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SQUID-based measuring systems

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Abstract. A program has been developed and initiated at the Indira Gandhi Centre for Atomic Research (IGCAR) for the utilization of SQUID sensors in various application areas. DC SQUID sensors based on Nb–AlO_x–Nb Josephson junctions have been designed and developed inhouse along with associated flux-locked loop (FLL) electronics. A compact low field SQUID magnetometer insertible in a liquid helium storage dewar has also been developed inhouse and is in use. Efforts to build a high field SQUID magnetometer, SQUID-DAC system, are in progress. A planar gradiometric DC SQUID sensor for non-destructive evaluation (NDE) application to be used in relatively unshielded environment has been designed and developed. An easily portable NDE cryostat with a small lift-off distance, to be used in external locations has been designed and tested. The magnetic field produced by a given two-dimensional current density distribution is inverted using the Fourier transform technique.

Keywords. SQUIDs; Josephson junctions; NDE.

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1. Introduction

Superconducting quantum interference devices (SQUIDs) are the most sensitive detectors for measurement of magnetic flux. A SQUID is essentially a magnetic flux to voltage transducer. SQUIDs are amazingly versatile, being able to measure any physical quantity that can be converted to flux. DC SQUIDs are structures involving two Josephson junctions connected by a low inductance superconducting loop. The basic phenomena governing the operation of the SQUID devices are flux quantization in a superconducting loop and the Josephson effect [1]. SQUID sensors have been used in various applications like SQUID magnetometer for physical property measurements of small samples, non-destructive evaluation (NDE) of sub-surface defects, bio-magnetic evaluation of human heart and brain, geomagnetic prospecting, detection of gravity waves etc. Judging the importance of SQUIDs as a versatile sensor for a wide spectrum of applications, a program for indigenous development of SQUID sensors was undertaken at the Indira Gandhi Centre for Atomic Research (IGCAR), Kalpakkam. As a part of this program a complete range of laboratory scale fabrication facilities have been set up for design, fabrication and characterization of DC SQUID sensors. Having completed the development of the basic SQUID sensor with its output linearized by an indigenously developed flux locked loop (FLL) electronics, efforts are currently on for the development of SQUID-based instruments and systems. Particularly low-field and high-field SQUID magnetometer, SQUID-NDE system and SQUID-DAC system for high pressure research are being developed. Magnetic field produced by a known two-dimensional current density distribution has been inverted to get the original current density distribution for use in SQUID-NDE of thin plates. Here we present an overview of our recent work on the development of the SQUID sensor and its utilization.

2. Fabrication of SQUID devices

To reduce the output noise it is necessary to have small area Josephson junctions (typically 3 μm × 3 μm) and low inductance SQUID loop (typically 200 pH). To couple the external flux picked up by the large inductance pickup coil efficiently into the low inductance SQUID loop, we have adopted the Ketchen–Jaycox slit washer design. The inner hole dimension of 100 μm is much smaller than the outer edge of the washer of 1 mm, providing a loop inductance of 160 pH. Two small-area Josephson junctions are placed symmetrically at the outer periphery of the slit washer. The input coil having up to 40 turns is overlaid as a spiral coil on the slit washer for tight coupling. We have fabricated good quality Josephson junctions from trilayers deposited by electron beam evaporation technique [2]. We have standardized the whole wafer sandwich process based on SNEP (selective niobium etching process) of Nb–AlO_x–Nb trilayers for fabrication of Josephson junctions and SQUIDs. This involves deposition of Nb–AlO_x–Nb trilayer by electron beam evaporation over the whole wafer without breaking vacuum and subsequent isolation of junctions by photolithography and reactive ion etching process. SiO_2 is used as insulation layer with anodic oxidation as additional insulation for the edges of the Josephson junctions. At the final stage, molybdenum is deposited and patterned to form the shunt resistors across the Josephson junctions in SQUIDs to make the SQUID I–V characteristic non-hysteretic.

3. Characterization of Josephson junctions and SQUIDs

Josephson junctions and SQUID devices are characterized by mounting them at the end of a dipstick, wrapped by several layers of μ metal and a superconducting shield surrounding the sample holder. The typical dc I–V characteristic of Josephson junction measured at 4.2 K indicates a clearly resolved gap structure at 2.8 mV with a quality parameter V_m attaining 60 mV in some of the junctions, which is comparable to the best values reported internationally. The critical current (I_c) dependence on the magnetic field, applied parallel to the plane of the barrier, reveals a near ideal Fraunhoffer pattern, implying good barrier uniformity. The output voltage of the SQUID fabricated incorporating these high-quality Josephson junctions and properly shunted, measured at 4.2 K indicates a modulation depth ranging between 10 μV and 50 μV suitable for using these SQUIDs for various applications.

4. Flux locked loop electronics

The output voltage of the DC SQUID is a periodic function of magnetic flux applied at the input with a periodicity of a flux quantum Φ_o (2.07×10^{-15} Wb). To linearize the output response of a SQUID for use in applications, a flux locked loop (FLL) electronics has been developed in our laboratory. A cooled resonant LC circuit is used as impedance matching device in order to effectively extract the signal from the SQUID. The FLL is based on the technique of 100 kHz flux modulation and phase sensitive detection [3]. Important characteristics of FLL circuit such as, linearity, gain, dynamic range, slew rate and spectral density of noise have been evaluated. The FLL shows a linearized output for a small signal at the input of SQUID with a gain of 75 mV/Φ_o. The flux noise observed in the white noise region for our SQUID is less than $26\mu\Phi_o/\sqrt{\mathrm{Hz}}$.

5. SQUID magnetometer

A low-field SQUID magnetometer based on DC SQUID sensors and its associated FLL has been designed and developed [4]. This is a top loading system insertible in a liquid helium storage dewar. The magnetometer consists of a double-walled vacuum isolated sample chamber for varying sample temperature, a solenoid to generate magnetic field, a superconducting axial gradiometric pickup loop, SQUID positioned in a low field region at 4.2 K shielded by a superconducting and several μ metal layers, and a non-inductively wound heater coil around the sample with a germanium thermometer for temperature measurement. The superconducting transition of a small sample of lead has been detected using the above apparatus. The high-field SQUID magnetometer being developed, houses a 6.5 T superconducting magnet made locally using multifilamentary NbTi wire. The magnetometer is housed in a cryostat with the sample transport assembly using a programmable stepper motor. The SQUID is placed in a low field region separately, shielded by a superconducting layer and several μ metal layers. A gradiometric superconducting coil is used as pickup loop. The measurement chamber containing the sample holder and the heater assembly along with the pickup loop is shielded by a superconducting shield to avoid fluctuations in the field. Various sub-units have been integrated and this system is now in the final stage of commissioning.

6. SQUID NDE

SQUID sensors are ideally suited for low frequency eddy current measurements for detection and quantitative measurements of location of deep lying flaws in metallic structures. This requires measurement of signals in unshielded environment, development of special cryostats and precision X-Y table with stepper motor for accurate positioning for the reconstruction of electrical current density from measured spatial variation of magnetic field. A planar gradiometric DC SQUID sensor for NDE has been designed and developed to be used in relatively unshielded environment and is shown in figure 1.

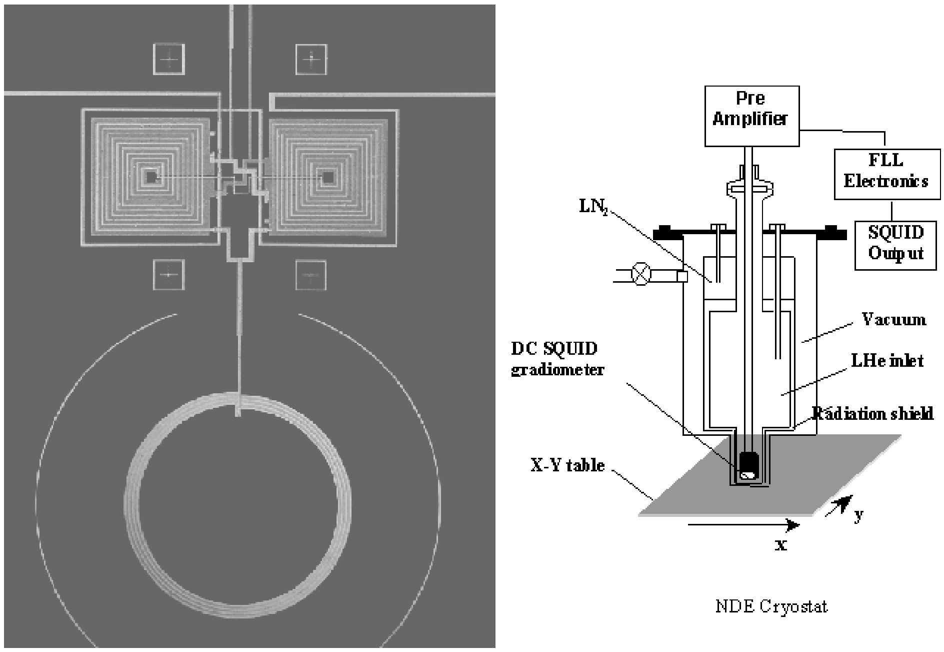

Figure 1. DC planar SQUID gradiometer with the NDE cryostat.

Externally coupled magnetic signals from a room temperature source have been measured using the planar DC SQUID gradiometer and quantified for a meander coil carrying current [5]. An easily portable NDE cryostat with a small lift off to be used in field measurements has been designed and tested (figure 1). The magnetic field produced by a given two-dimensional current density distribution is inverted using the Fourier transform technique [6] to obtain the original current density distribution. The inversion algorithm is modified to handle low level of noise, which is invariably present in real measurements. We start with a known two-dimensional current density distribution $J_x(x, y)$ and $J_y(x, y)$ in the form of a square loop of 1 mm × 1 mm with a Gaussian spread of 0.15 mm. The magnetic field due to this square current loop is then calculated using the forward problem at several grid points in the measurement plane. The measurement plane is located at a standoff distance of 1 mm vertically above the plane in which the current loop is located. To take a realistic approach, a small amount of Gaussian noise (1% of maximum of B_z) has been added to this magnetic field. The inverse problem is then solved using this magnetic field data including noise and an image current density $J_x^i(x, y)$ is extracted. In the above calculations, we have used a grid of 0.1 mm spacing with 101 points in x and y directions. To compare the image with the actual starting current distribution, a figure of merit is defined as the mean square deviation (MSD) between the original current density and its calculated image. The calculated image of the current distribution $J_x^i(x, y)$ is shown in figure 2 for the magnetic field data at 1 mm lift-off (z). The image current distribution $J_x^i(x, y)$ extracted for $K_{\max}$ of 11.25 mm^{-1} in a Hanning window has a MSD of 0.3676.

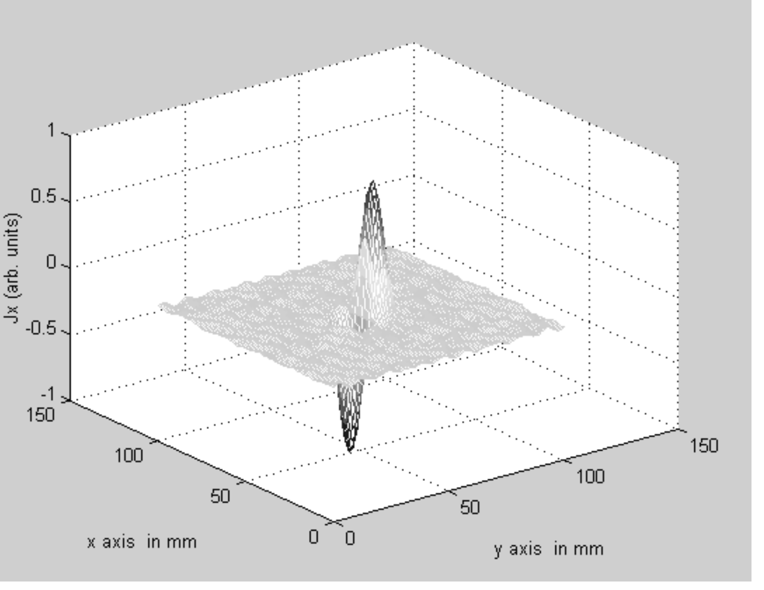

Figure 2. Inverted current density image $J_x^i(x, y)$.

7. Conclusion

After the successful development of the SQUID sensor, further efforts to utilize these sensors have been initiated. A low-field SQUID magnetometer has been designed and developed. A few other SQUID based instruments are under development. Efforts to build a stepper motor controlled X-Y table with a spatial resolution of 0.1 mm are in progress. SQUID based NDE program is thus on a strong pedestal for utilization in external locations.

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