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Chapter 8

Recent Trends in Printed Ultra-Wideband (UWB) Antennas

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1. Introduction

After the Federal Communication Commission (FCC)'s authorization of frequency band of 3.1 to 10.6 GHz for unlicensed radio applications, ultra-wideband (UWB) technology become the most promising candidate for a wide range of applications that will provide significant benefits for public safety, business and consumers, and attracted a lot attention both in industry and academia. The antennas are the key components of UWB system. In wireless communication system, an antenna can take various forms to fulfill the particular requirement. As a result, an antenna may be a piece of conducting wire, an aperture, a patch, a reflector, a lens, an assembly of elements (arrays). A good design of the antenna can fulfill the system requirements and improve overall system performance.

Over the past few years, significant research efforts have been put into the design of UWB antennas and systems for communications. The UWB antenna is essential for providing wideband wireless communications based on the use of very narrow pulses on the order of nanoseconds, covering an ultra-wide bandwidth in the frequency domain, and over short distance at very low spectral power densities. In addition, the antennas required to have a non-dispersive characteristic in time and frequency, providing a narrow, pulse duration to enhance a high data throughput [1]. Different kinds of antennas suitable for use in UWB applications have proposed in past few decade, each with its advantages and disadvantages.

In this paper, a review on printed UWB antennas has been done historically. Then, a technique to miniaturize the antenna's physical size by shrinking the ground plane is proposed. To develop the design technique by which the antennas can be able to achieve both UWB operating bandwidth and the stable radiation pattern across the entire frequency band by reducing the ground plane effect is also described. Finally, the enhancement of operating bandwidth as well as the pattern bandwidth by further modified the ground plane is achieved in order to fulfill the requirements defined by the FCC.

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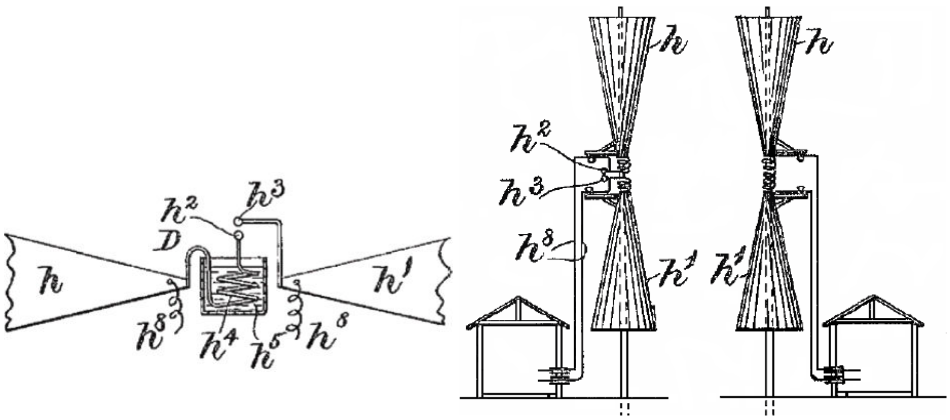
2. History of UWB antennas

The starting of UWB technology was the "spark-gap" transmitter, which broke new grounds in radio technology. The design was first not realized as UWB technology, but then later dug up by investigators. Also, even some of the ideas, which start out as designs for narrow-band frequency radio, reveal some of the first concepts of UWB antennas. The concept of "syntony", that is, the received signal can be maximized when both transmitter and receiver are tuned to the same frequency, was presented by Oliver Lodge in 1898. With his new concept, Lodge developed many different types of "capacity areas," or so called antennas. Those antenna designs include spherical dipoles, square plate dipoles, bi-conical dipoles, and triangular or "bow-tie" dipoles. The concept of using the earth as a ground for monopole antennas was also introduced by Lodge. In fact, Lodge's design drawing of triangular or bow-tie elements reproduced in Figure 1(a) clearly shows Lodge's preference for embodied designs. Bi-conical antennas designed by Lodge and shown in Figure 1(b) are obviously used as transmit and receive links [1].



(a) (b)

Figure 1. Lodge's (a) preferred antennas consisting of triangular "capacity areas," a clear precursor to the "bow tie" antenna (b) biconical antennas [1].

Due to demands of increased frequency band and shorter waves, a "thin-wire" quarter wave antenna dominated the market with its economic advantages over the better performance of Lodge's original designs. Especially, for television antennas, much interest was focused on the ability of handling wider bandwidths due to increased video signals. In 1939, the bi-conical antenna and the conical monopole (Figure 2) were reinvented by Carter to create wideband antennas. By adding a tapered feeding structure, Carter improved Lodge's original designs. Also, Carter was among the first to take the key step of incorporating a broadband transition between a feed-line and radiating elements. This was one of the key steps towards the design of broadband antennas [1]. In 1940, a spherical dipole antenna combined with conical waveguides and feeding structures was proposed by Schelkunoff. Unfortunately, Schelkunoff's dipole antenna does not appear to have seen much use.

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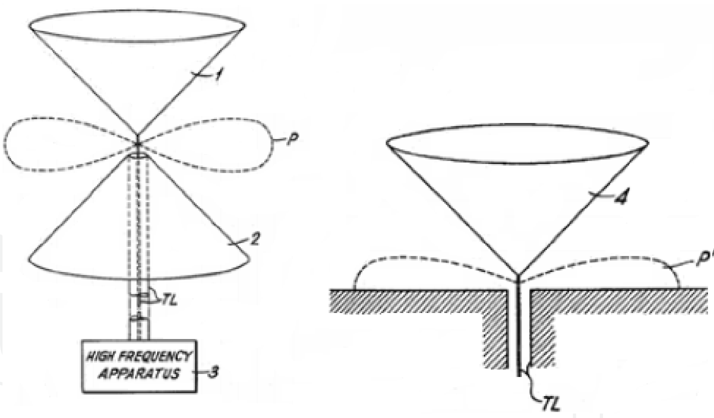
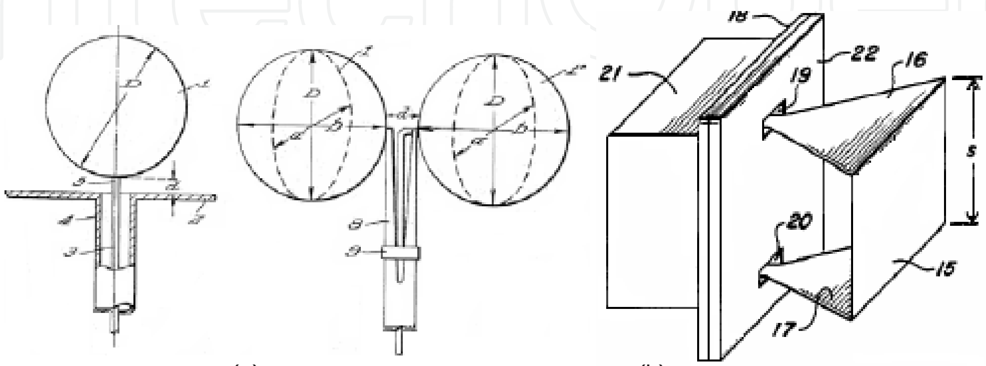


(a) (b)

Figure 2. Carter's (a) biconical (b) conical monopole antenna [1].

At that time, the most well-known UWB antenna was the coaxial horn element proposed by Lindenblad [1]. In order to make the antenna more broadband, Lindenblad took the design of a sleeve dipole element and introduced a continued impedance change. In the year of 1941, Lindenblad's elements were used by Radio Corporation of America (RCA) for experiments in television transmission. With the vision of broadcasting multiple channels from a single central station, the need of a wideband antenna was necessary for RCA. On the top of the Empire State Building in New York City, a turnstile array of Lindenblad's coaxial horn elements as an experimental television transmitter were placed by RCA for several years. In 1947, a wideband antenna concept was proposed by the staff of the U.S. Radio Research Laboratory at Harvard University [2]. The concept of a wideband antenna evolves from a transmission line that gradually diverges while keeping the inner and outer conductors ratio constant. Several variations of the concept were developed, such as the teardrop antenna, sleeve antenna and inverted trapezoidal antenna. By the year of 1948, two types of coaxial horn antennas were presented by Brillouin. One of them is omni-directional and the other one is directional [1]. Brilliant results were offered by conventional designs, but other aspects started to grow in significance. In 1968, more complex electric antennas in different variety were developed. Two of those antennas were ellipsoidal monopoles and dipoles which were proposed by Stohr as shown in Figure 3(a).



(a) (b)

Figure 3. a) Stohr's ellipsoidal monopole (left) and dipole (right) antenna (b) Harmuth's large current radiator [1].

Beside electrical antennas, major progress on magnetic UWB antennas has also been preceded. In 1984, an improved magnetic antenna was proposed by Harmuth as illustrated in Figure 3(b). By presenting the idea of the large current radiator surface in the antenna design, the antenna performance had been increased. The concept of this design is to make the magnetic antenna perform like a large current sheet. However, since both sides of the sheet radiate, a lossy ground plane was intentionally constructed to avoid any unwanted resonances and reflections. In this way, the lossy ground plane tends to cause limitations on the antenna's efficiency and performance.

One of the simplest practical resonant antennas is the dipole antenna. The antenna can only radiate sinusoidal waves on the resonant frequency. Thus, the dipole antennas are not suitable for UWB system. On the other hand, a non-resonant antenna can cover a wide frequency range, but special care must be taken in antenna design to achieve sufficient antenna efficiency. Moreover, the physical size of available non-resonant antenna is inappropriate for portable UWB devices. Even with appropriate size and sufficient efficiency, until now non-resonant antennas have not been suitable for UWB systems [3].

In 1950's, the spiral antennas were introduced in the class of frequency independent antennas. These Antennas whose mechanical dimensions are small compared to the operating wavelength is usually characterized by low radiation resistance and large reactance [4]. Due the effective source of the radiated fields varies with frequency, these antennas tend to be dispersive. The equiangular spiral and archimedean spiral antennas are the most well known spiral antennas. Spiral antennas have about a 10:1 bandwidth, providing the circular polarization in low profile geometry [5]. Transverse electric magnetic (TEM) horns and frequency-independent antennas feature very broad well-matched bandwidths and have been widely studied and applied [6-9]. However, for the log-periodic antennas structures, such as planar log-periodic slot antennas, bidirectional log-periodic antennas, and log- periodic dipole arrays, frequency-dependant changes in their phase centers severely distort the waveforms of radiated pulses [10]. Biconical antennas are the earliest antennas used in wireless systems relatively stable phase centers with broad well-matched bandwidths due to the excitation of TEM modes. The cylindrical antennas with resistive loading also feature broadband impedance characteristics [11]. However, the antennas mentioned above are rarely used in portable wireless devices due to their bulky size or directional radiation, although they are widely used in electromagnetic measurements. In 1982, R.H. Duhamel patented the sinuous antenna, which exhibits wide bandwidth characteristics with dual linear polarization in a compact, low profile geometry [12]. The sinuous antenna is more complicated than the spiral antenna. However, it provides dual orthogonal linear polarizations so that it can be used for polarization diversity or for transmition and reception.

From 1992, several microstrip, slot and planar monopole antennas with simple structure have been proposed [13-15]. They produce very wide bandwidth with a simple structure such as circular, elliptical or trapezoidal shapes. The radiating elements are mounted orthogonal to a ground plane and are fed by a coaxial cable. The large ground plane mounted orthogonal to the patch made these antennas bulkier and are difficult to fit into small devices. A novel UWB antenna with combination of two antenna concepts: a slot-line circuit board antenna and a bowtie horn were introduced in 1992 [16]. These two antenna concepts are put together to form a novel antenna type that is wide band with easily controllable E- and H- plane beam-widths. The bowtie horn is known for its broadband radiation pattern; whereas, the slot-line antenna provides a broadband and balanced feed structure. The microstrip and slotline are on opposite sides of the substrate. However, a broadband balun is needed for the transition between the microstrip and slotline transmission line. Proper design of broadband balun is crucial to improve the antenna bandwidth.

In 1998, a new balanced antipodal Vivaldi antenna was proposed for UWB application [17]. The author extended the tapers of the balanced antipodal Vivaldi to make the Vivaldi antenna works as a dipole in lower frequency where the slot can not radiate to extend lower edge frequency. However, the bandwidth of the antenna is limited by the transition from the feed line to the slot line of the antenna. In 1999, Virginia Tech Antenna Group (VTAG) invented and patented the Foursquare antenna. Even though this antenna does not offer as much bandwidth as other elements, it has its unique characteristics such as unidirectional pattern, dual polarization, low profile and compact antenna geometry [18-19]. The compact geometry of the Foursquare antenna is one of a desirable feature for wide scan, phased array antenna.

Several stacked patch antenna have also been proposed for UWB applications. To increase the gain and impedance bandwidth, various arrangements of stacked patch structures have been investigated. A dual layer stacked patch antenna with 56.8% bandwidth was proposed in [20] for UWB applications which does not increase the surface area and has a dimension of $26.5 \times 18 \times 11.5$ mm^3. Elsadek et al. proposed another wide bandwidth by electromagnetically couple the V-shaped patch with the triangular PIFA [21]. UWB operation with 53% bandwidth has been achieved by folding the shorting wall of the triangular PIFA in their research. These techniques can also be applicable to dual-band and wideband applications, albeit more complicated geometrical configurations. An ultra-wideband suspended plate antenna consisting four identical radiating top plates, connected to a common bottom plate is proposed in [22]. This antenna has achieved an impedance bandwidth of 72.7% with a dimension of $45 \times 47 \times 7$ mm^3. More recently, a novel compact stacked patch antenna with a folded patch feed is proposed in [23]. By using a stacked patch fed with a folded patch feed, the antenna achieved an impedance bandwidth of 90 %. Moreover, use of sorting wall significantly reduced the overall antenna size.

Most of the antennas discussed earlier have wider impedance bandwidth, high gain, non-dispersive properties, stable radiation patterns which satisfy the requirement for UWB applications. However, these antenna requires a perpendicular ground plane, which results in increased antenna size, and hence, it is difficult for integration with microwave-integrated circuits. Moreover, their bulky size and directional properties are not suitable for portable devices. When compared with these three-dimensional type of antennas, flat-type UWB antenna printed on a piece of printed circuit board (PCB) is a good option for many applications because it can be easily embedded into wireless devices or integrated with other RF circuitry.

3. Planar UWB antennas

As for portable applications, the planar antennas printed on PCBs are the most suited compared to other types of UWB antennas. Mainly printed antennas consist of the planar radiator and ground plane etched oppositely onto the dielectric substrate of the PCBs. The radiators can be fed by a microstrip line and coaxial cable.

Several techniques have been suggested to improve the antenna operating bandwidth. First, the radiator may be designed in different shapes. As for example, the radiators may have a bevel or smooth bottom or a pair of bevels to obtain good impedance matching [24]. Secondly, a different types of slot maybe inserted in the radiators to improve the impedance matching, especially at higher frequencies. Besides, use of an asymmetrical strip at the top of the radiator may decrease the height of the antenna and improve the impedance matching [25, 26]. Thirdly, a partial ground plane and feed gap between the ground plane and the radiator may used to enhance and control the impedance bandwidth [27]. In addition, a notch cut from the radiator may be used to control impedance matching and to reduce the size of the radiator. Fourthly, cutting two notches at the bottom portion of the rectangular or square radiators can be used to further improvement of impedance bandwidth since they influence the coupling between the radiator and the ground plane [28]. Finally several modified feeding structures may used to enhance the bandwidth. By optimizing the position of the feed point, the antenna impedance bandwidth can be widening further since the input impedance is varied with position of the feed point [24].

In the past, one major limitation of the microstrip antenna was its narrow bandwidth. It was 15-50% of the centre frequency. This limitation was successfully overcome and now microstrip planar antennas can attain wider impedance bandwidth by varying parameters like size, height, volume or feeding and matching techniques [29]. To achieve wide band characteristics, many bandwidth enhancement techniques have also been suggested, as mention earlier.

Many microstrip line-fed and coplanar waveguide-fed (CPW) antennas have been reported for UWB applications. These antennas use the monopole configuration, such as square, elliptical, circular ring, annular ring, triangle, pentagon, and hexagonal antennas [30-35], and the dipole configuration [36-39] such as double-sided printed rectangular and bow-tie antennas. Many of these antennas either have relatively large sizes or do not have a real wide bandwidth. For example, in [30] an investigation on a small UWB elliptical ring antenna fed by a coplanar waveguide had been carried out. This antenna achieved wideband performance on enlarging the length of the elliptical ring's major axis, and demonstrated a bandwidth from 4.6 to 10.3 GHz. Despite having fairly compact dimensions, the antenna did not cover the entire UWB. In [31], Rajgopal and Sharma proposed an UWB pentagon-shaped planar microstrip slot antenna for wireless communication. Combining the pentagon-shaped slot, feed line, and pentagon stub, the antenna obtained an impedance bandwidth of 124%. However, its use in small wireless devices was limited due to large ground plane. For UWB communication, a new ring antenna adopting a proximity-coupled configuration was proposed in [32]. The antenna had an overall dimension of 44×40 mm^2 with an average gain of 2.93 dBi. In [33], a novel design of printed circular disc monopole antenna with a relatively large size of 42×50 mm^2 was proposed. However, the antenna failed to fulfill the requirement of UWB

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with an operating bandwidth range of 2.78–9.78 GHz. A miniaturized crescent microstrip antenna for UWB application was proposed in [35]. The antenna had a relatively large size (45×50 mm^2) and did not cover the upper edge frequency of the UWB. An improved design of planar elliptical dipole antenna for UWB applications was recently developed in [36]. By using elliptical slots on the dipole arms, the antenna could achieve wideband characteristics having an operating bandwidth of 94.4%. However, the antenna does not possess a physically compact profile, having a dimension of 106 × 85 mm^2. A double-sided printed bow-tie antenna for UWB application was proposed in [37]. By cutting parts of the rectangular patch, the antenna achieved an impedance bandwidth of 3.1-10.6 GHz to cover the entire UWB frequency band. In [38], Zhang and Wang propose a double printed UWB dipole antenna with two U-shape arms. The antenna exhibit flat amplitude and linear phase responses in 3–8 GHz. However, the operating bandwidth of the antenna is insufficient to cover the entire UWB band.

Compared to the electrical antennas mentioned earlier, slot antennas have relatively large magnetic fields that tend not to couple strongly with near-by objects which make them suitable for applications wherein near-filed coupling is required to be minimized [40]. A conventional narrow slot antenna has limited bandwidth, whereas wide-slot antennas exhibit wider bandwidth. Recently, different printed wide-slot antennas fed by a microstrip line or coplanar waveguide have been reported [41, 42]. Apart from these antennas, monopole like slot antennas have also been reported to have wide bandwidth characteristics [43-45]. By using different tuning techniques or employing different slot shapes such as rectangle, circle, arc-shape, annular-ring [46-49], different slot antennas achieved wideband or ultra-wideband performance.

Many of these proposed antennas either have large physical dimensions or do not have sufficient impedance bandwidth to cover the entire UWB frequency range. Moreover, variation of the electrical length of antennas with frequency causes significant distortion in the radiation patters which posses a challenge to design new antennas for UWB application that achieve physically compact profile and sufficient bandwidth with stable radiation patterns.

After 2003, the trend in UWB antenna was to design antennas with band notch characteristics. This antenna made insensitive to particular frequency band. This technique is useful for creating UWB antennas with narrow frequency notch bands, or for creating multi-band antenna. Since then, many researchers extended their research to investigate the possible interference between UWB system and existing narrow band wireless communication systems such as WiMAX and WLAN. The commonly used techniques to achieve a notched band are cutting a slot on the patch or embedding a quarter wavelength tuning stub within a large slot on the patch. Recently different types of slots such as L-shaped slot [50], U-shaped slot [51], square-shapes slot [52], T-shaped slot [53], pi-shaped slot [54], H-shaped slot [55] and fractal slot [56] have been used to design band notched antenna. Another simple way is to put parasitic elements near printed monopole, playing a role as filters to reject the limited band. By adding either a split-ring resonator [57] or a multi-resonator load [58] in the antenna structure, the undesired frequencies can also be stopped with better system performance. An isolated slit inside a patch, two open-end slits at the top edge of a T-stub, two parasitic strips [59] and a square ring resonator embedded in a tuning stub [60] have also been used to design band-notched antennas.

4. Reduction of ground plane effect on antenna performance

Antennas play a vital role in wireless communication systems and to fulfill UWB technology requirement, various monopole-like UWB antennas have been proposed due to their attractive features of simple configuration and ease of fabrication and numerous techniques have been exploited to broaden their bandwidth as well as improving their performance. Several broadband antennas such as vertical monopole, Vivaldi, log-periodic, cavity-backed, waveguide, bow-tie, TEM horn and dielectric loaded rod antennas have been proposed to support UWB communications. Recently, several broadband configurations, such as stack patch, plate, elliptical, pentagonal and planar unidirectional with broadband feeding structure have been proposed for UWB applications. These antennas characterizes with wide bandwidth, stable radiation patterns, simple structures and ease of fabrication. However, these antennas are relatively large and their structures make them difficult for low profile system integration. Moreover, in these antennas, the radiators are perpendicular to the ground plane resulted in increased antenna size and are difficult to be integrated with microwave circuitry.

Compared with the three dimensional type of antennas, planar structure in which the antenna can be printed onto a piece of printed circuit board is one of the possible options to satisfy the requirements for small UWB antennas. For to this advantage, industry and academia have put enormous efforts on researches to study, design and develop planar antennas for UWB communication system. In the design of planar UWB antenna, the patch and the size and shape of the ground plane as well as the feeding structure can be optimized to achieve a wide operating bandwidth. However, the planar antennas consist of a radiator and ground plane is essentially an unbalanced design. The electric currents in these antennas are distributed both on the radiating element and on the ground plane, and the radiation from the ground plane is unavoidable. Therefore, the performance of the printed UWB antenna is considerably affected by the size and shape of the ground plane in terms of operating bandwidth, gain and radiation patterns [61, 62]. Moreover, due to large lateral size or asymmetric geometry of the radiator, the planar monopole antennas suffer high cross-polarization level in the radiation patterns.

4.1. Planar antenna geometry

The geometries of square patch planar monopole antennas that are considered in this chapter are shown in Figure 4. The planar monopole antennas is chosen due to their remarkably compact size, low spectral power density, simplicity, stable radiation characteristics and easy to fabricate and very easy to be integrated with microwave circuitry for low manufacturing cost. A shortcoming of this structure is limited bandwidth and high cross polarization levels. The objectives of this study are to modify the structure of the ground plane and incorporate the techniques to increase the bandwidth. The initial antenna in this study consists of an almost square radiating patch which is feed by microstrip line and ground plane. W_P and L_P

denote the width and length of the patch respectively while the ground plane has a dimension of $W \times L$. The width of the microstrip line is chosen as w_f to achieve 50 Ω characteristics impedance and is d_f mm away from the left edge of the substrate. The radiating patch and the microstrip feed line is printed on one side of a low cost FR4 PCB substrate of thickness 1.6 mm, with relative permittivity 4.6 and loss tangent 0.02 while the ground plane is printed on the other side. The radiating patch is 3.75 mm away from the left edge of the substrate.

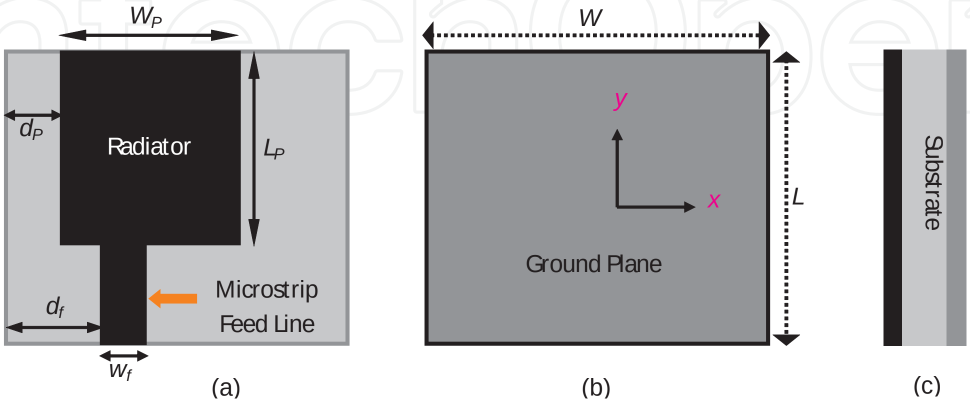

Figure 4. Geometry and dimensions of the proposed antenna (a) top view (b) bottom view and (c) side view.

4.2. Performance and characterization

The performance of the proposed initial design has been analyzed by commercially available full-wave electromagnetic simulator IE3D from Zeland which utilize the methods of moment (MoM) for electromagnetic computation. Figure 5 illustrates the simulated return loss curve for the initial design with a ground plane of dimension 30 mm × 22 mm and other parameters are $W_P = 14.5$ mm, $L_P = 14.75$ mm, $d_f = 6.75$ mm, $w_f = 3$ mm and $d_P = 3.75$ mm.

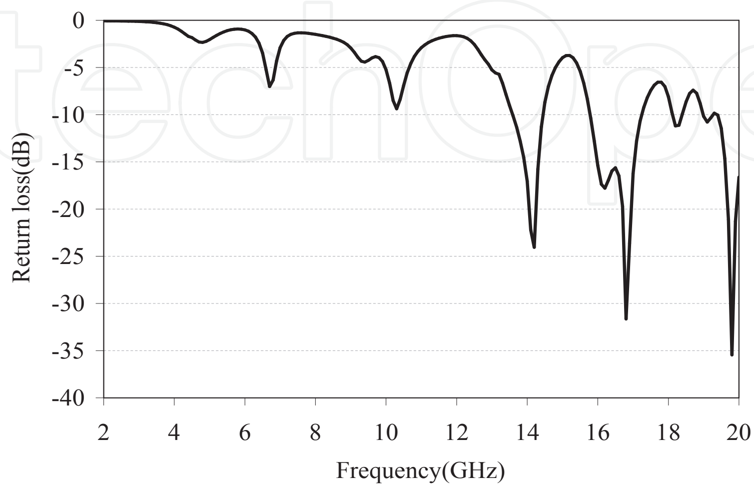

Figure 5. Simulated return loss curve of the initial antenna with $W = 30$ mm and $L = 22$ mm.

Its simulated input impedance curve is depicted in Figure 6. It is noticed in Figure 5 that first -10 dB bandwidth rages from 13.6 - 14.5 GHz, much away from UWB band. Although at higher frequencies the -10 dB bandwidth is much wider, still it is out of our desire band. This may be due to the impedance mismatching over an extremely wide frequency range resulting from large ground plane below the radiating element. From input impedance curve in Figure 6, it is seen that both the resistance and reactance fluctuate substantially in the frequency range of 0 - 13 GHz. From 0 - 6 GHz, the fluctuation in both resistance and reactance is quite high and has a peak value of around 1000 Ω. Furthermore, at the frequencies where resistance is close to 50 Ω, reactance is far from 0 Ω; when reactance reaches 0 Ω, resistance is either in its maximum or near its lowest value. Therefore, the input impedance mismatched to 50 Ω resulting in a very narrow impedance bandwidth. So it can be concluded from Figures 5 and 6 that the input impedance characteristics of the printed antenna with a ground size of 30 mm × 22 mm suffer from strong ground plane effects.

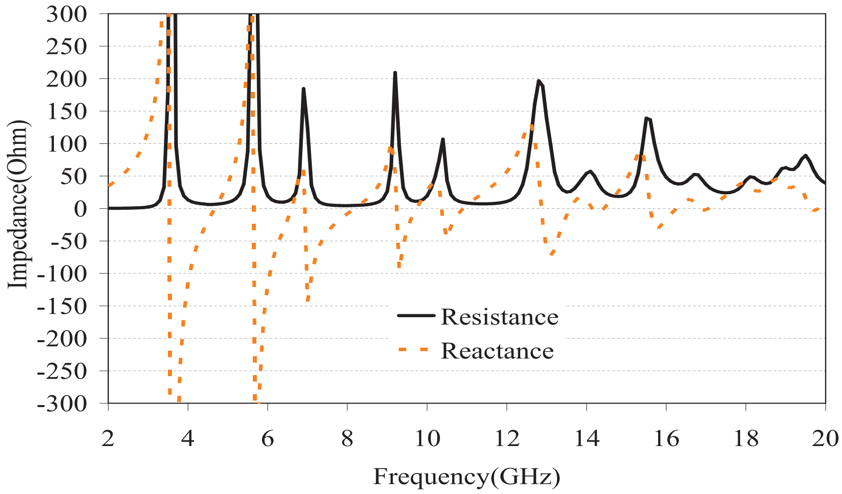

Figure 6. Simulated input impedance of the initial antenna.

This phenomenon can be explained when the ground plane is treated as a part of the antenna. When the ground plane size is large, the current flow on the top edge of the ground plane is increases. This corresponds to an increase of the inductance of the antenna if it is treated as a resonating circuit, which causes the first resonance mode either up-shifted or down-shifted in the spectrum. Also, this change of inductance causes the frequencies of the higher harmonics to be unevenly shifted. Therefore, the size of the ground plane makes some resonances become not so closely spaced across the spectrum and reduces the overlapping between them. Thus, the impedance matching becomes worse (return loss ≥ -10 dB) in ultra-wide frequency band.

The current distributions on the top (Patch) and bottom (Ground plane) surface of the initial antenna at 3.5, 6 and 14 GHz are shown Figure 7 and radiation patterns at these frequencies are depicted in Figure 8. As shown in Figure 7, at all frequencies the current is mainly distributed along the edge the radiating patch. This is due to the reason that the first resonance

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frequencies are associated with the size of the patch. On the ground plane, the surface current is strongly directed towards x-axis which assures that the antenna characteristic is critically dependent on ground plane size. At the low frequency of 3.5 GHz, Figure 7 (a)& (b) shows the current is evenly distributed on the radiator as well as in the ground plane, thus the radiation pattern in the *H*-plane as shown in Figure 8(a) is omnidirectional. At a higher frequency of 6.5 GHz, the current shown in Figure 7 (c) is still roughly evenly distributed on the radiator, and so the radiation pattern is still approximately omnidirectional. At these frequencies, both *E*- and *H*- plane radiation patterns are roughly the same as that of a monopole antenna. At the higher frequencies of 14 and 16.5 GHz, higher order current modes are excited, and the surface current density is no longer evenly distributed on the radiator as well as on ground plane. The radiation patterns, as can be seen in Figure 8 (c), become directional with some nulls.

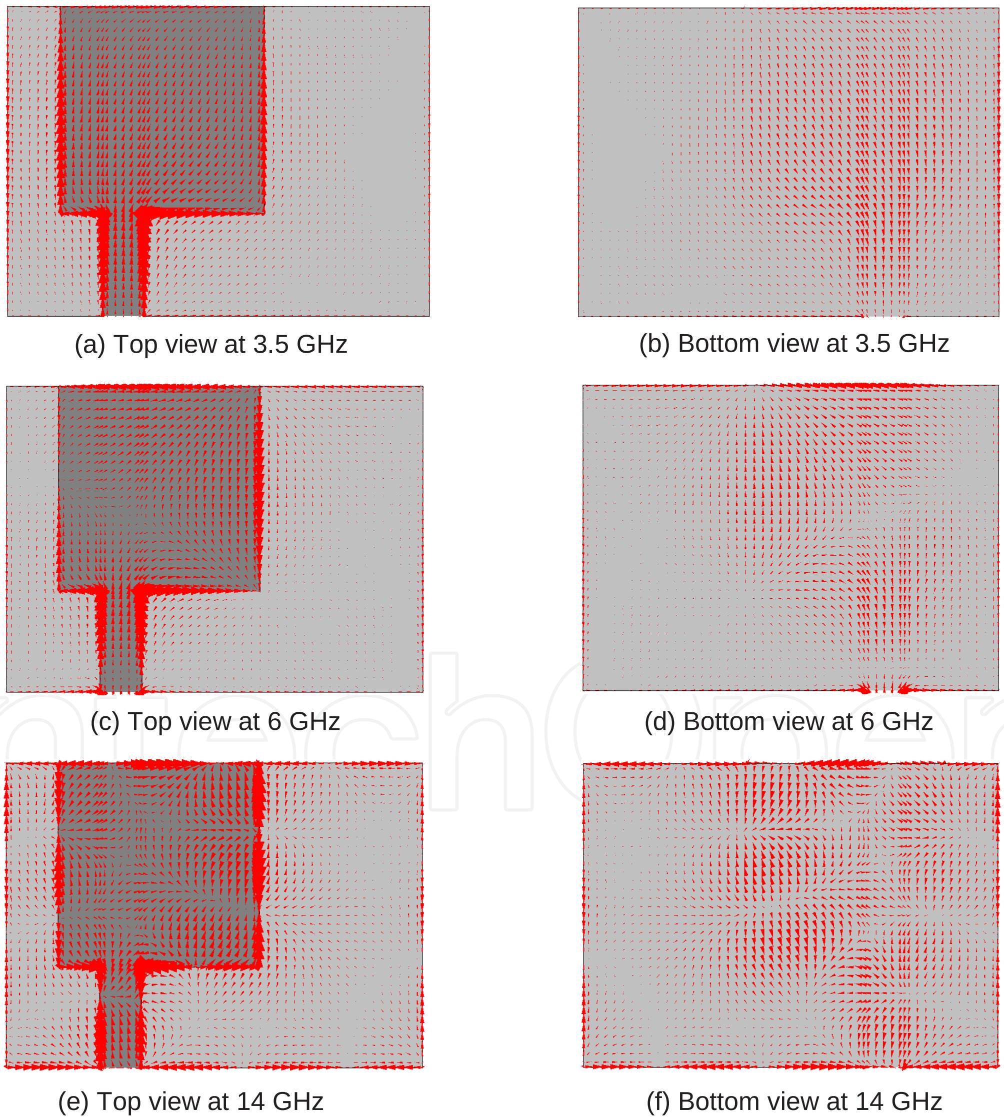

Figure 7. Surface current distributions at different frequencies.

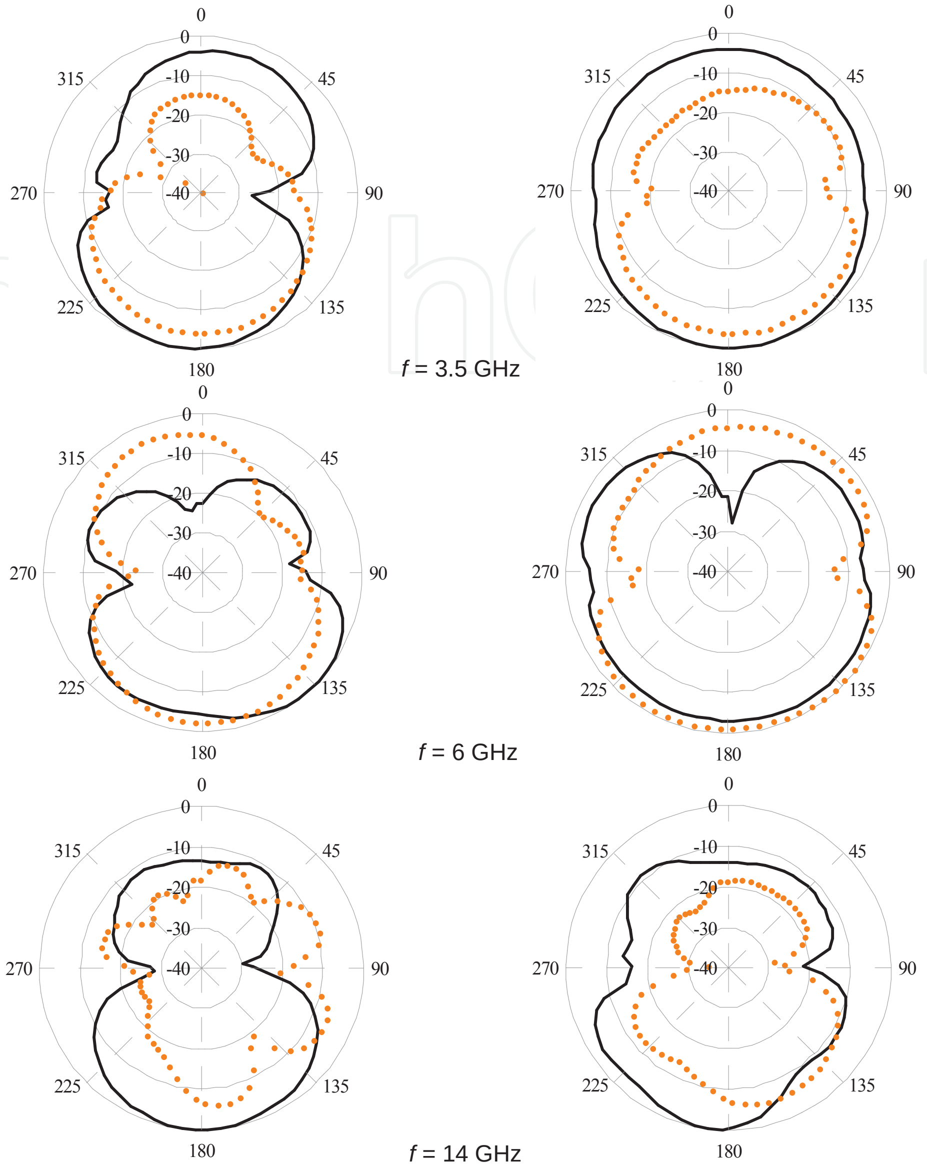

Figure 8. Simulated E (Left column) - and H (Right column)-field patterns at (a) 3.5, (b) 6 and (c) 14 GHz [solid line: co-polarization; dotted line: cross-polarization].

From the current distribution in Figure 7 it is observed that the electric currents are uniformly distributed in the ground plane of the initial design as like as radiating element and it become stronger at higher frequencies. However, such a radiation from the ground plane of planar antennas is undesirable because it creates an unbalanced structure between radiator and ground plane resulting in degradation of the antenna performance in terms of operating bandwidth and radiation patterns. Moreover, from radiation patterns display it is observed that the initial antenna suffer high cross-polarization levels in both *E*- and *H*-plane. This is due to large size of the ground plane. These sorts of ground plane effect may cause severe practical engineering problem such as deployment difficulties and design complexity [61]. That is why, it is necessary to introduce a technique to reduce the effect of ground plane on compact planar UWB antennas.

5. New bandwidth enhancement technique in UWB antenna

As the operating bandwidth of the initial antenna does not fulfill the requirements by FCC, i.e. 3.1 - 10.6 GHz, its ground plane (30 mm × 22 mm) is to be modified to improve the input impedance characteristics at the lower frequency band. Moreover, the lateral size of the ground plane has to be minimized to reduce the high cross-polarization level as well to compact the antenna which is desirable for many portable devices. For reducing the effect of ground plane on antenna performance, the ground plane is modified by using the following techniques.

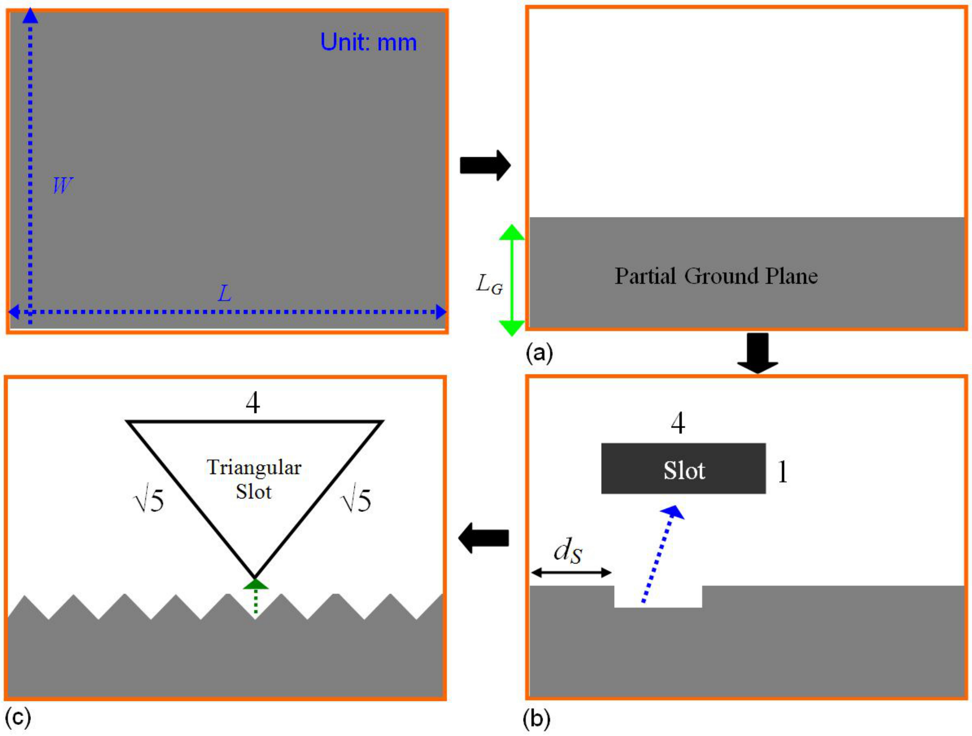

Figure 9. Modification of initial ground plane.

First, the length of ground plane decreased to L_G as shown in Figure 9, which is equal to the length of microstrip feeding line, l_f that is, the ground plane is printed only beneath of the feeding line and the size and position of the radiating patch remain unchanged. As the ground plane serves as an impedance matching circuit, it is seen the from the from the Figure 10 that the antenna with a partially shrunken ground plane of $W \times L_G$ can now achieved an impedance bandwidth (return loss ≥ -10 dB) of 8.8 GHz (3.1 - 11.9 GHz) which covers the entire ultra-wideband assigned by FCC. The overlapping of multiple resonance modes which are closing distributed across the spectrum resulting in such an ultra-wide operating bandwidth.

To further reduce the effect of ground plane on antenna performance and to improve operating bandwidth, a rectangular shape slot is introduced at the top side of the ground plane.

The slot is placed at a distance of d_S mm from left edge of the substrate. The resultant ground plane is shown in Figure 9(b). The return losses in Figure 10 shows that the rectangular slot of dimension 4 mm × 1 mm has small effect on the lower edge frequency while it increase the upper edge frequency of the operating band and the antenna can provide an impedance bandwidth of 9.3 GHz operating from 3.1 to 12.42 GHz. Compared to the partial ground plane without any slot, the antenna with single slot on the top edge of the ground plane can enhance the bandwidth by 520 MHz.

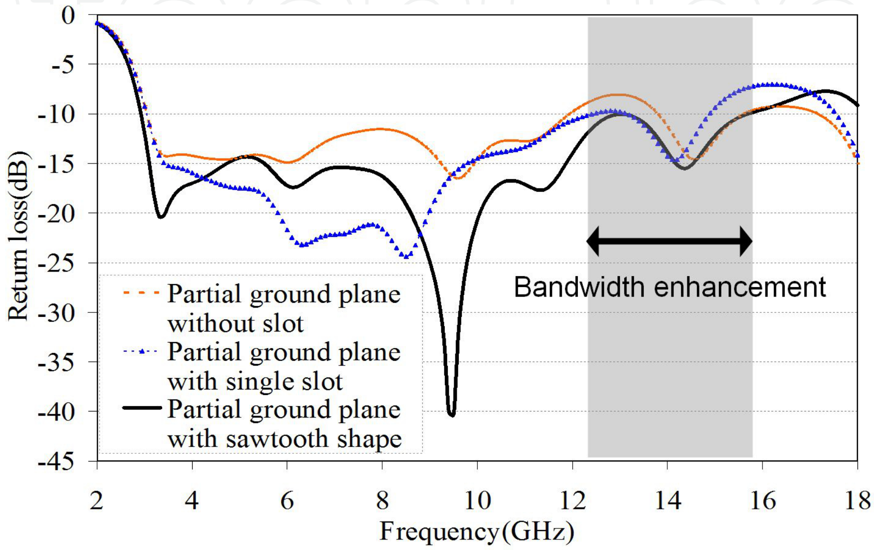

Figure 10. Comparison of return loss curves of the antenna with partial ground plane, partial ground plane with single slot and partial ground plane with sawtooth top edge.

To enhance the bandwidth and reduce the ground plane effect further, the top edge of the partial ground plane is reshaped to form a symmetrical sawtooth shape top edge by cutting of triangular shape slot as shown in Figure 9(c). This technique alter the distance between the ground plane and lower part of planar monopole antenna and tune the capacitive coupling between them resulting in wider operating bandwidth. The optimized dimension of the triangular shape slot is 4 mm × √5 mm × √5 mm. From the return loss curve shown in Figure 10 it is seen that the modified ground plane with sawtooth shape top edge has a little effect on lower edge frequency while it significantly influence the upper edge frequency of the operating band as expected. It is also seen from the Figure that the antenna with modified ground plane can be operated from 2.92 GHz to 15.70 GHz providing a -10 dB impedance bandwidth of 12.78 GHz. It is also observed that, introduction of triangular shaped slots not only widens the bandwidth but also reduces the return loss. The insertion of slots in the top edge of the ground plane increases the gap between the radiating patch and the ground plane and as a result the impedance bandwidth increases further due to extra electromagnetic coupling in between radiating element and the ground plane. Compared to the result associated with the initial design, the antenna with modified sawtooth shape ground plane can increase the bandwidth by 45.25% (3.98 GHz) as depicted in Figure 10.

The simulated input impedance curve with different types of partial ground plane is shown in Figure 11. It is seen that compared to partial ground plane without any slot and with a rectangular slot, the antenna with sawtooth shape ground plane exhibit less capacitive load to the antenna especially at higher frequencies of the operating band, which means the impedance match is getting better, thus leading to a wider operating bandwidth as illustrated in Figure 10.

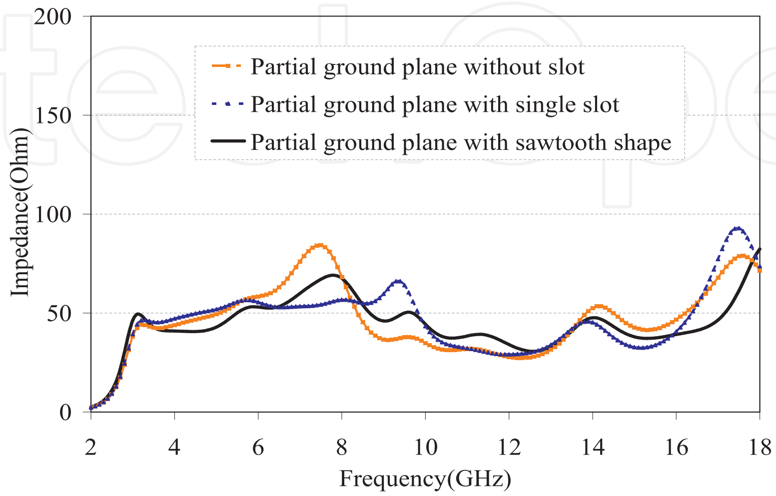

Figure 11. Simulated input impedance for different types of ground plane.

5.1. Operating principle of UWB characterization

It has been observed from the impedance characteristics that first resonance is occurs at 3.3 GHz when the ground plane is shrunk to 30 mm × 7.5 mm and modify its top edge. In input impedance characteristics, the resonance frequencies are defined where the dips are located. When the radiating patch is backed by a large ground plane of whole substrate size, the first resonance frequency is slightly shifted towards higher frequencies. If the ground plane is shrunk in length, the second and third resonance is also shifted slightly, but still not faraway from initial one as shown in Figure 5 and Figure 10. This demonstrates that these resonant frequencies is mostly determined by the radiating patch and slightly detuned by the ground plane dimension. Furthermore, it is observed that the first resonance frequency is dependent on the size of the patch while the second and third resonance frequencies as well as the bandwidth obey the size of the triangular slots that cut the top edge of the partial ground plane. However, the fourth and fifth resonance frequencies are strongly dominated by the size of the ground plane as seen from Figure 5 and Figure 10.

At lower frequency of the operating band (first resonance) where the corresponding wavelength is larger than the antenna dimension, the electromagnetic signal can couple easily into the antenna configuration therefore it act as an oscillator, i.e. a stationary wave as presented earlier in [33]. As the frequency increases, the antenna starts to operate in a dual mode of stationary and travelling waves. At the upper edge frequencies, the travelling wave becomes more influential to antenna operation since the electromagnetic signal required to go down to the antenna structure which is large in terms of wavelength.

The rectangular radiating patch of the printed planar antenna and the slots formed at top edge of the partial ground plane with an appropriate dimension can support travelling wave very well. Therefore the planar monopole antenna with modified sawtooth shape ground plane can exhibit an ultra-wide operating bandwidth (return loss ≥ -10 dB) with optimal design parameters. Furthermore, it is depicted from Figure 10 that the proposed antenna is capable of supporting multiple resonance modes and the higher order modes are the harmonics of the fundamental mode of the patch. It is also observed that these higher order modes are very much spaced. Therefore, the overlapping of these resonance modes leads to the characterization of ultra-wideband, as depicted in Figure 12.

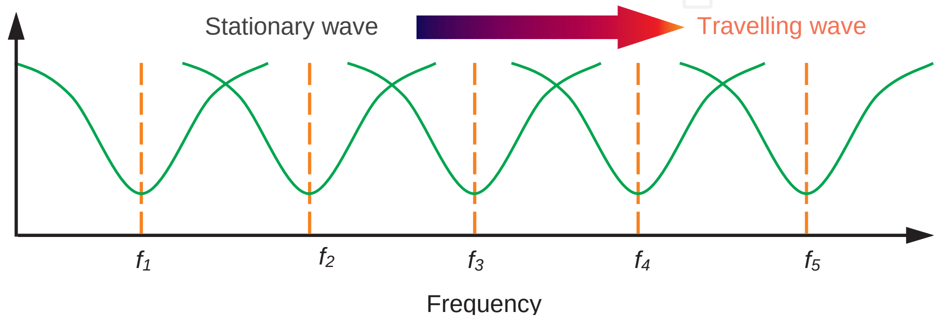

Figure 12. Overlapping of multiple resonances leading to UWB characterization.

5.2. Current distributions analysis

The current distributions usually present an insight into the physical behavior of the antenna. The simulated current distributions of the final design with modified ground plane at different frequencies are depicted in Figure 13. The current pattern at first resonance frequency of 3.1 GHz is illustrates at Figure 13(a). Figure 13(b) show the current distribution pattern at 6.1 GHz, representing a second order harmonics. A more complicated current distribution at third resonance frequency of 9.5 GHz, corresponding to third order harmonics is depicted in Figure 13(c). Figure 13(d) presents the fourth order harmonics at 11.3 GHz. These current distributions support the principle that the overlapping of closely spaced resonances resulting in the UWB characterization. At these frequencies the resonances are clearly observed on the edge of the radiating patch as well as in the ground plane.

It can be observed from the current distribution pattern that majority of the electric currents is concentrated around the edge of the radiating patch and the ground plane while the currents at the centre of the patch and ground plane are very weak. It is also seen that the current is coupled from the top and bottom edge of the ground plane to the patch through microstrip feed line and radiates to the free space. At lower frequencies, the current path length in antenna with modified sawtooth shape ground plane is much smaller than the antenna with large ground plan. In the antenna with modified ground plane, the currents at the junction between ground plane and patch is weaker than the currents in antenna large ground plane. Therefore, very small amount of current is flow into the ground plane and thus its effects on antenna performance reduced significantly. Moreover, triangular slots on the top edge of the partial ground plane effectively alleviate the changes in antenna impedance by altering the current path and creating a symmetrical current distribution to a small ground plane which reduce the effect of ground plane on antenna performances. However, at higher frequencies, the currents are mainly distributed on the microstrip line and the junction between patch and ground plane. As a result, the currents on the ground plane become stronger than lower frequencies and impedance matching becomes worse for travelling wave dependent modes.

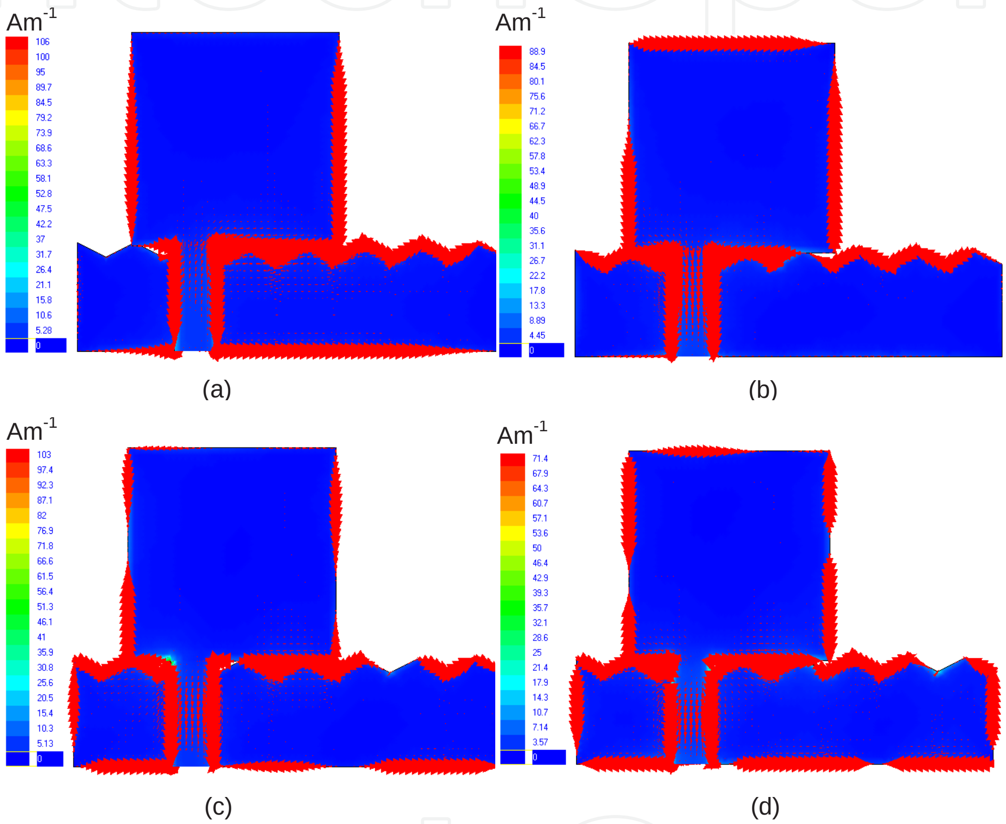

Figure 13. Surface current distributions at (a) 3.3 GHz, (b) 6.1 GHz, (c) 9.5 GHz and (d) 11.3 GHz.

5.3. Experimental verification

After a comprehensive investigation of the effect of different parameters and ground plane on antenna performance it is found that the final design had the optimized structural parameters of $W = 30$ mm, $L = 22$ mm, $L_G = 7.5$ mm, $W_P = 14.5$ mm, $L_P = 14.75$ mm, $w_f =$ 3 mm, $d_f =$ 6.75 mm, $d_S =$ 3.5 mm and $d_P = 3.75$ mm. The very small sized ground plane would be able to cope with the increasing demand for compact antenna for portable devices. Moreover, since the antenna is printed on substrate, no additional space is required for height of the antenna. A set of prototype of the final design of the proposed antenna with optimal parameters was fabricated for experimental verification as shown in Figure 14. The prototype consist of two 35μm-thick copper layers with the antenna printed on the top side for better radiation performance while the modified partial ground is etched out at the bottom side. The antenna is printed on a 1.6 mm-thick FR4 dielectric substrate with relative permittivity of 4.6 and loss tangent of 0.02. An SMA connector is connected to the port of the microstrip feed line.

The input impedance characteristic of the realized antenna has been measured in an anechoic chamber using Agilent E8362C vector network analyzer. Figure 15 plotted the measured and simulated return loss curves. The simulated -10 dB return loss bandwidth ranges from 2.92 GHz to 15.70 GHz which is equivalent to a fractional bandwidth of 137.3%. This UWB characteristic of the compact planar monopole antenna is confirmed in measurement, with only a small shift of the lower and upper edge frequency to 2.95 GHz and 15.45 GHz respectively. Despite very compact size, the performance of the proposed antenna exceeds the UWB as defined by FCC. Although there is a disparity between the measured and simulated resonances which possibly attributed due to manufacturing tolerance and imperfect soldering effect of the SMA connector, the measured resonance frequencies are nearly identical to the simulate one. This mismatch also may be due to the effect of the RF feeding cable, which is used in the measurements but not considered during simulation. Despite some mismatched as observed in Figure 15, it is confirmed that reduction of length and modification of shape of the ground plane is not lead to any sacrifice of the operating bandwidth.

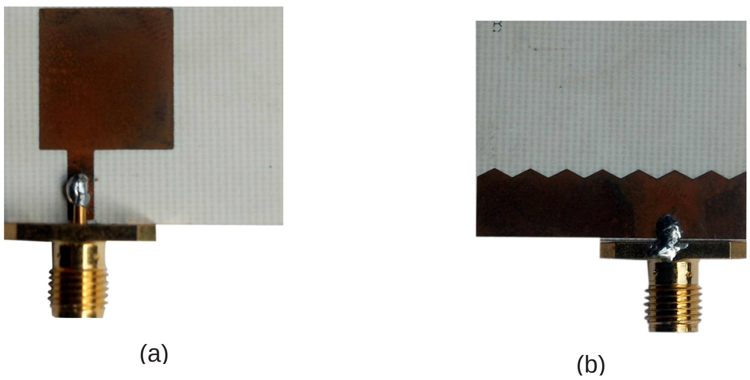

Figure 14. Photograph of realized antenna (a) Top view, (b) Bottom view.

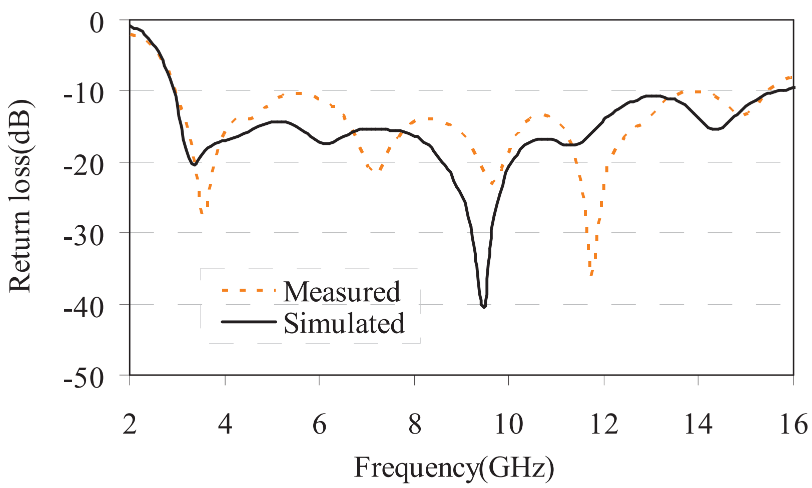

Figure 15. Measured and simulated return loss curves of the final design.

The phase of the input impedance is another important parameter of the planar UWB antenna. Since UWB antenna operates in wide range of frequencies, the phase across the operating band should be linear for preventing the pulse distortions. Figure 16 illustrates the measured phase variation of the input impedance of the final design measured in anechoic chamber using Agilent E8362C PNA series network analyzer. The phase variation across the entire operating band is reasonably linear except at around 10 and 14 GHz. This linear variation in the phase with frequency ensures that all the frequency components of signal have same delay leading to less pulse distortion.

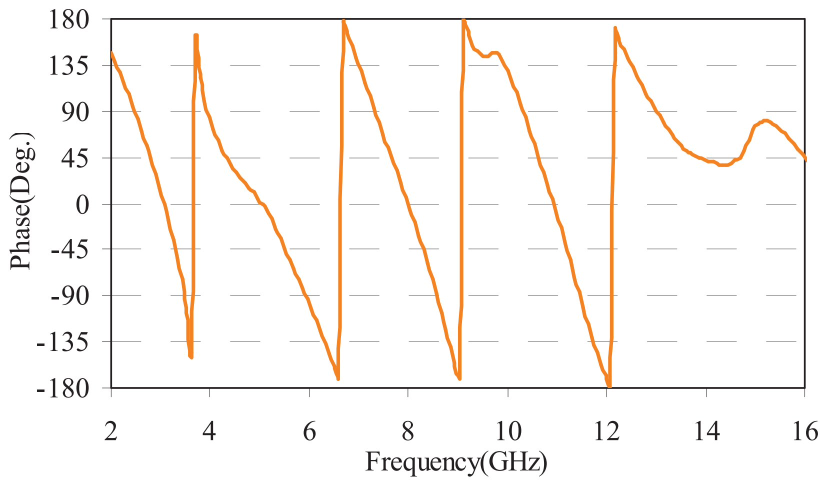

Figure 16. Measured phase variation of the input impedance.

The final design with symmetrical sawtooth shape partial ground plane was characterized in the anechoic chamber using SATIMO's StarLab antenna measuring equipment in order to measure the radiation patterns, peak gain and radiation efficiency. To achieve untruncated extent near field sampling using a probe array, the spherical scanning system was utilized for this near-field antenna measurement system.

Based on the antenna orientation with respect to the axes in Figure 4, *yz*-plane is the *E*-plane while *xz*-plane represents the *H*-plane and $\theta = 0^0$ corresponds to *z*-axis, while $\theta = 90^0$ corresponds to *y*-axis and *x*-axis for *E*-and *H*-planes respectively. The radiation patterns of the proposed antenna in *E*- and *H*- planes are measured at frequencies that are very close to resonance frequencies. The measured 2D radiation patterns at 3.3 GHz, 6.2 GHz and 9.4 GHz in *E*- and *H*- planes are presented in Figures 17. The radiation patterns are normalized by the taking the highest value as reference. It is observed that, in both *E*- and *H*-plane, the co-polarized field is omni-directional at lower frequencies and retain a good omni-directional patterns even at higher frequencies. In, *E*-plane the cross-polarized fields are much lower than that of the co-polarized one especially at lower frequencies. Although some harmonic is introduced at higher frequencies, the proposed antenna with modified partial ground plane exhibits a symmetric omni-directional radiation patterns that are same as that of a monopole antenna. Compared to radiation patterns of the antenna with large ground plane, the radiation pattern of the antenna with partial ground plane is more omni-directional and size reduction does not deteriorate the radiation characteristics.

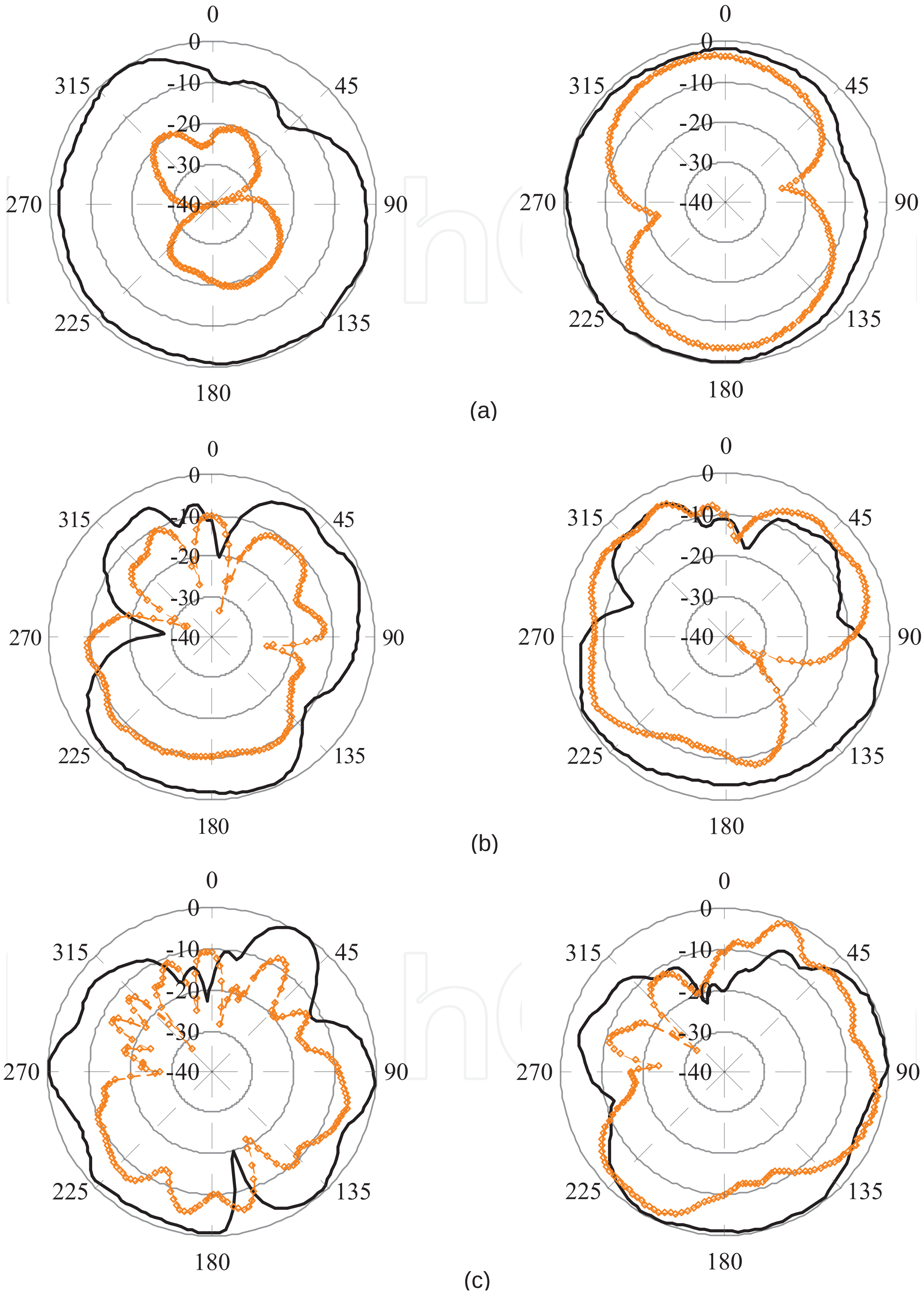

Figure 17. Measured *E*(left)-and *H*-(right)-plane radiation patterns at (a) 3.3 GHz, (b) 6.2 GHz and (c) 9.4 GHz[co-polarization :solid line; cross-polarization: cross line].

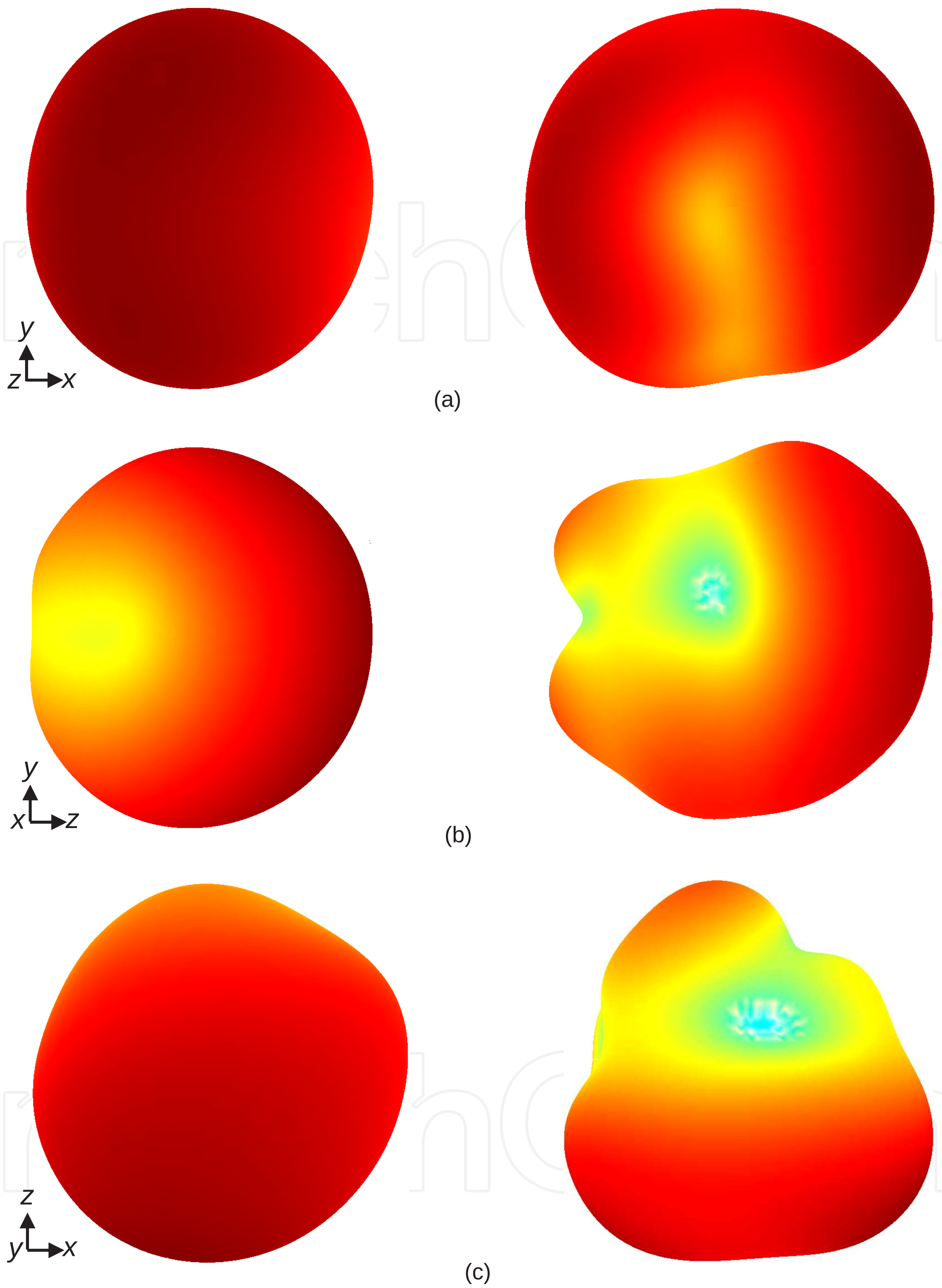

Figure 18. Measured 3D radiation patterns at 3 GHz (left column) and 8(right column GHz (a) *xy*-, (b) *yz*- and (c) *xz*-plane.

The measured 3D radiation patterns for total electric field at 3 and 8 GHz is shown in Figure 18. In the patterns the red color indicates the stronger radiated E-field and the sky blue is the weakest ones. The radiation is slightly weak in *z*-direction. It is observed from the figures that the proposed antenna exhibits almost omni-directional radiation patterns which similar like a typical monopole antenna. This 3D omni-directional radiation pattern is required for many wireless applications such as mobile communication.

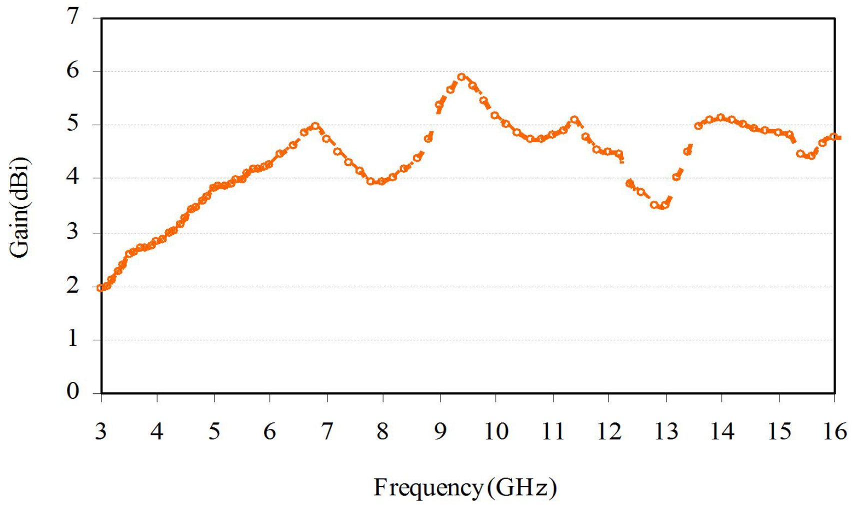

Figure 19. Measured peak antenna gain in UWB frequency range.

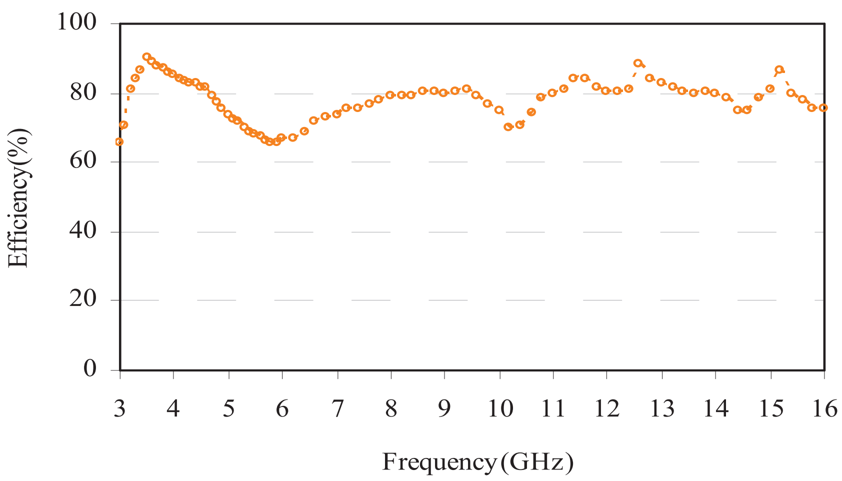

Figure 20. Measured radiation efficiency with sawtooth shape ground plane.

The measured peak gain of the final realized antenna at boresight (+*z* direction) is shown in Figure 19. It is observed that the antenna has a good gain with a maximum value of 5.9 dBi at 9.4 GHz. The average gain in the operating band is 3.97 dBi and the measured gain variation is less than ± 2 dBi. The measured radiation efficiency of the proposed antenna at boresight is shown in Figure 20. The antenna has a maximum of 90.2% radiation efficiency with an average of 76.79%. As the antenna was fabricated on FR4 dielectrics substrate with modified partial ground plane, the dielectric loss was high, which affected the gain as well as the efficiency.

Since UWB systems directly transmit narrow pulses rather than continuous wave, the time domain performances of the UWB antenna is very crucial. A good time domain performances is a primary requirement of UWB antenna. The antenna features can be optimized to avoid undesired pulse distortions. The group delay is defined as the negative derivative of the phase response with respect to frequency. The group delay gives an indication of the time delay of an impulse signal at different frequencies. Since UWB technology employed in short range communication systems, in the measurements the transmitting and receiving antennas are placed at distance 50 cm apart in face to face orientation.

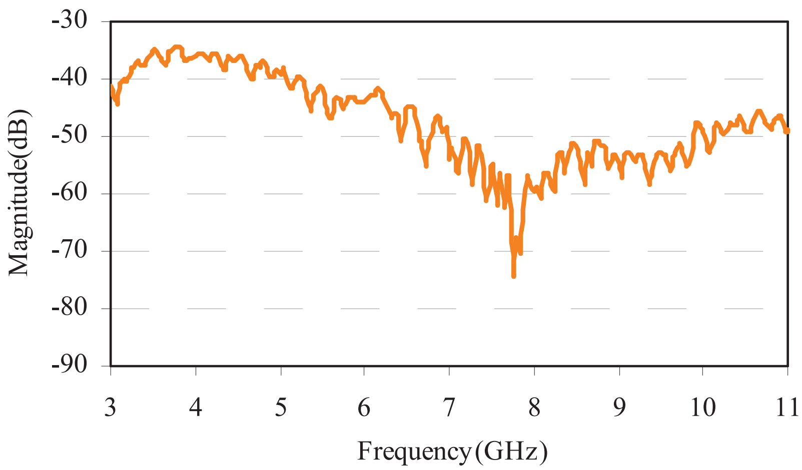

Figure 21. Magnitude of the measured transfer function in UWB range.

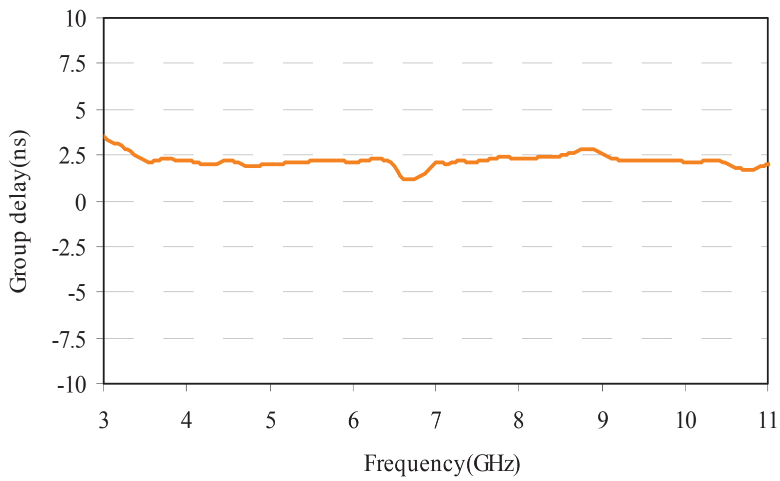

Figure 22. Measured group delay of the proposed antenna in UWB range.

The measured transfer functions of the proposed planar antenna with modified ground planes are shown in Figures 21 and 22. It is observed from Figure 21 that the magnitude curve has little variation with some ripples due noise. The group delay characteristics are almost smooth across the UWB frequency band as shown in Figure 22. The measured group delay is flat at about 2.2 ns and variation is only about 0.17 ns. This small variation in group delay indicates that the proposed antenna has good linear transmission function characteristics and could be useful for UWB impulse radios applications.

6. Conclusion

UWB is a promising technology that brings the convenience and mobility of communications to high-speed interconnections in wireless devices. As a vital part of the communication system, the design of antenna is challenging since there are more particular requirements for UWB antenna compared to its narrow band counterpart. In addition, in order to be easily integrated into portable devices, printed UWB antennas with small size and compact planar profile are highly desirable and essential for a wide variety of applications. Therefore, the design of printed planar antenna for UWB applications and its trends has been analyzed in this article. Rectangular planar antenna is initially chosen as conventional structure due to its low profile and ease of fabrication. However, its performance is significantly affected by the large ground plane. A technique, reducing the size of the ground plane and cutting of different slots has then been applied to reduce the ground plane dependency. It has been revealed that modification of large ground plane reduces the ground plane dependency as well the cross-polarization component and increases the impedance bandwidth while the addition of different types of slots enhances the bandwidth further. It has been observed that shortening of current path due to removal of the upper portion of the ground plane and insertion of the slots contributes to the wider bandwidth at low frequency end. Studies indicate that the rectangular antenna with modified sawtooth shape ground plane is capable of supporting closely spaced multiple resonant modes and overlapping of these resonances leads to the UWB characteristic. It is observed that the cutting triangular shape slots on the ground plane help to increase the bandwidth by 45.25% and in overall the antenna achieve an impedance bandwidth of 137.3% (2.92 GHz to 15.70 GHz). Moreover, it exhibits stable radiation patterns with satisfactory gain, radiation efficiency and good time domain behavior.

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