HF-STM 1

DC to 1GHz Broadband Cryogenic Buffer Amplifier
- Version E3a -

- Datasheet -

Version 1.5 / April 2022

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

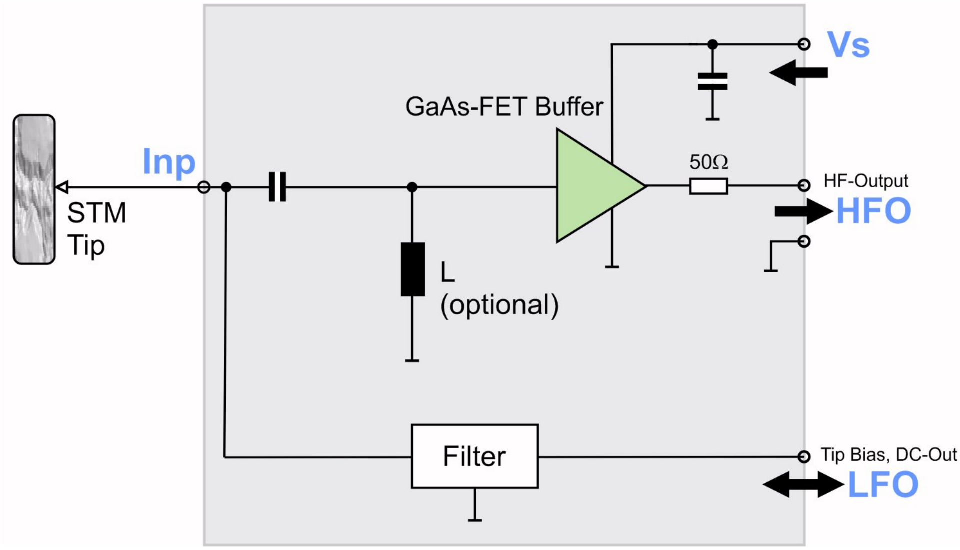


Figure 1: Internal structure of the HF buffer amplifier

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) or other kind of sensors. The input signal 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. Optionally, an inductor can be placed from the input to GND, thus a detection LC circuit can be formed in conjuction with parasitic capacitances, and the latters resonance enhances the sensitivity significantly at a selected fixed frequency.

Apart from the RF (radio frequency) part, the device features a Bias-T, which essentially is only a R-C-R network (about 500kOhm from Input LFO pad, other values on request), connecting the input to a low-frequency Bias port. The device is based on GaAs (Gallium Arsenide) semiconductor technology, which allows for operation over a wide temperature range and in magnetic fields. A Ceramic/Epoxi compound substrate structure ensures very low vacuum outgassing rates.

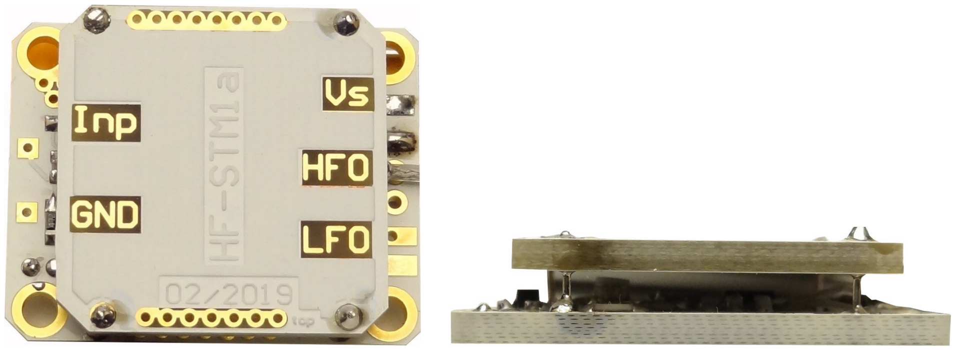


Figure 2: front and side view, Version E3; note that Version E3a (in production since 01/2022) features a recessed Top Plate for easier wiring access

Solder Pad Connections

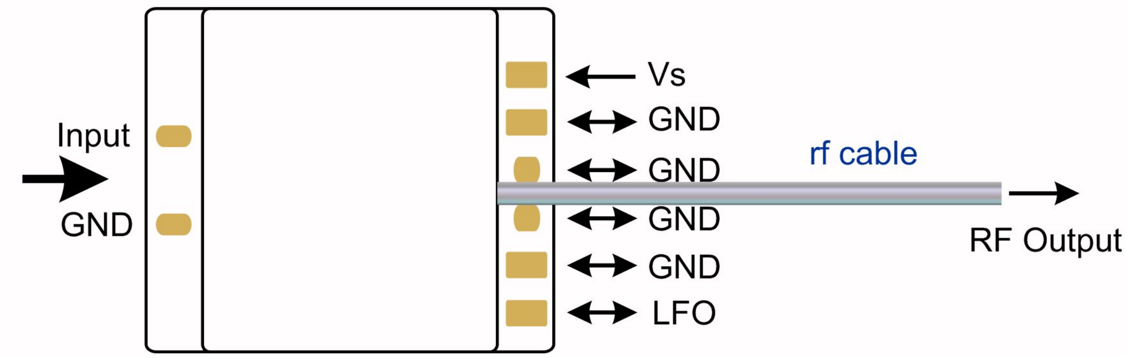


Figure 3: Location of solder and bonding pads
Wires and cables should be soldered with leaded tin alloy (Sn60Pb39Cu1) or, even more reliably with lead-tin-antimony alloy (Sn63Pb36,65Sb.35) to avoid contraction-based cracks during cool-down process.

Left Side:	**Function**
Input	amplifier input, to be connected to signal source for AC and DC signal components
GND	Reference GND for input signal
Right Side:	**Function**
Vs	positive voltage supply input (typ. + 0.25 to +1.2V_{DC} vs. GND, see text)
GND	Reference GND for output coaxial cable
RF Output /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. <u>Version E3a</u> features an attached SMA cryo cable
GND	Reference GND for LFO and Vs
LFO	low frequency (<100kHz) input/output, through 490 kOhm internally connected to the input

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	+2.0	
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	

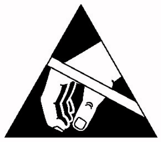
Table 1: Absolute Maximum Ratings

Characteristic Data and Operating Parameters (Biasing: Vs = +0.25 at T = 4 to 8K unless noted otherwise)

Parameter	**typical Value**	**Remarks/Conditions**
Freq. Range, -3dB high frequency buffer	approx. 0.4 MHz to 1 GHz	details see fig. 4
Voltage gain, T = 300K	0.45 V/V 0.25 V/V	high impedance load, 50 Ω output load
T = 4.2 K	0.9 V/V 0.45 V/V (i.e. 6 dB insertion loss, 50Ω)	high impedance load, 50 Ω output load
Output Impedance	typ. 50 Ω ±10%	f = 1MHz to 100MHz, T < 10K
Input Impedance vs. GND	DC: > 100MΩ AC: 2.9pF ±0.2pF // 500kΩ	LFO left open (unbiased) f = 1MHz to 20MHz
Bias-T Resistance between input and LFO terminal	490 kΩ	The LFO terminal can be regarded as access to the DC path in a Bias-T
Useful Resonance Inductance range in resonant mode (see text)	40nH … 300µH	Note that coil should be 4K suited
AC Output Power	< 1mW	
Input Voltage Noise Density f = 10 to 300MHz	0.55nV/√Hz to 0.75nV/√Hz	@ T = 4.2K
Input Current Noise Density	approx. 250 fA/√Hz @ 100MHz	@ T = 4.2K
Operating voltages Vs, positive supply voltage	+0.25V to +1.2 V	T = 300K down to 4.2K, see text
Supply Current supply current Pin Vs	2.0 mA	T= 4K to 300K
Power Consumption	0.3mW	Supply Vs = 0.25V, T = 4.2K
General Operating Temperature	T = 4.2 K … 300 K	
External magnetic field	B = 0 … 0.2T	
Geometrical Size	nom. 25mm x 20mm x 6.1 mm	Note: please allow for up to 0.5mm protrusion in all 3 dimensions
Outgassing	(to be determined)	
Remark: table represents typical values at low magnetic fields B < 0.2T. 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 pins or gold plated parts of case are 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 **1.25V at 300K** ambient temperature and **0.25V at 4.2K** ambient temperature. Note that during cool-down the supply voltage should be turned off for internal offset calibration reasons. Once the desired temperature is reached, one can power-up again.

Once a well-known signal is present at the input after stabilization of cryostat temperature, one may carefully adjust Vs (typically +/-30mV) to obtain a signal amplification calibration.

In general this device represents a voltage buffer, i.e. any signal in the frequency range between 1MHz and 1GHz appears as buffered voltage at the output with 50Ω impedance. 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 (corresponding to -6dB). The resulting transfer function is shown in the diagram below.

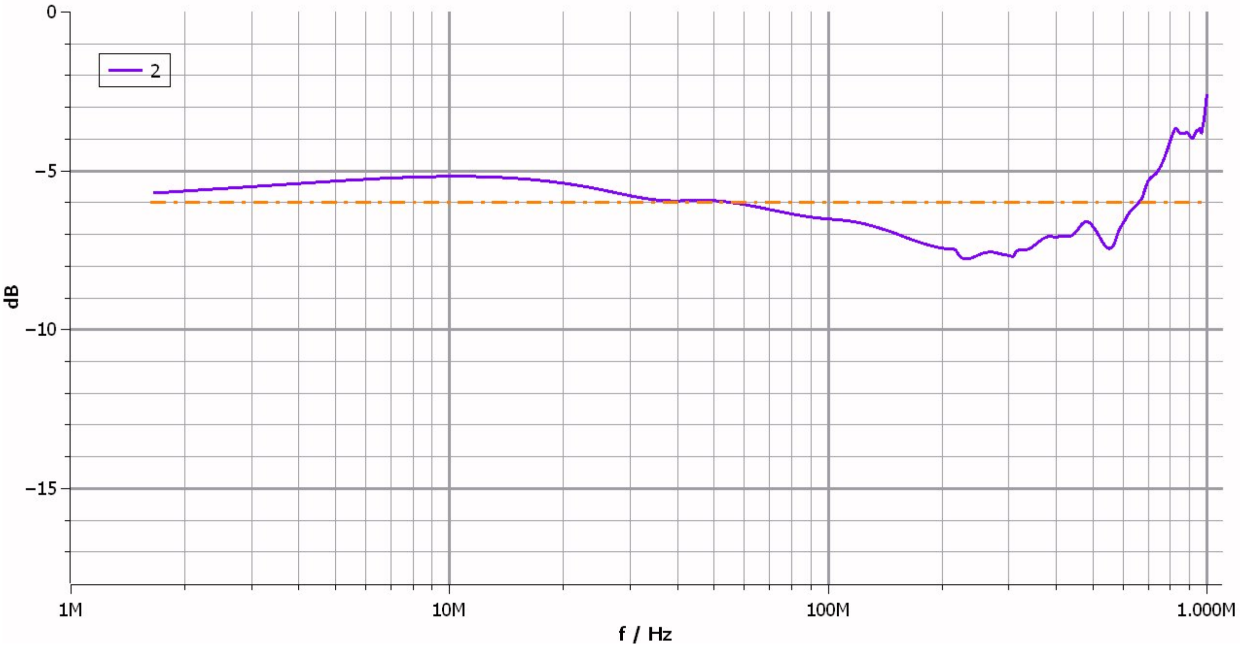


Figure 4: Voltage frequency response characteristics at 5K ambient temperature, Vs =0.25V
The dashed line at -6dB indicates the ideal behaviour at -6dB insertion loss

Input ***Currents***, like from STM tunneling tips essentially 'see' the input capacitance of approx. 2.9pF as termination impedance. A current I is therefor converted to a voltage U according to Ohm's law

$$U = I \cdot Z ,$$

where $Z = 1/(i\omega C)$ and $C = 2.9pF$.

$i = \sqrt{-1}$

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

e.g. f = 1MHz Z = 54.9kΩ / i
f = 10MHz Z = 5.49kΩ / i
f = 100MHz Z = 549Ω / i .

Regarding the resulting output signal, take into account (as said above) a factor of 2 decrease because of attached 50Ω cable impedance

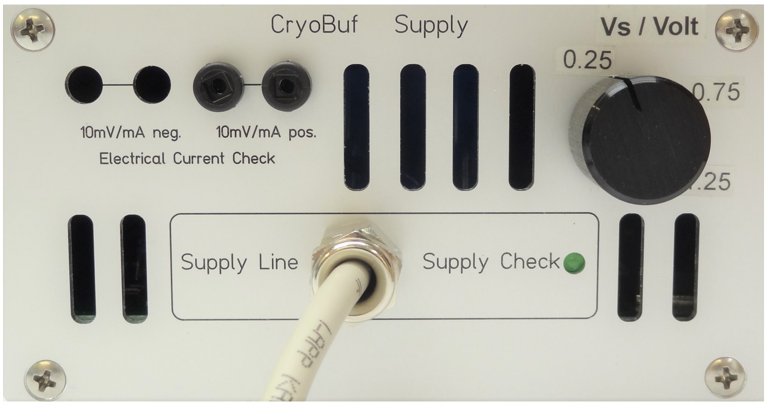
For most frequencies the resulting transimpedance, and therefor the current sensitivity, is orders of magnitude better (higher) than connecting a standard RF-amplifier with a small 50Ω input resistance. Even beyond 500MHz, where the transimpedance drops below 100Ω, the input current noise of this device, 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. Therefore, 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 500MHz or any frequency lower.

Note that these statements are valid for a direct and short (< 2mm) connection of a current source like tunneling tip to the input of the HF-STM 1, since excessive 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 few kHz) or other purposes (DC-resistance measurements, etc.).

DC Power Supply



- Fig. 5 -

A DC Power Supply is provided by the manufacturer in version E3a, which delivers a stabilized voltage between 0.25V and 1.25V, to be connected to the Vs pad and GND pad of the cryogenic buffer (white line Vs, brown line GND). The user may adjust the optimal supply voltage Vs by carefully turning the voltage selection knob and observing the obtained RF output signal.

Note that the actual supply voltage Vs can be monitored with a multimeter at the respective 2mm check-sockets versus GND, and current drawn from this DC output can be measured by the voltage drop across an internal 10 Ohm resistor (connect multimeter in voltage-mode to black sockets).

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. 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, or in case unexpected external noise interference is observed, 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 (e.g. at the vacuum feedthroughs) 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 whole 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 Cryoengineering), or Lakeshore Type C cable, or a cable from DelftCircuits with already mounted SMA plug, like Cri/o-Flex2 type. Note that despite the fact that the amplifier's output has nominally 50 Ohm impedance, the attachement of a cable of slightly different impedance (GVLZ 081: ~70 Ohm) usually poses no problem at frequencies below ~50MHz, as long as the other cable end is well-terminated with an appropriate termination resistor and therefore 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	typ. Resistance vs. GND	Remark
Vs	approx. 265Ω	value differs in the order of 25% over 4K to 300K range
HFO	10.5 kΩ	value only slightly differs over 4K-300K range
LFO	> 200 MΩ	input not connected otherwise

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, referring to table 3 above) as mentioned before. In case the latter is correct, one may temporarily power-up the device. A typical consumption current of 3mA at room temperature will be drawn from Vs = 1.25V 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.

Note that during cool down in a cryostat the device **should not be powered on**.

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 !**

After cooling down to about 4K, one should set the supply voltage to the minimum (i.e. left position of rotational button) and turn the power supply on.

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. 2.9pF. However, the device offers the possibility to add an RF inductor, 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 $Z = Q/(2\pi f_0 \bullet C)$. 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 $R = Z = Q/(2\pi f_0 \bullet C)$ 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 2.9pF, the tip or sensor capacitance (~ 0.2pF to 10pF typically) 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 $\mu_r=1$ may be preferable, which works at cryogenic temperatures usually without problems. Use leaded tin alloy or lead-tin-antimony alloy for soldering.

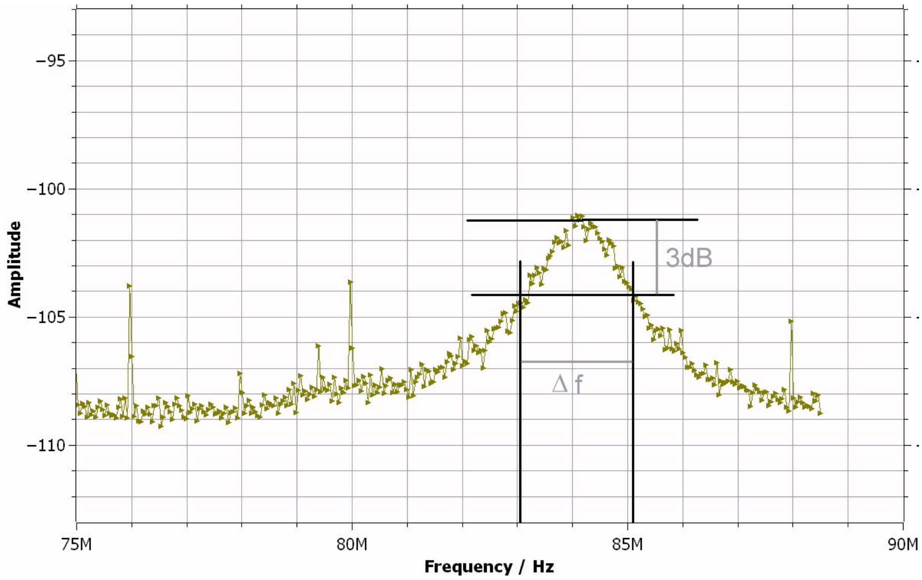


Figure 7: Power output and sensitivity spectrum with LC circuit usage, here L = 1.6µH and Q = 160. The -3dB width is given by the quality factor Q of the detection circuit.

Appendix:

Output Voltage Noise Density

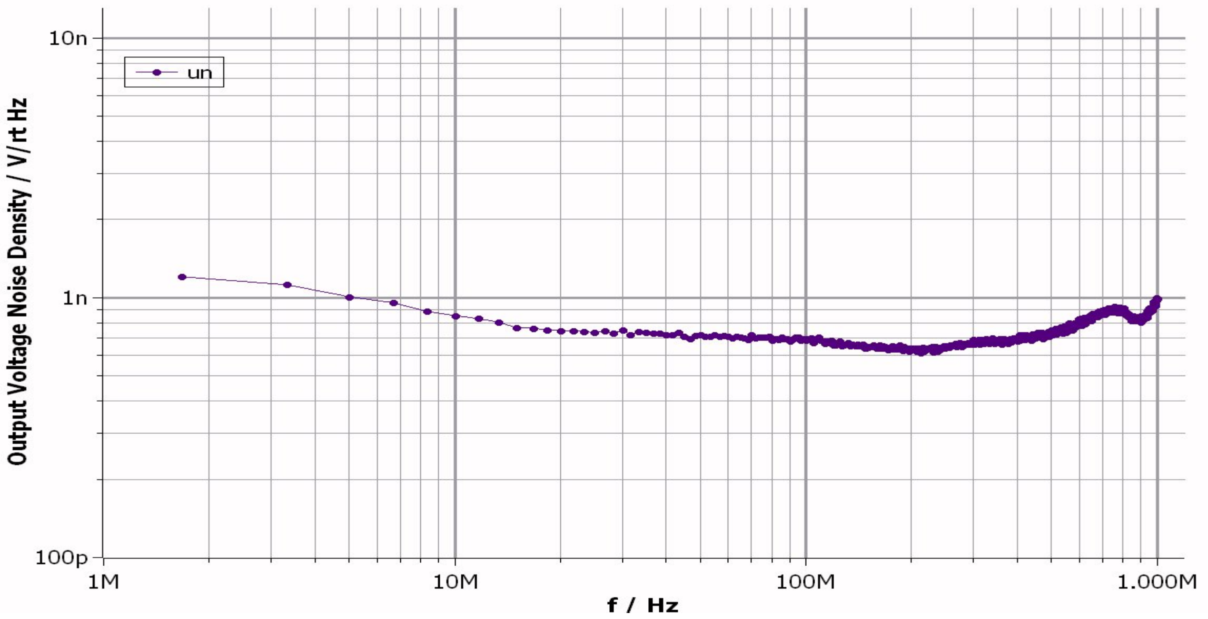
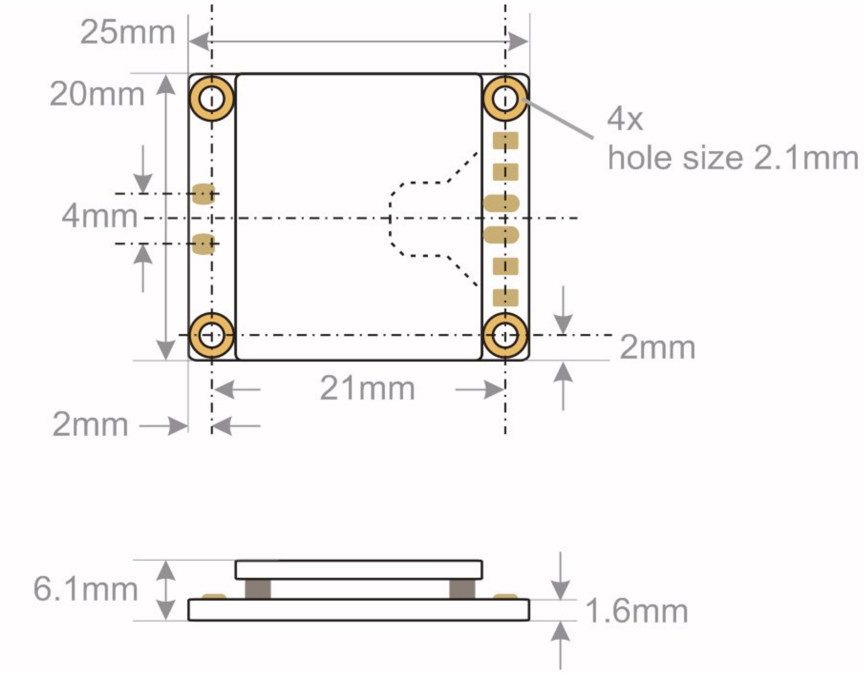


Figure 8: Output Voltage Noise Density u_n as function of frequency; note that these data rather represent the upper limit of voltage noise due to the used setup.

Geometrical Outline



Note: The circular gold plated screw pads are grounded.