Low-profile Equiangular Spiral Antenna Based on an Artificial Magnetic Conductor Reflector

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Abstract. In this paper, a low-profile equiangular spiral antenna is designed. The bi-directional beam from an equiangular spiral antenna (EAS) is changed to a unidirectional beam using an artificial magnetic conductor (AMC) reflector. The antenna height, measured from the upper surface of the AMC reflector to the spiral arms, is chosen to be extremely small to realize a low-profile antenna: 0.07 wavelength at the lowest analysis frequency of 3 GHz. The analysis shows that the EAS backed by the AMC reflector does not reproduce the inherent wideband axial ratio characteristic observed when the EAS is isolated in free space. To solve this problem, the AMC reflector is modified by gradually removing the patch elements from the center region of the reflector. The results show that the spiral antenna with a modified artificial magnetic conductor reflector reduces the axial ratio in the working frequency band from 3 to 10 GHz, and greatly broadens the working bandwidth of the spiral antenna. A viable way is proposed to optimize the performance of the low-profile equiangular spiral antenna without change the dimensions.

1. Introduction

It is known that an equiangular spiral (EAS) antenna isolated in free space operates as a wideband antenna that radiates a bi-directional circularly polarized (CP) beam [1]. Recent numerical studies have shown that when the EAS is backed by an extremely shallow conducting cavity (0.07 wavelength), which transforms the bi-directional beam into a unidirectional beam, the inherent wideband antenna characteristics deteriorate. To mitigate this deterioration, the authors have proposed the insertion of arc-shaped strip absorbers (ABSs) into the cavity [2]. It has been shown that the ABSs contribute to restoring the inherent wideband EAS antenna characteristics. However, this is achieved at the cost of radiation efficiency, because some of the power is absorbed by the ABSs. This paper solves the above mentioned issue regarding the frequency characteristics of the low-profile equiangular spiral antenna, without using ABSs. For this solution, an artificial magnetic conductor (AMC) plate is used as a reflector in place of the conducting cavity.

2. Low-profile equiangular spiral antenna

Our goal is to design a circularly polarized low-profile equiangular spiral antenna that operates from 3 GHz to 10 GHz. Figure 1 shows the configuration of the equiangular spiral antenna. The two arms are symmetric with respect to the center and are wound to be self-complementary [3]. The parametric equation of an equiangular spiral antenna is:
\[ r_1 = r_0 e^{\alpha \phi} \]  
\[ r_1' = r_0 e^{\alpha (\phi - \delta)} \]  
\[ r_2 = r_0 e^{\alpha (\phi - \pi)} \]  
\[ r_2' = r_0 e^{\alpha (\phi - \pi - \delta)} \]

where \( r_0 \) is a constant; \( r_0 \) is the arm growth constant; \( \delta \) is the angular width of the spiral antenna. Other parameters of the spiral antenna: \( a = 0.35, r_0 = 2\, \text{mm}, \varphi = 2.806\pi \).

2.1 Equiangular spiral with a PEC reflector
A bi-directional beam can be transformed into a unidirectional beam by placing a plate that is a perfect electric conductor (PEC) [4] behind the radiation element. Based on this simple idea, first, we analyze an equiangular spiral antenna with a PEC reflector. The PEC reflector is square and the side length is 140 mm. The antenna arms are located at height \( h_{\text{PEC}} \) above the reflector surface, as shown in Figure 2. Three representative cases, each having small antenna height \( h_{\text{PEC}} = 5\, \text{mm}, 7\, \text{mm}, \text{and } 9\, \text{mm}, \) which are all less than one quarter wavelength at the lower operating design frequency.

![Figure 1. Equiangular spiral.](image1)

![Figure 2. Equiangular spiral above a PEC reflector.](image2)

![Figure 3. Frequency response of the axial ratio for \( h_{\text{PEC}} = 5\, \text{mm}, 7\, \text{mm}, \text{and } 9\, \text{mm}. \)](image3)

It can be seen from Fig 3 that when the PEC is used as an antenna reflector, the axial ratio is seriously deteriorated. The closer the reflector is to the antenna, the worse the axial ratio. Based on the above simulations, an artificial magnetic conductor structure is attempted to reduce the axial ratio of severely deteriorating frequency bands while maintaining the low profile of the original antenna.

2.2 Equiangular spiral with an AMC reflector
The geometry of proposed wideband planar AMC unit cell is shown in Figure 4. It consists of a flower patch and four unconnected similar bow-shape arms on an FR4 (the dielectric constant is 4.4 and tan loss tangent is 0.02) substrate with a thickness of 2.4 mm. The length of the unit cell lunit is 9 mm,
radius of the circular patch R is 3.2mm and r is 2.1mm, the gap between circular patch and arms w is 0.4 mm and the angle of the similar bow-shape arm v is 80 deg.

![Figure 4. Geometry of the proposed AMC unit cell.](image)

In general, the operating frequency band of AMC is defined as the frequency band in which the reflection phase of AMC is between $\pm 90^\circ$ [5]. The simulated reflection magnitude and phase of the proposed AMC surface under normal incidence is shown in Fig5. It is obvious that the proposed AMC surface could work in the frequency band of 6.2-8.4GHz (relative bandwidth 30.1%) and in the working frequency band, the reflection amplitude of the AMC surface remains within 1 dB, which indicates a good in-phase and low-loss performance of the proposed AMC surface.

![Figure 5. Reflection magnitude and phase of the proposed AMC surface.](image)

The model of a low-profile equiangular spiral antenna loaded with an artificial magnetic conductor structure is shown in Figure6(a). The AMC reflector is the periodic structure of $16 \times 16$. 
Figure 6. (a). Equiangular spiral antenna above an AMC reflector. (b). Frequency response of the axial ratio for $h_{\text{AMC}}=5\text{ mm}, 7\text{ mm}, \text{and }9\text{ mm}$. Figure 6(b). shows the variation of the axial ratio with frequency when the distance between the AMC reflector and the spiral antenna is different. It can be seen that the axis ratio of the antenna after AMC loading is significantly reduced in the operating frequency band, but the axial ratio may suddenly deteriorate at a certain frequency. This is because the reverse current of the spiral arm (the current flowing from the end of the arm to the feed point) creates an unwanted cross-polarization part (left circular polarized wave), but the current flowing from the feed point to the end of the spiral arm is a right-hand circular polarization wave that is generated by the forward current[6].

2.3 Equiangular spiral with a modified AMC reflector

In this subsection, we modify the original AMC reflector, as shown in Figure 7(a), creating a space below the spiral by removing only the patches (the dielectric substrate remains). This space reduces the mutual effects between the antenna arms and the AMC reflector.

Figure 7 (a). Equiangular spiral backed by a modified AMC reflector. (b). Frequency response of the axial ratio for $h=7\text{ mm}$, the reflectors are PEC, AMC, and modified AMC, respectively.

Figure 7(b) compares the axial ratio when the reflectors are PEC, AMC, and modified AMC, respectively. It can be seen that the AMC reflector can significantly optimize the axial ratio, but there is a sudden increase in the axial ratio between 7 GHz and 8 GHz. The improved AMC reflector solves this problem and shows a good axial ratio over the entire operating frequency band.

3. Conclusion

This paper first analyzes low-profile planar equiangular spiral antennas with a metal conductor as reflector. It is found that the antenna has poor axial ratio performance. By loading a artificial magnetic conductor structure, the axial ratio is optimized within 3-9 GHz while maintaining the low profile of the original antenna, but a sudden increase in the axial ratio occurs between 7-8 GHz. To solve this problem the AMC reflector is modified by gradually removing the patch elements from the center region of the reflector. The improved structure solves the problem of axial ratio abrupt changes and
exhibits a good axial ratio over the entire frequency band. This design method also provides a research direction for optimizing the performance of a low profile equal angle spiral antenna without changing the external dimensions.

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