

A miniaturized planar antenna with defective ground structure for UWB applications

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Abstract Miniaturization of planar antennas is the first intention in antenna design for Ultra-Wideband (UWB) applications in which the surface wave effects reduce the antenna efficiency, gain and limit the bandwidth of microstrip antennas. The ground plane effects are minimized using a Defected Ground Structure (DGS) and multiple slots. A compact antenna size including both ground plane and radiator etched on the printed circuit board is 17 mm × 22 mm × 1.588 mm is proposed. Addition of an asymmetrical strip and cutting slots on the antenna provides an enhancement in operating bandwidth of 2.9 to 11.4 GHz for 10 dB return loss and the average radiation efficiency is 88.5% respectively. In particular, the impedance performance of the patch radiator is mainly due to the surface wave currents in the ground plane. The antenna results in an omnidirectional radiation pattern over the operating bandwidth with a gain of 2 dB and VSWR of 1 to 2.

Keywords: UWB antenna, miniaturized antenna, multiple slots, defected ground structures

Classification: Microwave and millimeter-wave devices, circuits, and modules

1. Introduction

High data rate transmission is the foremost challenging and requirement in any future communication technologies. The Federal Communication Commission (FCC) has defined the frequency range of 3.1 to 10.6 GHz as Ultra Wide-band Frequency for high data rate transmission. In recent times various types of UWB antennas are also utilized for radar sensing applications such as nondestructive testing and microwave imaging. The antenna resonates for low and high frequency so the resolution of the target image will be enhanced. The antenna needs to have satisfactory radiation characteristics and low voltage standing wave ratio value of less than 2 over 3.1 to 10.6 GHz [1]. A compact monopole UWB radiator with the reduced impact of ground plane works well and depicts excellent radiation performance in the far field [2]. A circular multifractal UWB monopole antenna is proposed which results minimum reflection around the higher frequencies [3]. Antenna miniaturization is the most challenging task for the antenna engineers in the design of UWB antennas to accommodate the broad operating frequency range in the forthcoming

compact wireless devices. On the demand of designing an UWB antenna at lower operating frequency ranges for medical diagnostics, the electrical length of the antenna should be large. Various size reduction techniques are included in the antenna design to cover the entire UWB frequency range [2, 3, 4, 5, 6, 7, 8, 9, 10]. The increase in substrate height and varying the dielectric constant improves the bandwidth and results in multi-resonator patch antenna. The thickness of the antenna increasing with the stacked structure is the most challenging problem in the modern communication system. The small planar radiator is used to study the performance of notch cutting in reducing the ground plane effects at lower frequencies [4]. A multi-band planar antenna reduces the ground-plane effects for all resonant bands of 2.4–2.484, 3.3–3.69 and 5.15–5.35 GHz significantly accomplished by cutting a rectangular notch and a circular slot in the planar structure [5]. In a conventional microstrip planar antenna design, the slotted patch and the feed line techniques are adopted to improve the traditional narrowband behavior into wideband. The methodology of the defective ground structure is used to enhance the gain [6] and reduce the ground plane effect on the antenna impedance performance [7, 8, 9, 10]. A novel periodical defected ground structure is introduced to improve the bandwidth of the antenna [11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30].

Antenna miniaturization is the major objective for the future wireless communication devices and medical systems. The reduction in antenna dimensions in order to resonate in a larger bandwidth results in a surface wave effects. The drastic increase in surface wave effects over the broad frequency range will minimize the antenna gain, efficiency and operating bandwidth of microstrip antennas. In the proposed work the surface wave effects are suppressed by introducing defective ground structures in the bottom ground plane and the bandwidth is improved by using multiple slots in the top side of the antenna.

2. Antenna geometry

The evolution of the proposed microstrip patch antenna is shown in Fig. 1. Initially, a rectangular patch antenna simulated without any additional slot. The rectangular patch antenna dimensions such as length L_p and width W_p are calculated from the substrate dielectric constant ϵ_r and thickness h . The calculated parameter values are the specifications of the antenna layout shown in Fig. 1(a). The obtained S11 value is below -10 dB at resonant frequency

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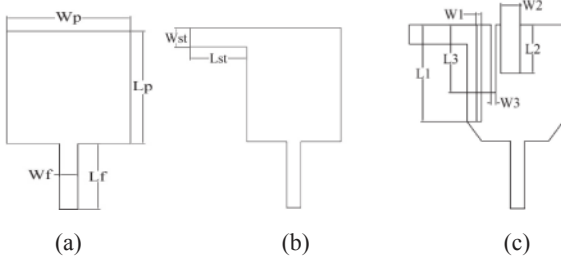


Fig. 1. Development of the proposed Rectangular Microstrip Patch Antenna (a) Rectangular Microstrip Patch Antenna (b) Antenna with added strip (c) Antenna with multiple slots

of 5.8 GHz and it has a narrow bandwidth around 4.5 to 6.5 GHz. The development of the antenna design is based on the approach of Chen et al. [4]. The proposed antenna layout geometry is shown in Fig. 2.

Various antenna dimensions are calculated using the following mathematical equations [12, 13], Given $\epsilon_r = 4.4$, height $h = 1.588$ mm and $f_r = 5.8$ GHz Width of the patch antenna is

$$W_p = \frac{v_0}{2f_r} \sqrt{\frac{2}{\epsilon_r + 1}} \quad (1)$$

Effective dielectric constant ϵ_{reff} of the substrate is

$$\epsilon_{\text{reff}} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left[1 + 12 \frac{h}{W} \right]^{-\frac{1}{2}} \quad (2)$$

The length extension ΔL of the patch is

$$\frac{\Delta L}{h} = 0.412 \left[\frac{\epsilon_{\text{reff}} + 0.2 \left(\frac{w}{h} + 0.264 \right)}{\epsilon_{\text{reff}} - 0.258 \left(\frac{w}{h} - 0.8 \right)} \right]^{-\frac{1}{2}} \quad (3)$$

Length of the patch antenna is

$$L_p = \frac{v_0}{2f_r \sqrt{\epsilon_{\text{eff}}}} \quad (4)$$

The calculated dimensions of the antenna are Length of the patch antenna is $L_p = 12.10$ mm and Width of the patch antenna is $W_p = 15.74$ mm

The rectangular patch antenna dimension width is optimized for better impedance matching between source and antenna impedance in order to resonate at 5.8 GHz. The optimized values of patch length $L_p = 12$ mm and patch width $W_p = 10$ mm.

The reduction in the antenna dimensions make the antenna to resonate only at higher frequency. To resonate at lower frequency an additional strip of dimension $L_{\text{st}} = 6$ mm and $W_{\text{st}} = 2$ mm is added at the top of the antenna. The introducing of slot improves the impedance bandwidth. The length of the slot should be a half the guided wavelength were the location of slots shift the antenna resonate frequency to the lower or higher frequency. The optimization of location of the slot $d = 1$ mm shifts the antenna to resonate from higher frequency to lower frequency of 3.4 GHz. The addition of another two slots widens the antenna bandwidth around 6.5 to 10 GHz respectively. The defective ground structure is introduced in

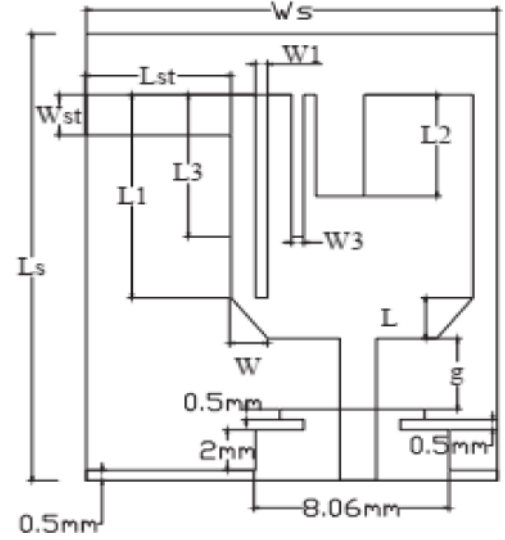


Fig. 2. Proposed UWB antenna geometry

the ground plane which minimizes the surface wave effects and results the antenna bandwidth from 2.9 GHz to 11.4 GHz. The gain of the antenna obtained is 2 dB which is also better for the required application. In addition to the rectangular patch, the bevel shapes are cut at both edges which improve the impedance matching over UWB frequency. The antenna dimension is minimized by optimizing the ground plane length for better impedance matching. The current distribution in the ground plane profoundly influences on the antenna performance parameters. The dimension of the proposed UWB antenna is shown in Table I.

3. Design and analysis

The variation in the ground plane length varies the impedance and radiation performance of the antenna without

Table I. Proposed UWB antenna design parameters

Antenna Parameters	Specifications
Dielectric constant of FR4 Substrate (ϵ_r)	4.4
Substrate height h	1.588 mm
Frequency range	2.9–11.4 GHz
Strip length L_{st}	6 mm
Strip width W_{st}	2 mm
length of the first slot L_1	10 mm
Width of the first slot W_1	0.5 mm
length of the second slot L_2	5 mm
Width of the second slot W_2	2 mm
length of the third slot L_3	7 mm
Width of the third slot W_3	0.5 mm
Gap between the patch and ground plane g	3.5 mm
Length of the substrate L_s	22 mm
Width of the substrate W_s	17 mm
Feed Length L_f	7 mm
Feed Width W_f	1.5 mm

any slot. Since the antenna resonates in the high frequency, a small strip is attached to the one side of the patch antenna. The addition of the piece of a strip at the one side of the antenna increases the length of the antenna that results in a shift in the resonant frequency towards the left at 3.4 GHz. The antenna dimensions are optimized for better impedance matching with the feed line.

The feed line L_f and W_f is the transmission line, matching the impedance between the edge impedance of the patch antenna with the source impedance 50Ω . It is the current carrying line between the source and the patch antenna. In the proposed antenna design, the reduction in antenna size results in high frequency resonance. Three different slots of dimensions $L_1 \times W_1$, $L_2 \times W_2$ and $L_3 \times W_3$ are the discontinuities in the top of the patch. The lengths of the discontinuity on the patch depend on the frequency of resonance. The performance of the multiple slots suppresses the ground plane effects over the conventional design without the slot.

The optimization of the attached strip length, feed width and dimensions of the various slots etched in the proposed antenna resulting in a good performance comparing to the previous report of [4, 10]. The reduction of overall dimension of the antenna will increase the surface wave currents, which is suppressed by introducing defects in the ground plane. The obtained return loss and radiation characteristics of the proposed antenna give better performance compared to earlier reports. The proposed antenna was fabricated using an FR4 dielectric substrate of $\epsilon_r = 4.4$ of dimension $17 \times 22 \times 1.588 \text{ mm}^3$ are shown in the Fig. 3.



Fig. 3. Top and bottom of the fabricated proposed UWB antenna

The fabricated antenna is measured using the Keysight Technologies FieldFox Handheld Microwave Analyzer N9917A for return loss characteristics and voltage standing wave ratio. From the measured result shown in the Fig. 4(a), the antenna return loss characteristics $|S_{11}|$ is 10 dB bandwidth exceed the UWB frequency range. However, the shift in the resonant frequency of the simulated and measured results is due to the connector loss. From Fig. 4(b), the measured value of VSWR is between the values of 1–2 within the UWB frequency range. It is observed from both the simulated and measured results that the proposed antenna can be utilized for UWB applications. The antenna parameters of the proposed UWB antenna are compared with the existing design from the literature is shown in Table II. The intended design antenna performance is better than the earlier models. In applications like microwave imaging Ultra-Wideband antenna plays a vital role in recent research. Only the low-frequency wave can propagate into the human skin, and the

higher frequency wave will reflect at the skin layer itself. In the proposed design the antenna resonates at the 3.4 GHz, and it also covers a larger bandwidth. This wider bandwidth characteristic of the antenna is suitable to reconstruct high-resolution images. So the proposed UWB antenna is very much adaptable to all UWB applications.

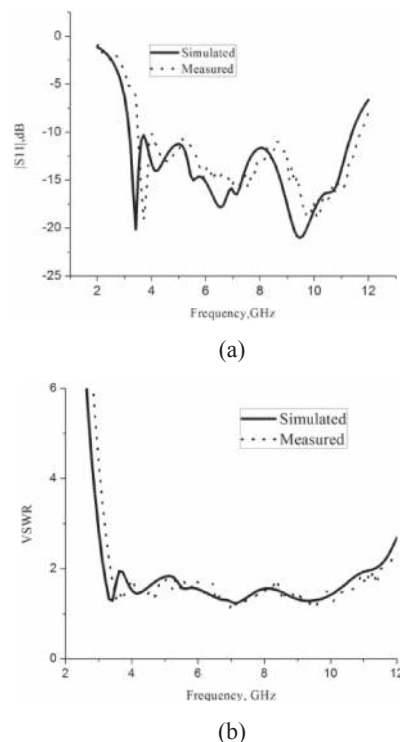


Fig. 4. The simulated and measured of (a) $|S_{11}|$ dB and (b) VSWR

4. Parametric study

4.1 Effect of the top strip

Initially, the simple patch antenna with the Defective Ground Structure (DGS) radiates within 5.8 GHz to 10.5 GHz. A piece of strip dimension $L_{st} \times W_{st}$ ($6 \text{ mm} \times 2 \text{ mm}$) is attached to the patch radiator which increases the length of the antenna radiating element. The addition of a small conductor initiates current flow along the extended strip conductor.

Table II. Antenna parameters comparison of proposed UWB antenna with the presented literature

Antenna Parameters	Chen 2007 [4]	A.P. Padmavathy 2015 [10]	Proposed UWB antenna
Dimension in mm	$25 \times 25 \times 1.52$	$12 \times 25 \times 1.6$	$17 \times 22 \times 1.588$
Resonant frequency f_r (GHz)	3.1	5, 8.9	3.4, 6.5, 9.5
Bandwidth (GHz)	8 GHz	8.1 GHz	9 GHz
Gain (dB)	≤ 2	1.32	> 2
VSWR	≤ 2	< 2	< 1.6

The length of the radiating elements is the fundamental parameter in an antenna design, where the radiating element length is inversely proportional to the frequency of operation. In the proposed model increasing the length of the antenna makes the radiator to resonate in the lower edge of the spectrum and minimize the peak arising at the 4 GHz shown in Fig. 5(a). Here the antenna feed is offset towards the right side which increases the length of the current element which is the sum of a horizontal length of 6.5 mm from the edge of the strip attached, a vertical length of 10 mm and horizontal length of 4.5 mm to the centre of the feed strip. Finally, increase in length looks like an inverted L shaped strip of total length 21 mm which miniaturize the overall dimension of the antenna structure, introduces a minimum reflection at 3.4 GHz. This similar way of reducing the antenna dimension is most a popular method such as planar inverted F antenna in mobile applications [14, 15].

4.2 First slot insertion

To improve the performance of impedance bandwidth various slots are etched on the planar radiator. The optimization of the length L_1 and also the position of the slot d_s , affect the resonance behavior of the antenna shown in Fig. 5(b). Choosing a better location and dimension of the slot length will change the operating frequency of the radiator. The increase in the length of the slot usually reduces the resonance towards the lower edge frequency. The optimization of the slot width w_1 might not introduce extreme variations in the antenna characteristics. Typically, the slot length is approximately equal to half the guided wavelength as given in the equation [13],

$$L_{\text{slot}} \cong 0.45\lambda_{\text{gnotch}} \quad (5)$$

where λ_{gnotch} is the guided wavelength of the slot.

4.3 Second and third slot-related

Recently the design of miniaturized antennas for wideband operation is of significant research. Minimizing the height of the radiating element makes changes only at the higher frequencies. To introduce multiband operation and also in increasing the bandwidth various structures of slots are incorporated. In the proposed work minimum reflection over the whole UWB frequency range of 3.1 to 10.6 GHz is accomplished using multiple slots etched on the patch antenna. The second and third slots of length L_2 and L_3 are used to upgrade the bandwidth around 6.5 to 10 GHz shown in Fig. 5(b). The width of the slot never changes the resonance frequency as the antenna resonance depends mostly on the length of the slot.

4.4 Effect of DGS in the ground plane

Usually, an infinite ground plane antenna radiates maximum energy above the patch radiator, resulting in an increased gain and directivity of the antenna. An infinite ground plane antenna never gives a broad bandwidth of operation; a finite ground plane is preferred to cover larger bandwidth [9]. The dimension of the feed gap g and the structure of the DGS in the ground plane optimize the current distribution on the radiating element.

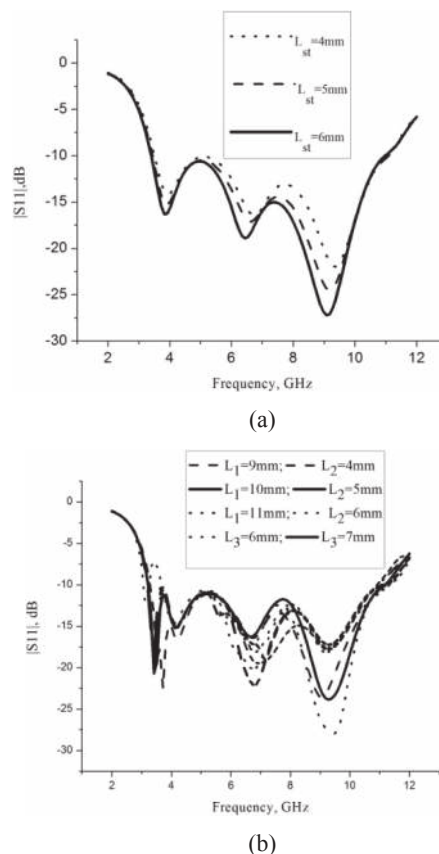


Fig. 5. The proposed UWB antennas return loss variation as a function of parameters: (a) L_{st} , (b) L_1 , L_2 & L_3

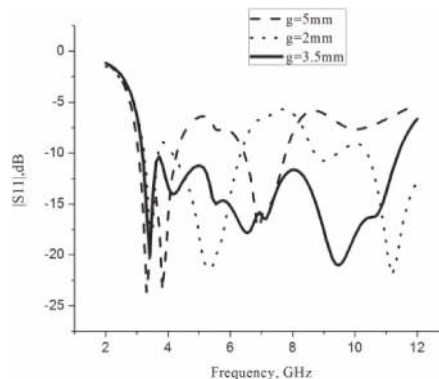


Fig. 6. The proposed UWB antenna return loss variation as a function of parameter g .

The optimization of feed gap and ground plane structure length affect mostly at the higher frequency than at lower frequency is shown in Fig. 6. The antenna radiation characteristics are evaluated by the current distributions at various frequencies. At low frequency around 3 GHz, the current vector is near the feed region and maximum at the L shaped strip. Hence the total length of the radiator includes the length of the added strip L_{st} , slot length L_1 and the horizontal distance from the feed to the first strip is the region where the current flow at the low frequency of 3.4 GHz and the approximate length of the radiator length is 21 mm. Increase in the frequency of operation the current in the feed region decreases and gradually accumulates

around the slot but at high frequency around 9.5 GHz the current distribution is only in the feed region as shown in the Fig. 7(a) and (b). From the observation of the current distributions at various frequencies describes that the antenna is operating between 2.9 GHz to 11.4 GHz. From the Fig. 7(b) it is observed that the influence of slot and attached strip optimize the current flow over the broad frequency range, which resulting the antenna to operate in the UWB frequency range.

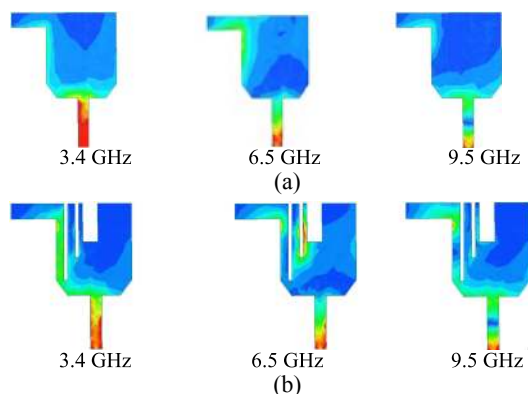


Fig. 7. The current distribution of the antenna (a) without slot and (b) with slots

4.5 Radiation fields

The proposed antenna has a better radiation pattern, with an average efficiency of 88.5% over the operating bandwidth. The radiation efficiency at 3.4 GHz is maximum value of 93% and it is depicted in Fig. 8. The antenna is efficiently radiating the signals over the UWB frequency range. The minimization of electrical length of the radiator will only storage the energy and the effect of radiation will decrease. In the proposed antenna the usage of slots and strip added creates an opening to radiate the signal into the free space. The radiation efficiency of the proposed UWB antenna is shown in the Fig. 8. The co and cross polarization pattern of the antenna for 3.4 GHz is depicted in the Fig. 9 and the patterns at higher frequencies are also similar. A realistic gain of 2 dB has obtained from the proposed single patch antenna. The simulated radiation pattern from the graph shown is bi-directional, which is suitable for the UWB applications.

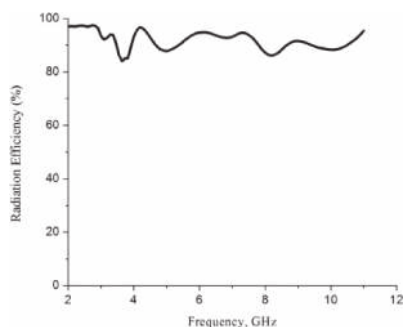


Fig. 8. The results of the proposed antenna radiation efficiency

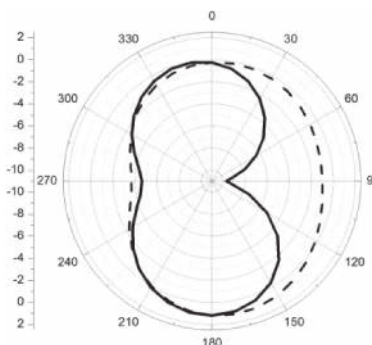


Fig. 9. The results of the proposed antenna Radiation pattern at 3.4 GHz

5. Conclusion

A compact UWB patch antenna is proposed. Addition of strip in the proposed antenna structure increases the length of the current flow on the radiator which shifts the antenna to operate at the lower frequency. This lowest operating frequency range of antenna is most suitable for medical diagnostic applications. Utilizing of multiple slots on the radiating patch and the defective ground structure results the antenna resonating over the required UWB frequency. The ground plane effect on the compact design is reduced by DGS and slots which improves the antenna bandwidth and radiation efficiency. The compact antenna of dimension $17 \times 22 \times 1.588 \text{ mm}^3$ is found to resonate over the frequency range of 2.9 GHz to 11.4 GHz with a 2 dB gain and an average radiation efficiency of 88.5%. This category of an antenna can be used in portable devices for high data rate transmission, nondestructive testing, and medical cancer diagnosis.

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