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Axial Ratio Bandwidth of a Circularly Polarized Microstrip Antenna

Li Sun, Gang Ou, Yilong Lu and Shusen Tan

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1. Introduction

Microstrip antenna has been widely used due to its many advantages, such as, small volume, light weight, easy to get various polarization and easy to be integrated (Dang & Liu, 1999). Microstrip antenna can adopt many methods to obtain circular polarization (Xue and Zhong, 2002). And some technologies can achieve the miniaturization of the microstrip antenna (Xue and Zhong, 2002). Also there are some methods to enhance the impedance bandwidth of the miniaturized microstrip antenna (Liu et al., 2002) ; (Wang & Gao, 2003).

In this chapter, we focus on the axial ratio bandwidth of a circularly polarized microstrip antenna. The previous reference books discussed the axial ratio bandwidth less, always said that the axial ratio bandwidth of a circularly polarized microstrip antenna was limited, and it was less than the impedance bandwidth of a linearly polarized microstrip antenna (Lin & Nie, 2002). The group of Professor Ahmed A. Kishk has done a lot of research work on the circularly polarized microtrip antenna recently (Yang et al., 2008); (Yang et al., 2007); (Yang et al., 2006); (Chair et al., 2006); (Kishk et al., 2006). We adopt theoretical analysis and simulation by CST Microwave Studio to give out the method of improving the axial ratio bandwidth of the circularly polarized microstrip antenna.

First, we briefly introduce the basic methods which can form the circular polarization for a microstrip antenna, including the single-feed and the multiple-feed. When using multiple-feed for one patch, the sequential rotation technology (Hall et al., 1989) can be adopted. Starting from the mechanism of circular polarization obtaining from multiple-feed method, the multiple-feed can improve the axial ratio bandwidth of a microstrip antenna effectively than the single-feed microstrip antenna is demonstrated by theoretical analysis and simulation. The more feeds, the better the axial ratio bandwidth is.

Then, the detail analysis of the axial ratio bandwidth including when the amplitudes have some difference and the phase excitation of the feed point has an offset according to the designed central frequency in manufacture are described.

At last, the example of circularly polarized microstrip antenna design and test are in the section 5. Due to the volume limited in the project, we choose two feeds for the microstrip antenna.

2. Circularly polarized method

2.1. Simple microstrip antennas

Generally, the configuration of the simple microstrip antenna (Ung, 2007) is showed as in Fig. 1. It can be simply formed by a dielectric substrate through photoetching technology or etching process. In the configuration, there are the metallic patch of certain shape on the top, the substrate layer of certain thickness and the ground plane on the bottom. The dielectric constant and the thickness of the dielectric substrate material, the shape and size of the top patch and the feeding method determine the performance of the microstrip antenna.
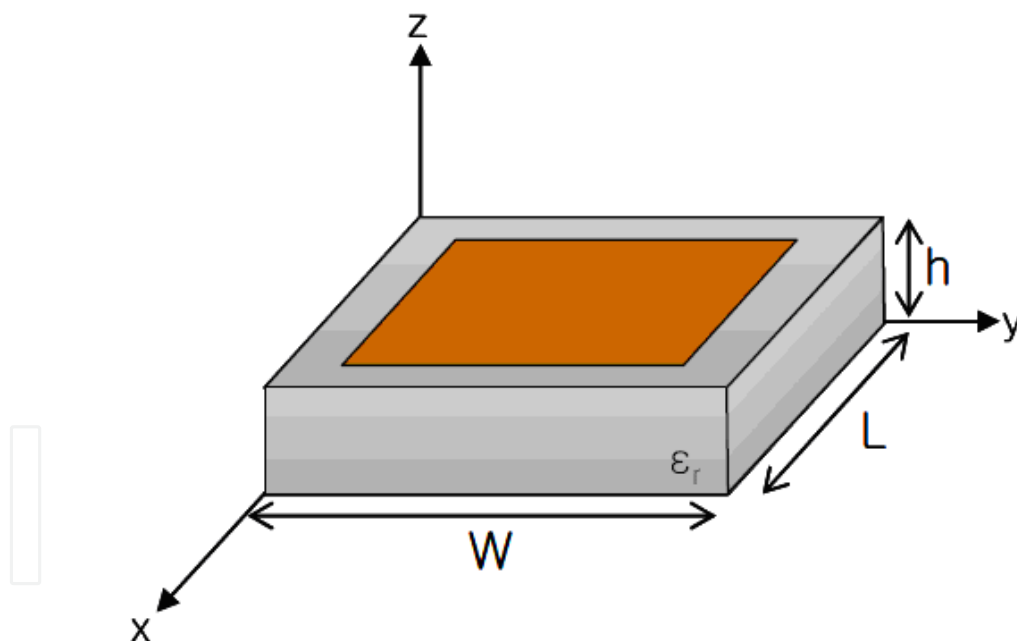
Figure 1. Configuration of the microstrip antenna

The shape of the top metallic patch can be various. Such as square, rectangle, circle, triangle, ellipse and unconventional shape, etc. The feed methods include coaxial probe feed, microstrip line feed, aperture couple feed, etc (Ung, 2007); (stutzman & Thiele, 1997). The simple micro-strip antenna is usually linearly polarized. The bandwidth of the linearly polarized microstrip antenna is described by the impedance bandwidth.
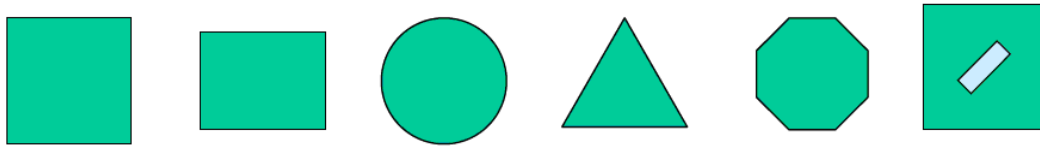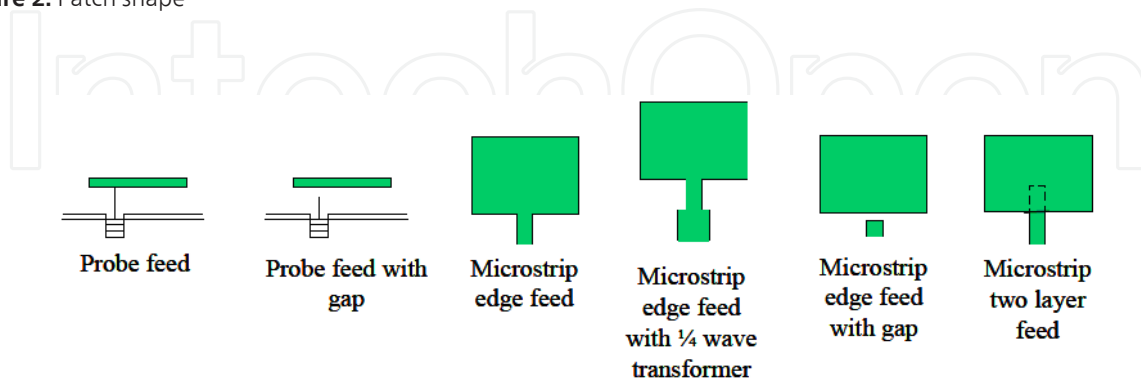
Figure 2. Patch shape

Figure 3. Feed methods

2.2. Single-feed realization method

Single-feed for the patch to form circular polarization is based on the cavity model of microstrip antenna. The two orthogonal polarized degenerate modes which can formed the circular polarization can be obtained by corner cut, quasi-square, slot, etc, and the patch shape (Lin & Nie, 2002) can be seen in Fig.4. The feed methods can adopt coaxial probe feed, aperture couple feed, etc.
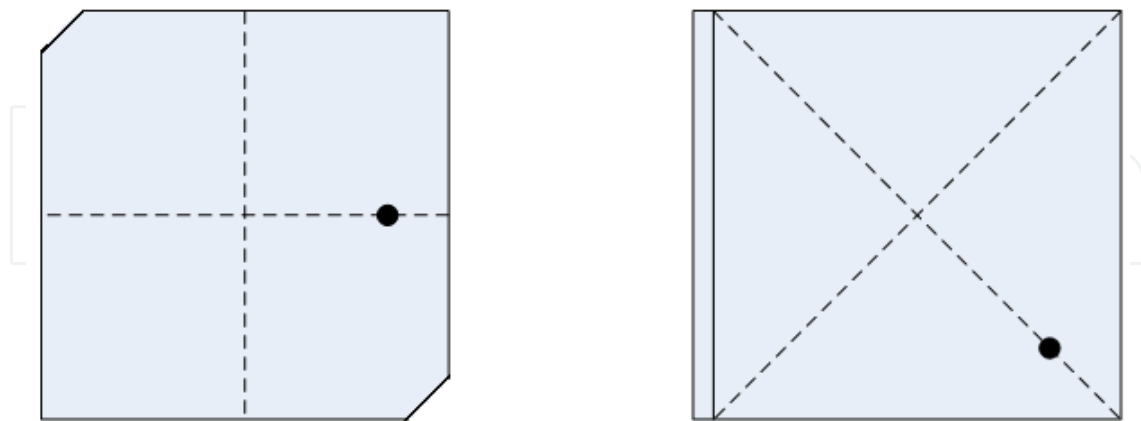

Figure 4. Patch shape of single-feed circularly polarized microstrip antenna

The axial ratio 3dB bandwidth of the circularly polarized microstrip antenna is much less than the impedance bandwidth of the linearly polarized microstrip antenna. Via application, the axial ratio 3dB bandwidth the single-feed circularly polarized microstrip antenna is limited at

about 35%of the difference of the two resonant frequencies (Lin & Nie, 2002). So we must find methods to improve the axial ratio bandwidth of the circularly polarized microstrip antenna.

2.3. Multiple-feed realization method

A circularly polarized electromagnetic wave can be divided into two equal amplitudes linearly polarized components both in space and in time. Suppose that the two orthogonal polarized components are

$$\vec{E}_x = E, \quad \vec{E}_y = E e^{j\frac{\pi}{2}},$$

then we have

$$\vec{E}_y = E e^{j\frac{\pi}{2}} = j\vec{E}_x. \tag{1}$$

Multiple-feed for one patch can adopt the sequential rotation technology. The technology of sequential rotation is successfully used in circularly polarized antenna array design (Hall et al., 1989). Multiple-feed has an appropriate phase difference between excitations, and this can improve the axial ratio bandwidth and reduce the cross-polarization. The mode exited by each feed for one patch can be regarded as the mode exited by each element in the array. So, in the case of using M feed points, the m_{th} feed point's phase φ_{em} can be expressed as

$$\varphi_{em} = (m-1)\frac{p\pi}{M} 1 \leq m \leq M, \tag{2}$$

where P is an integer.

Each feed point's physical position must have some symmetry, seen in fig.5. Through simulation, finding that fixing the first feed point position, other feed points rotate the corresponding phase differences between itself and the first feed point. The center is the disc center. In the case of $P<M$, and the last feed point does not rotate to the first feed point, it can improve axial ratio bandwidth.
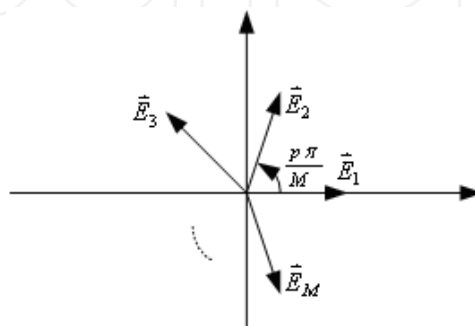
Figure 5. Feed position of multiple-feed

Suppose that

$$\vec{E}_1 = E, \ \vec{E}_2 = Ee^{j\frac{p\pi}{M}}, \ \vec{E}_3 = Ee^{j\frac{2p\pi}{M}}, \ \ldots, \ \vec{E}_M = Ee^{j\frac{(M-1)p\pi}{M}}$$

so the two orthogonal components are

$$E_x = \vec{E}_1 + \vec{E}_2 \cos\frac{p\pi}{M} + \vec{E}_3 \cos\frac{2p\pi}{M} + \cdots + \vec{E}_M \cos\frac{(M-1)p\pi}{M}$$

$$= E + Ee^{j\frac{p\pi}{M}}\cos\frac{p\pi}{M} + Ee^{j\frac{2p\pi}{M}}\cos\frac{2p\pi}{M} + \cdots + Ee^{j\frac{(M-1)p\pi}{M}}\cos\frac{(M-1)p\pi}{M}$$

$$= 1 + \cos^2\frac{p\pi}{M} + \cos^2\frac{2p\pi}{M} + \cdots + \cos^2\frac{(M-1)p\pi}{M} + \frac{1}{2}j\left[\sin\frac{2p\pi}{M} + \sin\frac{4p\pi}{M} + \cdots + \sin\frac{2(M-1)p\pi}{M}\right]$$

$$E_y = \vec{E}_2 \sin\frac{P\pi}{M} + \vec{E}_3 \sin\frac{2P\pi}{M} + \cdots + \vec{E}_M \sin\frac{(M-1)P\pi}{M}$$

$$= Ee^{j\frac{p\pi}{M}}\sin\frac{p\pi}{M} + Ee^{j\frac{2p\pi}{M}}\sin\frac{2p\pi}{M} + \cdots + Ee^{j\frac{(M-1)p\pi}{M}}\sin\frac{(M-1)p\pi}{M}$$

$$= \frac{1}{2}\left[\sin\frac{2p\pi}{M} + \sin\frac{4p\pi}{M} + \cdots + \sin\frac{2(M-1)p\pi}{M}\right] + j\left[\sin^2\frac{p\pi}{M} + \sin^2\frac{2p\pi}{M} + \cdots + \sin^2\frac{(M-1)p\pi}{M}\right]$$

According to the following formula,

$$\sum_{k=1}^{n} \sin(x + k\alpha) = \frac{\sin\frac{1}{2}n\alpha}{\sin\frac{1}{2}\alpha}\sin\left(x + \frac{1}{2}(n+1)\alpha\right),$$

we can get

$$\sin\frac{2p\pi}{M} + \sin\frac{4p\pi}{M} + \cdots + \sin\frac{2(M-1)p\pi}{M}$$

$$= \frac{\sin\frac{(M-1)p\pi}{M}}{\sin\frac{p\pi}{M}}\sin\left[\frac{1}{2}(M-1+1)\frac{2p\pi}{M}\right] = \frac{\sin\frac{(M-1)p\pi}{M}}{\sin\frac{p\pi}{M}}\sin(p\pi) = 0,$$

and according to

$$\sum_{k=1}^{n} \cos(x + k\alpha) = \frac{\sin\frac{1}{2}n\alpha}{\sin\frac{1}{2}\alpha}\cos\left(x + \frac{1}{2}(n+1)\alpha\right),$$

we can get

$$\cos\frac{2p\pi}{M} + \cos\frac{4p\pi}{M} + \cdots + \cos\frac{2(M-1)p\pi}{M}$$

$$= \frac{\sin\frac{(M-1)p\pi}{M}}{\sin\frac{p\pi}{M}}\cos\left[\frac{1}{2}(M-1+1)\frac{2p\pi}{M}\right] = \frac{\sin\left(p\pi - \frac{p\pi}{M}\right)}{\sin\frac{p\pi}{M}}\cos(p\pi) = -1.$$

$$1 + \cos^2\frac{p\pi}{M} + \cos^2\frac{2p\pi}{M} + \cdots + \cos^2\frac{(M-1)p\pi}{M}$$

$$= \frac{M}{2} + \frac{1}{2} + \frac{1}{2}\left(\cos\frac{2p\pi}{M} + \cos\frac{4p\pi}{M} + \cdots + \cos\frac{2(M-1)p\pi}{M}\right) = \frac{M}{2},$$

$$\sin^2\frac{p\pi}{M} + \sin^2\frac{2p\pi}{M} + \cdots + \sin^2\frac{(M-1)p\pi}{M}$$

$$= \frac{M}{2} - \frac{1}{2} - \frac{1}{2}\left(\cos\frac{2p\pi}{M} + \cos\frac{4p\pi}{M} + \cdots + \cos\frac{2(M-1)p\pi}{M}\right) = \frac{M}{2},$$

so

$$1 + \cos^2\frac{p\pi}{M} + \cos^2\frac{2p\pi}{M} + \cdots + \cos^2\frac{(M-1)p\pi}{M} = \sin^2\frac{p\pi}{M} + \sin^2\frac{2p\pi}{M} + \cdots + \sin^2\frac{(M-1)p\pi}{M} = \frac{M}{2}$$
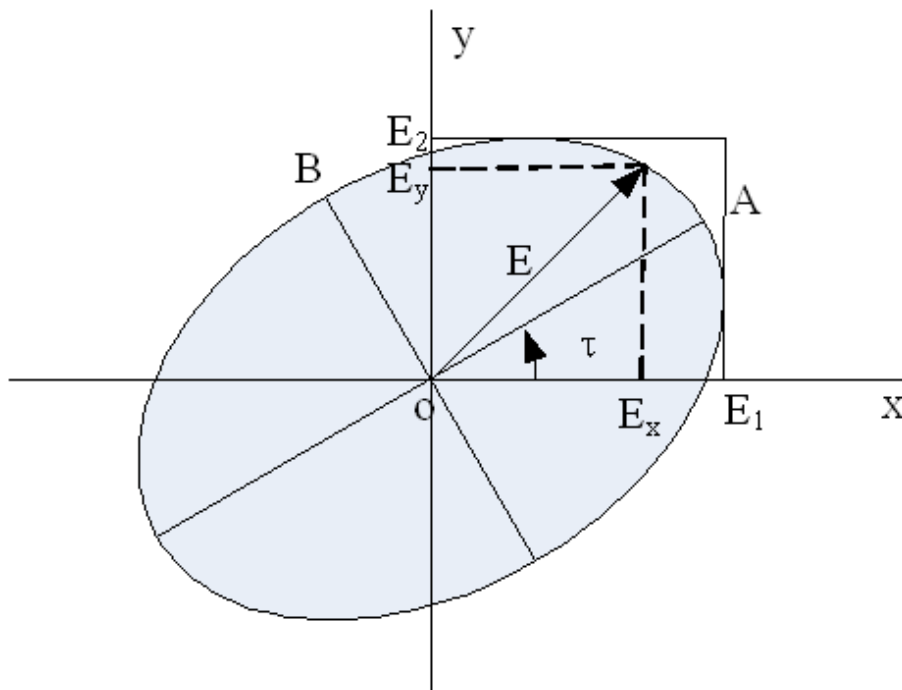
Therefore we can get

$$E_y = jE_x. \qquad (3)$$

That is (1), so the multiple-feed method above has realized the circular polarization.

3. Theoretical analysis of the axial ratio bandwidth

3.1. Axial ratio

We can use the polarization ellipse to describe the elliptical polarization. The instantaneous electric field orientation can figure out an ellipse in the space, seen in Fig.6.

Figure 6. Polarization ellipse

The axial ratio is defined as

$$AR = OA\big/OB \quad (1 \le AR \le \infty) \qquad (4)$$

where *OA* is the half major axis of the polarization ellipse, and the *OB* is the half minor axis of the polarization ellipse.

The elliptical polarization of electromagnetic wave can be divided into two linearly polarized components. One's orientation is along x-axis, and the other is along y-axis. Suppose that the two linearly polarized components are $E_x = E_1 \sin(\omega t - \beta z)$, $E_y = E_2 \sin(\omega t - \beta z + \delta)$,

where E_1 is the amplitude of the linear polarization along x-axis E_x, and E_2 is the amplitude of the linear polarization along y-axis E_y. δ is the phase difference between E_x and E_y. Based on the above, we will analyze the axial ratio bandwidth of the multiple-feed microstrip antenna in the next section.

3.2. Axial ratio bandwidth of two feeds

Assume that the amplitudes excitation of each feed are equal, mutual coupling is small, and it can be neglected. Only the frequency changes the phase excitation relationship between the feed points. In the real case, usually using power splitter with separation to realize the equal amplitude excitation, and using different microstrip line length to realize the phase excitation difference. So the assumption is reasonable.

Two feeds: *M=2, P=1*. The two orthogonal electric fields are

$$E_x = E_1 \sin(\omega t - \beta z), \tag{5}$$

$$E_y = E_2 \sin(\omega t - \beta z + \delta). \tag{6}$$

At *z=0*,

$$E_x = E_1 \sin \omega t, \tag{7}$$

$$E_y = E_2 (\sin \omega t \cos \delta + \cos \omega t \sin \delta), \tag{8}$$

where $\sin \omega t = \dfrac{E_x}{E_1}$, $\cos \omega t = \sqrt{1 - \left(\dfrac{E_x}{E_1}\right)^2}$

Substitute (7) into (8), we can get

$$a E_x^2 - b E_x E_y + c E_y^2 = 1, \tag{9}$$

where

$$a = \frac{1}{E_1{}^2\sin^2\delta}, \quad b = \frac{2\cos\delta}{E_1 E_2 \sin^2\delta}, \quad c = \frac{1}{E_2{}^2\sin^2\delta}.$$

Construct an ellipse equation

$$\frac{E_x'^2}{A^2} + \frac{E_y'^2}{B^2} = 1, \tag{10}$$

where

$$E_x' = E_x\cos\theta - E_y\sin\theta, \quad E_y' = E_x\sin\theta + E_y\cos\theta.$$

Thus (10) becomes,

$$\left(\frac{\cos^2\theta}{A^2} + \frac{\sin^2\theta}{B^2}\right)E_x^2 - \left(\frac{\sin 2\theta}{A^2} - \frac{\sin 2\theta}{B^2}\right)E_x E_y + \left(\frac{\sin^2\theta}{A^2} + \frac{\cos^2\theta}{B^2}\right)E_y^2 = 1. \tag{11}$$

Through (9) and (11), we can get

$$A = \sqrt{\frac{2}{a + c + \sqrt{(a-c)^2 + b^2}}},$$

$$B = \sqrt{\frac{2}{a + c - \sqrt{(a-c)^2 + b^2}}}.$$

So

$$AR = \frac{A}{B} = \sqrt{\frac{(E_1/E_2)^2 + 1 - \sqrt{(E_1/E_2)^4 + 1 + 2\cos 2\delta (E_1/E_2)^2}}{(E_1/E_2)^2 + 1 + \sqrt{(E_1/E_2)^4 + 1 + 2\cos 2\delta (E_1/E_2)^2}}}. \tag{12}$$

Two feeds, when $E1/E2=1$, we can get (13) from (12).

$$AR = tg\frac{\delta}{2}. \tag{13}$$

3.3. Axial ratio bandwidth of four feeds

We analyze the axial ratio bandwidth of multiple-feed antenna, in the case of amplitude excitations are equal, and mutual coupling is neglected. Four feeds, when $M=4$, $P=2$.

In other words, the phase excitation difference is 90°. At $z=0$, the two orthogonal electric fields are

$$E_x = E_1 \sin \omega t - E_3 \sin(\omega t + 2\delta), \tag{14}$$

$$E_y = E_2 \sin(\omega t + \delta) - E_4 \sin(\omega t + 3\delta), \tag{15}$$

where

$$E_y = (E_2 \cos \delta - E_4 \cos 3\delta) \sin \omega t + (E_2 \sin \delta - E_4 \sin 3\delta) \cos \omega t. \tag{16}$$

In the case of $E_1=E_2=E_3=E_4$,

$$\cos \omega t = \frac{2E_x \cos\delta - E_y}{-2E_1 \sin\delta}$$

$$\sin \omega t = \sqrt{1 - \left(\frac{2E_x \cos\delta - E_y}{-2E_1 \sin\delta}\right)^2}$$

Substitute into (16), we can get

$$aE_x^2 - bE_x E_y + cE_y^2 = 1, \tag{17}$$

where

$$a = \frac{1}{4E_1^2 \sin^4\delta},$$

$$b = \frac{\cos\delta \cos 2\delta}{E_1^2 \sin^4\delta} + \frac{\cos\delta}{E_1^2 \sin^2\delta},$$

$$c = \frac{\cos^2\delta}{4E_1^2 \sin^4\delta} + \frac{1}{4E_1^2 \sin^2\delta}.$$

So

$$AR = \frac{A}{B} = \sqrt{\frac{a + c - \sqrt{(a-c)^2 + b^2}}{a + c + \sqrt{(a-c)^2 + b^2}}} = \sqrt{\frac{1 - 2\cos^3\delta}{1 + 2\cos^3\delta}}. \tag{18}$$

That is

$$AR = \sqrt{\frac{1 - 2\cos^3 \delta}{1 + 2\cos^3 \delta}}.$$ (19)

3.4. Comparison of the two feeds and the four feeds

Next we give out the expression for phase excitation difference δ between the two feeds. The feed network substrate's relative dielectric constant is ε_r, the substrate thickness is h, and the width of the microstrip line is W. With the theory of the microstrip line, the effective dielectric constant ε_{re} is (Lin & Nie, 2002)

$$\varepsilon_{re} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}(1 + \frac{12h}{W})^{-\frac{1}{2}}.$$ (20)

The phase velocity's wavelength λ_p of the quasi-TEM wave propagated in the micro-strip line is

$$\lambda_p = \frac{c}{f\sqrt{\varepsilon_{re}}},$$ (21)

where c is the velocity of light in the vacuum, and f is frequency.

Assume that the microstrip line length x which providing 90° phase excitation according to the central frequency, provide δ phase excitation in fact due to the changing of the frequency, $\delta/x = 360/\lambda_p$, then

$$\delta = \frac{360xf\sqrt{\varepsilon_{re}}}{c}.$$ (22)

The phase excitation difference of each feed in the feed network is designed according to the central frequency. The phase excitation difference which provided by the microstrip line is changing according to the changing frequency. This will affect the circular polarization out side the central frequency.

We use the CST microwave studio to simulate the multiple-feed microstrip antenna. The simulation files are showed in Fig.7. Thorough simulation and calculation, we give out the axial ratio bandwidth comparison between two feeds and four feeds in Fig.8. Through the theoretical computation, we demonstrate that multiple-feed for one patch can effectively improve the axial ratio bandwidth. The axial ratio 3dB bandwidth of two feeds can achieve 42.6%, and four feeds can achieve 74%.
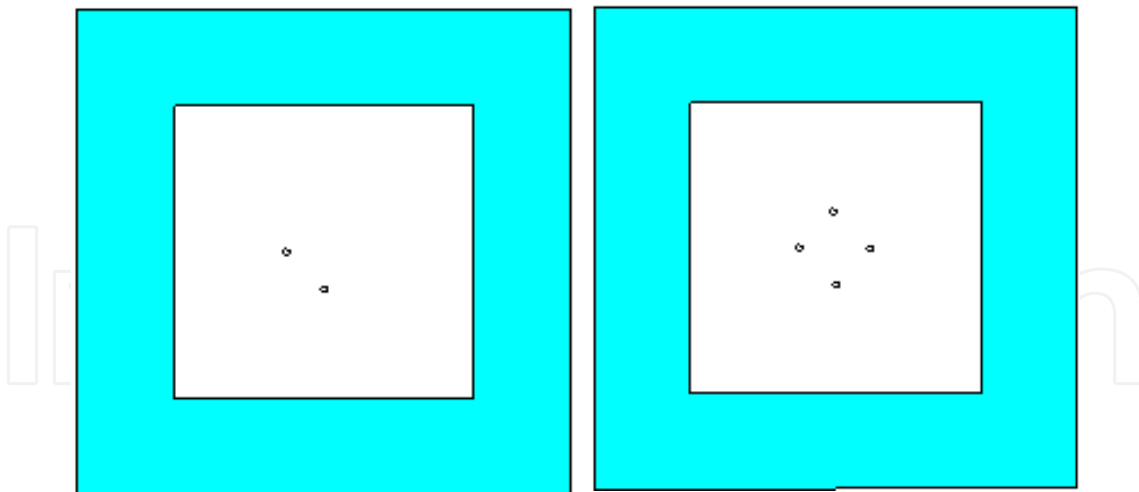
Figure 7. Simulation files of two feeds and four feeds
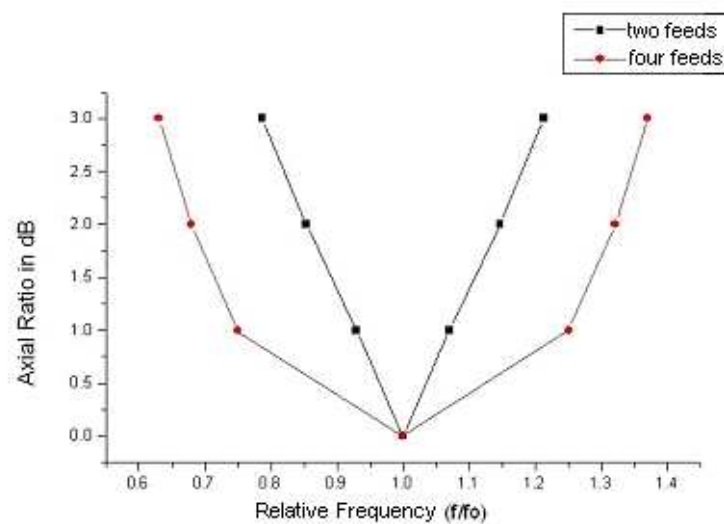
Figure 8. Axial ratio bandwidth comparison between two feeds and four feeds

4. Axial ratio bandwidth analysis when manufacture error exist

When two feeds, assume that the amplitudes excitation are equal at every frequency. But if we substitute (22) into (12), we can get the changing of the axial ratio bandwidth according to the different ratio of E1 and E2, showing in Fig.9.
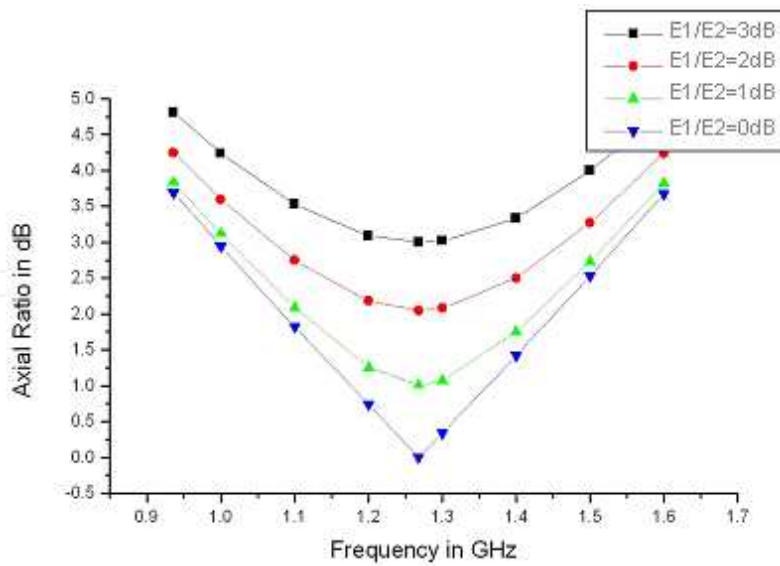
Figure 9. Axial ratio bandwidth of different amplitudes excitation of the two feeds

We can get the conclusion that the amplitude difference between the two feeds affects the axial ratio badly. When the amplitude ratio of the two feeds is 3dB, the axial ratio 3dB bandwidth has already disappeared.

Next we have a look at the axial ratio bandwidth changing when the phase excitation designed at the central frequency has an offset. In the feed network, change the microstrip line length x which provides 90° phase excitation to the length which provides 85.8° phase excitation. Using the same process, we can give out the changing of the axial ratio bandwidth when two feeds amplitudes are equal in Fig.10. When two feeds amplitudes ratio is 2dB in Fig.11.
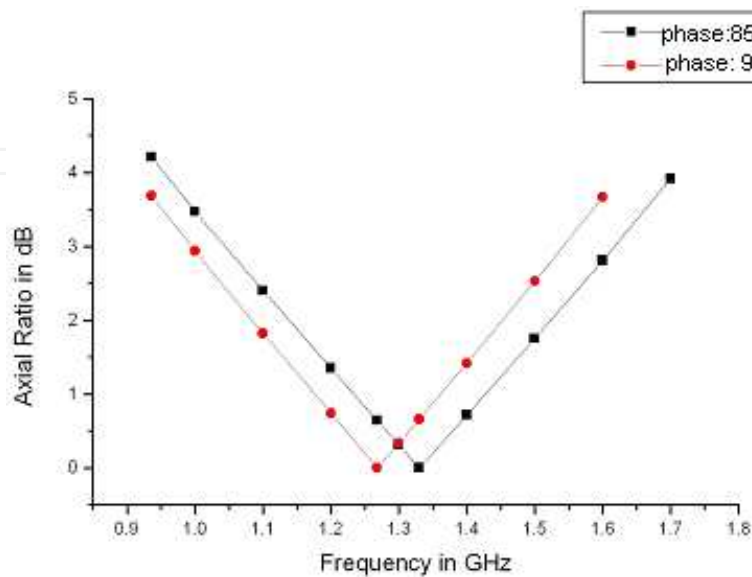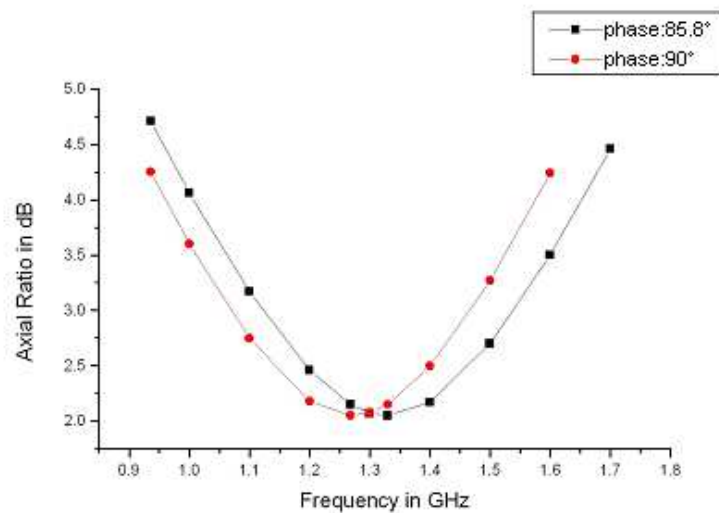

Figure 10. Axial ratio bandwidth of phase excitation has an offset at the central frequency in case of E1/E2=0dB

Figure 11. Axial ratio bandwidth of phase excitation has an offset at the central frequency in case of E1/E2=2dB

We can see that there is an offset on the axial ratio bandwidth when the phase excitation designed at the central frequency has an offset. From our theoretical analysis, we can get the conclusion that the multiple-feed technology can improve the axial ratio bandwidth of the microstrip antenna effectively. To get a wide band circularly polarized microstrip antenna, first, we must determine the most feed points we can use in the design according to the size limited in the project.

5. Antenna design example

5.1. Design

The more feeds, the better the axial ratio bandwidth of the circularly polarized microstrip antenna. But the feed network is more complicated and the feed network needs more space to realize.

We design a small antenna, using two feeds. Two linearly polarized components which are equal amplitude and 90°phase difference form the circular polarization. The patch shape is in Fig.12 (Hall et al., 1989), and the stubs on the patch are used to debug the resonant frequency in antenna manufacture. The feed network is in Fig.13.
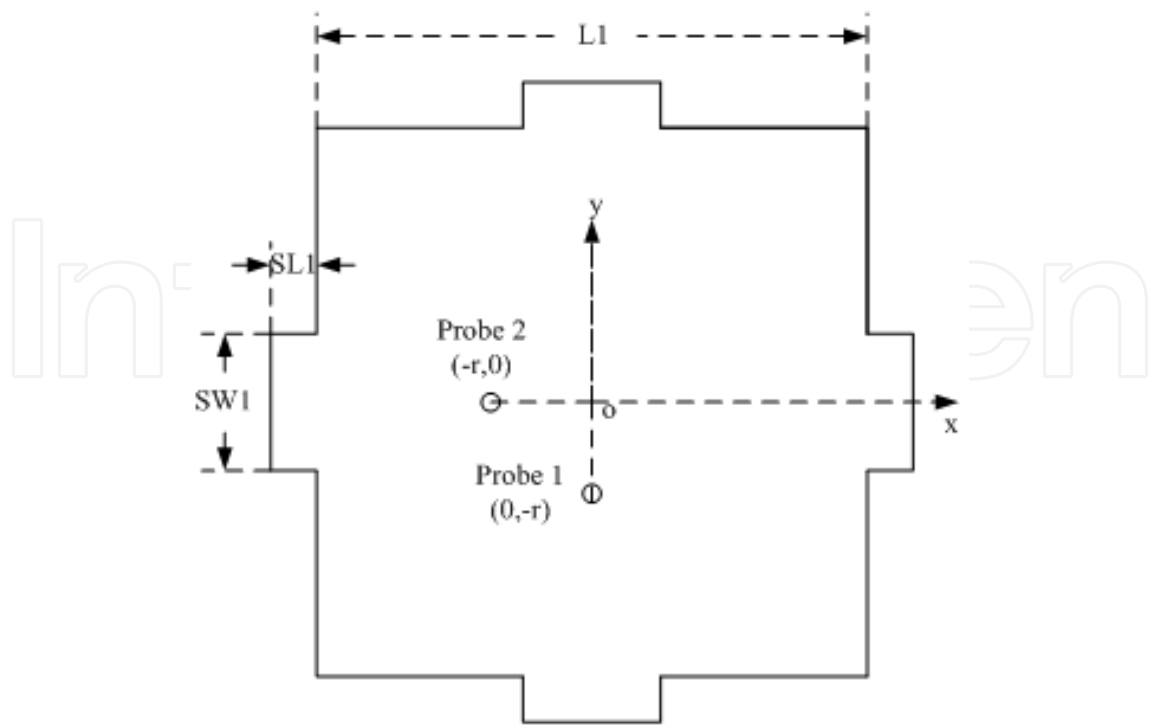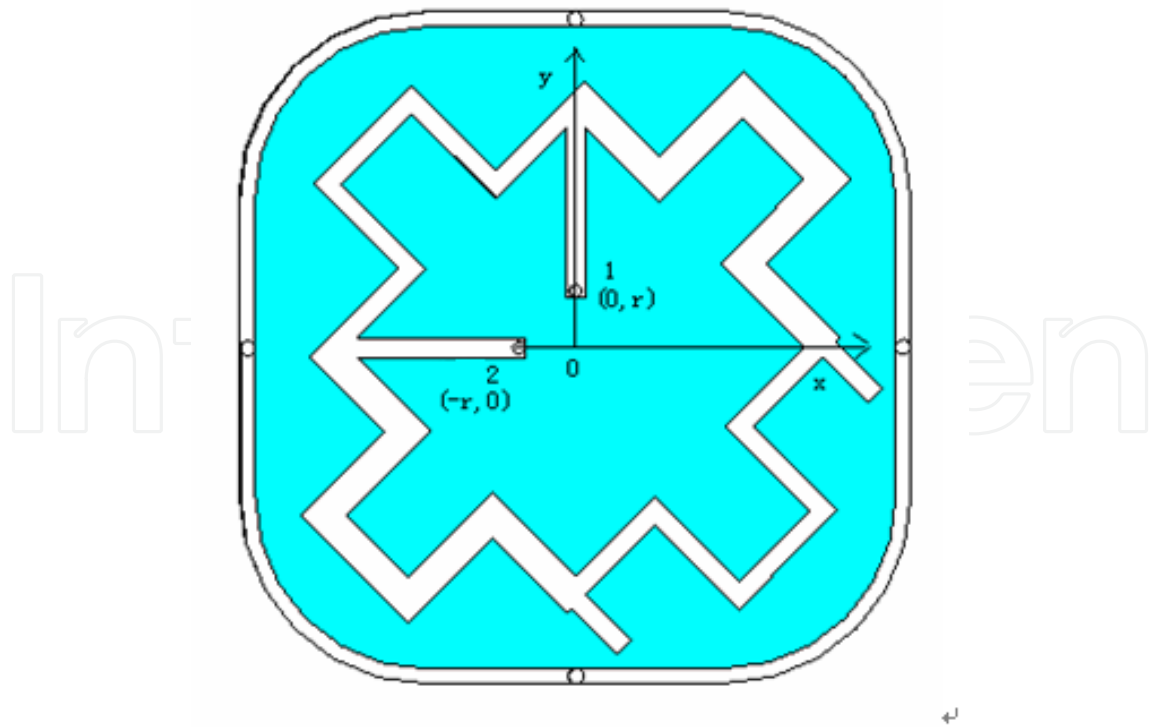
Figure 12. Patch shape


Figure 13. Feed network

5.2. Simulation analysis

Simulate the two feeds microstrip antenna we design in the above section using the CST microwave studio. We compare the difference in the axial ratio bandwidth between the single-feed and the two feeds through simulation. The configurations of the single-feed and the two feeds microstrip antenna are showed in Fig.14.
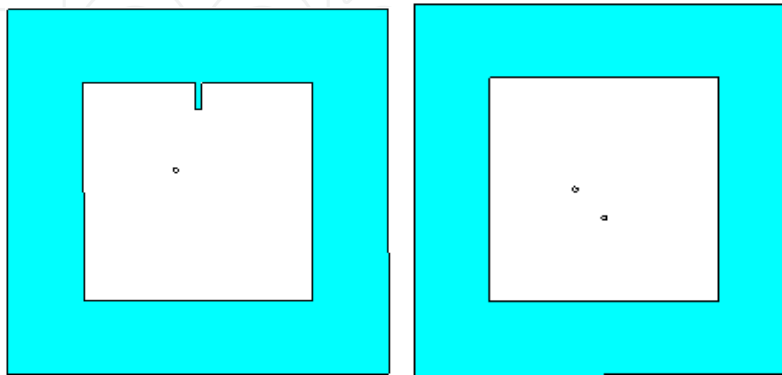
Figure 14. Simulation configuration of the single-feed and the two feeds

The simulation results of the axial ratio of the single-feed and the two feeds at zenith are showed in Fig.15. We can see that the axial ratio bandwidth of the single-feed is very limited. For the two feeds, the phase difference of the two equal amplitudes and 90° phase difference linearly polarized components according to the centre frequency change slowly and smoothly with the frequency band. This can improve the axial ratio bandwidth of a circularly polarized microstrip antenna.
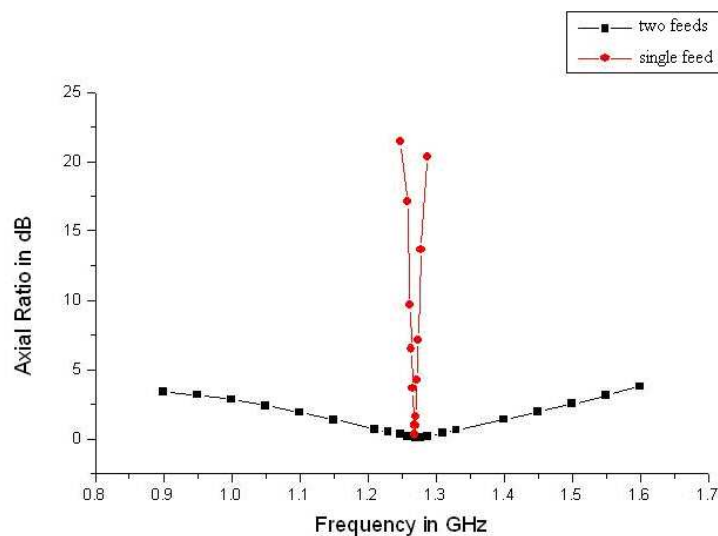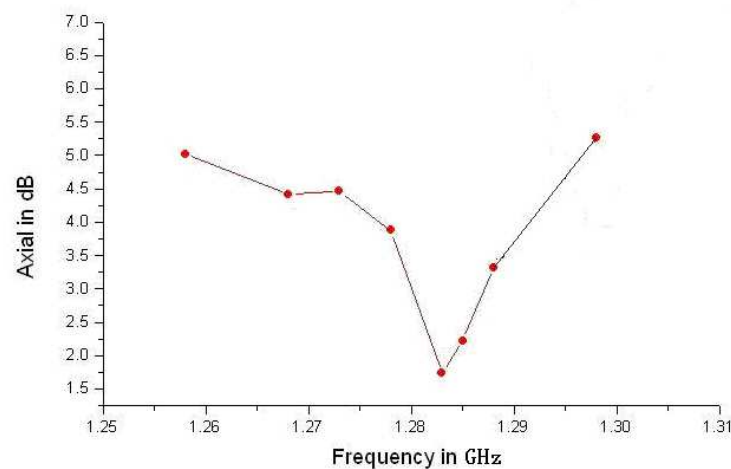
Figure 15. Axial ratio simulation results of the single-feed and the two feeds

5.3. Test result

The manufactured two feeds microstrip antenna is tested in the anechoic chamber. The test result of the axial ratio is showed in Fig.16.

Figure 16. Axial ratio test result

In simulation, the two feeds are ideal equal amplitudes and 90° phase difference. In the manufacture, the microstrip line feed network provides the two equal amplitudes and 90° phase difference excitations. Due to the dielectric constant error of the substrate material and error of manufacture, the axial ratio bandwidth of the microstrip antenna get worse compared to the simulation result. The axial ratio 3dB bandwidth tested of the microstrip antenna is about 10MHz.

6. Conclusion

Microstrip antenna has been used in every field, due to its many advantages. Our main research topic in this chapter was how to improve the axial ratio bandwidth of a circularly polarized microstrip antenna. Multiple-feed method can realize the circular polarization for a microstrip antenna. Circularly polarized microstrip patch antenna designed by the multiple-feed method adopting the sequential rotation technology can improve the axial ratio bandwidth effectively. In this chapter, we demonstrate it by theoretical analysis.

Through simulation by CST Microwave Studio and theoretical computation, the axial ratio 3dB bandwidth of two feeds can achieve 42.6%, and four feeds can achieve 74%.

In engineering, choosing the most feed points according to the feed network space limited in the project can improve the axial ratio bandwidth of a circularly polarized microstrip antenna. And it is at the price of a complicated feed network compared to the few feed points design.

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