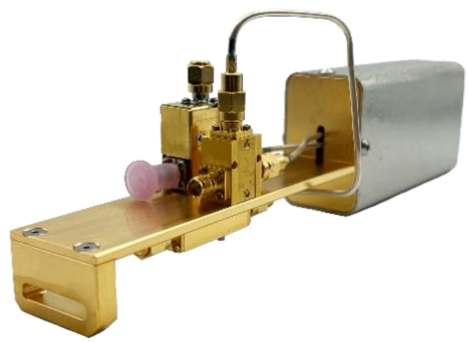
Quantum Microwave JPA Assembly
QMC-JPA-MCA01



Introduction

The QMC JPA assembly is a convenient package which includes all the required cryogenic components to operate the Raytheon/BBN 5-7GHz Wide Bandwidth Josephson Parametric Amplifier (JPA) (QMC #BBN-PS2-JPA-DEVICE-QEC). It is intended to be a cryogenic turn-key solution, saving the end-user time and money on design, development, and validation of the auxiliary cryogenic circuitry which is required before near quantum limited noise measurements with the JPA can be performed. Out of the box the QMC JPA Assembly is designed to be installed onto the mixing chamber plate of a dilution refrigerator and is compatible with standard RF microwave readout chains found in cryogenic measurement setups used to characterize superconducting devices. Each QMC JPA Assembly is fully characterized at < 20 mK before being shipped to determine tuning parameters for gain and noise. A datasheet with measurement data is provided with each QMC JPA Assembly to aid the end-user to tune-up the JPA for the first time.

This document is intended to serve as a datasheet for the QMC JPA Assembly and a setup guide to aid the end-user to bring up the JPA. This document is a supplementary to the Raytheon/BBN TM-2035 Application note for the JPA. Throughout this document values of pump power and DC tuning currents are given at the QMC JPA Assembly. These values are estimates based on approximations of cable losses and may be different for different cryogenic setups. The values provided is meant to be a starting point to bring up the JPA for the first time in a new system.

Description

The QMC JPA Assembly is composed of a cryogenic circuit built around the JPA to facilitate its operation. The JPA is a one-port amplifier, the weak signal to be amplified and the amplified signal are both incident and originate from the same port respectively. The cryogenic circuit of the QMC JPA Assembly routes the input and output signals to different ports aiding the integration into standard RF readout chains. A high-level functional diagram of the QMC JPA Assembly is shown in Figure 1. Throughout this document the weak signal to be amplified will be incident on port labeled IN and the amplified signal originates from port labeled OUT of the QMC JPA Assembly, see Figure 1. The RF pump for the JPA is provided to the QMC JPA Assembly through the port labeled RF Pump. The DC tuning bias current is provided to the QMC JPA Assembly through the port labeled DC.

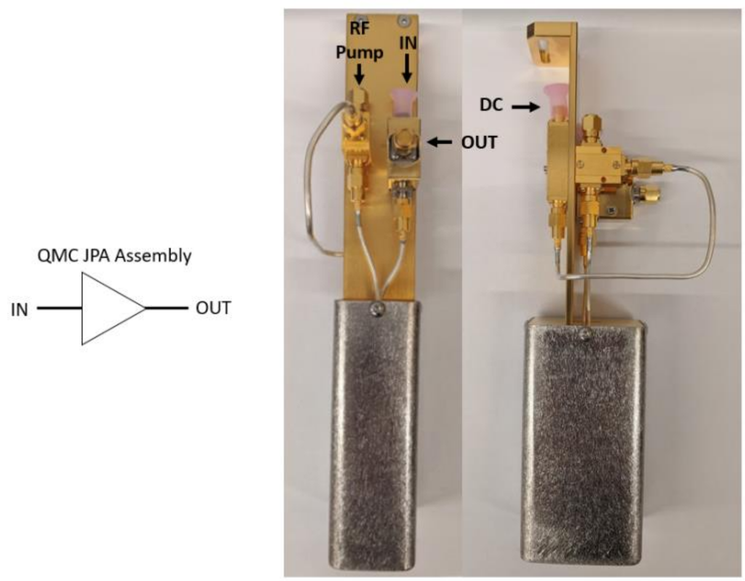


Figure 1 (left panel) High level functional diagram of the QMC JPA Assembly. (right panel) Port labels of the QMC JPA Assembly.

The cryogenic circuit for the QMC JPA Assembly is shown in Figure 2. The circuit is composed of a cryogenic Low Noise Factory circulator LNF-CIC4_8A, Quantum Microwave bias-Tee QMC-CRYOTEE-0.218SMA-FFF, Quantum Microwave LC/Infrared Eccosorb filter combination QMC-CLCE-160AFF, and Raytheon/BBN JPA #BBN-PS2-JPA-DEVICE-QEC. Critical for JPA performance is the impedance the JPA sees at its single port. In the circuit the JPA is matched to a cryogenic circulator through a short ~2.5” low-loss cable to minimize the standing waves and to achieve desired performance of the JPA. The JPA is based on a Superconducting Quantum Interference Device (SQUID) which is very sensitive to external magnetic fields. To minimize the impact of external magnetic field fluctuations in the environment the JPA in the QMC JPA Assembly is magnetically shielded with a mu-metal can made from A4K proprietary alloy from Amuneal Manufacturing Corporation. To minimize potential offsets in current bias tuning of the JPA or hysteretic effects, all components inside the mu-metal can are non-magnetic. The tuning bias of the JPA is provided to the QMC JPA

Assembly through the port labeled DC. In the QMC JPA assembly the DC bias is filtered by the QMC-CLCE-160AFF filter which provides a cutoff frequency at 160 MHz. The filter is also encapsulated with Eccosorb infrared absorber which provides strong attenuation out to the infrared.

Installation

Mount the QMC JPA Assembly to the mixing chamber plate of a dilution refrigerator as shown in Figure 3. The full length of the QMC JPA Assembly is 9 inches, ensure that this will clear any still or mixing chamber shields. Coaxial cable connections must be made to supply a DC tuning bias current, RF Pump source, an input signal IN, and take the amplified output signal OUT from the QMC JPA Assembly. Shown in Figure 3 is an example setup of the QMC JPA assembly.

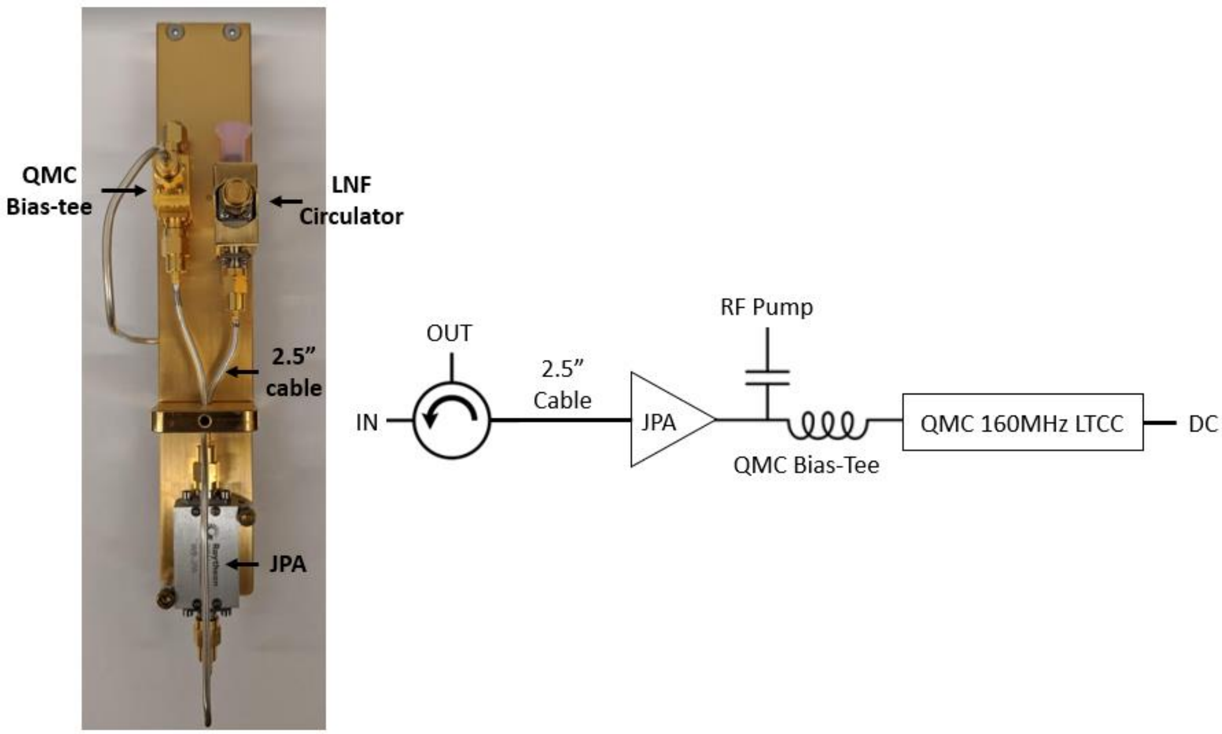


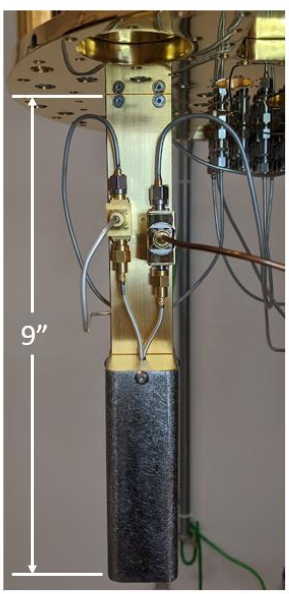
Figure 2 (left panel) QMC JPA Assembly with magnetic shield removed. (right panel) circuit schematic of the QMC JPA Assembly.

The RF Pump line has a total attenuation in the fridge of 30 dB (3 dB @ 50K, 10 @ 4K. 1 dB @ Still, 1 dB @ 0.1K, 10 dB @ MXC, and 5 dB cable loss @ 12 GHz). At room temperature the RF pump line is connected to a microwave signal generator with low phase noise and amplitude stability. The amplitude of the generator should be high enough ~5 dBm and with a resolution of 0.5 dB or better as the JPA tuning is highly sensitive to pump amplitude. To reduce potential ground loops inner-outer DC blocks at the input of the fridge are used for the RF Pump.

The DC tuning current to the QMC JPA Assembly can be supplied either through conventional twisted pair or coaxial cable in the dilution refrigerator. In the example system configuration of Figure 3 it is brought down through twisted pair. The tuning current from the differential twisted pair enters the QMC JPA Assembly as a single ended input connecting to one wire of the pair. The other wire of the pair is connected to the ground at the mixing chamber plate. It is advisable to install a differential filter at 4K with cutoff frequency of order 10 kHz. At room temperature in the example setup a Yokogawa GS200 is the current source used, but other laboratory grade sources can also be used. A 10 kHz RC filter is installed right after the current source and the signal is brought to the fridge with a coaxial cable. Be mindful of potential ground loops. The ground symbols in the diagram are the dilution refrigerator ground. The current source is grounded to the fridge only through the coaxial connection to the dilution refrigerator. When designing the filters be mindful of the resistance used. The JPA requires a tuning current of no more than 1 mA, too high a resistance can require voltages at the source which exceed the laboratory source limits, typically of order 20 V.

The output signal of the QMC JPA Assembly should be connected to a conventional readout amplifier chain used in the measurement of superconducting devices. In the example setup, the OUT of the QMC JPA Assembly is connected to a double junction isolator LNF-ISISC4_8A with a low-loss coaxial cable at 10 mK. After the isolator a superconducting NbTi is used between the isolator and HEMT at 4K. The signal at room temperature is further amplified with room temperature amplifiers before being connected to measurement electronics. To reduce potential ground loops inner-outer DC blocks at the output of the fridge are used for the OUT signal.

In the example measurement setup of Figure 3 the IN signal to the QMC JPA assembly is brought down a coaxial line with a total attenuation in the fridge of 66 dB (3 dB @ 50K, 20 dB @ 4K. 10 dB @ Still, 10 dB @ 0.1K, 20 dB @ MXC, and 3 dB cable loss @ 6 GHz) for JPA characterization. To reduce potential ground loops inner-outer DC blocks at the input of the fridge are used for the IN signal.



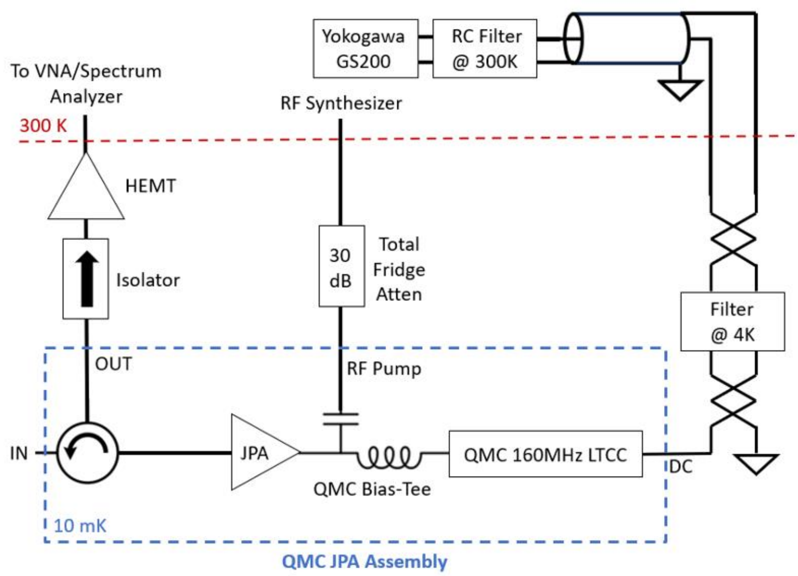


Figure 3 (left panel) Picture of the QMC JPA assembly installed onto the mixing chamber flange of a dilution refrigerator. The total length of the QMC JPA assembly is 9”, ensure this assembly fits inside any kind of still or mixing chamber infrared shields in the system. (right panel) Circuit schematic of QMC JPA Assembly and entire JPA characterization system. The IN port can be connected either to an attenuated coaxial line to bring down a test signal or to a circuit that is being measured.

JPA Tune-Up

Once a JPA has been cooled down, the first step is to determine the periodicity of the response of the JPA against DC tuning current to determine the correct operating point of the JPA. Use a Vector Network Analyzer (VNA) and a signal level of < -120 dBm at the QMC JPA Assembly to measure the transmission response S21 between the IN port and OUT port of the QMC JPA Assembly. Due to the broadband low-quality factor nature of the JPA the resonance may not be clear when measuring amplitude response of the signal. It is recommended to measure S21 phase to determine the periodic response of the JPA. A sample response is shown in Figure 4. The typical periodic response in DC tuning current is ~ 0.3 mA. It is recommended to bias the JPA around the first periodic response from zero and not to bias it with a tuning current above 10 mA. The range of tuning DC tuning currents to operate the JPA is indicated by the red box in Figure 4.

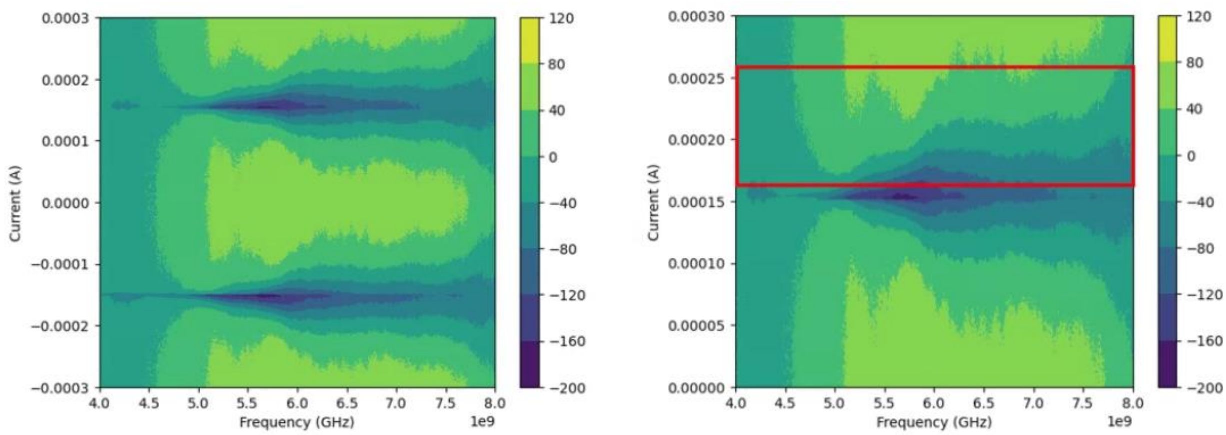


Figure 4 (left panel) Color contour plot of the S21 transmission between the IN and OUT port of the QMC JPA Assembly versus frequency and DC tuning current. The color scale is S21 phase in degrees. Periodic response of ~ 0.3 mA is observed and full frustration of the SQUID in the JPA occurs at 0.16 mA. (right panel) Blown up view of the periodic response for positive JPA DC tuning currents, red box illustrates the half of periodic response in DC tuning current in which to tune and operate the JPA.

Once the periodicity in DC tuning current and the first flux frustration in the SQUID of the JPA located near 0.15 mA in Figure 4 are determined, measurements of the gain of the JPA can then be performed. The next step in the JPA tune-up process is to measure the JPA gain as a function of DC tuning current, pump frequency and pump power, since the JPA is very sensitive to all these parameters. Using a VNA measure the S21 transmission magnitude between ports IN and OUT of the QMC JPA Assembly at half the pump frequency while sweeping the pump frequency and pump power. As pump frequency is swept the measurement frequency at half the pump frequency will need to be updated. Repeat the measurement of S21 transmission vs pump frequency vs pump power for DC tuning currents spanning half of one period as shown by the red box in Figure 4 from 0.15mA – 0.26 mA. Figure 6 shows an example sweep of S21 transmission versus pump frequency and pump power at a DC tuning current of Ibias = 0.18 mA. The data in Figure 5 was normalized against a S21 transmission sweep with the pump power to the JPA turned off, the color scale represents the signal gain in decibels.

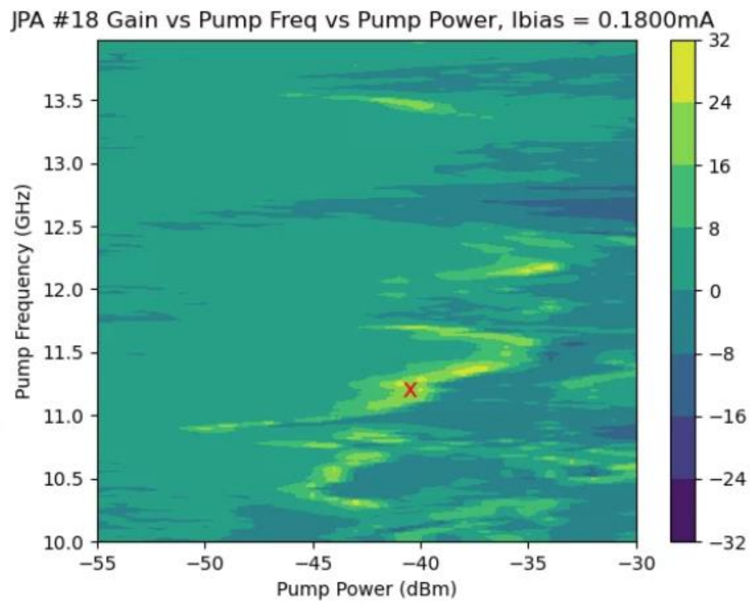


Figure 5 Color contour plot of JPA gain versus pump frequency and pump power (dBm) for a DC tuning current of 0.18 mA. Color scale is the JPA gain in decibels.

The S21 transmission measurement in Figure 5 gives an idea where to tune the pump frequency and pump power for a DC tuning current of 0.18 mA. For different DC tuning currents this picture will change, and different pump frequencies and pump powers will need to be applied for optimum operation of the JPA. The red "X" in Figure 5 is an example JPA tune-up parameter pump frequency of 11.199 GHz and Pump power of -40.5 dBm. Shown in Figure 6 are measurements of the gain vs signal frequency of the JPA versus different pump powers and pump frequencies illustrating the dependence of the JPA gain on each tuning parameter. Figure 7 shows the signal gain as a function of signal power with a 1 dB compression point or -111 dBm for this operating point of the JPA.

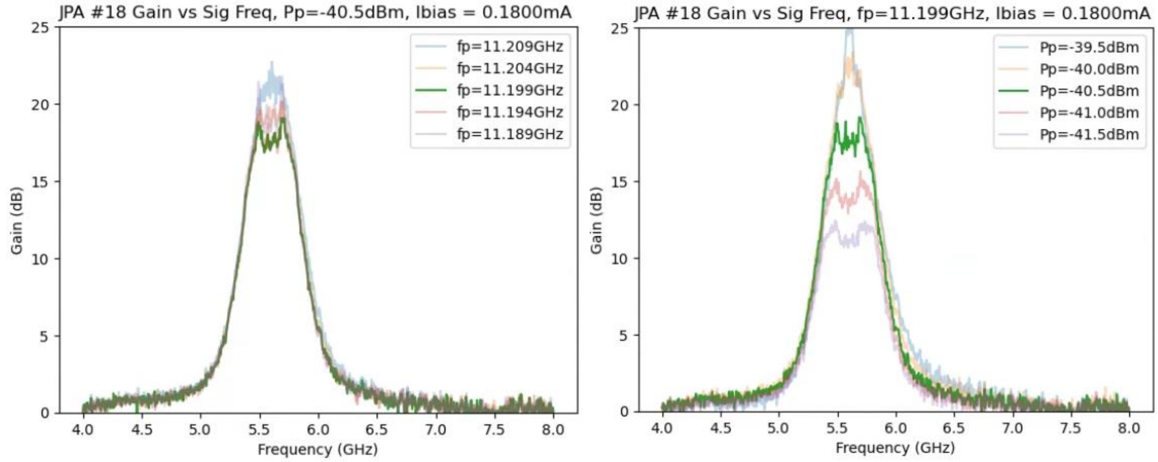


Figure 6 (left panel) JPA gain versus signal frequency for different pump frequencies (fp) around 11.199 GHz. (right panel) JPA gain versus signal frequency for different pump powers (Pp) around -40.5 dBm.

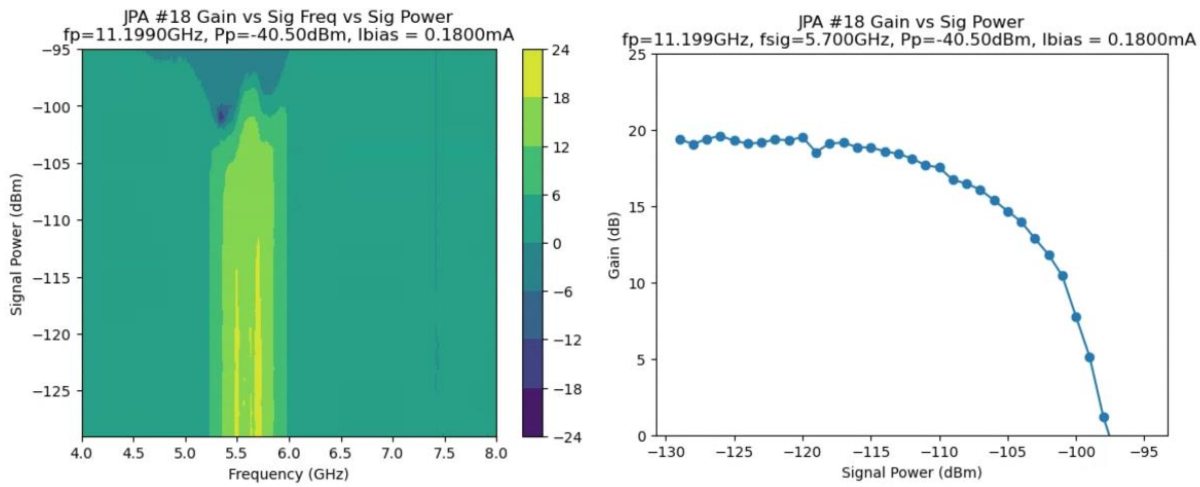


Figure 7 (left panel) Signal gain vs frequency as a function of signal power. Color scale is in decibels. (right panel) Since trace of signal gain versus signal power.

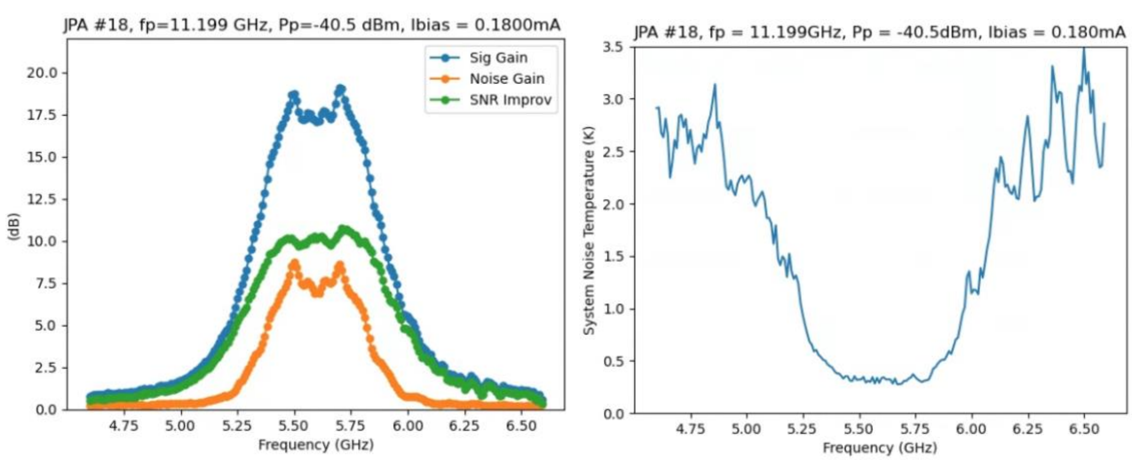


Figure 8 (left panel) Signal gain, noise gain, and signal-to-noise (SNR) ratio improvement versus frequency. (right panel) System noise temperature with the JPA versus frequency. Effective noise temperature of the HEMT is ~3.5 K

Utilizing a spectrum analyzer, measurements of the system effective noise temperature were performed with a Y-factor measurement of the 4K HEMT amplifier chain with a variable temperature load switched in right at the OUT port of the QMC JPA Assembly shown in Figure 3 with a cryogenic switch (not shown). The effective noise temperature at the reference plane, the OUT port of the QMC JPA Assembly was ~3.5 K over the frequency range 5 – 8 GHz. The spectrum analyzer was used to measure the signal and background noise level of the JPA when a pump was turned on and off at different signal frequencies to determine signal and noise gain. A plot of the signal gain (blue circles) and noise gain (orange circles) is shown in Figure 8. A comparison of the signal gain to the noise gain reveals the Signal-to-Noise ratio (SNR) improvement (green circles) that is provided by the JPA. From the signal gain and noise gain the system noise temperature can then be extracted and is shown in Figure 8. This noise data shows that this JPA is operating near the quantum limit of noise over the bandwidth of approximately 400 MHz.

The gain of the JPA is sensitive to DC tuning current, RF Pump frequency, and RF Pump power. The JPA was tuned to an operating point with a DC tuning current supplied by a Yokogawa GS200 current source and the RF Pump was applied with a Signal Core SC5510A signal generator. Measurements of the gain stability for a JPA tuning of fp = 12.179 GHz, Pp = -34.1 dBm, and DC current bias of 0.18 mA is shown in Figure 9. Variations in gain of approximately 1 dB were observed over a 72 hour period.

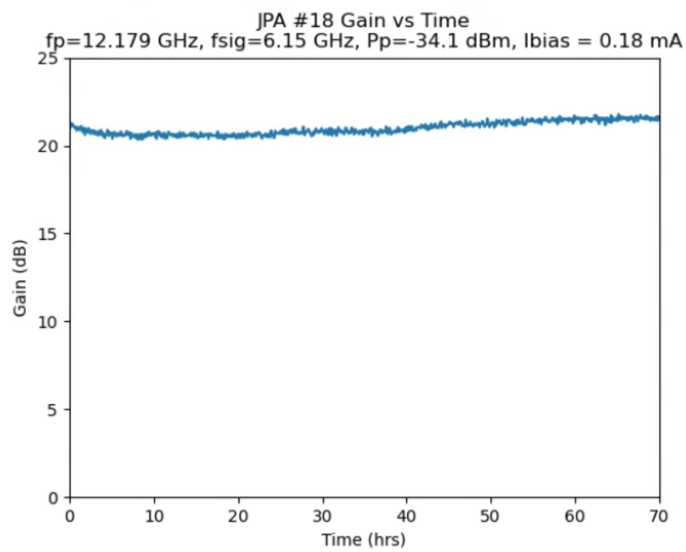


Figure 9 Signal gain vs time.