An Aperture-Coupled Linear Microstrip Leaky-Wave Antenna Array with Two-Dimensional Dual-Beam Scanning Capability

Cheng-Chi Hu, Christina F. Jou, and Jin-Jei Wu

***Abstract*—This paper describes an X-band 4 $\times$ 1 aperture-coupled series-fed electronically steerable microstrip leaky-wave antenna (LWA) array design, which has dual-beam radiation pattern and two-dimensional (2-D) beam-scanning capability. The LWA array is operated in the first higher order mode and excited by center-fed aperture coupled for dual-beam operation. The varactor-tuned phase shifters are placed between the antenna elements. The measured half-power beamwidth of the H-plane and quasi-E-plane radiation patterns are less than 30°. By tuning the reverse dc bias of the varactor diodes, the main beam can be scanned in azimuth plane from $-13°$ to $+13°$ off broadside. In the elevation plane, the beam-scanning angle is close to 20° as the operating frequency tuned from 11.58–12.5 GHz. Taking into account each phase-shifter insertion loss and phase progression, the measured results compared closely with the theoretical prediction. The proposed antenna array is suitable for wireless communication and collision warning radar systems.**

***Index Terms*—Antenna arrays, aperture-coupled antennas, leaky-wave antennas, microstrip antennas.**

I. Introduction

THE microstrip leaky-wave antenna (LWA) has been an area of growing interest in transmit/receive (T/R) modules and for quasi-optical power combining [1]. It has been shown that the first higher order mode of a microstrip line may leak in the form of a space wave, pointing in an angle $\theta_m = \sin^{-1}(\beta/k_o)$, where θ_m is the angle of the beam maximum measured from the z-axis and β is the phase constant of the first higher order mode of the microstrip line. The microstrip leaky-wave antenna has the characteristic of wider bandwidth, narrow beam, and frequency-scanning capability. They also have the advantage of low profile, light weight, easy fabrication, and suitability of mass production. Therefore, the printed microstrip leaky-wave antenna has been a candidate for active integrated antenna array applications involving active solid-state devices such as HEMT's, Gunn diodes, etc. [1]–[3].

Although the microstrip LWA has a narrow radiation beamwidth in the H-plane, however, it also produces a typical wide patch pattern in the cross plane (quasi-E-plane), given by a fixed angle 90° $- \theta$ to x-axis (see Fig. 2.) To prevent this wide patch pattern, an eight-element LWA array was developed, which was excited by a parallel CPW-slotine feeding network producing a narrow pencil beam [4]. However, the complexity of the feeding network may be a disadvantage of designing large array. To obtain a single feed network with dual-beam feature, a series-fed microstrip LWA array excited by slotted coplanar waveguide was proposed [5]. Especially, its dual-beam antenna characteristic has much value in the mobile communication and automotive radar systems.

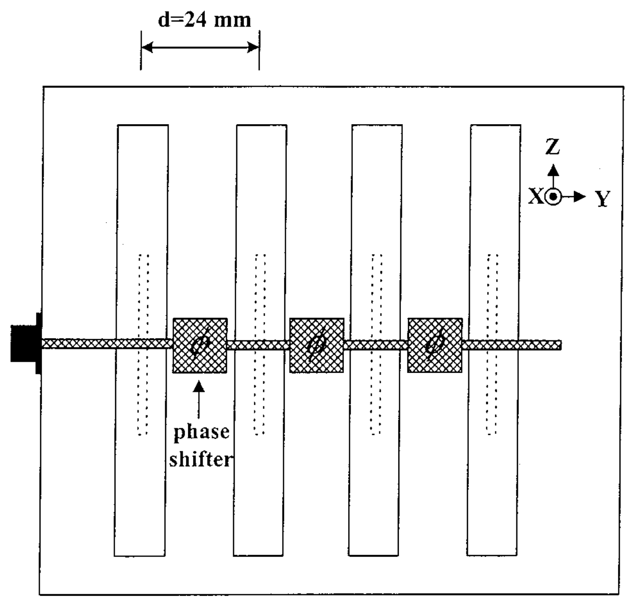


Fig. 1. Schematic of the aperture coupled linear 4 $\times$ 1 dual-beam 2-D scanning microstrip leaky-wave antenna array.

Meanwhile, controlling the radiation main beam of the active antennas using the microstrip leaky-wave antenna has received much attention in the recent year [6], [7]. In [6], Oliner proposed the idea of a two-dimensional (2-D) scanning array using one-dimensional (1-D) leaky-wave antenna line-source phased array. A narrow pencil beam can scan in both elevation and azimuth plane. In [7], an attempt has made to extend the work of encompassing the phase control technique of coupling oscillators [8], [9] and leaky-wave antenna characteristic, which leads to a novel method for 2-D electronic-tuned beam-scanning active LWA array. By tuning the free-running frequencies of the end oscillators, the pencil beam can be continuously scanned in quasi-E-plane.

Manuscript received February 17, 1999; revised April 5, 2000.

C.-C. Hu is with the Advanced Wireless Semiconductor Company, Tainan, Taiwan, R.O.C.

C. F. Jou is with the Institute of Communication Engineering, National Chiao Tung University, Hsinchu, Taiwan, R.O.C.

J.-J. Wu is with the Department of Electric Engineering, Kao Yuan College of Technology, Luchu, Taiwan, R.O.C.

Publisher Item Identifier S 0018-926X(00)05798-7.

0018–926X/00$10.00 © 2000 IEEE

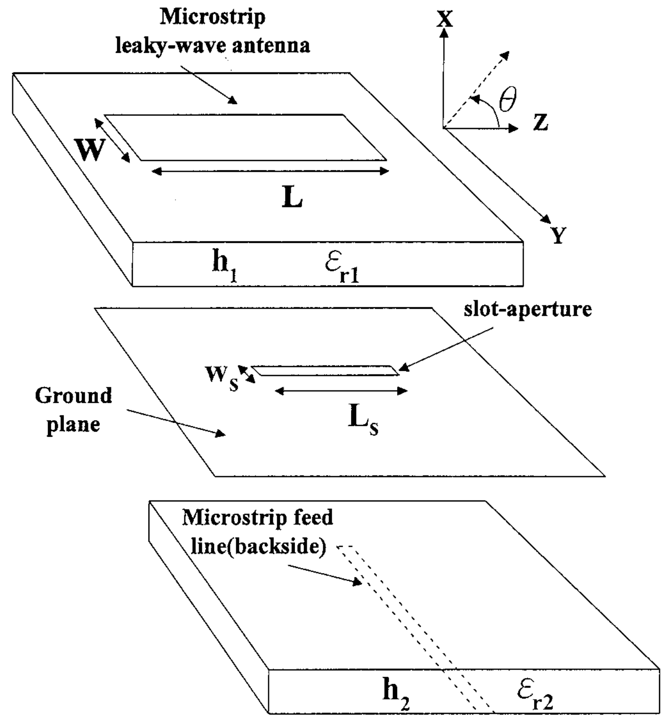


Fig. 2. Geometry of the aperture coupled dual-beam microstrip leaky-wave antenna array. ($W = 8.5$ mm, $L = 100$ mm, $W_s = 1.5$ mm, $L_s = 24$ mm, $h_1 = h_2 = 0.508$ mm, $\varepsilon_{r1} = \varepsilon_{r2} = 2.2$).

The work reported in this paper follows on the work of series-fed dual-beam microstrip LWA [5]. The idea is to perform 2-D beam-scanning using 1-D LWA array. Here, we demonstrated an aperture-coupled dual-beam series-fed array of LWA (Fig. 1) with 2-D beam-scanning capability using the varactor-tuned phase shifter in between the microstrip LWA elements. A constant phase progression is achieved by controlling the reverse dc bias of the varactor diodes. Therefore, the pencil beam of the microstrip LWA array can be scanned in the quasi-E-plane. The aperture-coupled structure has the advantage of avoiding interference between feeding networks and the antenna radiation. No complicated feeding networks or transition circuits are required here. This type of feeding structure has successfully being used for the excitation of LWA [10]. In addition, it is straightforward to obtain a dual-beam radiation pattern by feeding a microstrip leaky-wave antenna at its center. The aim was to fabricate a low-cost electronically steered dual-beam 2-D beam-scanning array for possible application in microwave systems such as wireless communication, smart antenna design, and collision warning radar.

II. Design and Construction

Fig. 1 shows the configuration of a four-element dual-beam aperture-coupled LWA. Each LWA is series-aperture-fed by a microstrip line with characteristic impedance of 50 Ω. This LWA array has a two-layer configuration, making it easy to fabricate due to its simple structure. The whole circuit is designed and fabricated on a RT/Duroid substrate with a dielectric constant $\varepsilon_r = 2.2$ and a thickness of 0.508 mm.

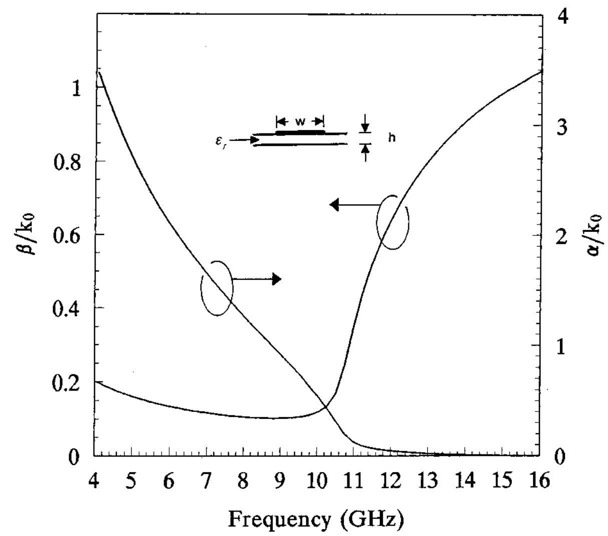


Fig. 3. The variations of phase constant β and attenuation constant α as a function of frequency. ($W = 8.5$ mm, $h = 0.508$ mm, $\varepsilon_r = 2.2$)

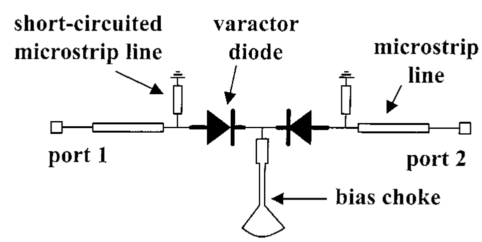


Fig. 4. The simplified schematic diagram of the varactor-tuned phase shifter.

The aperture is placed at the center of the LWA. We utilized a center-fed aperture in the ground plane, which not only can separates the two substrates, but also it can couple the signal and produced a dual-beam radiation pattern. The geometry and coordinate system for the microstrip LWA is shown in Fig. 2.

In order to understand the radiation properties of such a microstrip leaky-wave antenna, we obtained its complex propagation constants $\beta - j\alpha$ of the first higher microstrip mode in its leaky range, where β is the phase constant, and α is the attenuation constant. The complex constants are obtained by employing rigorous (Wiener–Hopf) solution mentioned in [11]. Fig. 3 shows the variations of phase constant β and attenuation constant α as a function of frequency. The width of the microstrip is properly chosen such that efficient leaky-mode radiation can be attained.

Varactor diode phase shifters are basically analog devices in which the variable reactance is achieved through voltage-tuned capacitance of the diode under reverse-bias condition. As the bias voltage of the varactor is varied from 0 V to a large negative value close to its breakdown voltage, the capacitance of the diode decreases from a maximum value $C_{\max}$ to a low value $C_{\min}$ and the maximum phase change can be achieved. Here, the GaAs varactor (M/A-COM MA46410) is used as the phase-tuning element. Due to the constant parasitic capacitance of the diode, the varactor diode has a capacitance ratio of about 5 : 1. The varactor-tuned phase shifter design adopts the simplified

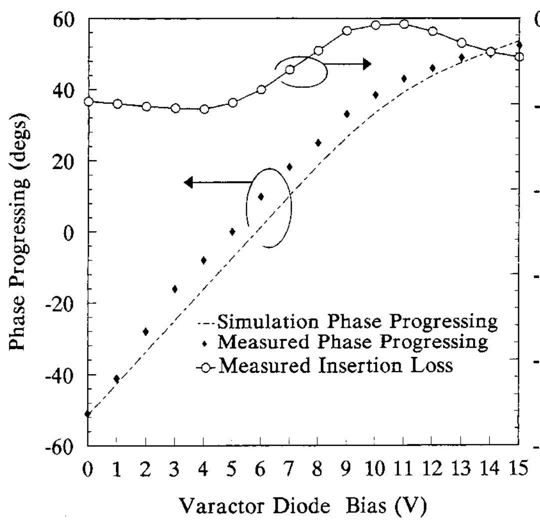


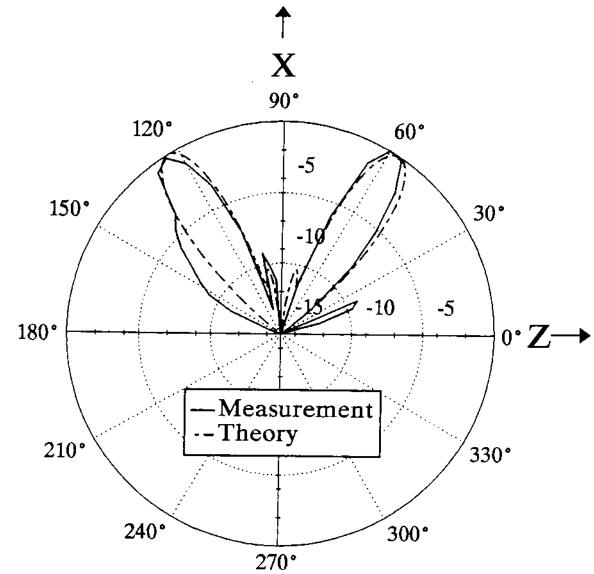
Fig. 5. Phase progressing and insertion loss of the varactor diode phase shifter as a function of bias voltage.

design proposed by Ref [12], [13]. Fig. 4 shows the simplified schematic diagram of the varactor-tuned phase shifter. The varactor is voltage-tuned to provide a continuous reactance change. In order to achieve the desired phase response, while maintaining as low an insertion loss as possible, the varactor diode is shunted with a shorted matching stub. Fig. 5 shows the measurement and simulation results of the phase progression as a function of the varactor bias. As expected, the phase progression of the phase shifter varies linearly with bias voltage.

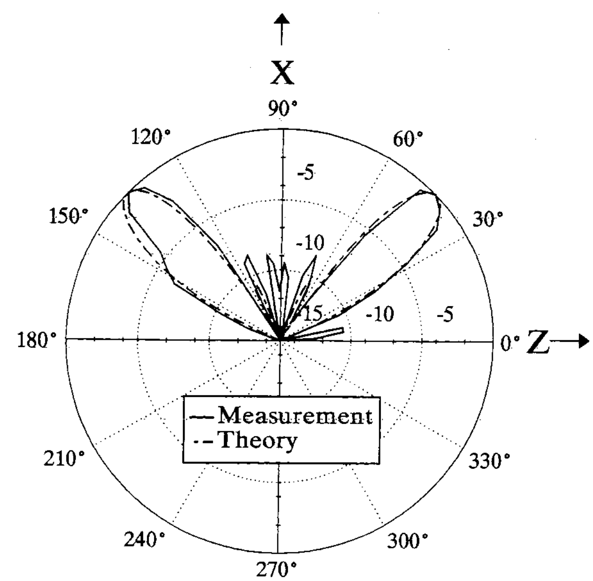
III. Simulation and Measurement Results

The measured return loss of this LWA array is below -10 dB over the specified bandwidth from 11.5 to 12.5 GHz without using any quarter-wave transformer. The radiation pattern was measured under the far field condition. The measured and theoretical prediction H-plane radiation patterns are shown in Fig. 6 at 11.58 GHz and 12.5 GHz. Two maximums are observed at about $\theta = \pm 60^\circ$ and $\theta = \pm 44^\circ$, respectively, which indicate the dual-beam and frequency scanning characteristics of this LWA array.

Based on the design of the varactor-tuned phase shifter, a constant phase progression can be achieved by tuning the reverse dc bias of the varactor diodes and the radiation pattern can be scanned with azimuthal symmetry in a conical scan manner. In addition, the amplitude distributions of each antenna element of this linear 4 × 1 LWA array depend on the insertion loss of the varactor phase shifter in different reverse bias condition. For example, the insertion loss of each varactor phase shifter has a 0.9-dB loss at the bias condition of 15 V, which implies an amplitude distributions from antenna element one to antenna element four such as $\#1 = 1$, $\#2 = 0.9$, $\#3 = 0.81$, and $\#4 = 0.729$. Taking this amplitude and phase distribution into account, we can predict the radiation pattern of this linear 4 × 1 LWA array. The radiation patterns of the linear 4 × 1 LWA array were measured on a conical surface (quasi-E -plane) corresponding to an angle of 45° from the x-axis. Fig. 7



(a)



(b)

Fig. 6. (a) Measured and theoretical H-plane patterns at 11.58 GHz. (b) Measured and theoretical H-plane patterns at 12.5 GHz.

shows the measured radiation patterns and theoretical predictions. The measured half-power beamwidth of the H-plane and quasi-E-plane radiation patterns are less than 30°. These measured quasi-E-plane patterns illustrates that the main beam can scan in azimuth from -13° to $+13^\circ$ off broadside, which corresponding to a reverse dc bias of the varactor diode from 0 to 15 V. This means that the LWA array has a maximum phase shift about 100° between two adjacent antenna elements, which agrees well with the previously design of the varactor-tuned phase shifter. The absolute gain measured from the Friss formula is about 10 dB.

IV. Conclusion

The work reported in this paper extends the ability of the microstrip LWA to obtain a dual-pencil beam 2-D scanning array

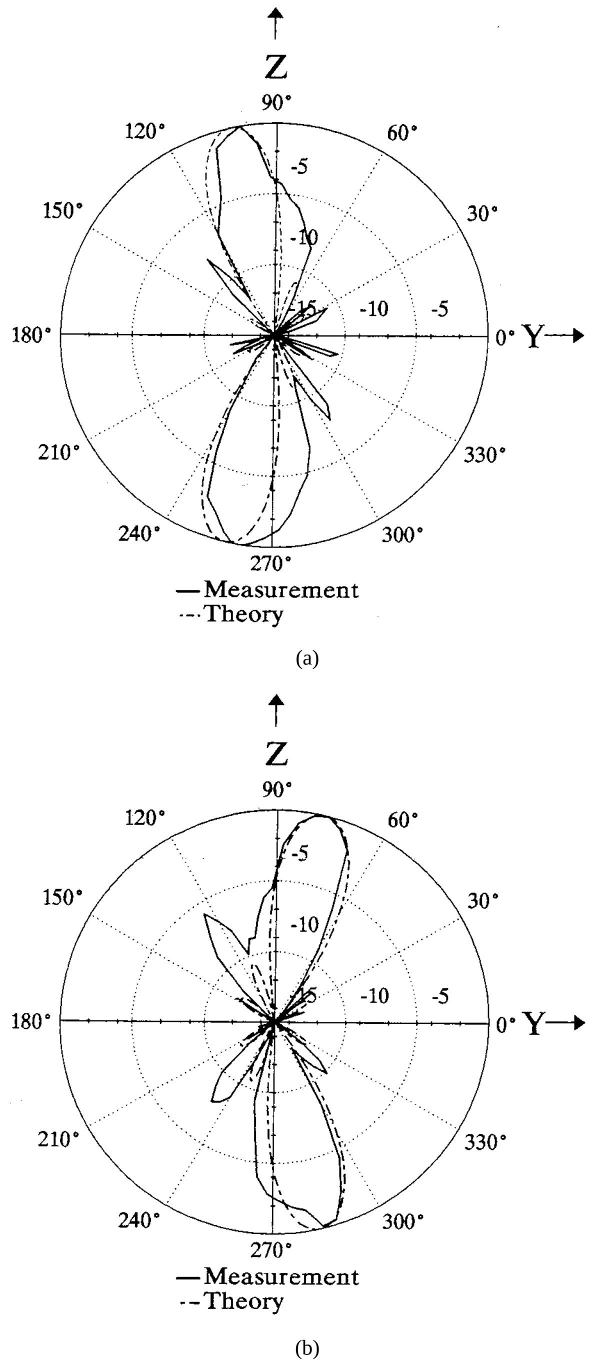


Fig. 7. (a) Measured and theoretical quasi-E-plane radiation patterns at varactor diode bias 0 V ($f = 12.2$ GHz). (b) Measured and theoretical quasi-E-plane radiation patterns at varactor diode bias 15 V ($f = 12.2$ GHz).

using varactor-tuned phase shifter and aperture coupled feeding structure. A 4×1 LWA array was demonstrated. A constant phase progression is accomplished by tuning the dc bias of the varactors phase shifter. The beam can be scanned in both azimuth and elevation in a conical scan manner. The measured half-power beamwidth of the H-plane and quasi-E-plane radiation patterns are less than 30°. The main beam can be scanned in azimuth plane from $-13°$ to $+13°$ off broadside. In the elevation plane, the beam-scanning angle is close to 20°. The measured results compared closely with the theoretical prediction. The initial results shows a good potential of using this dual-beam LWA array for low-cost transmitters and collision warning radar applications.

REFERENCES

[1] G.-J. Jou and C.-K. Tzuang, "Oscillator-type active-integrated antenna: The leaky-mode approach," *IEEE Trans. Microwave Theory Tech.*, vol. 44, pp. 2265–2272, Dec. 1996.

[2] C.-C. Hu, J.-J. Wu, and C. F. Jou, "An active frequency-tuned bean scanning leaky-wave antenna," *Microwave Opt. Technol. Lett.*, vol. 17, pp. 43–45, Jan 1998.

[3] C. J. Wang, J.-J. Wu, and C. F. Jou, "A new two-terminal feeding active leaky-wave antenna," *IEEE Trans. Antennas Propagat.*, vol. 46, pp. 1748–1749, Nov. 1998.

[4] C. N. Hu and C.-K. Tzuang, "Microstrip leaky-mode antenna array," *IEEE Trans. Antennas Propagat.*, vol. 45, pp. 1698–1699, Nov. 1997.

[5] C. Luxey and J.-M. Laheurte, "Dual-beam array of microstrip leaky-wave antennas," *Inst. Elect. Eng. Electron. Lett.*, vol. 34, pp. 1041–1042, May 1998.

[6] A. A. Oliner, "A new class of scannable millimeter wave antennas," in *20th Proc. Eur. Microwave Conf.*, Budapest, Hungary, Sept. 1990, pp. 95–104.

[7] C.-C. Hu, J.-J. Wu, and C. F. Jou, "A two-dimensional beam-scanning linear active leaky-wave antenna array," *IEEE Microwave Guided Wave Lett.*, vol. 9, pp. 102–104, Mar. 1999.

[8] R. A. York and R. C. Compton, "Quasi-optical power combining using mutually synchronized oscillator arrays," *IEEE Trans. Microwave Theory Tech.*, vol. 39, pp. 1000–1009, June 1991.

[9] P. Liao and R. A. York, "A new phase-shifterless beam-scanning technique using arrays of couple oscillators," *Trans. Microwave Theory Tech.*, vol. 41, pp. 1810–1815, Oct. 1993.

[10] N.-A. Kao, C.-C. Hu, J.-J. Wu, and C. F. Jou, "Active aperture-coupled leaky-wave antennas," *Inst. Elect. Eng. Electron. Lett.*, vol. 34, pp. 2183–2184, Nov. 1998.

[11] A. A. Oliner and K. S. Lee, "Microstrip leaky wave strip antennas," in *IEEE AP-S Int. Symp. Dig.*, Philadelphia, PA, June 1986, pp. 443–446.

[12] J. F. White, *Microwave Semiconductor Engineering*. New York: Van Nostrand, 1982.

[13] R. H. Hardin, E. J. Downey, and J. Munushian, "Electronically-Variable phase shifters utilizing variable capacitance diode," *Proc. IRE Lett.*, vol. 48, pp. 944–945, May 1960.

Cheng-Chi Hu was born in Tainan, Taiwan, in 1969. He received the B.S. degree in electronic engineering from the Tamkang University, Tamsui, Taiwan, in 1991, and the M.S. and Ph.D. degrees in communication engineering, both from the National Chiao Tung University, Hsinchu, Taiwan, in 1996 and 1999, respectively.

In July 1999, he joined Advance Wireless Semiconductor Company (AWSC), Tainan, Taiwan, as a Microwave Engineer and is currently developing computer-aided measurement and heterostructure-bipolar-transistor (HBT) modeling. His research interests include microwave active antennas, computer-aided measurement, and characterization of microwave and millimeter-wave devices and circuits.

Christina F. Jou was born in Taipei, Taiwan, in 1957. She received the B.S., M.S., and Ph.D. degrees in electrical engineering from the University of California, Los Angeles, in 1980, 1982, and 1987, respectively.

From 1987 to 1990, she was with Hughes Aircraft Company, Torrance, CA, as a member of the technical staff in the Microwave Products Division, where she was responsible for microwave device modeling. In 1990 she joined National Chiao-Tung University, Hsinchu, Taiwan, where she is now an Associate Professor of communication engineering. Her research is in developing microwave and millimeter-wave active circuits and antenna and antenna array design.

Jin-Jei Wu was born in Tainan, Taiwan, on March 5, 1963. He received the M.S. degree in physics from National Tsing Hua University, Hsinchu, Taiwan, in 1987, and the Ph.D. degree in electro-optics from Chiao Tung University, Hsinchu, Taiwan, in 1997.

He is an Assistant Professor of electrical engineering at Kao Yuan Institute of Technology, Lu-Chu, Kaohsiung, Taiwan. His research interests include propagation and scattering of dielectric waveguide, numerical analysis of dielectric grating, and designs and application of active and passive planar antennas.