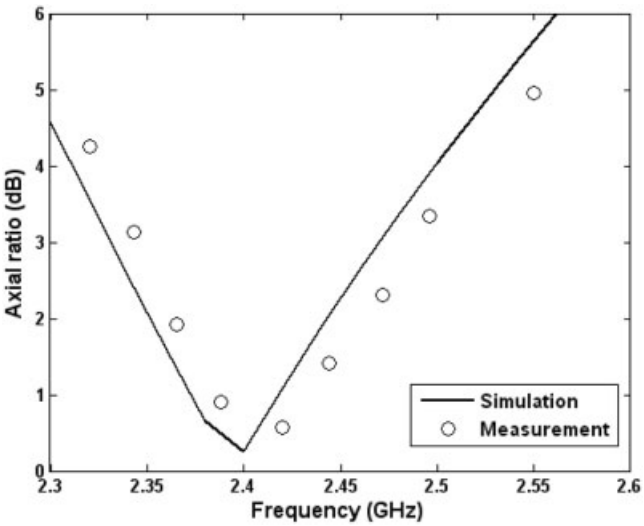


**Figure 6** Simulated and measured axial ratio against frequency

conical beam patterns was characterized and verified with measurements and shown to have acceptable axial ratio. The present antenna design can be used as a good candidate for applications in short-range wireless communication systems, particularly wireless sensor networks, where the conical beam will give advantages of energy saving and reduced co-channel interference. Other applications could include indoor WLAN antennas for mounting on ceilings or other horizontal surfaces.

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# SEVEN-BAND SURFACE-MOUNT LOOP ANTENNA WITH A CAPACITIVELY COUPLED FEED FOR MOBILE PHONE APPLICATION

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**ABSTRACT:** *A surface-mount loop antenna with a capacitively coupled feed capable of seven-band operation in the mobile phone is presented. The capacitively coupled feed successfully excites the 0.5-, 1.0-, and 1.5-wavelength modes of the loop antenna. Further, the presence of the capacitively coupled feed leads to a new loop path, whose length is slightly less than that of the original loop strip. The 0.5-, 1.0-, and 1.5-wavelength modes of the new loop path are also excited with good impedance matching. The two 0.5-wavelength modes of the new loop path and original loop strip form a wide bandwidth of 310 MHz for the antenna's lower band to cover GSM850/900 operation. The other modes of the two loops form a very wide bandwidth of larger than 1 GHz for the antenna's upper band to cover GSM1800/1900/UMTS/WLAN/WiMAX operation. With seven-band operation achieved, the proposed loop antenna only occupies a small volume of 60 × 10 × 3 mm$^3$ (1.8 cm$^3$), and owing to its thin thickness of 3 mm only, and the antenna is very promising for thin mobile phone applications.* © 2008 Wiley Periodicals, Inc. Microwave Opt Technol Lett 51: 81–88, 2009; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.23955

**Key words:** *internal mobile phone antennas; loop antennas; surface-mount antennas; capacitively coupled feed; multiband operation*

## 1. INTRODUCTION

Recently, a variety of multiband loop antennas for wireless wide area network (WWAN) operation in the mobile phone have been demonstrated [1–7]. These loop antennas are attractive for mobile phone applications in part, because their excited surface current paths are in a closed form, which is different from the conventional mobile phone antennas such as the monopoles or planar inverted-F antennas (PIFAs), whose excited surface current paths are in an open form [8]. Hence, the possible coupling between the loop antenna and the system ground plane of the mobile phone can be much smaller than that of the conventional mobile phone antennas. In this case, the variations in the dimensions of the system ground plane will show smaller effects on the performances of the loop antenna.

For the reported multiband loop antennas for mobile phone applications [1–7], most of them use a direct feed, and the obtained operating bands cover several of the GSM850 (824–894 MHz), GSM900 (890–960 MHz), GSM1800 (1710–1880 MHz), GSM1900 (1850–1990 MHz), and UMTS (1920–2170 MHz) bands for WWAN operation. In this article, we present a surface-mount loop antenna with a capacitively coupled feed for achieving seven-band operation covering all the five operating bands for WWAN operation, the 2.4-GHz band (2400–2484 MHz) for wireless local area network (WLAN) operation, and the 2.5-GHz band (2500–2690 MHz) for worldwide interoperability for microwave access (WiMAX) operation [9–15]. That is, WWAN/WLAN/WiMAX multinetwork operation can be achieved for the proposed antenna.

The capacitively coupled feed applied in the proposed loop antenna comprises a coupling strip and a tuning strip, which is

different from the conventional capacitive feed that has been studied for internal mobile phone antennas [5, 16–18]. The conventional capacitive feed mainly has a coupling strip or coupling portion only, and with the capacitive feed, widened bandwidth in the lower band (900 MHz band) of the antenna [16] or reduced size of the antenna [17, 18] has been demonstrated. In [5], by using a coupling stub as the capacitive feed, two wide operating bands are achieved to cover GSM850/900/1800/1900 quad-band operation for the loop antenna with an occupied volume of 3.4 $cm^3$.

In the proposed design, the loop antenna is formed by mounting a meandered loop strip onto the surfaces of a foam base of 60 × 10 × 3 $mm^3$ (1.8 $cm^3$) only. The antenna is then surface-mounted to the system circuit board of the mobile phone on top of the capacitively coupled feed printed on the system circuit board. Through the capacitive coupling of the coupling strip in the capacitively coupled feed, the 0.5-, 1.0-, and 1.5-wavelength modes of the surface-mount loop antenna can be successfully excited. In addition, the capacitively coupled feed can generate a new loop path, whose length is slightly less than that of the original loop strip, and the 0.5-, 1.0-, and 1.5-wavelength modes of the new loop path can also be excited. The two 0.5-wavelength modes of the new loop path and original loop strip form a wide lower band for the antenna to cover GSM850/900 operation. The 1.0- and 1.5-wavelength modes of the new loop path and original loop strip can also be formed into a wide upper band for the antenna by further selecting a proper length of the tuning strip in the capacitively coupled feed, and the obtained upper band can cover GSM1800/1900/UMTS/WLAN/WiMAX operation. The proposed loop antenna is hence capable of seven-band operation in three different wireless networks. The proposed antenna with the capacitively coupled feed is studied in the article. Experimental and simulation results of the constructed prototype are presented and discussed.

## 2. ANTENNA DESIGN

Figure 1(a) shows the geometry of the proposed seven-band surface-mount loop antenna with the capacitively coupled feed. The loop antenna is a surface-mountable element, and it is to be mounted on the front side of the top no-ground portion (area 60 × 10 $mm^2$) of the system circuit board of the mobile phone (a 0.8-mm-thick FR4 substrate of area 60 × 110 $mm^2$ used here) for practical applications. A ground plane of 60 × 100 $mm^2$ is printed on the back side of the FR4 substrate as the system ground plane of the mobile phone. The selected dimensions of the system circuit board and the ground plane are reasonable for general smart phones or PDA phones [19, 20].

The loop antenna is obtained by attaching a meandered loop strip onto the surfaces of a thin foam base of volume 60 × 10 × 3 $mm^3$ (1.8 $cm^3$). The meandering of the loop strip is to achieve a longer length (total length about 265 mm here, starting from point A, then through points C and D, to point B) on the fixed surfaces of the foam base. Detailed dimensions of the loop strip in its planar structure are given in Figure 1(b). The two ends (point A and point B) of the loop strips are grounded to the top edge of the system ground plane, and hence a closed loop path is formed. The loop strip has a narrow width of 0.5 mm, except at the widened section $\bar{CD}$ of length 15 mm and width 2.5 mm. The widened section is centered on top of the coupling strip in the capacitively coupled feed printed on the back side of the top no-ground portion. Through the capacitive coupling between the widened section and the coupling strip, the 0.5-, 1.0-, and 1.5-wavelength modes of the loop strip at about 0.75, 1.7, and 2.3 GHz can be excited with good impedance matching. The good excitation is easily controlled by adjusting the dimensions of the coupling strip whose preferred

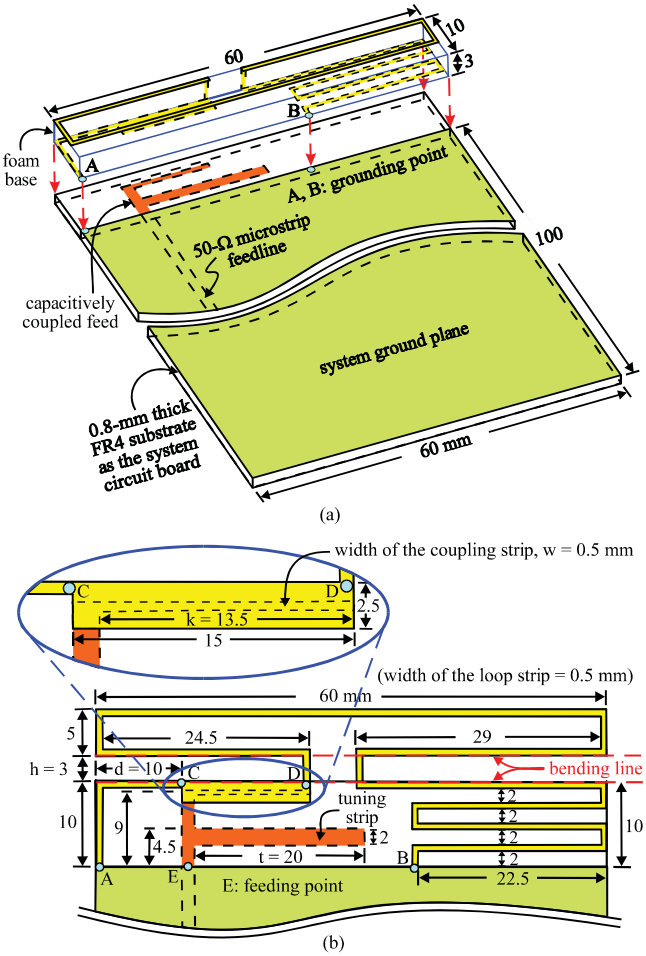


**Figure 1** (a) Geometry of the proposed surface-mount loop antenna with the capacitively coupled feed for seven-band operation in the mobile phone. (b) Dimensions of the antenna in its planar structure. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

width ($w$) is 0.5 mm and length ($k$) is 13.5 mm. Their detailed effects will be analyzed in Figure 5 in the next section.

In addition to the coupling strip, there is a tuning strip of length ($t$) 20 mm and width 2 mm in the capacitively coupled feed. The front end (point E) of the capacitively coupled feed is the antenna's feeding point, which is connected to a 50-Ω microstrip feedline printed on the back side of the system circuit board. It can be seen that, with the presence of the capacitively coupled feed, a new loop path starting from point E, through section $\bar{CD}$, to point B is formed, whose length is about 255 mm, slightly shorter than that of the original loop strip (loop ACDB or loop 1). The 0.5-, 1.0-, and 1.5-wavelength modes of the new loop path (loop ECDB or loop 2) at about 1.0, 2.1, and 2.7 GHz can also be excited with good impedance matching by selecting a proper length of the tuning strip (the preferred length $t$ is 20 mm here). Detailed effects of the length $t$ are studied in Figure 6.

With good excitation of the resonant modes of the two loops (loops 1 and 2), two wide operating bands for the antenna are achieved. The two 0.5-wavelength modes of loops 1 and 2 at about 0.75 and 1.0 GHz are formed into a wide lower band for the antenna to easily cover GSM850/900 operation. The 1.0- and 1.5-wavelength modes of the two loops at about 1.7, 2.1, 2.3, and 2.7 GHz are also formed into a very wide band for the antenna's upper band to cover GSM1800/1900/UMTS/WLAN/WiMAX op-

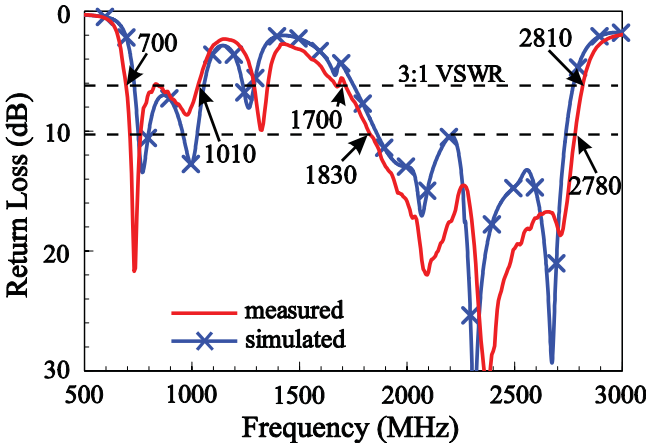


**Figure 2** Measured and simulated return loss for the proposed antenna. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

eration. A seven-band operation is hence achieved for the proposed antenna with a volume of 1.8 cm$^3$ only. In addition, the thickness $h$ of the proposed loop antenna or the thickness of the foam base can still be decreased from 3 to 2 mm, without large effects on the antenna performances. In this case, the antenna volume can further be reduced to be 1.2 cm$^3$ only. Detailed effects of the thickness $h$ are discussed in Figure 7 in the next section.

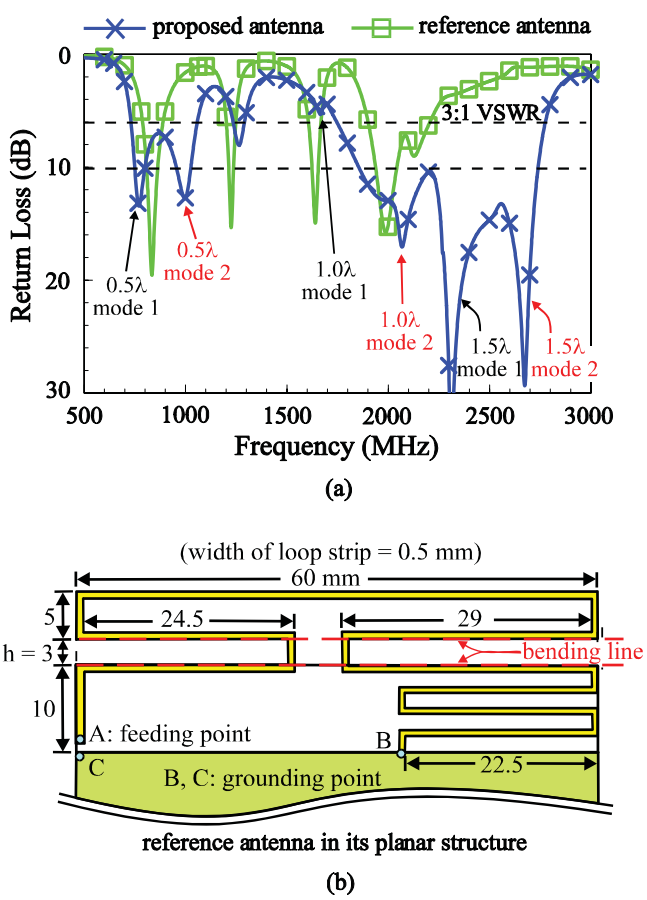


**Figure 3** (a) Simulated return loss of the proposed and reference antennas. (b) Dimensions of the reference antenna in its planar structure; the reference antenna occupies the same volume as the proposed antenna. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

## 3. RESULTS AND DISCUSSION

The proposed loop antenna shown in Figure 1 was fabricated and tested. Figure 2 shows the measured and simulated return loss for the constructed prototype. The simulated results are obtained using Ansoft HFSS [21]. From the results, good agreement between the measurement and simulation is seen. It can be seen that the antenna's lower band formed by two resonances (0.5-wavelength modes) has a wide bandwidth of 310 MHz ranging from 700 to 1010 MHz (3:1 VSWR or 6-dB return loss), allowing it to easily cover GSM850/900 operation. The antenna's upper band mainly formed by the 1.0- and 1.5-wavelength modes of loops 1 and 2 (loops ACDB and ECDB) shows a very large bandwidth of 1110 MHz (1700–2810 MHz) and easily covers GSM1800/1900/UMTS/WLAN/WiMAX operation. In addition, the impedance matching for frequencies over the WLAN (2400–2484 MHz) and WiMAX (2500–2690 MHz) bands is better than 10-dB return loss.

To study the excited resonant modes more clearly, a comparison of the simulated return loss of the proposed antenna and the reference antenna (the corresponding loop antenna with a conven-

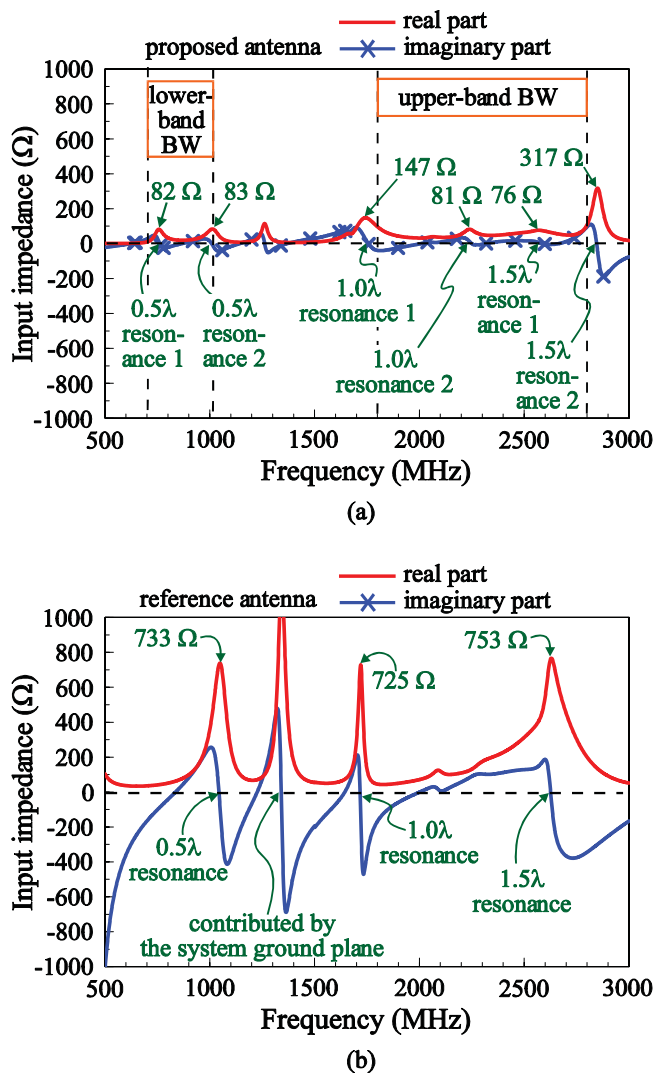


**Figure 4** Simulated input impedance for (a) the proposed antenna and (b) the reference antenna in Figure 3. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

tional feed) is shown in Figure 3(a). Dimensions of the reference antenna in its planar structure are shown in Figure 3(b), and the reference antenna occupies the same volume as the proposed antenna. Note that the excited modes of 0.5λ mode 1, 1.0λ mode 1, and 1.5λ mode 1 indicated in the figure at about 0.8, 1.7, and 2.3 GHz are contributed by loop 1 (loop ACDB), while the 0.5λ mode 2, 1.0λ mode 2, and 1.5λ mode 2 at about 1.05, 2.1, and 2.7 GHz are controlled by loop 2 (loop ECDB). Also, as compared to the reference antenna, the proposed antenna shows much wider lower and upper bands for covering GSM850/900 and GSM1800/1900/UMTS/WLAN/WiMAX operations.

To show the effects of the capacitively coupled feed more clearly, a comparison of the simulated input impedance for the proposed and reference antennas is also shown in Figures 4(a) and 4(b). The indicated 0.5λ resonance 1, 1.0λ resonance 1, and 1.5λ resonance 1 are zero reactance controlled by loop 1, and near these resonances, the three resonant modes of 0.5λ mode 1, 1.0λ mode 1, and 1.5λ mode 1 shown in Figure 3(a) are excited. Similarly, the 0.5λ resonance 2, 1.0λ resonance 2, and 1.5λ resonance 2 are zero reactance controlled by loop 2, which leads to the excitation of three related resonant modes controlled by loop 2 shown in Figure 3(a). Note that, in addition to these resonances generated owing to the use of the capacitively coupled feed, the input resistance level (real part of the input impedance) is also much smaller than that of the reference antenna shown in Figure 4(b). This makes the input resistance level much closer to 50 Ω. The variations in the input reactance (imaginary part of the input impedance) are also found to be much smaller for the proposed antenna. These attractive features result in good excitation of the 0.5-, 1.0-, and 1.5-wavelength modes of loops 1 and 2 in the proposed antenna. Also note that the resonance occurring at about 1.35 GHz in both Figures 4(a) and 4(b) is mainly controlled by the system ground plane and does not contribute to the desired operating bands for the proposed antenna.

Effects of the width $w$ and length $k$ of the coupling strip are studied Figure 5. The simulated return loss for the width $w$ varied from 0.5 to 1.5 mm is shown in Figure 5(a); other dimensions are the same as given in Figure 1. Results indicate that the dual-resonance excitation (two 0.5-wavelength modes of loops 1 and 2) of the antenna's lower band is achieved by using a small width of 0.5 mm. The effects on the antenna's upper band, however, are very small. Simulated results for the length $k$ varied from 9.5 to 13.5 mm are presented in Figure 5(b), with the width $w$ fixed as 0.5 mm. Results show that the three resonant modes contributed by

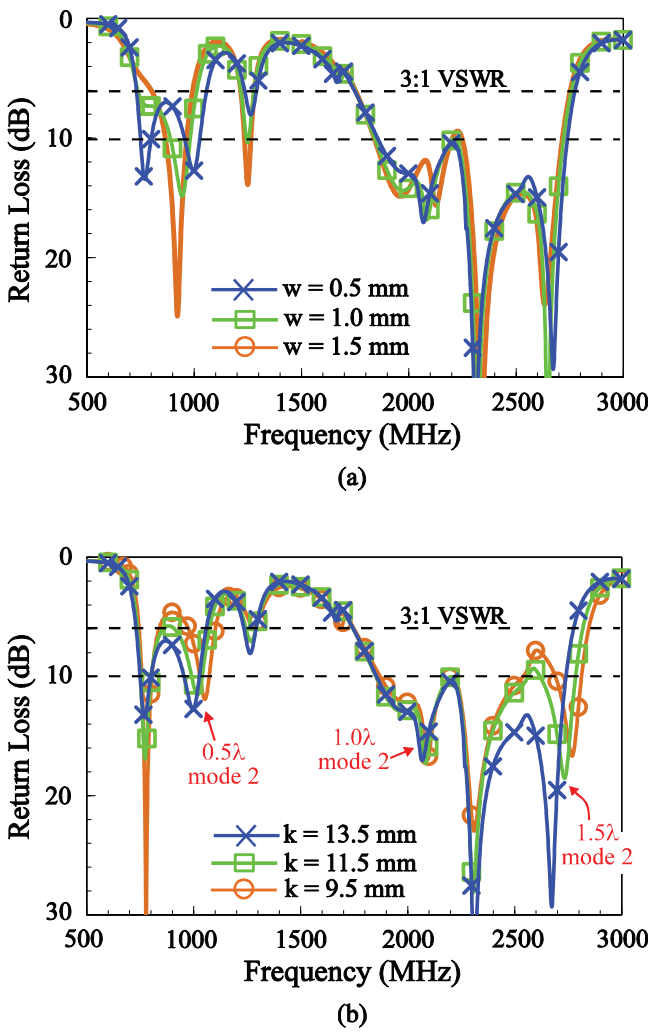


**Figure 5** Simulated return loss as a function of (a) the width $w$ and (b) the length $k$ of the coupling strip in the capacitively coupled feed. Other dimensions are the same as given in Figure 1. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

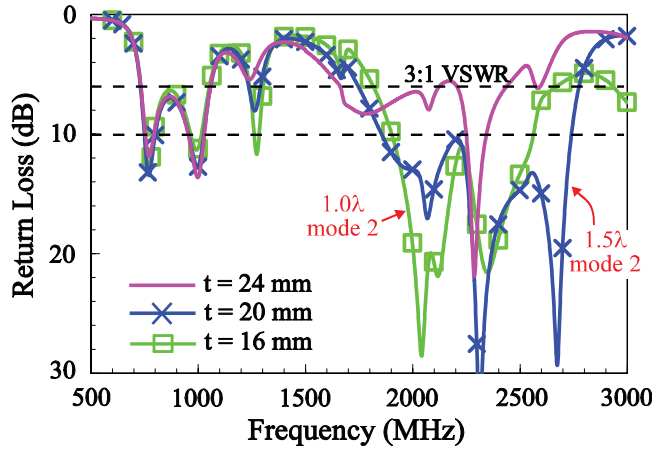


**Figure 6** Simulated return loss as a function of the length $t$ of the tuning strip in the capacitively coupled feed. Other dimensions are the same as given in Figure 1. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

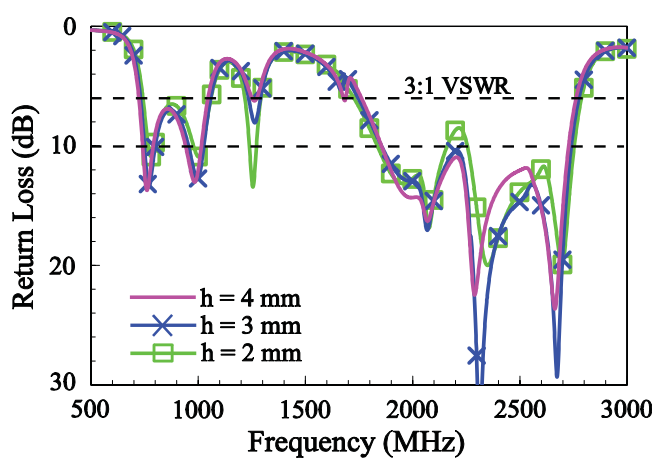


**Figure 7** Simulated return loss as a function of the thickness $h$ of the antenna. Other dimensions are the same as given in Figure 1. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

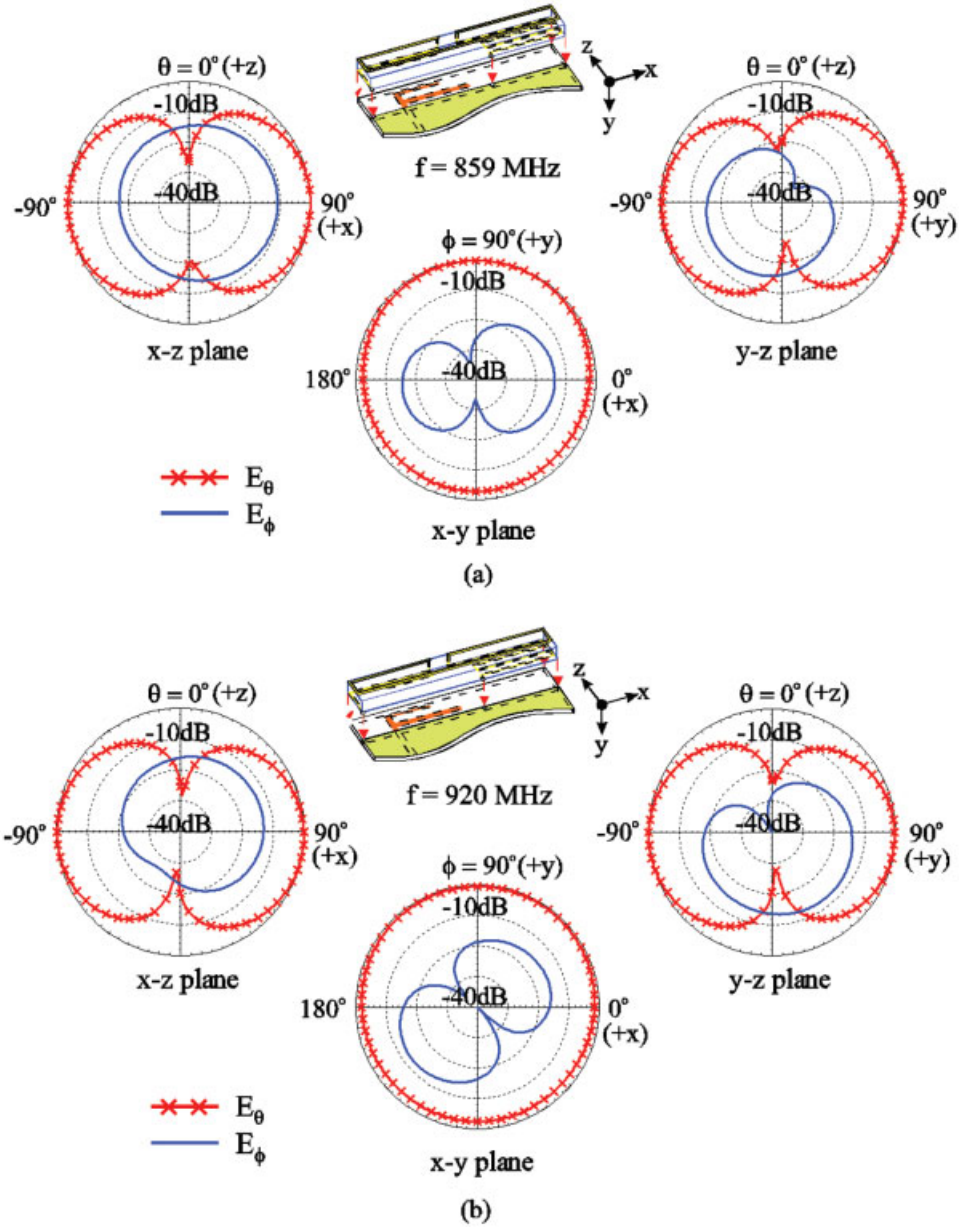


**Figure 8** Measured radiation patterns at (a) 859 MHz and (b) 920 MHz for the antenna. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

loop 2 (loop ECDB) are shifted to higher frequencies when the length $k$ decreases, while those controlled by loop 1 (loop ACDB) are almost not affected. This is largely because the variations in the length $k$ of the coupling strip can lead to some variations in the capacitive coupling, which in turn results in the effective length variations of loop 2.

Effects of the length $t$ of the tuning strip in the capacitively coupled feed are studied in Figure 6. Simulated results of the return loss for the length $t$ varied from 16 to 24 mm are presented, while other parameters are the same as given in Figure 1. Results show that the two modes in the antenna's lower band are almost not affected; however, the 1.0- and 1.5-wavelength modes of loop 2 show large variations. This is largely because the length of the tuning strip is very small as compared to that at 1 GHz, and hence relatively very small effects on the antenna's lower band can be expected. On the other hand, by adjusting the length $t$ of the tuning strip, good excitation of the 1.0- and 1.5-wavelength modes of loop 2 can be obtained.

Figure 7 shows the simulated return loss as a function of the thickness $h$ of the loop antenna or the foam base. Results for $h$ varied from 2 to 4 mm with other parameters fixed, as given in Figure 1, are presented. Small effects on the impedance matching of the antenna's lower and upper bands are seen, except that the impedance matching level around 2.2 GHz is slightly smaller than the 10-dB return loss for the case of $h = 2$ mm. However, the obtained operating bands for the case of $h = 2$ mm can still cover the desired seven-band operation in this study. This makes it possible to further reduce the thickness of the proposed antenna to 2 mm only, which makes the antenna attractive for applications in thin mobile phones [20, 22]. Also, with a thickness of 2 mm only, the occupied volume of the antenna can be reduced to 1.2 $cm^2$ ($60 \times 10 \times 2$ $mm^3$) only.

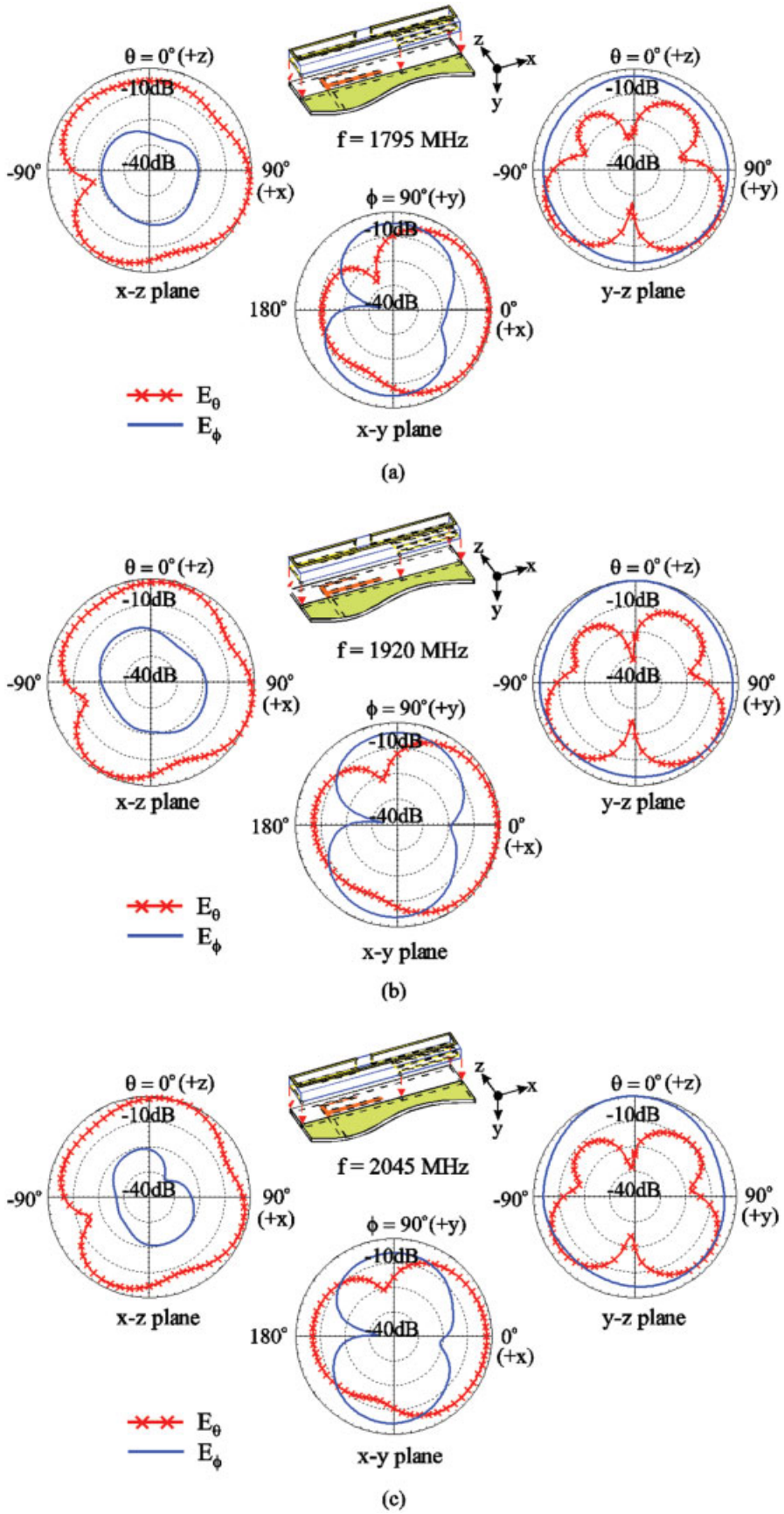


**Figure 9** Measured radiation patterns at (a) 1795 MHz, (b) 1920 MHz, and (c) 2045 MHz for the antenna. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

Radiation characteristics of the constructed prototype are also studied. Figure 8 plots the measured radiation patterns at 859 and 920 MHz. It can be seen that the radiation patterns at 859 and 920 MHz show monopole-like patterns and are similar to each other, which indicates that stable radiation characteristics are obtained over the antenna's lower band.

Figure 9 plots the measured radiation patterns at 1795, 1920, and 2045 MHz, which are the central frequencies of GSM1800, GSM1900, and UMTS bands, respectively. Figure 10 plots the measured radiation patterns at 2442 and 2595 MHz, central frequencies of the 2.4 GHz WLAN band and the 2.5 GHz WiMAX band. It is also seen that the radiation pattern at 1795, 1920, and 2045 MHz are similar to each other. This is reasonable since the operating bands of GSM1800/1900/UMTS are mainly provided by two 1.0-wavelength modes of loops 1 and 2. For the radiation patterns at 2442 and 2595 MHz, they are also similar to each other. Again, this is because the operating bands of WLAN/WiMAX are mainly covered by two 1.5-wavelength modes of loops 1 and 2.

Figure 11 shows the measured antenna gain and simulated radiation efficiency. In Figure 11(a), over the GSM850/900 bands, the antenna gain is about 0.5–1.3 dBi, and the efficiency is larger than 70%. Over the GSM1800/1900/UMTS bands shown in Figure 11(b), the antenna gain is about 0.5–2.7 dBi, and the efficiency is about 65–85%. While over the 2.4 GHz WLAN band, the antenna gain is about 1.5 dBi and the efficiency is about 87%. Over the 2.5-GHz WiMAX band, the antenna gain is about 1.3–2.8 dBi and the efficiency is about 75–85%.

## 4. CONCLUSION

A novel seven-band surface-mount loop antenna with a capacitively coupled feed has been proposed for mobile phone applications. The capacitively coupled feed provides an additional loop

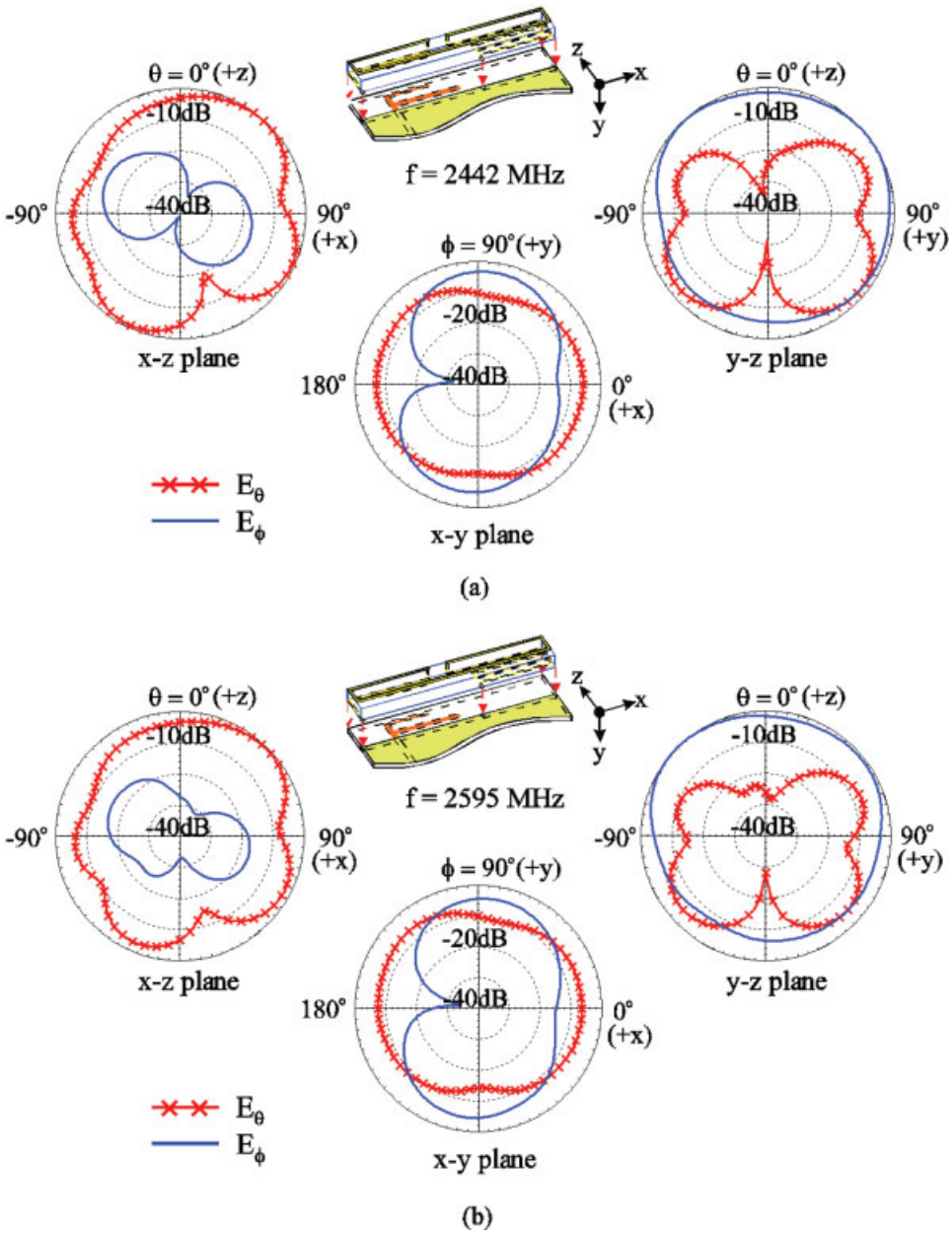


**Figure 10** Measured radiation patterns at (a) 2442 MHz and (b) 2595 MHz for the antenna. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

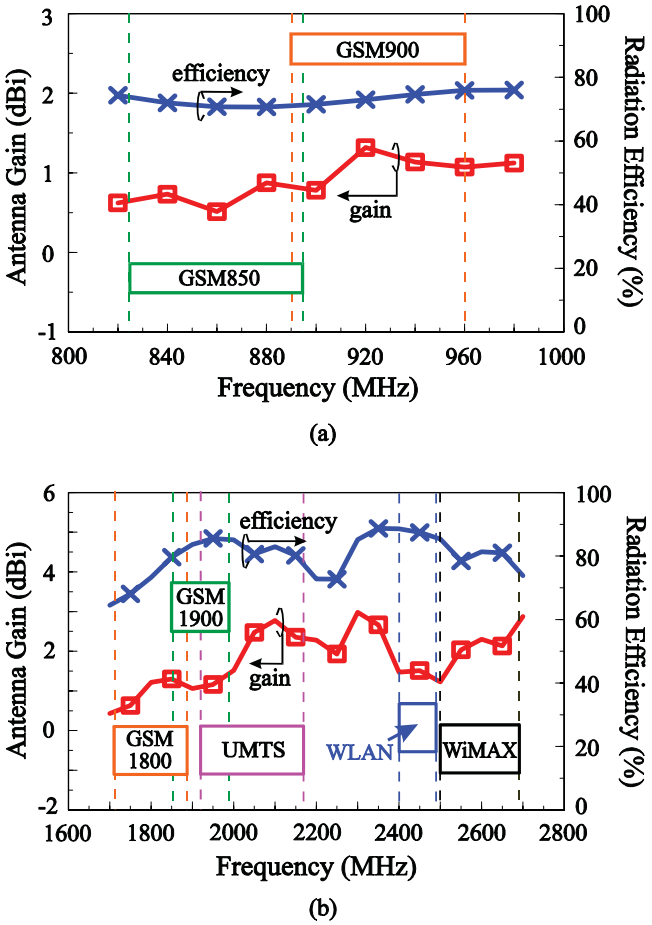


**Figure 11** Measured antenna gain and simulated radiation efficiency over (a) GSM850/900 bands and (b) GSM1800/1900/UMTS/WLAN/WiMAX bands. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

path to the original loop strip, and excites the 0.5-, 1.0-, and 1.5-wavelength modes of the two loops successfully. These excited resonant modes are formed into two wide operating bands for the antenna's lower and upper bands to cover GSM850/900 and GSM1800/1900/UMTS/WLAN/WiMAX operations. Good radiation characteristics over the seven operating bands have also been obtained. In addition, the antenna occupies a small volume of $60 \times 10 \times 3$ mm$^3$ (1.8 cm$^3$) only, with a thin thickness of 3 mm. It is also promising to reduce the thickness to 2 mm only, which can further decrease the occupied antenna volume to be 1.2 cm$^3$. The small volume and thin thickness make the proposed antenna very suitable for thin mobile phone applications.

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# DESIGN OF CPW-FED MONOPOLE UWB ANTENNA WITH A NOVEL NOTCHED GROUND

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**ABSTRACT:** *A novel CPW-fed monopole UWB antenna is presented in this article. To increase the impedance bandwidth, a notched ground is introduced. The parameters and the characteristics of the antenna are*