A Modified PEC-backed Spiral Antenna with Improved Pattern Symmetry

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***Abstract*—This paper discussed the pattern symmetry of a two-arm Archimedean spiral antenna which is designed to operate over the Ultra-Wide band (UWB) frequency range of 3.1 GHz to 10.6 GHz. The geometrical design of the spiral antenna is simulated and executed using CST Microwave Studio (CST MWS) software. The simulated radiation performances such as radiation pattern, maximum and minimum 3 dB beamwidth, current distribution and gain have been analyzed. The results are compared in three conditions; in free space (with no ground plane), above a solid PEC ground plane, and above a modified PEC ground plane (with circular patterns). Both the PEC reflectors are placed below the spiral antenna with a separation distance of $\lambda/4$ at lower frequency f_{low} = 3.1 GHz, center frequency f_{center} = 6.85 GHz, and higher frequency f_{high} = 10.6 GHz of UWB. It is shown that the spiral antenna above the modified PEC backing provides an overall better performance, giving a unidirectional radiation pattern with high gain and improved pattern symmetry compared to the other two configurations.**

***Index Terms*—Archimedean spiral antennas; Frequency independent antennas; Pattern symmetry; PEC reflector; Spiral antennas; Ultra-Wide band (UWB).**

I. INTRODUCTION

Antenna plays an important role in communication system as a device which transmits and/or receives electromagnetic energy with directional and polarization properties that are suitable for the intended application. In this paper, spiral antennas, which belong to the travelling wave and frequency independent antennas category, have been discussed.

Spiral antennas also belong to the Radio Frequency (RF) antennas, which were first developed in 1954 by Edwin Turner [1]. Spirals have the advantages above all other antennas in providing a very wide bandwidth. These antennas exhibit bidirectional radiation pattern with similar gain in the lower and upper hemisphere (left-hand and right-hand circular polarization). Spiral antennas are widely used for sensing applications in defense industry, military aircraft, GPS, satellite system, radar system and medical applications. A backing cavity, such as a perfect electrical conductor (PEC) reflector is usually added to the back of the spiral in order to provide a unidirectional radiation pattern and a high gain. However, the pattern symmetry of the spiral deteriorated with the presence of the backing cavity.

In this paper, an Archimedean spiral antenna is designed to operate within the frequency range of 3.1 GHz to 10.6 GHz. As issued by the Federal Communication Commission (FCC) in 2002, these frequencies fall under the Ultra-Wide band (UWB) frequency range [2]. The spiral is then placed above a modified PEC ground plane, which is shown to provide higher gain than the antenna in free space, and enhanced pattern symmetry compared to the solid PEC-backed antenna.

II. METHODOLOGY & DESIGN OF THE SPIRAL ANTENNA

The geometrical design of a two-arm Archimedean spiral antenna is executed and simulated using CST Microwave Studio (CST MWS) software [3]. The arms of the spiral are designed based on the lower frequency f_{low} = 3.1 GHz and higher frequency f_{high} = 10.6 GHz of UWB.

Next, a circular solid PEC ground plane is placed below the spiral with a separation distance of $\lambda/4$ at the designed frequency to increase the gain of the antenna and provide a unidirectional radiation pattern [4, 5] (as shown in Figure 1).

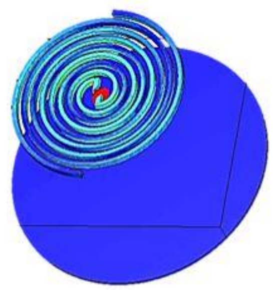
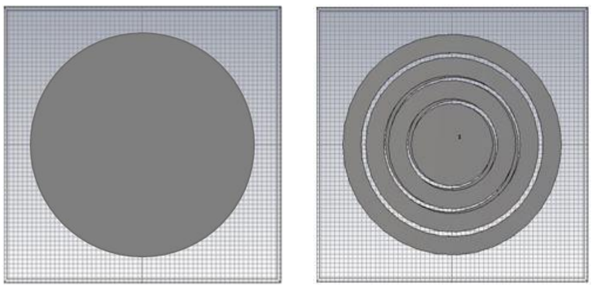


Figure 1: Archimedean spiral antenna above a solid PEC ground plane with $\lambda/4$ separation at the designated frequency. The geometrical parameters are as follows; outer diameter d_o = 15.4 mm, inner diameter d_i = 4.5 mm, spacing s = 0.64 mm, width w = 0.64 mm, number of turns N = 4, thickness t = 1 mm, and gap g = 1.92 mm.



(a) (b)

Figure 2: (a) Solid PEC ground plane, and (b) Modified PEC ground plane with circular patterns.

The solid PEC (Figure 2(a)) is then modified in order to enhance the pattern symmetry of the antenna which has been degraded due to the addition of the ground plane. Figure 2(b) shows the proposed modified PEC ground plane with circular patterns that has been analyzed for this paper.

III. SIMULATION RESULT

First, the frequency of the antenna is chosen to be between 3.1 GHz to 10.6 GHz, which falls under Ultra-Wide band category. The results in this paper are analyzed at three different frequencies; lower frequency f_{low} = 3.1 GHz, center frequency f_{center} = 6.85 GHz, and higher frequency f_{high} = 10.6 GHz of UWB. The geometrical design of the spiral antenna is then executed based on the selected frequency range. The outer and inner radius of the spiral can be calculated by using Equation (1) and Equation (2) respectively.

$$f_{low} = \frac{c}{2\pi r_2} \quad (1)$$

$$f_{high} = \frac{c}{2\pi r_1} \quad (2)$$

where:
- c = speed of light = 3×10^8 m/s
- f_{low} = lower frequency
- f_{high} = higher frequency
- r_1 = inner radius of spiral antenna
- r_2 = outer radius of spiral antenna

The pattern asymmetry of the antenna can be calculated by using Equation (3) [6];

$$\Delta\emptyset = \emptyset_{3\text{dB max}} - \emptyset_{3\text{dB min}} \quad (3)$$

where:
- $\Delta\emptyset$ = pattern asymmetry
- $\emptyset_{3\text{dB max}}$ = maximum 3 dB beamwidth
- $\emptyset_{3\text{dB min}}$ = minimum 3 dB beamwidth

The Archimedean spiral antenna starts to radiate when the circumference, C of the spiral is equal to one wavelength ($C = \lambda$). This region is known as the active region of the spiral [6, 7]. Higher order modes for the Archimedean spiral antenna are possible since the structure is made large enough to support the flow of excessive currents at odd multiple of a wavelength, i.e. $C = 3\lambda, 5\lambda, \ldots$ [7] The active region and higher order modes at 3λ and 5λ for the spiral antenna at 3.1 GHz, 6.85 GHz and 10.6 GHz are tabulated in Table 1.

Table 1
The circumference (mm) of the active region and higher order mode region of Archimedean spiral antenna at frequencies 3.1 GHz, 6.85 GHz and 10.6 GHz.

Frequency	Active region ($C = \lambda$)	Higher order mode ($C = 3\lambda$)	Higher order mode ($C = 5\lambda$)
3.1 GHz	94	282	470
6.85 GHz	44	132	220
10.6 GHz	28	84	140

Practically, due to reflections from the end of the spiral arms, the low frequency point, f_{low} will exhibit high axial ratio. This reflection can be reduced by adding conductivity loss to some portion of the outer turn of each arm, or by applying resistive loading at the end of each arm.

The antenna is initially designed as a free space structure. The surface current distribution of the spiral antenna in free space can be observed in Figure 3. The highest 3D maximum current distribution is allocated at the lower frequency of 3.1 GHz with 85.63 A/m, while the lowest 3D maximum current distribution is observed at the higher frequency of 10.6 GHz with 61.7 A/m.

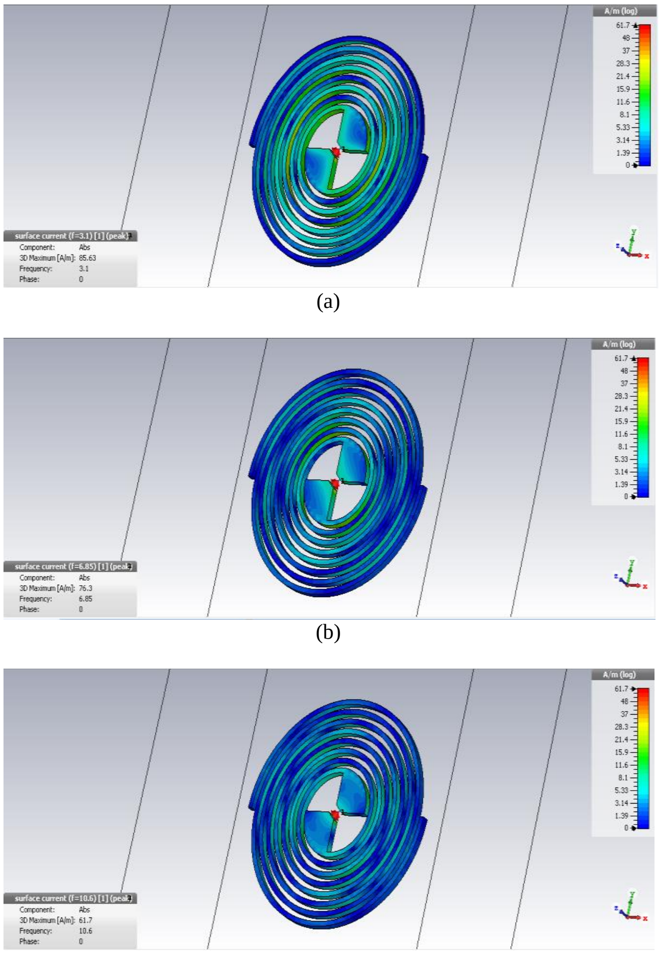


Figure 3: Simulated current distribution of Archimedean spiral antenna in free space at (a) 3.1 GHz, (b) 6.85 GHz, and (c) 10.6 GHz.

Next a solid PEC ground plane is inserted a quarter-wavelength away at the selected frequencies (i.e. $\lambda/4$ at 3.1 GHz, $\lambda/4$ at 6.85 GHz, and $\lambda/4$ at 10.6 GHz). This step is performed in order to improve the gain of the free space spiral. However, the addition of the cavity destroys the pattern symmetry of the antenna. Thus, the solid PEC is then modified by applying circular patterns to the structure (as shown in Figure 2(b)) to improve the pattern symmetry.

Table 2 shows the simulated maximum and minimum 3 dB beamwidth ($\emptyset_{3\text{dB max}}$ and $\emptyset_{3\text{dB min}}$) of the Archimedean spiral antenna in free space, above a solid PEC ground plane, and above a modified PEC ground plane with circular patterns. By using Equation (3), $\Delta\emptyset$ is then calculated and tabulated in Table 3. The results show that the antenna in free space provide a pattern asymmetry of 14.6°, 6.1° and 22.5° at frequencies 3.1 GHz, 6.85 GHz and 10.6 GHz, respectively.

Table 2

Simulated ($\emptyset_{3dB\ max}$ / $\emptyset_{3dB\ min}$)of Archimedean spiral antenna in free space, above a solid PEC ground plane, and above a modified PEC ground plane at 3.1 GHz, 6.85 GHz, and 10.6 GHz.

Frequency	Free space	Solid PEC	Modified PEC (circular patterns)
3.1 GHz	112.5° / 97.9°	82.6° / 77.7°	90.1° / 85.5°
6.85 GHz	79.5° / 73.4°	78.8° / 69.8°	81.9° / 76.1°
10.6 GHz	79.3° / 56.8°	100.2° / 43.9°	86.3° / 51.1°

Table 3

Calculated pattern asymmetry of Archimedean spiral antenna in free space, above a solid PEC ground plane, and above a modified PEC ground plane at 3.1 GHz, 6.85 GHz, and 10.6 GHz (by using Equation (3) and result Table 2).

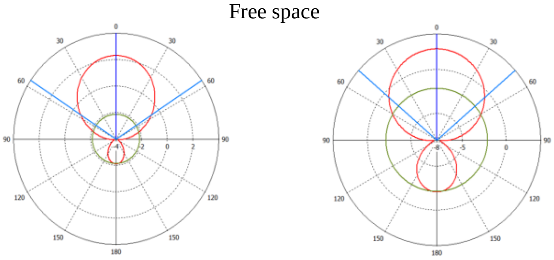
Frequency	Free space	Solid PEC	Modified PEC (circular patterns)
3.1 GHz	14.6°	4.9°	4.6°
6.85 GHz	6.1°	9.0°	5.8°
10.6 GHz	22.5°	56.3°	35.2°

Table 4

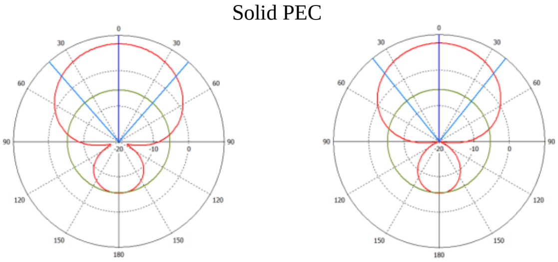
Simulated right-hand circular polarization (RHCP) of Archimedean spiral antenna in free space, above a solid PEC ground plane, and above a modified PEC ground plane at (a) 3.1 GHz, (b) 6.85 GHz, and (c) 10.6 GHz.

$\emptyset_{3dB\ max}$	$\emptyset_{3dB\ min}$

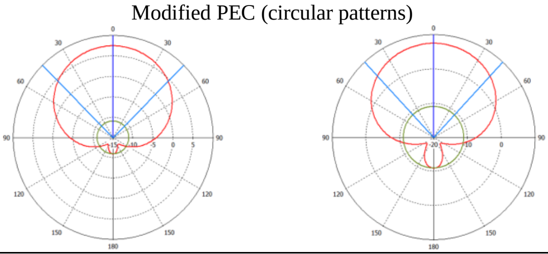
Free space



Solid PEC



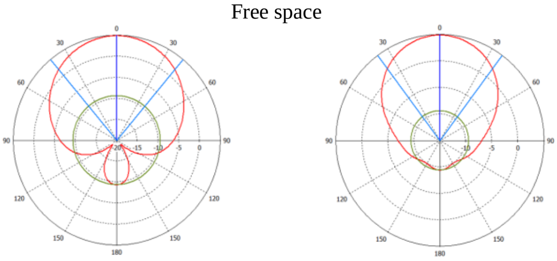
Modified PEC (circular patterns)



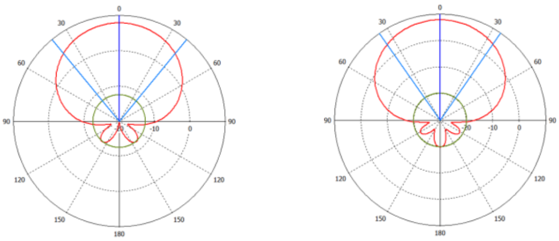
(a) 3.1 GHz

$\emptyset_{3dB\ max}$	$\emptyset_{3dB\ min}$

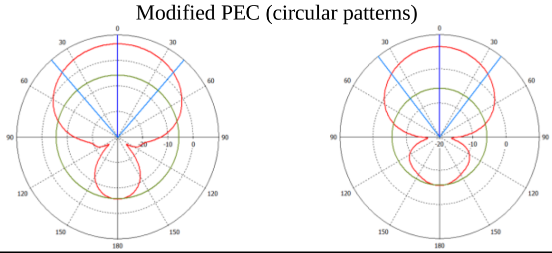
Free space



Solid PEC



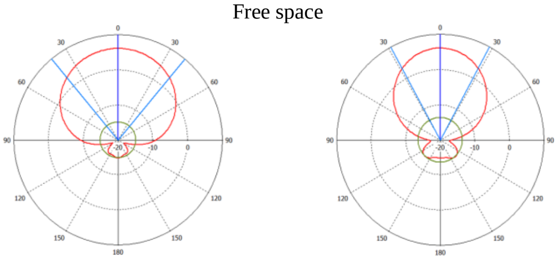
Modified PEC (circular patterns)



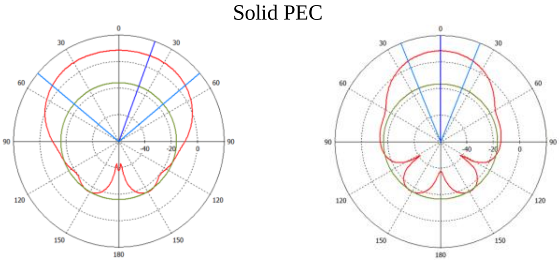
(b) 6.85 GHz

$\emptyset_{3dB\ max}$	$\emptyset_{3dB\ min}$

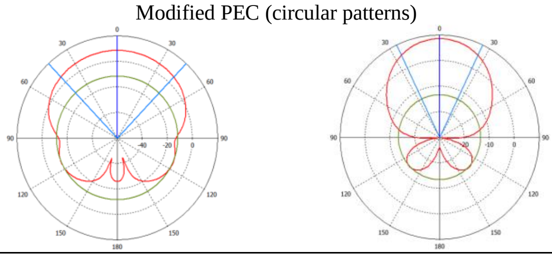
Free space



Solid PEC



Modified PEC (circular patterns)



(c) 10.6 GHz

As explained earlier, when a solid PEC ground plane is added to the back of the antenna, there is an increase in the pattern asymmetry $\Delta\emptyset$, at 6.85 GHz (9.0°) and 10.6 GHz (56.3°). The reason for the degradation of the pattern symmetry is due to the antenna structure that is physically large enough to support higher order modes at 3λ and 5λ (refer Table 1). Therefore, an attempt to improve the pattern symmetry is done by inserting circular slots (circular patterns) to the solid PEC ground plane. The results have shown that the pattern asymmetry of the solid PEC-backed spiral has been reduced from 9.0° to 5.8° at 6.85 GHz, and from 56.3° to 35.2° at 10.6 GHz by using the modified PEC structure. The simulated far field result (right-hand circular polarization (RHCP)) of the Archimedean spiral antenna at $\emptyset_{3dB\ max}$ and $\emptyset_{3dB\ min}$ in free space, above a solid PEC ground plane, and above a modified PEC ground plane with circular patterns at the three designed frequencies can be observed in Table 4.

Table 5
Simulated gain (dBi) of Archimedean spiral antenna in free space, above a solid PEC ground plane, and above a modified PEC ground plane at 3.1 GHz, 6.85 GHz, and 10.6 GHz.

Frequency	Free space	Solid PEC	Modified PEC (circular patterns)
3.1 GHz	2.31	7.58	7.43
6.85 GHz	4.85	7.84	6.44
10.6 GHz	6.07	8.59	8.54

Table 5 shows the simulated gain for the antenna in free space and above the two ground planes. It is shown that the unbacked antenna provide low gains at frequencies 3.1 GHz (2.31 dBi), 6.85 GHz (4.85 dBi) and 10.6 GHz (6.07 dBi). The gain of the antenna increases when either a solid PEC or a modified PEC backing is added to the back of the antenna; the solid PEC provide 7.58 dBi (3.1 GHz), 7.84 dBi (6.85 GHz) and 8.59 dBi (10.6 GHz), while the modified PEC provide 7.43 dBi (3.1 GHz), 6.44 dBi (6.85 GHz) and 8.54 dBi (10.6 GHz).

Table 6
Summary of overall performances of Archimedean spiral antenna in free space, above a solid PEC ground plane, and above a modified PEC ground plane at 3.1 GHz, 6.85 GHz, and 10.6 GHz.

	Frequency	Free space	Solid PEC	Modified PEC
$\emptyset_{3dB\ max}$	3.1 GHz	112.5°	82.6°	90.1°
	6.85 GHz	79.5°	78.8°	81.9°
	10.6 GHz	79.3°	100.2°	86.3°
$\emptyset_{3dB\ min}$	3.1 GHz	97.9°	77.7°	85.5°
	6.85 GHz	73.4°	69.8°	76.1°
	10.6 GHz	56.8°	43.9°	51.1°
Pattern asymmetry	3.1 GHz	14.6°	4.9°	4.6°
	6.85 GHz	6.1°	9.0°	5.8°
	10.6 GHz	22.5°	56.3°	35.2°
Gain	3.1 GHz	2.31	7.58	7.43
	6.85 GHz	4.85	7.84	6.44
	10.6 GHz	6.07	8.59	8.54

Table 6 shows the overall performances of Archimedean spiral antenna in free space, above a solid PEC ground plane, and above a modified PEC ground plane at 3.1 GHz, 6.85 GHz, and 10.6 GHz, in terms of $\emptyset_{3dB\ max}$, $\emptyset_{3dB\ min}$, pattern asymmetry and gain. It can be observed that the modified PEC configuration provide an overall better performance, giving a unidirectional radiation and higher gain compared to the antenna in free space, and with better pattern symmetry as compared to solid PEC ground plane, at all targeted frequencies.

IV. CONCLUSION

This paper discussed the pattern symmetry of a two-arm Archimedean spiral antenna which is designed to operate in the UWB frequency range. The analysis is done at three different frequencies; lower frequency f_{low} = 3.1 GHz, center frequency f_{center} = 6.85 GHz, and higher frequency f_{high} = 10.6 GHz of UWB. Spiral antennas exhibit bidirectional radiation pattern with equal energy in both lower and upper hemisphere. A solid PEC ground plane is usually added to provide a unidirectional radiation and high gain. Nevertheless, this degrades the pattern symmetry of the antenna at higher frequencies due to the additional current that exist in the higher order modes region. Thus, the PEC ground plane is modified by inserting circular rings to disrupt the current on the backing cavity. Results have shown that the proposed configuration provide an overall better performance, where the pattern asymmetry has been reduced from 9.0° to 5.8° at 6.85 GHz, and from 56.3° to 35.2° at 10.6 GHz, and still maintain a unidirectional radiation pattern with high gain at the designed frequencies, i.e. 6.44 dBi (6.85 GHz) and 8.54 dBi (10.6 GHz). The proposed antenna configuration can be used in many communication systems such as sensing applications in defense industry, military aircraft, GPS, satellite system, radar system and medical applications, which could potentially provide a wideband performance with symmetrical patterns.

ACKNOWLEDGMENT

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