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Near-field broadband antennas measured in cryogenic environment

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Abstract- Broadband bow-tie antennas have been studied in near-field configuration to transmit microwave signals in the 8-12GHz frequency band from the cold stage of cryogenic systems. The coupling between two antennas respectively placed on the cold stage and on a stage at room temperature has been measured for different temperatures of the cold stage ranging from 300K down to 12K. An average transmission of -5.8dB at 300K and -4.8dB at 12K has been measured in the 7.1-8.2GHz frequency band.

Index Terms- cryogenic measurement, near-field antenna, bow-tie, X-band antenna, microwave antenna.

I. INTRODUCTION

Rapid Single Flux Quantum digital electronics (RSFQ), based on superconducting Josephson junctions, currently operates at clock frequencies of tens of GHz. It is currently the only mature solution to increase the speed of present semiconductor technologies while decreasing the associated power consumption. Superconductivity requires low temperatures carried out either by liquid nitrogen at 77K for high critical temperature superconductors, or liquid helium at 4K for conventional low critical temperature superconductors. In a cryogenic system, the hold times are limited by radiative and thermal conductive losses from room temperature to the cryogenic stage. The use of antennas for short distance communication is a solution to improve the thermal budget and simplify the set up of complex cryogenic systems like microwave imagers, due to the absence of microwave thermally conductive cables. We have chosen to use antennas, placed in near-field configuration, to transmit the data in the 7.1-8.2GHz frequency band, as an intermediate frequency range for Superconductor-Insulated-Superconductor (SIS) mixers for radioastronomy applications [1]. A set of

emission-reception antennas has been placed in the cryogenic system to transmit signals between the cryogenic chips and the room-temperature measuring environment.

I. CRYOGENIC MICROWAVE CONFIGURATION

The cryostat that has been used to test the antennas comprises three different temperature stages: a cooled stage, an intermediate stage and the room temperature stage.

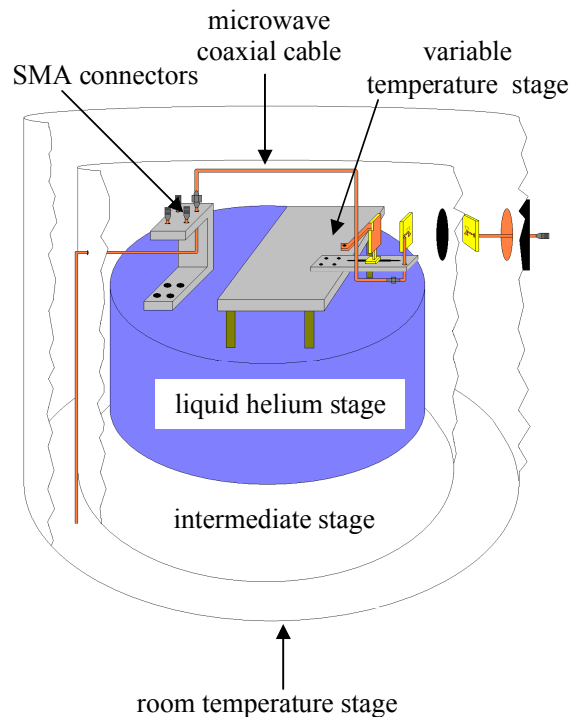


Fig.1. Cryogenic set up of microwave signal transmission with near-field antenna configuration

Thermal shields are used at the intermediate stage to reduce the heat load on the colder stage by blocking far-infrared radiations. Moreover, to transmit or receive different signals, four

microwave coaxial cables with SMA connectors to work up to 40GHz, more than 50 DC lines in manganin and copper, and four optical fibers, have been installed (see fig.1). The coaxial cables have been heat sunk on the cold stage with a brass mechanical assembly. The temperature of the cold stage can be varied with a thermal switch that puts it in contact with the stage of the liquid helium tank.

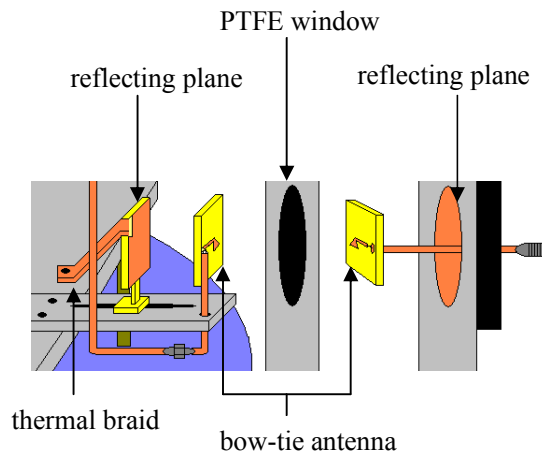


Fig.2. Close up view of antennas of figure 1

The two bow-tie antennas, placed across from each other respectively on the cold stage and on the room temperature stage of the cryostat, are separated by a thin polyethylene window thermalized at the intermediate stage (see fig.1 and fig.2) that blocks most of the radiation at infrared and optical wavelengths.

The cold antenna is heat sunk by an epoxy plate with a side covered by a copper layer in contact with the cold stage, on which the coaxial cable is soldered. Additionally, a thermal braid has been used to improve the thermal conduction between the antenna and the cold stage. The temperature inside the cryostat is measured with a sensor whose resistor varies strongly with temperature below 50K. This sensor is attached to a piece of brass foil with thermally conductive epoxy glue [2]. The foil is fixed on the cold stage of the cryostat with indium.

II. PRELIMINARY MEASUREMENTS

We departed from the geometry of bow-tie antennas presented in [3], to adapt it to operate in the 7.1-8.2GHz frequency band with Rogers RT/Duroid RO4003C 508 μ m-thick substrate

having a dielectric constant $\epsilon_r=3.38$ and a conductor loss with $\tan\delta=0.0035$. Fig. 3 shows the geometry and dimensions of the fabricated bow-tie antennas. Before placing the antennas inside the cryostat, we have measured and simulated with HFSS their coupling in free space [4]. Both antennas have been placed across from each other; the distance between antennas has been varied from 2mm to 23mm. The best coupling was obtained for the shortest distance of 2mm with $S_{21} = -3.8\text{dB}$ at 9.3GHz. In a second step we have added a conducting reflecting plane behind each antenna (see fig.2).

By keeping the best coupling measured previously with the distance of 2mm between antennas, the distances between each reflecting plane and its respective antenna have been varied in order to optimize the coupling of the microwave signal. The best coupling of $S_{21}=-1.5\text{dB}$ has been obtained for a distance of 9mm, the coupling stays better than -3dB over a frequency range of 1.7GHz centered at 8GHz. The bow-tie antennas have also been tested in an array configuration and the crosstalk has been measured [4] in order to verify that such arrays can be ultimately used in a cryogenic configuration.

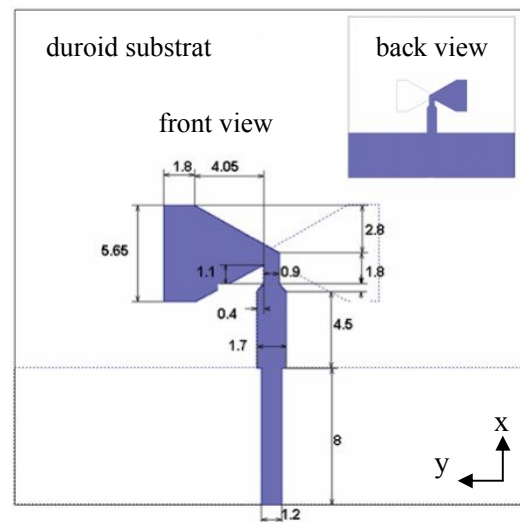


Fig.3. Geometry and dimensions (in mm) of bow-tie antennas studied in this work

With different simulations of the antenna directivity, we noticed that the addition of a conducting reflecting plane increased the directivity in the z-direction by 2.9 to 3dB. Figure 4 shows the simulation of a bow-tie antenna with its reflecting plane on the backside

at 9mm for three different frequencies. The directivity is maximum for an angle $\theta = 30$ degrees at 9GHz.

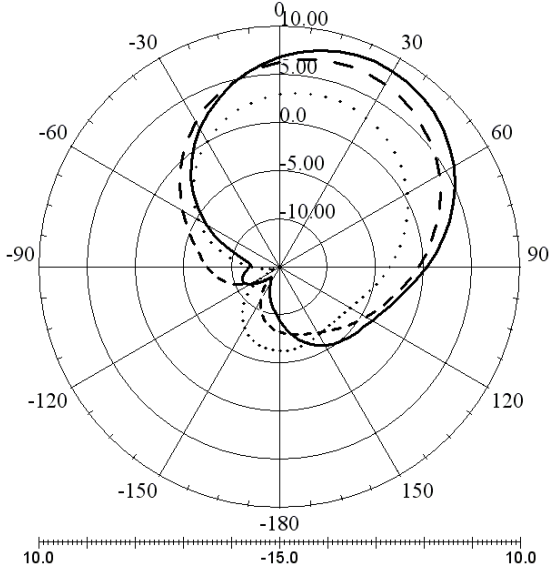


Fig.4. Directivity of a bow-tie antenna in dB with a reflecting plane at 9mm from the backside for $\phi=0^\circ$ and by varying θ from 0° to 360° at 5GHz (dotted line), 7GHz (dashed line) and 9GHz (solid line)

III. CRYOGENIC MEASUREMENT

To assess the performance of the antennas in a real configuration, they have been integrated with the conducting reflecting planes inside the cryostat to measure their coupling as a function of the temperature of the cold antenna from 300K down to 12K (see fig.1) using liquid nitrogen first and liquid helium in a second step. Inside the cryostat, we have chosen the optimal configuration with the antennas separated by 3mm and a distance between antennas and their conducting reflecting planes of 10mm.

Figure 5 shows the coupling S21 between antennas for the two temperatures of 12K and 300K of the antenna placed in the cold stage, as well as simulations over the 5 to 10 GHz frequency band. One can notice a reasonable agreement over our bandwidth of interest from 7 to 9 GHz. Nevertheless some mismatch clearly appears above 9 GHz, which does not hurt for our application purpose.

The contribution of the coaxial cables of about 2dB has been substrated after preliminary measurement of their losses. The average value of S21 in the 7.1-8.2GHz frequency band is -5.8dB at 300K and -4.8dB at 12K, it corresponds to an improvement of about 1dB when lowering the temperature of the cold stage down to 12K. This improvement is assumed to be due to the lower resistance of the copper metal that composes the bow-tie antennas and the feed lines.

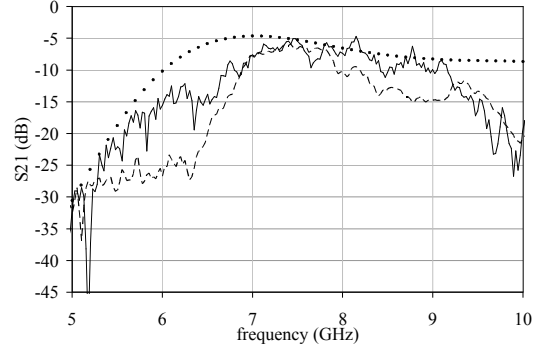


Fig.5. Measured S21 transmission coefficient between bow-tie antennas placed inside the cryostat. The antenna placed at the cold stage of the cryostat was at 300K (dashed line) and 12K (solid line). Simulations correspond to the dotted line.

IV. CONCLUSION

Bow-tie antennas associated with conducting reflecting planes to their backside, arranged in a near-field configuration, are a solution to transmit without heat conduction microwave signals inside/outside a cryogenic system. We found a 1.2dB improvement of the transmission in the 7.1-8.2 GHz frequency band when cooling the cold stage from 300K to 12K. The bow-tie antennas were separated by 3 mm with a conducting reflecting plane placed at 10 mm behind each antenna. The average transmission was -4.8dB with the cold antenna at 12K and -5.8dB at 300K. The improvement is likely due to lower losses in the metal layers that constitute the antennas and feed lines.

The direct transmission through antennas of the signals coming from the superconducting chips will permit to decrease the thermal losses due to the coaxial cables and increase the cryostat hold time. We plan to add an amplifier with the room-temperature antenna in the future to compensate for the transmission losses.

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