Ultra-wideband Planar Log-periodic Slot Antenna with Exponential Shapes on Slot Edges

Wei-Chung Weng and Min-Chi Chang

Department of Electrical Engineering, National Chi Nan University, 301, University Rd., Puli, Nantou 54561, Taiwan
wcweng@ncnu.edu.tw, s100323910@mail1.ncnu.edu.tw

Abstract **─** An improved method of using exponential curve shape on edges of log-periodic slots to decrease resonances and further reduce the antenna size is proposed. The proposed method is adopted to design a planar log-periodic slot antenna for ultra-wideband (UWB) applications. Numerical investigation shows that resonant frequencies can be decreased around 12.3% in low frequencies compared with the conventional planar log-periodic slot antenna with regular shape on edges of slots. Measured and simulated reflection coefficients and radiation patterns of the proposed antenna agree well with each other to demonstrate the validity. The measured |S11| shows that the operating frequency range (|S11| below -10 dB) is from 2.9 GHz to 11.36 GHz, covering the UWB spectrum (3.1 – 10.6 GHz). The proposed antenna has good radiation characteristics and antenna gains. The proposed antenna is a good candidate for the UWB applications.

Index Terms **─** Broadband antennas, log-periodic antennas, slot antennas, ultra-wideband antennas.

I. INTRODUCTION

Log-periodic structures have near frequency independent properties and are widely applied for wideband antennas. Metal poles or metal hollow cylinders are mainly used as radiators to design conventional log-periodic antennas [1]–[4] for television receiving/broadcasting and wireless communication in VHF band. Antennas with log-periodic structures are usually designed by formulas to determine the dimensions of radiators [5], [6]. In addition, log-periodic structures can be also designed using Koch fractals [7] or using optimization techniques [8], [9]. These conventional log-periodic antennas are huge and heavy. To overcome the disadvantages, planar log-periodic structures [10]–[16] were applied for wideband antennas. Planar structures have advantages of low cost, low weight, portability, and easy fabrication.

The shape of radiators on conventional UWB antennas is usually regular or uniform. However, irregular shapes and curve shapes are less applied to radiators [9], [17] since they are difficult to design. Irregular shapes provide more flexibility to design the antenna with wideband specifications. In this study, the improved method of using exponential curve shape on edges of log-periodic slots was adopted to design the proposed planar UWB antenna. Numerical investigation in this study demonstrates that resonant frequencies of the proposed antenna with unique exponential shapes on top or bottom edge of slots can be further decreased as compared with those of the conventional planar log-periodic slot antenna [15] when its shapes of slot edges are trapezoidal. This merit of using the proposed exponential shapes on log-periodic slot edges provides a novel design method for designing compact antennas. Comprehensive analyses as well as the mechanism and design procedure of the proposed antenna are given and discussed. Results of the proposed UWB log-periodic slot antenna show that the proposed antenna has good characteristics of impedance bandwidth, radiation pattern, and gain in the UWB band.

II. ANTENNA DESIGN

The proposed antenna's log-periodic slot structure and antenna design procedures are described in this section. Figure 1 (a) shows the geometry of the planar proposed log-periodic slot UWB antenna. The proposed antenna was fabricated on a cheap FR4 substrate with the thickness of 0.8 mm, dielectric constant of 4.4, and loss tangent of 0.02. The enlargement near the center or the apex of the antenna geometry is shown in Fig. 1 (b). The slot structure's center is located at the origin of the coordinates. The log-periodic slot structure is symmetric to the origin of the coordinates. Namely, the portion of the slot structure in the negative *x* region mirrors and reverses that in the positive *x* region.

The proposed slot antenna is fed by a four-segment CPW line, which serves as a wideband impedance transformer to transfer from the antenna input impedance around 105 ohms to the input port characteristic impedance 50 ohms. Each segment of the CPW fed-line has the same gap of g whereas its width and length are different from others. By adjusting the strips' widths

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(W1-W4) and lengths (L1-L4), the wideband impedance match ($|S11| < -20$ dB, 3 GHz $< f <$ 11 GHz) of the four-segment CPW fed-line can be achieved. The CPW fed-line is terminated at the antenna's center. The small spacing between the slot terminals is W4. No balun is used to feed the proposed antenna. Detailed dimensions of the slot antenna are listed in Table 1. All metal patches are printed on the top surface of the substrate. The photo of the antenna prototype is shown in Fig. 1 (c).

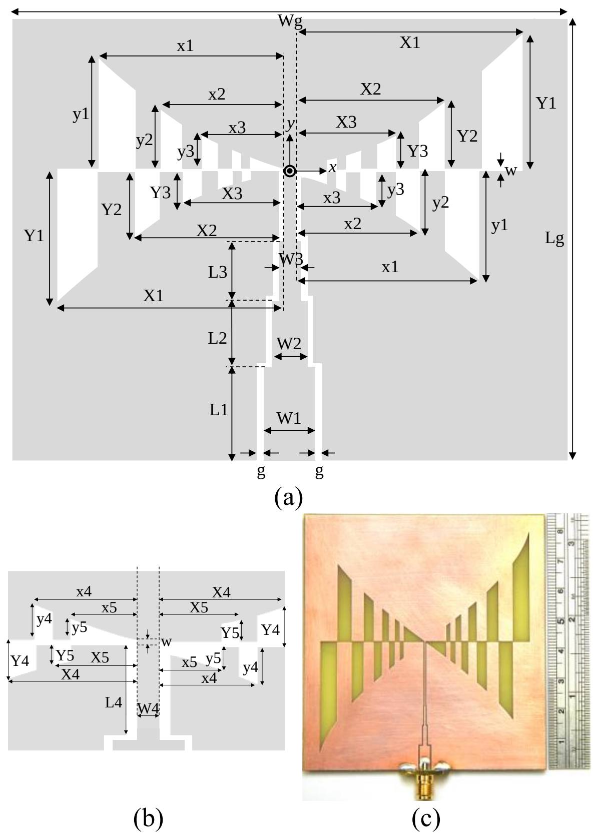


Fig. 1. The proposed log-periodic UWB slot antenna geometry and its prototype picture. (a) Geometry of antenna structure, (b) the enlargement around the center of the antenna, and (c) a photo of the antenna prototype.

The lowest frequency $f_{\min}$ in the working band is determined by the maximum physical dimension of the antenna [15]. The sum of X1 and Y1 is about half guided wavelength, $\lambda_{g,\min}$ when frequency is at $f_{\min}$. That is,

$$\lambda_{g,\min} \cong 2(\mathrm{X1}+\mathrm{Y1}). \tag{1}$$

The dimensions of each slot can be determined using (2) and (3) [5], [6]:

$$\frac{\mathrm{Xn+1}}{\mathrm{Xn}} = \frac{\mathrm{Yn+1}}{\mathrm{Yn}} = \frac{\mathrm{xn+1}}{\mathrm{xn}} = \frac{\mathrm{yn+1}}{\mathrm{yn}} = \tau\ , \tag{2}$$

$$\frac{\mathrm{xn}}{\mathrm{Xn}} = \frac{\mathrm{yn}}{\mathrm{Yn}} = \sqrt{\tau}\ ,\ \ (\mathrm{n} = 1 - N), \tag{3}$$

where n is the n-th slot on a quarter portion of the antenna and τ is the geometric ratio of the slot and its adjacent slot; τ is a value between 0 and 1. The total number of slots used in the antenna is $4N$. Each slot will excite its resonant frequencies. The more slots are, the more resonances. Therefore, wideband characteristics of the proposed slot antenna can be achieved by multi-resonances. If wideband characteristics of the antenna are desired, the N can be set to be larger. However, the drawbacks about large N are that the antenna configuration becomes complicated and a large size of the antenna is required. A compromise will be made for the advantages and disadvantages. τ can determine the distribution of resonant frequencies in the working band. Figure 2 shows different values of τ affecting the geometries and dimensions of slots when Y1 and X1 are fixed and N is 5. As the τ increases, the width of slots decreases and location of slots shifts towards to the outermost slot resulting in small spacing between slots; meanwhile, the slot located closest to the apex becomes larger. Hence, resonant frequencies are more concentrated each other. Nevertheless, if τ is a small value, the slot located closest to the apex becomes too small to implement. Therefore, τ is suggested to set to be the value between 0.6 and 0.9. In the proposed antenna design, τ is set to be 0.7; the X1 and Y1 are set to be 34 mm and 37 mm, respectively. Other parameters such as X2 to X5, Y2 to Y5, x1 to x5, and y1to y5 can be obtained using (2) and (3).

Table 1: Dimensions of the proposed log-periodic UWB slot antenna

Parameter	**Size (mm)**	**Parameter**	**Size (mm)**
X1	34.0	Y1	37.0
X2	23.8	Y2	25.9
X3	16.66	Y3	18.13
X4	11.66	Y4	12.69
X5	8.16	Y5	8.88
x1	28.45	y1	30.96
x2	19.91	y2	21.67
x3	13.94	y3	15.17
x4	9.76	y4	10.62
x5	6.83	y5	7.43
W1	3.3	L1	7.8
W2	1.19	L2	6.5
W3	0.4	L3	6.5
W4	0.2	L4	21.2
Wg	78.0	Lg	84.0
g	0.4	w	0.35

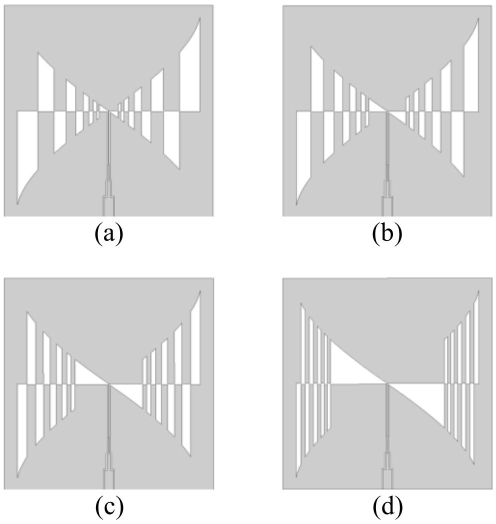


Fig. 2. The geometry variation of the proposed log-periodic slots with different values of τ when Y1 and X1 are fixed and N is 5. (a) $\tau = 0.6$, (b) $\tau = 0.7$, (c) $\tau = 0.8$, and (d) $\tau = 0.9$.

In this study, the edges of log-periodic slots are cut by exponential curves created by using (4) to further decrease resonant frequencies:

$$y = \frac{x}{\mathrm{X1}}\left(\frac{\mathrm{Y1}}{e^{p\mathrm{X1}}}\right)e^{px}, \quad x, y \geq 0. \tag{4}$$

Figure 3 shows the different exponential curves representing different curvatures by p. The curvature of exponential curve changes more when p is larger. A conventional planar log-periodic slot antenna configuration as shown in [15] is the trapezoidal slot teeth log-periodic structures when the edges of slots are linear; that is, when $p = 0$. In this design, p is set to be 0.025 and N is set to be 5.

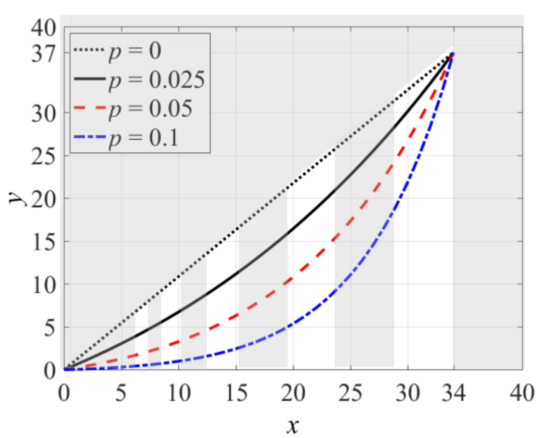


Fig. 3. Slot edges in the positive x and positive y region cut by different exponential curves representing different curvatures by p.

Parametric studies were performed to investigate effects of key parameters on reflection coefficients |S11|. Figure 4 to Fig. 6 reveal the parametric studies of Y1, X1, and w versus the |S11|, where Y1, X1, and w are varied respectively whereas the other parameters are fixed the same values as listed in Table 1. As shown in Fig. 4, a larger value of Y1 will result in lower resonant frequencies as indicated in the dotted blue arrow since it will increase the electrical length. However, a larger value of Y1 will result in larger antenna size. Increasing X1 will result in small effects in resonant frequencies as shown in Fig. 5. Hence, to obtain the lower $f_{\min}$, Y1 larger than X1 is desirable. Another reason for Y1 is larger than X1 is that more spaces can be available for slots in the y-direction since the CPW fed-line is already placed in the y-direction. To design a compact size of the antenna, the spaces in the y-direction can be effectively utilized. Parametric studies also show that the width of the horizontal narrow slot lines (w) does not significantly affect the |S11| of the proposed slot antenna as shown in Fig. 6. Hence, w is selected to be 0.35 mm in this design for easily feeding the smallest slot near the apex of the antenna. Numerical investigations have also shown that the X1, Y1, τ, and N are key parameters of the proposed log-periodic slot antenna to excite required resonances.

To design the proposed planar log-periodic UWB slot antenna, the design procedure is suggested and listed below.

Step 1: Determine the X1 and Y1 by (1).

Step 2: Choose the number of N and the geometric ratio τ, then determine the dimensions of each slot using (2) and (3).

Step 3: Determine the curvature of exponential curve using (4). Additionally, the value of τ can be slightly changed to adjust the resonant frequencies of each slot.

Step 4: Adjust the lengths and widths of the CPW fed-line for wideband impedance matching.

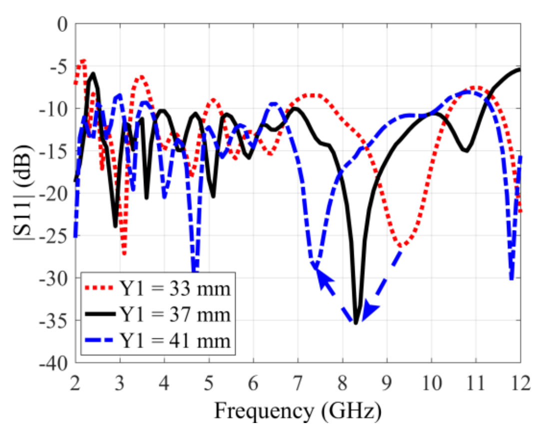


Fig. 4. Simulated |S11| with different dimensions of Y1. Other dimensions shown in Table 1 are fixed.

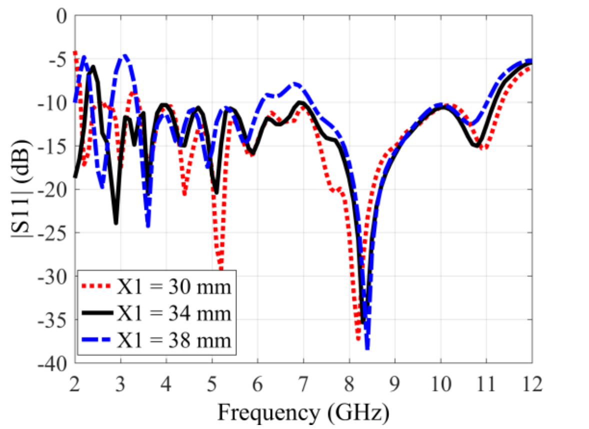


Fig. 5. Simulated |S11| with different dimensions of X1. Other dimensions shown in Table 1 are fixed.

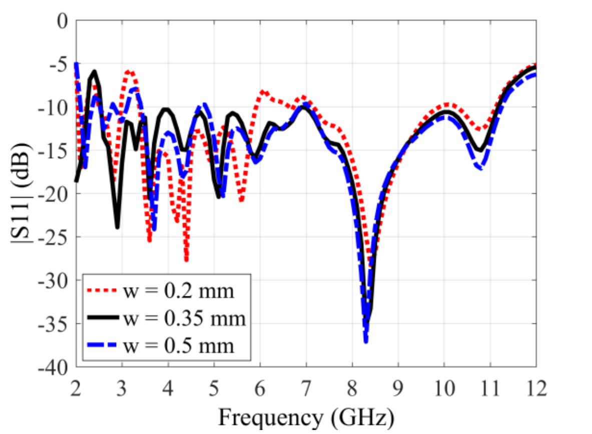


Fig. 6. Simulated |S11| with different dimensions of w. Other dimensions shown in Table 1 are fixed.

III. RESULTS AND DISCUSSIONS

A. Reflection coefficient

Simulated and measured reflection coefficients |S11| of the proposed antenna are obtained by using a full-wave electromagnetic simulator, Ansoft HFSS, and an Agilent N5230A network analyzer, respectively. |S11| results are shown together in Fig. 7 for comparison. Apparently the simulated results reasonably agree well with the measured ones, which validate the antenna design. The measured impedance bandwidth exhibits wideband performance from 2.9 to 11.36 GHz (118.7%) for |S11| < -10 dB, covering the entire UWB frequency band.

B. Log-periodic behavior

Figure 8 reveals the simulated magnitude of antenna input impedance $|Z_{\text{in}}|$ of the proposed antenna, where $Z_{\text{in}} = \text{R}_{\text{in}} + j\,\text{X}_{\text{in}}$; R_{in} and X_{in} are real part and imaginary part of $|Z_{\text{in}}|$, respectively. This plot is made against the logarithm of frequencies. It can be seen that the variation of $|Z_{\text{in}}|$ is near periodic in the working band. The three successive maxima of the impedance occur at 5.2 GHz (*f*1), 7.6 GHz (*f*2), and 10.3 GHz (*f*3). The three frequencies *f*1, *f*2 and *f*3 are related by [5]:

$$\frac{f1}{f2} \cong \frac{f2}{f3} \cong \tau \,. \tag{5}$$

The ratio for *f*1 and *f*2 and the ratio for *f*2 and *f*3 determined by (5) are 0.68 and 0.73, respectively, which is about the geometric ratio of τ (= 0.7) set in this study. This result shows that the proposed slot antenna does have near logarithmically periodic impedance properties; hence, the proposed antenna can be named *log-periodic antenna*.

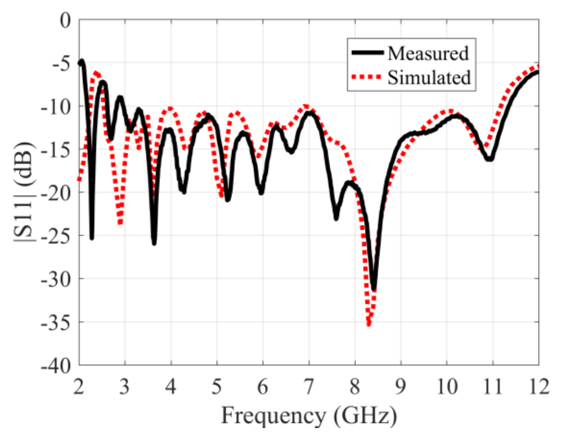


Fig. 7. Reflection coefficients |S11| of the proposed log-periodic UWB slot antenna.

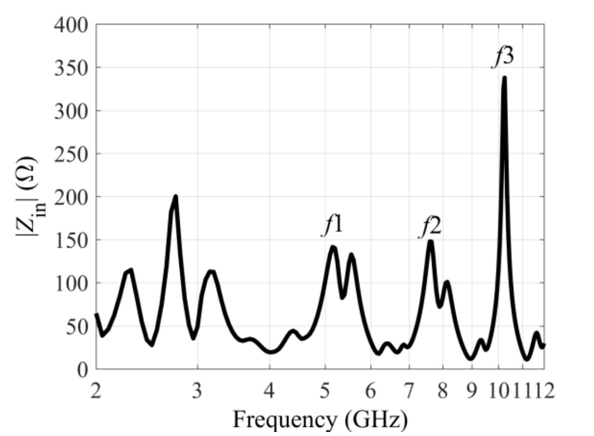


Fig. 8. Simulated magnitude of input impedance $|Z_{\text{in}}|$ of the proposed antenna against the logarithm of frequencies.

C. Benefit of exponential shape

Figure 9 shows the curves of simulated imaginary part (X_{in}) of antenna input impedance with cases of p = 0 and p = 0.025. The lowest resonant frequency $f_{r,\min}$

(at $X_{in} = 0$) of slot antenna without exponential curve cut ($p = 0$ case) on edges of slots is at 2.52 GHz, whereas the $f_{r,\min}$ with exponential curve cut on edges of slots ($p = 0.025$ case) decreases to 2.21 GHz. The $f_{r,\min}$ decreases 0.31 GHz (12.3%) as indicated by the dotted blue arrow. This frequency decrement demonstrates the fact that the required antenna size for the proposed antenna with exponential curve cut on edges of slots can be reduced 12.3% if the two antennas have the same $f_{r,\min}$. By the same token, the next resonant frequency also decreases from 2.95 GHz to 2.65 GHz (10.2%) as indicated by the dotted green arrow as also shown in Fig. 9. Hence, the obvious advantage of the exponential curve cut on edges of slots arises from the facts that resonant frequencies can be decreased. Meanwhile, more compact antenna size can be realized compared with the slot antenna with regular shapes on edges.

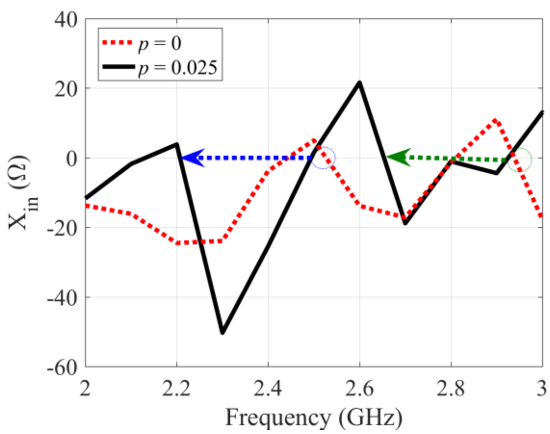


Fig. 9. The curves of simulated imaginary part (X_{in}) of antenna input impedance with cases of $p = 0$ and $p = 0.025$ near the lowest resonant frequency $f_{r,\min}$.

D. Surface current

Figure 10 (a) to Fig. 10 (d) reveal surface currents of the proposed antenna at 3.1, 5.5, 8.3, and 10.6 GHz, respectively. The region with more surface currents encompassing slots can be considered as radiating regions in which slots operate about half wavelength. The strong surface currents encompass the edges of both large and small slots in lower frequencies whereas surface currents encompass the edges of small slots onlyin higher frequencies. This phenomenon shows that large slots operate at both low and high frequencies while small slots operate only at high frequencies. Hence, ultra-wideband characteristics can be achieved by the proposed log-periodic slot structure. Although tiny slots can be used to extend the operating frequency to be higher, the highest frequency f_{max} in the working band is limited by the dimensions of the smallest slot near the apex of the antenna since it is required fine fabrication of the antenna structure. Moreover, a tiny slot is difficult to fit the CPW fed-line at the apex.

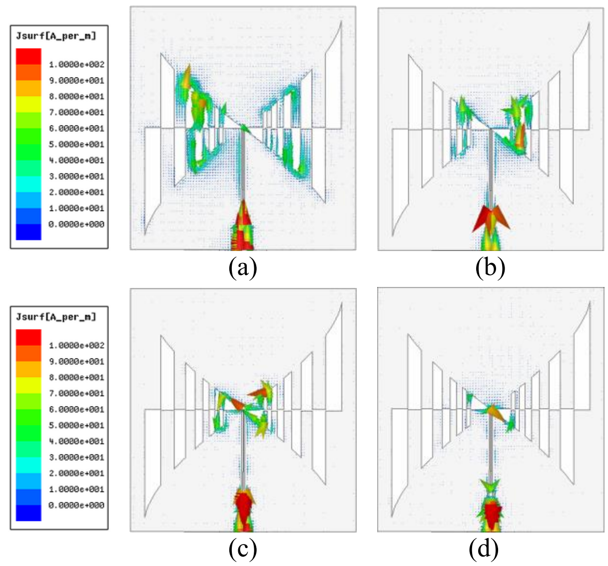
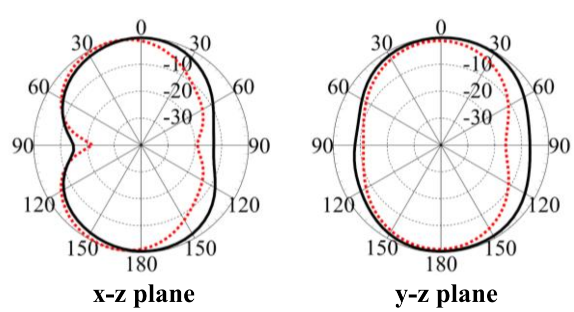


Fig. 10. Simulated surface currents of proposed antenna at: (a) 3.1 GHz, (b) 5.5 GHz, (c) 8.3 GHz, and (d) 10.6 GHz.

E. Radiation pattern

Radiation patterns were measured by using an MVG Satimo antenna measurement system. Figure 11 gives the normalized radiation gain patterns of the proposed log-periodic slot in two principal planes at 3.1, 5.5, 8.3, and 10.6 GHz. Good agreements between simulated and measured patterns are observed as well, which demonstrates the validity of the design. The antenna radiation gain patterns are bidirectional in the broadside direction. In addition, the proposed antenna maintains approximately constant radiation patterns in both principal planes from low to high frequencies, which reveals the characteristics of self-scaling at discrete log-periodically related frequencies [18] by using the proposed log-periodic slot structure. The measured antenna peak gains are 1.43, 4.49, 3.92, and 4.67 dBi at 3.1, 5.5, 8.3, and 10.6 GHz, respectively. The proposed antenna has satisfactory antenna gain and flat antenna efficiency around 78% in the UWB band.



(a)

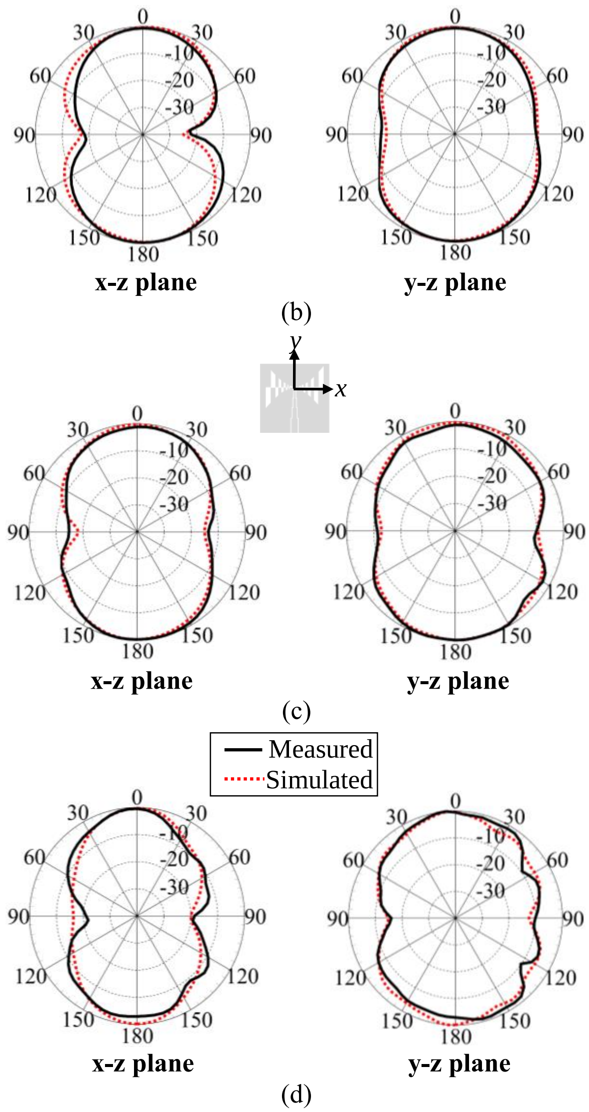


Fig. 11. Normalized radiation gain patterns of the proposed antenna in the x-z plane and y-z plane at: (a) 3.1 GHz, (b) 5.5 GHz, (c) 8.3 GHz, and (d) 10.6 GHz.

VI. CONCLUSION

This study presents a novel UWB log-periodic planar slot antenna design using exponential curves cut on edges of slots. The proposed antenna has a compact substrate size of 78 mm by 84 mm. Results have been verified by simulations and measurements. Mechanism and design procedures of the proposed antenna have been described. Numerical investigations have shown that the lowest resonant frequency can be decreased around 12.3% using the proposed exponential curve cut on edges of slots compared with the conventional planar log-periodic slot antenna with regular shapes on edges. This benefit provides a useful method to design an antenna with more compact size under the same lowest frequency $f_{\min}$ in the working band. Good properties of wideband impedance matching, radiation pattern, and antenna gain have been achieved in the band of interest. The proposed log-periodic slot antenna is promising for UWB applications.

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Wei-Chung Weng received the B.S. degree in Electronic Engineering from National Changhua University of Education, Changhua, Taiwan, in 1993, the M.S. degree in Electrical Engineering from I-Shou University, Kaohsiung, Taiwan, in 2001, and the Ph.D. degree in Electrical Engineering from The University of Mississippi, MS, USA, in 2007.

In 2008, he joined the Department of Electrical Engineering, National Chi Nan University, Puli, Taiwan, where he is currently an Associate Professor. From 2017 to 2018, he was a Visiting Scholar at the Department of Electrical Engineering, Colorado School of Mines, Golden, CO, USA. From 2004 to 2007, he was a Graduate Research Assistant in the Department of Electrical Engineering, The University of Mississippi. He has authored or coauthored over 50 journal articles and conference papers and a book entitled *Electromagnetics and Antenna Optimization Using Taguchi's Method* (Morgan & Claypool, 2007). His research interests include antennas and microwave circuits design, computational electromagnetics, electromagnetic compatibility, and optimization techniques in electromagnetics.

Weng is the Associate Editor-in-Chief for *Applied Computational Electromagnetics Society (ACES) Journal*. He has served many journals as a reviewer for years. He is a Member of ACES, a Senior Member of IEEE, and a Life Member of the Institute of Antenna Engineers of Taiwan (IAET). He was the recipient of Outstanding Teaching Award of National Chi Nan University in 2013 and 2016, respectively.

Min-Chi Chang was born in Yunlin, Taiwan. He received the B.S. degree in Electrical Engineering from National United University, Miaoli, Taiwan, in 2009. He is currently working toward the Ph.D. degree in the Department of Electrical Engineering, National Chi Nan University, Puli, Taiwan. His research interests focus on antenna design, computational electromagnetics, and optimization techniques in electromagnetics.