SUPERCONDUCTING MAGNETOMETERS WITH SENSITIVITIES APPROACHING 10^{-10} GAUSS

By M. NISENOFF,

Ford Scientific Laboratory, Newport Beach, California (U.S.A.).

Abstract. — As will be described elsewhere in this conference by Mercereau, when a superconducting film ring of appropriate geometry is placed in a time varying magnetic field, there will be a quantized Faraday induction signal in the ring which will be periodic in the applied flux with a period $\varphi_0 = h/2e = 2.07 \times 10^{-7}$ gauss.cm². Experimentally the induced emf is detected by inductively coupling the ring to a tank circuit resonant at radio frequencies (1-30 MHz) which has a Q factor of 200 to 1,000. At a pump frequency of 30 MHz, for optimum coupling of the ring device to the tank circuit, the amplitude of the detected voltage across the tank circuit is of the order of 10 to 50 microvolts. The periodic behavior of this detected voltage with applied magnetic flux has been used to make a number of very sensitive and accurate magnetometers.

For the measurement of very small magnetic fluxes ($\Delta\varphi \lesssim \varphi_0$), the tank circuit containing the ring device is connected to a feedback or mulling circuit. A small amplitude modulation field at frequency ω_{mod} ($\omega_{\text{mod}} < \omega_{\text{pump}}/1/2 Q$) is applied to the device and the detected signal across the tank circuit at frequency ω_{mod} is amplified, phase detected and the output signal applied to a coil surrounding the device. In this manner, the device is maintained or "locked" to some specific value of magnetic flux and the current in the feedback coil is a measure of the change of the magnetic flux at the device subsequent to the closing of the feedback loop. This type of circuit is capable of maintaining the field at the device constant to $10^{-4} \varphi_0$ rms for a 1 s time constant, which for devices with diameters 2 1/2 mm corresponds to a minimum detectable field of 4×10^{-10} gauss rms. A discussion of the sources of noise that will ultimately limit the sensitivity of these devices will be given.

The measurement of large changes in magnetic flux ($\Delta\varphi > \varphi_0$) can be accomplished by making use of the periodic response of the devices to ambient fields. A small amplitude modulation field at frequency ω_{mod} is again applied to the device and the detected signals across the tank circuit to which the device is coupled at the fundamental frequency ω_{mod} and the harmonic frequency $2\omega_{\text{mod}}$ are detected and processed by suitable logic circuits to produce an output which indicates digitally the change in the magnetic flux in units of $\varphi_0/4$ as well as the *sign* of the field change. The maximum counting rate of such a circuit is limited by the maximum modulation frequency that can be used which must satisfy the $2\omega_{\text{mod}} \lesssim \frac{\omega_{\text{pump}}}{Q/2}$. For a 30 MHz and $Q = 300$ the maximum counting rate achieved was about 10^4 per s. For a 1 mm diameter device, this circuit can track magnetic field changes as fast as 0.06 gauss per s digitally in units of 6×10^{-6} gauss. Much higher counting rate should be achieved by increasing the pump frequency to microwave frequencies. For example, for 10^{10} Hz, and $Q = 1,000$, modulation frequencies as high as 10^7 Hz can be used and thus, counting rates approaching this value should be realized assuming an adequate signal to noise ratio for this bandwidth can be obtained.

Although these devices are intrinsically sensitive to *changes* in the ambient magnetic flux, it is possible to modify either of the above configurations to determine *absolute* flux. If the device can be rotated exactly 180° about an axis normal to the axis of the cylinder on which the film ring is deposited, the absolute value of the magnetic field is obtained by appropriate averaging of the output readings of the circuits for the 0 and 180° orientations of the device.

In this paper I would like to describe a number of magnetometers that have been built based on the principle of flux entry into superconducting cylinders as described by Professor Mercereau.

In order to observe this flux entry into the superconducting cylinder, it is necessary to "weaken" the superconductivity at one point along the circumference of the cylinder. This weakening can be accomplished either by physically reducing the width of the film or by creating a localized region of weak superconductivity by a material inhomogeneity. In figure 1 we show a diagram of a superconducting cylinder in which the weak link has been produced by reducing the dimension of the cylinder ("Dayem bridge") [1]. The

superconducting film rings are made by evaporating the material onto a quartz rod which is rotated during the deposition. To make the constriction, such as shown in figure 1, the undesired material can be removed either by mechanical scratching or by a chemical photo etch technique. Mechanical scratching produces constrictions with widths down to about 10 microns, while chemical photo etch techniques have produced bridges with widths of the order of 1 micron, or less. Ring devices with bridges of the order of 10 microns or wider do show the desired phenomena. However, the magnitude of the signal is dependent on the physical perfection of the deposited superconducting film. On the other hand, if the

DAYEM BRIDGE

FIG. 1. — Diagram of superconducting film cylinder containing a dimensional constriction ("Dayem Bridge").

bridge width is of the order of 1 micron, the functioning of the bridge appears to be relatively insensitive to the quality of the deposited film.

The "weak link" for these ring devices can also be obtained by a material inhomogeneity as illustrated in figure 2. It has been known for several years, that

NOTARYS BRIDGE

FIG. 2. — Diagram of superconducting film cylinder containing a material inhomogeneity ("Notarys Bridge").

the superconducting transition temperature of a superconductor in close proximity to a normal metal is lower than the transition of the superconductor itself [2]. H. A. Notarys [3] has shown that the proximity effect can be used to produce a "weak link" if a very narrow strip of a normal metal is deposited across a superconducting film in such a manner that the dimension of the metal-superconductor sandwich in the direction of current flow is of the order of 1 to 2 microns. At temperatures in the vicinity of the reduced transition temperature of the metal superconductor sandwich, this narrow region acts to weakly couple together the strongly superconducting regions on either side of the sandwich. (In practice, the normal metal is deposited first as most superconducting materials readily form oxides which inhibit the proxi-

mity effect.) Ring devices containing Notarys bridges are manufactured in the following manner: The bare quartz rods are initially dipped into a varnish, such as collodion, producing a thin — approximately 1 micron thick — coating. A scratch is then made in the collodion layer parallel to the rod axis using the corner of a sharp razor blade or a pointed tungsten wire. A normal metal, such as gold or copper, is deposited onto the rod. The collodion is dissolved away removing the metal deposited on the collodion while the metal deposited onto the rod through the scratch in the collodion will remain. If a very sharp point had been used to make the scratch, the width of the film adhering to the rod will be of the order of several microns or less. A superconducting cylindrical film is then deposited onto the rod covering the normal metal ribbon. A rather wide constriction is then scratched into the cylinder in the region of the metal superconductor sandwich in order to define the weak link. The advantages of the Notarys bridge is that they are more easily fabricated than the 1 micron wide photo etched bridges discussed above. In addition, since the transition temperature of the Notarys bridge depend on the relative thicknesses of the metal film and the superconducting film, the operating temperature of devices containing the Notarys bridge can be adjusted to any desired temperature below the transition temperature of the superconductor itself.

Device can also be made using Josephson-type oxide junction as the weak link. However, oxide junctions are very delicate — thicknesses of these barriers are typically 20 angströms — and their characteristics change rather drastically over periods of days or weeks and thus oxide junctions are not suitable for device applications.

When these superconducting ring devices are placed in a time varying magnetic field of amplitude ϕ_{RF} at frequency ω_{RF} , as flux enters or leaves the ring there will be an emf induced in the ring which will have a component at frequency ω_{RF} whose magnitude and sign will depend on both the amplitude of the RF flux, ϕ_{RF} and on the ambient low frequency magnetic field that the ring sees. In order to observe this induced emf, the device is coupled to a coil of a circuit resonant at frequency ω_{RF} . In figure 3, we schematically show

FIG. 3. — Diagram of superconducting cylinder with a dimensional constriction coupled to a resonant circuit.

this arrangement. As discussed by Prof. Mercereau, the voltage across the tank circuit will have the form :

$$V = \left[\omega \varphi_{\text{RF}} + A J_1 \left(\frac{2\pi}{\varphi_0} \varphi_{\text{RF}} \right) \sin \frac{2\pi}{\varphi_0} \varphi_{\text{DC}} \right] \sin \omega + \dots$$

where the first term in the bracket is the classical Faraday induction signal, $V = d/dt(\varphi)$ and the second term is the “quantized” Faraday induction signal discussed by Mercereau. The coefficient A in front of the second term is the coupling parameter between the film and the tank circuit. This voltage after

FIG. 4. — Detected output voltage across tank circuit containing ring device as function of applied magnetic flux for several values of RF pump amplitude.

amplification and detection is shown in figure 4. For several values of φ_{RF} there is no induced signal at frequency ω_{RF} , these values of φ_{RF} correspond to zeros of the Bessel function. For intermediate values of applied flux, there are induced signals at ω_{RF} whose magnitudes varies sinusoidally with the low frequency ambient flux. The periodicity of this voltage with flux, φ_0 , was determined to be equal to $h/2e = 2.07 \times 10^{-7}$ gauss.cm² to better than about 0.1 percent,

FIG. 5. — Diagram illustrating principle of operation of feedback type of magnetometer.

the uncertainty of the present experiments (using precision ground rods and compensated solenoids, the determination of the flux periodicity to an accuracy of 10 ppm or better should be possible). It is this periodic variation of the induced voltage with applied flux which is the basis for the magnetometers that will now be described.

To measure small changes in magnetic flux, $\Delta\varphi \lesssim \varphi_0$, a feedback type of circuit is employed [4]. The principle of operation of such a circuit is shown in figure 5. The upper trace represents the detected output voltage across the tank circuit containing the superconducting device as a function of ambient magnetic field. A small amplitude modulation field at frequency ω_{mod} is superimposed on the ambient field. If the ambient field, B_0 , corresponds to a minimum in the output voltage, the detected signal will have a component at frequency $2\omega_{\text{mod}}$. If the ambient field corresponds to value B_1 , then the output voltage decreases with increasing modulation field. On the other hand if the ambient field corresponds to B_2 , the detected signal at frequency ω_{mod} will increase with increasing modulation field. If the detected signal is then amplified by a synchronous detector tuned to frequency ω_{mod} , the output of the synchronous detector will be zero if the ambient field corresponds to B_0 , negative if the ambient field is B_1 and positive if the ambient field is B_2 . Thus, the output of the synchronous detector can be used to sense changes in the ambient magnetic field from reference value B_0 .

A schematic circuit diagram of a circuit built to measure small changes in ambient flux is shown in figure 6. In this circuit, the same coil is used to apply

FIG. 6.

Circuit block diagram of feedback type of magnetometer.

the RF excitation to the ring device and to detect the “quantized” Faraday induction signal. A constant RF current is applied to the coil by a RF oscillator and a high impedance series element. The voltage across the tank circuit is measured by an RF amplifier that has a high input resistance first stage. A small amplitude magnetic field is applied to the device by an auxiliary coil driven by an oscillator at frequency ω_{mod} . The output of the synchronous detector is then applied to the auxiliary coil surrounding the device with the appropriate sign so that if the ambient field at the device drifts from an external value, the correction signal compensates for this drift. Thus, the correction current is a measure of the change in the ambient field with respect to the field the device saw when the feedback circuit was closed. For this type of circuit, the minimum detectable flux is of the order of $10^{-4} \varphi_0$

for a 1 second time constant. For a device with a diameter of 5 mm, this corresponds to a minimum detectable field change of the order of 10^{-10} gauss. Thermal noise in the feedback circuit limits the sensitivity that can be achieved by this type of instrument.

The measurement of large changes in magnetic flux, $\Delta\phi > \phi_0$, is best accomplished using another type of circuit in which the quantum nature of the phenomena is used [5]. In this circuit the number of flux quanta that enter or leave the ring is counted. The principle is illustrated in figure 7. A small amplitude modulation field at frequency ω_{mod} is again

FIG. 7. — Diagram illustrating principle of operation of digital magnetometer using superconducting ring device as magnetic field sensor.

applied to the device and the components in the output signal at frequency ω_{mod} as well as at frequency $2\omega_{\text{mod}}$ are monitored. This is equivalent to measuring the first and second derivatives of the output signal with respect to ambient field. As can be seen by inspection of the two lower portions of figure 7, if the period of the output voltage is divided into four parts or “quadrants”, each quadrant has a unique combination of signs for components at frequency ω_{mod} and $2\omega_{\text{mod}}$. As the ambient magnetic field changes from one quadrant to a neighboring one, the sign of the signal from only one of the channels, either that at ω_{mod} or at $2\omega_{\text{mod}}$, will change. A schematic circuit diagram for this type of circuit is shown in figure 8 [6]. The detected output of the signal across the tank circuit is applied to two synchronous detectors, one tuned to frequency ω_{mod} and the other to frequency $2\omega_{\text{mod}}$. The output of the synchronous detector drive Schmidt trigger circuits (“flip-flop” circuits) which will be in either of two states, plus or minus, depending on the sign of the particular component of the output voltage. The pulses from the two Schmidt circuits are applied to a

FIG. 8.

Circuit block diagram of digital type of magnetometer.

logic circuit which produces a pulse each time the field changes from one quadrant to another one and the sign of this pulse indicates whether the field change corresponds to an increase or a decrease in the applied field.

This type of circuit, therefore, obviously will count changes in the ambient flux digitally in units of $\phi/4$. The maximum counting rate of the circuit is limited to approximately $1/2f_{\text{mod}}$. However, the maximum value of modulation frequency that can be used is limited by the bandwidth of the circuit which is determined by the response of the tank circuit containing the superconducting device. For a pump frequency of 30 MHz and a $Q = 300$, the effective bandwidth is of the order of 10^5 Hz, the maximum modulation frequency that can be used is 50 kHz, and, accordingly, the maximum counting rate should be in the vicinity of 2.5×10^4 Hz. Experimentally for a circuit which had the characteristic mentioned above, the maximum counting rate achieved was 10^4 s $^{-1}$. Much higher counting rates should be achieved by increasing the pump frequency microwave frequencies. For example, for a pump frequency of 10^{10} Hz, and a $Q = 1,000$, counting rates approaching 10^7 s $^{-1}$ should be realized assuming that an adequate signal to noise ratio for this bandwidth can be obtained.

The magnetometers described above are sensitive only to changes in the ambient field. In principal, these devices could measure absolute fields by measuring with respect to zero absolute magnetic field. However, zero magnetic field regions are not readily available in the laboratory. However, these magnetometers can be made to determine absolute magnetic fields by constructing the probe so that the tank circuit and the superconducting device can be rotated precisely 180°. By properly averaging the readings in the two directions, the absolute field along a particular direction can be ascertained. Using this version of the feedback magnetometer, a magnetic field in the range of 10^{-9} gauss or smaller can be measured absolutely.

REFERENCES

- [1] DAYEM (A. H.) and WIEGAND (J. J.), *Phys. Rev.*, 1967, **155**, 419.
- [2] DE GENNES (P. G.), *Rev. Mod. Phys.*, 1964, **36**, 225.
HANSEN (J. J.), THERUER (H. C.) and WERTHAMER (N. R.), *Phys. Rev.*, 1964, **136**, A 637.
- [3] NOTARYS (H. A.), Private Communication, to be published.
- [4] FORGACS (R. L.) and WARNICK (A.), *I.E.E.E. Transactions*, 1966, IM-15, 113.
- [5] FORGACS (R. L.) and WARNICK (A.), *Rev. Sci. Instr.*, 1967, **38**, 214.
- [6] KELM (E.), Private Communication.