Fully differential cryogenic transistor amplifier

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Abstract

We have constructed a dc-coupled differential amplifier capable of operating in the 4.2 K – 300 K temperature range. The amplifier can be operated at high-bias setting, where it dissipates 5 mW, has noise temperature T_N < 0.8 K at 4 kΩ source resistance and >40 MHz bandwidth at 4.2 K bath temperature. The bias setting can be adjusted: at our lowest tested setting the amplifier dissipates <100 μW, has noise temperature $T_N \approx 2$ K at 25 kΩ source resistance and 2 MHz bandwidth. The 1/f noise corner frequency is a few times 10 kHz. We foresee the amplifier to have an application in the readout of Superconducting Quantum Interference Devices (SQUIDs), Superconducting Tunnel Junction Detectors (STJs) and Transition Edge Sensors (TESes). We have verified the practical use of the amplifier by reading out a 4.2 K 480-SQUID array with 40 MHz bandwidth and < 8×10^{-8} Φ_0 / $Hz^{1/2}$ flux noise.

Highlights

- we have built a fully differential cryogenic dc-coupled amplifier
- the amplifier has high bandwidth, low noise temperature and high CMRR
- our amplifier is suitable for readout of SQUIDs and superconducting detectors

Keywords

SiGe transistors, low-noise amplifier, SQUID readout

1. Introduction

Versatility of operational amplifiers has made them ubiquitous in room-temperature electronic circuits. A similar electronic building block would be equally useful as part of experimental setups operating at the 4.2 K liquid helium temperature. There have been attempts to use commercially available CMOS amplifiers [1], [2], but their noise performance has been rather poor. More recently, silicon-germanium heterojunction transistors have shown potential as cryogenic amplifiers both in custom-made devices [3] and units built with commercially available parts [4]. A custom-made dc-coupled cryogenic differential SiGe amplifier has been demonstrated in [5], but, to our knowledge, the first such amplifier built out of commercially available parts was our earlier circuit version [6]. The amplifier circuit described in the paper at hand has the same frontend construction, but the output stage uses discrete transistors instead of the OPA836 operational amplifier. The new output stage increases the bandwidth and facilitates operation down to 4.2 K temperature.

In the simple noise model for bipolar transistors [7], when base spreading resistance r_b is neglected, the dominant noise generating mechanisms are the uncorrelated shot noises of the base current I_B and the collector current I_C. As input-referred noise generators, the base shot noise $i_{N,B} = \sqrt{2\, e\, I_B}$ appears directly, while the collector shot noise must be scaled by the transconductance $g_m = I_C/V_T$, where $V_T = k_B T/e$ is the thermal voltage at temperature T.

Two mechanicms lead to improvement in the noise performance of SiGe transistors at low temperatures: the increase of current gain $\beta = I_C/I_B$ and decrease of V_T, which leads to higher transconductance g_m. It has been demonstrated that for some transistors [3], including NESG3031 [4], [6], β increases dramatically at low temperatures, enabling operating regimes with low I_B and subsequently low input-referred current noise i_N. In contrast, transconductance does not increase so much and practically saturates at a constant value when T <≈ 50 K [3], [4], causing only limited improvement of voltage noise. This phenomenon has been explained by non-equilibrium base transport that begins to dominate over classical drift-diffusion mechanisms at cryogenic temperatures [8].

2. Amplifier construction

The amplifier frontend uses a differential pair of NESG3031 SiGe heterojunction transistors, cascoded with another NESG3031 pair (Fig. 1). The frontend is buffered by a pair of NESG4030 –based emitter followers, which are capable of driving the 4.2 K to 300 K twisted pair over a large bandwidth.

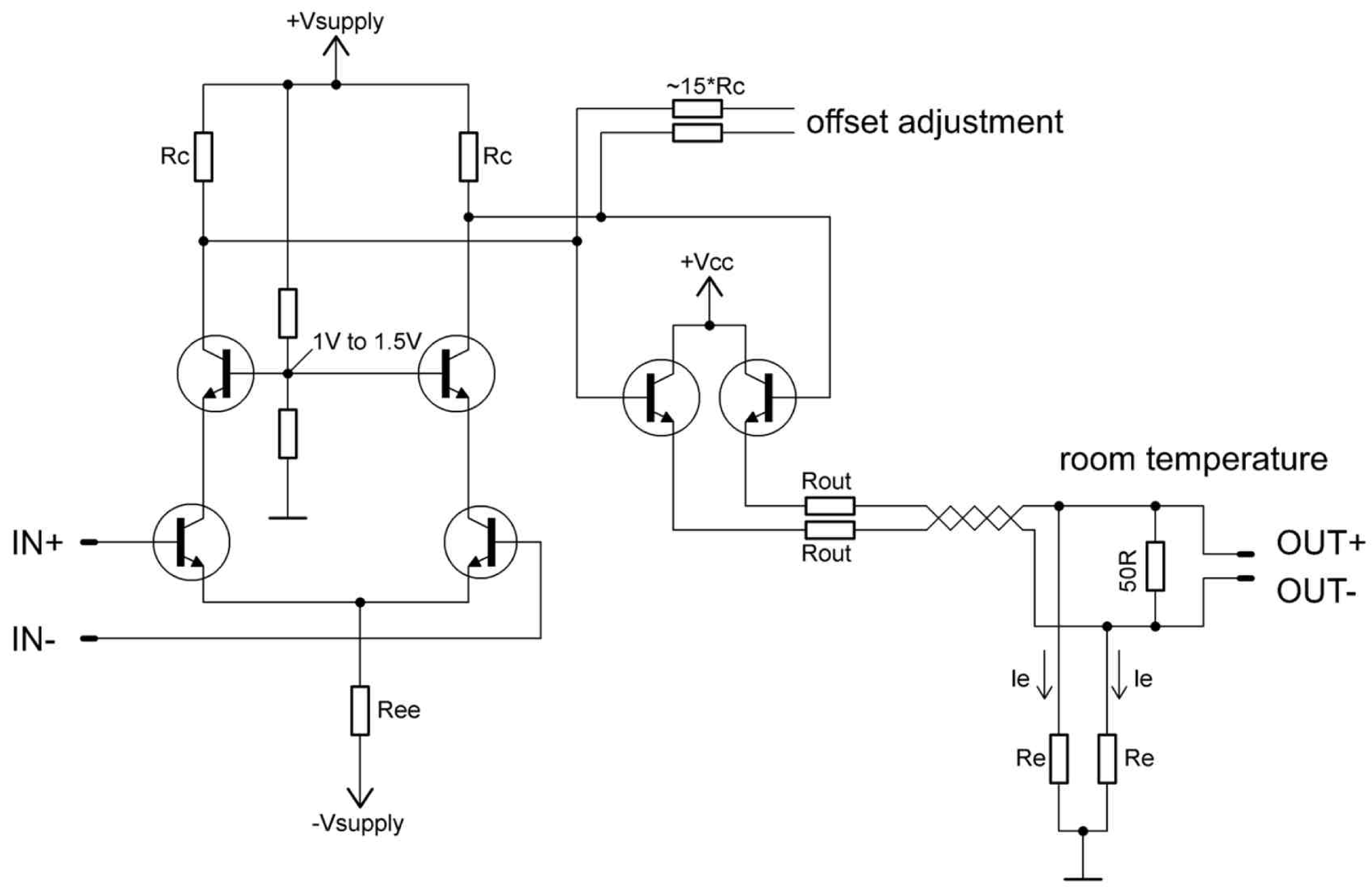


Fig. 1. Simplified schematic diagram of the fully differential SiGe amplifier

The signal from the twisted pair is received at the 300 K end by a 50 Ω terminated differential amplifier based on the OPA2822 integrated circuit. In [9] an analysis is presented, which shows that the fully differential topology enables high CMRR, since the common-to-differential gain G_{DC} dominates over the common-mode gain G_{CM}. In our amplifier G_{CM} is further suppressed by the room-temperature stage. Circuit balance determines G_{DC}, which in theory can be reduced to zero.

3. Experimental results

3.1. Amplifier performance

Current and voltage noise spectra of the amplifier measured at the high and low collector currents are given in Fig. 2. A switchable attenuator described in [6] provided low and high-impedance input loads, which enabled separate measurement of voltage and current noise. For the low-I_C current noise measurement we further increased the attenuator resistance to 510 kΩ. The spectra are truncated up to the points where the cryogenic amplifier noise dominates; beyond these points RC cutoff prevents accurate esimation.

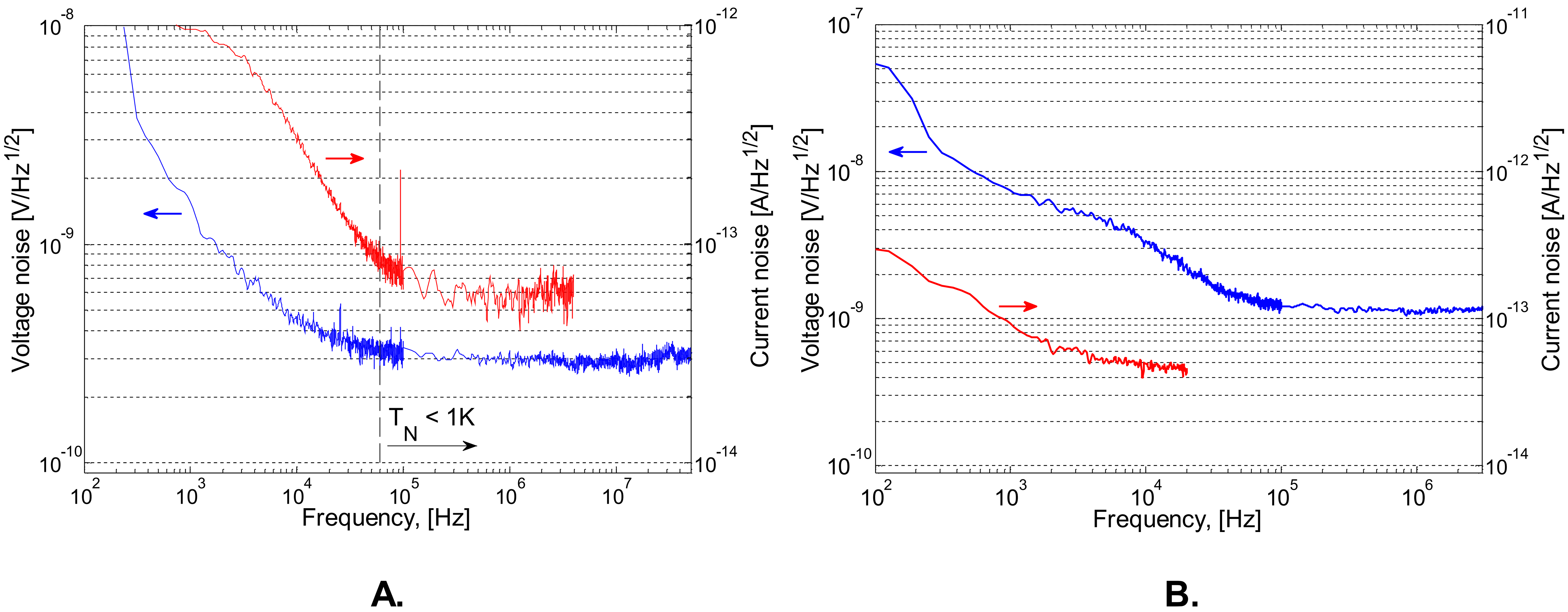


Fig. 2. Voltage and current noise of the SiGe amplifier at 4.2 K at **A.** I_C = 360 μA and **B.** I_C = 7.5 μA

Frequency response (Fig. 3) was obtained both at room temperature using a short connection and at 4.2 K using a dipstick equipped with ~1 m of phosphor bronze twisted pairs. High-frequency attenuation due to the skin effect of the twisted pair is visible in the plot.

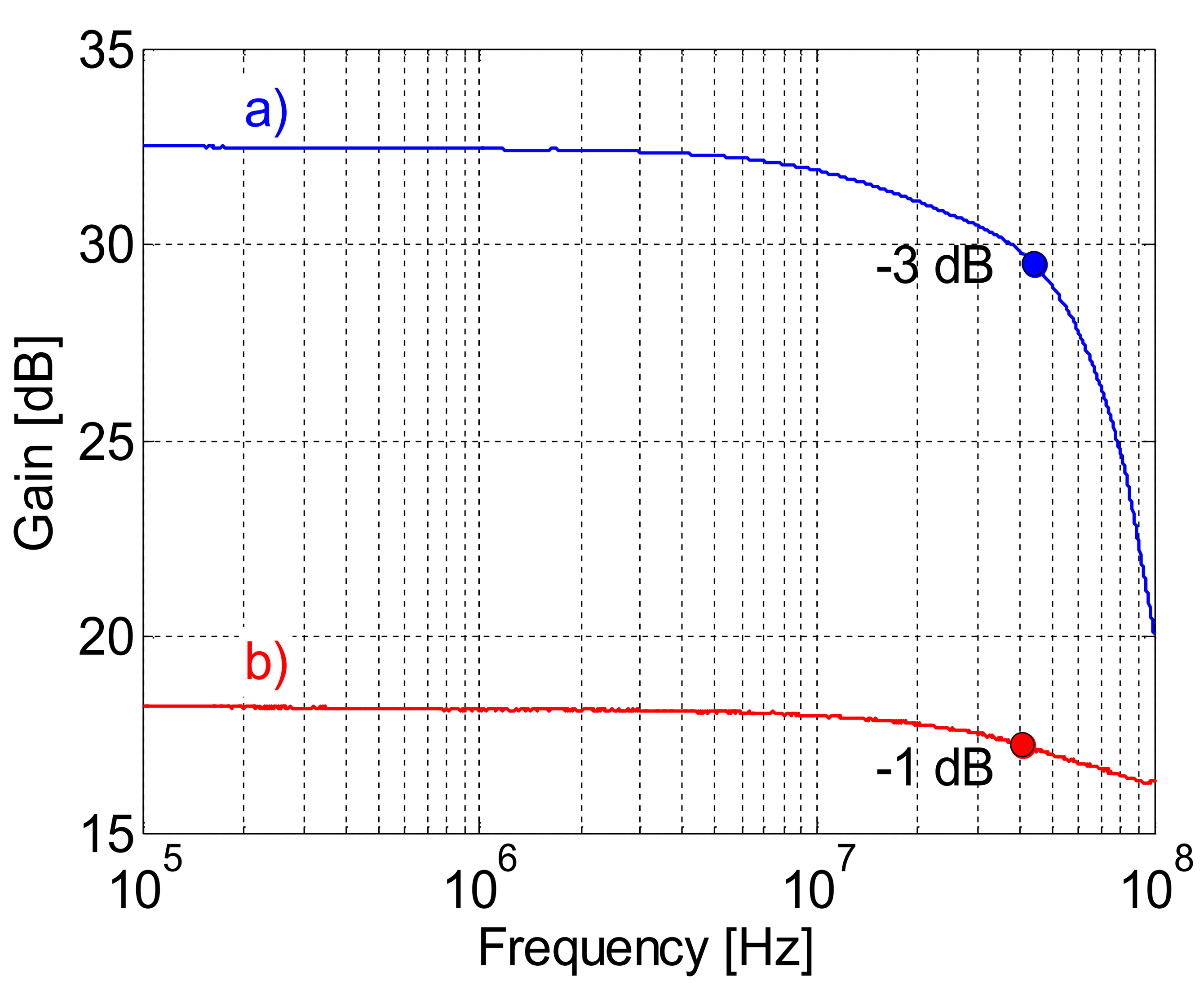


Fig. 3. Frequency response of the amplifier **a)**at 4.2 K with dipstick wiring **b)**at room temperature with short low-loss wiring

CMRR was measured at room temperature. For the common-mode gain measurement, the amplifier inputs were shorted together and connected to the amplifier's ground plane through a 50 Ω resistor. CMRR was estimated at two different settings of amplifier's output offset voltage (Fig. 4).

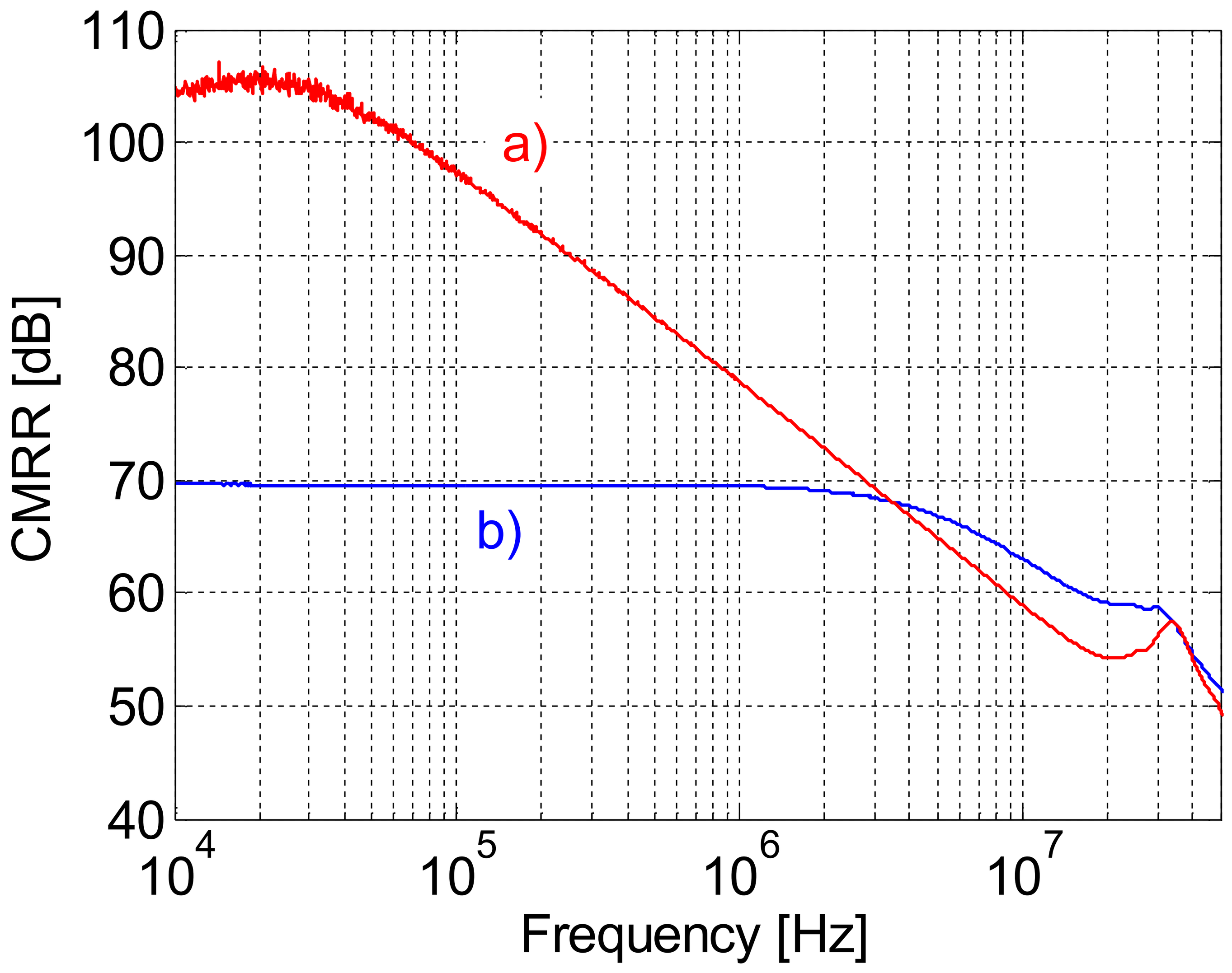
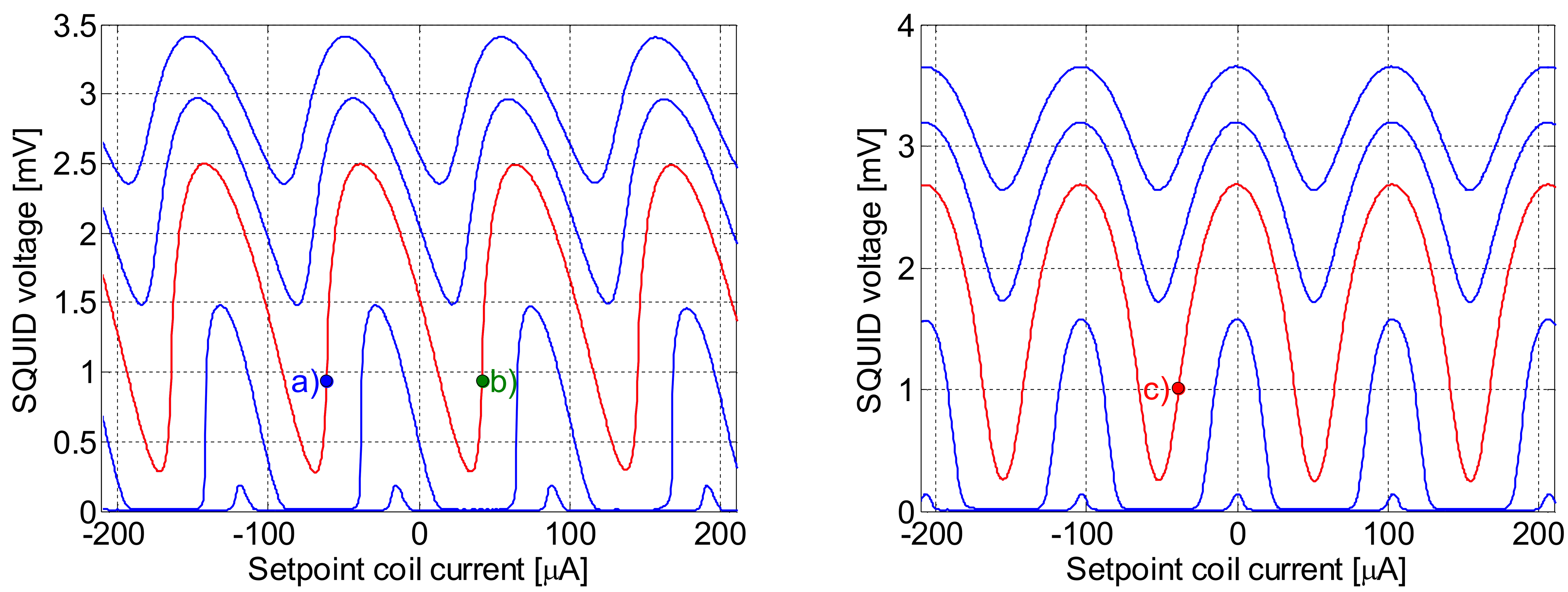


Fig. 4. CMRR of the amplifier **a)**at the offset point that yields maximum CMRR and **b)**at zero output offset

3.1. SQUID array readout

Flux characteristics of the 480-SQUID array [10] operated with and without local voltage-sampling feedback (V-FB) [11], [12] are given in Fig. 5. Flux noise and bandwidth measurements of the SiGe amplifier+SQUID array combination are given in Fig. 6. Various parameters measured at the three setpoints indicated in Fig. 5 are given in Table I. The SQUID array input inductance L_{IN} was estimated from the R/L cutoff with a 1 Ω resistor connected across the input coil. In all measurements the array was cooled and operated in the earth's magnetic field without any high-permeability or superconducting shield.



A. **B.**

Fig. 5. Current-to-flux characteristics at I_{BIAS} = 100, 150, 200, 225 and 250 μA **A.** with V-FB **B.** without V-FB

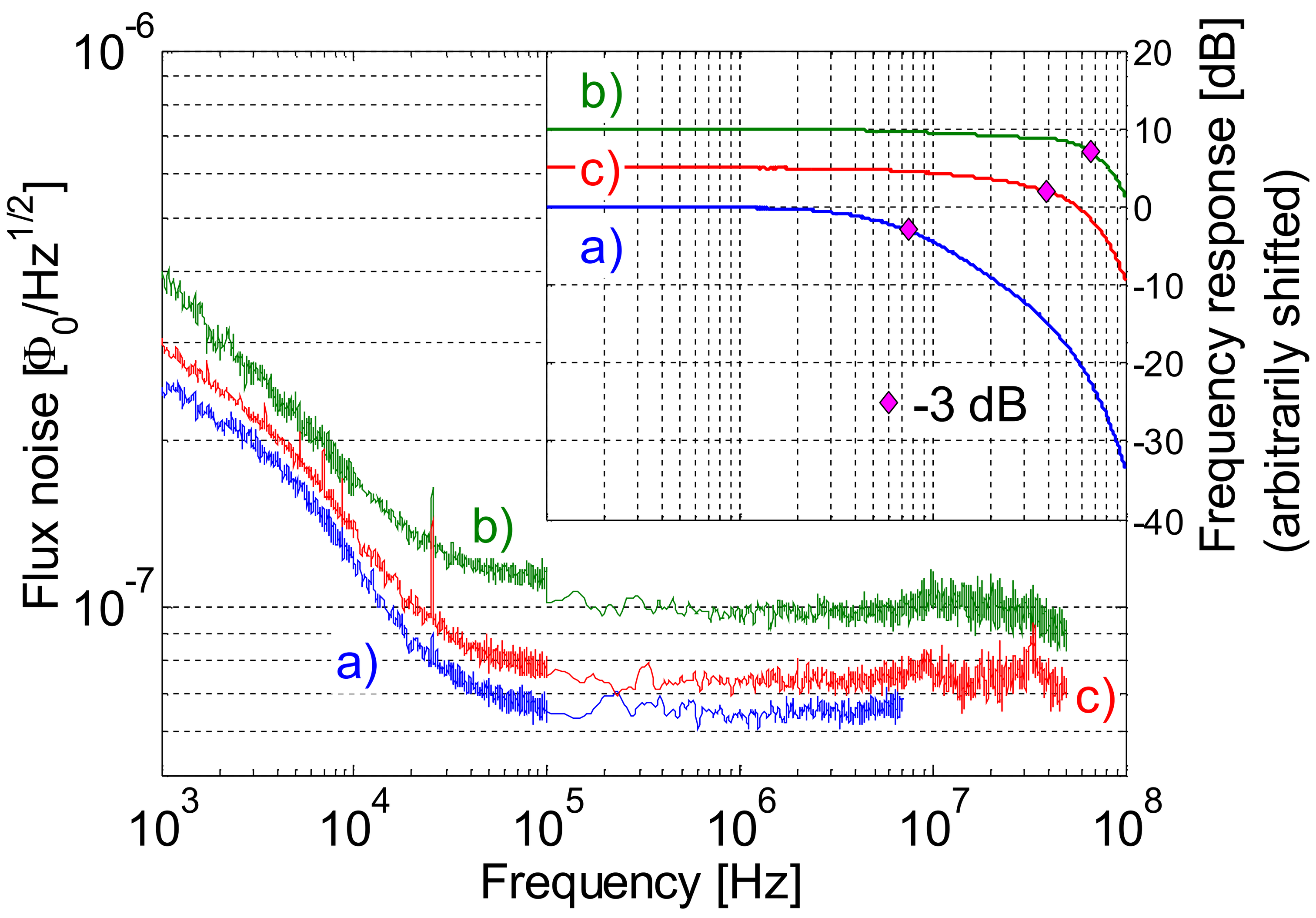


Fig. 6. Flux noise and bandwidth at the a)steep slope with V-FB b)gradual slope with V-FB c)steepest point without feedback

Table I. SQUID array parameters measured at different setpoints

Setpoint	Description	$\partial V/\partial \Phi$ [mV/ Φ_0]	-3 dB bandwidth [MHz]	Flux noise [$\Phi_0 Hz^{-1/2}$]	Measured L_{IN} [nH]
a)	steep slope with V-FB	36	7.5	6.5×10^{-8}	245
b)	gradual slope with V-FB	4	66	1×10^{-7}	100
c)	no feedback, steepest point	11	40	7.5×10^{-8}	135

4. Discussion

We have built a practical and robust cryogenic amplifier that has high bandwidth and very low noise temperature. Its practical use was demonstrated by reading out a large SQUID array. The achieved bandwidth of 40 MHz and flux noise below 8×10^{-8} Φ_0 / $Hz^{1/2}$ imply high Shannon channel capacity.

At the high collector current mode we measured $T_N \approx 0.7$ K, which is unprecedentedly low for SiGe transistors operated in liquid helium. We found that parts from different batches have dissimilar noise properties: an older batch used for the amplifier in [6] had higher current noise in the white region, but lower 1/f current noise than transistors used in the present work. Voltage noise does not seem to suffer from such extreme variations. It can be seen in Fig. 2 that low-frequency noise is also dependent on the transistor bias setting, therefore low-current operation is desirable not only from power dissipation point of view.

The high CMRR presented in Fig. 4 is characteristic of the fully differential topology. Our circuit does not achieve simultaneously zero output offset and maximum CMRR due to mismatch of collector resistors and and the use of an unmatched transistor pair. High precision resistors and a hand-selected well-matched transistor pair would improve the circuit balance.

Since the intrinsic bandwidth of the amplifier is higher than 100 MHz (Fig. 3 b), it can be used to operate SQUIDs in a short high-bandwidth flux-locked loop [4]. With different feedback networks the basic amplifier can also be configured as an integrator or a transimpedance amplifier.

One application for the amplifier would be in the signal chain for multiplexed arrays of cryogenic detectors [12], where typically a SQUID is used as the lowermost amplifier. In such a chain a large Shannon information flow is passed, therefore the post-SQUID amplifier must simultaneously have high bandwidth and large dynamic range. A concrete example is the Low Noise amplifier (LNA) needed for as the 136 K stage of the SPICA-SAFARI far-infrared spectrometer instrument [13]. Owing to its low noise temperature, our amplifier might also suit for direct readout of 4.2 K TESes [14] without SQUIDs, or even readout of sub-1K TESes when they are operated in the power amplification mode with external linearizing feedback [12], [15]. Direct readout of STJs [16] is also considered.

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