Nonlinear Near-Field Microwave Microscope for RF Defect Localization in Superconductors

Tamin Tai, X. X. Xi, C. G. Zhuang, Dragos I. Mircea, and Steven M. Anlage

***Abstract*—Niobium-based Superconducting Radio Frequency (SRF) cavity performance is sensitive to localized defects that give rise to quenches at high accelerating gradients. In order to identify these material defects on bulk Nb surfaces at their operating frequency and temperature, it is important to develop a new kind of wide bandwidth microwave microscopy with localized and strong RF magnetic fields. By taking advantage of write head technology widely used in the magnetic recording industry, one can obtain ∼200 mT RF magnetic fields, which is on the order of the thermodynamic critical field of Nb, on sub-micron length scales on the surface of the superconductor. We have successfully induced the nonlinear Meissner effect via this magnetic write head probe on a variety of superconductors. This design should have a high spatial resolution and is a promising candidate to find localized defects on bulk Nb surfaces and thin film coatings of interest for accelerator applications.**

***Index Terms*—Harmonic generation, magnetic write head, microwave microscope, near-field, nonlinear Meissner effect, RF superconductivity.**

I. Introduction

SUPERCONDUCTING Radio Frequency (SRF) cavities will be used in the International Linear Collider (ILC) to explore electron-positron collisions in high energy physics research. In order to achieve a 1 TeV beam energy it is necessary to build $\sim 10^4$ Nb cavities with electrodynamic properties approaching the intrinsic limit dictated by theory. Despite the maturity of material fabrication techniques and improvement of chemical and physical surface treatments and annealing processes in the past several years, it is still challenging to fabricate so many state-of-the-art Nb cavities without performance-limiting defects. In general, many types of defects are found on Nb cavity surfaces. Under intense RF loading, some of these defects can act as a hot spot to locally warm up the Nb superconductor above its critical temperature (T_c), leading to a quench of the cavity.

One approach to this problem is to postpone the quench of the superconductor by enhancing the RF breakdown field of the material at the surface. There is considerable interest in preparing novel coatings on Nb cavities. Superconductor/insulator multilayer thin film coatings have been proposed to enhance the RF breakdown field of the superconductor [1]. It is of interest to measure whether or not this enhancement is possible with practical materials.

However, the properties of uncontrolled localized defects present in the finished SRF cavities appear to limit their ultimate microwave performance. Therefore, there is an urgent need to understand the connections between localized defects, surface treatments, and the RF breakdown field in the high frequency regime. Optical microscopy techniques have been developed to identify defects in finished Nb cavities [2]. However this optical screening process may result in identification of relatively benign defects which will not result in a quench of the superconductor. Ideally, one would like a microscopic technique that identifies defects based on their poor microwave performance at low temperatures in the superconducting state. One of the best candidates for this job is the near field microwave microscope which has been developed to quantitatively image RF and microwave properties of a variety of materials on deep sub-wavelength scales [3], [4].

In order to generate a strong and localized RF magnetic field, and to enhance the spatial resolution of this microscope, a magnetic writer is utilized in our experiment. Taking advantage of magnetic write head technology with write-gap widths on the order of 100 nm [5], an RF field on the scale of 1 Tesla [6] with sub-micron spatial extent [7] can be created. In this work, we integrate the magnetic writer probe into our microwave microscope and demonstrate that this probe can develop a nonlinear Meissner effect signal from several kinds of superconductors such as MgB_2 and $Tl_2Ba_2CaCu_2O_8$ (TBCCO). This probe has great potential for high resolution nonlinear Meissner effect microscopy and in the future will be used in analyzing defects on Nb cavity surfaces at high frequencies and low temperatures.

II. Experiment

A. Experimental Setup

In previous work, we developed a low resolution near field microwave microscope to nondestructively measure the local harmonic generation from unpatterned superconducting samples [4], [8]–[10]. In this design, a loop probe [Fig. 1 (left)] is made by shorting the inner conductor and outer conductor of a commercial semi-ridge coax cable with inner diameter 200 μm and outer diameter 2 mm. The loop is brought to within 10 μm of the superconducting surface and a high frequency signal is applied to the loop. RF screening currents are induced in the sample. Due to its nonlinear response, harmonics of the drive

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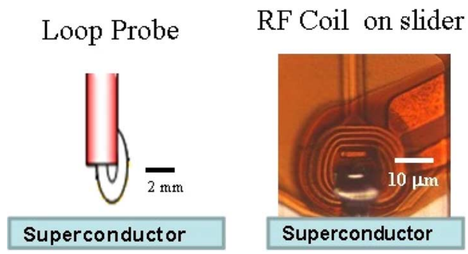

Fig. 1. (Left) Comparison of loop probe and (right) magnetic write head probe. A 4-turn coil is visible inside this magnetic write head, which develops a high frequency magnetic field in a write-gap near the surface of the superconductor.

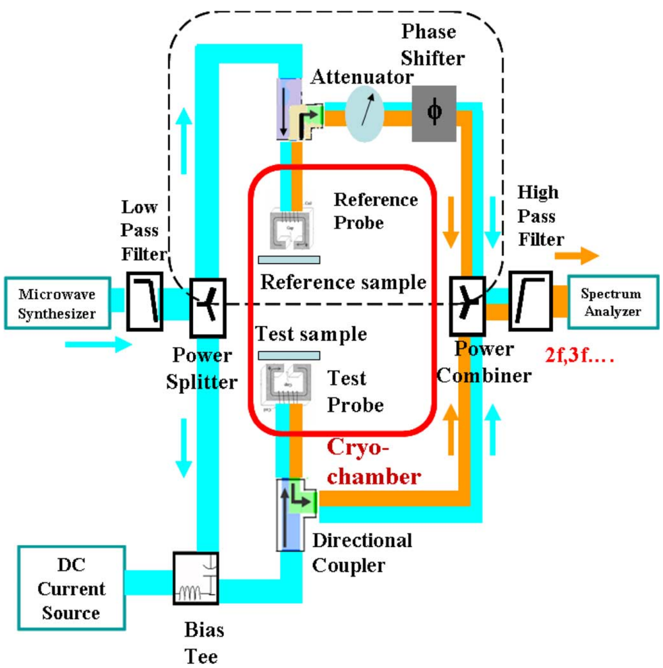

Fig. 2. Experimental setup. An excited wave (fundamental signal, blue) at approximately 3.5 GHz is low-pass filtered to eliminate higher harmonics and sent to the tip of the microwave test probe. The tip can be either a loop probe or magnetic write head probe. The dashed line encloses a reference arm setup only used for background signal cancellation. A DC current can be injected into the microwave circuit via the bias tee. Higher order harmonic signals induced in the superconductor (orange) are gathered by the probe tip and high pass filtered before being measured by the spectrum analyzer.

signal are created, and these couple back into the loop probe and are measured at room temperature with a spectrum analyzer. This experiment can determine both the second and third harmonic nonlinear products at the same location at any excited frequency and temperature of interest.

Here, we have modified this basic experiment to produce stronger and more localized RF magnetic fields. Based on the need to investigate Nb near the thermodynamic critical field, we require at least 200 mT magnetic field at the sample surface. In order to enhance the magnetic coupling between probe and superconducting sample, we replace the loop probe with a magnetic write head [Fig. 1 (right)].

The system setup is shown in Fig. 2. Both the magnetic write head probe and the superconductor are kept in a high vacuum cryogenic environment. Microwave fundamental frequency power P_f is generated by a microwave synthesizer. Low pass filters are used to filter out higher harmonics generated by the microwave source. Because of the perturbation of the super fluid density coming from the externally applied RF magnetic field, higher order harmonic response $(P_{2f}, P_{3f}, \cdots)$ will be induced on the sample for temperatures below T_c. Those harmonic signals will be radiated from the sample and can be extracted by high pass filtering the signal from the probe. Here we shall concentrate on P_{3f}, which arises from time-reversal invariant perturbations of the superconductor and can be used to examine both intrinsic and extrinsic nonlinear characteristics of the material.

In Fig. 2, the closed dashed line encloses a reference microwave circuit designed for cancelation of nonlinearity from the magnetic write head probe itself, and will be discussed below. In addition, a bias tee is integrated into the microwave microscope circuit to allow injection of a small DC current into the probe, also discussed further below.

The generated third harmonic power P_{3f} is estimated as [10]

$$P_{3f} \propto \frac{\omega^2 \lambda^4(T) \Gamma^2}{J_{NL}^4(T,x)} \quad \Gamma = I_0 \int \frac{\int K^4(x,y)dx}{\left(\int K_y dx\right)^2} dy \qquad (1)$$

where ω is the frequency of the incident wave, $\lambda(T)$ is the temperature dependent magnetic penetration depth, J_{NL} and Γ are the nonlinear scaling current and a current-distribution geometry factor, respectively. $K(x,y)$ is the surface current induced in the superconductor at the fundamental frequency and I_0 is the total current flowing through a cross section right beneath the bottom of the probe. From Eq. (1), a strong magnetic field from the magnetic write head probe will enhance the surface current K and confine the current distribution, both leading to an enhancement of Γ, and therefore P_{3f}, for a given excitation power. This has the added benefit of improving the spatial resolution of the probe. Defective regions of the sample, including those responsible for hot-spot generation, have smaller values of J_{NL} than the surrounding material, hence will develop larger P_{3f}, thus giving away their position to the microscope. Previous work has demonstrated the ability of this microscope to identify a grain boundary Josephson junction defect in a cuprate thin film [8]–[10].

B. Sample

The superconducting samples we study include a TBCCO thin film of thickness 500 nm, epitaxially grown by the magnetron sputtering method [11]. In addition, a high quality epitaxial MgB_2 thin film with thickness 25 nm is also examined. The MgB_2 film is deposited on a SiC substrate by a hybrid physical-chemical vapor deposition technique [12]. Both samples are examined at a single location in the center of the 10 mm $*$ 10 mm area. The spatial resoluton of the probe is the greater of the gap dimension (100 nm $*$ 1 μm; specification of the Seagate GT5 write head) and the probe-sample separation [3]. We estimate the latter scale to be on the order of 0.5–5 μm.

III. Data and Discussion

A. Magnetic Write Head Behavior at Microwave Frequencies

Before integrating the magnetic write head into our near field microwave microscope, we measured the complex load impedance that the head presents to the microwave generator. Fig. 3 shows the impedance measured with a Picoprobe

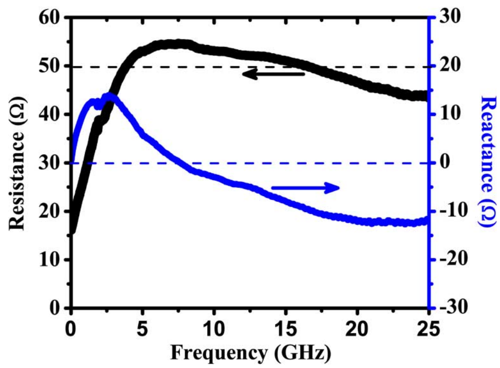

Fig. 3. Measured impedance of the magnetic write head as a function of frequency. The thick line indicates the resistance, and the thin line indicates the reactance values. The measurement is done with a PNA-X N5242A network analyzer and Picoprobe at room temperature.

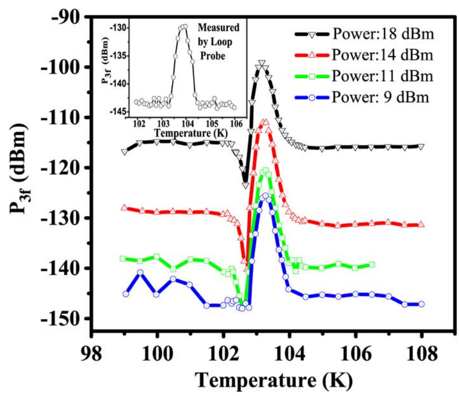

Fig. 4. Temperature dependence of third harmonic power P_{3f} of a TBCCO film, measured by a magnetic write head probe with an excitation frequency of 3.5 GHz. Inset is measured by the bare loop probe with excitation frequency of 3.5 GHz and excited power 18 dBm.

touching the contact pads on the slider. Remarkably, the write head is very well impedance matched to 50 Ω in resistance and 0 Ω in reactance over a broad frequency range from around 2 GHz to 25 GHz, which is quite ideal for the present application. Such good impedance match implies that we can deliver 45 mA of current to the write head using 100 mW (+20 dBm) of RF power, and we have found that this does not burn out the magnetic write head coil.

B. Third Order Nonlinear Response From Superconducting Samples

A measurement of the temperature dependent 3rd order harmonic power is performed at the center of the TBCCO film by the magnetic write head probe with different exciting powers. The inset of Fig. 4 shows $P_{3f}(T)$ measured by the bare loop probe. A peak in P_{3f} near T_c shows up, as expected. This enhancement of P_{3f} is due to the nonlinear Meissner effect near T_c. From Eq. (1), one sees that due to J_{NL} approaching zero and $\lambda(T)$ diverging at T_c the third harmonic power will increase strongly. The divergence is cut off by the distribution of transition temperatures in the sample, and the influence of quasiparticle electrodynamics. With the loop probe, the enhancement of P_{3f} above background is only 15 dB, for 18 dBm fundamental input power. Such a small enhancement can be easily achieved

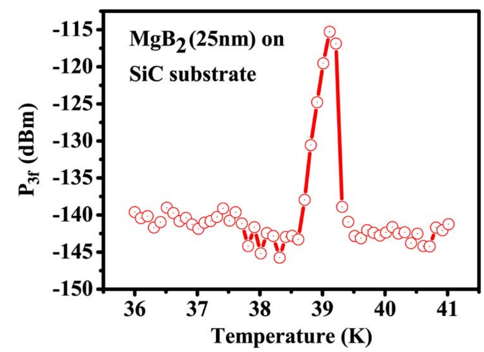

Fig. 5. Temperature dependence of third harmonic power P_{3f} from an MgB_2 film, measured with the magnetic write head probe with an excitation frequency of approximately 3.5 GHz and a power of 12 dBm.

by the magnetic head probe with only 9 dBm excited power (Fig. 4), which means that the magnetic write head generates a more localized and intense field, inducing stronger surface currents on the sample. From comparison of the 18 dBm data in Fig. 4, we find that the probe geometry factor Γ [10] is enhanced by a factor of 30 in the magnetic head probe compared to the loop probe. Note that localized heating would produce a shift of the $P_{3f}(T)$ peak to lower temperature with increasing input power. Despite these higher currents, there is no evidence of localized heating in the sample from the data in Fig. 4.

In order to test the magnetic write head probe in a liquid Helium cooled environment, temperature dependent 3rd order harmonic power is also measured in the center position of an MgB_2 thin film. In Fig. 5, a peak at 39.1 K shows up clearly near the T_c of the film. This proves that the magnetic probe can function in the low temperature region. Comparison of this peak with that of TBCCO, one finds a much sharper transition, implying a narrow distribution of T_c values in the MgB_2 thin film.

C. Cancellation of Nonlinearity From the Probe

One can see from Fig. 4 that as the excitation power to the probe is increased, the noise floor is also enhanced. This is due to the nonlinearity of the magnetic write head itself. Generally speaking, all of the tested magnetic write heads show some degree of nonlinearity. To clarify the origin of this probe nonlinearity, a DC current is injected into the write head drive coil to control the magnetization direction of the magnetic materials inside the probe. Third harmonic power from the probe under 3.5 GHz and 16 dBm illumination is shown in the inset of Fig. 6, as a function of DC current from -55 mA to $+55$ mA. The P_{3f} from the magnetic write head decreases dramatically at $+45$ mA and -45 mA, demonstrating that an applied DC current can suppress background nonlinearity. This decrease in P_{3f} may be due to establishment of a fully magnetized state of the ferromagnetic films in the write head, thus eliminating nonlinearity from minor hysteresis loops. The applied current may also reduce magnetic domain wall motion and magnetic moment precession, thus reducing background nonlinearity [13].

To experimentally reduce the background nonlinearity, a reference arm is created to cancel the contributions of the probe to the measured nonlinearity. The area circled by the dashed line in Fig. 2 includes an identical magnetic write head probe. The

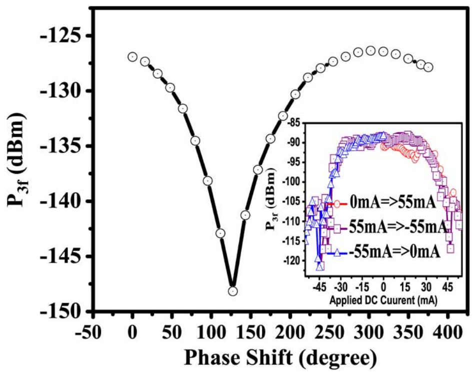

Fig. 6. Measurement of total third harmonic power P_{3f} from the test probe and reference probe, as a function of phase shift in the full setup shown in Fig. 2. The experiment is carried out with an excitation frequency of 2.12 GHz and power of 14 dBm at ambient temperature under vacuum. No samples are present in this measurement. The inset shows third harmonic response as a function of DC current in the probe. The test probe is driven at 3.5 GHz and 16 dBm while the DC current is varied.

phase shifter and variable attenuator are used to create an equal amplitude but 180-degree phase-shifted third harmonic signal from the reference arm. A plot of the total P_{3f} generated by both arms combined, at different phase shifts, is shown in Fig. 6. With 127.2^o of phase shift, the background nonlinearity is completely canceled (down to the noise level of the spectrum analyzer) by the reference probe. This result implies that the microscope can be made sensitive to just the P_{3f} signal from the superconductor, despite the presence of nonlinear magnetic materials in the write probe. With this modification we expect to achieve high spatial resolution in nonlinear near field microwave microscopy, and apply it to defect identification in Nb materials.

At present the cryostat housing this microscope is not able to achieve sample temperatures below the transition temperature of Nb. The Nb materials studied so far have a large thermal resistance to the cold plate, preventing them from being cooled below T_c. Further improvements in samples and probe cooling are required.

IV. Conclusion

A magnetic write head is successfully integrated into the near field microwave microscope operating at cryogenic temperatures. The magnetic write head should generate RF magnetic field on the scale of the thermodynamic critical field of Nb on sub-μm length scales. Using this probe, a clear reproducible nonlinear response signal from superconducting samples of TBCCO and MgB_2 are obtained. Although this probe can generate strong nonlinearity itself, a phase cancelation method is demonstrated to nearly zero out this contribution. This microscope will be employed to identify defects that degrade the RF performance of Nb used in SRF cavities.

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