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Compact Capacitively Coupled Triple Band Planar Inverted F Antenna

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Abstract—A simple, compact, and capacitively coupled triple band planar inverted F antenna for wireless applications is presented in this paper. By arranging two metal patches in a stacked manner and using capacitively coupled feeding method three resonant modes are generated. The three operating bands 1.8 to 1.9 GHz, 2.5 to 2.6 GHz, and 3.3 to 3.4 GHz for GSM 1800, LTE 2500, and WiMax applications, respectively with -10 dB return loss bandwidths of 5.4%, 3.9%, and 2.98% around the resonances. The antenna occupies a size of $40\,\text{mm} \times 5\,\text{mm} \times 6\,\text{mm}$ and is printed on an FR4 epoxy substrate of dielectric constant 4.3.

1. INTRODUCTION

With the rapid development of modern wireless communications, there has been an increased demand in design and exploration of a variety of compact and multiband antennas. Planar inverted F antenna (PIFA) is an integral part of modern wireless mobile handsets due to their compact size, suitable structure for mobile hand sets, and reduced SAR values. The PIFA radiator is mounted just above the ground layer, and there is a PCB plate between the antenna radiation plate and the human brain when using, thus greatly reducing the impact of radiation on the human brain, i.e., PIFA has less backward radiation towards the user's head and enhanced antenna performance [15, 16].

When an antenna is designed with very compact size it is better to do with an FR4 laminated copper clad sheet because with photo-lithographic method, the size of antennas can be reduced very much. There exist two models for which the antenna can be implemented with FR4 laminated copper clad sheets, Suspended microstrip and Inverted microstrip [1, 2]. They provide less dispersion than conventional microstrip. The principal reason for their utilization is that these configurations offer lower loss than conventional microstrip [3, 4], in which the suspended microstrip model is commonly used for PIFAs. Direct-feed method is normally used for exciting PIFA, and a number of multi-band PIFAs exist now [5–9]. In directly-fed PIFA structures the distance between feed point and shorting strip plays an important role for impedance matching. So short strip should be placed in a particular position to achieve better impedance matching.

Capacitively coupled feeding method provides an additional way in which multi-bands can be implemented in printed PIFAs [10–12], where all the metal patches are placed on the same plane. In the proposed PIFA, stacking of metal patches is utilized, and in this way, multiple bands can be achieved. In this antenna, the position of the short element has no role for impedance matching. Short element provides an additional current path through which resonance can be designed. Another advantage of stacked capacitively-fed method is that multiple radiating patches can be excited together with a single metal strip. Bandwidth can also be enhanced very much by optimizing the dimensions of the feed strip

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and its placement with respect to the radiator patch [13]. Here, a suspended microstrip configuration is utilized, and capacitively fed method is used in the proposed PIFA . By using a double sided laminated copper sheet, two radiating elements can be placed on both sides of FR4 as a stacked plane of two metals. In this study, a compact capacitively fed PIFA proposed to cover GSM 1800 (1.8–1.9 GHz), LTE 2500 (2.5–2.6 GHz) and WiMax (3.3–3.4 GHz) bands is presented.

2. EVOLUTION OF THE ANTENNA

Evolution of the proposed PIFA from fundamental PIFA structure fabricated on an FR4 substrate is shown in Figure 1(a). The initial stage of PIFA comprises a simple metal patch of length L_t and width W_t on the FR4 substrate. It is suspended from the ground plane of antenna and shorted to ground plane using a short metal plane. This PIFA is fed by direct feeding method, and it resonates at 2.3 GHz as shown in Figure 2. The resonance can be calculated from the length L_t and width W_t of the top radiating plane and the width of the short metal element [14]. The impedance matching of this fundamental PIFA is done by varying the distance of this short element from feeding point. Generally, direct feeding method is used in PIFA structures. The surface current distribution of fundamental PIFA

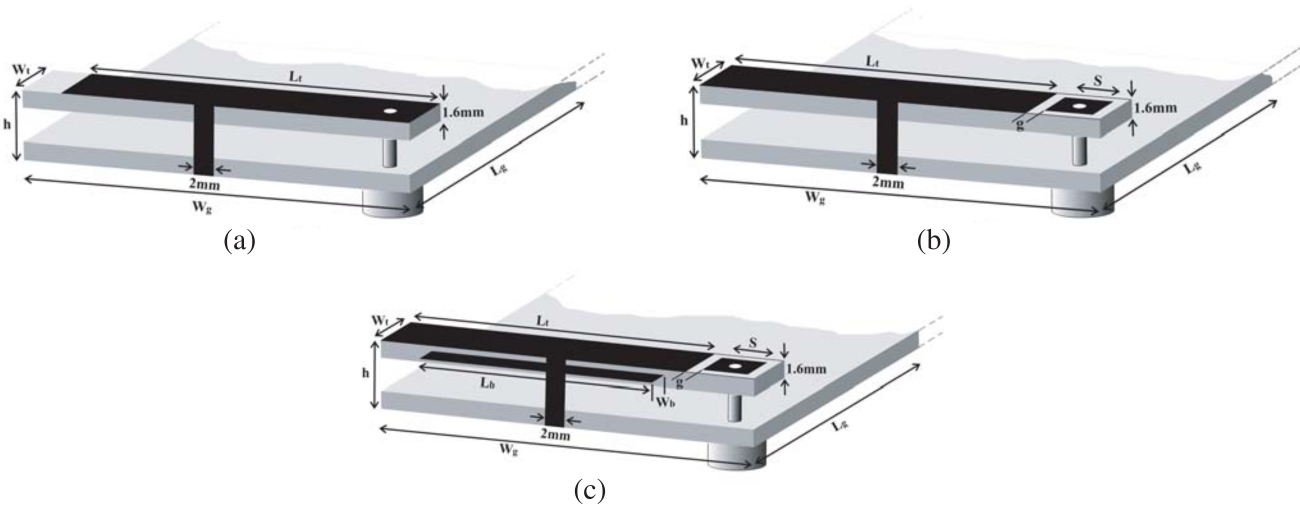


Figure 1. (a) Direct fed fundamental structure of PIFA, (b) capacitive fed PIFA antenna, (c) proposed triple band PIFA.

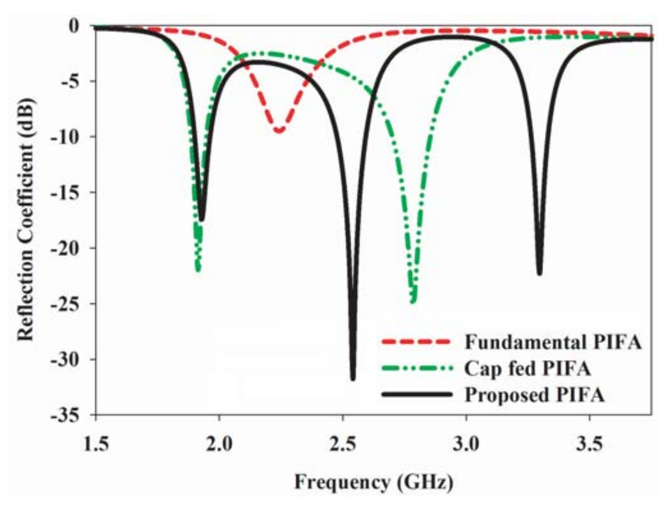


Figure 2. Reflection coefficients in the evolution of proposed antenna.

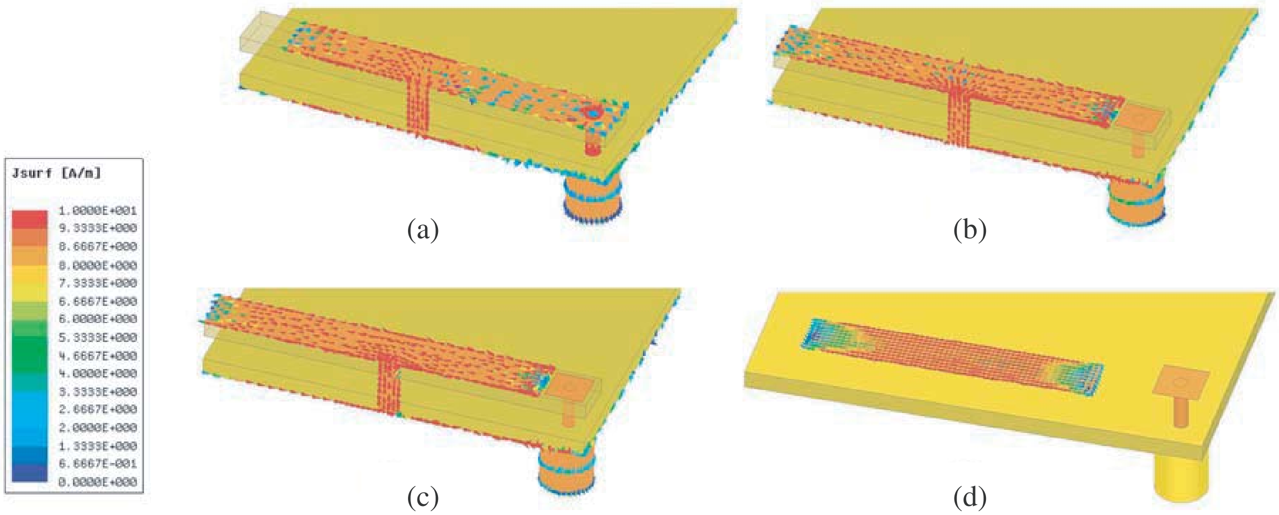


Figure 3. Surface current distribution, (a) fundamental PIFA, (b) first resonance of proposed PIFA, (c) second resonance of the proposed PIFA, (d) third resonance of the proposed PIFA.

structure at the resonating frequency of 2.3 GHz is shown in Figure 3(a).

The directly fed PIFA in Figure 1(a) is transformed to a capacitively coupled PIFA in Figure 1(b). The capacitive coupling makes the antenna compact and allows the impedance matching parameters to be independent of the position of the short metal element with respect to the feeding point. Hence, optimization of the position of the short element is not required. In this structure, antenna is fed directly to a square capacitive metal strip placed in the same plane as that of the top radiating element, and energy is coupled from this capacitive strip to the top plane. The fundamental resonant frequency at 1.8 GHz depends upon the top metal patch and short element. By adjusting the position of the short element, this resonant frequency can be tuned. When the position of short element is shifted from left most edge towards center edge, the effective length of current path decreases, and resonance goes to higher value. When the position the short element again shifts towards further edge, the effective length of current path increases, and resonance goes back to lower values. A symmetrical current path is obtained when the short element is placed at the center edge.

When a capacitively coupled feeding method is used, an additional resonance is obtained at 2.8 GHz (second) as shown in reflection coefficients in Figure 2. This new resonant frequency is obtained due to bare top radiating element, which is independent of the short element. The surface current distribution of both resonances of capacitively coupled PIFA is shown in Figures 3(b) and 3(c). For the first resonance, and the surface current path includes both the top metal plane and short element. The current distribution for the second resonance frequency includes bare top metal plane, and this resonance is obtained from $\lambda/2$ variation of surface current along top metal plane of length L_t.

The capacitively coupled feeding method also has the advantage of generating multiple resonances by exciting multiple radiating elements simultaneously. In order to achieve this, a new metal patch is placed just below the top metal patch in the third stage of PIFA as shown in Figure 1(c). The third resonance can be obtained at 3.35 GHz by stacking the second (bottom) metal patch. The resonance mechanism of the third resonant frequency is the same as that of the second resonant frequency, which is due to the $\lambda/2$ surface current variation. The surface current distribution of the third resonance of the proposed PIFA in Figure 3(d) shows that the resonance is due to the $\lambda/2$ variation of surface current along bottom metal patch of length L_b.

The parametric study of the position of the short element in Figure 4 shows that by adjusting the position of the short plane element with respect to feeding point, the impedance matching of the first resonance can be achieved easily. Based on the application band, optimized position of short element is selected on the centre of top edge of ground plane. The position of short element also affects the impedance matching of the second resonance of proposed antenna. Parametric analysis of length of top

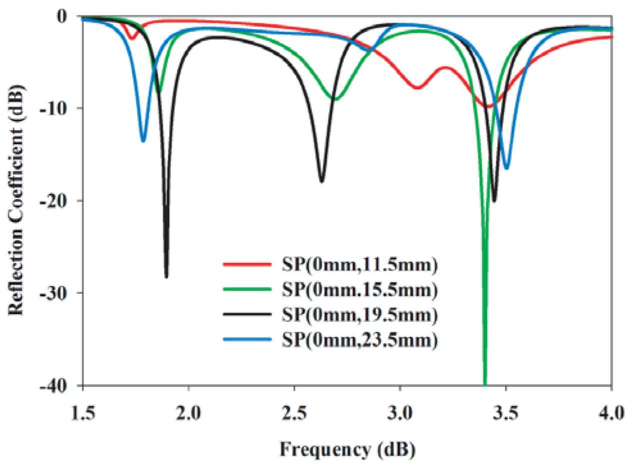


Figure 4. Parametric analysis of position of short element.

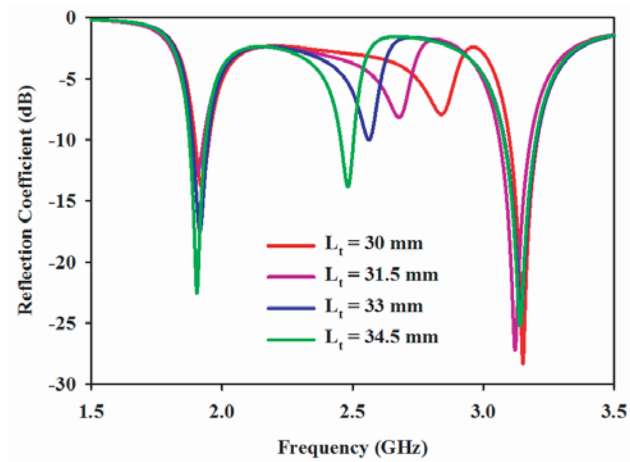
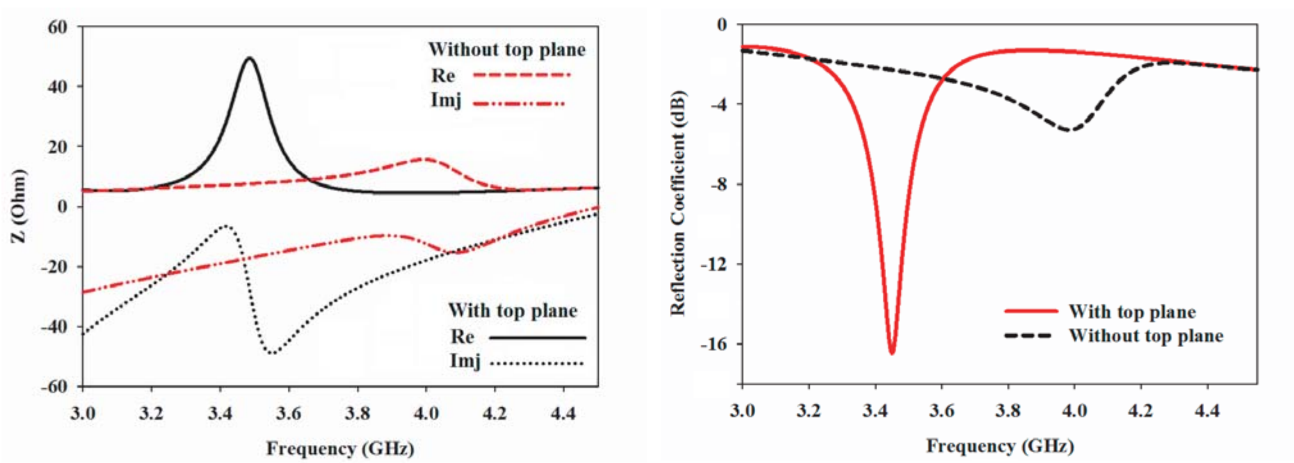


Figure 5. Parametric analysis of length of top radiating element, L_t.



(a) (b)

Figure 6. (a) Variation of impedance matching with the presence of top plane, (b) reflection coefficient of third resonance with and without top plane.

radiating element L_t with respect to the second resonant frequency is shown in Figure 5. By increasing the length of top radiating element L_t, the resonant frequency goes to lower values. Hence it can be concluded that the second resonance is obtained due to the length of top radiating element. The surface current distribution of the second resonance shows that there is current minima on both ends and current maxima at the centre of the top patch. It is the $\lambda/2$ variation of surface current distribution along L_t.

The third resonance is obtained due to the presence of bottom metal patch of substrate. The bottom metal patch is also excited by the same capacitively fed metal strip. This metal patch is not in the same plane as that of the capacitive strip. Hence large impedance mismatch can be observed between capacitive strip and bottom metal patch. However in the presence of top metal plane, the matching is improved significantly due to the coupling between the top and bottom planes. This causes the resonant frequency to shift to a low band as shown in Figure 6(a). An increase in the length of bottom element shifts the third resonant frequency to a lower band as shown in Figure 7. So the third resonance is obtained due to the length of bottom radiating element. It has the same working principle as that of the second resonance, which also has the $\lambda/2$ variation of surface current distribution along L_b. The variation of the length L_b slightly affects the second resonant frequency. This is due to the coupling effect of the bottom plane.

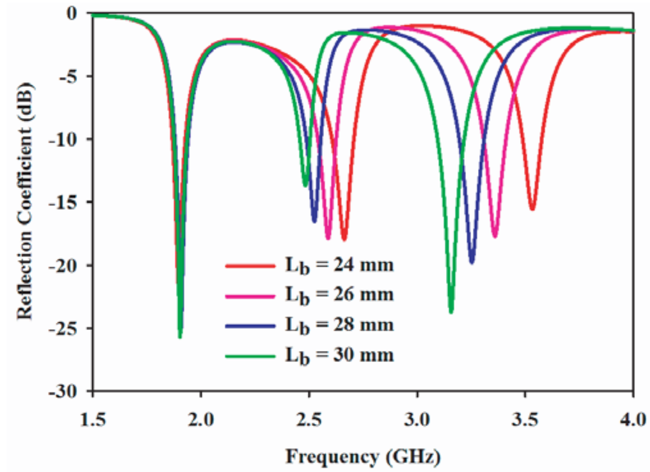


Figure 7. Parametric analysis of length of bottom radiating element, L_b.

3. ANTENNA GEOMETRY AND DESIGN

The proposed PIFA is designed on a low cost FR4 substrate with relative permittivity of 4.4, thickness 1.6 mm, and loss tangent tan δ 0.02. The geometry of the proposed PIFA is shown in Figure 8. Suspended microstrip model is utilized here. It consists of two substrates in which radiating element is placed on the top substrate and system ground plane placed on the bottom substrate. The dimension of the system ground plane is considered as the dimension of main board of mobile phone. The antenna is excited by a single probe feed connected to a square capacitive strip which is placed on the top substrate. The position of feeding point is exactly at centre of the capacitive strip. The antenna consists of two radiating elements placed on both sides of top substrate which is suspended from bottom substrate. The top metal plane is shorted to the ground plane with a thin metal strip.

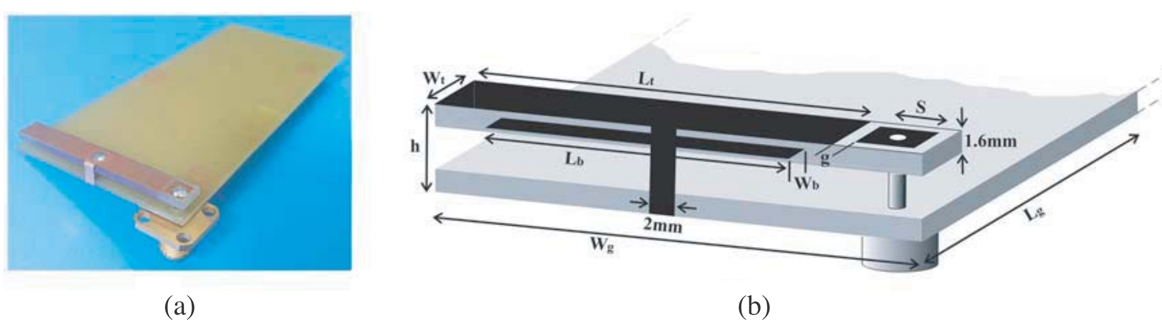


Figure 8. (a) Fabricated PIFA, (b) geometry of the proposed PIFA. The optimised design parameters are $L_t = 35$ mm, $W_t = 5$ mm, $s = 4$ mm, $L_b = 25$ mm, $W_b = 4$ mm, $g = 0.5$ mm, $h = 6$ mm, $L_g = 10$ mm, $W_g = 40$ mm.

According to antenna theory, directly fed PIFA has a fundamental resonance length of $\lambda/4$ which corresponds to $L_1 + L_2 - W$, where L_1 and L_2 are the length and width of radiating structure, and W is the width of shorting plane element. Proposed PIFA is a triple band antenna which is fed by capacitively coupled feed method. The first resonance 1.85 GHz is decided by the position of metal short element, and it is due to the current path from top metal plane to ground. The second resonant frequency 2.55 GHz is decided by its length L_t and width W_t with resonance length of $\lambda/2$, which is clearly visible in surface current distribution of top metal element. From the simulated surface current distribution of antenna at 3.55 GHz it is clear that the third resonance is due to the resonance length of $\lambda/2$ which is decided by the length and width of bottom element.

4. RESULTS AND DISCUSSIONS

The proposed PIFA is simulated using Ansoft HFSS software. The experiments are carried out using an Agilent PNA E8362B Vector Network Analyzer, and all far field pattern measurements are done inside an anechoic chamber. The results are verified by using RFxpert. The simulated and measured reflection characteristics of the proposed PIFA are shown in Figure 9. The proposed antenna resonates at three frequencies which cover three application frequency bands with the first band covers the GSM 1800 with 10-dB return loss bandwidth of 5.4% (1.8–1.9 GHz); band 2 covers the LTE 2500 with 3.9% (2.5–2.6 GHz) bandwidth; and band 3 covers the WiMAX with a bandwidth of 2.98% (3.3–3.4 GHz).

The measured two-dimensional radiation patterns for three resonant frequencies 1.85 GHz, 2.55 GHz, and 3.35 GHz are shown in Figure 10. It is clear that the radiation pattern of the first resonance is nearly omnidirectional. The radiation pattern becomes more directional with the second resonance, and it further increases with the third resonance.

The measured gain of the antenna in the entire operating band is shown in Figure 11. As seen in the figure, the antenna offers peak gain of 3.8 dBi in the operating band of GSM 1800, 4 dBi in the operating band of LTE 2500, and 0.88 dBi in the operating band of WiMax. The measured efficiency of the antenna is found to have a peak value of 45% for the first resonance, 49% for the second resonance, and 18% for the third resonance, which is shown in Figure 12.

The measured axial ratio is also plotted for the entire frequency bands, which is shown in Figure 13. It shows that axial ratio is less than 3 dB for all three bands, and thus one criterion for CP radiation is satisfied.

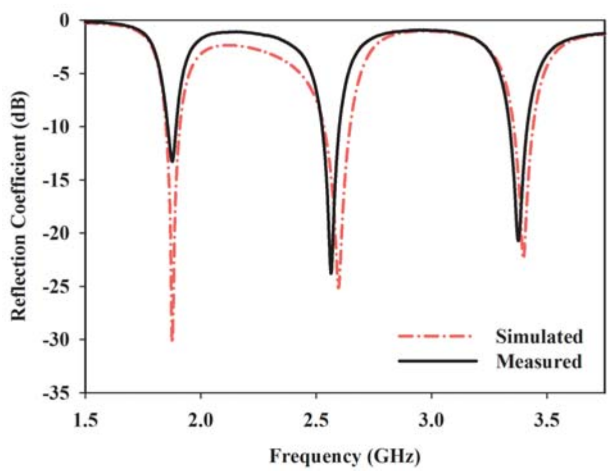
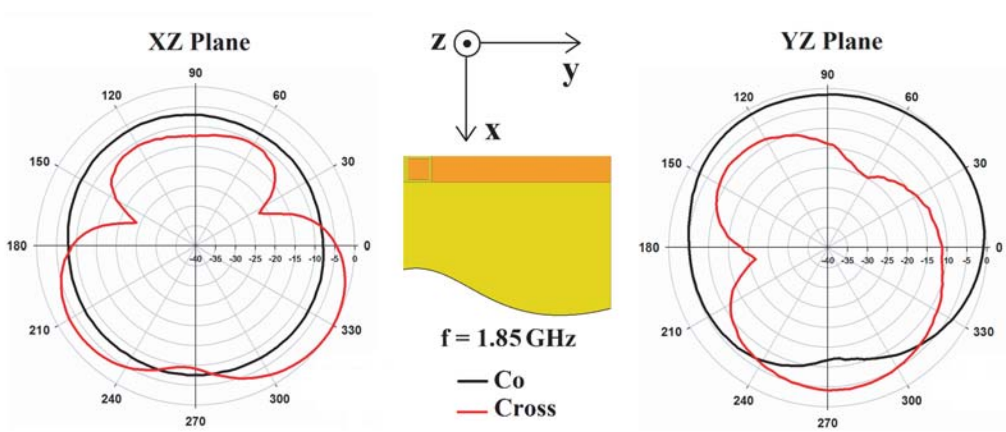


Figure 9. Measured and simulated reflection coefficient of proposed PIFA.



(a)

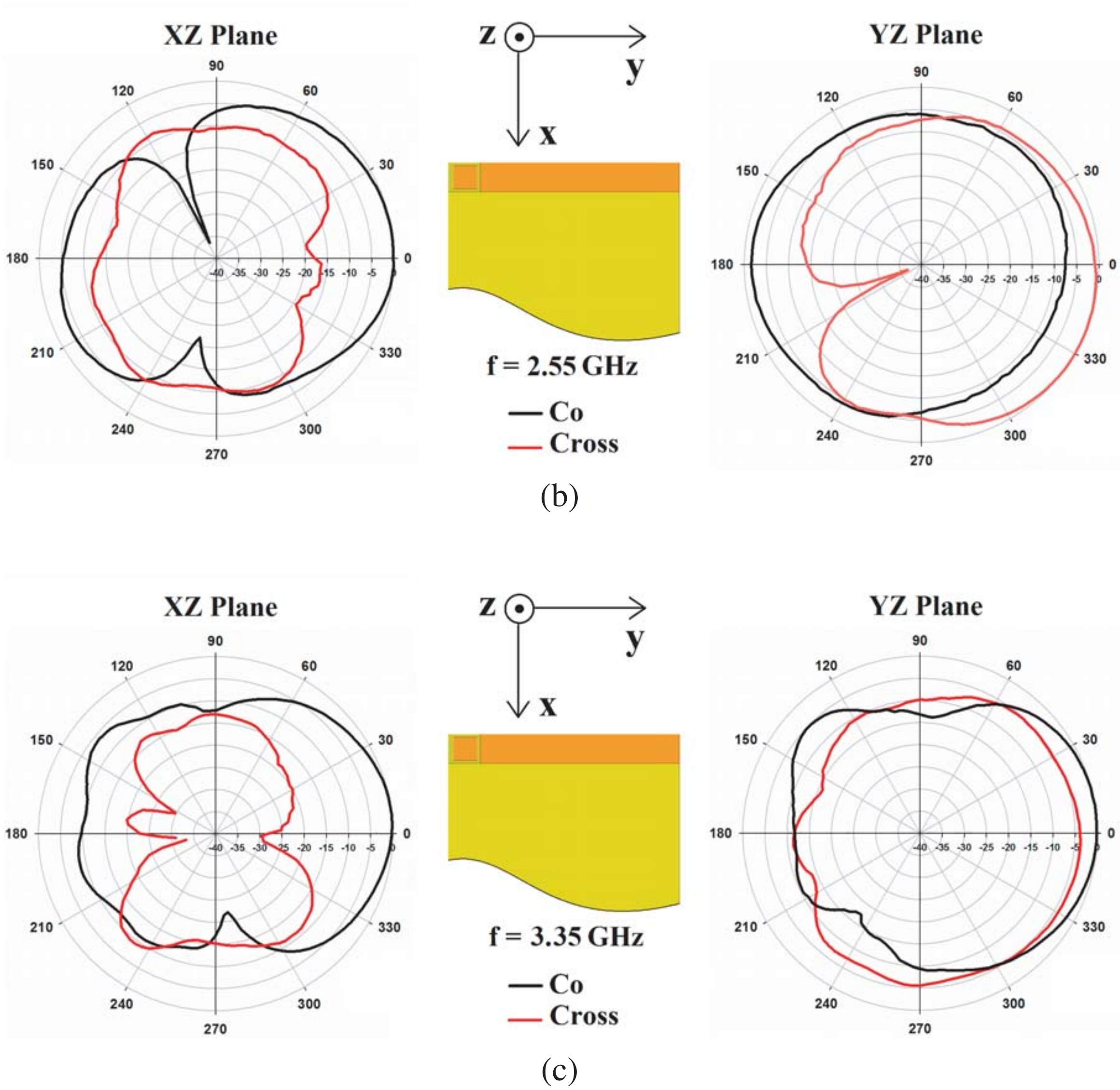


Figure 10. Measured radiation pattern of proposed planar inverted F antenna, (a) 1.85 GHz, (b) 2.55 GHz, (c) 3.35 GHz.

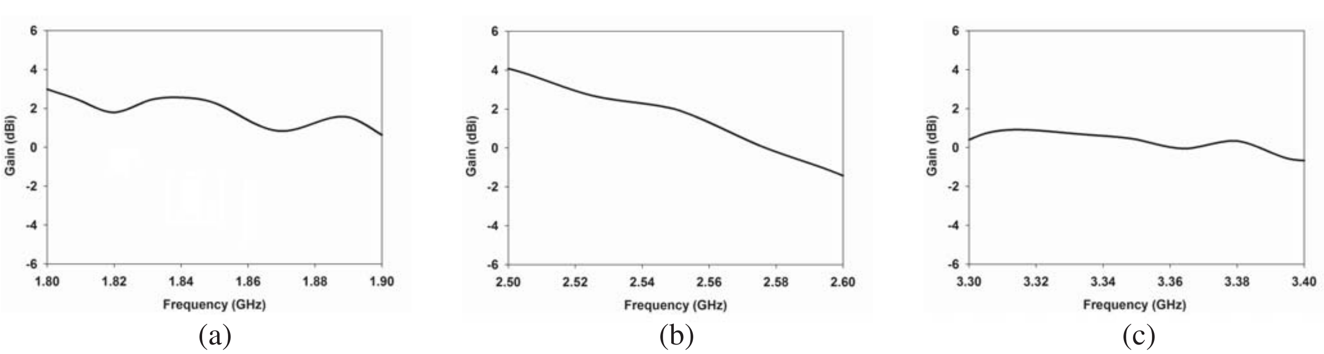
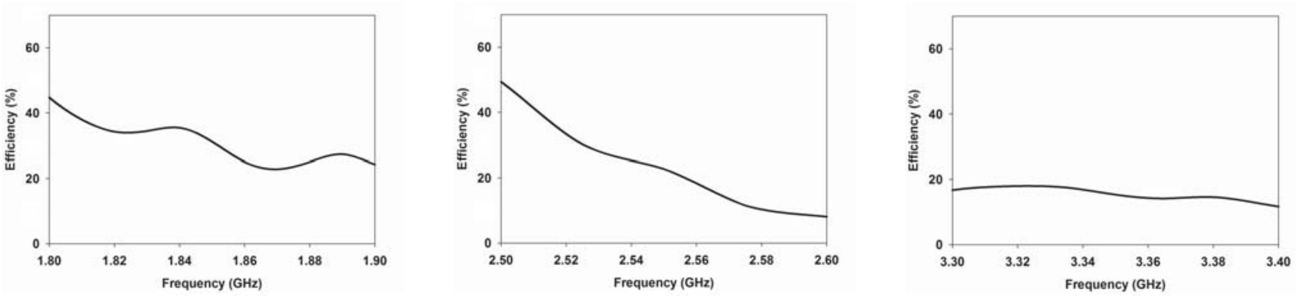


Figure 11. Measured gain response of the proposed antenna at (a) GSM 1800, (b) LTE 2500, (c) WiMax.



(a) (b) (c)

Figure 12. Measured efficiency response of the proposed antenna at (a) GSM 1800, (b) LTE 2500, (c) WiMax.

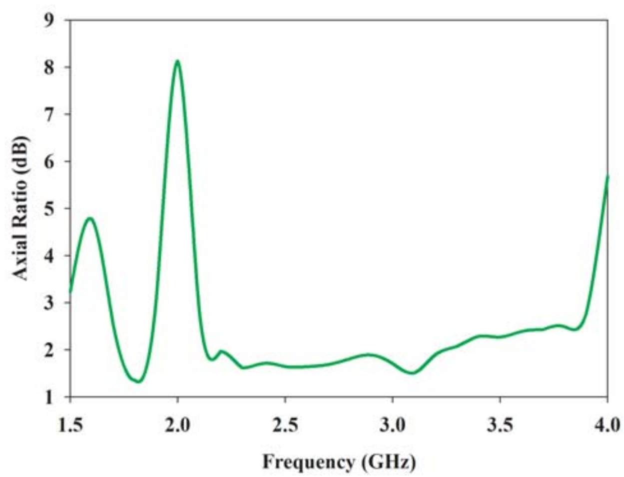


Figure 13. Axial ratio plot.

5. CONCLUSION

A compact capacitively coupled triple band planar inverted F antenna has been designed and fabricated on an FR4 substrate. It is able to achieve a compact, triple band PIFA by using the stacking method and capacitively coupling method. The overall dimension of the fabricated antenna is $40\,\text{mm} \times 5\,\text{mm} \times 6\,\text{mm}$ which is simple and very compact compared to existing designs. The antenna achieves the requirements needed to cover GSM 1800, LTE 2500, and WiMax bands.

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REFERENCES

1. Koul, S. K. and B. Bhat, "Inverted microstrip and suspended mictostrip with anisotropic substrate," *Proceedings of the IEEE*, Vol. 70, No. 10, 1230–1231, 1982.
2. Schellenberg, J. M., "CAD models for suspended and inverted microstrip," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 43, No. 6, 1247–1252, 1995.

3. Spielman, B. E., "Dissipation loss effects in isolated and coupled transmission lines," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 25, 648–656, 1977.
4. Kitazawa, T., et al., "Planar transmission lines with finitely thick conductors and lossy substrates," *1991 IEEE Inr. Microwave Sym. Dig.*, 769–772, 1991.
5. Al Ja'afreh, S., Y. Huang, and L. Xing, "Low profile and wideband planar inverted-F antenna with polarisation and pattern diversities," *IET Microwaves, Antennas & Propagation*, Vol. 10, No. 2, 152–161, 2016.
6. Thao, H. T. P., V. T. Luan, and V. V. Yem, "Design of compact frequency reconfigurable planar invert-F antenna for green wireless communications," *IET Communications*, Vol. 10, No. 18, 2567–2574, 2016.
7. Liu, N.-W., L. Zhu, and W.-W. Choi, "A low-profile wide-bandwidth planar inverted-F antenna under dual resonances: Principle and design approach," *IEEE Transactions on Antennas and Propagation*, Vol. 65, No. 10, 5019–5025, 2017.
8. Gomez-Villanueva, R., R. Linares-y-Miranda, J. A. Tirado-Mendez, and H. Jardon-Aguilar, "Ultra-wideband planar inverted-F antenna (PIFA) for mobile phone frequencies and ultra-wideband applications," *Progress In Electromagnetics Research C*, Vol. 43, 109–120, 2013.
9. Halaoui, M. E., A. Kaabal, H. Asselman, S. Ahyoud, and A. Asselman, "Multiband planar inverted-F antenna with independent operating bands control for mobile handset applications," *International Journal of Antennas and Propagation*, Vol. 2017, No. 8794039, 1–13, 2017.
10. Huang, H.-F. and J.-F. Wu, "Small-size antenna for seven-band WWAN/LTE mobile handset," *Microwave and Optical Technology Letters*, Vol. 57, No. 5, 1029–1033, 2015.
11. Huang, H.-F. and J.-F. Wu, "Uniplanar coupled fed printed PIFA for WWAN/WLAN operation in the mobile phone," *Microwave and Optical Technology Letters*, Vol. 51, No. 5, 1250–1257, 2015.
12. Wong, K.-L., M.-F. Tu, T.-Y. Wu, and W.-Y. Li, "Small-size coupled-fed printed PIFA for internal eight-band LTE/GSM/UMTS mobile phone antenna," *Microwave and Optical Technology Letters*, Vol. 52, No. 9, 2123–2128, 2010.
13. Kasabegoudar, V. G., D. S. Upadhyay, and K. J. Vinoy, "Design studies of ultra wideband microstrip antennas with a small capacitive feed," *Int. J. Antennas Propag.*, Vol. 2007, 1–8, 2007.
14. Garg, R., P. Bhartia, I. Bahl, and A. Ittipiboon, *Microstrip Antenna Design Handbook*, Artech House, Norwood, MA, 2001.
15. Hossain, M. I., M. R. I. Faruque, and M. T. Islam, "A comparative study of electromagnetic absorption of PIFA and helical antenna in the human head," *Theory and Applications of Applied Electromagnetics*, Vol. 344, 167–174, 2015.
16. Hossain, M. I., M. R. I. Faruque, and M. T. Islam, "A comparative study of the PIFA and printed monopole antenna EM absorption," *Biomedizinische Technik*, Vol. 62, 13–21, 2017.