Multiband Handset Antenna With a Parallel Excitation of PIFA and Slot Radiators

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***Abstract*—A handset antenna technique combining a parallel excitation of a PIFA and a slot is presented. The number of frequency bands is given by the sum of bands given per each radiator which can be controlled independently. Component interaction (battery, display, and speaker) is analyzed to determine the best place to mitigate performance degradation. Finally, a concept featuring a small footprint (39×11 mm^2) and low profile (2 mm) is proposed for multiband operation.**

***Index Terms*—Component interaction, handset antennas, multiband, planar inverted F antenna (PIFA), slot, specific absorption rate (SAR).**

I. INTRODUCTION

ONE of the decisive aspects of a portable radio device, such as for instance a hand-held telephone or a wireless device is its volume and size. From the consumer perception, the overall volume, mechanical design, ergonomics and aesthetics of the phone are decisive. There is an increased trend in making thinner phones that can better fit inside a shirt or jacket pocket or a bag or case.

This need in making smaller, thinner phones enters into conflict with the trend of adding more features to the phone. On one hand, phones are increasingly adding components and features such as large color screens, digital cameras, digital music players, digital and analogue radio and multimedia broadcast receivers (FM/AM, DVB-H, ...) and come with a wider range of form factors (bar phones, clamshell phones, flip-phones, slider phones, ...). On the other hand, new cellular and wireless services are being added, which in some cases means that multiband capabilities are required (to feature several standards such as for instance GSM850, GSM900, GSM1800, GSM1900, UMTS) or that other connectivity components (for instance for Bluetooth, IEEE802, WiFi, WiMax, ZigBee, Ultrawideband). All these trends put an increasing pressure on the antenna specifications, which need to feature a small footprint, a thin mechanical profile, yet performing efficiently at several frequency bands [1]–[16].

Several techniques employing PIFA and slots have already appeared in the literature. In [17] authors present a slot on the ground plane to make the ground plane resonant at the same frequency than the PIFA. This way, a broadband behavior covering from 800–1230 MHz approximately ($\mathrm{SWR} \leq 3$) is obtained, that is, an antenna that fulfills at least the standards GSM850 (824–894 MHz) and GSM900 (880–960 MHz). In [18] a similar approach using a resonating ground plane is shown (design covers from 750 to 1250 MHz approximately, $\mathrm{SWR} \leq 3$). In [19], a design using multiple slots on the ground plane is studied in order to achieve a multiband behavior. In spite of the good reflection coefficient results, the proposed structure is difficult to be integrated into a handset phone due to battery, displays, and speakers, among others that can short-out the slots effect. To overcome the component integration problem, in [20]–[23] a similar design is proposed using a slot underneath the antenna area. The slot has two objectives: on the one hand to tune the ground plane to resonate at lower bands (around 900 MHz) as in [17], [18] obtaining a broadband behavior: (GSM850-900); on the other hand, the slot is designed in such a way that operates as a parasitic antenna resonating at the upper band (1900 MHz). With a proper coupling between the slot and the PIFA [22], the bandwidth at the upper band is improved achieving GSM1800 (1710–1880 MHz), 1900 (1850–1990 MHz), and UMTS (1920–2170 MHz).

Characteristic modes [24] have been used to give a good understanding on how the ground plane can be used to enhance the behavior of a handset antenna [25]–[27].

Other techniques have been proposed in [28]. In this case, the slot in not printed on the ground plane but embedded on the PIFA geometry. This technique creates an extra mode which enhances the bandwidth at the upper band covering from GSM900-1800 for the original design to GSM900-1800 and 1900 for the embedded-slot design.

In [29] a multiband low profile handset designed only with slot antennas is analyzed. Slots are not only useful to antenna design but also for damping undesired modes for EMC purposes [30]. Finally, other solutions employing monopole antenna for multiband purposes can be found in [31].

The objective of the paper is to present a handset antenna technique that combines a PIFA and a slot suitable for slim-profile and multiband cell-phones [32]–[34]. Although PIFA is not low profile compared with a slot-type antenna, the ground plane underneath facilitates component integration as it is demonstrated in this paper. This paper is a detailed extension as well as new data (component interaction) of the author's previous work presented in [34]. A similar concept based on a parallel excitation of two different antenna types (slot and monopole) can

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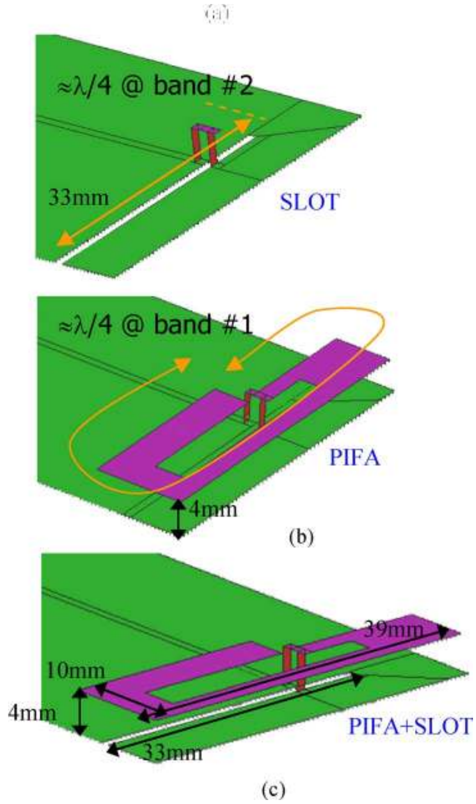

Fig. 1. Sequence showing the antenna concept. (a) a slot on the ground plane is tuned at 1.9 GHz (band#2); (b) PIFA is tuned at 900 MHz (band#1); (c) parallel excitation of both antennas $(\mathrm{PIFA} + \mathrm{Slot})$. Ground plane is 100 × 40 mm^2 for all cases.

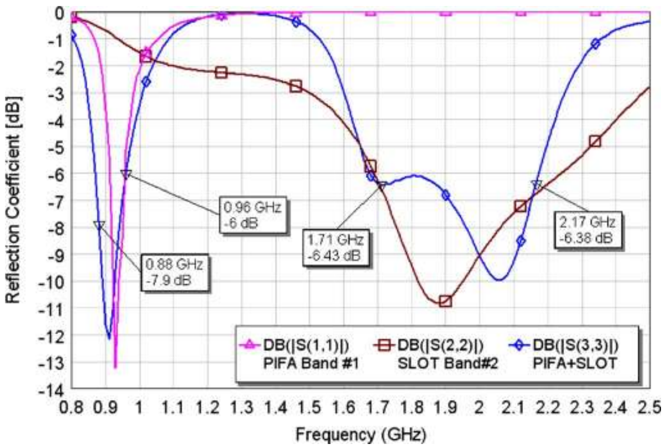

Fig. 2. Simulated reflection coefficient for the sequences shown in Fig. 1.

be found in [35] which also demonstrates to be very useful for multiband performance.

The paper is structured as follows: Section II explains the antenna concept. In Section III, simulation gives a physical insight into the antenna behavior. Component interaction (battery, display, and speaker) is analyzed in Section IV. Section V presents a low-profile design covering GSM900, 1800, 1900, UMTS, and S-DMB (2630–2655 MHz). Reflection coefficient, efficiency, radiation patterns, as well as SAR (specific absorption rate) results are shown. Finally, Section VI summarizes the work.

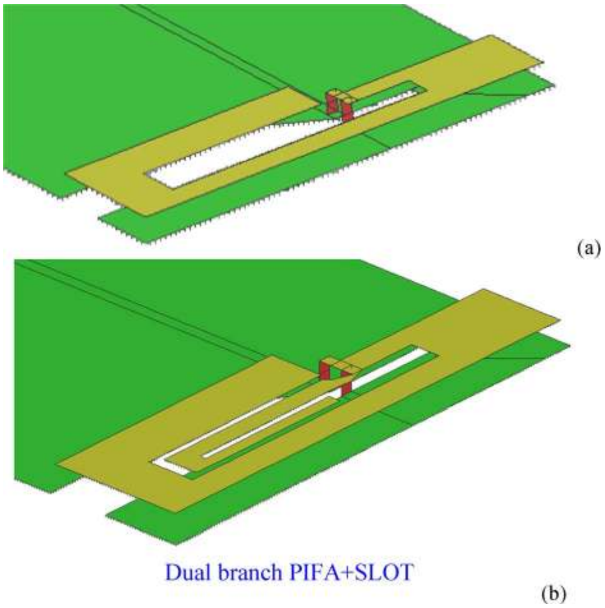

Fig. 3. (a) Single branch $\mathrm{PIFA} + \mathrm{Slot}$; (b) Dual-branch $\mathrm{PIFA} + \mathrm{Slot}$: Adding an extra resonance to the PIFA antenna.

II. ANTENNA CONCEPT

One of the techniques to obtain multiband behavior for handset antennas is to create several resonant paths [2], [16]. Parasitic elements or increasing height may be used to enlarge bandwidth. However both techniques increase antenna volume which is especially prohibitive for the new generation of slim phones. Some solutions remove the ground plane under the antenna area resulting in a monopole type antenna. For these particular cases, once the ground plane under the antenna has been removed, cell-phone components such a camera, vibrator or speaker may degrade the antenna behavior [22]. The antenna technique presented here overcomes the problem of the small bandwidth for low profile PIFA and facilitates component integration.

An illustration on how the concept works is shown next. Fig. 1(a) depicts a slot on a ground plane having 100×40 mm^2. In this case, the slot is excited around 1900 MHz. The obtained bandwidth covers GSM1800-UMTS at $\mathrm{SWR} < 3$. Fig. 1(b) shows a 900 MHz PIFA on the same ground plane. The feeding mechanism is in the same position used to excite the previous slot. The bandwidth is quite poor as the PIFA height is only 4 mm. Both designs are combined, that is, the PIFA and the slot share the same feeding mechanism [Fig. 1(c)]. It can be observed that the new antenna combines both reflection coefficients (Fig. 2). It is important to notice that bandwidth at 900 MHz has been improved. A rationale for this may be found since some ground plane has been removed under the PIFA area reducing its quality factor. Another justification may be explained as the currents follow a larger path due to the slot on the ground plane. The ground plane wave mode gets closer to 900 MHz reaching a better bandwidth [17]–[23]. For the combined solution, bandwidth $(\mathrm{SWR} \leq 3)$ at higher bands is similar as the single slot case. To increase the bandwidth at the second band, slot width may be increased [36].

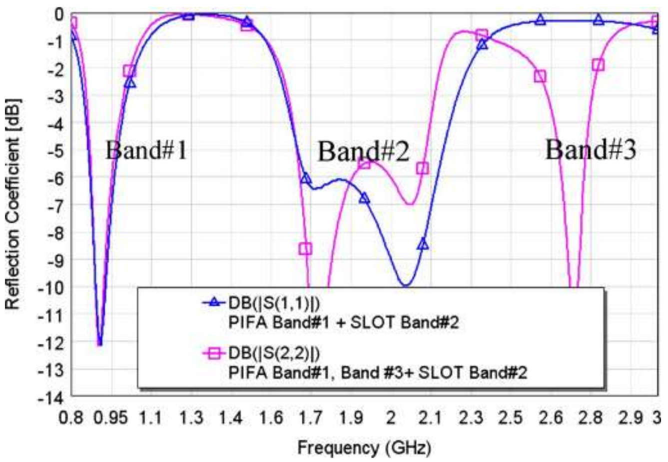

Fig. 4. Simulated reflection coefficient for the sequence shown in Fig. 3(a), (b).

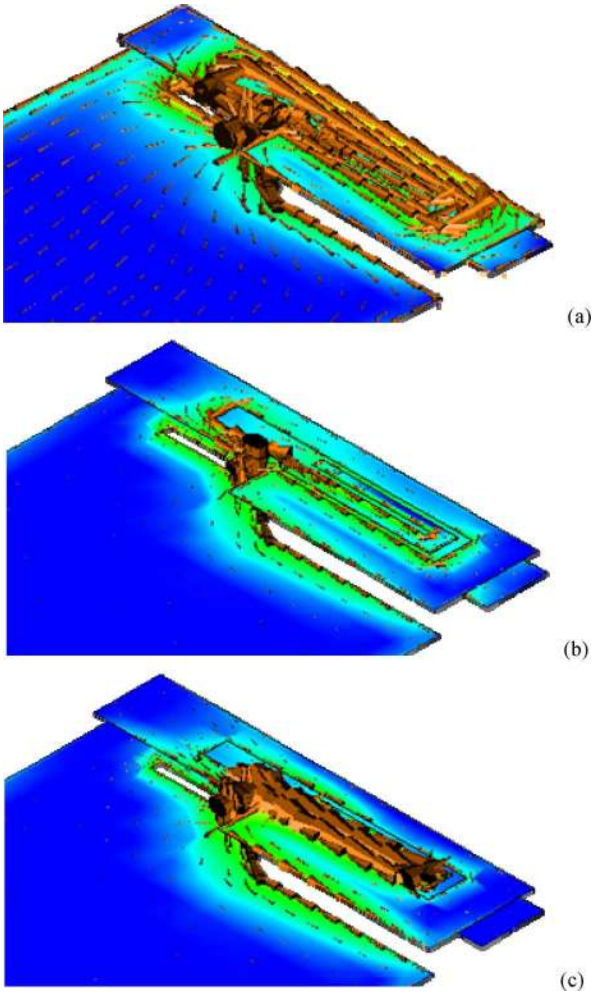

Fig. 5. Current distributions on the PIFA surface. (a) 900 MHz, (b) 1900 MHz, (c) 2600 MHz. The same dynamic range is used.

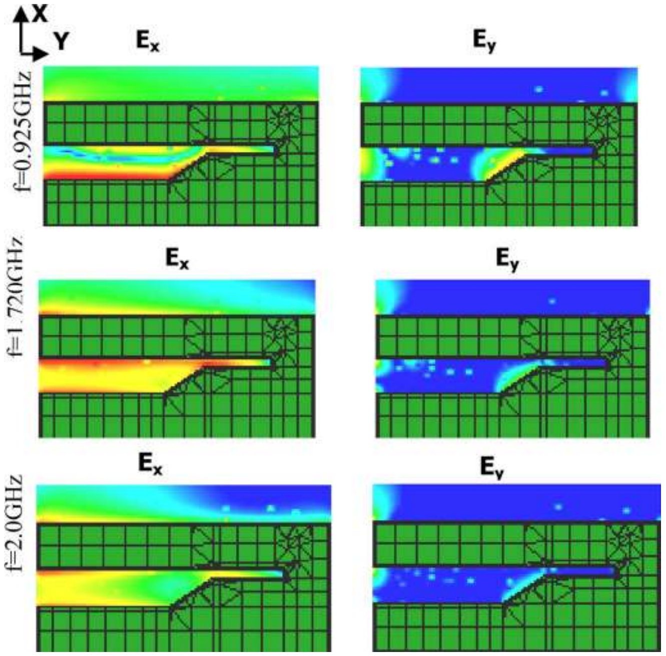

Fig. 6. Electrical field above the slot area.

Since the PIFA has only one branch, used for the low band, the space can be reused to create a second path, that is, a new resonant frequency [33]. In this case, a new electrical path has been tuned at 2600 MHz band which is centered at S-DMB approximately (Satellite Digital Media Broadcast); (Figs. 3, 4). For these two examples we can conclude that:

a) Number of bands = number of PIFA bands + number of slot bands.
b) Bands due to the PIFA and the slot can be adjusted independently.

III. CURRENT AND FIELD SIMULATIONS

Current distribution on the PIFA and electrical field on the slot has been computed using the IE3D MoM package to give an extra physical insight into the behavior of this antenna.

Fig. 5(a)–(c) shows the current distribution at 900, 1900, and 2600 MHz, respectively. It is remarkable that the PIFA is highly excited at 900 MHz [larger branch at Fig. 5(a)] and at 2600 MHz [short branch at Fig. 5(c)] whereas it is weakly excited at 1900 MHz. The PIFA modes for both resonances are fundamental ones, that is, maximum of current distribution is at the feeding/short area and the minimum is at the open edge.

To check the slot excitation, electrical field $(\mathrm{E_x}$ and $\mathrm{E_y})$ on the slot area is computed at several frequencies Fig. 6. Notice that at 900 MHz the slot is weakly excited compared to 1720 and 2000 MHz. At these frequencies, the field distribution corresponds to a quarter wave mode: minimum and maximum at the shorted and open edge, respectively having the illumination field $|\mathrm{E_x}| > |\mathrm{E_y}|$.

IV. COMPONENT INTERACTION

This section analyses the effect on the antenna performance of three particular cell-phone components such as a speaker, a battery, and a display.

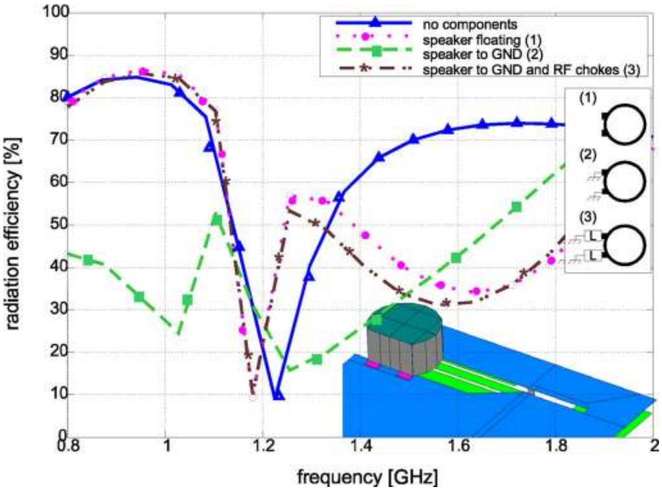

Fig. 7. Simulation to evaluate the effect to floating or connecting the speaker to the PCB.

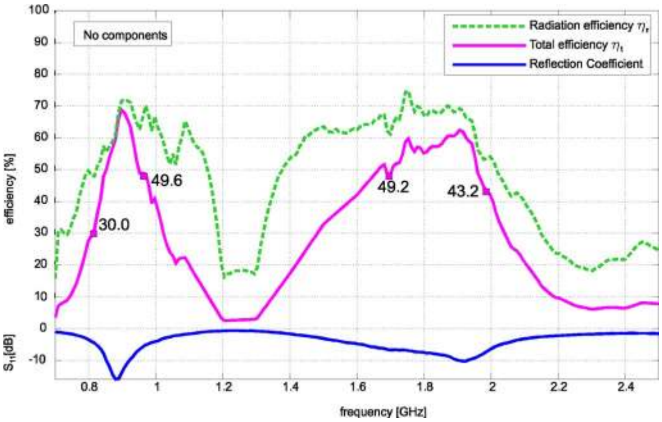

Fig. 8. Measured results without battery, speaker and display. Handset included both front and back plastic covers.

The characteristic of the components and their connection to the PCB or ground (GND) are described next.

- Speaker: circular shape of diameter 13 mm. Floating.
- Battery: width is the same as the ground $\text{plane} = 40$ mm. Material: externally shielded with metal. Adhesive surrounding the whole structure. It is GND connected using the ground pad connection.
- Display: width is the same as the ground $\text{plane} = 40$ mm. A thin metallic layer covers the back side of the display which is facing the slot radiator. It is GND connected.

The reason why the speaker has not been connected to the PCB is explained using simulations results (Fig. 7). The radiation efficiency is computed for four particular situations: without the speaker, with the speaker not connected, with the speaker connected to GND, and finally the speaker connected to the GND using $\mathrm{L} = 100$ nH. When the speaker is connected directly to the GND it degrades both lower and upper frequencies because the PIFA has more metallic part underneath and the slot is shielded. However, when the speaker is not connected, efficiency at lower frequencies is not degraded since the speaker is not an extension of the groundplane. The metal box of the speaker induces more ground effect to high-band slot and causes a poor efficiency. Since the speaker needs to be DC-connected to the GND, two RF chokes (100 nH) are introduced to achieve it and at the same time at RF frequencies the speaker is disconnected. This way, the negative effects of the speaker are mitigated. Since the results for floating and RF chokes cases are practically the same, the following experiments uses the speaker in floating conditions.

The analysis carried out in Figs. 8–11 is explained next.

a) A PIFA-Slot prototype based on Fig. 3(a) operating at GSM850, 900, 1800, 1900 bands has been designed (see slot in Fig. 9 and PIFA in Fig. 10). Groundplane is 100 mm × 40 mm and PIFA is 4 mm height.
b) Reflection coefficient and total efficiency (η_t) are measured using a plastic back-cover to emulate a more realistic scenario. Total efficiency is measured using 3D pattern integration with the Satimo Star-Gate 32 chamber at Fractus Lab.
c) Radiation efficiency (η_r) is calculated using (1)

$$\eta_r = \frac{\eta_t}{1 - |S_{11}|^2}. \tag{1}$$

It is important to outline that a component may shift reflection coefficient with minor changes in η_r which is true if the component introduces low losses or not degrades the antenna radiation; in other situations, a component may introduce losses or short out the antenna causing reflection coefficient to change and η_r to drop dramatically as it is shown next.

d) Aforementioned measurements are performed without components (Fig. 8) and with components at three different positions (Figs. 9–11). Note: for comparison purposes, 4 marks are included in all graphs indicating total efficiency at 824, 960, 1710, and 1990 MHz.

Fig. 9 shows the speaker effect when it is placed above the slot area. For position 1 neither the reflection coefficient nor η_r changes. Since the speaker is above the short-edge of the slot, the effect is negligible, meaning that the speaker may be integrated at this position without affecting antenna. However, as the speaker moves closer the open edge, there is a dramatic change in reflection coefficient as well as η_r at the higher band. This means that the speaker reduces radiation from the slot. Lower bands are affected in a much lesser way. This result corroborates data obtained from the simulation: slot is weakly excited at the lower bands.

Fig. 10 depicts the evolution of reflection coefficient, η_a, and η_r for the following situations: (a) battery at 9 mm, (b) 5 mm, and (c) 0 mm from the PIFA inner edge. It is shown that the performance remains almost the same for b and c situations compared to non-component situation. However, at 0 mm, reflection coefficient at GSM850-900 is shifted to lower frequencies and at the same time η_r drops degrading the antenna behavior. At GSM1800–1900 frequencies, antenna performance is slightly affected since the battery does not interfere with the slot area.

Fig. 11 explains the display effect when it is placed above the slot. The effect is pretty much the same as the speaker: to block the radiation from the slot. It is interesting to outline that in spite of the acceptable reflection coefficient at GSM1800–1900 bands, η_r is less than 30%. The lower bands are weakly affected.

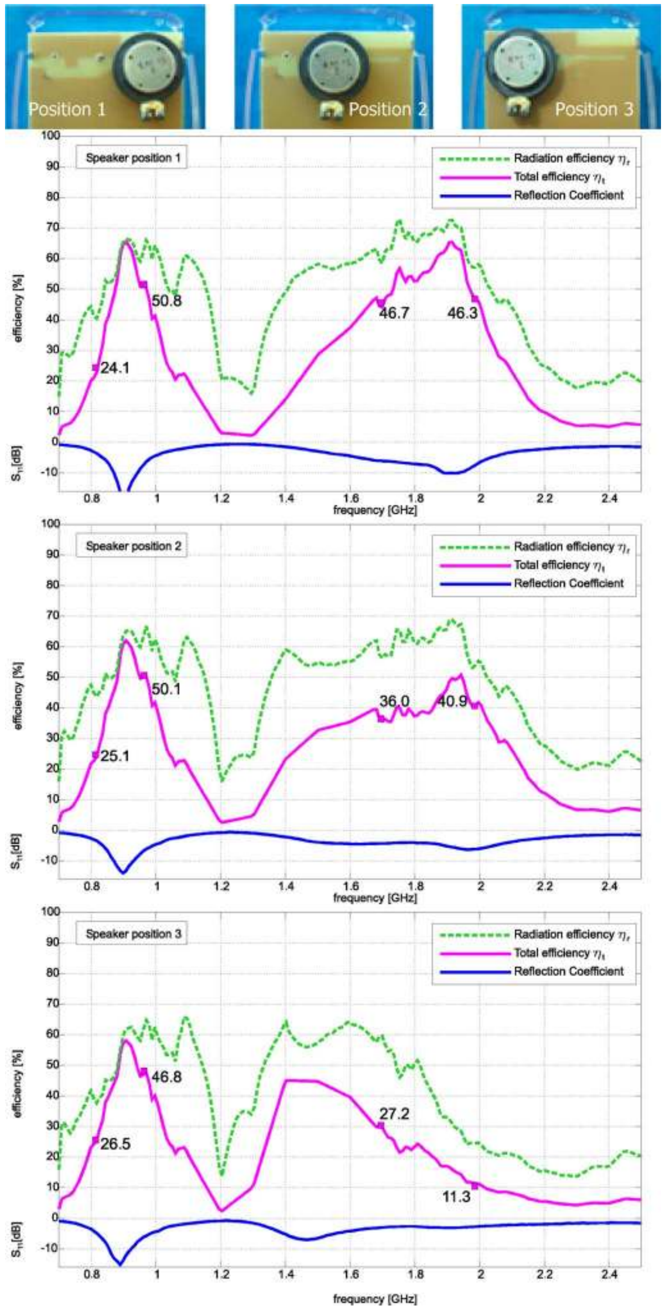

Fig. 9. Speaker effect.

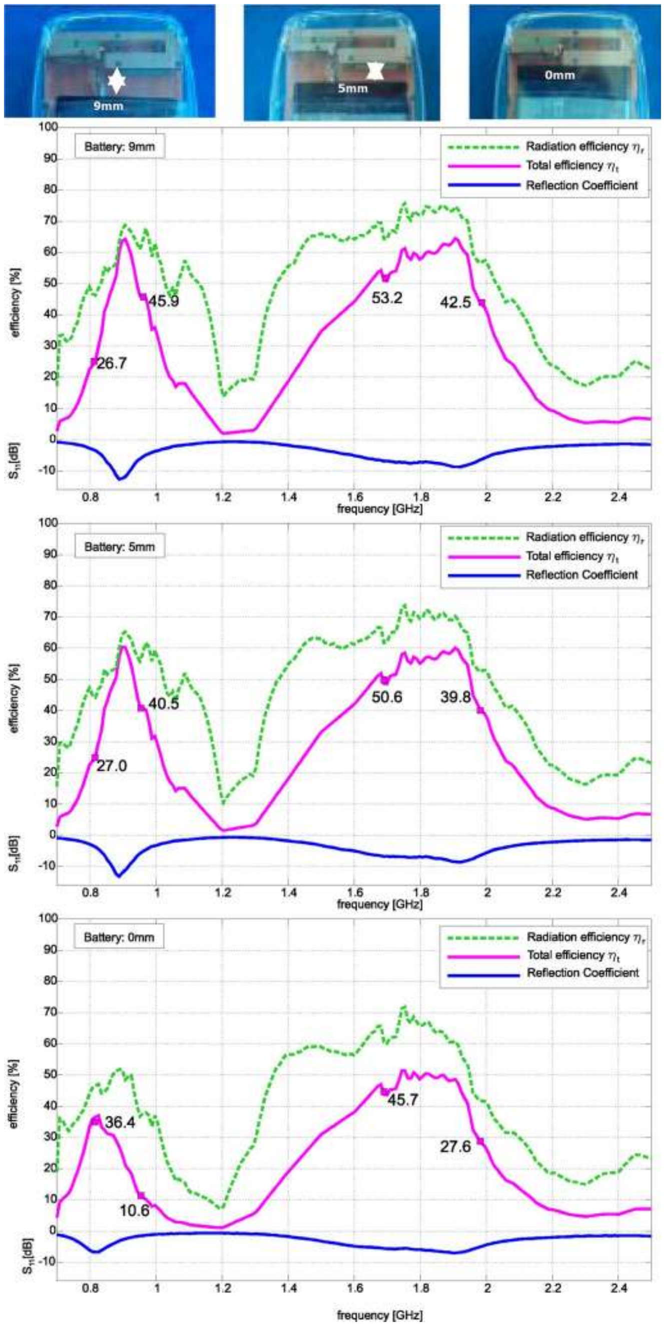

Fig. 10. Battery effect.

From this experiment it is concluded that the slot should be kept free from the display, being this one a critical component.

We can outline that the slot is an attractive solution in terms of a low profile antenna, but it is sensitive when handset components are close to the slot aperture.

V. SLIM HANDSET ANTENNA FOR MULTIBAND BEHAVIOR

This section illustrates a particular design for pentaband (GSM900, 1800, 1900, UMTS, and S-DMB) behavior using the geometry depicted in Fig. 3(b). Physical implementation is shown in Fig. 12 and Fig. 13. Slot uses a wide aperture to enhance bandwidth especially at the upper bands (DCS-UMTS frequencies) since the slot is the antenna operating at these frequencies. Increasing the slot width may have a lateral effect on the PIFA at GSM900 frequencies since it has less ground plane underneath even the slot is not resonating at GSM900. This way, the PIFA has a partial ground plane which decreases its quality factor, that is, more bandwidth may be obtained.

A similar explanation may be observed for a partial grounded microstrip patch. When a slot is placed underneath the microstrip patch, it reduces the quality factor, and therefore the bandwidth of the antenna is increased [37].

More research needs to be done to include GSM850 band which should be achieved by either increasing slot width, PIFA height, or using broad banding networks.

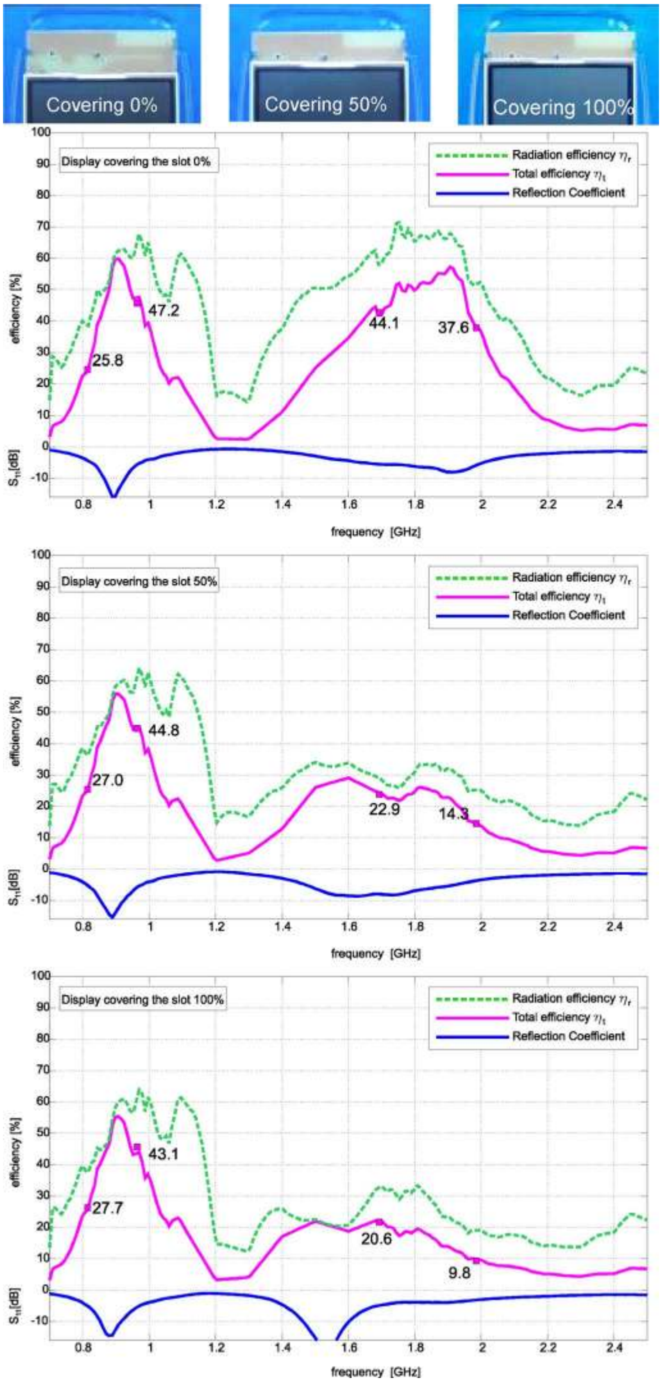

Fig. 11. Display effect.

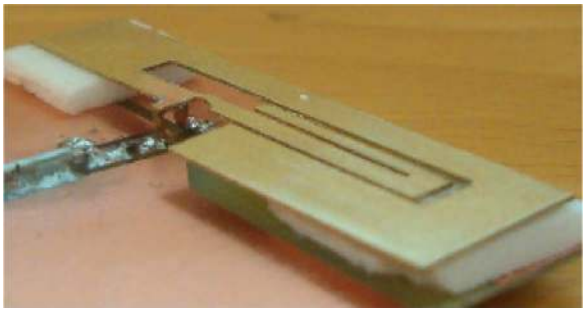

Fig. 12. Slim PIFA-Slot antenna: 39 mm × 11 mm × 2 mm (h). Substrate is polymethacrylimide foam.

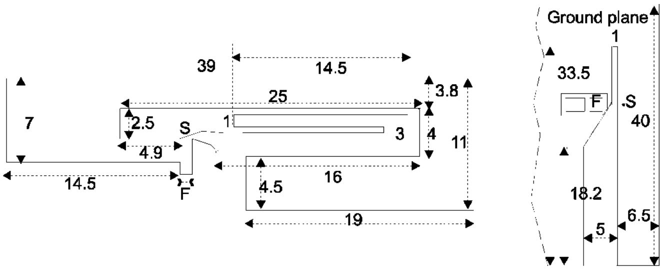

Fig. 13. PIFA and slot dimensions in mm. F: feeding point; S: short. F and S are two metal parts having 2 mm width × 2 mm (h).

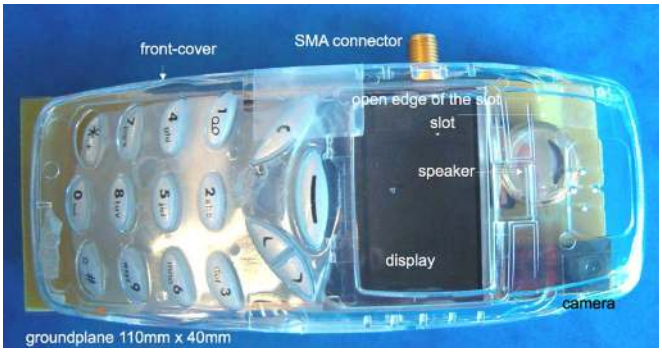

Fig. 14. The handset prototype using the PIFA-slot of Fig. 12. Speaker at position 2 (see Fig. 9). Battery at 9 mm from the PIFA. Display covering 0% the slot area.

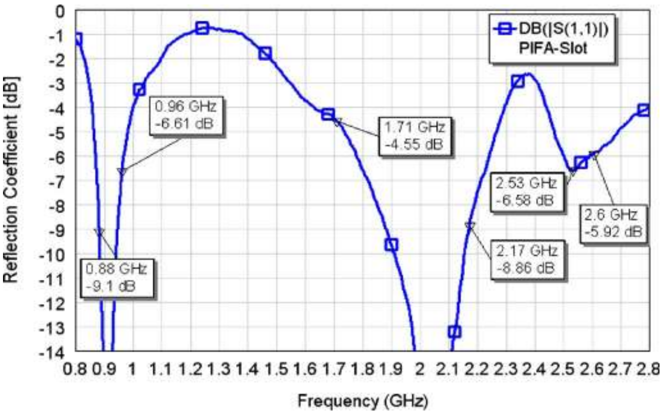

Fig. 15. Measured reflection coefficient for the antenna shown in Fig. 12.

Following the guideline presented in Section IV, a battery, a speaker, and a display have been attached to the ground plane. In addition, a camera has also been placed near the short-edge of the slot (Fig. 14). A front and a back cover are also taken into consideration for all the experiments.

Fig. 15 represents the reflection coefficient where it can be observed a good matching ($\mathrm{S}_{11} < -6$ dB). At 1710 MHz, which is the starting frequency of GSM1800, matching may be further improved as there is enough room since the end part of UMTS (2170 MHz) has almost -9 dB. It should be outlined that the PIFA height is only 2 mm; as shown in previous section, increasing to 4 mm would be useful to include also GSM850 band being still a low profile PIFA [38].

TABLE I
RADIATION (η_r), TOTAL EFFICIENCY (η_t), AND REFLECTION COEFFICIENT FOR THE ANTENNA HAVING ALL THE COMPONENTS SHOWN IN FIG. 14

f[MHz]	η_r [%]	η_t [%]	S_{11} [dB]
880	69	60	-9.1
925	65	64	-18.1
960	65	51	-6.6
1710	60	39	-4.5
1800	59	44	-5.9
1900	61	54	-9.4
2000	68	67	-18.3
2100	69	67	-15.3
2170	70	61	-8.9
2600	62	46	-5.9

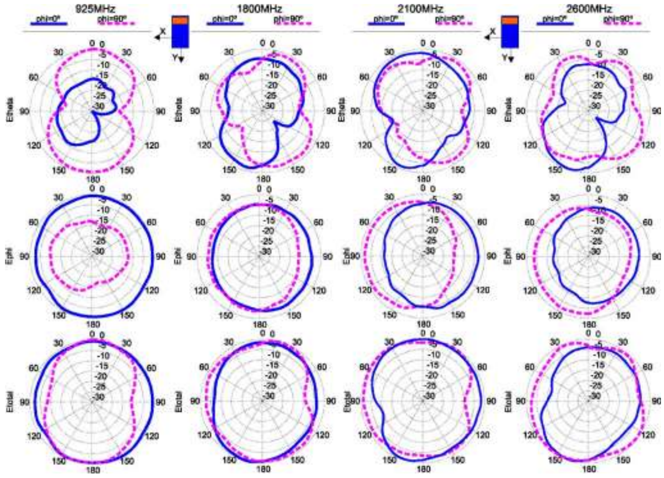

Fig. 16. Measured radiation cuts at 900, 1800, 2100, and 2600 MHz. Measured maximum gain at each frequency is 1.3, 0.7, 2.7, and 0.85 dBi.

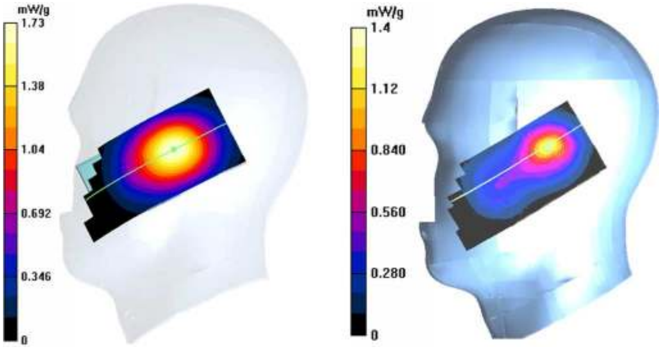

Fig. 17. Measured SAR distribution at right cheek position 900 MHz (left) and 1800 MHz (right).

TABLE II
MEASURED SAR VALUES FOR THE ANTENNA PROTOTYPE OF FIG. 14

frequency [MHz]	SAR 1g [mW/g]	SAR 10g [mW/g]
900	1.61	1.15
1710	0.92	0.56
1800	0.88	0.55
1900	1.23	0.74

Table I shows the measured η_r and η_t. Even the existence of several cell-phone components, η_t can fulfil mobile service requirements.

Radiation cuts have been measured at 900, 1800, 2100, and 2600 MHz (Fig. 16). Dipole-type radiation pattern can be observed at 900 MHz determined by the ground plane mode: omnidirectional at $\varphi = 0°$ having linear polarization following y-axis. Radiation patterns at higher frequencies present a larger directivity due to the larger electrical size of the ground plane.

Finally, specific absorption rate (SAR) in passive mode has been tested using Dasy-4 at Fractus-Lab. At GSM900 the maximum transmit power is 33 dBm; however, a transmit channel uses only $1/8$ of a time slot. This results in 24 dBm which is the power of a continuous wave to test SAR. Similar procedure is done at GSM1800; in this case, maximum transmit power is 30 dBm. Thus, SAR is tested using 21 dBm.

SAR passive testing is indicative of a preliminary measure since SAR is finally tested with an active device. However, it is interesting to test in a passive way to analyze if the antenna may pose a SAR problem. For example, from this passive data (Table II and Fig. 17) some conclusions can be obtained.

a) At the low frequencies (900 MHz), the hot-spot (maximum SAR value) is located at the centre of the ground plane confirming again that the ground plane mode determines radiation. The slot is weakly excited, meaning that it is not an issue for SAR.
b) At the higher frequencies, the hot-spot in mainly fixed by the slot on the ground plane since in this case the slot is excited, that is, SAR is more antenna dependent [17]. This is useful information since SAR can be dramatically reduced at higher bands by placing the antenna at the opposite short edge of the ground plane (180° rotation of the handset) [22].

VI. CONCLUSION

The concept based on a PIFA-slot has been shown to be useful to design multiband handset antennas where the number of frequency bands is given by the sum of the bands given by each radiator. Moreover, said bands can be controlled independently which adds an extra freedom design.

Component interaction has been analyzed showing that: a) the speaker mainly affects the slot radiator (introduces mismatch and losses) but its negative effect can be minimized by placing the speaker near the short-edge of the slot, b) battery affects the PIFA causing a detuning and introduce losses, c) the display is a critical component which should keep the slot free. This means that for planar handset antennas such as monopoles or slots, component interaction should be carefully taken into account. Although PIFA type occupies more space, components can be placed at the other part of the ground plane with a minimum impact on the performance of the antenna.

Thanks to the slot radiator, the PIFA volume can be reused to add more bands; for this research, an extra band centered at S-DBM has been added to finally design a pentaband prototype at GSM900, 1800, 1900, UMTS, and S-DMB. The total antenna volume results in only $39 \times 11 \times 2(\mathrm{h})\ \mathrm{mm}^3$. Results for total efficiency taking into account several components (battery, display, speaker, camera, and phone covers) are satisfactory and make this concept very attractive for the new generation of low-profile multiband handset phones.

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