CAPACITIVELY FED HYBRID MONOPOLE/SLOT CHIP ANTENNA FOR 2.5/3.5/5.5 GHz WIMAX OPERATION IN THE MOBILE PHONE

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ABSTRACT: *In this study, a promising design of the capacitively fed hybrid monopole/slot chip antenna for the 2.5/3.5/5.5 GHz WiMAX (worldwide interoperability for microwave access) operation in the mobile phone is presented. The antenna is printed on a thin FR4 substrate of small size 5.2 × 16 mm^2 as a surface-mount element to be placed at one corner of the system circuit board of the mobile phone. The antenna mainly comprises a resonant monopole patch, a resonant shorter slot, and a matching longer slot; the latter two slots are embedded within the monopole patch to achieve a compact integration. Two wide operating bands centered at about 3.3 and 5.5 GHz are generated through capacitive excitation of the resonant monopole patch and the shorter slot, while the matching longer slot helps to improve the impedance matching over the two operating bands. The lower band covers WiMAX operation in the 2.5 GHz (2500–2690 MHz) and 3.5 GHz (3300–3700 MHz) bands, while the upper band covers the 5.5 GHz (5250–5850 MHz) WiMAX operation. Details of the proposed hybrid monopole/slot chip antenna are presented.* Microwave Opt Technol Lett 50: 2689–2694, 2008; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.23777

Key words: *chip antennas; WiMAX antennas; monopole antennas; slot antennas; hybrid antennas*

1. INTRODUCTION

The WiMAX (worldwide interoperability for microwave access) system based on the IEEE 802.16 standard is becoming very attractive for wireless internet access, because of its high transmitting data rate and wide covering range [1, 2]. For this application, some promising small antennas for WiMAX operation have been reported recently [3–9]. These antennas can cover several or all operating bands of the WiMAX operation in the 2.5 GHz band (2500–2690 MHz), 3.5 GHz band (3300–3700 MHz), and 5.5 GHz band (5250–5850 MHz) with a reasonable antenna volume. However, it is a trend for the modern mobile devices that the occupied volume of their internal antennas, including the WiMAX antenna, should be as small as possible, yet with all the operating bands still desired. For this requirement, we present in this study a small capacitively fed hybrid monopole/slot chip antenna for WiMAX operation in the 2.5/3.5/5.5 GHz bands for mobile phone applications.

The proposed chip antenna has a small size of 0.8 × 5.2 × 16 mm^3 and mainly comprises a resonant monopole patch, a resonant shorter slot, and a matching longer slot; the latter two slots are embedded within the monopole patch to achieve a compact integration. Both the monopole patch and the shorter slot are excited capacitively by using a 50-Ω microstrip line with a tuning stub, and two wide operating bands centered at about 3.3 and 5.5 GHz for the antenna can be generated. The matching longer slot greatly helps to improve the impedance matching for frequencies over the lower and upper bands. The antenna's lower band is mainly contributed by the 0.25-wavelength mode of the monopole patch, and the upper band is formed by the 0.5-wavelength mode of the monopole patch and the 0.5-wavelength mode of the resonant shorter slot. That is, two different types of the resonant monopole mode and slot mode are both excited and incorporated [10–12] in the proposed chip antenna to achieve the desired operation.

In the reported design in [10], the hybrid antenna is obtained by incorporating a printed 0.25-wavelength slot element [13–16] and a monopole patch element. In [11], the hybrid antenna is formed by a printed loop strip element [17, 18] and a 0.25-wavelength slot element. However, in both designs, the two hybrid elements are separated and are not combined into one single element to achieve a compact antenna size. In [12], the hybrid antenna is achieved by embedding a 0.5-wavelength slot element [19, 20] inside a monopole patch element, and GSM850/900/1800/1900/UMTS penta-band WWAN (wireless wide area network) operation [21] is obtained. We further apply this integration technique [12] in this study for two hybrid elements to achieve a compact hybrid antenna design on a small chip base (a thin FR4 substrate of small size used here) as a surface-mount element [22, 23] for WiMAX operation in the mobile phone. The obtained lower band can have a wide bandwidth of about 50% or about 1.7 GHz, allowing it to easily cover the 2.5/3.5 GHz WiMAX operation. The obtained upper band can also have a wide bandwidth of about 17% or about 0.95 GHz to cover the 5.5 GHz WiMAX operation. The proposed chip antenna with hybrid monopole/slot mode excitation is described in detail in this study, and experimental and simulation results for the constructed prototype are presented.

2. HYBRID MONOPOLE/SLOT CHIP ANTENNA

Figure 1(a) shows the configuration of the capacitively fed hybrid monopole/slot chip antenna for the 2.5/3.5/5.5 GHz WiMAX operation in the mobile phone. The front and back views of the antenna are shown in Figure 1(b), and the back side of the system circuit board of the mobile phone is shown in Figure 1(c). The metal pattern of the antenna in its unfolded structure is given in Figure 1(d). The antenna is mounted at one corner of the system circuit board of the mobile phone, which is a 0.8-mm thick FR4 substrate of size 40 × 90 mm^2 used here. The dimensions of the system circuit board are reasonable for general mobile phones. On the back side of the circuit board, a system ground plane is printed, leaving a small no-ground region (2 × 16 mm^2) at the corner of the circuit board where the antenna is mounted [see Fig. 1(c)]. The antenna is also short-circuited to the system ground plane through a small shorting strip (width 1 mm and length 2 mm). This short-circuiting contributes some inductance to the large capacitive coupling between the antenna and the ground plane, hence allowing the use of the small no-ground region here.

As shown in Figure 1(d), the antenna mainly comprises three elements of a resonant monopole patch (length 26.6 mm, width or height h 5.2 mm), a resonant shorter slot (length c 12 mm, width 1.2 mm), and a matching longer slot (length e 24.6 mm, width 1 mm). The three elements are printed on the two sides of the 0.8-mm thick FR4 substrate [see Fig. 1(b)], which is the antenna's chip base. The antenna is excited using a 50-Ω microstrip line printed on the front side of the circuit board, which is connected to the antenna's inverted-L-coupling portion at point A (the antenna's feeding point). Both the resonant monopole patch and short slot are capacitively excited through the coupling portion, and fine-tuning of the capacitive excitation is achieved by adjusting the length a (4 mm) and width b (1 mm) of the tuning stub in the inverted-L-coupling portion.

The length of the monopole patch corresponds to about 0.25 wavelength at 3 GHz, which leads to the excitation of a 0.25-wavelength monopole mode at about 3.0 GHz and a 0.5-wavelength monopole mode at about 5.7 GHz for the antenna. With the

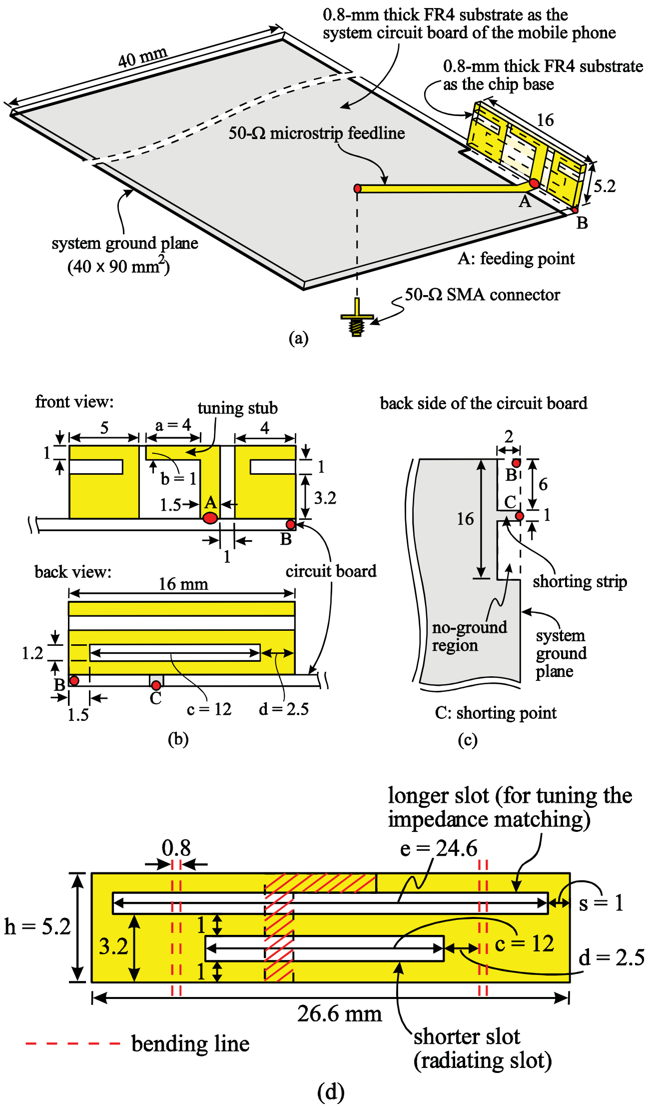


Figure 1 (a) Configuration of the capacitively fed hybrid monopole/slot chip antenna for 2.5/3.5/5.5 GHz WiMAX operation in the mobile phone. (b) Front and back views of the antenna. (c) Back side of the system circuit board of the mobile phone. (d) Metal pattern of the antenna in its unfolded structure. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

presence of the embedded slots (the shorter and longer slots, especially the longer slot) in the monopole patch, which help to improve the impedance matching of the excited resonant modes, the single-resonance behavior of the 0.25-wavelength monopole mode can become a dual-resonance one. With dual resonance achieved, the 0.25-wavelength monopole mode forms a wide operating lower band for the antenna to cover the 2.5/3.5 GHz WiMAX operation. In addition, the shorter slot of length 12 mm can also contribute a 0.5-wavelength slot mode at about 5 GHz, which incorporates the excited 0.5-wavelength monopole mode to form a wide operating upper band for the antenna to cover the 5.5 GHz WiMAX operation.

3. RESULTS AND DISCUSSION

The proposed monopole/slot chip antenna was fabricated and tested. Results of the measured and simulated return loss for the fabricated prototype are presented in Figure 2. Good agreement between the measured data and simulated results obtained using Ansoft HFSS [24] is seen. Two wide operating bands centered at about 3.3 and 5.5 GHz are successfully generated. The lower band shows a dual-resonance excitation as discussed in Section 2 and has a wide bandwidth (10-dB return loss) of 1685 MHz (2495–4180 MHz) or about 50% centered at about 3.3 GHz. The upper band is formed by two resonant modes and also shows a wide bandwidth of 945 MHz (5075–6020 MHz) or about 17% centered at about 5.5 GHz. The lower and upper bands cover WiMAX operation in the 2.5/3.5 GHz bands (2500–2690/3300–3700 MHz) and the 5.5 GHz band (5250–5850 MHz), respectively.

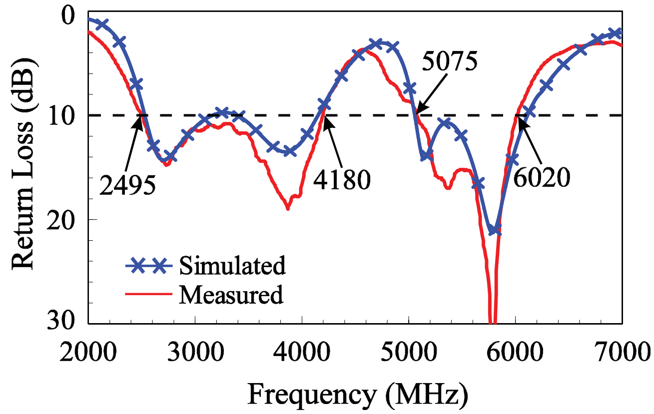


Figure 2 Measured and simulated return loss for the proposed antenna. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

Figure 3 shows a comparison of the simulated return loss of the proposed antenna and the reference antenna (without the longer and shorter slots). When there are no embedded slots, two excited resonant modes at about 3.0 and 5.7 GHz can be obtained. The two resonant modes are contributed from the resonant monopole patch, which are the 0.25- and 0.5-wavelength monopole modes, and their operating bandwidths are far from sufficient for covering the 2.5/3.5/5.5 GHz WiMAX operation. It is clearly seen that the resonant mode at about 3.0 GHz becomes a dual-resonance mode for the proposed antenna. Near the 0.5-wavelength monopole mode at about 5.7 GHz, a new resonant mode (0.5-wavelength slot mode) contributed by the resonant shorter slot is excited. The two adjacent modes are formed into a wide upper operating band for the proposed antenna.

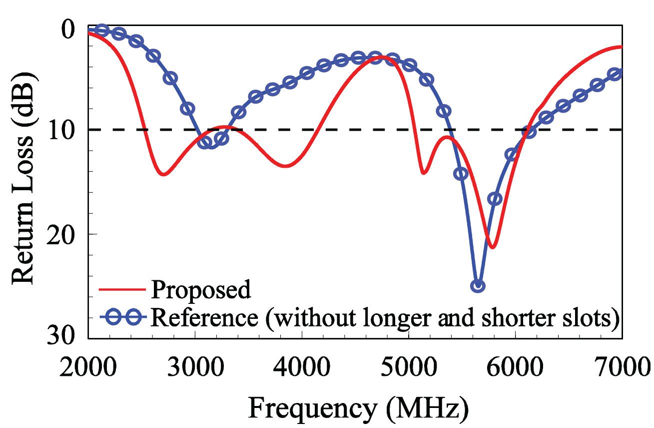


Figure 3 Simulated return loss of the proposed antenna and the reference antenna (without the longer and shorter slots in the monopole patch). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

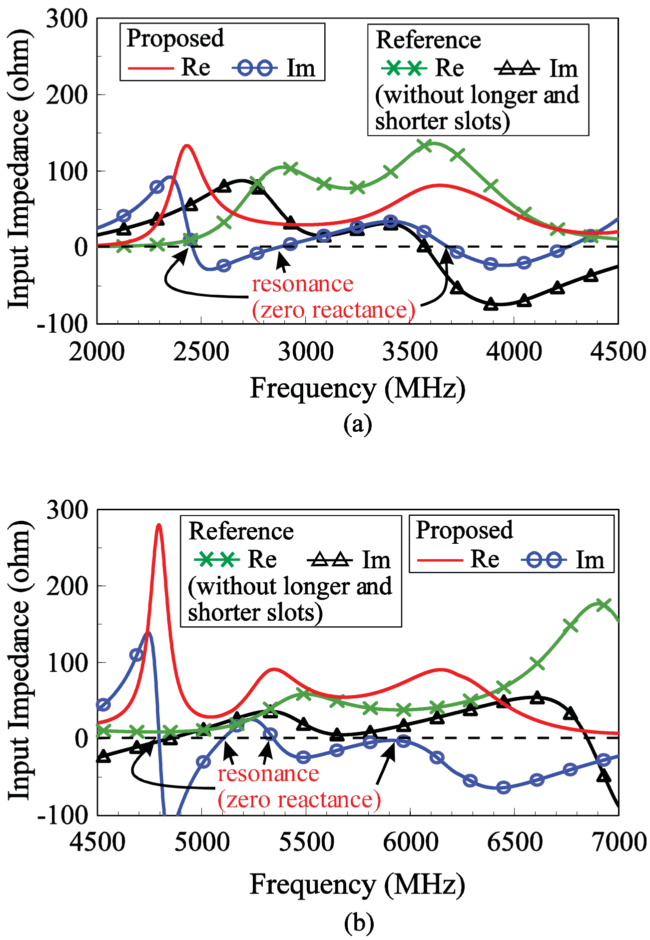


Figure 4 Simulated input impedance of the proposed and reference antennas studied in Figure 3. (a) Lower band for 2.5/3.5 GHz WiMAX operation. (b) Upper band for 5.5 GHz WiMAX operation. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

Figure 4 shows the simulated input impedance of the proposed and reference antennas studied in Figure 3. Results for the lower band are shown in Figure 4(a), while those for the upper band are in Figure 4(b). For the lower band, more resonances (zero reactance) are obtained for the proposed antenna, which leads to the dual-resonance excitation seen in Figure 3. For the upper band, there are also more resonances obtained for the proposed antenna. In addition, a new resonant mode at about 4.8 GHz is generated, which is the 0.5-wavelength slot mode. With the generation of this slot mode, good impedance matching can be achieved at the high-frequency tail of this slot mode at around 5.2 GHz, which leads to the resonant mode observed at about 5.2 GHz in Figure 3. This resonant mode contributed by the shorter slot and the 0.5-wavelength monopole mode are formed into a wide upper operating band for the proposed antenna.

The study on the major parameters of the proposed antenna is also conducted. Figure 5 shows the simulated return loss as a function of the height h of the monopole patch. Results for h varied from 5.2 to 7.2 mm are presented, and other dimensions are the same as given in Figure 1. Large effects on the antenna's lower band are seen. The second mode in the antenna's upper band is also greatly affected by the variations in h. This agrees with the discussion that they are mainly contributed by the resonant monopole patch.

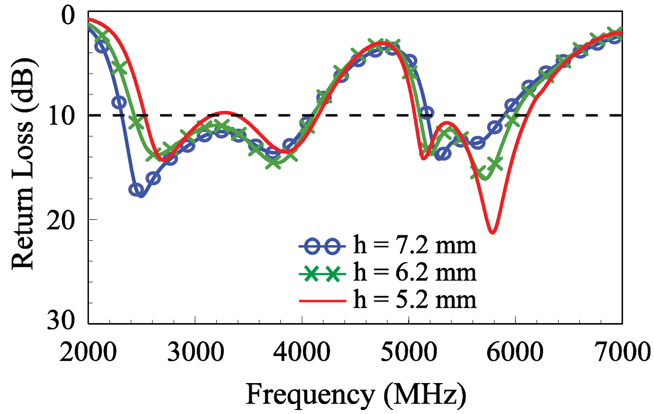


Figure 5 Simulated return loss as a function of the height h of the monopole patch. Other dimensions are the same as given in Figure 1. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

Figure 6 shows the simulated return loss as a function of the resonant shorter slot and the matching longer slot. Results for the length c of the shorter slot varied from 11 to 13 mm are presented in Figure 6(a), while those for the length e of the longer slot varied from 20.6 to 24.6 mm are given in Figure 6(b). For the two cases,

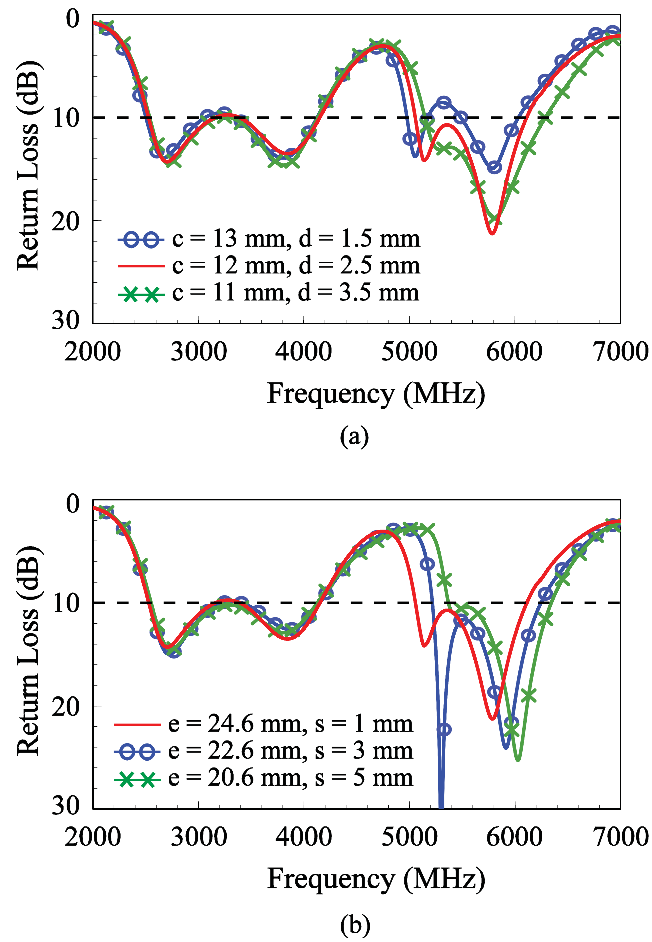


Figure 6 Simulated return loss as a function of (a) the length c of the resonant shorter slot and (b) the length e of the matching longer slot. Other dimensions are the same as given in Figure 1. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

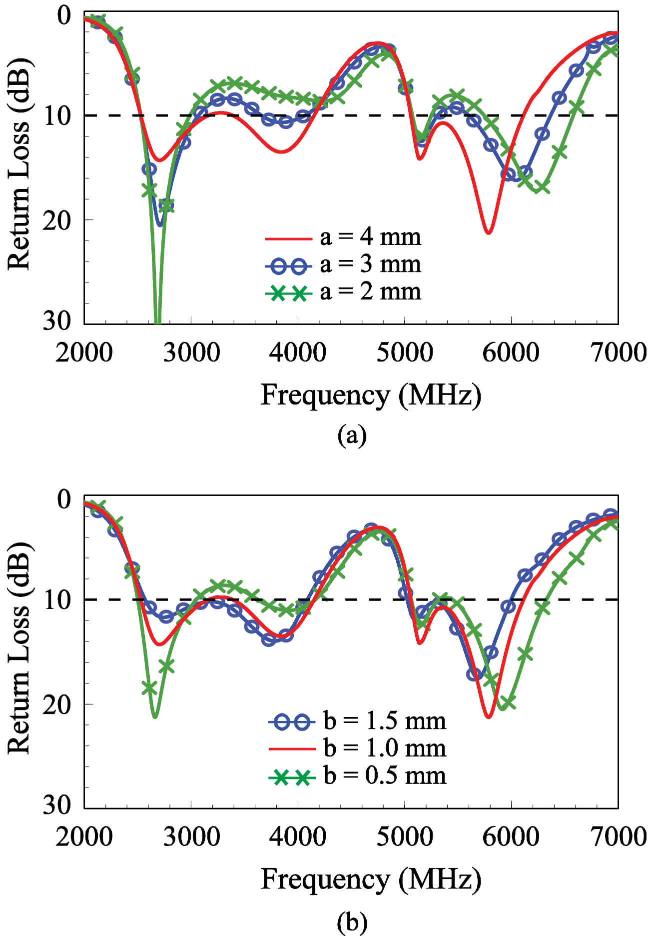


Figure 7 Simulated return loss as a function of (a) the length *a* and (b) the width *b* of the tuning stub in the inverted-L-coupling portion. Other dimensions are the same as given in Figure 1. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

very small effects on the antenna's lower band are seen. Conversely, there are large effects on the antenna's upper band. In Figure 6(a), the variation in the length *c* of the shorter slot results

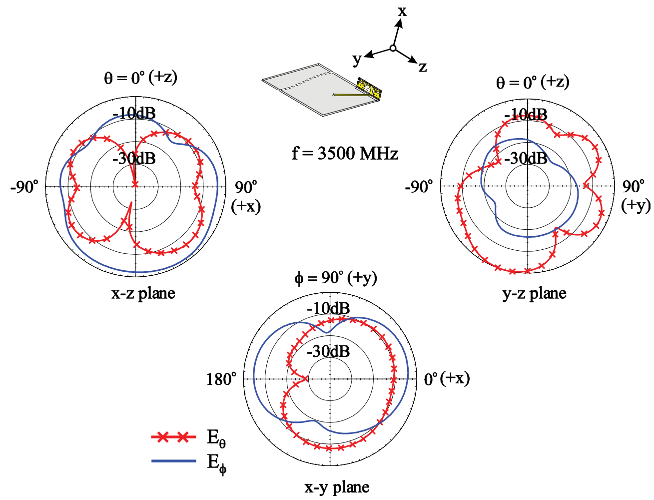


Figure 9 Measured radiation patterns at 3500 MHz for the antenna. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

in some resonant frequency shifting of the resonant mode at around 5.2 GHz; this behavior agrees with the discussion that this resonant mode is contributed by the resonant shorter slot. On the other hand, as seen in Figure 6(b), the longer slot shows large effects on the impedance matching for frequencies over the antenna's upper band. By selecting proper dimensions of the longer slot, good impedance matching can be obtained for the proposed antenna.

Figure 7 shows the effects of the tuning stub in the inverted-L-coupling portion. Results for the length *a* of the tuning stub varied from 2 to 4 mm are presented in Figure 7(a), and those for the width *b* of the tuning stub are given in Figure 7(b). For both cases shown in Figures 7(a) and 7(b), it can be seen that the impedance matching levels over the antenna's lower and upper bands can be effectively adjusted by selecting proper dimensions of the tuning stub.

Radiation characteristics of the proposed antenna are also studied. Figures 8–10 plot the measured radiation patterns at 2595, 3500, and 5550 MHz, which are the central frequencies of the 2.5,

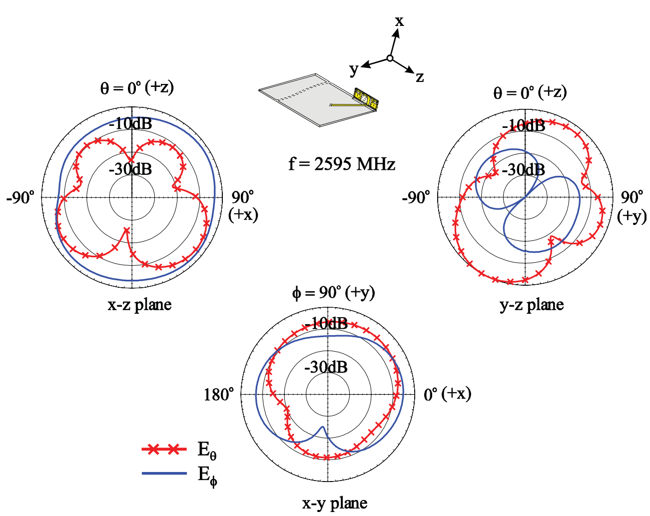


Figure 8 Measured radiation patterns at 2595 MHz for the antenna. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

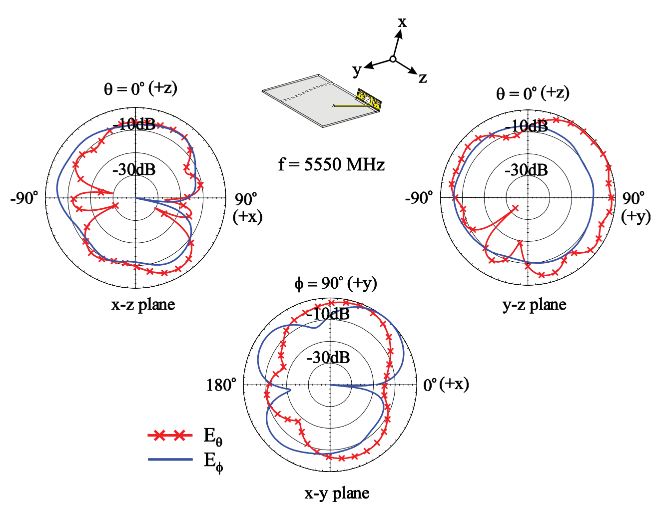
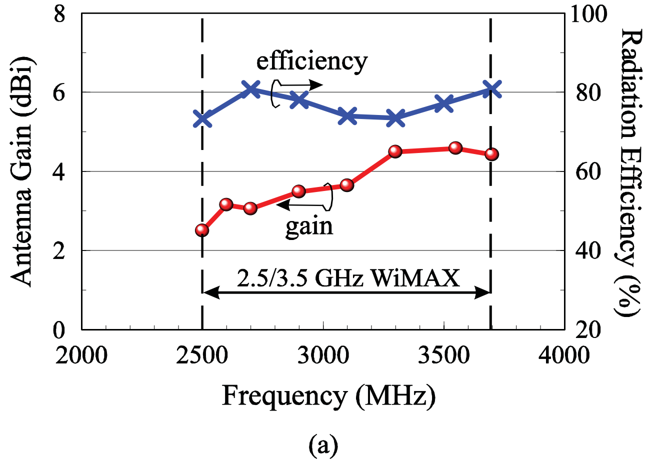


Figure 10 Measured radiation patterns at 5550 MHz for the antenna. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]



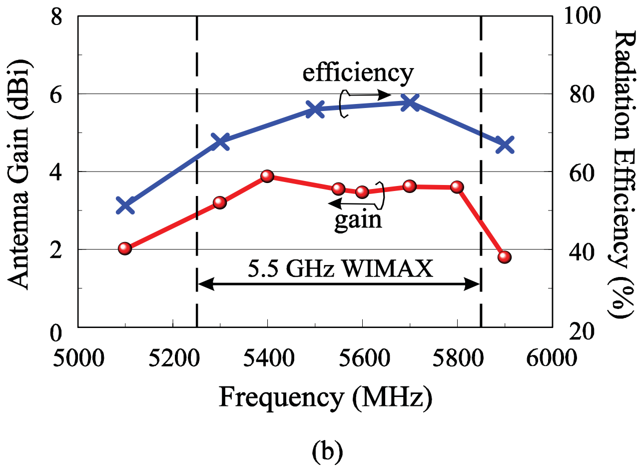


Figure 11 Measured antenna gain and simulated radiation efficiency. (a) Lower band for 2.5/3.5 GHz WiMAX operation. (b) Upper band for 5.5 GHz WiMAX operation. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com]

3.5, and 5.5 GHz WiMAX bands. The measured E_θ and E_ϕ components are generally comparable, especially in the x–y plane (azimuthal plane) and at 5500 MHz. This characteristic is advantageous for practical applications, since the practical wave propagation environment is usually complex. The measured antenna gain and simulated radiation efficiency for the antenna are presented in Figure 11. Over the lower band for the 2.5/3.5 GHz WiMAX operation in Figure 11(a), the antenna gain is varied from 2.6 to 4.6 dBi, and the efficiency is about 72–80%. In Figure 11(b), results over the upper band for the 5.5 GHz WiMAX operation are shown. The antenna gain is varied from 2.7 to 3.8 dBi, and the efficiency is about 64–77%. In general, good radiation characteristics for the 2.5/3.5/5.5 GHz WiMAX operation are obtained.

4. CONCLUSION

In this study, a small-size capacitively fed hybrid monopole/slot chip antenna capable of the 2.5/3.5/5.5 GHz WiMAX operation in the mobile phone has been presented. The metal pattern of the proposed hybrid antenna mainly consists of a resonant monopole patch, a resonant shorter slot, and a matching longer slot. The shorter and longer slots are embedded inside the monopole patch to achieve a compact size for the antenna. Resonant modes contributed by the monopole patch and the shorter slot have been successfully excited. With the presence of the longer slot in the monopole patch, good impedance matching of the excited monopole and slot modes have been achieved. These monopole and slot modes are formed into the antenna's lower and upper bands to cover WiMAX operation in the 2.5/3.5 GHz and 5.5 GHz bands, respectively. Good radiation characteristics for frequencies over the 2.5/3.5/5.5 GHz bands have also been obtained for the proposed antenna.

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DESIGN OF DUAL-BAND BANDPASS FILTER USING DIVERSE QUARTER-WAVELENGTH RESONATORS FOR GPS/WLAN APPLICATIONS

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ABSTRACT: *The novel compact dual-band bandpass filter (BPF) by using diverse quarter-wavelength (λ/4) resonators for global position system (GPS)/wireless local area network (WLAN) applications is proposed for the first time. The use of two interdigital-like λ/4 resonators of the proposed BPF effectively provides the responses for GPS/WLAN at 1.575/5.7 GHz by properly arranging the λ/4 SIRs. Full-wave simulator IE3D is used to design the proposed BPF. Good agreement with responses of electromagnetic (EM) simulation and measurement is compared.* © 2008 Wiley Periodicals, Inc. Microwave Opt Technol Lett 50: 2694–2696, 2008; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.23716

Key words: *stepped impedance resonators (SIRs); GPS; WLAN; dual-band; bandpass filter*

1. INTRODUCTION

In recent years, the development of multi-service mobile wireless communication system, such as combination of global position system (GPS) and wireless local area network (WLAN), global system for mobile communications (GSM) and GPS or GSM and WLAN, has become attractive for the commercial products. For example, the commercial product of N-series cellphone produced by Nokia provides the dual-service for GPS and GSM. Therefore, development of dual-band bandpass filter (BPF) is needed for the multi-service system.

Dual-band BPFs have been gaining a wide attention in recent years [1–7]. Several types of dual-band BPFs, such as the cascaded connection of bandpass and bandstop filters [1], coupled stepped impedance resonators (SIRs), [2–4] and combination of two or more individual resonators [5–7]. However, most of the reported dual-band BPFs only show the dual passband performance in single-service system, especially in WLAN with IEEE 802.11 a/b standard. There is still a challenge to the designers is to simultaneously achieve the compact size and low insertion loss when designing a dual-band BPF for the multi-service communication system. Quarter-wavelength (λ/4) SIRs are known to only exhibit higher order resonant modes at the odd harmonics [8] and to have reduced resonator size. Typical configuration of interdigital BPF uses λ/4 uniform impedance resonators (UIRs). However, such BPF requires via holes to be the ground of the resonator and has the spurious responses appeared at about odd times of the desired fundamental passband [9].

In this letter, we propose novel dual-band BPF using diverse λ/4 resonators for GPS (1.575 GHz)/WLAN (5.7 GHz) application. The BPF is constructed from two-stepped impedance resonators (SIRs) and two coupling enhanced lines, as shown in Figure 1. Each resonator has an electric length within 90° at the center frequency f_0 and is short-circuited at one end and open-circuited at the other end. The proposed BPF simultaneously achieves the compact size, low loss, and good dual-band performance for GPS/WLAN. The theory and guidelines for designing the λ/4 SIRs are clearly presented in next section. The dual-band BPF is designed, fabricated, and measured. A good agreement between the electromagnetic (EM) simulated result and measured resulted is obtained.

2. CIRCUIT DESIGN

2.1. Design of the Quarter Wavelength SIRs

The structure of a λ/4 microstrip SIR is shown in Figure 2(a). The SIR is constructed by two sections with both different characteristic impedance and physical length. The impedance ratio (K) is defined as $K = Z_2/Z_1$, which is an important designed parameter to tune the properties of SIR. The input impedance Z_i can be derived as:

$$Z_i = jZ_2\frac{Z_1\tan\theta_1 + Z_2\tan\theta_2}{Z_2 - Z_1\tan\theta_1\tan\theta_2} \tag{1}$$

Let $Y_i = 1/Z_i = 0$, the parallel resonant modes of SIR can be obtained as

$$\tan\theta_1\tan\theta_2 = K = Z_2/Z_1 \tag{2}$$

To obtain more design freedoms to control the resonant modes of the SIR, two sections can have different physical length. The length ratio of SIR is defined as $\alpha = \theta_2/(\theta_1 + \theta_2) = \theta_2/\theta_t$ [8]. Therefore, various K and α value are to determine the higher resonant mode of the λ/4 SIR. The commercial RO 3003 substrate with a dielectric constant $\varepsilon_r = 3$, a thickness $h = 0.508$ mm, and a loss tangent tan $\delta = 0.0013$ is used in this study. Figure 2(b) shows the normalized ratio of the resonant frequency of the higher order mode to the resonant frequency of the fundamental mode for the λ/4 SIR. Since the λ/4 SIR only resonates at odd mode over

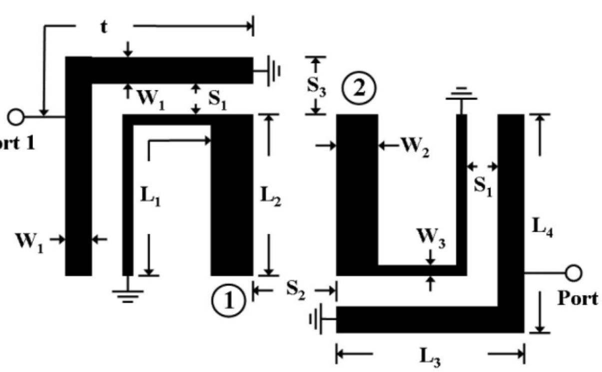

Figure 1 Configuration of the proposed dual-band BPF using diverse coupled λ/4 resonators