Superconducting IF biasing circuit for low-noise cryogenic applications

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Abstract. A planar superconducting circuit designed for use in low-noise cryogenic applications is presented. The circuit is a bias-T combined with a $4-8$ GHz impedance matching circuitry, which employs entirely planar design with a novel layout. The proposed and tested circuitry is intended to be used with a SIS mixer and incorporates a double section transformer based on microstrip line technology with a total impedance transformation of 5:1 within the frequency band. One of the transformer sections employs a three-line coupled line, which also serves as a DC block capacitor. The microstrip lines were manufactured using superconducting Nb metallization, which provides a conduction loss-free solution at the operation temperature of 4 K. S-parameter measurements at 4 K temperature were performed and found to be in a good agreement with the simulations. The device measured return loss is better than $-10$ dB within the frequency band. Furthermore, the circuit was tested as a part of 385–500 GHz double sideband heterodyne SIS receiver demonstrating a flat noise temperature response of 80–90 K over the entire IF band of 4–8 GHz.

1. Introduction
Low-noise cryogenic receiver components and technology development has made great progress in the last decade, especially boosted by many international instrumentation projects, such as ALMA [1], APEX [2], Herschel [3], etc., aiming for developing ultra-low noise receivers for sub-mm and mm radio astronomy. For these projects the technology is pushed towards a low noise performance close to the quantum limit and wide intermediate frequency (IF) bandwidth with a flatter response. The abovementioned performance criteria are of great importance especially for extragalactic observations where molecular lines are wider and fainter [4].

In order to achieve the best noise performance, an optimum match is required between the RF signal and the active device (mixer, diode, transistor etc.) and particularly, between the latter one and the IF output. In most receiver configurations, the active device exhibits an IF load impedance different than 50 Ω. Therefore, the IF output and the active component are generally connected via a bias-T circuitry that introduces not only the DC bias for the active device, but also serves as an impedance transformer to provide optimum matching conditions, for instance, the superconductor-insulator-superconductor (SIS) mixer at the IF frequency [5].

In this paper, we present an alternative approach to design such biasing circuit that provides entirely planar circuit layout where we eliminated lumped DC blocking capacitor by employing a three-line microstrip line. Thus, unwanted performance effects, from otherwise necessary surface-mount DC blocking capacitor, are removed. In addition, the entire circuitry is made of...
superconducting Nb metallization eliminating conducting loss in the circuitry. In this paper, we present a comparison of extensive simulations of the proposed circuitry and measured performance of the fabricated bias-T. Measurements were performed in liquid He with the active device (SIS mixer) replaced by a 12.5 Ω resistor in order to evaluate the return loss and the impedance transformation performance across the band of interest.

Furthermore, we present the experimental results of employing the suggested superconducting circuitry in a 385 – 500 GHz double sideband (DSB) SIS receiver with evident results that the superconducting bias-T contributes to the noise performance improvement and the receiver IF response flatness.

2. Circuit design
The design goal was to obtain a bias-T circuitry with IF band of 4 to 8 GHz together with a matching network to transform the 50 Ω IF output impedance to 10 Ω. For the impedance transformer, a double section λ/4-transformer is used, figure 1. The second section of the transformer is based on a three-line coupled-line technique, widely used for baluns [6], couplers [7] and DC blocks [8]. For our design, a quarter wavelength symmetrical coupled line structure with constant spacing is used. By adjusting the spacing and the coupled line widths, the required impedances can be obtained following the procedure as described in [9]. The coupled lines act also as a DC block capacitor, and so, eliminate the need to use lumped components, which were employed in previous versions of the circuitry [5]. The lump capacitor use has resulted in unwanted effects such as additional parasitic resonances or mechanical stability of the circuitry due to temperature dependent contraction stress. Another alternative to the surface-mount capacitor is to use a parallel-coupled suspended microstrip line as proposed in [10]. However, this solution requires additional machining of a cavity for the suspended microstrip section, which greatly complicates manufacturing and assembly. For the RF leak blockage, a radial stub is employed followed by a quarter-wavelength high impedance line. The DC bias circuitry is connected to the bias-T circuit through a cryogenic wire soldered at the edge of the radial probe. Palladium (Pd) thin film over Nb was used for contact pads.

At microwave frequencies, due to the skin-effect, the microstrip conductor thickness has to be at least three to four times thicker than the skin depth, \( \delta_S \), given as,

![Figure 1. Schematic diagram of the proposed biasing circuit.](image-url)
\[ \delta_S = \left( \frac{2}{\mu \sigma \omega} \right)^{1/2} \]  

(1)

Since the skin depth is a function of frequency, \( \omega \), magnetic permeability, \( \mu \), and conductivity, \( \sigma \), according to equation (1) [11] and accounting for the extreme anomalous skin-effect regime for gold at 4 K [12], it is required to have at least 2 \( \mu \)m thick gold to operate in the 4 – 8 GHz band. Applied to the proposed design with the coupled lines, such thick metallization is comparable to the line spacing (30 \( \mu \)m) and hence influences the capacitance value by changing the coupling. In order to achieve the desired capacitance, the slots between the coupled lines must possess vertical walls, which is hard to obtain through electroplating process required to obtain 2 \( \mu \)m thick gold. For a circuit operating at cryogenic temperatures, we employ DC magnetron sputtered Nb for the transmission lines and Pd for contact pads as a metallization scheme. The advantage of using Nb at RF and microwave frequencies at cryogenic temperatures is directly related to the absence of conduction loss. For a superconductor, such as Nb, at frequencies substantially lower than the gap frequency, the conductivity is considered totally imaginary [11] and given as,

\[ \sigma = -i\sigma'' \]  

(2)

where \( \sigma'' \) is the conductance imaginary part, which is associated with the kinetic inductance. For a London superconductor, the field penetration depth is independent on the frequency (for the frequency band of interest) and is simply the static London penetration depth, \( \lambda_L \), given by,

\[ \lambda_L = (\Lambda/\mu_0)^{1/2} \]  

(3)

where \( \Lambda \) is the London parameter and \( \mu_0 \) is the permeability of vacuum. For niobium, the London penetration depth at 4.2 K is about 85 nm [13]. Hence, the presented biasing circuit used \( \sim 3\lambda_L(Nb) \) thick magnetron sputtered Nb covered by thin Pd layer for wire bonding and soldering at the contact pad areas.

The circuit was designed using the full-wave simulator EMDS [14] based on finite element method (FEM). Limited to the particular application for the IF circuitry for SIS mixer, it is sufficient to have \(-10\) dB return loss across the band. Simulation results are shown in figure 2. The return loss is better than \(-10\) dB for the whole band and the insertion loss is lower than 0.3 dB within 4 to 8 GHz.

3. Measurements and results

The biasing circuits were fabricated using a 0.25-mm thick alumina substrate with dielectric constant of 9.9. First Au/Ti was deposited on the backside of the wafer to form the large area ground plane. The structure was patterned through a standard lift-off process using Shipley S1813 photoresist; DC magnetron sputtering of 300 nm niobium layer was performed on the topside followed by a 150 nm thick palladium. The circuit substrate dimensions are 9.0 \( \times \) 8.0 mm \(^2\). The line parameters of the proposed circuit according to figure 1 are \( W_1 = 1110 \) \( \mu \)m, \( W_2 = 170 \) \( \mu \)m, \( W_3 = 20 \) \( \mu \)m and the spacing, \( S \), of the coupled lines is 30 \( \mu \)m. After the fabrication, the wafer was further diced to get individual circuit substrates, and soldered on a designated fixture. We accounted for possible differential contraction between the alumina substrate of the bias-T and the metal housing of the fixture by introducing 200 \( \mu \)m spacing between the machined walls and the circuitry. For noise-temperature measurements of the SIS mixer, the circuit was integrated into the mixer block comprising SIS mixer chip and connected to the mixer chip via wire bonding with 17.5 \( \mu \)m diameter gold wire.

Measurements of the return loss was performed by immersing the bias-T circuitry in a liquid helium (4 K) using a dip-stick setup. In order to simulate the active component, e.g. the SIS mixer chip, the input was terminated with a 12.5 \( \Omega \) resistor. The resistor used for the
termination of the bias-T was specified for cryogenic applications with 25 ppm/°C, meaning that the resistance change due to cooling to 4 K would correspond to 7.2 mΩ. Whereas room temperature measurements can be done with good accuracy, it is more difficult to characterize circuit cooled down to cryogenic temperatures. The contribution from the cable in the dip-stick is difficult to model accurately, since the temperature gradient from 4 K up to the room temperature 300 K influences the losses. The temperature gradient depends strongly on the construction of the dip-stick, the actual level of the liquid helium in the vessel and the ambient temperature of the helium vapours. To minimize the effect of these factors, we have performed the measurement at relatively constant helium level by maintaining both the calibration (one port) and measurements within short period of time. The cable link between the dip-stick and the measurement equipment was kept with fixed length and shape by employing semi-rigid cable. This minimized the phase variation and ensured accuracy of the calibration and stability of the calibration during the measurement procedure.

The performance of the biasing circuit was measured using Agilent E8364B network analyzer. Results of the measurements compared to the simulated performance are presented in figure 2. The measured return loss is better than $-10$ dB for 85% of the IF band and are generally in agreement with the simulation results. The discrepancy between the measurements and simulations at upper band frequencies can be attributed to the more than 1 m long coaxial cables used for the dip-stick measurements, difficulties of calibration, uncertainty with the RF loss in the cable due to temperature gradient and parasitics of the resistive termination. The observed resonance at around 6 GHz can be eliminated by wire bonding the outer lines of the three-line microstrip line as demonstrated in [15]. However, we were not able to notice any influence of this resonance at the subsequent noise-temperature measurements.

Following the initial tests, the bias-T circuit was tested as part of the 385–500 GHz DSB low-noise SIS receiver [16]. The mixer layout is presented in figure 3 where the bias-T is integrated into the mixer block. Three bond wires connect the mixer chip to the bias-T circuit. The DC circuit for the SIS biasing is placed on the backside of the mixer block piece and is connected by a wire to the contact pad at the edge of the radial stub.

Noise temperature measurements were performed with the Y-factor technique. Figure 4 illustrates the noise temperature achieved across the IF band for the local oscillator frequency 390 GHz. The results show a reasonably flat response with the noise temperature of 80 – 90 K,
corresponding to about 4 to 5 times of the quantum noise, $h\nu/k$, over the IF band. Comparison with previous Au-based bias-T [17] with lumped DC blocking capacitor reveals that the new Nb-based bias-T increases the operating IF bandwidth by lowering the noise temperature noticeably at the edges of the band.

4. Conclusions

In this paper, we present an alternative approach to design an entirely planar superconducting 4–8 GHz bias-T circuit, incorporating 5:1 impedance transformation and a DC blocking employed as the IF circuitry in a 385–500 GHz SIS mixer. Experimental verification of the bias-T circuit at cryogenic temperatures was performed with a resistor termination, with measured return loss better than $-10$ dB for 85% of the band and reasonably close match circuit simulations. The circuit was integrated and successfully tested on a 385–500 GHz SIS DSB mixer; the measured noise temperature was 80–90 K over the whole IF band with noticeable improvements in the noise temperatures over normal conductor-based bias-T circuits.
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