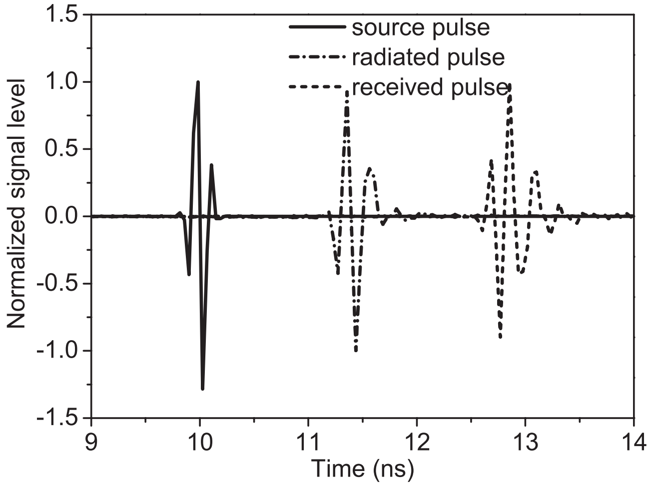


**Figure 7** The pulse waveforms in single band schemer

MHz. The excited voltage at the transmitting antenna is a series of modulated Gaussian pulses as defined in Eq. (3).

$$v_t(t) = \sum_{n=0}^{14} \sin[(2\pi(3.35 \times 10^9 + n \times 0.5 \times 10^9))t]\exp\left[-\left(\frac{t - 10(n+1)}{\sigma}\right)^2\right] \quad (3)$$

The received waveform in multiband schemer for head to head scenarios is shown in Figure 8.

It is clearly observed that the envelope of the envelope received pulses correspond well to the shapes of $S_{21}$ showed in Figure 2. The envelope of the received pulses in the first eleven sub-bands is relative flat. The last four pulses, spectral of which occupied 8.6–10.6 GHz band, may not be detected properly due to the low received power. With flat amplitude of $S_{21}$, the received signals in all the sub-bands can be detected well. In contrast, the uneven $S_{21}$ will lead to unequal amplitude of received pulses, thus results in different signal to noise ratio in the sub-bands [4]. So the double printed UWB dipole antenna is suitable to 3.1–8.6 GHz UWB application.

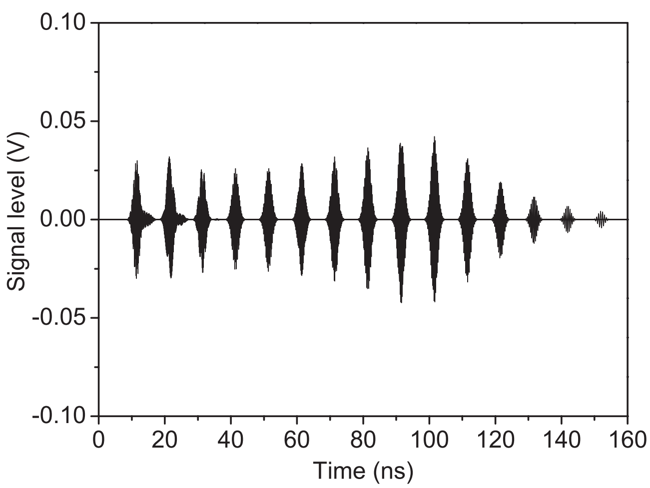


**Figure 8** The received waveforms in multiband schemer

## 4. CONCLUSION

Characteristics of a double printed UWB dipole antenna with U-shaped arms have been studied by using transfer functions experimentally and numerically. Flat amplitude and linear phase responses are observed from the transmitting antenna transfer function over the frequency range from 3.1 to 8.6 GHz. Impulse responses for both single band and multiband schemers are obtained based on the frequency domain results. The double printed UWB dipole antenna is suitable to 3.1–8.6 GHz UWB applications.

## REFERENCES


1. Y.-M. Lu, X.-X. Yang, and G.-X. Zheng, Analysis on a novel ultra-wide bandwidth antenna of double-printed circular disc, Microwave Opt Technol Lett 49 (2007), 311–313.
2. J.P. Young and J.H. Song, Development of ultra wideband planar stepped-fat dipole antenna, Microwave Opt Technol Lett 48 (2006), 1698–1701.
3. J. Sheng, X.X. Yang, J.T. Sun, and Y.M. Lu, Double-printed circular disc antenna having a frequency band notch function, development of ultra wideband planar stepped-fat dipole antenna, Microwave Opt Technol Lett 49 (2007), 2675–2677.
4. J.X. Xiao, X.X. Yang, G.P. Gao, and J.S. Zhang, Double-printed U-shape ultra-wideband dipole antenna, J Electromagn Waves Appl 22 (2008), 1148–1154.
5. X.H. Wu, Z.N. Chen, and N. Yang, Optimization of planar diamond antenna for single-band and multiband uwb wireless communications, Microwave Opt Technol Lett 42 (2004), 451–455.
6. X.M. Qing and Z.N. Chen, Characterization of ultra wideband antennas using transfer functions, Radio sci 41 (2006), Rs1002.
7. Y. Duroc, A. Ghiotto, T.P. Vuong, and S. Tedjini, UWB Antennas: Systems with transfer function and impulse response, IEEE Trans Antenn Propag 55 (2007), 1449–1451.




# PRINTED PIFA WITH A COPLANAR COUPLING FEED FOR PENTA-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; Corresponding author: wongkl@ema.ee.nsysu.edu.tw


*Received 4 April 2008*


**ABSTRACT:** *A printed planar inverted-F antenna (PIFA) with a novel coplanar coupling feed for GSM850/900/1800/1900/UMTS penta-band operation in the mobile phone is presented. The proposed PIFA is printed on one surface of the system circuit board of the mobile phone with an occupied area of 10 × 60 mm$^2$ only, making it promising for practical applications. In addition, the PIFA is easily fabricated at low cost and can be bent by half, such that it occupies a small volume of 5 × 5 × 60 mm$^3$ or 1.5 cm$^3$ inside the mobile phone. The coplanar coupling feed allows the PIFA to generate two wide operating bands for covering GSM850/900 and GSM1800/1900/UMTS operations, respectively. Detailed effects of the coplanar coupling feed on the performances of the proposed PIFA are studied.* © 2008 Wiley Periodicals, Inc. Microwave Opt Technol Lett 50: 3181–3186, 2008; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.23906


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

## 1. INTRODUCTION

For enhancing the operating bandwidth of the internal mobile phone antenna such as the planar inverted-F antennas (PIFAs) [1] for operating in the 900 and 1800 MHz bands, the techniques of adding an external matching circuit [2–6] or additional resonators [7–10] have been commonly applied. With the use of the external matching circuit [2–6], however, additional ohmic loss usually occurs, which will lead to some decrease in radiation efficiency of the antenna. The matching circuit will also occupy some valuable board space on the system circuit board. On the other hand, adding additional resonators [7–10] usually complicate the antenna structure and increase the occupied volume, especially for enhancing the operating bandwidth in the 900 MHz band to cover GSM850 (824∼894 MHz) and GSM900 (880∼960 MHz) operations.

Recently, it has been demonstrated that by using a coupling feed as an internal and integral part of the antenna [11], bandwidth enhancement of the 900 and 1800 MHz bands for covering GSM850/900 and GSM1800/1900 (1710∼1880/1850∼1990 MHz), respectively, can be achieved. This technique of using a coupling feed requires the two coupling sections of the coupling feed to be printed on two opposite surfaces of the dielectric substrate, hence very accurate alignment of the two coupling strips is required. To ease the problem, we report in this article a printed PIFA with a coplanar coupling feed, different from the coupling feed in Ref. 11, to provide two wide operating bands for covering GSM850/900 and GSM1800/1900/UMTS (1710∼1880/1850∼1990/1920∼2170 MHz) in the mobile phone for penta-band operation [12]. With the use of the coplanar coupling feed, its two coupling sections can be easily printed on the same surface of the dielectric substrate or the system circuit board. In addition, the total area of the proposed printed PIFA is as small as 10 × 60 mm$^2$ only, making it promising for practical applications. The proposed PIFA can also be bent by half, resulting in an occupied volume of 5 × 5 × 60 mm$^3$ or 1.5 cm$^3$ inside the mobile phone. Detailed design considerations of the proposed PIFA are described in the article. Effects of the coplanar coupling feed on enhancing the operating bandwidths of the PIFA for GSM850/900/1800/1900/UMTS penta-band operation are studied. The proposed PIFA is also fabricated and tested, and the obtained results are presented.

## 2. PROPOSED PRINTED PIFA WITH A COPLANAR COUPLING FEED

Figure 1(a) shows the geometry of the proposed printed PIFA with a coplanar coupling feed for GSM850/900/1800/1900/UMTS operation in the mobile phone. Dimensions of the proposed PIFA in its planar structure are given in Figure 1(b). A 0.8-mm thick FR4 substrate of length 110 mm and width 60 mm is used as the system circuit board of the mobile phone in this study. On the back surface of the circuit board, there is a printed system ground plane of length 100 mm and width 60 mm, leaving a no-ground region of 10 × 60 mm$^2$ at the top of the system circuit board. The proposed PIFA is printed on the no-ground region and then bent by half by following the bending line shown in Figure 1(b) to achieve a compact occupied volume of 5 × 5 × 60 mm$^3$ inside the mobile phone. Also, note that the dimensions of the system circuit board and ground plane studied here are practical for general smart phones or PDA (personal digital assistant) phones [13, 14].

The PIFA comprises two radiating strips (Strips 1 and 2), an inverted-L shorting strip and a coplanar coupling feed. Strip 1 starting from point G supports a resonant path to generate a wide operating band at about 1900 MHz for the antenna's upper band to cover GSM1800/1900/UMTS operation. Strip 2 starting from point G supports a longer resonant path for providing a wide operating band at about 900 MHz for the antenna's lower band to

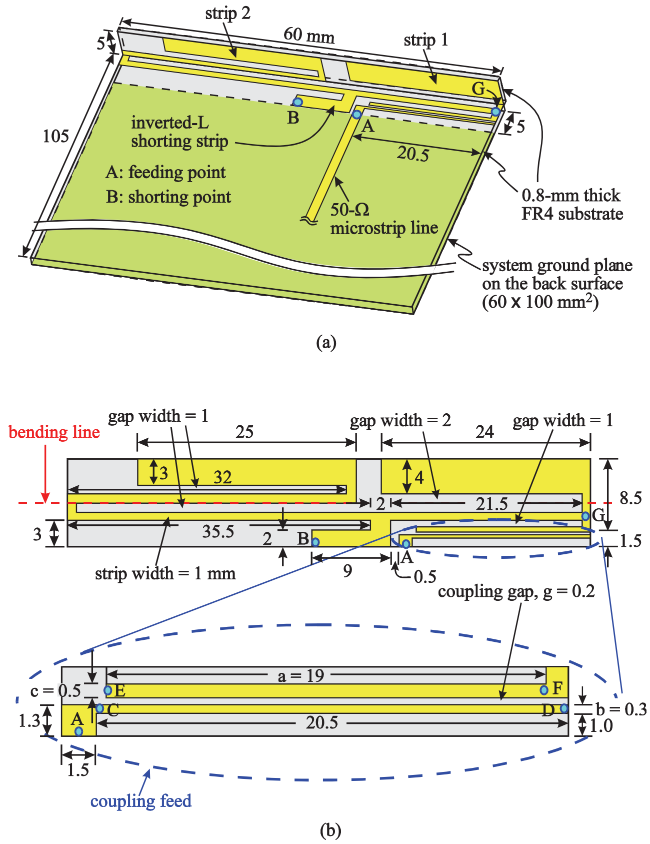


**Figure 1** (a) Geometry of the proposed printed PIFA with a coplanar coupling feed for GSM850/900/1800/1900/UMTS operation in the mobile phone. (b) Dimensions of the proposed PIFA in its planar structure. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

cover GSM850/900 operation. The inverted-L shorting strip short circuits the two radiating strips to the system ground plane through a via-hole at point B. This short circuiting is the same as that used in the conventional PIFAs to allow good excitation of quarter-wavelength resonant modes. Both the two radiating strips of Strips 1 and 2 have a widened end portion (4 mm for Strip 1 and 3 mm for Strip 2), which can achieve a more uniform excited surface current distribution on the radiating strips and is helpful in improving the impedance matching of the proposed PIFA [15, 16]. However, it should be noted that the wide operating bandwidths of the two excited resonant modes at about 900 and 1900 MHz supported by Strips 2 and 1, respectively, cannot be effectively achieved without the use of the coplanar coupling feed in this study.

In between point G and A is the coplanar coupling feed, which mainly consists of two coupling sections of CD and EF . Point A is the feeding point of the PIFA and is connected to a printed 50-Ω microstrip feedline for testing the PIFA in the experiment. The two coupling sections are spaced with a coupling gap $g$ of 0.2 mm. The length of the coupling section CD is fixed as 20.5 mm, and its width $b$ is 0.3 mm. For the coupling section EF, its length $a$ is 19 mm, and its width $c$ is 0.5 mm. By adjusting the dimensions $a$, $b$, $c$, and $g$ in the coplanar coupling feed, the contributed capacitance to the antenna's input impedance can be effectively controlled. With proper dimensions selected for the coplanar coupling feed, a dual-resonance excitation for the antenna's lower band at about 900 MHz and a wide operating band for the upper band at about 1900 MHz can be achieved, allowing the proposed PIFA to cover

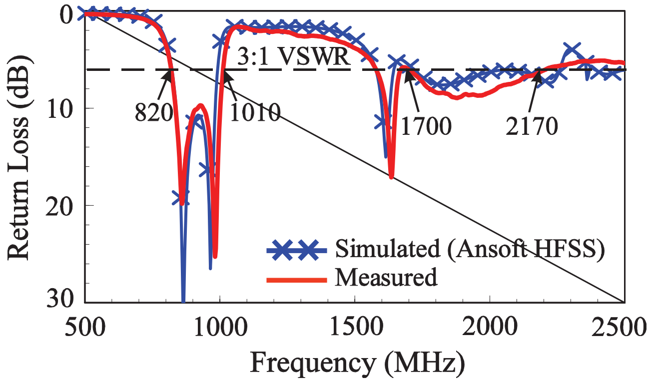


**Figure 2** Measured and simulated return loss for the proposed PIFA. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

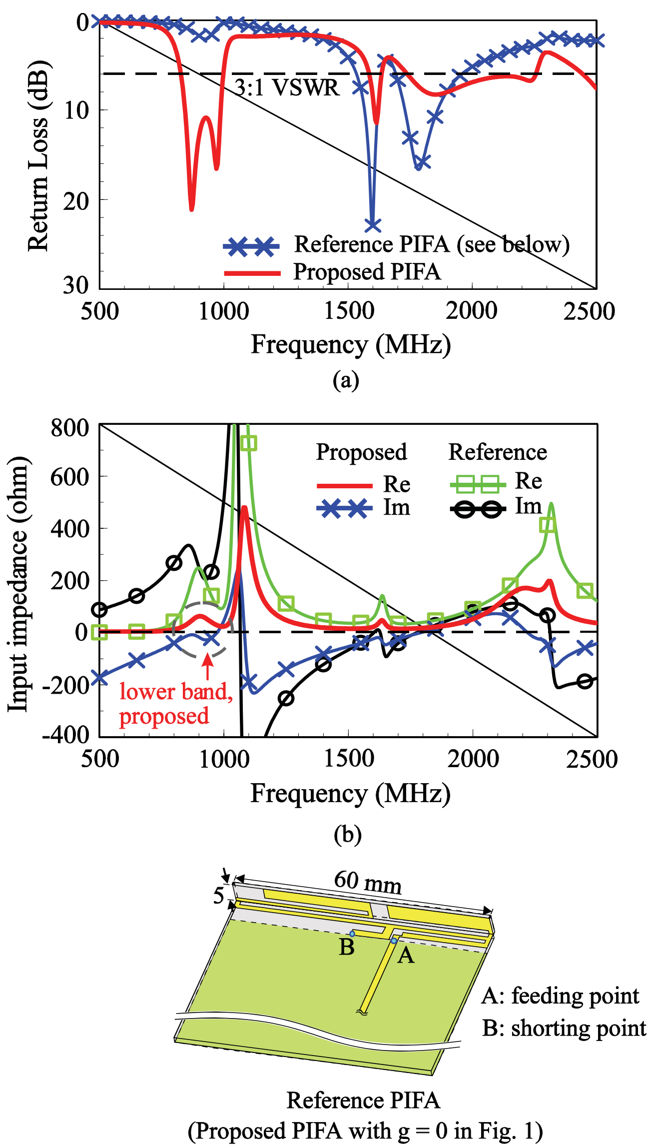


**Figure 3** Comparison of the simulated (a) return loss and (b) input impedance of the proposed PIFA and the reference PIFA (the proposed PIFA with $g = 0$ in Fig. 1; that is, a direct feed is used). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

GSM850/900/1800/1900/UMTS operation. Detailed effects of the parameters *a, b, c,* and *g* in the coplanar coupling feed are studied in Figures 4 and 5 in the next section.

## 3. RESULTS AND DISCUSSION

The proposed PIFA was fabricated and tested. Figure 2 shows the measured and simulated return loss for the fabricated prototype. Two wide operating bands at about 900 and 1900 MHz are excited with good impedance matching. The measured data agree with the simulation results obtained using Ansoft HFSS (High-Frequency Structure Simulator) [17]. For the lower band at about 900 MHz, a dual-resonance excitation is seen and the impedance bandwidth defined by 3:1 VSWR reaches 190 MHz (820∼1010 MHz), which easily covers GSM850/900 operation. The upper band at about 1900 MHz shows a much larger bandwidth of 470 MHz (1700∼2170 MHz), wide enough for covering GSM1800/1900/UMTS operation. Also, note that the resonant mode seen at about 1.65 GHz, although with good impedance matching, is a spurious resonant mode, which shows poor radiation efficiency and cannot be applied for practical applications. This spurious resonant mode will disappear when the PIFA is unbent into a planar structure (results are discussed in Fig. 6).

Figure 3 shows a comparison of the simulated return loss and input impedance of the proposed PIFA and the reference PIFA (the proposed PIFA with $g = 0$ in Fig. 1; that is, a direct feed is used). In Figure 3(a), it is clearly seen that without the use of the coplanar

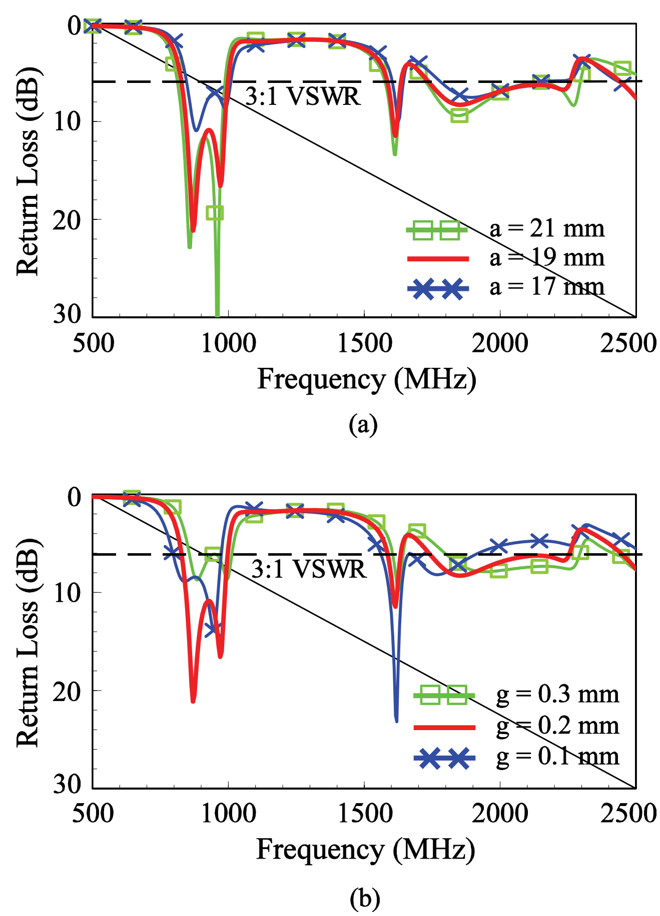


**Figure 4** Simulated return loss as a function of (a) the length *a* and (b) the coupling-gap width *g* in the coupling feed. Other dimensions are the same as given in Figure 1. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

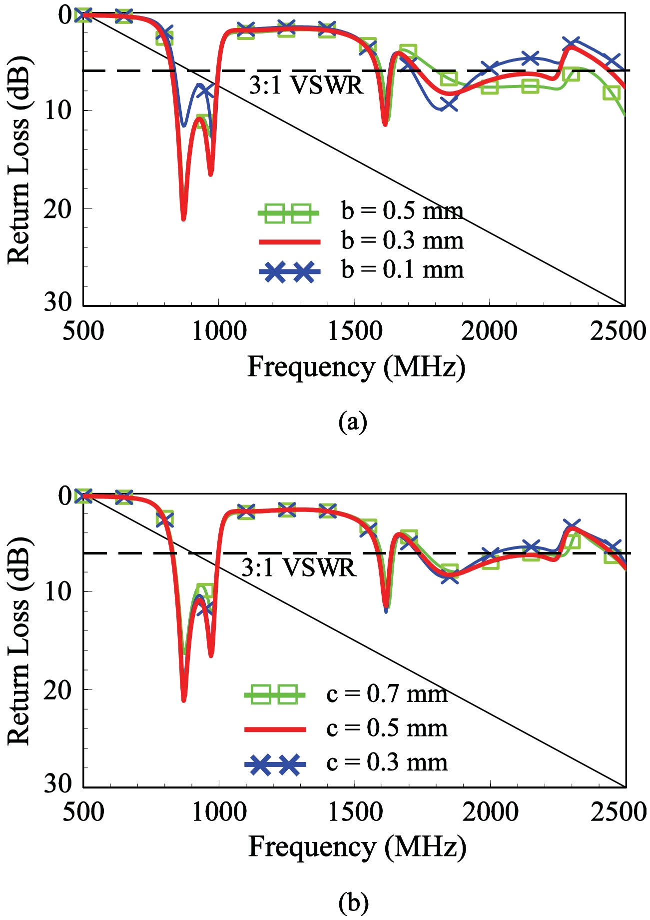


**Figure 5** Simulated return loss as a function of (a) the width *b* of the coupling section CD and (b) the width *c* of the coupling section EF in the coupling feed. Other dimensions are the same as given in Figure 1. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

coupling feed, the impedance matching becomes very poor for the lower band at about 900 MHz for the reference PIFA. A much smaller bandwidth is also obtained for the upper band for the reference PIFA than for the proposed PIFA. From the input impedance seen in Figure 3(b), the real (Re) and imaginary (Im) parts of the input impedance are greatly lowered for the proposed PIFA compared with the reference PIFA, especially for the desired lower band at about 900 MHz. This behavior is mainly owing to the use of the coupling feed in the proposed PIFA.

Effects of the length *a* and the coupling-gap width *g* in the coupling feed are studied in Figure 4. The results for the length *a* varied from 21 to 17 mm are presented in Figure 4(a); other dimensions are the same as given in Figure 1. By adjusting the length *a* of the coupling section EF, good impedance matching of the dual-resonance excitation for the lower band at about 900 MHz to achieve a wide bandwidth can be achieved. For the upper band, however, the length *a* shows a relatively smaller effect. In Figure 4(b), the results for the coupling-gap width *g* varied from 0.3 to 0.1 mm are shown, and other dimensions are the same as given in Figure 1. In this case, strong effects on the antenna's lower and upper bands are seen, indicating that the width *g* should be very carefully selected for the coupling feed in the proposed PIFA.

Figure 5 shows the effects of the width *b* of the coupling section CD and the width *c* of the coupling section EF in the coupling feed. Results of the width *b* varied from 0.5 to 0.1 mm are

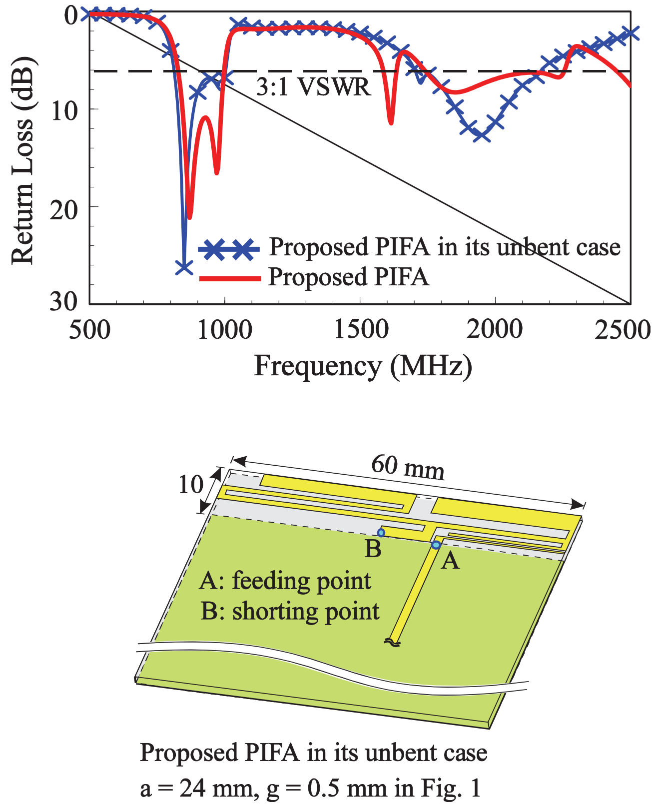


**Figure 6** Comparison of the simulated return loss of the proposed PIFA and its unbent case. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

presented in Figure 5(a). In this case, relatively larger effects on the antenna's upper band are seen. For the lower band, the effects are small, and good impedance matching can also be obtained for various widths of *b*. In Figure 5(b), results for the width *c* varied from 0.7 to 0.3 mm are presented. In this case, small effects on both the lower and upper bands are seen. From the results in Figures 5(b) and 4(a), it can be concluded that for the coupling section EF , it is more effective in adjusting its length *a* than its width *c* in achieving good impedance matching for frequencies over for the two desired lower and upper bands of the proposed PIFA.

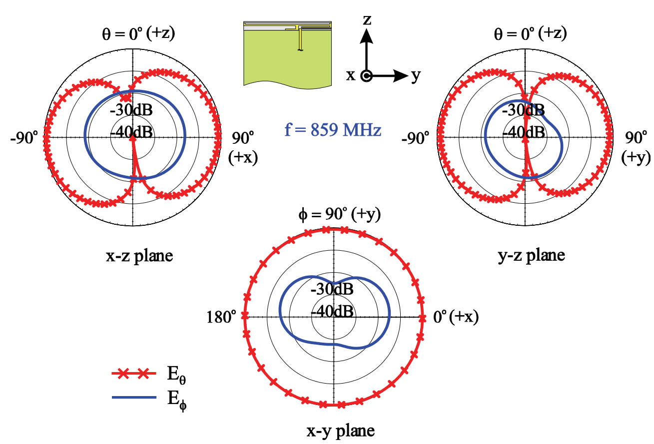


**Figure 7** Measured radiation patterns at 859 MHz for the proposed PIFA. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

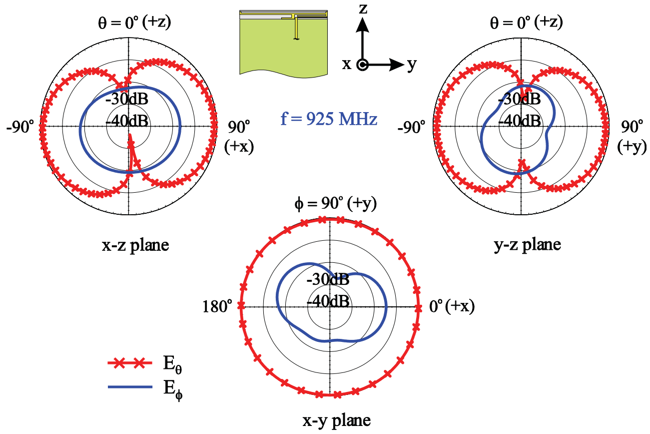


**Figure 8** Measured radiation patterns at 925 MHz for the proposed PIFA. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

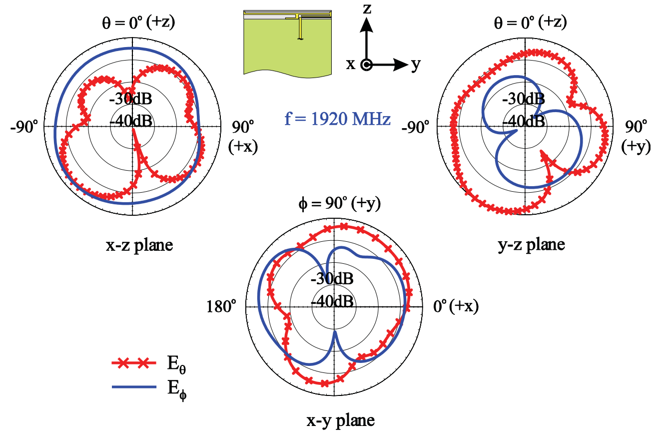


**Figure 10** Measured radiation patterns at 1920 MHz for the proposed PIFA. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

Figure 6 shows a comparison of the simulated return loss of the proposed PIFA and its unbent case. It can be seen that the spurious resonant mode at about 1.65 GHz is disappeared for the unbent case. Also, note that all the dimensions of the two cases are the same, except for the two dimensions *a* and *g,* which are adjusted to be 24 and 0.5 mm for the unbent case. From the results, the obtained bandwidths for the proposed PIFA in its unbent case can still cover GSM850/900/1800/1900/UMTS penta-band operation.

Radiation characteristics of the proposed PIFA studied in Figure 2 are also studied. Figures 7 and 8 plot the measured radiation patterns at 859 and 925 MHz and center frequencies of the GSM850 and GSM900 bands. Monopole-like radiation patterns are seen, and good omnidirectional radiation in the azimuthal plane (*x*–*y* plane) is obtained. Measured radiation patterns at 1795, 1920, and 2045 MHz, center frequencies of the GSM1800, GSM1900, and UMTS bands are also plotted in Figures 9, 10, and 11, respectively. Although more variations in the radiation patterns when compared with those at 859 and 925 MHz are seen, similar patterns at 1795, 1920, and 2045 MHz are obtained. This indicates that stable radiation patterns are obtained over the upper bands for GSM1800/1900/UMTS operation. The obtained radiation patterns also show no special distinctions to those of the conventional PIFA with a direct feed [1] and are suitable for practical applications. Figure 12 shows the measured antenna gain and simulated radiation efficiency for the proposed PIFA. In Figure 12(a), results over the lower band for GSM850/900 operation are presented. The antenna gain varies from about 0.2 to 1.9 dBi, whereas the radiation efficiency ranges from about 55 to 80%. Over the upper band for GSM1800/1900/UMTS operation shown in Figure 12(b), the antenna gain varies from about 1.5 to 2.7 dBi. Larger antenna gain is obtained, which is mainly owing to the relatively larger variations in the radiation patterns over the upper band. For the radiation efficiency, it is varied from about 52 to 73% and is good for practical applications.

## 4. CONCLUSION

A GSM850/900/1800/1900/UMTS printed PIFA with a coplanar coupling feed for application as an internal mobile phone antenna has been proposed, fabricated, and tested. The proposed PIFA is suitable to be directly printed on one surface of the system circuit board of the mobile phone, making it easy to fabricate at low cost. The printed PIFA can further be bent by half to achieve a compact volume of $5 \times 5 \times 60$ mm$^3$ or 1.5 cm$^3$ only inside the mobile phone. By using the coplanar coupling feed in place of the conventional direct feed, the proposed PIFA can provide two wide operating bands at about 900 and 1900 MHz to cover GSM850/

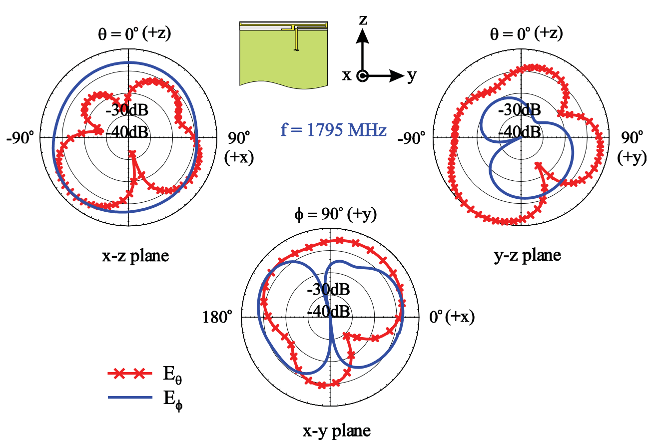


**Figure 9** Measured radiation patterns at 1795 MHz for the proposed PIFA. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

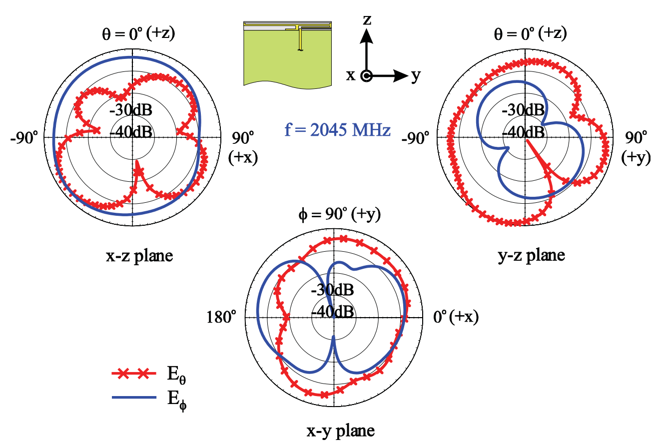


**Figure 11** Measured radiation patterns at 2045 MHz for the proposed PIFA. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

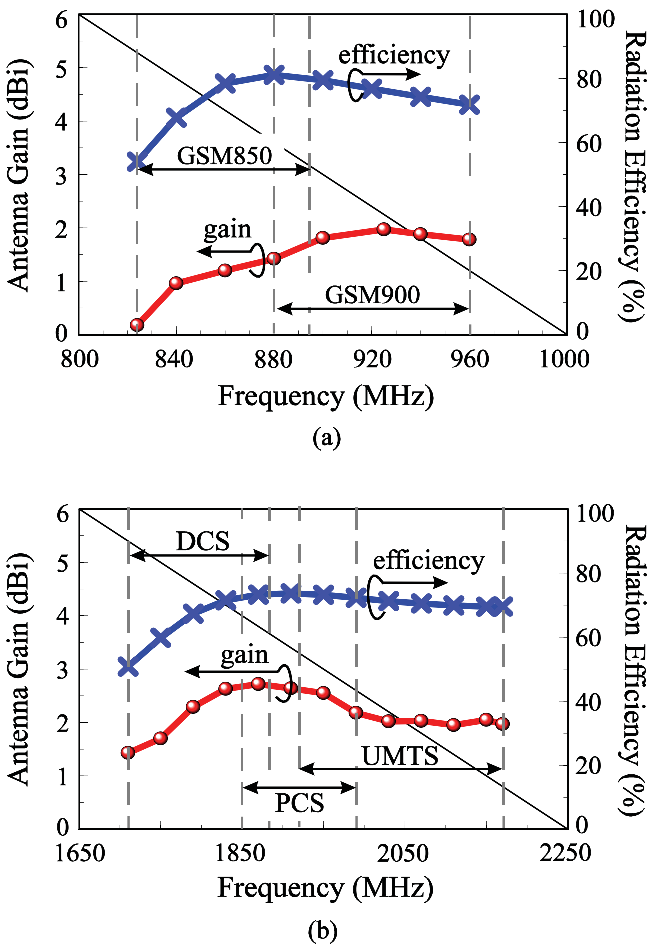


**Figure 12** Measured antenna gain and simulated radiation efficiency for the proposed PIFA. (a) The lower band for GSM850/900 operation. (b) The upper band for GSM1800/1900/UMTS operation. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

900 and GSM1800/1900/UMTS operations, respectively. Good radiation characteristics for frequencies over the operating bands have also been obtained. Detailed effects of the coplanar coupling feed on the antenna performances have also been analyzed.

**REFERENCES**


1. K.L. Wong, Planar antennas for wireless communications, Wiley, New York, 2003.
2. T. Oshiyama, H. Mizuno, and Y. Suzuki, Multi-band antenna, U.S. Pat Publ No. 2007/0249313 (2007).
3. J. Ollikainen, O. Kivekas, C. Ichein, and P. Vainikainen, Internal multiband handset antenna realized with an integrated matching circuit, Proc 12th Int Conf Antennas Propagat 2 (2003), 629–632.
4. M. Tzortzakakis and R.J. Langley, Quad-band internal mobile phone antenna, IEEE Trans Antennas Propagat 55 (2007), 2097–2103.
5. J. Villanen and P. Vainikainen, Optimum dual-resonant impedance matching of coupling element based mobile terminal antenna structures, Microwave Opt Technol Lett 49 (2007), 2472–2477.
6. 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.
7. 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 Propagat 53 (2005), 539–544.
8. J. Ollikainen and A. Lehtola, Internal multi-band antenna with improved radiation efficiency, U.S. Pat No. 6,552,686 B2 (2003).
9. Y.X. Guo, M.Y.W. Chia, and Z.N. Chen, Miniature built-in multiband antennas for mobile handsets, IEEE Trans Antennas Propagat 52 (2004), 1936–1944.
10. 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.
11. K.L. Wong and C.H. Huang, Bandwidth-enhanced PIFA with a coupling feed for quad-band operation in the mobile phone, Microwave Opt Technol Lett 50 (2008), 683–687.
12. C.I. Lin and K.L. Wong, Printed monopole slot antenna for internal multiband mobile phone antenna, IEEE Trans Antennas Propagat 55 (2007), 3690–3697.
13. K.L. Wong, Y.C. Lin, and T.C. Tseng, Thin internal GSM/DCS patch antenna for a portable mobile terminal, IEEE Trans Antennas Propagat 54 (2006), 238–242.
14. K.L. Wong and C.H. Chang, Surface-mountable EMC monopole chip antenna for WLAN operation, IEEE Trans Antennas Propagat 54 (2006), 1100–1104.
15. K.L. Wong, Y.C. Lin, and B. Chen, Internal patch antenna with a thin air-layer substrate for GSM/DCS operation in a PDA phone, IEEE Trans Antennas Propagat 55 (2007), 1165–1172.
16. 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 Propagat 51 (2003), 2187–2192.
17. Available at: http://www.ansoft.com/products/hf/hfss/, Ansoft Corporation HFSS, 2008.




# A HIGHER-ORDER OPTICAL TRANSFORMATION FOR NONMAGNETIC CLOAKING

**Ilaria Gallina, Giuseppe Castaldi, and Vincenzo Galdi**
Waves Group, Department of Engineering, University of Sannio, I-82100 Benevento, Italy; Corresponding author: vgaldi@unisannio.it

*Received 4 April 2008*

**ABSTRACT:** *In coordinate-transformation-based approaches to electromagnetic concealment ("cloaking") of objects, use of higher-order (quadratic) mappings has been proposed as an effective device to obtain satisfactory responses without the use of magnetic materials that are complicated to synthesize at optical frequencies. In this article, we explore a new higher-order algebraic transformation, which allows, in principle, for a broader range of applicability and further parametric optimization. Via full-wave numerical studies of near- and far-field observables, we assess its performance by comparison with various reference cases (nonreduced parameters, quadratic transformation, no cloak).* © 2008 Wiley Periodicals, Inc. Microwave Opt Technol Lett 50: 3186–3190, 2008; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.23905

**Key words:** *electromagnetic cloaking; transformation optics; metamaterials; scattering*

## 1. INTRODUCTION

During the past few years, transformation optics [1–3] has emerged as one among the most promising and active fields in optical and materials engineering, with the perspective of offering unprecedented control in the electromagnetic (EM) response of devices and components. Among the most exciting developments, besides the celebrated "invisibility cloaking" [4], it is worth mentioning "wormholes" [5], concentrators [6, 7], rotators [8], directive radiators [9], and optical devices [10–13].