SQUID Radio Frequency Amplifiers

The SQUID is the most sensitive detector of magnetic flux available. SQUIDs have long been used for a wide-range of low-frequency applications, including gravity wave detection, susceptometry, biomagnetism, nondestructive evaluation, and magnetic resonance imaging. There has been recent interest in the development of low-noise radio frequency and microwave amplifiers for particle detection, the readout of infrared sensors, or measurement of superconducting quantum bits. For these applications the SQUID has emerged as a leading candidate, as due to its extremely low power dissipation and unsurpassed noise properties.

In a typical SQUID amplifier, the input signal is converted to a current, which is injected into a thin-film input coil that is tightly coupled to the SQUID washer. The input current induces a flux in the SQUID, which in turn generates an output voltage V_o, which is a function of the applied flux (see Fig.1a). As the flux threading the SQUID loop changes, the voltage across the current-biased SQUID changes with periodicity Φ_0 (Fig. 1b).

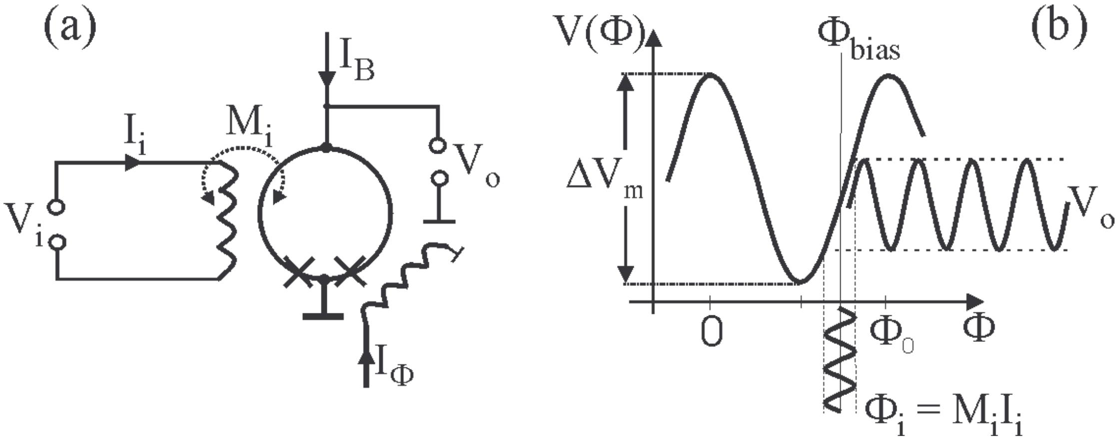


Fig. 1. (a). Configuration of dc SQUID amplifier. (b) Voltage vs flux for a current-biased dc SQUID showing conversion of an input flux Φi to an output voltage *Vo*.

To maximize the output voltage V_o, a static flux of $(2n-1)\Phi_0/4$ must be added to the ac input signal so as to bias the device at the steepest point of the $V(\Phi)$ curve. This is usually accomplished by passing a dc current I_Φ through a small wire-wound coil tightly coupled to the SQUID and adjusting this dc current for maximum gain.

The Microstrip SQUID Amplifier

To obtain maximum gain in a SQUID amplifier, the coupling between the input coil and the SQUID should be ~1. This can be achieved by integrating the input coil directly on top of the SQUID in thin-film technology. However, as an integrated input coil in a washer-type SQUID is separated from the SQUID washer only by a thin insulating film, coil and washer thus form a capacitor in parallel to the input coil inductance. Because of this parasitic capacitance, the input circuit is purely inductive only at frequencies below the self-resonant frequency of the tuned circuit formed by the coil and the parasitic capacitance. Above this resonant frequency, the gain drops quickly.

The deleterious effect of the parasitic capacitance of the input circuit can be addressed by operating the input coil of the SQUID as a transmission line resonator in the so-called microstrip SQUID amplifier (MSA). In this approach, one makes a virtue of the capacitance between the coil and the washer by using it to form a resonant microstrip, see Fig. 2 (b).

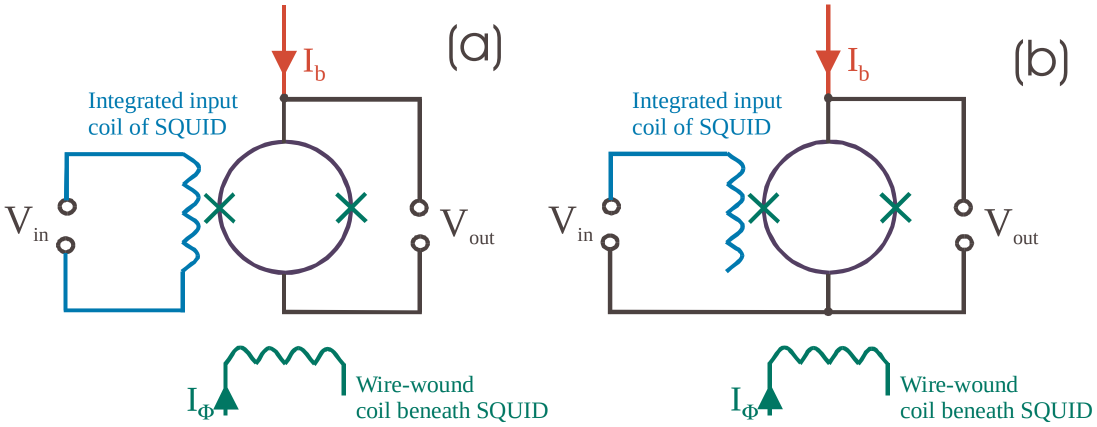


Fig.2 (a) Conventional SQUID amplifier; the input signal is coupled to both ends of the input coil. (b) Microstrip SQUID amplifier; the input signal is coupled to one end of the coil and the SQUID washer; the other end of the coil is left open.

The signal to be amplified is applied between one end of the coil and the washer, while the other end of the coil is left open (Fig. 2 (b)). Provided that the source impedance is greater than the characteristic impedance of the microstrip, there is a peak in the gain when the input coil accommodates approximately (but not exactly) one half wavelength of the input signal. Gains of well over 20 dB and noise temperatures well below the bath temperature can be achieved. We note that the actual behavior of the device differs markedly from that of a simple microstrip with a continuous ground plane because the inductance coupled into the input coil from the SQUID is generally substantially greater than the intrinsic microstrip inductance.

Operation of a microstrip SQUID amplifier

The SQUID amplifier requires two adjustable dc bias currents. One is passed in the SQUID to bias the it just above its critical current (SQUID bias, ~ 10 - 20 μA), the other one (flux bias) is produced by a coil close to the SQUID to flux bias the SQUID at a steep point on its V-Φ curve.

To adjust the bias currents for highest gain, one applies a signal to the SQUID amplifier (say, -100 dbm) and observes the output of the SQUID on a spectrum analyzer. Even if the SQUID does not amplify, there will be a small amount of rf passing through the SQUID. If possible, increase the rf level so that rf can be seen at the output of the SQUID. The SQUID bias current is now slowly increased. As the bias current exceeds the critical current of the SQUID (~ 10 - 20 μA, depending on the SQUID), the output signal of the amplifier increases (or at least changes). If the input power to the amplifier is above, say, -100 dBm, decrease it to a level at which the signal can still be observed, but is substantially lower than -100 dBm. Then adjust the flux bias for maximum gain. Due to internal feedback, the gain at a bias flux of $\Phi_0/4$ will be different from that at a bias flux of $3\Phi_0/4$.

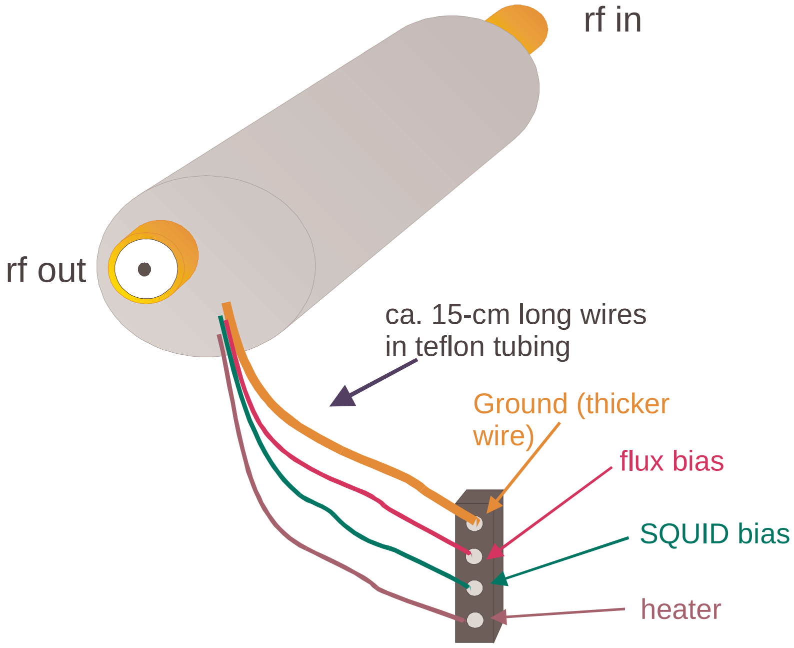
Note that the input signal to the SQUID amplifier must always be below -100 dBm or so, as, otherwise, the amplifier might saturate. In this case, the gain will drop and the noise temperature will increase.

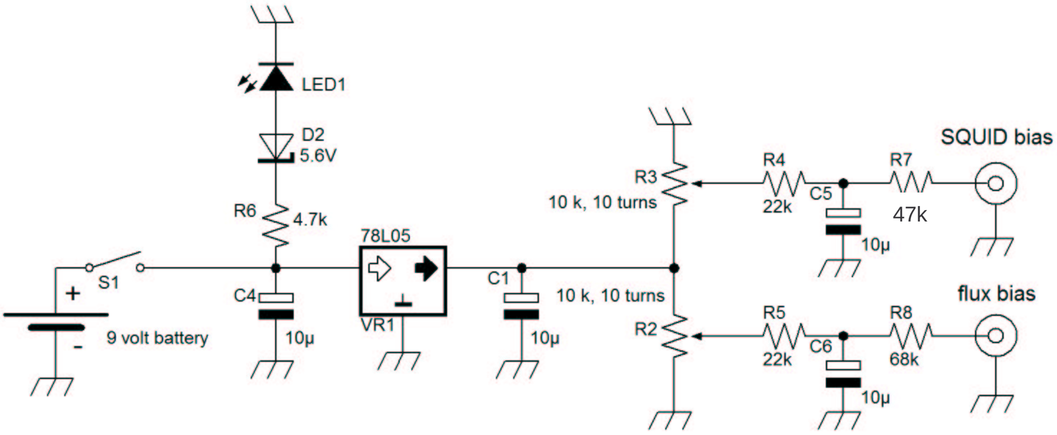
There is only one optimum setting for the SQUID current bias. The optimum flux bias setting is periodic in Φ_0. As external magnetic fields will also change the flux bias of the SQUID, the gain might drift or be modulated with changing external fields. If an ac-magnetic interference were present, the gain of the amplifier would be modulated by the interference. The amplifier is packaged in a stainless-steel tube. Thus, a superconducting magnetic shield must be used. The simple shield supplied consists of a lead-foil cylinder with an outer layer of (ferromagnetic) Conetic AA foil.

The bias currents to the SQUID and the wire-wound coil producing the static flux bias are applied through enameled copper wires inside a teflon sleeve, which are connected to a four-pin connector (2.54-mm pin separation, as used, e.g. in sockets for integrated circuits). Another wire (thick yellowish) is used for ground connection (not really required as the ground is also connected to the stainless-steel tube of the amplifier and the SMAs). A fourth wire is connected to a 1-kΩ resistor to ground, which can be used as a heater. The thicker wire with the yellowish enamel is ground. The wire with the green enamel is the bias current for the SQUID, the red wire is the current to the coil producing the static field. The purple wire is connected to the heater. The SQUID is very sensitive to electrostatic discharge. DO NOT touch the metallic parts of the connector ! Never solder to the connector !

There is a dc block between the SQUID output and the output SMA connector. The SMA input connector is directly coupled to the microstrip resonator on the SQUID, which is electrically insulated from the SQUID by a 400 nm-thick SiO film. Thus, there will be no dc current flowing in the input and output of the amplifier. However, especially at the input, any dc potential should be very small (~ mV) to prevent damage to the microstrip resonator. Also, the SQUID could be damaged by static discharge if the inner pin of the SMA connectors were touched.

There is a slight possibility that the Josephson junctions of the SQUID trap flux during cool down. As the critical current of the SQUID is reduced then, the gain might be relatively small or even zero. In this case the amplifier should be warmed up to above 9 K to remove the trapped flux. This can be done by passing a current in the 1-kΩ resistor used as a heater. This will only work if the amplifier is in a vacuum. If the amplifier is immersed in liquid helium, simply raise the amplifier to above the helium level to shortly warm it to T > 9 K. It should not be necessary to use the heater if there are no large fields present during cool down, and so the purple wire for the heater can be left unconnected.





Suggestion for a SQUID-amplifier power supply.