Wireless Microwave Signal Transmission for Cryogenic Applications

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***Abstract*—Microwave wireless signal propagation in cryogenic environments has applications in radio astronomy and quantum computing. This paper demonstrates for the first time a cryogenic wireless setup and investigates the antenna-to-antenna signal transmission in Liquid Nitrogen (LN) and inside the dilution refrigerator at room temperature (296 K). The antenna under investigation consists of a wideband antenna operating in from 8-12 GHz. The antenna was modelled and designed in CST MWS and fabricated on the Rogers RT/duroid 5880 substrate. The measured transmission coefficient (S_{21}) results demonstrate that there was reasonable signal transmission between the antenna pairs when tested in LN (77 K) and inside the dilution refrigerator (tested at 296 K). The results indicate that the proposed Over-The-Air (OTA) system is suitable for cryogenic applications down to 77K.**

Keywords—Cryogenics; Quantum Computing; Liquid Nitrogen; Microwave Antenna

I. INTRODUCTION

Cryogenic-based microwave technologies such as Quantum Computing and Radio Astronomy rely on operating microwave systems inside cryostats operating down to temperatures as low as tens of milli-kelvin. The capability to transmit and receive microwaves through a wireless interface inside these cryostats will reduce the thermal loading within various temperature stages [1] and act as low-loss microwave and/or quantum interconnects and carriers of high-frequency signals beyond 67 GHz. Developing OTA systems to operate in cryogenic environments can be challenging due to the difficulty in designing reliable antennas and free space components such as lens and filters. The material properties of the substrates, such as dielectric constant and loss tangent, are not known precisely at cryogenic temperatures. Therefore, the performance of antennas optimised for room temperature operation is subject to variation when deployed in cryogenic environments. Experimentally, it is also well understood that the electrical properties of conductors, such as electrical resistivity varies at low temperature. For example, materials such as Niobium and Aluminium become superconducting at 9.23 K [2] and 0.8 K, respectively [3]. The thermal contraction of materials at cryogenic temperatures would create mechanical stresses on components and also affect the electrical parameters, such as the characteristic impedance of the transmission lines of the feed structure of antennas. This could degrade the reflection and transmission performance of the antennas deployed inside the cryostat. A possible solution is to design antennas using substrate materials and conductors of known electrical, mechanical and thermal performance at cryogenic temperatures. Potential radiator conductors could be superconducting materials such as niobium, aluminium, and copper-based alloys to ensure low loss and high thermal conductivity. This paper investigates a wideband patch antenna design which uses Copper as a conductor and substrate as Rogers RT/duroid 5880. The antenna is tested at 77 K in the LN environment. The antennas are also mounted inside a dilution refrigerator and measured at 296 K and the suitability of the antennas for OTA systems is evaluated. This testing will facilitate the development of cryogenic OTA systems.

II. ANTENNA DESIGN

A microstrip patch antenna was modelled and designed in CST Microwave Studio. Figure 1 shows the layout of the proposed antenna. The antenna was designed on Rogers RT/duroid 5880 dielectric substrate with a dielectric constant of 2.2 and loss tangent of 0.0004 at 10 GHz. The centre patch antenna element is fed using a coaxial SMA connector. The capacitively coupled parasitic patch elements of different sizes are added to widen the bandwidth of the antenna. Copper was used as the conductor material due to its reduced electrical resistivity at cryogenic temperatures. This substrate is specifically chosen because of its low loss tangent at microwave frequencies and it is found to have a further reduction in loss tangent at cryogenic temperatures [4].

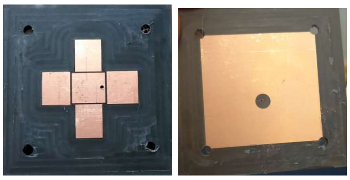

Fig. 1. Antenna Layout: a) Radiator surrounded by parasitic patches and b) Ground plane

The size of the antennas is kept around 4×4 cm^2 backed by a ground plane. The -10 dB impedance bandwidth was achieved over a frequency range of 8-12 GHz. The simulated gain for the antennas was around 5 dB which is typical for microstrip based patch antennas. To ease the mounting of the antenna on the

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dilution refrigerator plates, probe feeding was used, as described in the next section.

III. Experimental Setup

To characterise the antenna at cryogenic temperatures, a preliminary test was conducted in LN (77 K). This was followed by mounting the antenna inside the dilution refrigerator provided by Oxford Instruments [5]. The experimental setup at 77 K is shown in Figure 2. Each feed port of the transmit and receive antenna was connected to the test ports of a Vector Network Analyzer (VNA) operating at room temperature through coaxial cables.

The antennas are placed in a paraffin box which acts as a container for holding liquid nitrogen. The free space transmission response is observed first without LN in the box, as shown in Figure 2a. The antennas are then immersed directly into LN, as shown in Figure 2b to evaluate the signal transmission through LN. The antennas were submerged for about 10 mins to observe any effect on the performance. In the end, the antennas were taken out from LN and the transmission performance was recorded again at room temperature to see if LN has degraded the antenna performance permanently. The experimental setup inside the dilution refrigerator at 4 K is shown in Figure 3. The antennas were mounted on brass rods which were attached to the 50 K and 4 K stage. Note that the refrigerator was not cooled for this measurement. The motive was to gauge the reflections from metallic components and plate shields.

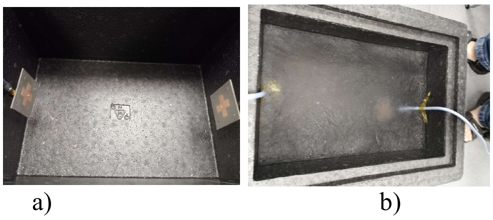

Fig. 2. Cryogenic OTA setup for microwave transmission in LN: a) Freespace and b) Antenna dipped in LN

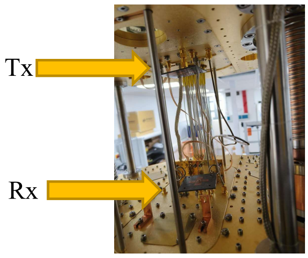

Fig. 3. Antenna setup inside the dilution refrigerator

IV. Result and Discussion

The results in Figure 4 and Figure 5 show the transmission response (S_{21}) in LN and inside the dilution refrigerator. It is observed in Figure 4 that the transmission response curve is shifted towards lower frequencies by 4% and no additional loss is observed compared to that in air. Furthermore, the peak transmission of the antenna-to-antenna setup inside the dilution refrigerator was observed to be -11.2 dB at room temperature inspite of the metallic components surrounding the antennas and the metal shielding, which is very promising. Currently, efforts are being made to extract calibrated transmission response of antenna-to-antenna setup at 4 K using cryogenic RF switches. It is expected that there will not be a considerable change in performance at 4 K compared to room temperature as the medium is vacuum inside the dilution refrigerator.

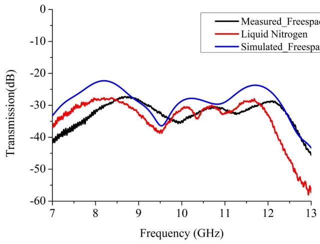

Fig. 4. Transmission under different conditions

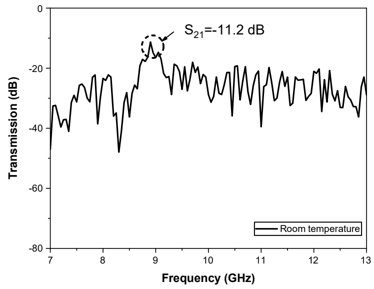

Fig. 5. Transmission response of OTA system inside the dilution refrigerator at ambient temperature

V. Conclusion

In this work, microwave signal transmission in LN and inside a dilution refrigerator was investigated using a wideband antenna fabricated on Rogers 5880 substrate. It was found that the signal transmission was not affected in LN and inside the dilution refrigerator. Measured results indicated the feasibility of using Rogers 5880 substrate to be used in cryogenic environments. The future work will involve testing the transmission response inside the dilution refrigerator.

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