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Novel stable and reliable readout electronics for HTS rf SQUID

Hans-Joachim Krause\(^a,c\) *, Norbert Wolters\(^b,c\) and Yi Zhang\(^a,c\)

\(^a\)Peter-Grünberg-Institute (PGI-8), Forschungszentrum Jülich, 52425 Jülich, Germany
\(^b\)Institute of Complex Systems (ICS), Forschungszentrum Jülich, 52425 Jülich, Germany
\(^c\)Jülicher SQUID GmbH (JSQ), 52428 Jülich, Germany

Abstract

Conventional readout electronics for radio-frequency SQUIDs exhibit long-term instabilities due to a temperature-dependent frequency drift of their voltage controlled oscillator. A novel electronics with a quartz-controlled synthesizer was developed to solve this problem. The frequency can be adjusted from 450 to 900 MHz with 2 ppm frequency stability, the amplitude range covers more than 60 dB. An adjustable phase shifter for demodulation is implemented to compensate for variable cable length. The total amplification is about 100 dB. The electronics with touchpanel and remote USB control is commercially available with up to three preamplifier units. Because thermal drift is eliminated, it is well suited for outdoor applications, e.g. in geophysics.

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1. Introduction

High-T\(_c\) radio-frequency superconducting quantum interference devices (rf SQUIDs) made of the ceramic superconductor Yttrium-Barium-Copper-Oxide (YBCO) have found widespread usage in the last fifteen years [1]. In Jülich, the SQUIDs are manufactured using laser-ablated YBCO films on monocrystalline LaAlO\(_3\) substrates prepared with a ion beam etched ditch to form a step-edge Josephson junction [2]. The best performance has been achieved when operating the SQUIDs in flip-chip configuration with a so-called substrate resonator consisting of a dielectric monocrystalline SrTiO\(_3\)

* Corresponding author.

E-mail address: h.-j.krause@fz-juelich.de.
substrate with a flux-focuser washer pattern [3]. With this design, the tank circuit noise is minimized and the quality factor Q of the tank circuit is maximized. The SQUID with its substrate resonator is operated in dissipative mode near its resonance frequency of typically 600 MHz and at an rf power level of approximately 0.1 pW (-100 dBm). An important advantage of this concept is that no galvanic connection leads from the electronics to the SQUID, therefore static discharges pose no threat to the SQUID's life.

The first high frequency readout electronics for rf SQUIDs integrated with a microwave resonator was developed by Mück [4]. In contrast to conventional rf SQUID readout [5], frequency tuning is required to match the resonator. For the substrate resonator SQUIDs, different versions of suitable electronics comprising a voltage controlled oscillator (VCO) were developed in Jülich and have been commercially available [6]. A 50 Ω transmission line connecting the readout electronics with the SQUID is terminated by a coupling coil adjacent to the SQUID via its tank circuit. The coupling coil serves two purposes: applying the pumping energy near the resonance frequency of the SQUID's tank circuit and generating the feedback flux. In order to linearize the transfer function, the SQUID is operated in a so-called flux-locked loop (FLL) [6]: The SQUID is kept at a well-defined external flux state by generating a magnetic feedback field compensating all measured external flux variations.

Usually, the voltage controlled oscillator (VCO) supplying the rf current exhibits a temperature-dependent frequency drift, thus impairing the long-term stability of the readout, especially when the environmental temperature changes strongly, e.g. in outdoor measurements. But even in laboratory measurements, the electronics has to be switched on a few minutes before starting a measurement in order to allow it to equilibrate thermally.

In order to solve this problem, a novel electronics with a quartz-controlled synthesizer was developed. The VCO is stabilized against a quartz reference in a phase-locked loop with a fractional-N divider. Thus, the output frequency achieves the same relative frequency stability of 2 ppm as the reference quartz. By this means, the frequency stability can be improved more than three orders of magnitude as compared to an unregulated VCO. Thus, temperature-dependent drift of working point adjustment is not an issue any more.

2. Design

The schematic of our novel SQUID electronics is depicted in Fig. 1a. On the generator side, it consists of a rf synthesizer, a subsequent low pass (LP) filter to suppress harmonics, a voltage-controlled attenuator to adjust the rf output power, and a directional coupler to direct the signal to the tank circuit. The rf source consists of a VCO (ROS-1300+ from Mini Circuits), a reference quartz with 2 ppm frequency stability (FT17T-10.0/2.0-3.3/18 from Freqtech) and a synthesizer including a fractional-n divider and a phase-locked loop (SKY72302). In principle, the frequency is stabilized by dividing the VCO output by a quotient $p/q$ of integer numbers $p$, $q$ and phase-locking it to the frequency of the reference quartz. The reflected rf signal modulated by the SQUID response signal passes though the directional coupler to the low noise preamplifier (LNA). For detection, the signal is amplified and subsequently guided to the mixer. In the new electronics, a phase shifter (JSPS-661+ from Mini Circuits) has been included which allows to adjust the phase of the reference signal for demodulation. It allows to compensate for the phase of the reflected signal due to different length of the SQUID cable, which is comparable to the wave length in this frequency range.

When the electronics is set to the test mode, the $V-\Phi$ characteristics is monitored at the output. When the electronics is set to the measurement mode, the integrated SQUID signal at the output is fed back to the SQUID by the coupling coil via the adjustable feedback resistor. It is proportional to the measured magnetic flux. Thus, the SQUID is kept in a state of constant magnetic flux, i.e. it is operated in a so-called flux-locked loop (FLL) [5]. This operating principle ensures a linear transfer function. Usually, it
allows a dynamic range from approximately $10^{-5}$ to about $10^3$ magnetic flux quanta with excellent linearity. The feedback is only limited by the maximum output voltage of the integrator which is $\pm 10 \, V$ in our case. The offset controller regulates the voltage of the working point which should be chosen at the maximum slope of the $V$-$\Phi$ characteristics.

The electronics is operated and remote-controlled by means of a micro controller integrated with the electronics box. It is based on the "Tiger" microcontroller board TP 1000 by Wilke Electronics, Aachen. Fig. 1 (b) shows the touch panel controller (top) which is used to operate the preamplifier electronics (bottom). Up to three preamplifiers can be connected for simultaneous control of three individual SQUID sensors. The controller can either be used as a stand-alone unit by touchpanel control or it can be remotely operated from a computer. It allows adjustment of all electronics parameters, frequency (VCO), rf power (attenuator), demodulation phase, dc-offset, feedback resistance and integrator capacitance. The "Tiger" board is equipped with an USB port which is configured as a virtual COM port. All settings and functions of the electronics can be set and queried by simple serial commands. For instance, the command “VCO1:573.75;” sets the frequency of channel 1 to 573.75 MHz, the command “GVCO;” queries the frequencies of all channels. They can be stored in and retrieved from the non-volatile memory of the controller.

The values of the integrator's capacitor and of the feedback resistor are both adjustable. The feedback resistor determines the flux-to-voltage coefficient and thus the dynamic range. The integrator's capacitor influences the velocity of the feedback loop, i.e. the frequency bandwidth.

The electronics is also equipped with a current source for SQUID heating. In case of large changes of the external magnetic field, magnetic flux may be trapped inside the superconducting thin films of the SQUID or the substrate resonator. It results in spontaneous signal jumps due to flux vortex hopping within the film, the so-called "shot noise", thus impairing SQUID operation. Warming up the SQUID and releasing the trapped flux solves this problem. The heating current of 100 mA can be applied for the selected heating time. At the beginning of the heating procedure, the SQUID is put into TEST mode, since heating leads to unlocking of the SQUID. Usually, a heating time of 3 s suffices.
3. Characterization and performance

The electronics was characterized regarding its total amplification, including preamplifier, demodulation and output amplifier. The amplification was measured by supplying a -100 dBm signal of variable frequency from a HP 8657A signal generator at the SMA input, setting the synthesizer of the electronics to the same nominal frequency, and measuring the amplitude of the beat signal at the electronics output in TEST mode with an oscilloscope. The beat frequency was typically in the range of a few hundreds of Hz, thus proving that the frequency precision of the electronics lies in the ppm range. Fig. 2 (a) (top) depicts the measured amplification as a function of the frequency. It varies from 102 dB at 450 MHz to 95 dB at 900 MHz. This level is high enough to ensure that noise of electronic components, e.g. demodulator (mixer) noise. Because of the low noise substrate resonator tank circuit with a high quality factor and the low noise preamplifier with a noise figure of 1.1 dB, the total noise should be dominated by intrinsic SQUID noise.

The rf pumping power at input of the electronics was measured as a function of attenuator voltage for different frequencies. The pumping power at input was pre-amplified using a Trontech W162H amplifier and connected to a HP 8596E spectrum analyzer. The measured rf pumping power was corrected for the frequency-dependent amplification factor and sketched as a function of the frequency for different attenuator settings, cf. Fig. 2 (a). When plotting the rf power as a function of the attenuator voltage, Fig. 2 (b), it becomes obvious that main rf power change occurs in the attenuator range from 0.5 V to 2.5 V. An adjustment range of 60 dB allows to adapt the electronics to nearly all SQUIDs with their different critical currents.

The demodulation phase of the electronics was also measured. It varies from 0° to approximately 210° when varying the control voltage from 0 V to 12.5 V. This adjustment range is sufficient to compensate for phase changes introduced by the coaxial cable connecting to the SQUID’s coupling coil.

The novel rf SQUID electronics was tested in conjunction with a rf SQUID with a 3.5 mm diameter washer and a 100 μm × 100 μm loop, flip-chip positioned on a 10 mm × 10 mm substrate resonator flux focuser [3]. The rf pumping power answers to the rf pumping current. Fig. 3 (a) shows the measured I-V characteristics of the rf SQUID for two different flux states of integer and half integer number of flux quanta. It demonstrates that the SQUID is operated in the inductive mode. One can nicely observe the different steps which correspond to the number of quantum transitions the SQUID undergoes during one
half rf cycle [7]. Fig. 3 (b) shows the difference between the two curves, i.e. the modulation depth between the two flux states of the SQUID, as a function of both frequency and attenuator value.

The feedback resistor $R$ determines the dynamic range of the electronics. Table 1 lists the voltage-to-flux coefficient measured with a mutual inductance of 55 pH between SQUID and coupling coil, and the resultant dynamic range. The dynamic range increases with decreasing $R$. Note that too small a feedback resistor $R$ will cause an additional noise. The dynamic range is also limited by the output current.

Table 1. Voltage-to-flux coefficient $[V/\Phi_0]$ measured with a SQUID for different values of the feedback resistor $R$, and resultant dynamic range $[\Phi_0]$ when operating the SQUID in flux-locked loop.

| Feedback resistor $R$ [k$\Omega$] | 1  | 1.5 | 2  | 3  | 4  | 6  | 10 | 20 |
|----------------------------------|----|-----|----|----|----|----|----|----|
| Voltage-to-flux coefficient $[V/\Phi_0]$ | 42 | 60 | 78 | 119 | 155 | 225 | 380 | 760 |
| Dynamic range $[\Phi_0]$ | ±238 | ±167 | ±128 | ±84 | ±64 | ±44 | ±26 | ±13 |

Finally, the electronics was characterized while operating the SQUID in flux-locked loop. The bandwidth was measured by applying a magnetic field of variable frequency and measuring the output with a lock-in amplifier (SR 830 from Stanford Research) for different settings of the feedback resistor $R$ and the integrator capacitance $C$. The measured frequency-dependent transfer functions could be fitted to first order low pass filter characteristics. Table 2 lists the low-pass corner frequencies of the transfer functions. As expected, the bandwidth reduces with increasing values of $C$ and $R$.

Intuitively, one would then choose a minimum capacitance and a minimum resistance in order to achieve maximum slew-rate, bandwidth and dynamic range. However, the larger the integrator's capacitance and the larger the feedback resistance, the more stable the flux-locked loop is. Therefore, the capacitance and the resistance should be chosen only as low as the application requires. One should try to achieve a compromise between performance and stability.
Table 2. Bandwidth [kHz] measured with a SQUID in FLL with the integrator capacitance C and the feedback resistor R. The missing values indicate that with the respective R-C combination, the FLL could not be locked.

| C [nF] | R [kΩ] | 1   | 1.5 | 2   | 3   | 4   | 6   | 10  | 20  |
|--------|--------|-----|-----|-----|-----|-----|-----|-----|-----|
| 0.33   | -      | -   | -   | -   | 183 | 133 | 90  | 52  |
| 1      | -      | -   | -   | -   | 126 | 98  | 72  | 49  | 28  |
| 2.2    | -      | 168 | 134 | 96  | 78  | 61  | 38  | 21  |
| 4.7    | 163    | 117 | 94  | 65  | 55  | 39  | 24  | 13  |
| 10     | 135    | 99  | 79  | 58  | 46  | 35  | 22  | 11  |
| 22     | 114    | 83  | 67  | 49  | 39  | 32  | 19  | 10  |
| 100    | 98     | 72  | 58  | 43  | 34  | 27  | 16  | 8   |

4. Conclusion

A novel electronics for readout of high-Tc rf SQUIDs has been developed. It is especially suitable for operation at variable ambient temperature, e.g. in outdoor environment. It features a frequency synthesizer with excellent stability and a large frequency range from 450 MHz to 900 MHz. The rf pumping power can be adjusted in a very broad range from -47 dBm to -119 dBm, thus allowing to operate rf SQUIDs with different parameters. An adjustable demodulation phase enables adaptation to variable cable length. The feedback range and the bandwidth of the flux-locked loop can be adjusted to the application’s needs. The electronics is equipped with a touchscreen control for convenient handling and is fully remotely controllable via USB port. It is commercially available with one to three preamplifier channels from Jülicher SQUID GmbH (JSQ) [6].

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