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Far-Field Symmetry Analysis and Improvement of the Cavity Backed Planar Spiral Antenna

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Abstract—The far-field pattern symmetry of the cavity backed planar spiral antenna is analyzed. We discover that the back radiation of the planar spiral and the cavity effects degrade the pattern symmetry. To improve the pattern symmetry, an improved method to reduce the back radiation is proposed. Then a novel antenna configuration is designed. The center section of the planar spiral is replaced with a conical spiral. So the back radiation at higher frequency band can be restrained. The broadside gain, axial ratio and pattern symmetry are compared. The results show that this novel configuration can achieve better far-field symmetry at a wider band.

1. INTRODUCTION

Spiral antennas [1–5] have been widely used due to their apparent characteristics, such as wide band circular polarization and wide beam. The planar spiral antennas produce bidirectional radiation-front radiation and back radiation. The conventional technique to obtain unidirectional radiation is to place a cavity behind the spiral antennas. But due to the bidirectional radiation and the reflection of the cavity, some high order radiation modes [6] can be activated and the semi-closed cavity resonant modes can be activated too. These effects degrade the far-field pattern symmetry [7–10]. In order to improve the pattern symmetry, the traditional way is to fill the cavity with the absorber materials. However, it will greatly lower the antenna efficiency, and about 50% power is dissipated in the absorber. There are still few studies focused on improving the pattern symmetry. Buck [7] proposed a slot spiral antenna which is backed by a spiral slotted cavity. This structure can improve the pattern symmetry with a low-profile. But for many applications, the antennas need to be mounted to a metal structure, and a spiral slot on the cavity will not be accepted.

In this paper, the causes of the pattern asymmetry of the cavity backed planar spiral antenna are analyzed and a method to improve its far-field symmetry is proposed. Then a novel configuration to reduce the back radiation at the higher frequency band is designed. The center section of the planar spiral is replaced by a conical spiral. Due to the conical spiral's natural unidirectional radiation, the small back radiation can weaken the cavity effects. This new configuration can improve the far-field symmetry at a wider band, and also achieve high efficient unidirectional radiation. The results are obtained by simulations in CST microwave studio.

2. CAVITY BACKED PLANAR SPIRAL

A cavity backed planar Archimedean spiral antenna is shown in Figure 1. The two arms of the self-complimentary planar Archimedean spiral antenna are wound symmetrically with respect to the center

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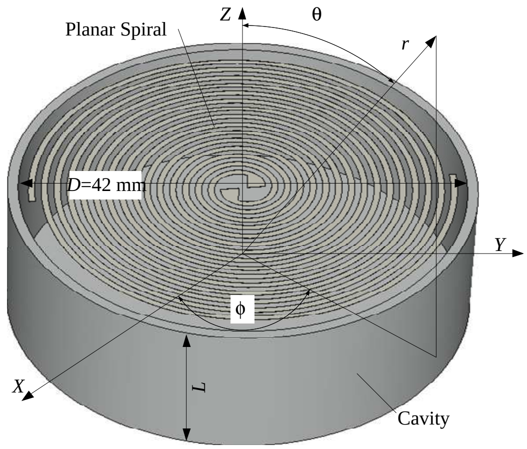

Figure 1. Configuration of cavity backed planar spiral antenna.

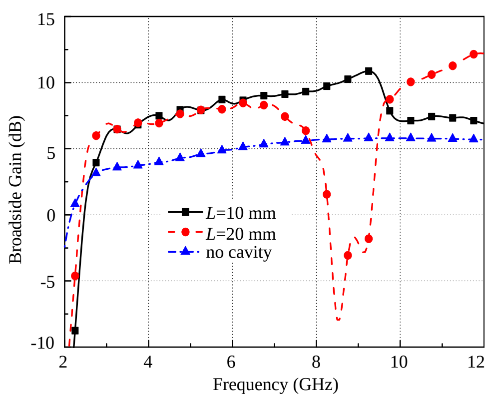

Figure 2. Broadside gain of the cavity backed planar spiral antenna versus frequency with different cavity depths.

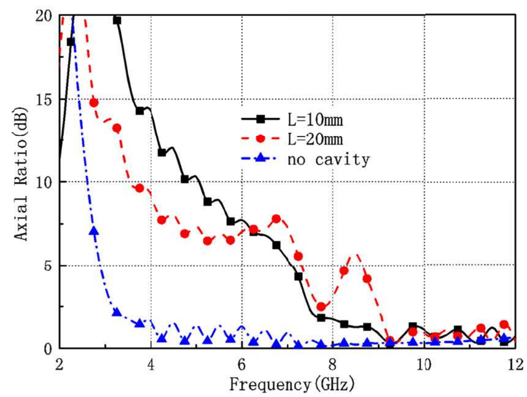

Figure 3. Axial ratio of the cavity backed planar spiral antenna versus frequency with different cavity depths.

point. The radial distance from the center point to a point on each arm is defined by the formula:

$$\begin{aligned} r_1(\varphi) &= r_0 + \frac{2w}{\pi}\varphi \\ r_2(\varphi) &= r_0 + \frac{2w}{\pi}(\varphi - \pi) \end{aligned} \tag{1}$$

where the inner radius is $r_0 = 1.5\,\text{mm}$, and the spiral arm width is $w = 0.4\,\text{mm}$. The planar Archimedean spiral is backed by a cavity with a diameter $D = 42\,\text{mm}$. Antennas with different cavity depths ($L = 10\,\text{mm}$, $20\,\text{mm}$ and no cavity) are simulated and compared.

Figure 2 shows the broadside gain of the cavity backed planar spiral antenna. When the cavity depth is 20 mm, due to the effects of the E-field cancellation between the cavity reflection field and the front radiation field, and the influence of the resonant modes in the semi-closed cavity structure, the broadside gain degrades from 7 GHz to 10 GHz.

Figure 3 shows the axial ratio versus frequency. The axial ratios of the cavity backed planar spiral are big especially at the lower frequency band. This is because the cavity reflection amplifies the terminal truncation effect. When the countercurrent flows back to the working region from the big end, the inverted circular polarized field will be radiated. When the current flows from the small end, the same circular polarized radiation will be activated.

Figure 4 shows the WoW (wobble of the wave) of the planar spiral antenna at the elevation angles

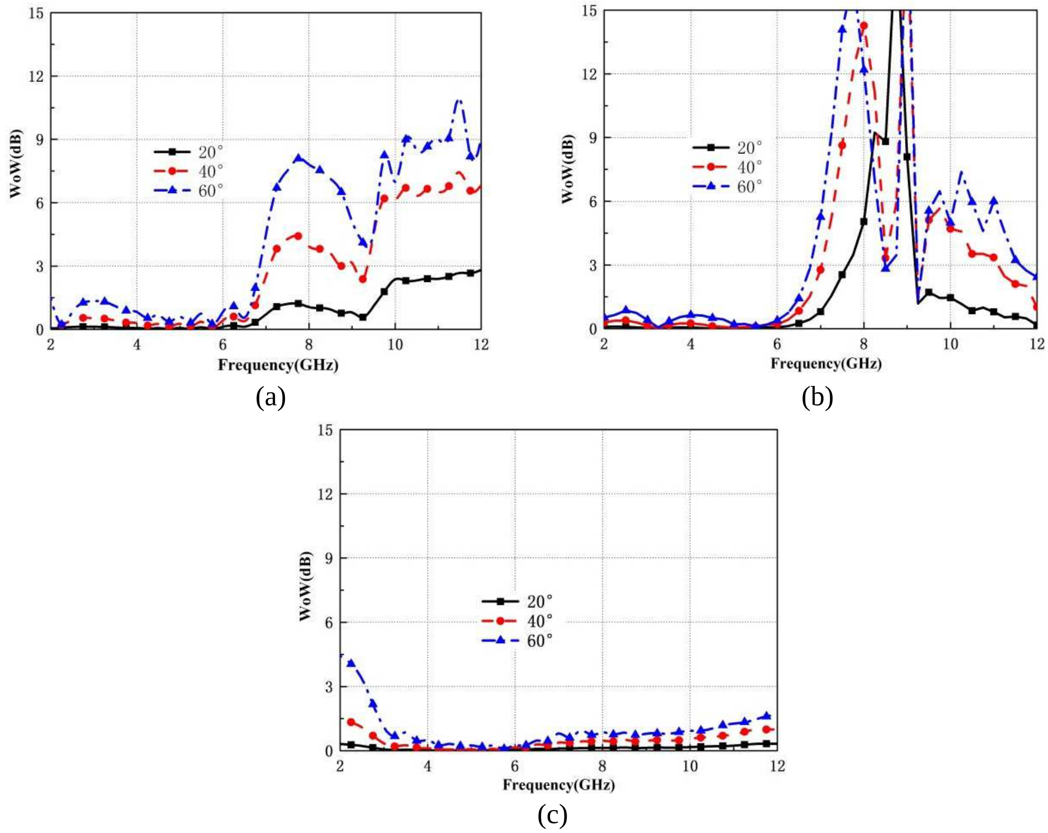

Figure 4. WoW of the cavity backed planar spiral antenna versus frequency with different cavity depths. (a) $L = 10\,\text{mm}$. (b) $L = 20\,\text{mm}$. (c) No cavity.

from 20° to 60° off broadside. The WoW is a measure of the pattern symmetry and is defined as the difference between maximum and minimum gains over all azimuth angles at a given elevation angle. The smaller the WoW is, the better the pattern symmetry is. As shown in Figure 4, the WoW of the cavity backed spiral antenna is almost below 3 dB at low frequency band ($< 6.8\,\text{GHz}$). But when the frequency is higher than 7 GHz, the WoW becomes bigger. Since current distributions of the second order modes (as shown in Figure 5) on one spiral and on the adjacent spiral are out of phase for a balanced fed two arms spiral antenna. The radiation of the second order mode is restrained. When the frequency is higher than 7 GHz, the third order modes can be activated. The radiation of the third order mode would degrade the pattern symmetry.

The WoW of the 20 mm-deep cavity backed spiral has more severe rises than the 10 mm's at band (7–9.3 GHz). The reason is that for a semi-closed structure, some resonant modes can be activated at this frequency band and these resonant modes can produce transverse E-field component. Such modes have greater effects on pattern symmetry. While the cavity depth is 10 mm, the resonant modes (below 12 GHz) can only produce Z-directional E-field component and the Z-directional E-field is perpendicular to the E-field of the spiral antenna, so the influence on the pattern symmetry can be ignored.

From 9.3 GHz to 12 GHz, the antenna with 20 mm deep cavity has better pattern symmetry than the one with 10 mm deep cavity. The reason is that the resonant modes with transverse E-field cannot be activated at this band in the 20 mm deep cavity and the other effects, such as the terminal truncation effect and the radiation of the higher spiral modes, are weaker than the 10 mm cavity's.

Figure 6 shows some samples of the far-field patterns at 7.5 GHz (Figure 6(a)) and 10 GHz (Figure 6(b)). An overlay of 72 different azimuthal cuts for $\phi = 0°$ to 355° in step of 5° is shown. This provides a good method to visualize the pattern symmetry by the spread of azimuthal cuts at a specific elevation angle. When there is no cavity backed, the spread of azimuthal cuts is small. So the pattern is very symmetrical. On the contrary when the planar spiral is backed by a cavity, the wide

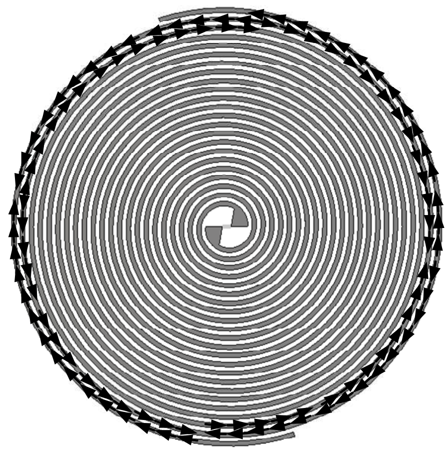

Figure 5. The current distribution of the second order mode.

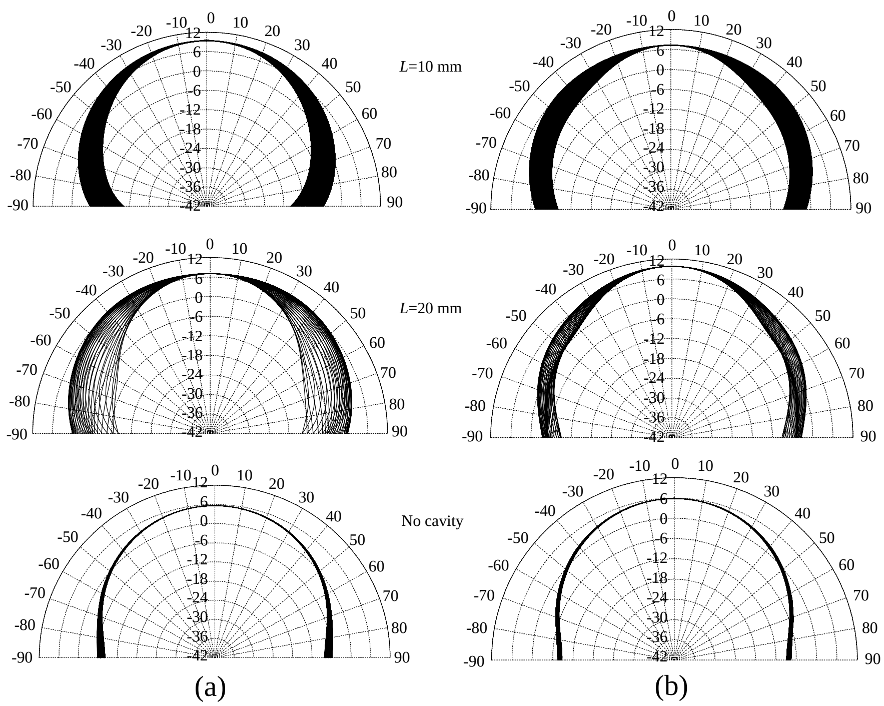

Figure 6. Far-field radiation patterns at (a) 7.5 GHz and (b) 10 GHz with different cavity depths.

spread shows that the far-field patterns become asymmetrical.

The big reflection of back radiation by the cavity has great influence on the far-field. These influences can be categorized to four effects: the first one is the reflection field amplifies the terminal truncation effect; the second one is the reflection field will directly add to the front radiation field; the third one is the reflection field may activate higher order modes on the spiral at higher band; and the last one is that some resonant modes of the semi-closed cavity which produce transverse E-field may be activated too.

According to the above analysis, we know that the back radiation is the power source of these effects, and the cavity is the structure to affect this radiation. Then we can conclude that there are two main methods to improve the far-field symmetry. One is to control the reflection from the cavity; the other is to reduce or to restrain the back radiation. Filling absorber in the cavity and using spiral cavity [7] are both belonging to the first kind. If we could restrain the back radiation, the cavity effect can be weakened. So in this paper, we design a novel configuration to improve the pattern symmetry, which belongs to the second kind. The center section of planar Archimedean spiral is replaced by a structure which could produce a unidirectional circular polarization far-field. So the back radiation of the higher frequency band can be reduced and then the symmetry bandwidth can be widened.

3. IMPROVED CONFIGURATION

Now we know that the back radiation of the planar spiral is the power source which causes the far-field asymmetry. And more higher order radiation modes could be activated at the higher frequency band. So if we can restrain the back radiation at the higher frequency band, the higher order modes will be restrained. The conical spiral antenna which produces unidirectional symmetrical circular polarization far-field can meet these demands. So we try to use the conical spiral to work at the high frequency band. A novel configuration composed of a conical spiral and a planar spiral is shown in Figure 7. The center section is substituted by a conical spiral, and the outer section remains the planar spiral. The conical spiral arms are connected with the planar spiral arms. The radius is a little bit bigger than the inner radius of the planar spiral, so the electric current can flow through smoothly.

The conical spiral arms are defined as:

$$\begin{aligned} r_1(\varphi) &= r_{0c} e^{\frac{\sin\theta_0}{\tan\alpha}\varphi} \\ r_2(\varphi) &= r_{0c} e^{\frac{\sin\theta_0}{\tan\alpha}(\varphi-\pi)} \end{aligned} \tag{2}$$

where cone angle $\theta_0 = 15°$, spiral angle $\alpha = 79°$. The conical spiral antenna is also self-complimentary.

To validate that this novel configuration can improve the pattern symmetry, antennas with cavity depth $L = 20$ mm and with three different center section radii (7 mm, 10 mm and 13 mm) are simulated. The broadside gain, axial ratio and WoW are compared.

Figure 8 shows the broadside gains of the improved configuration. While the frequency is higher than 6 GHz, the first trough of $R = 7$ mm, 10 mm and 13 mm is at about 8.4 GHz, 7.5 GHz and 6.8 GHz respectively. This is because the resonant frequency of the first resonant mode which produces transverse E-field moves to the lower frequency band with the increase of the center section radius. And the back radiations of this novel structure at these frequencies have become weak, so these troughs are much small.

Figure 9 shows that the axial ratios are almost below 3 dB while the frequency is higher than 5 GHz. And the 3 dB axial ratio band becomes wider with the increase of the center section radius. The reason

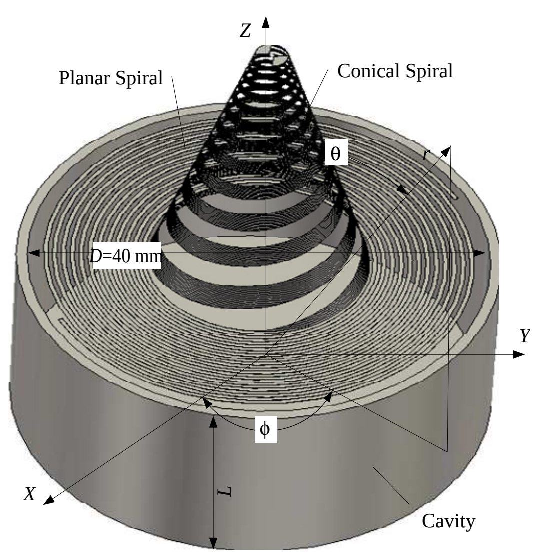

Figure 7. Configuration of the improved cavity backed spiral antenna.

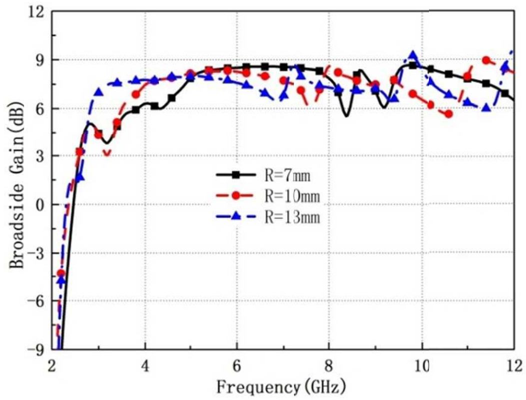

Figure 8. Broadside gain of the improved antenna versus frequency for different center section radii.

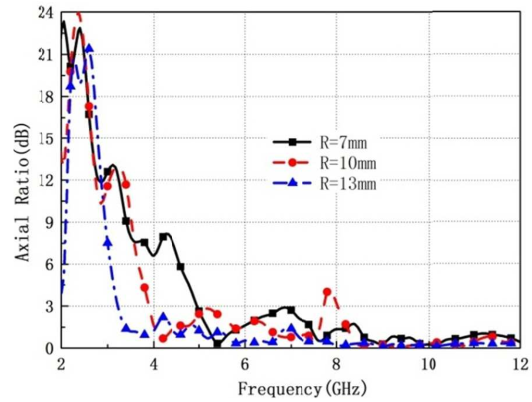

Figure 9. Axial ratio of the improved antenna versus frequency with for different center section radii.

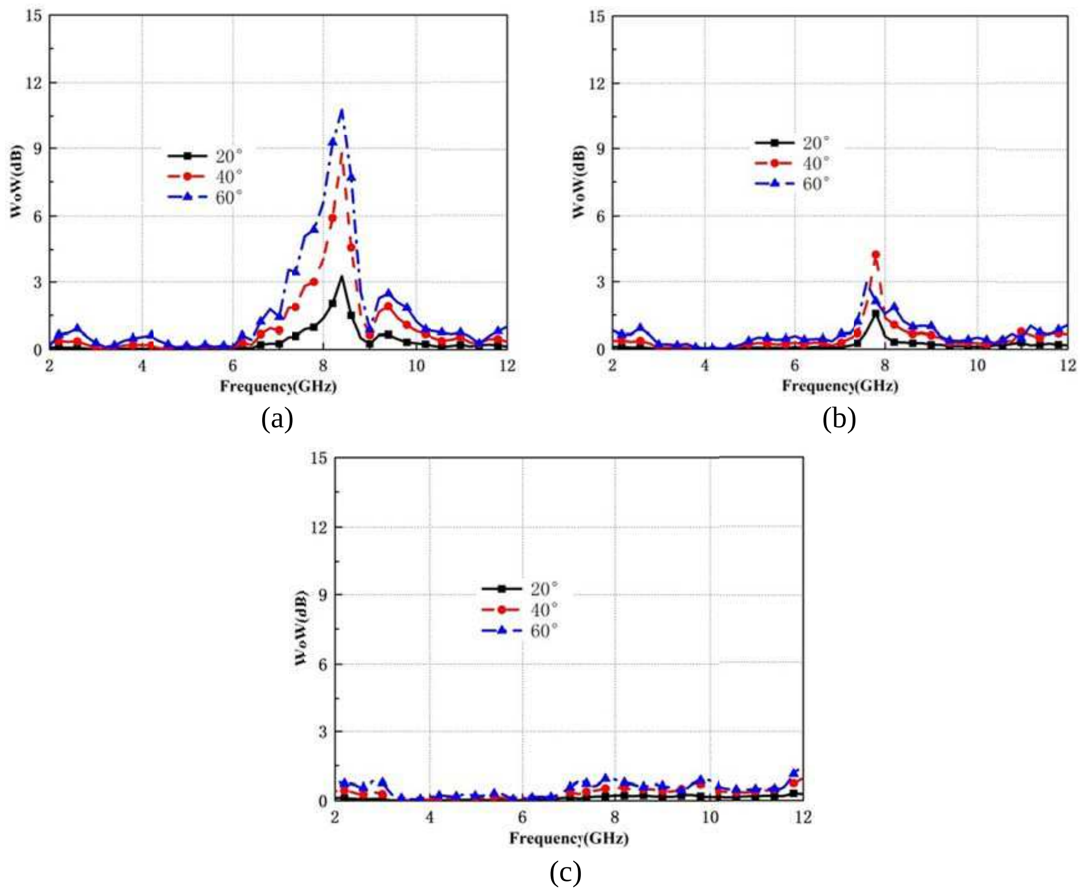

Figure 10. WoW of the improved antenna versus frequency with different center section radii. (a) $R = 7\,\text{mm}$. (b) $R = 10\,\text{mm}$. (c) $R = 13\,\text{mm}$.

is that the larger the radius of the center section is, the back radiation at more low frequency is reduced. Then the cavity effects are weaker too.

Figure 10 shows the WoW of the novel spiral antenna at the elevation angles from 20° to 60° off broadside. The results of three different center section radii ($R = 7\,\text{mm}$, $10\,\text{mm}$ and $13\,\text{mm}$) are compared. When the center section radius is 7 mm, since the back radiation is still big at band (7–

9 GHz), the third order modes can be activated and the resonant frequency of resonant mode of the semi-closed cavity is at about 8.4 GHz. All these effects make the patterns asymmetry at this band. While the center section radius is 10 mm, due to the same reasons, there is a bulge at about 7.8 GHz. The back radiation becomes smaller, so the bulge is smaller than the $R = 7$ mm's. The far-field pattern becomes more symmetric. And there are two small indentations in the 3D pattern at about 40°, so the WoW at 60° is lower than the WoW at 40° at 7.8 GHz. The WoW is all below 3 dB at the whole band while the center section radius is 13 mm. The WoW improves with the increase of the radius of the center section. But when the center section radius increases, the antenna height will increase. So we need to make a balance between the performance and the antenna height in a practical application.

Figure 11 shows some samples of the far-field pattern of improved structure for three different center section radii at 7.5 GHz (Figure 11(a)) and 10 GHz (Figure 11(b)). An overlay of 72 different azimuthal cuts for $\phi = 0°$ to 355° in steps of 5° is shown. At 7.5 GHz the spread is reduced with the growth of the center section radius and the pattern achieves much better symmetry than the cavity backed planar spiral.

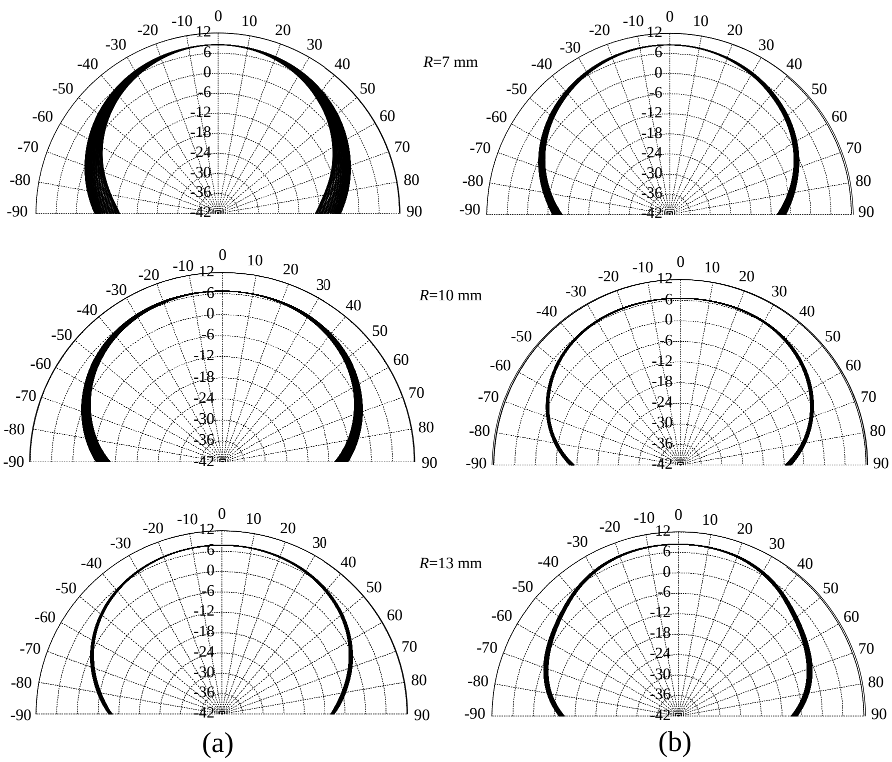

Figure 11. Far-field radiation patterns at (a) 7.5 GHz and (b) 10 GHz for different center section radii.

4. CONCLUSION

In this paper, we analyze the reasons of the far-field pattern asymmetry of the cavity backed planar spiral antenna, and a method to improve the pattern symmetry is proposed. By reducing the back radiation, an improved spiral antenna configuration is designed. Its inner planar spiral is replaced by a conical spiral. The results show that this novel configuration can achieve better pattern symmetry at a wider bandwidth.

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