

Kinetic Inductance Parametric Up-Converter

A. Kher¹ · P. K. Day² · B. H. Eom¹ ·
J. Zmuidzinas¹ · H. G. Leduc²

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Abstract We describe a novel class of devices based on the nonlinearity of the kinetic inductance of a superconducting thin film. By placing a current-dependent inductance in a microwave resonator, small currents can be measured through their effect on the resonator's frequency. By using a high-resistivity material for the film and nanowires as kinetic inductors, we can achieve a large coefficient of nonlinearity to improve device sensitivity. We demonstrate a current sensitivity of $8\text{pA}/\sqrt{\text{Hz}}$, making this device useful for transition-edge sensor (TES) readout and other cutting-edge applications. An advantage of these devices is their natural ability to be multiplexed in the frequency domain, enabling large detector arrays for TES-based instruments. A traveling-wave version of the device, consisting of a thin-film microwave transmission line, is also sensitive to small currents as they change the phase length of the line due to their effect on its inductance. We demonstrate a current sensitivity of $5\text{pA}/\sqrt{\text{Hz}}$ for this version of the device, making it also suitable for TES readout as well as other current-detection applications. It has the advantage of multi-GHz bandwidth and greater dynamic range, offering a different approach to the resonator version of the device.

Keywords Kinetic inductance · Nonlinear · TES readout · Current sensor

1 Introduction

Sensitive current detectors are essential for reading out the transition-edge sensors (TESs) used in applications including astronomy and quantum information [1,2].

✉ A. Kher
akher@caltech.edu

¹ California Institute of Technology, Pasadena, CA, USA

² NASA Jet Propulsion Laboratory, Pasadena, CA, USA

SQUIDs are the most sensitive current detector available [3] and currently the standard for reading out TESs [4], but SQUID multiplexers are complicated to fabricate and have limited ability to multiplex the large sensor arrays needed for next-generation instruments. SQUID readouts are thus the current limiting factor for array size of TES-based instruments [4].

Here we describe a new approach to current sensing based on the current dependence of the kinetic inductance of a thin superconducting film. We have designed, fabricated, and tested two devices based on this effect: a resonator, in which an inductance change results in a shift of the resonance frequency, and a transmission line, in which an inductance change results in a shift of the phase length. These devices, called kinetic inductance parametric up-converters (KPUPs), both have single-layer fabrication, large bandwidth, and are suitable for reading out large arrays of TESs.

2 Principle

The kinetic inductance of a strip of superconducting material depends on the current as $L_k(I) = L_k(1 + I^2/I_*^2)$, where I_* is a constant depending on the material and geometry of the strip. If we define the fractional change in kinetic inductance as $x = \Delta L_k/L_k$ and set $I = I_0 + I_s$, then for small currents I_s the sensitivity is $dx/dI_s = (l/2w)(L_s/E_p)$, where l and w are, respectively, the length and width of the strip, $L_s = \hbar\rho_n/\pi\Delta_0 t$ is the sheet kinetic inductance, and $E_p = 2N_0\Delta_0^2 V$ is the superconductor pairing energy. The steady-state bias current I_0 increases the sensitivity and is large compared to the signal current, making the response approximately linear. The sheet kinetic inductance must also be large, meaning we should use a material with a high normal state resistivity ρ_n . Titanium nitride (TiN) and niobium titanium nitride (NbTiN) are superconductors with $\rho_n \approx 100 \mu\Omega \text{ cm}$, and have been used for MKIDs and traveling-wave parametric amplifiers because of their high kinetic inductances [5, 6].

In a resonator, a change in the kinetic inductance results in a change in the resonance frequency: $\delta f/f = (\alpha/2)\delta L_k/L_k$, where α is the fraction of the total inductance that is contributed by the kinetic inductance. By using materials and geometries with large α , a change in the kinetic inductance can be easily seen as a change in the resonance frequency.

In a transmission line, the phase length of the line is determined by the phase velocity, $v_p = 1/\sqrt{\mathcal{L}\mathcal{C}}$, where \mathcal{L} and \mathcal{C} are, respectively, the inductance and capacitance per unit length of the line. A change in the kinetic inductance causes a change in the inductance per unit length, which results in a change in the phase velocity and thus the phase length.

3 Resonator KPUP

3.1 Design and Fabrication

The resonator KPUP is a lumped-element microwave resonator coupled to a co-planar waveguide through a coupling capacitor, which determines the quality factor. Both

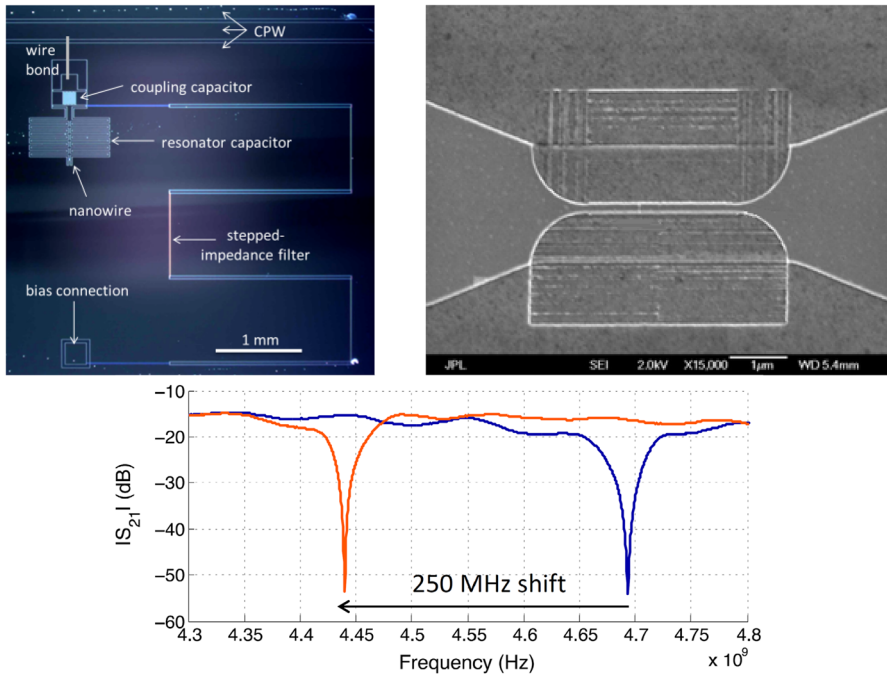


Fig. 1 (Top left) Photograph of resonator KPUP. The coupling capacitor is connected to the CPW center conductor with an Al wire bond. (Top right) Scanning-electron micrograph of nanowire. The striations are a fabrication defect with no bearing on the device integrity. (Bottom) Shift of KPUP resonance frequency with DC bias current of $\sim 60 \mu\text{A}$ (Color figure online)

capacitors are interdigitated, as this configuration has been shown to have reduced two-level systems noise compared to parallel-plate capacitors [7]. The resonator inductor is a nanowire that accounts for approximately one half of the total inductance of the resonator.

The device, shown in the top left of Fig. 1, is patterned from 10-nm-thick sputtered TiN on Si. The film has $T_c \approx 3.1 \text{ K}$ and $L_s \approx 44 \text{ pH}$. In addition to the resonator and feedline, there is a connection used for the low-frequency current signal and steady-state bias current. A stepped-impedance filter links this port to the device, suppressing leakage of microwave power from the resonator. The top right of Fig. 1 shows the nanowire, which was fabricated using electron-beam lithography and is 170 nm wide and 2.6 μm long. The curved ends reduce current crowding, increasing the critical current [8]. This is important for the device sensitivity as it allows for high bias current.

3.2 Measurements

The KPUP resonance frequency is about 4.7 GHz. We measured the response by injecting a DC bias current and observing the change in the resonance on a vector network analyzer. The bottom of Fig. 1 shows the maximum observed shift. At a bias

of $\sim 60 \mu\text{A}$, we see a shift of $\sim 250 \text{ MHz}$, a change of over 5 % relative to the unbiased resonance. Above $60 \mu\text{A}$, the nanowire transitions to the normal state as we surpass the critical current. It should be noted that a large bias current decreases the dynamic range. Although the sensitivity is the greatest near the critical current, a large enough signal current could drive the nanowire normal. However, signal currents are expected to be much smaller than the bias, particularly for TES readout.

The KPUP bandwidth is the resonance half-linewidth, limited by the quality factor. For this device, the bandwidth is $\sim 50 \text{ MHz}$. This means that the device can be AC-coupled and measure RF currents, making it potentially useful for reading out TES arrays multiplexed in this range.

To measure the noise, we injected an 11-MHz AC current through the same port as the DC bias. The parametric up-conversion provided by the nonlinearity results in sidebands 11 MHz from the microwave carrier. The sidebands are down-converted at room temperature using a mixer, and the low-frequency signal is sent to a lock-in amplifier. Using the lock-in, a current noise of $8 \text{ pA}/\sqrt{\text{Hz}}$ was observed, low enough for TES readout. In a separate noise measurement, the device was DC-coupled and $1/f$ behavior was observed below 20 Hz, but the spectrum was flat above this point.

The nanowire inductance is $\sim 0.3 \text{ nH}$, but due to the stepped-impedance filter, the total input inductance for the bias connection is $\sim 90 \text{ nH}$, comparable to the input coil for a SQUID amplifier [9]. This filter could be engineered to have a lower inductance in future iterations of the device.

4 Transmission Line KPUP

4.1 Design and Fabrication

The transmission line KPUP is a long co-planar waveguide. NbTiN was chosen because it has been used in long, highly nonlinear superconducting microwave transmission lines [6]. The top of Fig. 2 shows the device, patterned from 30 nm of NbTiN sputtered on Si. The film has $T_c \approx 14 \text{ K}$ and $L_s \approx 3.3 \text{ pH}$. The center conductor is $1 \mu\text{m}$ wide, and the line is 6 mm long. At either end of the line is a meandering section whose width tapers from 120 to $1 \mu\text{m}$ in the central part of the line. The taper transforms the characteristic impedance of the line from 50Ω to approximately 230Ω .

4.2 Measurements

We measured the current response by injecting a DC current through the center conductor and observing the change in the phase of the microwave carrier at the end of the line using a vector network analyzer. The middle left of Fig. 2 shows this measurement, converted into fractional inductance change over the entire line. It is quadratic as expected, but at higher currents, it is clear that there is a substantial quartic component as well. The critical current is $\sim 3.5 \text{ mA}$, and the greatest inductance change is over 30 %. With such a large critical current, the dynamic range of this device is much greater than that of the resonator device if it is sub-maximally biased.

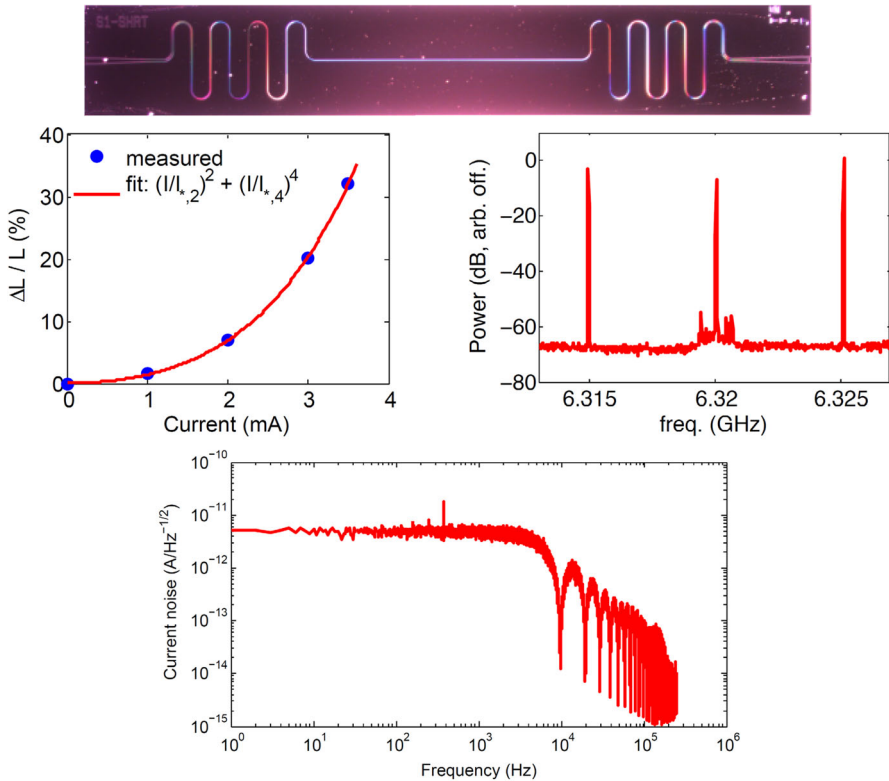


Fig. 2 (Top) Photograph of transmission line KPUP. (Middle left) Measured inductance change of the transmission line KPUP in response to DC current. (Middle right) Spectrum analyzer trace showing the suppressed microwave carrier and sidebands produced by the KPUP. (Bottom) Lock-in amplifier measurement of transmission line KPUP current noise (Color figure online)

Like we did with the resonator device, we injected an AC current along with the DC bias and the carrier. Since this is a traveling-wave device, the bandwidth is very large, and it could be used to detect currents in the same frequency range as the microwave carrier. For our experiment, we used an AC bias of 5 MHz, which resulted in sidebands 5 MHz away from the carrier, as shown in the middle right of Fig. 2. The spectrum shows strong up-conversion of 60 dB above the noise level. The resolution bandwidth here is 10 kHz. The carrier is suppressed below the sideband amplitude by applying a nulling tone after the KPUP but before the HEMT readout amplifier.

The noise was measured by down-converting the sidebands at room temperature using a mixer and sending the low-frequency signal to a lock-in amplifier. Figure 2 shows a noise spectrum, with the roll-off at 300 kHz due to the lock-in amplifier's input filter. The noise level of $5\text{pA}/\sqrt{\text{Hz}}$ corresponds to the expected intrinsic noise of the HEMT amplifier following the KPUP. Thus, the system is limited by the HEMT amplifier, and the KPUP noise is lower than $5\text{pA}/\sqrt{\text{Hz}}$. The total inductance of the line is ~ 130 nH, comparable to that of the input coil of a SQUID amplifier [9].

5 Conclusions and Future Work

We have demonstrated two superconducting devices, the resonator KPUP and the transmission line KPUP, which use the nonlinearity of the kinetic inductance to detect current. The current noise is $8\text{pA}/\sqrt{\text{Hz}}$ for the resonator KPUP and $5\text{pA}/\sqrt{\text{Hz}}$ for the transmission line KPUP. These values are consistent with the requirements for transition-edge sensor (TES) readout.

Future experiments will integrate both these devices with TES arrays. The KPUP's large bandwidth and microwave operation is compatible with a two-stage multiplexing approach, where several TES signals are combined and read out using a single KPUP, for example, by using radio-frequency LC filters; then several KPUPs are multiplexed in the microwave domain.

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