Design of Small and Broad-Band Internal Antennas for IMT-2000 Mobile Handsets

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***Abstract*—The objective of this paper is to design some small broad-band internal antennas for third-generation International Mobile Telecommunications-2000 (IMT-2000) mobile handsets. By introducing substrates of low dielectric constants and electromagnetically coupling two shorted microstrip patch elements, of either rectangular or semidisc shape, both compactness and broad bandwidth can be achieved. These novel internal antennas for IMT-2000 mobile handsets incorporate only one single probe feed in a driven patch element, while the broad-band feature is obtained by realizing dual-frequency operation. The typical impedance behavior and far-field radiation pattern characteristics of eight different antenna configurations are discussed theoretically and experimentally.**

***Index Terms*—Broad-band, dual frequency, handset, IMT-2000, internal antenna, microstrip antenna.**

I. INTRODUCTION

MOBILE cellular and cordless communications systems have been in constant demand during the last decade. The International Telecommunications Union (ITU) has been in the process of developing the family standard for the third-generation (3G) global mobile cellular system [1], namely, the International Mobile Telecommunications-2000 (IMT-2000) mobile communications system.

The IMT-2000 system will bridge the gap between the wireless world and the computing or Internet world, making inter-operation apparently seamless. The main benefit is that it will offer high-end service capabilities, which include substantially enhanced capacity, quality, and data rates than are currently available, and offer video-on-demand high speed multimedia data services, mobile Internet access, and built-in support for parallel usage of such services. The first networks of the IMT-2000 system are planned to be launched in Japan in 2001 (delayed until October 2002[1]), with European countries following in early 2002, while Korea will provide the IMT-2000 services in 2003.[2]

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[1][Online]. Available: http://www.3GPP.com
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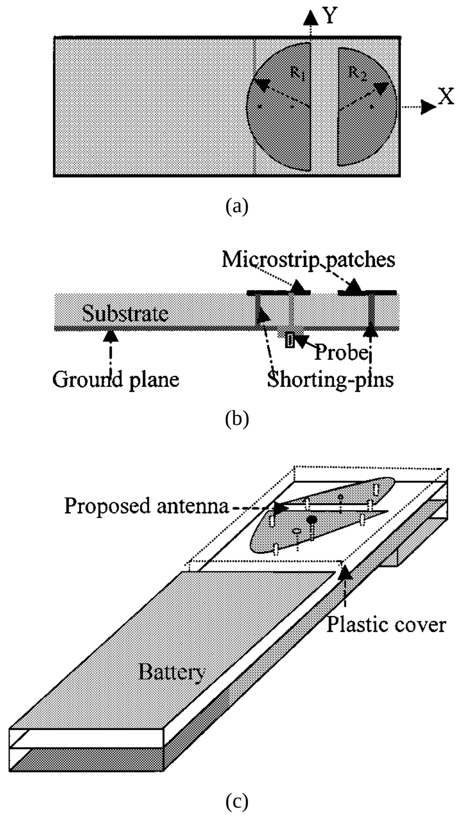


Fig. 1. Configuration of one proposed antenna using two similar semidisc patches (a) Top view. (b) Side view. (c) Integration into a handset body.

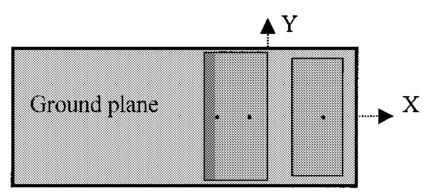
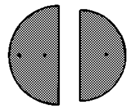
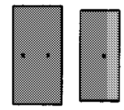
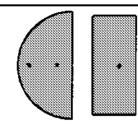
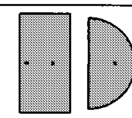


Fig. 2. Top view of proposed antenna using two similar rectangular patch shapes.

The 3G frequencies for the IMT-2000 mobile system were identified by the ITU at the 1992 World Administrative Radio-communications Conference (WARC 92) and appeared as number S5.388 of the Radio Regulations [2] (the 1885–2025- and 2110–2200-MHz bands are intended for use, on a world basis, by administrations wishing to implement the IMT-2000 system). Terrestrial IMT-2000 services will operate in the frequency-division duplex (FDD) mode in the 1920–1980-MHz bands paired with 2110–2170 MHz for mobile stations transmitting in the lower subband and base stations transmitting

TABLE I
DETAILED PARAMETERS AND TYPICAL CHARACTERISTICS OF EIGHT PROPOSED INTERNAL ANTENNAS

Geometry (Unit: mm)								
Substrate	Air	Foam	Air	Foam	Air	Foam	Air	Foam
Thickness	10	8	10	8	10	8	10	8
Patch Size	R_1 18.5 R_2 17	R_1 23 R_2 22.5	18*30 10*33	19.4*37.4 9.5*43	R_1 18.5 10*38	R_1 20 9.5*40	18*30 R_2 16	18.8*35.4 R_2 17.4
Δ	8	5.5	8	7	8	7	8	7
$(x_{s_1}, y_{s_1}) / r_{s_1}$	(-15, 0) /0.625	(-20, 0) /1.5	(-15, 0) /0.625	(-17, 0) /1.8	(-15, 0) /0.625	(-17, 0) /1.6	(-15, 0) /0.62	(-16, 0) /1.7
$(x_p, y_p) / r_p$	(-5.6, 0) /0.62	(-2, 0) /1.5	(-5.6, 0) /0.62	(-8, 0) /0.62	(-5.6, 0) /0.62	(-8, 0) /0.62	(-5.6, 0) /0.62	(-8, 0) /0.62
$(x_{s_2}, y_{s_2}) / r_{s_2}$	(18, 0) /0.625	(21.5, 0) /2.5	(16, 0) /0.625	(13, 0) /0.625	(16, 0) /0.625	(13, 0) /0.625	(16, 0) /0.625	(13, 0) /0.625
f_1 / f_2 (GHz)	1.76/2.05	1.89/2.1	1.92/2.06	1.81/2.02	1.71/2.0	1.85/2.12	1.89/2.04	1.86/2.08
BW	25.3%	24.5%	20.0%	20.4%	25.1%	22.7%	19.6%	19.0%

(Note: The coordinates cited in Table I are similar to that in Fig. 1; the subscripts s_1, s_2, and p stand for two shorting pins and the probe, respectively, while r_{s_1}, r_{s_2}, and r_p are their respective radii. The symbols f_1 and f_2 represent two excited resonant frequencies. The impedance BW is based on return loss ≤ -10 dB. The symbol Δ represents the coupling gap between two patches. The dimensions of the ground plane are 40 mm $\times$ 90 mm.)

in the upper subband. The 1885–1920- and 2010–2025-MHz bands are unpaired for time-division duplex (TDD) operation. The issue of extending the current spectra for the IMT-2000 service was also considered by the ITU.

Generally, it will be suitable for the 3G mobile handset antennas to satisfy the bandwidth (BW) in the range of the proposed 1885–2025-MHz uplink and 2110–2200-MHz downlink, i.e., around 15.4% impedance BW (return loss ≤ -10 dB) if the frequency spectra from 1885 to 2200 MHz is fully covered.

With the rapid evolution of mobile communications, the antennas preferred for the IMT-2000 mobile handsets are small, compact, highly efficient, low profile, and low specific absorption rate (SAR). Internal antennas, such as microstrip patch antenna (MPAs) [3], [4], have been used extensively in pagers, wireless local area networks (WLANs), cordless phones, and mobile cellular handsets [5] because they almost meet all the above requirements and, in particular, they can be integrated into the chassis of the mobile handsets easily. This will offer several advantages over conventional external antennas, such as whip and helical antennas. The internal antennas are mechanically robust, conformably compact, and less sensitive to geometry of handsets. They can also improve aesthetic appearance, increase total efficiency, reduce SAR, and, in particular, achieve multi-frequency or broad-band operation by the use of some special techniques.

While the IMT-2000 mobile system is now under intensive development worldwide, the research on its antennas for internal packaging is not so intensive. In this paper, some novel, small and broad-band internal antennas suitable for the IMT-2000 mobile handsets will be presented.

The proposed internal antennas incorporate two similar patch elements by electromagnetically coupling along their parallel edges. The shapes of the patch elements can be either semidisc or rectangle. Both patches are coplanar on the substrate and are shorted to the ground plane by shorting pins to substantially reduce the overall dimensions of the antennas. A probe feed is introduced to excite the antenna by directly connecting the driven patch through its ground plane. Substrate of low dielectric constant, either air or some kind of foam substrate, is applied to improve the impedance BW (return loss ≤ -10 dB). BWs of 19% to 25.3% are achieved, which fully cover the frequency spectra of the IMT-2000 system, i.e., from 1885 to 2200 MHz. The maximum antenna thickness is about 1/15 of a wavelength at the frequency of interest, while the maximum planar dimension of the proposed antennas is only a quarter-wavelength. The analysis, design, typical impedance behavior, and radiation pattern characteristics, both theoretical and experimental, are presented and discussed.

II. ANTENNA THEORY AND ANALYSIS

The internal antennas, or MPAs, are normally narrow band due to their resonant behavior. Fortunately, there are two main kinds of BW enhancement techniques, namely, the BW enhancement technique for antenna elements and arrays, and the frequency-agility improvement technique for antennas operating over several adjacent resonant frequencies or multifrequency operation. There are numerous antenna element designs for BW enhancement [3], [4]. Typically, they can be categorized into the following three methods:

1) impedance matching;
2) using multiple resonance;
3) reducing the effective permittivity (or dielectric constants) of substrates.

On the other hand, for some specific applications, particularly in the case of mobile cellular handsets, more compact and smaller antenna configurations are required to meet severe constraints on the physical dimensions of the mobile terminals. Miniaturization of the overall antenna dimensions can be accomplished by using high-permittivity substrates, using shorting pins, or modifying basic patch shapes [4].

Some single patches of simple shapes with a shorting pin, such as the shorted circular patch, shorted rectangular patch [6], [7], and shorted semidisc patch [8], [9] have been investigated to reduce the antenna dimensions. The main function of a shorting pin is to act as an inductive element to some extent and perturb the electric-field paths in the patch so as to reduce the antenna size significantly [10]–[12]. The desired impedance BW can be increased by the use of relatively thick air-filled substrate with low relative permittivity ($\varepsilon_r \approx 1$). By trading off the BW enhancement and size reduction, both low relative-permittivity substrates and simple shorting pins are introduced in the design of the internal antennas for the IMT-2000 mobile handsets. Meanwhile, two similar coplanar patch elements are electromagnetically coupled together to realize dual-frequency or dual-band operation. Two excited resonant frequencies are modified to be sufficiently close such that the return loss in between them is lower than -10 dB. Hence, wider impedance BW (return loss ≤ -10 dB) can be achieved satisfactorily, as compared to their individual impedance BWs.

To accurately predict the impedance behavior and the radiation characteristics of such antennas, a full-wave method of moments (MoM) with potential integral equations [13] is applied since the input impedance behavior is affected by the sizes of the shorting pins and the relative positions between the shorting pins and the probe feed. In addition, there also exist discontinuities between the probe feed, shorting pins, and patches. In our design, the commercial software package Ensemble [14] was used to predict design results.

III. Antenna Designs and Variations

Fig. 1 shows one configuration of the proposed antennas and its placement and orientation in a handset body. This antenna consists of a driven semidisc patch of radius R_1 (the left-hand-side one), an electromagnetically coupled semidisc patch of radius R_2 (the right-hand-side one), and a single probe-feed in the driven semidisc. Both patches are coplanar and shorted discreetly with a shorting pin. Between the patches and ground plane is an air-filled substrate (with several spacers to support the patches). The two shorting pins and the probe feed are placed along the center line of the semidiscs, with the probe feed located between the two shorting pins. The ground plane has the dimensions comparable to those of modern mobile handsets, e.g., 40 mm $\times$ 90 mm.

The antenna is proposed to be installed in the upper rear part of a handset and above the battery pack, which fits on the lower half of the handset. The molded plastic shell of the battery would be ergonomically designed to encourage its user to hold the handset here for reducing antenna–hand interaction.

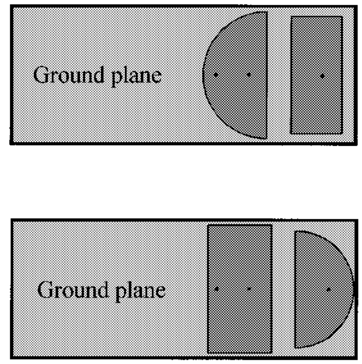
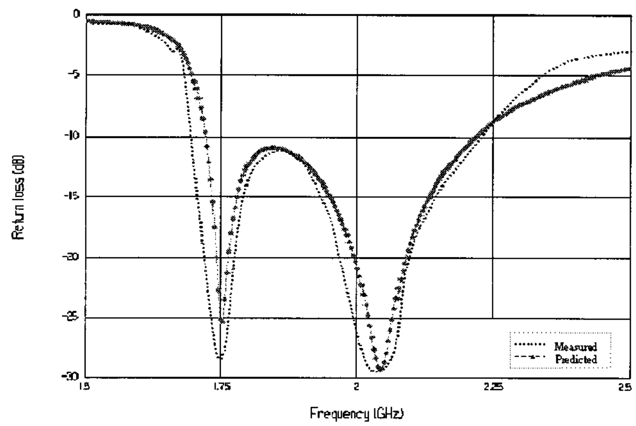
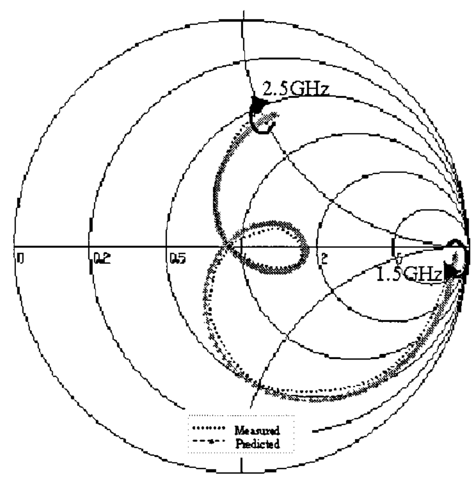


Fig. 3. Proposed antennas using the combination of semidisc and rectangular patch shapes.



(a)



(b)

Fig. 4. Input impedance of the proposed antenna using air substrate and two semidiscs. (a) Return loss. (b) Smith chart.

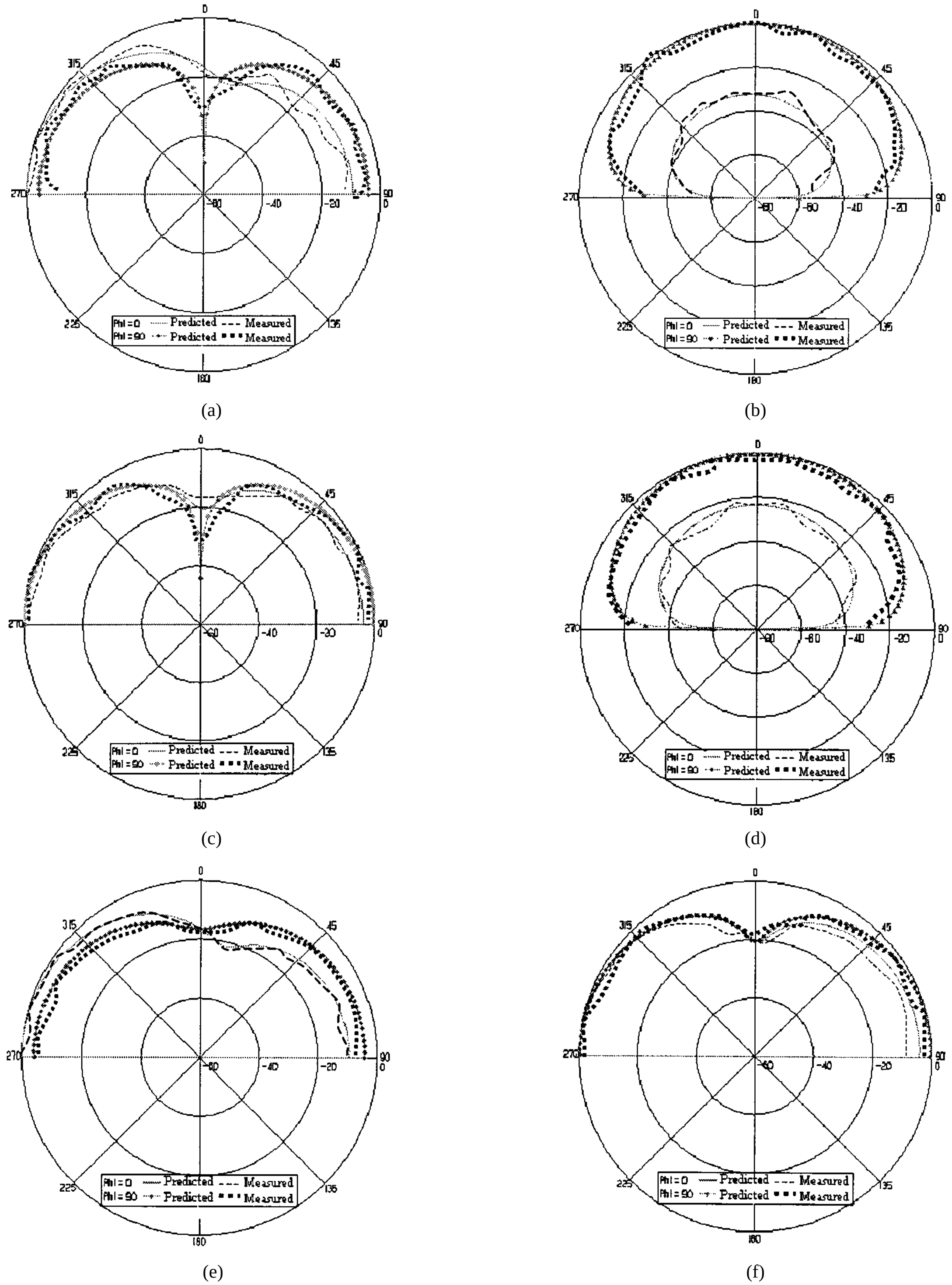


Fig. 5. Far-field radiation patterns of the antenna using air substrate and two semidiscs. (a) E/H-plane E_θ at 1.75 GHz. (b) E/H-plane E_ϕ at 1.75 GHz. (c) E/H-plane E_θ at 2.03 GHz. (d) E/H-plane E_ϕ at 2.03 GHz. (e) E/H-plane $E_{\rm total}$ at 1.75 GHz. (f) E/H-plane $E_{\rm total}$ at 2.03 GHz.

The antenna can be fabricated as a metallized layer in the rear plastic housing, further reducing the weight of the handset. If the air-filled substrate is replaced by a foam substrate of $\varepsilon_r \approx 1.07$, this antenna is still able to satisfy the requirements of the IMT-2000 mobile handsets after fine-tuning some parameters. Since the dielectric constant of the foam substrate is larger than that of the air-filled substrate, the antenna thickness using the foam substrate can be reduced correspondingly [3].

Fig. 2 depicts the top view of another proposed internal antenna for the IMT-2000 mobile handsets. The main difference between this configuration and that in Fig. 1 is that two rectangular patches are used instead of the two semidiscs. Other layouts of this structure, such as the relative positions of the shorting pins and probe feed, are similar to the original case with two semidisc patches. Such a configuration can also use either the air-filled substrate or the foam substrate.

Similarly, it is also possible to combine both semidisc and rectangular patches for the driven and coupling patch elements if relevant antenna parameters are modified accordingly. These antenna variations are shown in Fig. 3. The air-filled substrate or the foam substrate is still applicable to achieve compact and broad-band features for the IMT-2000 mobile handsets. These internal antennas will also be integrated into the upper rear parts of the mobile handsets.

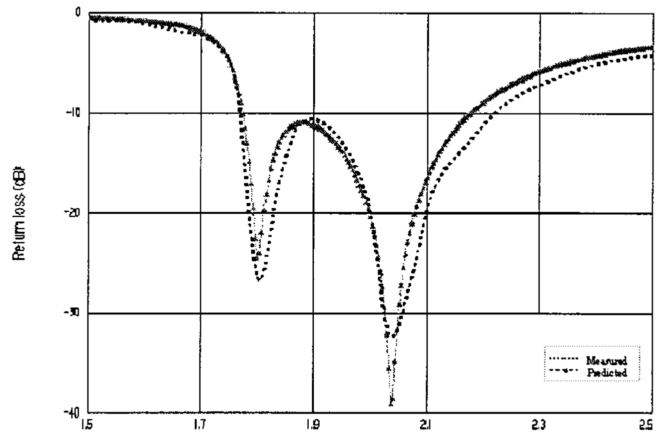
For simplicity and comparison, all the above-mentioned internal antennas are tabulated in Table I, where the detailed configuration parameters, typical resonant frequencies, and impedance BWs (return loss ≤ -10 dB) are given. In total, there are eight variations available if only rectangular and semidisc patches are considered. All the eight antennas are suitable for the IMT-2000 mobile handsets since their impedance BWs and radiation characteristics satisfy the requirements of the IMT-2000 mobile system.

IV. Comparisons of Predicted and Measured Results

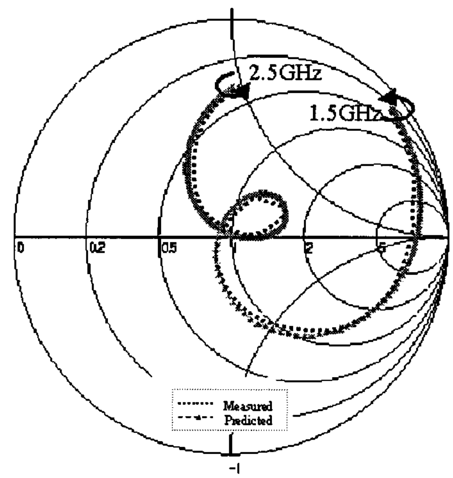
Fig. 4 depicts the predicted and measured input impedance behavior of the proposed internal antenna in Fig. 1 using the air-filled substrate and two semidisc patches. As can be seen from the return-loss plot, the measured impedance BW (return loss ≤ -10 dB) is 26.3%, from 1.71 to 2.23 GHz, which fully covers the frequency spectrum of the IMT-2000 from 1885 to 2200 MHz. The predicted or simulated impedance BW agrees very well with the measured result, except that the measured BW is slightly broader than the predicted one (25.3%). Two adjacent resonant frequencies in the range of return loss ≤ -10 dB are observed, i.e., 1.76 and 2.05 GHz. The predicted and measured antenna gains are 4.5 and 4.2 dBi, respectively, within the frequency spectra of interest. The location of the gain maximum is similar to that of a shorted semidisc patch antenna [8]. Our simulation revealed that the higher resonant frequency is mainly determined by the driven patch, while the lower one is probably excited by the combination area of the two patches. It should be noted that the coupling gap between the two patches is critically chosen for optimal coupling, otherwise, only a single resonant frequency with relatively narrower impedance BW will be observed.

The predicted and measured E_θ, E_ϕ, and E_{total} far-field radiation characteristics in the E and H planes at two resonant frequencies are shown in Fig. 5. There is a relatively deep null in the H-plane of E_θ pattern at broadside ($\theta = 0$). This may be due to the asymmetrical structure of the antenna. The E_ϕ pattern is similar to omnidirectional pattern. The antenna cross polarization in the H-plane of E_θ is relatively high, but this is not a major concern for the mobile cellular handset application since most of the electric fields will diffract off the edges of the small and limited handset ground plane [6]. The cross polarization in the E_{total} pattern is relatively low. The radiation patterns at two different resonant frequencies have similar characteristics as shown in Fig. 5.

For comparison, the typical impedance behavior (both predicted and measured) of another proposed antenna shown in Fig. 2 is presented in Fig. 6, where two rectangular patches and the foam substrate of $\varepsilon_r \approx 1.07$ are incorporated. It shall be noted that, in the case of the foam substrate, the far-field radiation patterns are similar to those in the case of the air-filled substrate. Although the respective resonant frequencies and relative return losses in different cases are shifted slightly, they are still sufficient to satisfy the requirements of the IMT-2000 system. The results suggest that this class of general antenna structure, incorporating one shorted driven patch and another shorted and coupled coplanar patch using a single probe feed, is viable to achieve broad-band and small internal antennas for the IMT-2000 mobile handsets.



(a)



(b)

Fig. 6. Input impedance of the antenna using foam substrate and two rectangular patches. (a) Return loss. (b) Smith chart.

It should be noted that the return losses within the frequency spectra of interest will become smaller (or lower) when a hand is placed over the antenna measured, while the resonant frequencies only shift a little. This may be due to the loading effect of the hand that makes the impedance matching of the antenna even better. In this sense, the internal antenna would be preferable to normal external antennas like helix or dipole. Unfortunately, the resonance will decay significantly when the antenna is directly touched by the hand. To mitigate such environment effects, a suitable plastic housing for the internal antenna is a must, as proposed in Fig. 1.

It should also be noted that electromagnetic coupling can be of either coplanar or stacked structure. However, only the coplanar structure has been considered here since the stacked (or multilayer) structure will make the antennas too thick if the simple patch shapes, i.e., rectangle and semidisc, are to be preserved.

V. Conclusion

By using both BW enhancement and size-reduction techniques, eight different internal antenna configurations have been designed, analyzed, and measured. All the antennas incorporate two simple patch elements, either rectangle or semidisc, electromagnetically coupled. Only one single probe feed is needed to excite each antenna. The antenna dimensions are significantly reduced by the shorting pin in each patch element, while the broad BWs are achieved by realizing dual-frequency operation. Impedance BWs (return loss ≤ -10 dB) from 19.0% to 25.3% have been obtained. The measured input impedance behavior and far-field radiation patterns agreed well with those predicted. The proposed antennas are suitable for 3G IMT-2000 mobile handsets.

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