Published paper

Tzortzakakis, M. and Langley, R.J. (2007) *Quad-band internal mobile phone antenna,* IEEE Transactions on Antennas and Propagation, Volume 55 (7), 2097 – 2103.

Quad-Band Internal Mobile Phone Antenna

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***Abstract*—A novel internal, quad-band antenna placed inside a "foldable" type of mobile phone is presented. Its structure consists of a helical and a monopole element exciting two broad frequency bands. Using a simple matching circuit the proposed antenna covers several frequency bands including the global system for mobile communication (890–960 MHz), digital communication system (1710–1880 MHz), personal communication system (1850–1990 MHz), and universal mobile telecommunication system (1920–2170 MHz). It achieves a voltage standing wave ratio (VSWR) of less than three across all frequency bands with total radiation efficiency of more than 50%. Its novel design and structure occupies only 1.8 cm^3 of volume making this antenna very small and very suitable for internal use inside mobile terminals.**

***Index Terms*—Antennas, handsets, internal, mobile antennas, multiband, multifunctional, phone, wideband, wireless.**

I. Introduction

THE most attractive mobile phone terminal design, nowadays, is the "foldable" or "clamshell" mobile phone. It has two main printed circuit boards, the upper and lower PCBs. In practice, the upper PCB supports a color liquid crystal display (LCD), together with a speaker, a camera, and maybe a camera flash. The lower PCB on the other side normally supports the radio frequency (RF) circuitry, the battery of the phone, the necessary keypads, and buttons and the antenna. Such mobile phones are, therefore, very attractive since they provide a large display, aesthetic design, and multifunctionality.

Antennas for mobile terminal applications have been investigated using various antenna types and structures. In [1], a shorted plate with two folding arms is used, in [2] a shorted patch with parasitic elements, in [3] a shorted monopole with an additional resonator, in [4] where stack monopoles are used or in [5] using a high dielectric constant substrate. These designs, although they manage to cover some frequency bands, have complex structures which make them difficult to manufacture.

Other antenna geometries have also been reported such as in [6] and [7] where circular or elliptical monopole disks are used which are relatively large making them unsuitable for mobile phone applications.

However, designs using simple structures occupying small volume without sacrificing the overall performance have been reported by the authors in [8] and in [9]. In these designs triple frequency band coverage is obtained for GSM (890–960 MHz), DCS (1710–1880 MHz), and PCS (1850–1990 MHz) frequencies, where the antenna occupies a total volume of only 1.68 [8] and 1.15 cm^3[9], respectively. These designs concentrate on normal, "bar" type mobile phones without any folding capability.

In this paper an antenna is presented which is specially designed for a "foldable" type mobile phone. In such mobile telephones due to the large display additional functions such as Internet or TV can be implemented. Such functions can be provided only from third-generation CDMA/UMTS (1920–2170 MHz) communication systems, which deliver higher data rate and maximum signal throughput compared to the previous second-generation (2G) systems. The quad-band antenna presented in this paper is designed to operate at the traditional 2G systems, such as GSM, DCS, PCS, and also at the 3G UMTS system, in order to deliver the aforementioned functions. The antenna is modeled in CST Microwave Studio and simulated results are compared with measurements in Section III.

II. Antenna Design Parameters

A. Antenna Structure

In the designs presented by the authors in [8] and [9], the antenna geometry was a combination of a wide monopole element connected in series with a small helical element.

By connecting these elements in series we can achieve a very small and compact design. However, such a design shows some limitations on the antenna structure, since the helical windings must be very close to each other to achieve a small antenna. Thus the helical element will be very small in size resulting to higher Q values and narrower bandwidth. In order to enhance the bandwidth of the helical element the pitch distance between its windings have to be as large as possible [10]. This will result to a physically larger element occupying more volume reducing its radiation Q factor which is directly related to the impedance bandwidth of the antenna [10]–[12].

Taking the above considerations into account, a new antenna structure is proposed which combines a monopole element and a helical element having one feed position. The detailed antenna elements and its final structure are shown in Fig. 1. The helical element will be used to provide a self-resonance in the GSM frequency band, around 920 MHz. The monopole element will be used to provide a self-resonance around 1900 MHz with a broad bandwidth to cover the DCS, PCS, and UMTS bands. The two radiating elements are electrically connected together through a ring element and feed which is especially used to provide a strong mechanical support for the complete structure. This feed line connects the complete antenna to the mobile phone.

Manuscript received March 30, 2006; revised January 30, 2007.

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Digital Object Identifier 10.1109/TAP.2007.898577

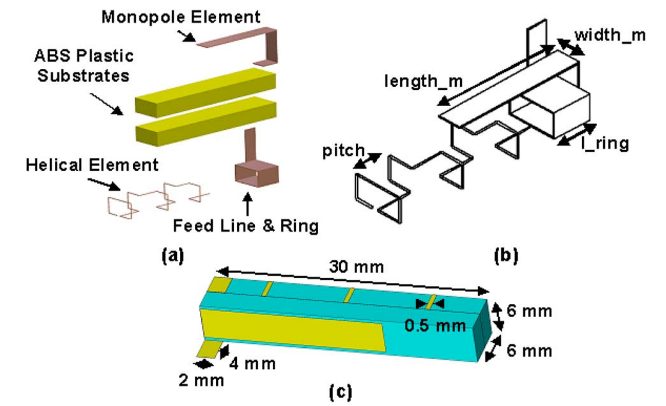


Fig. 1. Antenna geometry with (a) different elements, (b) final structure shown without substrate for clarity.

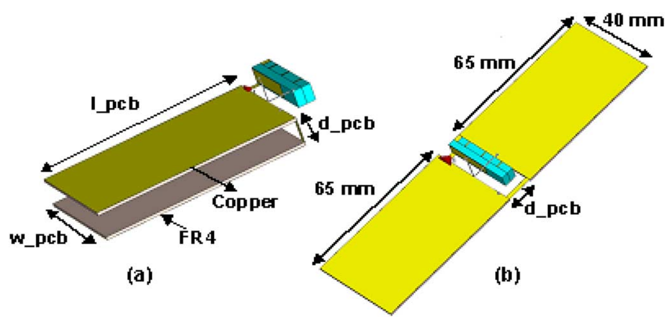


Fig. 2. Antenna and Mobile phone model for (a) close and (b) open state.

The different metallic elements, which are made out of copper, are supported by an Acrylonitrile Butadiene Styrene (ABS) plastic material that has a dielectric constant of 3 and a loss tangent of 0.05. The multiple turns of the helical element are designed using rectangular corners and not circular ones since they are formed on a rectangular and not on a circular substrate. A helical element, which is folded in this way, is easier and cheaper to manufacture as opposed to the conventional way of wounding it around a former. The pitch distance between the windings is sufficient to reduce the mutual coupling and self-capacitance in the multiturn helical antenna as discussed later.

In order to investigate the antenna the chassis of a foldable mobile phone must be included in our model. Such a phone consists of two main printed circuit boards (PCB), which are connected together using a narrow flexible cable. In addition the antenna has to be designed to operate in two states, the close state when the phone is folded and the open state when the phone is unfolded. Fig. 2, shows the mobile phone and antenna models for both states, as modeled inside Microwave Studio CST simulation software. The two PCBs are modeled using a copper metal and an FR4 substrate material, which has a dielectric constant of 4.5 and loss tangent of 0.0025.

The dimensions of the PCBs are based on a commercially available mobile phone, see Fig. 2. The antenna volume is predefined to have a length of 30 mm, height of 6 mm, and width of 10 mm. Also predefined is the length of the PCBs at 65 mm and its width 40 mm. The gap between the two PCBs is specified to be $d\_pcb = 12\ \mathrm{mm}$. Thus, the antenna proposed here has a physical length of 30 mm, physical height of 6 mm, and width of 6 mm, see Fig. 1. The gap between the antenna and

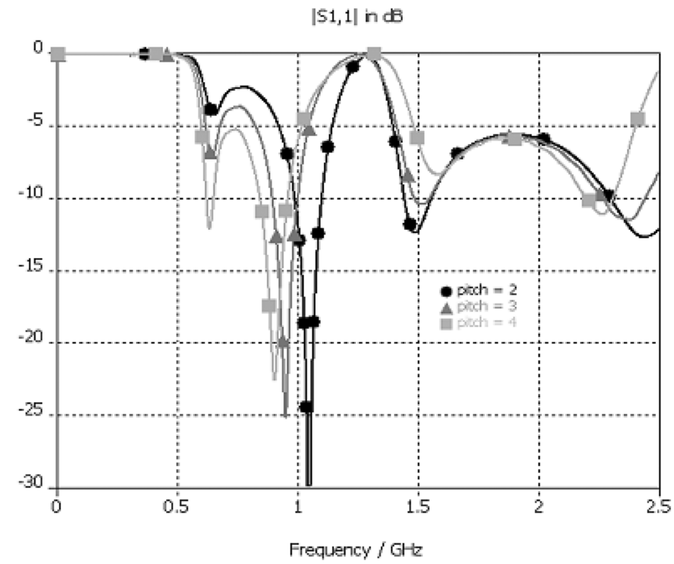


Fig. 3. Varying the pitch distance between helical arms in open state.

PCB is kept to 4 mm which from our previous work can provide good results [8], [9]. The feed line has a rectangular shape and its width is chosen to be 2 mm and the width of the helical traces 0.5 mm. These dimensions are chosen in order to provide an easy production of the antenna. The length of the ring that connects the feed line together with the helical and monopole elements is 2 mm, equal to the width of the feed line. From Fig. 1 we can also observe the general antenna design parameters. For the monopole element its length, *length_m* and to a small extent its width, *width_m* are important. For the helical element the length of the ring is important, *l_ring* and the distance between the helical arms named as pitch. These parameters will now be investigated in the following section.

B. Design Parameters—Open State

The antenna has to be designed to operate in both states, close and open, at the correct resonant frequencies. Hence in this section we will investigate how the most significant antenna parameters affect performance when the two PCBs are unfolded. The helical antenna element is designed to have a physical length of around 87 mm which corresponds to a quarter wavelength at around 920 MHz taking into account the effect of the ABS substrate. The width of the helical conductor has little effect on the resonant frequencies. In order to see the effect of the pitch distance between the helical arms the *pitch* was varied from 2 to 4 mm. The parameter *d_pcb* was kept to 11 mm.

The simulation results are shown in Fig. 3. Several resonances are present. The first resonance occurs around 600 MHz and this is due to the PCB. The next resonance varies from 900 to 1100 MHz and this is primarily due to the helix, the frequency varying as the pitch changes from 4 to 2 mm, respectively. Optimal resonance is achieved when the pitch parameter is equal to 4 mm. The resonances occurring at higher frequencies (above 1400 MHz) are basically due to the excitation of the monopole element that in this case has a length of 20 mm and width of 5 mm. However the interaction of the monopole with the PCB and helix also influence these higher frequency resonances.

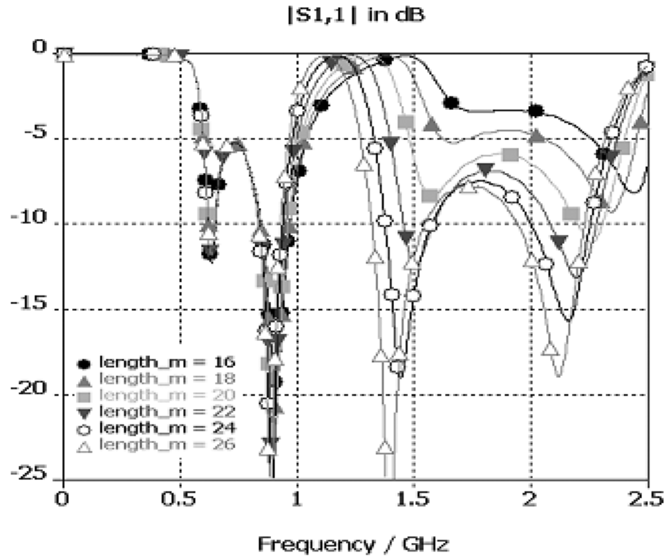


Fig. 4. Varying monopole parameter *length_m* in open state.

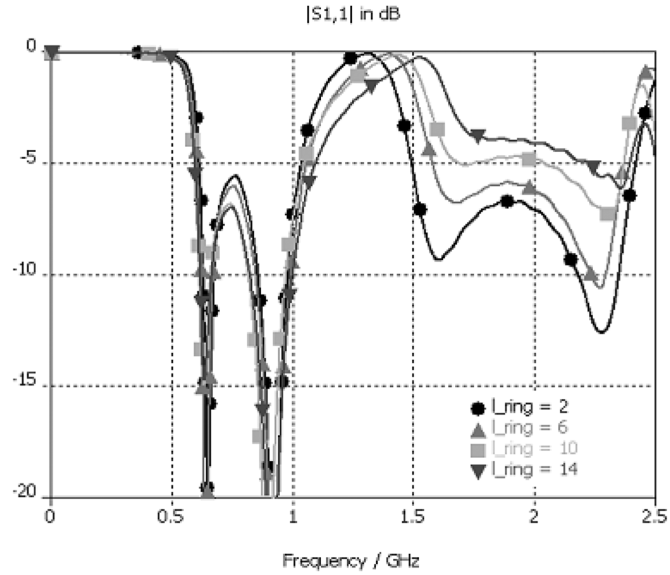


Fig. 5. Varying parameter *l_ring* in the open state.

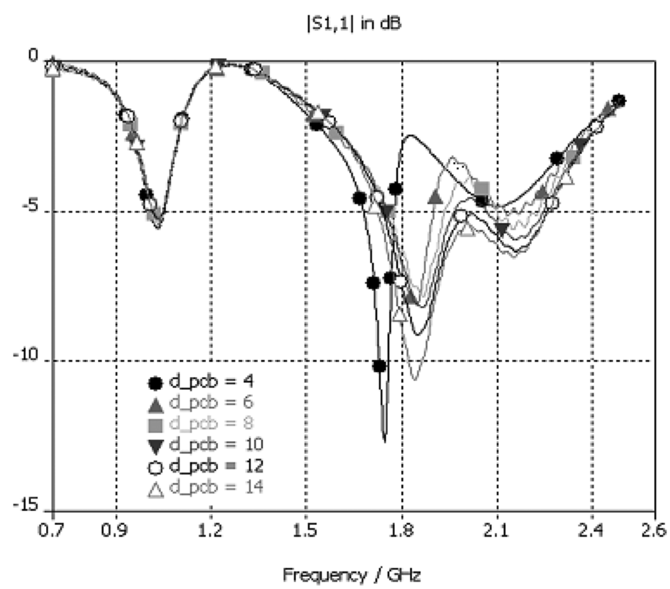


Fig. 6. Varying parameter *d_pcb* in close state.

The monopole element is designed to have a physical length equal to a quarter wavelength at around 2170 MHz, a length of 20 mm when applied on an ABS plastic substrate. The effect of changing the length and width of the monopole element on the resonant frequency bands was examined next. Varying the length of the monopole has the effect shown in Fig. 4. By changing $length_m$ from 16 to 26 mm, the upper resonances (above 1400 MHz) shift to lower frequencies resulting in a better input return loss. The lower resonances (for GSM band) were unaffected. The best result is obtained when the length of the monopole is equal to 20 mm with return loss of less than -6 dB from 1600 MHz up to 2400 MHz, easily covering the DCS, PCS, and UMTS bands. The width of the monopole had a very minor affect on all the bands, fine tuning the upper resonant (above 1400 MHz) matching only. A width of 5 mm was chosen to be as optimal for the monopole.

Of more importance is the ring element which is used to mechanically support and electrically connect the different antenna elements with the feed line. Its influence was studied by varying its length *l_ring*. The simulation results are shown in Fig. 5. As expected the length of the ring influences all the antenna resonances. The GSM band resonance is excited by the helical element and varying *l_ring* from 14 to 2 mm increases the resonant frequency from 870 to 925 MHz and maintains a good match. At the high frequency bands (above 1400 MHz) the influence is also pronounced, affecting the impedance and improving the match. An optimum length was achieved when *l_ring* was 2 mm providing a wide response with return loss of better than -6 dB.

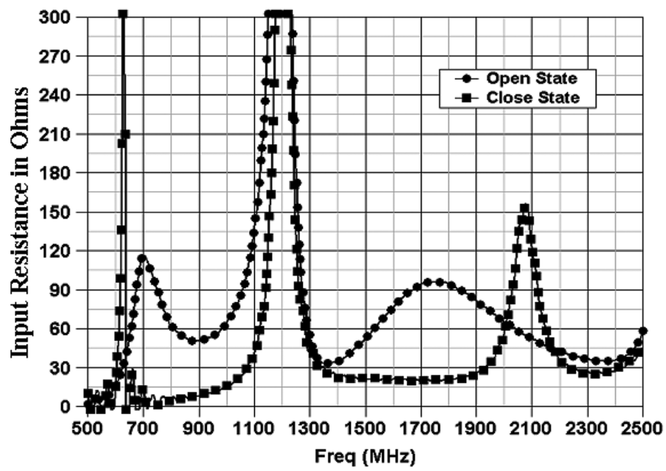
C. Design Parameters—Close State

The critical parameter in the close state is the gap between the two PCBs. In order to investigate this effect, the parameter *d_pcb* was varied from 4 to 14 mm. The rest of the parameters were kept to the optimum results determined so far.

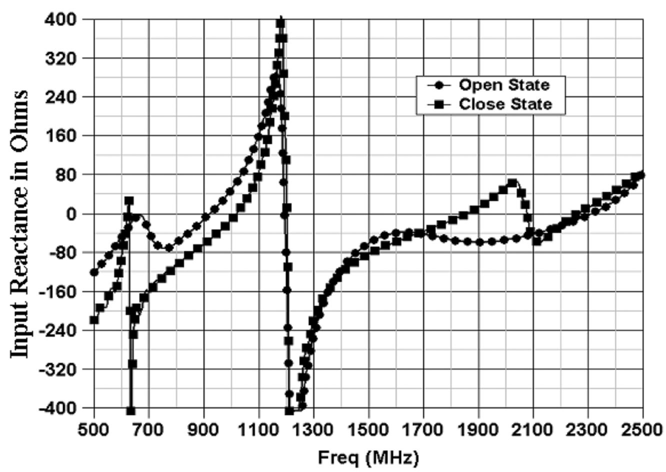
The simulation results are shown in Fig. 6. The gap between the two PCBs does not to have any influence on the lower frequency band, which is now less well matched due to the fact that the PCB is folded and the ground plane is effectively shortened. In the case of the higher frequency bands (above 1400 MHz) an antiresonance occurs and a maximum return loss occurs when the *d_pcb* is equal to 4 mm. As the gap increases the antiresonance becomes weaker, resulting in a maximum return loss of around -7 dB when the *d_pcb* is equal to 14 mm. An investigation of the current density in the close state reveals that the antiresonance takes place at around 2080 MHz when *d_pcb* is equal to 12 mm, see Section III-B. By increasing the distance between the two PCBs the coupling between them becomes weaker resulting in a lower return loss. Thus, this parameter is very important for this type of mobile phone. In our design the gap *d_pcb* was set to 12 mm, large enough to fit the antenna structure during the open state.

TABLE I
FINAL VALUES USED FOR THE PROPOSED ANTENNA

Parameter	Value in mm
l_pcb	65
w_pcb	40
d_pcb	12
width_m	5
length_m	20
l_ring	2
pitch	4



(a)



(b)

Fig. 7. (a) Input terminal resistance in open and close states. (b) Input terminal reactance in open and close states.

III. ANTENNA FINAL DESIGN

A. Input Terminal Impedance

From all the investigation from the previous sections we can now set some final values for the different antenna and PCB parameters. These are listed in Table I.

This final antenna design was then simulated in CST Microwave Studio for the open and close states. The antenna input impedance when the PCBs are in the open and close states are compared in Fig. 7(a) and (b). In the open state, Fig. 7(b) shows that two main resonances are occurring, one at 925 MHz and another near 2200 MHz. However, the reactance

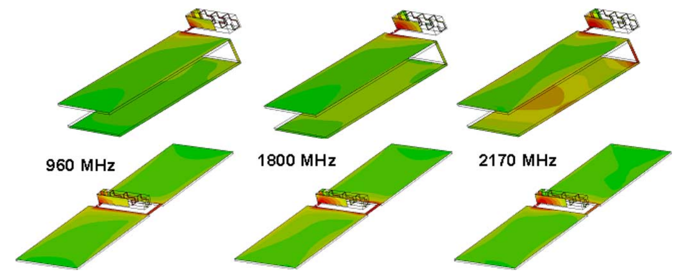


Fig. 8. Simulated currents in open and close states at frequencies 960, 1800, and 2170 MHz.

curve is very near to zero for a wide range of frequencies, particularly at the higher frequency bands above 1400 MHz. The input resistance at 925 MHz was equal to 48 Ohms and at the upper frequency bands varies from 80 to 20 Ohm. Thus, the input resistance is relatively high resulting to a wide matched impedance response.

In the close state the ground plane is effectively smaller resulting in a shift in the self-resonance and in a narrower input impedance response. Observing the input reactance curve in Fig. 7(b), the first self-resonance occurs around 616 MHz and this is entirely due to the printed circuit boards resonating. A second resonance occurs around 1025 MHz. At these frequency bands the input resistance is quite low, compared to the open state, and equal to around 12 Ohm. In the upper frequency bands various resonances occur, at 1800 and 2300 MHz, with the input resistance varying from 20 to 120 Ohm. Here we note the anti-resonance occurring at around 2080 MHz resulting in high input resistance values. This resonance occurs due to the coupling of the two PCBs. In general the input impedance behavior in the close state is less well controlled than in the open state.

B. Current Distribution

It is valuable to examine the current distribution at the various frequency bands, examples of which are shown in Fig. 8 for the open and close states at three frequencies, 960, 1800, and 2170 MHz. At all frequencies the strongest current distribution is found on the antenna but the PCBs are also excited and in general radiation is accomplished with the combination of the antenna and PCB. The monopole antenna was more excited at the higher frequencies as expected. At 960 MHz, the current distributions are somewhat similar in both the open and close states. However, near 1800 MHz, the current distribution for the lower plate PCB, not connected directly to the antenna, carries a higher current than when in the open state and at 2170 MHz this change is even more obvious where there was a significant increase in the current. This is due to coupling between the plates and is maximum at 2080 MHz corresponding to the high resistance and resonance noted in Fig. 7(a).

C. Measurement Results

In order to investigate the validity of the simulation model the proposed antenna was constructed together with a prototype phone consisting of two PCBs as shown in Fig. 9. A coaxial cable was used to measure the input terminal impedance of the antenna. At the open end of the cable a small ferrite material was

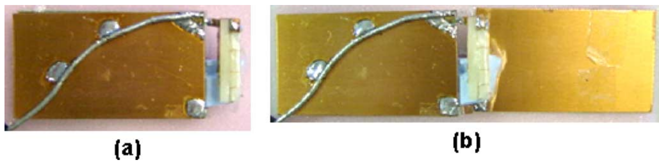


Fig. 9. Prototype antenna and phone model showing (a) close state and (b) open state.

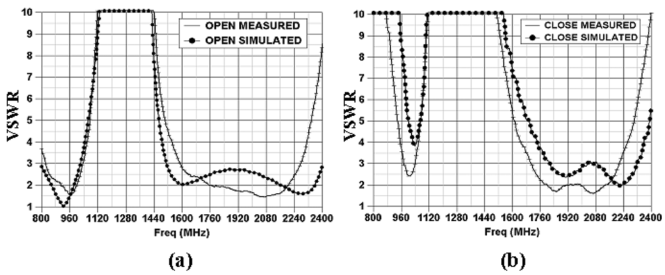


Fig. 10. Measured and Simulated VSWR responses, without matching circuit, for (a) open and (b) close states.

placed to attenuate any surface currents flowing along the outer conductor of the coaxial cable. The measured voltage standing wave ratio (VSWR) is shown in Fig. 10. In the case of the open state, Fig. 10(a), a good agreement between the simulated and measured response is observed. In Fig. 10(b) the simulated and measured response for the close state is shown. Here, the measured response is slightly shifted to lower frequency bands but is very close to the simulated response.

Note that in the simulation a discrete port was used and not a coaxial port to reduce the complexity of the model and calculation time. Overall the measured open state VSWR was less than three covering the GSM, DCS, PCS, and UMTS bands, in the close state the VSWR was more than three, especially at the GSM band. This is due to the small input resistance, which according to simulation is around 12 Ohms. From the measurements we get an input resistance of around 21 Ohms which lowers the VSWR from 4 to 2.5 at around 1000 MHz.

In order to improve the input impedance especially in the close state and keep the self-resonance around 900 MHz constant between open and close state, we include a small matching circuit. This circuit is a high pass filter consisting of a shunt lumped inductor of 6.8 nH and a series capacitor of 2.4 pF. The complete circuit is shown in Fig. 11. Such matching circuits are quite common inside mobile phones optimizing the step impedance between the antenna and front-end filters. The circuit used here consists of only two elements adding to the complete system around 0.2 dB of insertion loss.

The usual targets in such antenna projects are to achieve a VSWR response below three and a total efficiency of more than 50%. The same prototype antenna and PCBs are used together with the matching circuit to achieve the measured input VSWR as shown in Fig. 12.

The VSWR is now below three across the band at the GSM, DCS, PCS and UMTS bands and for both states of operation close and open. During the close state the coupling of the two

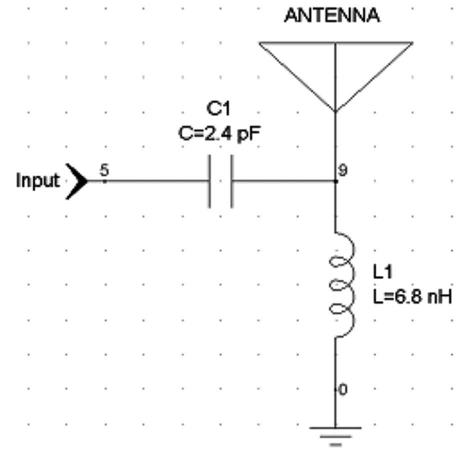


Fig. 11. Matching circuit for the improvement of the input impedance.

PCBs is still present but the peak VSWR was around 2.8. Furthermore, the shift of the GSM resonance between the open and close state has been reduced to provide low VSWR values.

In mobile phones the total efficiency of the complete system is extremely important and must include antenna and matching circuits. In this project the Wheeler cap method was used which results in accurate and repeatable results. The Wheeler cap used in this project is a cylindrical box with a movable top cover useful for adjusting the height of the complete box. The biggest problem with the Wheeler cap arises from the box resonances. However, the resonances from a box are dominated by its height. If therefore, we can adjust the height of the box we can move, or better, remove any unwanted box resonances from our frequency band of interest. In this way, a spurious free environment is achieved. These issues are discussed and analyzed in [13]–[15].

The total efficiency was measured in the GSM frequency band and is shown in Fig. 13(a). The minimum total efficiency was achieved at 880 MHz and in the case of the close state. This was expected since during close state the antenna has a smaller radiation resistance compared to the open state. In the open state the total efficiency remains at very good levels, varying from 70% to 80%. At the higher frequency bands the total efficiency retains values larger than 60%. The measured response is shown in Fig. 13(b). As seen in the figure the total efficiency measurement follows the VSWR curve tendency. In the center of the wide-band we have a maximum VSWR value resulting in a lower total efficiency due to higher miss-match losses and reflected signals. At the edges of the bands however, the total efficiency achieves values as high as 90%. Across the complete UMTS band, a total efficiency of more than 70% was achieved.

IV. Conclusion

In today's mobile phone terminals multiband antennas are needed which can receive many new services from third generation networks. For aesthetic and practical reasons this antenna must be integrated inside the terminal. This means that the antenna must occupy the smallest volume possible with a low profile without overly compromising radiation performance and

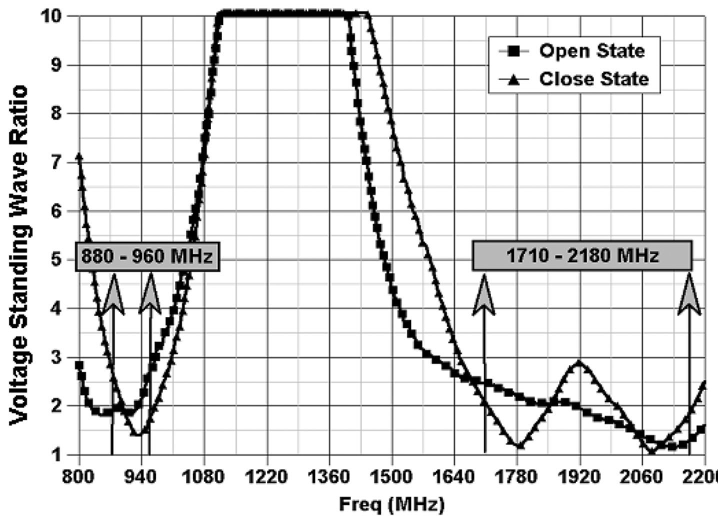
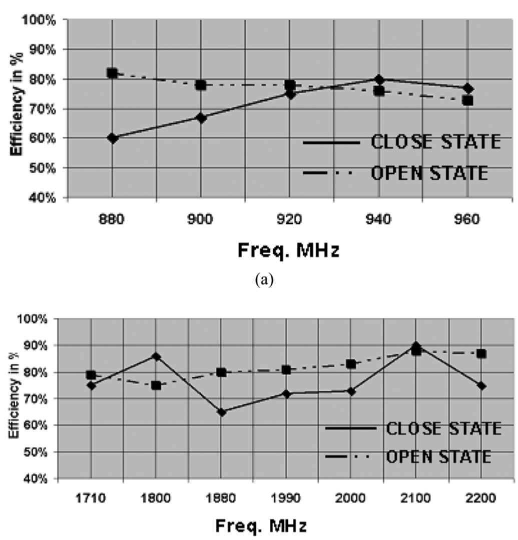


Fig. 12. Measured VSWR response using a simple matching circuit.



(a)

(b)

Fig. 13. Total efficiency as measured in: (a) GSM band and (b) DCS/PCS/UMTS bands.

impedance matching. In this paper, such a quad-band antenna was presented, which provides coverage across all four mobile telephone bands. The antenna has a low profile and very small volume and can be used inside a mobile terminal.

Simulated and measured results are presented when the antenna is inside a "foldable" type mobile phone and placed in the hinge position. The size of the mobile phone is taken from an existing and recent commercial mobile phone, thus the results are based on realistic sizes. The voltage standing wave ratio was better than 3:1 at all frequency bands and in all states of operation, when the mobile handset is folded or unfolded. The total efficiency (taking account the mismatch losses) was measured to be better than 60% in all cases. Finally the antenna, due to its innovative design, is very easy to construct and cheap to manufacture.

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Prof. Langley was Honorary Editor of the *IEE Proceedings on Microwaves, Antennas and Propagation* from 1995 to 2004.