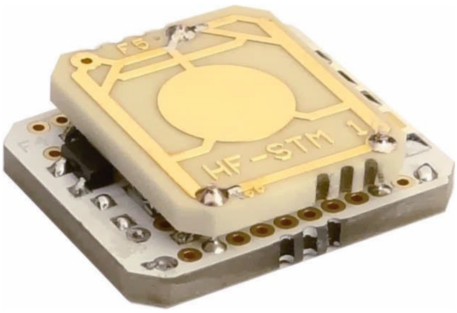
HF-STM 1

DC to 1GHz Broadband Cryogenic Buffer Amplifier



- Datasheet -

Version 1.0 / April 2017

Features:

- **Cryogenic High Impedance Buffer up to 1GHz**
- **Wide Temperature Range T = 300K down to T = 4.2K**
- **Low Outgassing UHV Operation**
- **Output Impedance approx. 50 Ohm**
- **Small Size, Small Heat Load**

Applications:

- **STM Tunneling Current Detection**
- **High Frequency Image Charge Detection**

Simplified Diagram

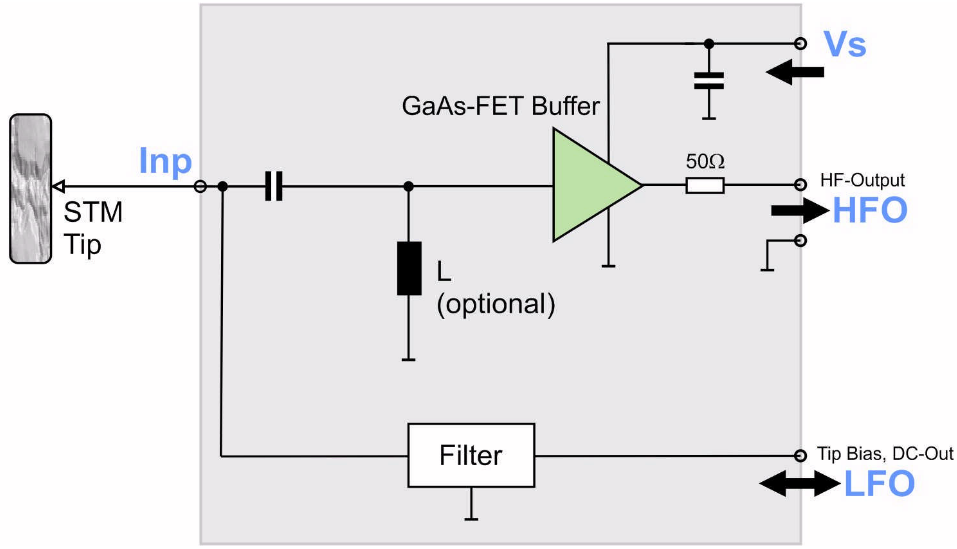


Figure 1: Internal structure of the HF-STM 1 amplifier

Introduction

The HF-STM 1 cryogenic amplifier is a device intended for the detection of small currents at DC to high frequencies, which are e.g. created by STM tips (scanning tunneling microscopy). The input current flows DC-related through a Bias-T and the high frequency part is buffered and presented at a low impedance output (nom. 50 Ω). The device operating range spans room temperature down to deep cryogenic environments (T = 4.2K, liquid Helium). The device's input sensitivity regarding currents can be expressed in terms of a conversion factor Z (in similar applications called 'transimpedance') characterising the conversion from input current I to output voltage U by Ohm's law Z = U / I. This conversion factor Z is given by the effective input capacitance. In order to keep this low, a STM tip holder has been integrated directly into the amplifier to achieve minimal possible distance and capacitance (<2pF). Optionally, an inductor can be placed from the input to GND, thus a detection LC circuit be formed, and the latters resonance enhances the sensitivity significantly at a selected fixed frequency.

After the conversion from current to voltage, the buffered signal can be guided to a subsequent low noise amplifier, before further processing of the signal, in time or frequency domain, takes place.

Apart from the RF (radio frequency) part, the device features a low pass filter ('Bias-T'), which allows for standard operation of the STM tip for STM imaging purposes in the frequecy range from DC to 50 kHz. The device is based on GaAs (Gallium Arsenide) semiconductor technology, which allows for operation over a wide temperature range and makes it possible to perform well in strong magnetic fields up to B = 5T. A Ceramic/Epoxi compound substrate structure ensures very low vacuum outgassing rates.

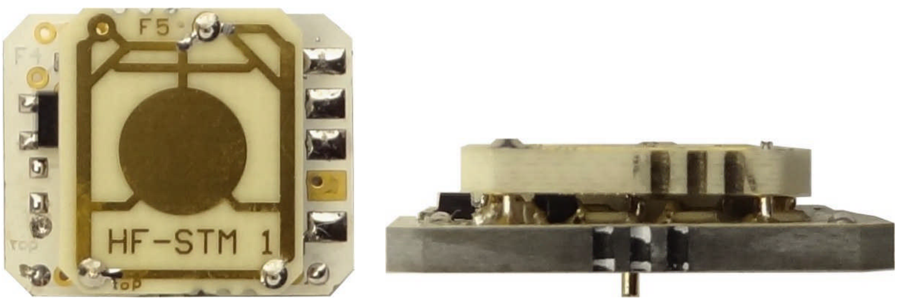


Figure 2: front and side view

Solder Pad Connections

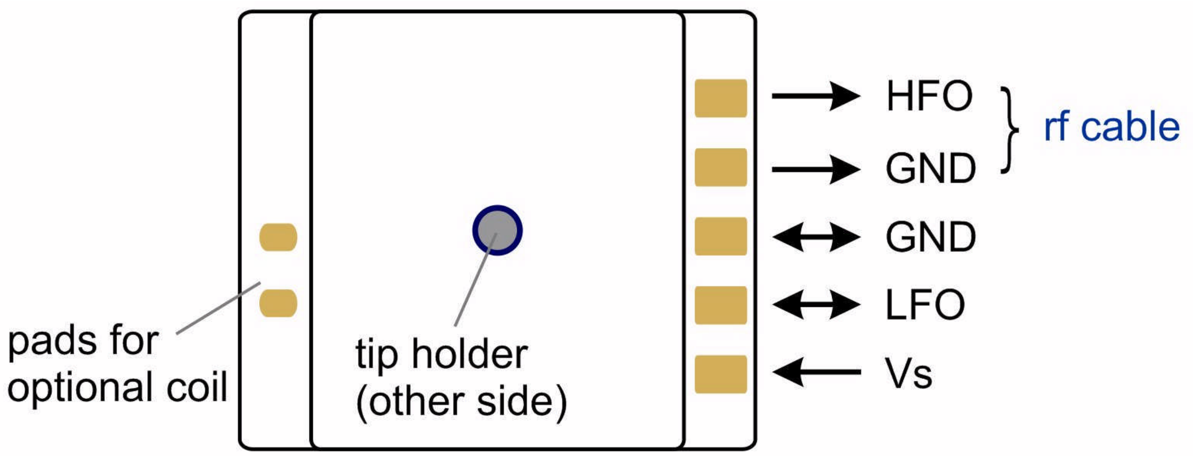


Figure 3: Location of solder pads
Wires and cables should be soldered with leaded tin alloy (Sn60Pb39Cu1) or, even more reliably with lead-tin-antimony alloy (Sn63Pb36,65Sb.35) to avoid contraction-based cracks during cool-down process.

Front Side:	**Function**
HFO	High Frequency Signal output, approx. 50 Ω, connect to subsequent low noise amplifier with coaxial cable. Note that an internal DC level is superposed for test purposes.
GND	Reference GND for output coaxial cable
GND	Reference GND for LFO and Vs
LFO	low frequency (DC…50kHz) output, through 75 kOhm internally connected to STM tip input
Vs	positive voltage supply input (typ. +1.5 to +1.7 VDC, vs. GND)

Rear Side	**Function**
Tip Holder	DC to High frequency (1000MHz) input, high impedance

Absolute Maximum Ratings

Note: Stress above these ratings may cause permanent damage or degradation of device performance. Exposure to absolute maximum conditions for extended periods is not recommended.

Quantity	Limits		Remarks
	min.	max.	
pos. Supply Voltage V_{D1}, V_{D3}	0	+5.0	
LFO Voltage	-10V	+10V	
Input Voltage absolute value AC		+/-10V pk (DC) 0.5Vpp	
Input Current		3mApp	continuous current through input
Output Voltage	Under normal conditions no voltage source must be applied to the outputs.		
Storage Temperature, Baking	1 K	135°C	Baking is possible up to 135°C, max. for 24 hours
Temperature changes	-	+/-15 degrees Kelvin per minute	exceeding this temperature slew/fall rate may damage the device due to formation of mechanical cracks
Storage Humidity		65% @ 40°C	

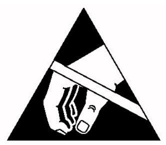
Table 1: Absolute Maximum Ratings

Characteristic Data and Operating Parameters

Parameter	typical Value	Remarks/Conditions
Freq. Range high frequency buffer .	approx. 1MHz to 1GHz	details see fig. 4
Voltage gain, T = 4 to 300K	0.66 V/V , 0.31 V/V corresponding to 9.4dB insertion loss (50Ω)	Biasing: Vs = 1.75V, f = 5MHz high impedance load, 50 Ω output load
Output Impedance	typ. 50 Ω	Vs = 1.75V
Input Impedance vs. GND	DC: > 100MΩ AC: 1.85pF ±0.2pF // 70kΩ	LFO left open (unbiased) DC to approx. 50kHz
Bias-T Resistance between input and LFO terminal Frequency range	75 kΩ DC to approx. 50kHz	The LFO terminal can be regarded as access to the DC path in a Bias-T
Useful Resonance Inductance range in resonant mode	40nH … 10µH	Note that coil should be 4K suited
AC Output Power	< 7mW	
Input Voltage Noise Density f = 10 to 300MHz Input Current Noise Density	0.4nV/√Hz approx. 150 fA/√Hz @ 100MHz	@ T = 4.2K @ T = 4.2K
Operating voltages Vs, positive supply voltage	 +1.5 to +3.3 V	 T = 300K down to 4.2K 1.75V recommended
Supply Current supply current Pin Vs	1.8 mA @1.5V =Vs 2.0 mA @1.75V =Vs	T< 10K
Power Consumption	2.7 to 3.5mW	Supply 1.5V to 1.75V
General Operating Temperature	T = 4.2 K … 300 K	
External magnetic field	B = 0 … 5T	
Geometrical Size	18.1mm x 14.6mm x 6 mm	
Outgassing	(to be determined)	
Remark: This table represents typical values at low magnetic fields B < 1T. Parameters may vary at higher B-fields.		

Table 2: Characteristic Data

Caution: Electrostatic Sensitivity



This device can be damaged by ESD (Electrostatic Discharge), especially the **input and output lines**. It is strongly recommended to handle the device with appropriate precaution. Failure to observe proper handling and installation procedures can cause serious damage. This ESD damage can range from subtle performance degradation to complete device failure.

Practical Hint:

*In case the device is picked up by hand, ensure that the ground pin or gold plated case is touched **first** before touching any other pin. Touching any other pin than ground first, may destroy this device. Similar precaution has to be applied when changing the place of the device: Most important the destinations ground has to be on the same potential as the devices ground. Therefore connect both grounds first before making any other connection or changing the device position. Please follow also the commonly known ESD rules in literature or internet.*

Voltage Supplies and Basic Operation

To bring the device into basic operation, a positive and stabilized supply voltage (connected to pin 'Vs') is required (connect the current return path to one of the GND pads). The recommended value for Vs equals 1.75V, even though it is not critical. Higher values (e.g. 3.3V) may slightly improve the signal to noise ratio, but also increase the tendency for unwanted self-oscillations, depending on the geometry surrounding the device and also inreases heat load. Any signal in the frequency range between 1MHz and 1GHz appears as buffered voltage at the output. For further signal processing a terminated (coaxial) cable should connect to subsequent signal processing stages.

Input ***Voltages*** are transferred in a 1:1 style from input to output; however, take into account a factor of 2 decrease because of attached 50Ω cable impedance and another factor of 1.5 for internal attenuation reasons. The resulting transfer function is shown in the diagram below (fig. 5).

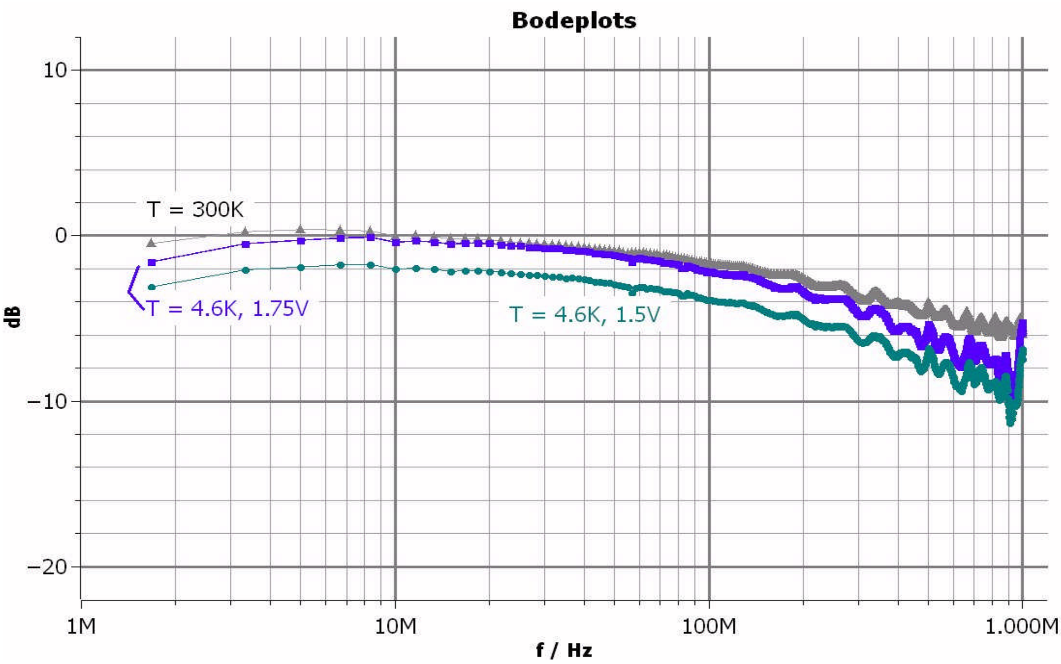


Figure 4: Voltage frequency response characteristics at 300K and 4.6K ambient temperature, Vs supply equals 1.75V (300K), and 1.75 V and 1.5V respectively at 4.6K. Amplification is normalized to the value at 10MHz, 300K.

Input ***Currents***, like from STM tunneling tips essentially 'see' the input capacitance of approx. 1.9pF as termination impedance. A current I is therefor converted to a voltage U according to Ohm's law

$$U = I \cdot Z,$$

where $Z = 1/(\omega C)$ and C = 1.9pF .

This input impedance Z therefor depends on the signal frequency of interest $\omega = 2\pi f$,

e.g.	f = 1MHz	Z = 86kΩ
	f = 10MHz	Z = 8.6kΩ
	f = 100MHz	Z = 860Ω.

Regarding the resulting output signal, take into account (as said above) a factor of 2 decrease because of attached 50Ω cable impedance and another factor of 1.5 for internal attenuation reasons:

$$\Rightarrow \; U_{out} = 1/3 \cdot I / (2\pi f \cdot C) \text{ in good approximation.}$$

The actual resulting current sensitivity (unit: volt/ampere) as function of frequency is depicted in the diagram below (fig. 5).

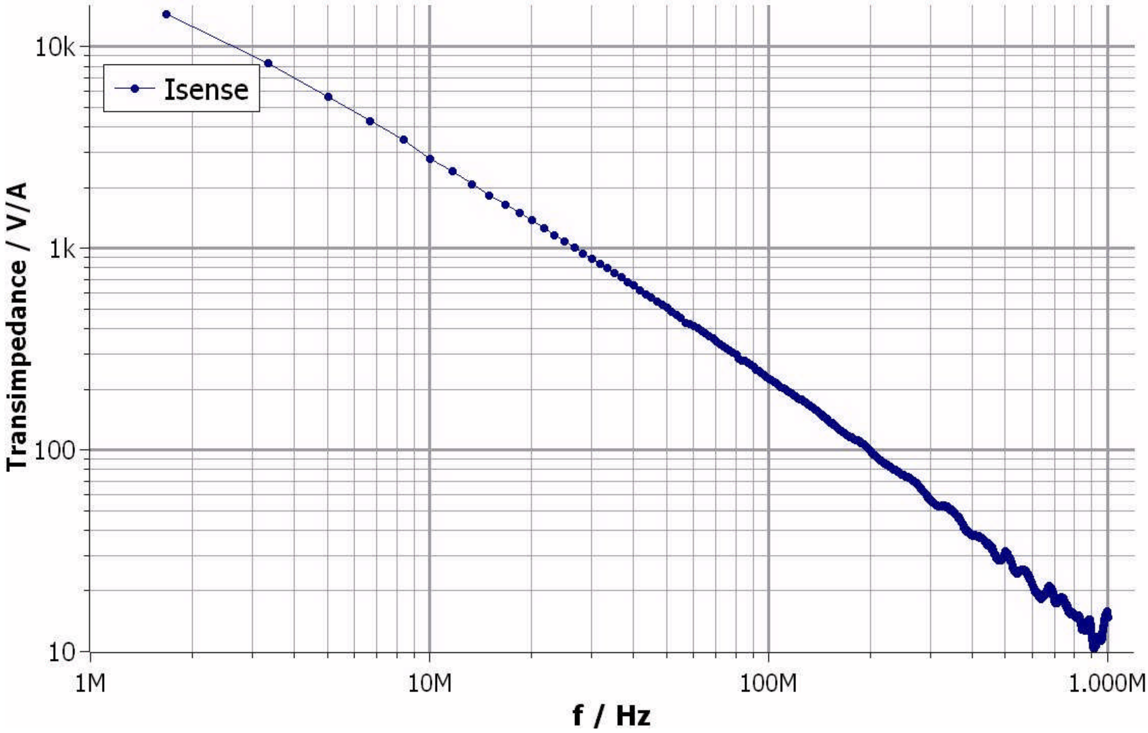


Figure 5: Current frequency response (also called 'current sensitivity' or 'transimpedance') at 4.6K ambient temperature, Vs supply is 1.75V. The values in this graph depict the conversion factor (current sensitivity) from a tip current into voltage at the output. To obtain these numbers, an input capacitance of 1.9pF was assumed and a only minor contribution (<0.2pF) of the actual tip, being positioned into the tip holder.

For most frequencies the resulting transimpedance, and therefor the current sensitivity, is orders of magnitude better (higher) than connecting a standard RF-amplifier with a small 50Ω input resistance. Even beyond 350MHz, where the transimpedance drops below 50Ω, the input current noise of this device, being less than 1pA/√Hz, delivers clearly a substantial improvement over a 50 Ω input resistance with approx. 2.5pA/√Hz even at 4.2 Kelvin environment. The latter number (2.5pA/√Hz at 50Ω, given by the Nyquist formula) assumes even perfect thermalization, which is very hard to achieve in a real-world cryostat and considerable heat load of a 1GHz amplifier. Therefor, the usage of a high impedance buffer stage like the HF-STM 1 in conjunction with a good 50Ω subsequent amplifier yields a greatly improved S/N ratio for all frequencies below 1GHz, specially those around 350MHz or lower.
Note that these statements are valid for a direct and short (< 2mm) connection of the tunneling tip to the input of the HF-STM 1, since unnecessary parasitic capacitance need to be avoided.

Further remark:
As described on page 2, a resistive connection ('Bias-T') provides direct access to the input at the LFO terminal. This may be used for standard low-frequency operation (DC to typ. 50kHz) of a STM tip or other purposes (e.g. tip forming, DC-resistance measurements of the tip, etc.).

Bias Filtering and Shielding

Grounding and Shielding at the input and output side are important issues of concern. A proper grounding and shielding is essential to maintain good device performance and low noise characteristics, and to avoid the creation of parasitic oscillations, which is a common problem to high-frequency amplifiers with a high-impedance input. To ensure a "clean" electrical environment, provide good ground connections especially around the amplifier input and STM tip. The signal output should be connected through a coaxial line to the subsequent amplifier.

In case of self-oscillations, these uncontrollable oscillations appear typically at frequencies of about 50 to 500 MHz and are mostly an indication of insufficient shielding or grounding. In case this occurs, a tight metal shield (Faraday cage), completely enclosing both signal source and amplifier input will normally remove that problem. This shield should be connected to one of the ground pads of the device.

For optimum noise performance the supply line (Vs) should be filtered well and be supplied from a well-stabilized power supply. Standard blocking capacitors of 100nF from the biasing supply line to ground may support power supply stabilization at the point of electrical feedthroughs leading into the vacuum vessel.

HFO Cabling

The cabling from the RF output ('HFO'-Pad) to the room temperature section (or subsequent amplifier) requires special attention. A coaxial cable should be used with a well-defined characteristic impedance along the <u>whole</u> distance between the cryo- and roomtemperature amplifier (or subsequent stage). This is important since the signals of interest reside in a region in which an interrupted cable impedance along the line distance can lead to severe signal reflections. The latter results in significant loss of signal (S/N drops) and furthermore increases the risk of unwanted self-oscillations of the buffer amplifier. A suitable cryo-compatible coaxial cable is for instance the GVLZ 081 (distributor: GVL Cryoengeneering) or e.g. Lakeshore Type C cable. Note that despite the fact that the amplifiers output has nominally 50 Ohm impedance, the attachement of a cable of different impedance (GVLZ 081: 75 Ohm) usually poses no problem as long as the cable end is well-terminated with an appropriate termination resistor and therefore no (or only little) signal reflections are created. The occurrence of unwanted self-oscillations of the device is an indication of a possible missing (or faulty) termination resistor, cable interruption or discontinuity of impedance after the output connection. Note that the latter (discontinuity of impedance) can normally not be detected with a standard multimeter, but with RF (radio frequency) equipment.

Geometrically the coaxial cable should be connected in a direct and very close kind to the pins HFO and GND, such that a defined (RF) impedance starts no more than 1mm away from the solder pads.

Thermal Anchoring

In a vacuum cryostat a good thermal coupling to the cold reservoir (cold finger, or Helium cryostat cold plate) is required to ensure proper operation and low noise. Thermal connection should be established using the round pad in the base plate of the amplifier, e.g. by pressing to a mating cooling plate or permanent connection (soldering, glueing with conductive epoxi). Note that a thermally conducting agent like “Apiezon N” grease between the metal pieces of different temperatures also greatly increases the thermal heat flow.

Commissioning in a Vacuum or Cryogenic Setup

After wiring the device and mounting into a cryogenic dewar or vacuum chamber (always connect ground lines first for ESD reasons), the device may be checked and eventually powered up with appropriate supply voltages.
However, *before* power is applied to the device, one should carefully check the cable connections in order to avoid damage or malfunction or cooling down in vain. With a standard multimeter (DMM) one can perform a quick check of resistances. The following table lists typical values of connection lines versus GND.

Line designator	Resistance vs. GND	Remark
Vs	approx. 620Ω	value differs in the order of 20% over 4K to 300K range
HFO	10.5 kΩ	value only slightly differs over 4K-300K range
LFO	> 200 MΩ	input STM tip not mechanically connected to substrate yet

Table 3: typical resistance values versus GND, measured with a standard multimeter.

Cool-Down Procedure

Once mounted inside a cryostat setup, it is recommended to re-check the cabling (using a DMM in Ω-Mode, table above) as mentioned before. In case the latter is correct, one may power-up the device. A typical consumption current of 2mA at room temperature will be drawn from Vs as positive supply current. A DC-output voltage of approx. 50% of the supply voltage (applied to Vs) is measured on the output line in case of proper operation.
During cool down in a cryostat or during the pumping process in a vacuum vessel one may from time to time recheck the resistance of lines (as described above), or, once the device is powered up the DC output value, since the latter represent an important check of the device functionality.
In general the device is operational over the complete range from 300K to 4.2K.
During cool-down/warm-up procedures always maintain a temperature rise or decrease of no more than +/-15 degrees Kelvin per minute. Note that exceeding this temperature slew/fall rate may damage the device due to formation of mechanical cracks. **Never apply thermal shocks to the device, like sudden dipping into a cryogenic liquid !**

Operation

Once placed into a experimental setup and checked for correct cabling the device can be powered up and its output should be checked with a sensitive spectrum analyzer or lock-In amplifier (the first is preferred). The subsequent figure shows a typical power output spectrum (recorded with a Rigol DSA815 spectrum analyzer) at 10kHz resolution bandwidth. The amplification of subsequent stage has already been taken into account for correct scaling on the Y-axis.

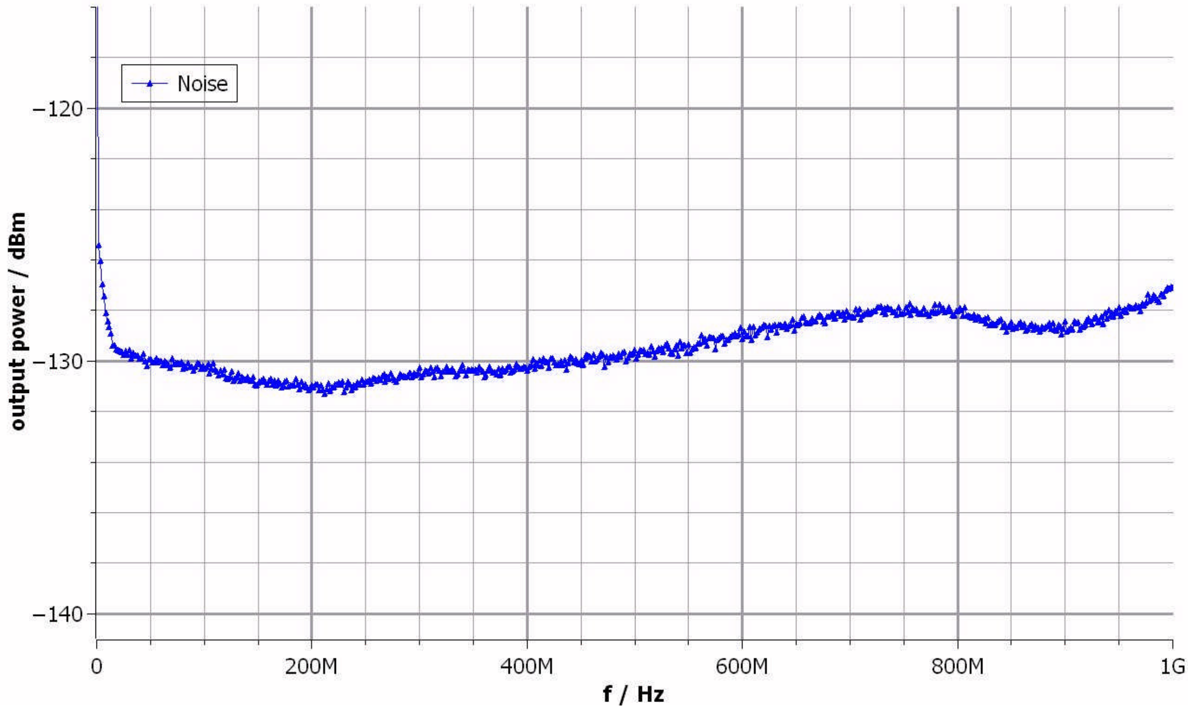


Figure 6: Power output spectrum (without tip current), being recorded by a spectrum analyzer after preamplifier correction. The Y-axis measures in $dBm_{50\ Ohm}$. Frequency range is DC to 1GHz, with 10kHz resolution bandwidth.

To obtain data like in the figure above, the input of the analyzer should be set to most sensitive mode (**attenuation = off**) and a **preamplifier**, in case existing, **turned on**. The analyzers sensitivity should be in the order of 1.5nV/√Hz or less (expressed as voltage noise density), otherwise an additional preamplifier is needed. Note that the numbers in the graph above correspond to an input voltage noise density of 0.6nV/Hz and can be, however, regarded as upper limit, since the setup at which the above data were taken contributed significantly to the overall noise. The intrinsic output voltage noise density of the HF-STM 1 is approximately a factor of 1.5 to 2 smaller.

Apart from checking the device output noise density, the DC level, as it can be measured with a normal multimeter (DMM) can be verified at the HFO output. This DC level should reside within 40% to 60% of the supply voltage Vs. In case it does not, a malfunction may have occurred, e.g. a cable interruption or short cut to GND. In this case carefully check again the resistances according to table 3.

Resonance Operation

A decisive characteristic number of a STM amplifier may be its transimpedance. In case of the HF-STM1 amplifier, the latter is defined and limited by the input capacitance of approx. 1.9pF. However, the device offers the possibility to add a RF inductor on soldering pads (case style 0603), which are accessible (see also figure 3) from outside, thus a LC filter can be created at the STM input to GND. The latter's resistance Z at the resonance maximum is given by $Z = Q/(2\pi f_0 \cdot C)$. So, assuming a realistic quality factor Q (e.g. Q = 40), the transimpedance is enlarged by 40 times at the resonance frequency f_0 within a certain bandwidth Δf, where $\Delta f = f_0/Q$. This significant improvement of signal strength may be highly desirable. Yet, it does not neccessarily reflect the improvement of S/N ratio, since the resistive part $R = Z = Q/(2\pi f_0 \cdot C)$ at the resonance maximum contributes to some degree to the input current noise density. The latter can be estimated by the Nyquist (Johnson) formula, $i_n^2 = 4kT/R$, and should be taken into acount at the frequency of interest. The effective improvement in signal-to-noise S/N therefor stays somewhat behind the improvement of the signal strength.

Before selecting a certain value for L using Thomson's formula, please take into account the parasitic amplifer capacitance of 1.85pF, the tip capacitance (~0.2pF) and the self-capacitance of the coil, which may be around 1pF and which is usually rated by the manufacturer. These capacitance contributions add up to an effective parallel capacitance. Note that not all inductive ($\mu_r > 1$) core material is suited for cryogenic operation, therefor a 'air-core' or 'ceramic' core type with μ_r=1 may be preferable, which works at cryogenic temperatures usually without problems. Use leaded tin alloy or lead-tin-antimony alloy for soldering.

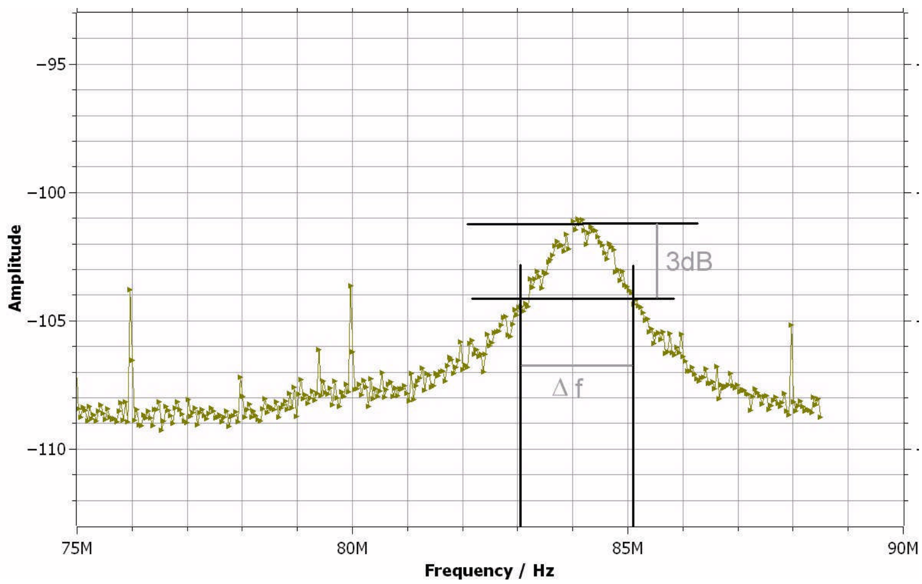


Figure 7: Power output and sensitivity spectrum with LC circuit usage, here L = 1.6µH and Q = 160.
The -3dB width is given by the quality factor Q of the detection circuit.

Appendix:

Output Voltage Noise Density

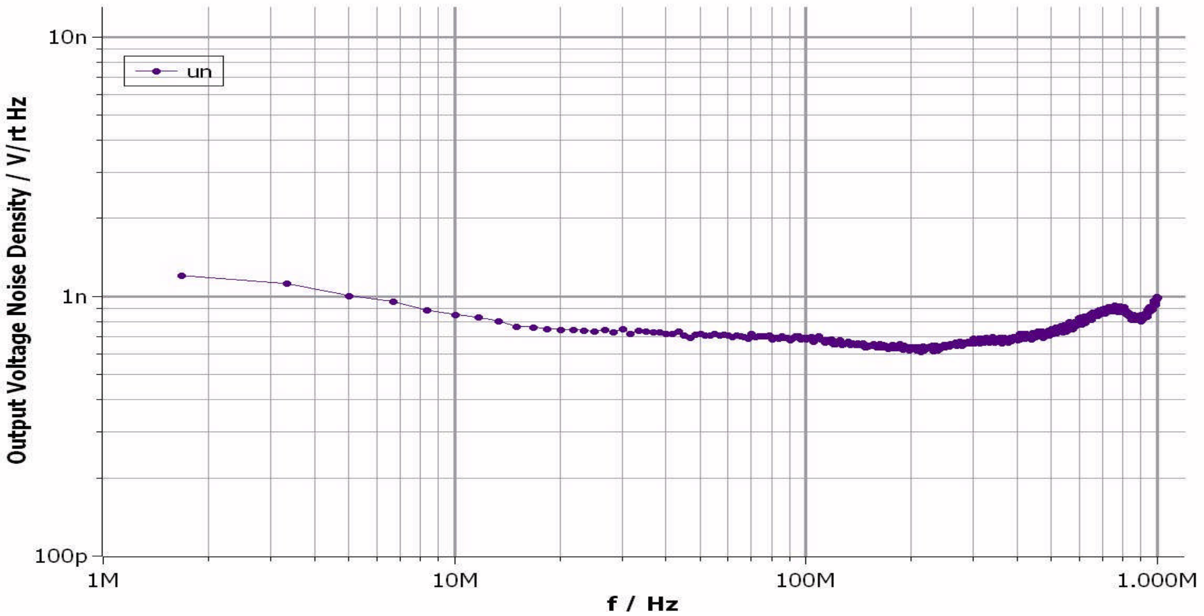
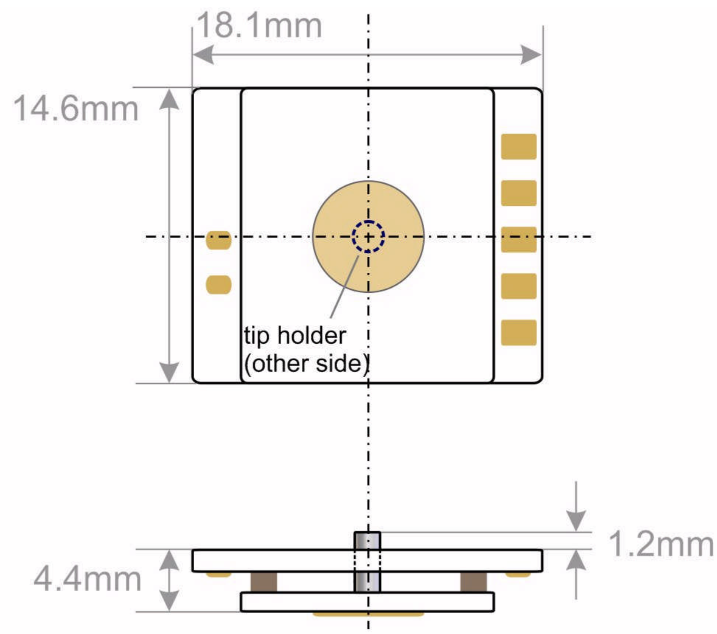


Figure 8: Output Voltage Noise Density u_n as function of frequency; note that these data rather represent the upper limit of voltage noise due to the used setup.

Geometrical Outline



Note: The circular gold plated pad is grounded.