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DESIGN OF DUAL-FREQUENCY MICROSTRIP PATCH ANTENNAS AND APPLICATION FOR IMT-2000 MOBILE HANDSETS

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Abstract—Two major objectives are concerned in this paper. On one hand, a multiplicity of typical methodologies available for achieving dual-frequency operation for microstrip patch antennas are summarized and classified into three categories, based on their intrinsic mechanisms. On the other hand, by employing the dual-frequency solutions, microstrip patch antennas are applied to the mobile handsets of the third-generation IMT-2000 system. Two novel microstrip patch antennas with broadband property and miniaturized size have been proposed and discussed theoretically and experimentally. Only a single simply-slotted patch, either semi-disc or square, is introduced in each of the two probe-fed antennas. Both antennas exhibit the impedance bandwidths (return loss ≤ -10 dB) of 25.6% and 34.4% respectively, which would be suitable for the practical application of the IMT-2000 mobile handsets.

1. INTRODUCTION

Microstrip patch antennas (MPAs) have a number of advantageous features, their narrow bandwidths, however, have been one of the most noticeable limitations hindering their wider applications [1, 2], such as mobile cellular telephones, cordless phones, pagers, WLAN, and mobile radios.

One possible means to widen the absolute bandwidth of a microstrip patch antenna (MPA) is simply by increasing the thickness of the substrate. This, however, introduces several problems. Firstly, a thick substrate introduces surface waves, which will produce undesirable effects on the radiation pattern as well as reduce the efficiency of the antenna. Secondly, as the thickness of the substrate increases, problems associated with the feeding of the antenna arise. Thirdly, higher-order cavity may be excited, introducing further distortions in the pattern and impedance characteristics. Therefore, it is essential to develop more sophisticated methods of improving the absolute bandwidth of MPAs [3].

There are also substantial amounts of effort devoted to increasing the frequency agility of MPAs. One possible approach is to design antennas that can be tuned over a range of frequency spectrum, which is achieved by realizing a tuneable single-frequency operation or dual-frequency operation with resonant frequencies separated by a certain range. The dual-frequency structure is useful in many situations [4, 5], where the antenna is required to operate at two distinct frequencies that maybe too far apart for a single antenna to perform.

2. SOLUTIONS TO DUAL-FREQUENCY MPAS

Dual-frequency MPAs [1–4] exhibit a dual resonant behavior in a single or multiple radiating structures. In principle, dual-frequency MPAs should operate with similar features, both in terms of radiation properties and impedance matching at two separate frequencies. Obtaining these features by using planar technologies is a complex matter, particularly when the intrinsic structure and technological simplicity typical of compact patch antennas is to be preserved. There are numerous solutions to dual-frequency operation [6–10]. Most of those can be classified into three important categories, i.e.,

1) Twin-mode dual-frequency MPAs,
2) Multiple-patch dual-frequency MPAs, and
3) Miscellaneous-loading dual-frequency MPAs.

A summary of typical techniques to achieve dual-frequency MPAs appeared in recent literature is tabulated in Table 1, where a total of 49 dual-frequency structures are listed and classified. The specific reference sources can be found in [11] for the details.

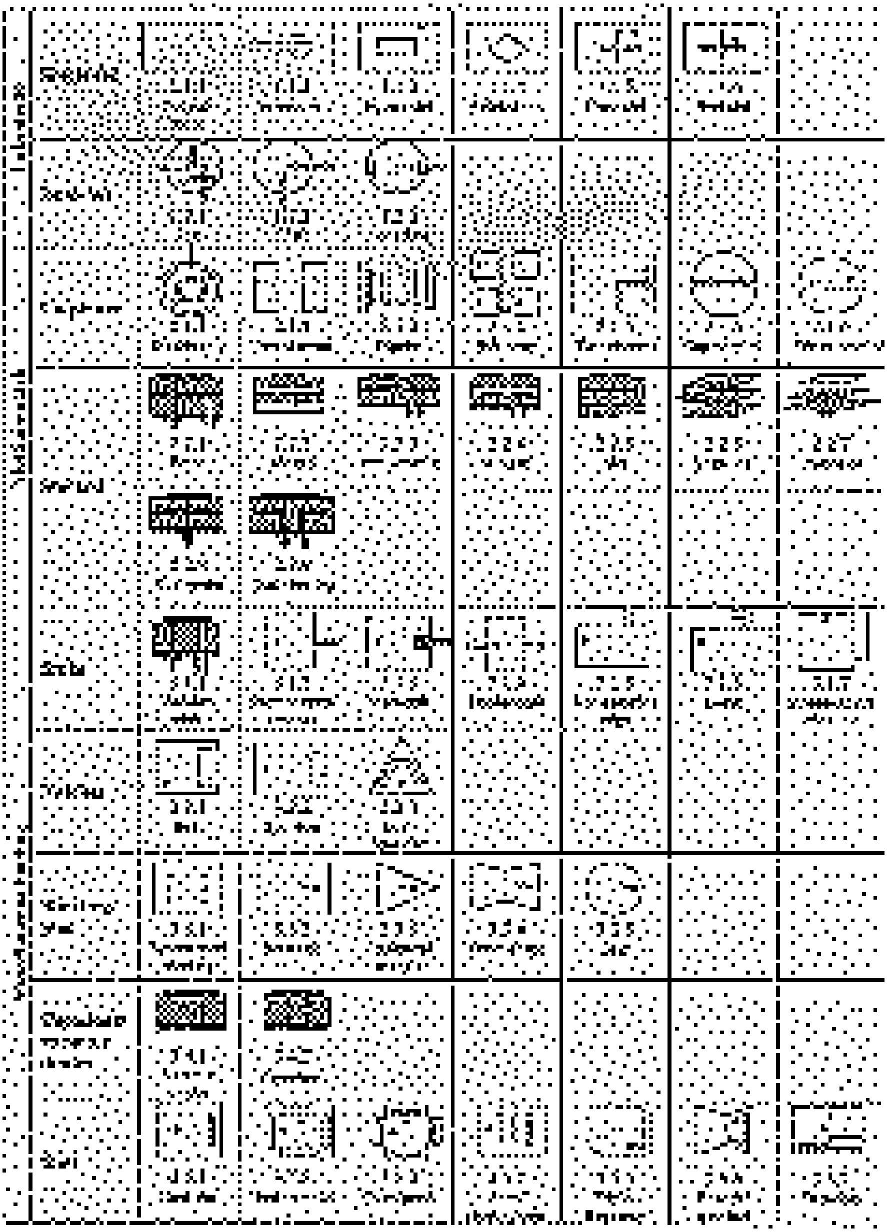
Twin-mode dual-frequency MPAs are achieved by realizing two different resonant modes in a single microstrip patch. Either single-feed (see View 1.1.1–1.1.6 in Table 1) or dual-feed (see View 1.2.1–1.2.3 in Table 1) can be applied to the patch structures. In the multiple-patch dual-frequency MPAs, the dual-frequency operation is obtained by means of multiple radiating patch elements, each of them supporting strong currents and radiation at one particular resonance. This category includes co-planar multiple-patch MPAs, in which several radiating patch elements are printed or etched on the same substrate (see View 2.1.1–2.1.6 in Table 1), and multi-layer stacked MPAs, where some radiating patches of similar or different shapes are used in discrete layers (see View 2.2.1–2.2.9 in Table 1). These antennas operate with the same polarization or dual polarization at two different resonant frequencies. When the MPAs are required to operate at two distinct resonant frequencies, the most popular technique is to introduce miscellaneous or reactive loading (see View 3.1.1–3.5.7 in Table 1) to a single patch for obtaining a dual-frequency operation, such as stubs, notches, shorting- pins, capacitors and slots.

3. DESIGN OF DUAL-FREQUENCY AND BROADBAND MPAS FOR IMT-2000 MOBILE HANDSETS

Mobile communications, wireless interconnects, local area networks (LANs), and cellular handset technologies are some of the major industrial growth markets presently. The antennas for these systems have naturally grown greatest with the mobile and cellular technologies. Generally, such antennas can be divided into two categories, namely external antennas and internal antennas.

The external antennas consist of the conventional whip, helix and whip-helix antennas [12] that are mounted outside the communications system terminals. Commercial handheld terminals that can integrate internal antennas and operate at two different bands, such as Nokia 3210, 8210, 3310, 8850 and Siemens S35I, have appeared on the market

Table 1. Categories of dual-frequency MPAs.



recently. Nevertheless, the design of dual-frequency handset antennas still presents a challenge for both antenna design engineers and antenna manufacturers.

Generally speaking, simple dual-frequency mobile cellular handset antennas can be divided into two structures [10], namely single feed and dual feed, whereas more complicated solutions are based on adaptive array technologies. However, they are divided into two categories, i.e., external and internal dual-frequency antennas, from the standpoint of antenna appearances. Most frequently used external dual-frequency antennas are monopoles (whips) and helices, while the planar inverted-F antenna (PIFA) is a typical internal antenna. Dual-feed antennas not only require two feeding points but also additional switches and diplexers in the radio frequency (RF) circuitry. Hence, the optimal way of reducing the complexity of a handset design is to use a single feed antenna.

In this work, a critical full-wave method of moment (MoM) with potential integral equations is used to arcuately predict the antenna characteristics. A commercial software package Ansoft Ensemble (Version 7.0) that is based on MoM is employed to simulate the far-field radiation patterns and input impedance behavior of the proposed antennas.

3.1. General Requirement of IMT-2000 Mobile Handsets

The frequency spectrum for the third-generation (3G) IMT-2000 mobile system were identified by the International Telecommunications Union (ITU) at the 1992 World Administrative Radio-communications Conference (WARC 92) and appeared as No. S5.388 of the Radio Regulations [13–15]: The bands 1,885 MHz–2,025 MHz and 2,110 MHz–2,200 MHz are intended for world-wide use by administrations wishing to implement the IMT-2000 system. Terrestrial IMT-2000 services will operate in the FDD (frequency division duplex) mode in the bands of 1,920 MHz–1,980 MHz paired with 2,110 MHz–2,170 MHz for mobile stations transmitting in the lower sub-band and base stations transmitting in the upper sub-band, respectively. The bands of 1,885–1,920 MHz and 2,010 MHz–2,025 MHz are unpaired for TDD (time division duplex) operation. The issue of extending the current band for the IMT-2000 service was also considered by the ITU. In general, it will be appropriate for the 3G mobile handset antennas to satisfy the bandwidth in the proposed up-link of 1,885 MHz–2,025 MHz and down-link of 2,110 MHz–2,200 MHz, i.e., around 15.4% impedance bandwidth (return loss ≤ -10 dB), if the frequency band from 1,885 MHz to 2,200 MHz is fully covered.

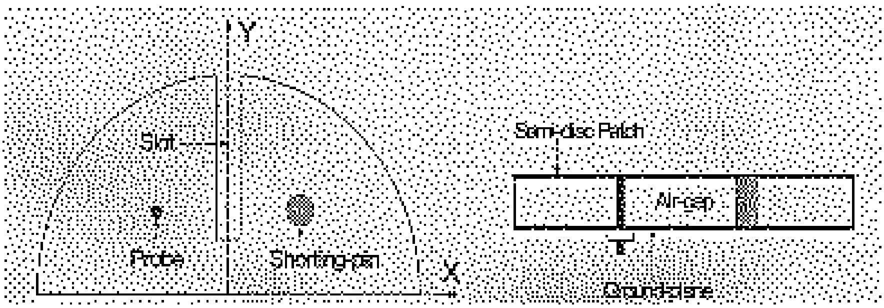
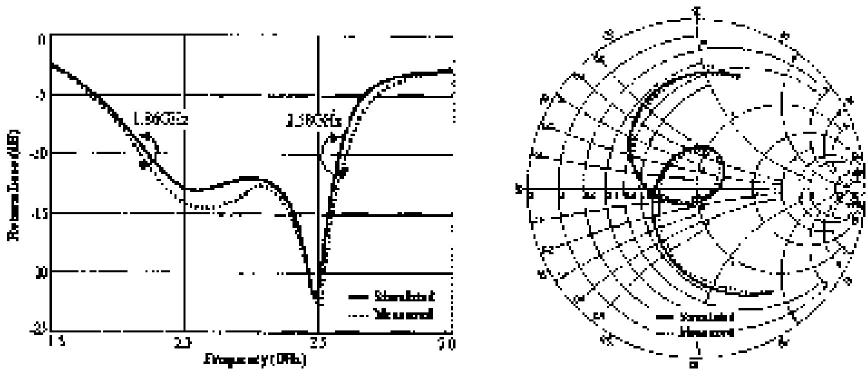


Figure 1. Configuration of the proposed semi-disc antenna.

3.2. Proposed Semi-disc Antenna for IMT-2000 Mobile Handsets

The proposed broadband antenna is shown in Figure 1, which is primarily comprised of a semi- disc microstrip patch, a narrow rectangular slot, a cylindrical shorting-pin, a probe-feed, and an air-filled substrate. The basic geometry of the antenna is the modified semi-disc patch, in which the rectangular slot of dimensions of 19 mm × 2 mm, is etched symmetrically with respect to the Y-axis. The shorting-pin is electrically joined to both the patch and the ground plane. The antenna is fed by a probe-feed, whose inner conductor (probe) is attached to the semi- disc patch through an opening on the ground plane, with its outer conductor directly connected to the ground plane. The shorting-pin and the probe-feed are symmetrically placed on either side of the rectangular slot. Between the semi-disc patch and the ground plane is the air-filled substrate (or air-gap) with relative permittivity of $\varepsilon_r \approx 1$. The semi-disc patch is a thin layer of copper with the thickness of 0.1 mm. Several non-conductive foam spacers with relative permittivity of $\varepsilon_r \approx 1$ are used to provide mechanical support to the semi-disc patch.

The shorting-pin acts as an inductive loading and perturbs the electric fields in the patch so as to reduce the antenna dimensions significantly [16–18]. Moreover, the use of the thin rectangular slot is to enhance the electric fields so that the antenna dimensions can be minimized further [19]. The additional benefit of the thin rectangular slot is to excite dual- frequency operation in the single semi-disc patch. The shorting-pin and the probe-feed are located symmetrically with respect to Y-axis. This will improve the radiation performance of the antenna to some extent. To optimize the impedance matching of the antenna over the frequency range of interest, the radius of the shorting-pin is chosen to be larger than that of the probe-feed. The simulation



a. Return Loss b. Input Impedance

Figure 2. Return loss and input impedance of the proposed semi-disc antenna.

results suggested that the distance between the slot and the shorting-pin, as well as that between the slot and the probe-feed, are critical for the broadband operation.

The thickness of the proposed antenna is about $0.07\lambda_1$, while the maximum dimension of the planar semi-disc patch is less than $0.35\lambda_1$, where λ_1 is the wavelength at the lowest frequency of interest (1.86 GHz). The overall antenna dimensions are smaller than the normal half-wavelength microstrip antenna without shorting-pins and slots.

The broadband performance of the proposed antenna, with the optimal impedance matching, was achieved with its parameters selected as those in Figure 1. Figure 2 shows the simulated and measured return loss and input impedance of the proposed broadband antenna. The measured and simulated results are in good agreements. The overall impedance bandwidth (return loss ≤ -10 dB) of 32.4% was obtained, from 1.86 GHz to 2.58 GHz, which fully covered the operating bands of the IMT-2000. It is noted that this broad bandwidth is realized by exciting two adjacent resonant frequencies, where all the return losses between them are less than -10 dB. The two resonant frequencies are 2.03 GHz and 2.48 GHz, respectively. The lower resonant frequency could be related to the entire semi-disc patch, while the higher resonant frequency could be associated with the left half of the semi-disc patch.

The typical far-field radiation patterns of the proposed antenna, in the E- and H-planes, at both resonant frequencies are shown in Figure 3. At the lower resonant frequency of 2.05 GHz, there is a

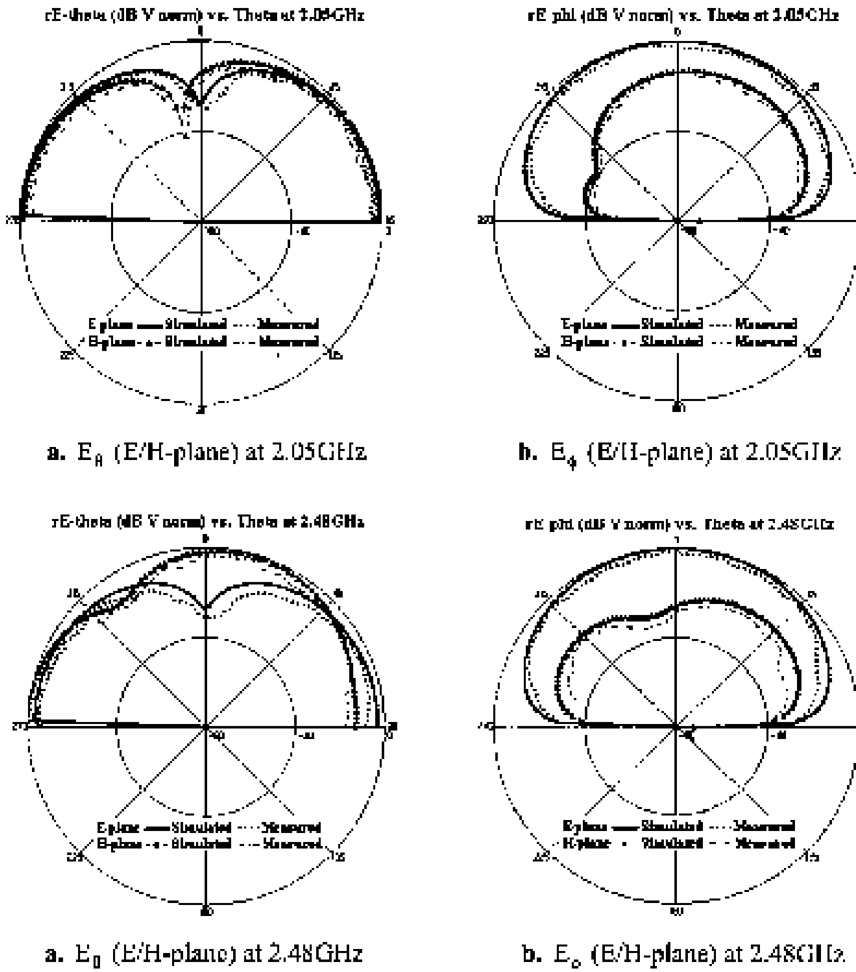


Figure 3. Far-field radiation patterns of the proposed semi-disc antenna.

null near the broadside ($\theta = 0$) for the E_θ in both the E- and H-planes, while the E_ϕ radiation patterns are almost omni-directional as expected. The radiation null could be due to the unsymmetrical geometry of the semi-disc patch and the rectangular slot. At the higher resonant frequency of 2.48 GHz, the E_θ component in the H-plane pattern is better, while the E component in the E-plane continued to have a null near the broadside. The E_ϕ component behaved similarly to that at 2.05 GHz.

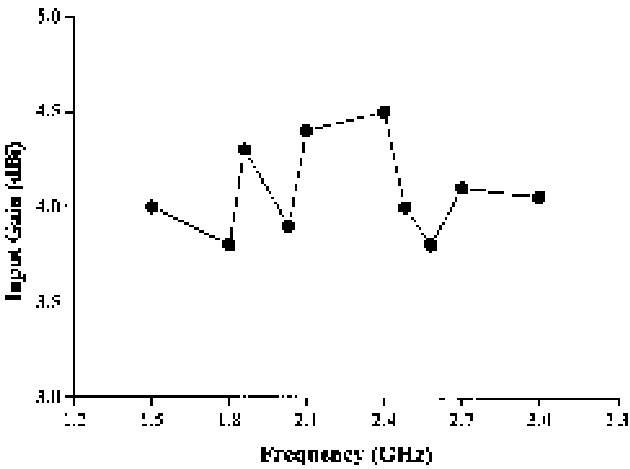


Figure 4. Measured maximum input gain of the proposed semi-disc antenna.

Figure 4 shows the measured maximum input gain of the proposed antenna within the frequency spectrum of interest. The peak antenna gain is about 4.5 dBi, and the gain variations within 1.8 dBi are observed. All the gains are greater than that of an ideal half-wave dipole (2.15 dBi). The measured antenna efficiency varies between 75% and 90% over the broadband operation, as it depends on the ohmic losses and the losses due to the impedance mismatching.

The simulations suggest that if the probe-feed position is not properly chosen, only one resonant frequency could be excited. By increasing the width or the length of the rectangular slot, both resonant frequencies will increase accordingly, with a corresponding increase in the separation between both resonant frequencies. If the rectangular slot is too narrow, only one single resonant frequency will be realized. The optimization of the rectangular slot is essential to achieve two resonant frequencies, and consequently the broadband operation.

Mechanically, to enhance the robustness of the proposed antenna structure, some kind of foam substrate with relative permittivity of $\varepsilon_r \approx 1.03$ or 1.07 can be utilized to replace the air-filled substrate without significant reduction in the desired bandwidth.

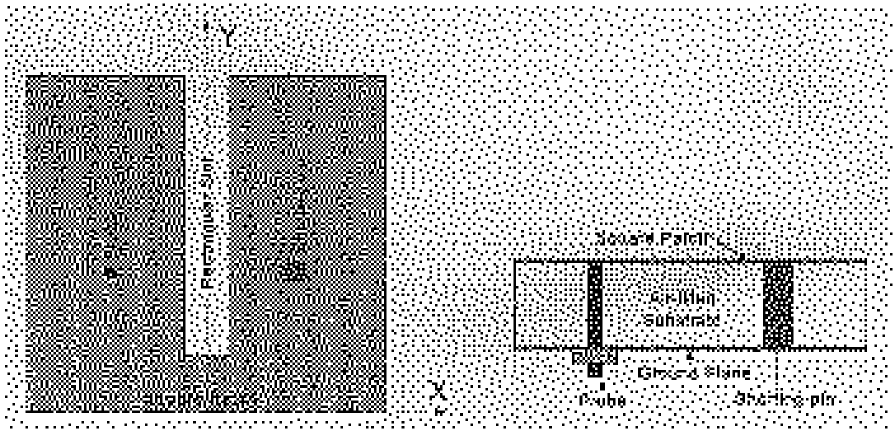
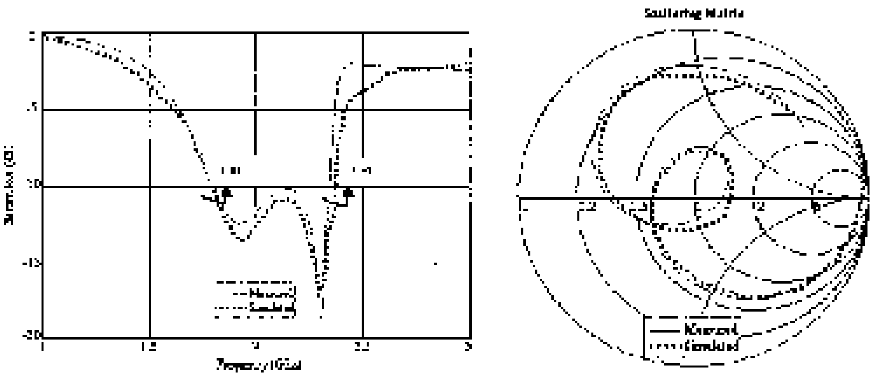


Figure 5. Configuration of the proposed square antenna.

3.3. Proposed Square Antenna for IMT-2000 Mobile Handsets

The configuration of the proposed internal square patch antenna is plotted in Figure 5. It consists of a single square patch, a thin rectangular slot, a single shorting-pin, an air-filled substrate, and a single coaxial cable feed with a standard SMA (Subminiature A) connector. The square patch of 34 mm × 34 mm, with a thickness of $t = 0.1$ mm, is fixed on some spacers with relative permittivity of $\varepsilon_r \approx 1$ and thickness of 11 mm to enhance the robustness of the structure. A rectangular slot of 25 mm × 2 mm is perforated parallel to the Y-axis symmetrically and is kept away from the X-axis by 9 mm. The shorting-pin of radius $r_s = 2.0$ mm and the probe-feed of radius $r_p = 0.6$ mm is located at either side of the thin slot, with their coordinates being (12 mm, 12 mm) and (−12 mm, 12 mm), respectively. The inner conduct (the probe) of the coaxial cable is connected to the patch through a hole in the ground plane, while the outer conductor of the coaxial cable is directly connected to the ground plane. The air-filled substrate with relative permittivity of $\varepsilon_r \approx 1$ is located between the square patch and the ground plane. The main objectives of the shorting-pin are not only acting as an inductive loading as well as perturbing the electric field paths in the patch so as to reduce the overall dimensions of the antenna significantly. In addition, the effect of the thin rectangular slot is to extend the electric field paths so that the antenna dimensions can be minimized further.

It should be noted that, as can be seen from the antenna configuration, there are a lot of degrees of freedom in the proposed



a. Return loss b. Input impedance

Figure 6. Return loss and input impedance of the proposed square antenna.

antenna. Apart from the edge size of the square patch, there are the rectangular slot (dimensions and location), the radii and positions of the shorting-pin and the coaxial cable feed, and the thickness of the antenna. A considerable number of simulations, by modifying the aforementioned parameters one by one, have been conducted to optimize the design that makes sure to satisfy the requirement of the frequency spectra for the 3G IMT-2000 mobile handset antennas.

The return loss and the input impedance of the proposed antenna, of both simulated and measured, are presented in Figure 6. Two adjacent resonant frequencies at 1.92 GHz and 2.31 GHz are observed, which are so close to each other that the overall impedance bandwidth (return loss ≤ -10 dB) has been broaden markedly, since the return losses between the two resonant frequencies are less than -10 dB. The resulted impedance bandwidth (return loss ≤ -10 dB) of the antenna is around 25.6% within the frequency spectra from 1.81 GHz to 2.34 GHz, which fully covers the frequency spectra allocated for the 3G IMT-2000 mobile system from 1,885 MHz to 2,200 MHz.

The simulations suggest that both resonant frequencies be mainly excited by two orthogonal modes that are related to the orthogonal radiating edges of the square patch. The probe-feed point should be critically chosen to realize both resonant frequencies in this simply slotted square patch. The position of the shorting-pin is selected so that the antenna structure remains symmetrical to some extent, which will be beneficial to optimize the far-field radiation pattens. The resonant frequencies are supposed to be determined by the patch sizes, the slot dimensions, and the antenna thickness, while the impedance matching for both resonant frequencies are optimized by adjusting the radii and the positions of the shorting-pin and the probe-feed. The measurement results agree well with the simulated outcomes. The measured and simulated antenna maximum gains are 4.5 dBi and 4.8 dBi, respectively, within the frequency spectra of interest.

The measured and simulated E_θ and E_ϕ far-field radiation pattens in both the E- and H-planes at both resonant frequencies are similar to those in the case of the aforementioned semi-disc MPA. In the course of this work, to satisfy the limited volume of a mobile handset case, the ground plane is cut to be 4 cm by 8 cm, which will fit the overall dimensions of some modem mobile handset. The proposed antenna is located close to the upper end of the ground plane. It should be noted that the air-filled substrate could also be replaced by some kind of foam substrate with the permittivity of $\varepsilon_r \approx 1.03$ or 1.07 to further ease the antenna manufacture [20].

It should also be noted that the return losses within the frequency spectra of interest will become lower (i.e., better impedance matching) when a hand of the user is placed over the proposed antenna, while both resonant frequencies only shift slightly. 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 compared to normal external antennas like helix or dipole. However, both resonant frequencies will decay significantly when the hand of the operator directly touches the antenna. To mitigate such environment effects, a suitable plastic housing for the internal antenna is essential.

4. CONCLUSIONS

Various methodologies for achieving dual-frequency MPAs have been summarized and tabulated into three efficient categories: twin-mode, multiple-patch, and miscellaneous- loading.

A single-layer and single-patch broadband antenna with an impedance bandwidth (return loss ≤ -10 dB) of 32.4% between 1.86 GHz and 2.58 GHz has been designed and discussed. The reduced dimensions of the proposed antenna are achieved by the use of a single cylindrical shorting-pin, while the broadband characteristics is obtained through a narrow rectangular slot that facilitated the dual-frequency operation, with both resonant frequencies sufficiently close to each other. The measured results of the proposed antenna agreed well with simulations.

Another novel slotted and shorted square patch antenna has also been proposed. Both bandwidth enhancement and size miniaturization techniques have been applied to the antenna structure. The impedance bandwidth (return loss ≤ -10 dB) of 25.6% from 1.81 GHz to 2.34 GHz has been achieved efficiently. A good agreement between the measured and the simulated results has also been obtained. Both simple, small, compact, and broadband MPAs will be suitable for the practical application of the 3G IMT-2000 mobile handsets.

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