New Insight into Voltage-biased SQUID Operation

December 14, 2012 (HP51). The need to optimally match the SQUID to the room-temperature preamplifier of the analog electronic readout, and to suppress of that preamp's noise has preoccupied the users from SQUID's early days [1]. Transformers and resonant circuits have been employed to improve impedance matching while the flux modulation technique was effective in the preamp noise suppression. Cryogenic amplifiers could also be used in special cases to reduce noise.

With the advent of multichannel SQUID systems in late 1980s and early 1990s, it became important to simplify the flux-locked loop readout and direct-coupled readout schemes were introduced. To suppress the preamp's noise they required some sort of additional feedback to enhance SQUID's dynamic resistance and ultimately $\partial V/\partial \Phi$. Two SQUID feedback schemes have been used in practice: the Additional Positive Feedback (APF) in current-biased SQUIDs, first proposed by Drung *et al*. [2], and the negative feedback Noise Cancellation (NC) scheme for voltage-biased SQUIDs first introduced by Kiviranta and Seppä of the VTT group [3]. The latter has been used in large multichannel systems fabricated by "Neuromag" for magnetoencephalo-graphy. However, both these schemes share a common disadvantage. They have narrow operating margins requiring either a rather tight SQUID parameter control in the fabrication process or an adjustable component, such as the FET transistor in the NC scheme.

Recently, Xie, Zhang *et al*. demonstrated for the voltage-biased SQUID a feedback circuit combining both voltage and current feedback, which they called SQUID Bootstrap Circuit (SBC) [4]. It has significantly improved operation margins but for a price of additional SQUID circuit complication so that only now the first planar integrated circuit version of SBC has been presented [5]. It is shown in Figure 1. However, in the process of its investigation Zhang and Liu realized that the voltage-biased SQUID can stably operate even when the Josephson junction Steward-McCumber parameter β_c exceeds 1 [5]. This is possible, because the low internal resistance of the voltage source shunts the junction resistance such that the effective $\beta_{ce} \leq 1$.

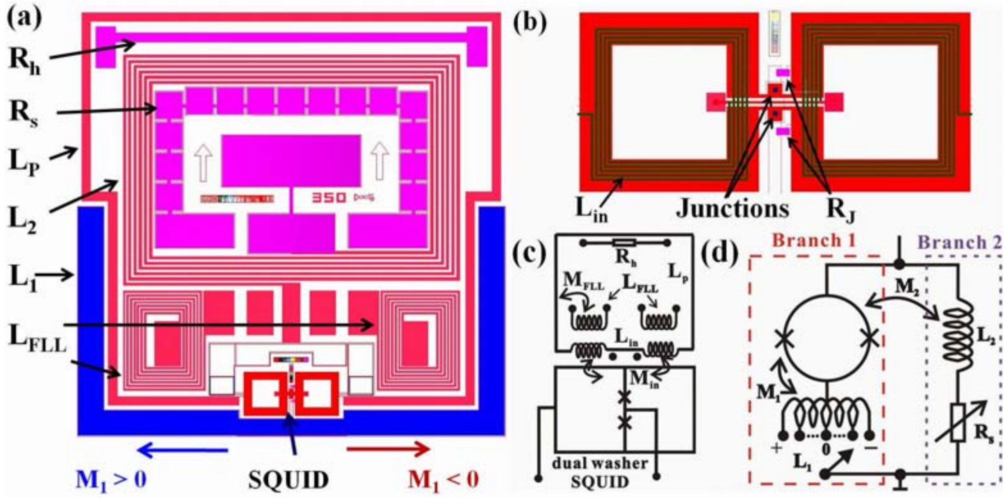

Figure 1. Layouts of (a) the SQUID chip with a size of 5 × 5 mm² and (b) the magnified dual-loop washer type SQUID with two opposite input coils with 4.5 turns each, also visible at the bottom of (a); (c) depicts the equivalent circuit of the SQUID magnetometer and (d) that of the bootstrap circuit [5].

The observation above led to a more systematic experimental investigation of the behavior of voltage-biased SQUIDs having nominal $\beta_c \geq 1$. The now published results demonstrate that the voltage-biased SQUID with $\beta_c \geq 1$, but $\beta_{ce} < 1$, can have sufficiently high dynamic resistance, which improves matching sufficiently to largely suppres preamplifier's noise and no feedback circuit may be needed at all [6]. This would represent a dramatic simplification of the readout scheme.

In the published work [6] the SQUID parameter spreads were quite wide. The SBC could be employed as supplemental circuitry alleviating the need for tight manufacturing control. In any event, manufacturers of multichannel SQUID systems have now an additional strong incentive to attain such tight control as it would lead to the ultimately possible simplification of the readout scheme.

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