Miniaturized UWB Triangular Microstrip Antenna Using Fractal Approach for Microwave Imaging Applications

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Abstract – **Original compact and efficient ultra-wide band (UWB) triangular microstrip antenna is made by applying Sierpinski triangle carpet to the patch of an initial UWB triangular antenna having stair shaped partial ground plane. The miniaturized triangular microstrip antenna has a compact dimension of 22.60 x 18.85 mm^2, which represents 69.50% of dimension reduction. It exhibits good return loss with fractional bandwidth over 127% from (3.56 to 16.20 GHz), nearly omnidirectional energy patterns and linearly increasing gain ranging from (0.83 to 4.72 dB) over the entire bandwidth. In addition to all these characteristics satisfying UWB applications, the designed antenna offers good time domain response in term of fidelity factor, upper than 96% and good group delay over its whole operating bandwidth which makes it suitable for microwave imaging applications. Prototype of the UWB miniaturized triangular patch antenna was also performed and studied experimentally. The measured results show a good promise with those simulated which validate the design procedure and confirm the benefits of miniaturization.**

Keywords – **Microstrip antenna, Ultra-wide band (UWB), Partial ground, Fractal, Sierpinski, Time domain analysis, Fidelity factor, Group delay, Microwave imaging domain.**

I. INTRODUCTION

The microwave imaging methods and systems exploit the electromagnetic waves scattering to attain information on a spatial region being discovered. Other technologies which employ various parts of the electromagnetic spectrum for screening can be considered such as X-ray systems; however, potential health risks due to ionizing radiation make it less acceptable to public safety. Thereby microwave-imaging systems are the most important factor of non-invasive and non-destructive techniques for examining structures and bodies. There are countless application fields of microwave imaging for both long and short-range configurations. These systems have been improved, from detection and localizations to more motivated objective of remodelling the scene in terms of the object shapes and material composition. Several works have been carried out in this direction such as medical diagnostics [1]-[2], surface prospecting [3]-[4], surveillance and security systems [5].

Ultra-wide band (UWB) transmission appears to be a very favourable technology for imaging structures due to the fact that the fractional bandwidth exceeding 100% contributes to the improvement of image resolution [5]. Ultra-wide band technology is among the emerging technologies that have attracted a great attention from scientists and industrialists, after booking the 3.1-10.6 GHz band for UWB applications by Federal Communication Commission (FCC) on 2002 [6]. This technology offers various advantages such as high data transmission capacity at very low power, large bandwidth, and excellent immunity to multi-channel interference and high gain in short range communications [7]. These potentials are desirable for both indoor and outdoor hand-held wireless applications as well as for imaging systems; and have presented copious challenges for antenna designers.

The design of UWB compact and efficient micro-strip antennas is a key step for microwave imaging structures, since it can reduce the complexity and size of antenna arrays often used in these systems. Different techniques and approaches have been mentioned to design small UWB antennas which meet the miniaturization requirements [8]-[10]. To reduce antenna dimensions while maintaining good to excellent efficiencies and gains; fractal geometries such as Koch fractal [11], Sierpinski gasket or carpet [12]-[13] and Hilbert fractal [14] turns out to be innovative and effective techniques. These geometries provide a radiation pattern and input impedance similar to larger antennas by occupying much smaller area because of their self-similarity and space filling.

In this paper, a miniaturized fractal UWB antenna is presented based on a conventional UWB Triangular Patch Antenna (TPA). The triangular fractalization is applied as the simplest solution to offer better miniaturization ratio while keeping the overall antenna performances in term of bandwidth, radiation and especially gain, unlike other techniques which can alter the antenna performance and require the use of performance improvement techniques. Moreover, our antenna seems to be the appropriate choice as it is intended for microwave imaging applications, which require a good impulse transmission (very low distortion to allow a better image reconstruction) and a compact size to be integrated in an array system.

The followed steps of the proposed miniaturized antenna design process will be presented in the next section; the third section will discuss simulated and experimental results while the fourth explain the time domain analyses of the miniaturized UWB-TPA. Conclusion and perspectives of this work were presented in the last section.

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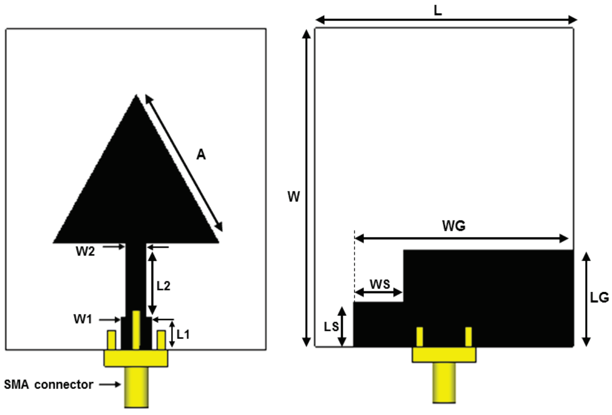
II. Miniaturized UWB Antenna Design Process

A. *Conventional UWB Antenna Configuration*

The basic antenna is an UWB triangular patch antenna (TPA) having equal sides, engraved on FR4 substrate with dielectric permittivity of εr=4.3, thickness h=1.6 mm and dielectric loss tangent of 0.025. The TPA is fed by 50 Ω quarter wave transformer feeding line and has a partial stair shaped ground plane placed on the bottom layer of the structure [15]. Fig. 1 shows the antenna design. Table I shows the antenna dimensions as quit as the performance of the antenna in term of bandwidth, while Fig. 2 represents its reflection coefficient.



(a) (b)

Fig. 1. Structure geometry of UWB antenna: (a) Top view, (b) Bottom view (Partial ground plane).

TABLE I
Dimensions of UWB TPA (in mm)

Parameters	**UWB TPA**
Side length (A)	16.75
Feeding Strip length (L1)	3.25
Feeding Strip width (W1)	3.1
Feeding length (L2)	7.23
Feeding width (W2)	2.00
Substrate length (L)	34.48
Substrate Width (W)	26.35
Partial Ground Length (LG)	9.50
Partial Ground Width (WG)	22.42
LS	4.3
WS	4.25
Bandwidth	18.09 GHz
FBW	**149.32%**

As shown in the Fig. 2, the -10 dB return loss bandwidth of the basic UWB antenna extends from 3.07 GHz to more than 21 GHz covering the required UWB band with a fractional bandwidth (FBW) exceeding 149%.

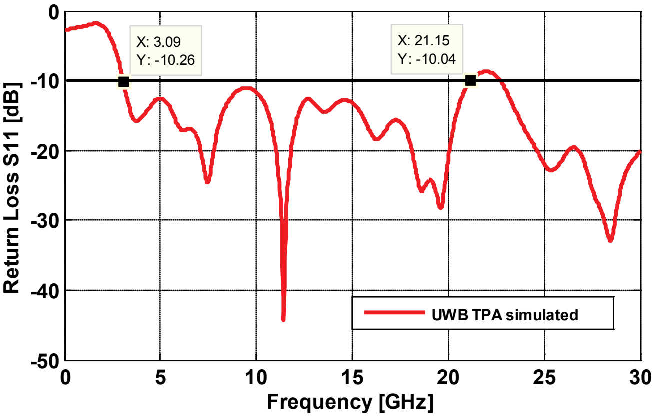


Fig. 2. S_{11} performance of the UWB patch antenna.

B. *Miniaturized Antenna Design*

Inasmuch that the main purpose of this study was the design of a compact UWB-TPA; we proceeded to the miniaturization of the antenna using Sierpinski fractal technique, which has several configurations. The one we had chosen can be produced by infinitely repeating the process of joining the midpoints of each side of the triangle to form four separate triangles, and cutting out the centred one [16], Fig. 3 depicts successive iterations of the Sierpenski gasket using the decomposition approach.

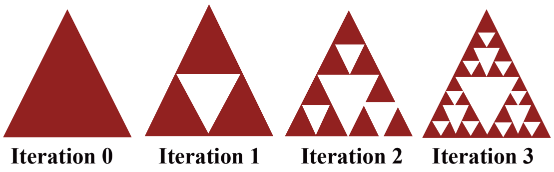


Fig. 3. Generation of the Sierpinski triangle by the decomposition approach method.

B.1. *Effect of the Iterations on Reflection Coefficient*

The insertion of fractal elements in the conventional UWB TPA keeping its original dimensions; decreases significantly its bandwidth and affects his impedance matching. Fig. 4 shows the iterations impact on the reflection coefficient of the antenna.

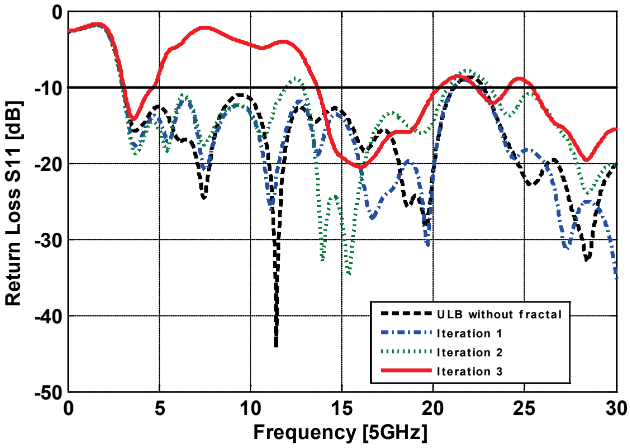


Fig. 4. UWB antenna (S_{11}) simulated results, without and with Sierpenski iterations.

According to the return loss of the antenna without fractals and that of each iteration presented in Fig. 4, the first two iterations have relatively kept the UWB performance of the antenna; while the third iteration has clearly affected its impedance matching and bandwidth. Therefore, the third iteration was adopted to allow the UWB antenna miniaturization.

B.2. Influence of the Partial Ground Length [LGm] on Antenna Bandwidth

To recover initial antenna performances in term of bandwidth and impedance matching; dimensions of the patch were reduced, and consequently those of the fed line, ground plane and substrate. Many parametric studies were executed on the different dimensions of the antenna in order to regain its initial response.

Fig. 5 displays the results of the last parametric study performed on partial ground plane dimensions since it contributes effectively in bandwidth enhancement and that for patch side length (Am=9.25mm).

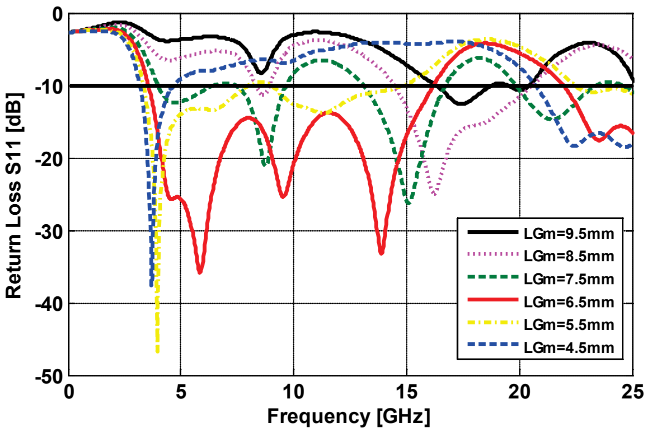
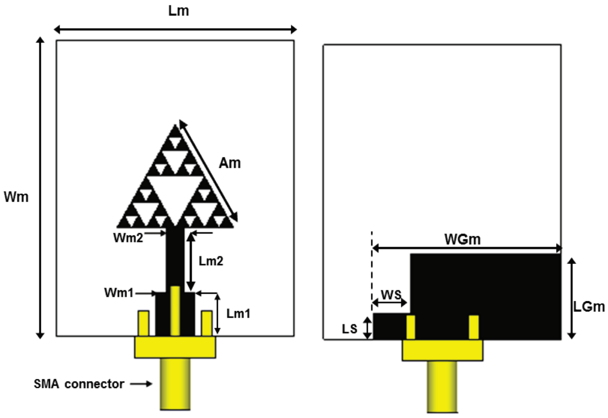


Fig. 5. Reflection coefficient S_{11} for different values of ground plane height (LGm).

By optimization and fine-tuning using particle Swarm Optimisation algorithm available on CST software, aiming for the broadest possible bandwidth, the final optimal dimension values of the miniaturized antenna were obtained. The top and bottom view of the proposed antenna layout are illustrated in Fig. 6, and Table II gives its dimensions.



(a) (b)

Fig. 6. Miniaturized UWB TPA design:
(a) Top view, (b) Bottom view.

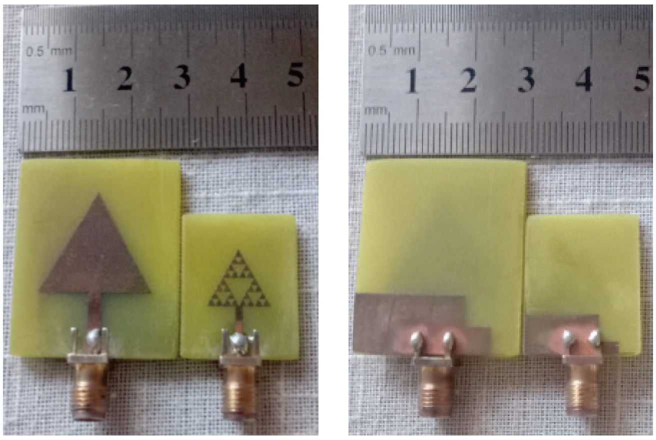
TABLE II
OPTIMIZED DIMENSIONS OF MINIATURIZED UWB-TPA (IN MM)

Parameters	**Miniaturized TPA**
Side length (Am)	9.25
Feeding Strip length (Lm1)	3.25
Feeding strip width (Wm1)	3.10
Feeding quarter strip length (Lm2)	5.00
Feeding quarter Strip width (Wm2)	1.40
Substrate length (Lm)	22.61
Substrate Width (Wm)	18.85
Ground Length (LGm)	6.50
Ground Width (WGm)	14.85
LS	2.00
WS	2.93
BANDWIDTH	12.64 GHz
FBW	**127.94%**

III. SIMULATED AND EXPERIMENTAL RESULTS PERFORMANCES

As displayed in Fig. 7, the basic and miniaturized TPAs were manufactured. Simulated and measured return loss of the proposed miniaturized TPA were demonstrated in Fig. 8; we have succeeded to recover a bandwidth ranging from 3.56 to 16.20 GHz bellow –10 dB which characterizes a fractional bandwidth of 127.94% satisfying the FCC mask and the UWB requirements.

Good agreement has been observed between both simulated and measured return loss results for the miniaturized design with a slight loss in impedance matching mostly due to fabrication constraints and the consequence of SMA connector.



(a) (b)

Fig. 7. Miniaturized antenna prototype:
(a) Top view, (b) Bottom view.

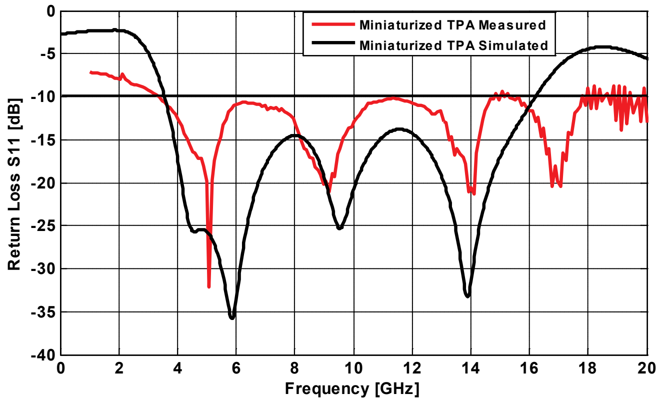


Fig. 8. Measured and simulated return loss of miniaturized antenna.

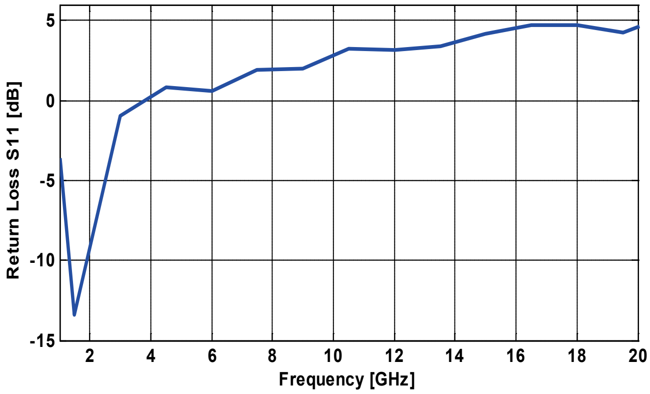


Fig. 9. Miniaturized antenna gain vs. frequency.

The realized gain variation with frequency of the miniaturized TPA is displayed in Fig. 9. The average antenna gain is about 3.2 dB over the operating band; the maximum gain achieved is 4.72 dB at 16.20 GHz. This result confirms that the antenna is successfully suitable for UWB applications.

Fig. 10 plots both E and H plane radiation patterns of the miniaturized TPA at 5, 10.5 and 15.5 GHz, respectively. The figure reveals nearly Omni-directional and stable radiation patterns in the entire operation band with a shallow null at 5 GHz and 10.5 GHz and three nulls at 15.5 GHz far field plots.

IV. TIME DOMAIN ANALYSIS OF THE MINIATURIZED TPA

The ultra-wideband impulse radio (UWB-IR) system uses very short rhythms in time (<2 ns) which covers a very broad frequency spectrum. Since narrow pulses are strictly affected by dispersion, the radiated pulse will never be the same as the excitation pulse at the antenna input. However, the receiver should recognize the incoming pulse [17]. Hence in order to predict the distortion produced by the proposed antenna, a time-domain study of the transmitted pulse is important.

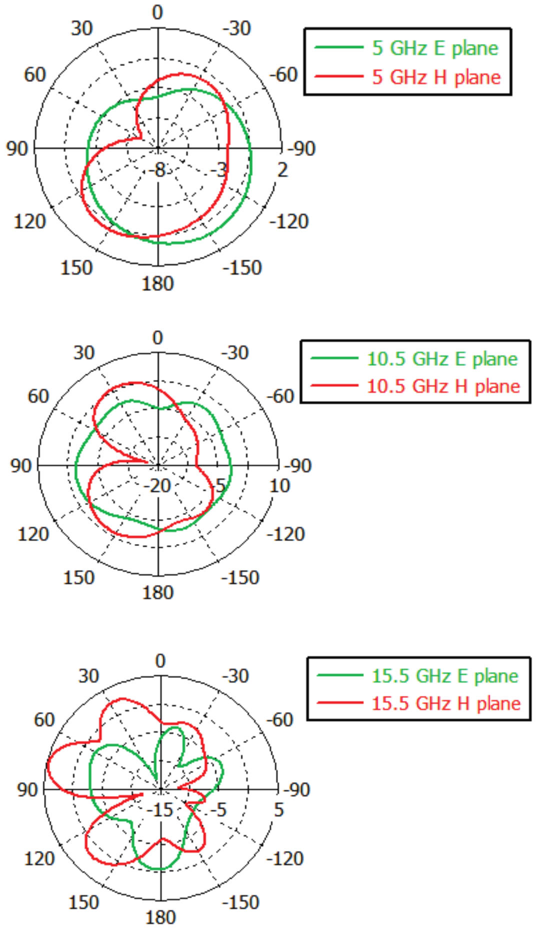
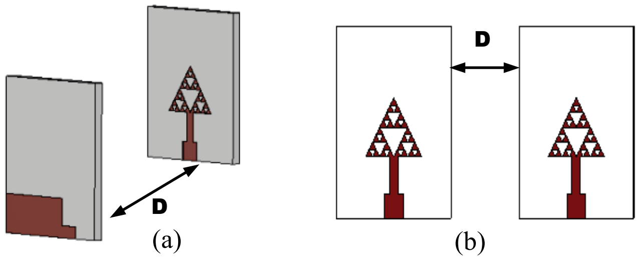


Fig. 10. E-plane and H-plane radiation patterns of the antenna at 5, 10.5 and 15.5 GHz.

A. *Transfer Function and Group Delay*

To investigate the performance of the miniaturized antenna as a transmitter and receiver in UWB system, pair of identical miniaturized antenna has been placed in 100 mm distance from each other (antennas are located in their far field) in face to face and side by side orientations, Fig. 11.

Group delay and Transfer function characteristics for both orientations are presented in Figs. 12 and 13, respectively.



(a) (b)

Fig. 11. Antennas orientations: (a) face to face, (b) side by side.

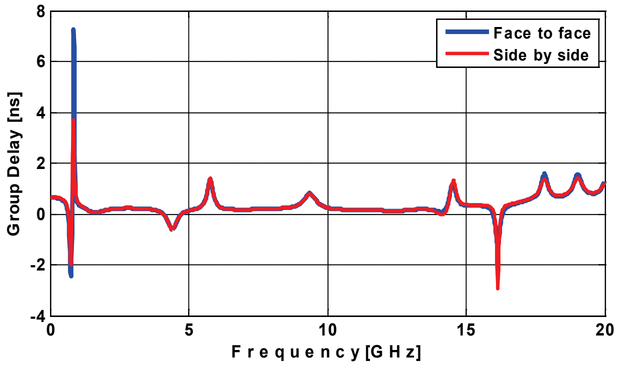


Fig. 12. Miniaturized antenna group delay for the two orientations.

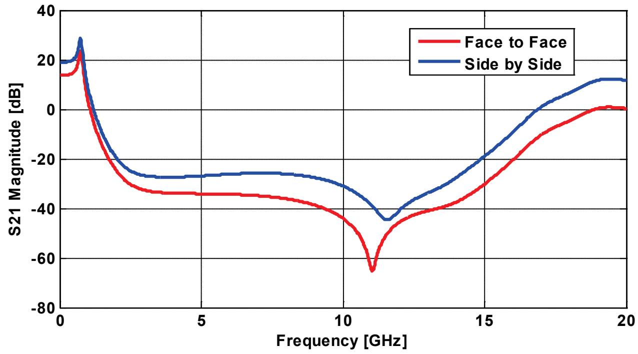


Fig. 13. Transmission coefficient S21 for the two orientations.

The group delay characteristic is defined as the rate of change of the transmission phase shift with respect to frequency. In the ideal case, a linear phase response corresponds to a constant group delay. The group delay curves of the miniaturized antenna for the two orientations exhibit a variation less than ±1 ns around 0.2 ns in the entire working band, which indicates the good linear phase response. While magnitude of the transmission coefficient S_{21} is flat and corresponds well to the group delay.

Hence it can be concluded that the antenna has small, even negligible waveform distortion due to the phase nonlinearity.

B. *Fidelity Factor*

Fidelity factor is the only factor which analyses the system in time, frequency and space dimensions together [18]. Called also correlation coefficient, it compares the waveforms distortion of transmitting patch antenna input signal and the receiving signal at the far-field region [19]-[21]. The System Fidelity Factor (SFF) can be evaluated using Eq. (1) [22]:

$$\boldsymbol{SFF} = \max_{\tau} \frac{\int_{-\infty}^{\infty} S_t(t) S_r(t-\tau) dt}{\sqrt{\int_{-\infty}^{\infty} |S_t(t)|^2 dt . \int_{-\infty}^{\infty} |S_r(t)|^2 dt}} \qquad (1)$$

where St (t) and Sr (t) are the transmitted and received signals respectively and τ is the time delay.

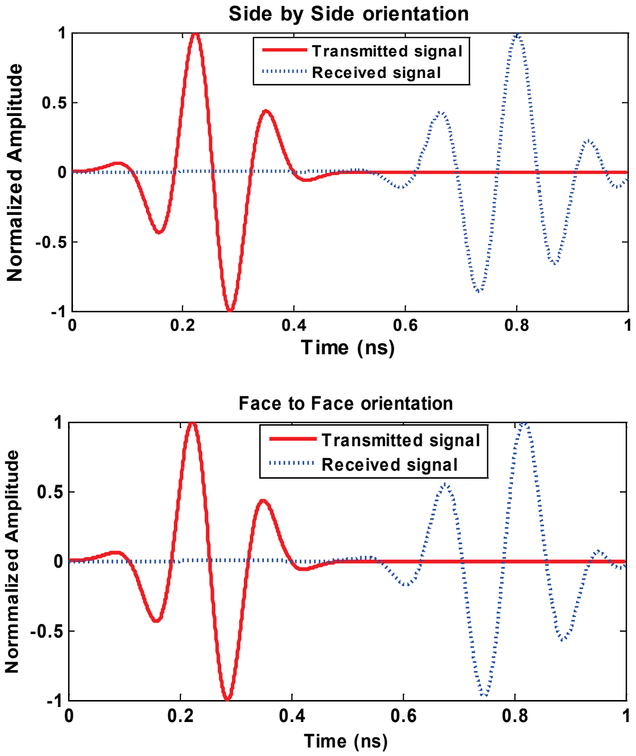


Fig. 14. Normalized transmitted and received signals for side by side and face to face orientation.

Fig. 14 displays the normalized transmitted and received signals in time domain. It is proved from the figure that the proposed antenna has a good potential in transmitting UWB signals with lowest distortion as well as the received pulse signal shows stable performance and is practically identical to the transmitted signal pulsation.

TABLE III

SYSTEM FIDELITY FACTOR OF THE MINIATURIZED ANTENNA

Orientation	**Maximum fidelity factor (in %)**
Face to face	96.48
Side by side	97.14

System fidelity factor is calculated for two orientations and the results are summarized in Table III. We can see that a better system fidelity factor is achieved (more than 96%). Therefore, the antenna shows a negligible dispersion.

V. COMPARISON AND DISCUSSION

In order to distinct the performances of the miniaturized UWB TPA proposed in this paper, a comparison with some recent related works from literature is summarized in Table IV.

TABLE IV
COMPARISON OF THE PROPOSED MINIATURIZED TPA WITH RECENT FRACTAL UWB ANTENNAS

REF	Dimensions (mm^2)	Miniaturization ratio	-10 dB bandwidth (GHz)	Max gain (dBi)	Fidelity
[11]	23.5 x 15	-	(3.2-13.2) 10.9	3.8	81-96 %
[23]	24 x 24	-	(2.99-11.16) 8.17	5	89-93 %
[12]	28 x 28	46.3 %	(3.41-15.37) 11.96	5.95	-
[13]	16.5 x 14.5	-	(3.03-10.77) 7.74	3.74	-
[24]	21 x 25	53 %	(3.1-10) 6.9	-	79.6-80.5 %
Proposed antenna	**22.6 x 18.85**	**69.5%**	**(3.56 to 16.20) 12.64**	**4.72**	**96.5-97%**

The miniaturized TPA proposed in this work offers the best performances in term of miniaturization rate, bandwidth and fidelity factor compared to the other contributions presented in Table IV, while ensuring a stable and appreciable gain for UWB applications.

VI. CONCLUSION

In this paper, original compact UWB Triangular microstrip antenna with partial stair shaped ground plane is performed using Sierpinski triangle fractal. The miniaturized UWB-TPA achieves 69.50% of dimension reduction compared to the conventional UWB antennas keeping good antenna performances in frequency domain with an impedance bandwidth from 3.56 GHz to 16.20 GHz for |S11| = -10 dB which represent 127.94% of Fractional Bandwidth, and a nearly omnidirectional radiation with stable positive gain over its whole frequency band.

The proposed antenna was analyzed in time domain also, where it exhibits a good fidelity factor that exceeds 96%, a flat transfer function and a linear group delay. This demonstrates good pulse preserving capability, which suggests the miniaturized antenna as a strong candidate for UWB microwave imaging systems. The structure was successfully designed, fabricated, and measured. Good accordance has been achieved between the simulated and measured results.

Frequency or polarization reconfigurability of the compact antenna will be the aims of future works.

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