High-Tc superconducting antenna for highly-sensitive microwave magnetometry
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We have fabricated arrays of High-Tc Superconducting Quantum Interference Devices (SQUIDs) with randomly distributed loop sizes as sensitive antennas for Radio-Frequency (RF) waves. These sub-wavelength size devices known as Superconducting Quantum Interference Filters (SQIFs) detect the magnetic component of the electromagnetic field. We use a scalable ion irradiation technique to pattern the circuits and engineer the Josephson junctions needed to make SQUIDs. Here we report on a 300 SQUIDs series array with loops area ranging from 6 to 60 µm², folded in a meander line covering a 3.5 mm × 8 mm substrate area, made out of a 150 nm thick YBa₂Cu₃O₇ (YBCO) film. Operating at a temperature T = 66 K in a un-shielded magnetic environment, under low DC bias current (I = 60 µA) and DC magnetic field (B = 3 μT), this SQIF can detect a magnetic field of a few pT at a frequency of 1.125 GHz, which corresponds to a sensitivity of a few hundreds of fT/√Hz, and shows linear response over 7 decades in RF power. This work is a promising approach for the realization of low dissipative sub-wavelength GHz magnetometers.

Detecting electromagnetic fields in the micro-wave domain with high precision and resolution is a pivotal issue for both basic science and applications. For instance in solid state studies, highly sensitive magnetometers are needed to detect electromagnetic fields in quantum information systems[1], to study electron spin dynamics[2] or to make advanced Nuclear Magnetic Resonance spectroscopy[3]. At the same time, further progress in security systems, wireless and satellite communications or radars requires significant improvement of state of the art Radio Frequency (RF) detectors. For a review see for instance Schröter et al and references therein[4].

While most of the electromagnetic wave detectors are based on a resonant electrical dipole for enhanced sensitivity, the need of sub-wavelength devices is increasing, to miniaturize the detectors and include them in compact and mobile ensembles, or to image electromagnetic fields at small scale[5–7]. Such lumped elements are usually broadband[8], which is of high interest for many applications. One way to fulfill all these requirements (high sensitivity, sub-wave length size, broad-band operation) is to detect the magnetic component of the wave instead of the electric one as usual.

The state-of-the-art magnetometers reach their best sensitivity in a narrow band of frequency, and typically operate at frequencies lower than 10-100 MHz[9]. Magnetic sensitivity in the range of (sometimes sub-) fT/√Hz can be achieved[10, 11] using two technologies: atomic magnetometers[12] and Superconducting Quantum Interference Devices (SQUIDs)[13]. The former are based on optical transition between magnetic sensitive atomic levels, while the latter rely on quantum interferences in a superconducting loop interrupted by Josephson Junctions (JJ). The high and comparable sensitivities of both systems hold at low frequency and rapidly degrade beyond typically a few MHz. Using Nitrogen Vacancy (NV) centers in diamond, Stark et al report a sensitivity of 1 µT/√Hz at 1.6 GHz[9], while Horsley et al reach 1.8 µT/√Hz up to 26 GHz with a Rb atomic vapor cell[14].

Limitations for high frequency operation also hold for SQUIDs. The need of an external feedback to overcome their periodic response in magnetic flux limits in practice the maximum frequency to 100 MHz[15] in the best cases, unless a special implementation is used to reach up to 7 GHz, but in a severely reduced bandwidth[10]. Arrays of SQUIDs with incommensurable loop areas put in series and/or parallel, referred as Superconducting Quantum Interference Filters (SQIFs), were developed in the last decade since the pioneer work of Oppenländer et al[17], and overcome these drawbacks[18–21]. Moreover, such devices can combine different roles such as sub-wavelength antennas and amplifiers for instance[22]. Based on the well-established technology of niobium-based Josephson Junctions (JJ) and optimized architectures[22, 23], SQIFs were successfully operated as RF amplifiers up to 15 GHz with gain in the 20-25 dB range[24, 25]. High-Tc Superconductors (HTS) have also been used to make SQIFs[26, 29] but the maximum operation frequency reported to date is about 100 MHz[30, 32] . In the present article, we report on an HTS SQIF operating in the GHz frequency range with a sensitivity in the hundreds of fT/√Hz range.

We fabricated an HTS SQIF using the ion irradiation technique in a two-step process (details on the fabrication techniques can be found in our previous papers[29, 32, 36]). Starting from a commercial 37 150 nm thick c-axis oriented YBa₂Cu₃O₇ (YBCO) film on a sapphire substrate, we first design the superconducting circuit, namely the SQUID rings, their interconnections and the contact pads: a photoresist mask protects the film from a 110 keV oxygen ion irradiation at a dose of 5 × 10¹⁵ ions/cm² to keep it superconducting. The unprotected part becomes insulating. In a second step, an e-beam sensitive resist mask covering the whole film is used, in which trenches of 40 nm wide and a few microns long have

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been opened at places where Josephson junctions (JJ) will be created, namely across the SQUIDs arms. Another ion irradiation at much lower dose \((3 \times 10^{13} \text{ ions/cm}^2)\) defines the JJ by lowering locally the superconducting \(T_c\). The SQUIF used in this study is made of 300 SQUIDS in series, with loop sizes randomly distributed between 6 and 60 \(\mu\text{m}^2\) folded in a meander line (see Figure 1(a)). The width of the SQUIDs arms is 2 \(\mu\text{m}\) in the vicinity of the JJs. The total size of the device is 3.5 mm times 8 mm. This is much smaller than the wavelength \(\lambda \sim 30 \text{ cm}\) of the RF waves used in this experiment (frequency \(\sim 1 \text{ GHz}\)). The SQUIF can therefore be considered as a lumped element at such frequencies.

The SQUIF is mounted on a Printed-Circuit Board (PCB) with a Co-Planar Wave guide (CPW) transmission line. It is then placed in a magnetically un-shielded cryogen-free cryostat, equipped with Helmholtz coils to generate a DC magnetic field, filtered wires to DC bias the device and coaxial cables for RF measurements. The measurement setup is schematically shown in Figure 1(b). The input RF signal is generated in a continuous mode at a fixed frequency \(f\) and a given source power \(P_{RF}\), band-filtered at room temperature (around 1.17 GHz) and then coupled to the sample through a circular antenna (5 mm in diameter) placed at about 1 cm from the SQUIF surface, i.e., in a near-field condition for \(\sim 1 \text{ GHz}\) frequency wave in vacuum. The RF output signal is isolated from DC by a bias-tee at low temperature, pre-amplified at room temperature (+ 40 dB gain) and measured with a spectrum analyzer in a zero-span mode with a 1-kHz resolution bandwidth. A circulator has been used to prevent the amplifier’s noise to radiate back onto the sample.

Figure 2(a) shows the resistance \(R\) of the SQUIF as a function of temperature \(T\). As reported previously \([29, 33, 36]\), a Josephson behavior is observed below a coupling temperature \(T_j = 67 \text{K}\). The normal state resistance measured at \(T = 80 \text{K}\) is \(R_N = 309 \Omega\). The Current-Voltage (IV) characteristic (inset Figure 2(a)) measured at \(T = 66 \text{K}\) is typical of ion irradiated YBCO JJ \([29, 35, 38, 39]\).

![Figure 1](image1.png)

**FIG. 1.** (a) Optical picture of the device. SQUIDs are in series in a meander line to make the SQUIF (central part of the picture), which is connected to the CPW line made of gold covered YBCO (on the right part of the picture). JJ are indicated by white lines. The region colored in red is pristine and superconducting. The superconducting line around the SQUIF is not used in this experiment. (b) Sketch of the measurement set-up (see text for detail).

![Figure 2](image2.png)

**FIG. 2.** (a) Resistance \(R\) of the SQUIF as a function of temperature \(T\). (Inset): Current \(I\) versus voltage \(V\) of the device at \(T = 66 \text{ K}\) (red point on the main panel). (b) Voltage difference \(\Delta V = V - V_{\text{min}}\) \((V_{\text{min}} = 1.37 \text{ mV})\) as a function of the applied DC magnetic field \(B\) at \(T = 66 \text{ K}\), for a bias current of \(I = 60 \mu\text{A}\). The maximum voltage swing \(\Delta V_{\text{max}} = \text{max}(\Delta V)\) and the maximum transfer function \(V_{\text{limax}} = \text{max} \left(\frac{\partial V}{\partial B}\right)\) are shown by arrows.

The device biased above its critical current \(I_c\) displays a typical SQUIF response under magnetic field \(B\). For the sake of clarity, \(B\) is the magnetic field after subtraction of a constant ambient field in the un-shielded environment. As shown in Figure 2(b) for a bias current \(I = 60 \mu\text{A}\) at \(T = 66 \text{K}\), the DC voltage \(V\) shows a pronounced anti-peak around zero magnetic field, whose amplitude \(\Delta V_{\text{max}} = \text{max}(V - V_{\text{min}})\) (voltage swing) and maximum slope \(V_{\text{limax}} = \text{max} \left(\frac{\partial V}{\partial B}\right)\) depend on \(I\) and \(T\). As already reported \([29, 32]\), there is an optimal \((I, T)\) couple for which these parameters are maximum, namely \(V_{\text{limax}} \sim 125 \text{ VT}^{-1}\) and \(\Delta V_{\text{max}} = 560 \mu\text{V}\). For this device, \(I_{\text{OPT}} = 60 \mu\text{A}\) and \(T_{\text{OPT}} = 66 \text{K}\). Figure 3(a) shows a
color-scale plot of the transfer function $V_B = \frac{\partial V}{\partial B}$ as a function of $I$ and $B$ at $T_{OPT}$. Two pronounced extrema can be seen, corresponding to optimal field and current conditions to detect a DC magnetic field. In the following, we are studying the ability of such a device to detect the magnetic component of RF waves, and therefore to be used as highly sensitive sensor in the GHz frequency range.

The device is then exposed to RF waves at a frequency of $f = 1.125$ GHz while DC biased with $I_{OPT}$ at $T_{OPT}$. The RF power delivered by the source is $P_{RF} = 0 \text{ dBm}$. As compared to our previous measurements\cite{32} where the RF wave was coupled through an on-chip line, we are in a situation of weak RF coupling. Even at the highest input RF power used here ($P_{RF} = 10 \text{ dBm}$), neither the $I-V$ characteristics nor the $V(B)$ one change with $P_{RF}$ within $1\%$.

The output RF voltage of the SQIF is measured with a spectrum analyzer under a swept DC magnetic field $B$. The amplitude of the signal $V_{RF}$ at frequency $f$ is partially modulated by $B$, which is a clear signature of a SQIF response. In Figure 3(b) we plot the pure SQIF response\cite{32} $\Delta V_{RF} = V_{RF}(B) - V_{RF}(B = 0)$ as a function of $B$ (red squares) at $T_{OPT}$. In the same graph is shown the variation of $V_B$ (black line), which is a cut of the Figure 3(a) for $I_{OPT} = 60 \mu\text{A}$. The two curves superimpose with a very good accuracy in a linear regime\cite{32}. Indeed, the total magnetic field seen by the SQIF is $B_{TOT} = B + b_{RF} \sin(2\pi f t)$, where $b_{RF}$ is the RF magnetic field amplitude, proportional to $\sqrt{P_{RF}}$. For small $b_{RF}$, one can make a first order Taylor expansion of the output signal, and $V_{RF} \propto \partial V / \partial B = V_B$. This is valid for temperatures corresponding to the Josephson regime, as shown in Figure 4(d). The evolutions of $V_B$ and $\Delta V_{RF}$ ($P_{RF} = 0 \text{ dBm}$) with the bias current $I$ also coincide as shown in Figure 3(c) at $T_{OPT}$, in which we have plotted $\Delta V_{RF} = \min(\Delta V_{RF}(B < 0))$ and $\Delta V_{RF}^+ = \max(\Delta V_{RF}(B > 0))$ as a function of $I$ (red symbols) to account for the relative signs of the magnetic field. On the same graph is shown (black line) $V_B^- = \min(V_B(B < 0))$ and $V_B^+ = \max(V_B(B > 0))$ as a function of $I$. This analysis clearly proves that the SQIF response is at play in the RF detection. Indeed, the evolution of the RF signal closely follows that of the DC transfer factor under $B$, $I$ and $T$ changes. This allows us going one step further and making parametric plots of the data to extract more quantitative information.

In the following, we estimate quantitatively the RF magnetic field sensitivity of the device. We express the first order Taylor expansion of the voltage for small $b_{RF}$ as follows $V(B_{TOT}) = V(B) + \frac{\partial V}{\partial B} b_{RF} \sin(2\pi f t) + C_{RF} \cos(2\pi f t)$, where the last term accounts for the regular induction (non-SQIF response) of the device and $C$ is a constant\cite{32}. The measured $V_{RF}$ at frequency $f$ is the Fourier amplitude of the linear term, and $\Delta V_{RF} = \partial V / \partial B \cdot b_{RF} = V_B \cdot b_{RF}$. The amplitude of the RF magnetic field is therefore just the ratio $b_{RF} = \Delta V_{RF} / V_B$. In Figure 4(a) $\Delta V_{RF}$ is plotted as a function of $V_B$ for different bias currents $I$ (solid symbols) and magnetic fields $B$ (open symbols) at $T_{OPT}$. The RF input power is $P_{RF} = 0 \text{ dBm}$. All the points align on a single straight line (dashed line in the Figure) as expected for this parametric plot. According to the above expression, the slope of this line is the RF magnetic field amplitude, which is here $b_{RF} = 12 \text{nT} \pm 2 \text{nT}$. The uncertainty is given by the reddish zone in Figure 4(a). The same parametric plot in $B$ made for different $P_{RF}$ ranging from $-60 \text{ dBm}$ to $10 \text{ dBm}$ also shows a linear behavior (Figure 4(b)). The slopes of these curves, that is $b_{RF}$, is then plotted as a function of $\sqrt{P_{RF}}$ on a log-log scale in Figure 4(c). The dashed line has a slope of 1 as expected. This shows that over 7 decades in RF power, the RF measured magnetic field is proportional to the input one, and that the minimum field measured in this series of experiments is of the order of $b_{RF} \approx 10 \text{ pT}$. The sensitivity of this SQIF in the 1kHz bandwidth of the zero-span mode of our analyzer is therefore $s \approx 300 \text{ fT/}\sqrt{\text{Hz}}$.

Such numbers are in line with what is expected. The amplitude of the magnetic field produced in the near-field by an antenna of diameter $d$ on its axis at a distance $D$ is $|B| = \frac{\mu_0 d^2 I_{OPT}}{8D^3}$.
where $I_{RF}$ is the RF current in the antenna [40]. Knowing the impedance of the antenna at $f = 1.125 \text{GHz}$ (resistance $= 1.8 \ \Omega$, inductance $\times 2\pi f = 50 \ \Omega$) and the reflection coefficient $S_{11} = 0.96$ of our set up, we estimate the produced RF magnetic field to be $b_{RF} \sim 25 \ \mu T$ for $P_{RF} = -60 \ \text{dBm}$, which is only twice the measured one. This is the maximum field produced by the antenna, and a more accurate calculation with the exact geometry of the antenna and the SQIF would give a lower value.

The field sensitivity around 1 GHz achieved with this device compares favourably with the best ones using atomic magnetometers, in the $\mu T \sqrt{Hz}$ range, recently reported by Stark et al [9] and Horsley et al [14] which operate at room temperature. In the latter case, detection up to 50 GHz has been recorded. We could observe a SQIF response up to 7.7 GHz, but not perform a quantitative analysis of the signal due to poor impedance matching of the circuit at this frequency. However, it is worthwhile noticing that this is the highest frequency ever reported for High-$T_c$ SQIF operation. Low-$T_c$ SQUIDs arrays have been successfully operated as RF amplifiers up to 15 GHz [24, 25], even though a SQIF response was not clearly evidenced in these experiments.

Better sensitivity can be achieved with our ion-irradiated HTS SQIF, by increasing the transfer factor $V_B$ which is quite low for the device described here ($\sim 125 \ V T^{-1}$) as compared to our previous results [29] ($\sim 1000 \ V T^{-1}$), or to the best results with step-edge HTS JJ of the CSIRO group $V_B \sim 1750 \ V T^{-1}$ [28] and $V_B \sim 40 \ V T^{-1}$ [41] using more complex architectures. A new design using 2D arrays is under test for enhanced transfer factor. In addition, one can improve the sensitivity by concentrating the magnetic field. The actual flux focusing factor of the individual SQUIDs is of the order of 3 in the actual geometry [42], which can be slightly increased. We can also put large superconducting pads in the vicinity of the SQIF to concentrate the flux even further [43].

In summary, we have studied the RF properties of a HTS 1D series SQIF array made of ion irradiated JJ, and tested its performance as a sensitive magnetometer in the GHz frequency range, in an un-shielded magnetic environment. Operating in the $60 \sim 68 \ K$ temperature range, the device showed a SQIF response under DC magnetic field, and could detect RF electromagnetic waves emitted by a loop antenna up to 7.7 GHz. We evidenced that the applied DC magnetic field modulates the RF output signal, sign of a SQIF operation, and that the absolute value of the RF magnetic field can be extracted from the measurement at 1.125 GHz. At optimum conditions, we have shown that the device can detect an RF magnetic field of about 10 $\mu T$ at this frequency, corresponding to a sensitivity of $\sim 300 \ \mu \text{T} \sqrt{Hz}$. Such result paves the way of highly sensitive RF magnetometers working at temperatures where cost- and energy-effective cryo-coolers operate, which are broadband in frequency and sub-wavelength in size. These are three major issues for a wide range of applications where compact RF antennas are required.

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FIG. 4. All measurements have been made at $T_{OPT} = 66 \ K$, $I_{OPT} = 60 \ \mu A$. (a) $\Delta V_{RF}$ ($P_{RF} = 0 \ \text{dBm}$) as a function of $V_B$, and $\Delta V_{RF}^{+}$ as a function of $V_B^+$ for different $I$ (solid symbols) and different magnetic fields $B$ (open symbols). $B$ ranges from $-3.3 \ \mu T$ to $+2.6 \ \mu T$ and $I$ from $47 \ \mu A$ to $91 \ \mu A$. The dashed line is the best linear fit of slope $b_{RF}$. (b) & (c) Same parametric plot in $B$ for different incident RF powers $P_{RF}$. (d) Detected RF magnetic field $b_{RF}$ as a function $\sqrt{P_{RF}}$. The dashed line is a line of slope 1.
