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A Novel Smiley Fractal Antenna (SFA) Design and Development for UWB Wireless Applications

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Abstract—Ultra Wideband (UWB) has been deliberated as a promising technology for short-range wireless communication with large unlicensed frequency band for commercial, enterprise private and public uses. Designing an antenna of compact size for portable wireless devices is one of the challenges especially for UWB based wireless communication technologies. In this paper, a novel Smiley Fractal Antenna (SFA), employed with N-notch feed and modified ground plane, is designed and developed to achieve the desired characteristics. The proposed antenna is of compact size with dimensions of $34 \times 32 \times 1.6\,\mathrm{mm}^3$, fabricated on an FR-4 substrate with $\varepsilon_r = 4.4$. The radiation pattern of the proposed antenna is omnidirectional with a maximum gain of 4.83 dB and efficiency of 93.55% obtained through 3D electromagnetic simulation software tools. The simulated results are compared with measured ones using RF equipment. The results obtained show that the proposed SFA is a suitable candidate for variety of UWB wireless communication applications.

1. INTRODUCTION

In the present scenario of wireless communication, people demand high data rate and reliable communication. Federal Communication Commission (FCC) has allocated the unlicensed frequency band of 3.1 GHz to 10.6 GHz with an EIRP of −41.3 dBm/MHz to avoid interference with present narrow band communication systems [1]. This has drawn the attention of scientists and researchers to the usage of UWB towards short-range high-data rate wireless communication applications as well as long-range but low data rate wireless connectivity applications. After the announcement of unlicensed 7.5 GHz of spectrum, there has been wide variety of applications developed for indoor/outdoor communications, high accuracy radars and imaging systems etc. [2].

In UWB Communication systems, antenna is one of the most critical components to be realized in order to have a good system performance. Hence, plenty of antenna structures [3–5] came into existence such as Vivaldi antenna, a directional antenna which makes it unsuitable for indoor communication, and bi-conical antenna limits its application because of its size. Microstrip antenna overcomes these limitations by its low profile characteristics such as low cost, conformal shaping, compact size, high efficiency and simple fabrication. But it has its own disadvantage of narrow impedance bandwidth [6, 7]. To overcome the limitations of microstrip antennas, fractal geometry is being used. Fractal appears irregular at all scales of length and is recursive in nature [8]. Its self-similarity property helps the multiple resonant frequencies to overlap, thus providing a wide bandwidth. It also has a space filling property which leads to the miniaturization of antenna elements [9, 10]. Several fractal shapes are in use, such as Hilbert Curve [8], Sierpinski carpet [11], and Koch curve [12], which provide narrow bandwidth. Various wideband fractal antennas as in [13–15] have been reported to date. Fractals are geometric forms that can be found in nature. Thus taking inspiration from nature, an antenna of human face with a smile is proposed using fractal geometry.

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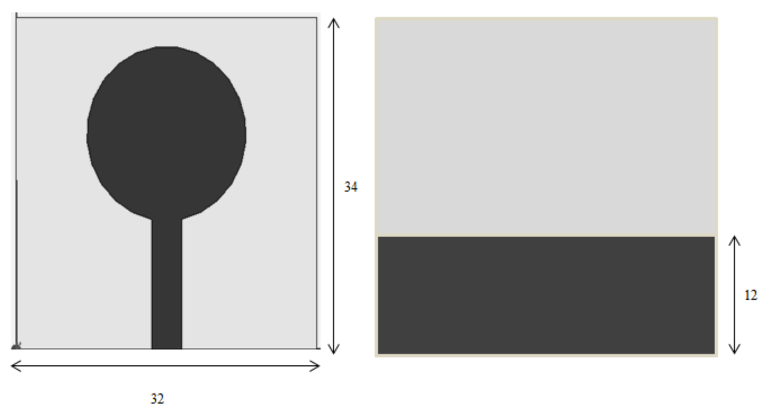
This proposed novel design of microstrip fed SFA has some uniqueness, such as compact size, antenna design with basic circle geometry, low cost, nearly omnidirectional, and it covers the entire UWB band frequency 3.1–10.6 GHz. N-notch and a ground slit have been introduced in order to achieve the desired UWB characteristics as defined by FCC. The radiation pattern of our proposed antenna is omnidirectional, which makes this antenna a good candidate for UWB based wireless applications. The rest of the paper is organised as follows. Geometry of the proposed fractal antenna is discussed in Section 2. In Section 3, need for introducing ground slit and N-notch is discussed. In Section 4, the measurement setup and prototype of the antenna are shown. The simulated and measured results of the proposed antenna is also analysed. Finally, in Section 5, the conclusion is discussed.

2. FRACTAL GEOMETRY OF THE PROPOSED ANTENNA

The proposed antenna is of smiley shape, where circle geometry is used for representing face and eye, because circle has maximum circumference as compared to square, triangle and polygon, etc. Moreover, with less iteration, maximum electrical length can be achieved. In the proposed design, the desired UWB characteristic is achieved within two iterations. As the entire shape is covered by many circles, the maximum current will be around its circumference and centre, providing good radiation characteristic and wide bandwidth. To have novelty in the antenna design, a human face with smile is proposed. Further, the length of smile arc affects the bandwidth.

The proposed fractal antenna is constructed from conventional microstrip monopole antenna. The patch and the partial ground plane are printed on an FR-4 substrate of relative permittivity $\varepsilon_r = 4.4$, dielectric loss tangent $\tan\delta = 0.02$. The dimension of the substrate is $34 \times 32 \times 1.6\,\text{mm}^3$, and the ground plane is $12 \times 32\,\text{mm}^2$. The 8.5 mm radius of the circular patch for resonant frequency of 4.7 GHz is calculated from the given Equation (1) taking fringing effect into considerations. The SFA is constructed from a conventional microstrip monopole antenna as depicted in Figure 1. A circular patch has been used in order to provide multiple resonant frequencies and omnidirectional radiation pattern.



(a) (b)

Figure 1. Microstrip antenna with (a) front view (initiator), (b) back view (partial ground). (All dimensions are in mm).

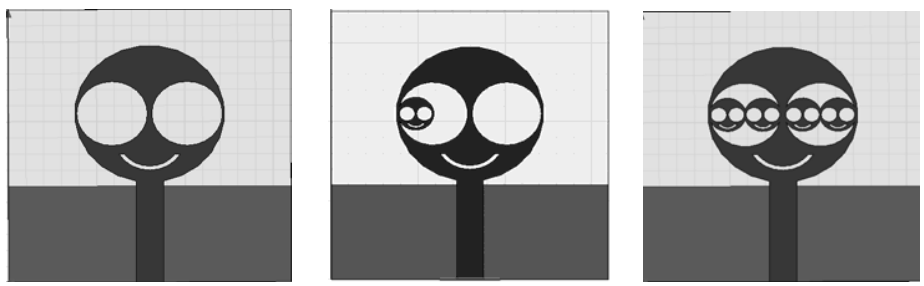
The radius of the circular patch is 8.5 mm for resonant frequency of 4.7 GHz which has been calculated from the given formula [3], taking fringing effect into considerations, where f_r is in Hz and h in cm.

$$a = \frac{F}{\left\{1 + \frac{2h}{\pi\varepsilon_r F}\left[\ln\left(\frac{\pi F}{2h}\right) + 1.7726\right]\right\}^{1/2}} \tag{1}$$

where,

$$F = \frac{8.791 \times 10^9}{f_r\sqrt{\varepsilon_r}} \tag{2}$$

This represents the Zeroth Iteration or initiator. The dimension of the microstrip feed line is $12.64 \times 3.08\,\text{mm}^2$ and is calculated using transmission line model equation [3], to achieve 50 ohm line impedance. The first iteration of the proposed antenna is created by removing two circles of radius 4 mm whose centre lies on the diameter of the main radiating patch (8.5 mm) i.e., the zeroth iteration. An arc of thickness 0.5 mm is introduced by subtracting it from main patch, and the length of the arc is 4.187 mm. This is the first iteration which resembles a smiling human face as shown in Figure 2(a). For the second iteration, the circle representing the face is drawn with radius 2.1 mm with its centre on the diameter of the main radiating patch. Two circles of radius 0.9 mm representing the eyes and the arc of thickness 0.25 mm are removed from the circle and the length of the arc is 1.04 mm. This is the second iterative fractal element which is shown in Figure 2(b). This fractal element is repeated four times, in order to increase the electrical length, by the space filling property of the fractals (Figure 2(c)). The number of iterations can be up to infinite number of times, but this cannot be done due to fabrication complexity and constraints. As the desired UWB characteristics have been obtained after the second iteration, the antenna has been finalized to be fabricated on the FR-4 substrate with $\varepsilon_r = 4.4$, $h = 1.6$ mm and dielectric loss tangent $\tan\delta = 0.02$.

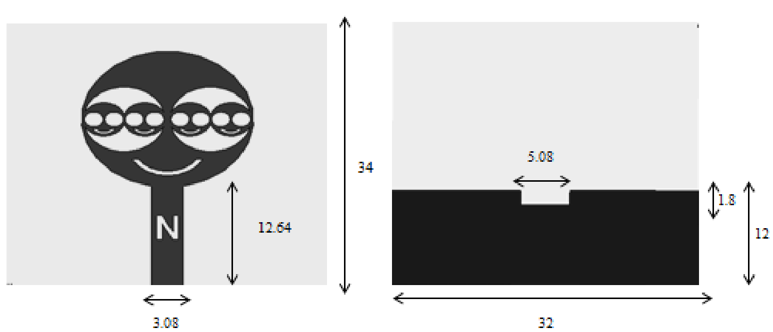


(a) (b) (c)

Figure 2. Proposed antenna with (a) first iteration, (b) second iteration, (c) second iteration with Space filling property.

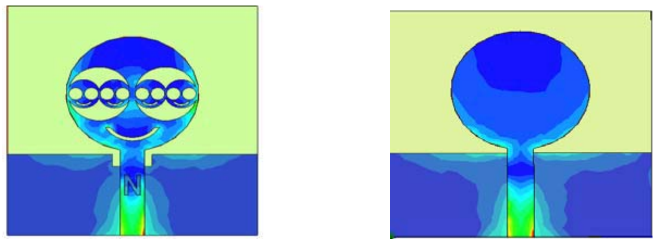
3. INTRODUCTION OF 'N' NOTCH AND GROUND SLIT

Figure 3 shows the geometry of the proposed antenna with 'N' notch and ground slit in order to obtain the desired UWB characteristic. The slot inserted in the feed line improves the impedance [14]. The antenna consists of two iterative fractal elements with a microstrip feed line. Microstrip feed line is the most widely used planar transmission line which is directly connected to the edge of the patch in order to provide input to the radiating patch. In this type of feed, radiating patch is on one side of the substrate and the partial ground plane on the other side. Ground plane is used to complete the circuit and to reflect the waves from the radiating patch.



(a) (b)

Figure 3. SFA antenna (a) front view, (b) back view. (All dimensions are in mm).



(a) (b)

Figure 4. (a) Current density of SFA, (b) current density of zeroth initiator.

First, a middle slit of dimension $1.8 \times 5.08\,\text{mm}^2$ is introduced in the ground plane, in order to eliminate the notched band ranging from 4.7 GHz to 6.22 GHz. After the introduction of middle slit, antenna also begins to operate on higher frequency component which results in the interference with the other communication systems. To overcome this, N-notch is introduced with width 0.5 mm and height 3 mm. A parametric study, with respect to slot width and length, has been carried out, in order to obtain desired UWB characteristics.

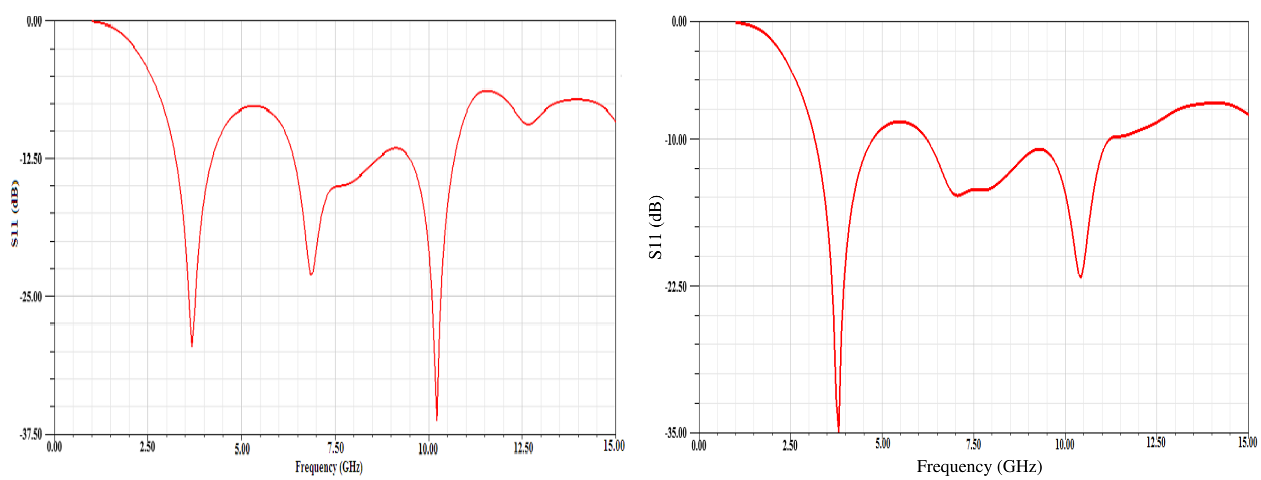
The current is generally distributed along the circumference of the circular patch. This states that the current density is minimum in the middle area; therefore, the current distribution will not be affected, even if any changes are made. The effective length of the current path can be increased by performing iterations. Thus, the first resonant frequency will shift from 4.7 GHz to 4.1 GHz, thus, the size of the antenna will be reduced. Figure 4 shows the current distribution of circular radiating patch with and without fractal geometry.

From the figure, it is inferred that the current distribution is maximum in the feed line and the edges of the circular patch of different iterations, which enhances the radiation characteristics.

In order to achieve the desired UWB characteristics, optimization has been performed with different antenna parameters.

4. RESULTS AND DISCUSSIONS

The proposed SFA has been designed on an FR-4 substrate with $\varepsilon_r = 4.4$ and thickness $h = 1.6$ mm, with N-shaped notch of length $L = 3$ mm and width $W = 0.5$ mm, and the overall width of notch is 2.08 mm. Two iterations are implemented, and their return loss characteristic is shown in Figure 5. Dimensions and specifications of the substrate and the feed line are kept constant. Any changes in the



(a) (b)

Figure 5. (a) Return loss for the first iteration, (b) return loss for the second iteration.

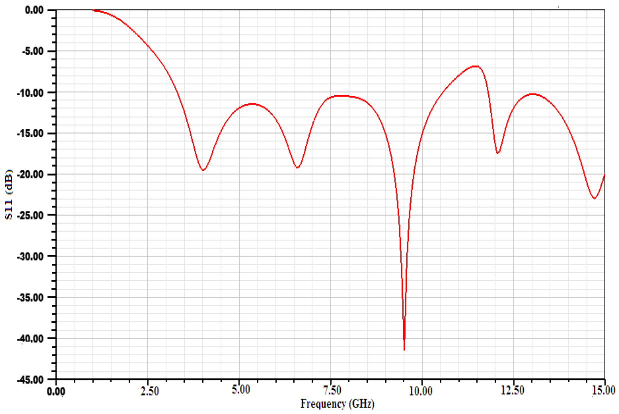


Figure 6. Return loss graph with ground slit.

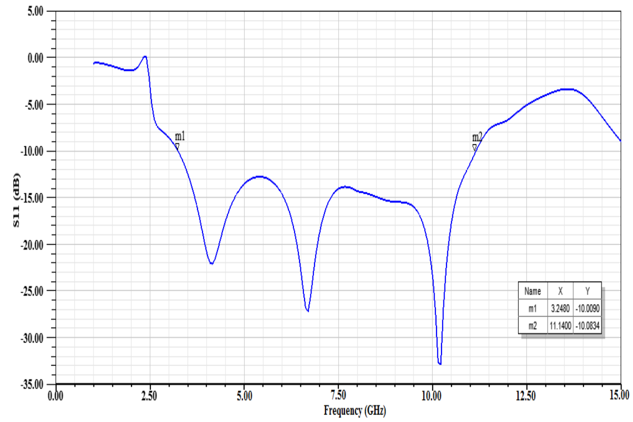


Figure 7. Return loss graph with N notch and ground slit.

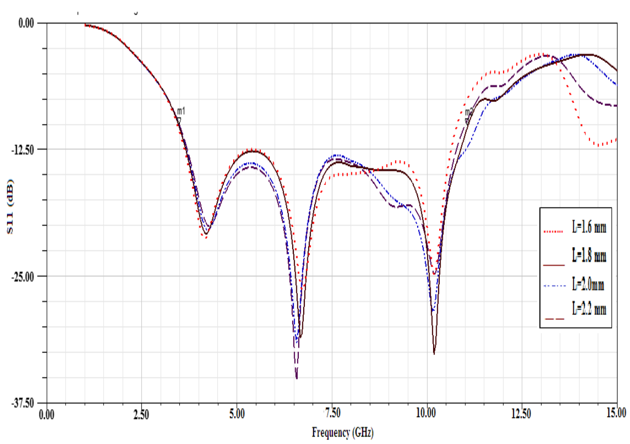


Figure 8. Return loss for variation in slit length.

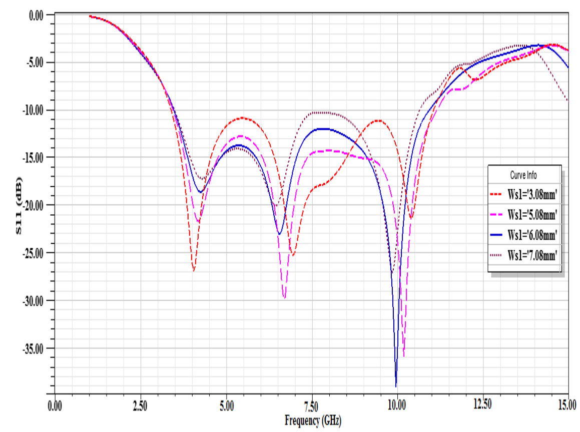


Figure 9. Return loss for variation in slit width.

return loss, efficiency gain and surface current distribution are due to slit and notch [13, 16, 17].

Design of the proposed antenna as well as the simulation is done using 3D Electromagnetic tools Ansys's HFSS [18] and Semcad X by SPEAG [19]. The return loss for the first and second iterations is shown in Figure 5. From the graph (Figure 5(b)), it is inferred that band notch is introduced in the frequency range from 3.1 GHz to 10.6 GHz. A slit is introduced in the ground plane, to remove this notched band i.e., from 4.72 GHz to 6.22 GHz, and the return loss is shown in Figure 6.

From the graph (Figure 6), it can be inferred that the slit allows antenna to operate on higher frequency component greater than 10.6 GHz. Figure 7 shows the return loss graph of fractal antenna with N-notch in feed line which eliminates the higher operating frequency component. To achieve better impedance bandwidth and return loss, slit length is taken as 1.6 mm, 1.8 mm, 2.0 mm and 2.2 mm, and its variations with respect to return loss are displayed in Figure 8. Similarly, Figure 9 displays the variation of slit width for different values at 3.08 mm, 5.08 mm, 6.08 mm and 7.08 mm. By observing the above two graphs, slit length of 1.8 mm and width of 5.08 mm are taken due to better return loss and impedance bandwidth. The return loss graph for different notch lengths is shown in Figure 10. It is seen that as length increases from 2 mm to 5 mm, impedance bandwidth decreases. The variation of the notch width for 0.3 mm, 0.5 mm and 0.7 mm is shown in Figure 11. N-notch of length 3 mm and width 0.5 mm is taken after optimization to achieve the desired UWB impedance bandwidth.

The Voltage Standing Wave Ratio (VSWR) of the Smiley Fractal (SFA) antenna with 'N' notch and modified ground plane is as shown in Figure 12. When N-notch of length 3 mm and width 0.5 mm is introduced, the antenna bandwidth (VSWR < 2 or about -10 dB return loss) of 3.24–11.14 GHz (Figure 7) can be achieved for the UWB applications.

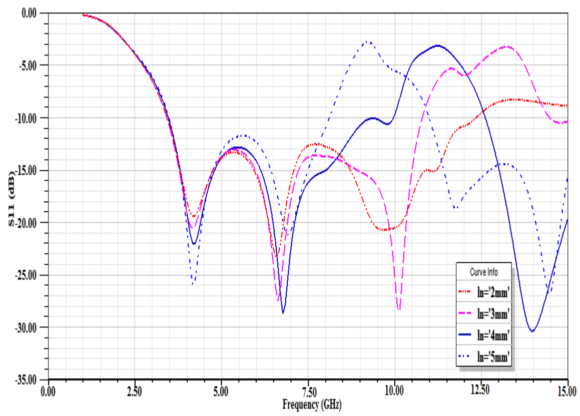


Figure 10. Return loss for variation in length of N notch.

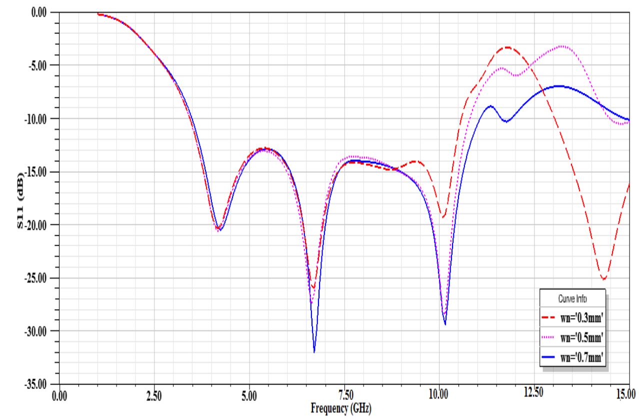


Figure 11. Return loss for variation in width of N notch.

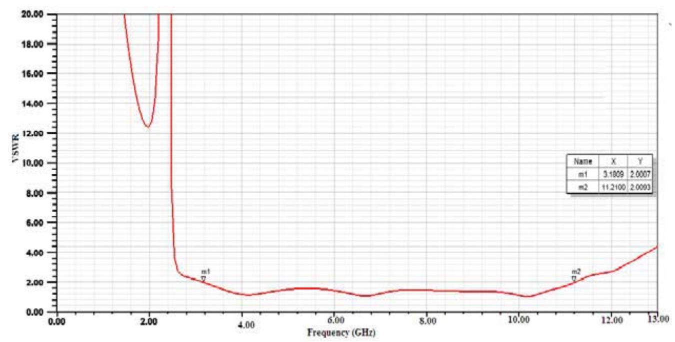
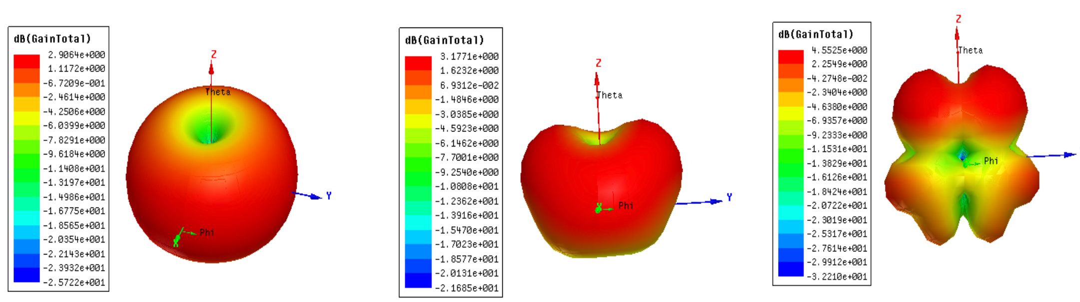


Figure 12. VSWR curve for SFA antenna.



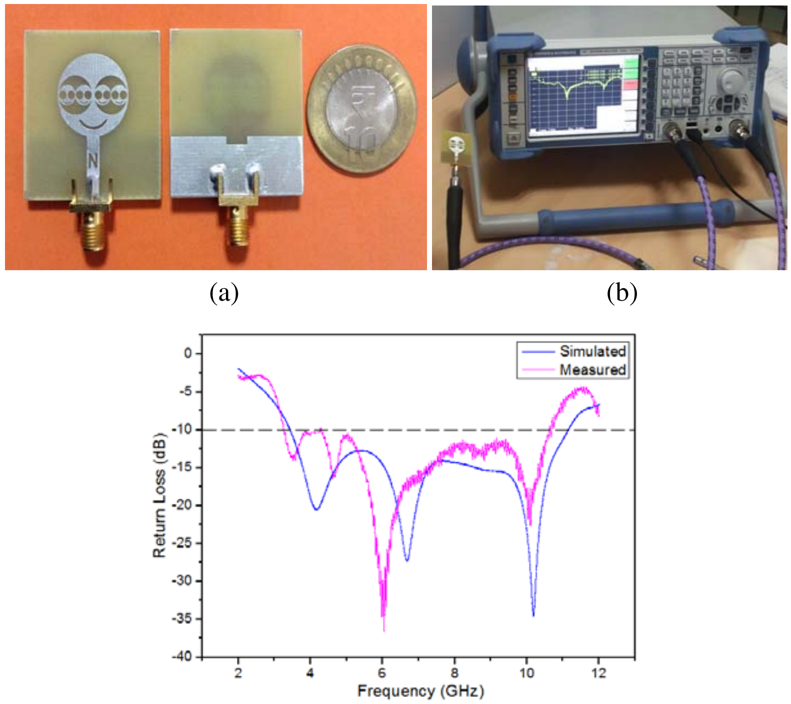
(a) 4.1 GHz (b) 6.7 GHz (c) 10.18 GHz

Figure 13. Radiation patterns.

Figure 13 illustrates the radiation patterns of antenna at different frequencies: 4.1 GHz, 6.7 GHz and 10.18 GHz. The radiation pattern in azimuth plane is nearly omnidirectional at lower frequency.

The omnidirectional radiation pattern thus obtained with the desired gain can be used for the indoor UWB applications. The prototype of the proposed antenna SFA has been fabricated, and the return loss measurement is carried out, using RS-ZVL vector network analyser and as depicted in Figure 14(a) and Figure 14(b), respectively.

Figure 14(c) shows the measured return loss and simulated return loss for the proposed SFA. The frequency value of both simulated and measured return loss ranges from 3.26 GHz to 10.68 GHz which is in good agreement with UWB frequency band as defined by FCC. And hence, it is suitable for UWB wireless applications.



(a) (b)

(c)

Figure 14. (a) Photograph of the proposed SFA, (b) measurement setup and (c) measured and simulated return loss for the proposed antenna.

5. CONCLUSIONS

A compact microstrip fed antenna has been designed and fabricated with a circular patch of radius 8.5 mm with smiley-face shaped fractal geometry, iterated twice and printed on an FR-4 substrate resulting in a overall dimensions $32 \times 34 \times 1.6\,\text{mm}^3$. The proposed antenna has nearly omnidirectional radiation pattern and operating band ranging from 3.26 GHz to 10.68 GHz with an impedance bandwidth of 7.42 GHz. A rectangular slit in the ground plane and 'N' notch in feed has been introduced in order to improve the better return loss, impedance bandwidth and to eliminate the operation of the antenna in higher frequency bands. The proposed antenna is of small size, low cost and can be integrated with MMIC/MICs. This antenna can be a good candidate for UWB wireless communication applications which are going to proliferate in wide variety of ways in all wireless scenarios.

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