Microstrip superconducting quantum interference device radio-frequency amplifier: Effects of negative feedback on input impedance

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We present the results of measurements of the scattering parameters of microstrip amplifiers (MSAs) based on the dc superconducting quantum interference device. The amplifier input impedance is poorly matched to typical transmission line impedances, resulting in high input return loss around −2 dB. We show that negative feedback can lower the MSA input impedance to achieve a robust match to 50 Ω. In the presence of capacitive and inductive feedback, the input return loss of the MSA can be reduced below −10 dB, opening the door to the practical use of the MSA for a variety of demanding applications. © 2009 American Institute of Physics. [DOI: 10.1063/1.3114419]

The dc superconducting quantum interference device (dc SQUID) has been used as an ultralow noise amplifier at frequencies of up to several gigahertz.1–6 In the most common mode of SQUID operation, the input signal is applied across the two ends of a superconducting coil that is separated from the SQUID washer by a thin insulating layer and tightly coupled to the SQUID loop.7 At signal frequencies above several tens of megahertz, however, the parasitic capacitance between the input coil and the SQUID washer results in a drastic decrease in the useful gain of the device. This problem can be circumvented by coupling the input signal between one end of the coil and the washer of the SQUID.4 The input circuit now acts like a microstrip resonator: when the input coil is driven at a frequency close to the λ/2 standing-wave resonance of the microstrip, there is a current enhancement in the input circuit by a factor of Q (the microstrip quality factor), leading to enhanced gain and reduced noise in the SQUID. We refer to a SQUID operated in this fashion as a microstrip SQUID amplifier (MSA).

The noise temperature of a MSA cooled to 20 mK in a dilution refrigerator has been measured to be 50 mK at a frequency of 540 MHz, in agreement with the simple model of the MSA.10 dB, opening the door to the practical use of the MSA for a variety of demanding applications. © 2009 American Institute of Physics.

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Finally, negative feedback improves amplifier nonlinearity, yielding a reduction in total harmonic distortion by a factor of $T$. For example, in order to reduce the input impedance of a MSA operating at 500 MHz from 500 to 100 $\Omega$, we require a loop gain of $T=4$. For a device with $Q=5$, $M=3.5$ nH, and $V_q=200 \mu V/\Phi_0$, we find that a feedback capacitance $C_{fb}=1$ pF reduces the input return loss from $-2$ to $-10$ dB with an acceptable decrease in gain of around 3.5 dB.

We have made measurements of the gain and input and output impedance of MSAs with and without capacitive feedback. The SQUIDs had inner and outer washer dimensions of 200 $\mu$m and 1 mm, respectively, an estimated SQUID inductance of $L_S=350$ pH, typical values for the SQUID critical current of $I_c=8-10$ $\mu$A, and resistance of $R=15-20$ $\Omega$. Measured values of $V_q$ are typically 200 $\mu$V/\Phi_0. The microstrip resonator had a width of 5 $\mu$m and a length of 12 mm, forming a nine-turn coil on top of the SQUID washer. The SQUIDs incorporated Nb–AlO$_x$–Nb tunnel junctions and Pd resistors and were fabricated using conventional sputter deposition and photolithographic techniques.

The performance of several amplifiers was measured at 4.2 K using current and flux biases $I_I$ and $I_0$ set to achieve maximum gain; Fig. 1 shows the measurement configuration. A cold 30 dB attenuator prevented noise from the room temperature signal generator from saturating the SQUID and presented a 50 $\Omega$ impedance to both the input coaxial line and the microstrip. For the same reasons, a cold 2 dB attenuator coupled the SQUID output to a low-noise amplifier at room temperature via a coaxial line. The gain of the entire system excluding the SQUID was calibrated by connecting together the input and output attenuators, and the SQUID gain measurements were referred to the baseline so obtained. In all measurements, the washer of the SQUID was grounded and the counterelectrode was at the potential of the output signal. The input and output return losses were measured with a cold directional coupler mounted close to the SQUID. A coaxial relay switched the output of the SQUID or the directional coupler to the spectrum analyzer. This was to avoid having to manually change connectors on the probe, which could have changed the bias flux in the SQUID due to vibrations of the probe. Figure 2 shows a typical measurement of the forward gain $|S_{21}|^2$, input return loss $|S_{11}|^2$, and output return loss $|S_{22}|^2$ of a MSA operated without (nfb) and with (fb) a 1 pF feedback capacitance. The feedback capacitance was provided by a surface mount ceramic capacitor placed on the same printed circuit board as the SQUID, in close proximity to the SQUID chip.

At higher frequencies in the range of 1–2 GHz, the inductance of the leads used to ground the SQUID washer causes the SQUID washer to develop a nonzero rf potential due to the finite output current. In this case, coupling from the SQUID washer to the microstrip input circuit provides sufficient feedback to reduce the MSA input impedance below 100 $\Omega$ even in the absence of an explicit capacitance from output to input. In Fig. 3 we show $|S_{21}|^2$ and $|S_{11}|^2$.
versus frequency for a MSA with a resonant frequency of 1500 MHz and an estimated inductance between the washer and ground of 2 nH. This MSA had a smaller washer size of 10 × 200 μm², a shunt resistance of R = 10 Ω, and a 13-turn microstrip resonator. While one would naively expect an input impedance of the order of \( n^2R \approx 1700 \) Ω, the low input reflection indicates that \( Z_i \) is of the order of 100 Ω due to the inductive feedback.

In conclusion, we have shown that the input match of a MSA to a 50 Ω source can be improved by applying negative feedback either in the form of a capacitor connected between the input and output of the MSA or via a small inductor between the SQUID washer and ground. This negative feedback will reduce the available gain of the MSA by about 3–4 dB and will decrease the output impedance by a factor of about 1.5, which are both tolerable. The realization of MSAs that are well matched to transmission line impedances opens the door to the robust cascading of multiple MSA stages and to use of the MSA in a variety of demanding practical applications.

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