A Low Profile Wideband RHCP Printed Archimedean Spiral Antenna for Glacial Telemetry Applications

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***Abstract* — Suitability of a RHCP printed Archimedean spiral antenna for glacier telemetry applications in the 433 MHz band has been assessed for the first time. The developed antenna provides a gain of 7.4 dBic at 433 MHz and a -10 dB fractional bandwidth of 47% in snow. The antenna beamwidths in the vertical planes cater for misalignments between the transmitter and receiver antennas due to basal sliding. The measured axial ratio remained below 1.4 dB between 330-580 MHz. Lastly, evidence has been provided towards suitability of the 433 MHz band for achieving communication ranges up to 2300 metres in ice.**

Index Terms — Archimedean spiral antenna, planar design, RHCP, communication in ice, glacier telemetry

I. Introduction

This work contributes to the Thwaites project which is a joint venture between University College London (UCL) and the British Antarctic Survey (BAS). The project aim is to deploy a telemetry system at the Thwaites glacier, Antarctica. Wireless sensor probes would be deployed in 8 cm diameter boreholes. The probes will transmit geophysical data at 433 MHz to surface receivers through up to 2300 meters of ice. Due to the borehole size constraint, the probe antenna is electrically small and cannot offer much gain. The surface receiver antenna must provide enough gain to fit in the available link budget. To cater for transmitter (Tx) - receiver (Rx) antenna misalignments due to basal sliding over extended deployment periods, portable circularly polarized (CP) antennas are desirable with half power beamwidths (HPBWs) of at least 50º in both the vertical planes xz and yz. Following are the contributions of this paper: (1) feasibility of a printed planar Archimedean spiral antenna for glacier telemetry receiver applications has been assessed for the first time, (2) a novel design of the antenna type has been experimentally validated, and (3) 433 MHz band has been validated for multi-hundred metres communication through ice. The state-of-the-art works have used: (1) either a Yagi, helical, non-printed cross dipole, or a log periodic dipole array for similar applications, (2) 433 MHz band for communication ranges below 100 m and used lower frequencies of 173.25 MHz, 151 MHz, and 30 MHz for larger distances. In a similar project called Glacsweb [1], helical antennas tuned at 433 MHz were used to achieve a communication range of 80 m in ice. Considering the required range of 2300 m for the Thwaites project, the communication apparatus of [1] would require the Tx and Rx antennas to have much larger gains which are difficult to achieve with the size and HPBW requirements. Therefore, the Thwaites project needs a receiver with better sensitivity and different antennas for the probe and surface receiver. In other experiments done using the Glacsweb communication apparatus between 2003 and 2019, the maximum communication range remained 86 m and only two frequencies 433 MHz and 173.25 MHz were used. A wireless sensor (WiSe) network reported in [2] achieved communication ranges of up to 2500 m using a much lower frequency of 30 MHz. WiSe employed two kinds of surface Rx antennas, a non-printed cross dipole, and a log periodic dipole array. Although WiSe fulfils the range requirement for the Thwaites project, use of 30 MHz instead of 433 MHz necessitates large antenna sizes which would no longer be portable. Some spherical probes called ETracer and Cryoegg [3] transmitted measured sensor data while passing through englacial water channels. The sensor data was received at the surface using Yagi antennas tuned to 151 MHz at ranges of up to 2000 m. Though Yagi antennas usually offer high gains, their beamwidths are narrow and not suitable for the Thwaites project.

II. Planar Printed Archimedean Spiral Antenna

A. Link Budget

The Thwaites project link budget calculations were done using the modified Friis transmission equation [4] shown by (1):

$$\frac{P_R}{P_T} = \left(\frac{\lambda}{4\pi d}\right)^2 \text{ x } L_{ice} G_{Tx} G_{Rx} PLF \tag{1}$$

where $\lambda = \frac{c/f}{\sqrt{\varepsilon_r}}$ represents the wavelength, c is the speed of light, f is the centre frequency, and ε_r is the ice dielectric constant taken as 3.1 [5]. Ice dielectric attenuation L_{ice} is assumed as 0.02 dB/m [6]. The Tx power and Rx sensitivity are denoted by P_T and P_R respectively. HopeRF RFM96W transceiver modules were employed. The Tx and Rx antenna gains are represented by G_{Tx} and G_{Rx} respectively. A G_{Tx} of 0 dBic was assumed with a communication distance d of 2300 m. Same polarization i.e., right hand CP (RHCP) would be used for both the Tx and Rx antennas making the Polarization Loss Factor (PLF) = 0 dB. With f = 433 MHz, P_T = 20 dBm, P_R = -121 dBm (assuming that a data rate of 4.68 kbps suffices), an additional link margin of 2.6 dB to cater for unpredicted losses, link budget calculations revealed a Rx antenna gain G_{Rx} requirement of 5 dBic.

B. Antenna Design

Archimedean spiral antennas [7] are a popular choice for achieving wide bandwidth and high directivity. A planar printed Archimedean spiral antenna was designed and developed as shown in Fig. 1. The top layer of the PCB printed on a 1.6 mm FR-4 substrate ($\varepsilon_r = 4.3, \tan\delta = 0.025$) contains two counter clockwise rotating arms making the antenna RHCP. The inner and outer radii r_{inner} and r_{outer} define the highest and lowest frequencies f_{high} and f_{low} the antenna supports respectively. The relationships are shown in (2) and (3):

$$\frac{c}{f_{high}} = 2\Pi r_{inner} \quad (2)$$

$$\frac{c}{f_{low}} = 2\Pi r_{outer} \quad (3)$$

In Fig. 1, W and G define the width of an arm and the gap respectively. The antenna is self-complimentary since W and G are kept equal. This should theoretically provide a frequency independent input impedance of 188.5 Ω to the antenna as per Babinet's principle [8]. The radii of the two edge curves r_{arm1a} and r_{arm1b} that form arm 1 of the antenna can be represented as functions of the angle φ in radians by (4) and (5) respectively. B is a constant defining the growth rate of the arms:

$$r_{arm1a}(\varphi) = B\,\varphi + r_{inner} - \frac{W}{2} \quad (4)$$

$$r_{arm1b}(\varphi) = B\,\varphi + r_{inner} + \frac{W}{2} \quad (5)$$

Arm 2 of the antenna can be similarly represented by replacing the term $'B\,\varphi'$ in (4) and (5) with $'B\,(\varphi - \Pi)'$ since the two arms are fed signals having a 180º phase shift between them. When $W = G$, $B = \frac{2W}{\pi}$ [9]. The arms radiate when their circumference becomes equal to one wavelength and their currents are in phase and constructively interfere. The number of turns n was kept only large enough to allow a reasonable margin of operation around the center frequency of 433 MHz. The designed antenna size was 23.6 cm x 27.2 cm.

The Archimedean spiral antenna requires a balanced feed. Baluns for most spiral antennas extend into the third dimension like [10] making the antenna design 3D rather than planar. Without careful design, such baluns may radiate themselves influencing the antenna's net radiation pattern. Low profile baluns like an RF transformer IC or printed baluns like [11] are therefore more desirable. Next consideration is impedance match between the feed line and the antenna to ensure minimal reflections. A 1:3 RF transformer balun IC NCS-72+ from Mini-circuits® specified between 250-760 MHz was used to match the 50 Ω feed line to the antenna with a measured input impedance of 165 ± 7 Ω in the 330-580 MHz range. Any radiation incident on the antenna ground plane is lost. To keep a minimally sized ground plane, a SSMA connector with a smaller footprint compared to a SMA connector was used to feed the antenna. A 3 mm thick Aluminium sheet of size $0.75\,\lambda\,x\,0.75\,\lambda$ was placed on one end at $\lambda/4$ distance to convert the antenna's bidirectional radiation pattern into unidirectional. The antenna was simulated in snow medium ($\varepsilon_r = 2.5$) [7] using CST microwave studio suite. Table I lists the salient parameters of the antenna.

III. Results and Discussion

The antenna was simulated with a $\lambda/4$ reflector at one end in snow medium. The available resources did not permit in - snow testing, and an alternate experimental validation method was adopted. Measurements of the antenna were made in free space and compared with the free space medium simulations. If the simulation and measured results in free space agreed well, it provides evidence to expect the antenna to perform in snow in line with the snow simulations. While the designed antenna could potentially operate between 409 MHz up to almost 6 GHz, the upper frequency was capped at 760 MHz by the balun IC and the $\lambda/4$ reflector. The operating frequency was 433 MHz and measurements were made in the range of 330 MHz to 580 MHz. Simulations in snow medium as shown in Fig. 2 revealed that the antenna had a -10 dB fractional bandwidth (FBW) of 47% with the |S11| remaining below -10 dB from 369 MHz to 580 MHz. The realized gain at 433 MHz was found to be 7.4 dBic which is well above the requirement of 5 dBic and offers an additional link margin of 2.4 dB. The simulation and measured |S11| and gain in free space medium also plotted in Fig. 2 are in close agreement. The snow medium simulated radiation patterns in three planes are shown in Fig. 3(a). The antenna provides HPBWs of 72º and 58º in the vertical planes xz and yz respectively. Both the beamwidths remained above the desired value of 50º. The simulated and measured far field patterns in free space shown in Figs. 3(b) and 3(c) are in good agreement and validate the performance of the antenna in snow. The measured axial ratio shown in Fig. 3(d) remained below 1.4 dB over the frequency range 330-580 MHz and shows good quality of circular polarization. The snow medium simulated co- and cross polarizations of the RHCP spiral antenna in xz and yz planes are shown in Fig. 4. The co-polarization remained stronger by at least 7.7 dB than the cross-polarization in both the vertical planes within a beamwidth of at least 60º. This shows satisfactory purity of polarization. The free space polarization measurements in xz and yz planes shown in Fig. 5 suggested the co-polarization stronger by at least 10.6 dB than the cross polarization within a beamwidth of at least 60º. The simulated and measured results shown in Fig. 5 are in close agreement.

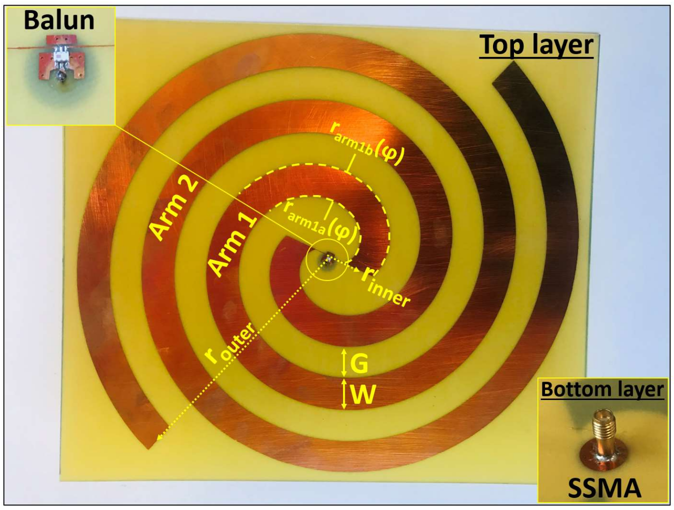

Fig. 1. Prototype planar printed Archimedean spiral antenna.

TABLE I
Parameters of the Designed Planar Spiral Antenna

Parameter	W	G	n	r_{inner}	r_{outer}
Value	1.6 cm	1.6 cm	1.7	0.8 cm	11.68 cm

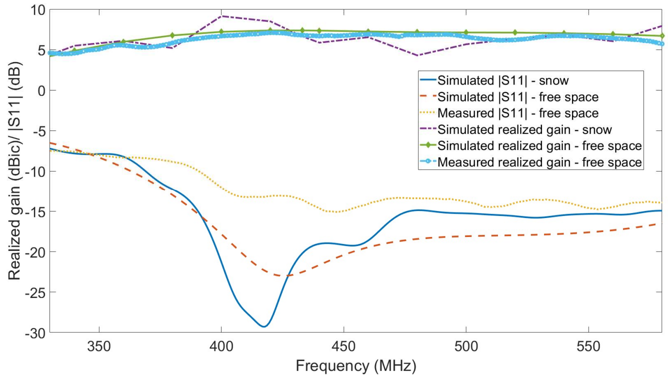

Fig. 2. Simulated and measured |S11| and gain of the planar printed Archimedean spiral antenna in snow and free space media (measured results in free space only).

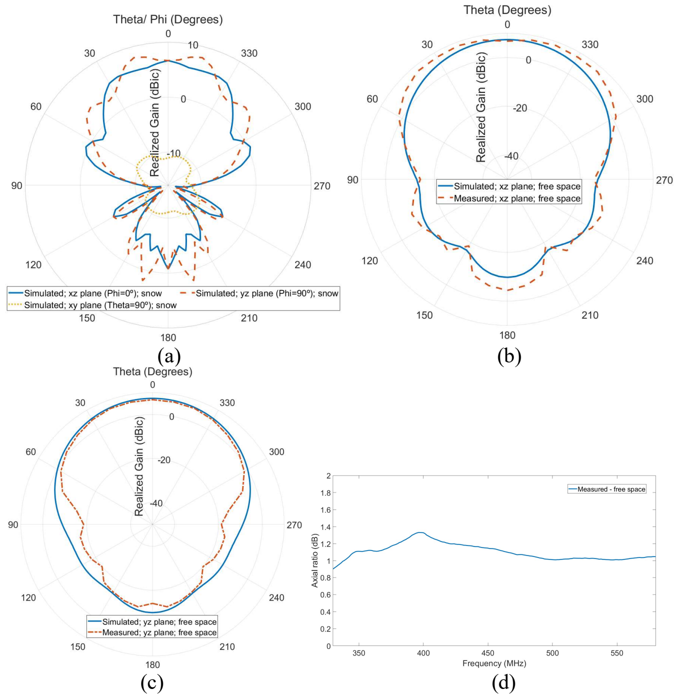

Fig. 3. (a), (b), and (c) show far field patterns at 433 MHz (a) shows the simulated far field pattern in snow medium in three planes xz, yz, and xy, (b) and (c) show the free space simulated and measured radiation patterns in xz and yz planes respectively (d) shows the measured axial ratio of the spiral antenna in free space.

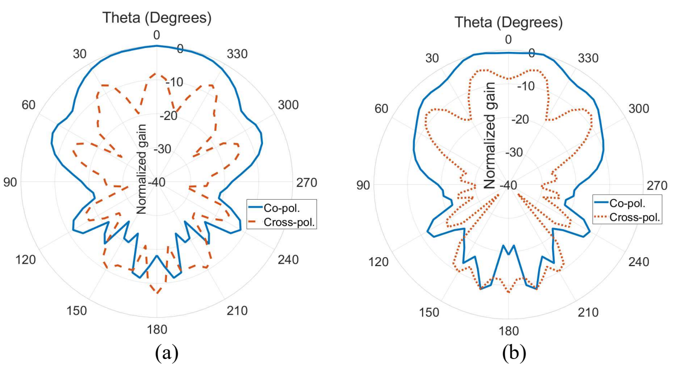

Fig. 4. Simulated co and cross polarizations at 433 MHz in snow, (a) xz plane, (b) yz plane.

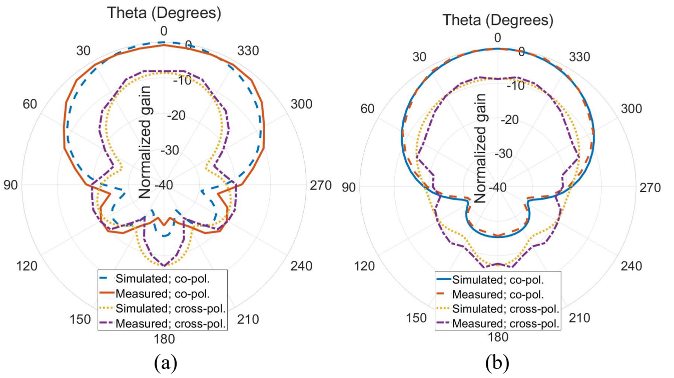

Fig. 5. Simulated and measured co and cross polarizations at 433 MHz in free space, (a) xz plane, (b) yz plane.

IV. Conclusion and Future Work

A compact wideband RHCP planar printed Archimedean spiral antenna for use with glacier telemetry surface receivers has been designed and experimentally validated. The antenna provides a realized gain of 7.4 dBic at 433 MHz in snow, a FBW of 47%, and HPBWs of 72º and 58º in the vertical planes xz and yz respectively. Good quality of circular polarization was achieved with the axial ratio remaining below 1.4 dB over the frequency range of 330-580 MHz. Further reduction in the antenna profile can be achieved through use of an artificial magnetic conductor [12] in place of the $\lambda/4$ reflector.

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