Demonstration of Multiplexed Operation of Hot-Electron Detectors Using MSQUIDs

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Abstract— **We have demonstrated the multiplexed operation of titanium hot-electron nanobolometers (nano-HEB). Because of their low thermal conductance and small electron heat capacity nanobolometers are particularly interesting as sensors for far-infrared spectroscopy and mid- and near-IR calorimetry. However, the short time constant of these devices (~ µs at 300-400 mK) makes time domain or audio-frequency domain multiplexing impractical. The Microwave SQUID (MSQUID) approach pursued in this work uses dc SQUIDs coupled to GHz-band microresonators which are, in turn, coupled to a transmission line. We used a 4-element array of Ti HEBs operated at 415 mK in a He3 dewar with an optical fiber access. The microwave signal exhibited 10-MHz wide resonances at individual MSQUD frequencies between 9 GHz and 10 GHz. The resonance depth is modulated by the current through the bolometer via a change of the SQUID flux state. The transmitted signal was amplified by a cryogenic amplifier and downconverted to baseband using an IQ mixer. A 1-dB per $\Phi_0/2$ responsivity was sufficient for keeping the system noise at the level of ~ 2 pA/Hz$^{1/2}$. This is more than an order of magnitude smaller than phonon noise in the HEB. The devices were able to detect single near-IR photons (1550 nm) with a time constant of 3.5 µs. A digital transceiver for simultaneous generation of 16 probing tones and for processing of 16 downconverting signals has been demonstrated as well.**

I. Introduction

Multiplexed readouts are becoming very important for the transition-edge sensor (TES) arrays continuously growing in size. Along with the requirements for having the least number of wires connecting the detectors residing at sub-kelvin temperatures to the room temperature electronics, the large multiplexing bandwidth is crucial for accommodating a large number of the detector channels. The high multiplexing speed is especially important for the sensors whose inherent signal bandwidth is large. This is the case for the hot-electron nanobolometers (nano-HEB) [1] with the thermal time constant of the order of a microsecond at 300-400 mK. Along with the short relaxation time, the nano-HEB has a very low thermal conductance and a very low electron heat capacitance, both due to the extremely small sensor volume. Compared to traditional micromachined TES bolometers, nano-HEB has a large sensitivity margin. For example, the NEP ≈ 10^{-18} W/Hz$^{1/2}$ is achieved at 320 mK [2] compared to the 50-100 mK temperature range, which is required for other types of bolometers. Also, the ability to detect single photons down to THz frequencies makes the nano-HEB an interesting candidate for sensitive FIR spectroscopic applications [1,3] and for infrared calorimetry.

In order to address the need for an adequately fast readout for nano-HEB, we have built and characterized a small-scale demo array using microwave SQUIDs (MSQUIDs) [4] for X-band frequency-domain multiplexing. In this technique, a dc SQUID is coupled to a high-frequency tank circuit with a relatively high Q-factor. The signal current from the bolometer causes a flux change through the SQUID, which changes the SQUID rf impedance and introduces the damping and/or frequency offset in the resonating circuit [5]. In our implementation, much larger resonator frequencies were used thus making possible the use of microfabricated resonators. The readout electronics for these microresonators are very similar to that used for the microwave kinetic inductance detectors [6].

II. The MSQUID Chip

We used a 4-element MSQUID chip introduced earlier in [4] (see Fig. 1). Each element consists of a dc SQUID capacitively coupled to a coplanar resonator, a signal coil, and a flux control/modulation coil. Each resonator is linked

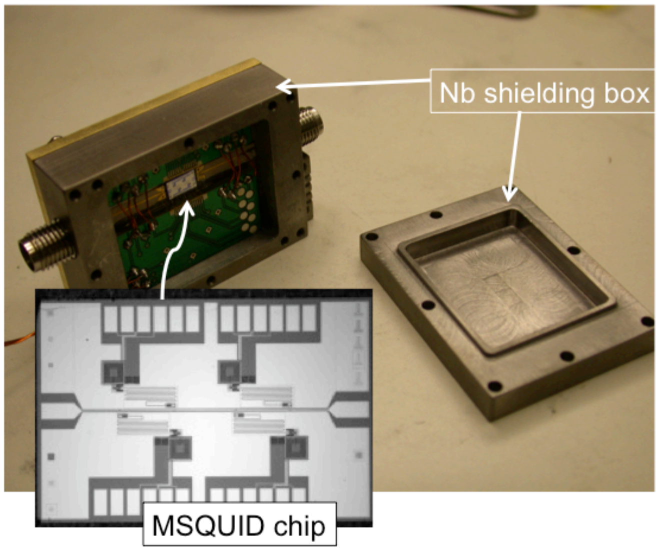

Fig. 1. A four-element Microwave SQUID chip in a Nb shielding enclosure. The coplanar transmission line runs horizontally across the chip; meander line shaped resonators are coupled to the line from the top and from the bottom.

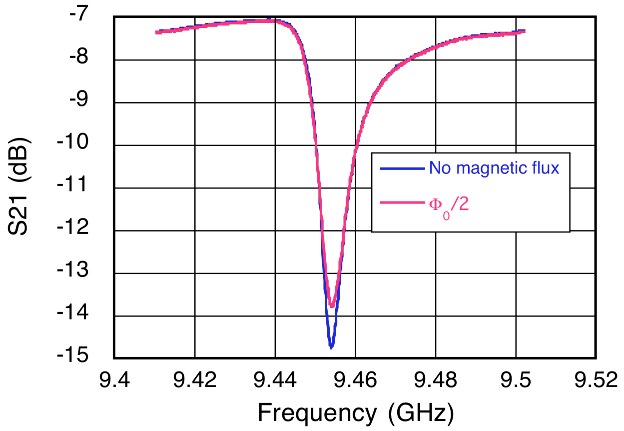

Fig. 2. A transmission of the coplanar line in the vicinity of the resonance frequency of one of the MSQUID resonators. A maximum change of the SQUID flux state ($\Phi_0/2$) causes an about 1-dB change of S_{21}. The phase shift for this MSQUID design was negligibly small.

to a common coplanar waveguide (CPW) transmission line through which the probing microwave signals was launched. The SQUIDs are biased by adjusting the transmitted signal power rather than by dc current. A separate common line connected to the flux control/modulation coils is used for tuning the SQUIDs flux bias points. The individual resonator lengths set the channel frequencies and their separation. For this particular design, all the resonator frequencies were between 9 and 10 GHz and separated by approximately 200 MHz. A typical microwave transmission of a single MSQUID resonator is shown in Fig. 2. The resonance width is about 10 MHz and its depth is decreasing by ~ 1 dB when the maximum flux ($\Phi_0/2$) is coupled to the SQUID. In these experiments, the SQUIDs were operated in open loop mode, therefore a periodic response was observed when the signal current exceeded $\Phi_0/2M$ (M is the mutual inductance of the signal coil).

III. The Test System

The experimental system was built in an IR Labs HDL-8 He3 cryostat (see Fig. 3). The HEB sensors along with bias filters were placed on a shielded He3 cold plate. The MSQUID chip was enclosed in an Nb magnetic shield and placed on a 4K cold plate (in the future work, a more compact casing will be

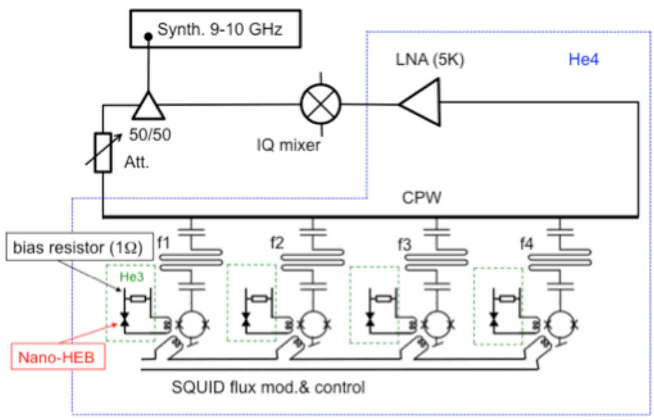

Fig. 3. A schematic of the test system. Components surrounded by the dotted blue line were on the He4 platform (4.3 K). The bolometer (dashed green line) were on the He3 platform.

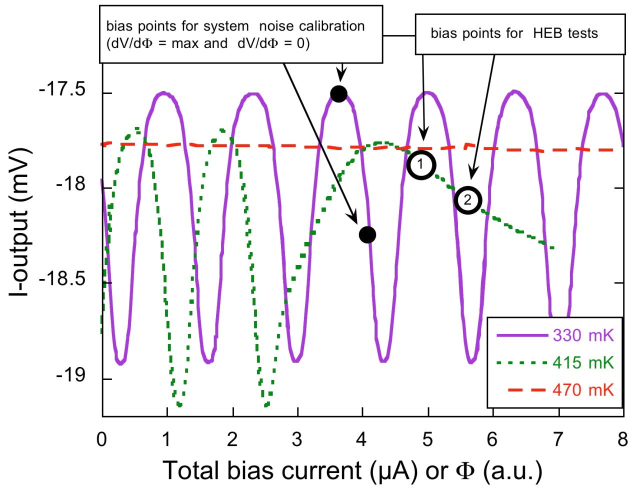

Fig. 4. Signal at the output of IQ-mixer as function of the total current through the HEB device in parallel with a 1-W resistor. When the HEB is in superconducting state, the total current is proportional to the SQUID magnetic flux. 330 mK: the HEB is in superconducting state. When the device was absent, a similar periodic response function was used for the system noise calibration. 425 mK: the device is in the resistive state. Bias points 1 and 2 were used for noise measurements of Fig. 6. 470 mK: the device is in the normal state.

used so the MSQUID chip can reside next to the detectors on the same millikelvin platform). The probe signal was generated by a microwave synthesizer and sent in the dewar through a tunable attenuator and stainless coax. We used a second synthesizer in order to simultaneously operate two pixels. The magnitude of the probe signal was tuned experimentally to provide the maximum sensitivity of the MSQUIDs to the magnetic flux. The probe signal was also fed to an IQ mixer. After passing through the MSQUID chip, the microwave signal was amplified by a broadband cryogenic low-noise amplifier (LNA) with noise temperature ≈ 5 K mounted next to the MSQUID housing and sent to the IQ mixer. We recorded both in-quadrature output signals but did not process the data to retrieve amplitude-phase coordinates. Only the signal exhibiting the largest response is discussed. The signal coils of MSQUIDs were connected to the HEB devices via 50-µm dia NbTi superconducting twisted pairs shielded individually with NbTi thin-wall capillaries. Each bolometer was voltage biased using a 1-Ω shunt resistor. The bias lines were filtered using 3-stage RC-filters embedded in Eccosorb CRS-124 microwave absorber.

To calibrate the system noise performance and the bandwidth we measured the noise at the output of the mixer as function of the temperature of a 1-Ω resistor directly connected to the SQUID input coil. To obtain the maximum sensitivity, the flux bias point was tuned to region where the derivative $dV/d\Phi$ reaches maximum (V is the output voltage, see Fig. 4). In order to measure the system noise, the flux bias was chosen to be at its maximum or minimum value (where $dV/d\Phi = 0$). In either case the resistor noise is effectively prevented from reaching the SQUID input coil and the total noise contribution of the MSQUID and the LNA could be measured.

Figure 5 shows the noise spectra for 3 different experimental settings. From these data, assuming that the resistor generates only Johnson noise, the effective

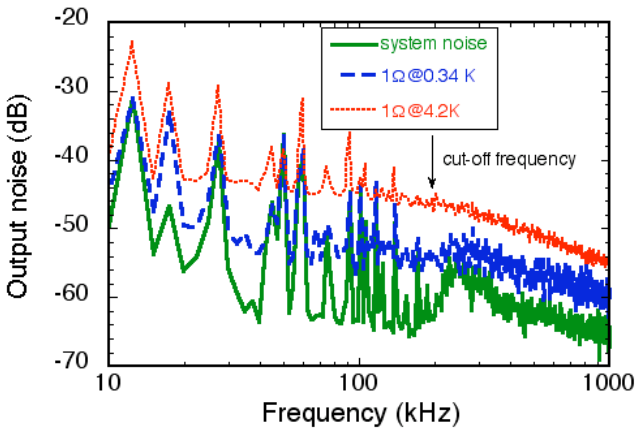

Fig. 5. System noise characterization using the Johnson noise of a 1-Ω resistor at 340 mK and at 4.2 K. The roll-off of the noise spectra is due to the low-pass Ls/R filter.

system noise is ~ 2 pA/Hz$^{1/2}$. The roll-of of the noise spectrum is due to the L_s/R low-pass filtering at the input coil (L_s is the input coil inductance). The cut-off frequency of ~ 200 kHz agrees with $L_s \approx 1$ µH.

IV. MSQUID Test Using HEB Devices

Two Ti HEB devices (20µm × 1µm × 40 nm) were used. The devices exhibited a superconducting transition with T_C = 430 mK with nearly zero residual resistance. Figure 4 shows the output signal for one of the devices as function of the bias. Well below T_C (330 mK) the response is periodic, and corresponds to a monotonically increasing subcritical current through the device. Just below T_C (415 mK), the critical current value is achieved at about 3 µA of the total bias current. After that the current through the device increases slower (all changes are within the $\Phi_0/2M$ range), reaches its peak value at ~ 4.2 µA and then decreases, exhibiting an N-shaped IV characteristic typical for the voltage biased TES.

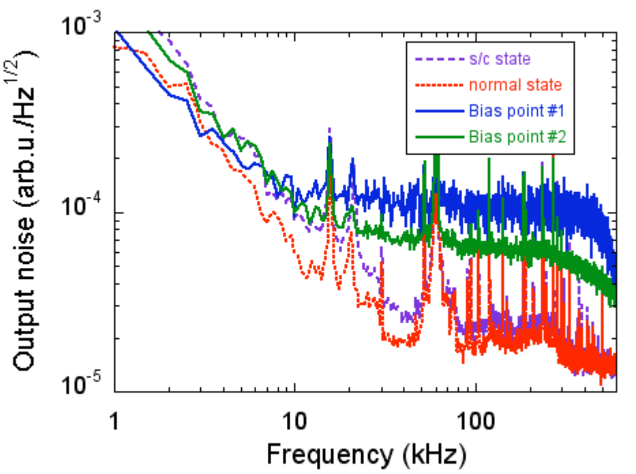

Fig. 6. Output noise from a Ti HEB device. When the detector device is biased to the points of high responsivity (two upper traces taken at points 1 and 2 in Fig. 4) its noise exceeds the system noise. The dotted line shows the noise when the device is in the normal state. The dashed line is the noise when the device is in superconducting state. The 1/f noise below 10 kHz is due to the TLS noise in the superconducting resonator.

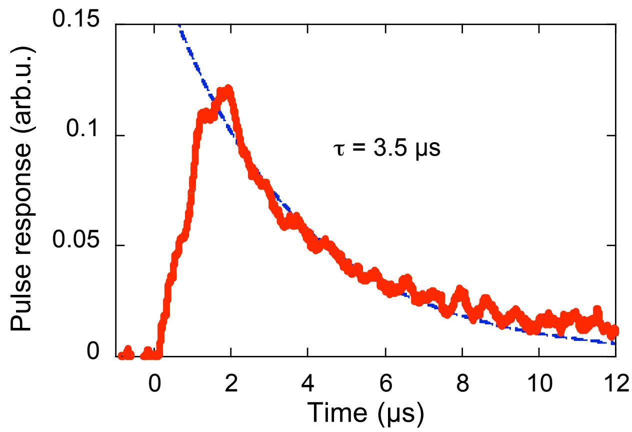

Fig. 7. Response of the HEB detector to a single NIR photon (λ = 1550 nm).

When the device is biased in the negative differential resistance region (bias points 1&2 in Fig. 4), the output noise increases reflecting the corresponding increase of the responsivity. This detector noise (traces "bias point 1" and "bias point 2" in Fig. 6) well exceeds the system noise except in the frequency range below 10 kHz where 1/f-noise is observed. This noise likely originates from the two-level system noise (TLS) observed in Nb superconducting resonators [7]. The presence of the TLS noise may represent a problem for slow bolometers. Fortunately, this is a minor problem for HEB detectors operating above 300 mK where the most of the signal bandwidth is above 10 kHz, and where some kind of modulation can be used to completely avoid the 1/f noise.

The detector's white noise level agrees well with our recent measurements [2] where we found the output noise for Ti HEB at ~ 320 mK to be about 60-70 pA/Hz$^{1/2}$. The noise is dominated by thermal energy fluctuations (TEF or "phonon" noise). The devices studied in [2] are smaller in size, but, since the TEF noise does not depend on the HEB sensor volume, the same magnitude should be expected in the current experiments. Indeed, the detector noise exceeds the system noise by an order of magnitude in the current setup that proves the low-noise operation of the MSQUID readout.
Finally, we measured the time constant of the HEB devices by detecting single NIR photons (1550 nm wavelength). Short pulses (~ 1 µs duration) were generated by a fiber-coupled laser diode. The fiber was fed into the dewar and then through a cold (4.2 K) 25-dB attenuator to the HEB device. A room temperature variable attenuator was used to adjust the energy per pulse to a sufficiently low level so that only one photon per pulse was typically detected. The amplitude of the single-photon response was a small fraction of the total output of the IQ-mixer so the exponential shape of the pulse was preserved (see Fig. 7) despite the non-linearity of the used readout technique. The observed microsecond time constant originates mostly from the electron-photon relaxation in Ti HEB at this temperature [1,2]. The electrical time constant L_s/R should be noticeably less in this case as the total resistance R > 1 Ω (compare to the data of Fig. 5).

V. Digital Readout of MSQUIDs

The prototype analog circuit of Fig. 3 allowed for reading of just one detector at a time. In order to demonstrate the real multiplexed operation all frequency tones corresponding to the superconducting resonators must be generated simultaneously. At the same time, all the signals passing the MSQUID must be downconverted and digitized fast enough to preserve the detector signal bandwidth and to maximize the signal-to-noise ratio of the system. In order to do this, we built and tested a circuit shown in Fig. 8. The general approach was proposed in [8]. Our particular implementation included generation of 16 frequency tones in a 80-MHz range (see Fig. 9) using an arbitrary waveform generator Tektronix AWG 5012B. The spectral purity of the individual tones was identical to that of a standard HP synthesizer. The entire frequency comb was upconverted to the GHz range and after passing the MSQUID array was downconverted to the baseband and fed into a broadband 16-bit ADC (Pentek 7852) which had the input bandwidth of 200 MHz (~ 100 MSPS) and a firmware core allowing for digital downconvertion of the baseband signal into 32 output channels. The digital local oscillator (LO) frequencies have to be synchronized with the frequencies of the comb generated by AWG5012B. Each channel's bandwidth could be tuned between 20 kHz and 10 MHz. The system was tested using sinusoidal signals with the frequency set apart from the digital LO frequency by 500 Hz – 50 kHz (that is, within the output channel bandwidth. Spectral analysis of the processed signals did not reveal any significant spurious components.

VI. Follow-on Development

The system setup is on-going and in the next phase we expect to test the entire system with up to 16 nano-HEB detectors operating at 650 GHz. Compared to the setup of Fig. 3 the nano-HEB array and the MSQUID chip will be at the same low temperature (He3) and be connected to the higher temperature (4.3K) platform via only 2 NbTi low thermal conductance coaxes, 2 detector bias wires and 2 SQUID modulation wires (Fig. 8). We plan to implement a

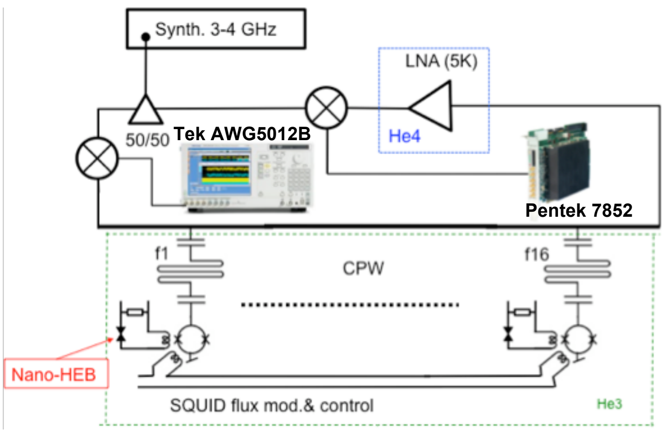

Fig. 8. A schematic of the test system with digital MSQUID readout. Components surrounded by the dotted blue line were on the He4 platform (4.3 K). Both the bolometers and the MSQUIDs (dashed green line) will be on the He3 platform.

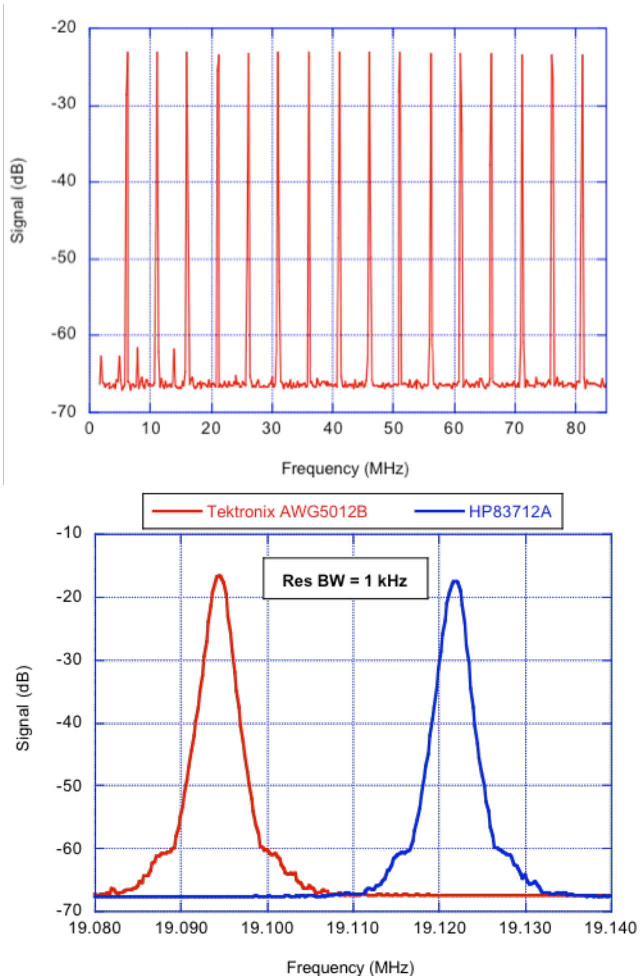

Fig. 9. Top panel: 16 digitally generated frequency tones for probing superconducting resonators. Bottom panel: comparison of the lineshape of one the tone to the frequency line produced by an HP synthesizer.

modification of the MSQUID chip in order to improve the overall system performance. The new prototype chip uses dissipationless MSQUIDs at 3-4 GHz [9] with lumped-element resonators, which should have a lesser 1/f noise [10]. Eventually the separation between the resonances should be tuned to ~ 1-2 MHz to allow for a maximum number of pixels per the ADC bandwidth without putting a limitation on the signal bandwidth or causing a crosstalk between pixels. We will also use antenna-coupled nano-HEB which have been recently tested in a separate optical setup having demonstarted an optical NEP below 10^{-17} W/Hz$^{1/2}$ at 360 mK [11-12].

VII. Conclusions

The obtained results clearly demonstrate the feasibility of low-noise and broadband readout scheme using microwave dc SQUIDs. Both the system noise and the bandwidth were sufficint to operate Ti HEB detectors without degradation of the sensitivity and the detector response time. Given the progress with ADC and DAC electronics much larger number of pixels per ADC/DAC (up to ~ 1000) can be expected in the future. A combination of the high sensitivity along with the μs response time and high operating temperature requiring only a simple He3 sorption cryostat is attaractive for using in ground based and suborbital submillimeter instruments

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