Numerical and Experimental Analysis of Impedance Matched Inverted-L and Stair Inverted-L Antenna for 5 GHz WLAN Operation

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Abstract—**This paper presents impedance matched high gain inverted-L antenna (ILA) and stair ILA for 5 GHz wireless local area network (WLAN) by means of numerical and experimental analysis. Numerical simulation is carried out using method of moments in Numerical Electromagnetic Code (NEC-2) and agilent vector network analyzer, watts antenna trainer, and microwave engineering trainer are used for the measurement. The experimental results show that ILA and stair ILA has 10-dB return loss bandwidth of 650 MHz (5170 – 5820 MHz) and 360 MHz (5320 – 5680 MHz) respectively covering the unlicensed national information infrastructure (U-NII) mid frequency bands for 5 GHz WLAN operation. Omnidirectional radiation patterns are achieved for both antennas in XY plane and the antennas have peak gain of 6.65 and 10.987 dBi respectively at center frequency (5.5 GHz) of antenna operating bandwidth. Moreover, the antennas have radiation efficiency of greater than 84% and 91% respectively within the return loss bandwidth.**

Index Terms— **ILA, Matching network, Stair ILA, WLAN.**

I. Introduction

WLAN links devices like notebook, video game console, smart phone, MP3 player, personal digital assistant etc. transmit/receive information through air via a wireless distribution method known as orthogonal frequency division multiplexing or spread spectrum. WLAN standards including IEEE 802.11a/b/g systems were established by the IEEE 802.11 group. IEEE 802.11b/g uses the 2.4 GHz industrial, scientific and medical (ISM) band and unlicensed national information infrastructure (U-NII) band used in IEEE 802.11a, which offers more non-overlapping channels than the channel offered in the 2.4 GHz ISM frequency band. This U-NII band has three separate frequency ranges as 5.15-5.35, 5.47-5.725 and 5.725-5.875 GHz. Various antennas designed on the printed circuit board (PCB), FR4 substrate have been proposed for 802.11a (5 GHz band) e.g., printed-spiral-strip [1] and T-shaped, double T-shaped, two step tapered monopole antennas [2-4].

A simple strip monopole has the advantages of low profile but the presence of horizontal strip to form T-shaped monopole introduces a capacitive coupling with the ground plane causes impedance matching problem which can be reduced by the use of a shorting line to form shorted T-shaped monopole antenna but the modified antenna has low gain though the bandwidth is improved [2-3]. Microstrip feeding provides higher efficiency in microstrip antenna design, whereas this feeding technique is used in two step tapered-monopole antenna to improve the antenna gain but the gain is limited [4-6]. Low antenna impedance problem can be solve by designing dipole and folded dipole antennas because they shows higher antenna impedance than monopole antenna but planar diversity folded dipole and M-slot folded patch antenna has lower gain in associated application [5-8]. Asymmetric annular-ring patch fed by a 50 Ω microstrip line, band-notched planar monopole antenna composed of an asymmetric annular-ring patch and a stair-style ground plane, ring monopole antenna with double meander lines and tap monopole antenna support wide frequency ranges have been proposed for 5 GHz WLAN operation [9-12]. In coplanar waveguide (CPW)-fed slot antenna design impedance matching problem minimized by varying the angle of tapering and the distance from the center strip [13]. Thus, different monopole structures, slot antennas, planar antennas for 5 GHz WLAN operation suffer from gain limitations though other performance parameters of those antennas are in acceptable level [1, 2, 4, 8, 11, 13].

For the antenna size reduction capacitive load can be used without degrading the antenna performance [14-16]. In designing antenna is of compact size matching is the key to enhance the performance parameters. If the antenna input impedance does not matched with the impedance of feeding cable/connector, microstrip line equivalent to resistor, inductor and capacitor (RLC) network can be used. For the RLC matching two

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techniques proposed one is parallel RLC resonator cell in series [17] and the other one is coupling element based method [18]. Inverted-L antenna (ILA) is of simple structure and compact size but designing of ILA is a problem because of its lower input impedance [19].

The purpose of this work is to propose a new antenna with high gain for 5 GHz WLAN operation. In this paper impedance matched, high gain ILA and loaded ILA titled as stair ILA is proposed and analyzed by means of numerical simulation and their performance tested by means of experimental measurement. Using filter transformation the input impedance matching problem of the antennas is solved by designing microstrip line equivalent to matching RLC network.

The antennas numerically analyzed using method of moments (MoMs) in numerical electromagnetic code (NEC-2) [20]. For the simulation we considered the RT/duroid 5880 substrate with permittivity of $\varepsilon_r = 2.2$ and substrate thickness of 1.58 mm. For the measurement of return loss Agilent Vector Network Analyzer is used and the gain and radiation pattern measured using Watts Antenna Trainer. Voltage standing wave ratio (VSWR) of the antennas measured using Microwave Engineering Trainer. In the simulation the central conductor of the feeding cable/connector is connected to the antenna feeding point and the outer conductor connected to the ground plane.

II. ANTENNAS AND MATCHING NETWORKS DESIGN

Starting from the low profile printed T-shaped monopole antenna [2] we examined the possibility of increasing the antenna gain by simplifying the structure of the antenna for 5 GHz WLAN operation. Inverted-L antenna is of very simple structure than T-shaped monopole antenna. Fig. 1 shows the structure of ILA and Fig. 2 shows the modified ILA including impedance matching microstrip line equivalent to matching RLC network. When a strip perpendicular to the monopole is added then it is called ILA. During simulation the dimension of the ground plane considered as 60×60 mm^2.

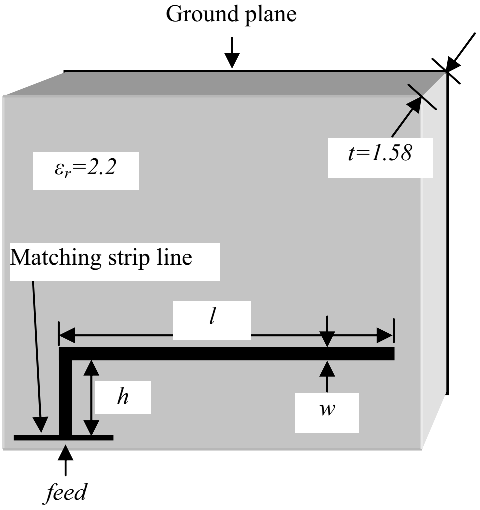


Figure 1. Inverted-L antenna (ILA).

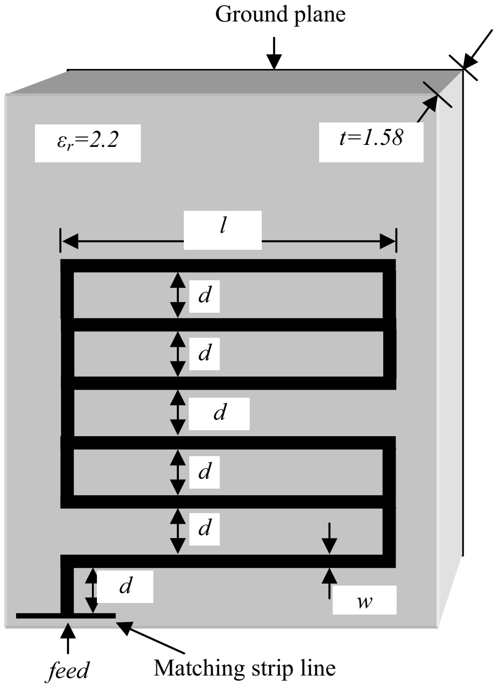


Figure 2. Stair inverted-L antenna (stair ILA).

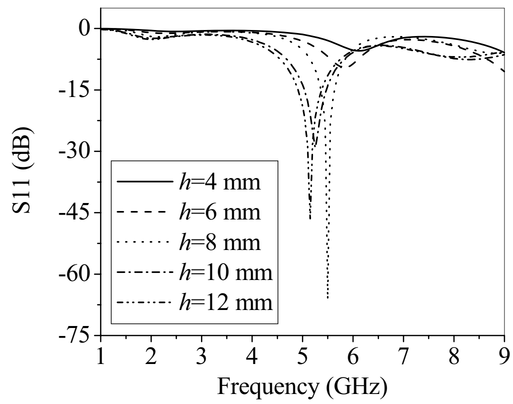


Figure 3. Effects of height (*h*) on the return loss of ILA of Fig. 1.

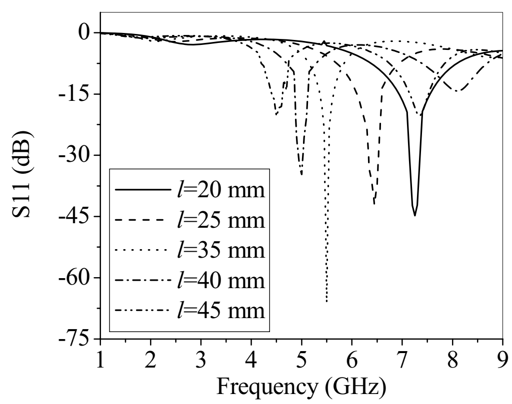


Figure 4. Effects of length (*l*) on the return loss of ILA of Fig. 1.

Effects of height on the return loss (S11) of the antenna (ILA) as a function of frequency are shown in Fig. 3. From the simulated results as the *h* decreases, the antenna resonance frequency shifted to the lower frequency. Fig. 4 represents the effect of *l* on S11 of ILA structure of Fig.1, and Fig. 5 represents the effect of strip width (*w*). From the simulated results of Fig. 4 and 5, as *l* increases the resonance shifted to lower frequency and similar cases take place for *w*. More negative value of antenna return loss means more effectively power transmitted by the antenna in electromagnetic form into free space. From the simulation results obtained, the optimum antenna geometry configuration of ILA is *l* = 35 mm, *h* = 8 mm, and *w* = 3 mm.

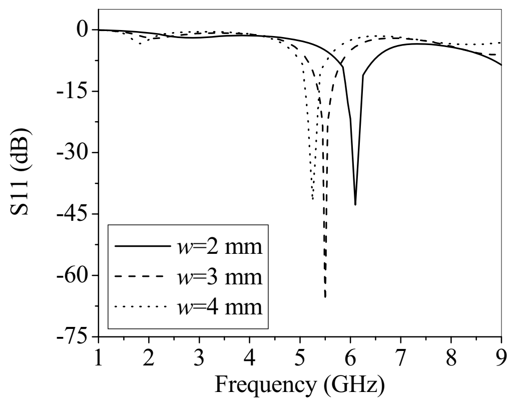


Figure 5. Effects of width (*w*) on the S11 of ILA of Fig. 1.

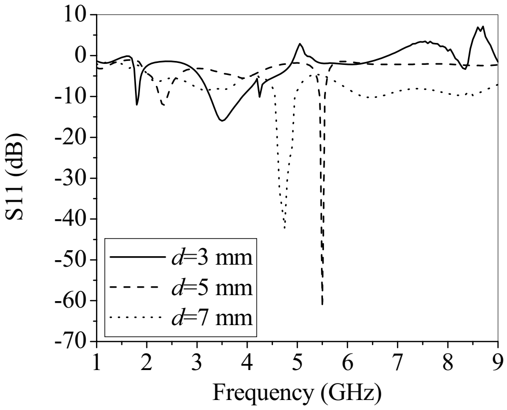


Figure 6. Effects of spacing (*d*) on the return loss of stair ILA of Fig. 2.

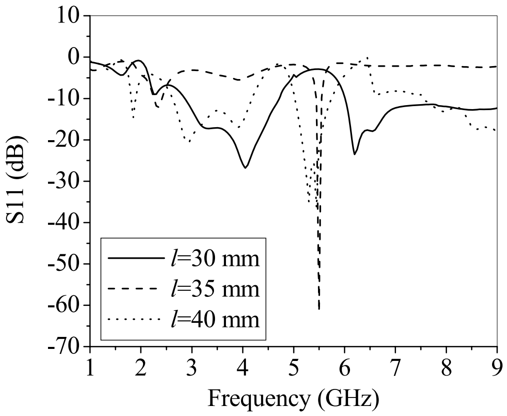


Figure 7. Effects of length (*l*) on the return loss of stair ILA of Fig. 2.

If load is applied to the ILA by using of similar structure, then the modified structure is titled as stair ILA. Variation of return loss of stair ILA with the variation of separation (*d*) as a function of frequency is shown in Fig. 6 and Fig. 7 represents the effects of length *l*. Small values of *d* and *l* cause's degradation of return loss hence poor power radiated from the antenna into free space. But increasing *d* and *l* shifts the antenna resonance to the lower frequency with decreasing return loss. Effects of *w* on S11 are shown in Fig. 8. From the obtained results *w* has similar effects as *d* on stair ILA. From the simulation results of stair ILA as shown in Fig. 6, 7, and 8, the optimum dimension of the stair ILA is *d* = 5 mm, *l* = 35 mm, and *w* = 3 mm.

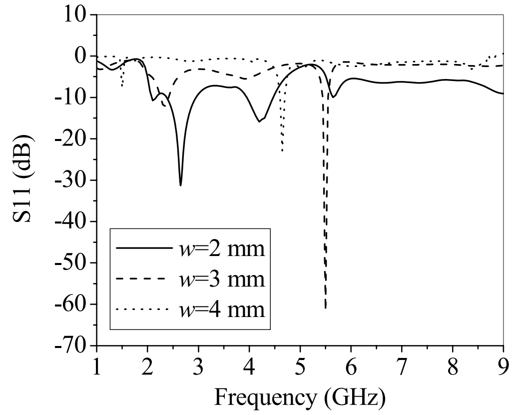


Figure 8. Effects of width (*w*) on the S11 of stair ILA of Fig. 2.

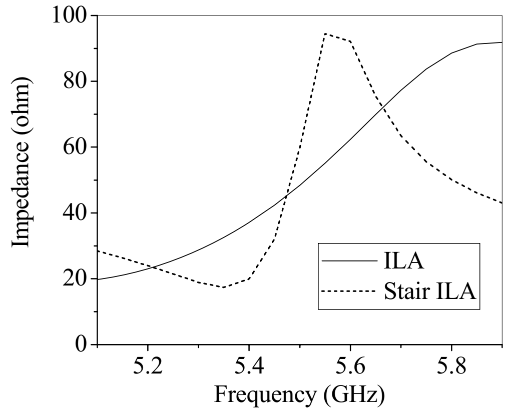


Figure 9. Impedance variation of ILA and stair ILA without matching.

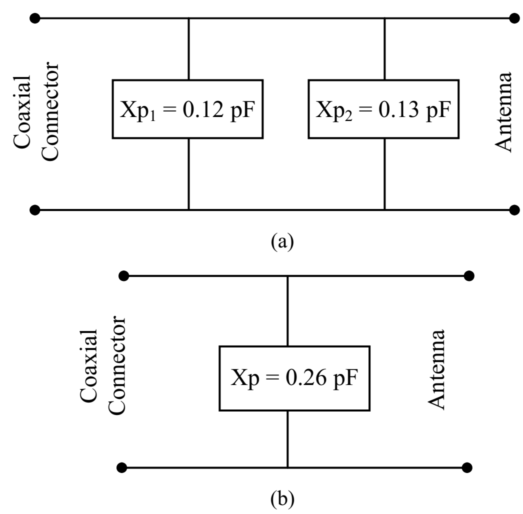


Figure 10. Matching network with its parameters for (a) ILA (b) stair ILA.

From the simulated results, the impedance of the proposed ILA and stair ILA is 48.39 Ω and 59.84 Ω respectively at its resonant frequency (5.5 GHz) as shown in Fig. 9. To match the antenna with the feeding cable/connector impedance matching network is required in between them which act as an impedance transformer. Fig. 10 shows the RLC matching networks used in between them as an impedance transformer. This matching network (shown in Fig. 10) converted into equivalent microstrip line using filter transformation theory [21]. The width (W) of the equivalent microstrip line is calculated as

$$\frac{W}{d}=\frac{8e^{A}}{e^{2A}-2} \quad \text{for } W/d<2 \qquad (1)$$

$$\frac{W}{d}=\frac{2}{\pi}\left[B-1-\ln(2B-1)+\frac{\varepsilon_r-1}{2\varepsilon_r}\left\{\ln(B-1)+0.39-\frac{0.61}{\varepsilon_r}\right\}\right] \text{for } W/d>2 \qquad (2)$$

Where,

$$A=\frac{Z_o}{60}\sqrt{\frac{\varepsilon_r+1}{2}}+\frac{\varepsilon_r-1}{\varepsilon_r+1}\left(0.23+\frac{0.11}{\varepsilon_r}\right)$$

$$B=\frac{377\pi}{2Z_o\sqrt{\varepsilon_r}}$$

Here d (= 1.58 mm) is the dielectric substrate thickness, ε_r is relative dielectric constant, and Z_o is characteristics impedance of the line. According to the theory of transformation, the impedance scaled and frequency transformed element values for the circuit of Fig. 10 is

$$L_1'=\frac{L_1Z_o}{\omega_o\Delta} \qquad (3)$$

$$C_1'=\frac{\Delta}{\omega_oL_1Z_o} \qquad (4)$$

$$L_2'=\frac{\Delta Z_o}{\omega_oC_2} \qquad (5)$$

$$C_2'=\frac{C_2}{\omega_o\Delta Z_o} \qquad (6)$$

Here $\Delta=\frac{\omega_2-\omega_1}{\omega_o}$, $L_1=g_1$ and $C_2=g_2$ and the values of g_1 and g_2 taken from the element values for maximally flat low pass filter prototype [21] and ω_o is the angular resonant frequency. From the values of $C_1'=X_{p1}$ and $C_2'=X_{p2}$ the product βl is calculated using (7) for the electrical length of the inductor section and (8) for the electrical length of the capacitor section as

$$\beta l=\frac{LR_o}{Z_h} \quad \text{(Inductor)} \qquad (7)$$

$$\beta l=\frac{CZ_l}{R_o} \quad \text{(Capacitor)} \qquad (8)$$

Where R_o is the filter impedance and L and C are normalized element values. Fig. 11 shows the phase angle variation of ILA and stair ILA. Due to the mismatch, the phase shift is 6.244^0 and 5.006^0 for ILA and stair ILA respectively. The matching filter equivalent microstrip transmission line length calculated as

$$\phi=\beta l=\sqrt{\varepsilon_e}k_ol \qquad (9)$$

$$k_o=\frac{2\pi f}{c} \qquad (10)$$

$$l=\frac{\phi(\pi/180)}{\sqrt{\varepsilon_e}k_o} \qquad (11)$$

Where $\varepsilon_e=\frac{\varepsilon_r+1}{2}+\frac{\varepsilon_r-1}{2}\frac{1}{\sqrt{1+12d/W}}$

Here ϕ is the phase shift due to mismatch, ε_e is the effective dielectric constant. Using the values of βl calculated from (7) or (8) according to the characteristics of the impedance; the length of the impedance transformation line is calculated from (9), (10) and (11). According to the theory of filter transformation (step impedance resonator) as discussed above, Table I shows the length and width of the microstrip line designed equivalent to matching network of Fig. 10.

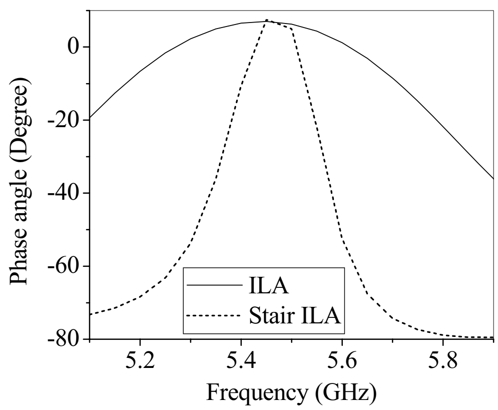


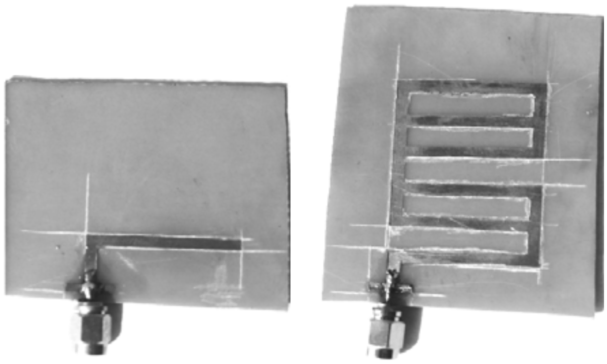
Figure 11. Phase shift of ILA and stair ILA under mismatch condition.

TABLE I.
IMPEDANCE MATCHING MICROSTRIP LINE PARAMETERS

Antenna name	Length, l (mm)	Width, w (mm)
ILA	1.28	10.464
Stair ILA	1.34	10.464

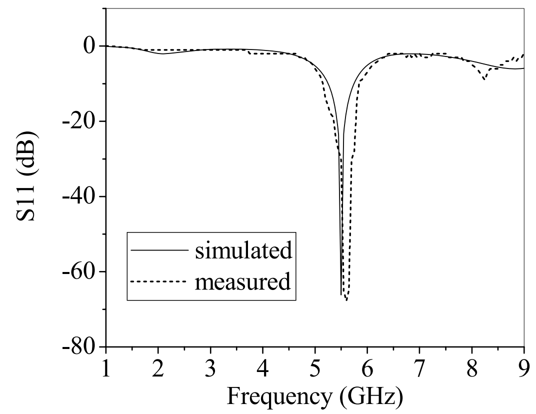
III. Simulation and Measurement Results

The antennas was constructed and tested. In experimental design copper is used as a ground plate with thickness of 0.127 mm. Antenna layout designed on the copper plate of RT/duroid 5880 substrate manually using permanent marker pen and $FeCl_3$ is used to remove the unwanted copper material section. In the experimental design the choice of RT/duroid 5880 because its cost is lower than the substrate of higher dielectric constant materials. In measurement, central conductor of the feeding cable is connected to the antenna feeding point and the outer conductor soldered to the ground plane.

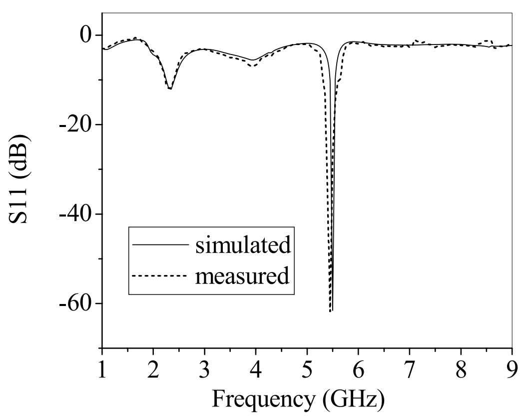


(a) (b)

Figure 12. Constructed prototype of the (a) ILA and (b) stair ILA.



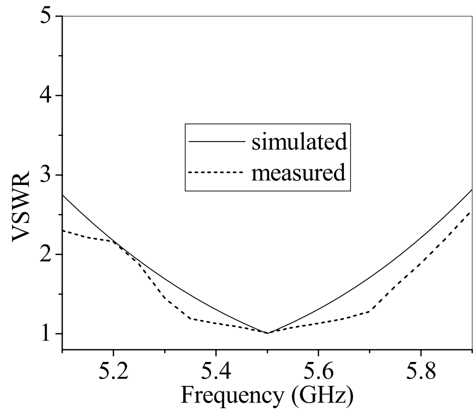
(a)



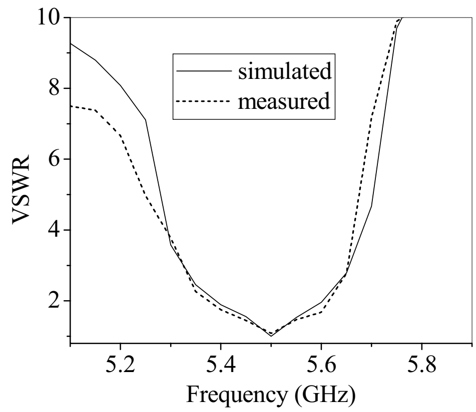
(b)

Figure 13. Measured and simulated return loss of (a) ILA and (b) Stair ILA.

Fig. 12 shows the implemented prototype of the antennas and Fig. 13 shows the measured and simulated return loss for the ILA and stair ILA. For the both antennas, the operating band centered at 5.5 GHz with good impedance matching. ILA has 10-dB return loss bandwidth of 650 MHz (5170 – 5820 MHz) and for stair ILA 360 MHz (5320 – 5680 MHz) covering the U-NII mid frequency bands for 5 GHz WLAN operation. ILA has much wider bandwidth that covers the U-NII low, mid and upper bands for WLAN operation. The variation of simulated and measured VSWR for ILA and stair ILA as a function of frequency are shown in Fig. 14. At resonant simulated and measured VSWR very closer to standard value 1.



(a)



(b)

Figure 14. Simulated and measured VSWR for (a) ILA and (b) stair ILA.

Fig. 15 and 16 shows the radiation pattern of ILA and stair ILA in vertical plane (XZ, YZ) and in horizontal plane (XY) at 5.5 GHz. The antenna is tested in normal laboratory environment for this reflection of wave's cause's abrupt change in the pattern in both planes. Simulated and measured radiation pattern agree each other quite well. One can observe from Fig. 17 that within the antenna bandwidth ILA has radiation efficiency greater than 84 % and stair ILA has greater than 91 %. Fig. 18 represents the variation of peak gain for both antennas as a function of frequency. The gain of ILA varies from 5.81 to 6.65 dBi within the return loss bandwidth and for stair ILA from 9.24 to 10.987 dBi.

Though ILA has more stable gain than the stair ILA but the gain of stair ILA is much higher than the ILA.

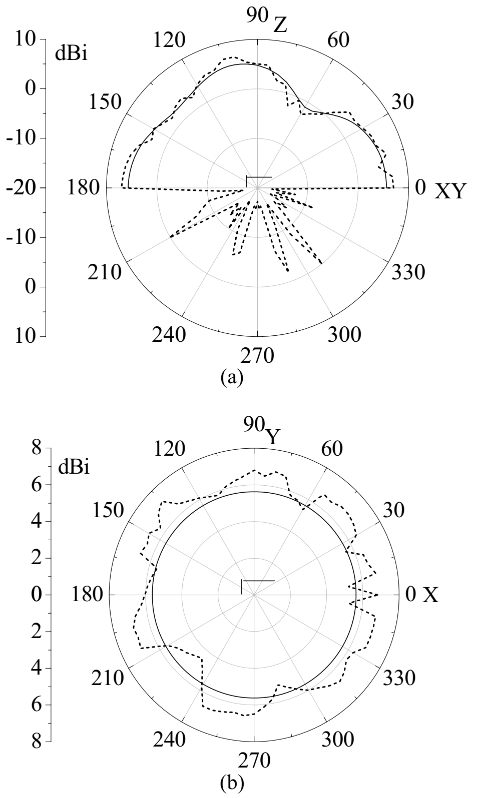


Figure 15. Simulated and measured radiation pattern of ILA at 5.5 GHz in (a) vertical plane (XZ, YZ), and (b) horizontal plane (XY).

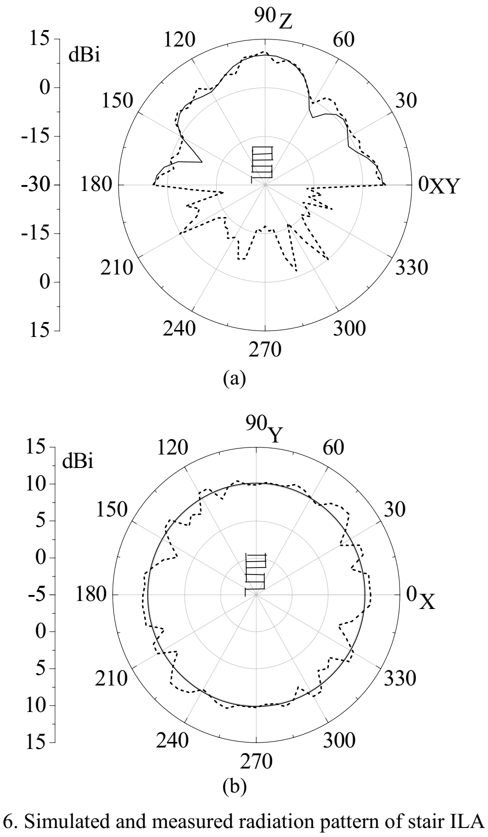


Figure 16. Simulated and measured radiation pattern of stair ILA at 5.5 GHz in (a) vertical plane (XZ, YZ) and (b) horizontal plane (XY).

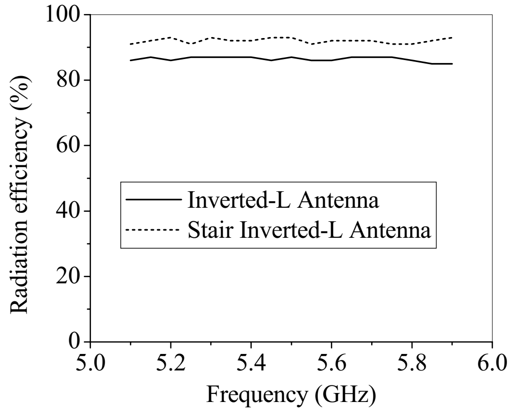


Figure 17. Simulated radiation efficiency of ILA and stair ILA as a function of frequency.

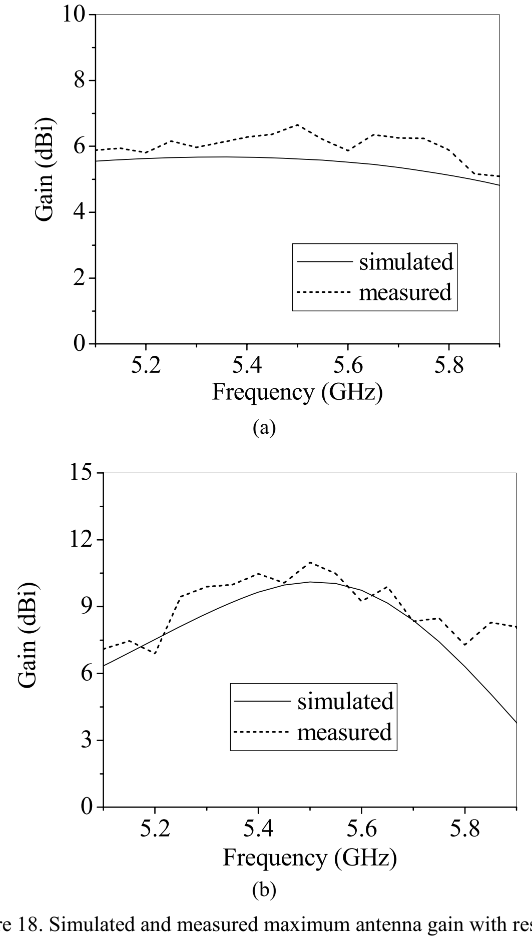


Figure 18. Simulated and measured maximum antenna gain with respect to the frequency for (a) ILA and (b) stair ILA.

Table II shows a comparison between the measured peak gain and peak return loss of the proposed and the existing antennas for 5 GHz WLAN operation where the antenna center frequency of 5.5 GHz. From the comparison table, ILA has higher gain than the antenna exist for the same application area. Stair ILA has much higher gain compared to other antennas. Moreover, ILA and stair ILA can transmit signal more effectively than the spiral strip [1], T-shaped monopole [2], two step tapered monopole [4], planar diversity folded dipole [8], slot [13], and CPW-feed slot [14] antennas because of their more negative return loss.

TABLE II.
GAIN AND RETURN LOSS COMPARISON BETWEEN PROPOSED AND REFERENCE ANTENNAS FOR 5 GHZ WLAN OPERATION

Antenna name	Measured peak gain (dBi)	Measured peak return loss (dB)
Printed-Spiral-Strip antenna [1]	5.97	-20
Printed T-shaped monopole antenna [2]	3.87	-43
Two step tapered monopole antenna [4]	5.22	< -10
Planar diversity folded dipole antenna [8]	5.67	-28
Slot antenna [11]	5.91	-40
CPW-fed slot antenna [13]	3.97	-43
ILA	6.65	-68
Stair ILA	10.987	-62

IV. CONCLUSION

An impedance matched ILA and its modified structure named stair ILA have been analyzed and tested in this paper. It shows that both antennas have impedance mismatch with the feeding connector in normal condition (without matching line). Impedance transformation microstrip line is designed using the filter transformation theory of microstrip line to obtain matching between the antennas and feeding system. Under this condition both antennas show good return loss bandwidth and measured results agree with the simulated results well. It is observed from simulated and measured results that the gain of the ILA is improved significantly when suitable structured load is applied to the horizontal strip of the ILA. The analysis of the antennas also shows that it can easily be used at 5.5 GHz and the measured radiation patterns are well-behaved with high gain. Moreover, the proposed antennas are very promising to operate as a small-size internal antenna for the case of 5 GHz WLAN operation.

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