A LHCP Printed Cross Dipole Antenna for Glacial Environmental Sensor Networks

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***Abstract* — A left hand circularly polarized antenna called SPD-PCD (Symmetric phase difference – printed cross dipole) has been designed, developed, and experimentally validated for use with glacier telemetry surface receivers. The antenna is portable and easy to fabricate. It provides a gain of 5.9 dBic at 433 MHz, a 57 % -10 dB fractional bandwidth, and a -3 dB angular width of 60º in the vertical planes. The antenna offers good circular polarization with the axial ratio remaining below 1.1 dB between 330-580 MHz. The co-polarization is at least 10 dB stronger than cross-polarization within a beam width of 80º in both the vertical planes. This work also validates the 433 MHz band is suitable to achieve communication ranges of up to 2300 m through ice.**

***Keywords* — cross dipole antenna, LHCP, communication in ice, glacier telemetry, circular polarization**

I. INTRODUCTION

University College London (UCL) and the British Antarctic Survey (BAS) have collaborated on the Thwaites project which aims to deploy an environmental sensor network at the Thwaites glacier, Antarctica. The sensor probes deployed into boreholes of 8 cm diameter would transmit the sensor data wirelessly to surface receivers at a centre frequency of 433 MHz. Circularly polarized (CP) antennas are best suited here to cater for basal sliding and changes in orientation of the englacial probes. Following are the novel contributions of this paper. Firstly, feasibility of a left hand circularly polarized (LHCP) printed cross dipole antenna is assessed for supraglacial receiver applications and a novel design of the antenna type named as Symmetric Phase Difference - Printed Cross Dipole (SPD-PCD) is presented. The previous works used either a helical, non-printed cross dipole, log periodic dipole array, or a Yagi antenna for similar purpose. Secondly, this work assesses the suitability of 433 MHz band for communication up to 2300 m through ice. The related works used the said frequency for a maximum range of 86 m and lower frequencies such as 30 MHz, 151 MHz, and 173.25 MHz were used to achieve longer ranges.

II. RELATED WORKS

Three previous projects had aims and methodologies similar to those of the Thwaites project except that they used different devices, frequencies, and the projects took place at different sites. These include the GlacsWeb project [1]-[8], Wireless Sensor (WiSe) system [9]-[10], and the Electronic Tracer (ETracer) project [11]-[13]. Table I provides a comparative analysis of these including some details of the surface receiver antenna design. Table II, on the other hand, provides a list of works that used an antenna for a similar purpose, but their antenna design and characteristics are unpublished.

Martinez *et. al.* [1] developed their design of an environmental sensor network called the Glacsweb for harsh environments such as a glacier. Several experiments [2]-[8] which involved receiving sensor data from englacial probes deployed in boreholes were completed. The wireless transmit-receive distances varied from 72 m up to 86 m, while only two centre frequencies of 173.25 MHz and 433 MHz were used. Relatively high link budgets were available in these works considering a maximum range of 86 m. A helical surface antenna was used in [2]. Helical antennas usually offer very good directivities. Unfortunately, their gain and other parameters have not been mentioned. Details of the antenna type and design are not provided in the other works [1], [3]-[8] to allow a direct comparison with the SPD-PCD antenna.

The WiSe system [9] used two types of surface receiver antennas, namely a cross dipole and a log periodic dipole array. Their communication frequency was 30 MHz. Use of low frequency in WiSe necessitated large sized receiver antennas to provide high gains since the coil ferrite transmit antennas in the probes are unlikely to offer large gains by virtue of their lower efficiency. The large sizes of antennas are less portable, and printed versions of such sizes would be costly. The SPD-PCD antenna on the other hand is printed on a FR-4 substrate and measures just 235 mm x 235 mm making it very portable

Table 1. Related works with limited surface antenna details.

Reference	Maximum englacial range achieved	Link type and frequency	Surface receiver antenna type
This paper	Designed for 2300m	Wireless, 433 MHz	Symmetric phase difference-printed cross dipole
[2]	72m	Wireless, 433 MHz	Helical
[9] Russell experiment	600m	Wireless, 30 MHz and Wired	(1) Cross dipole (2) Log periodic dipole array
NEEM experiment	2500m	Wireless, 30 MHz	--"--
[10]	320m	Wireless, 30 MHz	(1) Cross dipole (2) Log periodic dipole array
[11]	NA	Data stored in built-in memory	Yagi (used only to detect probe once it emerges from glacier portal)
[12]	2000m	Wireless, 151 MHz	Yagi
[13]	150m	Wireless, 151.6 MHz	Yagi

Table 2. Related works without published details of the surface antenna.

Work Reference	Maximum englacial range achieved	Link type and frequency
[1]	80m	Wireless, 433 MHz
[3]	70m	Wireless, 433 MHz
[4]	80m	Wireless, 173.25 MHz
	(Provision available to implement a wired backup link)	
[5]	69m approx.	Wireless, 433 MHz
[6]	80m	Wireless, 173.25 MHz
[7]	86m	Wireless, 433 MHz
[8]	30m	Wired RS-485 link
	(Backup 173 MHz wireless link)	

and easy to deploy at remote sites. In the field experiments of WiSe [9]-[10], a maximum communication range of 2500 m was achieved. Since the range requirement for the Thwaites project is similar, the WiSe antennas could possibly be used for the Thwaites project if a frequency of 30 MHz was used and arrangements for installing large sized antennas was made.

Bagshaw *et. al.* [11] designed a spherical sensor probe called ETracer to measure water pressure along the flow path of englacial water channels. Wireless transmissions were achieved from the subsequent devices: new ETracer, Cryoegg, [12] and ET+ [13] at a maximum range of 2000 m and sensor data were received using a Yagi antenna tuned at 151.6 MHz. Yagi antennas usually have narrow beamwidths with high gain. For the Thwaites project, -3 dB angular widths of at least 50º in the vertical planes are desired which may be difficult to achieve with a Yagi antenna.

III. SPD-PCD Antenna

A. Design Considerations

The Friis transmission equation [14] shown by (1) was used for the link budget calculations:

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

where wavelength $= \lambda = \frac{c/f}{\sqrt{\varepsilon_r}}, c =$ speed of light, f = centre frequency, ε_r is the relative permittivity of ice assumed as 3.1 [15]. Dielectric attenuation for ice L_{ice} is assumed as 0.02 dB/m [16] and caters for inhomogeneities in the dielectric due to presence of water channels, debris, etc. P_T is the transmit power and P_R represents the receiver sensitivity. HopeRF RFM96W transceiver modules were used at the transmitter and receiver front-ends. We assume the englacial probe transmitter antenna gain $G_{Tx} =$ 0 dBic, and a transmit distance d of 2300 m. Assuming both the probe and surface antennas are LHCP, no loss on account of polarization mismatch is considered. With the RFM96W transceiver, a receiver sensitivity of -121 dBm would allow a data rate of 4688 bps which is sufficient for the project. With this configuration and allowing an additional link margin of 2.68 dB, a surface receiver antenna gain G_{Rx} above 5 dBic is adequate. Higher data rates require higher SNR, higher value of receiver sensitivity, reducing the link budget and demanding better antenna gains. Other requirements included a bandwidth of at least 100 kHz, beamwidths of at least 50° in the vertical planes to account for misalignment due to basal sliding, and a portable, economical, and easily reproducible design.

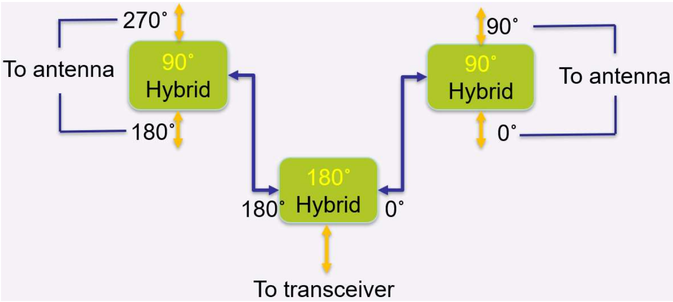


Fig. 1. Schematic diagram of the RF circuit to generate a quadrifilar output.

B. Antenna Design

The antenna was designed to be used on the surface of a glacier with a quarter wave reflector at one end to reflect the radiation in upwards direction back towards the glacier surface. A relative permittivity of 2.5 was assumed for the snow layer [15] extending up to at least two wavelengths in simulations. The antenna measures 235 mm x 235 mm and is printed on a 1.6 mm FR-4 substrate ($\varepsilon_r = 4.3, tan\ \delta = 0.025$). In the center of the PCB, there is a RF circuit that creates a quadrifilar output comprising four signals feeding the four antenna branches. The signals have phases in the sequence of 0º, 90º, 180º and 270º in the counter clockwise direction making the antenna LHCP. The quadrifilar functionality is achieved by using a 180º and two 90º hybrids. Schematic diagram of the RF circuit is shown in Fig. 1, while the fabricated SPD-PCD antenna is shown in Fig. 2. Mini-Circuits® QCN-5+ IC is used for the 90º hybrid, while Mini-Circuits® IC SBTCJ-1W+ is used for the 180º hybrid. These

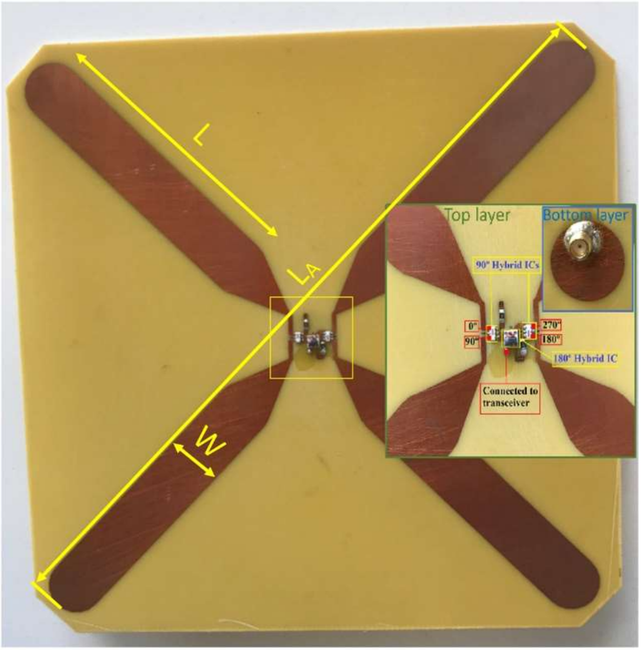


Fig. 2. Prototype SPD-PCD antenna with RF circuit (enlarged).

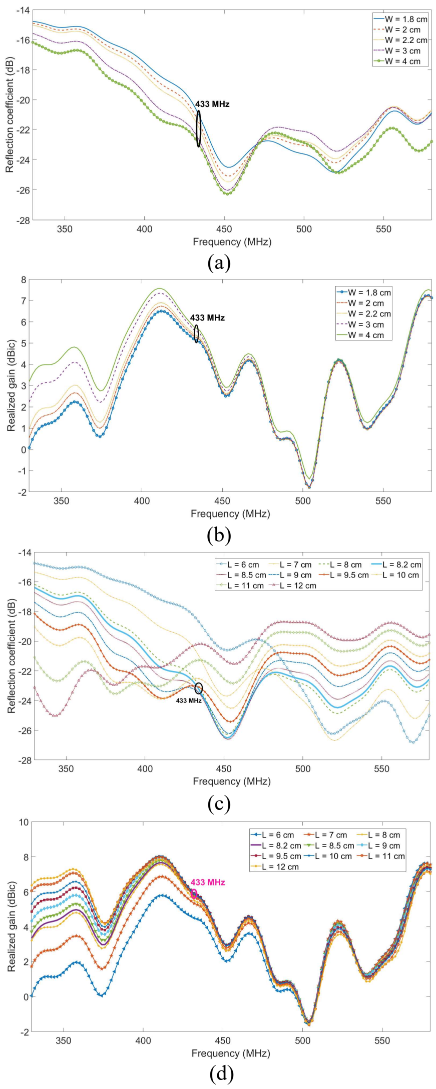


Fig. 3. Parameter sweep results (a) and (b) show the effect of changing width W on |S11| and gain respectively with a fixed length L = 8 cm, (c) and (d) similarly show the effect of changing length L with a fixed W=4 cm.

hybrids were selected because they have small footprints and help in minimising the ground plane area. Any radiation incident on the ground plane is lost and therefore it should be kept as small as possible. A picture of the ground plane is also shown in Fig. 2. Also visible is the female SSMA connector that connects the antenna to a transceiver. A SSMA connector has a smaller footprint than its SMA counterpart and helps in minimizing the ground plane area which spans a circle of just 8.3 mm radius. Each of the four antenna branches are tapered where they connect to the RF circuit and rounded at the edges towards the PCB boundary. These measures avoid reflections and help in maintaining good signal quality. The antenna was simulated using CST Studio suite, whereas Keysight Advanced Design System (ADS) was used to design the RF circuit.

IV. Parametric Study and Results

The SPD-PCD antenna with a quarter wave reflector were simulated as being placed inside an air-filled enclosure on the glacier surface with snow on all sides except the up side. Parametric study was done by varying the width W and length L. Figs 3(a) and 3(b) show the effect of changing width W on the |S11| and gain. Changing W from 0.02 λ (1.8 cm) to 0.05 λ (4 cm) with a fixed length L= 0.11 λ (8 cm) improved |S11| only by a decibel which is less significant because |S11| remained below -20 dB for all widths at 433 MHz. The λ here is the free space wavelength at 433 MHz. The effect of changing W was relatively more pronounced in the gain which improved by 0.55 dBic. With a fixed W=4 cm, Fig. 3(c) shows that changing length L caused an insignificant variation of only a quarter decibel in |S11| if L remained between 8.2 cm to 9.5 cm. A similar trend was observed in the gain shown in Fig. 3(d) where the variation remained ±0.1 dBic for L between 8 to 10 cm. The optimum values for W, L, and L_A remained 0.05λ (4 cm), 0.13 λ (9 cm), and 0.41 λ (28.62 cm) respectively. The available lab resources did not permit in-snow lab testing of the antenna. Instead, an alternative experimental validation method was adopted. A version of the antenna design (L=8.2 cm, W=1.8 cm) was optimised for free space and experimental testing was also carried out in free space. If the simulated and measured results in free space matched well, it provides evidence for expecting the antenna to perform in snow as per the relevant simulations.

Fig. 4 shows the |S11| and gain when the antenna was simulated with optimum dimensions in snow, as well as the simulated and measured results of the antenna in free space. The frequency range 330-580 MHz represents the specified limits of the ICs used for the RF circuit. Fig. 4 reveals that the antenna provides a realized gain of 5.9 dBic at 433 MHz in snow which satisfies the available link budget with an additional margin of 0.9 dBic. The antenna provides a -10 dB fractional bandwidth (FBW) of 57% validating wideband operation. The free space simulation and measured |S11| and gain also shown in Fig. 4 are in good agreement. Some differences between the simulated and measured results are attributed to fabrication tolerances. The antenna is symmetrical and the simulated radiation patterns at 433 MHz in both xz and yz planes as shown in Fig. 5 are identical. The snow medium simulation results in Fig. 5(a) show that the -3 dB angular widths in the vertical planes remained 60º well above the required minimum beam width of 50º, with the side and back lobes remaining below 0 dBic. The free space simulation and measured radiation patterns shown in Fig. 5(b) are in good agreement. From Fig. 6, the simulated axial ratios in both snow and free space media remained close to 0 dB while the measured axial ratio in free space remained below 1.1 dB. While an axial ratio of below 1.1 dB is quite acceptable, it might be possible to get a lower reading with more accurate fabrication and experimentation. Fig. 7(a) shows the simulated co- and cross polarizations at 433 MHz in snow. The co-polarization remained greater than 10 dB compared to the cross polarization within a beam width of 80º in the intended direction of reception. This shows good polarization performance. The free space simulation and measured results of co- and cross polarization shown in Fig 7(b) remained relatively better with the co-polarization stronger by at least 16 dB than the cross polarization within a beam width of 80º in both the vertical planes xz and yz. Fig. 7(b) also shows a good agreement between the simulated and measured results.

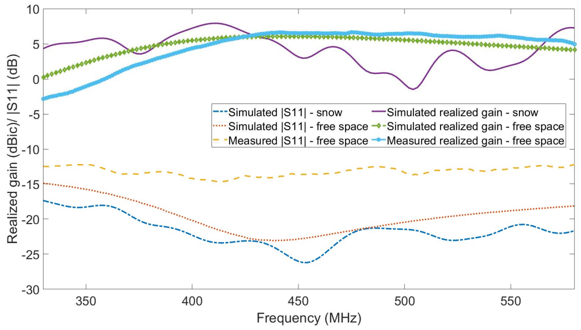
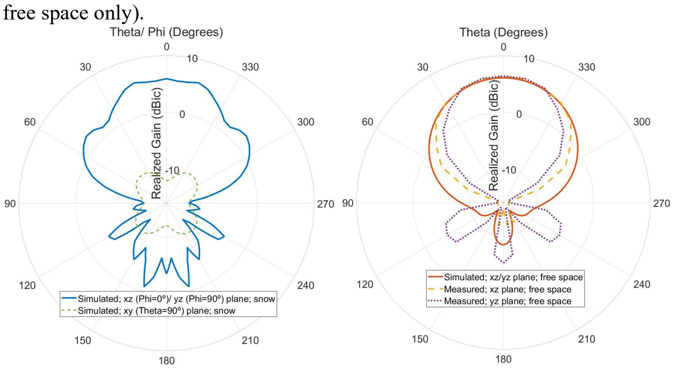


Fig. 4. Simulated and measured reflection coefficient |S11| and realized gain of the SPD-PCD antenna in snow and free space media (measured results in free space only).



(a) (b)

Fig. 5. Far field patterns at 433 MHz (a) shows the simulated far field pattern in snow medium in three planes xz (Phi=0º), yz (Phi=90º), and xy (Theta=90º) (b) shows the free space simulated and measured patterns in xz and yz planes.

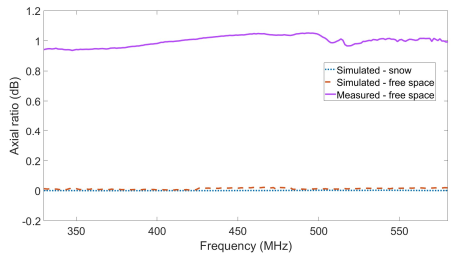
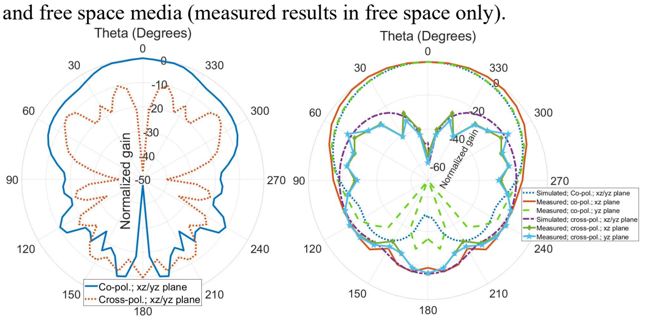


Fig. 6. Simulated and measured axial ratios of the SPD-PCD antenna in snow and free space media (measured results in free space only).



(a) (b)

Fig. 7. Simulated and measured co- and cross polarizations at 433 MHz (a) snow medium simulated results (b) simulation and measured results in free space.

V. Conclusion

It has been shown through experimental evidence that a printed cross dipole antenna is suitable for supraglacial telemetry receiver applications and could theoretically achieve englacial communication ranges of up to 2300 m. This work also validates 433 MHz as a usable frequency band for long range communication through ice. The previous works used a lower frequency for several hundred metres communication in ice and did not employ a printed version of the cross dipole antenna. A novel LHCP printed cross dipole antenna developed in this work can provide a gain of 5.9 dBic at 433 MHz, a FBW of 57% in snow with a -3 dB angular width of 60º in both the vertical planes. The axial ratio remained below 1.1 dB while the co-polarization remained at least 10 dB stronger than the cross polarization in both simulation and measured results done in snow and free space media. The results also indicate good circular polarization performance for the realised antenna.

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