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Magnetic field sensing with the kinetic inductance of a high-$T_c$ superconductor

We carry out an experimental feasibility study of a magnetic field sensor based on the kinetic inductance of the high critical temperature (high-$T_c$) superconductor yttrium barium copper oxide. We pattern thin superconducting films into radio-frequency resonators that feature a magnetic field pick-up loop. At 77 K and for film thicknesses down to 75 nm, we observe the persistence of screening currents that modulate the loop kinetic inductance. We report on a device with a magnetic field sensitivity of 4 pT/$\sqrt{\text{Hz}}$, an instantaneous dynamic range of 11 $\mu$T, and operability in magnetic fields up to 28 $\mu$T. According to the experimental results the device concept appears attractive for sensing applications in ambient magnetic field environments.

The kinetic inductance of superconductors has found many applications in fields as diverse as bolometry, parametric amplification, current detectors, and sensing of electromagnetic radiation, to name but a few. Each device harnesses a certain type of a non-linearity of the kinetic inductance $L_k$, such as that induced by temperature, electric current, or non-equilibrium quasiparticles. In sensor applications, radio-frequency (rf) techniques are often employed in observation of the variations of $L_k$: a high sensitivity follows from the intrinsically low dissipation of the superconductors, manifesting itself as a high quality factor of resonator circuits, for example.

The general advantages common to all $L_k$ sensors include a simple fabrication process involving only a single superconducting layer, and the ability to use frequency multiplexing for the read-out of large sensor arrays. These aspects have motivated the development of kinetic inductance magnetometers (KIMs), devices that combine the $L_k$ current non-linearity with magnetic flux quantization. In this Letter, we demonstrate KIMs fabricated from yttrium barium copper oxide (YBCO). YBCO is a high critical temperature (high-$T_c$) superconductor that enables KIM operability in liquid nitrogen.

Non-linear $L_k$ of YBCO has previously been evaluated for bolometric (direct) detection of infrared (optical) radiation. A further benefit of the material is its high tolerance against background magnetic fields, which has recently culminated in a YBCO rf resonator with a quality factor of about 10$^4$ at a temperature $T < 55$ K and at a magnetic flux density of 7 T applied parallel to the superconducting film. From a sensitivity viewpoint, an important benchmark for our KIM are state-of-the-art YBCO SQUID magnetometers that have a sensitivity better than 50 fT/$\sqrt{\text{Hz}}$. However, these SQUIDs suffer from a complicated Josephson junction fabrication process that makes mass production difficult, and in order to extend the magnetometer dynamic range beyond a few nT, they need to be operated in a flux-locked loop requiring at least four wires to each cold sensor. KIMs typically have a higher dynamic range, and they enable operation in demanding ambient magnetic field conditions.

We review the KIM operating principle, starting from the $L_k$ current non-linearity,

$$L_k = L_{k0}[1 + \left(I/I^*\right)^2].$$

In anticipation of using it for magnetometry, we have introduced a screening current $I_s$, the flow of which is enforced by magnetic
flux quantization. $L_{\Phi 0}$ is the kinetic inductance at $I_s = 0$, and $I^*$ is a normalizing current on the order of the critical current $I_c$. Assuming that $L_q$ is a property of a superconducting loop with an area $A$, we formulate the flux quantization as

\[(L_q + L_k)I_s - B_0 A = m\Phi_0,\]

where $L_q$ is loop geometric inductance, $B_0$ the spatial average of the magnetic flux density threading the loop, and $m\Phi_0$ an integer times the magnetic flux quantum. Sensitive magnetometry calls for a decent kinetic inductance fraction $\alpha_k = L_k/(L_q + L_k)$, and an effective method of observing the $B_0$-induced inductance variations. To establish an rf readout, two opposite edges of the loop are connected with a capacitor that leaves $I_s$ unperturbed, but creates an rf eigenmode together with the loop inductance. Then, the inductance variation translates into a changing resonance frequency, a quantity which is probed by coupling the resonator weakly into a 50-Ω readout feedline. Two KIMs of this kind have recently been reported: the materials of choice have been NbN and NbTiN, both of which are low-$T_c$ superconductors whose disordered nature provides a magnetic penetration depth $\lambda$ exceeding several hundreds of nm. For films with a thickness $d = 10 - 17\mu$m, the kinetic surface inductance equals $\mu_0\lambda^2/2d$, with $\mu_0$ the vacuum permeability.

In the design of our high-$T_c$ KIM [Fig. 1(a) and supplementary material], we use as a guideline the theoretical responsivity on resonance

\[\left| \frac{\partial V}{\partial B_0} \right| = \frac{Q^2 V_{in} I_A}{4 Q_b L_{tot} I^* \left[ (1/\alpha_k) + 3(I_c/I^*)^2 \right]}\]

that describes how the magnetic field sensitivity of the resonator voltage $V$ is related to the electrical and geometric device parameters. The readout rf power $P_{rd}$ arriving at the KIM is expressed through an excitation voltage amplitude $V_{in}$, $Q_b$ ($Q_b$) denotes the loaded (external) quality factor. We choose a maximal $A = (8\, \text{mm})^2$ allowed by fabrication technology. The total inductance $L_{tot}$ equals one quarter of the loop inductance plus the contribution of the parasitic trace connecting the two halves of the loop. We anticipate that reaching a significant $\alpha_k$ is the main bottleneck: The reported values of the YBCO $\lambda$ in the low-$T$ limit are only $150 - 200$ nm. Few devices have previously featured long superconducting traces with a small cross-section, because this is expected to increase the probability of defects. As a compromise, we select a trace width $w = 10\, \mu$m, and compare three devices (labeled A-C) with a variable $d = 225$ nm. The shunt capacitor $C = 16$ pF, which determines the unloaded angular resonance frequency through the relation $(L_{tot} C)^{-1/2}$, is formed from interdigitated fingers of width $10\, \mu$m and gap $5\, \mu$m. We analytically estimate that $L_q = 45.3$ nH, and the parasitic trace has a contribution of $25 - 45\%$ of $L_{tot}$. The lower (upper) end of the range corresponds to a high (low) $\alpha_k$. We aim at $L_{tot} \approx 24$ nH at $\alpha_k \approx 0.2$, and a loaded resonance frequency $f_L$ of about $250$ MHz. The $f_L$ is chosen to be well above the magnetic signal frequencies (up to tens of kHz), while allowing the modeling of the KIM a lumped element. All device features are fabricated from YBCO.

Sample A was fabricated on a $10 \times 10\, \text{mm}^2$ r-cut sapphire substrate with an yttria-stabilized zirconia and a CeO$_2$ buffer layer to support the epitaxial growth of a $d = 225$ nm thick YBCO film. Sapphire was initially chosen for its very low rf dielectric loss, but the deposition process of thin YBCO films is optimized for MgO.

Consequently, Samples B and C with a $d = 50$ nm and $75$ nm thick YBCO film, respectively, were fabricated on a $110$ MgO substrate without buffer layers. Low-loss microwave-resonant YBCO structures have previously been reported on both substrate materials. The YBCO films were deposited with pulsed laser deposition (PLD) and the devices were then patterned with optical lithography using a laser writer and argon ion beam etching. The etching process was monitored with secondary ion mass spectrometry for endpoint detection. We attach the KIMs on a printed circuit board (PCB) that has copper patterns for rf wiring and magnetic bias coils.
observe a quadratic dependence of $dc$ response as well. This makes us suspect a locally suppressed magnetic excitation, and at a lower proper flux quantization. However, also Sample B reacts to an ac field noise, but also prevents trapping of flux vortices during the magnetic shield that not only protects the sample from magnetic cooling in liquid nitrogen at $T = 77$ K. We use a high-permeability magnetic shield that not only protects the sample from magnetic field noise, but also prevents trapping of flux vortices during the time when $T$ crosses $T_c$. The core elements of the readout electronics are a low-noise rf preamplifier followed by a demodulation circuit (IQ mixer), and analog-to-digital converters [Fig. 1(c)] (see supplementary material for detailed setup schematics). We sweep the frequency of a weak ($P_{rf} \leq 66$ dBm) rf tone across the resonance. We simultaneously apply a static $B_0$ as well as a weak, magnetic ac probe tone at a frequency of 1 kHz. This frequency is well below $f_T/(2Q_t)$, the corner frequency of the KIM detection band roll-off. From the averaged in-phase ($I$) and quadrature ($Q$) components of the output we extract the complex-valued transmission parameter $S_{21} = 2V/V_{in}$. In addition, we use ensemble averaging of the modulated output voltage to extract the responsivity $\partial V/\partial B_0$ corresponding to the magnetic ac probe tone.

From the best fits $^1$ to $S_{21}$ we extract $f_T$, $Q_t$, and the internal quality factor $Q_i$. Applying $B_0$ shifts $f_T$ downwards in Samples A and C [Fig. 2(a,b)], but not in Sample B which has the thinnest film. We suspect that a non-uniform film quality, leading to a small residual resistance at $T = 77$ K in one arm of the loop, prohibits the proper flux quantization. However, also Sample B reacts to an ac magnetic excitation, and at a lower $T = 60$ K we observe the proper dc response as well. This makes us suspect a locally suppressed $T_c$ in the film. We convert the frequency shifts of Samples A and C (maximally $\pm 140$ kHz and $\pm 50$ kHz, or $\pm 0.15$ and $\pm 0.30$ resonance linewidths, respectively) into an equivalent change in $L_{tot}$. We observe a quadratic dependence of $L_{tot}$ on $B_0$ [Fig. 2(e)], which is in line with Eqs. (1–2). Unlike in low-$T_c$ KIMs, $^1,^2$ we do not observe resetting of the sample to $I_s = 0$ [i.e., into a finite $\mu$ in Eq. (2)] upon crossing a threshold $B_0$ corresponding to $I_s = I_c$. Instead, the resonance of Sample A (C) stays put at $B_0 \approx 28 \mu$T ($B_0 \approx 9 \mu$T). We attribute this to flux trapping, which most likely occurs at the loop corners where the inhomogeneous bias field of the square coil is the strongest (about 1.5$B_0$). Ref. $^9$ proposes a flux-trapping condition of the form $I_c \approx I_T \propto (J_{sd})^{3/4}w^{1/2}$ where $I_c$ is the critical current density. In the supplementary material we estimate that flux is trapped at $I_c \approx 37$ mA ($I_c \approx 11$ mA) in Sample A (C), which is below $I_c = 45$ mA ($I_c = 15$ mA).

Regarding the quality factors, we note that Sample A is overcoupled with $Q_i = 350$ much smaller than $Q_t \leq 2500$. Sample C is close to being critically coupled ($Q_i = 3500$, $Q_t \leq 3750$). Since material quality is known to affect YBCO rf loss, $^9$ the lower $Q_t$ of Sample A is designed to cover a wider $Q_i$ range more reliably. The observed $Q_i$ variations with respect to $B_0$ are on the order of 10% (see supplementary material for data). Low internal dissipation is key to achieving high device sensitivity. Thus, we discuss the possible mechanisms affecting $Q_i$. Firstly, the resistive part of the superconductor rf surface impedance generates loss that grows with increasing $T$, $I_s$, and surface roughness. The dielectric losses of the substrates should not play a role: both sapphire and MgO have low relative permittivity (sapphire: $\varepsilon_r = 9.3$ and $\varepsilon_{MgO} = 11.3$ anisotropic, MgO: $\varepsilon_r = 9.6$) and low dielectric loss tangents ($<4 \times 10^{-4}$) at $T = 77$ K. A loss mechanism related to the PCB deserves further attention: the presence of the bias coils made of resistive copper. In Ref. $^9$ as well as for the data presented in Figs. 2–3 for Sample A, bias coil rf decoupling is attempted with series impedances (resistance, inductance) on the order of hundreds of Ohms within the coils. This has allowed for $Q_i$ up to 2500, but we have learned that higher values can be reached with an arrangement where the bias coils are grounded at rf and the readout is mediated by stray coupling between the KIM and the coils (see supplementary material for details). Samples B and C as well as a subsequent cooldown of Sample A (Fig. 4) have been prepared using this better method, which presumably allows for a $Q_i$ that is limited by the intrinsic superconductor loss.

The measured device responsivities are presented in Fig. 2(c,d) as a function of the readout frequency. They are of the normalized form $|V^* \partial V/\partial B_0|$; this is a convenient quantity because both $V$ and $\partial V/\partial B_0$ experience the same gain of the readout electronics. We average these two quantities for 300 ms at each readout frequency. The measured readout frequency dependencies of $\partial V/\partial B_0$ are Lorentzians that peak on resonance. We use these data for the estimation of the sensor dynamic range, which is approximately $11 \mu$T (2.8 $\mu$T) for Sample A (C) at high responsivity. As expected, the responsivity vanishes at the first-order flux-insensitive points.
where $I_i = 0$. The peaks of $|V^{-1} \partial V/\partial B_0|$, shown as a collection in Fig. 2(f), are almost linearly proportional to $B_0$. If we normalize Eq. (3) in the limit of $1/a_k \gg 3(I_i/I^*)^2$, we obtain a responsivity model where we further assume an approximately linear mapping from $B_0$ into $I_i$ [consider Eq. (2) at $m = 0$]. The theory implies that the quadratic term in the normalized inductance, $L_{tot}(B_0)/L_{tot}(0) \propto kB_0^2$ with $k$ the slope [see Eq. (1)], is closely related to the normalized responsivity in Eq. (4): $|V^{-1} \partial V/\partial B_0| = 2Q_i^2 kB_0/(Q_i + Q_s)$. To demonstrate this relationship, we extract $k$ from best fits to the normalized responsivity data. The fit of Sample A [Fig. 2(e)] is slightly curved because it takes into account the independently measured $Q_i$ variation (by contrast, Sample C has a $Q_i$ which is close to a constant). We put the $k$ into use in theory overlays on top of the measured inductance in Fig. 2(c), and observe good agreement. The uncertainties in the overlays are calculated from the error estimates of $k$. The best-fit $k$ is about six times steeper in Sample C in comparison to Sample A, which is primarily an indication of a higher $a_k$ and a lower $I^*$ resulting from the thinner film. Despite the difference in the resonance lineshape, the term in Eq. (4) related to the quality factors, $Q_i^4/(Q_i + Q_s)$, is of similar magnitude in the two KIMs [about 2000 (1900) in Sample A (C)].

To determine the magnetic field sensitivity of Samples A and C, we record time traces of $V$ and average the squared modulus of their Fourier transform $14 \approx 10^{-3}$ to $10^{-4}$ times to reduce the uncertainty of the noise estimate. This type of averaging retains the noise power that is present in $S_V$, the spectrum of $V$. The trace duration is $1.0$ s and the sample rate is one megasample per second (see the supplementary material for the setup and the interference peaks in $S_V$). Importantly, an rf carrier cancellation circuit [Fig. 1(c)] is activated now to prevent the saturation of the readout electronics. To avoid adding phase noise to $V$, we take the cancellation tone, the readout tone, and the reference for demodulation from the same rf generator. We measure the sensitivity at $f_s$ as a function of $P_{rf}$, and we also compare $B_0$ bias points with a high and a vanishingly small $|\partial V/\partial B_0|$. At low $P_{rf}$ we observe a white $S_V$ determined by thermal noise and noise added by the preamplifiers. As we increase the power, an $S_V \propto 1/f$-like spectrum emerges and eventually dominates the voltage noise, increasing linearly with $P_{rf}$ (see supplementary material for details). The voltage spectra at the high responsivity and at the highest $P_{rf}$ have been converted into the magnetic domain in Fig. 3, yielding a sensitivity $|\partial V/\partial B_0|\cdot S_V^{1/2}$ of about $4$ pT/Hz at $10$ kHz for both KIMs. The $1/f$ corner frequency is about $2$ kHz ($500$ Hz) for Sample A (C). However, the noise of Sample C appears to scale according to a different exponent in the power law of the frequency dependence at $0.1$ – $1$ kHz. We can rule out direct magnetic field noise because $S_V$ is similar at the operating point with vanishing responsivity (see supplementary material for data). The origin of the low-frequency noise mechanism is currently not fully understood.

Finally, we probe the resonances of Samples A and B at a variable temperature. The extracted $f_i(T)$ and $Q_i(T)$ are the most sensitive to $T$ when the devices are just below $T_c$ (Fig. 4). An analytical model

$$f_i(T) - f_i(T_{\text{min}}) \approx \lambda(T = T_{\text{min}}) - \lambda_0 \left[1 - \left(\frac{T}{T_c}\right)^{-\lambda_0} \right]^{1/2}$$

exists where $T_{\text{min}}$ is the lowest $T$ in the dataset, and $\lambda_0 = \lambda(T = 0)$. For both samples, the best fits of this form have $T_c = 90.5 \pm 0.2$ K and $\lambda(T = 77\,^\circ K) = 1.9\,\lambda_0$ [Fig. 4(a)]. According to the fit, the sensitivity of $f_i$ to $T$ in Sample A is about $-0.64$ MHz/K at $T = 77$ K. We use this information to estimate $\lambda$ that a $1$ mK change in $T$ would produce the same swing in $V$ as a $57$ nT change in $B_0$ at the operating point where the noise of Sample A has been measured. Furthermore, we combine the $f_i(T)$ data with geometric considerations to estimate that Samples A, B and C have $a_{\gamma} \approx 0.06, 0.4, 0.16$, respectively, at $T = 77$ K. In Fig. 4(b) we deduce that the $Q_i(T)$ drop below $10^2$ near $T_c$ is a result of a remarkable increase of intrinsic rf losses.

In conclusion, we have demonstrated high-$T_c$ kinetic inductance magnetometers with a sensitivity of $4$ pT/Hz at $10$ kHz and $T = 77$ K. They tolerate background fields of $9 - 28 \mu$T, which is close to the Earth’s field. We anticipate that changing the sensor geometry by implementing narrow constrictions to reduce $I_s$ should allow for periodical resets, enabling operation at even higher fields. This could open the road to applications in, e.g., geomagnetic exploration or quantum computation with electron spins or trapped
ions. The constrictions should also help to increase $\alpha((s)$, a likely route towards a higher responsivity. Considering the sensitivity, we would find useful a further study of the cause of the low-frequency noise, and methods to minimize it.

See supplementary material for detailed information on the samples, the experimental setup, the estimates of $I_c$ and $I_s$, as well as extended measurement data.

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