Comprehensive Parametric Study of a Novel Dual-Band Single Feed Planar Inverted-F Antenna

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Abstract–This paper presents a new configuration of a dual frequency, single feed, planar inverted-F antenna, which is suitable for implementation in different handsets. A parametric study, using finite element simulation software, high frequency structure simulator, has been carried out on each of the frequencies of this antenna and closed formulas in terms of antenna parameters have been obtained, which makes the designing process much easier. The proposed antenna has been fabricated according to the obtained formulas. Both, numerical simulation and experimental data are presented.

Index Terms– Dual-band, microstrip antenna, mobile antenna, and planar inverted-F antenna (PIFA).

I. INTRODUCTION

It is a well-known fact that the demand for wireless communication systems is ever-growing. Therefore, compact antennas employed in these systems have become the center of attention of numerous researchers. In many places around the world, cellular communication systems operate in two distinct frequency bands simultaneously. For example, some cellular phones work in GSM at 0.9 GHz and DSC1800 at 1.8 GHz. Two separate antennas can be used, with one of them resonating at GSM and the other at DSC, but this is not space efficient. At present both GSM and DSC provide services in the same network, which means that antennas that work in these two bands simultaneously are needed.

Designing such a dual band antenna presents a challenge, because it should operate properly in both frequency bands, while being small enough to fit in different handsets. Despite their low manufacturing cost and light weight, microstrip antennas [1-3] are not suitable for dual-band cellular handsets, because they are bulky at the lower frequency bands.

The solution is using planar inverted-F antennas (PIFAs) [4, 5], which are a modification of microstrip antennas. PIFAs have attracted much interest due to their small size, easy manufacturing, moderate gain, being less prone to breakage, and their potential to work at several frequencies with only minor modification. PIFAs are in fact, grounded half-quarter wavelength path antennas consisting of a finite ground-plane, a radiating top layer, and a short-circuiting mechanism that connects the top radiator to the ground-plane. The ease of design in order to obtain multiple resonances has made PIFA a very popular choice for mobile handset antennas. However, when we are dealing with multiple resonance frequencies, tuning them proves to be tricky [6-10]. Therefore, obtaining closed formulas in terms of the antenna parameters, which give us the operating frequencies will definitely make the designing process much easier [11].

In this paper a new configuration of a dual-band planar inverted-F antenna is proposed and parametrically evaluated. Studying the effects of antenna parameters on its operating frequencies, will help us find the key control elements and will result in easier frequency tuning. Moreover, by collecting the data from the parametric evaluation of each of the PIFA frequencies, closed formulas in terms of the key control antenna parameters are presented. By using these formulas, designing a

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dual-band PIFA with desired operating frequencies is achievable.

II. ANTENNA DESIGN

The design procedure for this antenna is simple and straight forward. The first step is to start with a simple classical PIFA, which is basically a short circuited quarter wave patch that works only in GSM. By short circuiting a quarter wave patch, the current at the end of the patch does not have to be zero so a current-voltage distribution of a half wave patch is obtainable with reducing the required space needed on the phone by half.

A single band PIFA is shown in Fig. 1 and as the name implies it is distinguished by the loop formed by the short right angle elements, which resembles the letter “F”. Slits are made in this patch, which results in branches which are basically resonating paths. The smaller path resonates at DSC and the longer path resonates at GSM resulting in a dual band planar inverted F antenna.

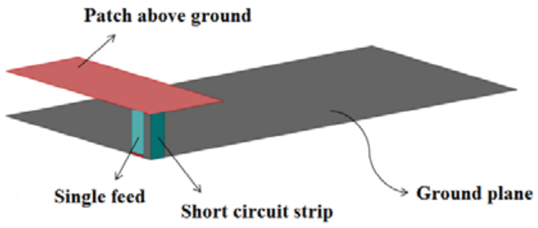
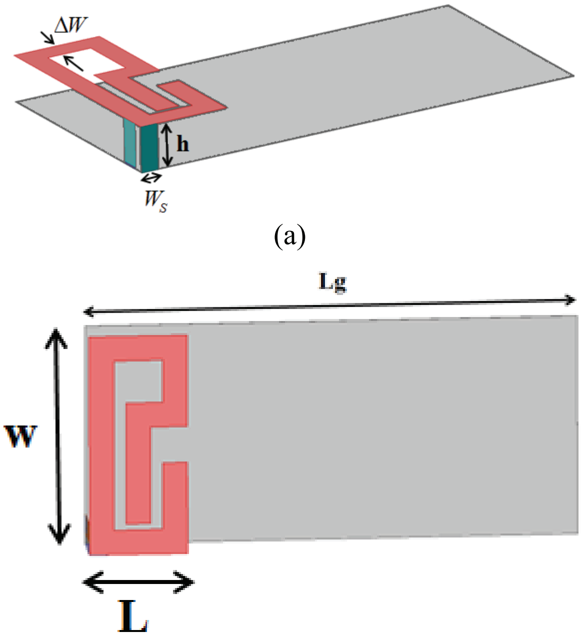


Fig. 1. Classic single band single feed PIFA.

III. ANTENNA STRUSTURE

The geometry of the proposed antenna is shown in Fig. 2. The top radiating element consists of several branches, which allow the antenna to work at two distinct frequencies. The total planar dimensions of the radiating top layer, which is made of copper are w and L, and the antenna height is shown with h. In order to see the effects of the substrate permittivity, ε_r, it has gradually changed from 1 to 4 in the simulations.

There are different shorting mechanisms, like using shorting pins, shorting plates, or a shorting wall [7]. In this antenna, a short-circuiting plate has been used, which is a vertical conducting strip with dimensions $W_S \times h$. This short circuiting plate connects the patch to the ground plane. The initial antenna dimensions have been chosen so that the operating frequencies are approximately 0.9 GHz and 1.8 GHz. In the next section, these dimensions will be changed for parametric evaluation.



(a)

(b)

Fig. 2. (a) Side view of the dual band PIFA and (b) top view of the dual band PIFA.

IV. NUMERICAL RESULTS

A. Parametric study

This section includes the parametric evaluation of the PIFA in terms of substrate relative permittivity, antenna height, ground plane dimensions, feed position, strip width, and the overall length of the radiating element. It will be shown that the resonance frequencies of the proposed structure can be controlled with the proper choice of its parameters [11-14]. The numerical results given in this section, has been obtained by using finite element simulation software, high frequency structure simulator, ANSOFT HFSS13 [15], which employs the adaptive finite element method. It will be seen that by varying the parameters, the designed antenna shows a dual-band performance in different operating frequencies; and by evaluating the effects of these parameters and collecting the data, closed formulas have been obtained in the following sections.

Ground plane dimension effects:

The antenna ground plane has an important effect on its performance. Currents excited on the radiating element will induce currents on the ground plane and the magnetic field is produced as the result of interaction between the radiating element and its image in the ground plane. The ground plane acts as a perfect reflector of energy only when it's infinite, but in practical situations, its dimensions are comparable to the radiating element and is used to control the resonance frequencies [12, 13]. The effect of ground plane dimensions has been shown in Fig. 3. If the length of the ground plane is considerably smaller than λ/4, tuning of the antenna will get increasingly difficult and the overall performance will deteriorate.

Antenna height and substrate permittivity effect:

PIFA bandwidth is inversely proportional to its quality factor: Q = stored energy/power loss. Substrates with higher ε_r, store more energy and radiate less. This is similar to assuming that the PIFA is equivalent to a lossy capacitor with high ε_r, resulting in a higher Q and lower bandwidth. Similarly, by increasing the substrate thickness, considering the inverse proportion of the capacity and the thickness, the energy increases while the quality factor decreases [16]. These effects have been shown in Figs. 4 and 5, respectively. The electrical properties of the substrate as well as the thickness of the substrate can affect the gain and bandwidth of the antenna. A thin substrate with a high ε_r will result in a weak radiation and a narrow bandwidth. Substrates with high loss tangent result in lossy antennas and consequently lower gains. Therefore, these kinds of antennas are usually mounted on thick low ε_r and low δ substrates just like what has been done in this paper.

Substrates with higher dielectric constant store energy rather than radiating it. We can model a patch antenna with a lossy capacitor with a high Q. It is obvious that a high Q factor results in a narrow band width. Although microstrip antennas mounted on high dielectric constant substrates have benefits like smaller size, they suffer from lower radiation efficiency and narrow bandwidth. The antenna bandwidth is inversely proportional to the Q-factor. This Q-factor is defined for a resonator as follows,

$$Q = \frac{energy\ \ stored}{power\ \ lost}\,. \tag{1}$$

A substrate with bigger width and lower ε_r like air can result in a wider bandwidth and better radiation efficiency by lowering the Q-factor, and it can also solve the antenna surface excitation. The radiating element is usually made of copper and the substrate serves as a mechanical support for the radiating element. The dielectric constants of the substrates are usually between 1 and 10 and can be separated into three groups.

1- Some dielectric constants are between 1 and 2. These substrates are usually air, polystyrene foam, and dielectric honeycomb.
2- Relative dielectric constants between 2 to 4. These materials consist of dielectric reinforced Teflon.
3- Materials with relative dielectric constants between 4 and 10. These materials can be ceramic, quartz, or alumina.

The microstrip antenna theory ([1-5]) shows a degradation in antenna performance with increasing ε_r. Substrates with higher ε_r will decrease the antenna size at the cost of lower gain and matching bandwidth. These parameters can be observed in two ways. First the dimensions of the antenna and the resonance frequency are fixed while the effect are studied. In previous researches the comparison between the effects of Duroid, FR4, mica, silicon nitrate, alumina, rogers3210, silicon, and gallium arsenide substrate show that for a PIFA with fixed dimensions, antennas with the air, duroid, and FR4 substrate have an acceptable matching bandwidth, but the FR4 substrate has low gain and the other substrates, with higher ε_r cannot resonate without a change in the antenna structure [17-18]. It can be seen that the impedance bandwidth decreases with the increase in ε_r. If we study the effects of the substrate with a fixed resonance frequency and tuning the dimensions we can see that the maximum gain and return loss is obtained by using the substrates with lower dielectric constants. As stated before, an increase in ε_r results in an antenna with a higher Q-factor. Consequently, we have only studied the effect of substrates with dielectric substrates between 1 and 4 and it can be seen that the best result can be obtained with an antenna with air substrate.

Strip and short circuit plate width effects:

The width of the shorting plate has a very important effect on frequency tuning [19]. As shown in Fig. 6, by reducing the shorting plate width, the resonance frequency decreases. Strip width is another parameter that allows an independent control of resonance frequencies because it has an opposite effect on them; i.e., by increasing the strip width, the lower resonance frequency decreases and the higher frequency increases. This effect has been shown in Fig. 7.

Antenna overall length:

As expected, the overall length of the radiating element has the most important effect on tuning the resonance frequencies [20]. By increasing this length, both of the resonance frequencies will decrease. This effect has been shown in Fig. 8.

B. Formula derivation

In the previous section the effect of PIFA parameters on its resonance frequencies has been studied. As shown earlier one of the parameters (strip width) has an opposite effect on the resonance frequencies so it could be used to independently tune them and achieve the desired f_1/f_2. The parameters have been finely varied and extensive data has been gathered. Fitting the data has resulted in closed formulas for each of the resonance frequencies. In these formulas, h is the antenna height, L_g is the length of the ground plane, ε_r is the substrate permittivity, L is the overall radiating length, and Δw and W_S are the strips and the ground plane widths, respectively

$$f_1 = 2.2 \times \frac{0.7h+L_g}{\varepsilon_r^{\frac{1}{4}}(1.5L+\Delta w+W_s)}\ , \qquad (2)$$

$$f_2 = 9.06 \times \frac{0.2h+0.5L_g+0.2\Delta w}{\varepsilon_r^{\frac{1}{4}}(1.5L+1.8W_s)}\ . \qquad (3)$$

By using these formulas, a PIFA has been designed, which works in GSM at 0.9 GHz and DSC1800 at 1.8 GHz. The values obtained for the parameters in millimeters are: $h = 8, W_s = 10, \Delta w = 4, \varepsilon_r = 1, L = 132, L_g = 81$

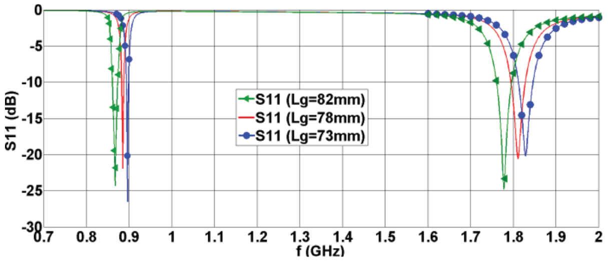


Fig. 3. Ground plane dimension effects on the resonance frequencies.

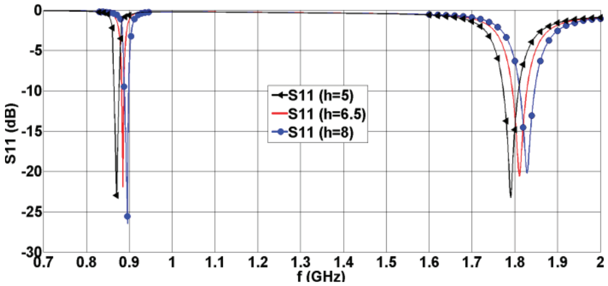


Fig. 4. Antenna height effects on the resonance frequencies.

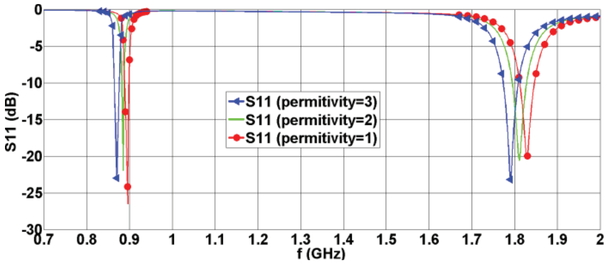


Fig. 5. Substrate permittivity effect on the resonance frequencies.

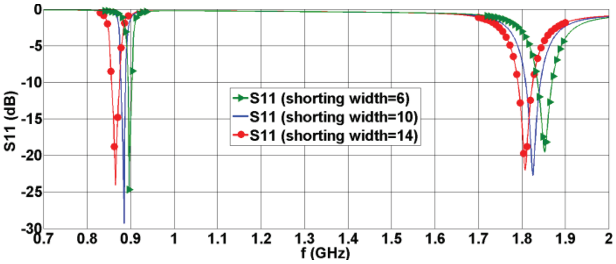


Fig. 6. Short circuit plate width effects on the resonance frequencies.

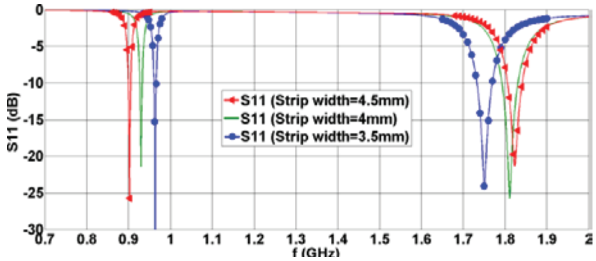


Fig. 7. Strip width effects on the resonance frequencies.

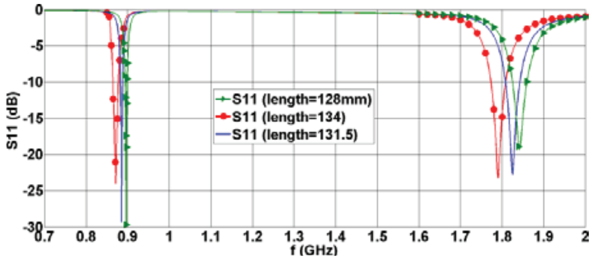
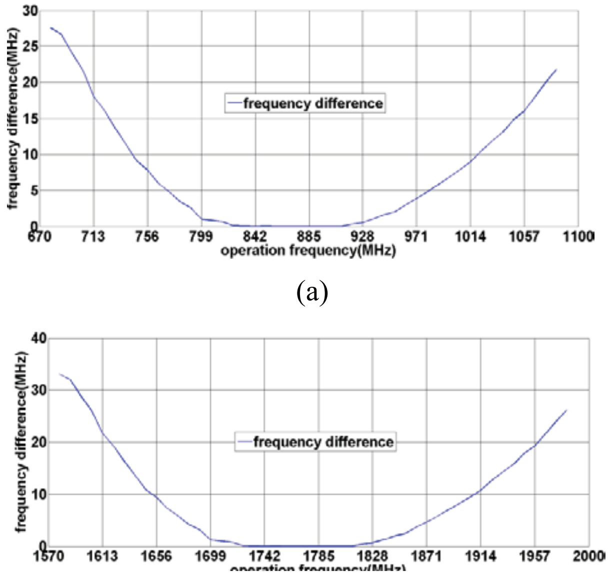


Fig. 8. Antenna overall length effects on the resonance frequencies.

C. Credibility range and accuracy of the formulas

In this section the frequency credibility range of the closed form formulas are evaluated for each of the resonance frequencies. First, the antenna is designed and simulated multiple times in HFSS; each time obtaining resonance frequency pairs with the first frequency between 670 MHz and 1100 MHz and the second one between 1570 MHz and 2000 MHz, and the antenna parameters in each simulation has been gathered. The parameters obtained by the simulation have been used in the formulas and the resulting frequency pairs have been compared to the simulated ones in order to find the validity range of the proposed formulas. The results have been shown in Fig. 9.

In order to study the accuracy of the formulas, the accurate values of the parameters according to full wave simulation are used in the formulas and the resulting frequency has been compared to the accurate frequency. The figures have been obtained by calculating the difference between the frequencies resulted from the formula to the accurate frequency obtained from simulation. Tables I and II, show the accuracy of the formulas in percentage in each frequency band. As expected from the figures, the formulas are accurate in the operation frequency bands.



(a)

(b)

Fig. 9. (a) Credibility range for f1 and (b) ccredibility range for f2.

Table I: Accuracy of formulas for the lower frequency band.

Frequency range(MHz)	Percentage of error
f<740	$\Delta f > 1.3\%$
740<f<760	$0.9\% < \Delta f < 1.3\%$
760<f<800	$0.1\% < \Delta f < 0.9\%$
800<f<930	$\Delta f < 0.1\%$
930<f<980	$0.1\% < \Delta f < 0.5\%$
980<f<1030	$0.5\% < \Delta f < 1\%$
f>1030	$\Delta f > 1\%$

Table II: Accuracy of formulas for the higher frequency band.

Frequency range(MHz)	Percentage of error
f<1650	$\Delta f > 0.6\%$
1650<f<1680	$0.3\% < \Delta f < 0.6\%$
1680<f<1700	$0.07\% < \Delta f < 0.3\%$
1700<f<1830	$\Delta f < 0.07\%$
1830<f<1870	$0.07\% < \Delta f < 0.3\%$
1870<f<1900	$0.3\% < \Delta f < 0.6\%$
f>1900	$\Delta f > 0.6\%$

In order to evaluate the accuracy another example has been given. By using these formulas, another PIFA has been designed, which works in GSM at 0.85 GHz and DSC at 1.75 GHz. The values obtained for the parameters in millimeters are: h = 6 mm, W_S = 10.3, Δw = 6, ε_r = 1, L =

134, and L_g = 80. Simulating the proposed PIFA with the mentioned parameters, results in 0.8502 GHz and 1.7498 GHz frequencies, which shows the accuracy of the formulas. The Antenna can be designed to work in any frequency pair stated in the tables or figures and the parameters must be chosen accordingly for each frequency pair. It should be kept in mind that although many values might be chosen for the parameters; these values have a direct effect on the performance of the antenna. As stated earlier, the antenna has the best performance by choosing the highest value for h, and the lowest value for ε_r and a very small L_g will result in overall performance deterioration [21]. There is no specific limitation in L, Δw and W_s therefore, these parameters can be used to obtain the desired frequencies.

D. Antenna gain variation with frequency

Furthermore, the antenna gain variation with frequency at each band has been studied. Figure 10 shows the simulated antenna gain versus frequency in GSM and DCS bands. As shown in Fig. 10 , maximum gains are 2.4 dBi and 3.95 dBi at 0.9 GHz and 1.8 GHz center frequencies of each frequency band and the total gain is above 2.2 dBi in the working bands. It can be observed that the antenna gain is sufficient for mobile terminals. The gain in the DSC band is higher than the GSM band and that was predictable because of the higher electrical length of the antenna at the DCS band.

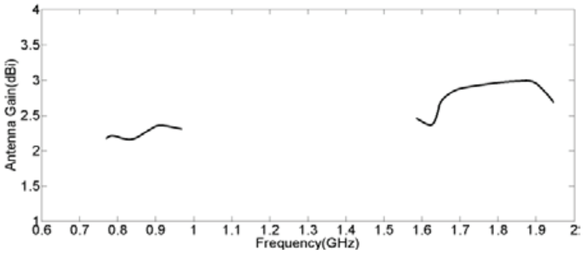
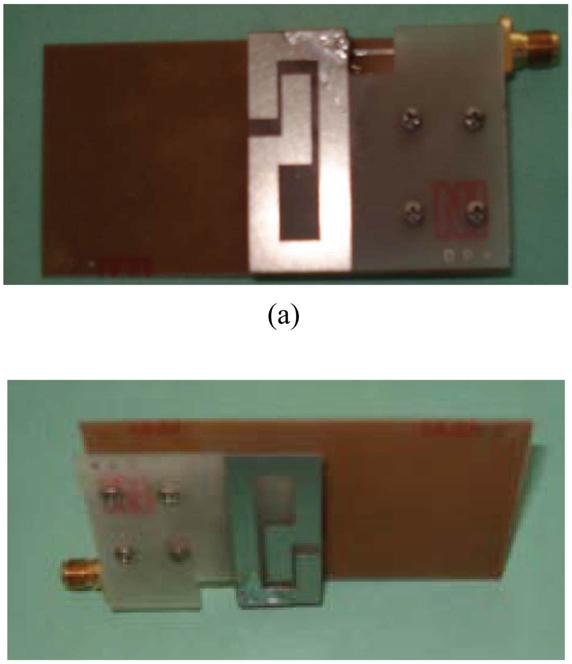


Fig. 10. Antenna gain variation with frequency.

V. FABRICATION AND MEASUREMENT

The antenna parameters have been found by using the formulas for GSM and DSC1800, namely 0.9 GHz and 1.8 GHz, respectively, and it has been fabricated according to the obtained dimensions. The fabricated antenna is shown in Figs. 11 (a) and (b). The comparison between the measured and simulated S11-parameters in Fig. 12 shows a complete agreement between the simulation and fabrication results, which proves the accuracy of the analysis and the formulas. The measured radiation pattern of the antenna at both frequencies is presented in Fig. 13. The radiation pattern in both planes is almost omni-directional, which means good coverage in both frequency bands.


(a)

(b)

Fig. 11. The fabricated dual band PIFA; (a) top view and (b) side view.

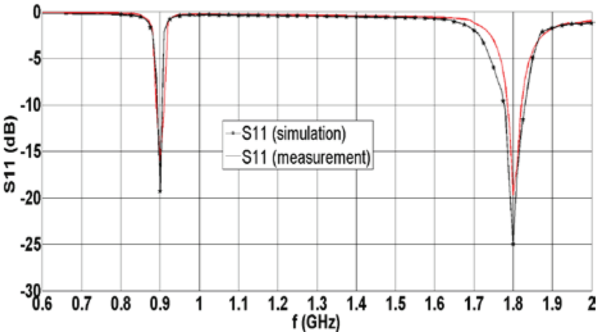
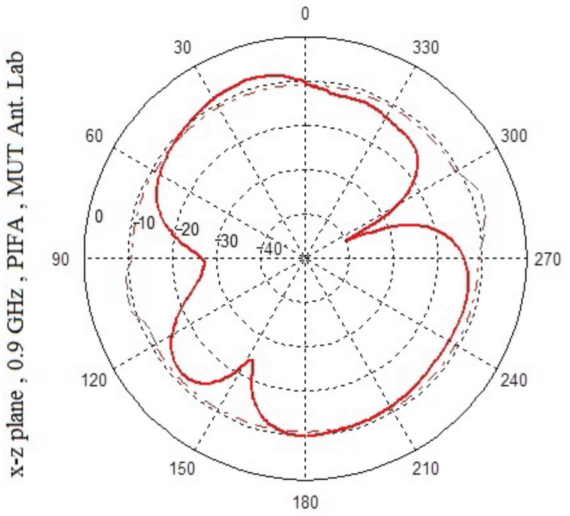
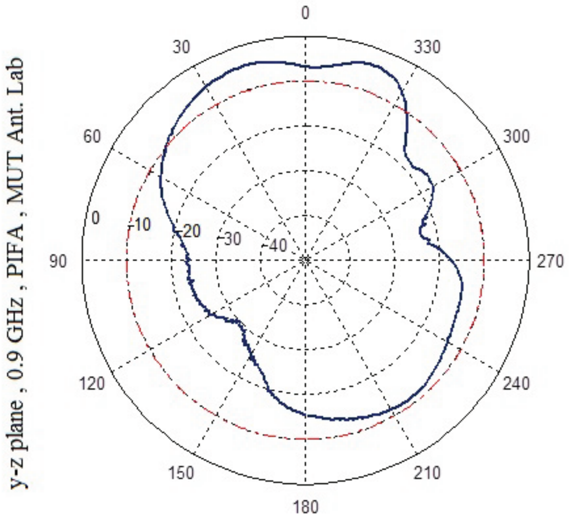


Fig. 12. Numerical simulation and measurement results.



(a)



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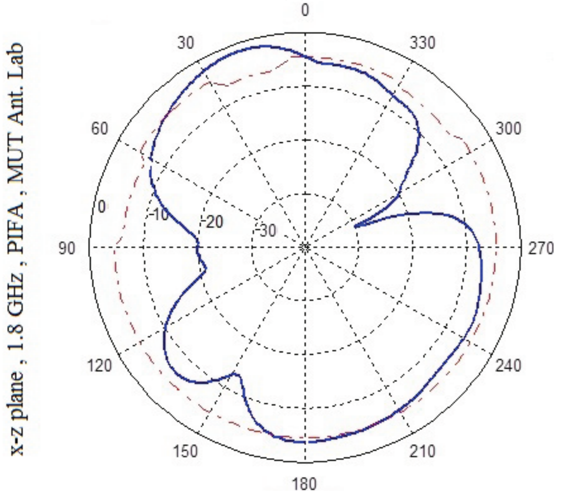
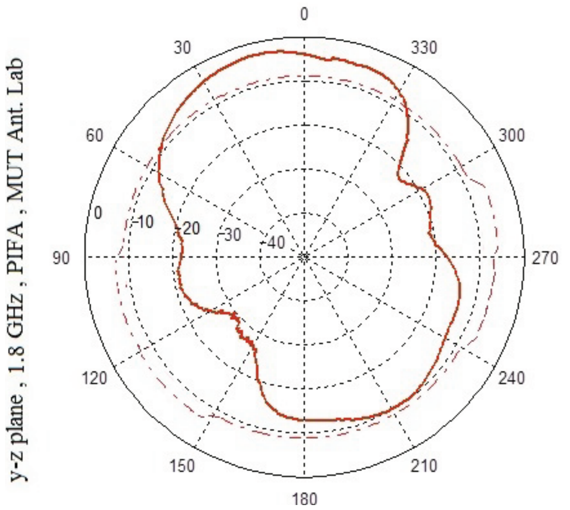


(c)



(d)

VI. CONCLUSION

In this paper a dual frequency, single feed, planar inverted-F antenna has been presented. This antenna is well suited to telephone handsets used in today's mobile communication systems operating in two frequency bands for example both GSM and DCS 1800 bands. The PIFA has been parametrically evaluated in terms of substrate relative permittivity, antenna height, ground plane dimensions, strip width, shorting plate width, and the effective dimension of the radiating element. It has been shown that the resonance frequencies of the proposed structure can be controlled with the proper choice of its parameters resulting in closed form formulas, which are very useful in designing this antenna. The proposed antenna has been fabricated according to the obtained formulas. Both numerical simulation and experimental data show the accuracy of analysis and formulas.

REFERENCES

[1] J. James and P. Hall, *Handbook of Microstrip Antennas*, Peter Peregrinus Ltd., London, UK, 1989.

[2] D. Pozar and D. Schaubert, *Microstrip Antennas: The Analysis and Design of Microstrip Antennas and Arrays*, IEEE press, New York, USA, 1995.

[3] I. Bahl and P. Bhartia, *Microstrip Antennas*, Artech House, Nonvood, MA, 1980.

[4] V. Nguyen, R. Bhatti, and S. Park, "A simple PIFA-based tunable internal antenna for personal communication handsets," *IEEE Ant. and Wir. Prop. Lett.*, vol. 7, pp. 130-133, May 2008.

[5] G. Kossiavas, R. Staraj, P. Le Thuc, C. Luxey, and A. Diallo, "Enhancement of the isolation between

two closely spaced mobile phone internal antennas by a neutralization effect," *22nd Annual Review of Progress in Applied Computational Electromagnetics (ACES)*, pp. 733-737, Miami, FL, March 2006.

[6] S. Liam, O. Boon P. Koh, P. Song, and L. Lau, "From a simple IFA to a dual band PIFA," *International Workshop on Antenna Technology: Small Antennas and Novel Metamaterials*, IWAT 2008.

[7] N. Karmakar, "Shorting strap tunable single feed dual-band stacked patch PIFA," *IEEE Ant. and Wir. Prop. Lett.*, vol. 2, pp.68-71, 2003.

[8] S. Haverals and T. Gilles, "Design and realisation of a quad band antenna for mobile telephony applications," *26th Annual Review of Progress in Applied Computational Electromagnetics (ACES)*, pp. 586-591, Tampere, Finland, April 2010.

[9] S. Ali, H. Kanj, D. Wang, and W. Geyi, "Design and analysis of a novel pent-band antenna for handheld applications," *24th Annual Review of Progress in Applied Computational Electromagnetics (ACES)*, pp. 899-902, Niagara Falls, Canada, March 30 - April 4, 2008.

[10] S. Jeon, H. Lee, S. Park, S. Lee, and N. Kim, "Design of mobile phone antenna with multi-band for SAR reduction," *23rd Annual Review of Progress in Applied Computational Electromagnetics (ACES)*, pp. 1739-1745, Verona, Italy, March 2007.

[11] H. Chattha, Y.Huang, Xu. Zhu, and Y. Lu "An empirical equation for predicting the resonant frequency of planar inverted-F antennas," *IEEE Ant. and Wir. Prop. Lett.*, vol. 8, pp. 856-860, 2009.

[12] M. Abedin and M. Ali, "Modifying the ground plane and its effect on planar inverted-F antennas (PIFAs) for mobile phone handsets," *IEEE Ant. and Wir. Prop. Lett.*, vol. 2, pp. 226-229, 2003.

[13] M. Huynh and W. Stutzman, "Ground plane effects on planar inverted-F antenna (PIFA) performance," *IEE Proceedings on Microwaves, Antennas, and Propagation*, 8 Augst 2003.

[14] S. Ibnyaich, J. Elbakouchi, A. Ghammaz, and M. Hassani, "Effects of changing dimensions on the planar inverted-F antenna performances," *Faible Tension Faible Consommation (FTFC)*, pp. 119-122, May-June 2011.

[15] HFSS 3D Full-Wave Electromagnetic Field Simulation ver. 13.

[16] J. He and K. Chung, "Design of a dual-band microstrip-fed meandered-tail PIFA for WLAN applications," *Antennas and Propagation Society International Symposium*, 2009.

[17] Y.-T. J.-Charles ,V. Ungvichian, and J. Barbosa, "Effects of substrate permittivity on planar inverted-F antenna performances," *Journal of Computers*, vol. 4, no. 7, July 2009.

[18] Y.-T. J.-Charles, V. Ungvichian, and A. Barbosa, "A study of substrate permittivity effects on the gain of planar inverted-F antennas," *IEEE Southeast Con.*, Huntsville, Alabama, April 2008.

[19] H. Chattha, Y. Huang, and Y. Lu "PIFA bandwidth enhancement by changing the widths of feed and shorting plates," *IEEE Ant. and Wir. Prop. Lett.*, vol. 8, pp.638-640, 2009.

[20] Y. Yu and J. Tarng, "A novel modified multiband planar inverted-F antenna," *IEEE Ant. and Wir. Prop. Lett.*, vol. 8, pp.189-192, 2009.

[21] I. Bonev, O. Franek, M. Christensen, and G. Pedersen, "Impact of the mobile phone dimensions on the hearing aids compatibility," *Applied Computational Electromagnetics Society (ACES) Journal*, vol. 25, no. 11, pp. 984-989, Nov. 2010.