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Near-field bow-tie antennas for microwave cryogenic applications

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Abstract — Printed bow-tie antennas have been designed to operate in X-band in near-field configuration in order to transmit signals over very short distances for cryogenic applications. Transmission between two bow-tie antennas directly placed across from each other has been simulated and measured for different configurations. It is shown that, by placing back-reflecting planes at a proper distance behind each bow-tie antenna, a transmission with losses below 3 dB can be achieved in the 8.0-9.7 GHz range. Detailed experimental results are presented.

Index Terms — Antenna measurements, bow-tie, microwave power transmission, microwave antennas.

I. INTRODUCTION

Wireless communication is a field of growing interest for miscellaneous applications for several reasons, including simplicity of use and mobility. Another field for which wireless microwave communications is badly needed is connected to cryogenic systems, widely used for scientific applications, like millimeter and submillimeter astronomy [1] and Earth observation [2], or in the space telecommunication sector for which some microwave systems comprise some cooled sub-systems. Indeed, in such fields, detectors very often need to be cooled at low temperature to be very sensitive or because they make use of superconducting materials [3] that are useable under their critical temperature. In practice, when cryostats are used, the temperature of operation is often the one of liquid nitrogen, e.g. 77K or of liquid helium at 4K. Nevertheless, nowadays, cryogenerators allow cooled systems to operate in the whole temperature range comprised between these.

For such cryogenic applications that receive, transmit and/or process microwave signals, there are mainly two ways to bring the external signal to the cryogenic stage:

1) by using free-space propagation through a transparent window in the cryostage where the microwave device is placed: this solution is only useable for high-frequency millimeter wave signals since the window would be too big for lower frequencies. In any case the number of channels is limited by the thermal power entering the cryogenic stage through the windows;

by using coaxial cables, more suitable for lower frequencies since their RF losses are lower. But in this case, some thermal power is brought to the cooled stage by the cables: this solution is more suitable for systems comprising only a low number of cables.

When a large number of channels is necessary in a cryogenic system, the two above-mentioned solutions rapidly show their limits. So far, the only possibility to overcome this issue is to design a cryogenic stage that can handle large amounts of cryogenic power. This has some clear consequences in terms of volume, weight, quantity of cryogenic fluid for cryostats or electrical power for cryogenerators. A solution to bypass these problems would consist of transmitting the microwave signals inside the cryogenic stage through wireless communication means. To evaluate such a solution we propose to adapt bow-tie antennas developed for C- and X-bands in [4] for this specific cryogenic application. Indeed, on top of their capabilities of being used for wide-band applications, they can be easily integrated in arrays with dual-polarization mode.

II. BOW-TIE ANTENNAS IN NEAR-FIELD CONFIGURATION

To perform the study we departed from the geometry of bow-tie antennas presented in [4], to adapt it to operate in the frequency band of 8-12 GHz with a more suitable material for the planned cryogenic applications, based on a 508 μm -thick Rogers RT/Duroid RO4003C substrate with a dielectric constant $\epsilon_r = 3.8$. This frequency range has been chosen as a typical intermediate frequency (IF) range used for superconductor-Insulator-Superconductor (SIS) mixers cooled at 4K for radioastronomy applications. Fig. 1 shown below has been taken from [4] in order to illustrate the dimensions of the bow-tie antennas used in this work, derived from the antenna design presented in [4]. The dimensions optimized for our particular application, measured directly on the fabricated antennas, are given in Table I.

Both antennas of the same geometry have been placed across to each other, as shown in Fig. 2. The distance of the two planes supporting the printed antennas, parallel to each other, has been varied from 2 to 23 mm, e.g. in a range of distances of interest for the cryogenic applications, in order to study experimentally the coupling in the frequency band of interest. The minimum distance of 2 mm was limited by the size of the two SMA connectors located at the microstrip input ports of the antennas, while 23 mm was the distance above which the coupling was poor.

Measurements of the antenna return loss have been performed in the frequency range of interest, they are

presented in Fig.3 for different distances between the two antenna planes.

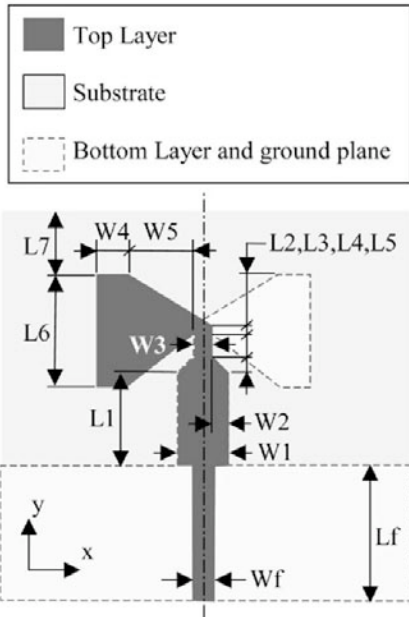


Fig. 1. Geometry of bow-tie antennas used in this work. This figure has been taken from the paper of Ref. [4] for convenience since the work is an extension of [4] for particular applications.

TABLE I
DIMENSIONS OF BOW-TIE ANTENNAS

Insulator dielectric constant (RO4003C)	3.38 at 10 GHz
$\tan \delta$	0.0035 at 10 GHz
Insulator thickness	0.508 mm
Enclosure box size	30 x 29 mm
W_f	1.22 mm
W_1	1.67 mm
W_2	0.42 mm
W_3	0.87 mm
W_4	1.84 mm
W_5	3.96 mm
L_f	8 mm
L_1	4.5 mm
L_2	0.44 mm
L_3	1.11 mm
L_4	1.78 mm
L_5	2.77 mm
L_6	5.64 mm
L_7	9.68 mm

This figure shows that the broadest band input impedance match is below -10 dB of return loss in the 9.5-10.4 GHz for the dotted line, corresponding to a 10 mm distance between

both antenna planes. Other distances correspond to a better return loss but over a narrower bandwidth.

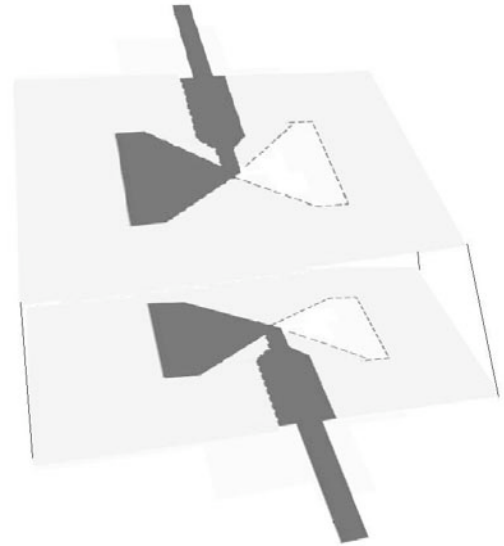


Fig. 2. Respective placement of the two bow-tie antennas placed in near-field configurations. The distance between the planes of the antennas has been varied from 2 to 23 mm.

Fig. 4 shows the coupling between both antennas located in the near-field configuration for different distances between their respective planes. One can point out that the coupling is better if the distance is shorter. The best obtained transmission is -3.8 dB at 9.3 GHz for a distance of 2 mm between the antenna planes. This value does not correspond to the value found in Fig. 3 for best impedance match, which suggests that that the inductive coupling dominates the behaviour of the signal transmission of the antennas, in good agreement with the near-field configuration that has been used.

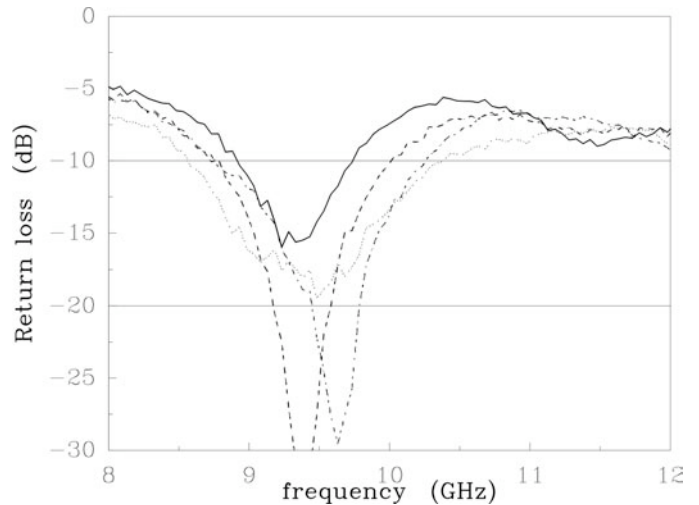


Fig. 3. Antenna return loss for different distances d between antenna planes: $d = 2$ mm (solid line); $d = 5$ mm (dashed line); $d = 10$ mm (dotted line) and $d = 16$ mm (dotted-dashed line).

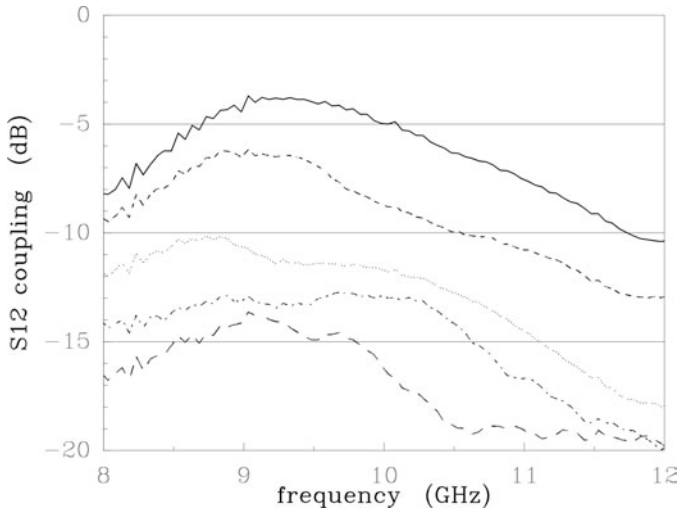


Fig. 4. Coupling between the two bow-tie antennas for different distances d between antenna planes: $d = 2\text{mm}$ (solid line); $d = 5\text{mm}$ (dashed line); $d = 10\text{mm}$ (dotted line); $d = 16\text{mm}$ (dotted-dashed line) and $d = 23\text{mm}$ (long-dashed line).

III. BOW-TIE ANTENNAS WITH BACKSIDE REFLECTING PLANES

Though this performance can be acceptable for some cryogenically-cooled detectors, it is preferable to obtain a better coupling to compete with existing solutions based on coaxial cables. Moreover, the cryogenic environment is such that each antenna will be placed close to a metallic plane located parallel to its back side. Indeed, these antennas will be associated to a specific stage of the cryogenic system made out of a conducting material. In order not to short the bottom plane of the bow-tie antenna, the substrate that holds it has to be maintained at a certain distance of the cryostat stage that consequently acts as a back reflecting plane for the microwave signal.

In order to simulate this fact, a conducting reflecting plane has been placed behind each antenna plane at a distance - the same for both antennas - that has been varied in order to optimize the coupling of the microwave signal. An epoxy plate, covered by a copper layer has been used to simulate the behaviour of the conducting cryostat stage. Fig. 5 displays a photograph of the setup under test. The reflecting plane of the top antenna has been removed to show the full configuration used for the measurements.

For this configuration, the optimum distance between the two planes of the antennas has been set to 2 mm, which corresponds to the best coupling found in Fig. 4 without back reflecting planes. This value has been used for the measurements presented below. Fig. 6 shows the influence on the bow-tie antenna return loss of the distance between the back reflecting plane and the antenna plane. One can observe that the best return loss is obtained for an optimum distance of 9 mm. Indeed, above this value, the return loss starts again to increase.

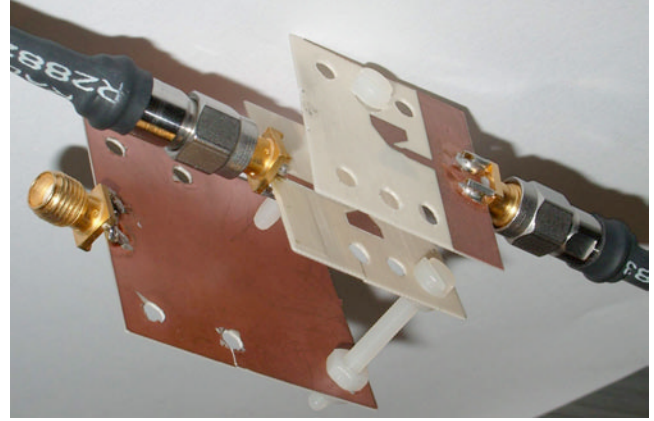


Fig. 5. Photograph of the two bow-tie antennas in near-field configuration, with the back reflecting plane located parallel to the antenna plane. The reflecting plane of the top antenna has been removed for clarity.

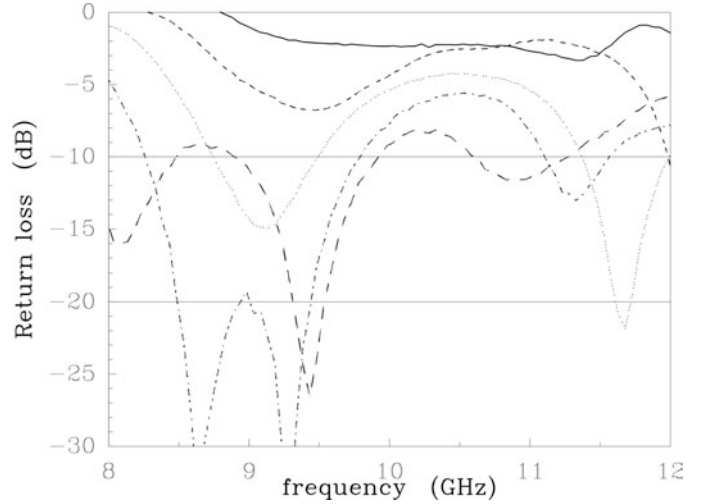


Fig. 6. Bow-tie antenna return loss for different distances h between the antenna plane and its associated back reflecting plane: $h = 2\text{mm}$ (solid line); $h = 5\text{mm}$ (dashed line); $h = 7\text{mm}$ (dotted line); $h = 9\text{mm}$ (dotted-dashed line) and $h = 11\text{mm}$ (long-dashed line). The distance d between antennas is kept at 2 mm.

Fig. 7 shows the coupling between the antennas in presence of a reflecting plane behind each antenna. In good agreement with Fig. 6 one can notice that the best coupling is obtained for a distance of the reflecting plane to the antenna plane of 9 mm. For such a value a coupling lower than -1.5 dB is obtained around 8.4 GHz. The coupling stays better than -3dB over a frequency range of 1.7 GHz, located between 8 GHz and 9.7 GHz. This bandwidth decreases to 1.1 GHz if the back reflecting plane is located at 8 mm from the antenna plane and to 1.55 GHz if the distance is increased to 10 mm.

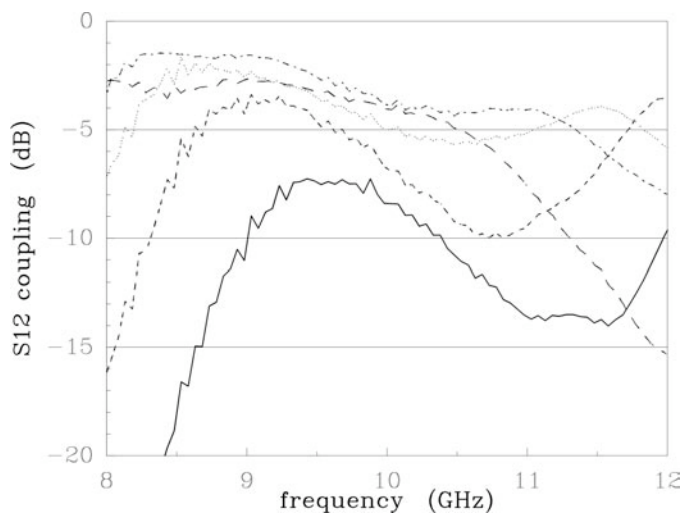


Fig. 7. Coupling between the two bow-tie antennas for different distances h between the antenna plane and its associated back reflecting plane: $h = 2$ mm (solid line); $h = 5$ mm (dashed line); $h = 7$ mm (dotted line); $h = 9$ mm (dotted-dashed line) and $h = 11$ mm (long-dashed line). The distance d between antennas is kept at 2 mm.

VII. Conclusion

A set of two bow-tie antennas designed for X-band has been optimized and measured in near-field configuration to transmit microwave signals into cryogenic systems. It has been shown that the combination of the near-field configuration of the antennas, associated to a back reflecting plane carefully located behind each antenna, enables the transmission of a microwave signal in the 8 to 9.7 GHz range with a loss lower than 3 dB. The transmission loss stays below 2 dB over a

1 GHz bandwidth and can be as low as 1.5 dB over a narrower bandwidth centered at 8.45 GHz. These measurements are very encouraging for designing microwave cryogenic systems with improved performance regarding thermal loads and microwave losses.

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