A New Technique for Measurement of the IF Output Impedance of SIS Mixers

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***Abstract*—A new method is presented to measure the Intermediate Frequency (IF) output impedance (Z_{IF}) of superconducting tunnel junction (SIS) mixers at cryogenic temperatures. The setup uses a commercial Vector Network Analyzer (VNA) with high-sensitivity enhancements to increase the dynamic range of calibration and to perform low-power one-port measurements. The coupler inside the VNA is bypassed and replaced with an equivalent cold coupler inside the cryostat. A bias module connected to an isolator provides the bias to the mixer. A cryogenic low-noise amplifier (CLNA) in the return path to the VNA increases its dynamic range. One-port calibration standards (Short, Open, and Load) are connected to a cryogenic SP4T switch and VNA Software is used to de-embed fixtures. The new method allows direct measurement of the amplitude and phase of the reflection coefficient Γ_{IF} and hence Z_{IF}, from 2 to 16 GHz with very low power levels at the device under test.**

***Keywords*—VNA, SIS Mixer, CLNA, Γ_{IF}, Z_{IF}.**

I. Introduction

The ALMA Band 6 version 2 receiver upgrade specifies a wide IF band of 4–16 GHz and potentially 4–20 GHz [1]. The use of a cryogenic isolator between the SIS mixer and CLNA is currently under investigation. However, another approach is contemplated in which the SIS mixer is connected directly to the CLNA with the potential of obtaining lower noise across the IF band. To achieve high IF bandwidth it has been proposed that SIS mixers with higher critical current density J_C could lower the mixer's IF output impedance Z_{IF} to a range of values closer to 50 Ω where the available cryogenic IF amplifiers deliver optimum low-noise performance [2]. With the resulting lower junction capacitance it is possible to achieve wider RF and IF bandwidths as required by the receiver upgrade. This approach requires a careful mixer design as well as optimization of the IF network between the SIS junctions and IF amplifier.

From Tucker's quantum theory of mixing the IF output impedance at the junctions of an SIS mixer is known to be dependent on the intermediate frequency, but it has been shown [3] that for ratios $F_{IF}/F_{LO} < 0.1$ (our case) this variation is small. The IF output impedance, Z_{IF}, at the output port of the SIS mixer chip is calculated using Tucker's quantum theory of mixing and electromagnetic simulations of the embedding mixer circuit.

The goal of the present work is to describe the new SIS mixer IF output impedance measurement technique and compare with predicted Z_{IF} values over the full IF band.

II. The Measurement Setup

VNAs can easily measure one-port impedances at room temperature and medium power levels, but challenges arise when measuring devices inside a cold cryostat and where the incident signal power levels should be low enough to avoid saturating the SIS mixer. While a single port measurement normally uses the same cable for the incident and reflected signals, for accurate measurements at very low power levels it is necessary to separate the outgoing and returning signals between the VNA and the device under test as shown in Fig. 1.

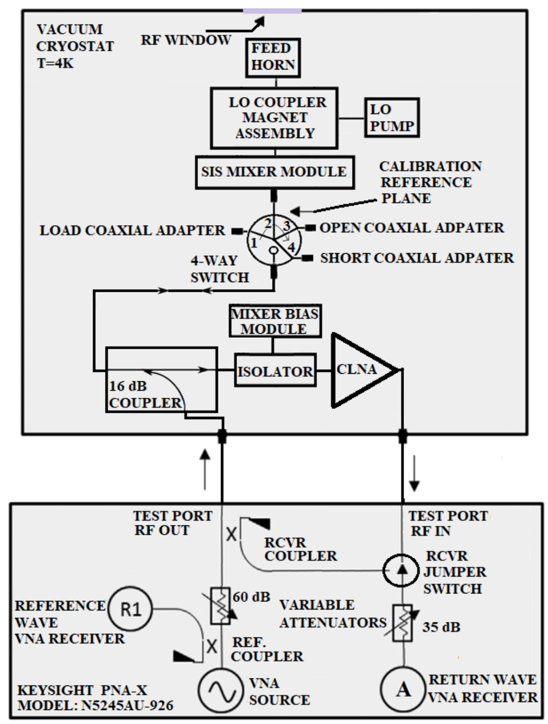

Fig. 1. The one-port Z_{IF} measurement setup. The lower block is a schematic of one of the four ports of the VNA. The upper block represents the schematic of the Band 6 receiver. The outgoing and returning signals are separated inside the VNA and inside the cryostat.

The lower block in Fig. 1 is a schematic of one of the four ports of the VNA. It shows the VNA source, the reference- and return-wave receivers, the reference and receiver couplers, two

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variable attenuators, the receiver jumper switch, and the RF input and output test ports. The base VNA model is upgraded to include a hardware kit (Keysight N5245AU-926) to decrease the source power from -30 to -90 dBm. The added variable source attenuator increases the range of the Automatic Source Levelling Circuit (ALC) and allows higher power during calibration than during measurement without losing calibration integrity. The VNA is equipped with front panel jumpers which can be used to bypass the receiver coupler and select an alternative return path for the RF. This allows the use of an external cold amplifier to increase the level of signals returning to the VNA and increase the dynamic range. The additional gain of the external amplifier, and removal of the 16 dB loss of the receiver coupler, compensates for the attenuation of the test signal.

The upper block in Fig. 1 shows the components of the SIS receiver: the feed-horn, LO coupler and SIS mixer module and LO source, a 4-way switch, 16 dB coupler, mixer bias module, IF isolator, and the cold IF amplifier. Cryogenic open, short, and load coaxial standards are connected to three positions of the computer controlled 4-way switch [4], while an 8-inch long semi-rigid coaxial cable is connected between the switch and the SIS mixer module.

III. The Calibration Technique

The location of the measurement plane is important. The previous technique referenced in [5] placed this plane deeper within the mixer chip, at the SIS junctions. Therefore, one has to transform the measurement to the IF output pad of the chip; and the amplitude and phase may become less accurate. Furthermore, the previous technique used the low resistance, high resistance, and linear resistance regions of the unpumped SIS mixer's I(V) curve as the calibration loads. These regions approximate short circuit, open circuit, and resistive calibration loads.

The new technique locates the calibration plane at the output port of the mixer chip, which is convenient for accurate determination of the complex reflection coefficient. we use coaxial short, open, and 50 Ω terminations so that the one-port 3-term errors of the VNA (directivity, port match, and tracking) are accurately determined and the amplitude and phase of the measurements are properly corrected. The VNA calibration reference plane located at the short-circuit termination on the 4-way switch must be moved electrically past an 8-inch semi-rigid coaxial cable to the mixer chip inside the SIS mixer module. The Automatic Fixture Removal (AFR) Software utility from Keysight Technologies [6], built into the VNA, is used to de-embed the coaxial cable and fixture circuitry between the calibration reference plane and the mixer chip output port. The utility requires a calibration step in which the fixture is terminated with an electrical short at the intended "de-embedding" reference plane.

Calibration and measurement accuracy hinges on using an appropriate incident stimulus power level at the mixer port. Too much power causes the SIS mixer to saturate, altering its characteristics and leading to unreliable data. We characterized the reflection coefficient of the SIS mixer biased at the gap voltage and observed that it undergoes compression at high power levels. We determined that to avoid saturation the RF power level at the mixer port should not exceed approximately -72 dBm. This allowed us to define a safe operating range below the saturation threshold, ensuring accurate measurements for our experiment.

IV. Calibration Technique Validation

Verification of the calibration quality in the previous technique [5] may be difficult. A key advantage of our technique is the ability to verify the calibration by measuring the output impedance of other cryogenic devices at room temperature, such as a low-noise IF amplifier, within the cryostat. This allows for a comparison with direct VNA measurements.

We validated the new calibration technique by measuring the output reflection coefficient S22 of an unbiased low-noise amplifier inside the cryostat at room temperature and compared it with direct measurements on the VNA. We found good agreement of amplitude and phase across the 2 to 16 GHz frequency range. The maximum phase error was 6°, and maximum magnitude error was 0.5 dB.

V. Z_{IF} Measurement Results

The SIS mixer chip used to demonstrate the output impedance measurements was a production chip from ALMA Band 6 which operates in sideband separating mode with 211–275 GHz RF and 4–12 GHz IF [7]. AWR Microwave Office [8] was used to model the SIS mixer using data from the complex five-frequency conversion admittance and noise-current correlation matrices of the pumped SIS junction based on Tucker's quantum theory of mixing [9] [10], and electromagnetic simulation of the RF and IF circuits.

The Γ_{IF} characteristics of the pumped SIS mixer at LO frequencies from 221 to 265 GHz, with IF swept from 2 to 16 GHz were measured showing good agreement with simulated results at lower IFs. A discrepancy between simulation and measurement observed at higher IF frequencies is being investigated.

VI. Conclusions

We presented a new technique for measuring the IF output impedance at the output IF bond pad of the SIS mixer using a commercially available VNA with dynamic range enhancement. Additionally, a simulation program was used to predict the IF output impedance and compare with measurements. While good agreement between measurements and simulations was observed at low IF, some discrepancies emerged at higher frequencies.

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