Chapter 8

Advancements and Prospects of Forward Directional Antennas for Compact Handheld RFID Readers

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Additional information is available at the end of the chapter

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1. Introduction

In the current age of rapid technological progress and development, radio frequency identification (RFID) technology has found many applications in various areas such as supply chain, warehouse, and retail store management. Alike mobile communications, the high data performance and compact profile are becoming obvious expectations of the users of handheld RFID devices. In this regard, directional antennas have a bright prospect for a more user friendly experience even in the rugged environments.

This chapter presents a comprehensive review of RFID technology concerning the prospects of directional especially forward directional antennas and propagation for multi-band operation. The technical considerations of directional antenna parameters are also discussed in details in order to provide a complete realization of the parameters in pragmatic approach to the directional antenna designing process, which primarily includes scattering parameters and radiation characteristics. The antenna literature is also critically overviewed to identify the possible solutions of the directional antennas to utilize in single and multi-band handheld RFID reader operation. However, it has been seen that these techniques can be combined to enhance the directional antennas with wider bandwidths and higher gain. Last but not least, the possibilities of forward-directional antennas which spectacularly use the surface wave for the radiation will be explored, and the difference with the conventional directional antennas with them will be discussed.

2. Prospects of forward directional antennas for handheld RFID readers

Radio frequency identification (RFID) technology having a huge potential with higher production efficiency, real-time inventory updates, greater product security and restricting counterfeit products, is becoming rapidly engaged in production, transportation, and retailing of products. On the investment front, more than 40% of shippers have increased their investment in RFID technology for supply chain applications (Research and Markets 2012). RFID technology is rapidly evolving due to (Cole P. H. 2003):

- increased awareness of the technology;
- development of improved techniques for multiple tag reading;
- realization in the business community of the benefits of widespread adoption in the supply chain;
- adoption by designers of sensible concepts in the arrangement of data between labels and databases;
- development of efficient data-handling methodologies in the relevant supporting communication networks;
- appreciation of the need for cost reduction, and
- development of new manufacturing techniques that will achieve manufacture of billions of labels at acceptable costs.

The global RFID market is projected to reach US$18.7 billion by the year 2017 where growth will be primarily driven by fast paced deployments of RFID projects in developing Asian countries, especially in China. Developments in the field of smart labels are projected to hold the key to future revenue growth (Research and Markets 2012). However, RFID is now at a stage where there are potentially large benefits from wider application but still some barriers remain.

It is widely known that handheld RFID readers need more compactness in design than fixed or mounted readers. Thus it is more challenging to make the designs more compact to meet the expectations of the users. Similar to mobile communications, the multi-standard capability, high data performance and compact profile are becoming obvious expectations of the users of RFID devices. Among the frequency bands that have been assigned to RFID applications, higher-frequencies have the advantage of high data transfer rate with far field detection capability (Islam et al. 2010).

Directional antennas usually radiates in a directive manner. They force the electromagnetic energy into a specific and desired direction. This type of antenna decreases the interferences of other tags in the undesired direction, while also increasing the reading range as well, since the gain of the directional antennas are higher than the omni-directional antennas.

In order to reduce the overall size of the handheld RFID readers, the need to reduce the size of the antenna is highly essential. But reducing the size of antenna limits its performances.

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Also when the operating frequency of RFID systems rises to the microwave region (2.45/5.8 GHz bands), the reader antenna design becomes more delicate and critical. This is especially true when a directional antenna is needed for handheld applications. However, it is a popular practice for handheld RFID readers to assemble a vertically radiating directional antenna in right angle with the reader; thus the radiation literally becomes front-directional to the reader (Fig. 1). This arrangement significantly increases the actual RFID reader profile. Hence it is greatly advantageous for a compact RFID reader to produce antennas with front-directional radiation patterns.

(a) (b)

Figure 1. Handheld RFID reader with an external antenna module (a) (Ukkonen et al. 2007), (b) (MC3190-Z Handheld RFID Reader 2012).

3. Evolution of forward directional antennas & limitations: A literature scenario

In this section we will focus on the development of multi-band antenna designing process. In last few years, there are a lot of antennas multi-band antennas has been designed, but most of them are omni-directional in radiation manner. But still some novel structures can be found in recent researches, that provide multi-band operation with directional radiation characteristics (Li et al. 2012, Mobashsher et al. 2010, Sabran et al. 2011). However, all of these antennas use a big metallic ground plane in order to reflect the radiation from the patch. Hence the actual applied antenna profile is bigger than the patch alone. So these antennas are not suitable for portable RFID applications. Another technique is widely applied in antenna domain in order to achieve directional radiation patters- the utilization of surface waves (also called trapper waves) (Zucker 1993).

In literature, surface-wave or end-fire antennas are mostly used to produce front-directional radiation patterns. Folded dipole (Fan et al. 2009) and folded (Yang et al. 2010) antennas are reported to have this type of radiation. Although these antennas produce good directional patterns, they are inappropriate for compact multi-band applications as they are printed in both sides of the substrate and resonate only in one operating frequency. The reported conformal (Dong & Huang 2011) and plate (Yao et al. 2011) end-fire antenna with good radiation patterns have a bulky profile and are unsuitable for a portable use. It is worth to mention that for handheld compact applications, uni-planar antennas are more beneficial than double-sided microstrip in terms of compactness and the integration capability with solid-state active and passive components. The uni-planar compact yagi antenna, reported in (Nikitin & Rao 2010), is difficult to be incorporated with the circuitry due to its construction.

Several quasi-Yagi (Kan et al. 2007) and bow-tie (Eldek et al. 2005) antenna provides wide bandwidth, but they do not give flexibility to choose specific frequencies of operation, thus in turn increases interference with neighboring operating bands. The frequency reconfigurable planar quasi-Yagi antennas (Qin et al. 2010) are also unsuitable for its complex feeding structure. A printed dipole (He et al. 2008) with etched rectangle apertures on surface has reported to have dual-band characteristics; but it suffers mostly in the consistency of the radiation patterns. Again, these are mostly double sided planar antennas. A multi-band Quasi-Yagi-type antenna is reported in (Ding et al. 2011). However, the feeding transition takes a wide area which in turn increases the antenna size significantly. It is obvious that the front directionality of the antennas will provide the handheld RFID readers a compacter solution and there is a huge research interest in this area in recent years to achieve optimum solution for the practical application.

4. Possibilities of forward-directional antennas for compact handheld RFID readers: An example from single & multi-band perspectives

Forward directional antennas can provide the RFID readers the desired compactness both in single and multi-band applications. In this section an example of forward directional antenna is discussed which is enhanced from single band to multi-band operation. The frequency of operation is chosen from the microwave ISM bands (2.45/5.8GHz), while the same methodology and design procedures are applicable for any combination of narrow RFID bands as the design has much flexibility. The details of the design process and the optimization are also discussed for the better understanding of the readers.

The flow chart in Fig. 2 describes the design and fabrication process of a desired single antenna. Firstly the requirements of the RFID antenna are collected according to the specifications of the RFID reader module. An extensive literature is reviewed for the design purpose. In this case some models are chosen which provides proper forward directionality. These are discussed in previous section. However, every design has some advantages and also some disadvantages. Proper understanding of the antenna operation is effective for proper chose of the antenna model. Meanwhile the familiarization with the simulation software IE3D EM simulator has been performed and an appropriate model is chosen for the design by using mathematical models. The design is simulated and its performance is examined and optimized until satisfactory result is obtained. When the optimized antenna is achieved, it is time to enhance the performances by using some techniques. This section is discussed more in the next sections. The last but not the least step is the fabrication process where the prototype is going to be built and finally the measurement of the antenna parameters for validation and comparison with the simulated results. At the end of this process the desired antenna with the given specification is attained. However, if any step fails to achieve its objectives, it is repeated again until the aims are met.

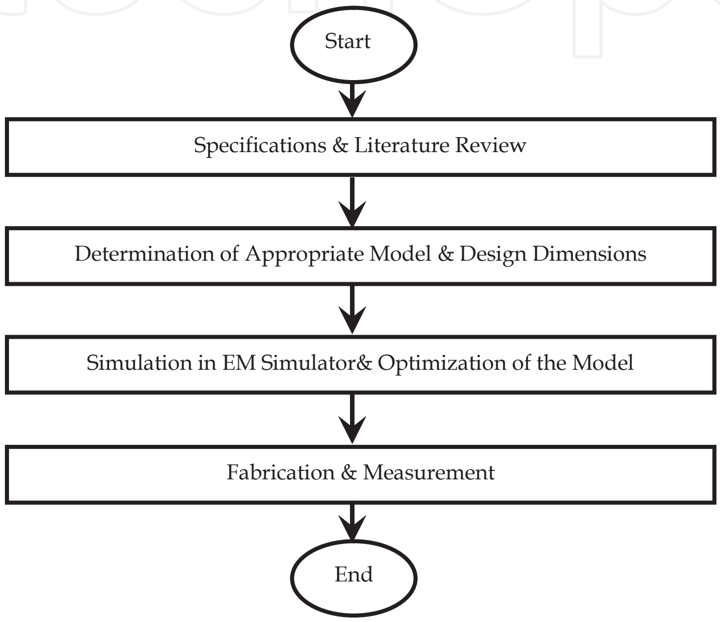

Figure 2. Flow chart design and fabrication process of a desired single band RFID antenna

The dual-band operation of the any antenna is an additional advantage. The design procedure of the dual band antenna is slightly different from the previously discussed the single band antenna. The design process is illustrated in the Fig. 3.

In order to meet the requirements of dual-band RFID reader antenna specifications, first the lowest cutoff frequency of the operation should be met. It is because of the fact that at the lowest frequency means the biggest wavelength in comparison to other higher frequencies and hence the respective current path should be the longest. Thus, the basic dimension of the antenna is defined by the lowest operating frequency. Electromagnetic simulation is an advanced technology to yield high accuracy analysis and design of complicated microwave and RF printed circuit, antennas and other electronic components. In antenna designing process, after the determination of the antenna dimensions with suitable model, the next step is to simulate the design in suitable electromagnetic software. The modeling and formulation are mainly derived through the use of Green's functions.

In simulation there may be some disagreements with calculated designed dimensions. In that case, the antenna should be optimized varying the parameters. When the lowest frequency is attained, then as the next step, further simulation and optimization is needed to meet the next operational frequency band with the same antenna. The possible solution is to achieve multi-resonance by employing notches, slots or additional current paths. Similarly, when optimizing, it should be taken care that the lowest frequency should not shift from the desired frequency. At the end of this design process, the antenna goes for prototyping and performance evaluation process.

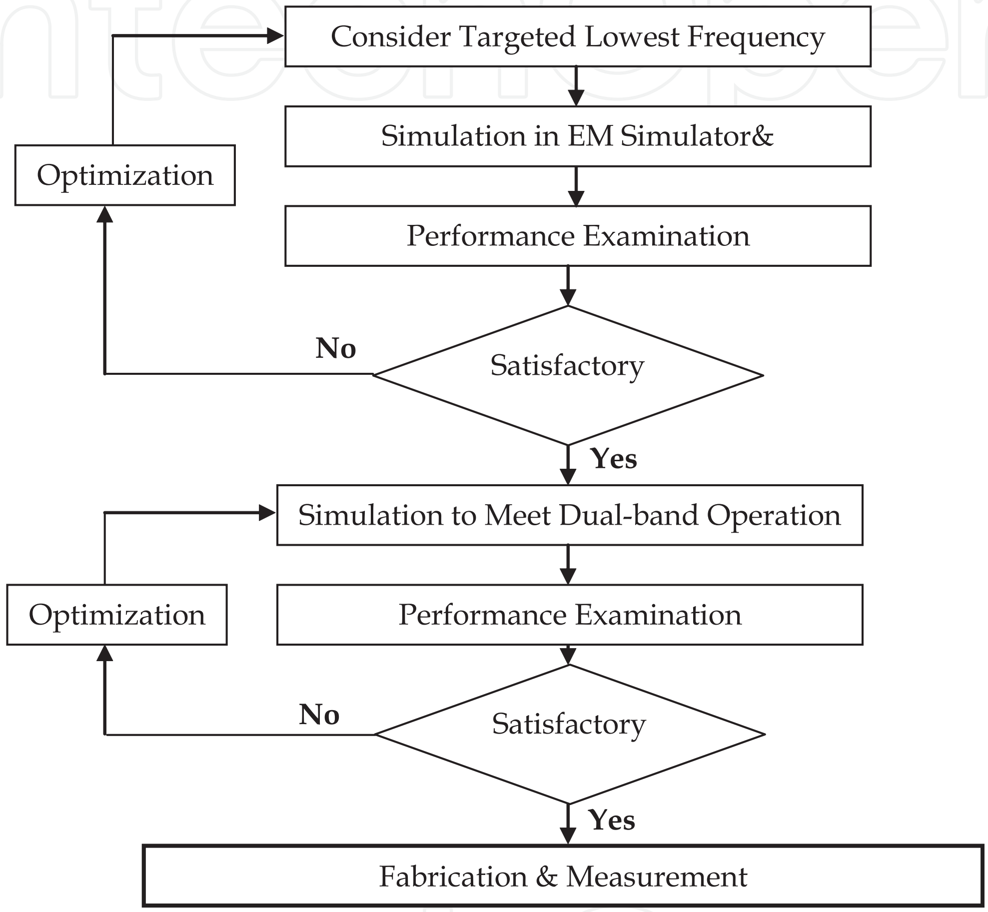

Figure 3. Flow chart simulation process of the multi-band RFID antenna

4.1. Antenna geometry

The schematic diagram of the proposed antenna is exhibited in Fig. 4. The antenna is fabricated on a low-loss substrate of medium permittivity (Rogers TMM4 ε_r = 4.5, $tan\delta$ = 0.002) with height 1.52 mm. Metallization of 1 oz copper cladding is used in only one side, which makes the antenna uni-planar and suitable to incorporate into the circuitry of the RFID reader. Also, the fabrication process of the antenna is relatively easy and cost effective. The antenna consists of a microstrip feeding line, two unsymmetrical ground planes and a folded strip with a small top branch. The width of the CPW feed line is fixed at F_w = 3mm. In order to achieve 50Ω characteristic impedance, the feeding line section (X-axis) is separated by a gap of g = 0.3mm from both right and left sides of ground plane. At the end, the antenna is

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fed by a 50Ω SMA coaxial connector from the side. Three triangular periodic open-end stub (POES) cells are infixed on the upper edge of each side of ground plane. The POESs are symmetrical with respect to the center line of the feeding strip in longitudinal direction (Y-axis). The POESs are optimized to improve the impedance matching of the antenna with no other effect on other characteristics of the antenna.

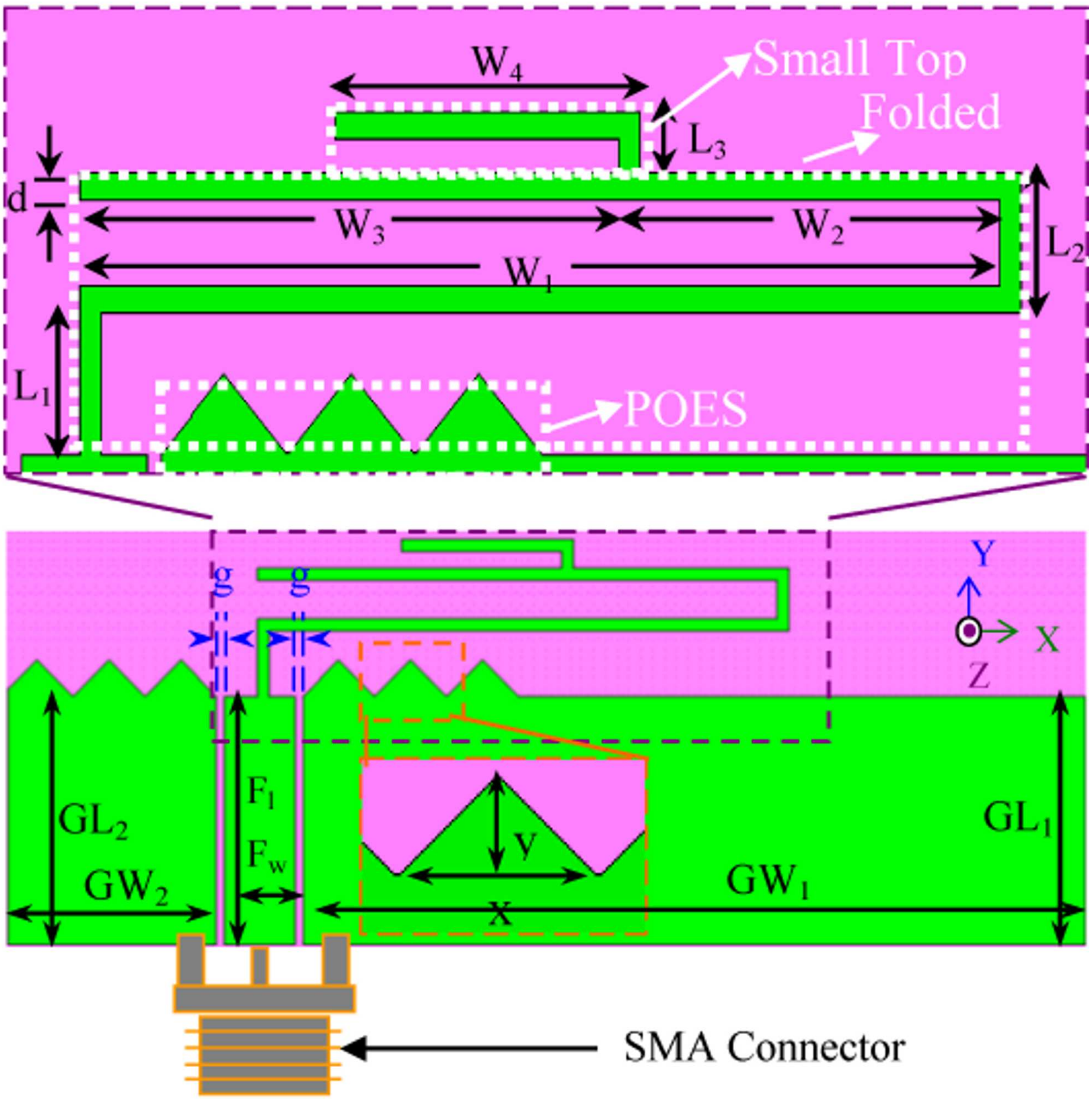

Figure 4. Geometric structure of the proposed antenna

4.2. Design procedure

Fig. 5 shows the design procedure of the proposed antenna. In design process, the lower band was first designed, since the antenna profile is usually circumscribed by the wavelength of lower frequencies. Inspired from (Yang et al. 2010) Design A was optimized to operate in the lower band with a small and uni-planer orientation. The 3D full-wave commercial package, Ansoft HFSSv10 was utilized in assisting the optimization of the antenna.

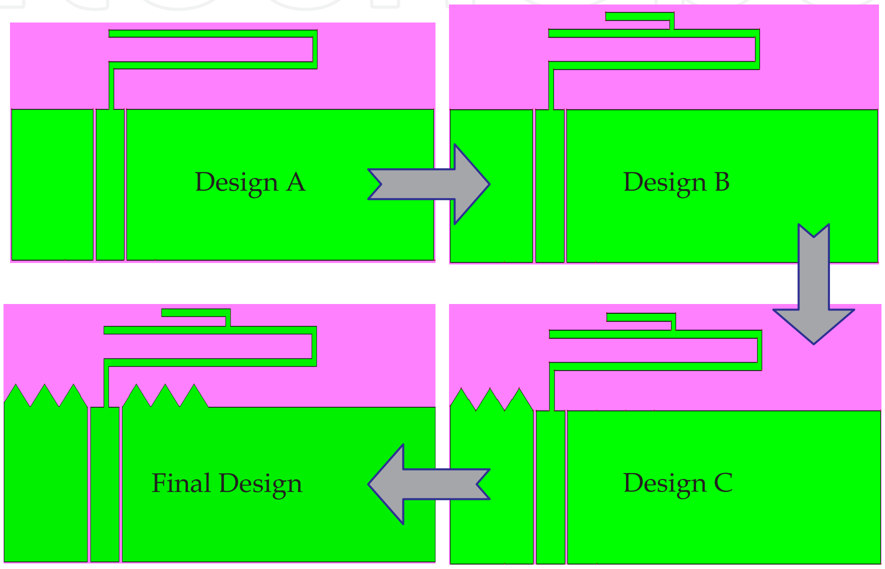

Figure 5. Adopted design steps of the proposed antenna

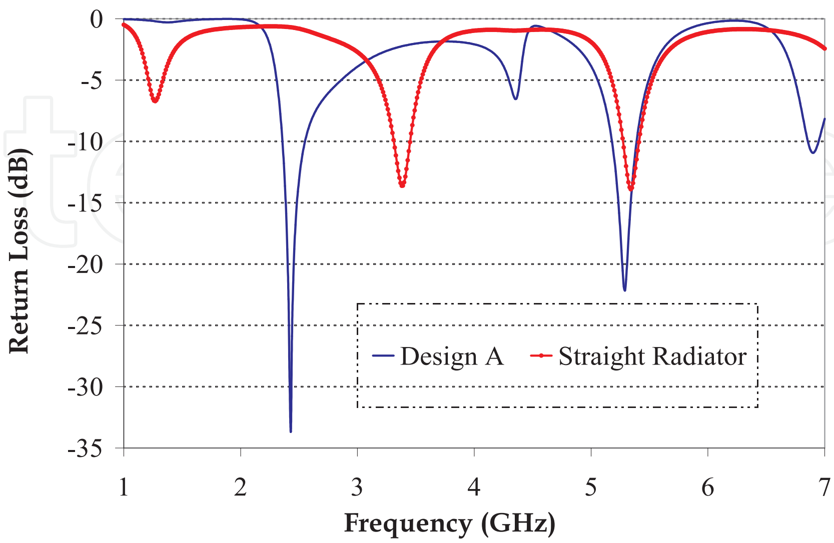

Figure 6. Comparison between straight and folded design (Design A)

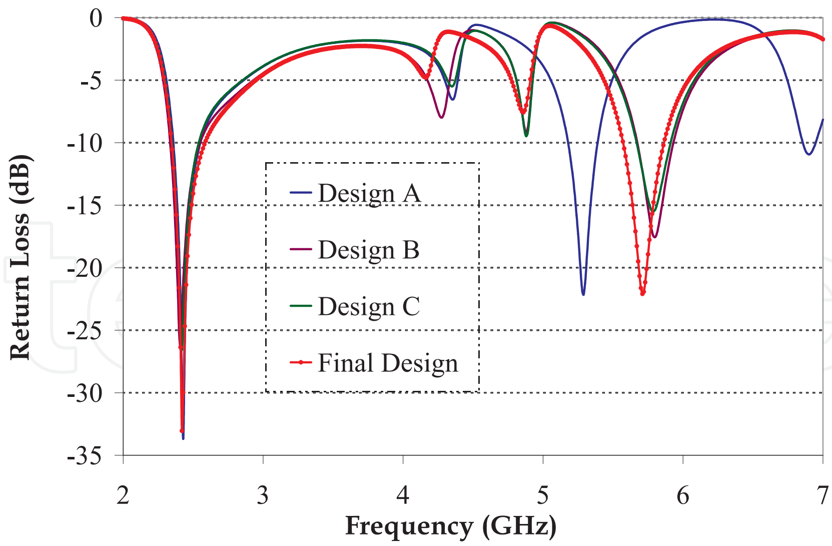

Figure 7. Improvement in impedance matching

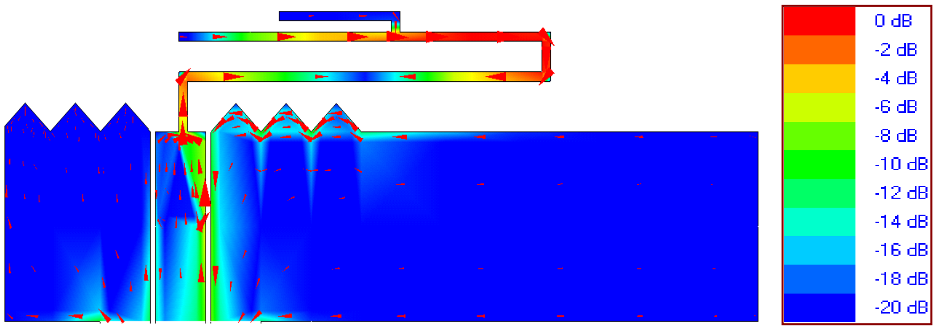

Figure 8. Surface current distributions of the antenna at 2.45 GHz

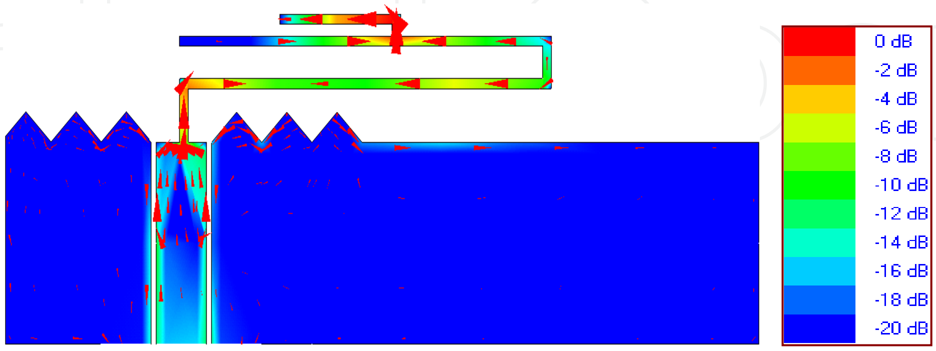

Figure 9. Surface current distributions of the antenna at 5.8 GHz

As shown in Fig. 6, it was observed that folded configuration is better suited for a good impedance matching and directional characteristics; while the radiating strip is placed straight, it acts as a long monopole antenna, resonating (f_{r1}) in some lower value. When folded, the coupling effects among the horizontal parts and ground plane appear and the radiating strip acts like a quasi-folded dipole antenna.

Design B was then introduced to provide desired dual band characteristics. The basic folded strip was designed to support the lower frequency band of ISM 2.45GHz and the forth resonance (f_{r4}) was dragged down to the desired 5.8GHz by introducing the small top branch. Thus small top branch confirms the proper selection of upper band to ISM 5.8GHz. However, it is the main folded strip which supports the small top branch for its radiation and impedance matching. Next, three optimized POES cells were inserted on the top edge of the left co-planar ground plane in Design C, which provides better impedance matching. Lastly, the final optimal design (Final Design) of the proposed antenna was derived by introducing another three POES cells in the upper left edge of the right ground plane. This orientation of POES cells improves both the impedance matching and bandwidths of both the desired bands (f_{r1}, f_{r4}). It is noted that the second resonance (f_{r2}) is generated mostly from the lower arm of basic folded strip; and the third resonance (f_{r3}) is influenced by the upper arm. Hence introduction of the small top branch vitally changed f_{r3}, while the resonance did not change with the application of POES. On the other hand the matching of f_{r2} varies by the affixation of POES cells. Fig. 7 describes the improvement in impedance matching through the design procedure.

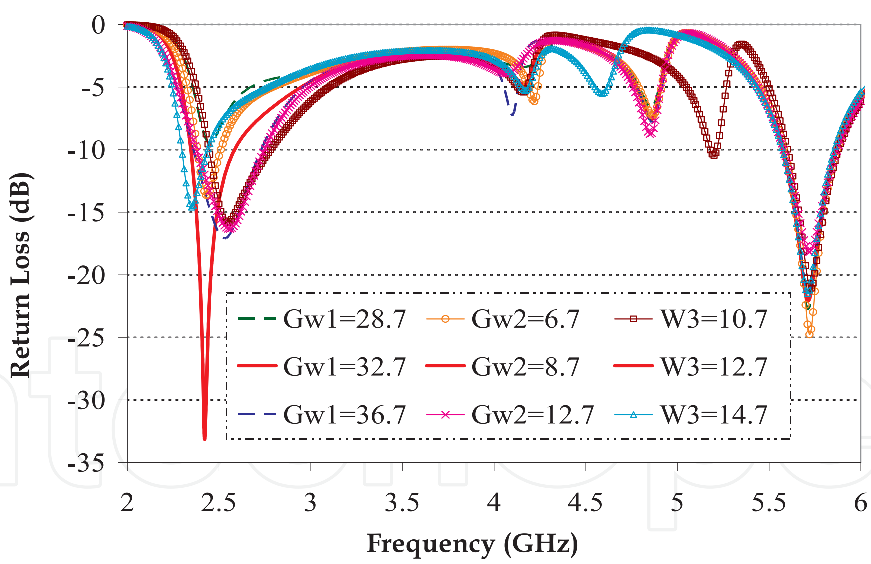

Figure 10. Comparison of Return Loss of the proposed antenna as a function of G_{w1}, G_{w2} & W_3 which dominate only lower operating band

In order to gain further understanding of the way resonances are excited, we also examine surface current distributions of the proposed antenna extracted from the full-wave, method-of-moment based electromagnetic simulator Zeland IE3D. From Fig. 8 & 9, it is evident that at both resonating frequencies, the current density is indeed higher on the folded strip of the antenna, thus the dimensions of the folded strip are assumed to govern both bands. The top small branch is active only in the upper frequencies, and has so effect for the 2.45 GHz resonance. So the optimal value of top small branch is vital for 5.8 GHz operation. Nevertheless, it is noted that the ground plane do not resonate in any of the desired resonances, but it provides better impedance matching for the desired bands. It is seen that the triangular POES cells increase the current path in the ground plane without influencing the currents on the radiating strip; hence only effects the scattering parameters, not radiation characteristics.

4.3. Optimization, parametric analysis & guidelines

A parametric analysis of the proposed antenna was carried out in order to illustrate the optimization process of the proposed antenna. The results are exhibited in Figs. 11 to 14. All the parameters have been studied to find the impact of the impedance matching, especially on the resonance frequencies and bandwidth.

It is observed that both the bands varied in terms of resonance, whenever the dimensions of the lower portion of folded strip, like L_1, L_2, W_1 and W_2 are changed. The length, x of the triangular POES cell do not have much effect on the antenna performances, but the height, y is very crucial for the bandwidth of the lower band and adjusting the upper band. Also, the number of POES cells are important for adjusting the impedance matching of both bands.

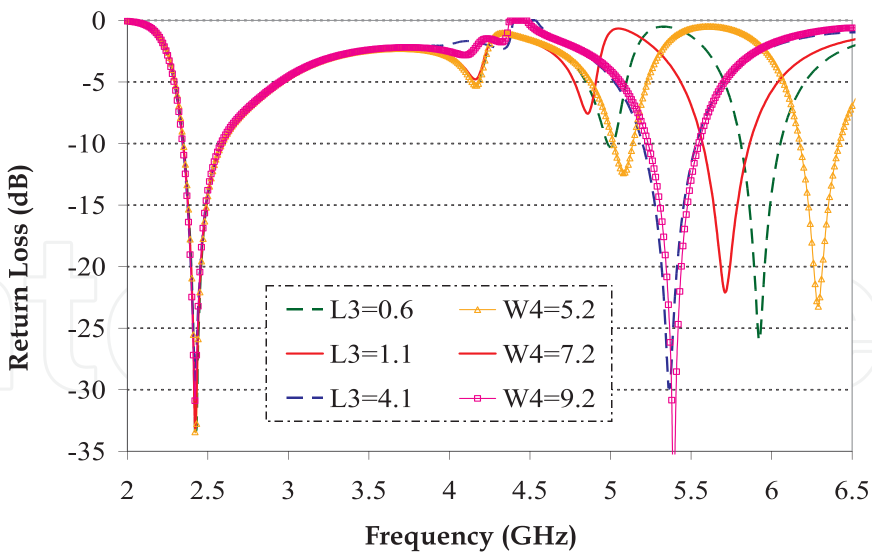

Figure 11. Performance comparison of Return Loss of the proposed antenna for the variation of L_3 & W_4 which dominate only higher operating band

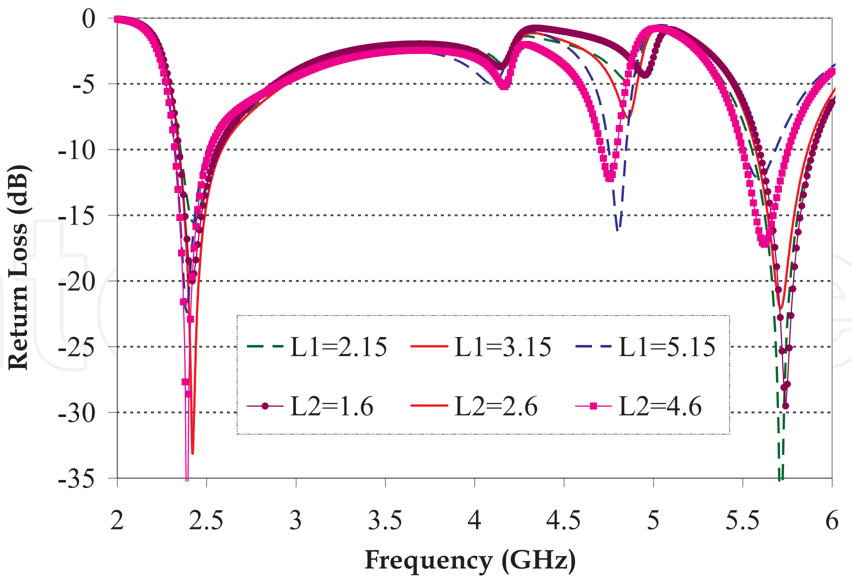

Figure 12. Return Loss comparison of the proposed antenna as a function of L_1 & L_2 which dominate both the higher and lower operating bands

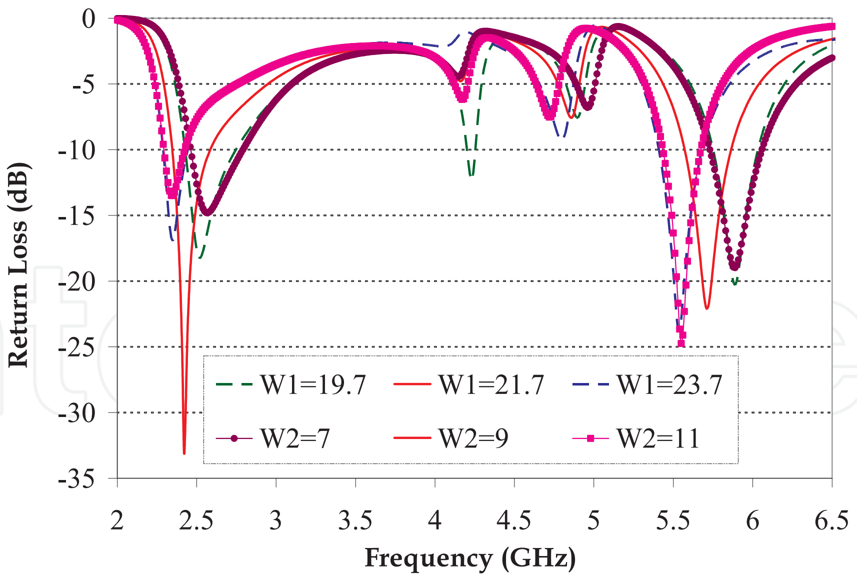

Figure 13. Comparison of Return Loss Vs Frequency of the proposed antenna when the values of W_1 & W_2 are varied that dominate both the operating bands

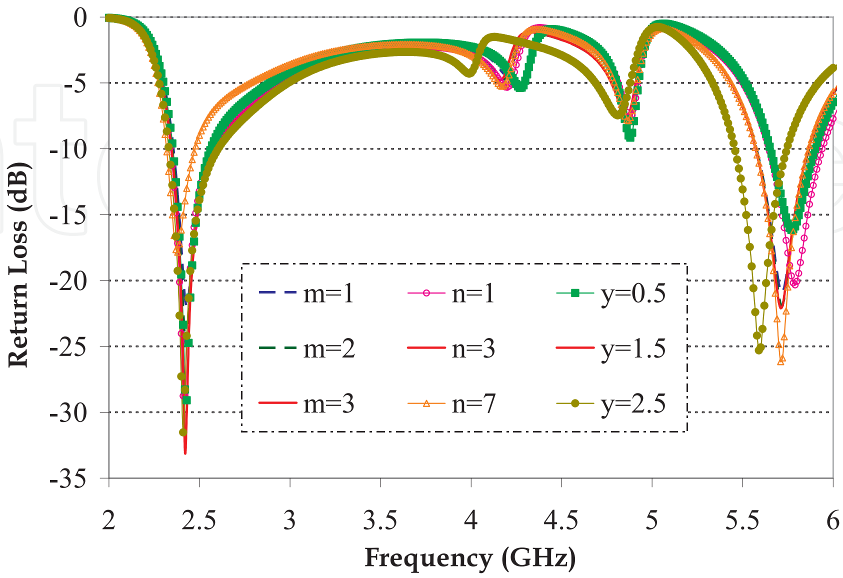

Figure 14. Dependencies of lower & higher operating bands for various heights (y) of the POES as well as for various left POES numbers (m) & right POES numbers (n)

The bandwidth and resonating frequency of the lower frequency band can be further improved by increasing the structure of the ground plane. However, in that case the return loss degrades and the antenna becomes bigger in size. As a design guideline, it is suggested that the dimension of W_3 is very useful for tuning up the lower resonance without changing the overall antenna profile. It is also feasible to generate another resonance near 2.45GHz by adding another radiating upper element with the existing one. But the high electromagnetic coupling makes it difficult to match the reflection coefficient; even in some cases the antenna might loose its front-directive radiation characteristics when achieving multi resonance near lower operating band.

After dealing with the lower band, the upper band can be tuned by proper selection of L_3 and W_4. Nevertheless, if the investigated front-directional antenna was required to operate in a number of discrete bands for higher frequencies, a set of top branches equal to the number of the resonating bands could be used. In that case, the coupling effect should be carefully eliminated by adjusting the width, W_4 and distance, L_3 for each top branch.

These are illustrated in Table 1 for better realization of the antenna geometry. The calculated parametric values of the radiating strip are based on the guided quarter wavelength of the substrate of the predicted dominating portion at the resonances; the rest are assumed in an arbitrary manner. Afterwards all the parameters are optimized through empirical observations.

Parameters	Calculated Value	Optimized Value	Variation	Lower Band			Upper Band		
				f_{r1}	$\|RL\|$	BW	f_{r4}	$\|RL\|$	BW
GW_2	-	8.7	>	↑	↓	↑	-	↑	-
			<	-	↓	↓	-	↓	-
GW_1	-	32.7	>	↑	↓	↑	-	-	-
			<	-	↓	↓	-	-	-
GL_1=GL_2	-	10	>	↓	↓	↓	-	↓	-
			<	↑	↓	↓	~	-	~
L_1	-	3.15	>	↓	↓	-	↓	↓	↓
			<	-	↓	-	-	↑	↑
L_2	-	2.6	>	↓	↑	-	↓	↓	-
			<	-	↓	-	↑	↑	-
L_3	-	1.7	>	-	-	-	↓	↑	-
			<	-	-	-	↑	↑	-
W_1	19.7	21.7	>	↓	↓	↓	↓	↑	-
			<	↑	↓	↑	↑	↓	-
W_2	12.9	9	>	↓	↓	↓	↓	↑	-
			<	↑	↓	↑	↑	↓	-
W_3	12.9	12.7	>	↓	↓	↓	-	-	-
			<	↑	↓	↑	-	-	-
W_4	6.8	7.2	>	-	-	-	↓	↑	-
			<	-	-	-	↑	~	-
x	-	3	>	-	-	↓	-	-	-
			<	-	-	-	-	-	-
y	-	1.5	>	-	-	↑	↓	↑	-
			<	-	-	↓	↑	↓	↓
m	-	3	>	-	↑	↑	-	↑	↑
			<	-	↓	↓	-	↓	↓
n	-	3	>	↓	↓	↓	~	~	-
			<	-	↓	↓	↑	↓	↓

* '-' represents the frequency phenomenon is independent for the increment of the parameter. '~' represents the non-monotonic fluctuation of the criteria upon increasing the geometry. '↑' and '↓' represent the enhanced and deteriorated phenomenon of the antenna upon changing parameter-values.

Table 1. Sensitivity of the antenna resonance frequencies (f_{r1}, f_{r4}), return loss ($|RL|$) and bandwidth (BW) when varying geometric parameters

4.4. Prototyping & measurements

The antennas were fabricated with the optimized parameters for experimental verification. A photograph of the prototypes is presented in Fig. 15. An Agilent N5230A PNA-L network analyzer was used to measure the electrical performance of the prototype. The simulated and measured return loss of the prototype is presented in Fig. 16. A good agreement between the simulated and measured results is observed. The small difference between the measured and simulated results is due to the effect of SMA connector soldering and fabrication tolerance. The measured return loss curve shows that the proposed antenna is excited at 2.45 GHz band with a –10 dB return-loss bandwidth of 320 MHz (2.35–2.67 GHz) and at 5.8 GHz band with an impedance bandwidth of 310MHz (5.6–5.91 GHz). The maximum return loss of -28.4dB and -34.2dB is obtained at the resonant frequencies of 2.46 GHz and 5.76 GHz respectively. Most of the desired frequencies are below -15dB level. The narrowband characteristics are useful to minimize the potential interferences between the RFID system and other systems using neighboring frequency bands such as UWB, WiMAX etc.

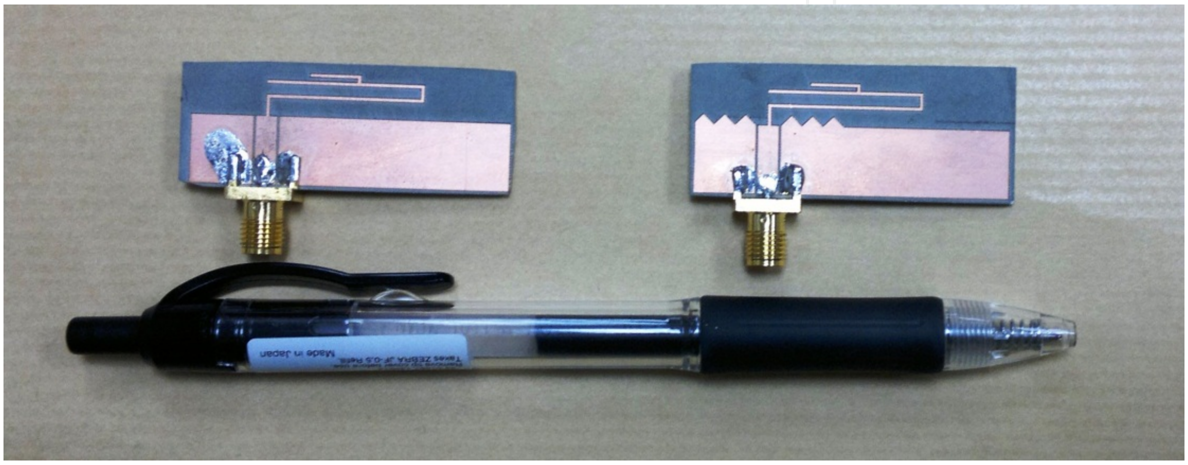

Figure 15. Photograph of the fabricated prototypes

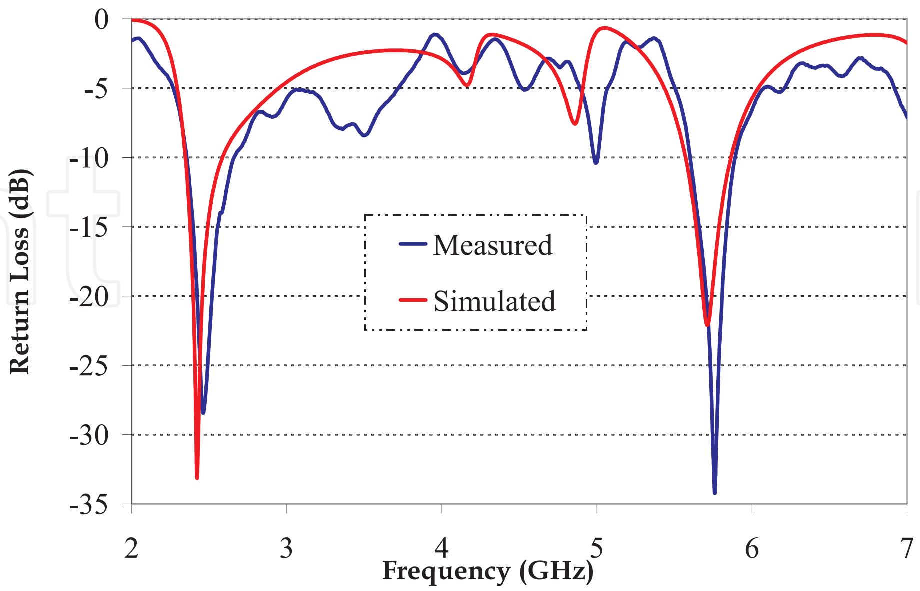

Figure 16. Return loss comparison of the proposed prototype

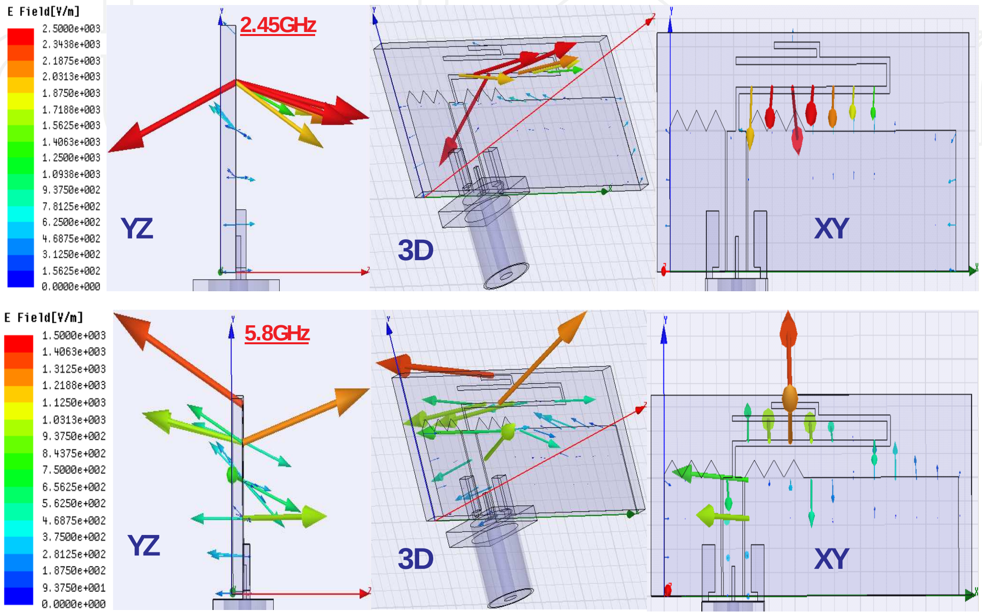

Figure 17. Electric field vector distribution of the proposed antenna

The electrical field vector distribution of the proposed antenna at frequencies 2.45 and 5.8 GHz is illustrated in Fig. 17. This distribution is extracted from HFSS software. It is noticed that the vital electric fields are generated from the folded resonating portion. The middle horizontal portion of the strip generates the radiation and the upper horizontal directs the energy propagation towards the end fire direction. The ground plane acts more likely as a reflector or suppressor. It mainly suppresses the back radiation and improves the impedance matching of the radiation element. The electric fields generated from the top edge of the ground plane are observed to extend in the forward direction. Thus it forces the electromagnetic energy and produces the front-directional radiation patterns. The measured radiation patterns of the fabricated prototype antenna at 2.45 and 5.8 GHz are illustrated in Fig 18. It is seen that the antenna provides front-directional radiation pattern for both bands. More importantly the cross-polarization levels are low (at least -10 dB) in both E- and H-planes. Also the front to back ratio in the scale of -10 dB is observed in the lower resonance; and at upper band it increases around the scale of -20 dB. The peak gain of the prototype is found to be 3 and 3.2 dBi at 2.45 and 5.8 GHz respectively.

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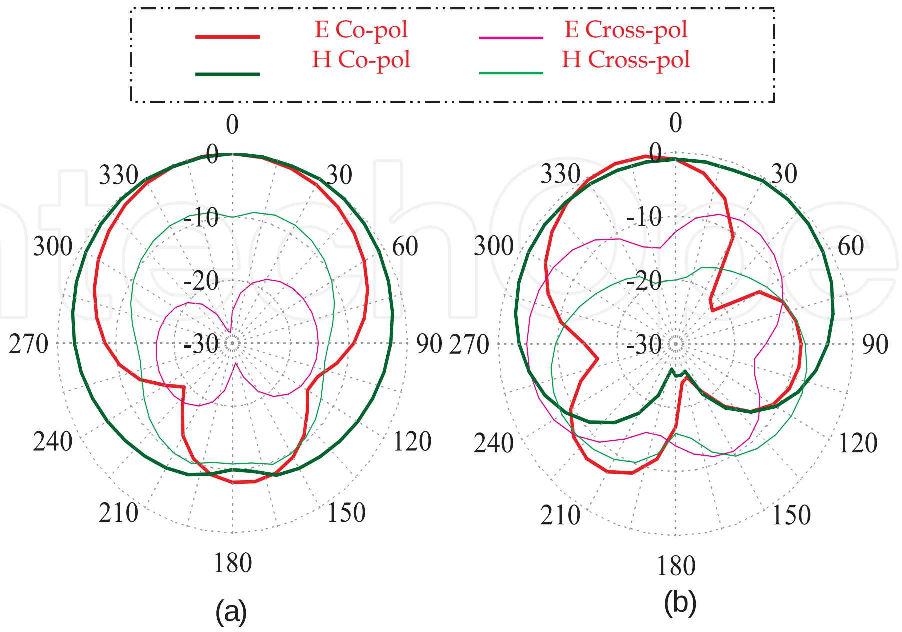

Figure 18. Measured normalized radiation patterns of the fabricated prototype at (a) 2.45 and (b) 5.8 GHz

4.5. Guidelines of future works

The design procedure of the presented dual-band antenna is applicable for multi-band extension. Following this design and optimization steps a more efficient antenna covering triple band including UHF and ISM microwaves is quite feasible. However, the antenna profile will increase when the operating frequency decreases, but yet the front directionality of the antenna is very effective for the compact handheld RFID reader design.

5. Conclusion

This chapter reveals the advantages and limitations of forward directional antennas to the readers for compact handheld RFID operation for multi-band operation. A comprehensive review and limitations of RFID technology concerning the prospects of directional antennas and propagation for both single and multi-band operation are presented in this chapter. The technical considerations of directional antenna parameters are also discussed in details in order to provide a complete realization of the parameters in pragmatic approach to the directional antenna designing process, which primarily includes scattering parameters and radiation characteristics. The antenna literature is also critically overviewed to identify the possible solutions of the directional antennas to utilize in single and multi-band handheld RFID reader operation.

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