to calculate the resonant frequency of the lower patch [18]

$$F_{r2} = \frac{C_0}{2L_2\sqrt{\varepsilon_{e2}}} \cdot \frac{1-\zeta_2}{1+\zeta_2 \ln\left(\frac{1.123 L_2 \sqrt{\varepsilon_{e2}}}{\sum_{i=1}^{2} h_i}\right)} \tag{10}$$

where C_0 denotes the velocity of light in free space, and

$$\zeta_2 = \frac{2\sum_{i=1}^{2} h_i}{\pi T_2 \varepsilon_{e2} L_2} \tag{11a}$$

$$T_2 = \frac{\sum_{i=1}^{2} h_i}{L_2}\left[\frac{L_2}{\sum_{i=1}^{2} h_i} + 1.393 + 0.667\ln\left(\frac{L_2}{\sum_{i=1}^{2} h_i} + 1.444\right)\right]. \tag{11b}$$

In a similar fashion, the resonant frequency of the top patch can be expressed as

$$F_{r4} = \frac{C_0}{2(L_4 + 2\Delta L_4)\sqrt{\varepsilon_{e4}}}. \tag{12}$$

where the effective permittivity, ε_{e4}, is expressed as

$$\varepsilon_{e4} = \frac{\varepsilon_{rc}+1}{2} + \frac{\varepsilon_{rc}-1}{2}\left[1 + \frac{10.0\sum_{i=1}^{4} h_i}{L_4}\right]^{-\frac{1}{2}} \tag{13}$$

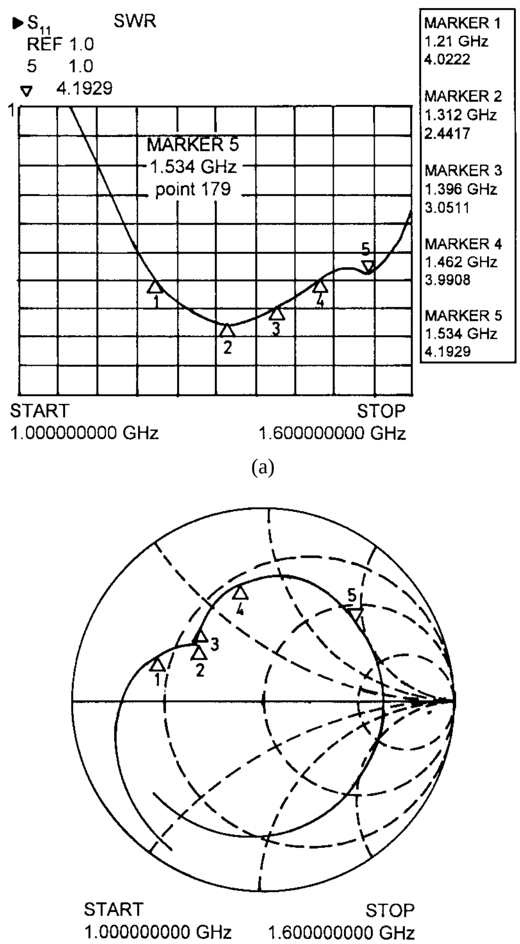
and the expension of the lower patch, $\triangle L_4$, is given by

$$\Delta L_4 = 0.412 \sum_{i=1}^{4} h_i \left[\frac{\varepsilon_{e4}+0.3}{\varepsilon_{e4}-0.258}\right] \cdot \left[\frac{\frac{L_4}{\sum_{i=1}^{4} h_i} + 0.264}{\frac{L_4}{\sum_{i=1}^{4} h_i} + 0.8}\right]. \tag{14}$$

As an example, we have calculated the resonant frequencies for different sets of relative permittivities of the layered substrate. The thicknesses of the layers are assumed as follows: $h_1 = h_3 = 8$ mm and $h_2 = h_4 = 1.5$ mm whereas the diameter d as 1 mm. Also, dimensions of both patches are considered to be 62.5 by 62.5 mm. Further information for the computed resonant frequencies versus different permittivities is detailed in Table I.

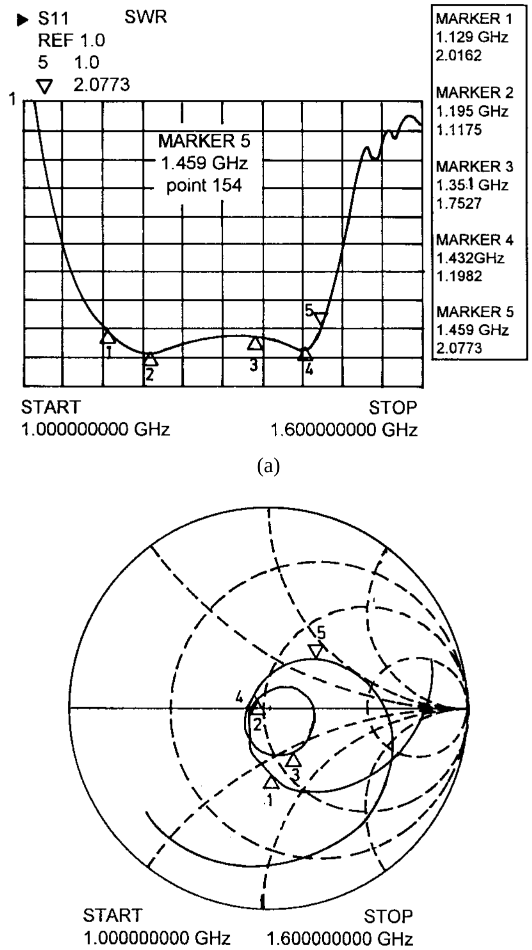
TABLE II
RESONANT FREQUENCY VERSUS LAYER THICKNESS

h_1 (mm)	h_2 (mm)	h_3 (mm)	h_4 (mm)	F_{r2} (GHz)	F_{r4} (GHz)	$F_{r2} - F_{r4}$ (MHz)
4.0	6.0	4.0	6.0	1.469	1.288	181.002
4.0	4.0	4.0	4.0	1.486	1.344	142.534
4.0	1.5	4.0	1.5	1.521	1.431	90.458
6.0	1.5	6.0	1.5	1.517	1.383	134.082
8.0	1.5	8.0	1.5	1.511	1.336	175.272



(b)

Fig. 2. VSWR and Smith Chart of a two-layered microstrip patch fed by a coaxial probe.



(b)

Fig. 3. VSWR and Smith Chart of same two-layered microstrip patch fed by a capacitor of diameter 11.5 mm and capacitance 2.16 × 10^{-12} F.

As another example, Table II shows the resonant frequencies of two patches versus the thicknesses of the layers. The permittivities of the layers are assumed as follows: $\varepsilon_{r1} = \varepsilon_{r3} = 2.2$ and $\varepsilon_{r2} = \varepsilon_{r4} = 2.6$ whereas the diameter d remains at 1 mm. Also, the area dimensions of both patches are considered to be 62.5 by 62.5 mm.

From Tables I and II, it is found that the frequency separation between lower and upper patch is quite independent of one another. The required frequency separation can be obtained by adjusting the parameters and thicknesses of the layers. It is also found from Table I that the resonant frequency separation will increase by reducing ε_{r3}, ε_{r4} while increasing ε_{r1}, ε_{r2} will result in a decrease of the resonant frequency separation.

Once the resonant frequencies of the lower and upper patches are determined, the bandwidth can be enlarged considering the center frequency as the matching frequency given as follows:

$$F_r = \frac{F_{r2} + F_{r4}}{2}. \tag{15}$$

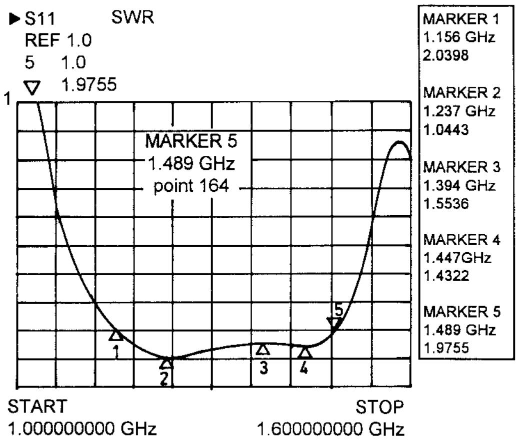
Substituting (15) into (2), we can obtain the diameter D for a given capacitance, a computed relative permittivity ε_{r2}, and a given thickness h_2 from the following nonlinear equation [6]:

$$C = \varepsilon_0 \varepsilon_{r2} \left[\frac{\pi D^2}{4h_2} + 2D \ln\left(\frac{0.38D}{h_2} \right) \right]. \tag{16}$$

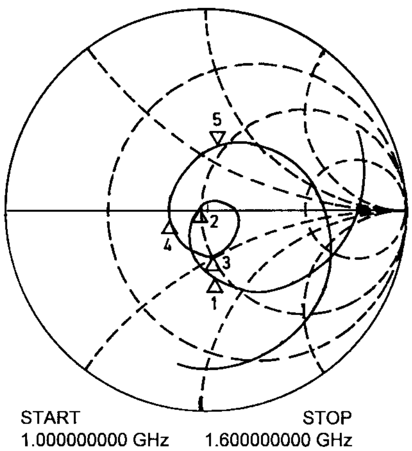
Equation (16) is a transcendental equation. Thus, the capacity-dependent diameter D can be easily determined by an iterative method.

III. DESIGN RESULTS

In accordance with the design method mentioned above, we have theoretically designed a two-layered microstrip patch antenna with a bandwidth of up to 25.7%. Two feeding conditions are considered in the design. To demonstrate whether the design technique is applicable, two antennas were designed and fabricated. The following antenna parameters have been



(a)



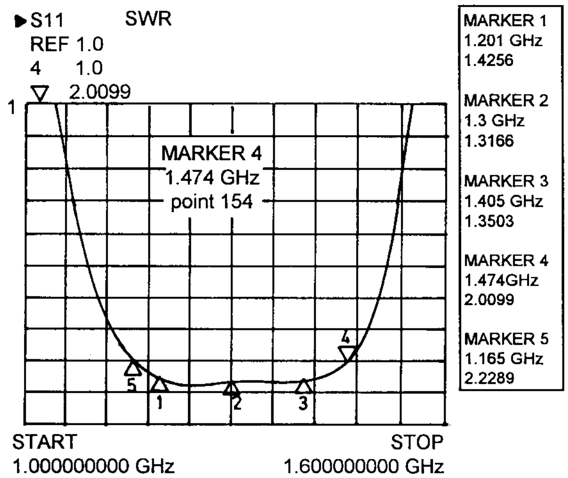
(b)

Fig. 4. VSWR and Smith Chart of same two-layered microstrip patch fed by a capacitor of diameter 12 mm and capacitance 2.35×10^{-12} F.

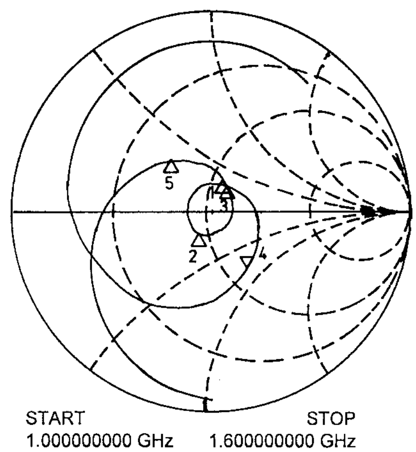
chosen: $L_2 = L_4 = 62.5$ mm, $\varepsilon_{r1} = \varepsilon_{r3} = 2.2$, $\varepsilon_{r2} = \varepsilon_{r4} = 2.6$, and $d = 1$ mm. As shown below in Fig. 2 are the VSWR and Smith chart plots for a two-layered patch antenna fed directly by a coaxial probe. Figs. 3–5 show the VSWR and Smith chart plots for the same antenna but fed by a serial capacitor of different diameters, i.e., 11.5 mm in Figs. 3(a) and 4(b), 12 mm in Figs. 4(a) and 5(b), and 12.5 mm in Figs. 5(a) and 6(b). Obviously, the bandwidth of the microstrip antenna shown in Figs. 3(a)–5(a) is significantly improved as compared to that in Fig. 2(a). Fig. 6 shows the gain of the last antenna, it is apparently that the gain of this antenna is larger than that of a traditional microstrip antenna.

IV. CONCLUSION

This paper presents a technique for designing wide-band multilayered microstrip antennas. The design procedure together with the nonlinear design equation have been provided. To verify the applicability of the design method, a practical design of a multilayered microstrip antenna has been conducted. Two experiments where both a coaxial probe feed and a capacitor feed are utilized have been carried out to examine the results of the designed microstrip antenna. According to the results obtained, using the design method presented in this paper can increase the impedance bandwidth of a L-band microstrip antenna up to 25.7%. Although the design equation given by (15) is valid for the microstrip antenna of two-layers, it can be easily revised and extended for the design of other types of wide-band multilayered structures.



(a)



(b)

Fig. 5. VSWR and Smith Chart of same two-layered microstrip patch fed by a capacitor of diameter 12.5 mm and capacitance. 2.55×10^{-12} F.

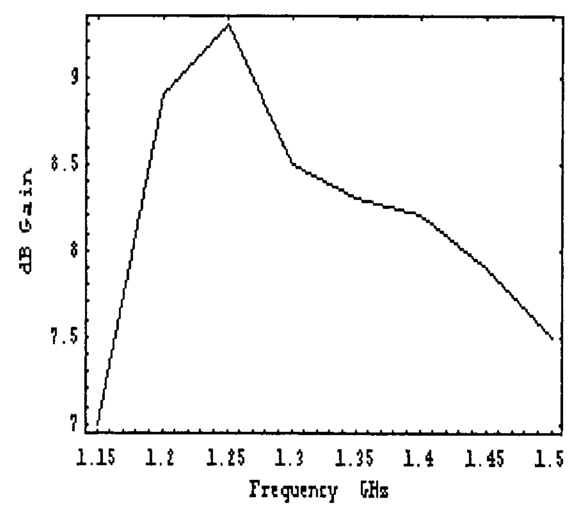


Fig. 6. The gain of the antenna.

ACKNOWLEDGMENT

The first author would like to express his appreciation to Prof. S.-Z. Li at Beijing Institute of Technology for his help and useful suggestions.

REFERENCES

[1] D. M. Pozar and D. H. Schaubert, *Microstrip Antennas*. New York: IEEE Press, 1995.
[2] Y. T. Lo, D. Solomon, and W. F. Richards, "Theory and experiment on microstrip antennas," *IEEE Trans. Antennas Propagat.*, vol. AP-27, pp. 137–145, Mar. 1979.
[3] K. R. Carver and J. W. Mink, "Microstrip antenna technology," *IEEE Trans. Antennas Propagat.*, vol. AP-29, pp. 2–24, Jan. 1981.
[4] D. M. Pozar and B. Kaufman, "Increasing the bandwidth of a microstrip antenna by proximity coupling," *Electron. Lett.*, vol. 23, no. 8, pp. 368–369, Apr. 1987.
[5] J. F. Zurcher, "The SSFIP: A global concept for high performance broadband planar antennas," *Electron. Lett.*, vol. 24, no. 23, pp. 1433–1435, Nov. 1988.
[6] F. Croq and D. M. Pozar, "Millimeter-wave design of wide-band aperture-coupled stacked microstrip antennas," *IEEE Trans. Antennas Propagat.*, vol. AP-39, pp. 1170–1176, Dec. 1991.
[7] G. Kossiavas and A. Papiernik, "A circular or linearly polarized broadband microstrip antenna operating in L-band," *Microwave J.*, pp. 266–272, May 1992.
[8] J.-F. Zurcher and F. Gardiol, *Broadband Patch Antennas*. Norwood, MA: Artech House, 1995.
[9] G. Kumar and K. C. Gupta, "Non-radiating edges and four-edges gap-coupled with multiple resonator, broadband microstrip antennas," *IEEE Trans. Antennas Propagat.*, vol. 33, pp. 173–178, 1985.
[10] I. Park and R. Mittra, "Apertur-coupled small microstrip antenna," *Electron. Lett.*, vol. 32, no. 19, pp. 1741–1741, Sept. 1996.
[11] S. D. Targonski, R. B. Waterhouse, and Pozar, "Wideband aperture coupled stacked patch antenna using thich substrates," *Electron. Lett.*, vol. 32, no. 21, pp. 1941–1942, Oct. 1996.
[12] M. Yamamoto and K. Itoh, "Slot-coupled, icrostrip antenna with a triplate line feed where parallel-plate mode is suppressed," *Electron. Lett.*, vol. 33, no. 6, pp. 441–442, Mar. 1997.
[13] A. Hongming, B. K. J. C. Nauwelaers, and A. R. Van de Capelle, "Broadband active microstrip antenna design with the simplified real frequency technique," *IEEE Trans. Antennas Propagat.*, vol. 42, pp. 1612–1619, Dec. 1994.
[14] K. F. Lee, K. M. Luk, K. F. Tong, Y. L. Yung, and T. Huynh, "Experimental study of a two-element array of U-slot patches," *Electron. Lett.*, vol. 32, no. 5, pp. 418–420, Feb. 1996.
[15] K. S. Fong, H. F. Puse, and M. J. Withers, "Wideband multilayer coaxial-fed microstrip antenna element," *Electron. Lett.*, vol. 21, no. 11, pp. 497–499, May 1985.
[16] M. A. Blischke, K. M. Chen, and E. J. Rothwell, "Broadband analysis of a single post-fed circular patch antenna," in *URSI Radio Science Meeting Abstracts*, June 1989, p. 32.
[17] E. H. Newman and D. M. Pozar, "Electromagnetic modeling of composite wire and surface geometries," *IEEE Trans. Antennas Propagat.*, vol. AP-26, pp. 784–789, Nov. 1978.
[18] H. Pues and A. Van de Cappele, "Accurate transmission-line model for the rectangular microstrip antenna," *Proc. Inst. Elect. Eng.: Microwave Antennas Propagat.*, vol. 133, pt. H, pp. 334–340, Dec. 1984.

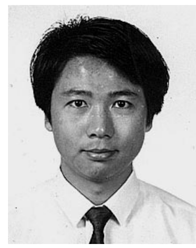
Zhang-Fa Liu received the of B.Sc. degree in physics and the M.Eng. and Ph.D. degrees in electrical engineering from Fuyang Normal College, Fuyang, China, in 1986, China Research Institute of Radiowave Propagation (CRIRP), Xinxiang, China, in 1989, and Beijing Institute of Technology, Beijing, China, in 1996, respectively.

From 1989 to 1993 he worked as a Research Engineer at CRIRP. He is currently with Department of Electrical Engineering at the National University of Singapore as a Postdoctoral Research Fellow. His main research interests include electromagnetic theory, microstrip antennas, and millimeter-wave circuits.

Pang-Shyan Kooi (M'75) received the B.Sc. degree in electrical engineering from the National Taiwan University, Tapei, in 1961, the M.Sc. (Tech.) degree in electrical engineering from the University of Manchester Institute of Science and Technology (UMIST), Manchester, U.K., in 1963, and the D.Phil. degree in engineering science from Oxford University, U.K., in 1970.

Since 1970, he has been with the Electrical Engineering Department of the National University of Singapore where he is currently a Professor of Electrical Engineering. His current research interests are microwave and millimeter-wave circuits, antennas, and solid-state microwave sources.

Dr. Kooi is a Fellow of the Institution of Electrical Engineers, London, U.K.



Le-Wei Li (S'91–M'92–SM'96) received the B.Sc. degree in physics and the M.Eng.Sc. and Ph.D. degrees in electrical engineering from Xuzhou Normal University, Xuzhou, China, in 1984, China Research Institute of Radiowave Propagation (CRIRP), Xinxiang, China, in 1987, and Monash University, Melbourne, Australia, in 1992, respectively.

In 1992, he worked at La Trobe University (jointly with Monash University), Melbourne, Australia as a Research Fellow. Since 1992, He has been with the Department of Electrical Engineering at the National University of Singapore where he is currently an Associate Professor. His current research interests include electromagnetic theory, radio wave propagation and scattering in various media, microwave propagation and scattering in tropical environment, and analysis and design of various antennas.

Dr. Li was a recipient of the Best Paper Award from the Chinese Institute of Communications for his paper published in *Journal of China Institute of Communications* in 1990, and the Prize Paper Award from the Chinese Institute of Electronics for his paper published in *Chinese Journal of Radio Science* in 1991. He was selected to receive a Ministerial Science & Technology Advancement Award by the Ministry of Electronic Industries, China in 1995 and a National Science & Technology Advancement Award with a medal from the National Science & Technology Committee, China, in 1996. He has been invited to serve on the Editorial Board of the *Journal of Electromagnetic Waves and Applications* and has been a member of The Electromagnetics Academy since 1998.

Mook-Seng Leong (M'81–SM'98) received the B.Sc. degree in electrical engineering (with first class honors) and the Ph.D. degree in microwave engineering from the University of London, U.K., in 1968 and 1971, respectively.

He is currently a Professor of Electrical Engineering at the National University of Singapore. His main research interests include antenna and waveguide boundary-value problems and semiconductor characterization using the Spreading Resistance Profiling (SRP) technique.

Dr. Leong is a member of the MIT-based Electromagnetic Academy and a Fellow of the Institution of Electrical Engineers, London. He received the 1996 Defence Science Organization (DSO) R&D Award from DSO National Laboratories, Singapore, in 1996. He is a member of the Editorial Boards of *Microwave and Optical Technoloogy Letters* and *Wireless Mobile Communications*.

Tat-Soon Yeo (M'80–SM'93) received the B.Eng. (Hons.) and M.Eng. degrees from the National University of Singapore in 1979 and 1981, respectively, and the Ph.D. degree from the University of Canterbury, New Zealand, in 1985.

Since 1985, he has been with the Electrical Engineering Department of the National University of Singapore where he is currently an Associate Professor. His current research interests are in wave propagation and scattering, antennas, and numerical techniques.

Dr. Yeo is a Fellow of the Institution of Electrical Engineers, London. He received the 1997 Defence Science Organization (DSO) R&D Award from DSO National Laboratories, Singapore, in 1997. He is the Chairman of the MTT/AP/EMC joint Chapter, Singapore IEEE Section. He has been invited to serve as a Guest Editor for a Special Issue of the IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING in 1998, and an Editorial Board member of the IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES since 1997.