Chapter 4

Compact Planar Multiband Antennas for Mobile Applications

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Additional information is available at the end of the chapter

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1. Introduction

This chapter focuses on the design of compact planar multiband antennas intended for existing wireless services including LTE, GPS, GSM, PCS, DCS, GPS, UMTS, WLAN and WiMAX bands. The present techniques available in the open literature include the modification of the main radiator via bending, folding, meandering and wrapping. Each approach offers different advantages, depending on the required application. The constraint for the lower band generation is the main challenge in radiator miniaturization. The quarter wavelength radiator that is subjected to miniaturization may suffer from limited bandwidth and low radiation efficiency. An alternative approach which relies on modifications to the ground plane is a promising technique, which often has been previously overlooked by antenna designers. The introduction of a ground slot in a finite antenna ground plane can be further extended to include reconfigurable features. Thus, such antennas that are compact and have multiband capability can be promising candidates for many wireless applications.

2. Design guidelines for planar antenna configurations

Antennas for wireless communications are commonly developed in the form of passive planar structures, which consist of a main radiating element, a supporting ground plane, a supporting substrate, and a feeding structure. The design configurations, sizes and type of substrates will depend on the desired frequency of operation and its radiation performances. Nowadays, planar antennas for wireless devices are mainly constructed using printed planar technology. Fundamentally, the small antenna design is based on the configuration of a *monopole*. Following the expansion of research on antenna design, the monopole configuration started to change, forming many alternative designs such as the popular *planar inverted-F antenna* abbreviated as PIFA and co*planar inverted-F antenna* abbreviated as CIFA.

In general, there are two main considerations that govern planar antenna designs; antenna miniaturization techniques and multiband operation. In antenna designs, multiband operation can be achieved by modifications to the main radiator applied using two strategies. The first strategy is to create several radiators for different resonances from a single feeder. The second strategy is to elongate the main radiator's physical length to achieve multiple resonant modes. However, creating several radiating branches may occupy more space, hence making the antenna physically larger than the desired volume. For this reason, while designing a multiband antenna, the designs must also apply miniaturization approaches, such as the ones presented in the following design strategies section.

3. Design strategies

3.1. Modification of the main radiator

The main radiator of a monopole/PIFA/CIFA type antenna plays a major role in determining the resonant frequency of the antenna. For a small antenna, particularly the $\lambda/4$ radiator configuration, miniaturization can be achieved in many ways. The main radiator arm can be modified by changing its configuration in such a way that it occupies optimally the limited area/volume provided for it.

One of the design techniques to achieve multiband operation is to have branches for the main antenna radiator. The branches are of monopole strips or arms to create different current paths for different resonances. This technique allows the excitation of multiple resonant frequencies at their fundamental mode. Multi-stacking or multi-layering is another technique that offers similar operation as the multi-branching technique. Similarly, it is capable of creating different current paths and thus different resonances.

A multi-resonator configuration is also achievable through proper application of some sort of slot or slit, sometimes also known as a notch geometry. In this approach, the radiator is modified in such a way that its original geometry is introduced with fine-tuned defined configurations of slots or slits. The resulting modification separates the main current stream into several other paths, which in turn create different resonators. It is worthwhile to mention that designs utilizing slots are not necessarily limited to straight lines or rectangular geometries. Other shapes have also been proposed such as a U-slotted PIFA, a V-slot loaded patch antenna, a Z-shaped slot antenna, or an open-ended Rampart-slot antenna.

The second strategy for the antenna design has the goal of obtaining a compact design and multi-band operation while using a single radiator without splitting it into branches. A considerable number of work employing this design strategy can be identified in the antenna literature. Among the popular techniques to elongate a single radiator to achieve multiple mode resonances without diminishing the antenna's compact feature include spiralling, looping, folding into a 3-D geometry, and bending.

Miniaturization can also be accomplished by meandering the antenna structure. The working principle is similar to that of spiralling. The meandered geometry preserves the original length of the radiating element but miniaturizes its overall size. The resulting input impedance of the meandered geometry is usually different from its spiral counterpart. Several factors determine the variation of the input impedance such as the gap between the opposite meandered lines and the width of the meandered structure. The meandered geometry can be applied in a variety of antenna types.

All the above-considered techniques for compact multi-band antennas offer reasonable solutions. However, they introduce considerable complexity with regard to the control of matching the input impedance of the antenna. Because of this problem, some antenna designers have focused their attention on providing better control of the input impedance match without being constrained by miniaturization. This strategy is the main motivation behind the approach involving parasitic elements within the antenna geometry. The aim of using parasitic elements is to compensate the impedance mismatch and to achieve better resonant frequency tuning.

3.2. Modification of the ground plane

As a result of the advancement in RF transceivers, the space allocated for its radiating element has become smaller. The reduced space is due to the increase in the number of new circuitry needed to provide better data channelling. The modification of the radiating element in a compact volume has been very challenging. An alternative solution is a better utilization of its ground plane. Even though the geometry of the main radiating element plays a main role in determining the resonant frequency and other performances of an antenna, the importance of the ground plane as the natural complimentary agent to a radiating current must not be neglected. The modification includes size variation, location of radiating element within the ground plane area or inserting slots in the ground plane.

Variations in a finite ground plane size and geometry affect the performance of an antenna. The resonant frequency of a conventional PIFA starts to converge to that of the case of an infinite ground plane when the size of the finite ground plane is increased above a unit wavelength. Also, the bandwidth increases with the length of the ground plane. With respect to the PIFA antenna used in a cellular phone, it was shown that an increased bandwidth, especially with respect to the lowest resonant frequency of operation, is achieved with a longer ground plane.

With respect to the complimentary role of ground plane to the main radiator, any modification to its geometry should also affect the overall antenna performance. Inserting slots is one obvious example. The insertion of ground slots creates some sort of discontinuity which causes the electric current launched by the primary radiator to reroute its path along the conducting surface of the ground. As a result, the electrical length of the ground is increased. With the strong coupling from the radiator, the ground slots cause a considerable impact on the input impedance. This positive impact includes the introduction of new resonances which are advantageous for the multiband design

3.3. Reconfigurable approach

With multiband capability, reconfigurable antennas can utilize more efficiently the radio frequency spectrum, facilitating better access to wireless services in modern radio transceivers. Reconfigurable antennas are generally divided into two main categories: frequency tunable and pattern diversity antennas. Furthermore, the selection of electronic switches is of paramount importance. Depending on the type of antennas, switches such as RF MEMS, varactors and PIN diodes can be used. The choice is governed by electrical specifications, fabrication complexity, bias requirement, switching time, and price.

4. Design examples

4.1. Coplanar IFA with fixed ground slots

Coplanar inverted-F antennas (CIFA) feature a low profile, compact size, and easy integration with an RF front-end. On the other hand, they feature a narrow operational bandwidth. Several techniques to increase the operational bandwidth or achieve multiband operation can be applied as discussed in [1, 2]. However, most of these techniques focus on modifications of the radiating element to either provide several radiating branches or elongating the radiator's dimension to generate multiple resonant modes. This approach faces a problem when the antenna has to be embedded into a small space as demanded by a compact transceiver. An alternative technique to provide multiple resonant frequencies or bandwidth enhancement is through a better utilization of the ground plane [3-10]. In this technique, secondary radiators are formed by ground slots, which introduce new resonant frequencies or enhance the already existing ones. The feasibility of this approach to enhance an impedance bandwidth has been demonstrated for a planar inverted-F antenna (PIFA) [6-8]. It has been shown that with the proper tuning of slot parameters, new resonant frequencies can be generated to provide multiband operation or increase the bandwidth [7, 8]. In all of these designs, a coaxial probe was used to feed the radiating patch. This configuration requires ground slots to be in close proximity of the primary radiator to excite efficiently new resonances. A shortfall of such a configuration is a limited means for tuning the slot dimensions. Also, the restricted slot locations may limit the antenna integration with the RF circuitry [9]. Recently, an alternative approach involving a CIFA and a microstrip feedline coupled to ground slots has been proposed [10]. According to the work described in [10], the use of the microstrip feedline in conjunction with the CIFA eliminates the shortcoming of a coaxial probe-fed patch. The reason is that this feeder can be positioned arbitrarily on the printed circuit board (PCB) and thus offers a more flexible coupling with ground slots to introduce new resonant frequencies. The work presented in [10] considers a single ground slot and was limited to WLAN frequency bands. In the following design, the work is extended to multiple ground slots and includes detailed simulation and experimental investigations.

Two configurations of CIFAs with slots in the ground plane are simulated, fabricated, and measured to validate the proposed multiband design technique. The design is accomplished with the aid of CST Microwave Studio 2009 [11].

4.1.1. Single and double ground slot configurations

The two investigated configurations of CIFAs are shown Figure 1. The design assumes a 0.508 mm thick RO4003 substrate with a relative permittivity $\varepsilon_r = 3.38$ and tan $\delta = 0.0027$. The total length of the meandered CIFA tail is designed to be of quarter wavelength of its operational frequency which is 2.45 GHz. The meandered tail including the shorting strip is set to be contained within an area of $W_p \times L_p = 6 \times 13$ mm^2. A 50 Ω microstrip line which is arranged in the same plane as the main radiator is used to feed this antenna. Note that the length and position of the microstrip feedline is only limited by the size of the finite ground, otherwise it can be arbitrary. The shorting strip of the CIFA is connected to the ground plane via the substrate. The other parameter of the CIFA are the shorting strip to the antenna feeder gap, $g = 1.15$ mm, while the width and gap of the meandered tail are set to 1 mm. On the opposite side of the substrate, the size of the ground plane is set to $W \times H = 40 \times 50$ mm^2.

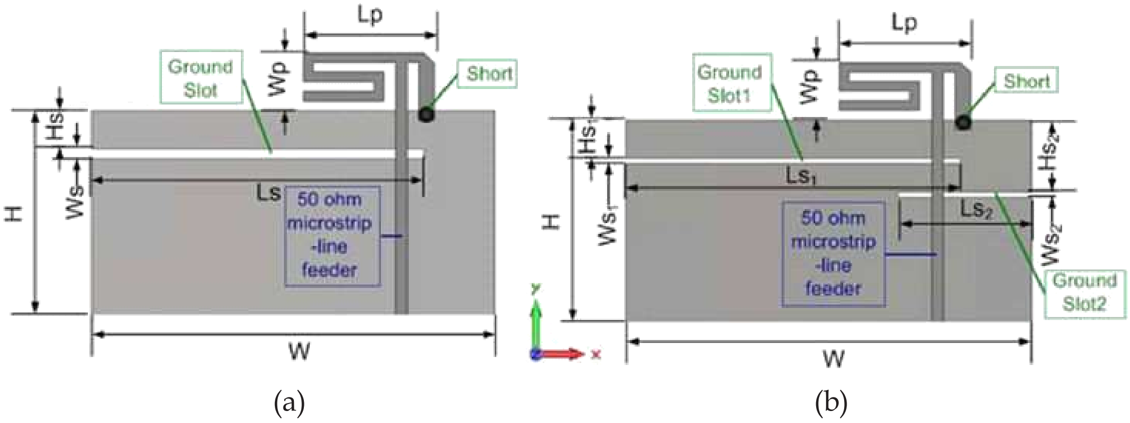

Figure 1. Antenna configurations. (a) Single ground slot CIFA for dual-band operation. (b) Double ground slot CIFA for tri-band operation.

Two configurations of CIFAs are introduced with two different ground slot outlines, as shown in Figure 1. As observed in Figure 1(a), the introduced slots are open-circuited in one arm and short-circuited at the other. The open-circuited arms of the ground slots are responsible for introducing new resonances, while the short-circuited ones act as tuning stubs. The initial lengths of the radiating arms are about one quarter-wavelength. The coupling locations along the microstrip feedline are selected to avoid an adverse loading of the primary radiator. The final dimensions are obtained from a parametric analysis performed using CST Microwave Studio. For the first configuration (Figure 1 (a)), an open-end slot with an optimized distance of $W_s \times L_s = 1 \times 33$ mm^2 and at a distance of $H_s = 4$ mm from the upper ground edge is designed. The second configuration (Figure 1 (b)) features two slots of dimension $W_{s1} \times L_{s1} = 0.5 \times 33$ mm^2 and $W_{s2} \times L_{s2} = 0.5 \times 13.2$ mm^2, respectively, placed at opposite edges. The distance of both slots with respect to the upper ground edge are H_{s1} = 4 mm *and* H_{s2} =7.5 mm. These two configurations indeed indicate that the microstrip feedline feed offers more flexibility to the ground slot coupling than a coaxial probe operating in conjunction with a PIFA.

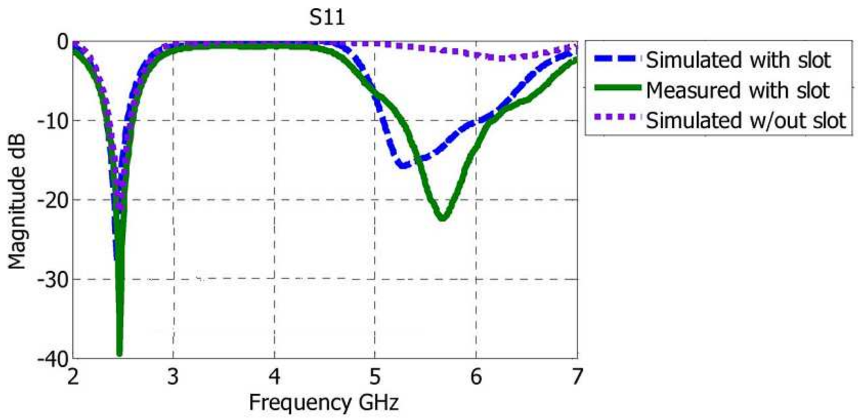

Figure 2. Simulated and measured reflection coefficient, $|S_{11}|$, for the CIFA of Figure 1(a) with and without a single slot.

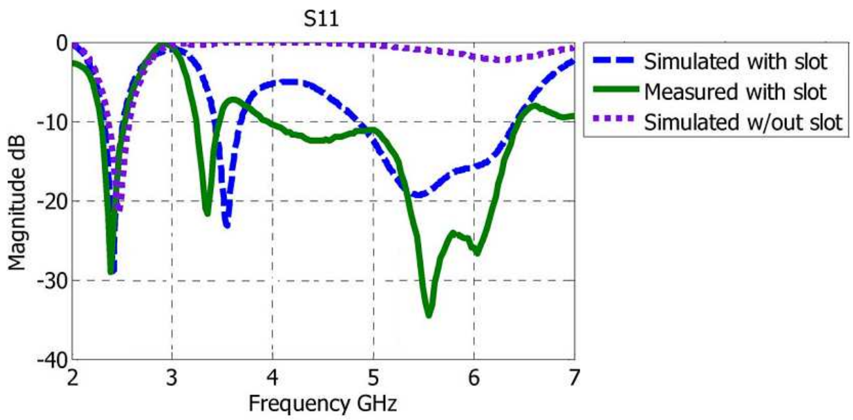

Figure 3. Simulated and measured reflection coefficient, $|S_{11}|$, for the CIFA of Figure 1(b) with and without a double slot.

The performances of both the CIFA configurations are assessed in terms of their reflection coefficients, radiation characteristics, and gain. Figure 2 shows the simulated and measured reflection coefficients of the first slot configuration of the CIFA. The presented results validate the proposed idea that the coupling of a single open-ended slot with a microstrip feedline is capable of generating a new resonant frequency at about 5.5 GHz (900-MHz impedance bandwidth with $|S_{11}|$ below -10 dB). Together with the fundamental resonance of the CIFA radiator at 2.4 GHz, the dual-band CIFA can support the WLAN 2.4/5.5-GHz system. There is good agreement between the simulation and experimental results. The simulated and measured reflection coefficients for the CIFA configuration with a double ground slot are shown in Figure 3. The presented results demonstrate a promising multiband operation of the CIFA. The proposed technique introduces two additional resonant frequencies. The first one is above 3 GHz, and another one is above 5 GHz. The impedance bandwidths are quite wide and accommodate not only the 2.4/5.5-GHz WLAN, but also include 2.5/3.5/5.5 GHz for WiMAX. Again, there is a relatively good agreement between the simulated and measured results for the reflection coefficients. In addition, the proposed coupling to the ground slots does not affect the reflection coefficient performance of the CIFA around the original resonance of 2.4 GHz. This means that the design procedure does not introduce any extra complexities.

(a) (b) (c)

Figure 4. Fabricated prototypes of the meandered-tail CIFA. (a) Top view. (b) Bottom view of the single-ground-slot CIFA for dual-band operation. (c) Bottom view of the double-ground-slot CIFA for tri-band operation.

The measured radiation patterns for these antennas indicate approximately omni-directional characteristics along the principal planes. The measured gains of the dual-band CIFA are greater than 1.6 dBi, while for the tri-band CIFA they are more than 2.2 dBi. The photographs of the two manufactured varieties of CIFAs with ground slots are shown in Figure 4. They confirm a simple manufacturing structure for these multi-band antennas. Their overall size is quite compact and the slotted ground leaves still plenty of space for inclusion of RF and signal processing electronics.

4.1.2. Parallel and perpendicular ground slot configurations

In the following work, an investigation to study the effect of different orientations of open-end ground slots that are coupled to the microstrip feedline is presented. In contrast to the previous work, the CIFA configuration with a straight quarter wavelength radiating arm accompanied by differently oriented ground slots is considered. The substrate used is Rogers RO4003 with a dielectric constant of 3.38, tan δ = 0.0027 and thickness of 0.508 mm. The antennas are fabricated and their prototypes are experimentally tested. In the investigated antennas, a basic CIFA with a straight radiating arm is assumed, as shown in Figure 5. The microstrip feedline was then chosen to achieve coupling to ground slots that were located and oriented in different positions. In Figure 5(a), the open-end ground slot is offset by some distance from the CIFA and its orientation was chosen to be parallel to the CIFA radiating arm. Assuming a 0.508 mm thick RO4003 substrate, the total length of the PIFA arm is a quarter wavelength at 2.45 GHz. The width of the radiating arm is set to 1 mm. The total area of the antenna including the shorting strip is set to be contained within an area of $l_a \times h_a$ = 24 mm × 3.5 mm. A 50 Ω microstrip feedline is arranged in the same plane as the CIFA. The length of this feedline is governed by the location of the input port of the RF front-end to which it has to be connected. A shorting connection of the CIFA is made using a conducting strip through the substrate. The shorting strip to the antenna feeder gap is g = 1.15 mm.

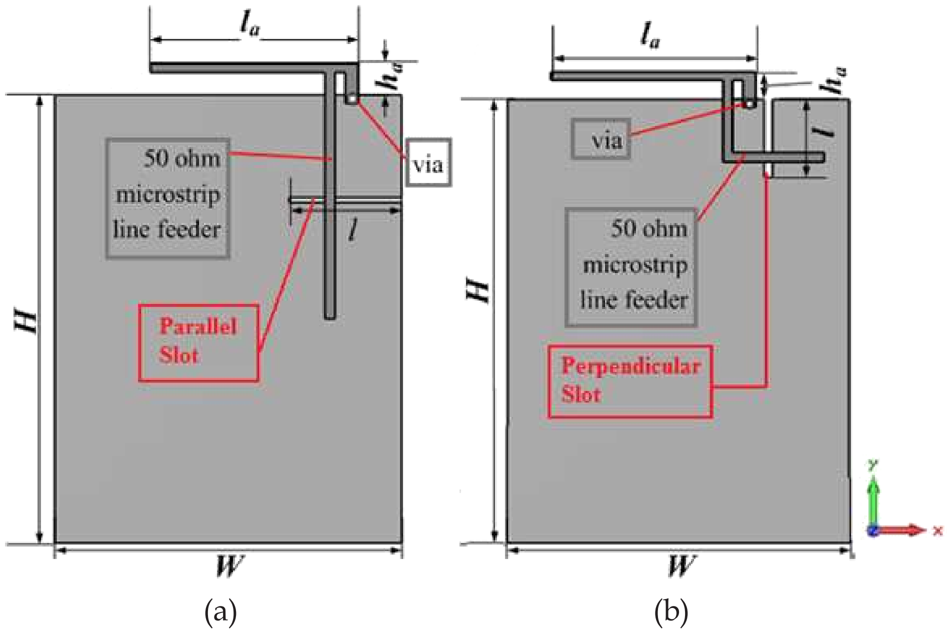

Figure 5. The first (a) and second (b) configurations of CIFAs with ground slots parallel and perpendicular to the main radiating arm, respectively.

On the opposite side of the substrate, the size of the ground plane is set to $W \times H$ = 40 mm × 55 mm. An open-end slot with a length (l) and width of 13 mm × 0.5 mm is inserted in a parallel position with respect to the radiating arm as shown in Figure 5(a). The second configuration with the ground slot perpendicular to the CIFA is shown in Figure 5(b). In this case, the microstrip feeder is bent halfway exactly at a right angle towards the RHS edge of the ground plane, as shown in Figure 5(b). Concerning the length of the feeder, it can be arbitrary. However it must be properly coupled to the slot. Notice that the overall location of the primary radiator has been shifted by a few millimeters to the left to avoid the microstrip feed point from overpassing the edge. This time, the open-end slot with length (l) and width of 10 mm × 1 mm is inserted in a position that is perpendicular with respect to the radiating arm. It is noticeable that the length, width and position of the slots for both configurations are different. Their optimum dimensions are derived from parametric analyses performed with the use of CST Microwave Studio.

Figures 6 and 7 show the simulated reflection coefficients for the CIFAs without and with the slots. It is apparent from the results for the first configuration of CIFA shown in Figure 6 that the introduction of the slot has successfully introduced two additional resonant frequency bands apart from the original 200 MHz band ($|S_{11}|$ below -10 dB) at around 2.45 GHz due to the primary CIFA radiating element. From the simulated reflection coefficient, the new frequency bands can approximately cover a bandwidth of almost 300 MHz at 3.3 GHz and up to 1.14 GHz around 5.5 GHz with reference to the -10 db $|S_{11}|$ coefficient criterion. These bands cover WLAN 2.45/5.25/5.85 GHz, HiperLAN/2 5.6 GHz and WiMAX 2.5/5.5 GHz. The 3.3 GHz resonant frequency band however is close to WiMAX 3.5 GHz. Figure 7 shows the simulated reflection coefficient for the second configuration of CIFA. Again, the multiband operation of this antenna is clearly observed. The slot insertion is again responsible for the introduction of a new frequency band of 720 MHz bandwidth ($|S_{11}|$ below -10 dB) at around 5.4 GHz. Together with the original 2.45 GHz resonant frequency band for the primary radiating element, the second configuration of the antenna covers WLAN 2.45/5.25 GHz, HiperLAN/2 5.6 GHz and WiMAX 2.5/5.5 GHz.

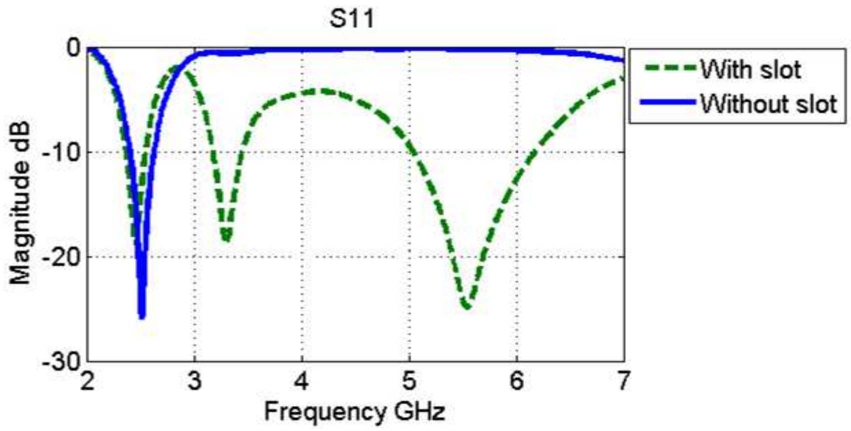

Figure 6. Simulated reflection coefficient, $|S_{11}|$, for the first configuration of the proposed CIFA shown in Figure 5 (a) with and without a parallel slot.

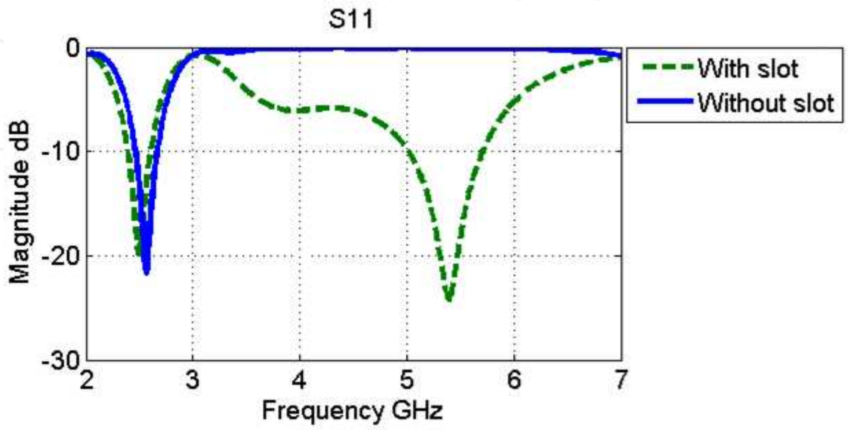

Figure 7. Simulated reflection coefficient, $|S_{11}|$, for the second configuration of the proposed CIFA shown in Figure 5 (b) with and without a perpendicular slot.

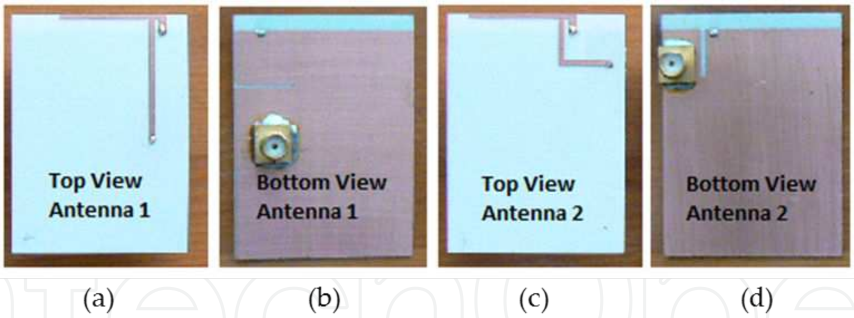

Figure 8. Fabricated prototypes of the two antenna configurations. (a) Top view of the first configuration of the CIFA. (b) Bottom view of the first configuration of the CIFA. (c) Top view of the second configuration of the CIFA. (d) Bottom view of the second configuration of the CIFA.

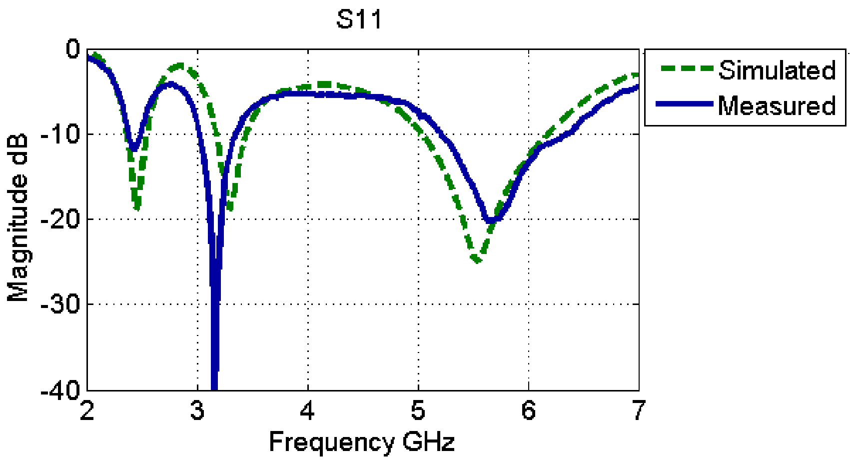

Figure 9. Measured reflection coefficient, $|S_{11}|$, for the first configuration of the CIFA prototype shown in Figures 8 (a) and (b), compared to the simulated result.

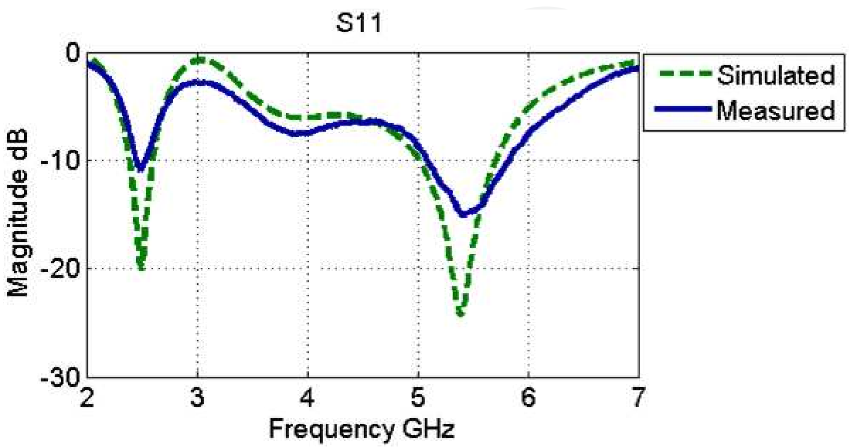

Figure 10. Measured reflection coefficient, $|S_{11}|$, for the second configuration of the CIFA prototype shown in Figures 8 (c) and (d), compared to the simulated result.

To verify the simulated performance, the two antennas were fabricated and experimentally tested with respect to their reflection coefficients, radiation patterns and gain. Photographs (front and back view) of the fabricated antenna prototypes are shown in Figure 8. Figures 9 and 10 present the measured reflection coefficient of the fabricated antennas compared with the simulated results presented earlier. A very good agreement between the experimental and simulation results for the two antenna prototypes is obtained confirming the validity of the presented designs. The measured radiation patterns for both the antenna configurations are shown in Figures 11 and 12. They were obtained in an indoor far-field range using a broadband linearly polarized horn antenna as a receiving antenna. For the first configuration of the CIFA, the co-polar component of the radiation pattern, except for one dip, is nearly omni-directional in the xy plane at 2.45 GHz, 3.3 GHz and 5.5 GHz, as observed in Figure 11. The cross-polar component in that plane is quite weak at 2.45 GHz but increases with frequency and is comparable to the cross-polar component at 5.5 GHz. In the remaining xz and yz planes the co- and cross-polar components are comparable in magnitude across the frequencies of 2.45, 3.3 and 5.5 GHz. This is the desired feature for portable wireless devices in mobile applications. For the second configuration of CIFA, the cross-polar component of the merasured radiation patterns at 2.45 GHz and 5.5 GHz show nearly omni-directional properties in the xy-plane. In this plane the cross-polar component is considerably larger than the cross-polar component. For the remaining xz and yz planes, the co- and cross-polar components are of similar strength. The measured gain of the antennas ranges between -0.45 to 3.95dBi.

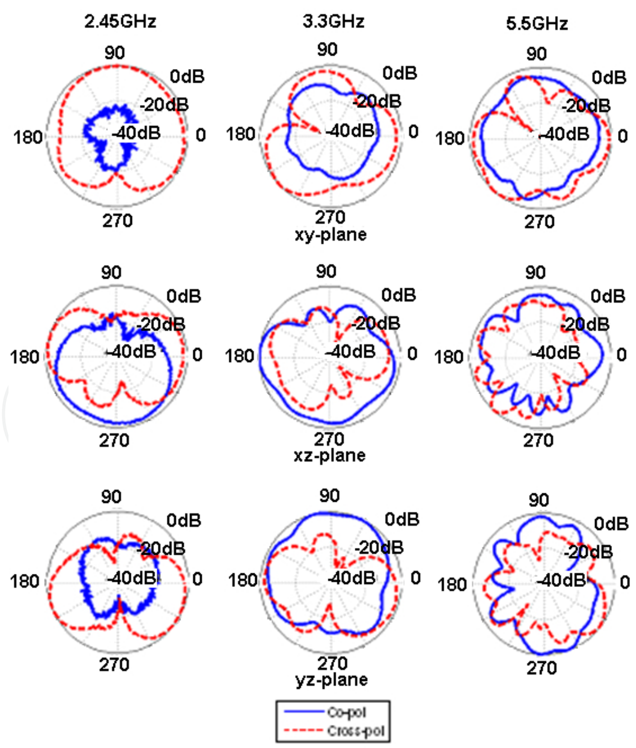

Figure 11. Measured radiation patterns for the first configuration of the CIFA prototype shown in Figures 8 (a) and (b) with a parallel ground slot, at 2.45 GHz, 3.3 GHz and 5.5 GHz.

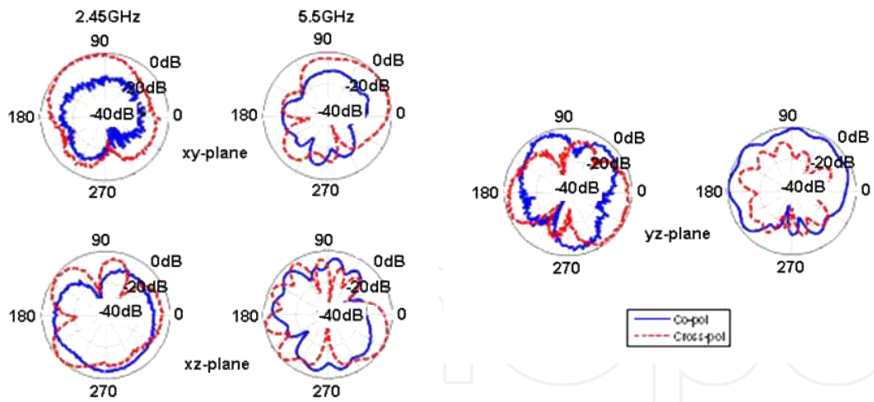

Figure 12. Measured radiation patterns of the second configuration of the CIFA prototype shown in Figures 8 (c) and (d) with a perpendicular ground slot, at 2.45 GHz and 5.5 GHz.

4.2. Coplanar IFA with reconfigurable ground slot

A reconfigurable coplanar inverted-F antenna to operate at the lower bands of wireless services; the GSM, PCS and UMTS service bands is presented. By introducing a dimension-tunable ground slot, the original resonance from the antenna main radiator is not affected. At the same time, frequency reconfigurability is achieved at the ground slot excitations. With multiband capability, reconfigurable antennas can utilize more efficiently radio frequency spectrum, facilitating a better access to wireless services in modern radio transceivers. Several methods have been reported in the literature to achieve reconfigurable antennas. Generally, they are divided into two main categories: frequency tunable and pattern diversity antennas. For frequency tunable antennas, much attention has been given to reconfigurable slot antenna designs [5, 12-14] due to the flexibility of slots in integrating electronic switches. The frequency tuning characteristics of a slot antenna can be achieved by changing the slot effective length [5, 12, 13] or by switching the connection between the feed and the ground [14]. Apart from using ground slots, frequency reconfigurability can also be achieved by changing the induced current distribution [15] or varying the ground plane electrical length [16] supporting a patch antenna. For pattern diversity antennas, reconfigurability can be obtained by adjusting the physical configuration of the antenna radiator to produce tunable radiation patterns [13, 17-22]. Another important element in reconfigurable configuration is the selection of electronic switches. Depending on the type of antennas, the switches such as RF MEMS [23-25], varactors and PIN diodes can be used. The choice is governed by electrical specifications, fabrication complexity, bias requirement, switching time, and price. For instance, RF MEMS switches are very low loss and their other advantages are that they do not require bias lines [23]. However, they are costly. PIN and varactor diodes are low cost and have a simple fabrication process. They require a proper bias network isolating the dc bias current from the RF signal, which usually leads to a complicated biasing network. The complicated dc bias network can sometimes be avoided, and one such solution has been reported in [13]. Furthermore, the limited operating frequency of some commercial low cost PIN diodes can be overcome using solutions proposed in [26]. Most of frequency reconfigurable slot antennas generate only single operating bands at a particular reconfigurable mode. Although many conventional multiband techniques exist such as multi-mode resonator or multi-resonator [27], they are difficult to implement in reconfigurable slot antennas. However, as mentioned in Section 4.1, a coplanar inverted-F antenna (CIFA) with ground slots is capable of generating a new higher-band resonance from a ground slot without affecting the original resonance of the patch radiator. This work on reconfigurable ground slots provides a logical extension to the previous work using a fixed ground slot CIFA, and describes a new solution to achieve a reconfigurable antenna capable of generating multiband operation at each reconfigurable mode. By means of a length-tunable ground slot, a new reconfigurable coplanar inverted-F antenna achieves dual-band operation at four different modes. The generated frequency bands cover several popular wireless services including GSM900, PCS1900 and UMTS2100.

In the antenna configuration, a $\lambda/4$ 900 MHz microstrip radiator of width L_2 = 2 mm is designed in CST Microwave Studio v2010. The radiator is fed by a 50 Ω microstrip feedline of width W_f = 3 mm and placed W_d = 6 mm from the antenna edge. To occupy a small area of L_r = 10 mm × W_g = 40 mm, one end of the radiator is folded twice with L_1 = 3 mm and W_1 = 26 mm to form the configuration shown in Figure 13. To realize an inverted-F antenna, the other end of the radiator is grounded through a via. This is to compensate the large capacitance introduced from the coupling of the folded arm to the ground. The other parameters are the gap between the feedline to the shorting strip G = 4 mm and the L_g = 90 mm × W_g = 40 mm ground plane supporting the antenna. The chosen ground plane size is typical for many wireless transceivers such as a mobile phone.

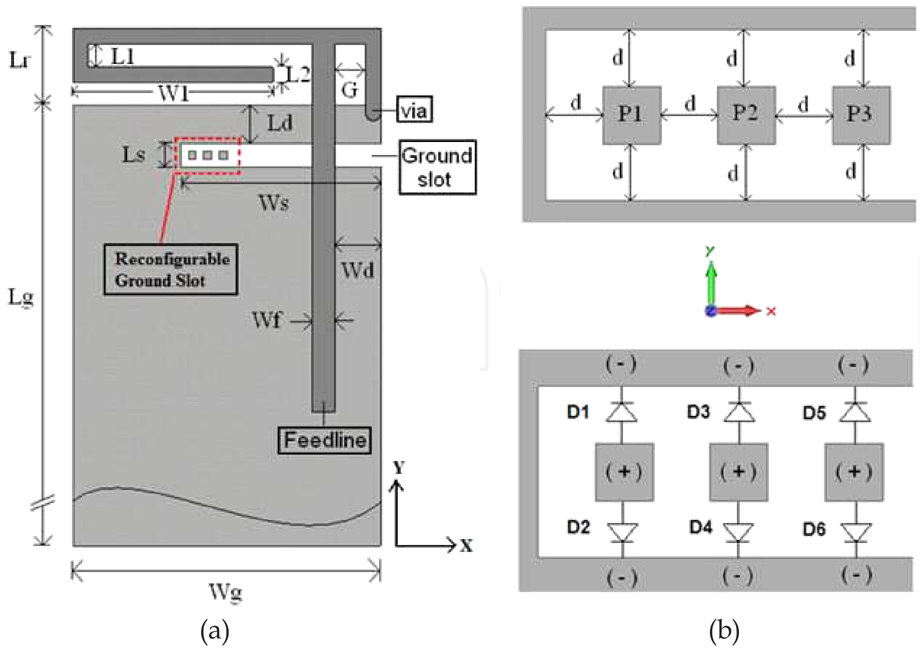

Figure 13. Proposed reconfigurable antenna. (a) Passive antenna configuration. (b) Close-up view of the short-end section of the ground slot and the configuration of the PIN diode switch bias network (marked by the red box in (a)).

Following the technique in [28], a slot is introduced in the ground plane to excite the higher frequency band centred about 1850 MHz. The ground slot is placed L_d = 5 mm from the ground top edge and has a dimension of L_s = 3 mm × W_s = 26 mm as shown in Figure 13(a). In order to achieve an electronically variable (reconfigurable) slot length, three identical 1 mm × 1 mm conducting pads (P1, P2 and P3) and three pairs of PIN diode switches are introduced in the ground slot as presented in Figure 13(b). The gap d = 1 mm in Figure 13(b) is chosen to allow uniform decrease of the slot effective length, thus allowing uniform increase in the excited resonant frequency. All final dimensions are achieved through optimization using a parametric study in CST Microwave Studio. The PIN diode used in the antenna is MAP4274-1279T (MACOM). It is a single-diode series with dimension of 1 mm × 0.7 mm and height of 0.6 mm. It is forward biased with a voltage of 0.7 V_{DC} and a current of 10 mA. During forward bias, it exhibits an intrinsic capacitance of 0.1 pF with forward bias resistance of 3 Ω.

Diode Combination	Diode States			
	Mode 1	Mode 2	Mode 3	Mode 4
D1 & D2	OFF	ON	OFF	OFF
D3 & D4	OFF	OFF	ON	OFF
D5 & D6	OFF	OFF	OFF	ON

Table 1. Reconfigurable Antenna Modes of Operation

The switches are designed to operate in three diode pairs. The switch states at each mode are given in Table 1. From the table, the ON-state indicates the diode is forward biased while the OFF-state indicates it is reverse biased. For simplicity in the simulation model, the ON-state diode is represented by a 1 mm × 1 mm PEC. In this case, the effect of the PIN diode forward biased resistance is neglected. The PEC is removed to represent the OFF-state diode. The photograph of the manufactured reconfigurable antenna is shown in Figure 14. The antenna is fabricated on a 1.6 mm FR4 substrate with relative permittivity of ε_r = 4.4. During measurements, the PIN diode switches are biased with a simple DC bias network as proposed in [13]. Each conducting pad (P1, P2 and P3) is initially soldered to a 1.2 kΩ resistor to protect the diodes and the VNA, as shown in Figure 14(d). A GW GPC-3030D dc power supply unit is used to bias the diodes. The S-parameter measurements are carried out using a R&S ZVA24 VNA.

Figure 15 shows both the simulated and measured S11 of the proposed antenna. A close agreement between the measured and simulated results is observed in each mode. The discrepancies are due to the idealized switches used in CST simulations. The measured results show that the proposed reconfigurable antenna covers two frequency bands: between 850 MHz to 960 MHz at the lower band and between 1800 MHz to 2140 MHz at the upper band (at 6 dB reflection coefficient or VSWR 3:1). As a result, the proposed antenna can be considered as a good candidate for wireless services application such as GSM900, PCS1900 and UMTS2100. In fact, the proposed antenna can cover additional bands surpassing mode 4, with extra pairs of switches in the tunable ground slot. In addition, the parameter d can be easily adjusted to obtain the desired band separation between adjacent modes. The measured radiation patterns at the desired frequencies are close to omni-directional. The antenna gain ranges from 1.4 dBi to 3.45 dBi, while the efficiency is between 63% and 80%. The gains are expectedly low due to the small electrical size of the antenna. The obtained efficiencies are due to conduction losses partially incurred in the PIN diodes switches, and are acceptable for portable wireless applications [27].

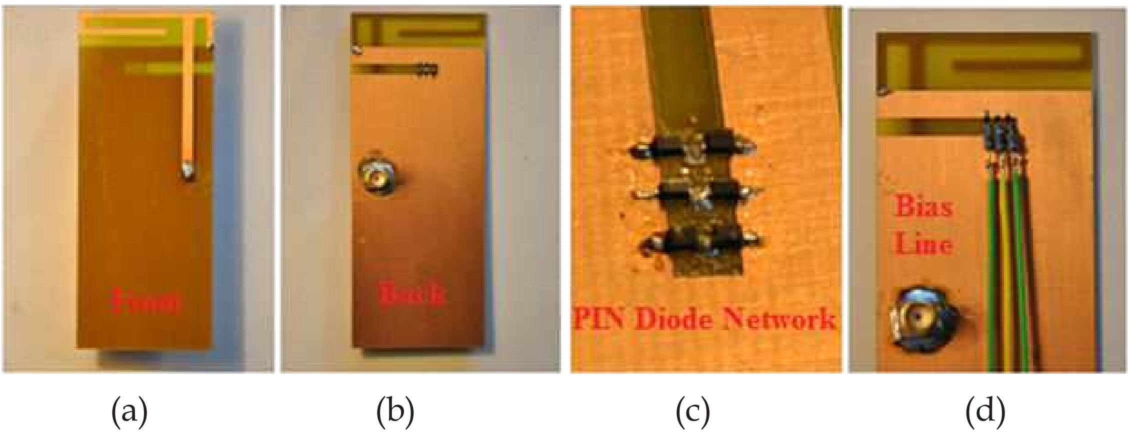

Figure 14. Fabricated prototype of the reconfigurable antenna. (a) Front view. (b) Back view. (c) Integrated PIN diode configuration. (d) Bias line connection to PIN diode switches.

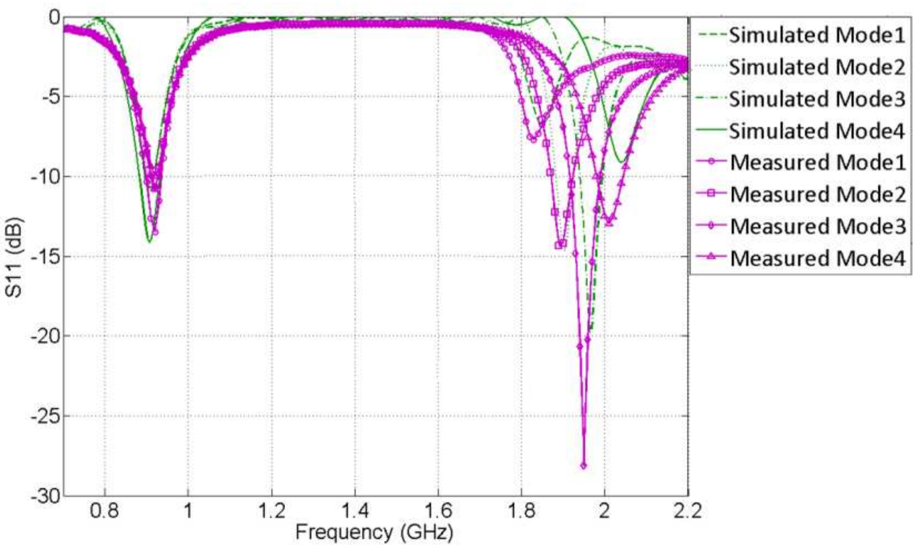

Figure 15. Measured and simulated results for the antenna input refection coefficient, $|S_{11}|$, for the four modes when the individual diodes are turned on or off.

4.3. Slim IFA with a modified ground plane

Apart from the coplanar configurations, inverted-F antennas can also be designed without a dielectric substrate for different transceiver applications. However, without the size-reduction factor by the substrate, the main problem with this antenna configuration is the large size of the main radiator and the ground. In the following work, a novel configuration of an antenna that combines wrapping, folding, ground slots/strips to achieve a super-slim (IFA) with enhanced operational bandwidth is proposed. To fulfill this challenging configuration, multiband radiators have to be miniaturized to fit into the small volume available for modern tranceiver modules. At present, there are many approaches used by antenna designers to reduce the overall projection area of a typical antenna to fit a portable wireless transceiver. Most of them require the use of a single feed structure, as preferred by the majority of wireless device manufacturers. The commonly used antenna for these purposes is a planar inverted-F antenna (PIFA). To meet the multiband operation requirement, its main radiator consists of either an increased single arm/branch or multiple arms/branches to excite multiple resonant modes [7]. The length of each radiating arm has to be at least one quarter wavelength ($\lambda/4$) at the lowest resonance frequency to meet the operation requirements in the lowest frequency band [7]. As a result, this is the longest part of the PIFA which requires miniaturization to fit the available space in a compact transceiver. Nevertheless, folding, meandering and wrapping of the arm and the remaining parts of the PIFA can drastically reduce its projection area. However, these miniaturization techniques have to be carefully applied as they shift resonant frequencies and adversely affect the radiation efficiency [29]. The shift in resonant frequencies is due to the constructive/destructive effects of parasitic reactances which are created during the PIFA structure modification. Usually the length of the electric current path becomes reduced when a thick radiating arm is bent or folded. In turn, a reduction in radiation efficiency is due to the coupling between adjacent parts of radiating arms introduced by folding, meandering or wrapping [29]. The opposite directions of current paths created in this process are responsible for a gradual cancellation of the radiated electromagnetic fields. As a result, the above mentioned miniaturization techniques include a tradeoff between the antenna size and its efficiency. To ease the design challenge, tuning and optimization is usually accomplished with the use of commercial full EM wave simulators such as CST Microwave Studio or Ansoft HFSS. For a typical portable device, such as a cellular phone, the height (thickness) of the primary radiator from 11 mm is reduced down to 7 mm [30]. However with the recent demand for slimmer transceivers, an even smaller height is required and can be as little as just 3 mm. One of the most attractive approaches to meet this miniaturization challenge is to wrap the main radiator in three dimensions. The main advantage of this technique is that it provides extra size reduction on top of folding and meandering of the radiating element. The benefits of this technique in relation to achieving compact antenna designs have been demonstrated in many recent works. For example, the wrapped monopole antenna proposed in [31] features a small volume of 12 x 15 x 7 mm while providing GSM/DCS operation. A similar slim design of a monopole antenna, which is based on wrapping, has been described in [32]. The presented antenna has a height of only 5 mm and delivers GSM, DCS and PCS

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operation. Another example of a wrapped monopole antenna has been shown in [33] and covers almost all popular the frequency bands between 850 MHz to 6 GHz at 6 dB reflection coefficient (VSWR 3:1). This antenna only occupies a volume of 60 x 13 x 5.6 mm. In [34], a wrapped PIFA capable of operating in frequency bands between 850 MHz and 3 GHz features a volume of 44 x 15 x 8 mm. A further example presented in [35] has shown that the height of the wrapped PIFA can be further reduced to only 4.8 mm while the coverage of GSM/PCS/DCS/UMTS/WLAN bands can still be well maintained. However all these designs do not met the super-slim height of 3 mm. In the following proposed solution, a super slim wrapped inverted-F antenna for GSM/DCS/PCS operation is initially designed by miniaturizing the main radiator. To achieve a reduced-size ground plane, the proposed solution includes the use of a narrow side strip and a small size ground slot. The proposed antenna occupies a low profile volume of just 40 x 10 x 3 mm^3 with a ground plane of 40 x 90 mm^2. The proposed antenna covers several LTE Bands, GSM850 (824-894 MHz) and PCS1900 (1850-1990 MHz) at 6 dB reflection coefficient or 3:1 VSWR.

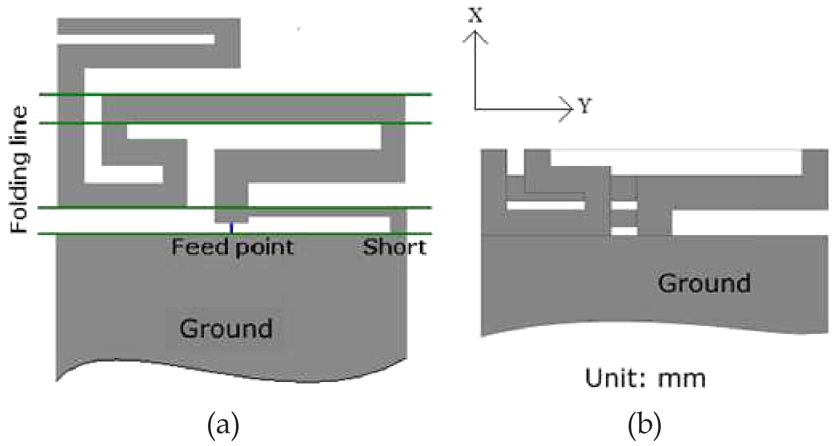

Figure 16. (a) Unwrapped, and (b) wrapped antenna configuration.

Initially, the main radiator configuration of the proposed antenna is shown in Figure 16. The antenna is 40 x 10 mm in area (in the xy-plane) and its height is 3 mm (along the z-axis). The supporting ground plane is 40 x 120 mm. The antenna uses no plastic substrate and is formed by a copper foil. Its very low profile is obtained using a fourth order folding/wrapping technique. As shown in Figure 16(a), it is fed at the middle part of the lowest folded arm with a 50 Ω U.FL mini coaxial cable that is commonly used in many portable devices such as computer notebooks. The lower end of the antenna main radiator arm is shorted to the ground as shown in the figure. The figure also shows the folding transition of the proposed antenna to transform its main radiator into a smaller wrapped dimension. It starts with an inverted-F radiator that has a $\lambda/4$ projection length between its open and short ends at 850 MHz. The arm is folded and meandered as shown in Figure 16(a). Finally the antenna is wrapped using the fourth order folding technique, giving the final height of 3 mm. Figure 17 presents the comparison between the measured and simulated reflection coefficient of the developed antenna. Good agreement between the measured and simulated results is apparent. The measured lower and upper resonant frequency bands of the proposed antenna for the 6-dB reflection coefficient (or VSWR 3:1) reference are 770 MHz to 970 MHz and 1710 MHz to 1990 MHz respectively. They cover the GSM 850/900/1800/1900 MHz, DCS 1800 MHz and PCS 1900 MHz wireless services.

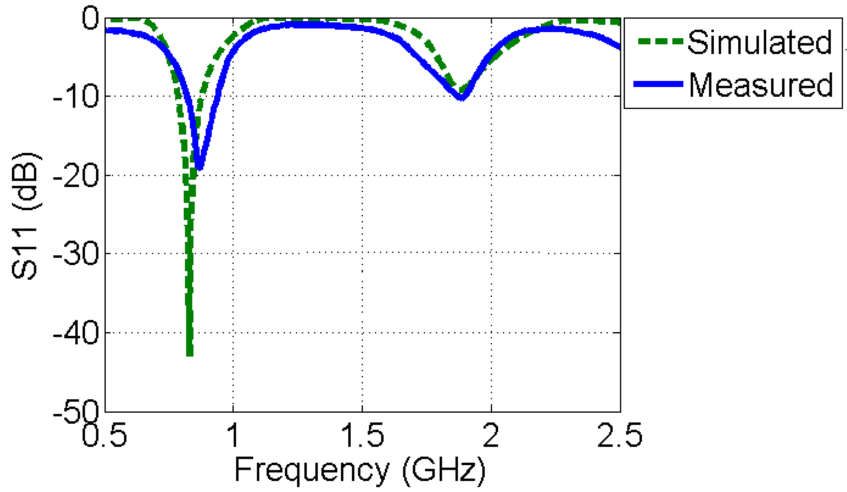

Figure 17. Measured and simulated (CST) reflection coefficient, $|S_{11}|$, for the wrapped antenna of Figure 16 (b).

To achieve a smaller size ground plane, the original 120 mm length is reduced to 90 mm. This reduction is about 25% from the original length. To maintain its original electrical length, the 30 mm long section could be folded. However, this idea does not work because of a large capacitance between the two sections.

A viable alternative is presented in Figure 18 where a 1 x 10 mm^2 slot and 2 x 83 mm^2 strip are introduced in the ground plane following the earlier work presented in [33]. As observed in Figure 18(b), the introduced modifications do not adversely affect any RF or signal processing modules that are usually placed on the ground plane. The small slot is in the close vicinity of the PIFA while the narrow strip is on the side of the ground plane. The two modifications use less than 5% of the reduced size ground plane area. Photographs of the proposed antenna with the ground modifications are shown in Figure 19. From the photographs, it can be seen that in these structures the plastic foam with air-like dielectric constant is used to support the wrapped radiator and the strip.

In the simulation results, the bandwidth of the lower frequency band reduces with the reduction of the ground plane length. However, the quality of the impedance match improves at the upper band. The reduction of the impedance bandwidth in the lower band is due to the analogous reduction of the optimal electrical length of the ground plane [7, 27].

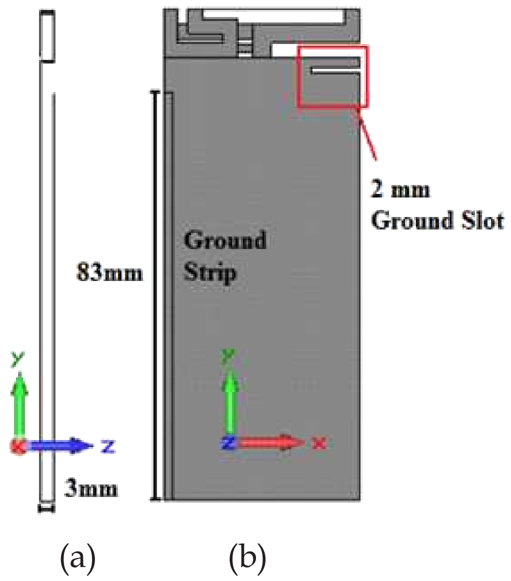

Figure 18. Detailed view of the proposed antenna with a ground plane modification. (a) Side view of the strip configuration. (b) Front view.

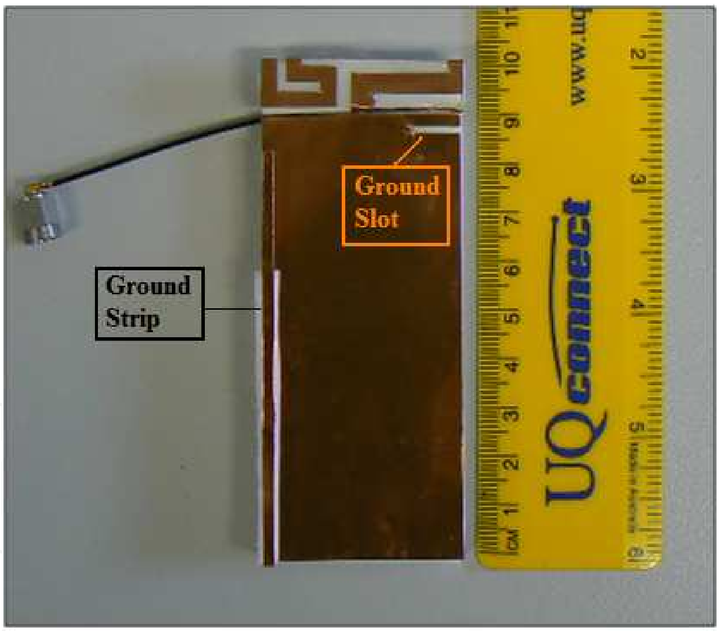

Figure 19. Fabricated prototype of the slim IFA with a modified ground plane.

Figure 20 shows the comparison between the measured and simulated values of the reflection coefficient for the developed antenna that includes the ground plane modifications. It is observed that at 6 dB reflection coefficient (3:1 VSWR), the measured bandwidths cover two bands; from 775 to 925 MHz and from 1800 to 2080 MHz. These bands include several LTE Bands, GSM850 and PCS1900 services.

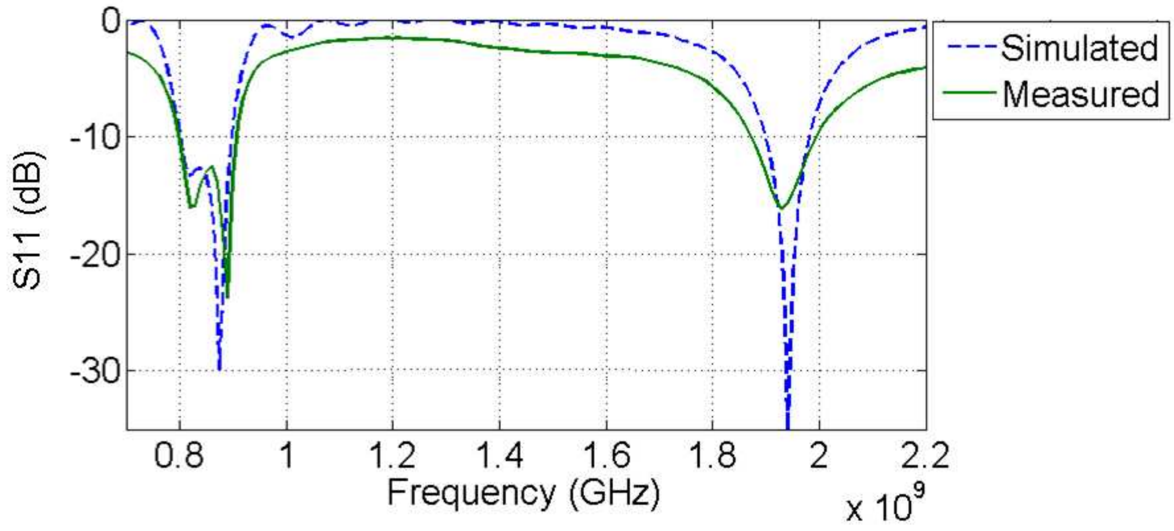

Figure 20. Measured and simulated reflection coefficient, $|S_{11}|$, for the slim IFA with a modified ground plane shown in Figure 19.

The measured radiation patterns in the lower band reveal that the developed antenna features high levels of cross-polarization which are welcome in mobile applications. In this case, the signal reception is unaffected by the orientation of the transceiver. Similar properties of the radiation pattern of the developed antenna are observed in the results for the upper band. The E-theta component dominates in the x-z plane while the E-phi component is predominant in the y-z plane. The cross-polarization is smaller than observed in the lower band. The measured peak gain of the antenna at both bands ranges between -1 to 2.5 dBi in the GSM bands and about 3 dBi in the PCS bands. These obtained gains are adequate for modern portable transceivers [27].

5. Conclusions

This chapter has presented the designs of compact planar multiband antennas for mobile and portable wireless devices. The antennas presented use miniaturization techniques of the main radiator, including meandering, bending, folding and wrapping to achieve compact size features, while the multiband operation of the antennas is generated from ground plane modifications using fixed slots, reconfigurable slots, and a ground strip. All the designs have utilized their ground planes to achieve multiband operation. Following the design guidelines, several novel solutions have been presented. All the presented design models have led to promising configurations for applications in wireless and mobile services.

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