Wideband Tunable PIFA Antenna with Loaded Slot Structure for Mobile Handset and LTE Applications

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Abstract. *A compact planar inverted F antenna (PIFA) with a tunable frequency response is presented. Tuning of the resonant frequency is realized by loading a varactor on an embedded slot of the proposed antenna structure without further optimizing other antenna geometry parameters. The antenna exhibits a wide frequency range from 1570 to 2600 MHz with a good impedance matching ($S11 \leq -10dB$) covering the GPS, PCS, DCS, UMTS, WLAN and LTE systems. To validate the theoretical model and design concept, the antenna prototype was fabricated and measured. The compact size of the antenna is 15 mm × 8 mm × 3 mm, which makes this antenna a good candidate for mobile handset and wireless communication applications.*

Keywords

Tunable antenna, varactor diode, PIFA antenna.

1. Introduction

In the past decades there has been an ever increasing growth in wireless technologies and communication systems. Wireless communications have not only expanded simply as a technology, but also in an economically and socially ubiquitous fashion. The increasing demand for cell phone services, wireless internet access, and related enabling technologies e.g. video streaming and location based service delivery, etc, has forced the operators to seek additional bandwidth, and vendors to design multi-access user terminals. This has led to new design challenges for the antenna engineer to meet these operational requirements with antennas, and integrated antenna modules, which can deliver the desired multi-standard performance, in terms of the key antenna performance criteria and frequency agility. The move towards a greater broadband delivery has seen a steady migration to higher radio frequency bands, as well as continued development of higher microwave frequencies for backhaul and specialist services. In the moderately higher RF bands, slot antennas have been often seen as a standard design option. However, the basic slot designs are bandwidth limited, and how to overcome this has been the subject of much well documented research, e.g. [1] where the antenna response is tuned by altering the antenna dimensions. However, this is not convenient in practice for most antenna types, as these results in design families which may require non-trivial differences as operational requirements are modified or added. It is therefore desirable to achieve the same response through electrical tuning.

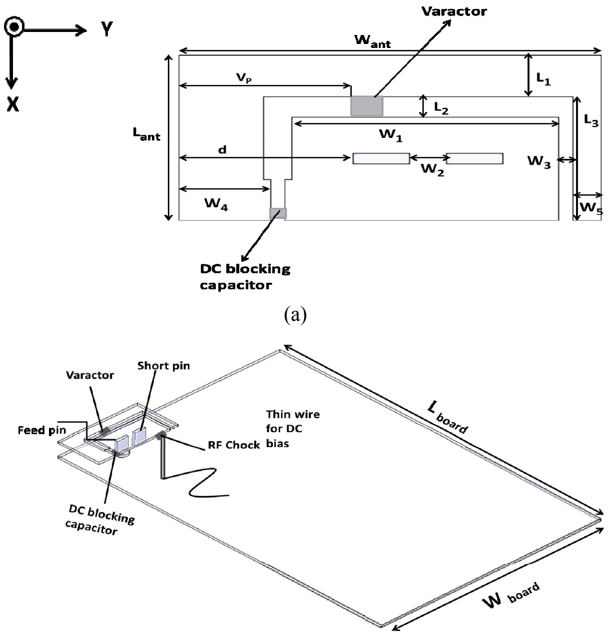
Additionally, PIFAs can be easily modified for multiband operation and hidden in mobile phone housings [2]. The PIFA concept has been researched over decades [3-8]. Recently, PIFA structures covering the frequency range of five and six telecommunication standards have been reported for applications in mobile terminals and base stations [9], [10]. However, these antennas have fixed frequency bands and cannot be changed once fabricated.

A persistent theme in this work is the need for tuned or reconfigurable antenna designs [11], [12]. This is driven by the large variety of distinct and over-lapping frequency bands required by mobile operators and the increased use in location aware services. This is coupled with the trend for slimmer highly integrated handsets and terminals, e.g. smart phones and tablet PCs. However, this migration towards slimmer, more space efficient integrated designs, poses a significant problem for the antenna designer. The trade-off between small antenna size, adequate bandwidth, and high efficiency, creates a difficult competing multi-objective optimization, which is also subject to fundamental physical constraints. To some extent this coverage problem can be solved by using multiple antennas, but the design of such an antenna module would add mutual coupling effects to an already substantial list of physical constraints.

Varactor diodes are promising solutions here, as they combine the advantages of a large capacitance ratio, a suitable small size, and DC voltage control over the tuning of the resonant frequency. PIFA structures are eminently suited to this approach, in spite of the relatively narrow operating bandwidth [13]. Since a varactor tuned AUT uses a DC bias, two DC blocking capacitors are typically required. In the PIFA case, the antenna shorting pin is already connected to ground, and one of the DC capacitors can be removed. Many efforts have been made on PIFA antenna using the varactor diode as tuning techniques [14-19]. However, the proposed work provides a size reduction compared to work in [14-19], improved power gain in contrast to [14], [18] and a wider continuous tuning compared to antenna designs in [18], [19].

2. Antenna Design Concept

Fig. 1 shows the geometry of the proposed antenna suspended over a 42 mm × 80 mm (W_{board}, L_{board}) ground plane with a 2 mm × 3 mm shorting pin .The antenna is fed by a vertical plate with a maximum height of 2.5 mm and width of 2 mm, in which it is connected to the feeding probe through the slot in the ground plane which is very similar to our previous work [14], [15]. By further optimizing the proposed antenna geometry parameters, the size of this antenna has been further minimized and the impedance bandwidth has been widened in comparison with earlier work [14], [15].The substrate is air .The patch is suspended on one corner of the PCB (shown on the top portion of Fig. 1(a)). These are only few areas where the antennas can be positioned regarding the restrictions imposed from mobile phone manufacturers and this is usually on the top edge of the PCB. The rectangular patch dimensions are listed in Tab. 1.



(a)

(b)

Fig. 1. Basic antenna structure: (a) Top view. (b) 3D.

Parameter	Value mm	Parameter	Value mm
L1	2	W4	3.125
L2	1	W5	1
L3	6	d	7.2
W1	9.5	Vp	7.5
W2	1.8	Want	15
W3	0.5	Lant	8

Tab. 1. Detailed dimensions of radiator patch.

To evaluate the effectiveness of the embedded slot, the simulated reflection coefficient (S_{11}) with and without slot of the proposed unloaded antenna are shown in Fig. 2. The slot forces the antenna to operate at lower frequency and this is due to the fact that there are currents flowing at the edge of the shaped slot, and therefore the resulted capacitive loaded slot reduces the resonance frequency and thus the electrical antenna dimensions drastically. The slot has two objectives: firstly, to tune the radiator structure to resonate at lower bands which is closer to our target band of LTE (2.6 GHz) as shown in Fig. 2; secondly, the slot is designed in such a way that could accommodate the varactor for tuning purposes. As can be seen, the proposed antenna without slot only operates at 5.2 GHz. However, by introducing the slot onto the patch surface; the resonant frequency has been shifted downwards from 5.2 GHz to 3.5 GHz which hugely reduces the electrical antenna size. It should also be noted that another resonant frequency was developed at 6.6 GHz from the inclusion of the slot structure that is considered far away frequency band from the present target application and thus was neglected in this study. The tuning range was investigated by accommodating the varactor over the embedded slot with one DC blocking capacitor value of 100 pF to connect the additional patch element with the main PIFA radiating element to avoid the DC shorting. A 100 nH RF choke was attached at the top corner of the radiator to isolate the DC voltage from the RF signal. The locations of the varactor diode, DC blocking capacitor and 100 nH RF choke are optimized in HFSS program [20]. By changing the capacitance of varactor from 0.1 pF to 3 pF, it will basically affect to change the electrical length of current path flow as well as to shift the resonant frequency from 2600 MHz to 1575 MHz accordingly.

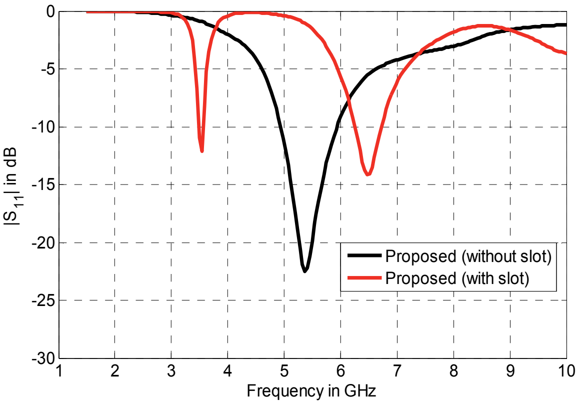
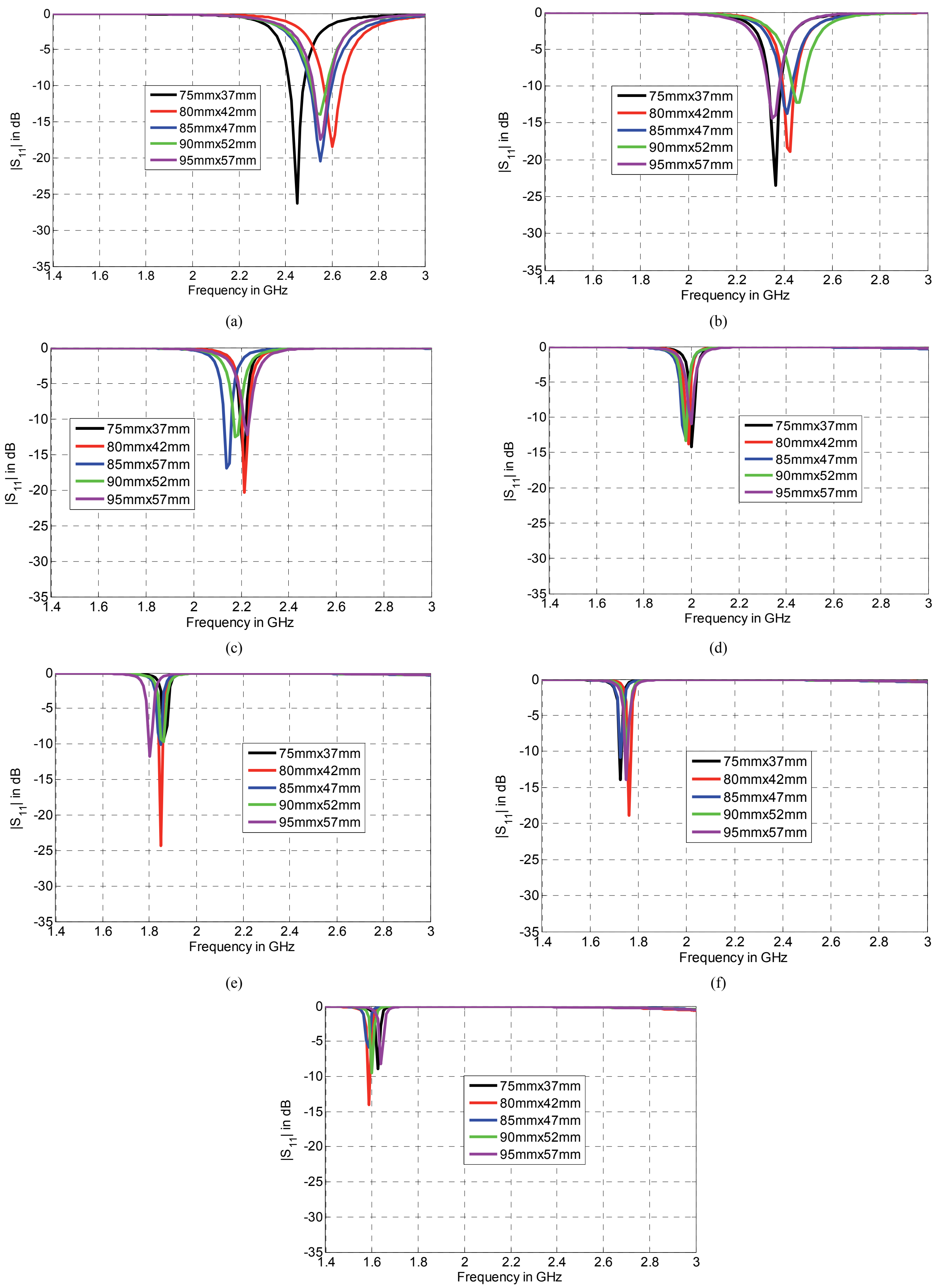
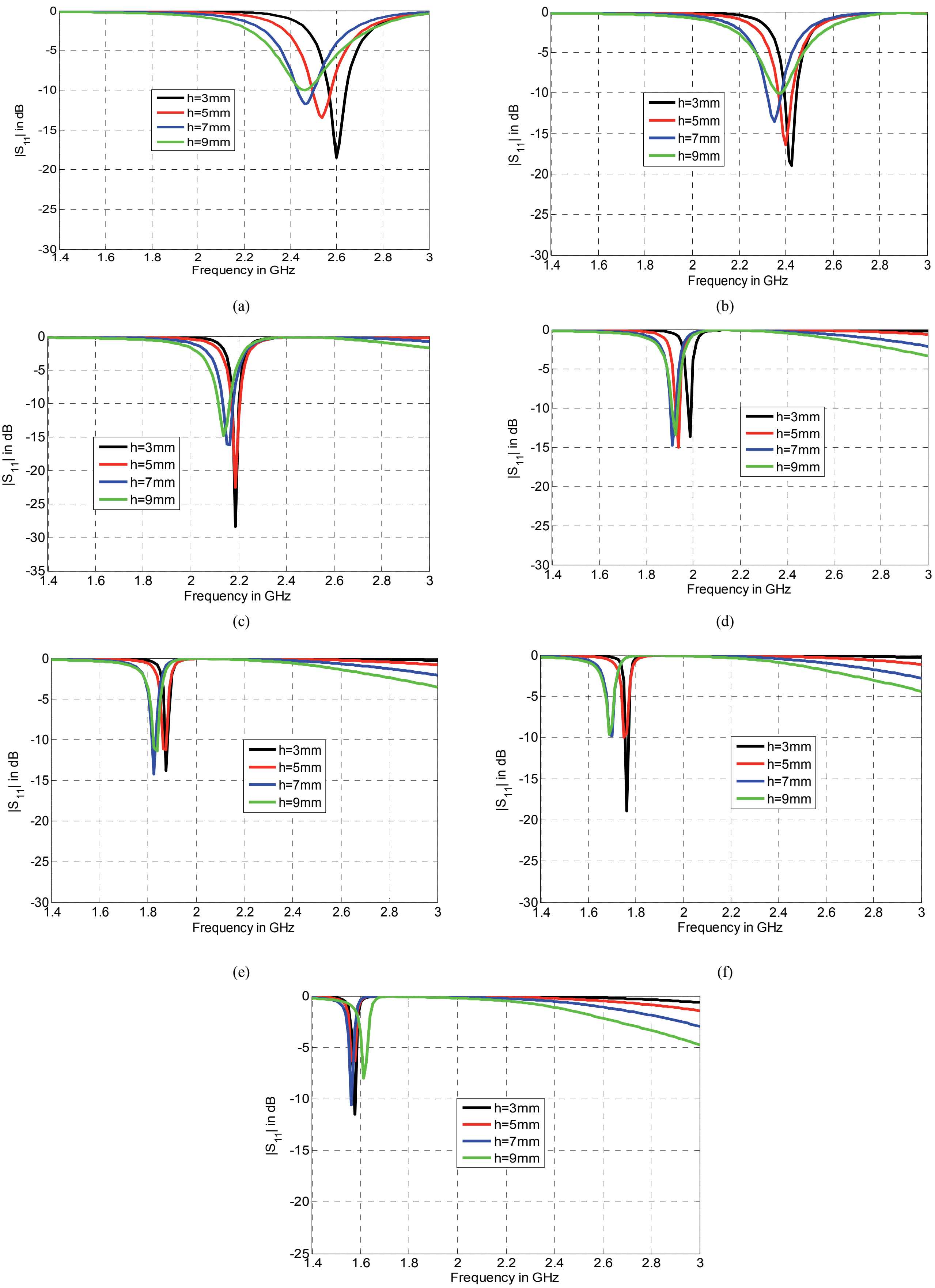


Fig. 2. Refection coefficient of proposed unloaded antenna.



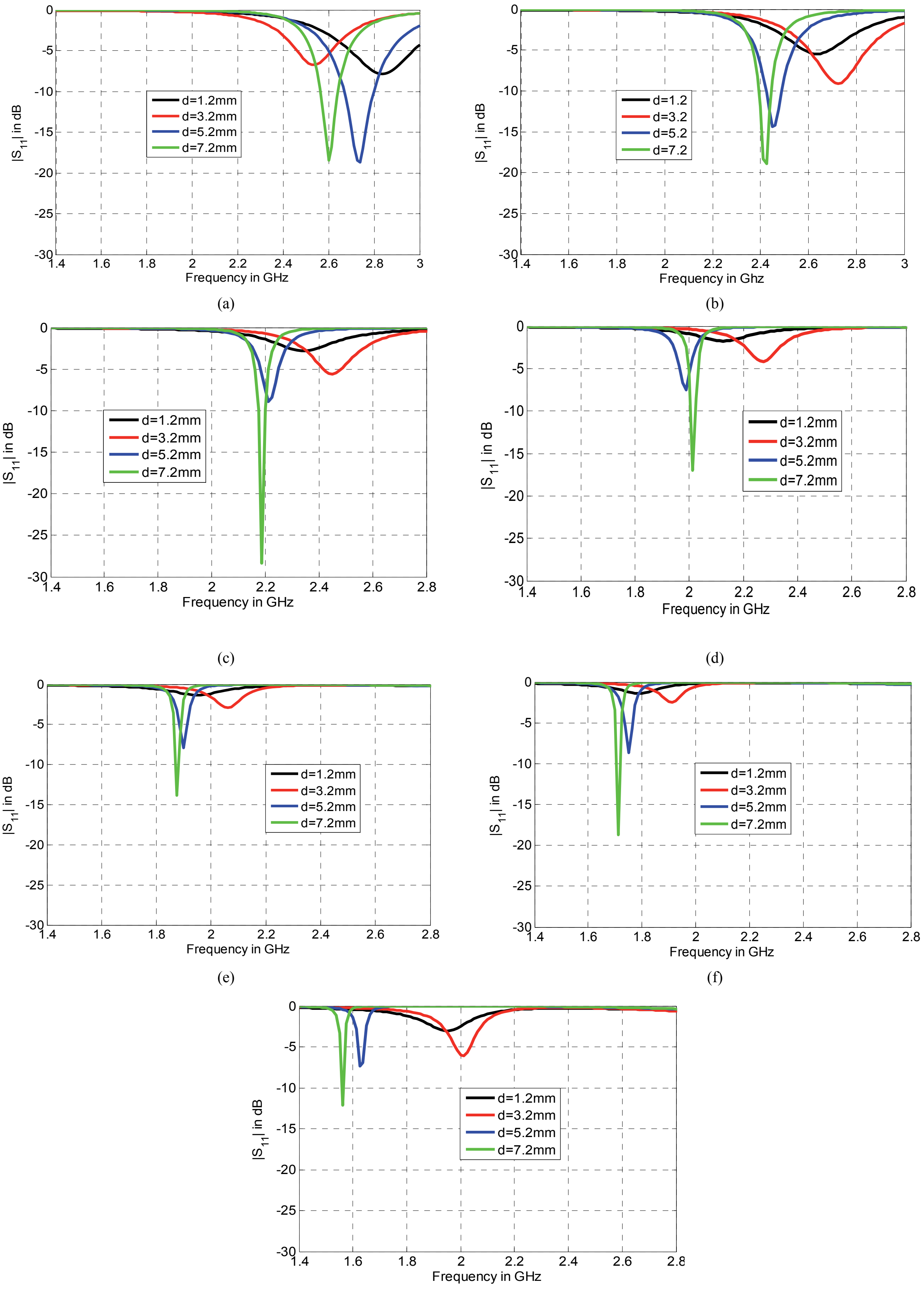
(a) (b) (c) (d) (e) (f) (g)

Fig. 3. Parametric study of ground plane size of the PIFA antenna with loaded C:(a) 0.1 pF, (b) 0.5 pF, (c) 1 pF, (d) 1.5 pF, (e) 2 pF, (f) 2.5 pF, (g) 3 pF



(a) (b) (c) (d) (e) (f) (g)

Fig. 4. Parametric study of radiator height of the PIFA antenna with loaded C:(a) 0.1 pF, (b) 0.5 pF, (c) 1 pF, (d) 1.5 pF, (e) 2 pF, (f) 2.5 pF, (g) 3 pF.



(a)

(b)

(c)

(d)

(e)

(f)

(g)

Fig. 5. Parametric study of feed pin position of the PIFA antenna with loaded C:(a) 0.1 pF, (b) 0.5 pF, (c) 1 pF, (d) 1.5 pF, (e) 2 pF, (f) 2.5 pF, (g) 3 pF.

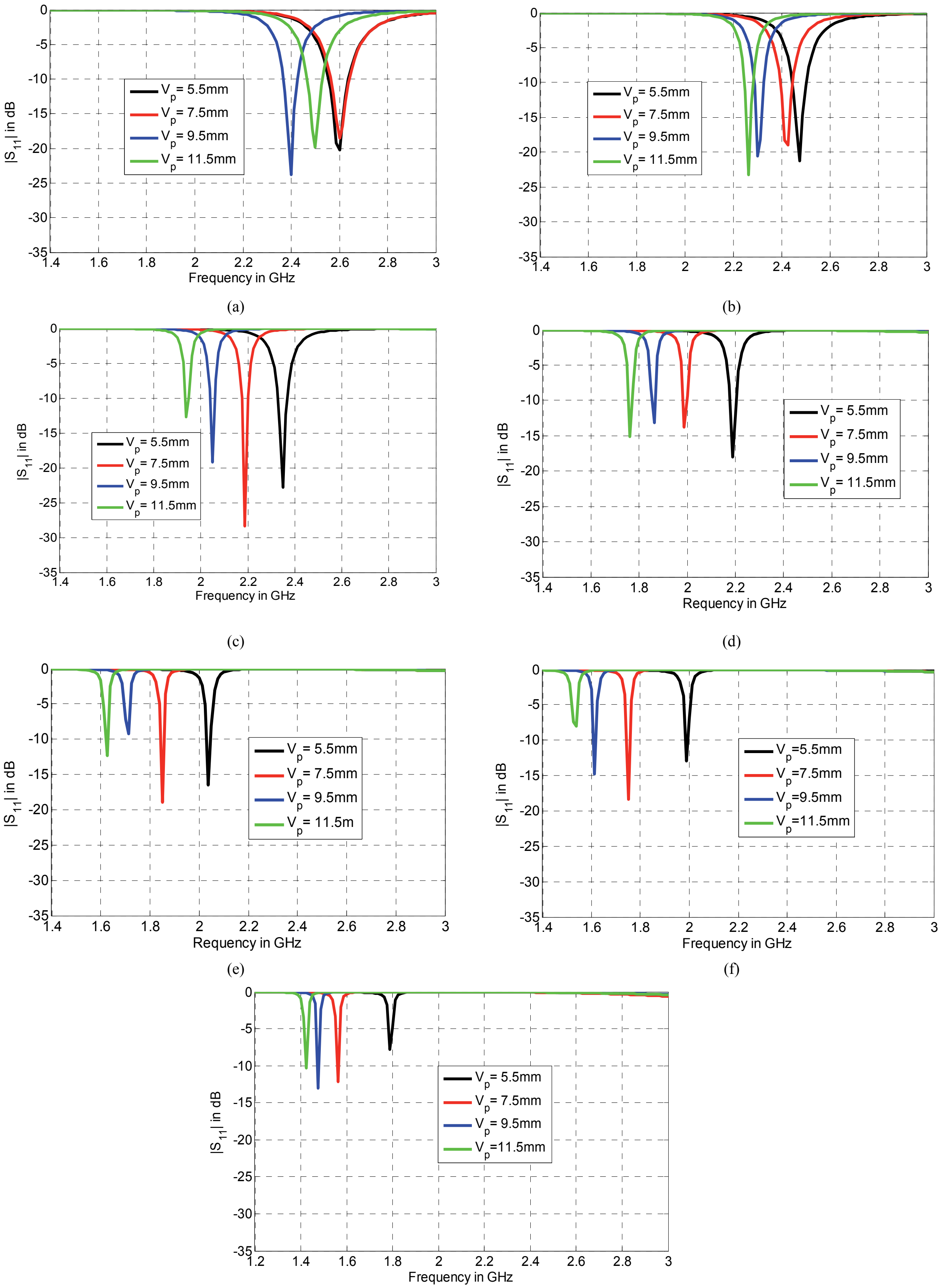


Fig. 6. Parametric study of varactor position of the PIFA antenna with loaded C:(a) 0.1 pF, (b) 0.5 pF, (c) 1 pF, (d) 1.5 pF, (e) 2 pF, (f) 2.5 pF, (g) 3 pF.

To achieve sufficient optimal size and maintain a good impedance matching over the desired frequency band, a parametric study was carried out in this study. Four parameters were selected for this study; these are the ground plane size, antenna height, feed pin position and varactor position. These parameters are considered as critical parameters in determining the frequency of the operating bandwidth. Each simulation was run with only one parameter varied, while other parameters stayed unchanged.

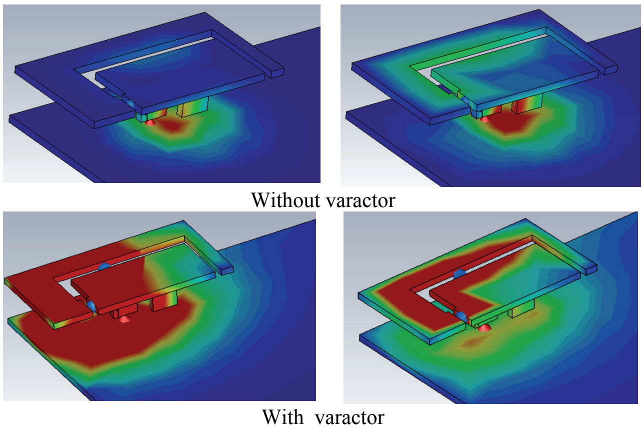
The effect of the ground plane was examined by considering the variations in the S_{11} against the size of the ground plane for the following selected capacitance values (0.1, 0.5, 1, 1.5, 2, 2.5 and 3 pF). Fig. 3 shows the effect of ground plane with five selected sizes over the mentioned capacitance values: 75 × 37 mm^2, 80 × 42 mm^2, 85 × 47 mm^2, 90 × 52 mm^2 and 95 × 57 mm^2. As can been noted that there is no obvious variation in reflection coefficient $|S_{11}|$ for the cases where the ground plane sizes were 85 × 47 mm^2, 90 × 52 mm^2 and 95 × 57 mm^2 with the capacitance values of 0.1, 1.5, and 2.5 pF. Also, the resonant frequency was not clearly shifted when the ground plane size set at 75 × 37 mm^2 for the capacitance values of 0.1 and 0.5 pF. It is apparently that, an impedance mismatch was occurred over all the ground plane size when applying the capacitor values of 2.5 pF, except when the size set at 80 × 42 mm^2. Therefore, the optimal ground plane size is selected to satisfy the entire tuned frequency range for all capacitance values when it is set to 80 × 42mm^2. Surprisingly, the impedance matching for the entire frequency range of the antenna improved as the ground plane size decreased. This indicates that the proposed antenna has a high degree of sensitivity to ground plane size, implying that the same antenna design could potentially be adopted for many different mobile devices provided other geometry parameters were optimized to mitigate the ground dependency effect.

The height of the radiator over the PCB was as shown in Fig. 4. The antenna height h was varied from 3 mm to 9 mm, with a 2 mm step. As can been seen obviously when h is set at 7 and 9 mm the antenna performance would not satisfy the desirable target bandwidth aim over the 0.1, 0.5, 2.5 and 3 pF. When the height of the proposed antenna is set at 5 mm, the impedance matching occurs, however this has not met the frequency target; however when h is set at 3 mm the target bandwidth can be obtained over the desirable bands for all the selected capacitance values (0.1, 0.5, 1, 1.5, 2, 2.5 and 3) pF, as well obtaining smaller size compared to the height of 5 mm as shown in Fig. 4. So, the optimum value of h is chosen to be 3 mm in this study.

The influence of the feeding positions is depicted in Fig. 5. The feed position is one of the most sensitive parameter in this study. This is because its variation can significantly impair the impedance matching over the desired operating frequency bands. In this study, the feeding position is initially set to the edge of the structure which corresponds to 1.2 mm, then, it is gradually moved with increments of 2 mm close to the short pin which is 7.2 mm. As can be seen, when d is 1.2 , 3.2 and 5.2 mm, the antenna more or less exhibits an impedance mismatch for most of the capacitance values. However, when the feed pin is set at 7.2 mm, the antenna exhibits the required frequency band for all the capacitance range as shown in Fig. 5.

The varactor position is investigated by starting from 5.5 mm and increasing to 11.5 mm with increments of 2 mm as shown in Fig. 6. It is clear that when it is 5.5 and 9.5 mm, the targeted frequency bands would not be accomplished as the capacitance varies from 0.1 to 3 pF; also mismatching occurred at 3 pF for 5.5 mm and at 2 pF for 9.5 mm. By further increasing it to 11.5 mm, an impedance mismatch occurs at 2.5 pF as well as not satisfying the desired frequency bands. However, as it is set at 7.5 mm, a good impedance matching can be achieved over the entire bands at $S_{11} < -10$ dB for all capacitance values as depicted in Fig. 6. This leads to the conclusion that for the best impedance match the varactor position should be kept at 7.5 mm.

In order to have more indications on the varactor contribution and its effect in the antenna, the surface currents distributions on the antenna structure were studied. Two resonant frequencies (1750 MHz and 2600 MHz) with and without the varactor were selected to demonstrate the surface current distributions at these resonant frequencies as shown in Fig. 7. It is quite clear that, with the inclusion of capacitors strong resonances were generated in which the surface currents on the antenna surface were dominated the total radiation. It should also be noted that the strong coupling with the ground plane was resulted at lower resonance frequency under consideration.



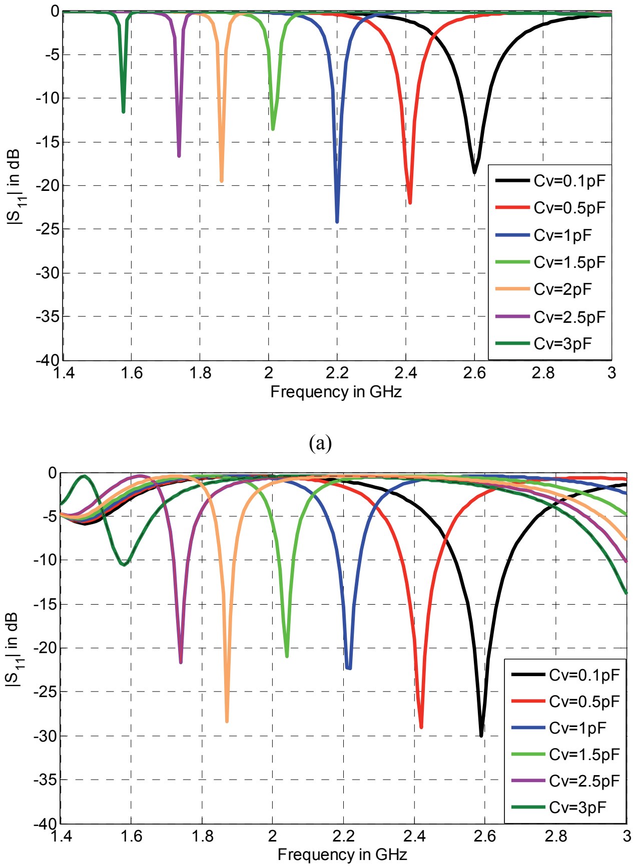
(a) 2.5 pF at 1750 MHz (b) 0.1 pF at 2600 MHz

Fig. 7. The surface current distribution on the antenna structure with and without loading capacitor;
(a) 2.5 pF at 1750 MHz, (b) 0.1 pF at 2600 MHz.

3. Results and Discussion

To validate the simulated reflection coefficient results of the proposed antenna system, a prototype of the proposed loaded antenna as shown in Fig. 8 was first constructed and measured based upon on the design and dimensions as described in Fig. 1. Fig. 9 shows the simulated and measured reflection coefficients of the proposed design. By varying the capacitance value from 0.1 to 3 pF, the resonant frequency can shift downwards from 2600 MHz to 1570 MHz.

Fig. 8. Prototype of fabricated antenna design.



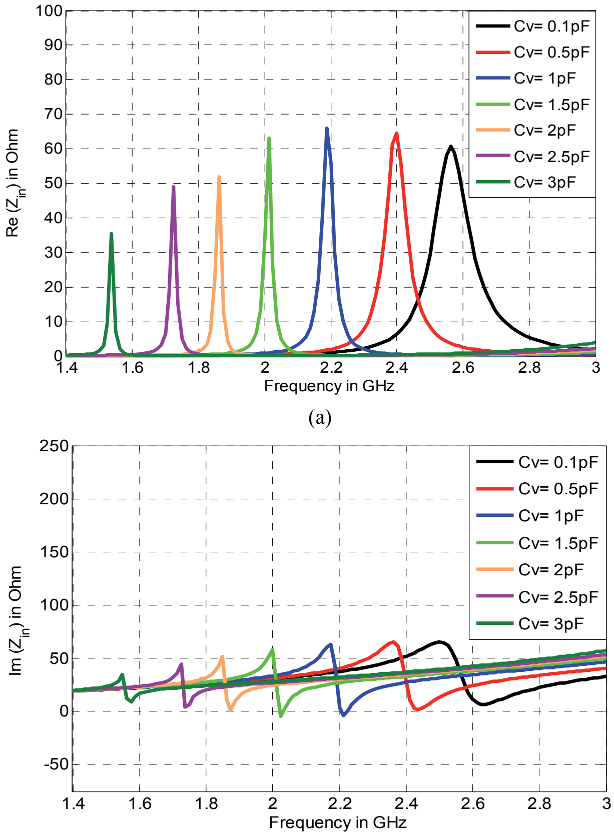
(a)

(b)

Fig. 9. Refection coefficient of loaded proposed antenna. (a) Simulated (b) Measured.

The simulated reflection coefficient was obtained using the HFSS EM software package while the Vector Network Analyzer is used to measure reflection coefficient. Both of them clearly show S_{11} better than -10 dB, which is sufficient to cover the GPS, PCS, DCS, UMTS, WLAN and LTE systems. As can be seen, the experimental data agree with the simulation results. This figure also shows that the simulated S_{11} of the proposed antenna agrees well with the measured one. The small discrepancy can be found between the measured and simulated results and can be attributed to misalignment of the capacitor and manufacturing tolerances in the antenna assembly.

To further investigate the physical behavior of the antenna, the input impedance of the proposed antenna is illustrated in Fig. 10. As can be seen, the proposed antenna exhibits more or less good impedance match over the targeted frequency band where the reactance value is zero and the resistance value is around 50 Ω as shown in Fig. 10.



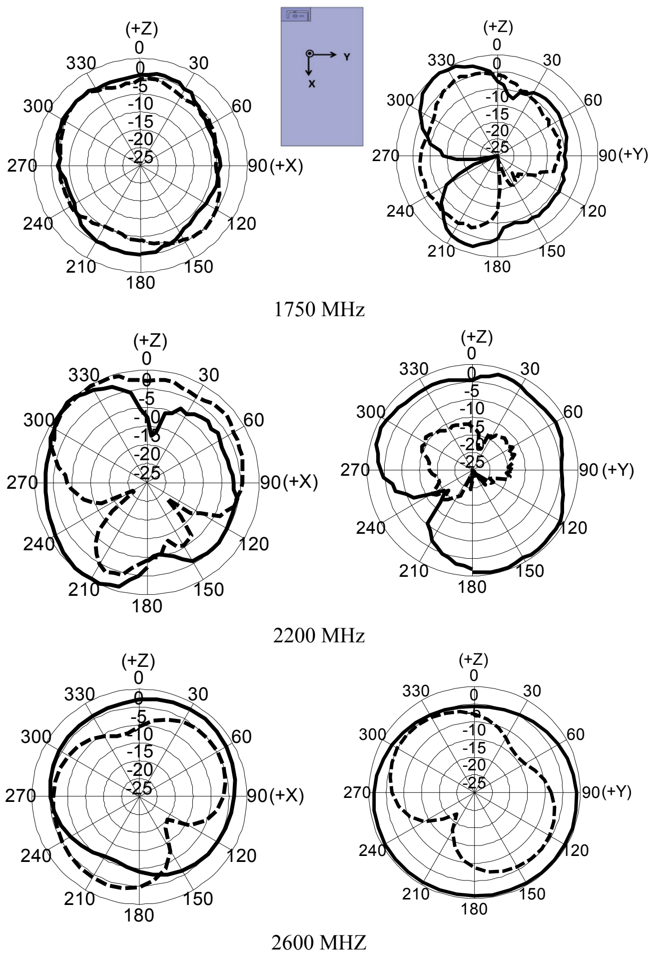
(a)

(b)

Fig. 10. Input impedance of the proposed antennas: (a) Real, (b) Imaginary.

The far-field radiation characteristics of the proposed antenna were also investigated at 1750, 2200, and 2600 MHz covering the whole of the designated bandwidth in this paper. Two cuts of the radiation patterns, i.e., xz-plane and yz-plane are given to describe the far-field performance of the antenna. As observed in Fig. 11, a satisfactory consistent omnidirectional radiation behavior is obtained at all the presented frequencies.

Fig. 12 illustrates the simulated and measured gains of the proposed antenna in xz-plane and yz-plane over frequencies between 2600 to 1575 MHz subject to the capacitance values varied from 0.1 pF to 3 pF accordingly. The simulated and measured gain values are in reasonable



1750 MHz

2200 MHz

2600 MHZ

Fig. 11. Normalized antenna radiation patterns of the proposed loaded antenna for two planes (left: x-z plane, right: y-z plane) at 1.75, 2.2 and 2.6 GHz;
——: co-polar, ------- cross-polar.

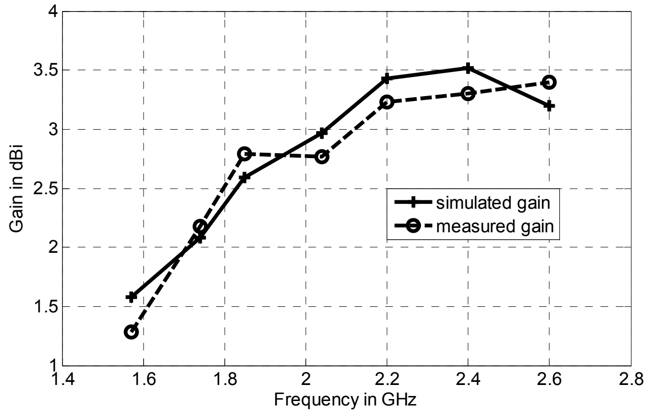


Fig. 12. Power gain of the proposed antenna.

agreement. The range of gain values were found between 1.28 and 3.3 from the measurements and 1.58 and 3.52 from modeling. The slight fluctuation can be attributed to misalignment of the capacitor in the antenna assembly and the presence of SMA connector in the measurement which was not taken into consideration in the simulated modeling processes. Nonetheless, the deviation from the simulated result can be neglected, and can be said to be in reasonable agreement. The gain of the proposed antenna proves the fact that the gain is affected by the capacitance. When the capacitance is larger, a current through the varactor increases so that the loss is increased. The gain is low at large capacitance of the varactor. Also, the compact and small size of the antenna would result in reducing the gain at low frequency.

4. Conclusion

A wideband frequency tunable antenna geometry has been designed and presented. The proposed antenna occupies a compact envelope dimension of $15 \times 8 \times 3$ mm^3 while covering the required wide band with a sufficient impedance matching (S11 $\leq$ -10 dB) covering the GPS, PCS, DCS, UMTS, WLAN and LTE systems .The resonant frequency shift was quite stable and consistent over the selected spectrum without a serious change in bandwidth. The measured and simulated results are in good agreement. The antenna can satisfy typical requirements of multi-band and interference reduction arising from current trends in wireless communications towards reconfigurable, energy compliant, ergonomically thin handsets.

Acknowledgements

This work has been performed in the framework of ARTEMOS project under work programme ENIAC JU 2010 and FCT (Fundação para a Ciência e Tecnologia).

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