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UWB (Ultra wideband) wireless communications: UWB Printed Antenna Design

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1. Introduction

The admirable benefits of a wireless lifestyle have resulted in a huge demand for advanced wireless communications. The quick-tempered growth of the wireless communication market is expected to continue in the future since the claim of all wireless services is increasing. New wireless generations systems endeavor to provide high data rates as well as a wide range of applications like video and data to the portable users while supplying as many users as possible. However, this trend is limited by available resources like spectrum, power and coexistence of wireless devices. Thus, innovative technologies, that can coexist with devices operating on the crowded bands, are required to overcome the limited bandwidth and provide high data rates [Arslan, et al., 2006].

In February 2002, Federal Communications Commission (FCC) released a wide new unlicensed spectral band of 7.5 GHz for the commercial operation of ultra wideband (UWB) technology [FCC, 2002]. Since then, UWB has has been considered as one of the most promising wireless technologies to revolutionize high data rate transmission. UWB technology has offered unique advantages not achievable by conventional narrowband technology. These advantages are low power consumption, high speed transmission, immunity to multi-path propagation, and simple hardware configuration [Wentzloff, et al., 2005].

UWB communication techniques have attracted a great deal of interest both in the academia and industry in the past few years because of the high merit of their advantages. All Wireless systems and applications including UWB ones need a mean of transferring energy or signal from the apparatus to free space in the form of electromagnetic waves or vice versa which is an antenna. It has been recognized as a critical element of the successful design of any wireless device since the wireless systems are highly dependent on their antenna characteristics. Based on that, UWB antennas have been an important and active area of research and have presented antenna engineers with major design challenges [Alshehri, 2008].

In this chapter, the following topics are discussed. First, an introduction to UWB technology is presented in terms of its history, definition, advantages and applications. Second, the importance of UWB antennas is highlighted. Next, the major requirements for a suitable UWB antenna are discussed. Then, several general methods to achieve a wide bandwidth are presented. After that, an overview on UWB antennas including UWB planar monopole antennas and UWB printed antennas is provided. Then, two novel designs of UWB printed antennas are introduced and investigated. Before we discuss these antenna designs in greater detail, we first introduce the numerical technique and its software package utilized to calculate the electromagnetic performance of the proposed antennas. The designs, optimizations, and simulations are conducted using the Ansoft High Frequency Structure Simulator (HFSS™). It works based on the Finite Element Method (FEM). After that, the design and fabrication of two novel UWB printed antennas are presented in details. The structural properties and performance characteristics of these antennas are investigated via numerical simulations and verified by measurements. The design process, parametric study, optimization as well as simulated and measured results, such as return loss, radiation characteristics and gain are provided.

1.1 UWB history

Now, Ultra Wideband technology is a potentially viable-revolutionary approach to wireless communication however it is certainly not a new concept. UWB systems have been historically based on impulse radio since it has transmitted very high data rates by sending pulses of energy instead of using a narrowband frequency carrier [Liang, 2006]. The concept of impulse radio dates back to the pulse-based spark-gap radio developed by Guglielmo Marconi in the late 1800's [Siwiak & McKeown, 2004]. It was used for several decades to transmit Morse code through the airwaves. But, it also caused strong interference to narrowband radio systems, which were developed in the early 1900's. Consequently, by 1924, the communications world abandoned wideband communication in preference of narrowband communication that was easy to regulate and coordinate [Schantz, 2003].

In the late 1960's, significant research was conducted by antenna designers, including Rumsey and Dyson [Rumsey, 1957: Dyson, 1959], who developed logarithmic spiral antennas, and Ross, who applied impulse measurement techniques to the design of wideband, radiating antenna elements [Ross, 1968]. As a result of these antenna advances, the development of short pulse radar and communications systems had begun. In 1973, the first UWB communications patent was awarded for the short-pulse receiver [Ross, 1973]. For the nearly 40 year period of 1960-1999, over 200 papers were published in accredited IEEE journals and more than 100 patents were filed on topics related to ultra wideband technology [Barrett, 2000].

On february 14th, 2002, FCC permitted the commercial operation of UWB technology [FCC, 2002]. After this official permission, research interest has exponentially grown with several researchers exploring RF, circuit, system and antenna designs related to UWB techonlogy. Also, several industrial companies have started investing in order to deliver revolutionary high-speed, short range data transfers and higher quality of services to the user [Powell, 2004].

1.2 UWB definition

Ultra-Wideband is a wireless communication technology that transmits an extremely low power signal over an extremely wide swath of radio spectrum to deliver very high transmission rates. It transmits and receives pulse-based waveforms compressed in time instead of sinusoidal waveforms compressed in frequency. Figure 1 depicts the equivalence of a narrowband pulse in the time domain to a signal of very wide bandwidth in the frequency domain. Also, it reveals the equivalence of a sinusoidal signal in time domain to a very narrow pulse in the frequency domain [Powell, 2004].

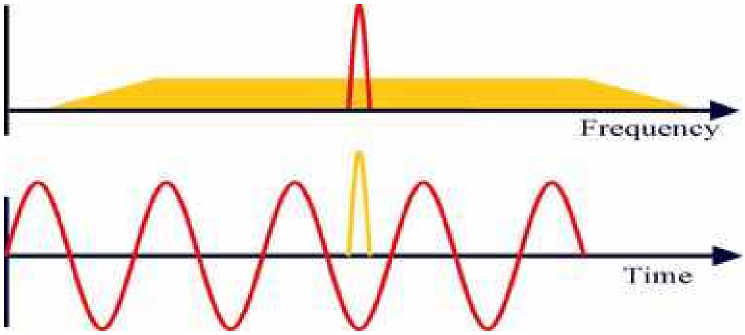


Fig. 1. The equivalence of pulse-based waveforms compressed in time to a signal of very wide bandwidth in the frequency domain [Powell, 2004]

In February 14th, 2002, The FCC allocated an unlicensed bandwidth from 3.1 GHz to 10.6 GHz to UWB applications, which was the largest spectrum for unlicensed use the FCC has ever granted. According to the FCC rulings, UWB operation is defined as any transmission scheme that occupies a fractional bandwidth greater than or equal to 0.2, or a signal bandwidth greater than or equal to 500 MHz [FCC, 2002].

1.3 UWB advantages

Due to the ultra wideband nature, UWB offers several motivating advantages that qualify it to be a more attractive solution to broadband wireless, radar communications and many applications than other technologies [Liang, 2006]. The extremely large bandwidth provided by UWB gives the potential of very high capacity resulting very high data rates. It can provide hundreds of Mbps or even several Gbps with distances of 1 to 10 meters [Oppermann, et al., 2004]. UWB communication systems transmit signals with extremely low spectral power density. By splitting the power of the signal across UWB spectrum, the effect is below the acceptable noise floor on any frequency. Consequently, UWB signals do not produce harmful interference to other coexisting wireless systems in the same frequency spectrum [Siriwongpairat, 2005].

Other merit of UWB includes low power transmission and robustness against eavesdropping since the UWB signal appears as noise-like signal. UWB also offers great flexibility of spectrum usage. In fact, this system can be designed as a function of the required data rate, range, power, quality-of-service, and user preference. By trading-off among these parameters, it can provide the required serivce based on the applications types or provide service for multiple applications with a diversity of requirements devoid of additional hardwares [Arslan, et al., 2006].

1.4 UWB applications

As mentioned in the previous section, UWB offers many elegant advantages and benefits that are very attractive for a wide variety of applications. UWB is being targeted as a cable replacement technology since it has the potential for very high data rates using very low power at very limited range. It makes UWB became part of the wireless world, including wireless home networking, high-density use in business cores, wireless speakers, wireless USB, high-speed WPAN, wireless sensors networks, wireless telemetry, and telemedecine [Arslan, et al., 2006].

Due to the excellent time resolution and accurate ranging capability of UWB, it can be used in positioning and tracking applications such as vehicular radar systems for collision avoidance, guided parking, etc. The UWB capabilities of material penetration allows UWB to be used for radar imaging systems, including ground penetration radars, wall radar imaging, through-wall radar imaging, surveillance systems, and medical imaging [Oppermann, et al., 2004]. UWB radars can detect a person’s breath beneath rubble or medical diagnostics where X-ray systems may be less desirable [Liang, 2006].

1.5 Why UWB antennas

The attractive nature of UWB coupled with the rapid growth in wireless communication systems has made UWB an outstanding candidate to replace the conventional and popular wireless technology in use today like Bluetooth and wireless LANs.

A lot of research has been conducted to develop UWB LNAs, mixers and entire front-ends but not the same amount of research has initially been done to develop UWB antennas. Later [Tsai & Wang, 2004; Lee, et al., 2004], academic and industrial communities have realized the tradeoffs between antenna design and transceiver complexity. In general, when new advanced wireless transmission techniques have been introduced, the transceiver complexity has increased. To maximize the performance of transceiver without changing its costly architecture, advanced antenna design should be used since the antenna is an integral part of the transceiver. Also, it has played a crucial role to increase the performance and decrease the complexity of the overall transceiver [Alshehri, 2004].

In addition, the trend in modern wireless communication systems, including UWB based systems, are to build on small, low-profile integrated circuits in order to be compatible with the portable electronic devices. Therefore, one of the critical issues in UWB system design is the size of the antenna for portable devices, because the size affects the gain and bandwidth greatly. The use of a planar design can miniaturize the volume of the UWB antennas by replacing three-dimensional radiators with their planar versions. Also, their two-dimensional (2D) geometry makes the fabrication relatively easy. As a result, the planar antenna can be printed on a PCB and thus integrated easily into RF circuits [Chen, et al., 2007].

2. Ultra Wideband Antenna Requirements

There are further challenges in designing a UWB antenna as compared to a narrowband one. A UWB antenna is different from other antennas in terms of its ultra wide frequency bandwidth. According to the FCC's definition, a suitable UWB antenna should provide an absolute bandwidth no less than 500 MHz or a fractional bandwidth of at least 0.2. This is the minimum bandwidth but generally the UWB antenna should operate over the entire 3.1-10.6 GHz frequency range resulting in spanning 7.5 GHz [Liang, 2006; Yang & Giannakis, 2004].

The UWB antenna performance is required to be consistent over the whole equipped band. Ideally, antenna radiation patterns, gains and impedance matching should be stable across the entire band [Wong, et al. 2005]. The radiation efficiency is another significant property of the UWB antenna. Since the transmit power spectral density is extremely low in UWB systems, high radiation efficiency is required because any unwarranted losses incurred by the antenna could affect the functionality of the system [Liang, 2006].

A suitable antenna should be physically compact and preferably planar to be compatible to the UWB unit, especially in mobile and portable devices. It is also greatly desired that the antenna attributes low profile and compatibility for integration with a printed circuit board (PCB) [Liang, 2006].

Finally, a UWB antenna should achieve good time domain characteristics. In narrowband systems, an antenna has mostly the same performance over the entire bandwidth and fundamental parameters, such as gain and return loss that have slight discrepancy across the operational band. Quite the opposite, UWB systems occupy huge operational bandwidth and often utilize very short pulses for data transmission. Consequently, the antenna has a more critical impact on the input signal. Indeed, minimum pulse distortion in the received waveform is a main concern of a suitable UWB antenna in order to provide a good signal to the system [Wong, et al. 2005].

3. Methods to Achieve Wide Bandwidth

As discussed in previous section, operating bandwidth is one of the most essential parameters of an antenna. It is also the main characteristic that distinguishes a UWB antenna from other antennas. Historically, a lot of effort has been made toward designing broadband antennas such as the helical antenna, biconical antenna and log periodic antenna. Most of these antennas are designed for carrier-based systems however their bandwidth is still considered narrowband in the UWB sense. Nevertheless, the design theory and experience associated with these antennas are very useful in designing UWB antennas [Lu, 2006]. Accordingly, several methods have been employed to widen the operating bandwidth for different types of antennas [Liang, 2006]. Some of these methods are explained in the following subsections.

3.1 The concept of frequency independence

The pattern radiation and the impedance characteristic of any antenna can be determined by its specific shape and size in terms of wavelength at a given operating frequency. However, a frequency independent antenna is an antenna that does not change its properties when its size has changed. This was first introduced by Victor Rumsey in the 1950's [Rumsey, 1957]. According to Rumsey's principle, the impedance and pattern properties of any antenna will be frequency independent if the antenna geometry is specified only in terms of angles irrespective of any particular dimensions. For this concept, there are basically three principles to achieve frequency independent characteristics. They are smoothing principle as in the biconical antenna, combining principle as in the log-periodic antenna and self-complementarity principle such as the case of spiral antenna [Alshehri, 2008].

3.2 The concept of overlapping resonances

In general, a resonant antenna has narrow bandwidth since it has only one resonance. However, the combination of two or more resonant parts, each one operating at its own resonance while living closely spaced together, may generate overlapping of multiple resonances resulting in multi-band or broadband performance. Actually, the two resonant parts technique has been broadly applied in antenna design, especially for mobile handset antennas that are required to operate at diverse wireless bands. The two resonant parts can be combined either in parallel [Chen & Chen, 2004], or one works as the passive radiator and the other as parasitic element [Muscat & Parini, 2001]. However, there is a main disadvantage of this concept. It can not provide constant radiation patterns over the operational bandwidth since the patterns differ from each other at different frequencies.

In theory, an ultra wide bandwidth can be attained by using a sufficient number of resonant parts provided that their resonances can be well-overlapped. Nevertheless, it is more difficult to practically obtain impedance matching over the entire bandwidth when there are more resonant parts. Furthermore, the antenna structure will be further complicated and expensive to fabricate. In addition, it is hard to have constant radiation characteristics when using multiple radiating elements [Liang, 2006].

3.3 The concept of increasing the radiator surface area

The conventional monopole is well-known antenna. It is composed of a straight wire perpendicular to a ground plane. It is one of the main antennas used widely in wireless communication systems due to its great advantages. These advantages include simple structure, low cost, omni-directional radiation patterns and ease for matching to 50Ω system [Balanis, 2005]. The -10dB return loss bandwidth of straight wire monopole is naturally around 10 %– 20 %, based on the radius-to-length ratio of the monopole [Liang, 2006].

The bandwidth of the monopole antenna increases with the increase of the radius-to-length ratio. This means that when the radius increases, the bandwidth will increase. In other words, the larger surface area (i.e. thicker monopole) will lead to a wider bandwidth due to the increase of the current area and thus the radiation resistance is increased [Rudge, et al. 1982]. Based on the concept of increasing the radiator surface area, instead of enlarging the radius of the conventional monopole, the wire is replaced with a planar plate yielding a planar monopole. By using this technique, the bandwidth can be greatly enlarged. This planar plate can be designed using several shapes such as square, circle, triangle, trapezoid, Bishop's Hat and so on [Ammann & Chen, 2003; Agrawall, et al., 1998].

Many studies and analyses have been performed on the various shapes of the planar monopole antennas in order to understand their physical performance and to acquire enough knowledge of their operating principles. One study used the Theory of Characteristic Modes to determine how the planar monopole shape affects the input bandwidth performance of the antenna. Characteristic modes (Jn) are the real current modes on the surface of the antenna that depend on its shape and size but are independent of the feed point. These current modes produce a close and orthogonal set of functions that can be used to develop the total current. To characterize the electromagnetic behavior of electrically small and intermediate size antennas, only a few modes are needed, so the problem can be simplified by only considering two or three modes. This theory was used to analyze different planar monopole geometries such as square, reverse bow-tie, bow-tie and circular shapes. As a result of this analysis, the first characteristic mode J_1 was found to be similar to that of a traveling wave mode and its influence on the antenna impedance matching extends to high frequencies. Then, to obtain broad input bandwidth performance, it is necessary to obtain a well-matched traveling mode which can be achieved by reinforcing the vertical current distribution (mode J_1) and minimizing horizontal current distributions (mode J_2). This can be accomplished by using different techniques as will be discussed later [Bataller, et al. 2006].

A few simple formulas have been reported to predict the frequency corresponding to the lower edge of the -10 dB return loss impedance bandwidth for different shapes of the monopole antennas [Agrawall, et al., 1998; Evans, Amunann, 1999]. However, the prediction of the upper edge frequency requires full-wave analysis. Also, it is found that the upper edge frequency depends on the part of the planar element near to the ground plane and feed probe where the current density concentrates. Thus, different techniques are proposed to control the upper edge frequency such as beveling the square element on one or both sides of the feed probe [Ammann, 2001].

3.4 Techniques to improve the planar antenna bandwidth

Some shapes like the square and circular planar monopole antennas have a drawback of a relatively small impedance bandwidth [Ammann & Chen, 2004]. Consequently, several techniques have been suggested to improve the antenna bandwidth.

First, the radiator may be designed in different shapes. For instance, the radiators may have a bevel or smooth bottom or a pair of bevels to obtain good impedance matching. The optimization of the shape of the bottom portion of the antenna can lead to the well-matched traveling mode [Ammann & Chen, 2003].

Secondly, a different type of slot cut may be inserted in the radiators to improve the impedance matching, particularly at higher frequencies, [Chen, et al., 2003]. The effect of slots cut from the radiators is to vary the current distribution in the radiators in order to change current path and the impedance at the input point. Besides, using an asymmetrical strip at the top of the radiator can decrease the height of the antenna and improve impedance matching [Cai, et al., 2005].

Thirdly, a partial ground plane and feed gap between the partial ground plane and the radiator may be used to enhance and control the impedance bandwidth. The feed gap method is crucial for obtaining wideband characteristics and it particularly affects mode J_1 (the vertical current distribution) resulting in the well-matched traveling mode [Agrawall, et al., 1998]. Also, a cutting slot in the ground plane beneath the microstrip line can be used to enhance the bandwidth [Huang & Hsia, 2005]. In addition, a notch cut from the radiator may be used to control impedance matching and to reduce the size of the radiator. The notch cut significantly affects the impedance matching, especially at lower frequencies. It also reduces the effect of the ground plane on the antenna performance [Chen, et al., 2007].

Fourthly, cutting two notches in the bottom portion of rectangular or square radiators can be used to further improve impedance bandwidth since they influence the coupling between the radiator and the ground plane. Also, transition steps may be used to enhance the bandwidth by attaining smooth impedance transition between the radiator and feeding line [Lee, et al., 2005].

Finally, several modified feeding structures may be used to enhance the bandwidth. By optimizing the location of the feed point, the antenna impedance bandwidth will be further broadened since the input impedance is varied with the location of the feed point [Ammann & Chen, 2004]. A shorting pin can be used to reduce the height of the antenna as used in a planar inverted L-shaped antenna [Lee,et al., 1999]. A double-feed structure highly enhances the bandwidth, especially at higher frequencies [Daviu, et al., 2003].

4. Overview on Ultra Wideband Antennas

Different kinds of wideband antennas are designed, each with its advantages and disadvantages. The history of wideband antennas dates back to those antennas designed by Oliver Lodge in 1897. Later, they led to some of the modern ultra-wideband antennas. These antennas were early versions of bow-tie and biconical antennas which had significant wideband properties. In the 1930's and 1940's, more types of wideband antennas were designed, such as spherical dipole conical and rectangular horn antennas. In the 1960's, other classes of wideband antennas were proposed such as wideband notch antennas, ellipsoid mono and dipole antennas, microstrip antennas and tapered slot and Vivaldi-type antennas. Also, frequency independent antennas were applied to wideband design like planar log-periodic slot antennas, bidirectional log-periodic antennas and log-periodic dipole arrays [Dotto, 2005].

The wideband characteristics of these antennas depend on two main antenna features, which are the geometry shape and the dielectric material type, if any. The antenna bandwidth is affected by the impedance match between the feeding circuit and free space. The bandwidth of these antennas fluctuates significantly, from hundreds of MHz to tens of GHz based on the antenna design [Dotto, 2005]. However, these antennas are rarely used in portable devices and are difficult to be integrated in microwave circuits because of their bulky size or directional radiation. Alternatively, planar monopoles, dipoles or disc antennas have been introduced due to their wide bandwidths and small size. The earliest planar dipole is the Brown-Woodward bowtie antenna, which is a planar version of a conical antenna [Chen, et al., 2006].

4.1 Ultra wideband planar monopole antennas

Planar monopole antennas are constructed from a vertical radiating metallic plate over a ground plane fed by a coaxial probe. It can be formed in different shapes such as rectangular, triangular, circular or elliptical. The main features of these shapes are their simple geometry and construction. Planar monopole antennas have been explored numerically and experimentally and have shown to exhibit very wide bandwidth [Schantz, 2003; Ammann & Chen, 2003].

A circular monopole antenna yields a broader impedance bandwidth as compared to a rectangular monopole antenna with similar dimensions. This is because the circular planar monopole is more gradually bent away from the ground plane than the rectangular monopole. This provides smooth transition between the radiator and feed line resulting in a wider impedance bandwidth [Azenui, 2007].

The planar monopoles, suspended in space against ground plane, are not suitable for printed circuit board applications due to their vertical configuration. However, they can be well matched to the feeding line over a large frequency band (2 - 20 GHz) with gain of 4 - 6 dBi. But they suffer from radiation pattern degradation at higher operation frequencies [Chen, et al. 2006]. Therefore, some efforts have been made to develop the low-profile planar monopoles with desirable return loss performance in the 3.1 - 10.6 GHz frequency range. So, the antenna can be integrated to a PCB for use in UWB communications, which will be discussed in the following section.

4.2 Ultra wideband printed antennas

The UWB antennas printed on PCBs are further practical to implement. The antennas can be easily integrated into other RF circuits as well as embedded into UWB devices. Mainly, the printed antennas consist of the planar radiator and ground plane etched oppositely onto the dielectric substrate of the PCBs. In some configurations, the ground plane may be coplanar with the radiators. The radiators can be fed by a microstrip line and coaxial cable [Chen, et al. 2006].

In the past, one major limitation of the microstrip or PCB antenna was its narrow bandwidth characteristic. It was 15 % to 50 % of the center frequency. This limitation was successfully overcome and now microstrip antennas can attain wider matching impedance bandwidth by varying some parameters like increasing the size, height, volume or feeding and matching techniques [Bhartia, et al. 2000]. Also, to obtain a UWB characteristic, many bandwidth enhancement techniques have been suggested, as mentioned earlier.

Numerous microstrip UWB antenna designs were proposed. For instance, a patch antenna is designed as a rectangular radiator with two steps, a single slot on the patch, and a partial ground plane etched on the opposite side of the dielectric substrate. It provides a bandwidth of 3.2 to 12 GHz and a quasi-omni-directional radiation pattern [Choi, et al. 2004]. A clover-shaped microstrip patch antenna is designed with the partial ground plane and coaxial probe feed. The measured bandwidth of the antenna is 8.25 GHz with gain of 3.20 - 4.00 dBi**.** Also, it provides a stable radiation pattern over the entire operational bandwidth [Choi, et al. 2006].

5. Ultra Wideband Printed Antennas Design

The planar antennas, printed on PCBs, are desired in UWB wireless communications systems and applications because of their low cost, light weight and ease of implementation. In addition, they can be easily integrated into other RF circuits as well as embedded into UWB devices such as mobile and portable devices. However, it is a well-known fact that the bandwidth of patch antennas is narrow. Thus, many attempts have been made to broaden the bandwidth of printed antennas.

Therefore, in this chapter, two novel designs of microstrip-fed printed antennas, using different bandwidth-enhancement techniques to satisfy UWB bandwidth, are introduced. According to their geometrical shapes, they can be classified into two types: the first type is a stepped-trapezoidal patch antenna. The second one is a double-beveled patch antenna.
In designing these antennas, it considers UWB frequency domain fundamentals and requirements, such as far field radiation pattern, bandwidth, and gain. The design parameters for achieving optimal operation of the antennas are also analyzed extensively in order to understand the antenna operation. It has been demonstrated numerically and experimentally that the proposed antennas are suitable for UWB communications and applications, such as wireless personal area networks (WPANs) applications.

Before we discuss these antenna designs in greater detail, we will first introduce the numerical technique and its software package utilized to calculate the electromagnetic performance of the proposed antennas. The designs, optimizations, and simulations are conducted using the Ansoft High Frequency Structure Simulator (HFSS™). It works based on the Finite Element Method (FEM).

5.1 Finite elements method (FEM)

The finite element method (FEM) is created from the need to analyze and solve complex structure analysis. The FEM is a partial differential equation (PDE) based method. FEM is a powerful numerical technique since it has the flexibility to model complex geometries with arbitrary shapes and inhomogeneous media. The FEM begins with discretizing the computational domain into smaller elements called finite elements. These finite elements differ for one-, two-, and three-dimensional problems. The next step is to implement the wave equation in a weighted sense over each element, apply boundary conditions and accumulate element matrices to form the overall system of equation [Sadiku, 2009].

5.2 High frequency structure simulator (HFSS™)

Ansoft's High Frequency Structure Simulator (HFSS) is a commercially available and state-of-the-art electromagnetic simulation package. HFSS is one of the industry leading 3D EM software tools for radio frequency (RF) applications. It employs the finite element method (FEM) to simulate any arbitrary three-dimensional structure by solving Maxwell's equations based on the specified boundary conditions, port excitations, materials, and the particular geometry of the structure [HFSS^{TM}, v10].

6. The Stepped-Trapezoidal Patch Antenna

6.1 Overview

A novel planar patch antenna with a circular-notch cut fed by a simple microstrip line is proposed and described. It is designed and fabricated for UWB wireless communications and applications over the band 3.1 - 10.6 GHz. This antenna is composed of an isosceles trapezoidal patch with the circular-notch cut and two transition steps as well as a partial ground plane. Because of its structure, we have called it “the stepped-trapezoidal patch antenna” [Alshehri, et al., 2008]. To obtain the UWB bandwidth, we use many bandwidth enhancement techniques: the use of partial ground plane, adjusting the gap between radiating element and ground plane technique, using steps to control the impedance stability and a notch cut technique. The notch cut from the radiator is also used to miniaturize the size of the planar antenna. The measured -10 dB return loss bandwidth for the designed antenna is about 116.3% (8.7 GHz). The proposed antenna provides an acceptable radiation pattern and a relatively flat gain over the entire frequency band. the design details and related results are presented and discussed in the following subsections.

6.2 Antenna design

First, the substrate is chosen to be Rogers RT/Duroid 5880 material with a relative permittivity ε_r=2.2 and a thickness of 1.575 mm. Second, the radiator shape is selected to be trapezoidal since it can exhibit a UWB characteristic. Next, the initial parameters are calculated using the following empirical formula reported in [Evans & Amunann, 1999] after adding the effect of the substrate:

$$f_L(GHz) = \frac{904}{(4\pi h + W + W_1)} \tag{1}$$

Where:

f_L: the frequency corresponding to the lower edge of the bandwidth for the trapezoidal sheet.

W and W_1: the width of the trapezoidal patch bases.

h: the height of the trapezoidal patch.

The dimensions are expressed in mm. This formula is used to predict the lower edge frequency of the bandwidth for the trapezoidal sheet suspended in the space over the ground plane. It is accurate to +/- 9 % for frequencies in the range 500 MHz to 6 GHz. In our design, the sheet will be a patch printed on substrate, so, the effect of the substrate has to be incorprated to the formula. After adding it, the formula becomes:

$$f_L(GHz) = \frac{904}{(4\pi h + W + W_1)\sqrt{\varepsilon_{reff}}} \tag{2}$$

Where the effective relative permittivity ε_{reff} can be calculated using:

$$\varepsilon_{reff} = (\varepsilon_r + 1) / 2 \tag{3}$$

Where
ε_r: the relative permittivity of the substrate

Since the antenna is designed for UWB, it has to operate over 3.1 - 10.6 GHz. Therefore, the lower edge frequency at which the initial parameters will be calculated is 3.1 GHz. Initially, the antenna consists of an isosceles trapezoidal patch and partial ground plane etched on opposite sides of the substrate. The radiator is fed through a microstrip line with 50-Ω characteristic impedance. After setting up the configuration of the antenna, determining the initial parameters and fixing the lower frequency, the simulation is started to confirm the calculated parameters. Then, several bandwidth enhancement techniques are applied to widen the bandwidth and to obtain the UWB performance. These techniques are: adjusting the gap between radiating element and ground plane technique, using steps to control the impedance stability and the notch cut technique. It used after studying the current distribution and found out that the current distributions before and after the cut are approximately the same. Also, the notch cut from the radiator is used to miniaturize the size of the planar antenna. Figure 2 illustrates the final geometry of the printed antenna as well as the Cartesian coordinate system.

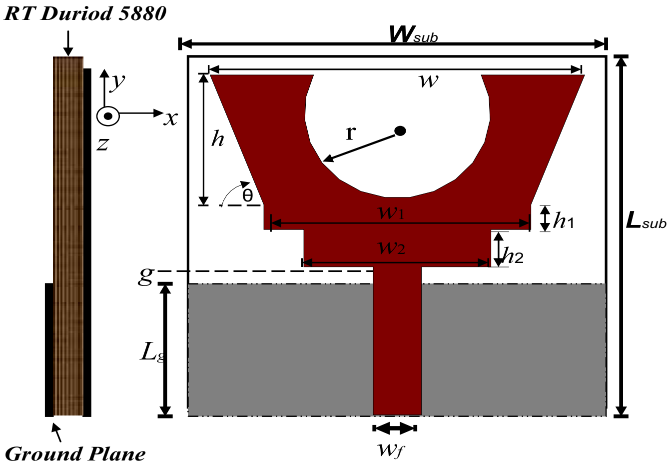


Fig. 2. The geometry of the stepped-trapezoidal patch antenna

It consists of an isosceles trapezoidal patch with notch cut and two transition steps and a partial finite-size ground plane. The Cartesian coordinate system (x,y,z) is oriented such that the bottom surface of the substrate lies in the x-y plane. The antenna and the partial ground plane are etched on opposite sides of the Rogers RT/Duroid 5880 substrate. The substrate size of the proposed antenna is 30 × 30 mm^2. The dimensions of isosceles trapezoidal patch are w=28 mm, w_1=20 mm and h=10.5 mm. The first transition step of $w_1 \times h_1$ = 20 mm × 2 mm and second transition step of $w_2 \times h_2$ = 14 mm × 3 mm are attached to the isosceles trapezoidal patch. To reduce the overall size of the printed antenna and to get a better impedance match, the circular-shaped notch with radius r =7 mm is symmetrically cut in the top middle of the isosceles trapezoidal radiator. The shape of the partial ground plane is selected to be rectangular with dimensions of 11 × 30 mm^2. The radiator is fed through a microstrip line having a length of 12 mm and width w_f =3.6 mm to ensure 50-Ω characteristic impedance with a feed gap of g = 1 mm.

6.3 Parametric study

The parametric study is carried out to optimize the antenna and provide more information about the effects of the essential design parameters. The antenna performance is mainly affected by geometrical and electrical parameters, such as the dimensions related to the notch cut and the two transition steps.

(a) Notch cut

The circular-shaped notch cut is described by its radius and the location of its center. Both parameters are studied. The effect of varying the notch radius on the impedance matching is depicted in Figure 3. When the radius is increased, the entire band is highly affected, especially the middle and higher frequencies experience higher mismatch levels. It is obviously observed that the notch can be used to reduce the size of the radiator provided that the current distribution has low density in the notch part. On the other hand, when the center of the notch moves in the upper side of the patch, the entire band is slightly influenced. In general, the notch cut parameters affect the impedance matching to a certain extent.

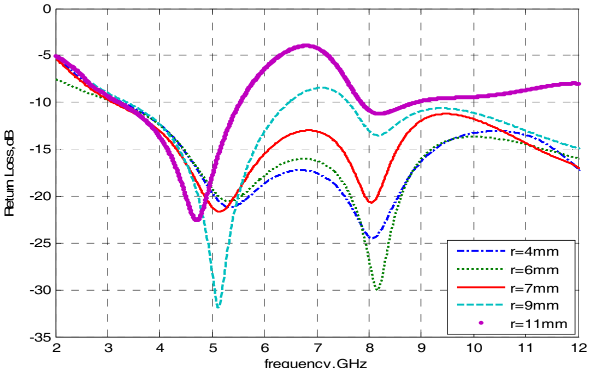


Fig. 3. Effects of notch cut radius

(b) Transition steps

The effects of the two transition steps are studied. They have great impact on the matching impedance for the whole band. For example, the effect of the width of the second step is depicted in Figure 4. From the plot, the step width greatly affects the entire band, especially at the high frequencies range, because the two steps influence the coupling between the radiator and the ground plane. Thus, by adjusting the steps parameters, the impedance bandwidth can be enhanced. In Figure 6, it is clear that a net improvement on the antenna bandwidth is obtained when the two transitions steps are used.

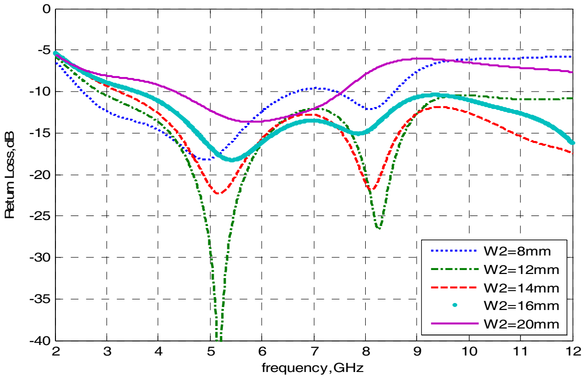


Fig. 4. Effects of step width

6.4 Results and discussion

After taking into account the design considerations described on antenna structure, current distributions and parametric study done to optimize the antenna geometry, the optimized antenna is constructed as shown in Figure 5. Then, the antenna is experimentally tested to confirm the simulation results. The simulated and measured return loss and radiation patterns are presented. Also, the simulated gain is provided.

(a) Front view (b) Back view

Fig. 5. The prototype of the stepped-trapezoidal patch antenna

(a) Return loss

The return loss (S_{11}) of the proposed antenna is measured. As depicted in Figure 6, the measured and simulated results are shown for comparison and indicate a reasonable agreement. In fact, the simulated return loss of the antenna is found to remain below -10 dB beyond 12 GHz but that range of frequencies is omitted in Figure 6 since it is far out of the allocated bandwidth for UWB communications under consideration. The measured -10 dB return loss bandwidth of the antenna is approximately 8.7 GHz (3.13 - 11.83 GHz). Excellent performance is obtained since the measured return loss is very close to the simulated one in most range of the frequency band. The measured return loss shows that the antenna is capable of supporting multiple resonance modes, which are closely distributed across the spectrum. Therefore, the overlapping of these resonance modes leads to the UWB characteristic.

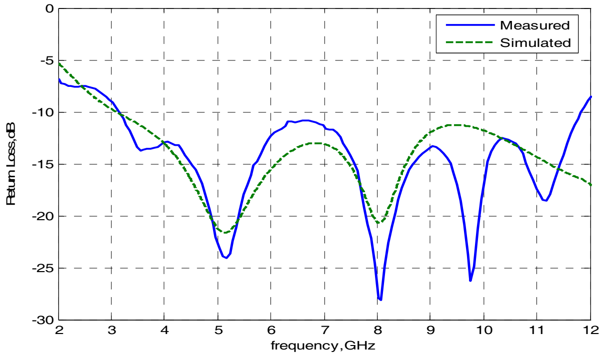


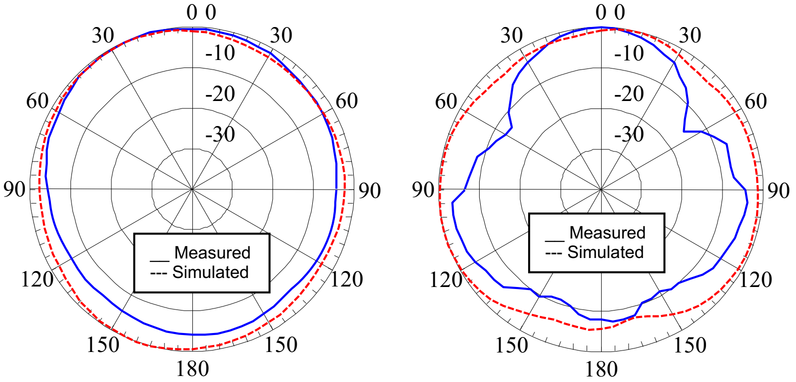
Fig. 6. The simulated & measured return loss

(b) Antenna radiation patterns

The radiation characteristics of the proposed antenna are also investigated. The two dimensional radiation patterns presented here is taken at two sets of principal cuts, Θ=0° and Φ=90°. Referring to the coordinate system attached to the antenna geometry in Figure 2, the H-plane is the xz-plane and the E-plane is the yz-plane. Figures 7 and 8 illustrate the simulated and measured H-plane and E-plane radiation patterns respectively at 3.5 and 9.5 GHz. In general, the simulated and measured results are fairly consistent with each other at most of the frequencies but some discrepancies are noticed at higher frequencies, especially in the E-plane. These discrepancies are most likely a result of the cable leakage current on the coaxial cable that is used to feed the antenna prototype in the measurements [Kwon & Kim, 2006]. This leakage current is known to be frequency sensitive as well. Also, intrinsic noise within the anechoic chamber may contribute to these discrepancies.

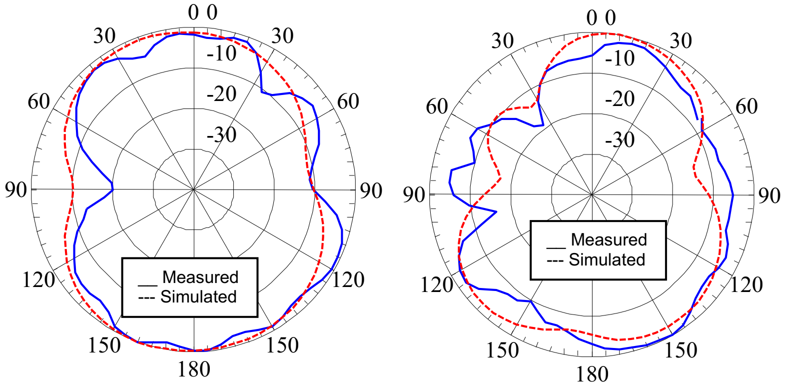
Nevertheless, an analysis of the radiation pattern results shows that the proposed antenna is characterized by omni-directional patterns in the H-plane for all in-band frequencies, as in Figure 7. The measured *H*-plane patterns follow the shapes of the simulated ones well, except at 9.5 GHz where there is little difference.

For the E-plane patterns, Figure 8 shows that they form a figure-of-eight pattern for frequencies up to 7.5 GHz but at 9.5 GHz the shape changes. However, the measured *E*-plane patterns generally follow the simulated ones well. In general, the stepped-trapezoidal patch antenna shows an acceptable radiation pattern variation in its entire operational bandwidth since the degradation happens only for a small part of the entire bandwidth and it is not too severe.



(a) H-plane at 3.5 GHz (b) H-plane at 9.5 GHz

Fig. 7. The simulated and measured radiation patterns in the H-plane



(a) E-plane at 3.5 GHz (b) E-plane at 9.5 GHz

Fig. 8. The Simulated and measured radiation patterns in the E-plane

(c) Antenna gain

The gain of the proposed antenna is also found to be suitable for the UWB communications and applications. It is greater than 2.9 dBi for all in-band frequencies and varies from 2.9 dBi to 5.2 dBi over the operating frequency range, resulting in the maximum gain variation of 2.3 dB.

7. The Double-Beveled Patch Antenna

7.1 Overview

A novel planar patch antenna with a notch-cut fed by a simple microstrip line is proposed and described. It is designed and fabricated for UWB wireless communications and applications under the band (3.1-10.6 GHz). This antenna is composed of a symmetrical double-beveled planar patch antenna with notch cut fed by a microstrip line folded on a partial ground plane. Because of its structure, we have called it "the Double-Beveled Patch

Antenna” [Alshehri & Sebak, 2008]. To obtain UWB bandwidth, we use several bandwidth enhancement techniques: the use of partial ground plane, adjusting the gap between radiating element and a ground plane technique, the use of bevels technique and a notch cut technique used also to reduce the size of the planar antenna. A parametric study is numerically carried out on the important geometrical parameters to understand their effects on the proposed antenna and therefore optimize its performance. The measured -10 dB return loss (VSWR<2) bandwidth is about 123.8% (9.74 GHz). The proposed antenna provides an acceptable radiation pattern and a relatively flat gain over the entire frequency band. The measured and simulated results for both bandwidth and radiation pattern show a very reasonable agreement. In the following subsections, the design details and the related results are presented and discussed.

7.2 Antenna design

First, the substrate is chosen to be Rogers RT/Duroid 5880 material with a relative permittivity $\varepsilon_r = 2.2$ and a thickness of 1.575 mm. Second, the radiator shape is selected to be rectangular. Next, the initial parameters are calculated using the empirical formula reported in [Agrawall, et al., 1998] after adding the effect of the substrate:

It is found that the frequency corresponding to the lower edge of the bandwidth of the monopole antenna can be predicted approximately by equating the area of the planar configuration to that of a cylindrical wire and given by:

$$2\pi r l = hW \tag{4}$$

So, the resonant frequency is given by:

$$f_L(GHz) = \frac{c}{\lambda} = \frac{30 \times 0.24}{l + r} \tag{5}$$

Where:
f_L: the frequency corresponding to the lower edge of the bandwidth.
C: the light speed.
λ : the wavelength
l: the height of the cylindrical wire which is same as that of planar configuration height
r: the equivalent radius of the cylindrical wire
W: the width of the rectangular patch.
h: the height of the rectangular patch.

The dimensions are expressed in centimeters. This simple formula is used to predict the lower edge frequency of the bandwidth for the monopole suspended in the space over the ground plane. It is accurate to +/- 8 %. In our design, the sheet will be a patch printed on the substrate, so, the effect of the substrate has to be included to the formula. After consideing it, the formula becomes:

$$f_L(GHz) = \frac{30 \times 0.24}{(l + r)\sqrt{\varepsilon_{reff}}} \tag{6}$$

where the effective relative permittivity ε_{reff} can be calculated using Equation 3.

Since the antenna is designed for UWB, it has to operate over 3.1 - 10.6 GHz. Therefore, the lower edge frequency at which the initial parameters will be calculated is 3.1 GHz. Initially, the antenna consists of a rectangular patch and partial ground plane etched on opposite sides of the substrate. The radiator is fed through a microstrip line with 50-Ω characteristic impedance. After setting up the configuration of the antenna, determining the initial parameters and fixing the lower frequency, the simulation is performed to confirm the calculated parameters. Then, several bandwidth-enhancement techniques are applied to widen the bandwidth and obtain UWB performance. These techniques are: adjusting the gap between radiating element and ground plane technique, the bevels technique and notch cut technique used after studying the current distribution as will be discussed later.

Figure 9 illustrates the geometry of the printed antenna as well as the Cartesian coordinate system. It consists of a symmetrical double-beveled patch with notch cut and a partial ground plane. The Cartesian coordinate system (x,y,z) is oriented such that the bottom surface of the substrate lies in the x-y plane. The antenna and the partial ground plane are oppositely etched on the Rogers RT/Duroid 5880 substrate. The substrate size of the proposed antenna is 40 × 31 mm^2.

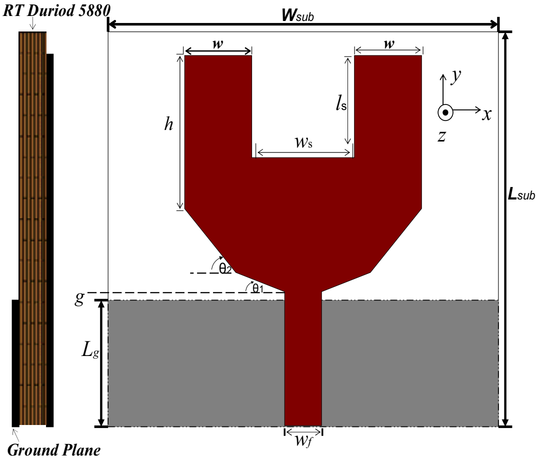
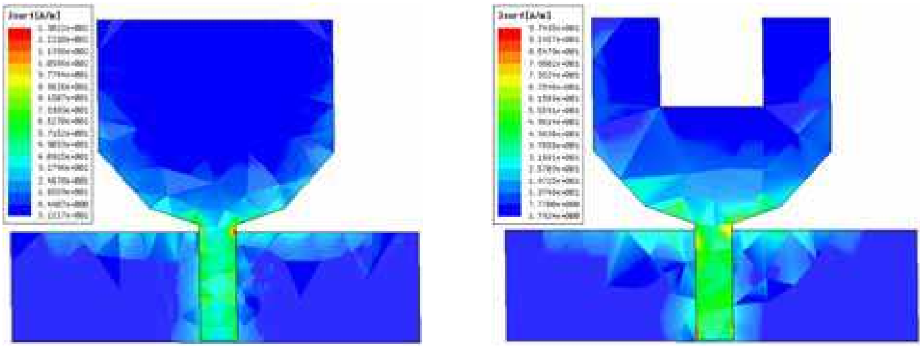


Fig. 9. The geometry of the double-beveled patch antenna

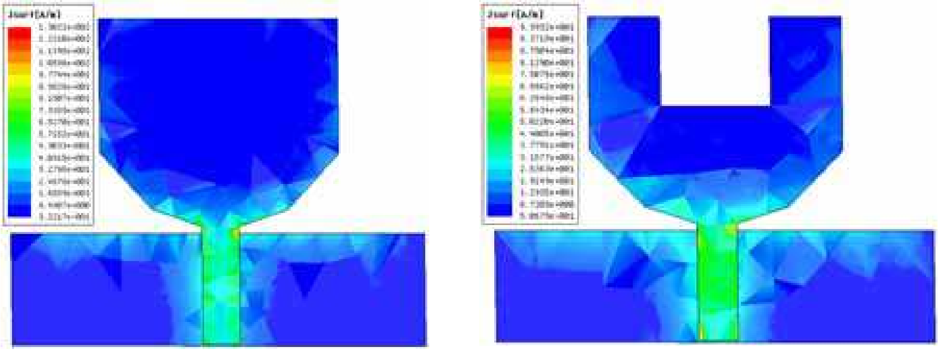
The parameters of the symmetrical double-beveled patch are w=6.5 mm, h=12 mm, θ_1 =17.5° (the angle of the first bevel) and θ_2 =45° (the angle of the second bevel). To reduce the overall size of the printed antenna and to get better impedance matching, a rectangular-shaped notch with dimensions of $l_s \times w_s$ = 8 mm × 10 mm is symmetrically cut in the top middle of the radiator. The shape of the partial ground plane is rectangular with dimensions of 10 × 40 mm^2. The radiator is fed through a microstrip line having a length of 10.5 mm and width w_f =3.6 mm to ensure 50-Ω input impedance with a feed gap of g = 0.5 mm. The 50 Ω-microstrip line is printed on the same side of the substrate as the radiator.

7.3 Current distribution

The current distribution is studied. The simulated current distributions of the initial antenna geometry before cutting the region of low current density at 3.5 and 9.5 GHz (as examples) are shown in Figure 10 (a) and (b) respectively. The current is mainly concentrated on the bottom portion of the patch with very low density toward and above the center and it is distributed along the edges of the patch, except the top edge, for all frequencies. Thus, it can conclude that the region of low current density on the patch is not that important in the antenna performance and could therefore be cut out. Consequently, a rectangular section with dimensions of $l_s \times w_s$ = 8 mm × 10 mm is symmetrically cut out from the top middle of the rectangular radiator to eliminate a region of low current density as shown in Figure 9. After this cut, the current distributions at 3.5 GHz and 9.5 GHz (as examples) are depicted in Figure 10 (c) and (d), respectively. It is observed that the current distributions in this case are approximately the same as before the cut. As a result of this cut, the size of the antenna is reduced and has lighter weight, which is very desirable for more degree of freedom in design and possibly less conductor losses.



(a) at 3.5 GHz (c) at 3.5 GHz



(b) at 9.5 GHz (d) at 9.5 GHz

Fig. 10. The current distributions

7.4 Parametric study

The parametric study is done to optimize the antenna. Its performance is mainly affected by geometrical parameters, such as the dimensions related to the notch cut and the bevels.

(a) Notch cut

The effect of the rectangular-shaped notch dimensions (l_s, w_s) on the return loss is studied. It is observed that the width of the notch has a major effect on the impedance matching over the entire frequency range, as shown in Figure 11. The lower edge frequency of the bandwidth is shifted to higher frequencies once the width increases. Also, the middle and higher frequencies are affected with higher mismatch levels. On the other hand, the length of the notch slightly influences the lower edge frequency. It is also observed that the notch can be used to reduce the size of the radiator, as explained earlier using the current distribution.

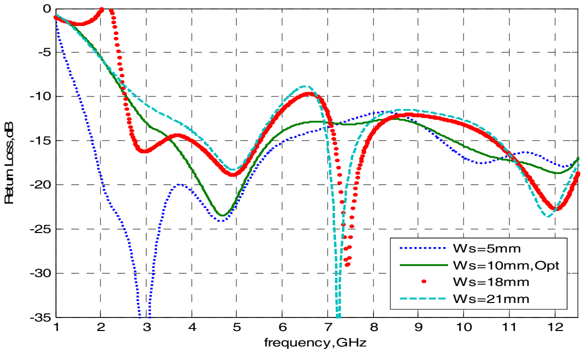


Fig. 11. Effects of the width of notch cut

(b) Bevels

The double bevels dimensions influence the matching impedance for the whole band, especially at high frequencies. The high frequencies can be controlled and the entire band can be enhanced by adjusting the bevel angles. By varying the angle of the first bevel (θ_1), the low and middle frequencies are highly influenced. As shown in Figure 12, by varying the angle of the second bevel (θ_2), the whole band is affected especially at middle and high frequencies. Thus, using two progressive bevels provides more degree of freedom and by adjusting them, the bandwidth will be widened as well as excellent level of matching can be achieved.

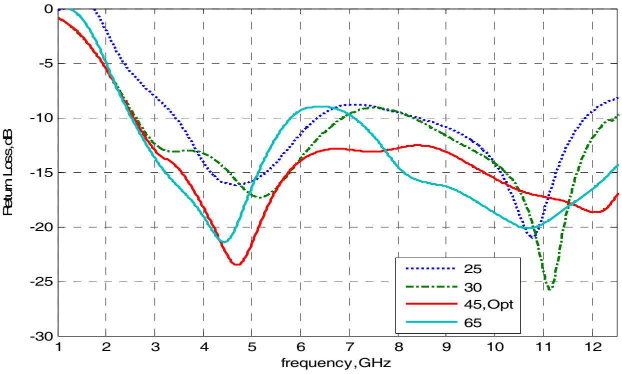


Fig. 12. Effects of second bevel angle

7.5 Results and discussion

After taking into account the design considerations described on antenna structure, current distributions and parametric study done to optimize the antenna geometry, the optimized antenna is constructed as shown in Figure 13 using the optimum values as mentioned earlier . Then, the antenna is experimentally tested to confirm the simulation results. The simulated and measured VSWR is presented as well as the simulated and measured radiation patterns in principle planes. Also, the simulated gain is provided.

(a) Front view (b) Back view

Fig. 13. The prototype of the double-beveled patch antenna

(a) VSWR

The VSWR of the proposed antenna is measured as depicted in Figure 14. The measured -10 dB return loss (VSWR<2) bandwidth of the antenna is approximately 9.74 GHz (3.00-12.74 GHz) and the antenna shows stable behaviors over the band. Thus, the measurement confirms the UWB characteristic of the double-beveled patch antenna as predicted in the simulation.

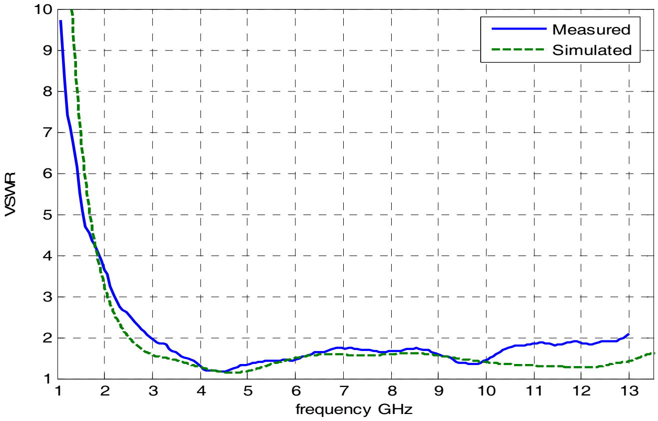
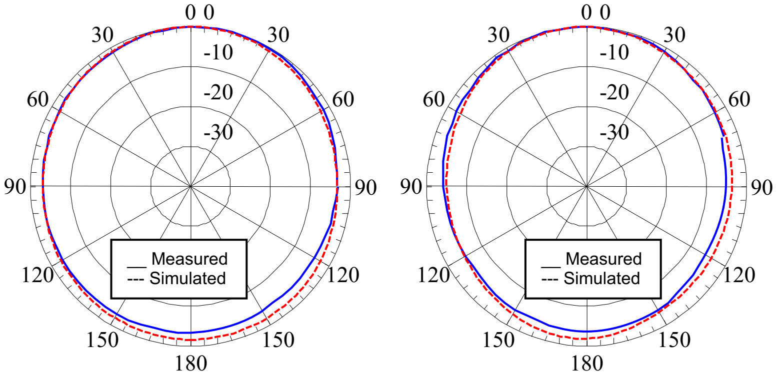


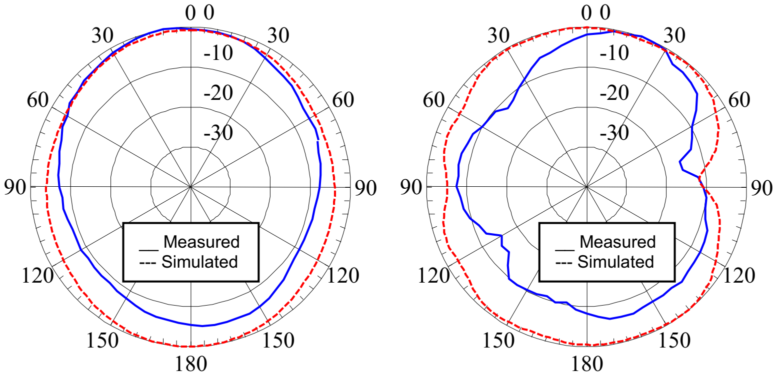
Fig. 14. Simulated & measured VSWR

(b) Antenna radiation patterns

The radiation characteristics of the proposed antenna are also investigated. Figures 15 and 16 illustrate the simulated and measured H-plane and E-plane radiation patterns respectively at 3.5, 5.5, 7.5 and 9.5 GHz. In genral, the simulated and measured results are fairly consistent at most of the frequencies but some discrepancies are noticed at higher frequencies especially in the E-plane. Nevertheless, the proposed antenna is characterized by omni-directional patterns in the H-plane for all in-band frequencies as in Figure 15. For the E-plane patterns, Figure 16 shows that the simulated ones at low frequencies form figure-of-eight patterns but at high frequencies, there are dips, especially at 9.5 GHz. In general, the double-beveled patch antenna shows an acceptable radiation pattern variation in its whole operational bandwidth since the degradation happens only for a small part of the entire bandwidth and it is not too drastic.

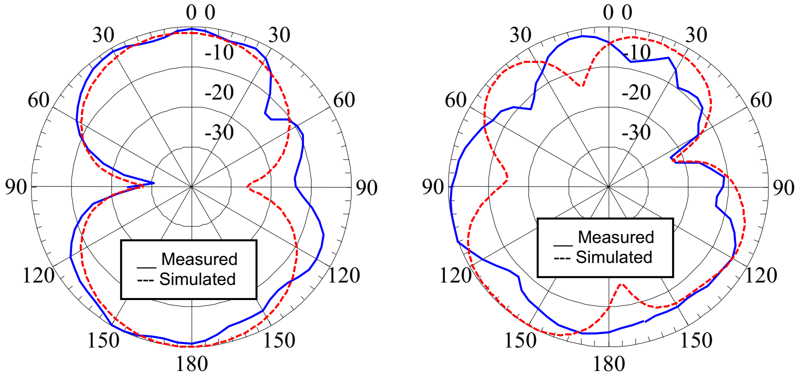


(a) H-plane at 3.5GHz (b) H-plane at 5.5GHz



(c) H-plane at 7.5GHz (d) H-plane at 9.5GHz

Fig. 15. The simulated and measured radiation patterns in the H-plane



(a) E-plane at 3.5GHz (b) E-plane at 9.5GHz

Fig. 16. The simulated and measured radiation ratterns in the E-plane

(c) Antenna gain

The gain versus frequency of the proposed antenna is also found to be suitable for the UWB communications and applications. The simulated antenna gain versus frequency is shown in Figure 17. It is greater than 3.4 dBi for all in-band frequencies and varies from 3.4 dBi to 6.1 dBi over the operating frequency range, resulting in the maximum gain variation of 2.7 dB.

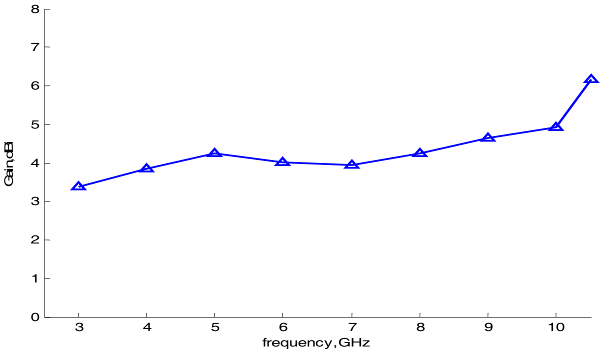


Fig. 17. Simulated gain

8. Conclusion

An overview on Ultra Wideband wireless communications is given. Two novel, small, low-profile, microstrip-fed printed UWB antennas are analyzed, designed and implemented to satisfy UWB technology requirements. The focus is on UWB frequency domain characteristics such as the far field radiation patterns, bandwidth and gain. The antenas provide excellent performance in the entire operational bandwidth. Because of their low cost, light weight and ease of implementation, these printed designs are desired in UWB wireless communication systems and applications, especially in portable devices and indoor applications such as WPAN. These antennas are namely: the stepped-trapezoidal patch antenna and the double-beveled patch antenna. Both provides a nearly omni-directional radiation pattern and a relatively flat gain over the entire frequency band with a maximum variation of 2.3 dB for first one and 2.7 dB for the second one. Both antennas offer reduced patch size, more degree of freedom for design, extra space that could accommodate other RF circuit elements. However, the effect Analysis of the notch cut show that within a certain limit of the cutout size, the radiation properties do not change drastically. But beyond that limit, the notch cut highly affects radiation patterns in the entire operational bandwidth.

UWB systems occupy huge operational bandwidth and often utilize very short pulses for data transmission. Therefore, an appropriate time domain performance is a key requirement for UWB antennas. Accordingly, investigations and analysis will be carried out on the effect of the proposed antennas on the transmitted pulse to hence improve the time domain behavior by optimizing the antenna designs.

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Mobile and wireless communications applications have a clear impact on improving the humanity wellbeing. From cell phones to wireless internet to home and office devices, most of the applications are converted from wired into wireless communication. Smart and advanced wireless communication environments represent the future technology and evolutionary development step in homes, hospitals, industrial, vehicular and transportation systems. A very appealing research area in these environments has been the wireless ad hoc, sensor and mesh networks. These networks rely on ultra low powered processing nodes that sense surrounding environment temperature, pressure, humidity, motion or chemical hazards, etc. Moreover, the radio frequency (RF) transceiver nodes of such networks require the design of transmitter and receiver equipped with high performance building blocks including antennas, power and low noise amplifiers, mixers and voltage controlled oscillators. Nowadays, the researchers are facing several challenges to design such building blocks while complying with ultra low power consumption, small area and high performance constraints. CMOS technology represents an excellent candidate to facilitate the integration of the whole transceiver on a single chip. However, several challenges have to be tackled while designing and using nanoscale CMOS technologies and require innovative idea from researchers and circuits designers. While major researchers and applications have been focusing on RF wireless communication, optical wireless communication based system has started to draw some attention from researchers for a terrestrial system as well as for aerial and satellite terminals. This renewed interested in optical wireless communications is driven by several advantages such as no licensing requirements policy, no RF radiation hazards, and no need to dig up roads besides its large bandwidth and low power consumption. This second part of the book, Mobile and Wireless Communications: Key Technologies and Future Applications, covers the recent development in ad hoc and sensor networks, the implementation of state of the art of wireless transceivers building blocks and recent development on optical wireless communication systems. We hope that this book will be useful for students, researchers and practitioners in their research studies.

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