

## DESIGN AND ANALYSIS OF A NOVEL CPW-FED KOCH FRACTAL YAGI-UDA ANTENNA WITH SMALL ELECTRIC LENGTH

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**Abstract**—A novel Koch fractal printed Yagi-Uda antenna fed by coplanar waveguide (CPW) is proposed and analyzed. The antenna has first-order Koch fractal monopoles, and the monopoles' ground plane acts as the ground plane of the antenna. The radiation characteristics of the antenna are simulated by CST Microwave Studio<sup>®</sup> and explained by the simulated results. The antenna's currents distribution becomes more uniform after being fractal, which is conducive to increasing antenna's radiation directivity. The proposed Koch fractal Yagi-Uda antenna has an operating band of 885–913 MHz (relative bandwidth 3.1%) with the center frequency of 900 MHz. The total antenna size is 171 mm × 85 mm ( $0.51\lambda \times 0.25\lambda$ ) and the length in the antenna's polarization direction is only 25% of the wavelength corresponding to the center frequency. Compared to traditional Yagi-Uda antenna, the proposed antenna can achieve a 50% miniaturization effect.

### 1. INTRODUCTION

Yagi-Uda antenna is a kind of directional antenna with simple structure. It has been widely used since Hidetsugu Yagi proposed it in 1928. However, with the rapid development of communications technology, the antenna's characteristics of being difficult to integrate with communication circuits and narrow bandwidth have limited its application scope. To solve the problem, researchers have put forward a series of printed Yagi-Uda antennas, which can be easier to integrate with communication circuits. Those antennas include: (1) the Quasi-Yagi antenna with balanced feeding structure [1] and its arrays [2, 3] proposed by Qian, which usually have double-sided printed structure,

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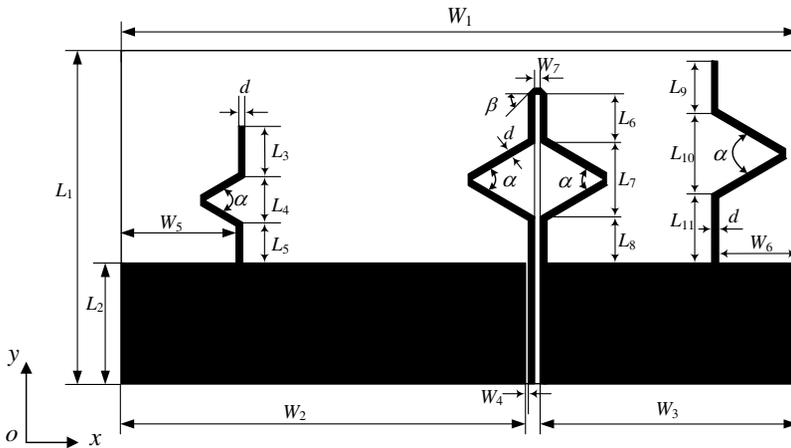
broad bandwidth but large feeding size. (2) Yagi-Uda antennas fed by balanced microstrip line [4, 5], which usually have broad bandwidth (relative bandwidth more than 30%) but comparatively bigger size in the polarization direction (usually more than 40% of the center wavelength). (3) Yagi-Uda antenna with special-shaped reflector [6], which has a ground plane with parabolic boundary, a relatively high gain but a narrow bandwidth. The common characteristic of the antennas above is that their active dipoles are symmetrically structured, their feeding size is large and thus their size in the polarization direction is comparatively bulky.

This paper proposed a novel Koch fractal monopole Yagi-Uda antenna fed by coplanar waveguide (CPW). The antenna has first-order Koch fractal monopoles and the monopoles' ground plane acts as the ground plane of the antenna, which can help lower the resonant frequency when the size in the polarization direction stays the same. The proposed antenna achieves a good miniaturization effect and a gain of 4.0 dBi in its operating band. The antenna size in the polarization direction is only 25% of the center wavelength. The detailed simulated and measured results are included in this paper.

## 2. ANTENNA STRUCTURE

Figure 1 provides the sketch of the proposed antenna with associated geometrical parameters. The antenna is printed on one-side of a FR-4 epoxy resin board with relative permittivity  $\epsilon_r = 4.4$ , which is easy to be manufactured and has a promising future application. The resin board's length is 171 mm, width 85 mm and thickness 2 mm. What should be noted is that in Fig. 1, the monopoles' electric length refers to the length along the  $+y$  direction, but the length of the resin board is the length along the  $+x$  direction and the width of the resin board is the length along the  $+y$  direction. The black area in Fig. 1 represents the metal parts of the antenna, the antenna's feeding part is at the bottom and it is CPW-fed structured. It should be noted in Fig. 1 that near the CPW transmission line, the left slit width  $W_4$  is not equal to the right slit width  $W_7$ , different from what traditional CPW-fed antennas did. The upper part of the antenna, from left to right, contains a director, a folded active monopole and a reflector.

The Koch fractal curve [7] is obtained by equally dividing a line segment into three parts and replacing the middle part with an isosceles triangle, whose bottom side lies where the middle part ever was. A common case is that the isosceles triangle is an equilateral triangle, which forms the first-order Koch fractal and is applied in this paper. By dividing the three divided parts as the same steps above, higher-



**Figure 1.** Sketch of the first-order Koch fractal CPW-fed Yagi-Uda antenna with associated geometrical parameters ( $\alpha = 60^\circ$ ,  $\beta = 45^\circ$ ,  $W_1 = 171$  mm,  $W_2 = 105$  mm,  $W_3 = 63$  mm,  $W_4 = 0.3$  mm,  $W_5 = 35$  mm,  $W_6 = 15$  mm,  $W_7 = 1.1$  mm,  $L_1 = 85$  mm,  $L_2 = 30$  mm,  $L_3 = 11.7$  mm,  $L_4 = 11.7$  mm,  $L_5 = 10.7$  mm,  $L_6 = 14.7$  mm,  $L_7 = 14.7$  mm,  $L_8 = 13.7$  mm,  $L_9 = 17.9$  mm,  $L_{10} = 17.9$  mm,  $L_{11} = 16.9$  mm,  $d = 2$  mm).

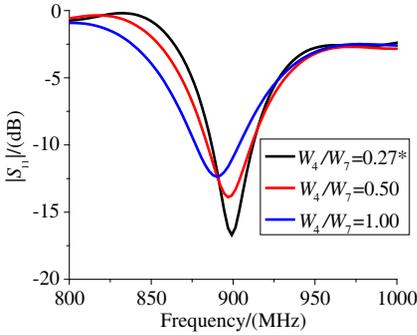
order Koch fractal curve can be obtained. The curve theoretically can achieve an infinite length while the area surrounded by the curve stays the same. Therefore, this practice has recently been widely applied to achieve antenna miniaturization [8–10].

### 3. SIMULATIONS AND ANALYSIS

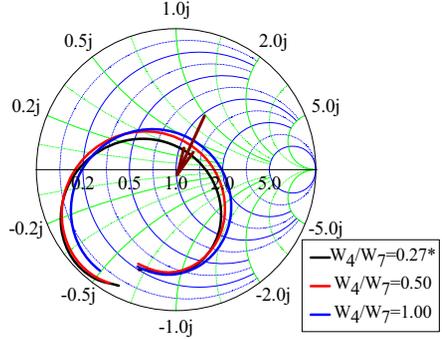
#### 3.1. Antenna Impedance

Simulated results of the antenna’s reflection coefficient are shown in Fig. 2. The antenna has a resonant frequency from 800 MHz to 1000 MHz. The impedance bandwidth with the reflection coefficient less than  $-10$  dB is 885–913 MHz (relative bandwidth 3.1%). This value is equivalent to that from a common Yagi-Uda antenna [11]. Fig. 2 also provides the simulated results of  $|S_{11}|$  with varying values of  $W_4/W_7$  as a variable.

As the value of  $W_4/W_7$  decreases, the depth of the reflection coefficient increases at resonant frequency but the bandwidth changes little. Due to limits in actual production,  $W_4$  cannot be made too small; as a result, this paper adopts that  $W_4/W_7 = 0.3$  mm/1.1 mm =



**Figure 2.** Simulated results of reflection coefficient (in dB) with varying values of  $W_4/W_7$  ( $W_4/W_7 = 0.27, 0.50, 1.00$ ). \* $W_4/W_7 = 0.27$  is applied in Fig. 1.

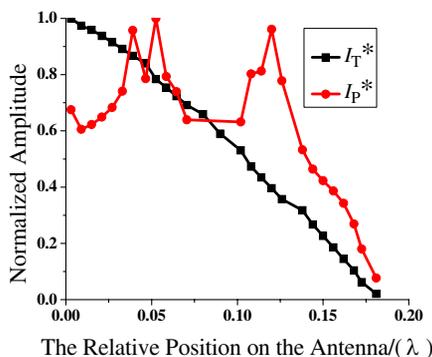


**Figure 3.** Simulated results of smith charts with varying Values of  $W_4/W_7$  ( $W_4/W_7 = 0.27, 0.50, 1.00$ ). \* $W_4/W_7 = 0.27$  is applied in Fig. 1.

0.27. The characteristic presented in Fig. 2 comes from the fact that an asymmetric transmission line structure is equivalent to loading a reactance with distribution parameters, which helps regulate the antenna's input impedance. This is proved by the simulated results of the antenna's Smith charts with varying values of  $W_4/W_7$  in Fig. 3. Different values of  $W_4/W_7$  mean different reactance. In Fig. 3, after equivalently loading different reactance corresponding to Fig. 2, the impedance curve moves towards the matching point on the axis.

### 3.2. Surface Currents Distribution and Radiation Characteristics

After simulating and extracting the surface currents' amplitudes and phases on antenna's metal elements by CST Microwave Studio<sup>®</sup>, normalized current amplitude distribution on the folded active monopole at 900 MHz is depicted in Fig. 4. In Fig. 4, the value on  $x$ -axis is the coordination of the point position on the antenna starting from the monopole's bottom to the  $+y$  direction in Fig. 1 and in wavelengths  $\lambda$  at 900 MHz. The length of the folded active monopole's left side is 45 mm, equivalent to  $0.135\lambda$ , where  $\lambda$  is the wavelength at 900 MHz. Fig. 4 also provides the comparison of normalized current amplitude distribution between the current on the proposed antenna's folded active monopole and the sinusoidal current from traditional transmission line theory. The comparison results



\* $I_T$  is the sinusoidal current from traditional transmission line theory.

\* $I_P$  is the current on the proposed antenna’s folded active monopole.

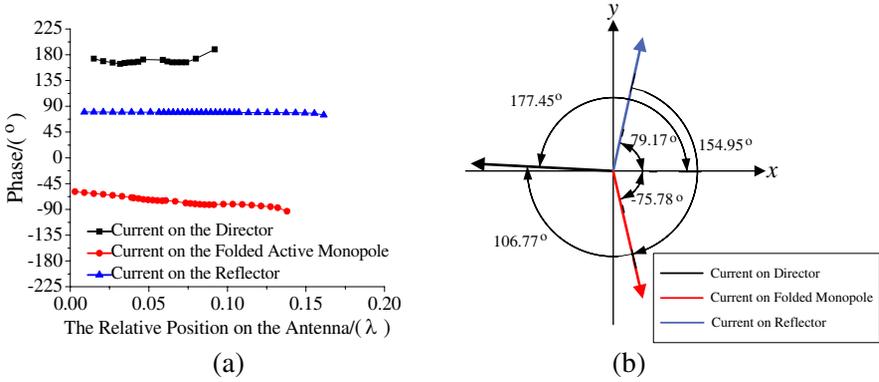
**Figure 4.** Comparison of normalized current amplitude distribution between the current on the left side of the proposed antenna’s folded active monopole and the sinusoidal current from traditional transmission line theory.

indicate that, compared to the sinusoidal current from traditional transmission line theory, the current on the proposed antenna’s folded active monopole is more uniform: under this paper’s circumstances, the average normalized current amplitude of the traditional transmission line theory’s sinusoidal current is 0.557 calculated by formula (1), however, the average normalized current amplitude from the proposed antenna’s folded active monopole is 0.617, 10.8% higher than the former one. This good characteristic is largely due to the use of Koch fractal curves in designing the antenna, which helps increase the mutual coupling of the metal conductors and thus make the current distribution on them more uniform. A more uniform current distribution on all the metal parts will lead to an increase of the radiation directivity as an element and a more uniform current distribution of the reflector, the director and folded active monopole will thus result in an increase in antenna directivity.

$$I_{av} = \frac{1}{L} \int_0^L I(x) dx \tag{1}$$

where  $I_{av}$  — the average value of the normalized current amplitude,  $L$  — the electric length of the normalized current distribution,  $I(x)$  — the normalized current space distribution function (one-dimensional).

Figure 5 presents the phase distribution of the currents on the director, folded active monopole and reflector of the proposed antenna at 900 MHz. It can be obtained from Fig. 5(a) that the phase of each

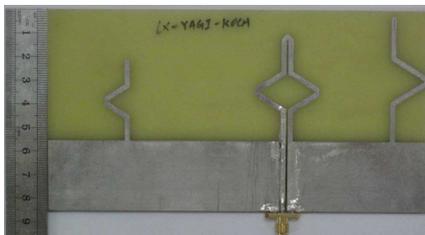


**Figure 5.** Phase distribution of the surface currents on the three radiated parts at 900 MHz. (a) Phase distribution of the surface currents at 900 MHz. (b) Sketch of the phases distribution.

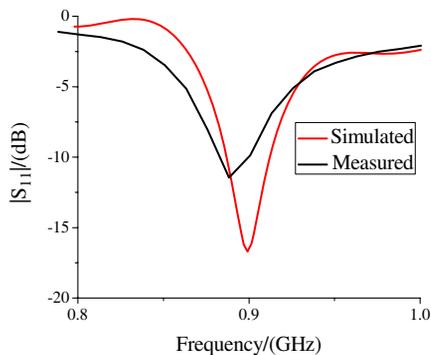
part stays the same, indicating that the currents on the three parts are standing-wave currents. Additionally, in Fig. 5(b) the phase of the current on the reflector advances that of the folded active monopole and the phase of the folded active monopole advances that of the director, which helps make the proposed antenna a directional antenna. This mechanism is similar to traditional theory of Yagi-Uda antenna.

#### 4. MEASURED RESULTS

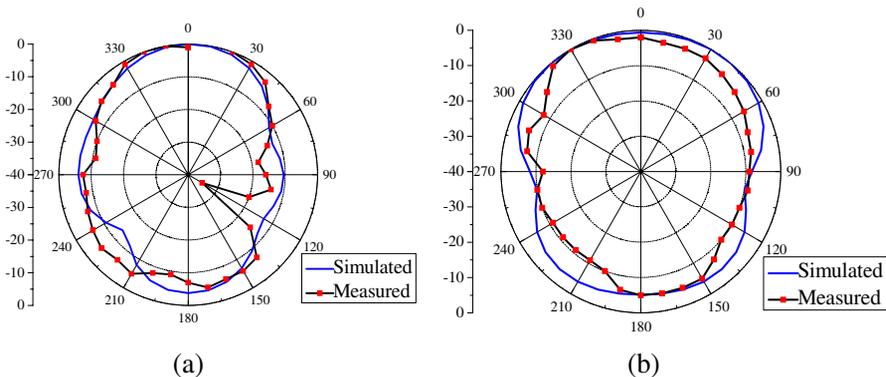
According to the associated geometrical parameters of the proposed antenna, an antenna prototype (Fig. 6) has been manufactured and measured in an anechoic chamber, using the Agilent E8363B Vector Network Analyzer. The experimental results include reflection coefficient, radiation patterns and antenna gain, which are all shown in Fig. 7 and Fig. 8. Measured results indicate that the impedance bandwidth of the proposed antenna is 885.4 MHz–913 MHz with reflection coefficient less than  $-10$  dB (relative bandwidth 3.1%). The measured result of  $|S_{11}|$  well matches the simulated one with only small deviance in the depth at the resonant center frequency (900 MHz). The measured antenna gain at 900 MHz is 4.0 dB, which has little difference compared to the simulated antenna gain of 4.1 dB. The measured results of radiation patterns and simulated ones are pretty much the same within the scope of main lobe but differ a little in side lobes. For printed antennas, the difference between simulated results and experimental results are mainly caused by: (1) the antenna welding



**Figure 6.** Koch fractal antenna prototype.



**Figure 7.** Simulated and measured results of reflection coefficient.

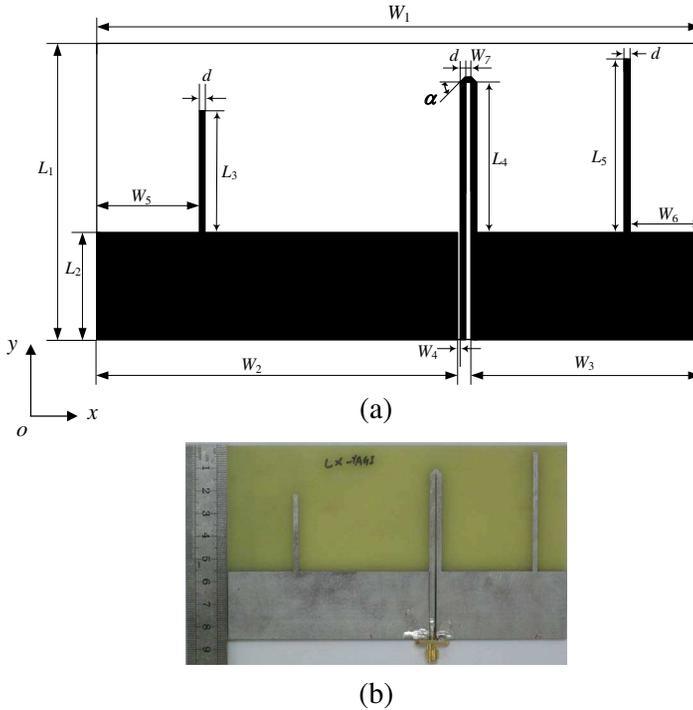


**Figure 8.** Simulated and measured results of radiation patterns. (a) *E*-plane at 900 MHz. (b) *H*-plane at 900 MHz.

and holding fixtures used in measuring antenna radiation patterns can influence the measured results of side lobes of antenna radiation patterns. (2) The FR-4 material's consumption and instability can influence the measured results of antenna radiation patterns and reflection coefficient.

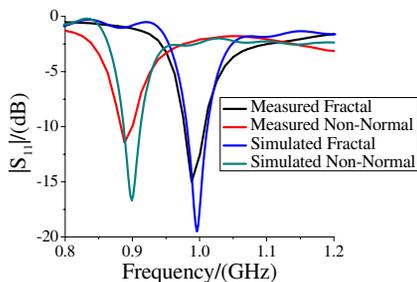
### 5. CHARACTERISTICS OF THE PROPOSED ANTENNA

The proposed antenna applies the Koch fractal monopoles and thus achieves a high gain and small size. This conclusion can be obtained from the comparison between the proposed antenna and the ordinary

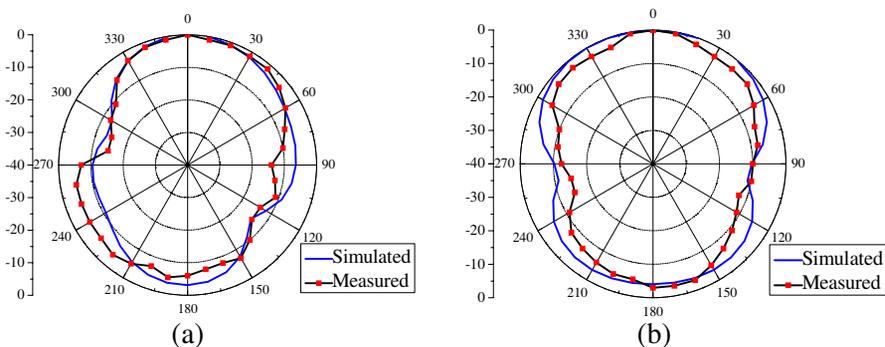


**Figure 9.** Non-fractal CPW-fed Yagi-Uda antenna. (a) Sketch of the ordinary non-fractal Yagi-Uda antenna with associated geometrical parameters ( $\alpha = 45^\circ$ ,  $W_1 = 157$  mm,  $W_2 = 93$  mm,  $W_3 = 60$  mm,  $W_4 = 0.3$  mm,  $W_5 = 30.5$  mm,  $W_6 = 14$  mm,  $W_7 = 1.1$  mm,  $L_1 = 86$  mm,  $L_2 = 30$  mm,  $L_3 = 34$  mm,  $L_4 = 43$  mm,  $L_5 = 53$  mm,  $d = 2$  mm). (b) Non-fractal antenna prototype.

non-fractal Yagi-Uda antenna. Fig. 9 provides the sketch of the designed ordinary non-fractal Yagi-Uda antenna and its prototype. Fig. 10 and Fig. 11 supply the simulated and measured results of the non-fractal antenna. The relationship between the Koch fractal antenna and non-fractal one is: (1) They have identical feeding structure. (2) They have identical size of CPW ground plane and identical position of reflector, folded monopole and director. (3) The non-fractal antenna has been folded following the law of Koch fractal curve to obtain the Koch fractal antenna. (4) The total height and position distribution on the resin board of the reflector, folded monopole and director stay the same after they are made Koch fractal. The designed non-fractal antenna has the same antenna size with the



**Figure 10.** Nonfractal and fractal antennas’ simulated and measured results of the reflection coefficient.



**Figure 11.** Non-fractal antenna’s measured and simulated results of radiation patterns. (a) *E*-plane at 1000 MHz. (b) *H*-plane at 1000 MHz.

proposed antenna but has a center operating frequency at 1000 MHz. Compared to the designed non-fractal antenna; the proposed antenna has a lower center operating frequency at 900 MHz, which means its electric length is 10% lower than that of the non-fractal one. Other radiation characteristics of the non-fractal antenna, such as the impedance bandwidth in Fig. 10, the radiation patterns in Fig. 11 and the antenna gain, have little difference from the proposed fractal antenna.

It should be noted that this paper focuses on designing a novel miniature Yagi-Uda antenna by using Koch-fractal structure, ground plane structure and CPW-fed structure. The simulated results of the antenna indicate that the relative bandwidth of the Koch fractal antenna and non-fractal one is identical and both narrow. Their gain also differs little. Formula (1) and simulated results are applied to calculate the current distribution on the proposed antenna to well

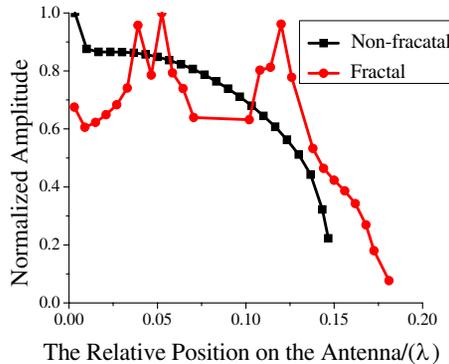
explain this. The calculated distribution indicates that the current distribution on the fractal antenna is more uniform, which means an extra gain can be achieved to offset the polarization loss due to current distortion caused by Koch-fractal structure. This is the reason why the fractal antenna and non-fractal antenna achieve a similar gain and a similar relative bandwidth.

Table 1 lists the comparison of radiation characteristics between the proposed antenna and ones in other papers, which indicates that the polarization directional electric size of the proposed antenna is the smallest among all the antennas in Table 1, only 25% of the wavelength corresponding to the center frequency. The large decrease in polarization directional electric length of the antenna greatly results from the application of Koch fractal monopoles and the CPW-fed structure. Fig. 12 depicts the comparison of current amplitude

**Table 1.** Comparison between the proposed antenna and other antennas.

Antenna	Antenna Size	Center Operating Frequency	Polarization Directional length in Center Wavelength	Gain at Center Frequency	Operating Band	Relative Bandwidth
The Proposed Antenna	171.1 mm × 85.68 mm (0.51λ × 0.25λ)	0.9 GHz	0.25λ	4.0 dB	885–913 MHz	3.1%
The Antenna in [12]	86.13 mm × 58 mm (0.70λ × 0.46λ)	2.4 GHz	0.46λ	4.5 dB	2.305–2.495 GHz	7.9%
The Antenna in [13]	> 15.055 mm × 5.6 mm (1.20λ × 0.45λ*)	24 GHz	0.45λ	22 dB	23.695–24.305GHz	2.5%
The Antenna in [14]	> 190 mm × 227 mm (0.42λ × 0.50λ*)	0.66 GHz	0.50λ	5 dB	640–675 MHz	5.3%

\*Notice: this value is an approximate estimated value from the paper.



**Figure 12.** Current distribution of fractal and non-fractal antenna's folded active monopole.

distribution between on the non-fractal folded active monopole and fractal folded active monopole. It can be obtained from Fig. 12 that the current amplitude distribution on the non-fractal folded active monopole is similar with the sinusoidal current from traditional transmission line theory. The current length of the current on the non-fractal folded active monopole is  $0.15\lambda$  and its average normalized amplitude calculated by (1) is 0.722, where  $\lambda$  is the wavelength at 1000 MHz. Compared to that, the current length of the current on the fractal folded active monopole is  $0.19\lambda$  and its average normalized amplitude calculated by (1) is 0.617, where  $\lambda$  is the wavelength at 900 MHz. The products of the current length and the average normalized current amplitude of the non-fractal and fractal folded active monopole is approximately a constant; therefore, the effective height of the two ones is nearly the same. This can explain that the non-fractal antenna and the fractal antenna can have the same gain under the circumstance that the fractal antenna's electric length in its polarization direction is 10% less than that of the non-fractal one.

## 6. CONCLUSION

A novel CPW-fed Koch fractal Yagi-Uda antenna with small electric length is proposed. The antenna is fed by asymmetric CPW and obtains improvements in antenna's matching characteristics. First-order Koch fractal monopoles are applied to obtain a more uniform current distribution on the director, folded active monopole and reflector, which helps increase the antenna's radiation directivity. Compared to non-fractal antenna with the same antenna size, the

Koch-fractal antenna can achieve a 10% miniaturization effect. The polarization directional length of the proposed antenna is only 25% of the center wavelength, which means the proposed antenna achieves a smart miniaturization effect.

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