BANDWIDTH ENHANCEMENT OF INTERNAL WWAN ANTENNA USING AN INDUCTIVELY COUPLED PLATE IN THE SMALL-SIZE MOBILE PHONE

Chih-Hua Chang and Kin-Lu Wong
Department of Electrical Engineering, National Sun Yat-sen University, Kaohsiung 80424, Taiwan; Corresponding author: wongkl@ema.ee.nsysu.edu.tw

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ABSTRACT: *By adding a small inductively coupled plate of size 10 × 45 mm² to the system ground plane of the mobile phone with a short length of 60 mm only, wide lower and upper bands of its internal WWAN antenna (a printed monopole slot antenna in this study) to respectively cover the GSM850/900 and GSM1800/1900/UMTS bands can be obtained. The coupled plate is connected and vertically oriented to the system ground plane through a 10-nH chip inductor, which effectively causes the small coupled plate to resonate at about 925 MHz. A new resonant mode contributed by the coupled plate is hence provided to enhance the bandwidth of the antenna's lower band, which is quickly decreased with decreasing ground plane length of the mobile phone. With the coupled plate added to the ground plane of length 60 mm, the obtained lower-band bandwidth is about the same as that of the internal WWAN antenna for the ground plane of length 105 mm and without the coupled plate. Further, the antenna's upper band for the short ground plane of length 60 mm can still have wide bandwidth for both the cases with and without the coupled plate. Detailed effects of the inductively coupled plate on the bandwidth enhancement of the internal WWAN antenna are analyzed.* © 2010 Wiley Periodicals, Inc. Microwave Opt Technol Lett 52: 1247–1253, 2010; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.25196

Key words: *mobile antennas; handset antennas; printed antennas; WWAN antennas; bandwidth enhancement*

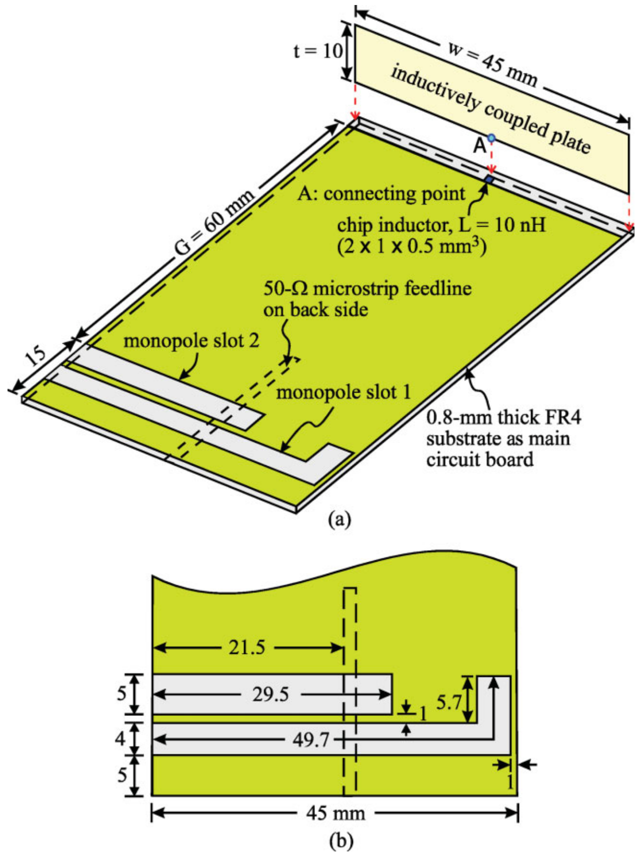


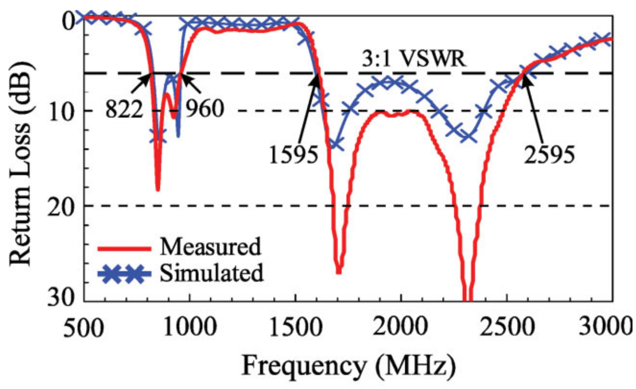
Figure 1 (a) Geometry of the internal WWAN antenna (printed monopole slot antenna) with an inductively rectangular coupled plate in the small-size mobile phone. (b) Dimensions of the printed monopole slot antenna as the internal WWAN antenna. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

1. INTRODUCTION

It has been known that for the internal WWAN mobile phone antenna, the ground plane length of the mobile phone is a dominant factor in achieving a wide bandwidth to cover the GSM850/900 operation [1–4]. This is mainly because, in addition to the embedded internal WWAN antenna, the system ground plane in the mobile phone is also an efficient radiator, especially in the 900-MHz band. Hence, for the small-size mobile phone, it is usually a big challenge to obtain a wide bandwidth in the 900-MHz band to cover the GSM850/900 (824–960 MHz) operation. To achieve widened bandwidth for the 900-MHz band, modifying the ground plane such as making a slotted meandered ground plane to have electrically increased ground plane length has been studied [5]. However, the locations of the embedded slots on the system ground plane will be in conflict with the RF modules of the mobile phone, making it not acceptable for practical applications [6].

In this article, we present a simple yet effective bandwidth-enhancement technique in achieving a wide 900-MHz band for the internal WWAN antenna to cover the GSM850/900 operation in the mobile phone with a short ground plane of length 60 mm only. Note that at 60 mm, about 0.18 wavelength at 900 MHz, the bandwidth of the antenna is about at its minimum, whereas at 120 mm, about 0.36 wavelength at 900 MHz, the bandwidth reaches its maximum [3]. The bandwidth enhancement in this study is achieved by adding a small inductively coupled plate connected to the system ground plane through a chip inductor of proper inductance. Owing to the connecting chip inductor, additional inductance is contributed, which can make the coupled plate with a small size of 10 × 45 mm^2 to resonate at lower frequencies at about 925 MHz. This behavior is because the inductance contributed by the chip inductor can effectively compensate for the increased capacitance resulting from the decreased length of the resonant path provided by the coupled plate [7–9]. This additional new resonant mode can incorporate with the one generated by the internal antenna to form a wide lower band at about 900 MHz to cover the GSM850/900 operation, although the system ground plane has a short length of 60 mm only.

Further, for operating at frequencies in the antenna's upper band, the coupled plate is not at resonance and hence shows small effects on the impedance matching for frequencies over the upper band. For the mobile phone with a short ground plane of length 60 mm (about 0.38 wavelength at 1900 MHz, the bandwidth can reach its maximum [3]), the internal WWAN antenna can have wide bandwidth for both the cases with and without the small coupled plate to cover the GSM1800/1900/UMTS (1710–2170 MHz) operation. Details of the proposed inductively coupled plate for bandwidth enhancement in the small-size mobile phone are described, and results of the fabricated prototype are presented. The specific absorption rate (SAR) [10–13] results obtained using the simulation SAR model provided by SEMCAD [14] are also analyzed.



(a)

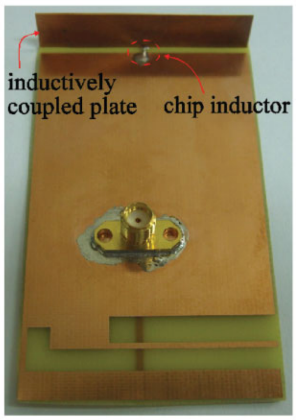


photo of the fabricated antenna

(b)

Figure 2 (a) Measured and simulated return loss for the fabricated antenna. (b) Photo of the fabricated antenna. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

2. BANDWIDTH ENHANCEMENT USING INDUCTIVELY COUPLED PLATE

Figure 1(a) shows the geometry of the internal WWAN antenna with an inductively rectangular coupled plate in the small-size mobile phone. The WWAN antenna studied here is a printed monopole slot antenna or quarter-wavelength slot antenna that has been reported in [15]. Figure 1(b) shows the dimensions of the printed monopole slot antenna, which comprises a longer monopole slot of length 49.7 mm (slot 1) and a shorter monopole slot of length 29.5 mm (slot 2). The antenna is directly printed on the system or main circuit board (a 0.8-mm thick FR4 substrate here) of the mobile phone, occupying a board space of 10×45 mm^2. Note that the lengths of the two slots are larger than those in [15] (49 vs. 44 mm for slot 1 and 29.5 vs. 27.5 mm for slot 2) where the 1-mm thick plastic housing enclosing the main circuit board is included in the study, which can decrease the resonant frequency of the internal antenna enclosed therein. That is, for practical applications with the plastic housing included, the occupied size of the monopole slot antenna studied here will be smaller.

In the studied antenna, slot 1 and slot 2 control the excitation of the antenna's lower and upper bands at about 900 and 1900 MHz, respectively. Both slot 1 and slot 2 are operated as quarter-wavelength structures [15–22], although their lengths are smaller than one-quarter wavelength at 900 and 2000 MHz, respectively. This is owing to the presence of the FR4 substrate (relative permittivity 4.4) on one side of the printed slot, which decreases the resonant frequency of the antenna [23]. Such a printed slot antenna is hence described as a quarter-wavelength slot antenna or monopole slot antenna and is different from the traditional half-wavelength slot antenna [23–25]. By using the monopole slot antenna, compact size of the internal WWAN antenna for mobile phone application can be achieved. Details of the operating principle of the printed monopole slot antenna in this study has been described in [15], and it can cover GSM850 (824–894 MHz), GSM900 (880–960 MHz), GSM1800 (1710–1880 MHz), GSM1900 (1850–1990 MHz), and UMTS (1920–2170 MHz) bands in the mobile phone with a ground plane length 85 mm. However, results have shown that when the ground plane length decreases, the obtained bandwidth quickly decreases and can no longer cover the desired five operating bands for WWAN operation [15].

In this study, the mobile phone with a short system ground plane is considered. The ground plane length G is only 60 mm and is printed on the front surface of the main circuit board. When the inductively coupled plate is not present, the monopole slot antenna provides a narrow resonant mode at about 900 MHz, which is far from covering the GSM850/900 bands (see Fig. 3). With the proposed coupled plate connected to the ground plane through a 10-nH chip inductor (length 2 mm, cross-sectional area 1×0.5 mm^2), a new resonant mode contributed by the coupled plate at about 925 MHz can be provided to enhance the bandwidth of the antenna's lower band, although the coupled plate has a small size of 10×45 mm^2 only. This behavior is mainly because the coupled plate functions as a parasitic resonator, which is inductively coupled to the ground plane. Moreover, owing to the additional inductance contributed by the chip inductor to effectively compensate for the increased capacitance resulting from the decreased length of the resonant path provided by the coupled plate [7–9], the new excited resonant mode of the coupled plate can be controlled to incorporate with the one generated by the studied internal antenna to form a wide lower band at about 900 MHz to cover the GSM850/900 operation. Detailed effects of the dimensions of the rectangular coupled plate and the inductance of the connecting chip inductor are analyzed in the following section with the aid of Figures 5 and 6. Also, the proposed coupled plate can be of other shapes, such as the T-shape and loop shape, as shown in Figure 7. The obtained results on the coupled plate of various shapes will be analyzed in the following section.

On the other hand, the coupled plate does not resonate at frequencies in the antenna's upper band (will be discussed in Fig. 8). This makes the coupled plate have small effects on the impedance matching of the frequencies over the upper band. In this case, because the ground plane length 60 mm corresponds to about 0.38 wavelength at 1900 MHz, the bandwidth of the antenna's upper band can reach its maximum [3] to cover the GSM1800/1900/UMTS operation.

Also, note that when the connecting chip inductor is replaced by a simple metal strip (that is, the coupled plate is a simple directly coupled plate [26, 27] to the ground plane printed on the main circuit board), the small coupled plate of size 10×45 mm^2 will resonate at higher frequencies at about 2.1 GHz (detailed results will be discussed in Fig. 5). By applying the chip inductor and adjusting its inductance, the resonant mode generated by the coupled plate can be controlled to occur at frequencies in the antenna's lower band. In addition, because the coupled plate has a small size, it can be oriented to be perpendicular to the ground plane and embedded inside the housing of the mobile phone, without increasing the physical length of the mobile phone and also occupying no board space of the main circuit board of the mobile phone.

3. RESULTS AND DISCUSSION

Figure 2(a) shows the measured and simulated return loss for the fabricated antenna, and Figure 2(b) gives the photo of the fabricated antenna. Good agreement between the measurement and simulation obtained using Ansoft HFSS [28] is obtained. Two wide operating bands at about 900 and 1900 MHz are generated for the proposed antenna. The antenna's lower band is formed by two resonant modes and shows a wide bandwidth of 138 MHz (822–960 MHz), allowing the antenna to cover the GSM850/900 operation. The upper band is formed by a dual-resonant mode contributed by the shorter slot (slot 2), and the result is similar to that obtained for the mobile phone with a ground plane of length 85 mm studied in [15]. The bandwidth of the upper band reaches 1 GHz, from 1595 to 2595 MHz, and covers the GSM1800/1900/UMTS operation.

A comparison of the simulated return loss for the proposed antenna and the case without the chip inductor and coupled plate is shown in Figure 3(a). The ground plane length G is 60 mm. It is seen that when the chip inductor and coupled plate are not present, only one resonant mode with degraded impedance matching is obtained at around 900 MHz for the antenna's lower band. For the proposed antenna, there are two resonant modes occurred at around 900 MHz for the antenna's lower band. The resonant mode at frequencies close to 925 MHz is contributed by the coupled plate as discussed in Section 2, and the one at about 860 MHz is mainly generated by the longer slot (slot 1) in the studied monopole slot antenna. Moreover, improved impedance matching of the resonant mode at about 860 MHz is seen, owing to the presence of the coupled plate. This can be seen more clearly from the corresponding results of the simulated input impedance shown in Figure 3(b). The large real and imaginary parts of the input impedance for frequencies over the first mode in the lower band are decreased, leading to improved impedance matching seen in Figure 3(a) for the resonant mode at about 860 MHz. An additional resonance corresponding to the second mode in the lower band as obtained in Figure 3(a) is seen. On the other hand, the impedance matching for frequencies over the antenna's upper band is about the same. This is because the coupled plate is not at resonance over the antenna's upper band.

Figure 4 shows the simulated return loss for the proposed antenna (ground plane length $G = 60$ mm) and the two cases without the chip inductor and coupled plate for $G = 95$ and 105 mm. For the latter two cases, different from the proposed antenna, no additional resonant mode in the antenna's lower band is seen. It is also seen that the obtained bandwidth of the proposed antenna with $G = 60$ mm is about the same as that for the case of no coupled plate and with $G = 105$ mm. That is, the proposed antenna with a short ground plane of length 60 mm can achieve the same bandwidth as the general mobile phone with a ground plane of length 105 mm.

Figure 5 shows the simulated return loss as a function of the inductance L of the chip inductor. Other dimensions are the same as given in Figure 1. Note that for the case of $L = 0$, a simple metal strip of length 2 mm and width 1 mm is used to replace the chip inductor to connect the coupled plate to the ground plane of the mobile phone. For $L = 0$, the coupled plate contributes a new resonant mode occurred at about 2.1 GHz, making large variations in the impedance matching over the antenna's upper band. Poor impedance matching over the lower band is also seen. For L varied from 8 to 12 nH, improved impedance matching for the original resonant mode at about 860 MHz is obtained. In addition, the new resonant mode contributed by the coupled plate is adjusted to occur at frequencies

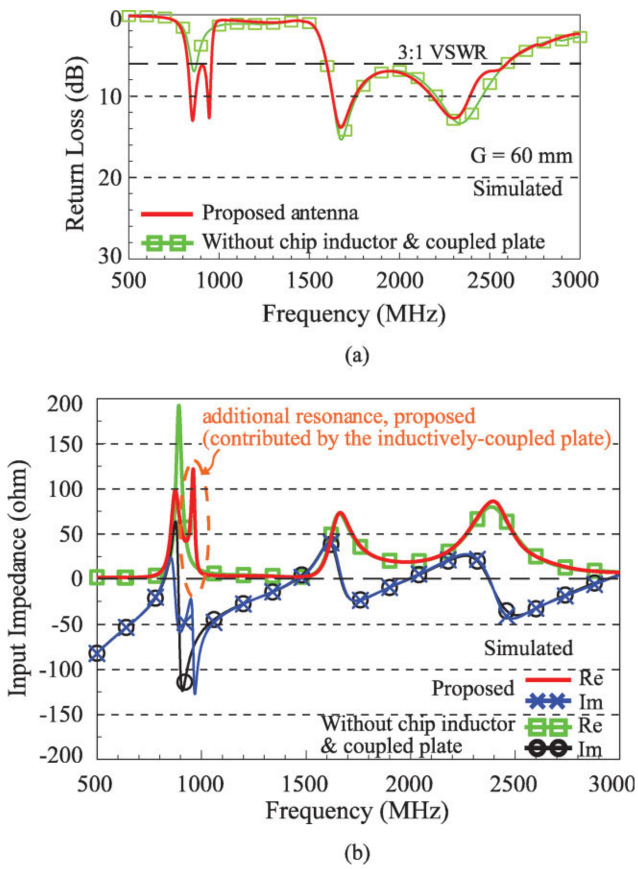


Figure 3 Simulated (a) return loss and (b) input impedance for the proposed antenna and the case without the chip inductor and coupled plate. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

close to about 925 MHz. For $L = 10$ nH, the new resonant mode can be tuned to incorporate the original mode to form a wide lower band to cover the GSM850/900 operation.

Effects of the dimensions of the coupled plate are also analyzed. Results of the simulated return loss for the length t varied from 8 to 12 mm are shown in Figure 6(a) whereas those for the width w varied from 35 to 45 mm are given in Figure 6(b). Small variations in the resonant frequency of the first mode in the lower band for various lengths and widths of the coupled plate are seen. The second mode in the lower band, however, is shifted to lower frequencies with decreasing length or width of the coupled plate. This behavior indicates that the additional resonant mode or the second mode in the lower band can be controlled by adjusting the length and width of the coupled plate. Also, small variations in the impedance matching over the upper band are observed for various lengths and widths of the coupled plate. This is again owing to the coupling plate not at resonance for frequencies over the antenna's upper band.

Figure 7 shows the simulated return loss for the proposed antenna (rectangular coupled plate with $L = 10$ nH), the case with a T-shape coupled plate ($L = 18$ nH), and the case with a loop-shape coupled plate ($L = 10$ nH). Other dimensions are the same as given in Figure 1. The three cases, studied in Figure 7, show about the same impedance matching over the antenna's lower and upper bands. The loop-shape coupled plate requires the same inductance as that for the rectangular coupled plate in the proposed antenna to achieve the desired bandwidth for the lower band. This indicates that the resonant path provided by

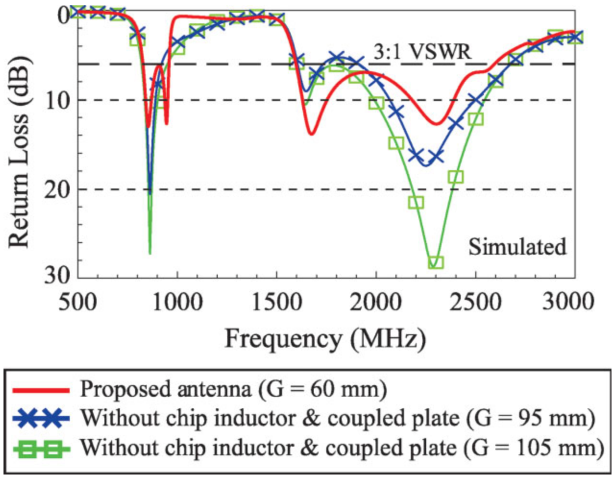


Figure 4 Simulated return loss for the proposed antenna and the two cases without the chip inductor and coupled plate for ground plane length $G = 95$ and 105 mm. Other dimensions are the same as given in Figure 1. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

the rectangular coupled plate in the proposed antenna can be considered to be about the same as that in the loop-shape coupled plate. The T-shape coupled plate, however, requires a larger inductance than that for the rectangular coupled plate (18 vs. 10 nH). This is largely because the resonant path provided by the T-shape coupled plate is shorter than that in the rectangular and loop-shape coupled plates. Hence, a larger inductance is required to compensate for the larger capacitance resulting from the shorter length of the resonant path provided by the coupled plate [7–9].

Figure 8 shows the simulated excited surface current distributions at 859, 925, 1795, 1920, and 2045 MHz for the proposed antenna studied in Figure 2. It is clearly seen that the coupled plate is at resonance at 925 MHz only. At other frequencies, the coupled plate is not at resonance. The results confirm that the new resonant mode occurred at about 925 MHz is contributed by the coupled plate, and the impedance matching over the upper band is generally not affected because the coupled plate is not at resonance.

Figure 9 plots the measured three-dimensional total-power radiation patterns for the proposed antenna studied in Figure 2. The radiation patterns at 859 and 925 MHz (central frequencies of the GSM850 and GSM900 bands in the antenna's lower band) are close to dipole-like patterns, especially for those at 859 MHz. The slight variations in the patterns at 859 and 925 MHz are very likely owing to the different dominant resonant

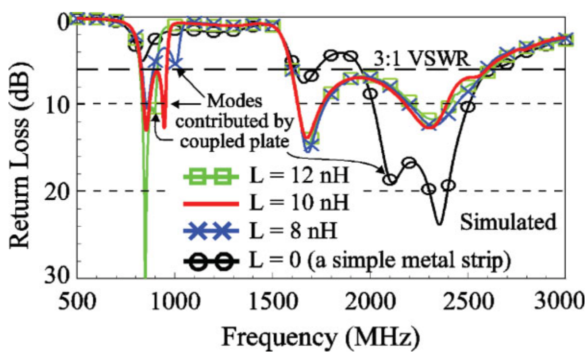


Figure 5 Simulated return loss as a function of the inductance L of the chip inductor. Other dimensions are the same as given in Figure 1. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

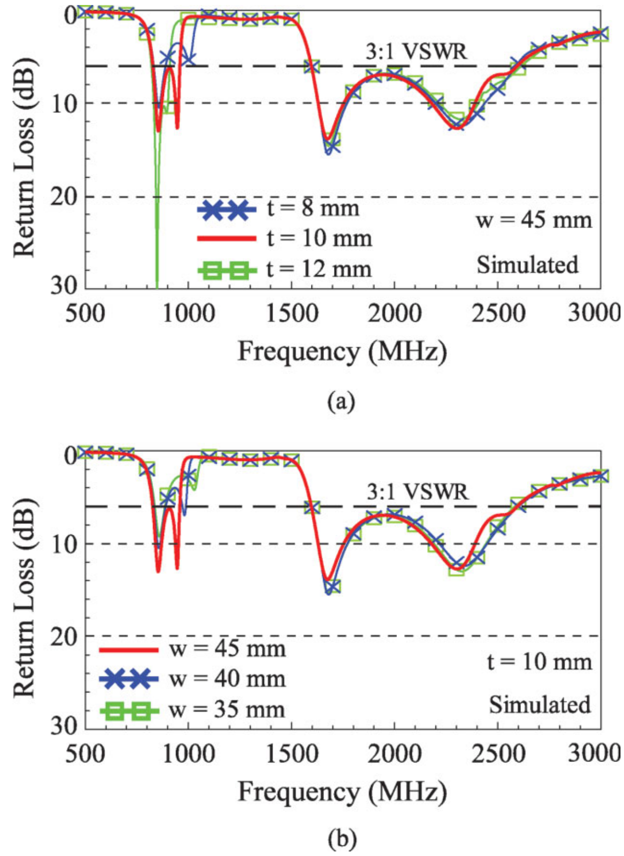


Figure 6 Simulated return loss as a function of (a) the length t and (b) the width w in the inductively coupled plate. Other dimensions are the same as given in Figure 1. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

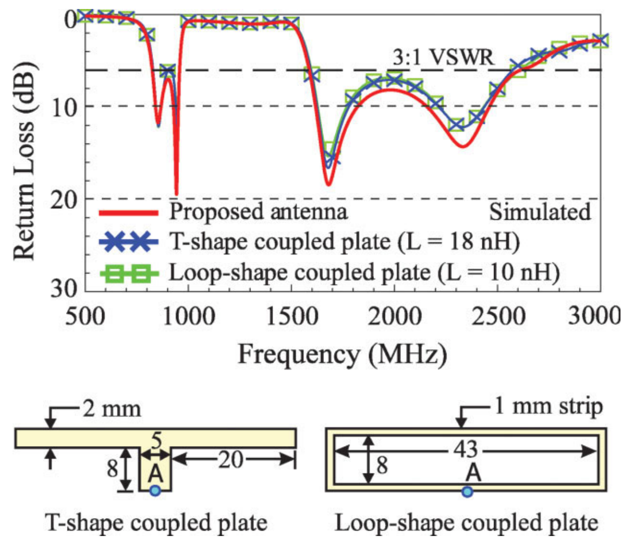


Figure 7 Simulated return loss for the proposed antenna, the case with a T-shape coupled plate and the case with a loop-shape coupled plate. Other dimensions are the same as given in Figure 1. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

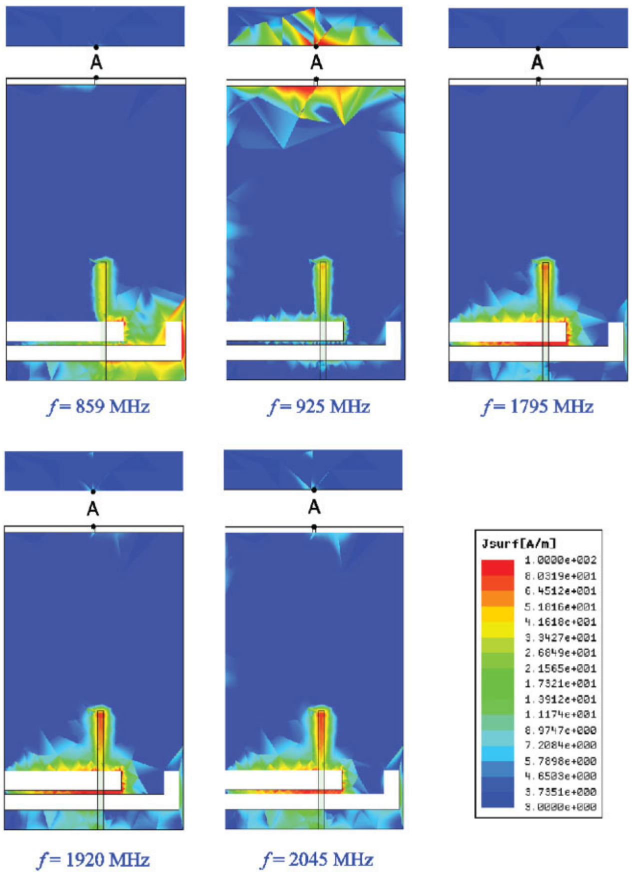


Figure 8 Simulated excited surface current distributions at 859, 925, 1795, 1920, and 2045 MHz for the proposed antenna studied in Figure 2. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

modes at the two frequencies (the monopole slot mode at 859 MHz and the resonant mode contributed by the coupled plate at 925 MHz). Similar radiation patterns at 1795, 1920, and 2045 MHz (central frequencies of the GSM1800, GSM1900, and UMTS bands in the antenna's upper band) are observed. The result is reasonable because the three frequencies are in the upper band formed by the same monopole slot mode contributed by the shorter slot (slot 2).

Figure 10 shows the measured antenna gain and radiation efficiency for the proposed antenna. Over the GSM850/900 bands shown in Figure 10(a), the antenna gain varies from 0.8 to 1.8 dBi, and the radiation efficiency is about 54–72%. Over the GSM1800/1900/UMTS bands in Figure 10(b), the antenna gain varies from 2.7 to 3.8 dBi, and the radiation efficiency is about 78–95%. The radiation efficiency is all better than 50% over the five operating bands, which is acceptable for practical mobile phone applications.

Figure 11 shows the SAR simulation model provided by SEMCAD [14] for the proposed antenna. Because it is known that the internal WWAN antenna with no ground plane on back is promising to be placed at the bottom position of the mobile phone to obtain decreased SAR values [7, 13], only the simulated SAR values for 1-g and 10-g head tissues for the antenna placed at the bottom position of the mobile phone with the presence of the phantom head are given in Table 1. The cases of the ground plane of the mobile phone spaced 5 mm (Case A) and 10 mm (Case B) to the phantom ear are studied. The central line of the mobile phone is oriented by 60° to the vertical axis of the phantom head. The testing power is 24 dBm (2-W continuous input power with a user channel being 1/8 of a time slot) at 859 and 925 MHz for the GSM operation, and 21 dBm at 1795, 1920, and 2045 MHz (1-W continuous input power with a user channel being 1/8 of a time slot at 1795 and 1920 MHz for the GSM operation and 0.125-W continuous input power at 2045 MHz for the UMTS operation). For the 10-g head tissue

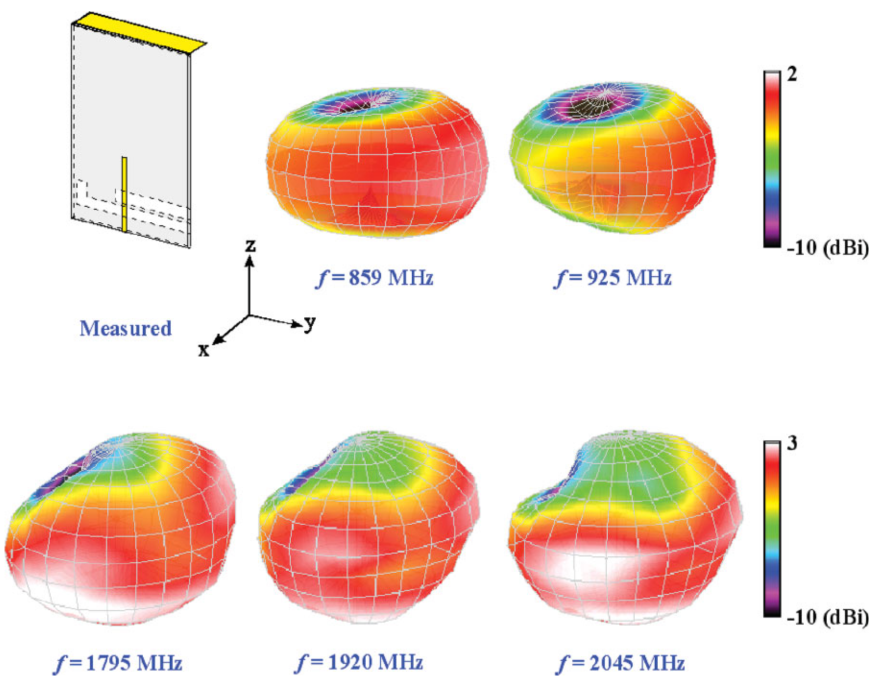
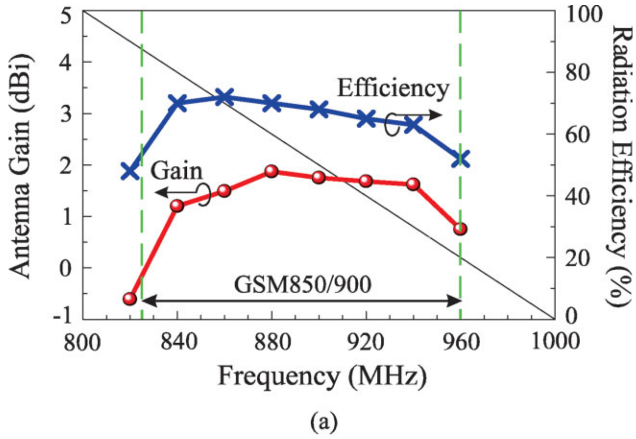


Figure 9 Measured three-dimensional total-power radiation patterns for the proposed antenna. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]



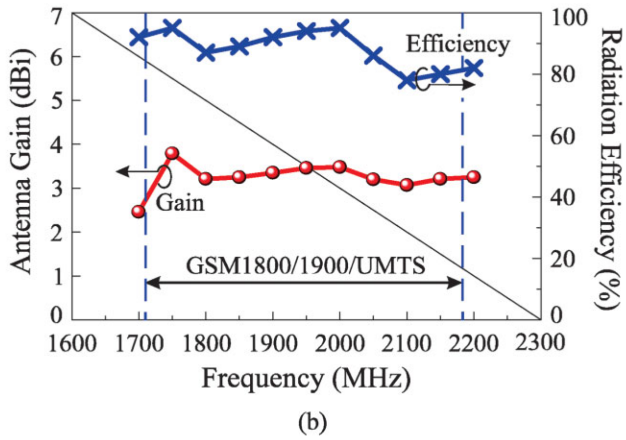


Figure 10 Measured antenna gain and radiation efficiency for the proposed antenna. (a) GSM850/900 bands. (b) GSM1800/1900/UMTS bands. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

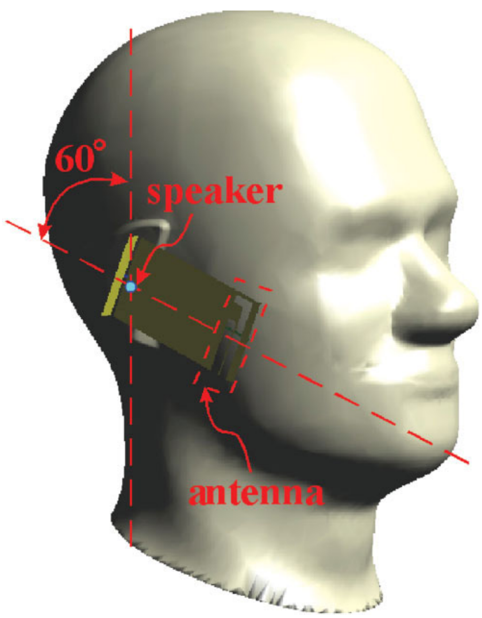


Figure 11 SAR simulation model provided by SEMCAD [14] for the proposed antenna. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

TABLE 1 Simulated SAR in 1-g and 10-g Head Tissues Obtained Using SEMCAD [14] for the Antenna Placed at the Bottom Position of the Mobile Phone With the Presence of the Phantom Head; Two Cases of the Ground Plane Spaced 5 mm (Case A) and 10 mm (Case B) to the Phantom Ear Are Studied

Frequency (MHz)	SAR_{1g} (W/kg)	SAR_{10g} (W/kg)
Case A: Ground plane spaced 5 mm to the phantom ear		
859	2.04	1.43
925	2.03	1.32
1795	1.78	1.09
1920	1.58	0.97
2045	1.37	0.86
Case B: Ground plane spaced 10 mm to the phantom ear		
859	1.43	1.02
925	1.53	1.07
1795	1.17	0.69
1920	0.96	0.62
2045	0.92	0.57

for Case A and B, the SAR values are all less than 1.43 W/kg, well below the SAR limit of 2.0 W/kg demanded for practical applications [11]. For the 1-g head tissue, when the spacing is increased from 5 mm (Case A) to 10 mm (Case B), which is still promising for general mobile phones, the SAR values are decreased by about 1.5 dB for the lower frequencies (859 and 925 MHz) and decreased by about 2.0 dB for the higher frequencies (1795, 1920, and 2045 MHz). The 1-g SAR values for Case B are 1.43, 1.53, 1.17, 0.96, and 0.92 W/kg at 859, 925, 1795, 1920, and 2045 MHz, respectively, which meet the SAR limit of 1.6 W/kg for practical applications [11].

4. CONCLUSIONS

The bandwidth-enhancement technique for the internal WWAN antenna by adding a small-size inductively coupled plate to the mobile phone with a short ground plane of length 60 mm has been proposed and studied. With a chip inductor of proper inductance connected to the ground plane of the mobile phone, the coupled plate can generate a resonant mode at about 925 MHz to result in a wide lower band for the antenna to cover the GSM850/900 operation. At the same time, this coupled plate causes no degraded effects on the wide upper band of the antenna to cover the GSM1800/1900/UMTS operation. In addition, this coupled plate can be of different shapes, such as of the rectangular shape, the loop shape and the T-shape, and is small enough to be embedded inside the mobile phone housing, without increasing the size of the mobile phone. The proposed inductively coupled plate is hence very promising for practical application in effectively compensating for the quickly decreased lower-band bandwidth of the internal WWAN antenna in the small-size mobile phone.

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CONCURRENT DUAL-BAND SIX-LOOP-ANTENNA SYSTEM WITH WIDE 3-dB BEAMWIDTH RADIATION FOR MIMO ACCESS POINTS

Saou-Wen Su
Network Access Strategic Business Unit, Lite-On Technology Corporation, Taipei County 23585, Taiwan; Corresponding author: susw@ms96.url.com.tw

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ABSTRACT: *A high-gain, wide-beamwidth, six-loop-antenna MIMO system suited for wireless access points in the concurrent WLAN 2.4 and 5 GHz bands is presented. The antenna system mainly comprises an antenna ground plane and single-band loop antennas, among which the three antennas are designated for 2.4 and 5 GHz operation, respectively. The antennas are set in a sequential, rotating arrangement on the ground plane with an equal inclination angle of 60° to form a symmetrical structure, and the 2.4 and 5 GHz loops are facing each other one by one. The experimental results show that good port isolation can be obtained between antenna ports. High-gain, directional radiation patterns with wide 3-dB beamwidth in elevation planes are also observed. Details of a design prototype are described and discussed in the article.* © 2010 Wiley Periodicals, Inc. Microwave Opt Technol Lett 52: 1253–1258, 2010; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.25208

Key words: *antennas; loop antennas; access-point (AP) antennas; WLAN antennas; concurrent dual-band operation; multiple-input multiple-output (MIMO); antennas; self-balanced loop structure*

1. INTRODUCTION

To increase data throughput without using extra spectrum and at the same time, to make use of multi-path propagation to improve signal quality and reliability, multiple-input multiple-output (MIMO) technology including multiple transmit and receive antennas are widely deployed. In fact, a lot of ‘‘11n’’ [1] wireless products are readily accessible in the marketplace. Numerous research papers on internal MIMO antennas in mobile devices, the client end, have been reported [2–9], which usually focus on decoupling techniques because of limited system circuit-board space left for the antennas. As to access-point (AP) or router applications, the base-station end, quite scant studies on internal MIMO antennas are conducted [10, 11]. Conventionally, external dipole and monopole antennas are commonly used AP antennas, especially high-gain, omni-directional dipole arrays [12, 13], and collinear antennas [14–18]. However, there has been a strong demand for internal AP antennas simply from an esthetic point of view that external antennas are not very pleasing to the end user and prone to be vandalized. To begin the design of internal AP MIMO antennas, it is significant to understand what exact orientation of the AP is going to be when the AP is in use. For example, the on-table AP, commonly available on the market, requires omnidirectional antennas [10], and the ceiling-mount AP usually needs the antenna capable of providing conical radiation patterns in elevation planes [11].