Archimides multiband micro ribbon spiral antenna for energy harvesting

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ABSTRACT

The current need to conserve natural resources and find new ways to advance without damaging the environment has led to the search for different energy sources. In this sense, the availability of radio frequency (RF) energy is found as a favorable option for new energy sources. This work describes the design of a microstrip antenna for the collection of radiofrequency energy in the megahertz band. Using the automatic optimization software computer simulation technology (CST) Studio, a circular spiral antenna is simulated using the low-cost FR4 substrate with a thickness of 1.57 mm and copper as the conductive material with a thickness of 0.035 mm. The proposed design presents resonance frequencies in multiple bands from 550 MHz to 1900 MHz, with bandwidths between 15 MHz and 150 MHz. The antenna design is based on the resonant cavity model and presents circular polarization due to its design coil type, with modified geometry using symmetrical orthogonal slots to generate multiple working bands. The design of this antenna can capture the power emitted by the frequency bands used in mobile telephony, radio communications, broadcasting, and television.

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1. INTRODUCTION

The rapid advances and growing demand for wireless systems have driven the development of telecommunications technologies, including 3G, 4G and 5G networks. Among these advances is the development of antennas, especially microstrip antennas due to their compact characteristics, low cost, simple construction, and ability to be integrated with electronic devices. However, they have narrow bandwidth (BW) characteristics [1]–[4]. In recent years, numerous investigations have been presented on the geometry, materials and utilities that can be given to this type of antennas such as; microstrip antennas for sensors [5]–[7], antennas with vertical or horizontal slots have also been designed [8]–[11] to improve parameters such as BW, the gain and the radiation pattern. The latter corresponds to the strength of the electromagnetic (EM) fields emitted by the antenna in a given direction, expressed in a polar diagram [12], [13].

Antenna arrays have also been designed to improve the above parameters [14]–[17]. Another application of microstrip antennas is the harvesting of wireless or radio frequency (RF) energy circulating in the environment, also known as (EH) for its acronym in English (energy harvesting). EH consists of exploiting the energy dissipated by RF systems and is based on the conversion of EM waves into direct current (DC) electricity [11], [18]–[21]. These antennas are coupled to a rectifier circuit that converts the RF waves to DC, and the combination of these two elements is known as a rectenna [22]–[26]. The rectennas are mainly used for charging low power sensors, for power systems in the internet of things (IoT).

The rectennas can minimize the environmental impact caused by the use of batteries, and they can be used in remote locations where access for battery replacement and maintenance is difficult [4], [23], [27]–[31]. The antennas are essential elements for the RF EH systems, since they are the ones that capture the EM waves that will later be directed to the rectifier and converted into DC. For this reason, it is important to design antennas that operate in multiple bands so that RF waves can be received from any nearby emitting source, such as transmitters, base stations, repeater antennas, and routers [32]–[35]. Some investigations have been based on the study of fractal-type antennas, which correspond to geometric, irregular or fragmented structures that are repeated at different scales [36], [37].

The concept of fractal antenna originated in 1950 with the French mathematician Benoit B. Mandelbrot, a French mathematician, observed in nature the self-similar repetitive forms that were repeated on a different scale with respect to the main structure [38]. The word fractal comes from the Latin word fractus (to break into pieces) [39]. This type of geometries increases the resonant frequencies, improves the BW when making antenna arrays and allows the miniaturization of the structure, as in [23] where a rectangular antenna is designed with Koch fractal geometries (slots with different order of iteration), with this antenna a BW of 2.15 GHz and 2.9 GHz was obtained. Other authors present a simple antenna design with arrow-shaped slots in the radiating patch to collect energy in the LTE band to feed IoT sensors, the proposed design presents three types of resonant frequencies at 1.73 GHz, 2.47 GHz and 2.53 GHz. For the global system for mobile communications (GSM) bands, a fractal loop antenna is designed to enclose the radiating patch to resonate in the 1.8 GHz band to take a cell tower as a power source [32].

In other research, an iterative star-shaped fractal geometry is used with a semi-elliptical slotted ground plane to achieve a resonant frequency response of 5.6 GHz, 8.5 GHz, 14.3 GHz, and 18 GHz [40]. Similarly, fractal structures such as square and circular resonant rings have been investigated; this type of structure is easy to design, in addition, they also generate multiple working bands and allow antenna designs to resonate at frequencies in the MHz band and GHz without the need for significantly large antennas. For example, a hexagonal and split-ring antenna is designed using a low-cost substrate (FR4) to operate in the 2.4 GHz, 3.4 GHz and 5.8 GHz bands, which belong to the industrial scientific and medical (ISM) band [41]. Other authors analyzed three structures of multilayer rectangular coils in spirals in order to minimize the variation of the magnetic field and thus concentrate it so that its flux is directed uniformly over the created spirals and improve the efficiency of the coil antenna [42]. Likewise, in another study, a monopole antenna with a textile substrate together with a coil was proposed to improve the efficiency and miniaturize the size of this antenna to collect the maximum amount of energy [4].

On the other hand, using the low-cost FR4 substrate, a multi-band antenna with complementary split ring resonator (CSRR) is designed to collect RF in the 1.8 GHz, 2.1 GHz, WiFi. 2.45 GHz and 2.6 GHz bands [19]. As a result, the results that fractal geometries generate when applied to the design of microstrip antennas, such as easy fabrication, low cost, light weight and easy integration with microwave circuits and coupling to low power sensor systems, This type of antennas can be useful for the capture of RF energy and the transfer of wireless energy or wireless power transmission (WPT), which consists of the transfer of wireless energy by means of antennas, this type of technology is viable when antenna designs with square resonator ring or coil ring geometries are used [15]–[17], [43]–[47]. Based on the above characteristics, this paper presents the design of a microstrip antenna with double coil spiral slots as a radiating patch to achieve multiband antenna behavior and thus collect the maximum amount of RF energy circulating in the air. Spiral antennas have been used for sensors and as radio-frequency identification (RFID) tags, however, as a scientific contribution, in this document the simulation of a spiral antenna for wireless energy collection that circulates in the environment is carried out because this geometry has the ability to resonate in multiple bands, it is easy to build and low cost, which makes this an ideal antenna for collecting energy from various RF emission sources compared to the spiral antenna reviews that are carried out in [1]. The design process, simulation and results obtained are obtained as shown in Figure 1.

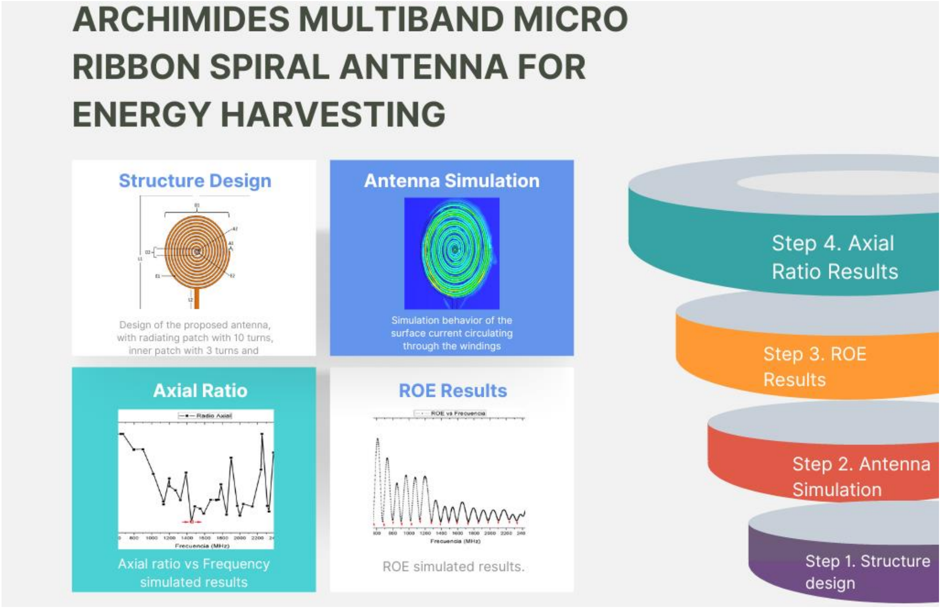


Figure 1. Block diagram of the antenna design process and obtaining results

2. METHOD

Spiral antennas are those that generally have two or more arms, they are usually classified as frequency independent antennas because they are capable of resonating over a wide range of frequencies while maintaining stable polarization, radiation pattern and impedance. The Archimedean spiral is characterized by the fact that the length of the radius increases proportionally to the angle of twist [48]–[50]. It is a flat geometric curve, so when making a physical design, this geometry fits optimally into the substrate used, and the inner radius of the spiral grows linearly with respect to its initial angle [51], [52]. Thus, to perform the design and simulation of this antenna, the computer simulation technology (CST) Studio Suite software is used, which is a powerful 3D EM analysis program for designing, analyzing and optimizing EM components and systems such as antennas, filters, among other types of systems.

In this document, the design of an antenna with spiral geometry is carried out to generate multiple resonance bands for the collection of RF energy from the environment. The design consists of a circular spiral antenna where the separation and number of turns are varied until a multiple band resonance is achieved. After obtaining these multiple bands, a smaller turn is inserted into the main spiral to Improve the resonance in multiple bands and thus adjust parameters such as BW, and impedance and voltage standing wave ratio (VSWR) of the designed antenna. This aspiration added inside the main spiral is known as a parasitic element used in different geometries to adjust parameters in microstrip antennas. The design of the structure is presented below along with the parameters used to obtain the structure and the simulation of its results.

2.1. Structure design

The proposed antenna is designed with the low-cost FR4 substrate, its main characteristics are a relative permittivity (ε_r) of 4.4, a loss tangent of 0.02, the thickness of the substrate (h) is 1.57 mm and the thickness of copper as conductive material. is 0.035 mm. The dimensions of the substrate are 70×70 mm, it consists of 10 turns in the main patch and 3 turns in the inner patch, this multi-band antenna has resonant frequencies at 554 MHz, 675 MHz, 800 MHz, 900 MHz, 1019 MHz, 1135 MHz, 1270 MHz, 1390 MHz, 1490 MHz, 1590 MHz, 1730 MHz, 1850 MHz, 1970 MHz, 2100 MHz, 2240 MHz and 2330 MHz. The BWs of the proposed antenna are 12.8 MHz, 15.9 MHz, 17.6 MHz, 21.0 MHz, 21.0 MHz, 21.0 MHz, 19.3 MHz, 31.1 MHz, 26.1 MHz, 32.8 MHz, 34.5 MHz, 38.0 MHz, 37.9 MHz, 41.3 MHz, 44.7 MHz and 48.1 MHz.

The power line is a coplanar waveguide with an impedance of 50 Ω. The power line is coupled to an SMA female connector to drive the radiating patch. To design the antenna, the basic design equations for microstrip antennas presented below are used, where (W)=patch width, (L)=patch length, (ε_{eff}) (effective dielectric constant), μ_0 the permeability of free space, ΔL (extension length); c is the speed of light $= ([3 \times 10]^8 m/s) f_r$ is the central resonance frequency, and ε_r is the effective substrate index. However, to obtain better results in simulating the S_{11} return loss parameter curve, the values of the dimensions of the radiating structure are modified using the parametric sweep function in the CST Studio simulation software.

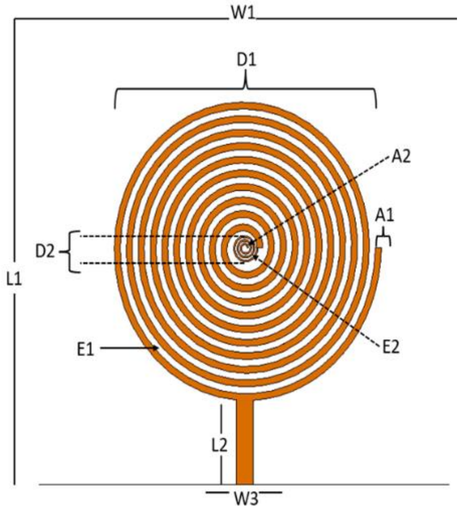
$$w = \frac{c}{2f\sqrt{\frac{\varepsilon_r + 1}{2}}} \tag{1}$$

$$L = \frac{1}{2f_r\sqrt{\varepsilon_{eff}}\sqrt{\mu_0\varepsilon_0}} - 2\Delta L \tag{2}$$

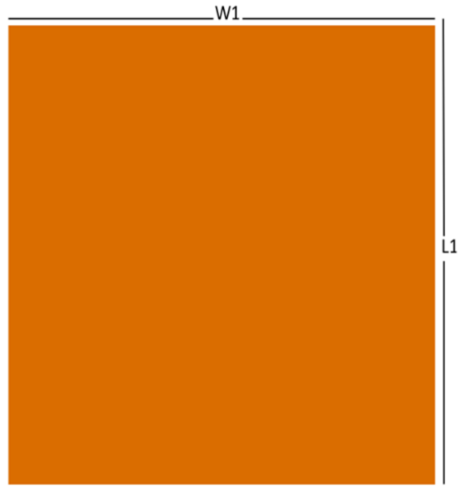
$$\varepsilon_{eff} = \frac{1}{2}(\varepsilon_r + 1) + \frac{1}{2}(\varepsilon_r - 1)\left[\frac{1}{\sqrt{1+12\left(\frac{h}{w}\right)}}\right] \tag{3}$$

$$\Delta L = 0.412h\left[\left(\frac{\varepsilon_{eff}+0.3}{\varepsilon_{eff}-0.258}\right)\left(\frac{\left(\frac{w}{h}+0.264\right)}{\left(\frac{w}{h}+0.813\right)}\right)\right] \tag{4}$$

For the design of the circular spiral, the CST Studio software allows the design of planar, circular, logarithmic, and trapezoidal structures in the Macros section. Figure 2 shows the design of the proposed circular spiral antenna with the design parameters Figure 2(a) main radiating patch of 10 turns, inner circular patch of 3 turns and Figure 2(b) ground plane. Table 1 shows its dimensions along with the design parameters. This way, Figure 2 illustrates the meticulously designed circular spiral antenna using CST Studio software, showcasing its key components: a radiating patch with 10 turns, an inner circular patch with 3 turns, and a ground plane. This depiction provides a detailed visual reference for the antenna’s intricate structure and dimensions, further detailed in Table 1, highlighting the deliberate configuration chosen for optimal performance in specific frequency ranges and intended applications.



(a)



(b)

Figure 2. Design of the proposed antenna: (a) radiating patch with 10 turns, inner patch with 3 turns and (b) ground plane

Table 1. Antenna dimensions

Parameter	Dimension (mm)
Substrate width (W1)	70 mm
Substrate length (L1)	70 mm
Patch diameter (D1)	23 mm
Internal patch diameter (D2)	2.0 mm
Main head coil thickness (A1)	1.0 mm
Internal patch coil thickness (A2)	0.25 mm
Main turning distance (E1)	1.05 mm
Internal lead (E2)	0.30 mm
Power line length (L2)	12.6 mm
Feed line width (W3)	2.8 mm

2.2. Antenna simulation

In relation to simulating the antenna, Figure 3 presents the reflection coefficient portrayed by the (S_{11}) parameters, revealing the resonant frequencies produced by the suggested antenna. At first, basic equations for designing microstrip antennas were utilized, specifically concentrating on a circular design aimed at functioning within the 900 MHz spectrum. Following this, the initial setup was fine-tuned using CST Studio Suite, an advanced three-dimensional analysis and assessment software tailored for EM systems in components. Consequently, Figure 3 demonstrates the reflection coefficient or (S_{11}) parameters, indicating the operational frequencies generated by the proposed antenna.

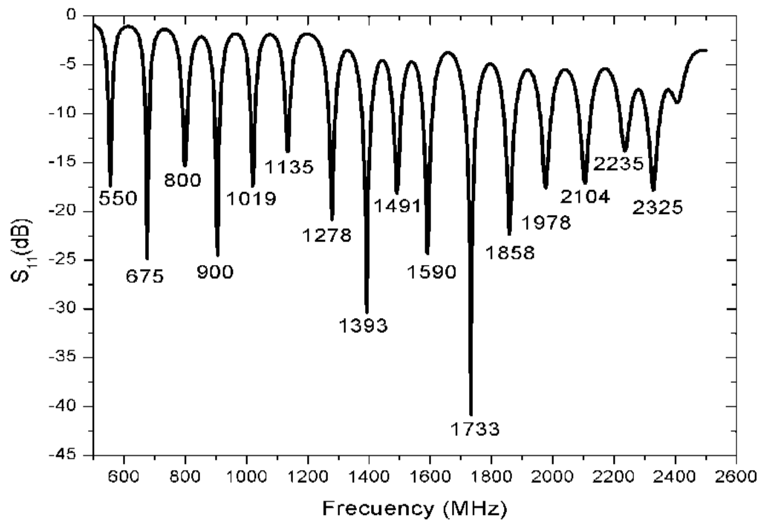


Figure 3. Results of simulation parameters S_{11} resonance frequencies

First, using the basic equations for the design of microstrip antennas mentioned above, an antenna with a circular geometry is modeled to operate initially in the 900 MHz range. The design is then optimized using CST Studio Suite, a powerful 3D analysis and evaluation software for components and EM systems. Designs created in CST Studio can be parameterized with respect to their geometric dimensions or material properties. This makes it possible to evaluate the behavior of a device as its physical and geometric properties change. CST Studio includes several automatic optimization algorithms, both local and global [53]. Local optimizers provide fast convergence, but run the risk of converging to a local minimum rather than the best overall solution. On the other hand, global optimizers search the entire problem space, but they usually require more computations, which could affect the performance of the machine used for the simulation.

After the model is designed in the software, the mesh generation procedure is applied, which can be automatic or manual, before the simulation is started. The simulator uses the algorithm finite integration technique (FIT), trying to ensure greater precision of the results. This is one of the best numerical discretization methods for simulating EM fields. In this part of the design, Maxwell's equations are applied integrally in a set of staggered grids. The use of a dual orthogonal or Cartesian grid together with a hopping or meshing scheme makes the algorithms used more efficient to perform the calculations without compromising the memory of the equipment when performing EM field analysis in RF applications. Based on the results obtained, the square geometry with which the microstrip antenna design process generally begins is changed to a geometry resembling a coil, as shown in Figures 4(a) and (b). Where it can be seen that this design consists of only one coil as a radiating patch with the corresponding dimensions mentioned above in Figure 2(a). Hence, once the antenna model design is completed within the software, the subsequent step involves mesh generation, either automated or manual, before simulation. Utilizing the FIT algorithm for precision, this method effectively applies Maxwell's equations across staggered grids, employing a dual orthogonal or Cartesian grid with a meshing scheme for efficient calculations in RF electromagnetic field analysis. Based on the obtained results, a fundamental shift occurs from the initial square geometry to a coil-like configuration depicted in Figure 4.

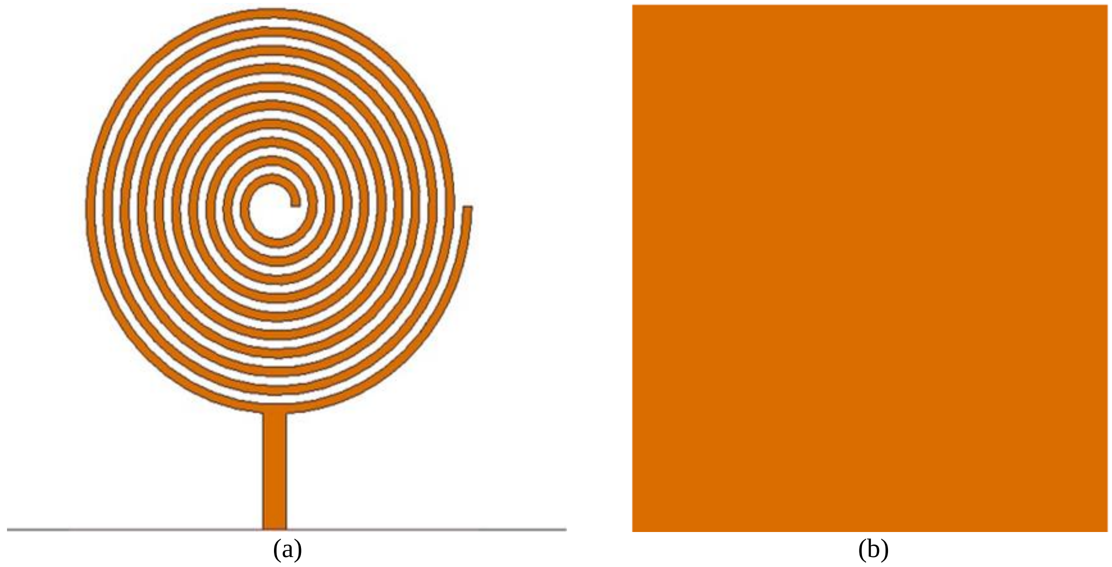


Figure 4. Initial design of the proposed single-turn antenna: (a) spiral radiating patch and (b) ground plane

Figure 5 shows the simulated behavior of the resonance frequency or S_{11} parameter of the initial evaluation of the simulated single-turn antenna in black and the final evaluation of the double-turn antenna in red. It can be seen that the single turn design produces low losses per dB and low resonant frequencies. Adding the smaller inner loop increases the dB losses and creates new resonant frequencies from 1800 MHz to 2400 MHz, increasing the range of possibilities for collecting RF energy from multiple sources.

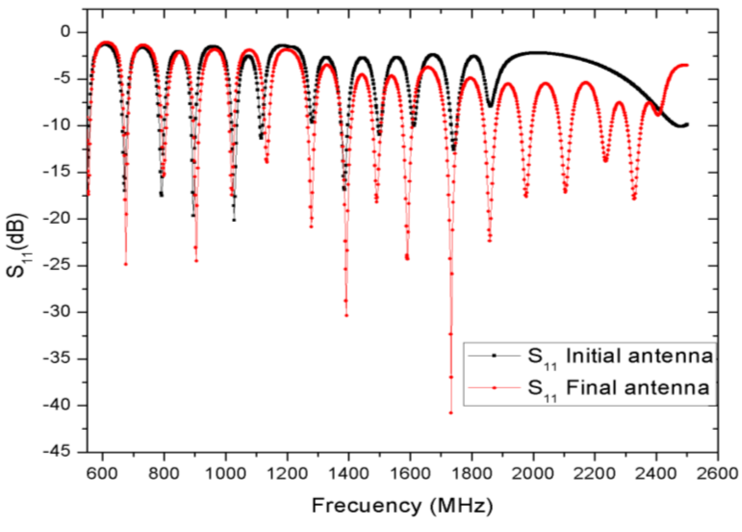
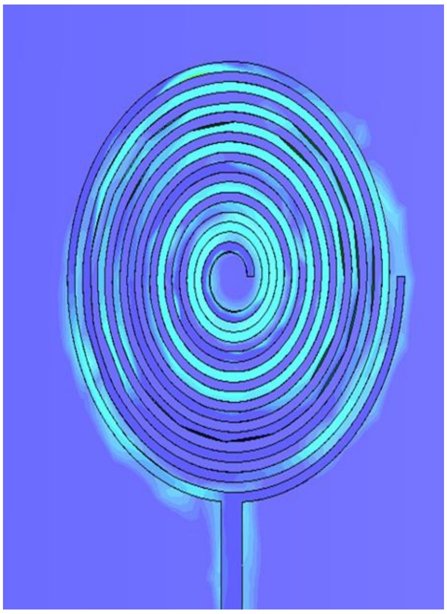
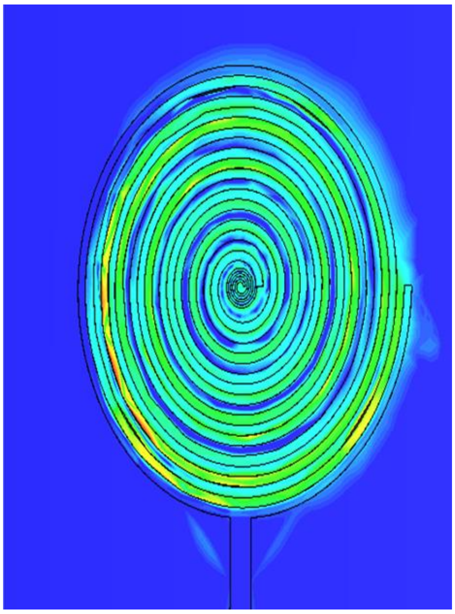


Figure 5. Parameter S_{11} frequency response of the simulation. Black line initial antenna, red line final antenna frequency respons

The following Figure 6 shows the behavior of the surface current circulating through the windings. Figure 6(a) shows less fluctuation in the structure, while Figure 6(b) shows a greater coverage of the energy circulating through the turns of the driver. This is due to the embedding of the smaller coil within the larger coil. Thus, the inner turn acts as a parasitic element that helps distribute the surface current throughout the structure, thus increasing the multiple working bands and circulating the surface current throughout the structure.



(a)



(b)

Figure 6. Simulation behavior of the surface current circulating through the windings: (a) less energy fluctuation and (b) greater coverage energy fluctuation

3. RESULTS AND DISCUSSION

Spiral or coil type microstrip antennas are part of fractal geometries [36], [54], this type of geometry is capable of producing antennas that work in multiband useful for sensors, transmission and reception of wireless communications [35] and for our case capture energy wirelessly from RF [55]–[57]. The FR4 substrate is used because this type of material can be easily obtained in our country, it has qualities such as its low cost, it is easy to handle and it can be obtained in different sizes. Below is a comparison between other spiral fractal microstrip antennas and the proposed antenna as show in Table 2.

Table 2. Comparison between spiral antennas and the proposed antenna: own work

Ref	BW	Bands	Dimension	Gain	Efficiency	Polarization	Substrate
[58]	1.7-3 GHz	3	100×110 mm	6.5 dBi	41%	Circular	Duroid 5880
[59]	1.2-5 GHz	4	58×55 mm	4.5 dBi	30%	Dual	FR4
[19]	1.58-2.41 GHz	4	40×40 mm	2.7 dBi	67%	Dual	FR4
[60]	0.8-0.95 GHz	2	37×35 mm	4 dBi	70%	Dual	Duroid 4003
Proposal	15-150 MHz	17	70×70 mm	3-6 dBi	70%	Dual	FR4

Figure 7 shows the VSWR for its acronym in English VSWR which refers to the relationship between the maximum intensity of the signal and its minimum, it also refers to the measurement of the standing wave produced by a reflection waveguide and measures the reflected voltage and the reflected power in percentages of the power loss that leaves the antenna [61]–[63] as expressed in Table 3. Since an standing wave ratio (SWR) of 10% represents 10% of the power loss and 100% of the power leaving the antenna and an SWR of 3 represents 25% of the power loss and 75% of the power leaving the antenna, this value is from then on insufficient for a correct operation of the antennas in relation to the power emitted or received.

Now, it is possible to see that no resonance frequency has exceeded the value of 2 on the axis Figure 6, which means that the simulated SWR of the presented antenna is at an optimal value with less power losses and the percentage of power output is around 98.3% as indicated in the following Table 3.

Figure 8 represents the axial relationship versus frequency where the polarization of a radiated wave or the curve drawn by the end of the electric field vector as a function of time is described. The point marked in red in Figure 9 represents the frequency that in circular polarization since it is less than or equal to 3 dB, the other points in the figure demarcated with black points represent linear polarization since they are greater than 3 dB and exceed 20 dB.

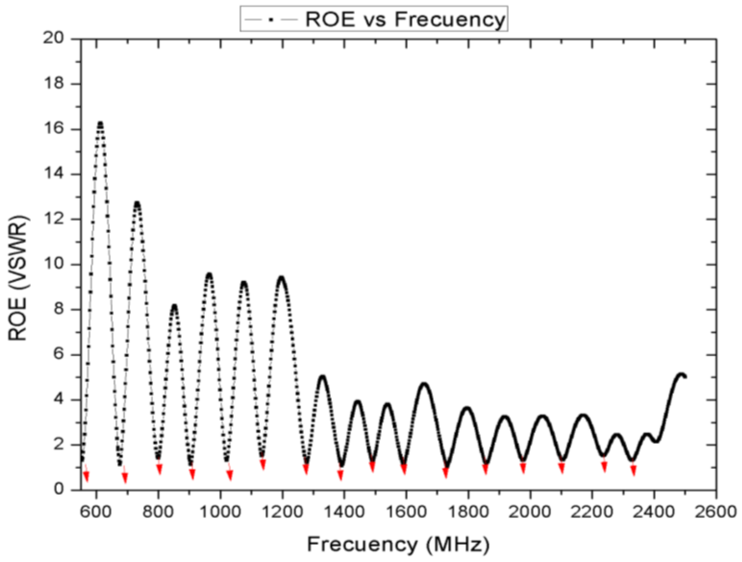


Figure 7. SWR simulated results. The red line represents the SWR value for each resonant frequency

Table 3. SWR table: author’s calculations

SWR	% Power loss	% of power going to antenna
1.0	0.0 %	100 %
1.1	0.3 %	99.7 %
1.2	0.8 %	99.2 %
1.3	1.7 %	98.3 %
1.4	2.7 %	97.3 %
1.5	3.0 %	97.0 %
1.6	5.0 %	95.0 %
1.7	6.0 %	94.0 %
1.8	8.0 %	92.0 %
2.0	11.0 %	89.0 %
2.2	14.0 %	86.0 %
2.4	17.0 %	83.0 %
2.6	20.0 %	80.0 %
3.0	25.0 %	75.0 %

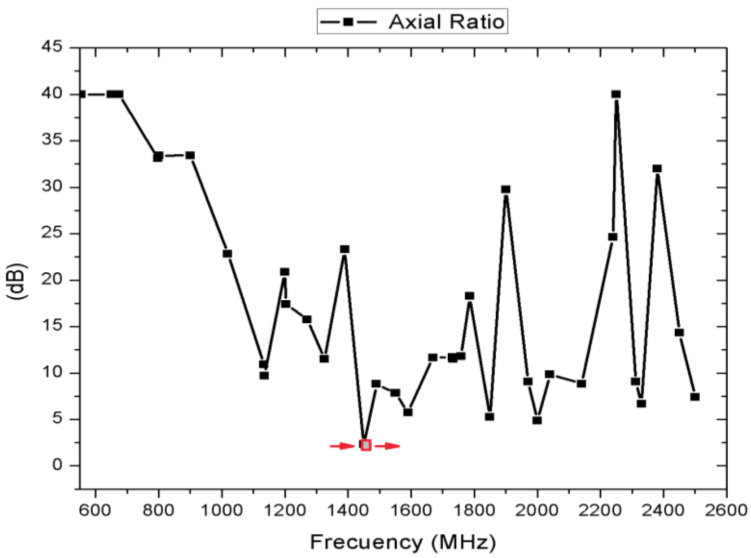


Figure 8. Axial ratio vs frequency simulated results

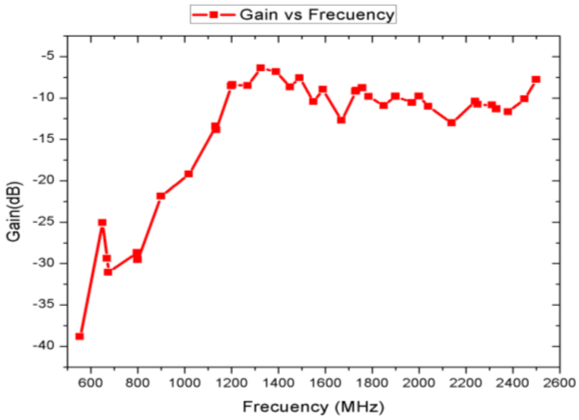


Figure 9. Gain vs frequency simulated results

The results obtained from the simulation indicate that the antenna exhibits an optimal resonance frequency, not exceeding the value of 2, indicating a favorable simulated SWR with minimal power losses. The power output efficiency reaches approximately 98.3%, as detailed in the accompanying table. Additionally, the graphs presented in Figures 8 and 9 clearly depict the axial relationship versus frequency and the polarization of the radiated wave, highlighting the difference between circular and linear polarization. These findings support the effectiveness and optimal performance of the antenna under various frequency and polarization conditions.

The design and simulation process of the circular spiral antenna using CST Studio software showcased a comprehensive approach towards crafting an optimized radiating structure [64], [65]. Figures 2, 3, 5, and 6 visually encapsulated the intricate configurations and behavioral outcomes, providing a tangible representation of the antenna’s performance parameters [66]. Leveraging the foundational equations for microstrip antennas and employing advanced software tools like CST Studio Suite, the iterative refinement resulted in a finely-tuned design resonating within the intended frequency range [67], [68]. The shift from a basic square geometry to a coil-like configuration, as seen in Figure 4, speaks volumes about the nuanced alterations made to enhance the antenna’s efficiency and resonance characteristics [66], [69].

Moreover, the simulation analysis demonstrated the antenna’s adaptability across multiple frequency bands, emphasizing its potential for collecting RF energy from diverse sources [70]. The comparison presented in Table 2 against other spiral fractal microstrip antennas showcased the proposed antenna’s competitive edge in terms of bandwidth, gain, efficiency, and polarization characteristics within a comparable form factor [66], [69]. Additionally, the SWR analysis, depicted in Figure 7 and detailed in Table 3, underscored the antenna’s effectiveness in minimizing power losses while maximizing the power output, affirming its operational suitability for wireless communication and RF energy harvesting applications [71].

The simulation results consistently validated the effectiveness of the antenna design, corroborating its optimized resonance frequencies, power efficiency, and polarization attributes [64], [65]. The comprehensive analysis conducted through various visual representations and comparative evaluations not only attests to the antenna’s performance but also establishes its potential for diverse applications in wireless communication systems and RF energy harvesting technologies [72], [73]. The iterative design process, fortified by sophisticated simulation tools, culminated in an antenna design poised to address the demands of modern wireless technologies across multiple frequency bands with commendable efficiency and adaptability [74].

This way, the comparative analysis Table 2 highlighted the antenna’s dimensions, gain, efficiency, polarization, and substrate in contrast to other existing spiral fractal microstrip antennas, emphasizing their attributes and contributions to the field. Figure 7 illustrates the VSWR, a critical metric quantifying signal intensity relationship, demonstrating the measurement of the standing wave and power loss implications detailed in Table 3. The data indicate that simulated VSWR values align optimally, minimizing power losses. Furthermore, Figures 8 and 9 elucidate the axial ratio versus frequency and the polarization characteristics of the radiated wave, distinguishing between circular and linear polarization.

4. CONCLUSION

This document proposes the design of a microstrip antenna with spiral fractal geometry based on antennas known as Archimedes type, generally this type of antennas present an ideal multiband behavior for the collection of RF energy that is dissipated in the medium. atmosphere. For RF energy harvesting using microstrip antennas, it is ideal for the harvesting antenna to have resonance in multiple bands, as this opens up a wide range of RF energy supply sources. The energy sources include broadcasting stations, television stations, surveillance and security radios, and mobile phone antennas. The aforementioned sources operate in the bands in which the proposed antenna interferes in such a way that the presented design has the qualities of resonant frequency, BW, VSWR and characteristic impedance to be coupled to low power wireless sensor systems and to a rectifier system to capture, rectify and feed a low power system, and also to power systems for IoT technology. In addition, the low cost of the substrate and the usefulness of the CST Studio design software for antenna design minimizes production costs and provides an opportunity to improve the design and evaluate new fractal structures for use in energy harvesting technology. RF using microstrip antennas.

The use of FR4 substrate material in the antenna simulation was justified due to its accessibility, cost-effectiveness, ease of handling, and availability in various dimensions, primarily within our country, considering the antenna's future implementation. The characteristics of this antenna such as, accessibility, cost-effectiveness, ease of handling, and availability in various dimensions could enable the use of this antenna for applications in long-distance, low-frequency wireless communications that require a low data transmission rate but extensive coverage, such as sensor networks, remote monitoring systems, or emergency communications in rural or hard-to-reach areas. It could also be employed in wireless power transmission systems, specifically for applications in the IoT. In low-power communication networks like implantable medical devices, tracking systems, or monitoring in energy-constrained environments.

It's notable that the antenna exhibits an optimal resonance frequency below the value of 2, ensuring minimal power losses and high output efficiency. Besides, the graphs showcase the antenna's effectiveness under various frequency and polarization conditions. These results collectively confirm the antenna's efficacy and superior performance, marking a significant advancement in this field. Finally, as future work, the manufacturing of the proposed design for applications in the Institution could be considered, since the institution does not have a milling machine that has the capacity and caliber of drill bits to make holes with dimensions as minimal as those of the design proposed.

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Vanessa García Pineda	✓	✓				✓	✓		✓	✓	✓	✓		
Alejandro Valencia Arias	✓					✓	✓			✓		✓	✓	✓
Francisco Eugenio López Giraldo	✓	✓		✓			✓			✓		✓	✓	✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Derived data supporting the findings of this study are available from the author E.A.Z.O on request.

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