Cryogen-free operation of a voltage-biased superconducting bolometer

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We report on the performance of a Nb voltage-biased superconducting bolometer cooled by a closed cycle pulse tube cooler. The VSB has a Tc ~ 8.1 K and an operating impedance of R ~ 800 Ω. A preliminary value for the system optical noise equivalent power (NEP) = 1.8 × 10 -12 WHz-1/2 and τ = 0.6 ms.

I. Introduction And Background

Historically, the sensitive detection of light at far-infrared wavelengths has been achieved using semiconductor bolometers[1,2]. Bolometers are high impedance devices that typically operate with a temperature coefficient of resistance α ~ 30 and are limited in speed of response due to the heat capacity of the Ge thermistor. In contrast Transition Edge Superconducting (TES) bolometers exhibit many superior qualities when compared with traditional semiconductor bolometers[4,5] including: very high α (~1000), significantly lower NEP for a given bath temperature, fast response and low operating impedance. Another important difference is that whereas NTD thermistors have to be attached individually to array receivers the TES devices can be manufactured using standard processing techniques enabling the fabrication of large format arrays.

Most TES devices fabricated to date have been optimized for operation at temperatures between 100 and 300 mK with impedances of a few mΩs which require SQUID readout electronics. Here we report experimental results from a Nb voltage-biased superconducting bolometer (VSB) that has an impedance of 800 ohms enabling it to be directly coupled to a room temperature amplifier. This simple design retains high sensitivity when compared to semiconductor bolometers operating at similar temperatures.

In this device a 3 mm diameter Au absorber is supported in the center of a 6 mm x 6 mm low stress silicon nitride membrane together with a large area Nb TES sensor. This results in a device that does not easily saturate under high incident power and one in which the operating impedance is relatively large at R ~ 800 Ω.

This detector design enables operation with cryogen-free cooling systems which achieve temperatures near 4K and has the sensitivity and speed of response which is competitive with semiconductor bolometers operating at similar temperatures. A standard external low noise preamplifier is used for readout which allows the use of the inherent high dynamic range enabling a broad range of applications.

II. Results

Experimental evaluation of this detector was conducted in a Vericold CO-5 [6] closed cycle pulse tube cooler (PTC) with 250mW cooling capacity at 4 K. Thermal oscillations at the pulse frequency (in this case, ±200mK at ~1Hz) are common in PTC's. Thermal buffering between the detector and the 2nd PTC stage is therefore necessary and is achieved using a two stage weak thermal link with PID servo control on the detector block giving a temperature stability of σ = 90 µK at 8.1 K over several hours.

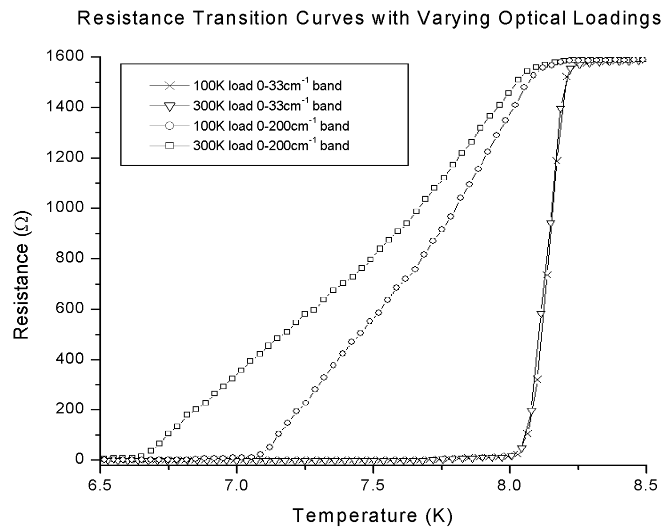

Figure 1 – Resistance transition curves for a Nb detector under different optical loading conditions.

The detector comprises four identical superconducting devices that are optically coupled using a single f/2 Winston cone in line with a series of cooled low-pass metal-mesh filters and a 500 µm thick HDPE vacuum window. A room temperature aperture defines a throughput of $A\Omega \sim 1 \times 10^{-8}$ m^2 sr. Tests were carried out under low and high background loading, defined by low-pass filters with transmission cut-off frequencies of 1THz and 6THz. Resistance transition curves were measured at different optical loadings using a low excitation constant current AC bridge connected in a four-wire configuration. The temperature coefficient of resistance was calculated to be α = 60 for 1THz illumination and α = 40 for the 6THz arrangement – still superior to a typical semiconductor bolometer even under load. Figure 1 demonstrates how detector saturation is suppressed under increasing optical load due to a broadening of the transition curve. This broadening occurs as a result of the increased temperature differential across the device which in turn defines the proportion of the device that is superconducting. For high background conditions, it is necessary to reduce the bath temperature in order to maintain peak sensitivity at the resistance midpoint of the transition curve. Currently, this is a manual process that will be automated in the next generation of readout electronics.

The readout electronics are being developed in parallel with detector testing. We have developed both integrating and non-integrating voltage bias readout amplifiers for use in speed of response and NEP calculations. Both amplifiers have an adjustable bias between 0 and 100mV. A low bias (typically < 20mV) is used so that self heating at lower detector resistances is minimized. The effect of bias voltage on the resistance transition curve is demonstrated in figure 2.

With the existing electronics, we observe a system optical NEP of 1.8×10^{-12} W $Hz^{-1/2}$ and a response time constant of $\tau = 0.6$ms for the low background 1THz band. We estimate a detector NEP of ~ 2×10^{-13} W $Hz^{-1/2}$. At high background loadings the detector becomes less sensitive with an increased NEP (~3×10^{-12} W $Hz^{-1/2}$ for the 6 THz band). Measurements of the response time constant show the device speed to be independent of optical and electrical (bias) load. With the next generation of readout electronics, we aim to reduce the readout noise by an order of magnitude and thus improve on the quoted NEP.

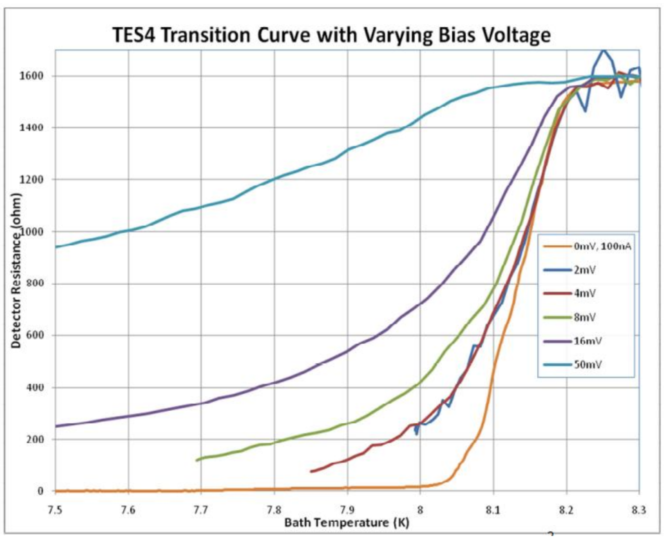

Figure 2 – Voltage bias self heating for 0 to 50mV. 0mV was measured using an AC bridge with low excitation current and so exhibits negligible self heating. 2 to 50mV curves are measured using the voltage bias readout electronics.

A superconducting device of this type is well suited for use with a rapid-scan Fourier transform spectrometer (FTS)[7]. We have successfully coupled our detector system to a room temperature Mach-Zehnder FTS and measured spectra from a narrow line 330GHz source (figure 3). The effects of detector non-linearity are visible as harmonics in the transformed spectrum. We are currently using the FTS to further explore the effects of non-linearity in VSB devices and to validate correction algorithms of which our group has significant experience.

We are now working towards improving the performance of the VSB by further reduction of the device resistivity, heat capacity, and electronic readout noise.

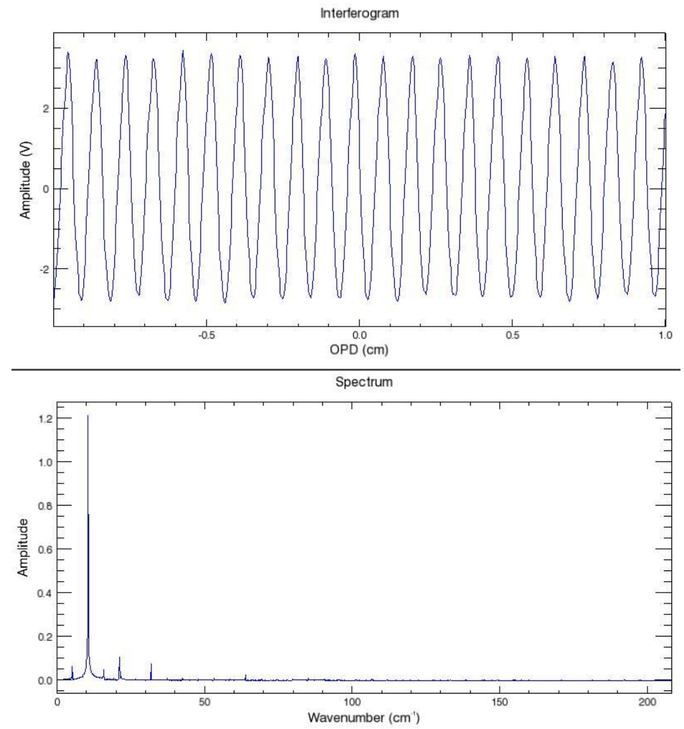

Figure 3 – Fourier transform data for a 330GHz narrow band source.

In addition to the Cardiff supplied detectors, we have recently begun a detector development program in Canada using the well equipped NanoFab Laboratory situated at the University of Alberta in Edmonton [8]. A selection of the first batch of new detectors, prior to Au absorber deposition, have recently been cryogenically tested and shown to superconduct and at the intended transition temperature and to detect at 330GHz. A selection of detector designs and Nb film thicknesses, including small arrays, are now near completion.

This work is being conducted in our laboratories in Cardiff and Lethbridge.

References

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