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DESIGN AND ANALYSIS OF A CIRCULAR POLARIZATION MICROSTRIP ANTENNA WITH KOCH FRACTAL EDGES

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Abstract—A circular polarization microstrip antenna with a single feeding point is designed in this paper. The microstrip patch has a structure of Koch fractal edges, and the circular polarization is realized by inspiring two degenerate modes that are orthogonal to each other. The software CST MWS® is used to simulate the designed antenna. The simulation results indicate that circular polarization radiation could be achieved though feeding at one of the diagonal lines of the patch by a probe. Antennas considering substrate medium loss are also simulated, and the results are approximate to those with ideal substrates. According to the simulated results of the surface currents at the edges of the patch, an equivalent line current radiation model is proposed to describe the radiation characteristics of the designed antenna. A circular polarization microstrip antenna is fabricated and tested. The simulated, calculated, and the measured results agree well. The designed antenna operates at 1.575 GHz, with an impedance bandwidth of 3% for VSWR <2, the gain of the antenna is 2.6 dB, and the axial ratio in the maximum radiation direction is 2.7 dB.

1. INTRODUCTION

Microstrip antennas are widely used in satellite communications, satellite positioning systems and other fields since they have the advantages of small size, light, low profile, and easy to be integrated and manufactured. While Circular polarization microstrip antennas are used more widely in mobile communication and GPS systems, because they can restrain the interference of rain and fog and resist the multipath reflections [1].

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The condition of realizing circular polarization on a microstrip antenna is by inspiring two linear polarization waves that are orthogonal in polarization directions and have the same amplitude and 90° phase difference. At present, there are three main methods of realizing circular polarization on a microstrip antenna, single feed [2], multi feed [3] and wide slot coupling [4]. The single feed method which based on the cavity model theory generates two orthogonally polarized degenerate modes by the subdivisions. Multi feed method realizes circular polarization by the feeding network composed of multi feeding points. The wide slot coupling can realize the radiation of orthogonal circular polarization in wide bandwidth by loading in the wide slot. However, the radiation is bi-directional.

One way to achieve circular polarization with the single feed method is to use a fractal patch. In this paper, a circular polarization microstrip antenna, which can be used in GPS system, is researched. Characteristics of the antenna are researched by simulating on CST MWS® and doing experiments. Through adjusting the structure parameters of the antenna, we obtain the designed circular polarization antenna that operates at 1.575 GHz. Besides, an equivalent line current radiation model, which is based on the simulated results of the surface currents at the edges of the patch, is proposed to describe the radiation characteristics of the designed antenna. According to this model, the radiation patterns of the antenna are calculated and compared with both the simulated and experimental results. Since they are in good agreement, the proposed model is proved correct.

2. DESIGN OF THE ANTENNA

The structure of the microstrip antenna with Koch fractal edges [5] and the generation process of the patch are shown in Fig. 1. Taking the place of 1/3 part of a line in the center by two segments, successively, the Koch fractal curve forms. Choosing this type of curve as the edges of the patch, we obtain the structure of the antenna. Supposing that the outer edge lengths of the patch are $L = W = l$, and $\theta_x = \theta_y = \theta$, after n times iterations, the edge length of the patch l_n can be described as Equation (1),

$$l_n = \left(\frac{2\cos\theta + 1}{3\cos\theta}\right)^n l \tag{1}$$

In this paper, the once fractal patch is chosen, printed on a 3 mm thick FR4 substrate with a relative permittivity $\varepsilon_r = 4.4$. The ground plane is printed in the opposite side of the substrate and the antenna is fed through a coaxial cable with a characteristic impedance of 50 Ω.

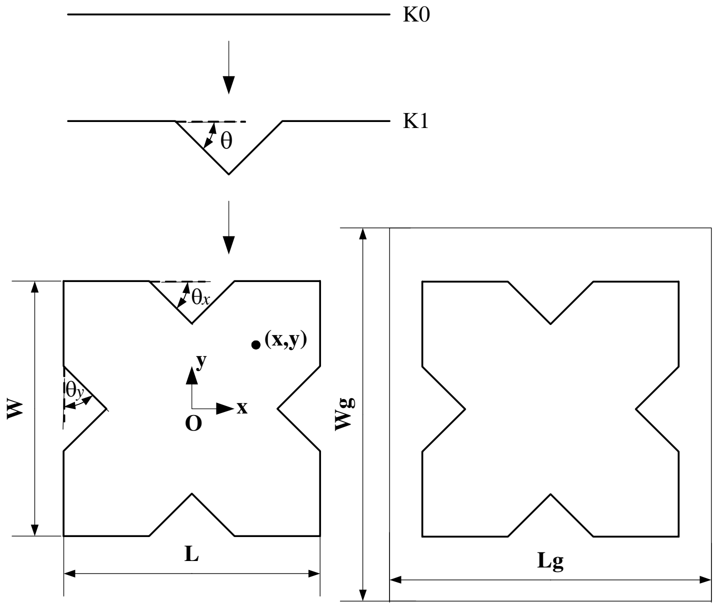

Figure 1. Structure of the koch fractal patch.

Through simulating the antenna on CST MWS®, the following conclusions are drawn,

1) As for a once fractal patch, the guide wavelength corresponding to the center frequency is proportional to the patch size. The structure of Koch fractal patch only depends on two parameters, l and θ. The relationship between the guide wavelength and the edge length of the patch is given in Equation (2),

$$\frac{L}{\lambda_g} = 0.45 - 0.47 \tag{2}$$

where L is the length of the patch and λ_g the guide wavelength corresponding to the center frequency. When θ is big (around 45°), 0.45 should be chosen in Equation (2), while 0.47 when θ is small (around 35°).

2) Two degenerate modes TM_{01} and TM_{10}, which are orthogonal to each other, are formed due to feeding the antenna at an accurate point on the diagonal line of the patch. To achieve circular polarization, these two modes must share the same amplitude while have a phase difference of 90°. The polarization type can be confirmed by Smith chart simulated result. The inflection point on the impedance curve indicates that two degenerate modes are formed, as shown in Fig. 2.

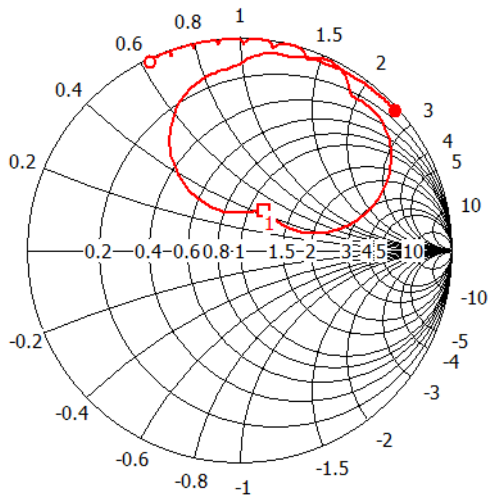

Figure 2. Simulated result of the input impedance (marker 1 is at a sharp point near the matching area. Two degenerate modes TM_{01} and TM_{10} are generated at this sharp point).

The circular polarization frequency bandwidth is usually not that wide.

3) The antenna shown in Fig. 1 is right-handed circularly polarized, and if the feeding point is moved to the symmetrical positions in the NW-quadrant or the SE-quadrant, the antenna turns to be left-handed circularly polarized.

3. SIMULATED RESULTS

According to the research above and the requirements of the GPS system, an antenna that matches the following indicators is designed,

1) Operating frequency band: 1.565–1.585 GHz;
2) Right-handed circular polarization with the axial ratio below 6 dB;
3) Gain: above 2 dB.

The final structure parameters of the antenna are as follows.

The edge length of the patch is $L = W = 42.6\,\text{mm}$, $\theta_x = 23°$, $\theta_y = 35°$, the edge length of the FR4 substrate is $L_g = W_g = 70\,\text{mm}$, the thickness of the substrate $h = 3\,\text{mm}$, the relative permittivity $\varepsilon_r = 4.4$, and the loss tangent 0 & 0.02. The antenna is fed through a coaxial cable, and the feeding position is $x = y = 5.0\,\text{mm}$. The simulated results are shown in Fig. 3, where $\tan\delta = 0$ means that the substrate is ideal and of zero loss.

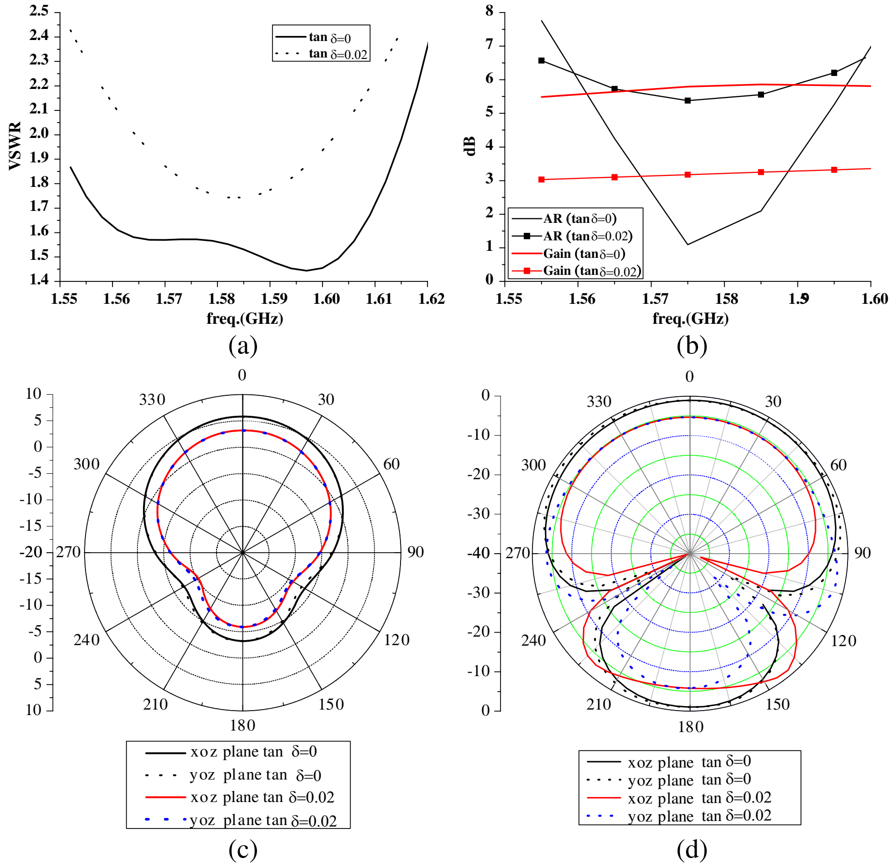

Figure 3. The simulated results of the designed antenna. (a) VSWR. (b) Gain and axial ratio. (c) Radiation pattern at 1.575 GHz. (d) Axial ratio pattern at 1.575 GHz.

If $\tan\delta = 0$, the impedance bandwidth of the antenna is 66 MHz (4%) for VSWR < 2 from 1550 MHz to 1616 MHz. The gain is 5.8 dB, and the axial ratio is 1.1 dB at 1575 MHz. When tangent delta increases, the loss brings field quantities changes, and phase lags, which may lead to a degradation of the circular polarization characteristic. Since the FR4 epoxy substrate is lossy and somewhat inhomogeneous, a lossy dielectric setting is taken in simulation, and the simulated results show that the degradation of the AR is acceptable. The measured results are between the simulated results of lossy and free lossy. If $\tan\delta = 0.02$, the frequency band tends to move to higher frequency segment. Moreover, the gain and axial ratio deteriorate. However, the antenna still meets the design requirements. The stability of axial ratio versus angular at 1575 MHz is good. Within the range of ±60° of the direction of maximum radiation, the axial ratio keeps stable. Besides, the axial ratios, which are rotationally symmetrical, are generally equivalent in the two main planes for the antenna has a symmetrical physical structure.

4. ANALYSES ON THE SURFACE CURRENTS AND THE RADIATION CHARACTERISTIC

The simulated results indicate that the surface currents densities at the edges of the patch and the ground plane are the strongest, therefore, contribute the most to radiation. Thus, the radiation of the antenna can be described by an equivalent radiation array that consists of eight line currents I_{top1}–I_{top4} and I_{bot1}–I_{bot4}, as shown in Fig. 4. Besides, the amplitudes and phases at 1575 MHz of these eight currents are shown in Figs. 5–8. The abscissas defined by the relative position represent distances (in electrical dimensions) between viewpoints on the patch edges and the original point O (Fig. 4). The datum current used in currents normalization is the maximum one of the eight currents obtained from simulation.

According to the simulated results, the currents can be described

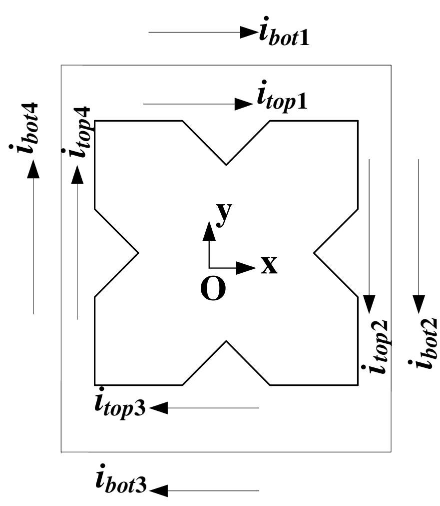

Figure 4. Schematic diagram of the surface currents.

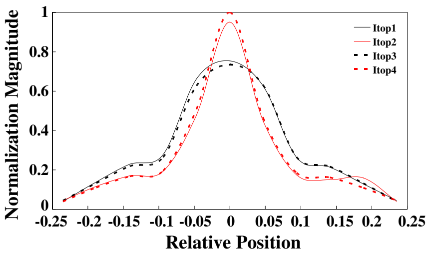

Figure 5. Amplitude of the top surface currents.

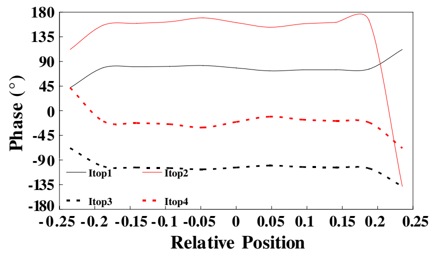

Figure 6. Phase of the top surface currents.

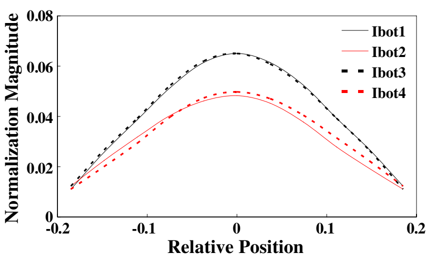

Figure 7. Amplitude of the bottom surface currents.

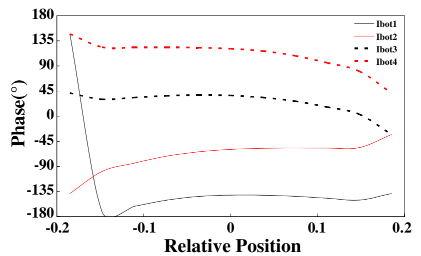

Figure 8. Phase of the bottom surface currents.

Table 1. Normalized amplitudes and phases of the eight currents.

Currents	I_{top1}	I_{top2}	I_{top3}	I_{top4}	I_{bot1}	I_{bot2}	I_{bot3}	I_{bot4}
Normalized Amplitudes	0.754	0.951	0.734	1.000	0.065	0.048	0.065	0.050
Phases(°)	77.6	160.6	−103.7	−20.5	−150.2	−67.4	28.3	112.7

by formula (3),

$$I(\xi) = I_m \cos\left(\frac{\pi}{l}\xi\right) \tag{3}$$

where I_m is the currents amplitudes, ξ the position parameter, and l the ratio of the line length of the current to the wavelength. What needs more attention is that to calculate I_{top}, the wavelength refers to the guide wavelength, while to calculate I_{bot} means wavelength in free space. The amplitudes and average phases of the currents are listed in Table 1, where the amplitudes are normalized. The phases of the eight currents are all below 133° except at the singularities in both ends. This value is equal to the phase shift of a wave propagating across the current line length in free space. Therefore, they are standing wave currents.

It can also be observed that the biggest amplitude of the I_{bot} is about 23.7 dB lower than that of the I_{top}, which indicates that radiation from I_{top} is the dominant part in the whole radiation field. Considering this conclusion, the radiation of the designed antenna can be further simplified as that generated by I_{top1}–I_{top4} array.

In the XOZ plane, the E-field generated by I_{top1} and I_{top1} in the far field is in θ direction, while the one generated by I_{top2} and I_{top4} is in φ direction.

$$E_\theta = \frac{60\exp(-jkr_0)}{r_0} \cdot \frac{\cos\left(\frac{\pi}{2}\sin\theta\right)}{\cos\theta}\left[I_{top1m}\exp\left(j\varphi_{top1}\right) - I_{top3m}\exp\left(j\varphi_{top3}\right)\right] \tag{4}$$

$$E_\varphi = \frac{60\exp(-jkr_0)}{r_0}\left\{I_{top4m}\exp\left[j\left(\varphi_{top4} - k\frac{L}{2}\sin\theta\right)\right] - I_{top2m}\exp\left[j\left(\varphi_{top2} + k\frac{L}{2}\sin\theta\right)\right]\right\} \tag{5}$$

Similarly, the far field radiation in the YOZ plane can also be calculated, where the situation of the E-fields directions is just opposite to that in the XOZ plane.

$$E_\theta = \frac{60\exp(-jkr_0)}{r_0} \cdot \frac{\cos\left(\frac{\pi}{2}\sin\theta\right)}{\cos\theta}\left[I_{top2m}\exp\left(j\varphi_{top2}\right) - I_{top4m}\exp\left(j\varphi_{top4}\right)\right] \tag{6}$$

$$E_\varphi = \frac{60\exp(-jkr_0)}{r_0}\left\{I_{top1m}\exp\left[j\left(\varphi_{top1} - k\frac{W}{2}\sin\theta\right)\right] - I_{top3m}\exp\left[j\left(\varphi_{top3} + k\frac{W}{2}\sin\theta\right)\right]\right\} \tag{7}$$

In the formulas above ((4)–(7))

k — wave number,

r_0 — distance between viewpoint and original point,

θ — angular between view direction and $+z$ axis,

I_{topim} — maximum value of I_{topi} in Fig. 5 (listed in Table 1, $i = 1, 2, 3, 4$),

φ_{topi} — average value of the currents phases (listed in Table 1, $i = 1, 2, 3, 4$),

L, W — dimensions of the patch (labeled in Fig. 1).

According to the formulas above, the radiation patterns in the XOZ and YOZ planes can be calculated, as is shown in Fig. 9.

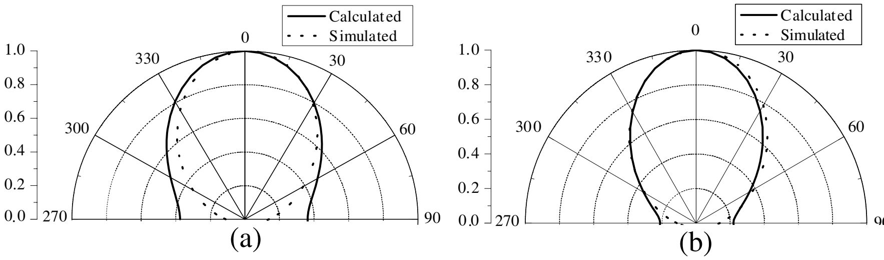

Figure 9. Calculated results of the radiation patterns based on formula (4)–(7) (linear values). (a) Radiation pattern in the XOZ plane. (b) Radiation pattern in the YOZ plane.

It is obvious that the calculated results coincide with the simulated ones when $z > 0$, and the main lobe widths are mainly the same, which indicates that the equivalent currents model proposed in this paper is credible. The model can be explained as follows. The amplitude of I_{top} in the horizontal direction is 2.7 dB lower than that in the vertical direction (Table 1). I_{top2} lags behind I_{top1} for 90° in phase, and the same thing occurs between I_{top2} & I_{top3} as well as I_{top3} & I_{top4}. Therefore, the radiation field of the currents array can be considered circularly polarized, approximately, which may explain why the designed antenna radios are circular polarization waves. More specifically, the resultant E-field from I_{top1} and I_{top3} in $+Z$ direction in the far field is $E_x = 1.49e^{j77^\circ}$, while the one from I_{top2} and I_{top4} in $+Z$ direction in the far field is $E_y = 1.95e^{-j20^\circ}$. Combining E_x and E_y, the right-handed elliptical polarization field generated by the currents array is obtained. The calculated axial ratio of the antenna is 2.56 dB, which nearly coincides with the simulated result 1.1 dB.

5. EXPERIMENT RESULTS

According to the structure parameters obtained through simulating, an antenna is fabricated. The measured results are shown in Fig. 10.

It can be observed that the measured results have better consistency with the simulated one obtained through taking the substrate loss into account, which indicates that the substrate loss should not be ignored in designing some certain antennas. The gain at 1575 GHz is around 2.6 dB, and the axial ratio in the maximum radiation direction is 2.7 dB, both of which match the design requirements.

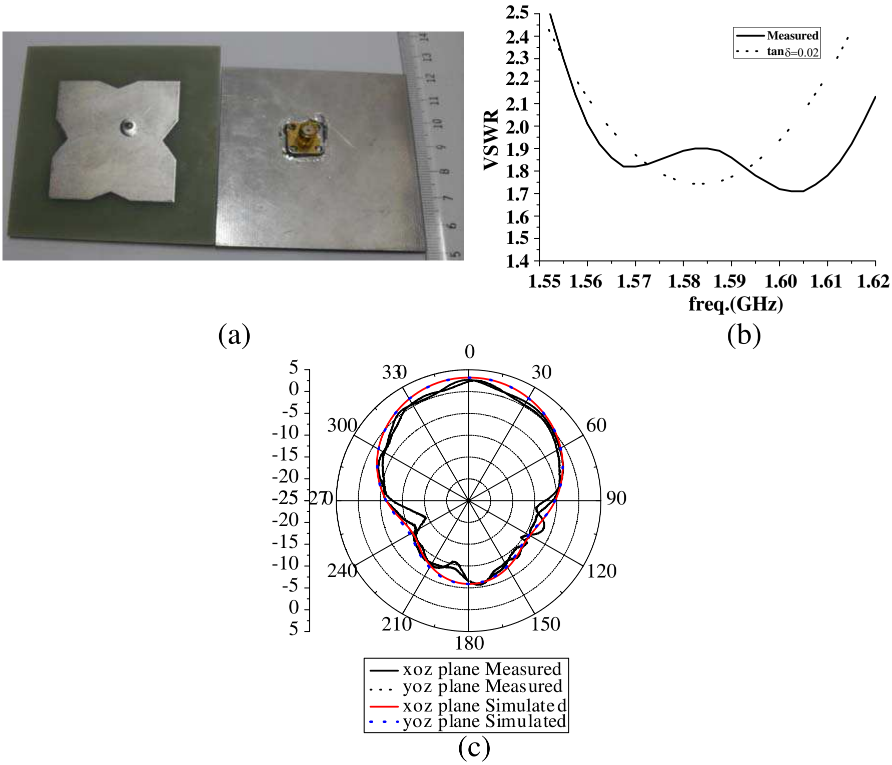

Figure 10. Photo of the fabricated antenna and the measured results. (a) Photo of the fabricated antenna. (b) Measured result of VSWR. (c) Measured results of circular polarization gain and radiation patterns.

6. CONCLUSIONS

A single-feed circular polarization microstrip antenna is researched in this paper. The details of the designing process are provided with the simulated and measured results. Based on the simulated data, an equivalent line currents array model is proposed to explain the radiation characteristics of the designed antenna. Both the calculated results from the model and the measured results from the experiment coincide to the simulated results, which proves the correctness of the simulation ideas and the proposed model. The designed antenna has a stable impedance characteristic in a relatively wide frequency band. Due to the substrate loss, the gain is not that high. The performances on gain and axial ratio of the antenna can be improved further if a lower loss substrate is used.

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