ULTRA-WIDEBAND LOOP ANTENNA COUPLED-FED BY A MONOPOLE FEED FOR PENTA-BAND FOLDER-TYPE MOBILE PHONE

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ABSTRACT: *An ultra-wideband coupled-fed loop antenna for penta-band operation in the folder-type mobile phone is presented. The antenna comprises a loop strip and a monopole feed; the latter not only serves as a coupling feed for the loop strip to generate a 0.5-wavelength loop resonant mode, but also provides a 0.25-wavelength monopole resonant mode for enhancing the operating bandwidth of the antenna. Hence, with an occupied volume of 2.6 cm^3 only, the antenna can provide a very wide operating band of larger than 100% or about 1.7 GHz (from 790 to 2480 MHz), allowing the antenna to cover GSM850/900/DCS/PCS/UMTS penta-band operation with radiation efficiencies larger than 70% for the folder-type mobile phone in the open state (talk condition). For the antenna in the close state (idle condition), it can still provide a very wide operating band just by including a matching circuit of a series chip capacitor at the antenna's feeding point, and the radiation efficiencies over the five operating bands are still better than 53%. Details of the proposed antenna are studied.* © 2008 Wiley Periodicals, Inc. Microwave Opt Technol Lett 50: 2706–2712, 2008; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.23753

Key words: *internal mobile phone antennas; loop antennas; ultra-wideband operation; folder-type mobile phone; penta-band operation*

1. INTRODUCTION

The loop antennas have been shown to be a very promising candidate for dual-band or multiband mobile phone applications, and many related internal multiband loop antennas have been reported [1–7]. This promising application is partly owing to the loop antenna having a closed excited surface current path, different from the conventional monopoles or planar inverted-F antennas (PIFAs) which show an open excited surface current path [8]. Hence, the conventional monopoles or PIFAs usually show strong coupling with the system ground plane of the mobile phone. On the contrary, the possible coupling between the loop antenna and the system ground plane will be much smaller. In this case, the variations in the dimensions of the system ground plane will show smaller effects on the performances of the loop antenna. With this attractive behavior, it is expected that the loop antenna can find very promising applications in the folder-type mobile phone [9–12], where there are large groundplane variations for the mobile phone in the open state (talk condition) and the close state (idle condition).

For the reported multiband loop antennas [1–7], however, they are studied for applications in the conventional bar-type mobile phone only. Further, most of the reported designs achieve multiband operation by using a direct contact feed to excite the resonant modes of the loop antenna. In [7], the loop antenna is excited using a coupling stub, and quad-band operation is obtained. In these available designs, penta-band operation covering GSM850/900 (824–894/880–960 MHz), DCS (1710–1880 MHz), PCS (1850–1990 MHz), and UMTS (1920–2170 MHz) is still a big challenge.

In this article, we present an ultra-wideband loop antenna promising for penta-band operation in the folder-type mobile phone. The loop antenna is coupled-fed by a monopole feed, which not only successfully excites the 0.5-wavelength loop resonant mode at about 0.9 GHz but also contributes a 0.25-wavelength monopole resonant mode at about 2.3 GHz. In addition, an additional resonant mode at about 1.5 GHz mainly controlled by the two shorted ground planes (the upper and main grounds) of the folder-type mobile phone is also generated. The three resonant modes are formed into a very wide operating band (3:1 VSWR or 6-dB return loss) of larger than 100% centered at about 1.6 GHz for the antenna to cover GSM850/900/DCS/PCS/UMTS operation for the mobile phone in the open state or talk condition. Further, when the mobile phone changes from the open state to the close state (idle condition), it is found that the variations in the real part of the input impedance of the antenna are small, although the groundplane conditions seen by the antenna are greatly different. For the imaginary part of the input impedance, however, the zero reactance is shifted to higher frequencies, causing some impedance matching degradation at around 900 MHz. This condition can be easily compensated by adding a series chip capacitor at the antenna's feeding point to effectively shift the zero reactance to lower frequencies. In this case, the obtained operating band for the antenna in the close state can still cover GSM850/900/DCS/PCS/UMTS operation. Detailed design considerations of the proposed ultra-wideband loop antenna for penta-band operation are described in the article. The proposed antenna was also fabricated and tested. Results of the fabricated prototype are presented and discussed.

2. DESIGN CONSIDERATIONS OF THE PROPOSED ANTENNA

Figures 1(a) and 1(b) show the geometry and side view of the ultra-wideband loop antenna coupled-fed by a monopole feed for the folder-type mobile phone in the open state or talk condition. There are a main ground plane and an upper ground plane for the folder-type mobile phone, and both are of the same size 45×90 mm^2. The two ground planes are connected by a connecting strip (1 mm in width and 8 mm in length) in this study. Note that the upper ground plane is for the cover of the mobile phone and usually accommodates the speaker, the embedded digital camera, and the LCD display. The main ground plane is printed on a 0.8-mm-thick FR4 substrate (considered as the main circuit board of the mobile phone studied here), which has a relative permittivity of 4.4 and a loss tangent of 0.0245 and usually accommodates the microphone, the keypad, and the battery. The inclination angle α of the upper ground plane to the axis of the mobile phone is set to 15° [see Fig. 1(b)] in this study, which is reasonable for general folder-type mobile phones in the open state. When the mobile phone is in the close state (idle condition), the inclination angle α becomes 180°.

Figure 1(c) shows the dimensions of the antenna in its planar structure. The antenna has a symmetric structure and comprises an E-shaped loop strip and a T-shaped monopole feed; both are printed on a 0.8-mm-thick FR4 substrate and then bent (see the bending lines in the figure) to achieve a compact size of $5.8 \times 10 \times 45$ mm^3 or 2.6 cm^3 only. With the small volume occupied, the antenna is very promising to be embedded inside the housing of the mobile phone as an internal antenna. Also note that the antenna can be easily fabricated on a flexible printed circuit board (FPCB) in practical applications, instead of the FR4 substrate in this study. With the use of the FPCB, the antenna will be much easier to be bent or rolled into the similar compact configuration as studied here.

Note that the loop strip is bent into an E shape to achieve a longer length in a limited area, and the two ends (Points B and D)

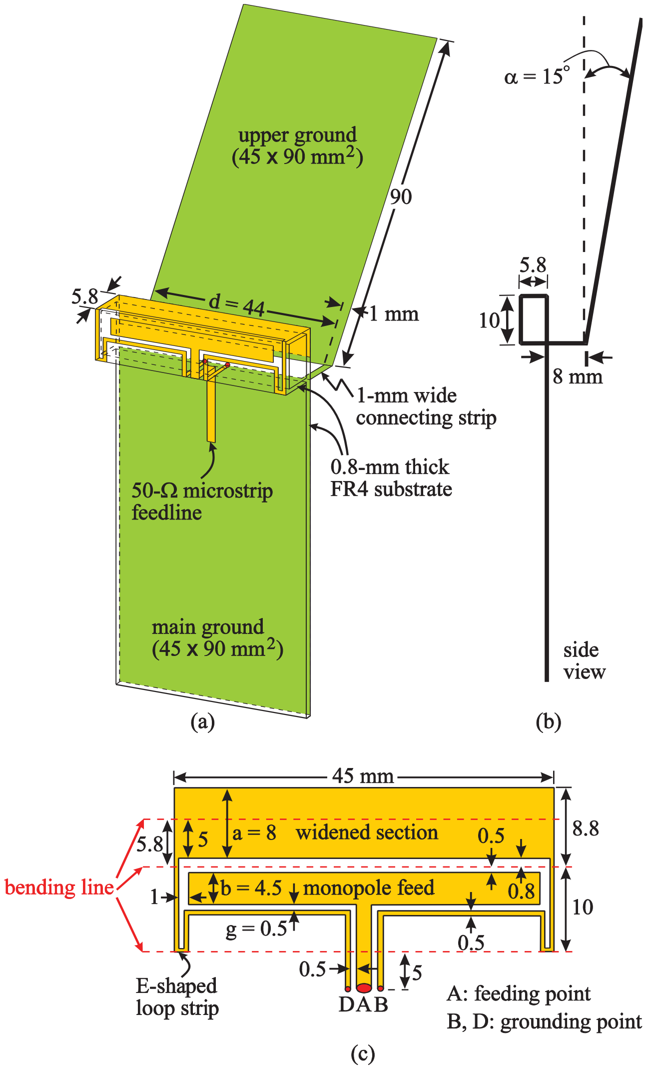

Figure 1 (a) Geometry of the ultra-wideband loop antenna coupled-fed by a monopole feed for the folder-type mobile phone. (b) Side view of the studied folder-type mobile phone in the open state. (c) Dimensions of the antenna in its planar structure. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

of the loop strip are grounded to the main ground plane at about the center of its top edge. The total length of the E-shaped loop strip, however, is still not long enough to be close to 0.5 wavelength of the frequency at 0.9 GHz to generate the 0.5-wavelength loop mode covering GSM850/900 operation. For this purpose, the central section of the loop strip is widened, with other sections of the loop strip having a narrow width of 0.5 mm. With the presence of the widened central section (width a = 8 mm), the excited 0.5-wavelength loop mode can be effectively shifted to lower frequencies. This is mainly because, at the central section of the loop strip, the excited surface current is null for the 0.5-wavelength loop mode. Hence, with its central section widened, the effective resonant length in the null-current region of the 0.5-wavelength loop mode can be increased, thus causing the 0.5-wavelength loop mode to be shifted to lower frequencies. More detailed effects of the width a of the widened section on the excited resonant modes of the antenna will be analyzed with the aid of Figure 4 in the next section.

The monopole feed is of a T shape [13], and its front end (Point A) is the antenna's feeding point, which is connected to a 50-Ω microstrip line printed on the front side of the main circuit board. The monopole feed capacitively excites the 0.5-wavelength loop resonant mode at about 0.9 GHz. Also, an additional dipole-like resonant mode at about 1.5 GHz controlled by the two shorted ground planes (the upper and main grounds) of the studied folder-type mobile phone can be excited by the monopole feed. Hence, when the position of the connecting strip d is varied, this dipole-like resonant mode can be adjusted to achieve good impedance matching. The optimal position d is found to be 44 mm in this study. More detailed effects will be studied with the aid of Figure 6 in Section 3.

In addition, the monopole feed can also operate as an efficient radiator. The length of the monopole feed from Point A to one of the two open ends is about 34 mm, which is about 0.25 wavelength of the frequency at 2.3 GHz. Hence, the monopole feed can also generate a 0.25-wavelength monopole mode at about 2.3 GHz. By varying the width b of the monopole feed, the excited 0.25-wavelength monopole mode can be fine-adjusted. The preferred width b in this study is 4.5 mm. Its detailed effects will be explored with the aid of Figure 5 in Section 3. Also note that by selecting a proper value of the gap g (0.5 mm) between the monopole feed and the E-shaped loop strip, good excitation of the three resonant modes at about 0.9, 1.5, and 2.3 GHz can be obtained. The three resonant modes can be further formed into a very wide operating band of about 1.7 GHz, hence allowing the antenna to easily cover GSM850/900/DCS/PCS/UMTS operation for the mobile phone in the open state. Detailed effects of the gap g will be analyzed in Figure 7.

When the mobile phone is in the close state for the idle condition, the upper ground plane will be in parallel to the main ground plane with α = 180°. Although this groundplane condition is greatly different from that in the open state, there is slight variation in the real part of the input impedance of the proposed antenna. However, the zero reactance of the input impedance is shifted to higher frequencies, causing the excited loop resonant mode occurred at frequencies larger than 1 GHz. This behavior can be easily adjusted by adding a proper series chip capacitor (3.9 pF here) at the antenna's feeding point [see the inset in Fig. 3(a)], which can shift the zero reactance back to lower frequencies. Hence, the excited 0.5-wavelength loop mode can also occur at about 0.9 GHz, the same as that in the open state. In this case, the obtained operating band for the antenna in the close state can still cover GSM850/900/DCS/PCS/UMTS operation. More detailed re-

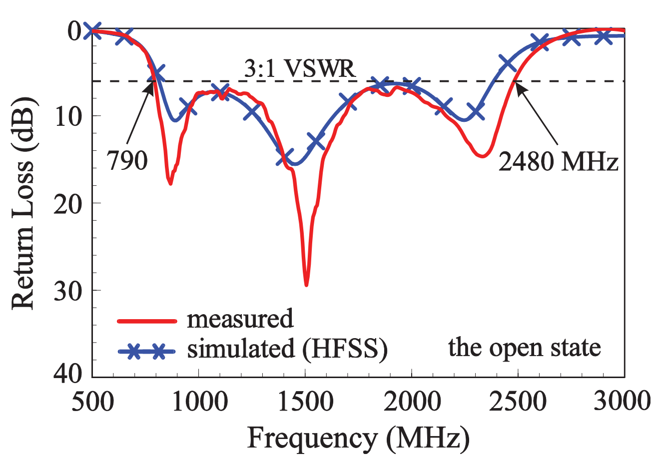

Figure 2 Measured and simulated return loss for the antenna in the open state (α = 15°). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

sults of the antenna for the mobile phone in the close state are discussed in Figure 3 in the next section. It should also be noted that for practical applications, the inclusion of the series chip capacitor to the antenna in the close state can be achieved using a switching circuit (not shown here), which can switch-off the added chip capacitor when the mobile phone changes from the close state to the open state for the talk condition.

3. RESULTS AND DISCUSSION

The proposed coupled-fed loop antenna with the design dimensions given in Figure 1 was fabricated and tested. Figure 2 shows the measured and simulated return loss of the fabricated prototype. The simulated results are obtained using Ansoft simulation software HFSS [14], and good agreement between the simulation and measurement is observed. From the measured results, a very wide impedance bandwidth of 1690 MHz (790–2480 MHz, about 103% centered at 1635 MHz) formed by three resonant modes is obtained, which allows the antenna to easily cover GSM850/900/DCS/PCS/UMTS operation in the open state. Note that the bandwidth definition used here is 3:1 VSWR or 6-dB return loss), which is generally used for practical applications for the internal mobile phone antennas.

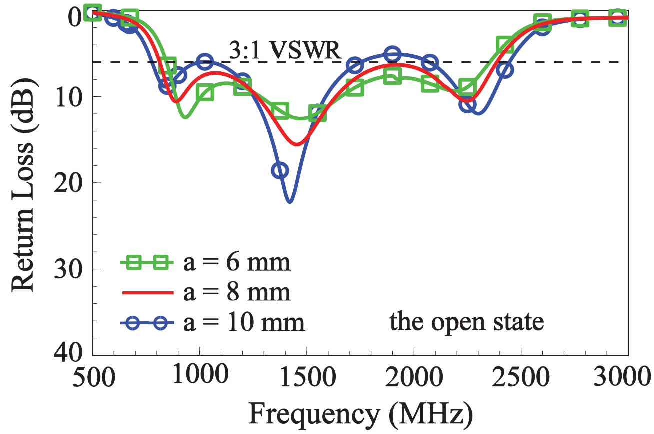

Figure 4 Simulated return loss as a function of a (width of the widened section in the loop strip). Other dimensions are the same as studied in Figure 2. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

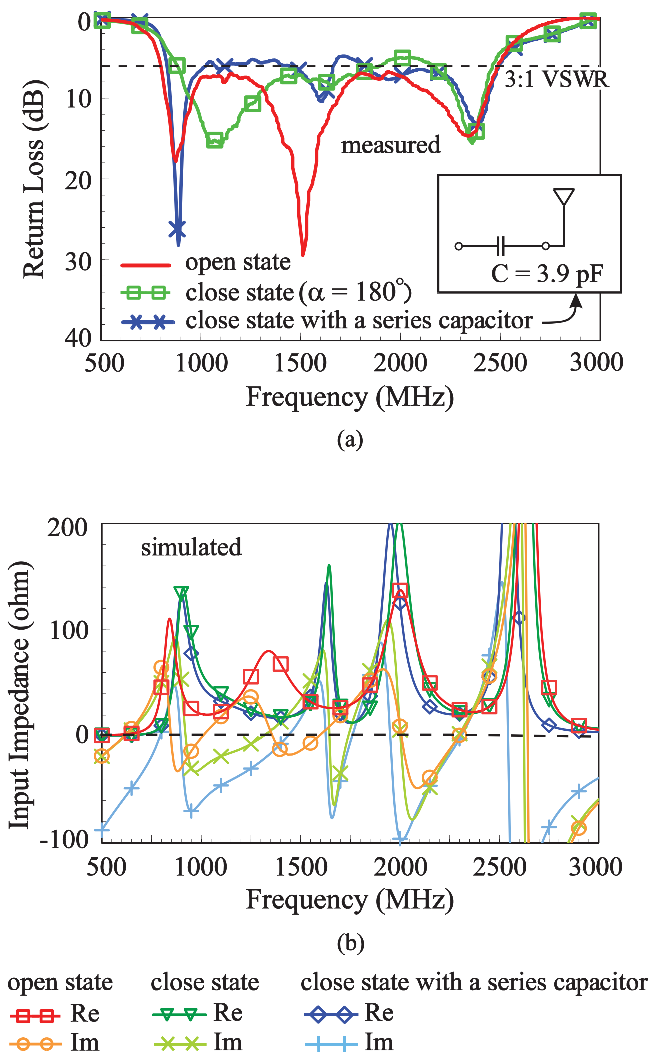

Figure 3 (a) Measured return loss and (b) simulated input impedance for the antenna in the open state ($\alpha = 15°$), the close state ($\alpha = 180°$), and the close state ($\alpha = 180°$) with a series capacitor of 3.9 pF. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

For application in the folder-type mobile phone, the antenna performances should be studied for the mobile phone in the two states: the open state for the talk condition and the close state for the idle condition. Hence, in this study, the proposed antenna in the close state is also considered. Measured results for the antenna in the open state ($\alpha = 15°$), the close state ($\alpha = 180°$), and the close state ($\alpha = 180°$) with a series chip capacitor of 3.9 pF are shown in Figure 3(a). For the close state without the chip capacitor, the 0.5-wavelength loop mode is shifted to higher frequencies at about 1.1 GHz and the dipole-like mode at about 1.5 GHz is degraded, although it still shows acceptable impedance matching of about 3:1 VSWR for frequencies over the mode. By simply including a chip capacitor of 3.9 pF, the 0.5-wavelength loop mode is shifted back to occur at around 0.9 GHz, making the impedance matching over the desired operating bands of GSM850/900/DCS/PCS/UMTS still better than about 3:1 VSWR. This can be seen more clearly from the comparison of the simulated input impedance of the antenna in the three cases shown in Figure 3(b). It is seen that when the mobile phone is in the close state with the series chip capacitor of 3.9 pF added, the more inductive behavior of the input reactance (imaginary part of the input impedance) around 900 MHz is compensated, and the zero reactance is also shifted to occur at about 900 MHz. Hence, the measured return loss for the close state can still show similar impedance matching level over the desired operating band as that for the open state [see Fig. 3(a)]. That is, the proposed antenna can cover penta-band operation for the mobile phone in either the open state or the close state.

The simulation study on the major parameters a, b, d, and g is also conducted. Figure 4 shows the simulated return loss as a function of the width a of the widened section, and the results for a varied from 6 to 10 mm are presented. From the results, it is seen that when the width a increases, the 0.5-wavelength loop mode can be effectively shifted to lower frequencies to achieve a lower edge frequency with 3:1 VSWR for the antenna. This behavior is expected as discussed in Section 2. For the two other modes (the dipole-like mode at about 1.5 GHz and the monopole mode at about 2.3 GHz), their central resonant frequencies are slightly affected. This confirms that the width a of the widened section in the loop strip mainly affects the excitation of the 0.5-wavelength loop mode.

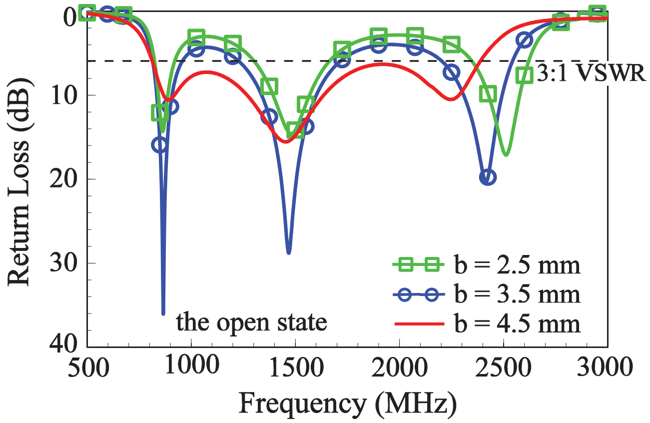

Figure 5 Simulated return loss as a function of *b* (width of the monopole feed). Other dimensions are the same as studied in Figure 2. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

In Figure 5, simulated results of the return loss for the width *b* of the monopole feed that varied from 2.5 to 4.5 mm are shown. Results clearly indicate that the third resonant mode (0.25-wavelength monopole mode) can be effectively controlled by adjusting the width *b*. This behavior is reasonable, because the variation in *b* can lead to variations in the effective resonant length of the excited monopole mode. For the other two modes (the 0.5-wavelength loop mode at about 0.9 GHz and the dipole-like mode at about 1.5 GHz), their central resonant frequencies are again slightly affected.

Figure 6 presents the simulated return loss for the position *d* of the connecting strip varied from 34 to 44 mm. In this case, the antenna's second mode (the dipole-like mode) is greatly affected. For the two other modes, the effects are again much smaller. This agrees with the discussion in Section 2, and the dipole-like mode is greatly dependent on the two shorted ground planes. Effects of the gap *g* between the monopole feed and the E-shaped loop strip are studied in Figure 7. Results in Figure 7(a) indicate that the gap *g* should be selected to be small (0.5 mm is preferred in this study) to achieve good excitation of the three resonant modes to form a very wide operating band for penta-band operation. In Figure 7(b), it can be seen that, with a small gap of 0.5 mm, a zero reactance

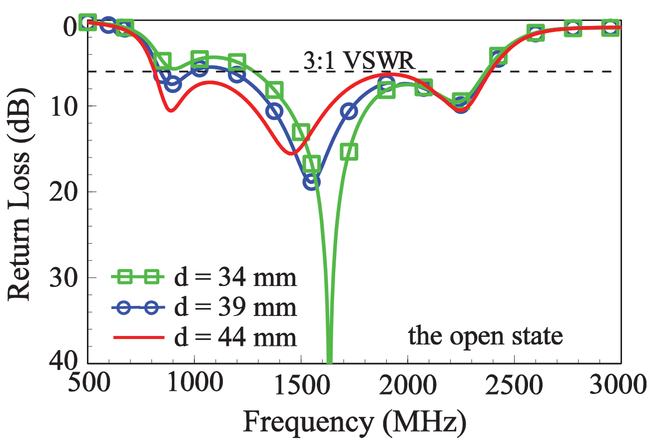

Figure 6 Simulated return loss as a function of *d* (position of the connecting strip). Other dimensions are the same as studied in Figure 2. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

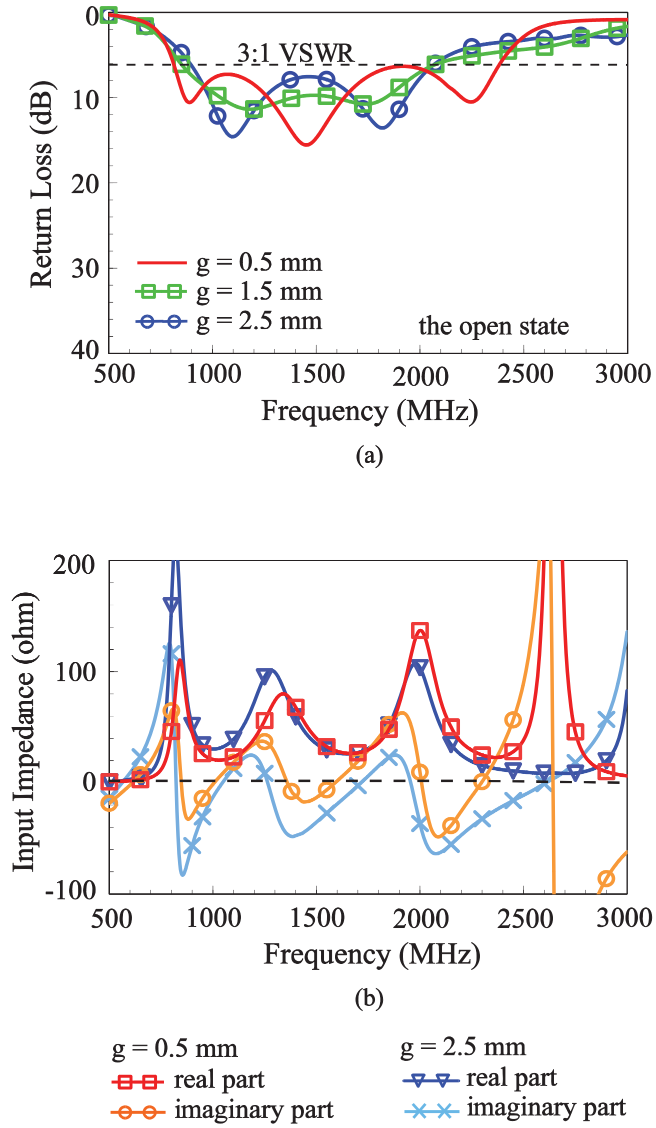

Figure 7 Simulated (a) return loss and (b) input impedance as a function of *g* (gap between the monopole feed and the loop strip). Other dimensions are the same as studied in Figure 2. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

can occur at about 2.3 GHz, which hence leads to good excitation of the 0.25-wavelength monopole mode at about 2.3 GHz. Enhanced bandwidth for the antenna is thus obtained.

Radiation characteristics of the antenna in the open state are also studied. Figure 8 plots the measured radiation patterns at 890 and 1795 MHz, while those at 1920 and 2045 MHz are shown in Figure 9. Note that the radiation patterns in three principal planes at each frequency are normalized with respect to the antenna's peak gain, which is 2.0, 2.4, 2.7, and 3.4 dBi for 890, 1795, 1920, and 2045 MHz, respectively. Monopole-like radiation patterns at 890 MHz are seen, which is similar to those of the conventional internal mobile phone antennas operated in the GSM band [8]. It is also observed that the radiation patterns at 1795, 1920, and 2045 MHz are similar to each other. That is, stable radiation characteristics for frequencies over the DCS/PCS/UMTS band are obtained. Figure 10 presents the measured antenna gain and simulated radiation efficiency when the antenna is in the open state. Over the GSM850/900 band, the measured antenna gain is varied from about 0.1 to 2.4 dBi, while the radiation efficiency is varied from

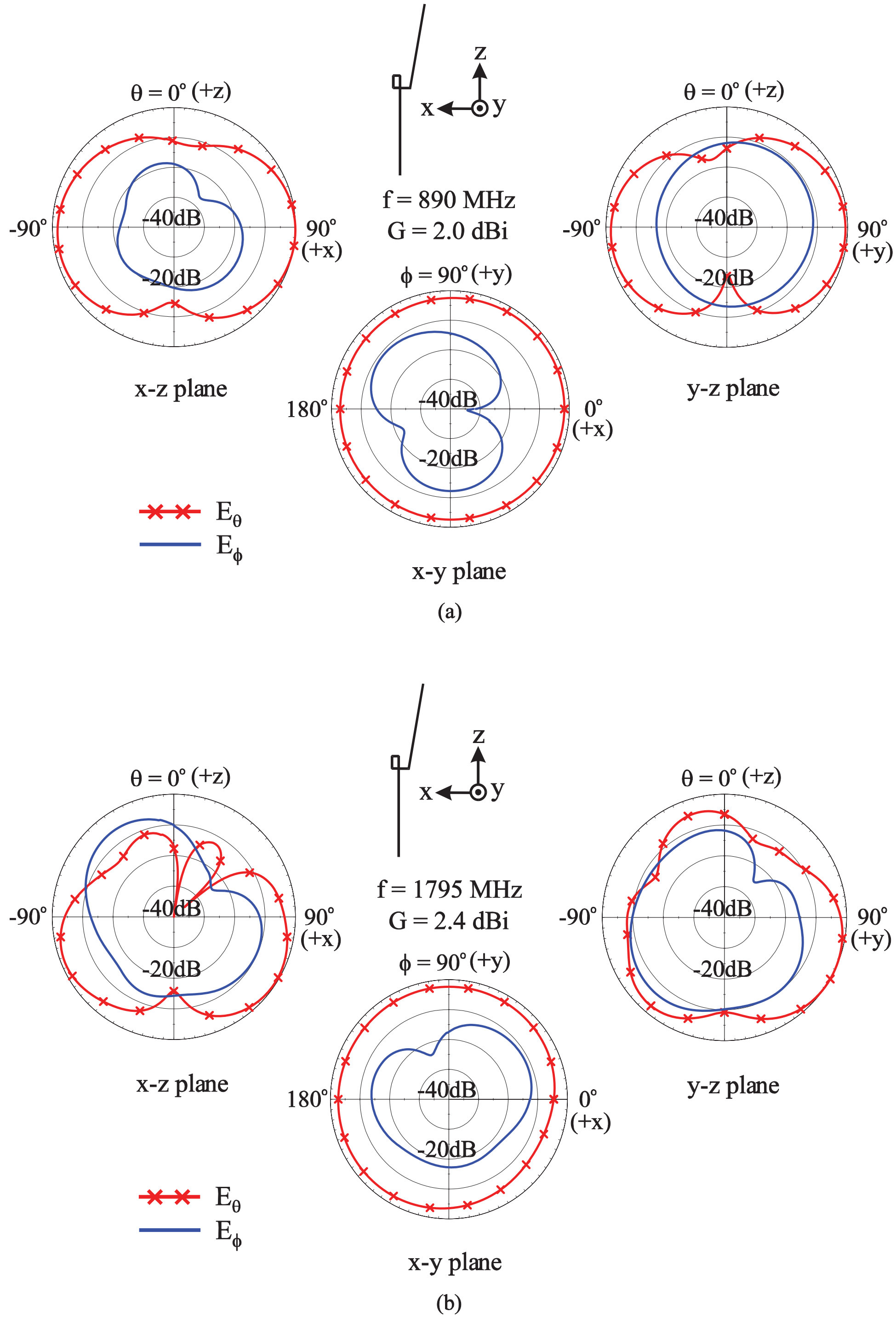

Figure 8 Measured radiation patterns at (a) 890 MHz and (b) 1795 MHz for the antenna studied in Figure 2. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

about 70–87%. Over the DCS/PCS/UMTS band, the antenna gain is varied from about 2.2–4.0 dBi, and the radiation efficiency is all larger than 75%.

The simulated radiation efficiencies for the antenna in the open state and in the close state with a series chip capacitor of 3.9 pF are also studied in Figure 11. For the latter case in the close state, the radiation efficiencies over the five operating bands are all larger than 53%, while those for the former case in the open state are all larger than 70%. The obtained radiation efficiencies are promising for practical folder-type mobile phone applications.

4. CONCLUSION

An ultra-wideband coupled-fed loop antenna suitable for penta-band operation in the folder-type mobile phone has been demonstrated. The loop antenna is coupled-fed by a monopole feed and is configured to occupy a small volume of 2.6 cm^3 only. The monopole feed can successfully excite the loop antenna and can also generate a 0.25-wavelength monopole mode, which greatly enhances the operating bandwidth of the antenna. The obtained bandwidth reaches about 1.7 GHz (790–2480 MHz,

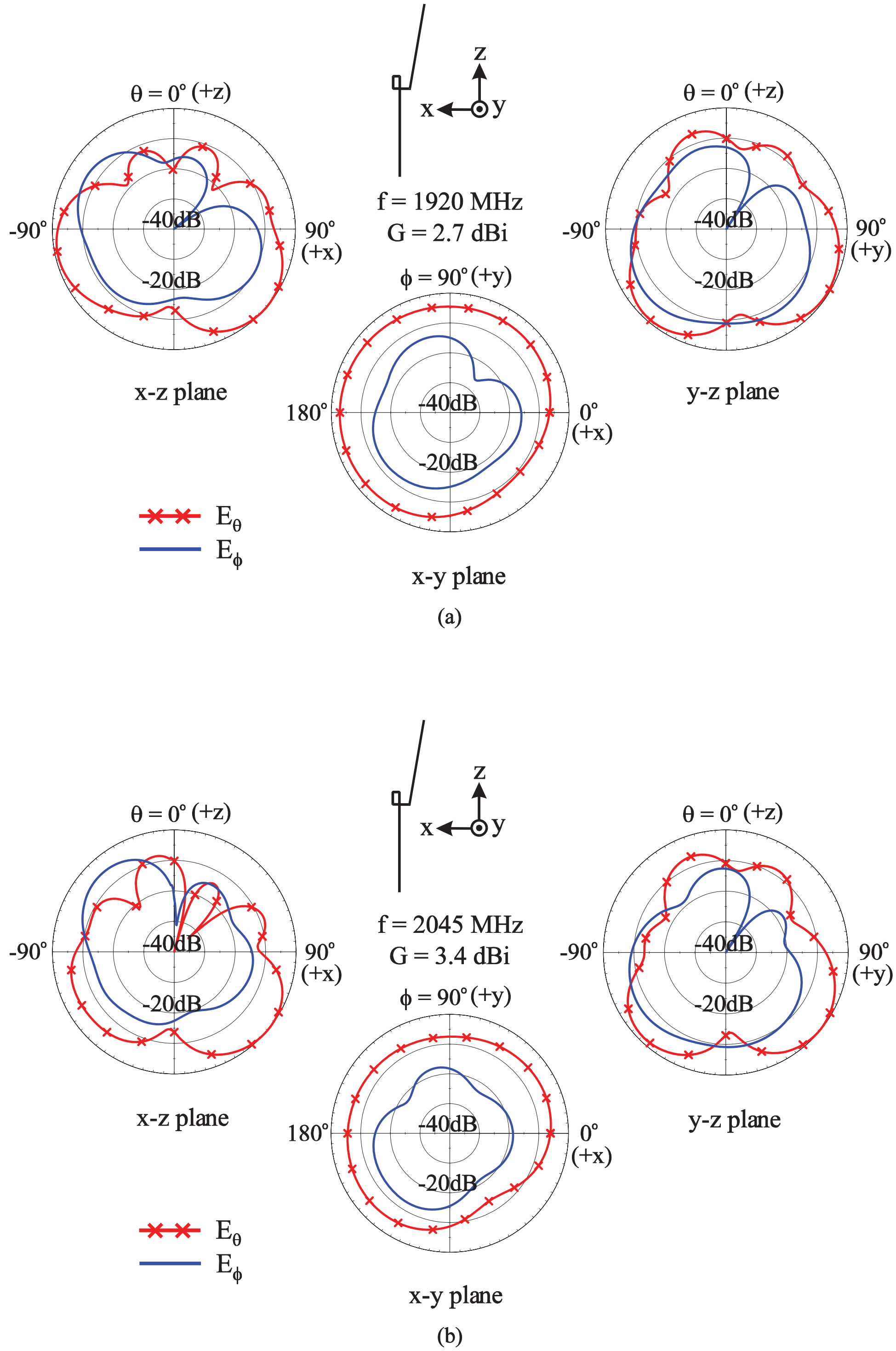

Figure 9 Measured radiation patterns at (a) 1920 MHz and (b) 2045 MHz for the antenna studied in Figure 2. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

about 103% centered at 1635 MHz), allowing the antenna to easily cover GSM850/900/DCS/PCS/UMTS operation with good radiation efficiencies larger than 70% for the mobile phone in the open state (talk condition). When the mobile phone changes from the open state to the close state (idle condition), good impedance matching over the desired operating band can still be obtained by including a series chip capacitor of 3.9 pF at the antenna's feeding point, and the radiation efficiencies over the band can still be better than 53%. With ultra-wideband achieved, small volume occupied, and good radiation characteristics obtained for the mobile phone in either the open or close state, the proposed antenna is very promising to be embedded inside the housing of the folder-type mobile phone to operate as an internal antenna for covering GSM850/900/DCS/PCS/UMTS operation.

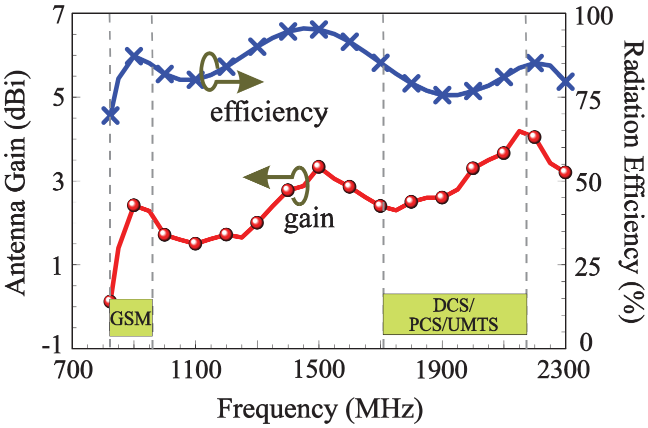

Figure 10 Measured antenna gain and simulated radiation efficiency for the antenna studied in Figure 2. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

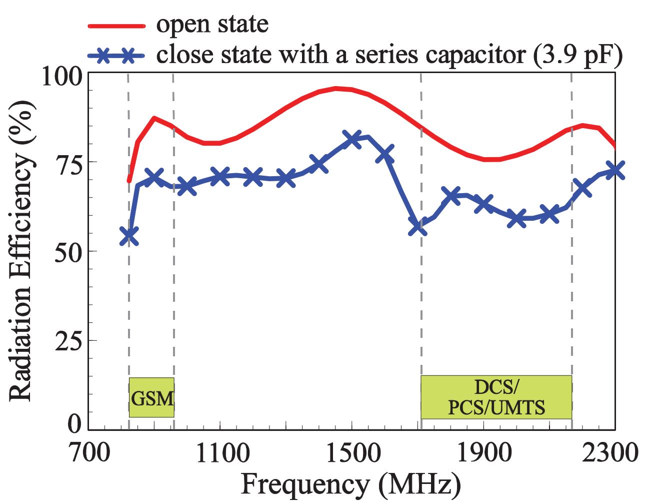

Figure 11 Comparison of simulated radiation efficiency for the antenna in the open state ($\alpha = 15°$) and the close state ($\alpha = 180°$) with a series capacitor of 3.9 pF. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

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TUNABLE SHARP NOTCH FILTER FOR UWB APPLICATION

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ABSTRACT: *This article presents a novel tunable sharp notch filter using open stub structure with varactor for implementing detect-and-avoid method into ultrawideband radio system. On the basis of the experimental results on the open stub structure with lumped capacitor, we introduced two techniques in this work to realize a tunable sharp notch filter using open stub structure with varactor to perform narrow stop-band and using resistors to build a DC bias circuit, so that no influence to the tunable notch filter over a wide band. The developed tunable notch filter has excellent performance: wide tuning range from 3.65 to 4.35 GHz with low tuning voltage from 0 to 6 V, narrow bandwidth less than 270 MHz of the notch filter (at 10 dB insertion loss at 0 V), and compact size of the developed filter: about 2.0 cm × 4.0 cm.* © 2008 Wiley Periodicals, Inc. Microwave Opt Technol Lett 50: 2712–2715, 2008; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.23773

Key words: *lumped capacitor; open stub resonator; varactor; UWB; detect and avoid*

1. INTRODUCTION

Recently, ultrawideband (UWB) communication systems have been used as wireless personal area networks, particularly in audiovisual data transmission applications [1]. Federal Communication Commission (FCC), USA, released the UWB spectrum for the commercial applications in February 2002 [2]. In Europe and Japan, the temporally UWB spectral mask for the commercial applications was released [3, 4], where implementing detect-and-avoid (DAA) method is a regulatory requirement to ensure that the UWB and other narrow band (NB) radio systems can coexist without interfering with each other. In November 2007, it was reported by ITU-R that the fourth generation mobile phone will use the frequencies from 3.456 to 3.6 GHz in Japan [5]. Therefore, it will be an important issue to solve the