A design of Archimedean spiral antennas applied in passive radar

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ABSTRACT

Currently, spiral antennas are widely studied and applied for both military and civilian purposes. However, ensuring that the antenna system operates effectively across a wide frequency range while still meeting gain and directionality requirements is a complex problem. In this article, the authors present the results of research and design of spiral antennas operating in the 2 to 4 GHz frequency range (S band). The analysis of operating principles, calculations, and simulations using CST 2019 software demonstrates that the antenna system operates over a broad frequency range, meeting the requirements of passive radar stations.

Keywords: Passive radar; Spiral antenna.

1. INTRODUCTION

Passive radar systems are a class of radar systems that detect and track targets by receiving and processing waves emitted by the target itself to determine its location and coordinates. Passive radars offer several significant advantages, foremost being their undetectability by radio reconnaissance systems. Unlike active radars, passive radars do not emit any radio waves, making them invisible to radar detection systems, as they rely solely on receivers with wideband multi-channel antenna systems. Consequently, the receiving antenna of a passive radar system must operate across a wide frequency range to detect and locate targets operating at different frequencies.

Existing passive radar antenna designs often incorporate various types of antennas, including horn antennas, parabolic antennas, array antennas, dipole antennas and spiral antennas. Among these, spiral antennas are widely used for diverse applications. In [1-2], a log-periodic antenna with a wide operating frequency range is used; however, the radiation pattern does not concentrate energy in a single direction, and the side lobe levels are high. In [3], a patch antenna with a compact size is used; however, it has a narrow operating bandwidth and high losses. In [4], a dipole antenna is used, featuring a simple structure but with a narrow operating frequency range and a large reflector size. In [5-7], the antenna is designed for a wide frequency range, utilizing internal absorbing materials, resulting in a complex structure with low directivity. In [8] and [9], the antenna is designed for narrow frequency range and low directivity. In [10], the antenna is designed for the 2÷18 GHz frequency range, with a controlled standing wave ratio (VSWR) and ensured directivity; however, the side lobe level is high at certain frequencies. The antenna in [11] is designed for the 1÷9 GHz frequency range, featuring a complex structure with multiple spirals, but its directivity remains low (greater than -2 dBi). To address these issues, the research team proposes an antenna design with a reduced number of spirals and the incorporation of open spaces in the casing to minimize size and enhance directionality. This approach enables the achievement of highly directional radiation patterns in both planes and low side lobe levels, meeting the requirements of passive radar systems. This paper presents the research findings and design for a spiral antenna operating in the 2 ÷ 4 GHz frequency band (S-band).

2. PROBLEMS

2.1. Calculation and design of Archimedean spiral antenna

The Archimedean spiral antenna is a common spiral antenna structure, which can be flat, circular or rectangular in shape. The design of these antennas can be done on a printed circuit board or as a wired connection in free space. The housing used to support the antenna can be a metal cylinder with a depth of λ/4, where λ corresponds to the center frequency of the operating band. On the broad side, to achieve a unidirectional pattern, the spiral antenna is mounted above a reflector or an absorbing container. A perfectly conducting reflector should be at an optimal distance of λ/4 from the antenna. The basic structure of a 2-arm Archimedean spiral antenna is shown in figure 1 below. The input impedance can be determined using Babinet's principle.

$$Z_{metal}Z_{air} = \frac{\eta^2}{4} \tag{1}$$

Where, η is the characteristic impedance of the antenna's surroundings.

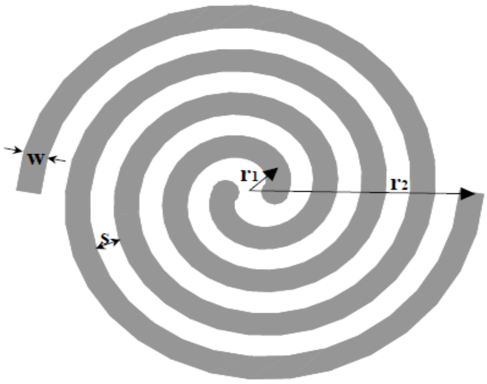


Figure 1. *Shape of the Archimedean spiral antenna.*

For a free-space Archimedean spiral antenna, the input impedance will be:

$$Z_{in} = \frac{\eta_0}{2} = 188.5\Omega \tag{2}$$

In the Archimedean spiral antenna design, each arm of the spiral is linearly proportional to the angle and is determined by:

$$r = r_0\varphi + r_1 \text{ và } r = r_0(\varphi - \pi) + r_1 \tag{3}$$

where, r_1 is the inner radius of the spiral. The proportionality constant is determined from the width of each arm (w) and the distance between turns (s), which for a spiral is given by:

$$r_0 = \frac{s + w}{\pi} = \frac{2w}{\pi} \tag{4}$$

The width between the turns is determined by:

$$s = \frac{r_2 - r_1}{2N} - w = w \tag{5}$$

The Archimedean spiral antenna radiates from a region whose circumference is half a wavelength. This is called the active region of the spiral. Each arm of the spiral is phase-shifted by 180^0, so that when the circumference of the spiral is one wavelength, the currents at additional points or on each arm of the spiral will be in phase with each other in the far field. The low-frequency operating point of the spiral is theoretically determined by the outer radius.

$$f_{low} = \frac{c}{2\pi r_2} \tag{6}$$

Similarly, the high frequency operating point of the spiral is theoretically determined by the inner radius:

$$f_{high} = \frac{c}{2\pi r_1} \tag{7}$$

In practice, the low frequency point will be larger than expected, due to reflections from the end of the spiral. Reflections can be reduced by using a resistive load at the end of each branch or by adding additional power loss to the outer loop of each branch. Additionally, the high frequency limit may be smaller than expected, due to the feed band effect.

2.2. Balun calculation and design for Archimedean spiral antenna

The structure of the designed Balun is shown in figure 2. The Balun can perform impedance conversion at the input and output, so as to match the required impedance. Baluns play an important role in distributing power from the input to the spiral, ensuring proper impedance. The author used Balun with Rogers RT5880 dielectric substrate ε_1 and thickness e.

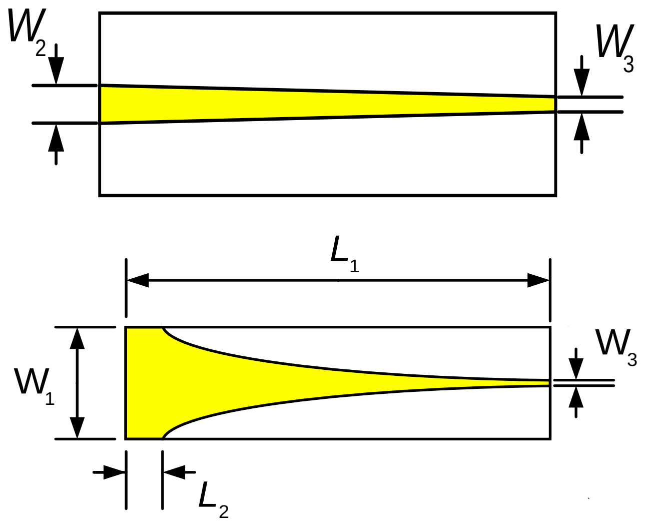


Figure 2. *Top and bottom view of the designed Balun.*

Both the top and bottom leads of the Balun are designed to be tapered, from the unbalanced input port to the equal width balanced parallel strip at the output. The change in characteristic impedance with distance is determined by the formula:

$$\ln Z(z) = \frac{1}{2}\ln(Z_0 Z_L) + \frac{\Gamma_0}{\cosh A} A^2 \varphi\left(\frac{2z}{L} - 1, A\right) \tag{8}$$

With $0 \le z \le L$.

Where: $\varphi(x, A) = -\varphi(-x, A) = \int_0^x \frac{I_1 A\sqrt{1-y^2}}{A\sqrt{1-y^2}} dy$, with $|x| \le 1$ and $I_1(x)$ is a modified Bessel function.

3. RESULTS AND DISCUSSION

3.1. Define design requirements

The derived spiral antenna parameters are based on the calculations and system design of S-band passive radar. The spiral antenna design problem is carried out with the specification presented in table 1.

Table 1. *Spiral antenna specifications.*

№	**Technical parameters**	**Unit**	**Required value**
1	Operating frequency range	GHz	2 ÷ 4
2	Standing wave ratio (VSWR)		≤ 2.5
3	Gain	dBi	≥ 1
4	Beamwidth at -3 dB	Degree	$60^0 \pm 30^0$

The problem is to design an small size antenna with high directivity while still ensuring the operating frequency range. Therefore, the authors used Rogers RT5880 dielectric substrate ε_2 and thickness g with low loss and created an open space inside with box walls (heigh h and radius d) as shown in figure 3.

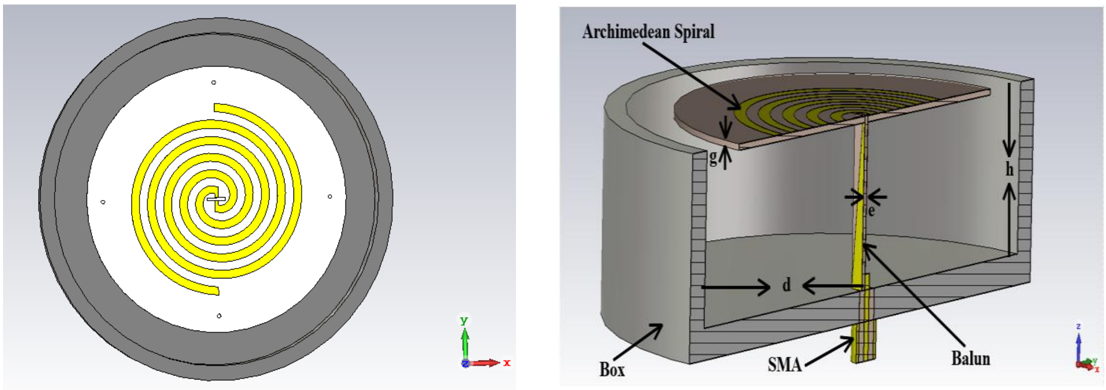


Figure 3. *3D model of spiral antenna on CST simulation software.*

Build a 3D model of the spiral antenna with basic size parameters after optimization as shown in table 2.

Table 2. *Basic dimensions of spiral antenna.*

№	**Parameters**	**Value**	**№**	**Parameters**	**Value**	**№**	**Parameters**	**Value**
1	s (mm)	2.4	6	W_2 (mm)	3.5	11	ε_2	2.2
2	w (mm)	1.3	7	W_3 (mm)	1.3	12	e (mm)	1.6
3	r_1 (mm)	2.99	8	L_1 (mm)	101.2	13	g (mm)	0.8
4	r_2 (mm)	32.91	9	L_2 (mm)	2	14	h (mm)	22
5	W_1 (mm)	13	10	ε_1	2.2	15	d (mm)	45

3.2. Calculation results

Figure 4 to figure 8 shows the calculation and simulation results of the designed spiral antenna on CST software.

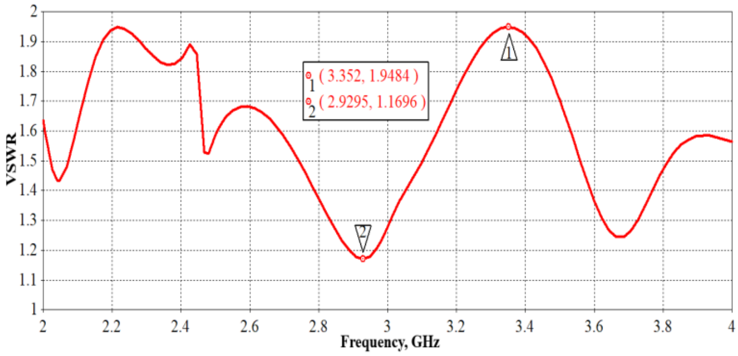
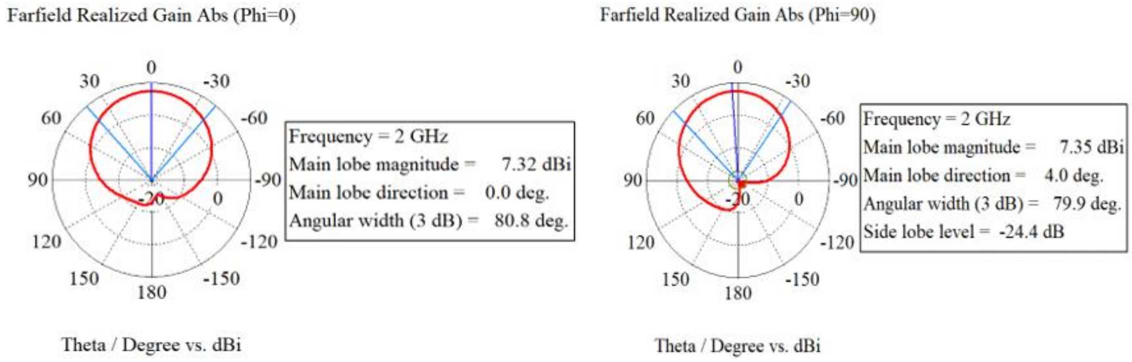


Figure 4. *Standing wave ratio of the designed spiral antenna.*

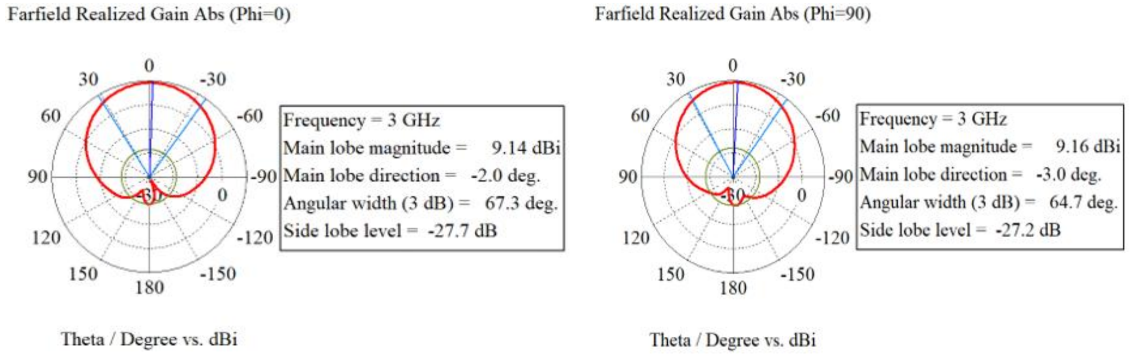
In figure 4, the standing wave ratio of the antenna is less than 2 in the frequency range of 2 ÷ 4 GHz, which is good for passive radar stations. The radiation pattern at 2 GHz is shown in figure 5.



a) in plane E *b) in plane H*

Figure 5. *Simulation results, calculated radiation pattern at f = 2 GHz.*

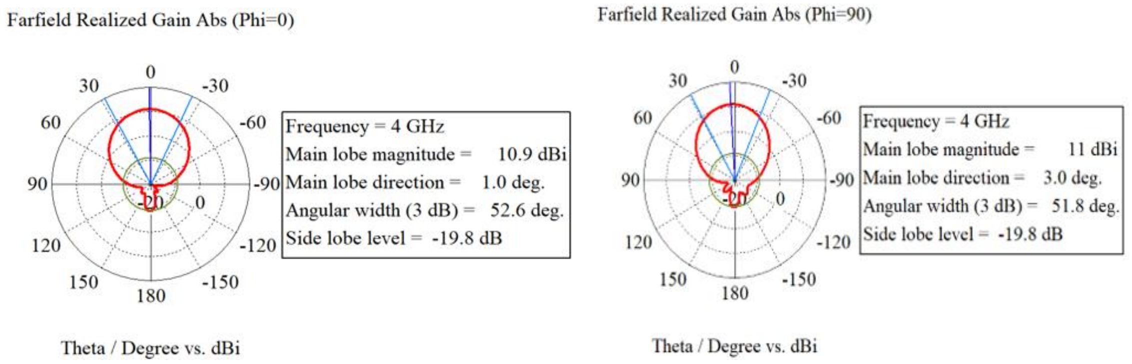
In figure 5, the antenna gain in both planes is 7.3 dBi and the side lobe level is less than -24.4 dB. The radiation pattern at 3 GHz is shown in figure 6.



a) in plane E *b) in plane H*

Figure 6. *Simulation results, calculated radiation pattern at f = 3 GHz.*

From figure 6, the antenna gain in both planes is 9 dBi and the side lobe level is less than -27.2 dB. The radiation pattern at 4 GHz is shown in figure 7.



a) in plane E *b) in plane H*

Figure 7. *Simulation results, calculated radiation pattern at f = 4 GHz.*

From figure 7, the antenna gain in both planes is 11 dBi and the side lobe level is less than -

19.4 dB. The antenna gain results in the 2 ÷ 4 GHz band are shown in figure 8.

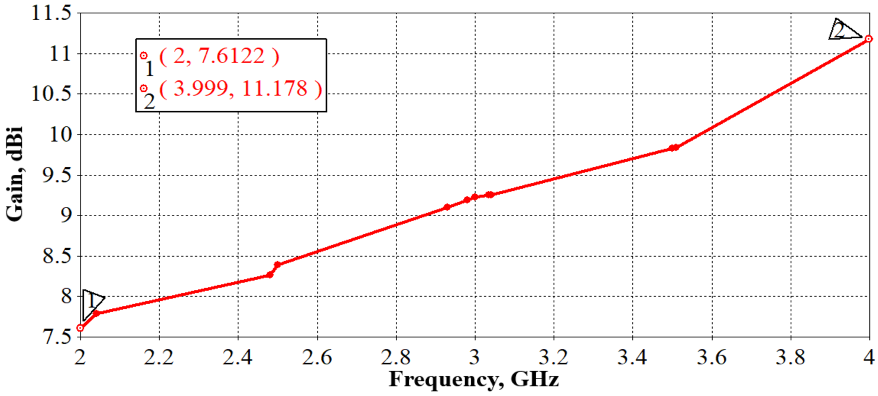


Figure 8. *Gain of a spiral antenna.*

From figure 8, the antenna gain is greater than 7 dBi in the 2 ÷ 4 GHz range.

Tables 3 and 4 present the results of the spiral antenna calculations and compare them with some published antenna types.

Table 3. *Spiral antenna calculation results.*

№	Technical parameters	Unit	Required value	Simulation results
1	Frequency range	GHz	2 ÷ 4	2 ÷ 4
2	Standing wave ratio (VSWR)		≤ 2.5	≤ 1.95
3	Gain	dBi	≥ 1	≥ 7
4	Beamwidth at -3 dB	Degree	$60^0 \pm 30^0$	$60^0 \pm 20{,}8^0$

Table 4. *Comparison of the proposed spiral antenna with some published types.*

№	Operating frequency range (GHz)	Standing wave ratio (VSWR)	Gain (dBi)	Dimension (mm)
[1]	1.4 ÷ 12	≤ 2	≥ 4.5	115 x 72.2
[2]	0.5 ÷ 6	≤ 2	≥ 4.6	170 x 160
[3]	2.5	1.12	≥ 8.49	46.5 x 0.6
[4]	1.89 ÷ 2.48	≤ 2	≥ -20	1000 x (0.22 ÷ 1)λ_0
[5]	2 ÷ 18	≤ 1.8	≥ -2.65	50 x 17.5
Article	**2 ÷ 4**	**≤ 1.95**	**≥ 7**	**90 x 22**

3.3. Analysis of calculation results

The simulation results show that the method of creating an open space inside the box shell is clearly effective. The calculation results show that the technical parameters meet the requirements. To evaluate objectively, the authors compared the calculation results of the proposed antenna with some published types. From the comparison results, it can be seen that the proposed antenna not only meets the requirements of compact size but also ensures high standing wave coefficient and gain coefficient in the operating frequency range. Published results show that, if the standing wave ratio result is good, the directivity remains low.

4. CONCLUSIONS

The authors have provided an overview of the calculation and design of a spiral antenna with a proposed structure that uses fewer turns and incorporates open space in the shell to reduce size and increase gain. By analyzing the theoretical basis of spiral antenna types and performing simulations using CST software, the antenna's performance was evaluated against published designs. The calculation results demonstrate that the antenna meets the technical requirements for passive radar stations. These findings lay the groundwork for further research and design of antennas for passive radar applications, ensuring operation across a wide frequency range while meeting size and directionality requirements.

REFERENCES

[1]. Kwanhatai Pojang, Paitoon Rakluea, *"The design of Log Periodic Dipole Array Antenna for WLAN/LTE/UWB Applications,"* ISCIT (2018).

[2]. Abdulghafor A.Abdulhameed, Zdenek Kubik, *"Design a Compact Log-Periodic Biconical Dipole Array Antenna for EMC Measurements,"* MDPI (2022).

[3]. Rao Kashif, Oluwole John Famoriji, Fujang Lin, *"Design and Modeling of S band circular patch and Ka band horn antenna, intergration with future multifunctional radio over fiber network,"* Open Journal of Antennas and Propagarion, (2017).

[4]. Jui-Hung Chou, Ding-Bing Lin, Che-Hsu Lin, Hsueh-Jyh Li, *"S-Band circularly polarized crossed dipole antenna for automotive applications,"* Proceedings of the international symposium on antennas & propagation, (2013).

[5]. Muhammad Hamza, Wasif T. Khan, *"Hybrid Utilization of Loading Techniques and Cavity Groove for Performance Enhancement of the UWB (2–18 GHz) Spiral Antenna,"* International Journal of Antennas and Propagation. (2018).

[6]. H. Kim, K. Hwang, Hyeong-Seok Kim, *"Cavity-backed Two-arm Spiral Antenna with a Ring-shaped Absorber for Partial Discharge Diagnosis,"* Journal of Electrical Engineering & Technology. (2013).

[7]. Seungyong Park, Kyung Young Jung, *"Design of a circularly-polarized UHF Antenna for Partial Discharge Detection,"* IEEE Access. (2020).

[8]. Hisamatsu Nakano, Tomoki Abe, Junji Yamauchi, *"Circularly Polarized Conical Radiation from a metaspiral antenna,"* Taiwan Microwave Association. (2021).

[9]. Yuan Yao, Qiuyue Ge, Junsheng Yu, Xiaodong Chen, *"A Novel antenna for UHF RFID near-field applications,"* MDPI. (2021).

[10]. Mashury Wahab, Yussi Perdana Saputera, Yuyu Wahyu, *"Design and Realization of Archimedes Spiral Antenna for Radar Detector at 2-18 GHz Frequencies,"* Research Centre for Electronics and Telecommunications of The Indonesian Institute of Sciences. (2013).

[11]. Jiang Ming, Song Lizhong, *"Design and Experimental Research on a Miniaturized Archimedean Spiral Antenna,"* Mechanical and Electrical Technology IV. (2012).

TÓM TẮT

Thiết kế ăng ten xoắn ốc Archimedean ứng dụng trong ra đa thụ động

Hiện nay, ăng ten xoắn ốc được nghiên cứu và ứng dụng rộng rãi trong mục đích quân sự và dân sự. Tuy nhiên, để đảm bảo hệ thống ăng ten hoạt động trong dải tần số rộng, đồng thời vẫn đáp ứng được hệ số khuếch đại và độ định hướng là một bài toán phức tạp. Trong bài báo này, nhóm tác giả trình bày kết quả nghiên cứu và thiết kế ăng ten xoắn ốc hoạt động trong dải tần số từ 2 đến 4 GHz (băng tần S). Kết quả phân tích nguyên lý hoạt động, tính toán và mô phỏng trên phần mềm CST 2019 cho thấy hệ thống ăng ten hoạt động trong dải tần số rộng, đáp ứng được yêu cầu trong các đài ra đa thụ động.

Từ khóa: Radar thụ động; Ăng-ten xoắn ốc.