Journal of Electrical Engineering
The Institution of Engineers, Bangladesh
Vol. EE 36, No. II, December 2009

Analysis of Inverted-F and Loaded Inverted-F Antennas for 2.4 GHz ISM Band Applications

Debabrata Kumar Karmokar[1] and Khaled Mahbub Morshed[2]

[1]Department of Electrical & Electronic Engineering
[2]Department of Electronics and Communication Engineering
Khulna University of Engineering and Technology, Bangladesh
E-mail: debeee_kuet@yahoo.com, kmm_ece@yahoo.com

***Abstract*— This paper addresses the numerical simulations of Inverted-F and loaded inverted-F antennas for improving the performance of 2.4 GHz industrial, scientific and medical (ISM) band applications. The proposed antennas are directly feed by coaxial connector and the antenna arms effectively control the excited resonant modes for the required operation. Total area occupies by the antennas are 15×34 and 17×34 mm^2 respectively. The antennas contain an incredibly high peak gain of 8.50 and 8.89 dBi with less than 1.13 and 1.29 dBi gain variation within the 10 dB return loss bandwidth. Also, the antennas have return loss bandwidth of 150 (2355 – 2505 MHz) and 155 MHz (2370 – 2525 MHz) with peak return loss of -25.72 and -30.96 dB respectively.**

***Index Terms*— Inverted-F antenna (IFA), Loaded inverted-F antenna (LIFA), return loss, ISM band.**

I. Introduction

THE ISM radio bands were originally reserved internationally used for an increasingly diverse range of applications. These include: military (aircraft, missile telemetry), electronic news gathering/outside broadcast, radio frequency identification devices, lighting, microwave ovens, public telecommunications, short range radio devices and low power audio, video and data links (including WLAN, Bluetooth, HomeRF). This diverse, and increasingly intensive, use of the band brings with it the potential for congestion and consequent possible degradation in service quality. Rapid growing research works on micro-strip antennas take part in an imperative role in the development of swiftly rising commercial communication applications. An antenna of compact size, light weight, cost-effective, high efficiency and better radiation in horizontal and vertical plane, which is directly mounted on the system circuit board or the ground plane of the mobile device is preferred for short range wireless communications. In recent times the ISM band (2.40~2.485 GHz) is a significant means of wireless communication. Wireless local-area networks (WLANs), Bluetooth and wireless sensor networks all uses ISM band (IEEE 802.11b and IEEE 802.11b/g standard) [1-5]. The applications based on this technology are increasing numerously day by day and its applications is not only limited within the home and offices but also spreading in outdoor too.

A chip antenna suitable to be mounted above the system ground plane of a mobile device with a gain of less than 3.5 dBi and bandwidth of 126 MHz (2382-2508 MHz) is proposed for the 2.4 GHz ISM band [1]. Though the antenna dimension is small but the gain is limited. Printed circuit board wire antennas on a FR-4 substrate have the gain of 2 dBi with wider bandwidth (200 MHz) [2]. On the other hand inverted-F antenna printed on a PCMCIA card proposed at earlier has the gain of 2.50 dBi at 2.45 GHz and the antenna has quasi-omnidirectional pattern in XY plane [3]. A compact monopole antenna for dual ISM band with a gain of 1.354 dBi and bandwidth of 330 MHz at lower operating band (2.4 GHz ISM band) [4]. Though the antenna supports dual band operation but the gain at 2.4 GHz ISM band is limited. Performing the antenna miniaturization the researchers have been proposed compact micro-strip antenna based on shorting pin technique provides gain of 0 dBi at 2.45 GHz and bandwidth of 104 MHz [5].

The printed integrated inverted-F antenna has a free-space peak gain of 1.5 dBi [6]. The dual-band multi-slot antenna operated at 2.4 GHz and 5 GHz, with gains of the double-Z-slot and triple-Z-slot antennas are about 1.4 and -1.4 dBi at 2.4 GHz [7]. Among the various feeding techniques, micro-strip line fed better to achieve high gain and impedance matching between the antenna and coaxial connector [8]. The micro-strip line fed half-cylindrical dielectric resonator antenna (DRA) has a peak gain of 5.5 dBi in the elevation plane and 3.5 dBi in the azimuth plane [9]. However a micro-strip coupled printed inverted-F antenna has wider bandwidth but the gain is not over 2dBi [10]. For the wireless sensor networks application rectaxial antenna suffer for the low gain of 2.2 dBi [11]. The equilateral-triangular slot antenna (ETSA) support two operating bands but the gain of this antenna at 2.45 GHz is 2.8 dBi [12]. Considering the antenna gain and bandwidth for the application related to the ISM band an antenna with high gain and adequate return loss bandwidth is required.

To provide the increasing demand of ISM band in military, WLAN, Bluetooth, wireless sensor network and cover up the wide applications, an antenna with high gain, sufficient bandwidth and less gain variation within the antenna bandwidth is desired. For this miniaturized antenna are extremely enviable [13].To meet up most of the mentioned requirements, Inverted-F antenna is one of the good candidates within the micro-strip printed antennas.

Our objectives are to design high gain Microstrip antennas which fully cover the 2.4 GHz ISM band.

II. Antenna Design

The geometry of the promising proposed antennas for achieving enhanced performance at 2.4 GHz ISM band are shown in Figs. 1 and 2. Using method of moments (MoM's) in Numerical Electromagnetic Code (NEC) [14], we conducted parameter studies to ascertain the effect of different loading on the antenna performance to find out the optimal design. For the analysis of the accuracy optimum segmentation of each geometrical parameter are used in NEC. Fig. 1 represents the basic geometry of the IFA. Here one leg of IFA directly connected to the feeding and another leg spaced *s* from the ground plane. But in conventional IFA spacing is always is zero. For the numerical analysis we considered the substrate permittivity of the antenna is $\varepsilon_r = 2.2$ (RT/duroid 5880) with substrate thickness 0.127 mm. For our study we assume the copper conductor and the antenna was intended to be matched to 50 Ω system impedance, with its central conductor connected to the feeding point and its outer conductor soldered to the ground plane just across the feeding point. In the analysis the dimensions of the ground plane considered as 60 mm × 60 mm. Fig. 2 represents the structure of loaded IFA for 2.4 GHz application.

Initial geometry considerations were taken from the theory of low profile antennas and IFA [15-16]. Figures 3, 4, 5 and 6 shows the effects of length (l), height (h_1), tap distance (t) and spacing (s) on the return loss of the antenna structure of Fig. 1. When antenna l, h_1, t and s varies from low to high value antenna return loss behaves as like a resonant circuit as the resonant circuit provide better performance when it is matched. From the initial considerations and numerical analysis the best performance of the antenna were obtained when l=28, h_1=15, t=6 and s=0.4 mm. Our aim was to improve the performance of IFA for 2.4 GHz ISM band applications. For more improvement in the return loss of IFA we apply a small suitable structured load on the horizontal branch of the IFA and the modified antenna titled as loaded IFA (LIFA) as shown in Fig. 2. In order to find the optimum value of the load we made numerical analysis on the height as well as on the length of the load.

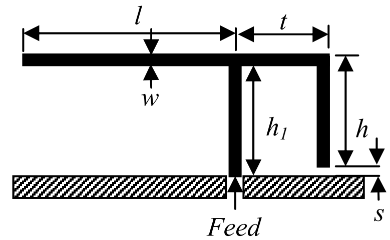


Fig. 1. Proposed geometry of inverted-F antenna.

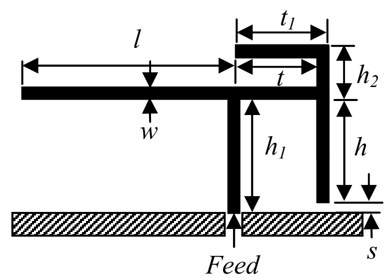


Fig. 2. Proposed geometry of loaded inverted-F antenna.

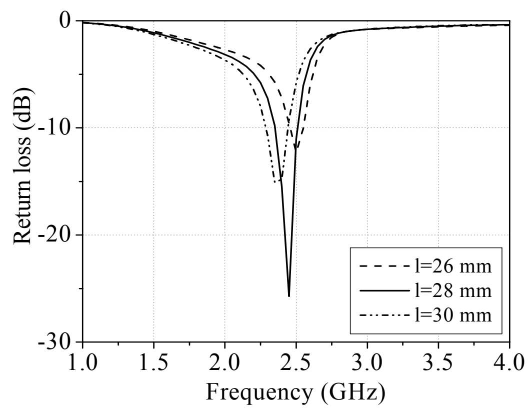


Fig. 3. Effects of length l on the return loss as a function of frequency on the antenna structure of Fig. 1.

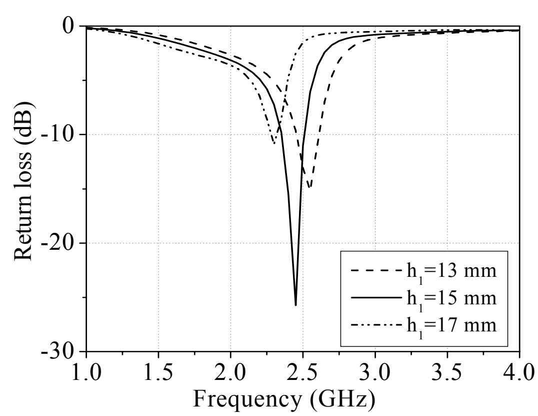


Fig. 4. Effects of height h_1 on the return loss as a function of frequency on the antenna structure of Fig. 1.

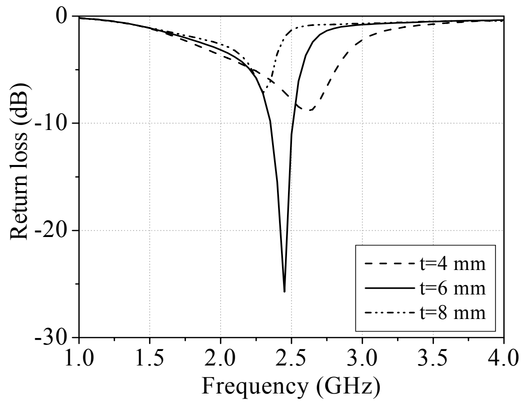


Fig. 5. Effects of tap distance *t* on the return loss as a function of frequency on the antenna structure of Fig. 1.

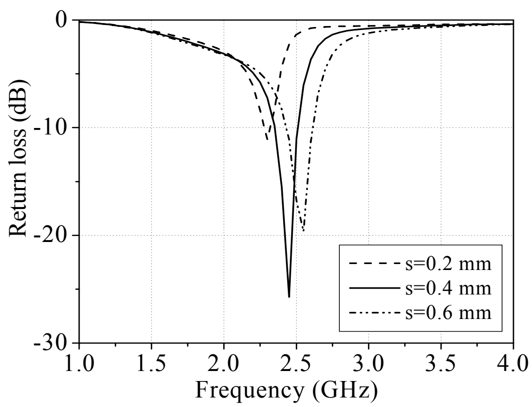


Fig. 6. Effects of spacing *s* on the return loss as a function of frequency on the antenna structure of Fig. 1.

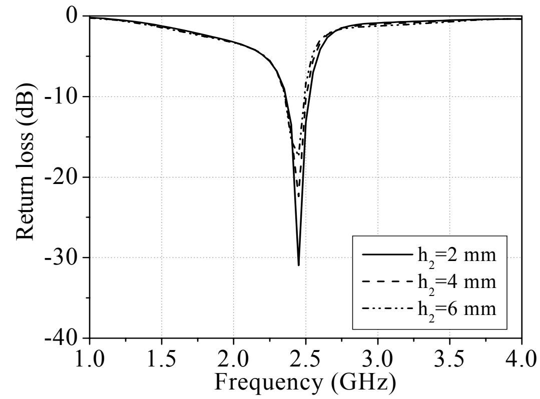


Fig. 7. Effects of height h_2 on the return loss as a function of frequency on the antenna structure of Fig. 2.

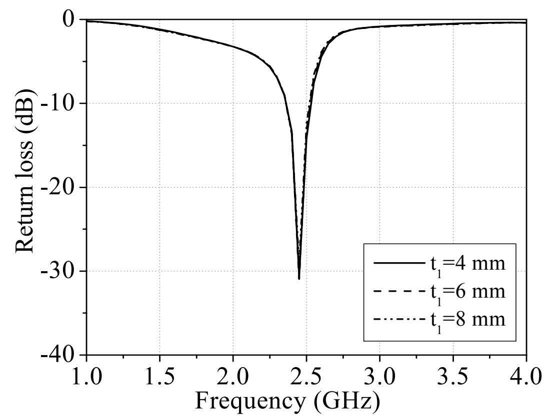


Fig. 8 Effects of tap distance t_1 on the return loss as a function of frequency on the antenna structure of Fig. 2.

Figures 7 and 8 show the effects of height of load (h_2) and length of load (t_1) on the performance of LIFA (antenna structure of Fig. 2). From Figs. 7 and 8 we observe that a higher value of h_2 decreases the antenna return loss and for any value of t_1 the return loss remains almost the same. From Fig. 7 we observe that the antenna provide better return loss characteristics when $h_2=2$ and for design simplicity the value of t_1 is considered equal to the value of tap distance t, so $t_1=t=6$. The geometry parameters of the antennas are listed in Table I.

TABLE I
DIMENSIONS OF THE PROPOSED ANTENNAS FOR 2.4 GHZ ISM BAND

Antenna Name	Antenna Parameters	Values (mm)	Dimension (mm^2)
Inverted-F Antenna	*l*	28	15×34
	t	6	
	h	14.6	
	h_1	15	
	w	2	
	s	0.4	
Loaded Inverted-F Antenna	*l*	28	17×34
	t	6	
	t_1	6	
	h	14.6	
	h_1	15	
	h_2	2	
	w	2	
	s	0.4	

III. NUMERICAL SIMULATION RESULTS

The numerical analysis results of two proposed structures as IFA and LIFA to realize the 2.4 GHz ISM band applications are presented below. Fig. 9 shows the variation of voltage standing wave ratio (VSWR) for IFA and LIFA as a function of frequency. The antennas have VSWR of 1.1091 and 1.0583 at 2.45 GHz respectively (the centre frequency of 2.4 GHz ISM band is 2.45 GHz [17]). VSWR for IFA varies from 1.1091 to 1.7815 within the operating band whereas for LIFA it varies from 1.0583 to 1.5622. Return loss variations of the antennas are shown in Fig. 10. The proposed antennas have the return loss appreciable than the commonly required return loss 10 dB level. Due to the application of load to the IFA, significantly increases peak return loss as shown in Fig. 10. IFA has 10 dB return loss bandwidth of 150 MHz (frequency range 2355 – 2505 MHz) while LIFA has 155 MHz (2370 – 2525 MHz) bandwidth. From the obtained results, both antennas fully cover the 2.4 GHz (2400 – 2485 MHz) ISM band. Application of load increases the antenna return loss bandwidth by 3.33 %. Peak return loss of the antennas for 2.4 GHz band is -25.7229 and -30.9563 dB respectively.

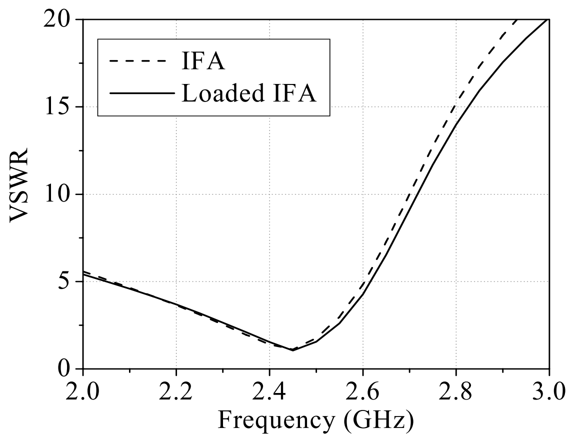


Fig. 9. VSWR variation of proposed IFA and LIFA as a function of frequency.

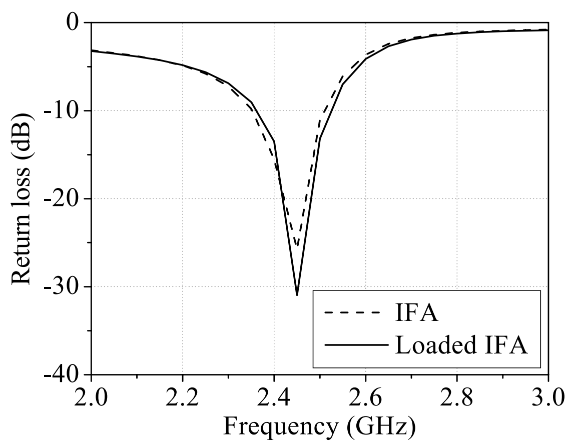


Fig. 10. Return loss variation of proposed IFA and LIFA as a function of frequency.

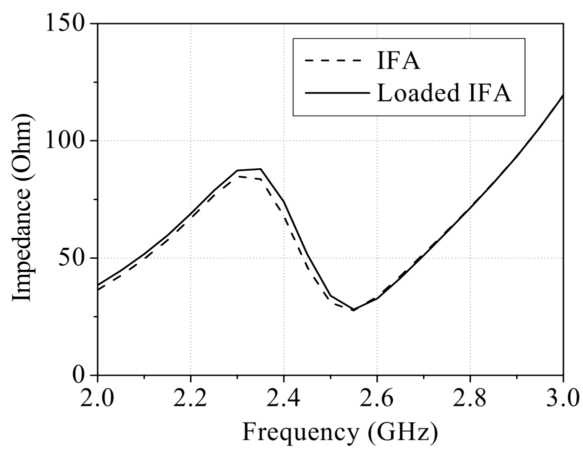


Fig. 11. Impedance variation of proposed IFA and LIFA as a function of frequency.

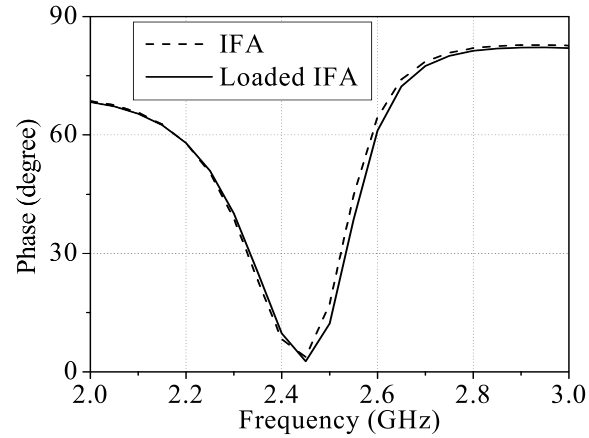


Fig. 12. Phase variation of proposed IFA and LIFA as a function of frequency.

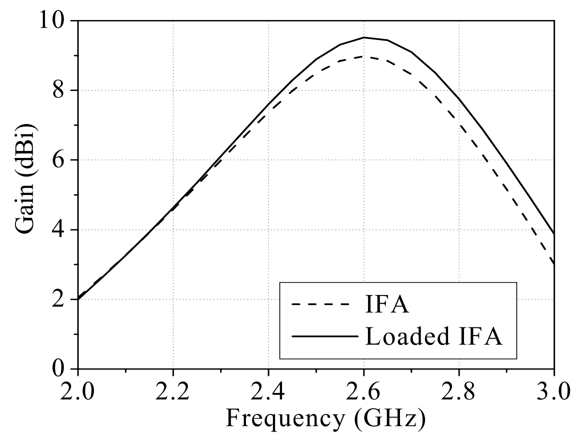
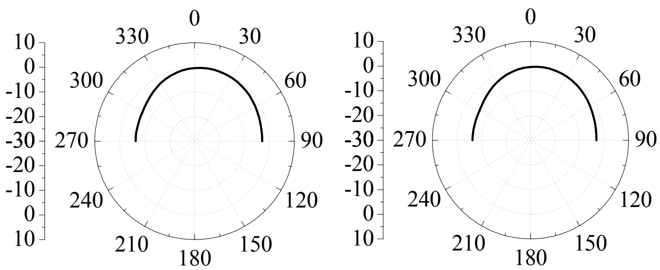


Fig. 13. Total gain variation of proposed IFA and LIFA as a function of frequency.

Figures 11 and 12 show the antennas input impedance and phase variation with frequency. For better impedance matching with the 50 Ω micro-strip line or coaxial connector the antenna input impedance should be near about 50 Ω. The antennas have input impedance of 46.130 and 51.649 Ω respectively at 2.45 GHz. Thus with the application of load to IFA causes to improve the antenna input impedance and very close to matching impedance of 50 Ω. Also load has minimal effect on the antenna phase. Total gain variations of IFA and LIFA within the 10 dB return loss bandwidth are shown in Fig. 13. From the figure gain of IFA varies from 7.37 to 8.5 dBi while gain of LIFA varies from 7.6 to 8.89 dBi means less than 1.13 and 1.29 dBi gain variation respectively within the antenna return loss bandwidth. Thus the antennas have stable gain within the antenna operating bandwidth.

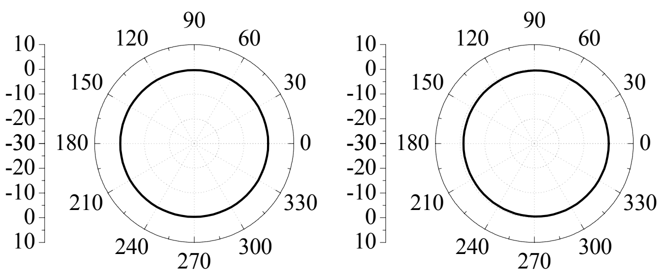
TABLE II
COMPARISON BETWEEN THE PARAMETERS OF IFA AND LIFA

Antenna Parameters	IFA	LIFA
VSWR	1.1091	1.0583
Peak return loss (dB)	-25.7229	-30.9563
Peak gain (dBi)	8.50	8.89
Input impedance (Ω)	46.130	51.649
Phase (degree)	3.724	2.659
Bandwidth (MHz)	150	155



(a) (b)

Fig. 14 Total gain pattern of (a) IFA (b) LIFA at 2.45 GHz in vertical plane (XZ/YZ plane).

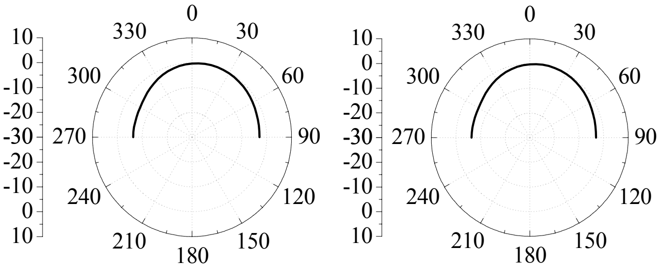


(a) (b)

Fig. 15. Total gain pattern of (a) IFA (b) LIFA at 2.45 GHz in horizontal plane (XY plane).

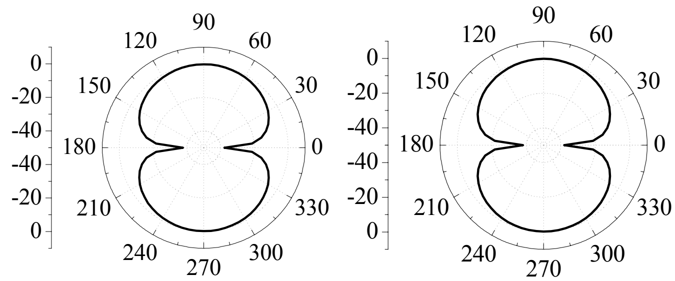
Table II represents the proposed antennas parameters comparison. From the obtained results introduction of load to the IFA improves the antenna performance parameters significantly specially for antenna input impedance, VSWR and return loss.

Fig. 14 represents the normalized total gain pattern of the antennas in vertical plane (XZ/YZ plane) and Fig. 15 represents the normalized total gain pattern in horizontal plane (XY plane). In XZ/YZ plane the antennas have radiation characteristic like half circle while in XY plane it is almost omnidirectional.



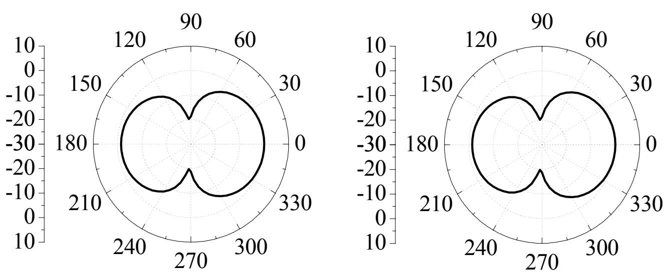
(a) (b)

Fig. 16. Vertical gain pattern of (a) IFA (b) LIFA at 2.45 GHz in vertical plane (XZ/YZ plane).



(a) (b)

Fig. 17. Horizontal gain pattern of (a) IFA (b) LIFA at 2.45 GHz in horizontal plane (XY plane).



(a) (b)

Fig. 18. Vertical gain pattern of (a) IFA (b) LIFA at 2.45 GHz in horizontal plane (XY plane).

Fig. 16 shows the antennas normalized vertical gain pattern in vertical plane (XZ/YZ plane) and Fig. 17 represents the antennas normalized horizontal gain pattern in horizontal plane (XY plane). From the obtained patterns antennas have vertical radiation characteristics in XZ/YZ plane as like monopole antenna and the horizontal gain in XY plane as like dipole antenna. Moreover the antennas have no horizontal gain in XZ/YZ plane. Fig. 18 represents antennas vertical gain in XY plane in normalized form. A comparison of peak gain between proposed antennas and references antennas for 2.4 GHz ISM band are listed in Table III.

TABLE III
GAIN COMPARISON BETWEEN THE REFERENCE AND PROPOSED ANTENNAS

Antenna	**Peak gain (dBi) at 2.4 GHz ISM Band**
IFA (Proposed)	8.50
LIFA (Proposed)	8.89
Chip antenna [1]	3.5
Printed circuit board wire antennas on FR4 substrate[2]	2.0
Inverted-F antenna printed on a PCMCIA card [3]	2.5
Compact monopole antenna [4]	1.354
Compact micro-strip antenna based on shorting pin technique [5]	0
Printed integrated inverted-F antenna [6]	1.5
Double-Z-slot antenna [7]	1.4
Triple-Z-slot antenna [7]	-1.4
The micro-strip line fed half-cylindrical dielectric resonator antenna [9]	5.5 (E-plane) 3.5 (H-plane)
Micro-strip coupled printed inverted-F antenna [10]	2.0
Rectaxial antenna [11]	2.2
Equilateral-triangular slot antenna (ETSA) [12]	2.8

A chip antenna suitable to be mounted above the system ground plane [1], printed circuit board wire antennas on a FR-4 substrate [2], inverted-F antenna printed on a PCMCIA card [3], compact monopole antenna [4], compact micro-strip antenna based on shorting pin technique [5], printed integrated IFA [6], multi-slot antenna [7], micro-strip line fed half-cylindrical dielectric resonator antenna (DRA) [9], micro-strip coupled printed IFA [10], rectaxial antenna [11], equilateral-triangular slot antenna (ETSA) [12] suffer from the gain limitations for the 2.4 GHz ISM band. But the gain of the proposed antennas is much higher as shown in Table III with stable gain variation within the antenna bandwidth than the antennas proposed earlier.

IV. CONCLUSION

A simple structured low profile IFA and LIFA suitable to be applied in a portable device as an internal antenna having high gain property for the 2.4 GHz ISM band are presented. Also effects of antenna geometry parameters on the performance of the antennas are presented. The proposed antennas cover the 2.4 GHz band by 100%. Suitable structured loading to the IFA causes increase in antenna bandwidth by 3.33%. In addition loading also helps in improvement of antenna VSWR, return loss, gain, antenna input impedance and phase. Due to the compact area occupied, the proposed antennas are promising to be embedded within the different mobile devices employing 2.4 GHz ISM band applications. Our future target is to design low profile planar LIFA to support multi-band operation.

REFERENCES

[1] K.- L. Wong and C.- H. Chang, “WLAN Chip Antenna Mountable Above the System Ground Plane of a Mobile Device,” *IEEE Transactions on antennas and Propagation*, Vol. 53, No. 11, pp. 3496-3499, 2005.

[2] H. Y. D. Yang, “Miniaturized Printed Wire Antenna for Wireless Communications,” *IEEE Antennas and Wireless Propagation Letters*, Vol. 4, pp. 358- 361, 2005.

[3] C. Soras, M. Karaboikis, G. Tsachtsiris and V. Makios, “Analysis and Design of an Inverted-F antenna Printed on a PCMCIA Card for the 2.4 GHz ISM Band,” *IEEE Antennas and Propagation Magazine*, Vol. 44, No. 1, pp. 37-44, 2002.

[4] J. Jung, H. Lee and Y. Lim, “Compact Monopole Antenna for Dual ISM-Bands (2.4 and 5.8 GHz) Operation,” *Microwave and Optical Technology Letters*, Vol. 51, No. 9, pp. 2227-2229, 2009.

[5] X. YU, G. LI and Z. WANG, “Design of Compact 2.45 GHz Microstrip Antenna,” In *Proc. IEEE International Symposium on Microwave, Antenna, Propagation and EMC Technologies for Wireless Communications*, pp. 153-156, 2005.

[6] M. Ali and G. J. Hayes, “Small Printed Integrated Inverted-F Antenna for Bluetooth Application,” *Microwave and Optical Technology Letters*, Vol. 33, No. 5, pp. 347- 349, 2002.

[7] C. -J. Wang and S. -W. Chang, “Studies on Dual-Band Multi-Slot Antennas,” *Progress in Electromagnetics Research, PIER*, Vol. 83, pp. 293–306, 2008.

[8] C. A. Balanis, “*Antenna Theory: Analysis and Design*,” Third Edition, John Wiley & Sons, Inc., Hoboken, New Jersey, Canada, 2005.

[9] A. V. P. Kumar, V. Hamsakutty, J. Yohannan and K. T. Mathew, “Micro-strip line-Fed Half-Cylindrical Dielectric Resonator Antenna for 2.4-GHz WLAN Application,” *Microwave and Optical Technology Letters*, Vol. 48, No. 4, pp. 724-726, 2006.

[10] C. -M. Su, K. -L. Wong, W. –S. Chen and Y. –T. Cheng, “A Microstrip-Coupled Printed Inverted-F Monopole Antenna,” *Microwave and Optical Technology Letters*, Vol. 43, No. 6, pp. 470-472, 2004.

[11] Griogair W. M. Whyte, Neil Buchanan, Iain Thayne, "An Omnidirectiona, Low Cost, Low Profile, 2.45 GHz Microstrip Fed Rectaxial Antenna for Wirelss Sensor Network Applications," In *Proc. Loughborough Antennas and Propagation Conference*, 2006.

[12] J. –W. Wu, “2.4/5-GHz Dual-Band Triangular Slot Antenna with Compact Operation,” *Microwave and Optical Technology Letters,* Vol. 45, No. 1, pp. 81- 84, 2005.

[13] S. Schulteis, C. Waldschmidt, C. Kuhnert and W. Wiesbeck, “Design of a Capacitively Loaded Inverted-F Antenna for Wireless-LAN Applications,” In *proc. International ITG Conference on Antennas, German*, 2003.

[14] G. J. Burke and A. J. Poggio, *“Numerical Electromagnetic Code-2,”* Ver. 5.7.5, Arie Voors, 1981.

[15] M.- C. T. Huynh, “*A Numerical and Experimental Investigation of Planar Inverted-F Antennas for Wireless Communication Applications,*” Virginia Polytechnic Institute and State University, 2000.

[16] K. Hirisawa and M. Haneishi, “*Analysis, Design, and Measurement of small and Low-Profile Antennas,*” Artech House, Boston, 1992.

[17] *http://en.wikipedia.org/wiki/ISM_band*