on the measured data, and the MAEs were calculated to confirm the feasibility. The MAEs of S_{11} and S_{21} extracted from the equivalent circuit using lumped elements were 0.591 dB and 0.146 dB, respectively. The S_{11} and S_{21} extracted from the equivalent circuit using physical microstrip lines show MAEs of 0.926 dB and 0.179 dB, respectively. The measured RF characteristics showed good agreement with both the proposed electrical equivalent circuits using lumped elements and physical microstrip lines from 1 to 30 GHz. The proposed packaging method has a good RF performance as well as a simple process, easy integration, and good compatibility with IC and RF MEMS devices. It is expected that the proposed LTCC-based packaging structure and the electrical modeling can provide a practical reference in designing and demonstrating the RF MEMS devices.

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SMALL-SIZE COUPLED-FED SHORTED T-MONOPOLE FOR INTERNAL WWAN ANTENNA IN THE THIN-PROFILE MOBILE PHONE

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ABSTRACT: *A coupled-fed shorted T-monopole with a small size of 15 × 26 mm² (390 mm²) printed on the system circuit board of the mobile phone for WWAN operation is presented. By using a simple inverted-L feeding strip to capacitively excite the shorted T-monopole, two wide operating bands at about 900 and 1900 MHz, respectively, to cover GSM850/900 and GSM1800/1900/UMTS operations are obtained. The antenna is an all-printing structure, with no external matching circuit on the system circuit board or lumped circuit elements embedded in the antenna required for size reduction or bandwidth enhancement. The antenna is hence easy to fabricate at low cost and is especially suited for thin-profile mobile phone applications. The occupied area (less than 400 mm²) of the antenna printed on the system circuit board of the mobile phone in this study is among the smallest for the internal uniplanar printed antenna capable of penta-band WWAN operation that have been reported. Details of the proposed antenna are described, and the obtained results, including its SAR (specific absorption rate) study, are presented and discussed.* © 2009 Wiley Periodicals, Inc. Microwave Opt Technol Lett 52: 257–262, 2010; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.24907

Key words: *mobile antennas; handset antennas; WWAN antennas; multiband antennas; internal mobile phone antennas*

1. INTRODUCTION

Thin-profile mobile phones are becoming very attractive for mobile users on the market. For such mobile phone applications, thin-profile internal antennas become a necessity. For WWAN (wireless wide area network) operation, the antenna designs using the low-profile patch PIFA (planar inverted-F antenna) with a thickness of 3–4 mm, about one half of that of the conventional internal patch PIFAs [1], have been reported [2–5]. This kind of low-profile patch PIFA, with a large footprint (for example, 1400 mm² in [3] or 960 mm² in [5]) occupied on the system circuit board of the mobile phone, is still very difficult to cover all the five operating bands of GSM850 (824–894 MHz), GSM900 (880–960 MHz), GSM1800 (1710–1880 MHz), GSM1900 (1850–1990 MHz), and UMTS (1920–2170 MHz) for WWAN operation. This is owing to the small distance between the radiating patch and the ground plane or slotted ground plane below the radiating patch, causing large coupling between the radiating patch and the ground plane and hence limiting the achievable bandwidth that can be obtained [6, 7].

Different from the conventional patch PIFAs [1–5], the wideband internal antennas can be obtained by removing the ground plane below the radiating portion of the antenna [6, 8] or printing the antenna directly on the no-ground portion of the system circuit board of the mobile phone [9–23]. The antennas in the former case [6, 8] still show a 3D structure and their fabrication cannot be simplified. For the latter case, they generally show no thickness above the circuit board of the mobile phone and can be easily fabricated at low cost, making the internal printed antennas very good candidates for thin-profile mobile phone applications. The reported promising internal printed WWAN antennas include the use of printed monopole elements [9, 10], the printed PIFA or shorted monopole elements [11–13], the printed loop elements [14–18], the printed slot or monopole slot elements [19–23], and so on. Most of the reported internal printed WWAN antennas cover all the five WWAN bands of GSM850/900/1800/1900/UMTS. In addition, the occupied printed area on the circuit board of the mobile phone for covering penta-band WWAN operation can be less than 500 mm² [9, 13, 17, 18], which is much less than the footprint of the low-profile patch PIFAs [2–5].

To achieve size reduction in the reported printed WWAN antennas, lumped circuit elements such as the chip inductor embedded in the printed monopole [9, 24] and external matching circuits such as the band-stop matching circuit [17, 18] on the system circuit board have been applied. Also, external matching circuits such as the high-pass matching network on the system circuit board have been added to enhance the antenna's operating bandwidth [10]. These additional lumped circuit elements and external matching circuits may complicate the fabrication process and increase the fabrication cost of the antenna. In this article, we present a small-size internal penta-band WWAN

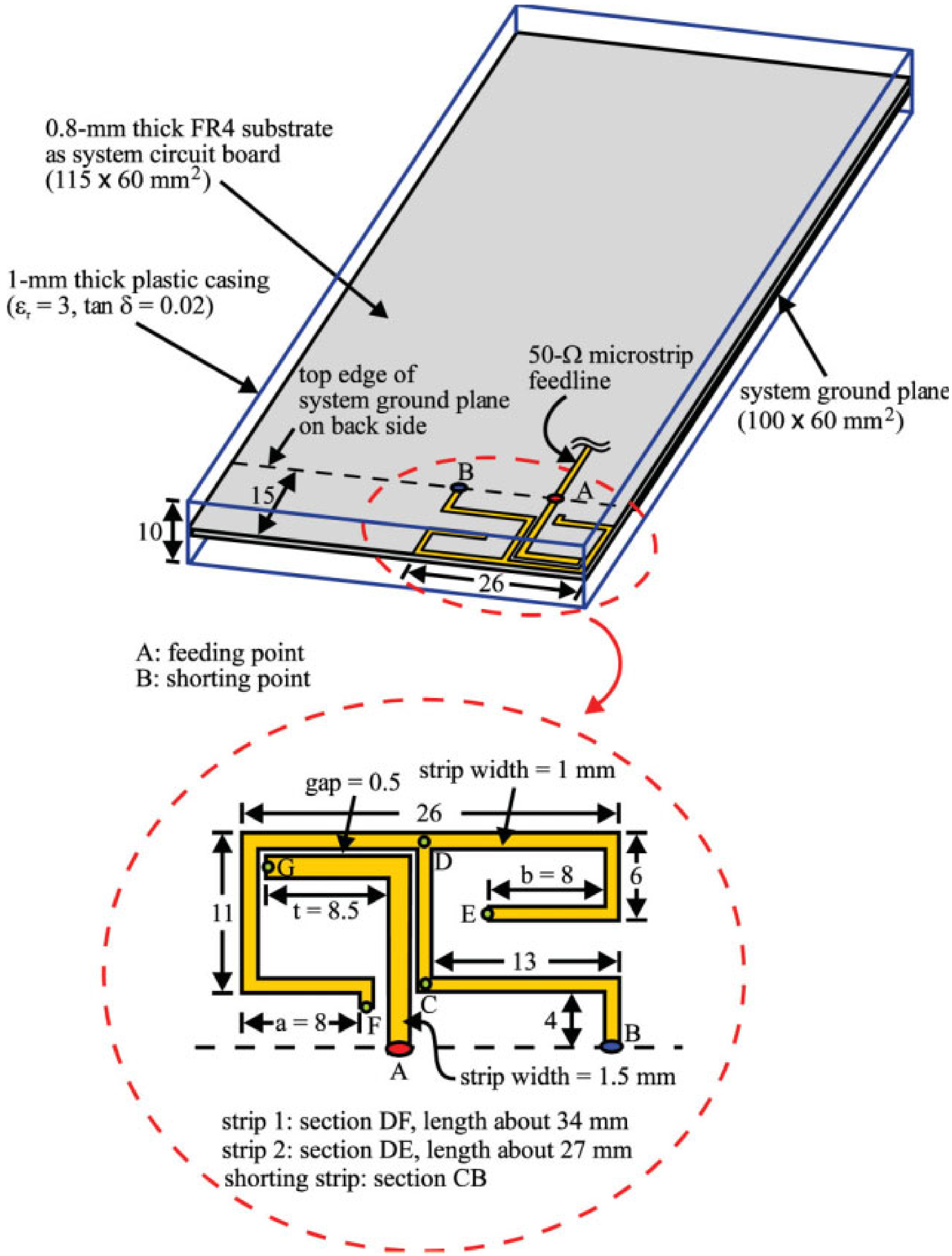


Figure 1 (a) Geometry of the proposed small-size coupled-fed shorted T-monopole for WWAN operation in the thin-profile mobile phone. (b) Dimensions of the metal pattern of the antenna. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

mobile phone antenna with a simple all-printing structure. No external matching circuits on the system circuit board or lumped circuit elements embedded in the antenna for size reduction or bandwidth enhancement are required.

The antenna is a coupled-fed shorted T-monopole with a small printed area of less than 400 mm^2 required on the circuit board of the mobile phone. Simply by applying an inverted-L feeding strip to capacitively excite the shorted T-monopole, two wide operating bands at about 900 and 1900 MHz, respectively, to cover GSM850/900 and GSM1800/1900/UMTS operations are obtained. The coupling-feed technique used in the proposed antenna has been applied in the uniplanar printed PIFA [11–13] in which the occupied printed area of the antenna is 600 mm^2 [11, 12] and 465 mm^2 [13] for achieving penta-band WWAN operation in the mobile phone. This study presents a simpler coupling-feed structure suitably applied to a shorted T-monopole and thus achieves a smaller printed size of less than 400 mm^2 for the internal penta-band WWAN mobile phone antenna. Furthermore, from the SAR study [25–27] with the aid of the SEMCAD simulation software [28], the obtained SAR for 1-g head tissue can easily meet the limit of 1.6 W/kg for the proposed antenna mounted at the bottom position of the mobile phone. Details of the proposed antenna and the obtained results are presented and discussed.

2. PROPOSED COUPLED-FED SHORTED T-MONOPOLE

The geometry of the proposed coupled-fed shorted T-monopole for WWAN operation in the thin-profile mobile phone is shown Figure 1(a), and detailed dimensions of the metal pattern of the

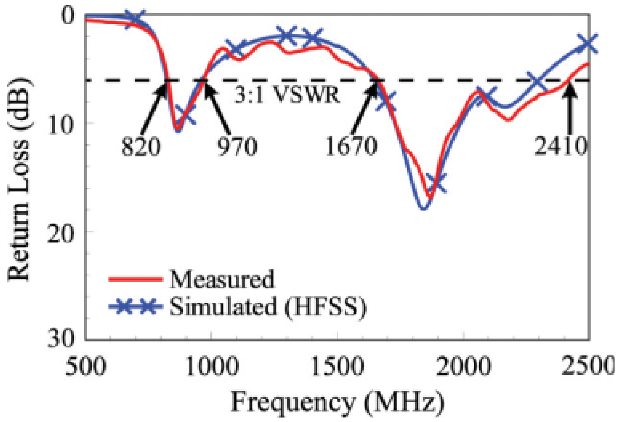


Figure 2 Measured and simulated return loss for the proposed antenna. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

antenna are given in Figure 1(b). Owing to the small printed size (15 × 26 mm^2) for the antenna, it can be arranged to locate on one corner of the no-ground portion at the bottom position of the system circuit board, saving a large portion of the no-ground portion to accommodate other associated electronic elements in the mobile phone. Note that by arranging the printed internal antenna at the bottom position of the mobile phone can result in decreased radiated wave energy absorption by the user's head tissue [9, 13, 16–18], resulting in much lower SAR values obtained. This arrangement of the internal WWAN antenna in the mobile phone is hence attractive and has been applied in practical applications.

In the study a 0.8-mm thick FR4 substrate of relative permittivity 4.4, length 115 mm, and width 60 mm is used as the system circuit board of the mobile phone. The system ground plane of length 100 mm and width 60 mm is printed on the back side of the circuit board, and there is a no-ground portion of 15 × 60 mm^2 at the bottom position of the circuit board. The dimensions selected in this study are reasonable for practical mobile phones, especially for the smart phones or PDA (personal digital assistant) phones.

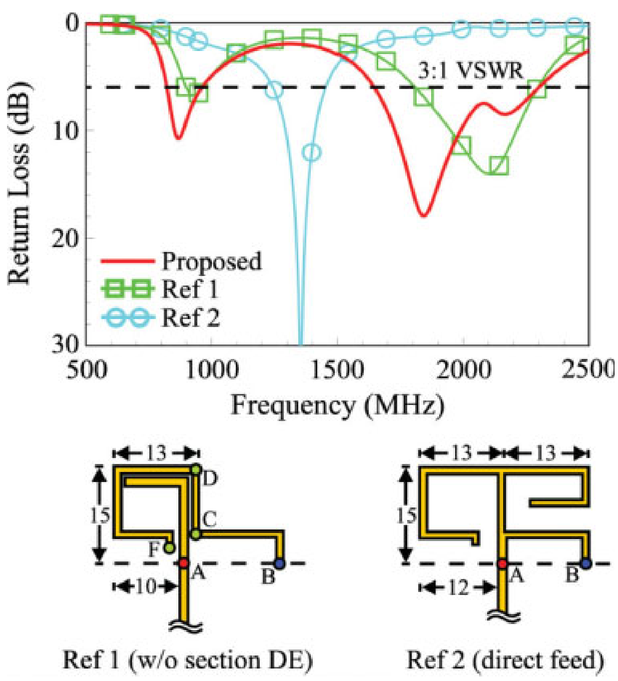


Figure 3 Simulated (HFSS) return loss for the proposed antenna, Ref. 1 [the case without section DE (strip 2)] and Ref. 2 (the corresponding direct-fed shorted T-monopole). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

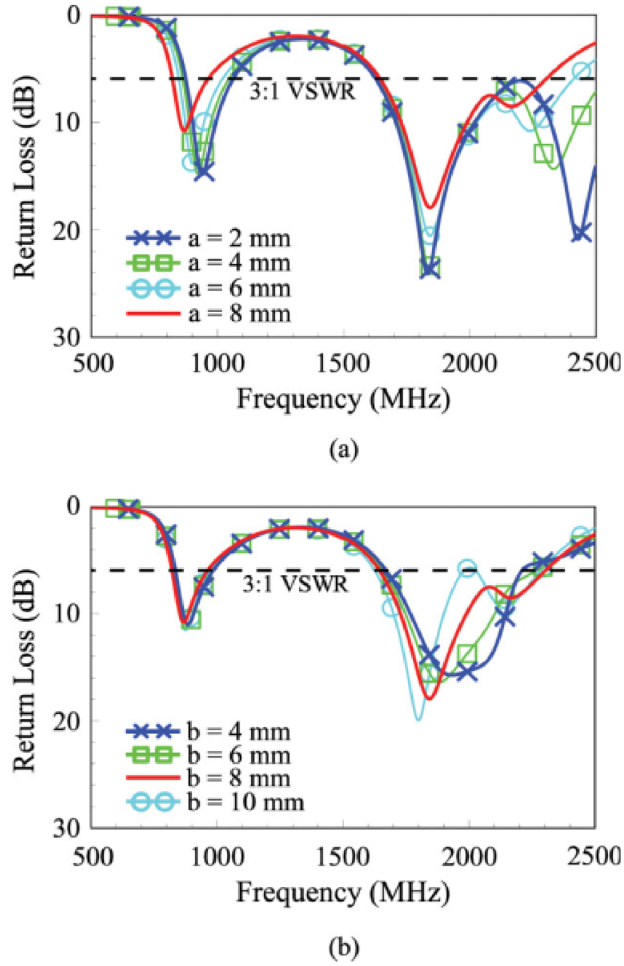


Figure 4 Simulated (HFSS) return loss for the proposed antenna as a function of (a) the tuning length a of section DF (strip 1) and (b) the tuning length b of section DE (strip 2). Other dimensions are the same as given in Figure 1. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

The proposed printed antenna is formed by a T-monopole (section CD, DE, and DF), a shorting strip (section CB), and a feeding strip (section AG). The shorting strip of length 17 mm short-circuits the T-monopole to the system ground plane on the back side through a via-hole in the circuit board. The T-monopole has a central arm (section CD) and two extending arms of strip 1 (section DF) and strip 2 (section DE). With a small coupling gap of 0.5 mm, the feeding strip of an inverted-L shape capacitively couples the central arm and strip 1 to excite the T-monopole. Two resonant modes (mode 1 and 3 in this study) at about 900 and 2100 MHz are contributed by strip 1 and central arm, and by adjusting the length a (tuning length at the end of strip 1), the two modes can be controlled to occur at the desired frequencies. With the adding of strip 2, an additional resonant path (central arm and strip 2) is created, which has a length of 42 mm or about 0.25 wavelength at 1850 MHz and hence

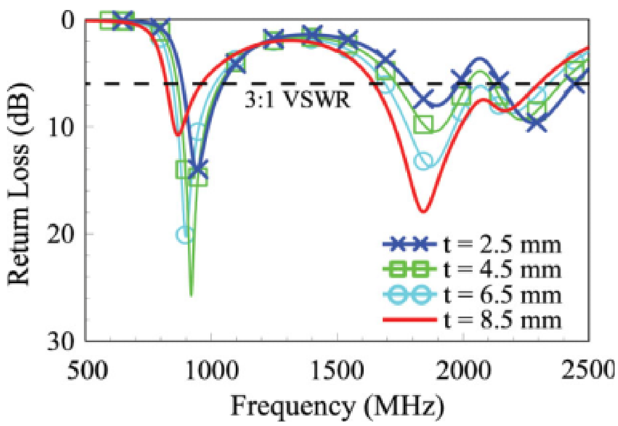


Figure 5 Simulated (HFSS) return loss for the proposed antenna as a function of the tuning length t of the feeding strip. Other dimensions are the same as given in Figure 1. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

resulting in the generation of a quarter-wavelength resonant mode (mode 2 in this study) at about 1850 MHz. By tuning the length b of the end portion of strip 2, mode 2 can be controlled to occur at the desired frequencies to incorporate mode 3 to form a wide operating band for the antenna to cover GSM1800/1900/UMTS operation. Also, mode 1 at about 900 MHz easily controlled by the tuning length a covers GSM850/900 operation. In this case, the proposed antenna covers all the five operating bands for WWAN operation.

Notice that strip 1 and central arm together have a total length of about 50 mm only, about 0.15 wavelength at 900 MHz. With such a short length, much less than 0.25 wavelength, the successful excitation of mode 1 is resulted from the use of the simple coupling-feed structure applied here. The decreased resonant length required for the 900 MHz band operation makes it possible for the proposed antenna to have a much reduced size on the circuit board of the mobile phone. Detailed effects of the coupling-feed structure and the control of the excited resonant modes are discussed in Figures 3–5 in the next section.

3. RESULTS AND DISCUSSION

The proposed antenna with the dimensions given in Figure 1 was fabricated and studied. Figure 2 shows the measured and simulated return loss for the proposed antenna. Two wide operating bands at about 900 and 1900 MHz are obtained for the proposed antenna. Good agreement between the measured data and simulated results obtained using Ansoft HFSS [29] is also obtained. With 3:1 VSWR (6-dB return loss) definition, which is widely used for the internal mobile phone antennas, the antenna's lower band formed by mode 1 described in section 2 covers GSM850/900 operation, whereas the upper band formed by mode 2 and 3 described in section 2 covers GSM1800/1900/UMTS operation. The proposed antenna hence covers all the five operating bands for WWAN operation.

The operating principle is discussed in Figures 3–5. Figure 3 shows the simulated return loss for the proposed antenna, Ref. 1 [the case without section DE (strip 2)] and Ref. 2 (the corresponding direct-fed shorted T-monopole). The corresponding dimensions in the three cases are all the same. For Ref. 2, there is only one resonant mode occurred at about 1350 MHz, owing to the resonant length of the T-monopole about a quarter-wavelength at 1350 MHz. For Ref. 1, with the simple coupling-feed structure applied, two resonant modes at about 900 MHz (mode 1) and 2100 MHz (mode 3) are generated. The successful excitation of the resonant mode at about 900 MHz with a resonant length (about 0.15 wavelength at 900 MHz for section CD and DF) much smaller than 0.25 wavelength is resulting from the additional capacitance contributed by the coupling feed effectively compensating for the large inductance with the decreased resonant length. For the resonant mode at about 2100 MHz, it is the higher-order mode of Ref. 1. By including section DE (strip 2) to Ref. 2 (that is, the proposed antenna), an additional resonant mode (mode 2 here) at about 1850 MHz is generated, which incorporates mode 3 to form a wide operating band as the antenna's upper band. Also, improved impedance matching

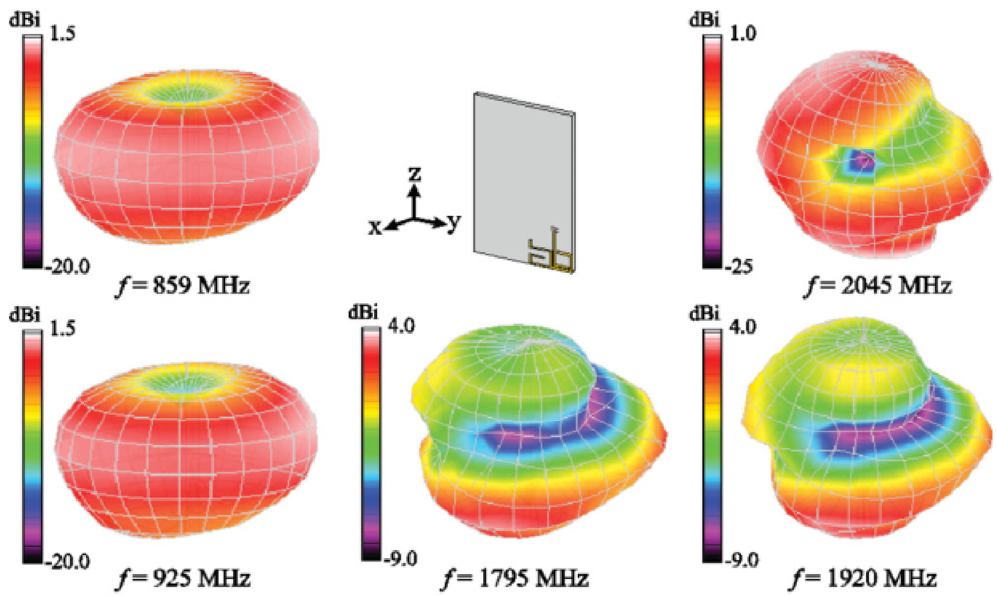


Figure 6 Measured 3D total-power radiation patterns for the proposed antenna. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

for mode 1 is obtained with the adding of strip 2, thus leading to a wideband at about 900 MHz for the antenna's lower band.

Effects of tuning length *a* and *b* at the end of strip 1 and 2 are analyzed in Figure 4. Results of the simulated return loss for the tuning length *a* varied from 2 to 8 mm are presented in Figure 4(a). Relatively large effects on mode 1 and 3 are seen, and effects on mode 2 are small. This behavior agrees that mode 1 and 3 are the resonant modes mainly contributed by strip 1 and central arm of the T-monopole. Figure 4(b) shows the results for the tuning length *b* varied from 4 to 10 mm. In this case, large effects on mode 2 are seen, and effects on mode 1 are very small. Since mode 3 is at frequencies very close to mode 2, some variations on mode 3 are also seen. The obtained results also indicate that mode 2 can be effectively controlled by the tuning length *b* of strip 2.

Figure 5 shows the simulated return loss for the proposed antenna as a function of the tuning length *t* of the feeding strip. Results for the length *t* varied from 2.5 to 8.5 mm are shown. Results suggest that the impedance matching for frequencies over mode 1, 2, and 3 can all be fine-tuned by adjusting the tuning length *t* of the feeding strip.

Figure 6 plots the measured 3D total-power radiation patterns for the proposed antenna. The patterns at 859, 925, 1795, 1920, and 2045 MHz (central frequencies of the five WWAN bands) are shown. Note that the antenna is placed at the bottom position of the mobile phone. Good dipole-like radiation patterns with omni-directional radiation in the *x-y* plane (azimuthal plane) are observed for lower frequencies at 859 and 925 MHz.

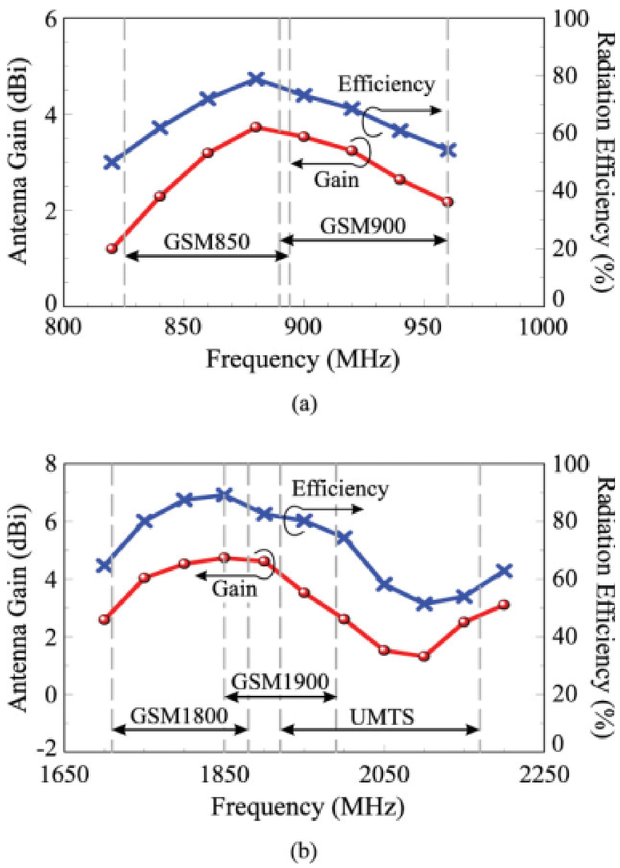
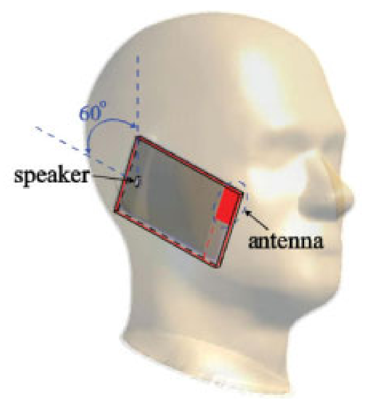


Figure 7 Measured antenna gain and radiation efficiency of the proposed antenna. (a) GSM850/900 bands. (b) GSM1800/1900/UMTS bands. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]



Frequency (MHz)	859	925	1795	1920	2045
1-g SAR (W/kg)	0.84	0.96	0.60	0.54	0.34
Return loss (dB)	7.1	7.0	25.8	15.0	11.3

Figure 8 SAR simulation model (SEMCAD [28]) and the simulated SAR for 1-g head tissue for the proposed antenna. The return loss indicates the impedance matching level at the tested frequency. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

For higher frequencies at 1795, 1920, and 2045 MHz, there are more variations in the radiation patterns. The obtained patterns show no special distinctions compared with those for the cases that the internal WWAN antenna is placed at the top position of the mobile phone.

Figure 7 shows the measured antenna gain and radiation efficiency of the proposed antenna. For frequencies over the GSM850/900 bands shown in Figure 7(a), the radiation efficiency is about 54 to 79%, and the antenna gain is about 1.5 to 3.7 dBi. Figure 7(b) shows the results over the GSM1800/1900/UMTS bands. The radiation efficiency is about 50 to 90%, whereas the antenna gain is about 1.2 to 4.6 dBi. The obtained radiation characteristics are good for practical applications in the mobile phone.

The SAR results are also analyzed. Figure 8 shows the SAR simulation model provided by SEMCAD [28], and the simulated SAR values for 1-g head tissue at 859, 925, 1795, 1920, and 2045 MHz are also shown in the figure. The impedance matching level at the tested frequencies is also shown (the return loss in the table), which indicates that good impedance matching for the proposed antenna in the testing is still maintained. Note that in the SAR simulation model, the system ground plane is spaced 5 mm from the phantom ear, and the mobile phone is oriented 60° to the vertical axis of the phantom head. The testing power in the study is 24 dBm at 859 and 925 MHz, and 21 dBm at 1795, 1920, and 2045 MHz. From the results, the obtained SAR values are 0.84, 0.96, 0.60, 0.54, and 0.34 W/kg, respectively, at 859, 925, 1795, 1920, and 2045 MHz. All the results meet the SAR limit of 1.6 W/kg [25], making the proposed antenna very promising for practical mobile phone applications.

4. CONCLUSIONS

A small-size coupled-fed shorted T-monopole easy to be printed on the system circuit board for penta-band WWAN operation in the thin-profile mobile phone has been proposed and studied. The occupied printed size of the antenna on the circuit board is 390 mm^2 only, and the antenna can still provide two wide operating bands to cover GSM850/900/1800/1900/UMTS operation. The small size and wideband operation are achieved by applying a simple inverted-L feeding strip to capacitively excite the printed shorted T-monopole. Detailed operating principle of the antenna has been analyzed. Good radiation performances for frequencies over the WWAN bands have also been obtained. For the antenna placed at the bottom position of the mobile phone, the obtained SAR values for 1-g head tissue have been found to be less than 1.0 W/kg over the WWAN bands, hence easily meeting the SAR limit of 1.6 W/kg and making the antenna very promising for practical mobile phone applications.

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NEW AND ACCURATE SYNTHESIS FORMULAS FOR OPEN SUPPORTED COPLANAR WAVEGUIDES

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ABSTRACT: *In this article, new and accurate synthesis formulas to compute the physical dimensions of open supported coplanar waveguides (OS-CPWs) are presented. The synthesis formulas are obtained with the use of differential evolution (DE) and particle swarm optimization (PSO) algorithms. They are useful for the computer-aided design of OS-CPWs. The average percentage errors of the synthesis formulas obtained by using DE and PSO algorithms are computed to be 1.26% and 1.67%, respectively, for 4560 OS-CPW samples having different electrical parameters and physical dimensions, as compared with the results of quasi-static analysis.* © 2009 Wiley Periodicals, Inc. Microwave Opt Technol Lett 52: 262–269, 2010; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.24908

Key words: *supported coplanar waveguides; synthesis formulas; differential evolution algorithm; particle swarm optimization*

1. INTRODUCTION

Coplanar waveguides (CPWs) and multilayered CPWs have received great attention due to their attractive features over the conventional microstrip lines in designing and manufacturing microwave integrated circuits (MICs) [1–13]. The advantages of CPWs are low dispersion, high flexibility in the design of