A Precise Low Temperature dc Ratio Transformer

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A prototype low temperature dc ratio transformer is described. This transformer, which uses a new technique for the precise equalization of current ratios, provides dc ratios which have accuracies of the order of 0.01 ppm and may be calibrated to 0.002 ppm. The ratio transformer may be applied in low temperature current and resistance ratio measurements of high accuracy and may, without modification, be used as a sensitive current detector.

INTRODUCTION

The advent of techniques utilizing the Josephson effects[1] has introduced a number of promising new applications in the field of precise measurement.[2] The practical application of the ac Josephson effect to the maintenance of standards of emf has been demonstrated in a number of laboratories.[3–8] Translation of existing room temperature techniques to the low temperature environment has begun and a number of devices which exploit the unique properties of the superconducting state have been developed.

The precision of the ac Josephson effect monitoring of emf standards is currently in the region of 0.1 ppm and is limited, at the mV levels available from Josephson junctions, by variation of thermal emf's in the leads from the cryostat to the measuring apparatus at room temperature. Thermal agitation noise in the room temperature components of the measurement apparatus is the ultimate limit which is now being approached. In the quest for greater precision, it is clearly of benefit to devise means whereby the complete experiment is carried out at the low temperatures required for the operation of the Josephson junctions.

Apart from the low thermal agitation noise generated by resistive components, a superfluid helium bath offers a nearly ideal heat transfer medium for the operation of resistors. Sensitive current detectors have been developed based on superconducting quantum interference devices (SQUIDs) developed by Zimmerman.[9,10] Such a detector may have a sensitivity sufficient to observe the thermal agitation noise of resistors in the low temperature environment.

A low temperature potential divider based on the series–parallel interchange of resistors has been developed by Sullivan[11] and has been combined with a SQUID detector to produce a fully low temperature apparatus for the monitoring of emf standards.

The magnetic shielding properties of superconductors also make possible other unique applications.

The prototype dc ratio transformer described in this paper may be utilized in a fully low temperature experiment and permits the attainment of accurate potential ratios with far fewer resistors and switches than are required using a series–parallel ratio. Without modification, the low temperature dc ratio transformer may be used as a detector with sensitivity limited by the thermal agitation noise in resistive components of the cold divider.

dc RATIO TRANSFORMER

The low temperature dc ratio transformer has a similarity to the dc ratio transformer developed by MacMartin and Kusters[12] in that the magnetic flux in a high permeability magnetic core is sensed in order to determine the ampere turn balance condition. In the low temperature ratio transformer, this flux is maintained near zero by a closely coupled superconducting secondary winding, the current in which is sensed by a SQUID.

The equality of the ratio windings wound on the magnetic core is ensured by winding them with a multistrand cable having a superconducting sheath. It may be shown that a current flow in any one of the inner wires of the composite cable results in an identical counter current on the inside surface of the superconducting sheath. This current returns via the outer surface of the sheath in the direction of the original current.

The ratio windings comprise 11 Formvar insulated niobium–zirconium wires of 0.127 mm diam enclosed in a superconducting sheath of indium with a wall thickness of 0.127 mm. This sheath runs the length of the windings and may itself be used as a ratio winding. The requirement that the wires be superconducting relates to the use of the ratio transformer for the calibration of resistance ratio as described in a later section.

The composite cable is in the form of a tape with the 11 wires adjacent. An indium tape runs the length of the wires and is folded over and pressure-welded. A Teflon tape surrounds the indium to provide insulation. The cable was wound on a toroidal high permeability core to form a 50-turn winding. The permeability of this core was found to diminish by a factor of 6 between 290 and 2 K.

The core, with shielded ratio windings, was contained in a lead-lined superconducting shield as shown in Fig. 1. This shield also serves as a superconducting single turn secondary winding which is completed by the center post. In the center post is contained a single-hole SQUID the detail of which may be seen in Fig. 1. This SQUID senses the circumferential magnetic flux resulting from current flow in the center section of the superconducting secondary.

The shielded output leads of the ratio windings pass through a superconducting lead-lined tube which attenuates external magnetic disturbances and reduces spurious coupling of the external unshielded leads of the ratio windings to the superconducting secondary and SQUID detector.

The use of a high permeability core minimizes the effect of such spurious coupling and also provides a ratio to the single-turn superconducting winding which departs from that of the turns ratio by an amount dependent on the leakage inductance. Magnetic coupling between the ratio windings and the superconducting secondary may be made without the use of a magnetic core with correspondingly more stringent demands on shielding.

A superconducting toroidal lead shield surrounds the core. This shield has a circumferential gap around its inner surface to permit excitation of the core by the ratio windings. A further cylindrical lead shield not shown in Fig. 1 closely surrounds the SQUID. This shield is insulated on its inner surface.

Environmental magnetic disturbances are minimized by a shield external to the cryostat and all sources of entry of external flux through lead and vent holes in the ratio transformer are minimized.

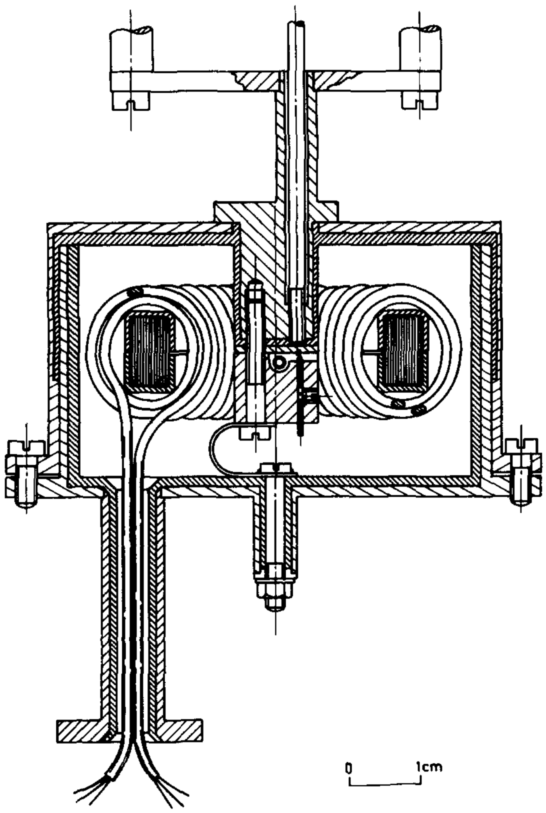

FIG. 1. Diagram of low temperature dc ratio transformer.

SQUID

The SQUID, Fig. 1, comprises a niobium block with a removable niobium point contact. An upper disk of niobium completes the superconducting loop of the SQUID. Deformation of this disk by a fine screw permits adjustment of contact pressure. This SQUID is easily adjusted and holds its adjustment despite severe mechanical disturbance. Modification to use a preadjusted SQUID is an obvious future improvement.

The SQUID loop has an approximate area of 0.06 cm^2 and is operated so that it senses the circumferential magnetic field resulting from current flow through its body. Sensitivity available is 9 μA per flux quantum (one flux quantum is 2.07×10^{-15} Wb) and may be enhanced using a superconducting multiturn coil in the second port of a preadjusted SQUID.[9]

Current sensitivity of a single 50-turn ratio winding is 0.18 μA for one flux quantum.

The electronics associated with the SQUID is shown in Fig. 2.

Magnetic flux within the SQUID loop is sensed using rf techniques in which a 60 MHz oscillator provides a low level scan of field in the SQUID using an inductively coupled coil. The coil, resonated at 60 MHz, is coupled by means of a half-wave coaxial transformer to a low noise preamplifier external to the cryostat. rf output from the preamplifier is further amplified in a 60 MHz amplifier and is then detected.

A low frequency square wave current modulation is also applied to the SQUID coil producing a modulation of half a flux quantum peak to peak in the SQUID loop. Variation of rf detector output at the modulation frequency is detected using a phase sensitive detector. A typical output is shown in the recorder trace of Fig. 3, in which a linear

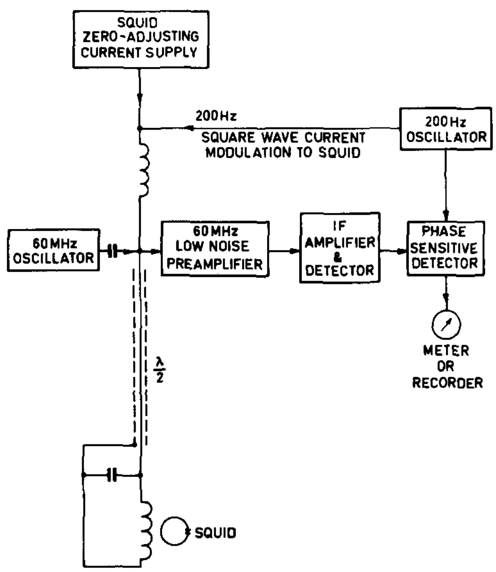

FIG. 2. Block diagram of SQUID electronics.

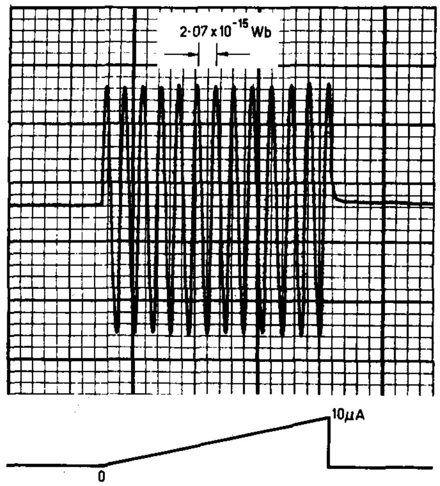

FIG. 3. Recording of the periodic SQUID response to a linear current scan.

current scan having an amplitude of 10 μA was applied to the SQUID coil.

An adjustable direct current is also fed to the SQUID coil to provide a means of zero adjustment. This zero adjustment has a range of several flux quanta.

Limiting sensitivity of the SQUID in its present arrangement has been found to be approximately 5×10^{-4} of a flux quantum for 1 sec averaging time. This is equivalent to a current sensitivity of approximately 10^{-10} A for a single 50-turn ratio winding or an ampere turn sensitivity of approximately 5 nA turn.

The sensitivity of the low temperature dc ratio transformer is shown in the record of Fig. 5, in which the indicated current change represents a 50 nA turn excitation of the transformer. This sensitivity is of the order of 200 times the sensitivity achieved in dc ratio transformers of the Kusters type.

The low temperature ratio transformer has been tested at temperatures below 2.2 K by pumping the helium bath. Pressure changes affect the magnetic core and result in a variation of SQUID zero. This effect is thought to be a consequence of trapped remanent magnetization of the core. Good stability has been achieved without the need of pressure control, once the system has reached equilibrium.

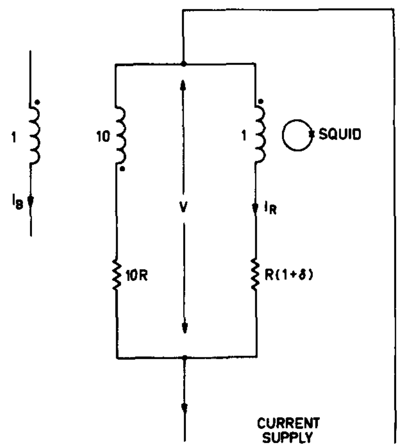

FIG. 4. Ratio calibration of low temperature resistors.

CALIBRATION OF dc RATIO

The dc ratio transformer, comprising 11 windings within the superconducting sheath, was calibrated by measuring each winding in turn against a single reference winding. A final 10:1 current ratio is obtained by series connection of 10 individual ratio windings.

In the comparison of two ratio windings, an external current generator supplied direct current to the two windings in series opposition. The ampere turns unbalance was determined by observation of a chart record of the SQUID output, the sensitivity of which was previously measured by the injection of a small known current to a single winding. The current supply used in these measurements was reversible. By the use of an RC filter, buildup of current in the transformer windings was slowed. This eliminated a spurious effect observed as a small shift in the SQUID zero.

A maximum current of ± 50 mA was used for ratio calibration. With the present SQUID sensitivity and transformer turns, the measurement of ratio was limited to approximately 0.002 ppm at this current.

A calibration of the low temperature dc ratio transformer showed that the ratio of seven individual windings and the sheath to the reference winding differed by less than 0.01 ppm. The largest deviation of the remaining three was 0.025 ppm. Departures from unity ratio are considered to be due to magnetic coupling of external leads to the interior of the shield.

CALIBRATION OF RESISTORS

The application of the low temperature dc ratio transformer to the measurement of resistance ratio is shown in Fig. 4. The windings, arranged in this case for a 10:1 ratio, are connected with the polarity shown. The resistors used are two-terminal with superconducting terminations and all connections are superconducting. Windings of the ratio transformer, as previously described, are superconducting. Application of a potential V as shown results in the same potential being applied to both resistors.

For small deviation of the resistors from the nominal ratio, the SQUID may be calibrated directly in terms of error if the ampere turn unbalance is sufficiently small that nonlinearity due to the periodic nature of the SQUID response results in negligible error. In the case of larger errors a subsidiary balance winding may be used. The current through this winding required to achieve balance is measured and related to the current through a single resistor.

In Fig. 4 consider resistance $R(1+\delta)$ in which a current I_R flows. The fractional deviation δ from the nominal value R results in an ampere turn unbalance of the transformer which, by adjusting I_B, may be returned to balance. The fractional deviation is then given by

$$\delta = I_B/I_R.$$

A fundamental limitation to the accuracy of such a measurement is set by thermal agitation noise in the low temperature resistors being measured. Noise from this source will be of consequence for low value resistances where the total resistance is less than 1 Ω. The dominant noise contribution for resistance ratio measurement where the total resistance is greater than 1 Ω arises in the ratio device. For a standardizing current of 50 mA, this source of noise results in a limit to the accuracy of ratio measurement of 2 parts in 10^9.

A load coefficient determination pertinent to the use of the resistors in a potential divider may be made by making measurements at different current values.

An initial ratio measurement of two low temperature resistors having nominal values of 10 and 100 Ω has been made. These resistors were of Evanohm, bifilar wound, and enclosed in a superconducting shield.

APPLICATION OF THE RATIO TRANSFORMER AS A DETECTOR

Apart from the use of the ratio transformer in the detection of ampere turn unbalance in current and resistance ratio measurements, it may be simply applied as a sensitive current detector. A recording of noise with a detector time constant of 1 sec together with a current change of 1 nA in a single winding is shown in Fig. 5. A sensitivity of approximately 10 pA would be obtained by extrapolation to the use of all windings in series.

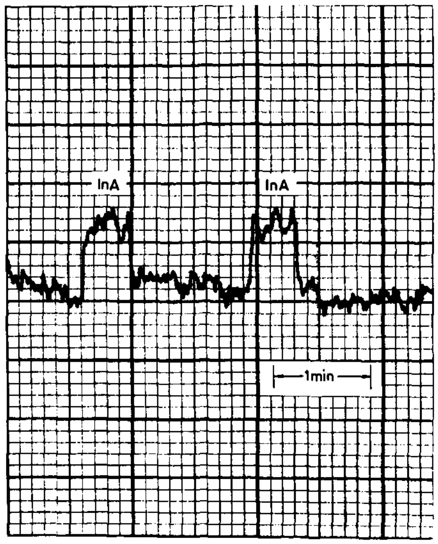

FIG. 5. Recording of noise from the low temperature dc ratio transformer.

ACKNOWLEDGMENT

The low temperature resistors used for the resistance ratio measurement were made by H. Collins.

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