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FEMTOVOLTmeter AND VOLTAGE TUNABLE HETERODYNE RECEIVER BASED ON THE dc RESISTIVE SQUID

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Résumé.- Un voltmètre de sensibilité, $\delta V_{\text{rms}} = 1 \times 10^{-15} \text{ V}/(\text{Hz})^{1/2}$, (soit, $1 \text{ fV}/(\text{Hz})^{1/2}$), et un récepteur heterodyne pour l'infrarouge lointain, avec la fréquence réglable par tension, et une résolution de fréquence intrinsèque de 0,5 Hz à une fréquence de signal de $0,7 \times 10^{12} \text{ Hz}$ (0,7 THz), avec une efficacité de 0,2 en puissance pour la deuxième conversion, a été construit sur la base d'un "dc resistive SQUID".

Abstract.- A voltmeter with femtovolt sensitivity, $\delta V_{\text{rms}} = 1 \times 10^{-15} \text{ V}/(\text{Hz})^{1/2}$, (i.e., $1 \text{ fV}/(\text{Hz})^{1/2}$), and a voltage tunable far infrared heterodyne receiver, with intrinsic frequency resolution of 0.5 Hz at signal frequency $0.7 \times 10^{12} \text{ Hz}$ (0.7 THz) and a second power conversion efficiency of 0.2, were constructed on the basis of a dc resistive SQUID.

The dc resistive SQUID (dc R-SQUID) can act as a sensitive voltage amplifier [1,2] through direct voltage to frequency conversion, as a null detector for a negative feedback voltage amplifier, and also as a mixing element in a voltage tunable heterodyne receiver. The key difference between the usual dc SQUID and the dc R-SQUID is the normal section of figure 1a, the resistance of figure 1b included in the superconducting loop containing two Josephson junctions. The voltage sensitivity of the amplifier, as well as the frequency resolution and the tuning range of the mixer are directly proportional to R . These parameters can be varied by choosing R .

As a femtovoltmeter or sensitive voltage amplifier, the voltage to frequency converter (VF) mode is particularly suited for measurement of small voltage differences V directly across a sample. Due to its smaller total size, the VF mode is less subject to spurious voltages produced by thermal gradients, than the negative feedback amplifier. The VF mode is absolute in that a frequency is measured; no low temperature reference resistor is required. The negative feedback mode, similar to that for an rf SQUID [3,4], is useful to raise the input impedance of the amplifier, and to produce a voltage output directly proportional to the input voltage V .

The dc R-SQUID operates like a totally superconducting dc SQUID [5], except that the relative junction phase $\phi = \phi_2 - \phi_1$ now contains a contribution $2\pi f(V/\Phi_0) dt$ from the voltage across R , as

well as the magnetic flux contribution $2\pi\Phi/\Phi_0$, where $\Phi_0 = h/2e$ is the quantum of magnetic flux. The interferometer critical current remains periodic in ϕ with period 2π . At constant magnetic flux, when V is nonzero, the critical current $I_c(\phi)$ oscillates at frequency $f_V = V/\Phi_0$. For constant bias current I_b , the resulting bias voltage oscillation ΔV_2 can be observed as shown in figure 1c. Johnson-Nyquist voltage fluctuations in R broaden the line at f_V to about $\delta f_V = \delta V_{\text{rms}}/\Phi_0 \sim (2k_B T/\pi L)^{1/2} R/\Phi_0$, limiting the voltage sensitivity to $\delta V_{\text{rms}}/(\text{Hz})^{1/2}$, where T is the temperature of R , and L the inductance of the loop containing the junctions.

The present experiments [6] used point contact junctions in the geometry of figure 1a, with a $30 \mu\text{m}$ thick copper foil resistor R , with PbSn solder electrodes melted on opposite sides over a 0.5 cm^2 area. The resistance $R = 3.3 \times 10^{-9} \Omega$ was measured to be linear via the voltage to frequency relation $f_V = RI/\Phi_0 + \text{const}$, for measured injected currents I . Voltage resolution $\delta V_{\text{rms}} = 1 \times 10^{-15} \text{ V}/(\text{Hz})^{1/2}$ was determined from the measured linewidth $\delta f_V = 0.5 \text{ Hz}$.

Applications of a voltage tunable far infrared heterodyne receiver include astronomical observations of interstellar molecular line emission, laboratory spectroscopy, and plasma diagnostics such as Thomson scattering for measurement of ion temperature, and rapid frequency scan of electron cyclotron emission to observe the time evolution of the electron temperature spatial distribution in the plasma.

As a mixer /2/, the dc R-SQUID is particularly useful in the far infrared where laser lines f_L suitable as a local oscillator may not lie near the desired signal frequency f_S . Here, the internal oscillation of the dc R-SQUID can span the gap between f_L and f_S to arrive at a convenient intermediate frequency $f_I = f_S - f_L - f_V$, or to scan the spectrum of the signal by varying the current I injected into R . The intrinsic frequency resolution, determined by δf_V is proportional to R . Linewidths can be much narrower than in the single junction self-oscillating mixer /7/. Typical values of R range from $10^{-9} \Omega$ to $10^{-3} \Omega$ for frequency resolutions from 1 Hz to 10^6 Hz. The tuning range for convenient I is also proportional to R . Although typical values of R are small, the input impedance at the signal frequency depends on the junction normal shunt resistance R_N , which, for point contact junctions, can be tens to hundreds of ohms to facilitate signal coupling. The double junction structure can be designed as an antenna to couple to the signal.

Fig. 1 : The dc R-SQUID used as a femtovoltmeter and voltage tunable far infrared (FIR) heterodyne receiver was constructed with point contact geometry (a), described by the simplified equivalent circuit (b) in which the portion inside dashed lines was located at liquid helium temperature. The readout mode (c) assumes that the sample resistance R is several orders of magnitude smaller than the junction normal resistance R_N .

Mixing in a dc R-SQUID with an external local oscillator is best viewed as a two step process, $f_S \rightarrow f_D = f_S - f_L \rightarrow f_I = f_D - f_V$. The first step occurs in a manner similar to mixing in a single Josephson junction. The second step from f_D to f_I occurs with power conversion efficiency η_2 . The second conversion efficiency η_2 is the additional cost for the convenience of voltage tunability, a cost that in practice can be recovered through lower i.f. amplifier noise temperature by reducing f_I to the lowest frequency consistent with the required

signal bandwidth. Values of η_2 up to 0.2 were observed experimentally /8/. A formic acid laser line at $693 \mu\text{m}$ (0.7 THz) served as local oscillator, part of which was split off and Doppler shifted by amounts f_D ranging from 100 Hz to 50 kHz to serve as signal. The sum and difference components $f_+ = f_D - f_V$, and $f_- = f_I = f_D - f_V$ were observed with an audio frequency spectrum analyzer after preamplification, and found to be of equal intensity. Intrinsic frequency resolution, determined by $\delta f_V = 0.5$ Hz, was 1 part in 10^{12} .

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