SIMPLE PRINTED MONOPOLE SLOT ANTENNA FOR PENTA-BAND WIRELESS WIDE AREA NETWORK OPERATION IN THE MOBILE HANDSET

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ABSTRACT: *A simple printed monopole slot antenna for penta-band wireless wide area network operation (824–960/1710–2170 MHz) in the mobile handset is presented. The monopole slot has a length of 50 mm only and is embedded close to the bottom edge of the system ground plane of the handset with a small distance of 11 mm. By adding a small-size C-shaped strip connected orthogonal to the bottom edge of the system ground plane, good excitation of the monopole slot antenna at its fundamental (0.25 wavelength) and higher-order resonant modes can be obtained. The excited resonant modes form two wide operating bands to cover the GSM850/900 operation (824–960 MHz) and GSM1800/1900/UMTS operation (1710–2170 MHz). Detailed operating principle and radiation characteristics including the specific absorption rate results of the proposed monopole slot antenna are described. Measured results of the fabricated antenna are also presented.* © 2011 Wiley Periodicals, Inc. Microwave Opt Technol Lett 53:1399–1404, 2011; View this article online at wileyonlinelibrary.com. DOI 10.1002/mop.26017

Key words: *internal handset antennas; monopole slot antennas; WWAN antennas; printed antennas; multiband antennas*

1. INTRODUCTION

Monopole slot antennas have an open end and can be operated as a quarter-wavelength resonant structure [1–9], which is different from the traditional slot antennas with two closed ends and generally operated as a half-wavelength resonant structure [10–12]. Because of this advantageous feature which can lead to a decreased antenna size at a fixed operating frequency, monopole slot antennas also known as quarter-wavelength slot antennas or open-slot antennas are attractive for mobile handset applications. Several monopole slot antennas to be directly printed on the main circuit board of the mobile handset as internal antennas have hence been demonstrated [8, 9, 13–17]. In Ref. 13, to achieve wideband operation to cover multiband wireless wide area network (WWAN) operation, the printed slot antenna is placed at the center of the main circuit board. With such a symmetric arrangement of the monopole slot printed on the main circuit board, the microstrip feedline for feeding the monopole slot can also efficiently excite the chassis dipole-type resonant mode of the system ground plane printed on the main circuit board. Thus, a wide operating band can be excited for the WWAN operation. However, such a symmetric structure will complicate the circuit floor planning and signal line routing on the main circuit board [13], which greatly limits its possible application in a practical mobile handset.

When the monopole slot is placed close to either the top or bottom edge of the main circuit board, the chassis dipole-type resonant mode becomes difficult to be excited to assist in forming a wide operating band for the antenna. This greatly decreases the achievable operating bandwidth for the antenna. To overcome this problem, two monopole slots of different lengths are printed on the main circuit board to obtain two wide operating bands for penta-band WWAN operation (GSM850/900/1800/1900/UMTS) in the 824–960 and 1710–2170 MHz bands [8]. In this case, the occupied board space of the two monopole slots is 15×40 mm^2 or 600 mm^2 [8]. In this article, we present a simple monopole slot antenna design by using a single monopole slot printed close to the bottom edge of the main circuit board to achieve penta-band WWAN operation. Note that with the internal antenna located at about the bottom edge of the main circuit board, especially for the antenna with no background plane [18–22], the specific absorption rate (SAR) values can be greatly decreased, making it easy to meet the limit of 1.6 W/kg for 1-g head tissue [23, 24].

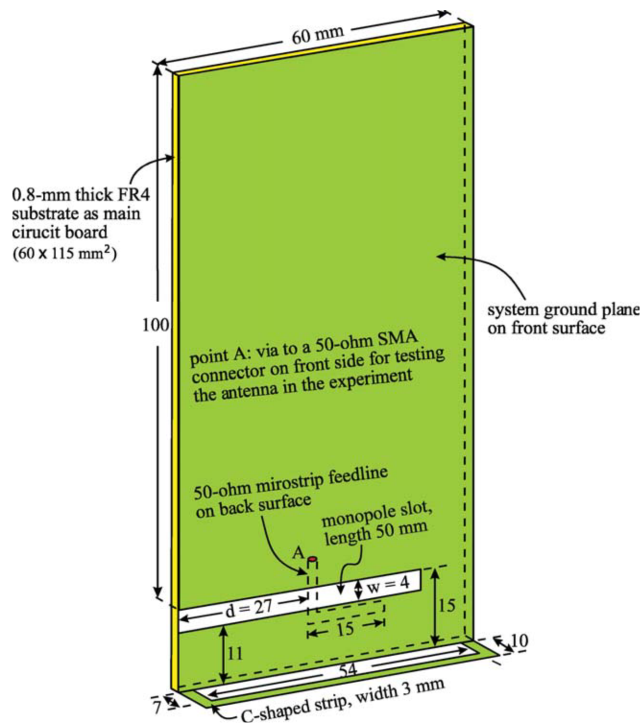


Figure 1 Geometry of the proposed simple monopole slot antenna for penta-band WWAN operation in the mobile handset. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

The simple monopole slot has a length of 50 mm and width 4 mm (that is, slot size 200 mm^2 only) and is spaced 11 mm to the bottom edge of the main circuit board. To compensate for the short distance to the edge of the main circuit board which leads to an asymmetric structure of the system ground plane on the main circuit board, a small-size C-shaped strip is connected orthogonal to the bottom edge of the system ground plane. This C-shaped strip can effectively enhance the impedance matching

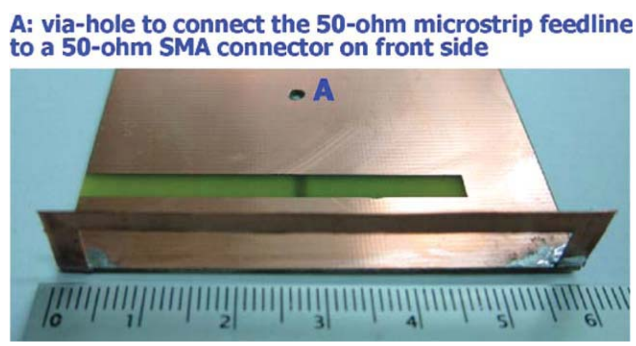


Figure 2 Photo of the fabricated antenna. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

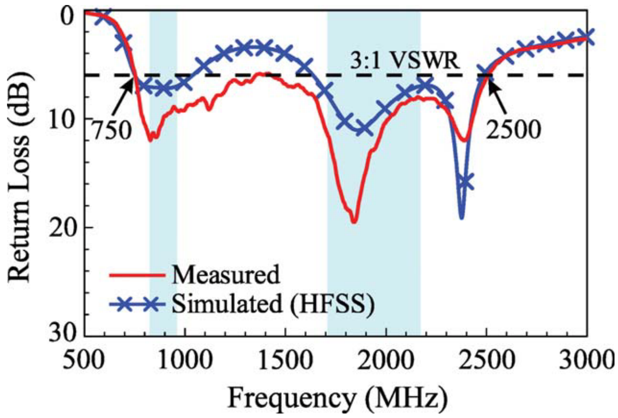


Figure 3 Measured and simulated return loss for the fabricated antenna. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

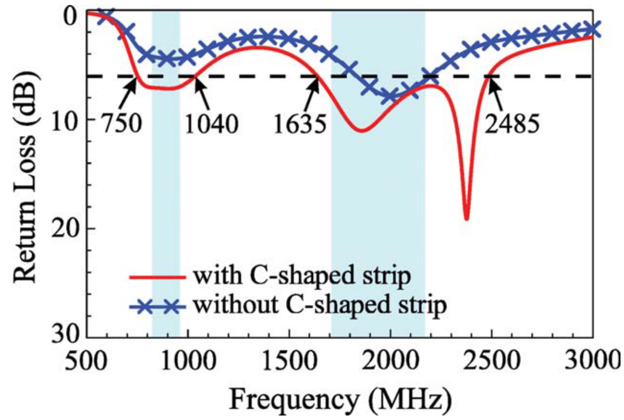


Figure 4 Simulated return loss for the proposed antenna and the case without the C-shaped strip connected orthogonal to the bottom edge of the system ground plane. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

for frequencies over the antenna's lower and upper bands such that two wide operating bands are obtained to cover the desired penta-band WWAN operation. Further, with the proposed monopole slot antenna design, the ground portion between the monopole slot and the bottom edge of the system ground plane can be used to accommodate associated electronic elements such

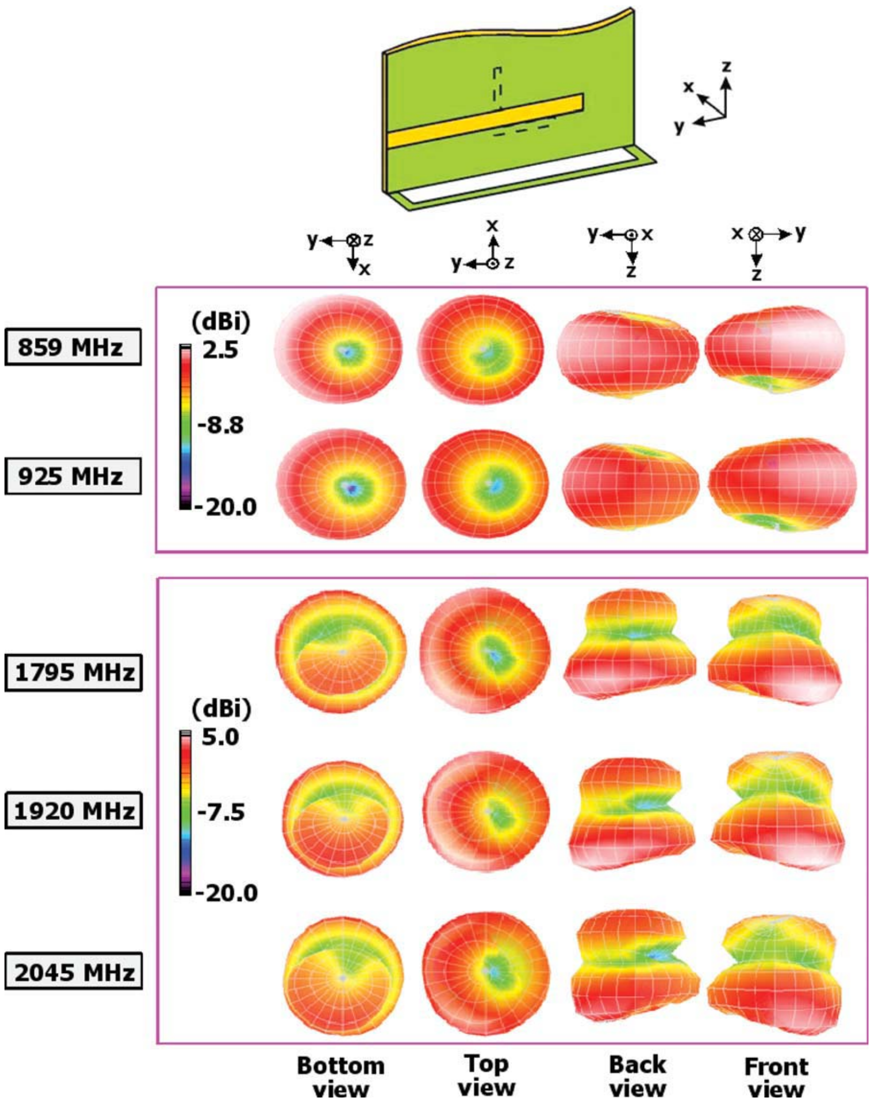


Figure 5 Measured three-dimensional total-power radiation patterns for the antenna. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

as the lens of the embedded digital camera [25, 26], universal serial bus (USB) connecter [27, 28] as the data port, and so on. Hence, the proposed antenna not only occupies a very small board space on the main circuit board but also can be closely integrated with associated electronic elements inside the mobile handset. Details of the proposed monopole slot antenna are described in the article. The antenna is also fabricated and tested. The obtained results including the SAR values for 1-g head tissue are presented and discussed.

2. PROPOSED MONOPOLE SLOT ANTENNA

Figure 1 shows the geometry of the proposed simple monopole slot antenna for penta-band WWAN operation in the mobile handset. A photo of the fabricated antenna is shown in Figure 2. The monopole slot has a length of 50 mm and is embedded in the system ground plane which is printed on the main circuit board of the mobile handset. In the study, an FR4 substrate of relative permittivity 4.4, loss tangent 0.024, size 115 $\times$ 60 mm^2 is used as the main circuit board of the mobile handset. The size of the main circuit board is selected for that of a practical smartphone. The width (w) of the monopole slot is selected to be 4 mm, thus the area of the monopole slot is 50 $\times$ 4 mm^2 or 200 mm^2 only, which is much smaller than that of using two monopole slots for penta-band WWAN operation in Ref. 8. As stated in Section 1, the monopole slot is printed close to the bottom edge of the main circuit board in the study for decreased SAR values, and the ground portion between the monopole slot and the bottom edge is 11 mm only. This ground portion can be used to accommodate associated electronic elements. An example is shown in Figure 10, in which a USB connector as a data port for external devices is mounted on this ground portion. This attractive feature can lead to compact integration of the monopole slot antenna and the associated electronic elements inside the mobile handset.

A C-shaped strip of width 3 mm is connected orthogonal to the bottom edge of the system ground plane. The C-shaped strip is limited to have a low profile of 10 mm above the system ground plane such that it can be enclosed inside the casing of the mobile handset. This C-shaped strip increases the effective length of the ground portion between the monopole slot and the bottom edge of the main circuit board and decreases the length difference between the two ground portions in the two sides of the monopole slot. That is, with the C-shaped strip, some modifications to the asymmetric structure of the system ground plane with respect to the monopole slot are obtained. In this case, although the chassis dipole-type resonant mode cannot be excited efficiently as the case that the monopole slot is placed at the center of the main circuit board [13], impedance matching of the excited resonant modes of the monopole slot antenna can be greatly improved. Hence, two wide operating bands can be obtained for the antenna to cover penta-band WWAN operation in the 824–960 and 1710–2170 MHz bands.

Also, the monopole slot can be easily fed by using a 50-Ω microstrip feedline printed on the back surface of the main circuit board. The tuning stub of the microstrip feedline (the feedline section in the ground portion between the monopole slot and the bottom edge of the main circuit board) has a length of 15 mm and is oriented to be parallel along the edge of the monopole slot. This minimizes the occupied area of the tuning stub of the microstrip feedline in the ground portion between the monopole slot and the bottom edge of the main circuit board so that more degrees of freedom in the circuit floor planning and signal line routing can be obtained in this ground portion.

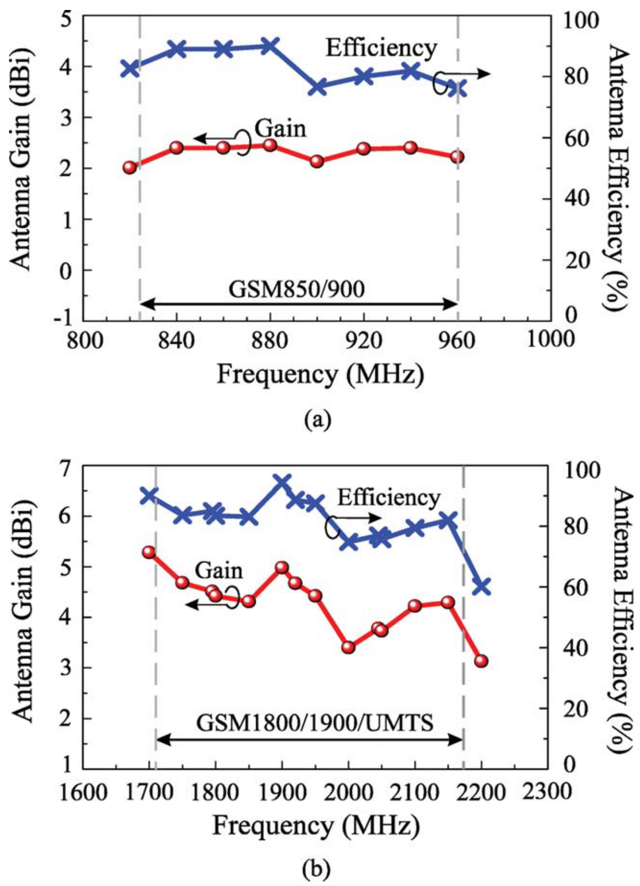


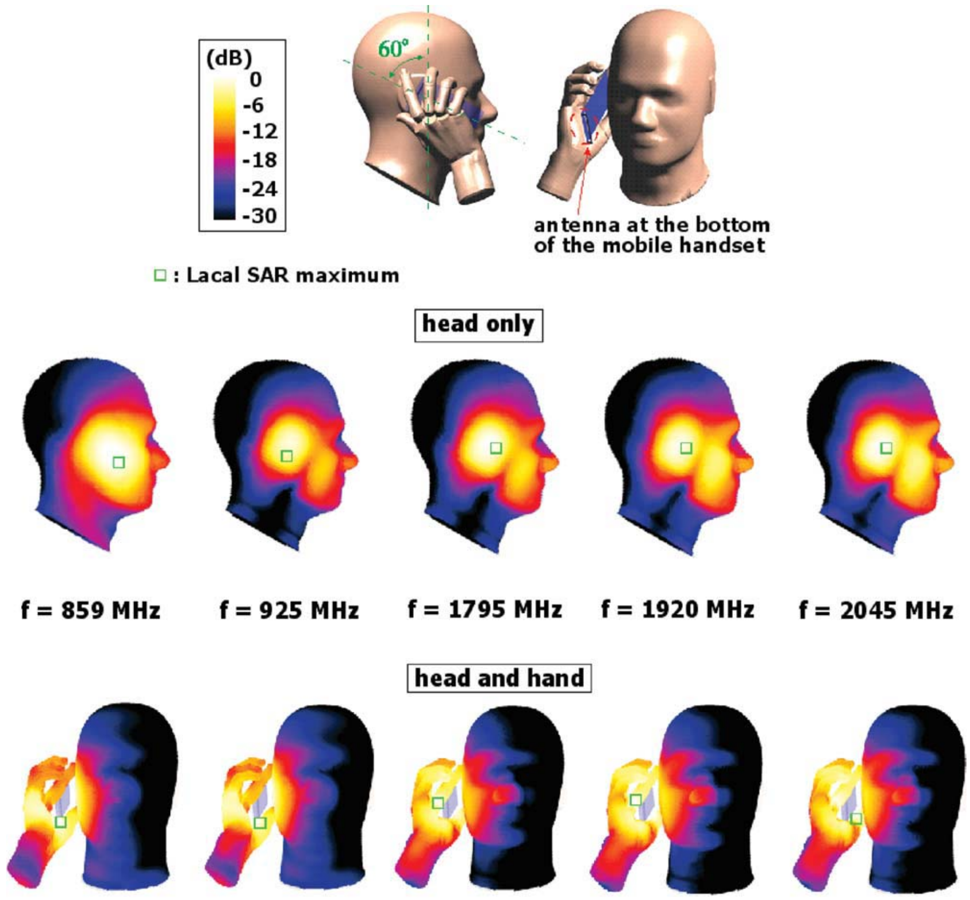
Figure 6 Measured antenna gain and antenna efficiency (mismatching loss included) for the antenna. (a) GSM850/900 bands. (b) GSM1800/1900/UMTS bands. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

Also note that the feeding position d of the microstrip feedline across the monopole slot is an important parameter in obtaining two wide operating bands for the antenna. By varying the feeding position d, the antenna's two wide operating bands for penta-band WWAN operation can be effectively controlled. In this study, the feeding position is selected to be 27 mm, which is at about the center of the monopole slot. More detailed results are analyzed in the next section.

3. RESULTS AND DISCUSSION

In the experiment for testing the fabricated antenna shown in Figure 2, the microstrip feedline is connected to a 50-Ω SMA connector through a via-hole at point A as shown in the figure. Figure 3 shows the measured and simulated return loss for the fabricated antenna. The simulated results are obtained using simulation software high frequency structure simulator version 12 [29]. Agreement between the simulation and measurement is seen. With the definition of 6-dB return loss or 3:1 VSWR (voltage standing wave ratio), which is widely used as the internal WWAN handset antenna design specification, the obtained bandwidths of the antenna cover the desired frequency ranges of 824–960 and 1710–2170 MHz (see the shaded regions in the figure).

To analyze the effects of adding the C-shaped strip at the bottom edge of the system ground plane, Figure 4 shows the simulated return loss for the proposed antenna and the case without the C-shaped strip. For the lower band, the impedance matching is seen to be greatly improved by adding the C-shaped



Frequency (MHz)		859	925	1795	1920	2045
1-g SAR (W/kg)	head only	0.72	0.78	0.58	0.51	0.44
	head and hand	1.21	1.10	0.79	0.74	0.76
Return loss (dB)	head only	8.1	10.0	10.2	13.6	11.2
	head and hand	9.8	12.2	14.0	16.5	12.3

Figure 7 SAR simulation model and the simulated 1-g SAR values and distributions. The return loss given in the table is the impedance matching level with the presence of the phantom head only or the phantom head and hand at the testing frequency. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

strip. For the upper band, dual resonance is obtained for the excited resonant mode. This behavior is similar to the dual-resonance mode excited for the antenna's upper band in the design of using two monopole slots [8] to achieve a wide operating band. This behavior indicates that with the C-shaped strip, a second or additional monopole slot is no longer required to obtain a wide upper band for the antenna to cover the GSM1800/1900/UMTS bands.

Radiation characteristics of the fabricated antenna were also measured. Figure 5 shows the measured three-dimensional total-power radiation patterns at 859, 925, 1795, 1920, and 2045 MHz, which are central frequencies of the five operating bands. At each frequency, four radiation patterns seen from four different directions (bottom, top, front, and back views) are presented. For lower frequencies at 859 and 925 MHz, dipole-like radiation patterns are seen. While for higher frequencies at 1795, 1920, and 2045 MHz, more variations in the radiation patterns are observed, and there is a dip seen in the azimuthal plane (x-y plane). The obtained radiation patterns are similar to those of many reported internal WWAN handset antennas [30, 31]. This suggests that the system ground plane in this study is also a part of the radiator and contributes significantly to the radiation characteristics of the mobile handset [32].

Figure 6 shows the measured antenna gain and antenna efficiency with mismatching loss included for the antenna. Over the GSM850/900 bands shown in Figure 6(a), the antenna gain varies from about 2.0 to 2.4 dBi, and the antenna frequency varies from about 76 to 89%. While over the GSM1800/1900/UMTS bands shown in Figure 6(b), the antenna gain and the antenna efficiency vary from about 3.4 to 5.2 dBi and 72–82%, respectively. The obtained results indicate that good radiation characteristics are obtained for the proposed monopole slot antenna.

The SAR simulation study is conducted using the simulation model provided by SEMCAD X version 14 [33]. The SAR simulation model including the phantom head and hand is shown in Figure 7. The simulated 1-g SAR values and distributions for two cases of head only and head and hand are listed in the table in the figure. The return loss given in the table is the impedance matching level with the presence of the phantom head only or

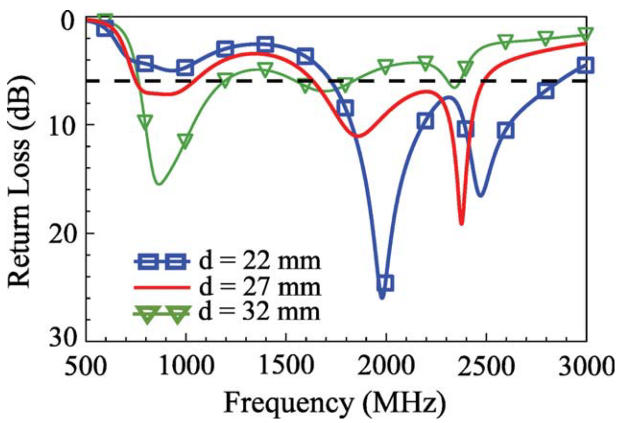


Figure 8 Simulated return loss as a function of the feeding position *d* of the microstrip feedline. Other dimensions are the same as in Figure 1. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

the phantom head and hand at the testing frequency. The grip of the phantom hand is shown in the figure, and the system ground plane is placed near the phantom head with a distance of 12 mm. As there is no handset casing enclosing the system ground plane in the study, this distance is to simulate for the practical case in which there is a handset casing and the acoustic output near the top edge of the handset casing is attached onto the phantom head. The simulated SAR values are obtained using input power of 24 dBm at 859 and 925 MHz for the GSM850/900 operation and 21 dBm at 1795, 1920, and 2045 MHz for the GSM1800/1900/UMTS operation. For the head only case, the SAR values are all well below the limit of 1.6 W/kg for 1-g head tissue. The local SAR maximum at each frequency is represented by an open square in the SAR distributions. For the head and hand case, the local SAR maximum is all seen to be shifted to the phantom hand, and the SAR values are increased. However, the SAR values for the head and hand case are still well below the limit of 1.6 W/kg.

A parametric study for the feed position *d* and the slot width *w* is also conducted. Figure 8 shows the simulated return loss as a function of the feeding position *d* of the microstrip feedline. Other dimensions are the same as in Figure 1. Results for the feed position *d* varied from 22 to 32 mm are presented. Significant effects are observed, which indicates that the feeding position *d* is a crucial parameter in controlling the excited resonant modes of the antenna. In this study, the preferred feed position is about 27 mm, close to about the center of the monopole slot.

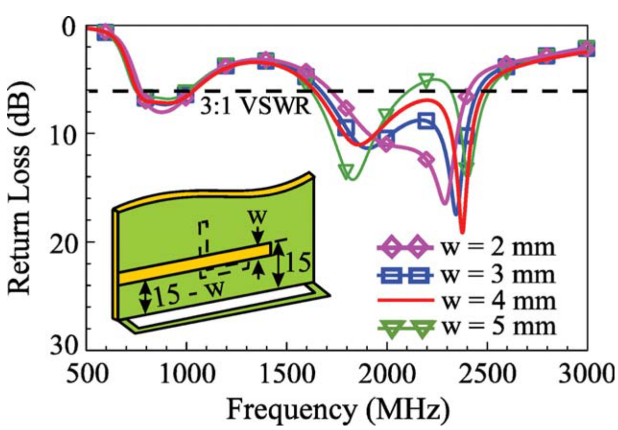


Figure 9 Simulated return loss as a function of the width *w* of the monopole slot. Other dimensions are the same as in Figure 1. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

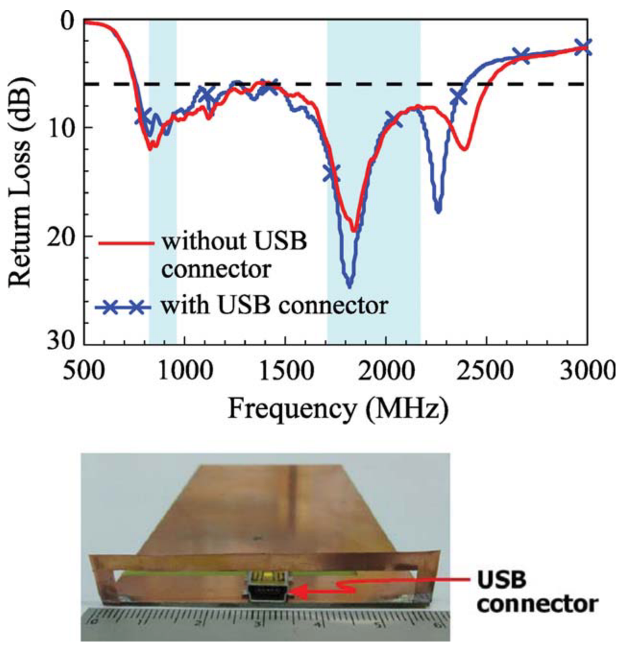


Figure 10 Comparison of the measured return loss of the proposed antenna with and without a practical USB connector mounted at the ground portion between the monopole slot and the bottom edge of the system ground plane. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com]

Figure 9 shows the simulated return loss as a function of the width *w* of the monopole slot. In the study, when the width *w* varies, the distance between the monopole slot and the bottom edge of the system ground plane varies as 15 mm $-$ *w*, and the tuning stub of the microstrip feedline is still oriented to be parallel along the edge of the monopole slot. A smaller width *w* will in general lead to smaller bandwidths for the antenna, especially for the upper band. However, for larger width ($w = 5$ mm in the figure), as the ground portion between the monopole slot and the bottom edge of the system ground plane is decreased to be 10 mm only, some degradation in the impedance matching for frequencies in the upper band is seen. The width *w* is hence selected to be 4 mm in this study.

Finally, mounting a practical USB connector of size $9 \times 7 \times 4$ mm^3 on the ground portion between the monopole slot and the bottom edge of the system ground plane is studied. Figure 10 shows the comparison of the measured return loss of the proposed antenna with and without a practical USB connector. A photo showing the case with a practical USB connector is also given in the figure. Small effects on the measured return loss are seen. The results indicate that the ground portion between the monopole slot and the bottom edge of the system ground plane can indeed be used to accommodate associated electronic elements inside the mobile handset.

4. CONCLUSIONS

A simple monopole slot antenna of small size 4×50 mm^2 printed on the main circuit board of the mobile handset for penta-band WWAN operation in the 824–960 and 1710–2170 MHz bands has been presented. The monopole slot is placed close to the bottom edge of the system ground plane in the study to facilitate the circuit floor planning and signal line routing on the main circuit board. Two wide operating bands for the desired WWAN operation can be obtained by selecting the feed position of the microstrip feedline at about the center of the monopole slot and adding a C-shaped strip connected orthogonal to the bottom edge of the system ground plane. Good radiation characteristics for frequencies over the obtained antenna's lower and upper bands have also been obtained. The simulated SAR values of the antenna with the presence of the phantom head and hand are also well below the 1.6 W/kg limit for 1-g tissue, which makes the antenna very promising for practical mobile handset applications.

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ANTENNA REPRESENTATION IN TWO-PORT NETWORK SCATTERING PARAMETER

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ABSTRACT: *This paper proposes a representation of antenna in two-port network s-parameter, by exploiting the analogy between the antenna and a two-port network, to produce a suitable method for evaluating antennas in system and circuit simulation. Complicated steps required by previous methods to determine an antenna-specific equivalent-circuit and its corresponding resistor, inductor, and capacitor values are avoided. Simulations results obtained for the circuit and*