Optimal Design of an Ultra-Wideband Antenna with the Irregular Shape on Radiator using Particle Swarm Optimization

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Abstract **─** An ultra-wideband antenna with an irregular shape radiator for ultra-wideband applications has been designed by particle swarm optimization along with the simulator, HFSS. The proposed antenna design process is automated. Also, the better results can be obtained efficiently. The proposed antenna is fed by a coplanar waveguide line. The optimized antenna has a compact substrate size of 34.0 mm by 33.35 mm. Results show that the optimized irregular shape of the proposed antenna outperforms the antennas with uniform rectangular shapes in impedance matching. The optimized antenna can cover the spectrum of ultra-wideband (3.1 GHz - 10.6 GHz). The current distributions are investigated for describing the antenna characteristics. Moreover, the proposed UWB antenna has good characteristics of radiation, transmission, and impedance bandwidth.

Index Terms **─** Optimization, planar antennas, PSO, ultra-wideband.

I. INTRODUCTION

Ultra-wideband (UWB) [1] antennas have been received much attention from antenna designers and researchers. Many UWB antennas were designed using planar structure due to advantages of low profile, low cost, light weight, and easy fabrication. The dimensions and geometry of the radiator largely affect the impedance matching. To achieve the design goal, some of planar UWB antennas adopted different shapes such as rectangle [2, 3], circle [4], triangle [5], and octagon [6] as the radiators. Other studies used the staircase-shape on the edges of the radiators [7, 8]. However, those shapes have uniform or smooth edges on the radiator and the dimensions of the radiator were determined by experimental efforts.

This study uses the particle swarm optimization (PSO) method, combined with the finite element method based simulator, HFSS, to design and optimize the proposed UWB antenna. The radiator of the proposed UWB antenna consists of five rectangular patches. The dimension of each rectangular patch can be arbitrarily adjusted by the PSO method to achieve the design goal. Hence, the shape of the optimized radiator would be various. The developed PSO method can control the HFSS and can change the antenna dimensions without any manual adjustments during the optimization process. In this way, optimized results are obtained automatically. The main advantage of the proposed approach is that it reduces the time required to solve an electromagnetic problem. The better results can be obtained efficiently. Compared with the studies shown in [2-8], the irregular shape radiator obtained by the proposed approach can be considered as novel.

The PSO is an effective algorithm which was proposed in 1995 by James Kennedy and Russell Eberhart jointly [9]. Many electromagnetic problems [10-12] have been designed using PSO. The basic concept of PSO is from the study on animals' group behaviors, such as a swarm of birds randomly searching for food. The birds (particles) distribute randomly and fly with random direction and velocity in a finite area initially. If one of the birds finds a location close to the food (the optimum), the bird changes its flying direction and velocity toward the food.

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Simultaneously, the bird tells other birds to fly around the bird. The other birds would change their direction and velocity to get closer to the food. The birds search for the entire space until one of them finds the food. The PSO algorithm is inspired from this model. For the sake of brevity, other detailed concepts of PSO are excluded here and they can be found in [13].

Optimized dimensions of the proposed planar UWB antenna is fabricated on a cheap FR4 substrate. The antenna radiator is fed by a coplanar waveguide (CPW) line [14]. A good impedance matching is obtained in the UWB spectrum. Moreover, a reasonable agreement between simulated reflection coefficient and measured one is observed. Simulated results show that near omnidirectional radiation patterns are achieved. A parametric study was performed by simulation. This result shows that the optimized irregular shape of the proposed antenna outperforms the antennas with uniform rectangular shapes on the radiators in impedance matching. Good frequency-domain characteristics of maximum gain, group delay and phase of S21 were measured. The results verified that the proposed UWB antenna can apply to any short- or long-range communication systems.

Table 1: The dimensions and optimization ranges of the initial antenna (Unit: mm)

Parameter	Size	Optimization range
L0	5.0	0.5 - 7.0
Lg	15.0	9.0 - 17.0
Wg	15.0	16.0 - 26.0
L1	5.0	1.0 - 7.0
W1	4.4	0.5 - 8.0
L2	5.0	1.0 - 7.0
W2	4.6	0.5 - 8.0
L3	5.0	1.0 - 7.0
W3	4.8	0.5 - 8.0
L4	5.0	1.0 - 7.0
W4	5.0	0.5 - 8.0
L5	5.0	1.0 - 7.0
W5	5.2	0.5 - 8.0

II. PSO AND ANTENNA DESIGN

Figure 1 shows the geometry of the initial antenna whose radiator consisting of five different rectangular patches. Before the optimization, the initial antenna was created in the full-wave electromagnetic simulator, HFSS. In the PSO optimization, the optimizer has more flexibility when there are more numbers of parameters to be optimized. At the same time, more numbers of EM simulations is required in iteration. To compromise the order of complexity and flexibility, five rectangular patches of the radiator are adopted in this study. Table 1 lists the dimensions of the initial antenna. Five rectangular patches are denoted L1 to L5 and W1 to W5. The sizes of them are used for creating the initial antenna only. The initial values of five rectangular patches do not affect the optimization result since the PSO is a global optimizer. It is not required using any starting points in the optimization process of the PSO. The gap between the radiator and ground is L0. The length and width of the ground plane are Lg and 2Wg, respectively. The W0 (4.2 mm) and G (0.3 mm) are the width and the gap of the 50 Ω CPW, respectively. The W0 and G are fixed during optimization. The proposed antenna is to be fabricated on an FR4 substrate with thickness of 0.8 mm, relative permittivity of 4.4, and loss tangent of 0.02. In this optimization, thirteen parameters, L0, Lg, Wg, L1 to L5, and W1 to W5 are to be optimized within their optimization range to achieve the UWB specification. If the designer wants the antenna to

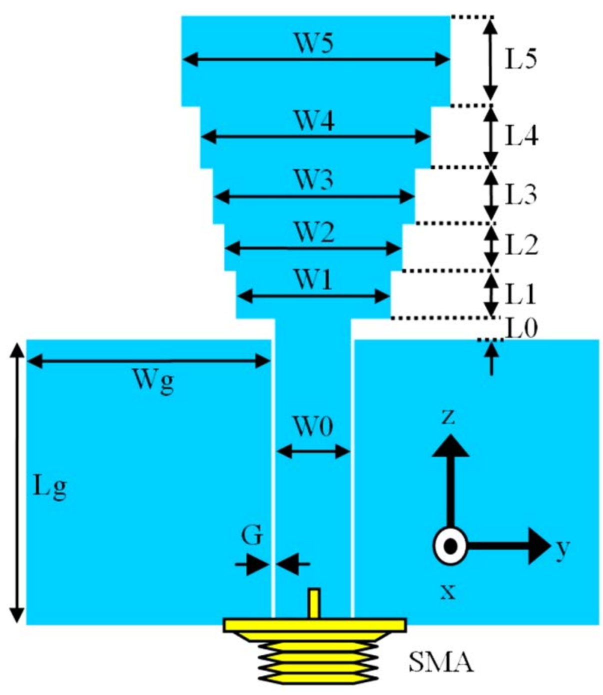


Fig. 1. The geometry of the initial antenna.

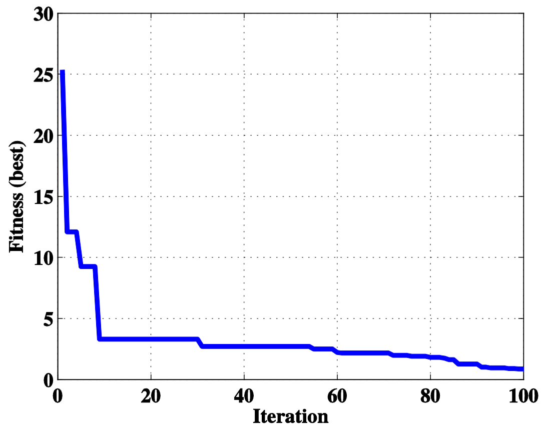


Fig. 2. The best fitness versus iteration.

Table 2: The dimensions of the optimized antennas (Unit: mm)

Parameter	Size	Parameter	Size
W0	4.2	L0	1.35
Wg	14.28	Lg	15.87
W1	13.97	L1	2.67
W2	12.77	L2	2.66
W3	15.49	L3	3.0
W4	16.0	L4	3.79
W5	11.29	L5	4.66

be compact, the designer may limit the optimization ranges of parameters. The reflection coefficient $|S_{11}|$ of the optimized antenna should be below -10 dB in the UWB spectrum (frequency between 3.1 GHz to 10.6 GHz).

To optimize the proposed antenna using PSO and HFSS, the first step is to create a script of HFSS. The HFSS script is recorded while creating the geometry of the initial antenna. The PSO serves as an external optimizer to control the HFSS. The next step is to modify the value of each parameter in the script. The PSO code can identify and modify the dimension of each parameter in the script. The third step is to execute the modified script. The HFSS simulates the antenna using the modified geometry to obtain the simulated results. The fitness is then used to evaluate the obtained results for PSO optimization process. In this study, the obtained $|S_{11}|$ is used to calculate the fitness using (1).

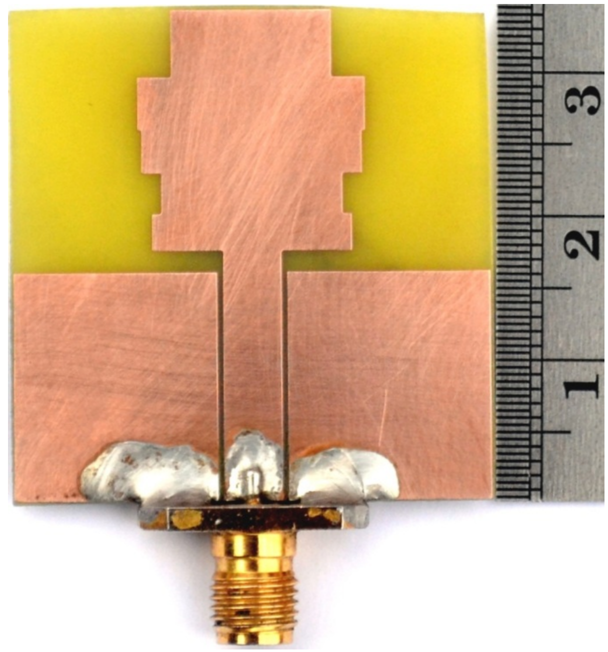


Fig. 3. The fabricated antenna on an FR4 substrate with the antenna size of 34.0 mm by 33.35 mm.

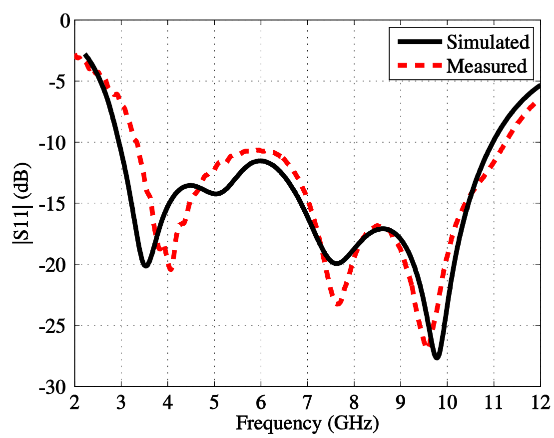


Fig. 4. The measured and simulated reflection coefficients $|S_{11}|$ of the proposed antenna.

$$\text{Fitness} = \sum (|S_{11}(f)| - |S_{11,d}(f)|)[\frac{1+\text{sgn}(|S_{11}(f)| - |S_{11,d}(f)|)}{2}]\Delta f \ ,$$
$$|S_{11,d}(f)| = \text{-12 dB}, \text{ for } 2.8 \text{ GHz} \le f \le 11.0 \text{ GHz}. \quad (1)$$

Where, the Δf is frequency interval set to 0.01 GHz. The $|S_{11,d}|$ is the desired reflection coefficient, which is stricter than that of the UWB

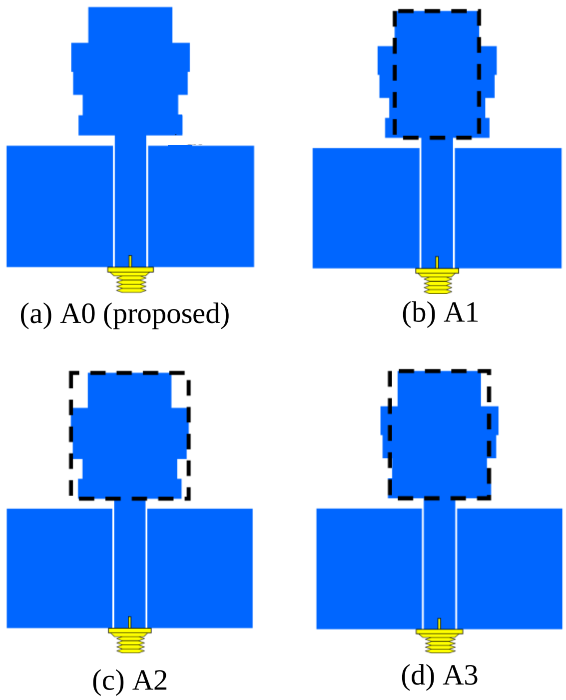


Fig. 5. The geometry of four different widths on the radiator of the UWB antennas.

specification. The fitness is the different area between $|S_{11}|$ and $|S_{11,d}|$ that should be as small as possible during optimization. The smaller the fitness is, the better optimization result obtained. The PSO optimization process is terminated when the maximum number of iterations is reached or when the fitness goes to zero. In the PSO setting, the maximum number iteration is set to 100. The reflecting boundary condition [13] and 27 particles and are used.

III. RESULTS AND DISCUSSIONS

The PSO optimization process is ended after the maximum number of iterations, 100, is reached. Figure 2 shows the curve of the best fitness versus iteration. The fitness value is dropped significantly during the first ten iterations. Then, the fitness slowly decreases as the number of iteration increases. The optimized dimensions of the global best are used to fabricate the proposed UWB antenna. Table 2 lists the optimized dimensions of the proposed antenna. Figure 3 reveals the picture of the antenna fabricated on an FR4 substrate with the antenna size of 34.0 mm by 33.35 mm. The measured $|S_{11}|$ is obtained using an Agilent N5230A vector network analyzer (VNA). Figure 4 shows the curves of measured and simulated $|S_{11}|$. A reasonable agreement between them is observed. The impedance bandwidth of the simulated $|S_{11}|$ is 8.04 GHz (2.94 - 10.98 GHz below -10 dB).

To compare the performance of the proposed antenna with that of the UWB antenna with a uniform shape of the radiator, a parametric study was performed in this study. The proposed antenna has five different widths, W1 to W5, on its radiator as shown in Table 2. The proposed antenna is denoted A0 as shown in Fig. 5(a). The minimum value of W1 to W5 is W5 (11.29 mm). The widths of the radiator are uniformed to W5, and the antenna is denoted as A1, which can be seen in Fig. 5(b). The lengths, L1 to L5, are fixed as those of A0. The other two antennas, A2 and A3, can be done by the similar way. The antenna, A2, has a uniform width W4 (16.0 mm, the maximum value of W1 to W5) of its radiator as shown in Fig. 5(c). The antenna, A3, has a uniform width (13.91 mm, the mean of W1 to W5) of its radiator as shown in Fig. 5(d).
Figure 6 shows the simulated reflection coefficients $|S_{11}|$ of A0 to A3. Poor $|S_{11}|$ of A1 and A2 can be found. After comparing A0 to A3, the results show that the two curves are almost the same below 4.0 GHz; whereas, the $|S_{11}|$ of A0 is better than that of A3 in the frequencies between 4.0 GHz and 10.5 GHz. However, the A3 has a higher cut-off frequency (below -10 dB) at 11.28 GHz.

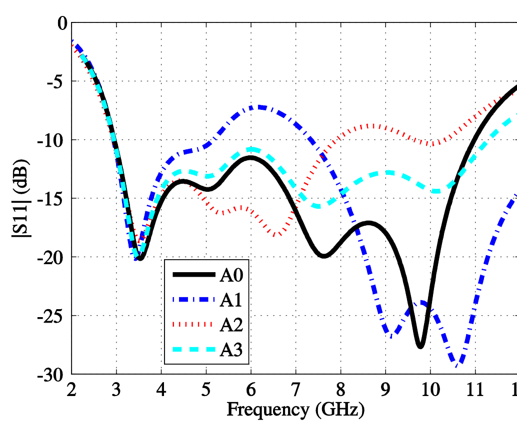
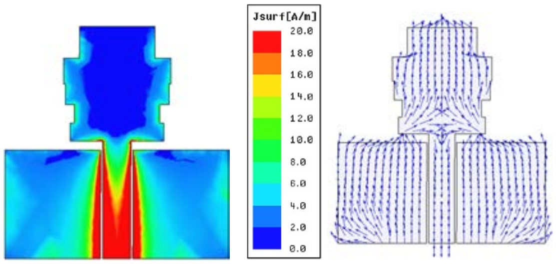
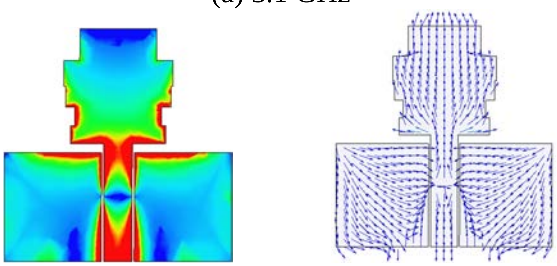


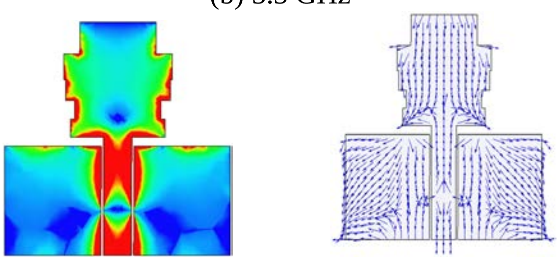
Fig. 6. The comparison of the antennas, A0 to A3, on simulated reflection coefficients $|S_{11}|$.



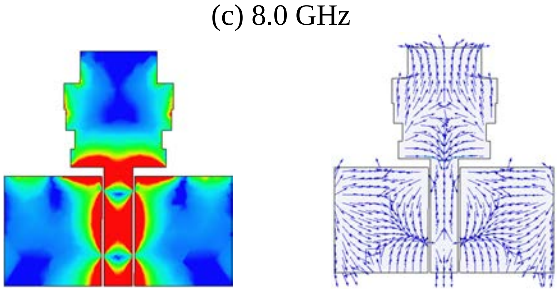
(a) 3.1 GHz



(b) 5.5 GHz



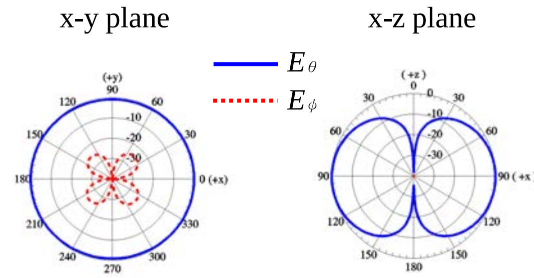
(c) 8.0 GHz



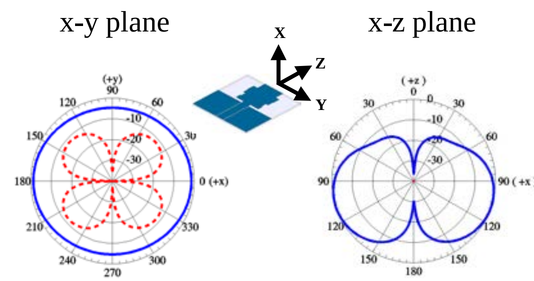
(d) 10.6 GHz

Fig. 7. The current distributions of the proposed UWB antennas at (a) 3.1 GHz, (b) 5.5 GHz, (c) 8.0 GHz, and (d) 10.6 GHz. The figures on the left-hand side and the right-hand side are magnitudes and directions, respectively.

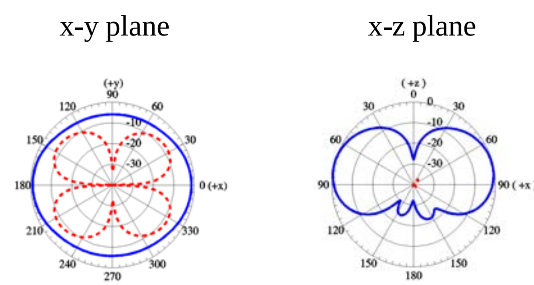
Figure 7 shows the magnitudes and directions of current distributions of the proposed UWB antennas at 3.1, 5.5, 8.0, and 10.6 GHz, respectively. The current distributions are kept symmetrical about the z-axis at all frequencies. The current densities are much stronger near the edges of the ground plane and the radiator. The currents on the irregular edges of the radiator increase the path length of the currents. It makes the antenna size reduction. Moreover, the irregular



(a) 3.1 GHz



(b) 5.5 GHz



(c) 8.0 GHz

Fig. 8. Simulated radiation patterns (normalized) of the proposed antenna at (a) 3.1 GHz, (b) 5.5 GHz, and (c) 8.0 GHz.

edges affect the impedance matching especially at higher frequencies as the results also can be confirmed and shown in Fig. 6. Figure 8 shows normalized E_θ and E_ϕ in the x-y and x-z planes at frequencies of 3.1 GHz, 5.5 GHz, and 8.0 GHz. The E_θ is near omni- irectional in the x-y plane at these three frequencies. The cross-polar component E_ϕ is very small (less than -40 dB) in the x-z plane. The results indicate that the proposed antenna is a good candidate for UWB applications. Figure 9 shows the measured maximum gain of the proposed antenna. The maximum gain increases as the frequency increases. The gain is 1.82 dBi at 3.0 GHz; whereas, the gain is 4.92 dBi at 11.0 GHz.

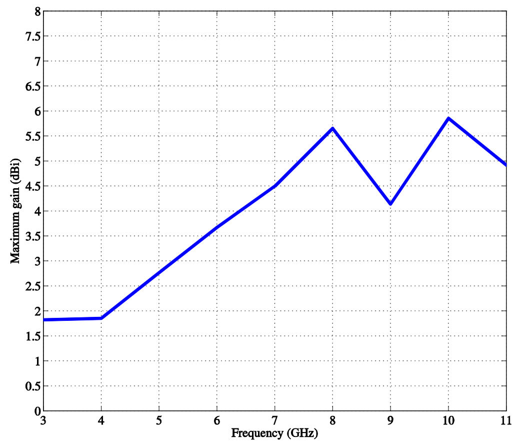
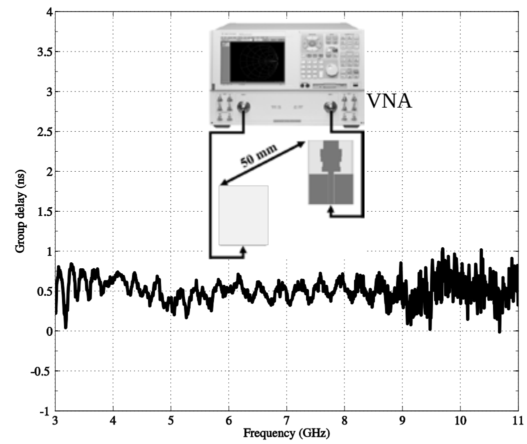
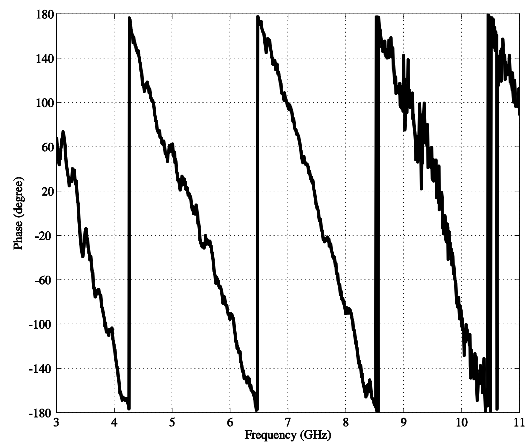


Fig. 9. The measured maximum gain of the proposed antenna.

To measure the dispersion and linearity of the proposed antenna, two identical proposed UWB antennas are placed in a face to face orientation (co-polarized direction) as shown in Fig. 10 (a). The two antennas are connected to port 1 and port 2 of the VNA (Agilent N5230A), respectively and fed by the low power 0 dBm coming from the two VNA ports. The two antennas are separated at a distance of 50 mm from each other. This short distance ensures a pure transmission relationship between two transmitted and received antennas. Other factors interfering with the transmission can be viewed as minor. Under this placement, the group delay was measured for the property of dispersion and measured the phase of the $|S_{21}|$ for the property of linearity. Figure 10 (a) shows the measured group delay of the proposed antenna. The variation of the group delay is less than 1 ns in the UWB spectrum. The result shows that a pulse distortion does not occur and a good linearity can be ensured in far-field region [7]. Figure 10 (b) shows the measured phase of $|S_{21}|$. A good linearity of the $|S_{21}|$ phase is observed between 3.0 GHz and 8.5 GHz. If the frequencies are larger than 8.5 GHz, the variation of the $|S_{21}|$ phase becomes large. The loss becomes larger in the higher frequencies due to using a high loss FR4 substrate in this study such that the linearity of the $|S_{21}|$ phase becomes a little poor. However, the proposed UWB antenna still has good properties of dispersion and linearity in the band of interest.



(a)



(b)

Fig. 10. Measured results of the proposed antenna, (a) group delay and (b) $|S_{21}|$ phase.

VI. CONCLUSION

This study presents a planar ultra-wideband antenna with an irregular shape on its radiator for UWB applications. The particle swarm optimization combined with the finite element method based simulator, HFSS to design and optimize the proposed antenna. The antenna design process is automated and better results can be obtained efficiently. The proposed approach successfully obtains the desired goal. The antenna has a compact substrate size of 34.0 mm by 33.35 mm. Optimization results indicate that the proposed antenna has good characteristics of impedance bandwidth and radiation pattern in the band of interest. The parametric study of the proposed antenna shows that the optimized irregular shape of the proposed antenna outperforms the antennas with uniform rectangular shapes in impedance matching in the UWB spectrum. The current distributions have been used to interpret the antenna characteristics. Measured results of the maximum gain, group delay, and phase of $|S_{21}|$ demonstrate good transmission properties of the proposed antenna. To sum up, the proposed antenna is suitable for UWB applications.

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