higher harmonic suppressions with less number of periodic structures compared to the conventional DGS filter.

3. EXPERIMENT AND RESULTS

To validate the proposed low pass filter, it was simulated and fabricated in the Taconic TLC with a relative permittivity $e_r = 3.2$ and a thickness $h = 0.787$ mm. Figure 8(a) shows the photograph of the proposed low pass filter with compact size of 25 ′ 40 mm^2. The measured results have shown a good agreement with the theoretical results. The experiment results demonstrate that the fabricated LPF has a 3 dB cut off frequency at 4.5 GHz and there is a shift of cutoff frequency of about 50 MHz. The insertion loss is low dB at the passband when measured and its stopband is well suppressed below 32-dB from 5.2 to 10 GHz.

4. CONCLUSIONS

In this article, a novel compact microstrip low pass filter using elliptic DGS cells is presented. The novel H shape open stub increases the equivalent parallel capacitance to improve the outband suppression. An equivalent circuit model was given to depict the novel DGS filter. The proposed structure with main dimension parameters was analyzed as a design guide to fabricate the filter. The measurement results have shown good agreement with the theoretical results. The cutoff frequency response is sharp and insertion loss is low with stopband from 5.17 to 10 GHz, which was suppressed more than 32 dB.

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GSM850/900/1800/1900/UMTS COUPLED-FED PLANAR λ/8-PIFA FOR INTERNAL MOBILE PHONE ANTENNA

Chih-Hua Chang and Kin-Lu Wong
Department of Electrical Engineering, National Sun Yat-Sen University, Kaohsiung 804, Taiwan; Corresponding author: changch@ema.ee.nsysu.edu.tw or d953010014@student.nsysu.edu.tw

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ABSTRACT: *A coupled-fed planar PIFA (planar inverted-F antenna) operated in its one-eighth wavelength (λ/8) mode, different from the traditional one-quarter wavelength (λ/4) mode, as the fundamental mode for mobile phone application is presented. The proposed PIFA comprises two radiating strips, both of slightly different lengths and close to about λ/8 at 900 MHz. By incorporating the use of the coupling feed, a wide operating band formed by the two λ/8 modes is excited at about 900 MHz for the antenna to cover GSM850/900 operation. Two λ/4 modes are also generated at close frequencies to from a wide operating band centered at about 1950 MHz to cover GSM1800/1900/UMTS operation. The proposed antenna hence can cover GSM850/900/1800/1900/UMTS penta-band operation for application in the mobile phone. In addition, the antenna has a simple structure and can be printed on a thin FR4 substrate of size* $1.6 \times 7 \times 40$ mm^3 *as a surface-mountable chip antenna. Details of the proposed antenna are presented and discussed.* © 2009 Wiley Periodicals, Inc. Microwave Opt Technol Lett 51: 1091–1096, 2009; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.24214

Key words: *internal mobile phone antennas; PIFA (planar inverted-F antennas); printed antennas; λ/8-PIFA; coupled-fed*

1. INTRODUCTION

Recently, it has been demonstrated that by using a coupling feed to replace the direct contact feed for the traditional PIFA (planar inverted-F antenna), embedded in the mobile phone for WWAN (wireless wide area network) communication, dual-resonance excitation in the antenna's quarter-wavelength (λ/4) mode can be achieved to form a wide operating band to cover GSM850/900 (824–894/890–960 MHz) operation [1]. This coupling-feed technique compensates for the large inductive reactance of the antenna's input impedance and leads to the occurrence of additional resonance (zero reactance) in the 900 MHz band. A wide operating band of larger than 140 MHz is hence easily achieved for the PIFA to cover GSM850/900 operation. The coupling-feed design can be considered as an internal matching circuit [2–5], which requires no additional board space on the system circuit board of the mobile phone and is hence advantageous over the use of the external matching circuits [6–9] to achieve improved impedance matching of the antenna.

Another attractive feature of the coupling feed in the PIFA for mobile phone application has also been reported [10], in which the one-eighth wavelength (λ/8) mode of the PIFA is successfully excited. In this case, the large inductive reactance of the input impedance seen at the λ/8 mode of the PIFA is effectively compensated. In addition, the large resistance of the input impedance is also decreased owing to the use of the coupling feed. Hence, a new resonant mode with its resonant length close to about λ/8 at 900 MHz is generated. The successful excitation of this new λ/8 mode allows the required resonant length of the PIFA for operating in the 900 MHz band greatly decreased; this can lead to a compact volume occupied by the PIFA inside the mobile phone to operate as an internal antenna. However, the obtained operating bandwidth is limited and can cover either GSM900 or GSM850 only. For promising applications in the general mobile phones, how to achieve a much wider bandwidth in the λ/8 mode at 900 MHz to cover both GSM850/900 operation is still an important design issue for this kind of coupled-fed PIFA.

In this article, we present a new promising coupled-fed PIFA operated at its λ/8 modes and capable of providing two wide operating bands at about 900 and 1950 MHz for covering GSM850/900 and GSM1800/1900/UMTS (1710–1880/1850–1990/1920–2170 MHz) operation, respectively. The proposed PIFA consists of two resonant strips of slightly different lengths, both close to about λ/8 at 900 MHz and excited by a common coupling feed. The antenna's lower band at about 900 MHz is formed by two λ/8 resonant modes contributed by the two resonant strips of the PIFA. In addition, two λ/4 resonant modes are also generated by the two resonant strips to form a wide operating band centered at about 1950 MHz. The two wide operating bands together cover GSM850/900/1800/1900/UMTS operation for WWAN communication. Further, the proposed PIFA shows a planar configuration, different from those studied in Refs. 1, 10, and can easily be printed on a thin FR4 substrate to operate as a surface-mountable chip antenna. Detailed design considerations of the proposed PIFA are described, and the experimental and simulation results are presented and discussed.

2. DESIGN CONSIDERATIONS OF PROPOSED λ/8-PIFA

Figure 1(a) shows the geometry of the GSM850/900/1800/1900/UMTS coupled-fed λ/8-PIFA for mobile phone application. The proposed λ/8-PIFA has a planar configuration and is printed on a 1.6-mm thick FR4 substrate of length 40 mm and width 7 mm in this study. Detailed dimensions of the metal pattern on the front side and back side of the FR4 substrate are shown in Figure 1(b). The proposed PIFA is suitable to operate as a surface-mountable chip antenna as shown in the figure. The PIFA is mounted at the top edge of the system circuit board of the mobile phone, with a distance of 7.4 mm to the top edge of the system ground plane printed on the back side of the circuit board. The PIFA is then short-circuited through a printed narrow (1 mm) strip $\overline{BD}$ of length 7.4 mm to the ground plane and excited through a 1.5-mm wide connecting strip $\overline{AC}$ of length 9 mm by a 50-Ω microstrip line printed on the front side of the circuit board. Note that the circuit board (a 0.8-mm thick FR4 substrate used in this study) has a length of 109 mm and a width of 40 mm, which are reasonable dimensions for general mobile phones. For the ground plane of length 100 mm and width 40 mm, it is also reasonable for general mobile phones. The no-ground region between the proposed PIFA and the ground plane can also be used for accommodating some associated electronic components such as the speaker [11–13] or the lens of the embedded digital camera [14, 15], and so on. There is also an inverted-L shorting strip in the proposed PIFA, which is similar to that in the conventional PIFAs [16].

As shown in Figure 1(b), the proposed PIFA mainly consists of two radiating strips of slightly different lengths excited by a common coupling feed. Strip 1 (section HF) and Strip 2 (section HG) have a narrow width of 0.5 mm and are of length 36 and 30.5 mm, respectively. Note that the lengths of Strip 1 and Strip 2 are both close to λ/8 at 900 MHz only. Owing to the use of the coupling feed, both Strip 1 and Strip 2 can generate λ/8 resonant modes at about 900 MHz. The two λ/8 modes are excited at close frequencies and can be formed into a wide operating band to cover GSM850/900 operation. In addition, Strip 1 and Strip 2 can also provide two λ/4 modes at close frequencies near 1950 MHz to form a wide operating band to cover GSM1800/1900/UMTS operation.

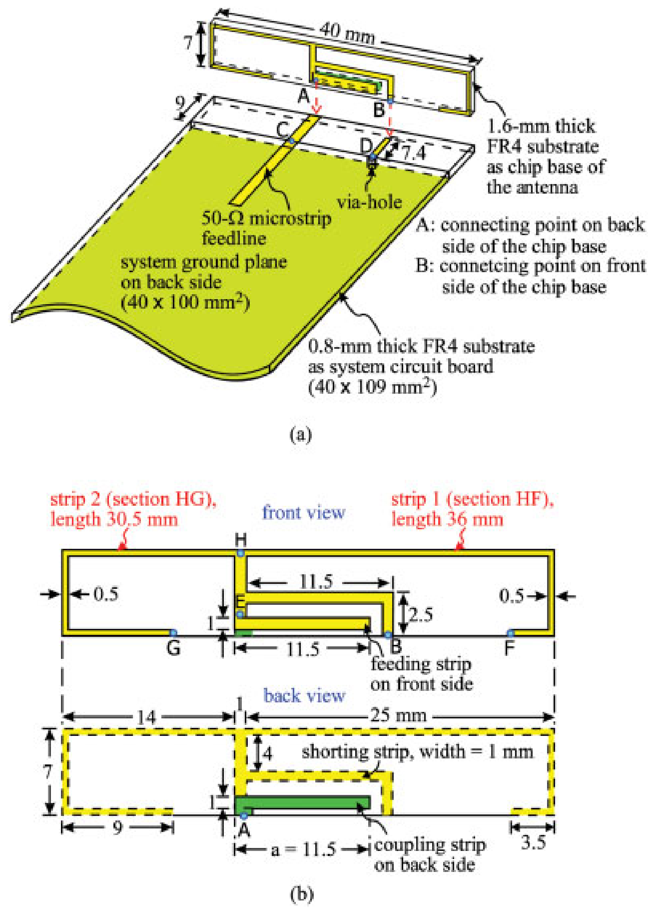


Figure 1 (a) Geometry of the GSM850/900/1800/1900/UMTS coupled-fed planar λ/8-PIFA for mobile phone application. (b) Dimensions of the metal-pattern on the front side and back side of the proposed PIFA. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

Note that the coupling feed comprises a coupling strip printed on the back side and a feeding strip on the front side of the 1.6-mm thick FR4 substrate. The coupling strip of length 11.5 mm (a) is connected to the connecting strip $\overline{AC}$ and then to 50-Ω microstrip line, whereas the feeding strip of length 11.5 mm (fixed in this study) is connected to the two radiating strips through a short strip of section HE. Hence, in between the coupling strip and feeding strip, a distributed capacitance is provided. By varying the length a of the coupling strip, the capacitance contributed by the coupling feed to the antenna's input impedance can be adjusted. Thus, fine tuning on the impedance matching of the frequencies over the two desired wide operating bands can be obtained by varying the length a (11.5 mm here) of the coupling strip in the coupling feed. Detailed effects of the length a on the impedance matching of the proposed PIFA are discussed in Figure 6 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. Good agreement between the measured data and the simulated results obtained using Ansoft HFSS (High Frequency Structure Simulator) [17] is seen. A wide lower band at about 900 MHz is

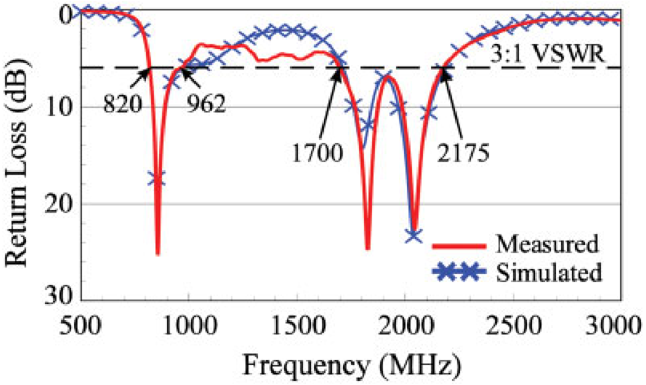


Figure 2 Measured and simulated return loss for the proposed PIFA. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

obtained. The impedance bandwidth defined by 3:1 VSWR, which is generally accepted for practical mobile phone antenna designs, for the lower band is 142 MHz (820–962 MHz). The bandwidth is large enough for GSM850/900 operation. For the upper band, a wide operating band is also obtained. The bandwidth reaches 475 MHz (1700–2175 MHz), which is large enough for GSM1800/1900/UMTS operation. The obtained lower and upper bands allow the proposed PIFA for GSM850/900/1800/1900/UMTS penta-band operation.

To show clearly the effects of the two radiating strips in the proposed design, Figure 3 shows the simulated return loss for the proposed PIFA and the two cases with Strip 1 only or Strip 2 only. The case with Strip 1 only generates two resonant modes (one λ/8 mode and one λ/4 mode) at about 1000 and 1800 MHz, and the case with Strip 2 also generates two resonant modes (one λ/8 mode and one λ/4 mode) at about 960 and 2000 MHz. It is then clearly seen that the two λ/8 modes are formed into a wide operating band for the antenna's lower band to cover GSM850/900 operation, whereas the two λ/4 modes are also formed into a wide operating band for the antenna's upper band to cover GSM1800/1900/UMTS operation.

Figure 4 shows the comparison of the simulated return loss of the proposed PIFA and the reference PIFA (the corresponding design with a direct contact feed). Note that the length of the inverted-L shorting strip in the reference PIFA is adjusted to achieve optimal impedance matching of the excited resonant

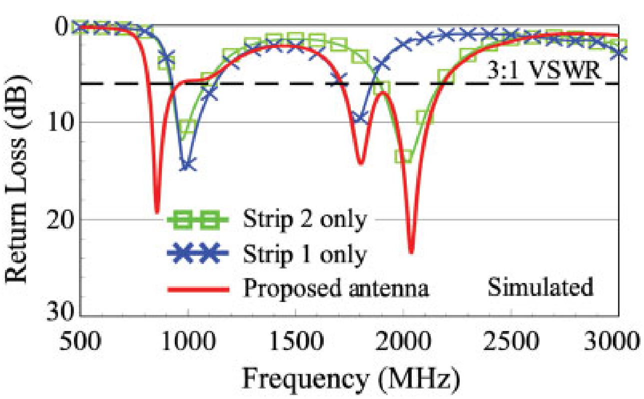


Figure 3 Simulated return loss for the proposed PIFA and the two cases with Strip 1 only or Strip 2 only. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

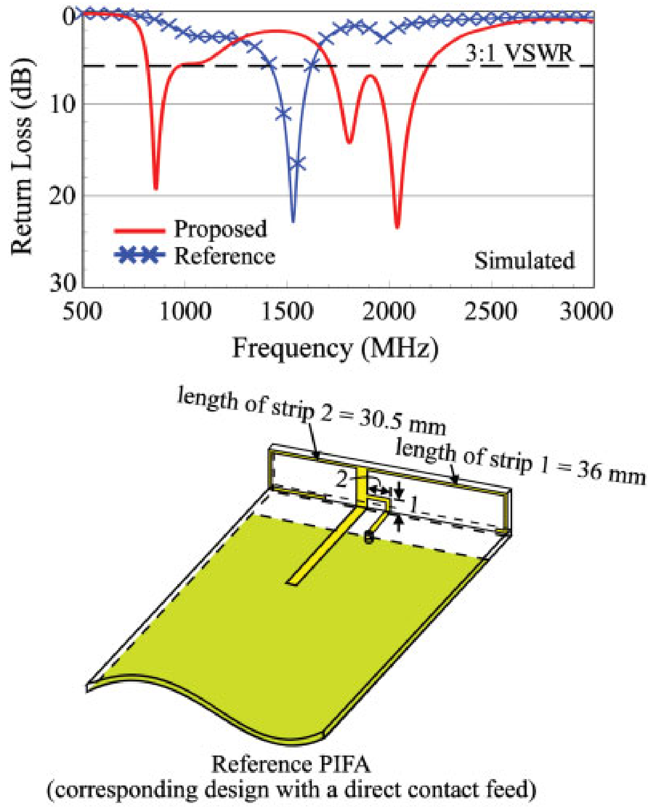


Figure 4 Comparison of the simulated return loss of the proposed PIFA and the reference PIFA (the corresponding design with a direct contact feed). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

mode; in this case, the excited mode is a λ/4 mode and occurs at about 1500 MHz as shown in the figure. From the comparison, it is seen that the fundamental (lowest) resonant mode of the proposed PIFA indeed has a much lower resonant frequency than that of the corresponding conventional PIFA. This behavior makes the proposed PIFA promising to have a much compact structure than the conventional PIFA for WWAN communication in the mobile phone. In addition, the obtained bandwidths of the proposed PIFA

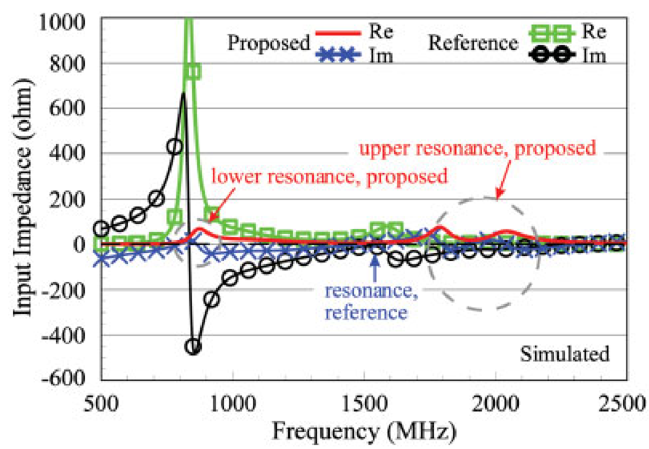


Figure 5 Simulated input impedance versus frequency for the proposed PIFA and the reference PIFA studied in Figure 4. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

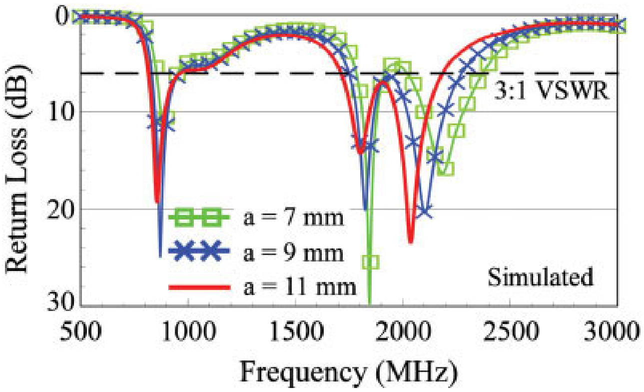


Figure 6 Simulated return loss as a function of the length *a* of the coupling strip in the coupling feed. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

are wide enough to cover the five operating bands for WWAN communication.

To demonstrate more clearly how the λ/8 and λ/4 modes are excited for the proposed PIFA, Figure 5 shows the comparison of the simulated input impedance versus frequency for the proposed PIFA and the reference PIFA studied in Figure 4. With the presence of the coupling feed, the input impedance at about 900 MHz for the proposed PIFA is much smaller than that of the reference or conventional PIFA. Around 900 MHz, the inductive reactance is greatly lowered to be less than 100 Ω, whereas the peak resistance is also decreased to be close to 50 Ω. This condition allows the proposed PIFA to have its λ/8 mode excited with good impedance matching (see the lower resonance indicated in the figure). With the λ/8 mode excited, its higher-order mode (λ/4 mode) is also excited at around 1900 MHz to provide a wide operating band for the antenna's upper band (see the upper resonance indicated in the figure).

Effects of varying the length *a* of the coupling strip in the coupling feed are studied in Figure 6. Results for the length *a* varied from 7 to 11 mm are presented. The two λ/8 modes at about 900 MHz or two λ/4 modes at about 1900 MHz are seen to be affected by the length *a*. By selecting a proper length of the coupling strip, good impedance of the frequencies over the desired lower and upper bands of the antenna can be obtained.

Radiation characteristics of the proposed PIFA are studied in Figures 7 and 8. The measured radiation patterns at 859 and 925 MHz, center frequencies of GSM850 and GSM900 bands, are plotted in Figure 7. Monopole-like radiation patterns with omni-

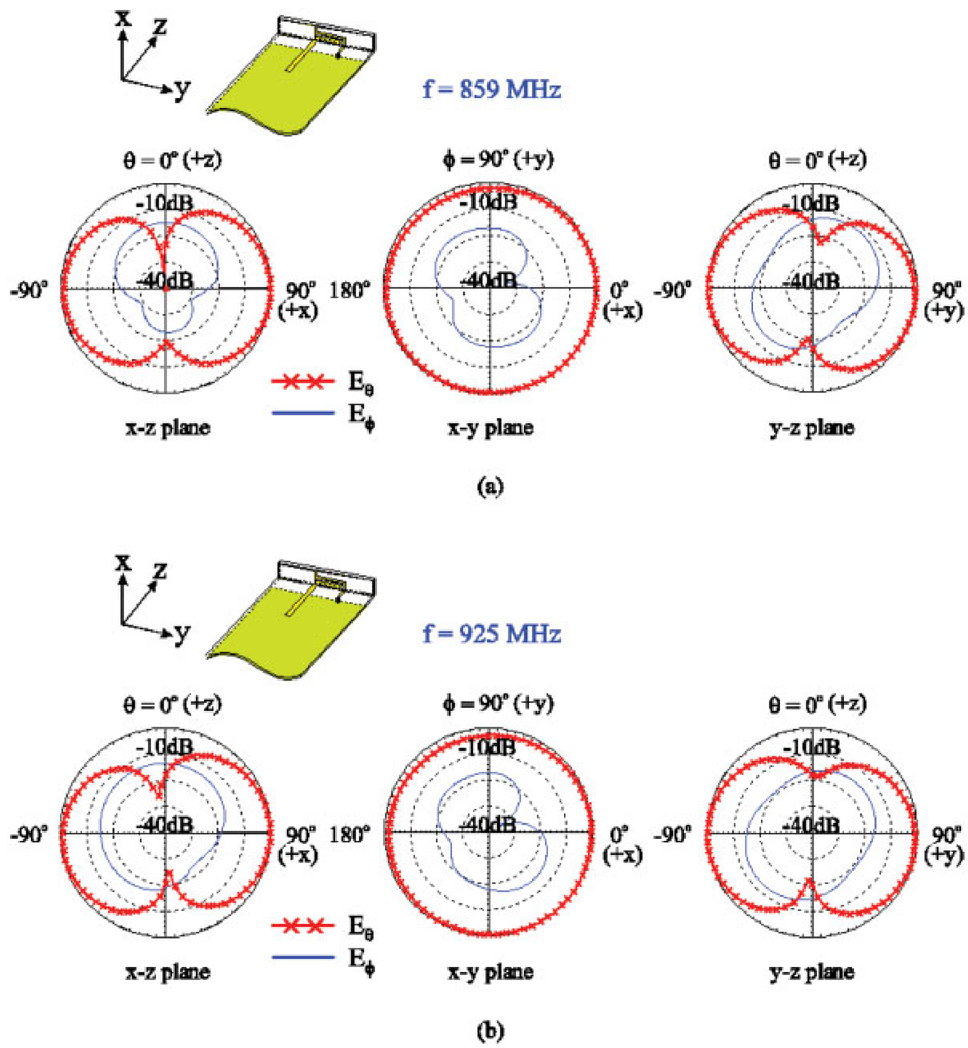


Figure 7 Measured radiation patterns at (a) 859 MHz and (b) 925 MHz for the proposed PIFA. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

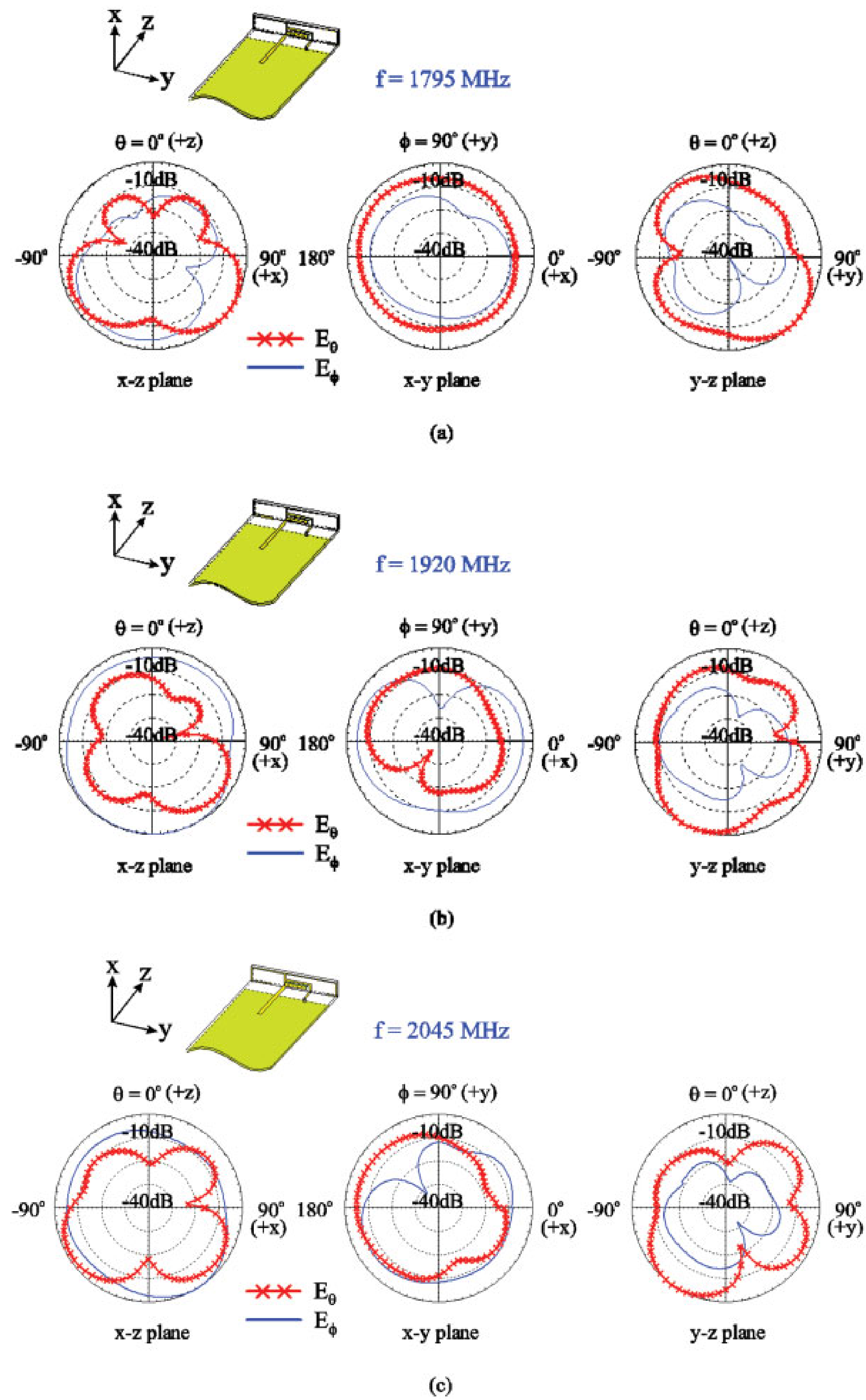
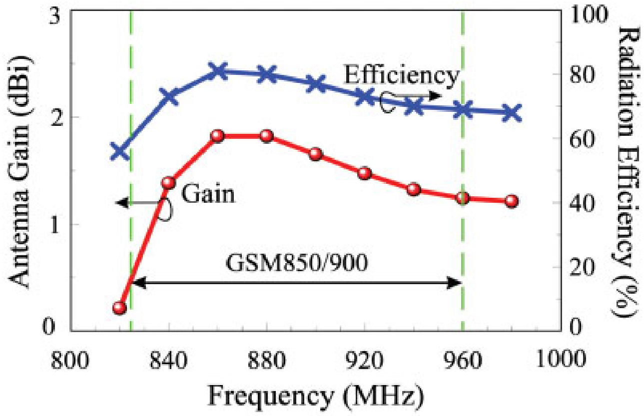


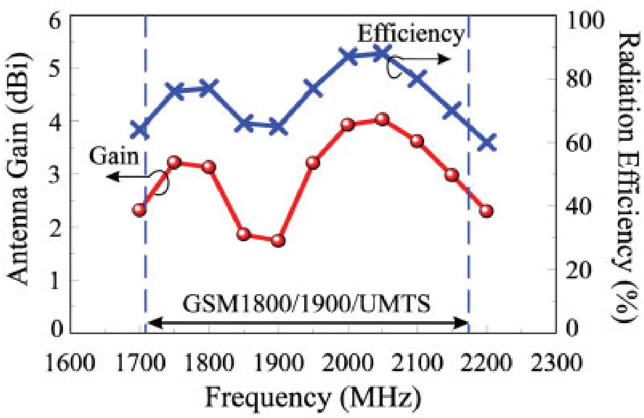
Figure 8 Measured radiation patterns at (a) 1795 MHz, (b) 1920 MHz, and (c) 2045 MHz for the proposed PIFA. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

directional radiation in the azimuthal plane (*x-y* plane) are seen. Figure 8 plots the measured radiation patterns at 1795, 1920, and 2045 MHz, center frequencies of GSM1800, GSM1900, and UMTS bands. The obtained radiation patterns for frequencies in the upper band show more variations when compared with those for lower band in Figure 7. These radiation patterns for the antenna's lower and upper bands are all similar to those obtained for the conventional PIFAs with a direct contact feed [15]. The obtained results suggest that the proposed PIFA is also suitable for practical applications in the mobile phone.

Figure 9 shows the measured antenna gain and simulated radiation efficiency for the proposed PIFA. Over the lower band



(a)



(b)

Figure 9 Measured antenna gain and simulated radiation efficiency for the proposed PIFA. (a) Lower band for GSM850/900 operation. (b) Upper band for GSM1800/1900/UMTS operation. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

for GSM850/900 operation shown in Figure 9(a), the antenna gain is varied from about −0.5 to 1.8 dBi, and the radiation efficiency is all larger than 60%. Over the upper band for GSM1800/1900/UMTS operation [see Fig. 9(b)], the antenna gain is varied from about 1.6 to 3.8 dBi, and the radiation efficiency is about 65 to 88%. Again, the obtained antenna gain and radiation efficiency are acceptable for practical applications in the mobile phone.

4. CONCLUSIONS

A planar $\lambda/8$-PIFA with a coupling feed for achieving GSM850/900/1800/1900/UMTS operation in the mobile phone has been proposed and studied. With penta-band operation obtained for WWAN communication, the proposed planar $\lambda/8$-PIFA occupies a small area of 7×40 mm^2 on an inexpensive 1.6-mm thick FR4 substrate, which also makes the proposed PIFA promising to operate as a surface-mountable chip antenna. The compact size of the proposed PIFA also makes it promising to be embedded inside the casing of the mobile phone to operate as an internal antenna. The successful excitation of the $\lambda/8$ mode in the proposed PIFA is owing to the use of the coupling feed replacing the direct contact feed in the conventional PIFA. In addition, two $\lambda/8$ modes are excited at close frequencies around 900 MHz to form a wide operating band for the antenna's lower band by using a common coupling feed. Further, two higher-order modes ($\lambda/4$ modes) are also successfully excited at close frequencies around 1900 MHz to provide a wide operating band for the antenna's upper band. The obtained wide lower and upper bands allow the proposed PIFA to cover GSM850/900/1800/1900/UMTS operation for WWAN communication. Results also indicate that good radiation characteristics for frequencies over the operating bands are obtained. The proposed planar $\lambda/8$-PIFA is promising for practical application in the mobile phone for WWAN communication.

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