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MULTIBAND HANDSET ANTENNA USING SLOTS ON THE GROUND PLANE: CONSIDERATIONS TO FACILITATE THE INTEGRATION OF THE FEEDING TRANSMISSION LINE

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Abstract—This research consists on a ground plane modification using slots of a PIFA (Planar Inverted F Antenna) handset antenna with the objective to facilitate the integration of the feeding transmission line which connects the antenna with the RF-module. Through this technique it is possible to obtain a multiband antenna while keeping the same antenna geometry, small volume

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and simplifying the PCB (Printed Circuit Board) design. Numerical simulation using MoM is used to understand the effect of the slots on the groundplane. Several prototypes have been built to validate the present technique.

1. INTRODUCTION

The mobile industry has grown a lot over the last years, and nowadays, market demand requires small and multifunctional devices. Since there is a constant evolution in mobile services (new frequency bands) and design innovation (handset phones having different form factors such as bar-type, clamshell, and sliders for instance), it is necessary to investigate multiband and miniature handset antennas.

As it has been shown in some market studies [1], there is a clear trend in removing external antennas from handsets and replacing them by internal antennas (antennas embedded into the handset platform). External antennas feature several drawbacks: they can break accidentally under mechanical stress or shock and they make the phone more inconvenient and uncomfortable to carry inside a pocket. Also, the user should extract it from inside for operation.

Many kinds of internal antennas can be used in handset devices, such as monopoles, PIFAs, IFAs, patches, etc., and there is a lot of interest in discovering new techniques in order to achieve smaller and multiband antennas.

Usually, optimizing the antenna geometry is the common way to design an antenna to get acceptable performance, but as it has been shown in [2–8], the ground plane of the handset plays a very important role in the antenna system behavior, because there is a tight relation between the ground plane length and the antenna bandwidth [9, 10]. When the ground plane length is close to 0.4λ, a ground plane mode is excited causing an improvement in the antenna bandwidth (the ground plane is the grounded metallic part etched on the PCB — Printed Circuit Board). Considering the length of 0.4λ in current devices, PCB length would be about 133 mm at 900 MHz. This is too long for current handset terminals which feature lengths typically around 90 mm to 110 mm for bar-type handsets. Therefore, some other solutions are needed.

In the previous literature, the use of slots in the ground plane has been analyzed as an alternative to the antenna design. In [2] and [3], a slot in the ground plane is used to enhance the matching at one band of the spectrum (900 MHz). Such a slot forces the ground plane to resonate at 900MHz approximately which, as a result, improves the bandwidth. On the other hand, [4] presents several slots in the ground plane to improve a multiband antenna. However, this design would become difficult to implement in a real mobile device because a PCB must host a battery, display, as well as other components which may shortcircuit the slot behavior. Finally, in [6–8] an open slot placed underneath the antenna area is introduced in the ground plane with two objectives: the first one is to tune the ground plane at low frequencies (GSM 850–GSM 900) and the other is to reuse the slot to be a parasitic element at higher frequencies (DCS-PCS-UMTS).

Slots have been also used in handset devices for the Signal Integrity solution [11].

Besides the good bandwidth results obtained when the ground plane is tuned to the same frequency of the handset antenna, one topic that has not been addressed yet is the integration of the feeding transmission line. Fig. 1 shows a schematic view of the printed circuit board design for three situations. The feeding port is situated in the same side of the open slot to get good results at low bands [6–8].

Fig. 1(a) shows the first design for an open-slot situation, where the RF module is located next to the feeding port. Some chipsets are needed to process the RF signal; this means that the antenna area would be full of metallic shielded components that disturb the antenna behavior, causing the bandwidth to decrease since the antenna height is reduced (distance of the PIFA to the metallic shielded components which are connected to ground). Considering that the antenna area should be free of metallic shields, Fig. 1(b) presents a new design. Now, the feeding line needs to follow a long meander shape path to reach the antenna feeding pad and RF module. This length may be critical in some situations due to the large density of components in the PCB. Therefore, the purpose of the present paper is to analyze a way to minimize the length of the feeding line maintaining as much as possible the advantages of the bandwidth benefits of the open-slots. For example, the slot used in Fig. 1(c) minimizes the length of the feeding line. The objective is to show how this solution can also provide a bandwidth enhancement.

The paper is divided as follows: Section 2 shows the important role of the ground plane in the antenna system and introduces the new ground plane design in order to get good results and facilitate the integration of the feeding transmission line. Section 3 shows the simulation results obtained for the proposed designs, and in Section 4, the measured results are presented. Finally, Section 5 presents the conclusions for this research.

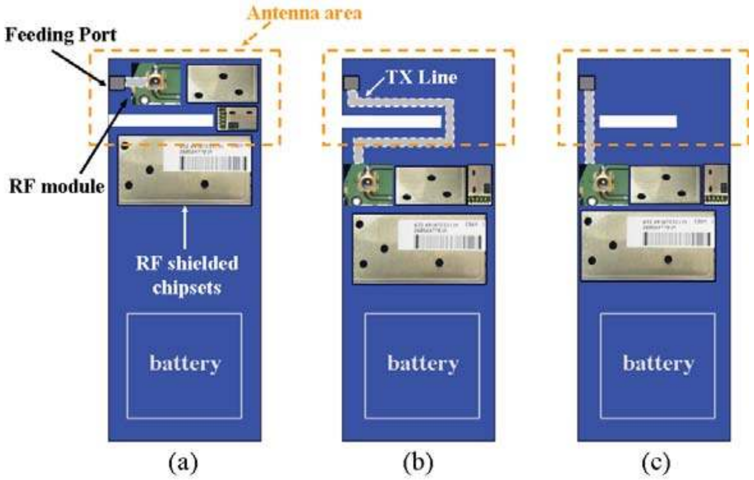


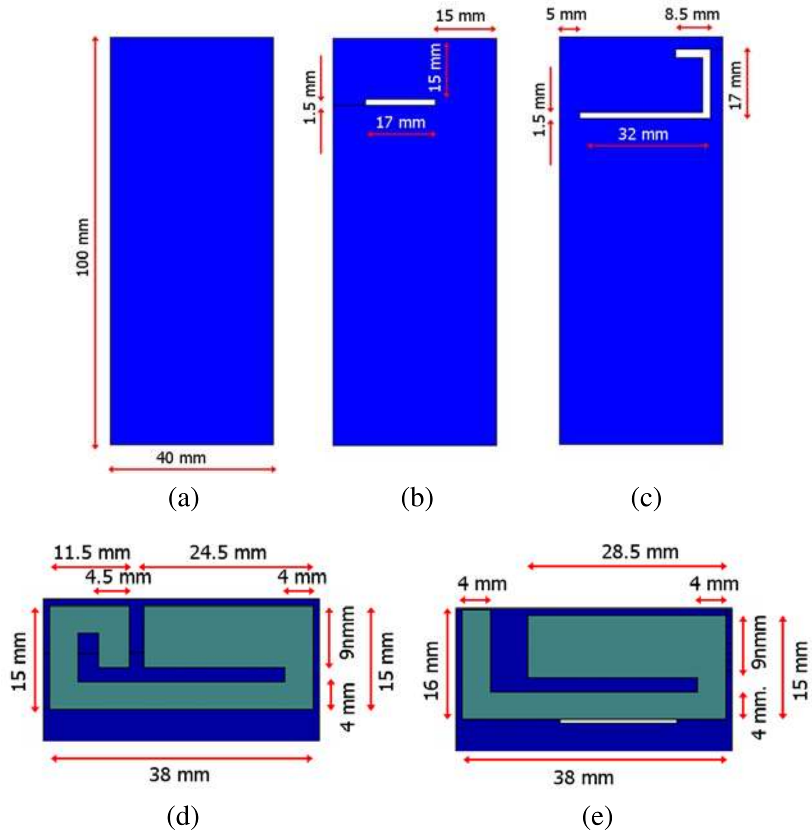
Figure 1. Schematic view of three handset PCBs [5]. (a) Shows an open slot situation where the RF-chip module is located near the antenna feeding pad; (b) the RF-chip module has been removed from the antenna area, and a long transmission line is now set to connect the antenna pad to the RF-chip module; (c) open slot has been removed allowing a short transmission line to connect the RF-chip module to the antenna pad.

2. ANTENNA AND GROUND PLANE CONCEPT

The aim of this paper is to analyze a particular slotted-ground plane to improve antenna bandwidth and at the same time simplify the integration of the transmission line feeding on the RF-chip module to the antenna pad. Three experiments are presented: the first one is a bare PCB with no slots. This case serves for comparison purposes (Fig. 2(a)). The second experiment uses a short slot on the ground plane in order to modify the resonant frequency of the ground plane mode to be close to that of the PIFA antenna resonance at the first operating band (around 900 MHz) (Fig. 2(b)). Finally, the third experiment uses a longer slot than the previous case (Fig. 2(c)). In this case, the objective is twofold: firstly, to tune the ground plane resonance mode to be close to that of the PIFA antenna resonance at the first operating band and secondly, to force the slot to be a parasitic element to enhance bandwidth of the PIFA antenna at the second operating band (around 2 GHz).

The proposed antenna is a PIFA for all the experiments having 6 mm height over the ground plane of $100 \times 40\,\mathrm{mm}^2$. The PIFA resonates at 950 and 1950 MHz, and it has a feeding and a short port (Fig. 3). Basically, the small branch is tuned to resonate at high frequencies, and the large one corresponds to low frequencies (strictly speaking the large branch also affects the high frequency tuning). The ground plane is on an FR4 substrate of 1 mm thick ($\varepsilon_r = 4.15$, $\tan\delta = 0.013$) to emulate a typical mobile phone.

As it can be shown in Fig. 2, the first geometry (Fig. 2(a)) does not have any slot on the ground plane, whereas the others (Fig. 2(b), and Fig. 2(c)) have slots of different lengths in the upper part of the ground plane. A MoM commercial package (IE3D software) has been used to simulate all these designs.



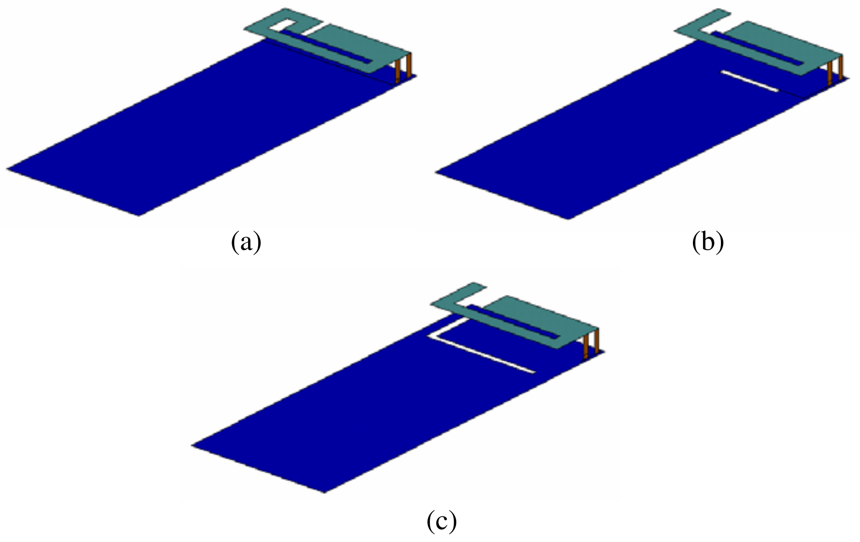
(a) (b) (c)

(d) (e)

Figure 2. Bottom view of the proposed ground plane and antenna designs [5, 12]. The standard ground plane (a) uses the PIFA (d). On the other hand, the PIFA (e) is used in the ground plane with central slot (b) and the ground plane with U-shaped slot (c).

In this example, since the ground plane length is shorter than the one needed to resonate at 900 MHz (100 mm is 0.3λ at 900 MHz) a narrow bandwidth is achieved as shown in the next sections. In order to solve this problem, increasing the ground plane length would be a possible solution, but then the mobile terminal would be too long (133 mm is 0.4λ at 900 MHz) to be competitive in the current demand market, where usually PCB dimensions are limited (typical lengths for bar-type handset phones are from 90 mm to 110 m). Adding open slots in certain locations of the ground plane improves the bandwidth of the antenna as shown in [6–8]. For those particular cases, the feeding line needs to follow a meander path similar to the one shown in Fig. 1(a). To minimize this length, open slots are avoided as shown in Figs. 2(b) and (c). Besides the mission of the slot which is to electrically enlarge the ground plane, the slot has another objective: to be a parasitic element at higher frequencies (usually the second band of operation, around 1900–2100 MHz). Therefore, the slot length and position play an important role to satisfy these two requirements: to enlarge ground plane at low frequencies (900 MHz) and be a parasitic element at higher frequencies (1900–2100 MHz).

The design of Fig. 2(b) has a small slot of 17 mm in order to change the ground plane surface currents and be able to achieve better results at low bands. However, this slot is electrically short at 1900–


(a) (b)

(c)

Figure 3. 3D views of antennas of Fig. 2. Antenna height is 6 mm. All ground plane designs use a PIFA [5, 12].

2100 MHz (0.1λ). To generate a slot resonating at the second band, the slot length is increased as shown in Fig. 2(c) as a longer U-shaped slot (the length of the slot is 57.5 mm. which is 0.4λ at 2100 MHz). As a consequence, the first slot enlarges the ground plane (useful to increase bandwidth at the first band) but can not resonate at the second band (not useful to increase the bandwidth at the second band). However, the U-shaped slot satisfies both requirements, so it may be useful to increase bandwidth at both bands. This hypothesis is validated through numerical experiments and measurements in the following sections. In both experiments proposed in Fig. 2(b) and Fig. 2(c), the slot is located under the antenna projection in order to get a good coupling between the PIFA and the slot and also to facilitate the integration of handset components such as battery, displays, and others (a slot on the middle of the PCB complicated the integration of displays and batteries for examples which may short-out the effect of the slot). The coupling between a driven and a parasitic element plays an important role in bandwidth [13, 14].

In these configurations, slots have short ends. This provides an advantage over other configurations of slots in the ground plane because the transmission line can reach the RF module as it is shown in Fig. 1, so PCB design is easier and facilities the integration of handset components. However, it is necessary to research how much bandwidth can be obtained with this technique.

3. SIMULATION RESULTS: QUALITATIVE ANALYSIS

In order to give a physical insight, the current distributions on the ground plane as well as electrical field on the slot aperture are calculated. These data are interesting to understand why the slots on the ground plane are useful to increase the bandwidth.

Figure 4 shows the current distributions on the three proposed ground planes. In case a, the current flows along a straight line: it follows a diagonal path from feeding port to the opposite short ground plane edge. In the other cases (b and c), since it has to follow the slot outline, a longer path is achieved. This way, the effective electrical length is larger (gets closer to the optimum value of 0.4λ). Therefore, a wider bandwidth may be achieved as it will be confirmed in Section 4.

The slot can also be used as a parasitic antenna. When the slot length is similar to 0.5λ the slot acts as an effective parasitic element and a coupling effect between PIFA and slot may be obtained. The slot used in Fig. 2(b) is too short to resonate at higher frequencies (1800–2000 MHz), this is why it only improves bandwidth at low bands (it will be shown in the Experimental Section). On the other hand, slot

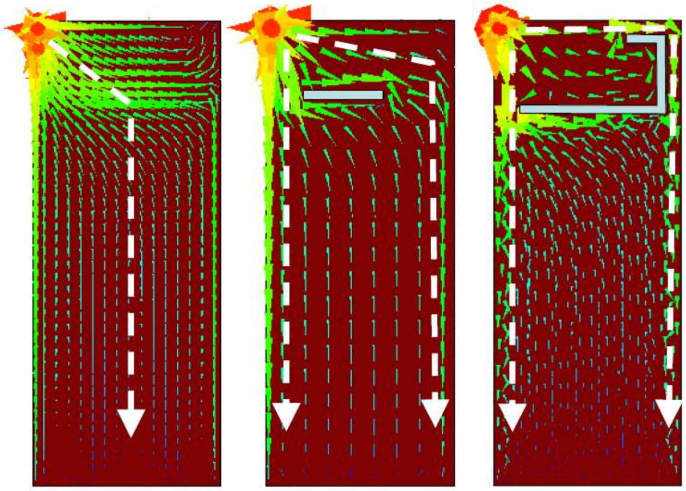


Figure 4. Simulated current distribution of the three proposed ground planes at 925 MHz. A qualitative current path is indicated in dashed white line. The longest current path corresponds to the PCB with the U-shaped slot (case *c*).

shown in Fig. 2(c) has a larger length. Therefore it can resonate at upper bands, so in this case, slot acts as a parasitic element and better results are obtained [6–8]. Using a dual band PIFA combined with this ground plane technique, a quad-band antenna system can be achieved.

To understand the slot coupling to the PIFA, the electric field has been calculated with IE3D. For this reason, the near electric field in two dimensions (X and Y directions) has been simulated.

The electrical length of the slot of Fig. 2(b) is too small to resonate at 900 or 2100 MHz. This can be seen in Fig. 5 because the electric field is very weak, so the slot is not excited at these frequencies. On the contrary, the U-shaped slot has a length to resonate at 2100 MHz (0.4λ). Comparing the E-field distributions, it is observed that at 900 MHz the slot excitation is weaker than 2100 MHz case (Fig. 6). Also, it is interesting to outline that the electric field intensity value of the Y component is stronger in the longest part of the slot, and the X component in the shortest part. Based on this, it can be stated that the E-field on the slot aperture follows the fundamental mode distribution of a $\lambda/2$ slot. For 2100 MHz, the E-field corresponds to fundamental mode, namely, E-field is zero at the edges and maximum at the center of the slot.

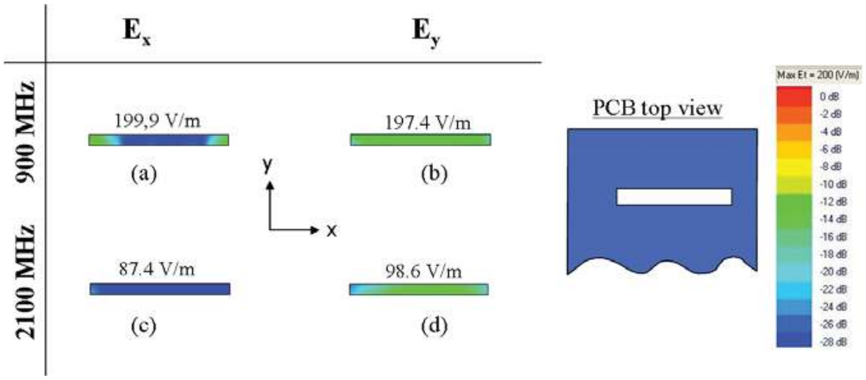


Figure 5. Normalized E field distribution at top of the ground plane with central slot. Maximum values are shown in each figure. (a) E_X at 900 MHz, (b) E_Y at 900 MHz,(c) E_X at 2100 MHz, and (d) E_Y at 2100 MHz.

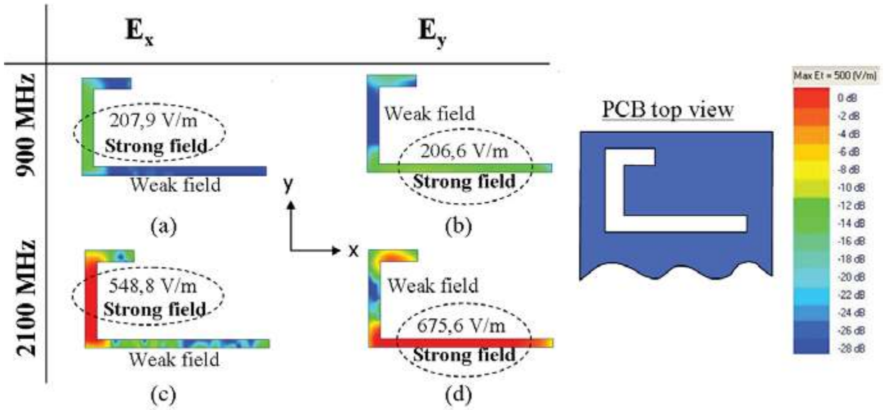
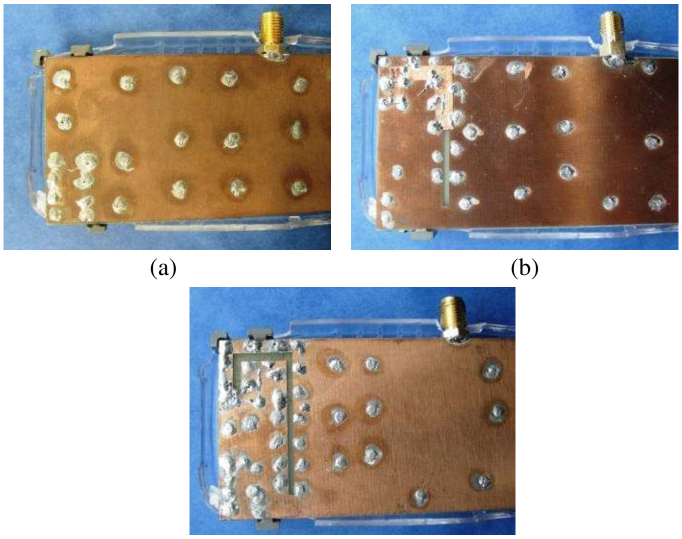


Figure 6. Normalized E field distribution at top of the ground plane with U-shaped slot. Maximum values are shown in each figure. (a) E_X at 900 MHz, (b) E_Y at 900 MHz,(c) E_X at 2100 MHz, and (d) E_Y at 2100 MHz.

4. EXPERIMENTAL RESULTS

In this experimental part, the three prototypes shown in Fig. 2 and Fig. 3 have been fabricated (Fig. 7). The reflection coefficient has been measured using a network analyzer and efficiency, and radiation patterns have been measured in Satimo Stargate-32 at Fractus-Lab.

Figure 9 shows the measured return losses for the three built



(a) (b)

(c)

Figure 7. Built antenna prototypes. (a) Reference ground plane, (b) Central slot, and (c) U-shaped slot [5].

Figure 8. Transmission line arrangement in ground plane with a short-ended slot. As explained in Section 2, the advantage of slots with shorted ends is their situation in the ground plane. PCB design becomes more flexible as it exists a direct way for the transmission line for connecting the feeding port and the RF module [5].

prototypes shown in Fig. 7. The reference antenna is a dual band antenna having 13.8% of bandwidth (SWR < 3) at low bands and 8.6% at high bands. On the other hand, a broader bandwidth is obtained in the other embodiments. The central slot has good matching at

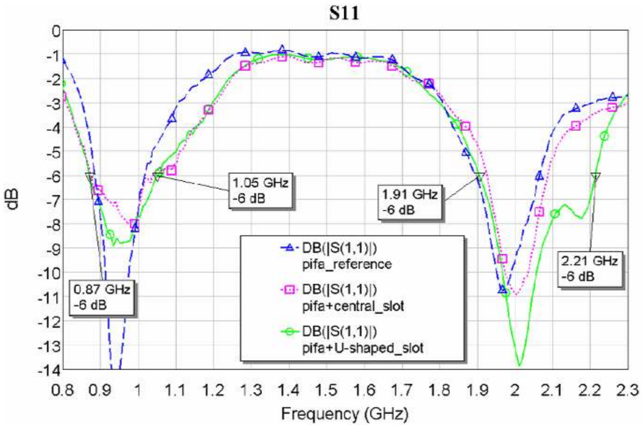


Figure 9. Measured return loss for the three studied designs.

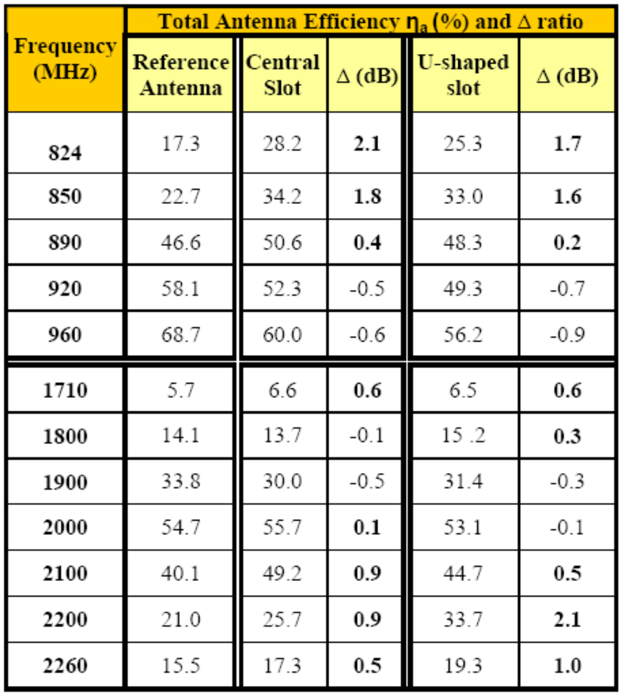
low bands (17.4%) but at higher bands it still behaves similar to the reference antenna (8.3%) since the slot is in the cut-off state. This means that the slot does not operate as a parasitic element. In this case, the slot only helps the current path to become longer at 900 MHz but it is not excited at high frequencies (1800–2000 MHz). Finally, the antenna with the U-shaped slot in the ground plane satisfies both requirements: good position to enlarge the current path at low bands and resonance length for slot excitation at high bands. This way, prototype with the U-shaped slot has good matching from 0.870 to 1.05 GHz and from 1.91 to 2.21 GHz. This means an 18.75% and a 14.56% of bandwidth in low and high bands respectively (Table 1).

The total antenna efficiency values ($\eta_a = \eta_r \cdot (1 - |S_{11}|^2)$, where

Table 1. Measured bandwidth at low and high bands of the three designs.

	f_1 (GHz)	f_2 (GHz)	BW (SWR < 3)	f_1 (GHz)	f_2 (GHz)	BW (SWR < 3)
Reference PIFA	0.885	1.016	13.8%	1.895	2.065	8.6%
PIFA with central slot	0.873	1.039	17.4%	1.919	2.086	8.3%
PIFA with central slot	0.870	1.050	18.8%	1.912	2.210	14.6%

Table 2. Measured total antenna efficiencies for the three prototypes. Δ is the ratio in dB between the efficiency of the slot case compared with the reference design (without slot).



Frequency (MHz)	Total Antenna Efficiency η_a (%) and Δ ratio				
	Reference Antenna	Central Slot	Δ (dB)	U-shaped slot	Δ (dB)
824	17.3	28.2	**2.1**	25.3	**1.7**
850	22.7	34.2	**1.8**	33.0	**1.6**
890	46.6	50.6	**0.4**	48.3	**0.2**
920	58.1	52.3	-0.5	49.3	-0.7
960	68.7	60.0	-0.6	56.2	-0.9
1710	5.7	6.6	**0.6**	6.5	**0.6**
1800	14.1	13.7	-0.1	15 .2	**0.3**
1900	33.8	30.0	-0.5	31.4	-0.3
2000	54.7	55.7	**0.1**	53.1	-0.1
2100	40.1	49.2	**0.9**	44.7	**0.5**
2200	21.0	25.7	**0.9**	33.7	**2.1**
2260	15.5	17.3	**0.5**	19.3	**1.0**

η_r is the radiation efficiency and S_{11} the reflection coefficient for the antenna) have also been measured (Table 2). A clear improvement is observed in the slot cases when compared to the reference antenna. Regarding to the antenna with the ground plane with the central slot, the efficiency is higher at low bands, and on the other hand, the U-shaped slot presents better results at both bands, which agree with the qualitative analysis.

Finally, 3D radiation patterns have been measured (Fig. 10). All the antennas have the same radiation pattern at low frequencies. Therefore, adding some slots in the ground plane does not modify the antenna radiation structure. At low bands, prototypes radiate as a standard dipole antenna with an omnidirectional pattern in $\varphi = 0°$ and a null in the y-axis.

At high bands, radiation patterns are almost the same (frequency 1800 MHz). This confirms that at this frequency the slot is not operating yet. However, when going up in frequency (2100 MHz), the

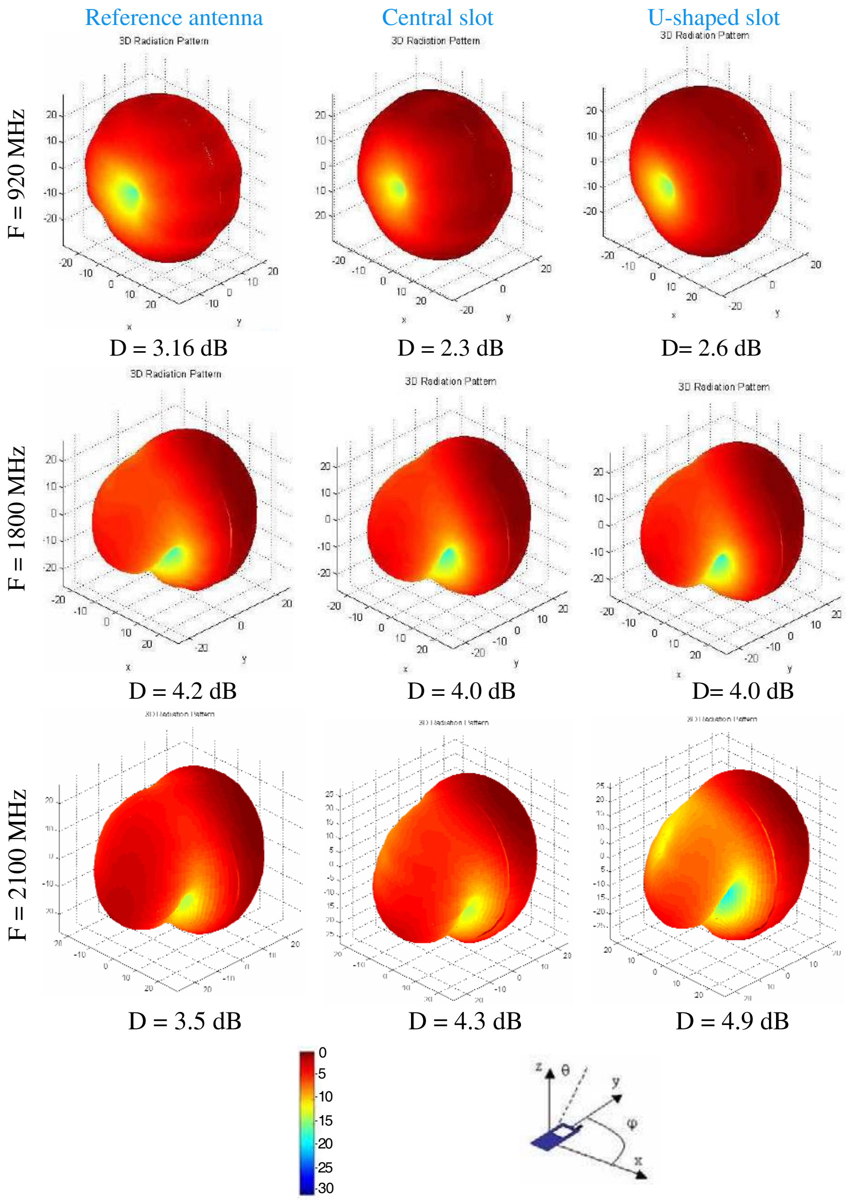


Figure 10. 3D measured radiation patterns of the reference antenna and the central slot design at 920, 1800 and 2100 MHz.

slot is doing its job: increasing the bandwidth due to the coupling with the PIFA. This causes a modification on the radiation pattern: directivity increases from 3.5 dB without the slot to 4.9 dB with the slot. This directivity increase deserves an extra research to analyze the impact of a multipath environment. The SAR results are also underway and will be presented in a future paper.

5. CONCLUSIONS

Introducing slots in the ground plane is a simple way to achieve a multiband antenna without modifying PIFA antenna geometry and increasing the handset volume.

From the qualitative analysis it has been shown that the bandwidth at low frequencies is improved, thanks to the current enlargement mechanism of the slot on the ground plane. At high frequencies, the bandwidth can be improved by a proper design of the slot length to make it resonating and the slot position, since it determines the coupling with the PIFA antenna.

A dual band PIFA antenna has been used to analyze the bandwidth and efficiency improvement when a slot in the ground plane is introduced: the original dual-band antenna has been enhanced to introduce more frequency bands. Comparing the antenna without a slot and the U-shaped slot case, bandwidth has been improved from 13.8% to 18.7% at low frequencies and from 8.5% to 14.5% at high frequencies.

Although bandwidth is not as wide as [7, 8], the present technique is useful since it simplifies the length of the feeding transmission line.

Therefore, a multiband antenna with good bandwidths and efficiency response can be obtained with only adding a slotted ground plane. Since the mobile phone industry requires small handset terminals with internal antennas, the proposed technique in this research is a good way to reach these requirements.

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