UWB Spiral Antenna with Balun for EM Energy Harvesting

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Abstract

Energy from most of the EM radiations can be harvested by designing an ultra wideband antenna having a bandwidth of 0.5 to 18.5 GHz. The most viable solution for ultra wide band coverage is the Archimedean spiral antenna. The bandwidth of this antenna is up to 40:1 for both the input impedance and the radiation pattern. The same antenna can be installed on radar, to harvest the energy from electromagnetic interference and jamming signals in the frequency range of UHF to KU band. The antenna has a gain of 5.77 dBi, return loss less than -10 dB and VSWR 1-2 for almost complete frequency range. Spiral antenna being a balanced one, needs Balun for balancing the feed as well. The Balun designed with a Micro Strip Line (MSL) to Parallel Strip Line (PSL) transition is used as a balanced feed. Back-to-back MSL to PSL Balun assembly has a return loss less than -15dB over the band of operation and the combined assembly gives a peak gain of 11 dBi for almost entire band.

**Keywords:** Back-to-Back Balun, Circular Polarization, Microstrip to Parallel Strip Planar, Self-Complementary Structure, Spiral Antenna, Ultra Wide-Band.

1. INTRODUCTION

Energy harvesting is a commercial reality, with many embedded devices being powered from natural or unwanted energy in the environment. Convergence between the increasing power output from the harvesters and the decreasing energy demand of electronic devices has popularised energy harvesting. Batteries have been used to power such devices, but they have a finite capacity, need recharge or replacement. Energy harvesting is an alternative for sufficient and appropriate energy [1]. Radio signals with frequency range from 0.5 to 18.5 GHz being used either in radar or electronic warfare, are good source of RF energy harvesting. The RF sources being used for energy harvesting are broadcasting towers, cell towers and nearby radars or intentional jamming from enemy sources. Though the harvested energy is in Micro-watts, but sufficient to feed the small electronic devices or charging of a battery for built in test facility in radar equipment [2]. Since the frequency range of interest expands from UHF to KU band, the antenna and its matching network to cover entire band, needs to be realized. To realize the efficient energy harvesting system a wide band antenna like Archimedean spiral needs to be designed. The smallest and largest circumference of the spiral structure determines their respective upper and lower cut-off frequencies. Archimedean spiral is the most popular configuration due to its wide bandwidth and tighter array spacing. It can be easily designed and fabricated using printed circuit techniques. Planar Archimedean spiral antenna is widely used due to its low profile, light weight, high efficiency, circular polarization, stable impedance and broad band characteristics.

2. DESIGN OF SPIRAL ANTENNA

Size of the antenna is computed from the lowest and highest frequency of operation. The outer radius \( r_2 \) of the spiral antenna determines the lower frequency operating point [3, 4] as given by eqn. (1)

\[
f_{\text{low}} = \frac{c}{2\pi r_2} \quad (C \text{ speed of light}) \tag{1}
\]

inner radius \( r_1 \), determines the highest frequency operating point as given by eqn. (2)

\[
f_{\text{high}} = \frac{c}{2\pi r_1} \tag{2}
\]

![Fig. 1 Structural view of Spiral](image)

The spiral antenna designed is self-complementary as in Fig. 1, where the metal and air regions of the antenna are equal. The input impedance of this antenna have been found using Babinet’s principle given by eqn. (3)

\[
Z_{\text{meta}}Z_{\text{air}} = \eta^2 / 4 \quad (3)
\]

\( \eta \) = characteristic impedance of the medium around the antenna. The input impedance of a self-complementary Archimede spiral antenna in free space is \( Z_{\text{air}} \eta / 2 = 188\Omega \).

Each arm of an Archimede spiral is linearly proportional to the angle \( \phi \), and is described by eqn. (4)

\[
r = r_0\phi + r_1 \quad \text{and} \quad r = r_0(\phi - \pi) + r_1 \tag{4}
\]

\( r_0 \) = proportionality constant, calculated from the width of each arm \( w \) and the spacing between each turn \( s \), as given by eqn. (5)

\[
r_0 = \frac{s + w}{\pi} = \frac{2w}{\pi} \tag{5}
\]

The strip width of each arm is found from eqn. (6)

\[
S = \frac{r_0 - r_1}{2N} \quad \text{(for} \ N \ \text{number of turns)} \tag{6}
\]

Assuming a self-complementary structure, the spacing or width is given by eqn. (7)

\[
S = \frac{r_1 - r_0}{4N} \tag{7}
\]
Equation (7) is applicable for a two-arm Archimedean spiral antenna, but if a four-arm spiral is desired, than the arm width becomes

\[ W_{\text{arm}} = \frac{\pi r_0}{R_{\text{arm}}} \]  

and the proportionality constant is given by eqn. (9)

\[ W_{\text{arm}} = \frac{\pi r_0}{\alpha} \]  

The Archimedean spiral antenna radiates from active region formed by designing the spiral to maintain circumference of spiral equal to one wavelength [5]. To operate the spiral antenna as a complementary one, it has been designed on FR-4 (lossy) substrate having a thickness of 1.6 mm and dielectric constant 4.3. The antenna is designed with spiral strip of height 0.017 mm with a coil thickness of 2.5 mm superimposed on a substrate with the space between the conductors = 2.5 mm; line width = 2.5 mm; with 9 turns . With these parameters, the antenna has an outer diameter of 98 mm at the lower frequency of 0.5 GHz, and the inner diameter of 2.3 mm at upper frequency of 18.5 GHz.

3. ANTENNA CHARACTERISTICS

The designed antenna was analyzed using the simulator CST. Fig. 2a illustrates the S11 parameter and Fig. 2b shows the \( E_0 \) far-field (\( \phi = 0 \)) radiation pattern for the operating frequency band of 0.5 to 18.5 GHz. Examination of the radiation pattern reveals insignificant changes with the variation of the frequency in terms of gain and return loss. The antenna gives a gain of 5.77 dBi with return loss of less than -10 dB throughout the frequency range and main lobe beam width (-3 dB), 83 deg at 9.5 GHz as given in radiation pattern. Though the main lobe radiation is bidirectional, contrary to the general radiation pattern needed, but this particular antenna is intended to be used for EM energy reception only and not as a transmitting element so it is acceptable for the purpose. However to make the radiation pattern unipolar, either a cavity or a reflector can be integrated with the antenna [6, 7].

\[ \text{Fig. 2a S11 parameter (simulated)} \]

4. CONFIGURATION OF BALUN

Whenever a balanced antenna i.e. dipole, loop or spiral is used, the issue of how to feed the antenna to match the impedance becomes relevant and can be resolved by a Balun. It is necessary to deliver the maximum power between the load and the source.

The Most common method used in microwave engineering for efficient power transfer is the impedance transformer which has the capability of transforming the impedance between the load and source. Usually \( \lambda/4 \) transformer is used for the transition. If the balanced (symmetrical) antenna is connected to a coaxial transmission line, the transition from the feed line to the balanced antenna is an unbalanced (asymmetrical) driven system. Frequency independent antennas such as spiral have a potential difference between the two arms with impedance of 188Ω. Due to the difference in impedance between the two-arms of the spiral antenna, the unbalanced coaxial cable as feed cannot be used. Hence it is necessary to provide an impedance match as well as balanced to unbalanced transformation [8]. As per the literature, a number of Baluns have been designed to match the impedance between a spiral antenna and the Feed. But these Baluns have limited bandwidth, hence unsuitable for wideband application. However a Balun which can operate over an ultra wideband has been designed to meet the application. The numerical configuration and test parameters along with the aimed spiral antenna have been studied to meet the requirement [9].

Design of a microstrip to parallel stripines Balun to transform and match the balanced and unbalanced devices for obtaining maximum power transfer between the source and the load has been implemented. For spiral antenna, the feed network consists of tapered microstrip transmission line and parallel strip lines. Hence a microstrip tapered Balun as a feed network for a low profile planar Archimedean spiral antenna is proposed. It consists of microstrip line where the ground plane is tapered to form an overlapped parallel stripline. The length of Balun for an ultra wideband Balun operating at a frequency of 0.5 to 18.5 GHz can be calculated from eqn. 10.

\[ L = 0.39 \lambda_L \]  

\( \lambda_L \) - wavelength of lowest frequency for Balun operation. The wavelength at our lowest operating frequency of 0.5 GHz is 600 mm and the Balun length calculated using the equation (10) is 234 mm (.39x600). Impedance of microstrip line at various lengths of Balun [10] is given by eqn. (11)

\[ Z_L (z) = Z_0 e^{\alpha z} \]  

Where \( 0 \leq z \leq L \) and \( \alpha = (1/L) \ln Z_L / Z_0 \) finally \( Z_L (z) = Z_0 e^{\alpha (z - \frac{L}{2})} \)  

For our Balun the parameters are as follows, \( f_L = 0.5 \text{ GHz} \), \( f_0 = 18.5 \text{ GHz} \), \( Z_0 = 50\Omega \), \( Z_L = 188\Omega \). Starting with a specific microstrip width \( w_L \) (\( w_L = w_s \)), with an impedance of 50 Ω, the ground plane width is found using parameter sweep method in CST. This procedure was repeated till the parallel strip line...
impedance (188 Ω) was achieved. At $Z_0 = 50 \, \Omega$, $w_s$ was found from eqn. (14) where $w/h > 1$ ($w_s = 3.1$, $h = 1.6 \, \text{mm}$).

$$Z_0 = \frac{120 \pi}{\sqrt{\varepsilon_{\text{eff}} \left( \frac{w}{h} + 1 \right)}} + 1.393 + 0.667 \ln \left( \frac{w}{h} + 1 \right)$$

for $w/h > 1$ (14)

Using impedance of the line and width of signal strip, width of ground plane was found with the help of parameter sweep method in CST. For known value of $w_s = 0.12$, the impedance of the microstrip line was found from the eqn. (15). Where $w_s/h < 1$ ($w_s = 0.92$, $h = 1.6 \, \text{mm}$). The ground width was obtained from parameter sweep method. The widths of the top and bottom conductors change gradually corresponding to the line impedances.

$$Z_0 = \frac{60 \pi}{\sqrt{\varepsilon_{\text{eff}}}} \ln \left( \frac{8h}{w} + \frac{w}{4h} \right)$$

For $w/h < 1$ (15)

5. DESIGN AND PERFORMANCE OF BALUN

A modeled design of the Balun which consists of two sided PCB layer is shown in Fig. 3. Top layer has the transition from microstrip line (MSL) to parallel strip line (PSL) and bottom layer acts as a ground plane for MSL and one side line for the PSL. It consists of microstrip line where ground plane is tapered to form an overlapped parallel stripline. The structure with PSL transition is soldered with the spiral antenna and the MSL connected to the standard SMA (SubMiniature version A) connector, where the width of the ground plane is gradually reduced to the PSL through parameter lofting. For simulation, the back to back configuration has been made to obtain the insertion loss of the Balun. Figure 3 shows that the top strip width changes from 3.1 mm ($Z_m = 50 \, \Omega$) to 0.11 mm ($Z_s = 188 \, \Omega$) and the ground plane changes from 7.1 mm to 0.11 mm. However during the experiment and subsequent fabrication it was found that the parameters and the width calculated through numerical means just fit in the practical designs vis-a-vis impedance matching. Hence the width was recalculated to reach the exact results through lofting method in (CST). Now the fresh width varies from 7.1 to 1.11 mm for bottom (ground) plane and from 3.1 to 1.11 mm for top plane respectively with the lofting value of 0.30 for a total length of 155mm [11]. The Balun was simulated with back to back configuration, and the results in terms of return loss and VSWR were good at all frequencies with return loss less than -15 dB and the VSWR below 1.4 much below 2.

6. INTEGRATION AND TESTING

The Balun shown in Fig. 3 is integrated with spiral antenna. The balanced output i.e., PSL of the Balun is connected to the antenna as shown in Fig. 4. The return loss of fabricated antenna with the Balun was measured with the VNA (Vector Network Analyzer) in the RF Lab, Electronics and Radar Development Establishment Bangalore. The results were encouraging, as the actual return loss remained below -10 dB with VSWR<2 as shown in Fig. 5 and 6.

7. EXPERIMENTAL RESULTS

The antenna was tested for a frequency band of 1.0–18.0 GHz in horizontal and vertical polarization [12]. The results were exceptionally good. The results are analysed for various frequency spots as placed below in figure 7 for 9 GHz and the analysis is placed in Table 1.

8. ANALYSIS OF RESULTS

The radiation patterns at 1, 9 and 18 GHz for vertical and horizontal polarization reveal that the overall performance of antenna assembly with Balun is good; however the radiation for horizontal polarization has been much better than radiation...
for vertical polarization. Also the -3dB bandwidth is better at lower frequencies as compared to highest frequency of 18 GHz. The effect of side lobes in horizontal polarization would deteriorate the performance more as compared to vertical polarization. Hence it is an overall compromise to achieve the optimum results out of the assembly. Figure 7 shows the Radiation pattern at 9.0 GHz, for vertical and horizontal Polarization.

![Radiation pattern 9.0 GHz, Vertical Polarization](image)

**Table 1a. Cut analysis 9.0 GHz, Vertical Polarization**

<table>
<thead>
<tr>
<th>Avg value</th>
<th>-14.156 dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>-3dB BW</td>
<td>4.41 deg</td>
</tr>
<tr>
<td>-6dB BW</td>
<td>5.45 deg</td>
</tr>
<tr>
<td>-10dB BW</td>
<td>6.36 deg</td>
</tr>
<tr>
<td>Left Sidelobe</td>
<td>-1.57 dB at -21.341 deg</td>
</tr>
<tr>
<td>Right Sidelobe</td>
<td>-5.20 dB at -7.294 deg</td>
</tr>
<tr>
<td>Frequency</td>
<td>9.0 GHz</td>
</tr>
<tr>
<td>Polarization Axis</td>
<td>Vertical</td>
</tr>
</tbody>
</table>

![Radiation pattern 9.0 GHz, Horizontal Polarization](image)

**Table 1b. Cut analysis 9.0 GHz, Horizontal Polarization**

<table>
<thead>
<tr>
<th>Avg value</th>
<th>-12.250 dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>-3dB BW</td>
<td>8.35 deg</td>
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<tr>
<td>-6dB BW</td>
<td>18.79 deg</td>
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<tr>
<td>-10dB BW</td>
<td>46.21 deg</td>
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<tr>
<td>Left Sidelobe</td>
<td>-3.30 dB at -33.407 deg</td>
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<tr>
<td>Right Sidelobe</td>
<td>-2.71 dB at -8.014 deg</td>
</tr>
<tr>
<td>Frequency</td>
<td>9.0 GHz</td>
</tr>
<tr>
<td>Polarization Axis</td>
<td>Horizontal</td>
</tr>
</tbody>
</table>

9. CONCLUSION

Ultra wide band dual polarized Archimedean spiral antenna operating at 0.5 to 18.5 GHz frequency has been designed to harvest EM energy from radar jamming and interference signals. Also the spiral antenna needs a Balun for impedance matching between spiral center and the end of connecting coaxial cable. To resolve the impedance matching requirement, a microstrip line (MSL) to parallel strip line (PSL) is designed to realize a wideband Balun. After fabrication of antenna with Balun, it is confirmed that the actual results are matching with the requirements. Thus the proposed design of Archimedean spiral antenna and Balun are best suited for harvesting EMI and jamming signals in radar to provide green energy for BITE (Built in test equipment /system) in receiver and transmitter.

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REFERENCES


