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Bias reversal technique in SQUID Bootstrap Circuit (SBC) scheme

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Abstract

Recently, a SQUID direct readout scheme called voltage-biased SQUID Bootstrap Circuit (SBC) is introduced to reduce preamplifier noise contribution. In this paper, we describe a concept of SBC with bias reversal technique which can suppress SQUID intrinsic 1/f noise. When applying a symmetrically rectangular voltage across SBC, two \( I-\Phi \) characteristics appear at the amplifier output. In order to return to one \( I-\Phi \) curve, a demodulation technique is required. Because of the asymmetry of typical SBC \( I-\Phi \) curve, the demodulation method is realized by using a flux compensation of one half \( \Phi_0 \) flux shift. The output signal is then filtered and returned to one \( I-\Phi \) curve for ordinary FLL readout. It was found, the reversal frequency \( f_R \) can be dramatically enhanced when using a preamplifier consisting of two operational amplifiers. A planar Nb SQUID magnetometer with a loop-inductance of 350 pH, \( f_R \approx 50 \text{kHz} \) and a second order low pass filter with 10kHz cut off frequency was employed in our experiment. Results prove the feasibility of SBC bias reversal method. Comparative experiment on noise performance will be carried out in further studies.

1. Introduction

Low frequency noise of SQUID is a main limitation of its low frequency applications (especially for high \( T_c \) SQUID). This low frequency noise mainly origins from two sources. For low \( T_c \) SQUIDs, preamp dominates. However, for high \( T_c \) SQUID, low frequency noise origins from fluctuations in the

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critical current and resistance of the junctions become obvious\cite{1,2}. This involves in-phase fluctuations and out-of-phase fluctuations. Several authors, such as Koch et al.\cite{3}, Fogliett.,\cite{4} and Do¨ssel.\cite{5} have proposed different bias current and flux modulation schemes which dramatically reduce the low-frequency noise levels in SQUIDs.

![Fig.1 Basic scheme diagram of SBC](image1)

Although current bias is widely used, voltage bias of more stable working point and better intrinsic linear range are suitable for application. Recently a voltage-biased SQUID bootstrap circuit (SBC) scheme is reported for simple direct readout circuit noise suppression. Three passive components connected to the SQUID are applied. A dc SQUID with inductively coupled coil L_1 in series constructs one branch for SQUID’s flux-to-current coefficient enhancement. Another inductively coupled coil L_2 with a shunt resistor in series constructs second branch for preamplifier noise suppression.\cite{6} The method is effective for pre-amp noise suppress, however, SQUID intrinsic noise still exists.

This paper mainly studies the bias reversal technique on SBC for intrinsic noise suppress. The basic principle is described and proved by experiments.

2. Basic principle

2.1 Step 1: Rectangular bias applied on SBC

The schematic diagram of the SBC is shown in Fig.2. Instead of the constant bias applied on positive input of op-amp, a symmetrically rectangular voltage appears and supplies the reversal bias voltage. Two I-\Phi curves appear at the output of the pre-amplifier after applying ac bias voltage. Fig.2 shows the two I-\Phi curves after applying the rectangular bias on SBC.

![Fig.2 (a) Rectangular bias circuit (b) Step1: I-\Phi curves](image2)
The two I-Φ curves of SBC are different from ordinary SQUID because of the asymmetrical SBC I-Φ curve. The phase of two I-Φ curves (in flux) of both the ordinary SQUID and the SBC are slightly different from Φ₀/2 due to the retained flux of L1 and L2 coupled to SBC while applying ac bias.

In order to return to one I-Φ curve for ordinary FLL (Flux Locked Loop) readout, a demodulation method is needed. Demodulation procedure is described as follows:

2.2 Step 2: Flux compensation

As the two I-Φ curves are asymmetrical, we have to compensate the flux phase of the two I-Φ curves. It is accomplished by applying a rectangular flux (with the same phase and frequency) into the feedback coil. The amplitude of compensate flux should be Φ₀/2 if the retained flux is not considered. Fig.3 shows the scheme diagram of flux compensation and the two I-Φ curves after flux compensation.

![Fig.3 (a) Flux compensation scheme diagram   (b) Step 2: I-Φ curves](image)

After applying flux compensation, the two I-Φ curves are compensated to same phase.

2.3 Step 3: Return to one I-Φ curve

Ordinary demodulation method is no longer effective for SBC because of the symmetric of its I-Φ curve. Here, we compensate the two I-Φ curves to same phase (Step 2), the two I-Φ curves can be regarded as the addition of a DC biased I-Φ curve and a bias carrier waveform (generated by AC bias). So a low pass filter can be applied for carrier wave removing. Demodulation is accomplished. The procedure is described in Fig.4.

![Fig.4 Step 3: Demodulation of SBC bias reversal](image)

After low pass filtering, the carrier wave of bias is removed from pre-amp output and the two I-Φ curves return to one for ordinary FLL readout.
3. Experiment and results

3.1 Bandwidth improvement

When applying a rectangular bias voltage on SBC, waveform distortion is observed at the pre-amp output. This is caused by the limitation of pre-amp gain-bandwidth-product. The problem is solved by a new pre-amp model constructed with two op-amps. The gain-bandwidth-product becomes much larger.

\[ \frac{BW_{\text{new}}}{BW_{\text{former}}} = \left(1 + \frac{R_{b2}}{R_{b1}}\right) \]

![Diagram](image)

Fig.5 (a) High bandwidth new circuit (b) waveform before (c) waveform after, SQUID is replaced by a 10Ω resistor, \( f_R = 15 \text{kHz} \)

3.2 SBC and circuit

In the experiment, a helium-cooled integrated SBC magnetometer with a loop inductance of 320 pH and a pickup area of 6×6 mm\(^2\) were used. The three superconducting coils \( L_1, L_2 \) and feedback coil were integrated on the SBC chip.

![Diagram](image)

Fig.6 (a) SBC Chip (b) Circuit

The testing circuit is shown in Fig.6. The SQUID, \( L_1, L_2 \) and \( R_s \) are helium cooled. Then it is connected to room temperature pre-amp through 1.5m long cable. The AC bias voltage is given by signal generator (reversal frequency \( f_R = 50 \text{kHz} \)), \( R_1 \) and \( R_2 \). Pre-amp is a transconductance amplifier with 10kΩ total gain. The output of the amplifier is fed into a low pass filter (\( f_c = 10 \text{kHz} \)) to remove the reversal rectangular bias wave. Another rectangular wave given by signal generator is fed into the feedback coil through \( R_3 \) for flux compensation.
3.3 Results

Experimental result proves the SBC bias reversal as we described. The waveform of each step above is recorded and shown in Fig.7. One I-Φ curve is finally obtained after a 2nd order low pass filter after applying ac bias voltage. The I-Φ curve of low pass filter output (Step 3 in Fig 7) is not the same as that of DC bias mode. This is due to the non ideal filter characteristics. A low pass filter with higher cut-off frequency and higher order might be introduced for better demodulation.

Fig.7  I-Φ curve of SBC bias reversal, (a) Step1; (b) Step 2; (c) Step 3; (d) DC bias

4. Conclusion

Bias reversal technique on SBC is studied in this paper. When a rectangular wave applied on SBC, two I-Φ curves appear at the amplifier output. Because of the asymmetrical SBC I-Φ curve, a method called flux compensation is introduced here to make two I-Φ curves in same phase. Then the bias carrier wave can be removed by a low pass filter and therefore two I-Φ curves return to one for ordinary FLL readout. In our experiment, a new structure of pre-amp consists of two op-amps is applied to extend bandwidth and suppress waveform distortion. Experimental result proves the feasibility of SBC bias reversal method. Further study will be carried out such as noise performance compared to DC bias.
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