A Novel Low-Profile Broadband Dual-Frequency Planar Antenna for Wireless Handsets

RongLin Li, *Senior Member, IEEE*, Bo Pan, *Student Member, IEEE*, Joy Laskar, *Fellow, IEEE*, and Manos M. Tentzeris, *Senior Member, IEEE*

***Abstract*—A new low-profile broadband dual-frequency planar antenna is developed for wireless handsets. The dual-frequency antenna consists of a two-strip monopole for the 2-GHz band and a planar monopole for the 5-GHz band. The developed antenna features a low profile due to the introduction of an S-strip and a T-strip which are separately printed on the two sides of a thin substrate (no via process is involved in the fabrication), forming the two-strip monopole. The bandwidth of the dual-frequency planar antenna is enhanced by taking advantage of the two-strip configuration and the mutual coupling between the planar monopole and the two-strip monopole. The dual-frequency planar antenna achieves a bandwidth of $\sim$35% at the 2-GHz band (1.6–2.3 GHz) and $\sim$15% at the 5-GHz band (5.0–5.9 GHz) with an antenna height of 7–8 mm, which may find applications in mobile/wireless communication devices. A theoretical analysis and verifying experimental results are presented.**

***Index Terms*—Broadband antenna, dual-frequency antenna, low-profile antenna, monopole, two-strip, wireless applications.**

I. Introduction

FOR applications concerning portable wireless communication devices, such as mobile phone handsets or notebook computers, antennas with low-profile planar structures are essential for low-cost manufacturing and high integrability with printed circuit boards (PCB). On the other hand, the requirement for a dual-frequency operation has become a common sense for accommodating multifunctional services, such as voice, video, and data transmissions [e.g., for voice-over IP (VoIP) cellular phones]. To cover the DCS-1800 (DCS 1710–1880 MHz), PHS-1900 (1895–1918 MHz), PCS-1900 (1850–1990 MHz), IMT-2000/UMTS (1885–2200 MHz) for mobile communications, and the 5-GHz UNII band for wireless LANs (5.15–5.875 GHz), a dual-frequency antenna with a bandwidth of $\sim$30% at the 2-GHz band and a bandwidth of $\sim$15% at the 5-GHz band is required.

In recent years, a lot of low-profile dual-frequency antennas have been developed for wireless applications [1]–[6]. Unfortunately, these dual-frequency antennas have a much narrower bandwidth at the lower-frequency band than that at the higher-frequency band. Theoretically, it is more difficult to achieve a broad bandwidth at a lower-frequency band than at a higher-frequency band due to the electrically smaller antenna size at a lower frequency for the same physical size. A lot of efforts have been made to increase the impedance bandwidth while maintaining a low antenna profile [7]–[11]. However, most of the techniques for bandwidth enhancement involve shorting metal walls and require a considerable antenna thickness, thus unsuitable for a fully photolithographic fabrication process. It is known that electromagnetic coupling and two-strip configurations are two effective methods for increasing the bandwidth of a compact antenna structure [12]–[14]. In this paper, we combine a two-strip monopole and a planar monopole onto a very thin substrate (10 mils) to achieve a broadband dual-frequency operation. The two-strip monopole is designed to operate at the 2-GHz band while the planar monopole is added for the 5-GHz band operation. The mutual coupling between the two-strip monopole and the planar monopole helps in the bandwidth enhancement for both bands. There is no shorting via involved in the antenna structure. The configuration and performance of the dual-frequency planar antenna is described in Section II. A simple analysis is made in Section III. Experimental results are presented in Section IV.

II. Antenna Configuration and Performance

The configuration of the dual-frequency planar antenna is illustrated in Fig. 1. The design of the antenna is based on an RT/Duroid 5880 planar substrate that has a dielectric constant of $\varepsilon_r = 2.2$ and a thickness of $t = 10$ mils (0.254 mm). The dual-frequency antenna consists of a two-strip monopole for the 2-GHz band and a planar monopole for the 5-GHz band. The two-strip monopole is formed by an S-strip and a T-strip. The planar monopole and the T-strip are printed on the front side of the Duroid substrate and fed by a 50-Ω microstrip line while the S-strip is etched on the backside of the substrate and terminated at a ground plane (its $\text{length} = L_g$ and $\text{width} = W_g$). The upper section (its $\text{width} = W_T$ and its $\text{height} = H_T$) of the T-strip is fitted (leaving a space of w_s) into an area surrounded by the upper section (its $\text{width} = W_S$) of the S-strip (its strip $\text{width} = w_s$) while the lower section of the T-strip overlaps with the lower section of the S-strip, forming a two-strip line. The width of the two-strip line is equal to the width (w_f) of the 50-Ω microstrip line. The total height of the dual-frequency antenna is equal to the height (H) of the two-strip monopole. The planar monopole is equally divided into a wider upper part (its $\text{width} = W_U$ and its $\text{height} = H/2$) and a narrower lower part (its $\text{width} = W_L$ and its $\text{height} = H/2$) that is connected to

Manuscript received October 4, 2006; revised October 25, 2007. This work was supported in part by the Georgia Electronic Design Center (GEDC), in part by the National Science Foundation through NSF CAREER Award Contract NSF #9964761, NSF Award ECS-0313951, and in part by the NSF Packaging Research Center.

R. Li, B. Pan, J. Laskar, and M. M. Tentzeris are with the Georgia Electronic Design Center, School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30308 USA (e-mail: rlli@ece.gatech.edu).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TAP.2008.919171

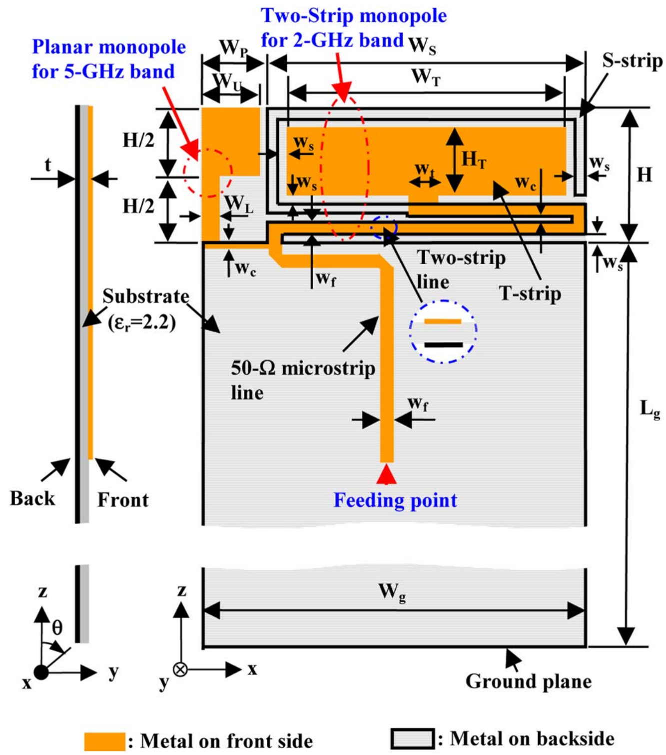


Fig. 1. Geometry of the dual-frequency planar antenna which consists of a two-strip monopole for the 2-GHz band and a planar monopole for the 5-GHz band.

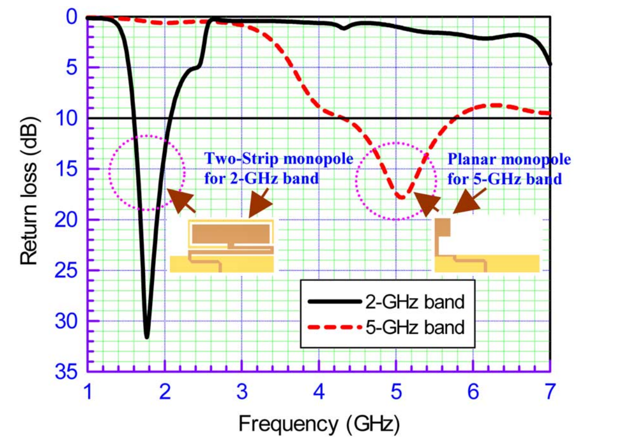


Fig. 2. Comparison of the return loss between the two-strip monopole for the 2-GHz band and the planar monopole for the 5-GHz band (the geometric parameters used are listed in Table I).

TABLE I
OPTIMIZED VALUES FOR THE GEOMETRIC PARAMETERS OF THE DUAL-FREQUENCY PLANAR ANTENNA

H	8 mm (6, 7, and 8 mm in Fig. 4)	w_s	0.5 mm
W_s	19 mm	w_t	1.5 mm
H_T	4.25 mm	w_c	0.25 mm
W_T	17 mm	w_f	0.75 mm
W_P	4 mm	t	0.254 mm
W_U	3.5 mm	L_g	60 mm (50, 60, and 70 mm in Fig. 5)
W_L	1 mm	W_g	23 mm (30 mm in Fig. 6, 35 and 40 mm in Fig. 7)

the 50-Ω microstrip line through a narrower microstrip line (its $\mathrm{width} = w_c$ and its length is equal to the total width (W_P) of the planar monopole). The total width (W) of the dual-frequency antenna is equal to the sum of the widths of the two-strip monopole (W_S) and the planar monopole (W_P), i.e., $W = W_S + W_P$. There is no direct electrical connection (e.g., by a shorting via) between the front side and the backside.

The feeding point is set up at the center of the ground plane. This setup is completely for the purpose of accurate measurement. If the feeding point were set up at the end of the ground plane, a coaxial cable connected for the measurement would change the antenna performance since the outer conductor of the coaxial cable serves as a part of the ground plane. The measured results would depend on the experimental setup, such as the size and/or the orientation of the coaxial cable.

The dual-frequency planar antenna was simulated using the transmission line matrix (TLM) based design tool-*MicroStripes 7.0*. In the simulation, a voltage gap feed was used. We began the design of the dual-frequency antenna with the two-strip monopole which was adjusted to have good impedance matching around 2 GHz. The resonant frequency at the lower frequency band can be adjusted by changing the width (W_S) of the two-strip monopole. A planar monopole is added to the two-strip monopole to achieve impedance matching around 5 GHz. The height (H) of the dual-frequency antenna determines the impedance matching and the resonant frequency at the higher frequency band. Fig. 2 shows the results for return loss of the two-strip monopole and the planar monopole when they operate separately (see the inset of the figure). Good impedance matching is observed at 2 GHz for the two-strip monopole and at 5 GHz for the planar monopole. Note that the bandwidths at the 2-GHz band and at the 5-GHz band are not satisfactory and require further enhancement. To realize the dual-frequency operation, we feed the two-strip monopole and the planar monopole simultaneously with the same 50-Ω microstrip line. To make the dual-frequency antenna have good impedance matching and sufficient bandwidths at the 2-GHz and 5-GHz bands, the geometric parameters of the antenna, such as H, $W_S, H_T, W_T, W_P, W_U, W_L, w_s$, and w_c, need to be optimized. The optimization design was carried out with the help of an extensive numerical simulation. The optimized values for the geometric parameters are listed in Table I. In the rest of the paper, all geometric parameters assume the values in this table unless they are given specifically. Fig. 3 shows the result of return loss for the optimal dual-frequency planar antenna. It is found that the bandwidths (for return loss $\geq$ 10 dB) at the 2-GHz and 5-GHz bands are 35% (1.58–2.27 GHz) and 15% (4.98–5.75 GHz), respectively. Note that there is a resonance between 3 and 4 GHz (called the 3-GHz band), which is due to the second-order mode of the antenna. The total height and width of the antenna are $H = 8.0$ mm and $W = 23$ mm, respectively. This result was cross-checked by using the MoM (Method of Moment) based *IE3D*. Good agreement is observed between the results obtained using *MicroStripes* and *IE3D*.

To cover the whole 5-GHz UNII band (i.e., 5.15–5.875 GHz), the frequency band at the 5-GHz band needs a slight adjust-

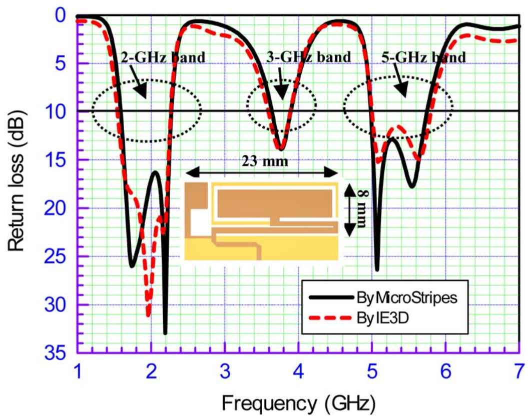


Fig. 3. Return loss of the dual-frequency planar antenna simulated using *MicroStripes* and *IE3D* (the geometric parameters used in the simulations are listed in Table I).

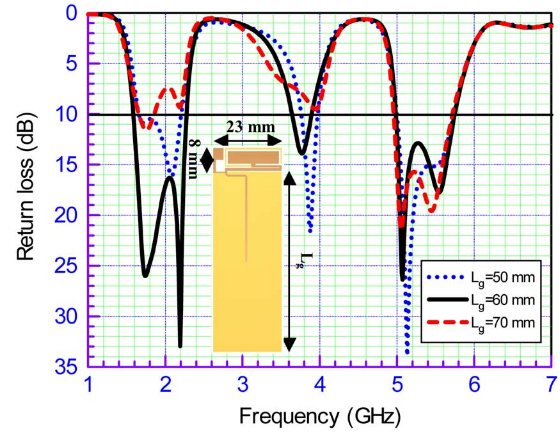


Fig. 5. Effect of the length (L_g) of ground plane on the return loss of the dual-frequency planar antenna, where L_g was changed from $L_g = 50$ mm to $L_g = 70$ mm. The optimized value for L_g is ~ 60 mm.

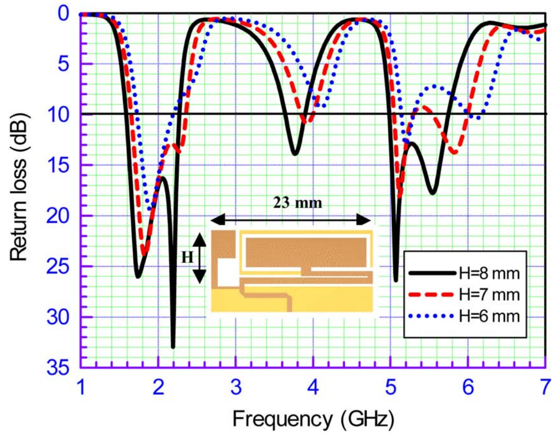


Fig. 4. Return loss of the dual-frequency planar antenna at different antenna heights ($H = 6$, 7, and 8 mm).

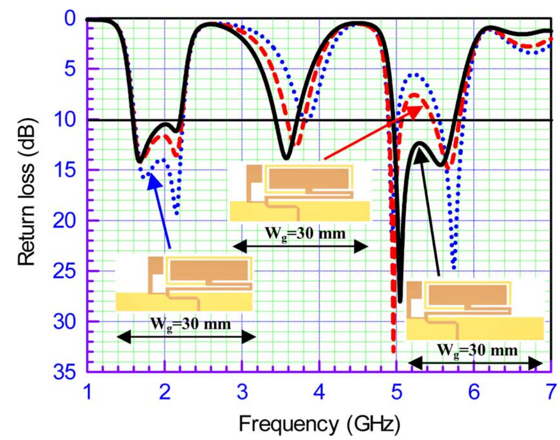


Fig. 6. Effect on the impedance matching of the position of the antenna mounted on the ground plane with a width of $W_g = 30$ mm.

ment. This can be done by slightly reducing the height (H) of the antenna while keeping all other geometric parameters unchanged (except for H_T). Fig. 4 displays the return loss at different antenna heights ($H = 6$, 7, and 8 mm). It is seen that as the height decreases, the frequency band shifts up while the level of return loss decreases. As $H = 7$ mm, the frequency band (5.05–6.0 GHz) at the 5-GH band completely covers the entire 5-GHz UNII band while the return loss still keeps almost higher than 10 dB. The effect of the length (L_g) of the ground plane on the return loss of the dual-frequency antenna is demonstrated in Fig. 5, where L_g was changed from $L_g = 50$ mm to $L_g = 70$ mm. It is observed that there is an optimum value for L_g where the dual-frequency antenna has the best performance for return loss at the 2-GHz band. The reason for the length dependence is that the ground plane also serves as a part of the radiating element. (It is noticed that the length L_g has little effect on the return loss at the 5-GHz band.) The optimum value for L_g is found to be around 60 mm (at which the ground plane with the S-strip and the T-strip probably becomes resonant around 2 GHz).

In practice, the width of a wireless handset may be larger than the total width of the antenna (i.e., $W = 23$ mm). Therefore, the influence of the position and the width (W_g) of the ground plane should be investigated. The impedance matching of the dual-frequency planar antenna depends on not only the width of the ground plane but also the position of the antenna mounted on the ground plane. Fig. 6 shows the effect of the antenna position on the impedance matching of the dual-frequency antenna, where the width of the ground plane is fixed at $W_g = 30$ mm. It is observed that as the ground plane extends on the side of the planar monopole for the 5-GHz band, the level of return loss at the 5-GHz band decreases. As the ground plane moves toward the side of the two-strip monopole for the 2-GHz band, the level of return loss at the 2-GHz band decreases while it increases at the 5-GHz band. The levels of return loss at both the 2-GHz band and the 5-GHz band are higher than 10 dB for $W_g = 30$ mm when the antenna is mounted on the left side of the ground plane. As W_g further increases (e.g., from $W_g = 30$ mm to $W_g = 35$ or 40 mm) (while the antenna is still fixed at the left side of the ground plane), the level of return loss at the 2-GHz band becomes lower than 10 dB. There is no significant change at the 5-GHz band. Fig. 7 shows that the levels of return loss at the 2-GHz band are about 8 dB and 7 dB for $W_g = 35$ and 40 mm, respectively. The return loss level can be increased by etching out a small part of ground plane on the side of the two-strip monopole. Fig. 7 also shows that the level of return loss at the 2-GHz band becomes higher than 10 dB

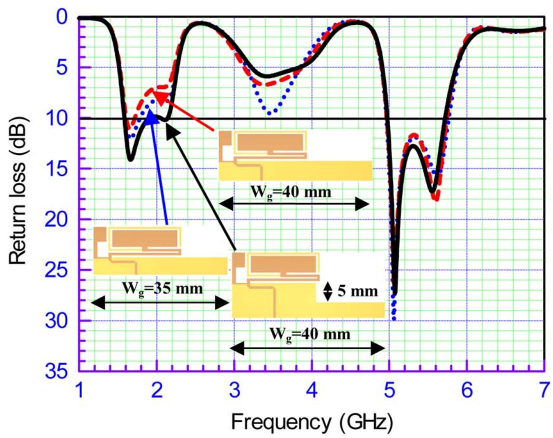


Fig. 7. Effect of the width of the ground plane (e.g., $W_g = 35$ and 40 mm) on the impedance matching and its improvement by etching out a small piece of the ground plane.

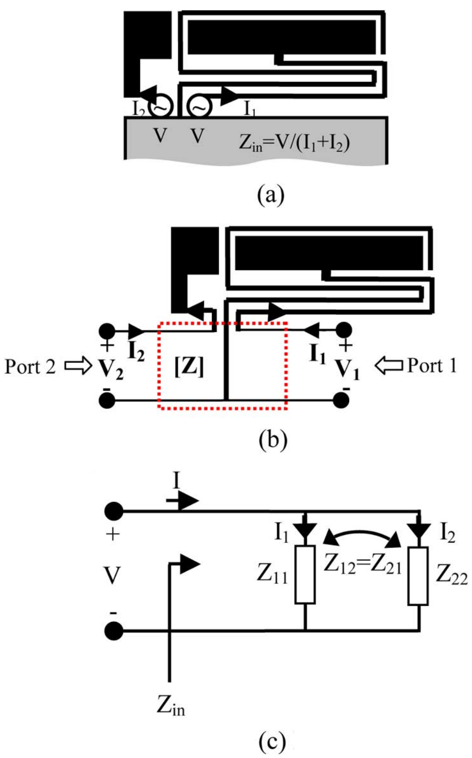


Fig. 8. Equivalent circuit model of the dual-frequency planar antenna. (a) Simplified model. (b) Two-port network representation. (c) Equivalent circuit for input impedance.

at $W_g = 40$ mm as etching out the ground plane at a depth of 5 mm. (Note that the etched 5-mm ground plane is only a little piece of the whole ground plane since its length $L_g = 60$ mm.) From this study, we conclude that i) the antenna should be mounted on the ground plane as left as possible and ii) if necessary, the impedance matching at the 2-GHz band can be improved by etching out a small piece of ground plane.

III. Analysis

To understand the operating mechanism of the dual-frequency antenna, we simplify the microstrip line feeding to two identical voltage sources V [see Fig. 8(a)], which are feeding the T-strip and the planar monopole, respectively. The currents in the T-strip and in the planar monopole are denoted by I_1 and I_2, respectively. Therefore, the input impedance of the dual-frequency antenna can be expressed as

$$Z_{\rm in} = V/(I_1 + I_2). \tag{1}$$

(The reference plane for the input impedance is defined at the interface between the antenna and the ground plane.) To investigate the mutual coupling between the T-strip and the planar monopole, we represent the simplified model as a two-port network with Port 1 connected to the T-strip and with Port 2 connected to the planar monopole [see Fig. 8(b)]. The two-port network can be described in terms of impedance parameters (i.e., the Z- parameters) as

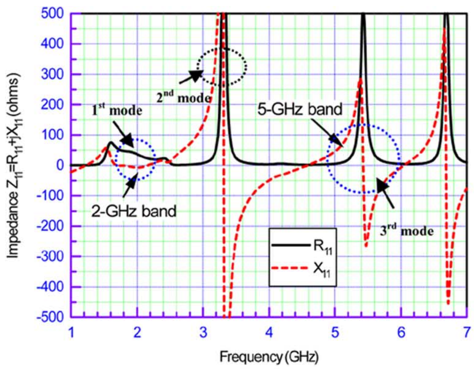
$$V_1 = Z_{11}I_1 + Z_{12}I_2 \tag{2a}$$

$$V_2 = Z_{21}I_1 + Z_{22}I_2 \tag{2b}$$

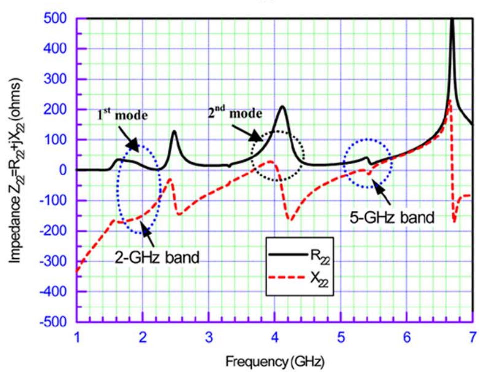
where $Z_{11}, Z_{12} = Z_{21}$, and Z_{22} are the self-impedance of the T-strip, mutual-impedance, and the self-impedance of the planar monopole, respectively. The Z parameters of the two-port network can be calculated from the S parameters by using the conversions between two-port network parameters (see [15, Table 4.2]). The S parameters were obtained directly using *MicroStripes* simulation. The input impedance can be found by letting $V_1 = V_2 = V$, which gives

$$Z_{\rm in} = \frac{Z_{11}Z_{22} - Z_{12}Z_{21}}{Z_{11} + Z_{22} - Z_{12} - Z_{21}}. \tag{3}$$

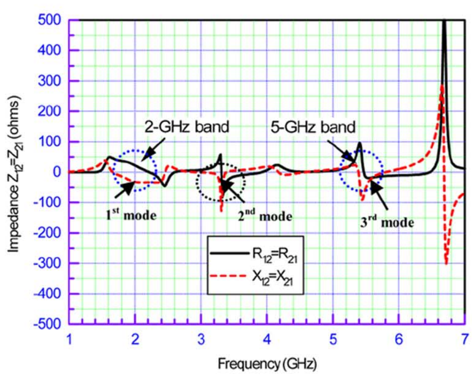
An equivalent circuit for the input impedance is drawn in Fig. 8(c). The input impedance can be considered to be a parallel combination of Z_{11} and Z_{22} mutually coupled with $Z_{12} = Z_{21}$. Fig. 9 presents the self-, mutual, and input impedances of the dual-frequency planar antenna calculated using the S parameters. Fig. 9(a) shows the self-impedance of the T-strip (Z_{11}). We can see that Z_{11} has a first-order (1st) mode at the 2-GHz band, a second-order (2nd) mode at the 3-GHz band (3–4 GHz), and a third-order (3rd) mode at the 5-GHz band. The 1st mode matches to the 50-Ω impedance at the 2-GHz band while the 2nd mode and the 3rd mode have high-value impedance; thus it is difficult to match with the 50-Ω impedance. This is the reason why there is no resonance appearing in Fig. 2 for the return loss of the two-strip monopole around the frequencies of the 2nd and 3rd modes. The self-impedance of the planar monopole (Z_{22}) is plotted in Fig. 9(b). In addition to a resonance at the 5-GHz band, there are also some lower-order modes due to the coupling with the S-strip. An important fact revealed in Fig. 9(c) is the high-value impedance (about 150 ohms) at the 2-GHz band. Without this high-value impedance, the addition of the planar monopole would change the impedance matching of the two-strip monopole at the 2-GHz band. Note that the bandwidths of the self-impedances Z_{11} at the 2-GHz band and Z_{22} at the 5-GHz band are narrow. After the introduction of the mutual coupling [i.e., $Z_{12} = Z_{21}$, see Fig. 9(c)], the bandwidth of the input impedance $Z_{\rm in}$ is enhanced [see Fig. 9(d)]. Note that the mutual coupling also has a 1st mode at the 2-GHz band, a 2nd mode at the 3-GHz band, and a 3rd mode at the 5-GHz band. It is the mutually coupled 1st and 3rd modes that improve the bandwidths at the



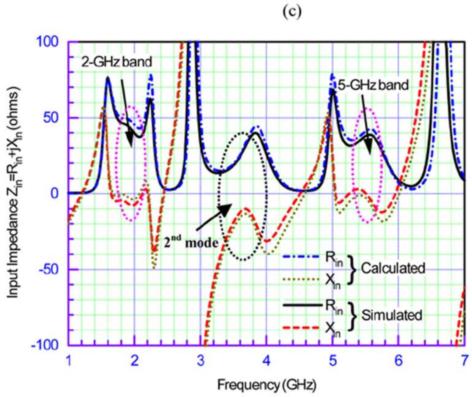
(a)



(b)



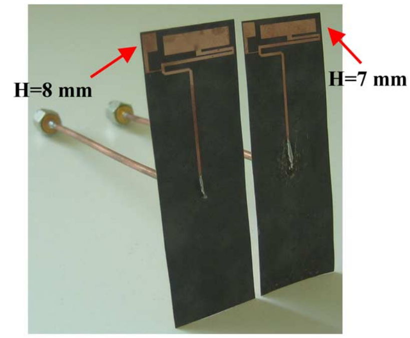
(c)



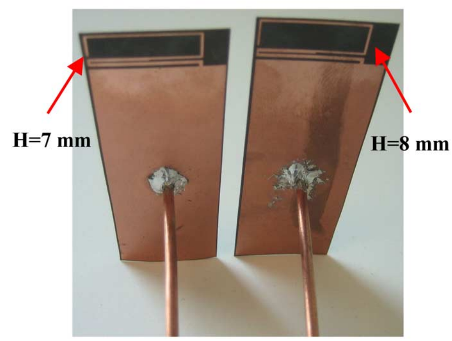
(d)

Fig. 9. Self-, mutual-, and input impedances of the dual-frequency planar antenna calculated using S parameters (the geometric parameters used are the same as listed in Table I). (a) Self-impedance (Z_{11}) of the T-strip for the 2 GHz band. (b) Self-impedance (Z_{22}) of the planar monopole for the 5-GHz band. (c) Mutual impedance $(Z_{12} = Z_{21})$ between the T-strip and the planar monopole. (d) Input impedance $(Z_{\rm in})$ calculated using (3) and simulated using *MicroStripes*.

2-GHz and the 5-GHz bands. The mutually coupled 2nd mode introduces a higher return loss at the 3-GHz band. (The good agreement between the calculated and simulated results for the input impedance validates the equivalent circuit model.) Therefore, we can conclude that the bandwidth enhancement of the dual-frequency planar antenna is a result of the mutual coupling between the two-strip monopole and the planar monopole. The impedance performance of the antenna depends on the self-impedance and the mutual-impedance. Therefore, the design and optimization of the broadband dual-frequency antenna should be carried out by considering the two-strip monopole and the planar monopole as a whole structure. The major factors that affect the antenna performance include the height (H) and width (W_S for the two-strip monopole, W_U and W_L for the planar monopole) of each monopole, the distance (W_P) between the two monopoles, as well as the dimensions of the ground plane.



(a)



(b)

Fig. 10. Photographs of two dual-frequency planar antennas with a height of $H = 7$ and 8 mm, respectively. (a) Front view. (b) Back view.

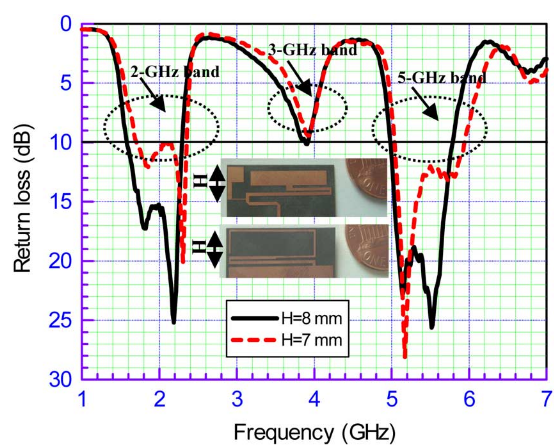


Fig. 11. Measured results for return loss of two dual-frequency planar antennas with a height of $H = 7$ and 8 mm, respectively.

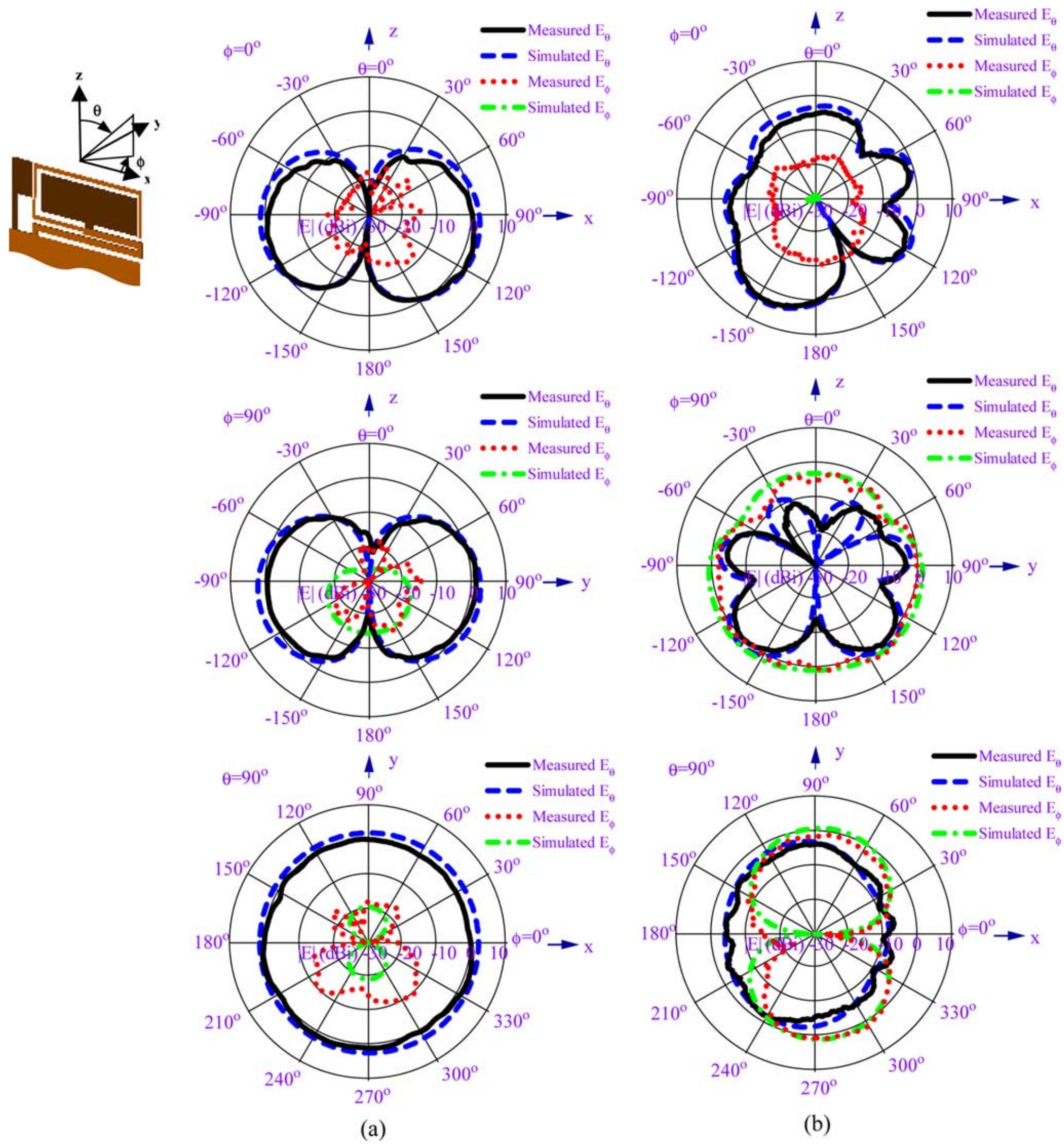


Fig. 12. Radiation patterns of the dual-frequency planar antenna with a height of $\mathrm{H} = 8$ mm. (a) At 2 GHz. (b) At 5.4 GHz.

IV. Experimental Results

To verify the performance of the dual-frequency antennas, two prototypes were fabricated and measured: one has a height of $\mathrm{H} = 8$ mm and the other has a height of $\mathrm{H} = 7$ mm. The antennas were fabricated on a 10-mil-thick RT/Duroid 5880 substrate with 0.5 oz copper on both sides by wet etching process. This process is based on standard double-side lithography using Karl Suss MA-6 Mask Aligner which is capable of backside alignment. Some alignment markers were printed on both sides to aid the backside alignment. After the photoresist was patterned and developed on both sides, the unwanted copper was removed by the 30% $FeCl_3$ saturated solution. Two photographs of the two prototypes are displayed in Fig. 10. For the purpose of measurement, the antennas are connected to a 0.085″ semi-rigid coaxial cable at the center of the ground plane. After adopting this feeding strategy, the measurement results became quite stable. The measured results for return loss are presented in Fig. 11. Compared to the simulated results shown in Fig. 4, good agreement is observed. The measured bandwidth for the antenna with a height of 8.0 mm is found to be 32% (1.68–2.32 GHz) at the 2-GHz band and 15% (4.95–5.80 GHz) at the 5-GHz band. The frequency band for the antenna with a height of 7 mm is slightly shifted up to 1.70–2.38 GHz at the 2-GHz band and 5.05–5.95 GHz at the 5-GHz band, which entirely cover the 2-GHz band for mobile communications and the 5-GHz UNII band for WLANs.

The radiation pattern of the dual-frequency planar antenna is almost independent of the antenna height H. Also, the radiation pattern has no significant change over each frequency band. Therefore, we only plot the simulated and measured patterns in Fig. 12 for the antenna with the height $\mathrm{H} = 8$ mm at the center frequencies for each frequency band (i.e., 2 GHz for the 2-GHz band and 5.4 GHz for the 5-GHz band). The radiation pattern at 2 GHz has a figure-eight configuration in the x-z and y-z planes, and an omni-directional shape in the x-y plane, similar to the radiation pattern of a dipole. The radiation pattern at 5.4 GHz exhibits an increased number of lobes because of the high-order modes (specifically the 3rd mode which generates three side lobes in the y-z plane) excited in the two-strip monopole even though it is suppressed somewhat by the high impedance of Z_{11} at the 5-GHz band [see Fig. 9(a)]. In the 2-GHz band, the peak gain is found to be around 2 dBi while in the 5-GHz band the peak gain is increased to about 4 dBi due to the higher-order modes. The simulated radiation efficiency is higher than 95%. (A conductivity of $\sigma = 5.8 \times 10^7$ S/m for the metal and a loss tangent of $\tan\delta = 0.0009$ for the dielectric substrate were used in the simulation.) In practice, the antenna may be realized in an inexpensive FR4 material which usually has a higher loss tangent, e.g., $\tan\delta = \sim 0.012$ for FR408. Fortunately, such a higher loss tangent will not lower the efficiency too much, as the near field is mainly in air and not too much in the substrate. We simulated the same antenna using a loss tangent of 0.012 while keeping the dielectric constant (in order not to detune the antenna too much). The simulated radiation efficiency is still higher than 90%, showing that FR4 can be used as the substrate for the dual-frequency planar antenna. The measured antenna gain agrees with the simulated result, which confirms that the dual-frequency planar antenna is an efficient radiator. We also checked the radiation pattern (not shown here) at the 3-GHz band. Two side lobes were observed in the y-z plane, which confirmed the 2nd mode at this band. It is interesting to note that the 2nd mode at the 3-GHz band may be utilized to cover the WiMax 3.3–3.6 GHz band. This is the future work for a triple-band planar antenna.

V. Conclusion

A new low-profile dual-frequency planar antenna has been developed for the 2-GHz- and 5-GHz-band wireless applications. The height of the dual-frequency planar antenna is only about 7–8 mm while the bandwidth can be $\sim$35% at the 2-GHz and $\sim$15% at the 5-GHz band. The dominant antenna element for the 2-GHz band is a two-strip monopole which consists of an S-strip and a T-strip while a planar monopole is added for the 5-GHz operation. The mutual coupling between the two-strip monopole and the planar monopole leads to a bandwidth enhancement in both the 2-GHz band and the 5-GHz band. The dual-frequency planar antenna is realized on a thin substrate without via process, enabling its easy integration with RF front-end circuits.

Acknowledgment

The authors would like to thank the reviewers for their valuable comments and suggestions.

References

[1] K.-L. Wong, G.-Y. Lee, and T.-W. Chiou, "A low-profile planar monopole antennas for multiband operation of mobile handsets," *IEEE Trans. Antennas Propag.*, vol. 51, no. 1, pp. 121–125, Jan. 2003.

[2] Y.-L. Kuo and K.-L. Wong, "Printed double-T monopole antenna for 2.4/5.2 GHz dual-band WLAN operations," *IEEE Trans. Antennas Propag.*, vol. 51, no. 9, pp. 2187–2192, Sep. 2003.

[3] J.-Y. Jan and L.-C. Tseng, "Small planar monopole antenna with a shorted parasitic inverted-L wire for wireless communications in the 2.4, 5.2, and 5.8-GHz bands," *IEEE Trans. Antennas Propag.*, vol. 52, no. 7, pp. 1903–1905, Jul. 2004.

[4] W.-C. Liu, W.-R. Chen, and C.-M. Wu, "Printed double S-shaped monopole antenna for wideband and multiband operation of wireless communications," *Proc. Inst. Elect. Eng. Microw. Antennas Propag.*, vol. 151, no. 6, pp. 473–476, Dec. 2004.

[5] K.-L. Wong, L.-C. Chou, and C.-M. Su, "Dual-band flate-plate antenna with a shorted parasitic element for laptop applications," *IEEE Trans. Antennas Propag.*, vol. 53, no. 1, pp. 539–544, Jan. 2005.

[6] H. Nakano, Y. Sato, H. Mimak, and J. Yamauchi, "An inverted FL antenna for dual-frequency operation," *IEEE Trans. Antennas Propag.*, vol. 53, no. 8, pp. 2417–2421, Aug. 2005.

[7] L. Zaid, G. Kossiavas, J.-Y. Dauvignac, J. Cazajous, and A. Papiernik, "Dual-frequency and broadband antennas with stacked quarter wavelength elements," *IEEE Trans. Antennas Propag.*, vol. 47, no. 4, pp. 654–660, Apr. 1999.

[8] S.-Y. Lin, "Multiband folded planar monopole antenna for mobile handset," *IEEE Trans. Antennas Propag.*, vol. 52, no. 7, pp. 1790–1794, Jul. 2004.

[9] M.-C. Huynh and W. L. Stutzman, "A low-profile compact multi-resonant antenna for wideband and multi-band personal wireless applications," in *Proc. IEEE AP-S Int. Symp.*, Jul. 2004, vol. 2, pp. 1879–1882.

[10] D.-U. Sim, J.-I. Moon, and S.-O. Park, "An internal triple-band antenna for PCS/IMT-2000/Bluetooth applications," *IEEE Antennas Wireless Propag. Lett.*, vol. 3, pp. 23–25, 2004.

[11] D.-U. Sim, J.-I. Moon, and S.-O. Park, "A wideband monopole antenna for PCS/IMT-2000/Bluetooth applications," *IEEE Antennas Wireless Propag. Lett.*, vol. 3, pp. 45–47, 2004.

[12] H. D. Foltz, J. S. Mclean, and G. Crook, "Disk-loaded monopoles with parallel strip elements," *IEEE Trans. Antennas Propag.*, vol. 44, no. 5, pp. 672–676, May 1996.

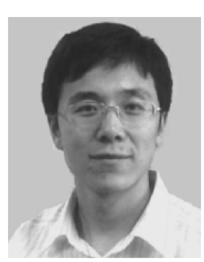
[13] J.-H. Jung and I. Park, "Electromagnetically coupled small broadband monopole antenna," *IEEE Antennas Wireless Propag. Lett.*, vol. 2, pp. 349–351, 2003.

[14] K. Noguchi, S.-I. Betsudan, T. Katagi, and M. Mizusawa, "A compact broad-band helical antenna with two-wire helix," *IEEE Trans. Antennas Propag.*, vol. 51, no. 9, pp. 2176–2181, Sep. 2003.

[15] D. M. Pozar, *Microwave Engineering*, 2nd ed. New York: Wiley, 1998, p. 211.

RongLin Li (M'02–SM'03) received the B.S. degree in electrical engineering from Xi'an Jiaotong University, China, in 1983 and the M.S. and Ph.D. degrees in electrical engineering from Chongqing University, China, in 1990 and 1994, respectively.

From 1983 to 1987, he worked as an Electrical Engineer at the Yunnan Electric Power Research Institute. From 1994 to 1996, he was a Postdoctoral Research Fellow at Zhejiang University, China, where, in 1998, he became a Professor. In 1997, he was with Hosei University, Japan, as an HIF (Hosei International Fund) Research Fellow. In 1999, he served as a Research Associate at the University of Utah, Salt Lake City. In 2000, he was a Research Fellow at Queen's University of Belfast, Belfast, U.K. Since 2001, he has been a Research Scientist II with the ATHENA Group at the Georgia Institute of Technology, Atlanta. His latest research interests include computational electromagnetics, modeling of antennas and microwave devices, and RF packaging design.



Bo Pan (S'03) received the B.S. and M.S. degrees (both with honors) from Tsinghua University, Beijing, China, in 2000 and 2003, respectively, and is currently working toward the Ph.D. degree at the School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta.

Prior to beginning his Ph.D. studies, he worked as a Visiting Student at Microsoft Research Asia. He is currently a Graduate Research Assistant with the ATHENA Research Group and MiRCTECH Research Group at the Georgia Institute of Technology. He is also a research member of the Georgia Electronic Design Center (GEDC) and GT-NSF Packaging Research Center (PRC). His research involves the design and fabrication of antennas for multiple wireless applications design, as well as development and characterization of various components and circuits for RF/microwave/millimeter-wave T/R modules, with the focus on micromachining technologies. He has authored and coauthored over more than 20 papers in refereed journals and conference proceedings.

Joy Laskar (S'84–M'85–SM'02–F'05) received the B.S. degree in computer engineering (highest honors) from Clemson University, Clemson, SC, in 1985, and the M.S. and the Ph.D. degrees in electrical engineering from the University of Illinois at Urbana-Champaign, in 1989 and 1991, respectively.

Prior to joining the Georgia Institute of Technology (Georgia Tech), Atlanta, in 1995, he held faculty positions at the University of Illinois and the University of Hawaii. At Georgia Tech he holds the Schlumberger Chair in Microelectronics in the School of Electrical and Computer Engineering. He is also the Founder and Director of the Georgia Electronic Design Center and heads a research group of 250 members (graduate students, research staff, and administration) with a focus on integration of high-frequency mixed-signal electronics for next-generation wireless and wire line systems. Between 1995 through summer 2007, he graduated 31 Ph.D. students. He has authored or coauthored more than 400 papers, several book chapters, three books (with two books in development), numerous invited talks and has more than 40 patents issued or pending. His work has resulted in the formation of two companies. In 1998 he co-founded an advanced WLAN IC Company: RF Solutions, which is now part of Anadgics (Nasdaq: Anad). In 2001, he co-founded a next generation analog CMOS IC company, Quellan, which is developing collaborative signal-processing solutions for the enterprise, video, storage and wireless markets.

Dr. Laskar's honors include the Army Research Office's Young Investigator Award in 1995, the National Science Foundation's CAREER Award in 1996, NSF Packaging Research Center Faculty of the Year in 1997, and co-recipient of the IEEE Rappaport Award (Best IEEE Electron Devices Society Journal Paper) in 1999. He was faculty advisor for the 2000 IEEE MTT IMS Best Student Paper award, was Georgia Tech Faculty Graduate Student Mentor of the year in 2001, received a 2002 IBM Faculty Award, and the 2003 Clemson University College of Engineering Outstanding Young Alumni Award. He was the 2003 recipient of the Outstanding Young Engineer award of the Microwave Theory and Techniques Society and was named an IEEE Fellow in 2005. For the 2004–2006 term, he served as an IEEE Distinguished Microwave Lecturer and currently is an IEEE EDS Distinguished Lecturer. He received Georgia Tech's "Outstanding Faculty Research Author" award in 2007, and has been appointed General Chairman of the IEEE International Microwave Symposium 2008.

Manos M. Tentzeris (S'89–M'98–SM'03) received the Diploma Degree in Electrical and Computer Engineering (*magna cum laude*) from the National Technical University of Athens, Athens, Greece and the M.S. and Ph.D. degrees in electrical engineering and computer science from the University of Michigan, Ann Arbor.

He is currently an Associate Professor with School of School of Electrical and Computer Engineering, Georgia Institute of Technology (Georgia Tech), Atlanta. He has published more than 260 papers in refereed journals and conference proceedings, two books, and ten book chapters. He has helped develop academic programs in highly integrated/multilayer packaging for RF and wireless applications using ceramic and organic flexible materials, paper-based RFID's and sensors, microwave MEM's, SOP-integrated (UWB, mutliband, conformal) antennas and adaptive numerical electromagnetics (FDTD, multiresolution algorithms) and heads the ATHENA Research Group, Georgia Tech, (20 researchers). He is the Georgia Electronic Design Center Associate Director for RFID/sensors research, and he has been the Georgia Tech NSF-Packaging Research Center Associate Director for RF Research and the RF Alliance Leader from 2003–2006. He was a Visiting Professor with the Technical University of Munich, Germany for summer 2002, where he introduced a course in the area of high-frequency packaging. He has given more than 50 invited talks in the same area to various universities and companies in Europe, Asia, and the United States.

Dr. Tentzeris was the recipient/co-recipient of the 2007 IEEE APS Symposium Best Student Paper Award, the 2007 IEEE IMS Third Best Student Paper Award, the 2007 ISAP 2007 Poster Presentation Award, the 2006 IEEE MTT Outstanding Young Engineer Award, the 2006 Asian-Pacific Microwave Conference Award, the 2004 IEEE Transactions on Advanced Packaging Commendable Paper Award, the 2003 NASA Godfrey "Art" Anzic Collaborative Distinguished Publication Award, the 2003 IBC International Educator of the Year Award, the 2003 IEEE CPMT Outstanding Young Engineer Award, the 2002 Int. Conf. Microwave and Millimeter-Wave Technology Best Paper Award (Beijing, China), the 2002 Georgia Tech-ECE Outstanding Junior Faculty Award, the 2001 ACES Conference Best Paper Award and the 2000 NSF CAREER Award, and the 1997 Best Paper Award of the International Hybrid Microelectronics and Packaging Society. He was also the 1999 Technical Program Co-Chair of the 54th ARFTG Conference, Atlanta, and the Chair of the 2005 IEEE CEM-TD Workshop. He is the Vice-Chair of the RF Technical Committee (TC16) of the IEEE CPMT Society. He has organized various sessions and workshops on RF/Wireless Packaging and Integration, RFID's, Numerical Techniques/Wavelets, in IEEE ECTC, IMS, VTC and APS Symposia in all of which he is a member of the Technical Program Committee in the area of "Components and RF." He will be the TPC Chair for IEEE IMS 2008 Symposium. He is an Associate Editor of the IEEE TRANSACTIONS ON ADVANCED PACKAGING. He is a member of URSI Commission D, the MTT-15 Committee, an Associate Member of EuMA, a Fellow of the Electromagnetic Academy, and a member of the Technical Chamber of Greece.