IIETA International Information and Engineering Technology Association
Advancing the World of Information and Engineering

Instrumentation Mesure Metrologie
Vol. 18, No. 1, February, 2019, pp. 75-81
Journal homepage: http://iieta.org/Journals/i2m

An Overview of Microwave UWB Antenna for Structural Health Monitoring of Wind Turbine Blades: Optimal Design and Analysis

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https://doi.org/10.18280/i2m.180112

Received: 18 December 2018
Accepted: 4 February 2019

Keywords:
low profile, rectangular slot, microwave, UWB antenna, structural health monitoring, wind turbine blade

ABSTRACT

In this research paper, a multi-slot rectangular shape with a compact size of 18x10 mm microwave UWB antenna for structural health monitoring of wind turbine blades is presented. The objective of microwave UWB antenna to measure defects in the wind turbine blades. In this work reported an ideal outline of 9.2 to 21.4GHz with wider bandwidth of 12.2GHz is enveloping the upper band of microwave UWB frequency. The low cost RT/Duroid 5880 substrate material with dielectric constant of 0.0004 is assembled and tested. A comparative experimental method is carried out to execute the required resonance frequency by using high frequency structural 3D simulator (HFSS) tool. The proposed UWB antenna is simulated different feed position to acquire the required bandwidth and result shows that moderate peak gain and peak directivity of 3.79dBi and 3.63dBi. The dispersion characteristics is simulated and occurred throughout the upper band of UWB and show that omni-directional pattern also compared proposed antenna with existing antenna. This low profile nature and compact size microwave UWB antenna behavior is best suited for structural health monitoring of wind turbine blades and flexible for wind mill monitoring system.

1. INTRODUCTION

Nowadays the structural health monitoring is most necessary for heavy electrical industries, civil, marine and automation industries. In daily life thousands of sensors and communication device linking together to report their equipment information in engineering environment especially the wind turbine blade performance analyzing is difficult for researchers and engineers. There is many equipment is involving during production period, maintain the quality, minimize the cost, number wire transmission and replacement of material is challenging for structural health monitoring [1-2] and in this way the microwave UWB antenna is introduced in this paper to monitor the turbine blade performance. The regular UWB spectrum from 3.1 to 10 GHz is commercially available bandwidth for regular communication with higher data rate up to 20mbps but the multipath environment condition the microwave UWB spectrum from 9 to 22 GHz is very much required for intra-vehicle monitoring. In [3] author reported dipole antenna for identifying material damage and its location remotely. In [4] author reported a 22x22mm size ladder-shaped monopole antenna is designed with bandwidth of 19.3 GHz which is compact nature and wider bandwidth characteristics. The 30 × 30 mm size hexagonal shape wide-slot antenna with UWB characteristics from 2.9 GHz to 18 GHz is reported in [5] which is highly wider bandwidth and required for modern communication. Another work [6] discusses about 2.54 GHz to 21.08 GHz printed type circular ring antenna with dimensions of 39×40mm which is moderate size and less return loss. The enhanced bandwidth of UWB antenna as discussed by Chia Ping Lee [7] report that the 15x14.5mm size antenna operated from 3.28 GHz to 19.64 GHz with fractional bandwidth of 120.68 %. A wider-bandwidth antenna from 3.9 GHz to 22.5 GHz is introduced in [8]. It has 25x15mm size and gain of 4.48dBi with different slot structure. Another work the author [9] signifies an antenna with dimensions of 16mm ×12mm× 0.787mm size having good impedance and operated from 6.5 GHz to 25 GHz which is covers the entire UWB. This projected antenna having gain about 2.5dBi at the frequency from 6 GHz to 22 GHz. In microwave sensing application the proposed antenna size is 19.36 × 27.72 mm with BW of 3.10–15.00GHz. The electrical dimension is 0.20 λ × 0.29 λ and FBW is 131.50 %. This antenna represents a good fractional bandwidth when compared with previous designed antennas reported in literature [10-11] which explains the tapered-shaped slot antenna with area of 12x38mm another author reported [12] 9.8 GHz to 22 GHz UWB antenna for UWB applications. In literature [13-14] discussed the various fractal iterative shapes antenna to increase the bandwidth for UWB applications with minimal size 16x12mm size and bandwidth of 12.2GHz. From the above discussion, the necessity of UWB antenna and the electrical dimension, gain and directivity of different antenna were studied. In this research paper, the proposed antenna achieved upper band UWB frequency with dimension of 18 x 10 mm size which is very compact compared the above literature also having low profile nature, moderate gain, omni-directional radiation pattern and good directivity. The overall radiation pattern is good compared to existing antenna.

2. SCOPE OF THE PAPER

From reference to the study and examination completed, the proposed antenna is created to improvise the scaling component and arrangement. In this examination the accompanying reproduction result are accomplished:

(1). The proposed UWB antenna radiation size is 18x10mm and ground structure size is 20x11mm.

(2). The first harmonic of 9.6GHz exhibit a bandwidth of 800MHz on the lower band and VSWR is 1.169, the higher band of 20.8GHz exhibit at a bandwidth of 1800MHz and VSWR value is 0.44.

(3). At second harmonic of 11.3 GHz exhibit at a bandwidth of 700MHz and VSWR value is 0.127

(4). The third and fourth harmonic of 16 and 18GHz frequency exhibit at a bandwidth of 600MHz and 1200MHz.

(5). Achieved omni directional radiation pattern with uniform dispersion characteristics.

(6). The proposed antenna radiation efficiency, peak gain and peak directivity is achieved at the rate of 96.6 %, 3.79 dBi and 3.63 dBi. The following sections will discuss about the antenna design and analyse the performance of reference antennas. In further Section 3 reported about antenna modelling and design and structure issues and Section 4 reported the comparative study of different reference antennas to achieve the required resonant frequency finally the Section 5 discusses the antenna simulation and measurements results and Section 6 concludes the paper with applications.

3. ANTENNA MODELLING AND DESIGN

The estimated geometry structure of proposed UWB antenna is shown in Figure.1 and Figure.2 with layout of coaxial probe-feeding. It is constructed by Duroid5880 high frequency laminate substrate material with a relative permittivity of 2.22 and loss tangent of 0.0004. This high frequency substrate fed by a micro strip line 50Ω with diameter of 0.8mm and feed position of coaxial system determine the impedance matching so in this proposed design the input resistance, conductance and feed reactance value calculated. The dimension of ground plane and radiation plane size is 20 × 11mm and 18x10mm size and is placed in 3D plane axis. The detailed antenna dimension is shown in Table 1.

The proposed antenna exhibits tri-band characteristics i.e., operated at X-band, Ku-band and K-bands. To match the impedance matching and improve the wide band behaviour coaxial feed is used. Based on the substrate material characteristics like permittivity and loss tangent value the antenna resonant frequency and bandwidth define. In Table.2 shows that different substrate material properties, it understand that Duroid5880 having low dielectric constant which is prove that to increase the bandwidth and good impedance matching for high frequency application. Duroid5880 has been used in circuitry for commercial wireless, mobile network and medical applications. For these reasons the Duroid5880 substrate material was referred for proposed work to attain the required band. To improve the attenuation loss and power factor the proposed design is used 50Ω coaxial feed. The characteristics impedance is necessary to match the input resistance and it's based on the feed position of coaxial feed

Table 1. Proposed antenna dimension in mm

Parameter in mm	W1	W2	W3	W4	W5	W6	W7
Antenna dimension	1.25	1	1.12	1.5	1.8	1.12	1
Parameter in mm	L1	L2	L3	L4	L5	L6	L7
Antenna dimension	12.75	8.5	10	9	9.75	6.5	4.5
Parameter in mm	L8	L9	L10	Lg	Wg	-	-
Antenna dimension	7	8.14	6	20	11	-	-

Table 2. Dielectric properties of different substrate materials

Material	Permittivity	Loss tangent
Duroid 5880	2.22	0.0004
Duroid 5870	2.33	0.0023
FR4	4.66	0.020
Bakelite	4.78	0.03045
RO4003	3.4	0.002
Taconic TLC	3.2	0.002

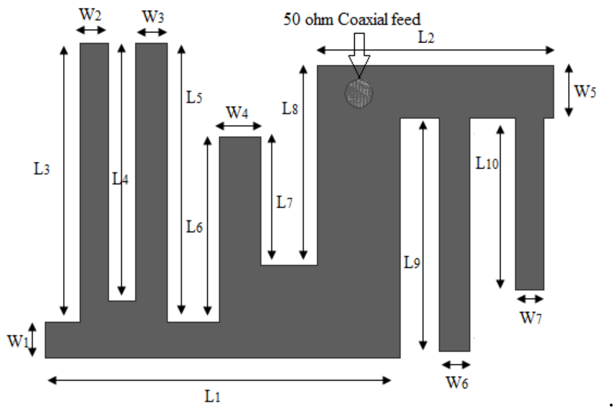


Figure 1. The Proposed UWB antenna design layout

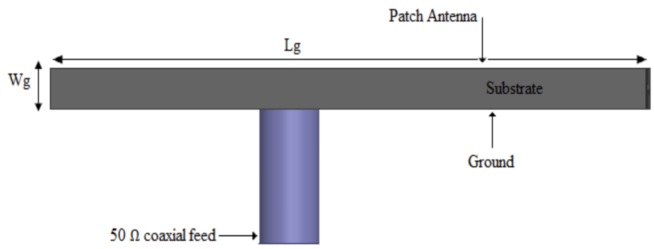


Figure 2. The proposed UWB antenna with coaxial feed structure

The input resistance can be written as,

$$R_{in}(\rho'=\rho_e)=R_{in}(\rho'=a_e)\frac{J_1^2(k\rho_0)}{J_1^2(k\rho_e)} \quad (1)$$

$$R_{in}(\rho'=a_e)=\frac{1}{G_t} \quad (2)$$

where, ($\rho' = \rho_e$) is the input resistance at any radial distance from the centre of the patch reported in Eq. (1) and (2). If input resistance is 50Ω the Eq. (2) becomes

$$R_{in}(50) = \frac{1}{G_t}$$

where, G_t is the total conductance and can be rewritten as,

$$G_t = G_{rad} + G_c + G_d \quad (3)$$

The G_t can be calculated by radiation, conductance and dielectric losses values. If the substrate dielectric losses value vary, the total conductance value change and finally the resonant frequency mismatch occur. When calculating resonant frequency, the impedance value should consider and include both resistances, reactance value. At 50Ω impedance the feed reactance can written as

$$x_f = -\frac{\eta kh}{2\pi}\left[\ln\left(\frac{kd}{4}\right) + 0.577\right] \quad (4)$$

where, d is the diameter of the feed probe.

The feed reactance indicates that the axis of feed position of patch antenna. If the feed position is improper the total reactance value varies and finally impedance mismatch occurs in the transmission line.

The feed position is independent of the input power but dependent on input resistance. If the feed position of the proposed design at (7,0,0) scale from x, y and z axis. The coaxial feed model of antenna excited by a coaxial transmission line and further improving of electric and magnetic field to applying the cartesian coordinated system the mathematical equations can be represents as an equivalent magnetic frill current. The magnetic frill current at axis (7,0,0) can be written as,

$$M(7,0,0) = \frac{-2V_{inc}(t) + Z_0\, I(t)}{a\ln(b/a)} \quad (5)$$

where, M is magnetic-frill current, V_{inc} is the incident voltage, I(t) is the feed current, the characteristic impedance is denoted by Z_0 for coaxial feed line and inner, outer conductor of the cable is represented by a and b in radius. In the above equations (1), (2), (3), (4) and (5) report that the impedance matching of coaxial probe feed with insert positions to achieve resonant frequencies and by using these equations to find the input resistance, reactance and total conductance value of patch antenna.

4. COMPARATIVE STUDY AND NUMERIC RESULTS

In this segment, the comparative study of the proposed antenna (Ant.1) was carried out with two different antennas (Ant.2, Ant.3). In Figure.3 author have analyzed Ant.1 performance level with Ant.2 and Ant.3 radiation dimensions of L4, L6 and L8 stem. The return loss and VSWR characteristics of Ant2 and Ant.3 were investigated and the performance of the antenna (Ant.1) is verified. Therefore, the aim of the parametric study is to examine the behaviour of multi length rectangular slot L4, L6 and L8 value and how this value can achieve ultra-wideband characteristics. The prototype model of proposed antenna front view with coaxial feeding structure is display in Figure 4 (a) and Figure 4 (b). The numeric result performance of both simulation and measurement is shown in Table 3 along the reference antenna.

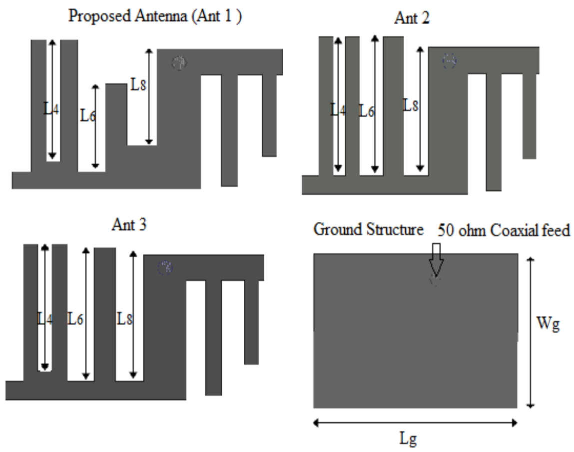
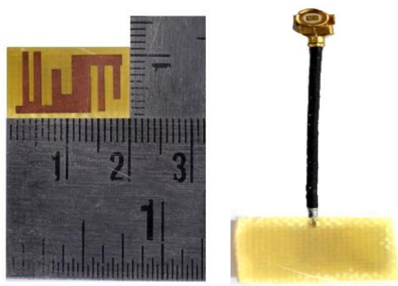


Figure 3. Geometry of proposed antenna (Ant.1), Ant.2, Ant.3 and ground Structure



(a) (b)

Figure 4. Prototype model of proposed UWB antenna (a) Front view with scaling (b) coaxial feeding structure

Figure 3 illustrates the parametric study used to develop the proposed UWB antenna as follows:

Step I) Geometry performance of Ant.2 length L4=9.75 mm, L6=9.75mm and L8=9mm with Ant.1

Figure 3 shows that the geometry structures of proposed antenna (Ant.1) and reference antenna (Ant.2), (Ant.3) and ground plane. To vary the dimensions of L4, L6 and L8 rectangular value of Ant.2 compare with proposed antenna (Ant.1) the resonant frequency is varied. The return loss curve and voltage standing wave ratio (VSWR) curve is shown in Figure 5 and Figure 6 also the Table 3 show that comparison of proposed antenna along with modified antenna.

Step II) Geometry performance of Ant.3 length L4=9mm, L6=9.5mm and L8=9mm with Ant.1.

Figure 3 shows the Ant 3 structure. In this analysis a comparison is carried out with Ant.3 and Ant.1.The Length L4, L6 and L8=9mm sizes vary from Ant.1. It was found that the first, second, third and fourth resonant frequency of Ant.3 is 11.8, 13.1, 16.3 and 21.2GHz which is vary from Ant.1.when compared to the first resonant frequency of Ant.1 9.8GHz not appeared in Ant.3 because of the change of rectangular length values L4, L6 and L8. From the above discussion the Ant.1 (proposed antenna) is the best parameter for good impedance bandwidth and reflection coefficient when compared with Ant2 and Ant3 and also from the Table 3, its observe that simulation performance of proposed antenna (Ant1), Ant2 and

Ant3 which shows that bandwidth, return loss and VSWR, it is observed that proposed antenna having Ultra-wideband characteristics and is having five resonant frequencies which cover entire band of microwave UWB frequency and lower band of K-band UWB frequencies.

The proposed UWB antenna with existing antenna literature survey performance report is shown in Table 4 from the above reference [4-11] were also studied and material characteristics, gain and bandwidth are discussed. To ensure that all the antennas covered UWB characteristics with different applications. Although the proposed antenna has optimal dimension 18x10mm size, moderate gain and wider bandwidth characteristics.

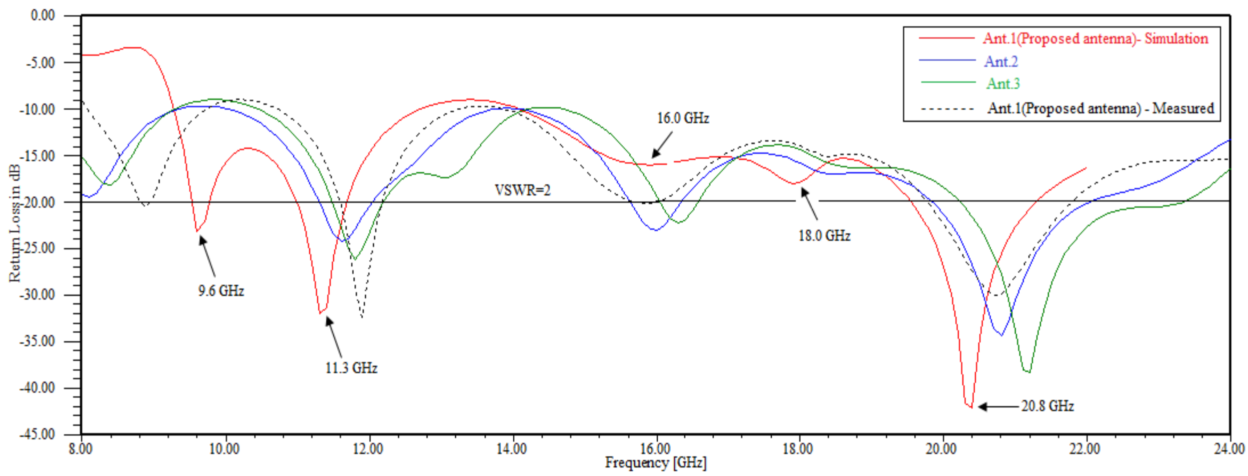


Figure 5. Measured and simulated return loss of proposed antenna (Ant.1), Ant.2, and Ant.3

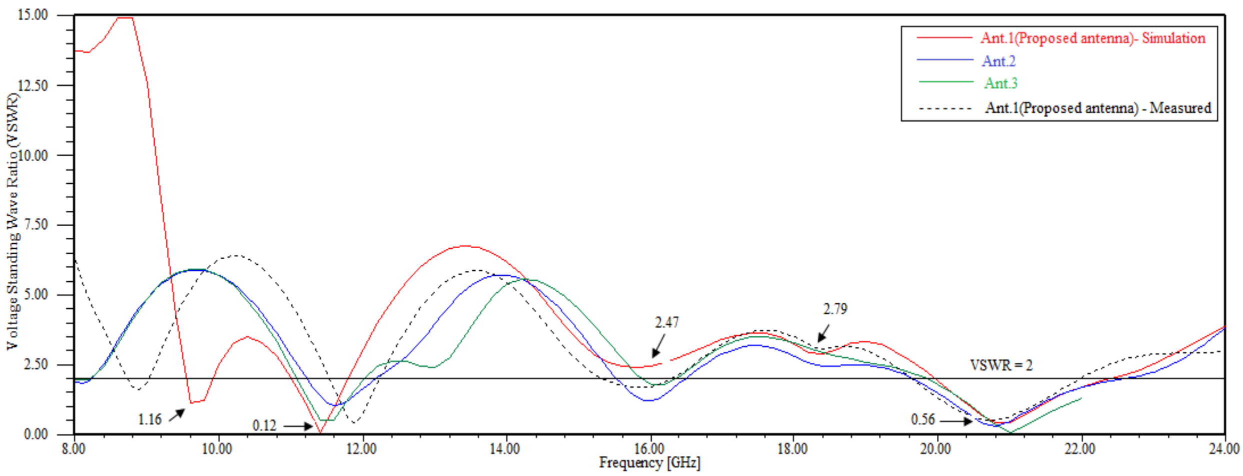


Figure 6. Measured and simulated VSWR of proposed antenna (Ant.1), Ant.2 and Ant.3

Table 3. Simulated and measured antenna characteristics for the proposed antenna (Ant.1), Ant.2 and Ant.3

Antenna /Length of Rect.slot in mm	Operating Freq. in GHz	Return loss in dB	VSWR	BW= F_{lower} ~ F_{higher} in GHz
Proposed antenna (Ant.1) (simulation)/ (measured)	9.6/ 8.9	-23.09/ -20.52	1.169/ 1.55	9.2 ~ 10.0/ 8.5 ~ 9.2
	11.3/11.7	-31.94/ -29.8	0.127/ 0.34	11 ~11.7/ 11.2 ~12.2
L4=9.0 mm,	16.0/ 16.0	-16.0/ -19.54	2.47/ 1.83	15.6~16.2/ 15.4~ 16.4
L6=6.5 mm,	18.0/ 18.1	-17.9/ -16.2	2.79/ 2.96	17.4~18.6/ 18.0~ 18.8
L8=7.0 mm.	20.8/ 20.5	-42.0/ -31.17	0.44/ 0.48	19.6~21.4/ 19.8~ 21.8
Ant.2	11.6	-24.2	1.06	10.9~ 12.7
(simulation)	16.0	-23.02	1.22	15.6~ 17.0
L4=9.75mm,	18.5	-17.0	2.4	18.0~ 19.0
L6=9.75mm,	20.8	-34.3	0.33	20.2~ 21.8
L8=9.0 mm.				
Ant.3	11.8	-26.1	0.85	11.2~ 12.2
(simulation)	13.1	-17.3	2.38	12.6~ 13.5
L4=9.0 mm,	16.3	-22.2	1.33	15.9~ 17.2
L6=9.5 mm,				
L8=9.0 mm.	21.2	-38.2	0.21	20.9~ 21.7

Table 4. Comparison of proposed UWB antenna with existing antenna

Ref. Ant	Size in mm	Operating Band in GHz	Gain in dBi	Application
[4]	22 × 22	2.7-20	Not reported	Ultra-Wideband
[5]	30 × 30	2.9-18	~3	Ultra-Wideband
[6]	39 × 40	2.54 -21.08	~0	Ultra-Wideband
[7]	15×14.5	3.28 -19.64	Not reported	Ultra-Wideband

[8]	25×15	3.95-22.5	4.44	Ultra-Wideband
[9]	16×12	6.5-25	2.5	Ultra-Wideband
[10]	19.36 × 27.72	3.10–15.00	1.2~6.57	Microwave Sensing
[11]	22x24	3-11.2	~6.5	Ultra-Wideband
Proposed Work (Ant.1)	18x10	9.2-21.4	~3.93	Ultra – Wideband Structural Health Monitoring

5. ANTENNA RESULTS AND DISCUSSION

In this segment, normalized radiation pattern, simulation performance of coaxial feed axis position and radiation efficiency are discussed. The Figure 7 shows that simulated radiation pattern of co-polar and cross-polar section which define how the E and H plane take place in the medium. By the way of y-z axis and x-z axis the E and H plane is defined with omni- directional pattern. It was observed that the standard radiation pattern is achieved which means that the co-polarization is higher than the cross polarization for the frequencies of 9.6, 11.3, 16.0, 18.0 and 20.8 GHz and it is exhibited better broadside radiation. This is suitable radiation patterns for higher band UWB applications.

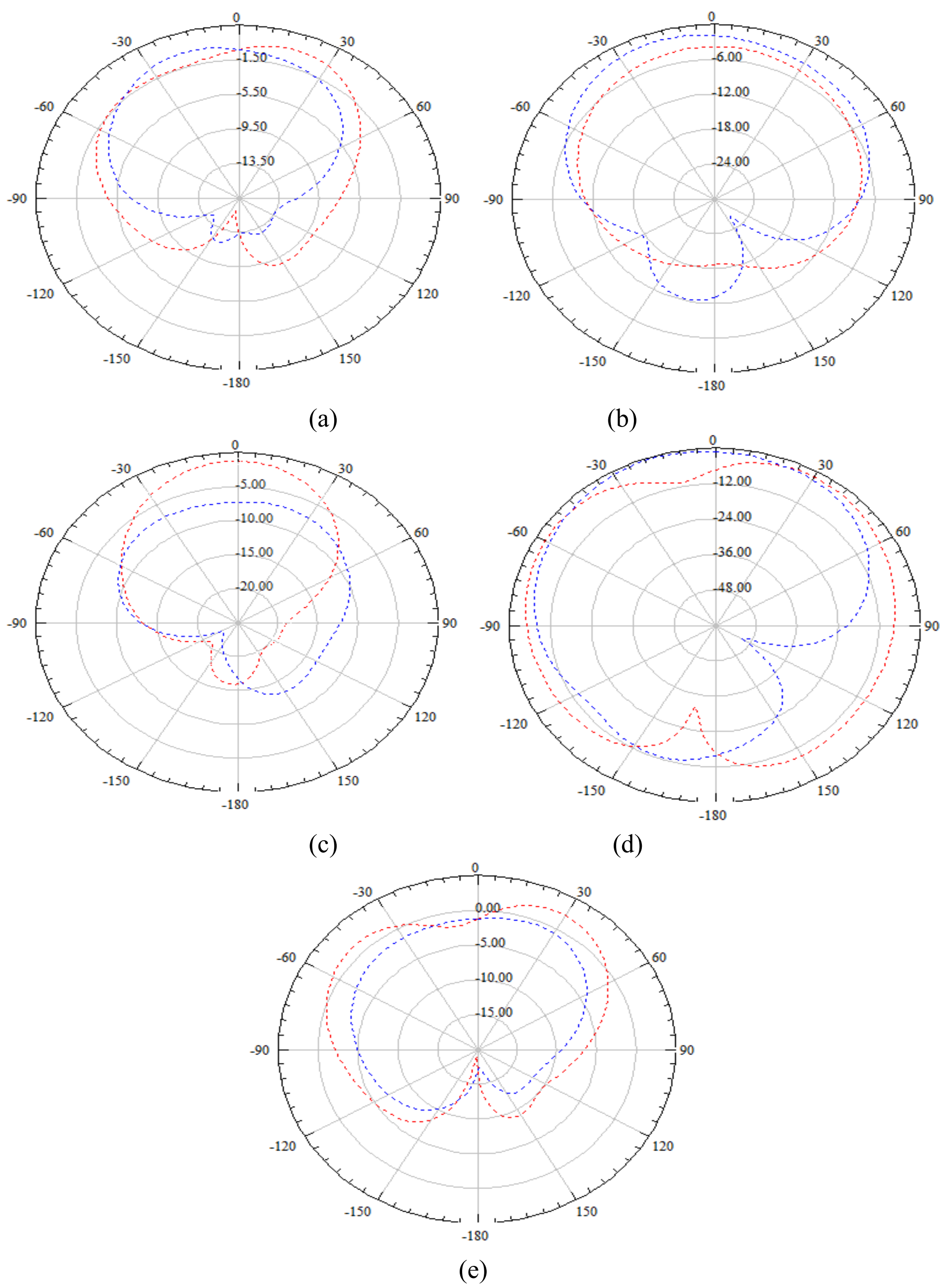


Figure 7. Simulated normalized radiation patterns at (a) 9.6, (b) 11.3, (c) 16.0, d) 18.0, and (e) 20.8 GHz

The feed position is necessary for coaxial feed to achieve required resonant frequencies. The proposed antenna insert feed position from centre of the patch position is (7, 0, 0) i.e., x, y and z axis which is produced five resonant frequency with ultra-wide bandwidth characteristics which is shown in Figure 5. The reference antenna feed position axis (15, 0, 0) is compare with proposed antenna shown in Figure. 8. When changing the insert feed position axis from (7, 0, 0) to (15, 0, 0) the total resonant frequency varied and its proved that the mismatch between the transmission lines. The Figure.8 observed that first and fifth resonant frequency appeared with some variations and remaining resonant frequency is discarded due to that feed position axis when compare with proposed antenna design feed position axis (7, 0, 0).

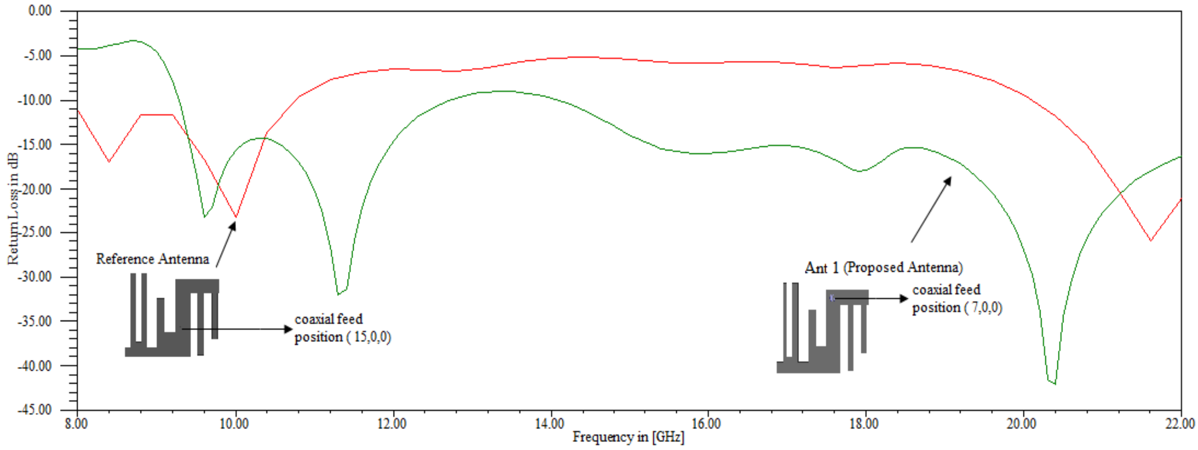


Figure 8. Simulated coaxial feed position of reference antenna with proposed UWB antenna

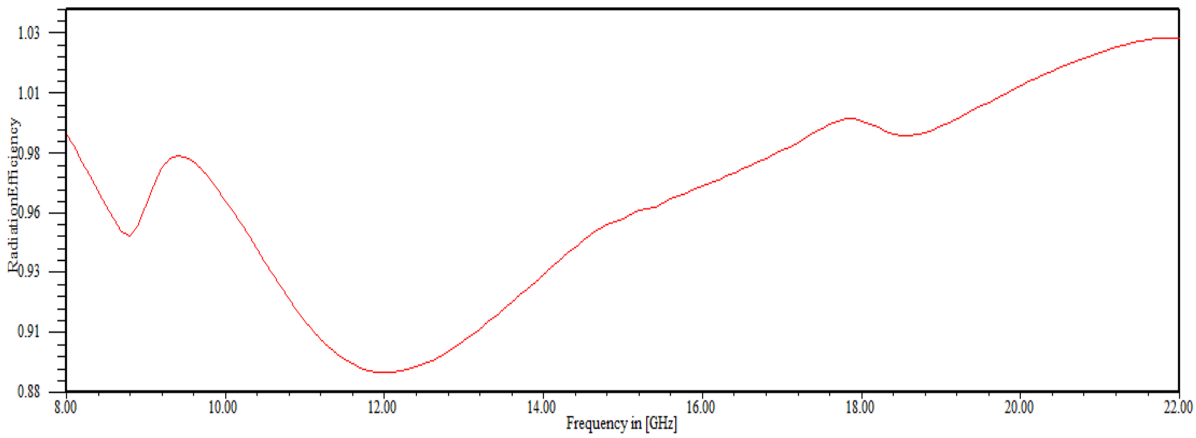


Figure 9. Radiation efficiency of proposed UWB antenna

The simulated frequency Vs radiation efficiency curve is shown in Figure 9. It shows that maximum radiation efficiency for the proposed design is 96.6 %. The UWB antenna cover from 89 % to 100 % for both lower band and higher band frequency of Microwave and K-band UWB frequency and only the middle band efficiency i.e., 16 GHz frequency appeared 89 % the remaining resonant frequency proved above 90 %.

Subsequently, in this research the proposed antenna has minimal size i.e., 18x10 mm and contrasting existing antenna demonstrating that great radiation pattern and its appropriate for UWB frequencies.

6. CONCLUSIONS

By essentially adjusted the length of the rectangular shape in the patch the whole band of microwave UWB and lower band of K-band UWB band frequencies can be accomplished in this examination. At long last, proposed antenna with UWB attributes is effectively simulated and measured, its demonstrating a near omni-directional pattern, stable peak gain and peak directivity proficiency over the required band structure. Consequently, the advantages of basic structure, smaller size, easy to fabricate and excellent performances make this antenna a decent candidate for structural health monitoring applications. The simulated result has peak gain of 3.79dBi and peak directivity of 3.63dBi which is very much required for structural health monitoring of wind turbine blades and future with help of microwave UWB antenna to monitor multi system using single element UWB antenna also three-dimensional point tracking to measure rotating dynamics of wind turbines.

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