This manuscript was published by Superconductor Science & Technology (SuST, IOP) 27, No. 4, 044032, (2014).

Near-field scanning SQUID microwave microscope

Vladimir V Talanov[1], Nesco Lettsome[1], Nicolas Gagliolo[1], Antonio Orozco[1], Alfred B Cawthorne[2], and Valery Borzenets[3]

[1]Neocera, LLC, Beltsville, MD 20705, USA
[2]Trevecca Nazarene University, Nashville, TN 37210, USA
[3]SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA

E-mail: talanov@neocera.com

Abstract. We developed a scanning SQUID microscope utilizing DC SQUID with novel readout electronics capable of sensing coherent magnetic fields from 50 to 200 MHz. To overcome the bandwidth limitation of traditional closed-loop SQUID magnetometers, we employ a flux-modulated closed loop to simultaneously lock the quasi-static magnetic flux and flux-bias the SQUID for amplification of RF flux. Demodulating the SQUID voltage with a double lock-in technique yields the signal proportional to the amplitude and phase of RF magnetic field. We describe the system performance and present images of a variety of samples.

1. Introduction

DC SQUIDs have been prominently employed as ultra-sensitive magnetic detectors in biology, medicine, magnetic property measurement systems, magnetic resonance imaging, and scanning SQUID microscopy (*e.g.*, see [1]). In resistive state the SQUID voltage is a non-linear function of magnetic flux, with a period equal the magnetic flux quantum Φ_0. To linearize the SQUID transfer function, practical SQUID magnetometers utilize an external closed loop (*e.g.*, see [2]). There, magnetic flux oscillating at kHz frequency is applied to the SQUID via modulation coil. The SQUID voltage is amplified, demodulated by a lock-in detector, inverted, integrated, and fed back into the modulation coil. If the SQUID quasi-static flux equals $n\Phi_0$, $n = 0,1,2,...$ the lock-in output is zero since the SQUID voltage contains no fundamental harmonic. If the flux is greater or less than $n\Phi_0$, the lock-in output is positive or negative, respectively, due to a fundamental harmonic present in the SQUID voltage. This produces a compensating flux equal and opposite to offset of the quasi-static flux from $n\Phi_0$, thereby “locking” the net SQUID flux at $n\Phi_0$.

Although DC SQUIDs possess GHz intrinsic bandwidth (*e.g.*, see [3]), the transmission line delay between the sensor and room temperature electronics fundamentally limits the closed-loop bandwidth by 20 MHz [2]. While substantial efforts had been spent increasing it up to 100 MHz [4], it was finally concluded that a wideband linearization of the closed-loop SQUIDs is not feasible [5]. Conversely, several scanning SQUID microscopes were designed for sensing microwave magnetic fields in the open-loop regime. R. Black, *et al.* made use of the SQUID nonlinearity to rectify fields up to 50 MHz [6]. They also designed a near-field scanning SQUID microwave microscope, which frequency can be set up to 200 GHz by the Josephson relation [7]. J. Matthews, *et al.* developed a SQUID microscope capable of measuring GHz fields via using hysteretic SQUID with the pulsed sampling technique [8]. The open-loop nature, however, makes these techniques unfeasible for practical applications due to limited linearity response and susceptibility to variations in the background (static) magnetic field.

This manuscript was published by Superconductor Science & Technology (SuST, IOP) 27, No. 4, 044032, (2014).

This paper presents a scanning SQUID microwave microscope capable of imaging coherent magnetic fields from 50 to 200 MHz while retaining the advantages of a closed-loop system.

2. Principle of SQUID operation

Consider an optimally biased DC SQUID with the net flux "locked" at $n\Phi_0$ by the flux-modulated closed loop utilizing modulation flux $\Phi_m \sin(\omega_m t)$. Application of RF magnetic flux with frequency $\omega_{RF} >> \omega_m$ makes the net SQUID flux $\Phi_{RF} \sin(\omega_{RF} t + \theta_{RF}) + \Phi_m \sin(\omega_m t) + n\Phi_0$. If $\Phi_m \sim \Phi_0 / 4$ and $\Phi_{RF} < \Phi_0 / 4$, the SQUID produces a binary-phase modulated voltage with the carrier and modulation frequencies of ω_{RF} and ω_m, respectively (see Fig. 1). Readout electronics, shown in Fig. 2, first demultiplexes the SQUID voltage with a bias-T, which DC output is fed back into the closed loop (shaded in gray). Bias-T's RF output is amplified, demodulated by RF lock-in amplifier, and fed into intermediate frequency (IF) lock-in amplifier referenced to the modulation frequency. The IF lock-in output depends on the amplitude and phase of RF magnetic flux

$$V_{IF} = G\Phi_{RF} \cos\theta_{RF} \tag{1}$$

where G is the magnetometer small-signal sensitivity.

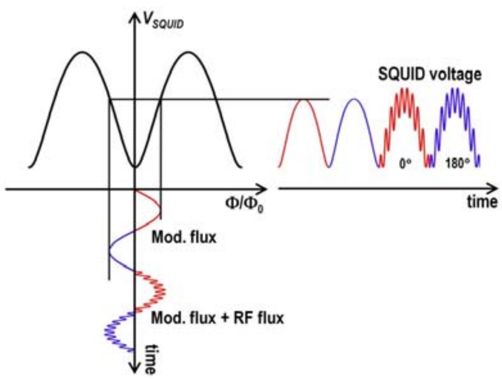

Figure 1. Principle of sensing a RF magnetic flux by DC SQUID. For clarity, the first period of input flux (output SQUID voltage) is shown without the RF flux (RF voltage).

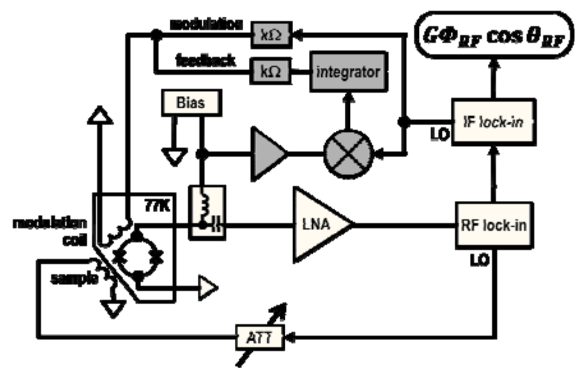

Figure 2. Readout electronics of the microscope. The closed loop components are shaded in grey. LNA is the low-noise RF amplifier, ATT is the variable RF attenuator, LO are the lock-in local oscillators.

3. Experimental setup

3.1. SQUID electronics

We utilized a direct-coupled $YBa_2Cu_3O_7$ SQUID on bi-crystal $SrTiO_3$ substrate with effective loop area of 1000 μm^2 and single modulation coil, with AC flux noise <10 $\mu\Phi_0/\sqrt{Hz}$ at 5 kHz.

To assess the method performance, the IF lock-in output was measured vs. RF flux at 190 MHz with the SQUID held at 77.4 K inside liquid nitrogen Dewar. At smaller Φ_{RF} the dependence is linear, limited by the noise floor $<4\times10^{-6}$ $\Phi_0/\sqrt{Hz}$, that is close to the white noise limit of 1×10^{-6} $\Phi_0/\sqrt{Hz}$ (see Fig. 3). At larger Φ_{RF} the IF signal reaches maximum near Φ_{RF}~$0.2\Phi_0$ due to the SQUID non-linearity. This yields a linear dynamic range of four orders in magnitude. A linear fit to the small signal data (see Fig. 3, inset) yields sensitivity G = 62 V/Φ_0.

3.2. Scanning SQUID Microscope

This manuscript was published by Superconductor Science & Technology (SuST, IOP) 27, No. 4, 044032, (2014).

The RF electronics was installed onto a commercial scanning SQUID microscope platform described in details elsewhere [9]. The SQUID sensor is cooled down to 77 K by a closed-cycle refrigerator and mounted inside a vacuum housing near the 25-µm-thick diamond window, which provides thermal isolation of the SQUID while allowing samples to be imaged in air at room temperature. Samples are mounted onto an *x–y* scanning table and can be brought to within about 50 µm of the window for imaging component of magnetic field normal to the sample. An inversion utilizing fast Fourier transform is employed to convert the magnetic field into a 2D current density image [10].

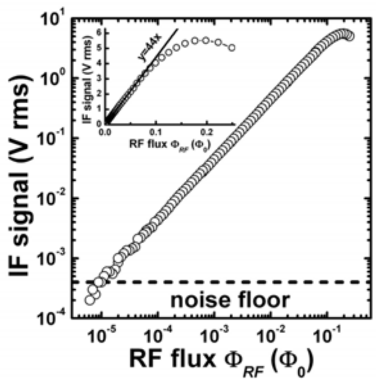

Figure 3. The apparatus transfer function at 190 MHz with SQUID held at 77.4 K.

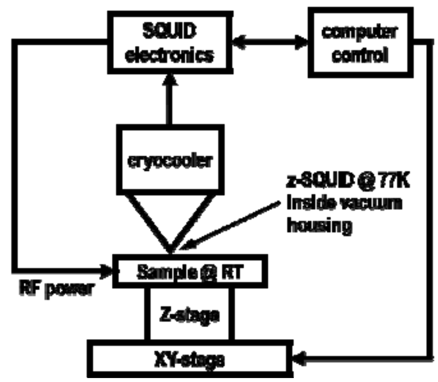

Figure 4. The microscope schematic.

4. Imaging examples

4.1. Travelling wave in CPW

Fig. 5 shows the *z*-component of magnetic field in travelling wave propagating in a coplanar waveguide (CPW) at 200 MHz (see Fig. 5). This image confirms, in particular, that our technique senses both the amplitude and phase of RF magnetic field.

4.2. Standing wave in microstrip transmission line

Fig. 6 shows the *z*-component of magnetic field produced by a standing wave in the open-circuited microstrip. The open boundary was created by making a 50-µm-wide cut across the entire microstrip. As expected, both magnetic field and current gradually vanish at the open.

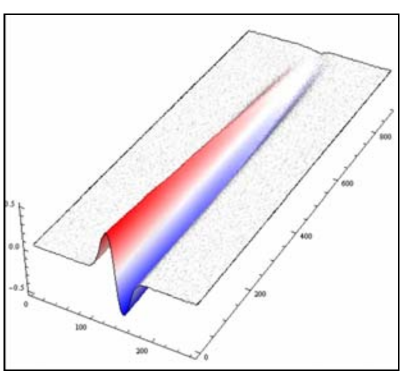

Figure 5. A "snap-shot" for the *z*-component of magnetic field of a travelling wave in CPW at 200 MHz.

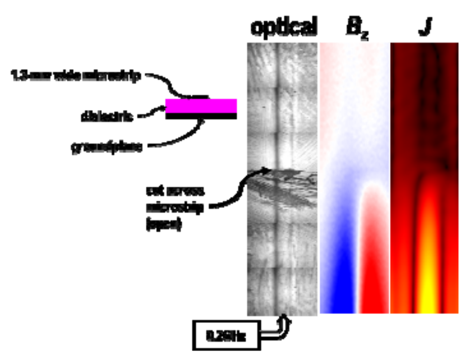

Figure 6. Standing wave in an open-circuited microstrip fed with 200 MHz. Left to right: cross-section (microstrip is 1.3-mm-wide), optical image; *z*-component of magnetic field; current density.

This manuscript was published by Superconductor Science & Technology (SuST, IOP) 27, No. 4, 044032, (2014).

4.3. Electrically small SMD antenna

Fig. 7 shows the 169 MHz image of a surface mounted device antenna mounted onto evaluation board with CPW feedline [11]. The anomalous current seen in one of the capacitors in the impedance matching circuit was incidentally caused by shifting the antenna bandwidth away from the nominal bandwidth of 164–175 MHz due to the groundplane formed by an aluminum chuck holding the sample.

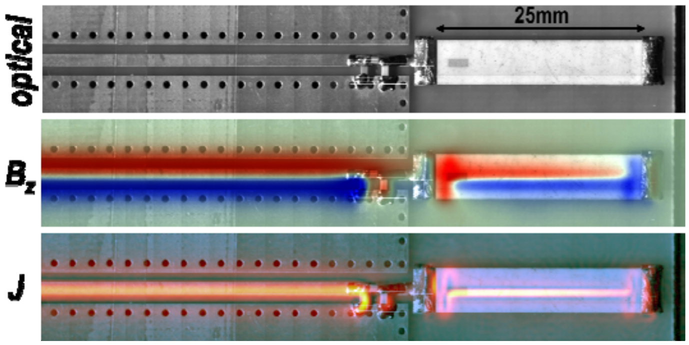

Figure 7. Electrically small antenna at 169 MHz. Top to bottom: optical image; *z*-component of magnetic field overlaid with optical; current density overlaid with optical.

Conclusion

We designed a scanning SQUID microwave microscope operating over frequency range of 50 to 200 MHz. This is limited by the bandwidth of commercial RF lock-in and may be extended into GHz range. With the sample held at room temperature and the direct-coupled 30-µm-sized SQUID at 77K, the microscope noise is 8 pT/√Hz @ 200 MHz. The linear dynamic range of four orders in magnitude suffices for virtually all scanning applications, such as failure analysis (FA) and design verification of semiconductor and RF integrated circuits.

Acknowledgments

This work has been supported by NSF-SBIR IIP-0924610. Authors acknowledge E. Wong and S. Garrahan for assistance with the experimental setup. V.V.T. is indebted to A. Stepanova and A. Grafov for the hospitality.

References

[1] Clarke J and Braginski A (Eds) 2004 *The SQUID Handbook: Fundamentals and Technology of SQUIDs and SQUID Systems* (Weinheim: Wiley-VCH Verlag GmbH & Co. KGaA)
[2] Drung D 2003 *Supercond Sci Technol* **16** 1320
[3] Mück M Christian Welzel C and Clarke J 2003 *Appl Phys Lett* **82** 3266
[4] Drung D Aßmann C Beyer J Peters M Ruede F and Schurig Th 2005 *IEEE Trans Appl Supercond* **15** 777
[5] Kornev V K Soloviev I I Klenov N V and Mukhanov O A 2009 *IEEE Trans Appl Supercond* **19** 741
[6] Black R C Wellstood F C Dantsker E Miklich A H Koelle D Ludwig F and Clarke J 1995 *Appl Phys Lett* **66** 1267
[7] Black R C Wellstood F C Dantsker E Miklich A H Nemeth D T Koelle D Ludwig F and Clarke J 1995 *Appl Phys Lett* **66** 99
[8] Matthews J Kwon S P Wellstood F C and Vlahacos C P 2005 *IEEE Trans Appl Supercond* **15** 688; Vlahacos C P Matthews J Wellstood F C 2011 *IEEE Trans Appl Supercond* **21** 412
[9] Knauss L A Orozco A Woods SI and Cawthorne A B 2003 *Microelectronics Reliability* **43** 1657
[10] Chatraphorn S Fleet E F Wellstood F C. Knauss L A and. Eiles T M 2000 *Appl Phys Lett* **76**, 2304
[11] ISM Chip Antenna 164 - 175MHz, Johanson Technology, Inc.