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TABLE 2 Impedance of the Half-Wavelength Resonant Printed Dipole on a Real Substrate: Analytical and Experimental Results (h is the Substrate Thickness)

ϵ_r	h/λ_0	R_{res} [Ω] [2]	R_{res} [Ω] Eq. (15)
3.25	0.1016	34.5	39
3.25	0.127	60	62
8.5	0.15	50	76

$$X_{in} \cong -\frac{30}{\sqrt{\epsilon_{reff}}} \left\{ -\frac{8\pi h}{\lambda} + \frac{8\pi h^2}{l\lambda} \right\} = \frac{120}{\sqrt{\epsilon_{reff}}} \pi \frac{h}{l} \left(1 - \frac{h}{l} \right). \quad (14)$$

The antenna complex impedance is finally obtained by combining the real and imaginary parts from Eqs. (9) and (14) as follows:

$$Z = Z_{in} = R_{in} + jX_{in} \cong \frac{600}{\sqrt{\epsilon_{reff}}} \left(\frac{h}{l} \right)^2 + j \frac{120}{\sqrt{\epsilon_{reff}}} \pi \frac{h}{l} \left(1 - \frac{h}{l} \right). \quad (15)$$

RESULTS

Table 1 presents the impedance of a half-wavelength printed dipole on a substrate with $\epsilon_r = 1$ (air) and for the different values of the substrate thickness. The analytical results from Eq. (15) have been compared with the numerical results simulated using the numerical electromagnetic code (NEC) for an infinite reflector plane. Very good agreement is observed between the analytical results and the numerical ones.

To investigate the effect of a real substrate and a finite ground plane, the analytical results have been compared (Table 2) with a few experimental results found in the literature [3]. The experimental tests are on the radiation resistance of a resonant printed dipole, although they may be compared with the real part of the impedance of a half-wavelength printed dipole. It can be observed that the resonance radiation impedance is not very different from the real impedance of the half-wavelength printed dipole [4]. As shown in Table 2, the results are coherent for ϵ_r of around 3. For the high permittivity of 8.5, this difference is important; it may be the result of the coupling beyond the "surface waves," which can be very effective in this case.

The feeding-gap effect on the experimental input impedance should also be considered in the theoretical treatment for more accuracy. The simple capacitive model of the feeding gap for a normal dipole [6] can be useful in this case.

CONCLUSION AND PERSPECTIVE

The analytical study presented here has successfully described the self impedance of a printed half-wavelength dipole on an arbitrary substrate. The obtained closed-form formulas clearly show the dependence of the dipole impedance on the dipole length as well as the substrate properties. The comparative results of the numerical simulation and the experiment have demonstrated the performance of these simple formulas. These compact formulas can be used to analyse patch antennas that are simulated by only a few thin printed dipoles.

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ISOLATION BETWEEN GSM/DCS AND WLAN ANTENNAS IN A PDA PHONE

Kin-Lu Wong, Jui-Hung Chou, Saou-Wen Su, and Chih-Ming Su

Department of Electrical Engineering
National Sun Yat-Sen University
Kaohsiung 80424, Taiwan

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ABSTRACT: The isolation performances of GSM/DCS and WLAN antennas embedded in a PDA phone for cellular/WLAN dual-network operations are studied. The two (GSM/DCS and WLAN) antennas are printed PIFAs with compact sizes and are mounted perpendicularly along the boundary of the system circuit board in order to perform as internal antennas for the PDA phone. It is found that the isolation between the two antennas is greatly dependent on their relative position inside the PDA phone. The measured and simulated results are presented, and the isolation performances are analyzed. © 2005 Wiley Periodicals, Inc. *Microwave Opt Technol Lett* 45: 347–352, 2005; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.20820

Key words: mobile antennas; global system for mobile communication/digital communication system (GSM/DCS); wireless local area network (WLAN) antennas; planar inverted-F antennas (PIFAs); personal digital assistant (PDA) phones

1. INTRODUCTION

Integration of cellular and WLAN communication networks can provide users with ubiquitous or seamless data services [1]. For such an integrated cellular/WLAN network application, many dual-mode or dual-network wireless devices (such as PDA phones) are expected to emerge in the market in the near future. For this application, it is required that a PDA phone be equipped with two antennas, for example, one GSM/DCS (890–960 MHz/1710–1880 MHz) antenna for cellular operation and one WLAN antenna for 2.4-GHz (2400–2484 MHz) WLAN operation [2]. However, due to the limited space available inside a PDA phone, special care is required for achieving optimized isolation between the two antennas in order to avoid performance degradation.

In this paper, we present a study on the isolation of two promising internal antennas (one GSM/DCS antenna and one 2.4-GHz WLAN antenna) for a PDA phone for cellular/WLAN dual-network operations. Both the GSM/DCS and WLAN antennas are printed PIFAs with compact sizes (see Fig. 1) and can be concealed within the casing of a PDA phone for operation as

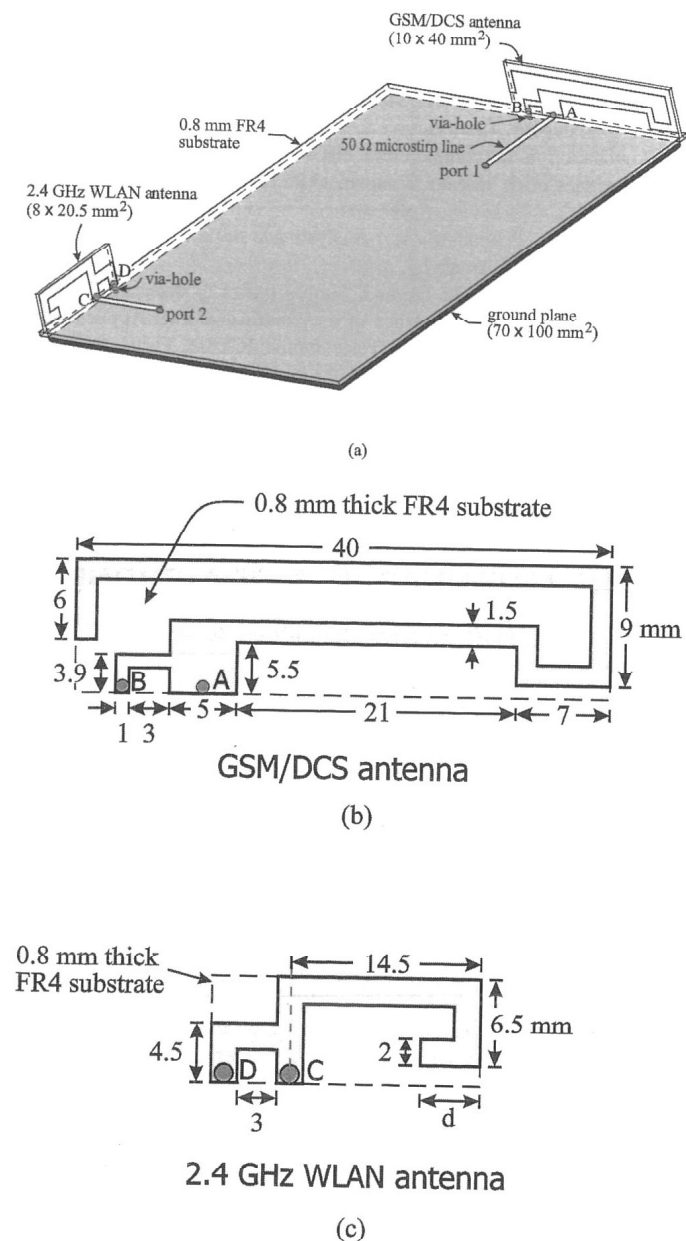


Figure 1 (a) Configuration of the internal GSM/DCS and WLAN antennas for a PDA phone for cellular/WLAN dual-network operations; (b) dimensions of the GSM/DCS antenna; (c) dimensions of the WLAN antenna. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

internal antennas. In this study, as in most conventional mobile-phone-antenna designs [2], the GSM/DCS antenna is arranged to be fixed at the top edge of the system circuit board. The WLAN antenna is then mounted at various possible locations along the boundary of the system ground plane. At each possible location, the isolation between the GSM/DCS and WLAN antennas is measured and analyzed. The simulation results obtained using Ansoft high-frequency structure simulator (HFSS) simulation software are also presented for comparison. The optimized isolation between the two antennas is discussed.

2. ARRANGEMENT OF TWO INTERNAL ANTENNAS FOR CELLULAR/WLAN DUAL-NETWORK OPERATIONS

Figure 1(a) shows the promising internal GSM/DCS and WLAN antennas for a PDA phone. Both antennas are printed on 0.8-mm-thick FR4 substrate and are in the form of a PIFA with a folded

radiating arm in order to achieve a compact structure [3]. The GSM/DCS antenna occupies a small area of $10 \times 40 \text{ mm}^2$ and is fixed at the top edge of a system circuit board having a ground plane of 100-mm length and 70-mm width in this study, which is a reasonable size for practical PDA phones. Also note that the GSM/DCS antenna is mounted perpendicularly to the system circuit board [4–6] and has a height of 10 mm only, which is less than the thickness of most PDA phones, thus making it possible to conceal the antenna within the casing of the PDA phone as an internal antenna. Given the design dimensions shown in Figure 1(b), the GSM/DCS antenna can generate two separate resonant modes at about 900 and 1800 MHz to cover the GSM (890–960 MHz) and DCS (1710–1880 MHz) bands.

The WLAN antenna, whose design dimensions are given in Figure 1(c), is designed for operating in the 2.4-GHz band (2400–2484 MHz). This antenna occupies a compact area of $8 \times 20.5 \text{ mm}^2$ and is also printed on 0.8-mm-thick FR4 substrate. Similar to the GSM/DCS antenna, the WLAN antenna can also be concealed within the casing of the PDA phone as an internal antenna.

The WLAN antenna is then moved along the boundary (locations P1 to P10 shown in Fig. 2) of the system circuit board in order to determine the optimized isolation to the GSM/DCS antenna. Note that there are two kinds of orientations (cases A and B) of the WLAN antenna mounted along the boundary of the system circuit board. Cases A and B represent the WLAN antenna extending [from point D (shorting point) to point C (feeding point) to the radiating arm of the antenna] counterclockwise and clockwise, respectively, at each specified location. The configuration shown in Figure 1 is denoted as case A at location P4 in this study.

Also note that, at the end of the radiating arm of the WLAN antenna [see Fig. 1(c)], there is tuning length of d (about 2.0–4.5 mm in this study) for tuning the antenna's resonant frequency to be at about 2.45 GHz at each possible location shown in Figure 2. This is because, for each location in this study, the isolation or

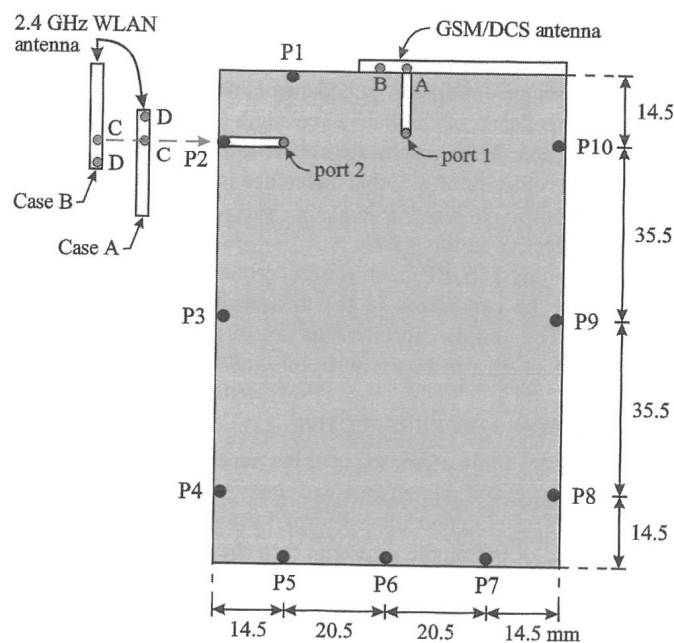


Figure 2 Locations (P1 to P10) of the WLAN antenna with the GSM/DCS antenna fixed at the top edge of the system ground plane; cases A and B represent the WLAN antenna extending (from point D to point C to the radiating arm of the antenna) counterclockwise and clockwise, respectively, at each specified location. The configuration shown in Fig. 1 is for case A at location P4. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

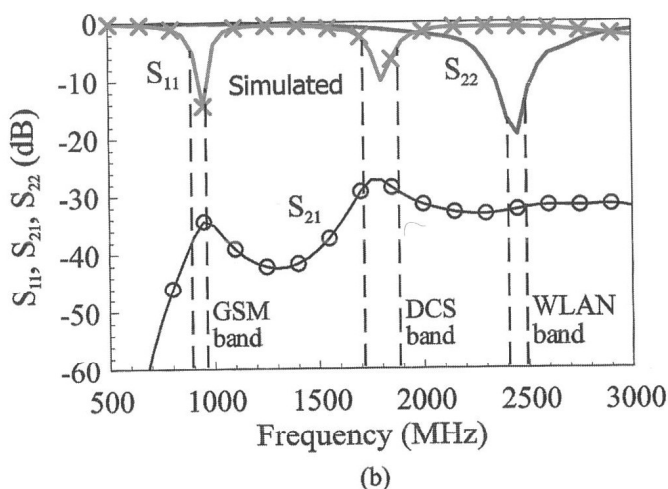
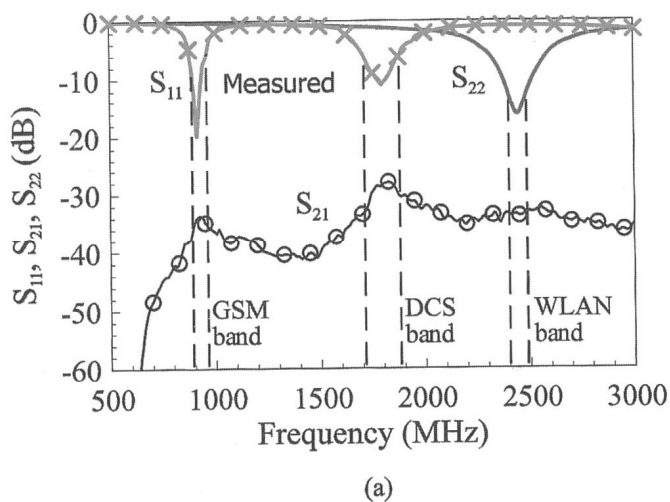


Figure 3 Reflection coefficients (S_{11} for GSM/DCS antenna, S_{22} for WLAN antenna) and isolation (S_{21}) between the two antennas for case A at location P4: (a) measured results; (b) simulated results. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

coupling between the two antennas is different, which tends to cause some shifting of the resonant frequency of the WLAN antenna. By slightly adjusting the length d , the WLAN antenna at each location can easily be tuned to cover the operating bandwidth of the 2.4-GHz band. On the other hand, the shifting of the resonant frequencies of the GSM/DCS antenna is found to be relatively small, which is largely because it is fixed at the top edge of the system circuit board in the study, unlike the WLAN antenna mounted at various locations of P1 to P10 in this study. Thus, no adjusting of the design dimensions shown in Figure 1(b) is required for the GSM/DCS antenna.

3. RESULTS AND DISCUSSION

The configuration shown in Figure 1, in which the WLAN antenna is at location P4 with case A orientation, is studied first. The measured reflection coefficients (S_{11} for the GSM/DCS antenna, S_{22} for the WLAN antenna) and isolation (S_{21}) between the two antennas are shown in Figure 3(a). The simulated results obtained

using Ansoft HFSS are presented in Figure 3(b). Reasonable agreement between the measurement and simulation results is obtained. It is also seen that the GSM/DCS antenna generates two separate resonant modes covering the operating bands of GSM and DCS systems. Similarly, for the WLAN antenna, a resonant mode is also successfully excited to cover the 2.4-GHz WLAN band. As for the isolation, the maximum S_{21} within the GSM, DCS, and WLAN bands is -33.6 , -27.9 , and -33.0 dB, respectively, which is quite good for practical applications.

On the other hand, when the WLAN antenna is mounted at location P10 with case A orientation, the obtained isolation is quickly degraded. The measured and simulated S parameters are shown in Figures 4(a) and 4(b), respectively. Again, reasonable agreement between measurement and simulation results is observed, and the maximum S_{21} within the GSM, DCS, and WLAN bands is only -14.9 , -5.9 , and -4.6 dB, respectively, which are not acceptable for practical applications.

The WLAN antenna mounted at various locations (P1 to P10) for both cases A and B are then extensively studied. The measured

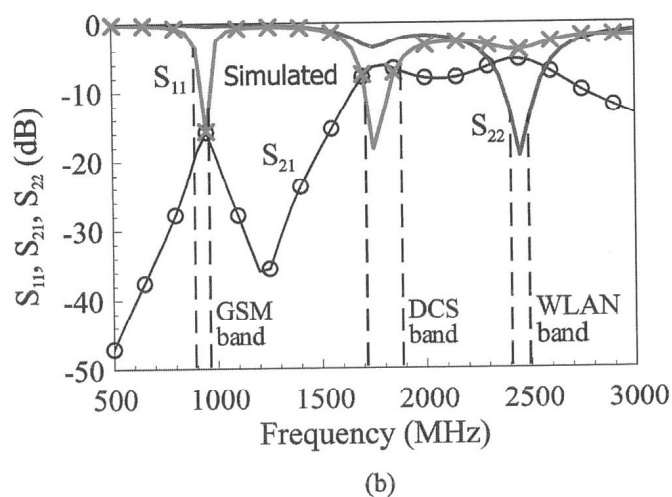
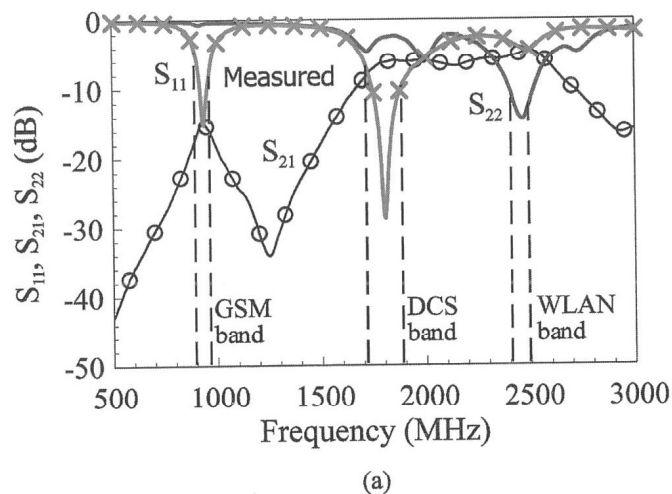


Figure 4 Reflection coefficients (S_{11} for GSM/DCS antenna, S_{22} for WLAN antenna) and isolation (S_{21}) between the two antennas for case A at location P10: (a) measured results; (b) simulated results. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

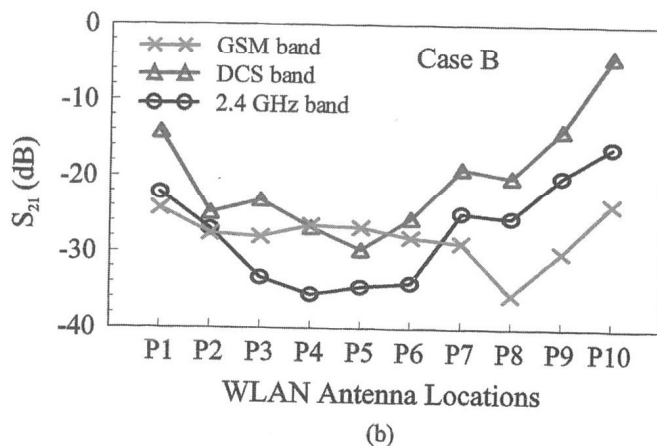
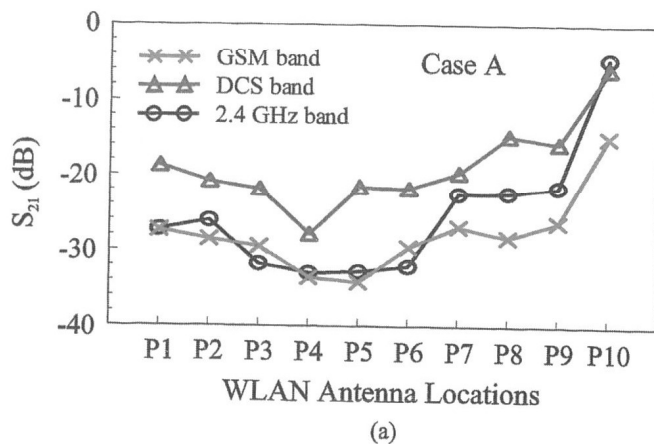


Figure 5 Measured maximum isolation (S_{21}) within the GSM, DCS, and WLAN bands at different locations from P1 to P10: (a) case A; (b) case B. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

TABLE 1 Measured Maximum Isolation (S_{21}) Within the GSM, DCS, and WLAN Bands, Respectively, at Different Locations (P1 to P10) of the WLAN Antenna Shown in Fig. 2

Location	Case	Max. S_{21} [dB] in GSM band	Max. S_{21} [dB] in DCS band	Max. S_{21} [dB] in WLAN band
P1	A	-27.4	-18.8	-27.3
	B	-24.3	-14.2	-22.2
P2	A	-28.6	-20.9	-26.1
	B	-27.6	-24.9	-27.0
P3	A	-29.5	-21.9	-31.8
	B	-28.0	-23.2	-33.4
P4	A	-33.6	-27.9	-33.0
	B	-26.5	-26.8	-35.6
P5	A	-34.2	-21.6	32.8
	B	-26.8	-29.7	-34.6
P6	A	-29.6	-21.8	-32.1
	B	-28.1	-25.6	-34.1
P7	A	-26.9	-19.7	-22.5
	B	-28.8	-19.0	-24.9
P8	A	-28.3	-14.8	-22.4
	B	-35.6	-19.8	-25.5
P9	A	-26.3	-15.8	-21.6
	B	-30.0	-13.9	-20.0
P10	A	-14.9	-5.9	-4.6
	B	-23.7	-4.2	-16.1

maximum isolation (S_{21}) within the GSM, DCS, and WLAN bands at different locations from P1 to P10 is shown in Figure 5(a) for case A and in Figure 5(b) for case B. The corresponding measured data are also listed in Table 1 for comparison. From the results shown, a significant dependence of the isolation on the location and orientation of the WLAN antenna is seen. By comparing the obtained results, it can be concluded that the isolation obtained at location P4 for case A orientation is optimal among all the locations and orientations of the WLAN antennas studied here.

To further analyze the isolation behavior between the two antennas, the excited surface-current distributions in the ground plane of the system circuit board are studied. By using Ansoft simulation software HFSS, the simulated surface-current distributions in the system ground plane are obtained, and the results are shown in Figures 6–8. For Figures 6 and 7, the results are obtained when the WLAN antenna is excited at 925 MHz (the center frequency of the GSM band) and 1795 MHz (the center frequency of the DCS band), respectively, with the GSM/DCS antenna terminated to a 50 Ω load. Whereas in Figure 8, the GSM/DCS antenna is excited at 2442 MHz (the center frequency of the 2.4-GHz WLAN band) with the WLAN antenna terminated to a 50 Ω load.

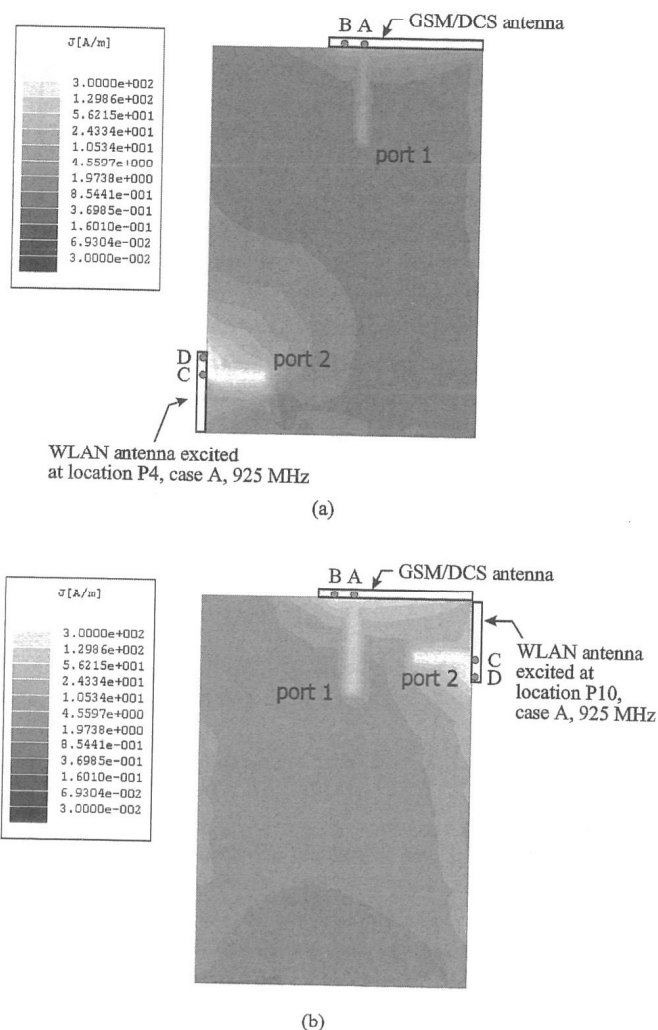


Figure 6 Simulated surface-current distributions in the system ground plane for case A; the WLAN antenna is excited at 925 MHz with the GSM/DCS antenna terminated to a 50 Ω load: (a) at location P4; (b) at location P10. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

The results shown in Figures 6–8 suggest that the isolation between the two antennas is strongly related to the excited surface-current distributions in the system ground plane. By comparing Figure 6(a) (location P4 with case A, the same as the study in Fig. 3) to Figure 6(b) (location P10 for case A, the same as the study in Fig. 4), it is clearly seen that the excited surface currents near the GSM/DCS antenna are much stronger in Figure 6(b) than in Figure 6(a). This behavior may explain the reason for the poor isolation obtained in the GSM band for location P10 with case A shown in Figure 4.

Similarly, by comparing Figure 7(a) (location P4 with case A, the same as the study in Fig. 3) to Figure 7(b) (location P10 for case A, the same as the study in Fig. 4), much stronger excited surface currents near the GSM/DCS antennas in Figure 7(b) are seen. This behavior may also explain the reason for the poor isolation obtained in the DCS band for location P10 with case A shown in Figure 4. Finally, the obtained results shown in Figure 8 also indicate that much stronger surface currents are excited near the WLAN antenna in Figure 8(b) than in Figure 8(a). This may also lead to the poor isolation obtained in the 2.4-GHz WLAN band for location P10 with case A shown in Figure 4.

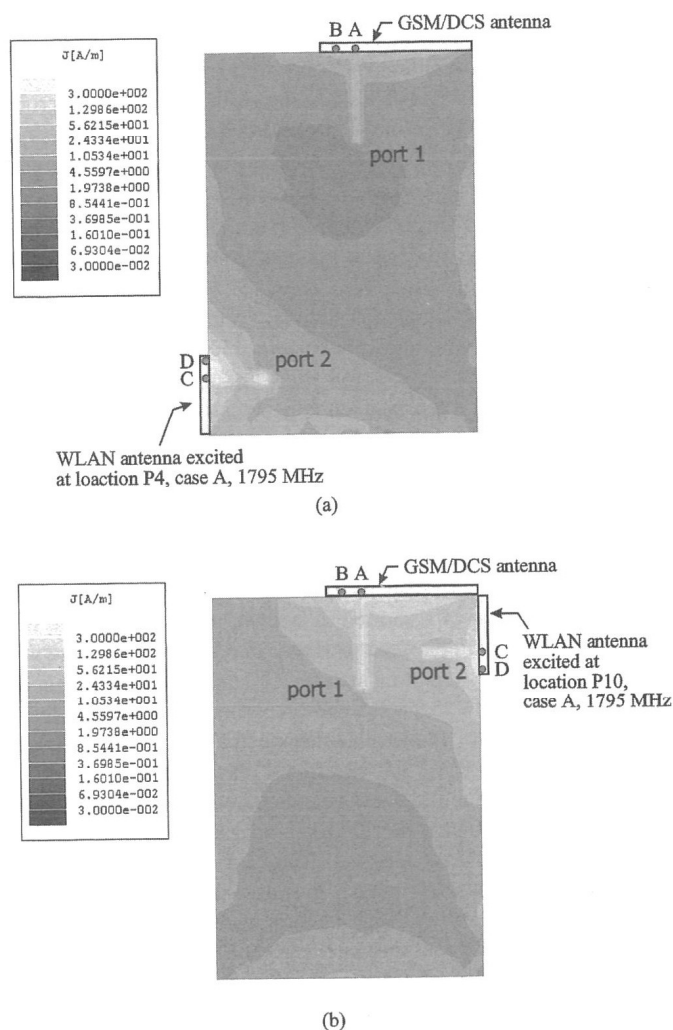


Figure 7 Simulated surface-current distributions in the system ground plane for case A; the WLAN antenna is excited at 1795 MHz with the GSM/DCS antenna terminated to a 50Ω load: (a) at location P4; (b) at location P10. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

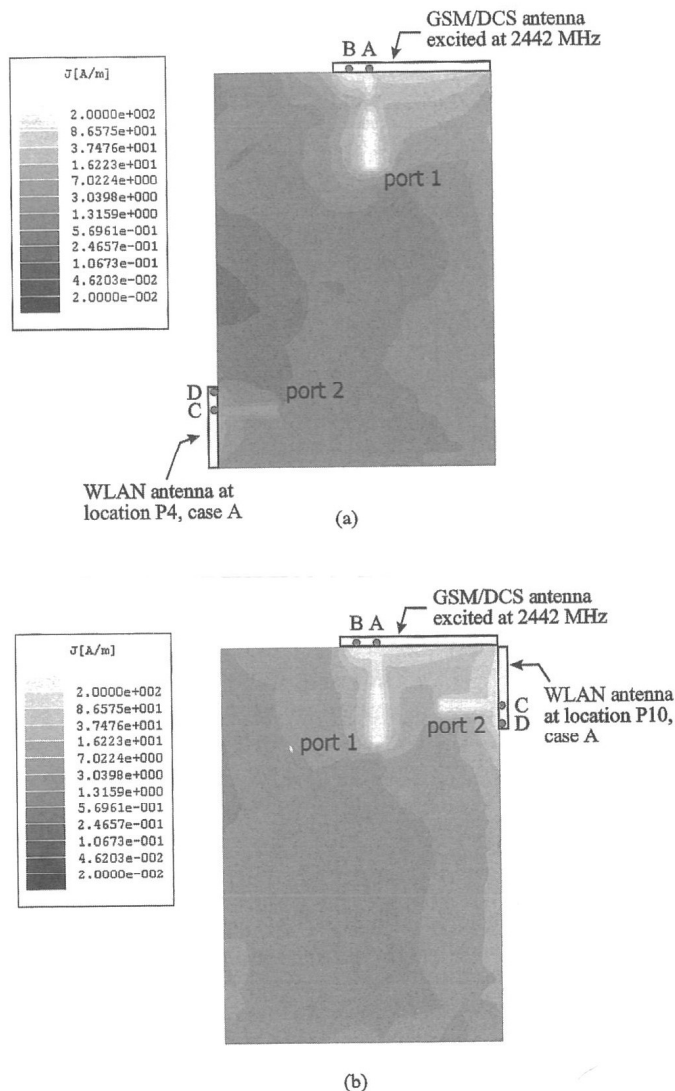


Figure 8 Simulated surface-current distributions in the system ground plane for case A; the GSM/DCS antenna is excited at 2442 MHz with the WLAN antenna terminated to a 50Ω load: (a) at location P4; (b) at location P10. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

4. CONCLUSION

Experimental and simulation studies for the isolation performances between two internal PIFA antennas for GSM/DCS and WLAN operations for a PDA phone have been presented. The results indicate that the isolation of the two antennas is greatly affected by their relative location inside the PDA phone. When the GSM/DCS antenna fixed at the top edge of the system circuit board, optimized or near-optimized isolation is achieved when the WLAN antenna is placed near the bottom edge of the system circuit board (location P4 in this study), with the WLAN antenna having its radiating arm extending away from the GSM/DCS antenna (case A in this study). It has also been observed that the isolation is strongly related to the excited surface-current distributions in the ground plane of the system circuit board of the PDA phone.

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WIDEBAND FOLDED-PATCH ANTENNAS FED BY L-SHAPED PROBE

Steven S. L. Yang and K. M. Luk
Department of Electronic Engineering
City University of Hong Kong
83 Tat Chee Avenue
Kowloon, Hong Kong SAR, P. R. China

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ABSTRACT: Simple folded-patch antennas fed by an L-shape probe are designed and studied experimentally. This simple antenna structure with thick air substrate attains a projection-length reduction of about 30% with reference to the conventional half-wave patch antenna. This antenna attains an impedance bandwidth of 35% and a gain of 6 dBi. © 2005 Wiley Periodicals, Inc. *Microwave Opt Technol Lett* 45: 352–355, 2005; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.20821

Key words: microstrip antennas; wideband antennas

1. INTRODUCTION

Microstrip-patch antennas have the attractive features of low profile and light weight. However, the size of the microstrip antenna may be too large for some applications, especially when the operating frequency is low. There are a number of proposed techniques to reduce the size of the conventional half-wave microstrip-patch antenna, such as using high-dielectric-substrate material, adding shorting pins, adding a shorting wall, or cutting slots on the patch. One of the designs is the shorted quarter-wave patch antenna [1–3], which can reduce the resonant length by half [3]. However, the cross-polarization level is high, thus leading to a significant gain reduction [1]. In the proposed multilayer patch technique [4–5], a rectangular patch antenna is folded into several layers; this would introduce a complicated structure, which may not be favored by manufacturers.

On the other hand, the L-shaped probe [6] has been applied successfully to microstrip-antenna design. This is a feeding technique to enhance the bandwidth of patch antennas, which is also applicable to thick-substrate antennas. The L-shaped probe incorporated with the radiating patch introduces a capacitance in order to partially suppress the inductance introduced by the probe itself. Compared with the capacitor-patch technique, which is based on a similar principle of operation, the L-shaped probe does not require the feed probe to be soldered to the capacitor patch. Bending a straight probe into an L-shaped probe is easy during fabrication, especially for an array design. With the use of a shorted quarter-

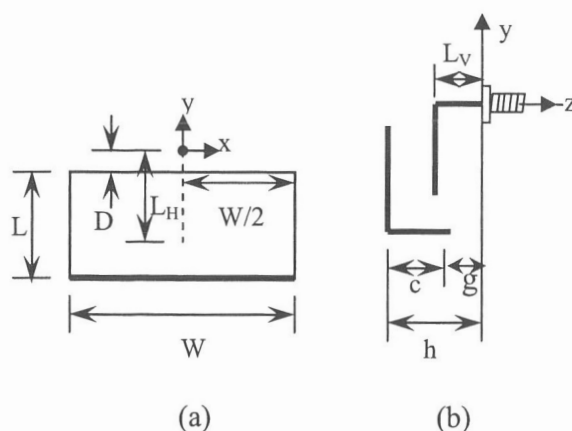


Figure 1 Geometry of the folded-patch antenna with L-probe feed: (a) top view; (b) side view

wave patch fed by an L-shaped probe, the bandwidth achieved is about 39% [6].

The shorted quarter-wave patch antenna fed by an L-shaped probe [2] combines the advantages of small size and wide bandwidth. However, large cross-polarization level in the H-plane and small gain are a weakness of this antenna design. Improving the performance of this antenna is challenging and of practical interest.

In this paper, a comprehensive experimental study of simple folded-patch microstrip-patch antennas with an L-shaped probe feed is presented. The results of these antennas will be compared with those of a similar antenna that has a simple and small-size structure—a quarter-wave microstrip-patch antenna shorted by a shorting wall fed by an L-shaped probe.

2. GEOMETRY

The geometry of the antenna is shown in Figure 1. A 2-mm-thick aluminum ground plane with dimensions 250×250 mm is used. A 0.07-mm-thick copper foil (foil shielding tape no. 1181 by 3M) is used to construct the folded antenna patches. The copper foil is taped on top of 1.5-mm-thick foam with a dielectric constant ≈ 1.06 . Air is filled in the rest of the space, and the dielectric constant is assumed to be unity.

The design of this antenna is derived from the quarter-wave patch antenna shorted by a shorting wall. The patch is constructed by folding a rectangular-shape patch in a right angle, which is similar to the patch of a shorted quarter-wave antenna, while the vertical patch is not connected to the ground. This disconnection introduces one more radiation slot, which may improve the gain of this antenna. The L-shaped probe is constructed by bending a copper wire of 1-mm diameter and connecting it to a 50 Ω 3.5-mm SMA connector mounted on the ground plane.

Several sets of the proposed antenna are constructed and their dimensions are tabulated in Table 1. Sets 3 and 6 are the shorted quarter-wave patch antennas, which have similar dimensions to those of our proposed antennas. The disconnection of the patch from the ground plane changed the electrical characteristic of the antenna; hence, the proposed antennas require a longer resonant length in order to match at a lower frequency. The projection length of the proposed antenna is about a quarter-wavelength long, especially when the gap g between the vertical patch and ground plane is small (sets 1 and 4).

The projection length of the proposed antennas is reduced. For the thick-substrate antennas, the projection length of set 1 is about $0.23\lambda_0$, whereas the projection length of the conventional half-wave patch antenna with similar thickness is about $0.33\lambda_0$, where