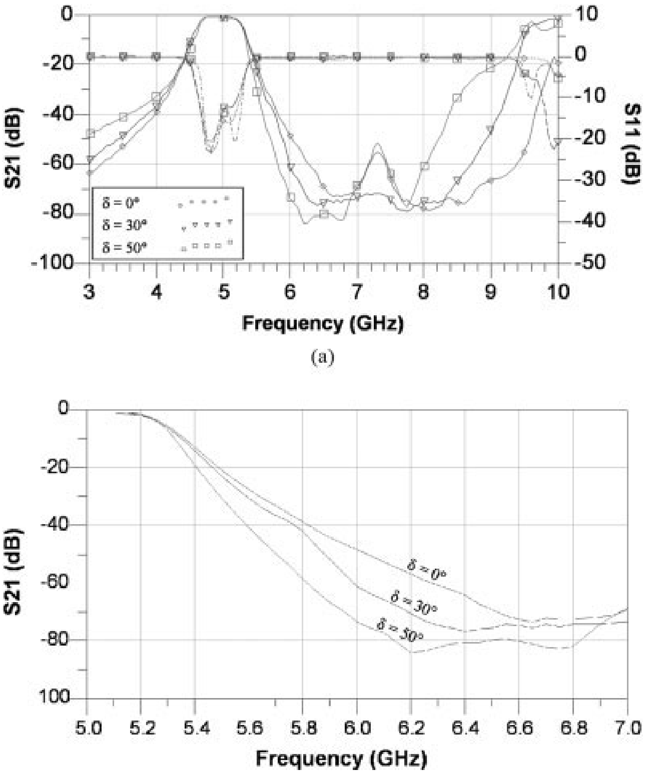


(a)

(b)

Figure 4 Momentum simulation results for $\delta = 0°, 30°, 50°$. Zoom in on rejection slope

TABLE 3 Summary of Measured and Simulated Rejection of Filters at (f_0 + 1) GHz

δ	Simulated Rejection (dBc)	Measured Rejection (dBc)
0°	45.9	45.7
30°	55.1	55.6
50°	73.4	68.9

with a lengthened or shortenedδ, the rejection slope at the upper frequency can be enhanced. A 4th order 10% FBW Chebyshev filter was designed at 5 GHz with additional rejection of 23 dB at 6 GHz. Since the overall filter resonator length remains unchanged, the improvement in performance does not compromise on circuit size.

REFERENCES

1. S.B. Cohn, Parallel-coupled transmission-line-resonator filters, IRE Trans Microwave Theory Tech MTT-6 (1958), 223-221.
2. M. Makimoto and S. Yamashita, Bandpass filters using parallel coupled stripline stepped impedance resonators, IEEE Trans Microwave Theory Tech MTT-28 (1980), 1413-1417.
3. J.-T. Kuo, S.-P. Chen, and M. Jiang, Parallel-coupled microstrip filters with over-coupled end stages for suppression of spurious responses, IEEE Microwave Wireless Compon Lett 13 (2003), 440-442.
4. C.-Y. Chang and T. Itoh, A modified parallel-coupled filter structure that improves the upper stopband rejection and response symmetry, IEEE Trans Microwave Theory Tech 39 (1991), 310-314.
5. J.S. Hong and M.J. Lancaster, Microstrip filters for RF/microwave applications, Wiley, New York, 2001.
6. M. Makimoto and S. Yamashita, Microwave resonators and filters for wireless communication, Springer, 2001.
7. D.M. Pozar, Microwave engineering, 3rd ed. New Wiley, Hoboken, NJ, 2003.

BANDWIDTH-ENHANCED INTERNAL PIFA WITH A COUPLING FEED FOR QUAD-BAND OPERATION IN THE MOBILE PHONE

Kin-Lu Wong and Chih-Hong Huang
Department of Electrical Engineering National Sun Yat-Sen University Kaohsiung 80424, Taiwan, Republic of China; Corresponding author: wongkl@ema.ee.nsysu.edu.tw

Received 11 August 2007

ABSTRACT: *A novel bandwidth-enhanced internal planar inverted-F antenna (PIFA) for quad-band operation in the mobile phone is presented. The proposed PIFA is capacitively excited using a coupling feed, which leads to a dual-resonance excitation in the antenna's lower band at about 900 MHz and a wide-band resonant mode excitation at about 1800 MHz. This makes the operating bandwidths of both the antenna's lower and upper bands larger than 20% (3:1 VSWR), thus easily covering GSM850/900 and DCS/PCS operation. In addition, with quad-band operation obtained, the proposed PIFA occupies a small volume of 5 × 6 × 60 mm³ or 1.8 cm³ only. Details of the proposed PIFA are described, and results of fabricated prototypes are presented and discussed.* © 2008 Wiley Periodicals, Inc. Microwave Opt Technol Lett 50: 683–687, 2008; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.23175

Key words: *internal mobile phone antennas; mobile antennas; PIFA; coupling feed; quad-band operation*

1. INTRODUCTION

Conventional PIFAs (planar inverted-F antennas) have been widely applied in the mobile phone as internal antennas for operating in the 900 and 1800 MHz bands [1]. However, owing to the limited available volume that can be allocated for the internal antenna inside the mobile phone, it is usually not an easy task to obtain multiband operation for the conventional PIFA, especially in the 900 MHz band to cover GSM850 (824–896 MHz) and GSM900 (880–960 MHz) operation. To achieve enhanced bandwidths for the internal PIFA, the technique of adding parasitic or direct-feed additional resonators to the main radiator to provide additional resonant modes has been applied [2-5]. This technique is especially suitable for increasing the bandwidth of the 1800 MHz band or the antenna's upper band, because the required length of the additional resonators is shorter for providing an additional resonant mode near 1800 MHz.

The use of an external matching circuitry has also been applied [6-9]. This technique is promising to enhance the bandwidth at either the 900 or 1800 MHz band or both the 900 and 1800 MHz bands. However, it will occupy some valuable board space on the system circuit board of the mobile phone and increase some insertion loss also. In this article, we present a novel bandwidth-enhanced internal PIFA using a coupling feed, which can be considered as an internal matching circuitry and will not increase the occupied volume of the antenna inside the mobile phone. With the coupling feed, the proposed PIFA can be excited to achieve a dual-resonance at about 900 MHz and a wide-band resonance at about 1800 MHz. This behavior makes the operating bandwidths of the antenna's lower and upper bands larger than 20% (3:1 VSWR), allowing the antenna to cover GSM850/900 and DCS/PCS (1710–1880/1920–2170 MHz) bands for quad-band operation. In addition, the proposed quad-band PIFA occupies a small volume of 1.8 cm^3 only inside the mobile phone. Design considerations of the proposed PIFA are described in the article. Exper-

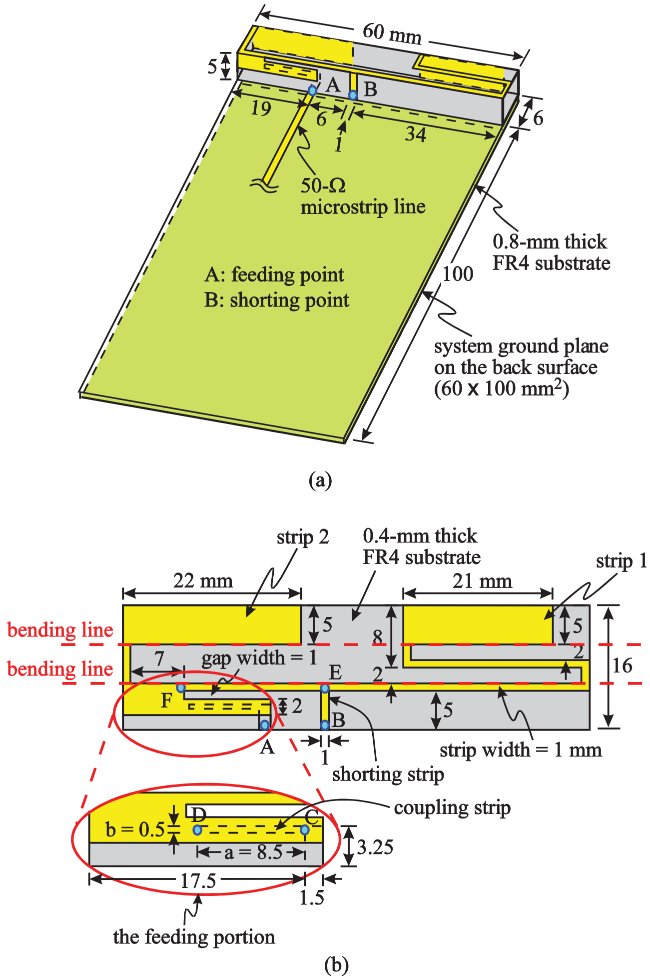


Figure 1 (a) Geometry of the proposed bandwidth-enhanced internal PIFA with a coupling feed for mobile phone application. (b) Dimensions of the proposed PIFA in its planar structure. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

imental and simulation results for fabricated prototypes of the proposed PIFA are presented and discussed.

2. DESIGN CONSIDERATIONS OF PROPOSED ANTENNA

Figure 1(a) shows the geometry of the proposed PIFA with a coupling feed for mobile phone application. The proposed PIFA occupies a small volume of $5 \times 6 \times 60$ mm^3 (1.8 cm^3) and is mounted at the top no-ground portion (size 6×60 mm^2) of the system circuit board of the mobile phone. In the study, a 0.8-mm thick FR4 substrate is used as the system circuit board; on its back surface, there is a printed system ground plane of length 100 and width 60 mm. The dimensions of the system circuit board and ground plane considered here are practical for general smart phones or personal digital assistant (PDA) phones available in the market. In the experiment, the proposed PIFA is fed at point A (the feeding point) using a 50-Ω microstrip line printed on the front surface of the system circuit board.

The dimensions of the proposed PIFA in its planar structure are shown in Figure 1(b). Similar to the conventional PIFA, the proposed PIFA mainly comprises a feeding portion, a shorting portion, and a radiating portion. However, instead of using a simple direct feed for the conventional PIFA, the feeding portion here consists of a coupling strip $\overline{CD}$ of length (a) 8.5 mm and width (b) 0.5 mm. This coupling strip, connected to the 50-Ω microstrip feedline through a short strip of length 3.25 mm, capacitively excites the proposed PIFA. This coupling feed incorporating the 5-mm long shorting strip $\overline{BD}$ forms as an LC internal matching circuitry (from the strip $\overline{CD}$ then through $\overline{FE}$ to $\overline{BE}$ point B is further connected to the top edge of the ground plane on the back surface of the circuit board (the via-hole through the circuit board not shown in the figure). By varying the parameters a and b of the coupling strip, the input impedance of the antenna can be adjusted. In the proposed PIFA here, the input reactance over the frequency range of interest (at about 900 MHz) can be decreased to a lower value, and an additional resonance (zero input reactance) can also be obtained. This can lead to a dual-resonance excitation at about 900 MHz for the antenna's lower band. At the same time, a wide-band resonance excitation at about 1800 MHz for the antenna's upper band can also be achieved. This behavior allows the proposed PIFA to easily cover GSM850/900/DCS/PCS quad-band operation. More detailed effects of the coupling feed will be discussed in the next section with the aid of Figures 3–5.

Also note that the proposed PIFA in the study is printed on a 0.4-mm thick FR4 substrate and then bent into an inverted-U shape to achieve a compact configuration. For practical applications, the proposed PIFA can be printed on a flexible printed circuit board (FPCB). In this case, smooth bending of the proposed PIFA can be obtained, which will make it more flexible to fit in inside the smooth casing of the modern mobile phones.

The radiating portion of the proposed PIFA is composed of two radiating strips of different lengths. Strip 1 starting from point E has a length of about 90 mm, close to about 0.25 wavelength at 900 MHz. This allows the excitation of a 0.25 wavelength mode at about 900 MHz for the proposed PIFA, which is further tuned to become a dual-resonance mode by using the proposed coupling feed. The dual-resonance excitation leads to bandwidth enhancement for the antenna's lower band to cover GSM850/900 operation. On the other hand, strip 2 starting from point F has a length of about 40 mm, which is close to about 0.25 wavelength at about 1800 MHz and allows the excitation of a wide-band resonance mode for the antenna's upper band to cover DCS/PCS operation. Note that both open-end portions of strips 1 and 2 are widened to have a width of 5 mm, which can lead to smooth excited surface current distributions at the strip's open ends and is helpful for achieving bandwidth enhancement for the excited resonant modes [10, 11].

3. RESULTS AND DISCUSSION

The proposed PIFA was fabricated and studied. Figure 2 shows the measured and simulated return loss for the proposed PIFA.

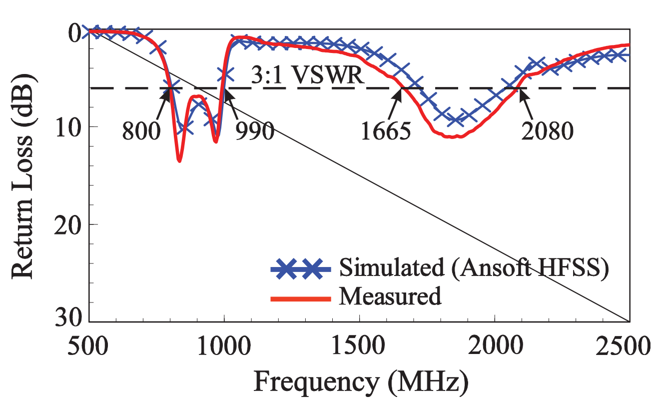


Figure 2 Measured and simulated return loss for the proposed PIFA. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

The simulated results are obtained using Ansoft simulation software high frequency structure simulator (HFSS) [12], and agreement between the simulation and measurement is obtained. Dual-resonance excitation at about 900 MHz is clearly seen, and a wide impedance bandwidth, defined by 3:1 VSWR or 6-dB return loss, of 190 MHz (800–990 MHz) is achieved. This wide bandwidth reaches about 21% with respect to 900 MHz and allows the antenna's lower band to easily cover GSM850/900 operation. For the antenna's upper band, a wide resonant mode centered at about 1800 MHz is excited. The obtained bandwidth reaches 415 MHz (1665–2080 MHz) or about 23% with respect to 1800 MHz, allowing the antenna to cover DCS/PCS operation.

To show the effect of the coupling feed used here, Figure 3 shows the comparison of the simulated return loss of the proposed PIFA and the reference antenna (the corresponding conventional PIFA with a simple feeding strip). The dimensions of the reference antenna are shown in the inset in Figure 3, which uses a direct feed and has the same antenna volume as that of the proposed PIFA. Note that the dimensions of the reference antenna are adjusted to achieve optimal impedance bandwidths of the lower and upper bands. From the obtained results as shown in the figure, the lower band of the reference antenna can cover GSM 900 operation only. Conversely, the proposed PIFA has a bandwidth-enhanced lower band, allowing it to cover GSM850/900 operation. For the upper band, both the reference antenna and the proposed PIFA have a wide bandwidth to cover DCS/PCS operation.

Figure 4 shows the simulated input impedance versus frequency and the simulated input impedance on the Smith chart for the reference antenna in Figure 3 and the proposed PIFA. In the figure, only the results for the antenna's lower band are shown. In Figure 4(a), the input reactance of the proposed PIFA is smaller than that of the reference antenna. The variations of the input reactance are also seen to be much smaller for the proposed PIFA than for the reference antenna. In addition, an additional resonance (zero input reactance) is occurred at about 840 MHz, which leads to a dual-resonance excitation for the antenna's lower band as seen in Figure 2. In Figure 4(b), the impedance curves for the frequency range of 700–1100 MHz are shown, and the frequency intervals between markers of the impedance curves are 60 MHz. It is seen that with the presence of the coupling feed (the proposed PIFA), the loop of the impedance curve is shifted inside the 3:1 VSWR circle, making the bandwidth enhanced from 70 MHz for the reference antenna to be 190 MHz for the proposed PIFA.

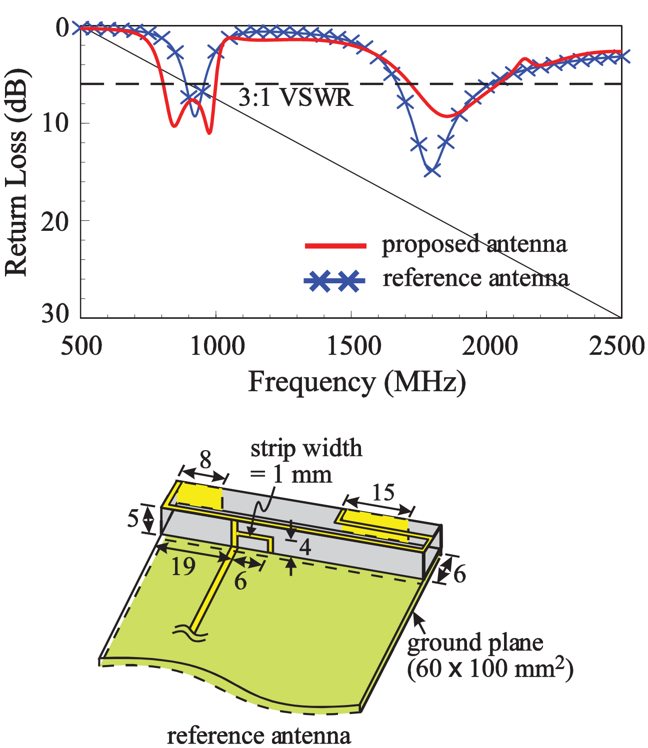
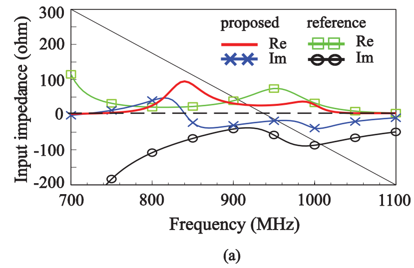


Figure 3 Comparison of the simulated return loss of the proposed PIFA and the reference antenna (the corresponding conventional PIFA with a simple feeding strip). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]



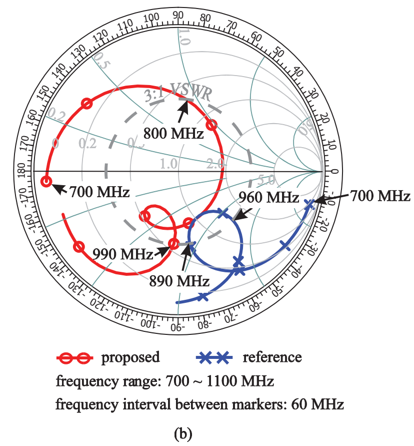
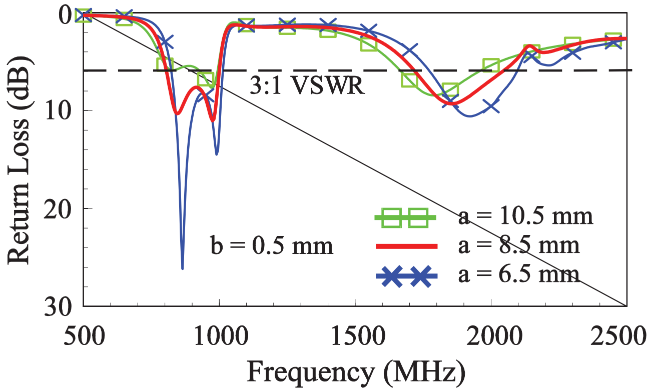


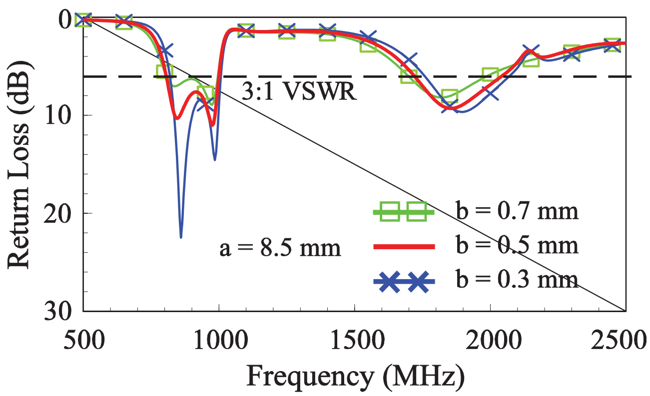
Figure 4 (a) Simulated input impedance versus frequency and (b) simulated input impedance on the Smith chart for the reference antenna in Figure 3 and the proposed PIFA. Only the results for the lower band of the antenna are shown. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

Effects of the parameters *a* and *b* of the coupling strip on the antenna performances are studied in Figure 5. Figure 5(a) shows the simulated return loss for the length *a* varied from 6.5 to 10.5 mm, while the width *b* is fixed to be 0.5 mm. Results indicate that dual-resonance excitation for the antenna's lower band can be obtained for different values of *a*. The antenna's upper band will also be affected by the variation in the length *a*. A longer length *a* can shift the upper band to lower frequencies. Figure 5(b) shows the simulated return loss for the width *b* varied from 0.3 to 0.7 mm, with the length *a* fixed as 8.5 mm. Similar effects as seen in Figure 5(a) are obtained. A larger width *b* will also shift the upper band to lower frequencies. Hence, by properly selecting the length *a* and width *b* of the coupling strip, dual-resonance excitation at about 900 MHz can be obtained for GSM850/900 operation, and a wide-band resonant mode can also be adjusted to occur at about 1800 MHz for covering DCS/PCS operation.

Radiation patterns of the proposed PIFA are also studied. Figures 6–9 plot the measured radiation patterns at 860, 925, 1795, and 1920 MHz, respectively. These frequencies are the central frequencies of



(a)



(b)

Figure 5 Simulated return loss as a function of (a) the length *a* and (b) the width *b* of the coupling strip in the coupling feed. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

GSM850, GSM900, DCS, and PCS bands. Results at other frequencies were also measured. Over each operating band, very similar measured radiation patterns as shown here are obtained, indicating that stable radiation patterns are achieved over GSM850, GSM900, DCS, and PCS bands. The radiation patterns shown in Figures 6 and 7 are also very similar to each other, and omnidirectional radiation in the *x-y* plane (azimuthal plane) is obtained, which is similar to that of the conventional PIFA [1]. The radiation patterns at 1795 and 1920 MHz are also similar to each other, which is expected since the antenna's upper band is formed by a single wide-band resonant mode. The obtained radiation patterns also show no special distinctions compared to those of the conventional PIFA for DCS or PCS operation [1]. The measured antenna gain and simulated radiation efficiency for the proposed PIFA are presented in Figure 10. Over the GSM850/900 operating bands shown in Figure 10(a), the antenna gain is varied from about 1.0 to 1.9 dBi, and the radiation efficiency is all larger than 65%. For the DCS/PCS operating bands, the results in Figure 10(b) indicate that the antenna gain is varied from 1.4 to 2.0 dBi, and the radiation efficiency is also larger than 65%. The obtained radiation characteristics are good for practical applications in the mobile phones.

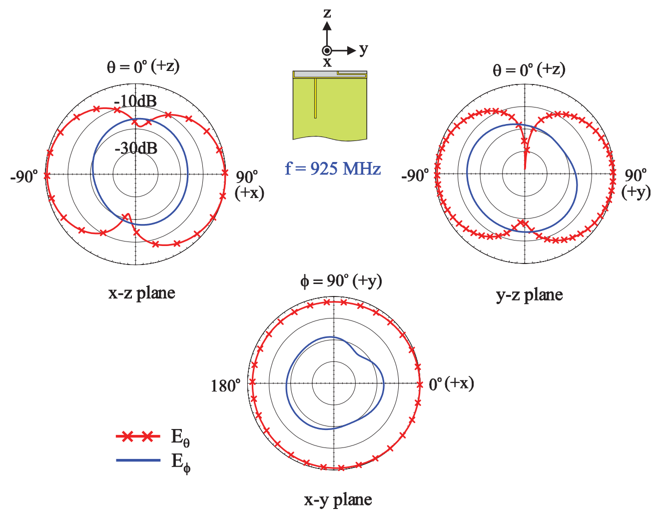


Figure 7 Measured radiation patterns at 925 MHz for the proposed PIFA. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

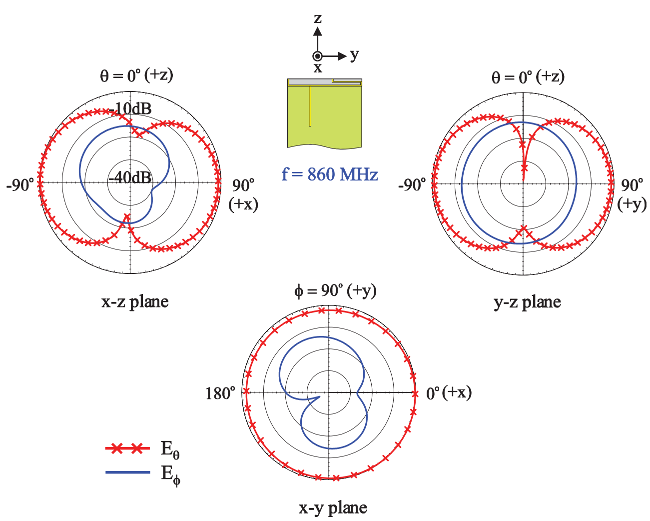


Figure 6 Measured radiation patterns at 860 MHz for the proposed PIFA. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

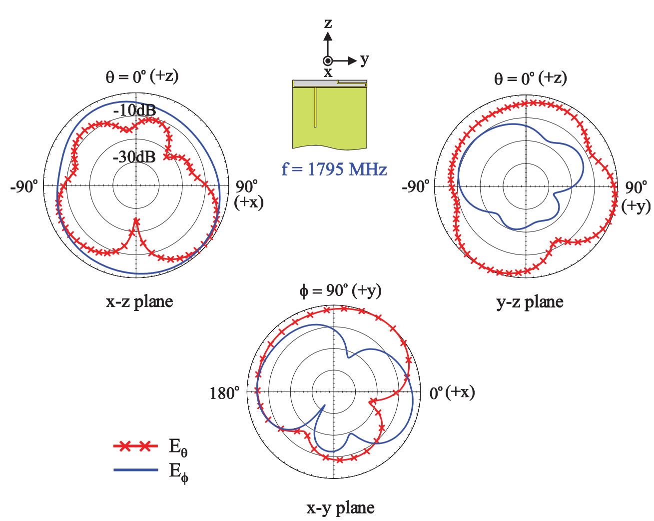


Figure 8 Measured radiation patterns at 1795 MHz for the proposed PIFA. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

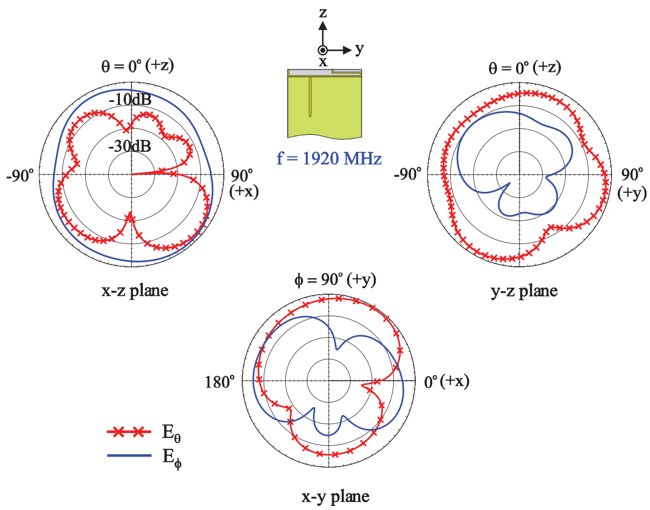


Figure 9 Measured radiation patterns at 1920 MHz for the proposed PIFA. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

4. CONCLUSION

A novel internal PIFA with a coupling feed for quad-band operation in the mobile phone has been proposed. Compared to the conventional PIFA with a simple direct feed, the coupling feed used in the proposed PIFA does not increase the volume of the antenna. This novel coupling feed can lead to a dual-resonance excitation at about 900 MHz for the antenna's lower band and a wide-band resonant mode excitation at about 1800 MHz for the antenna's upper band. Both the obtained bandwidths for the lower and upper bands of the proposed PIFA are larger than 20%, which makes it easily cover GSM850/900/DCS/PCS quad-band operation. Good radiation characteristics over the operating bands have also been obtained. Since the occupied volume of the proposed quad-band PIFA is 1.8 cm^3 only and it is also easy to be fabricated on a dielectric substrate, especially on a flexible printed circuit board, at low cost, the proposed PIFA is very promising for practical applications as a compact quad-band internal mobile phone antenna.

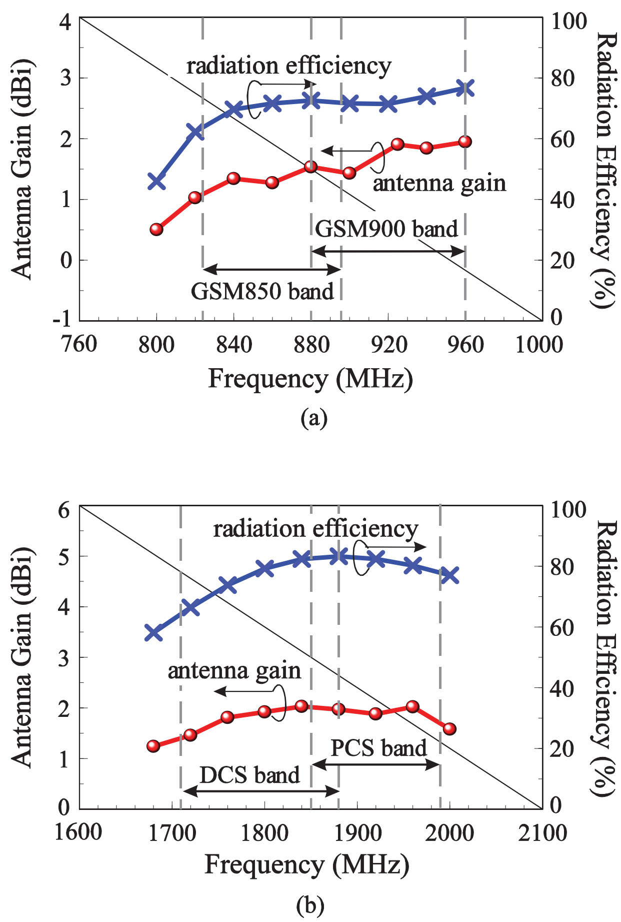


Figure 10 Measured antenna gain and simulated radiation efficiency for the proposed PIFA. (a) The lower band for GSM850/900 operation. (b) The upper band for DCS/PCS operation. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

REFERENCES

1. K.L. Wong, Planar antennas for wireless communications, Wiley, New York, 2003.
2. J. Ollikainen and A. Lehtola, Internal multi-band antenna with improved radiation efficiency, U.S. Patent No. 6,552,686 B2, April 22, 2003.
3. K.L. Wong, L.C. Chou, and C.M. Su, Dual-band flat-plate antenna with a shorted parasitic element for laptop applications, IEEE Trans Antennas Propag 53 (2005), 539-544.
4. Y.X. Guo, M.Y.W. Chia, and Z.N. Chen, Miniature built-in multiband antennas for mobile handsets, IEEE Trans Antennas Propag 52 (2004), 1936-1944.
5. K.L. Wong and Y.C. Lin, Thin internal planar antenna for GSM/DCS/PCS/ UMTS operation in a PDA phone, Microwave Opt Technol Lett 47 (2005), 429-432.
6. J. Ollikainen, O. Kivekas, C. Ichein, and P. Vainikainen, Internal multiband handset antenna realized with an integrated matching circuit, In: Proceedings of the 12th International Conference on Antennas and Prpagation, Vol. 2, 2003, pp. 629–632.
7. K.R. Boyle, M. Udink, A. de Graauw, and L.P. Ligthart, A novel dual-fed, self-diplexing PIFA and RF front-end (PIN-DF2-PIFA), In: IEEE Antennas and Propagation International Symposium Digest, Monterey, CA, Vol. 2, 2004, pp. 1935–1938.
8. M. Tzortzakakis and R.J. Langley, Quad-band internal mobile phone antenna, IEEE Trans Antennas Propag 55 (2007), 2097-2103.
9. J. Villanen, C. Icheln, and P. Vainikainen, A coupling element-based quad-band antenna element structure for mobile terminals, Microwave Opt Technol Lett 49 (2007), 1277-1282.
10. 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 51 (2003), 2187-2192.
11. K.L. Wong, Y.C. Lin, and T. C. Tseng, Thin internal GSM/DCS patch antenna for a portable mobile terminal, IEEE Trans Antennas Propag 54 (2006), 238-242.
12. Ansoft Corporation HFSS. http://www.ansoft.com/products/hf/hfss/.