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A Microwave-Operated Hot-Electron-Bolometric Power Detector for Terahertz Radiation

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and Gregory Gol'tsman

***Abstract*—A new class of microwave-operated THz power detectors based on the NbN hot-electron-bolometer (HEB) mixer is proposed. The injected microwave signal (~1 GHz) serves the dual purpose of pumping the HEB element and enabling the read-out of the internal state of the device. A cryogenic amplifier amplifies the reflected microwave signal from the device and a homodyne scheme recovers the effects of the incident THz radiation. Two modes of operation have been identified, depending on the level of incident radiation. For weak signals, we use a chopper to chop the incident radiation against a black body reference and a lock-in amplifier to perform synchronous detection of the homodyne readout. The voltage measured is proportional to the incident power, and we estimate an optical noise equivalent power of ~5pW/√Hz at 0.83 THz. At higher signal levels the homodyne circuit recovers the stream of steady relaxation oscillation pulses from the HEB device. The frequency of these pulses is in the MHz frequency range and bears a linear relationship with the incident THz radiation over an input power range of ~15 dB. A digital frequency counter is used to measure THz power. The applicable power range is between 1 nW and 1 µW.**

***Index Terms*—hot-electron-bolometer mixer, power measurement, THz radiation, direct detector, relaxation oscillations.**

I. Introduction

Hot-Electron-Bolometer (HEB) mixers, based on NbN thin film, are widely used as heterodyne detectors for THz radiation. However, for certain applications, they are also used as direct detectors [1, 2]. In such cases, the bath temperature of the HEB element is usually raised to around its critical temperature, Tc, and the variation of its bias current as a function of incident THz power provides the basis of detection. For NbN films operating at around a wavelength of 0.4 mm, a Noise Equivalent Power (NEP) of ~2 pW/√Hz has been reported [3].

Recently, it has been proposed that microwave injection can enhance the detection sensitivity of the HEB direct detector without the need to raise the bath temperature [4]. In this paper, we present an experimental study of such a microwave-operated HEB power detector for THz radiation. The use of microwave injection opens the door to novel readout schemes, which are similar in principle to those of the microwave kinetic-inductance detectors [5].

Two distinct modes of operation have been exploited, depending on the power level of the incident THz radiation. For weak signals the detector operates like most cryogenic bolometric detectors, which rely on a chopper to chop the input signal against a reference temperature, and the detected signal power level is read from a lock-in amplifier. However, the detector can also work at higher power levels. In this case, a digital readout technique has been developed for the power measurement. Here we report on both modes of operation.

II. Small-Signal Experimental Setup

The idea of the microwave-operated HEB direct detector came from the microwave stabilization scheme, described previously [6]. This scheme was proposed to improve the stability of HEB heterodyne detectors, and we used an almost identical set up in this work. A schematic of the setup is given in Fig 1.

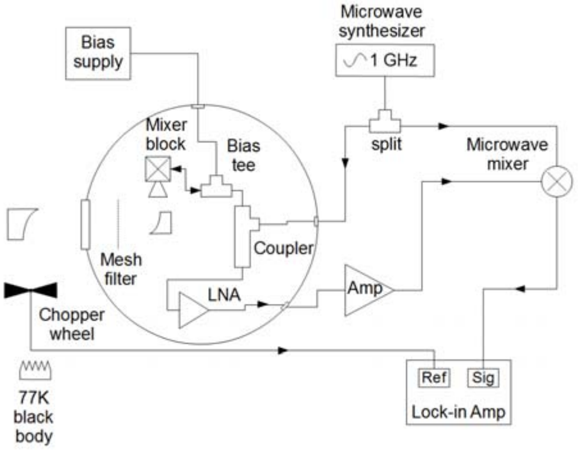

Fig. 1 Experimental setup for the small-signal detection scheme.

The size of the HEB elements are typically 0.5 µm long and 5 µm wide, and the typical normal state resistance is ~ 75 Ω. In the current setup, a broadband coupler is placed between the HEB mixer and the cryogenic low-noise amplifier (LNA) for microwave injection.

One key difference between the microwave stabilization

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scheme and the current work is that the injection frequency used here is much lower, typically ~ 1 GHz. In fact, the injected CW signal is chosen to be within the IF band of the HEB mixer, so that the LNA amplifies any reflected microwave power from the HEB element resulting from the microwave pump. A homodyne set-up demodulates the reflected wave, which is modulated by the incident THz power. The injected microwave, therefore, serves the dual purpose of pumping the HEB element and enabling a read out of the impedance change of the device. The amount of injected microwave power applied to the device is estimated to be about 10 μW, or -20 dBm.

In the small signal case, we use a liquid-nitrogen-cooled black body, chopped against a load at ambient temperature, as the signal source. The chopper operates at a frequency of about 700 Hz, and a mesh filter, placed in the signal beam inside the cryostat, defines the input bandwidth to the detector. The center frequency of this filter is 0.83 THz and its noise equivalent bandwidth is determined to be ~77 GHz. Thus, the HEB element sees an incident power variation, ΔP ~ 0.23 nW from the chopping loads. A lock-in amplifier, operating with a time constant of 30 ms, records the amplitude of the demodulated signal.

III. RESPONSIVITY TO SMALL SIGNALS

Previous studies showed that when an HEB element is subjected to a microwave pump, switching and hysteresis in the current-voltage (I-V) characteristic can be observed [7]. A set of I-V curves is displayed in Fig. 2 showing these effects. As the level of the pump increases, the bias voltage, at which the switching between the super-current and the normal state occurs, moves towards the origin. Above a certain pumping power, the super-current becomes completely suppressed and the I-V curve becomes fairly smooth, with no hysteresis.

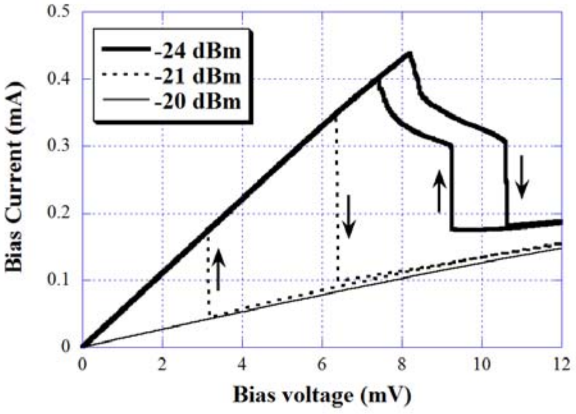

Fig. 2 Current-voltage characteristics of an HEB device pumped at different microwave power levels. Hysteresis is observed at low power levels.

The measured AC voltage from the lock-in amplifier is plotted as a function of bias voltage for different microwave pumping levels in Fig. 3. The curves were obtained when the bias voltage was swept towards zero bias. Also shown in the same plot is the noise floor measured by the lock-in amplifier when an ambient absorber was used to block the detector input. The noise floor was generally about 2 μV at high bias levels, and when the device was in the superconducting state.

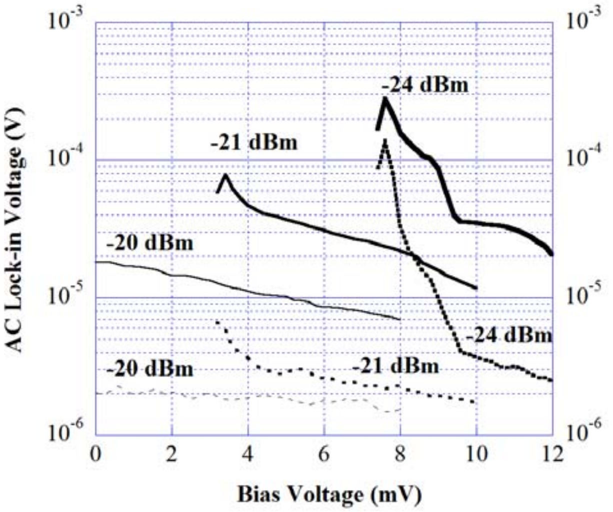

Fig. 3 Output of the small-signal detector as a function bias voltage and injected microwave power. The corresponding noise floor is also plotted (dotted lines).

By comparing these curves with the corresponding I-V curves displayed in Fig. 2, one notes that, for lower microwave pumping levels, the detector output rises as the bias voltage is swept towards the superconducting state, peaking when the bias current almost reaches the super-current for that pumping level. In the case of higher microwave pumping power, which produces a smooth I-V curve, the detector output voltage peaks at zero bias.

The increased responsivity close to the super-current is clearly associated with the steep negative slope of the I-V curve (see Fig. 2). When the device assumes a negative resistance, the reflection coefficient becomes larger than unity, so that that the LNA picks up more microwave power than the injected power. The steep negative slope around the super-current accentuates this situation and the detector actually offers significant reflective gain to the microwave pump.

Referring to Fig. 3, the detector noise is also a function of both bias voltage and pumping level, and follows the same pattern as the responsivity. The best signal-to-noise ratio (SNR) is obtained at intermediate bias voltages for weak microwave pump and at zero bias for high pump power. A maximum SNR of 15 was obtained at a pumping power of -21 dBm and a bias voltage of ~4.5 mV. The SNR can be translated into an optical NEP by using the equivalent noise bandwidth of the lock-in amplifier at the time constant used. An optical NEP of 5 pW/√Hz was inferred in the best case. This is slightly poorer than the NEP reported in [3] for the same frequency range but with calibration made using black bodies rather than CW sources.

When the device was pumped harder to suppress the super-current, the differential slope always became positive, with the highest slope occurring at zero bias. At this pump level, the highest responsivity and sensitivity were observed around zero bias. The prospect of operating the detector at zero bias with a slightly higher microwave pump power is fairly interesting

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since biasing electronics and wires may be eliminated. If the microwave pump power is set to be just sufficient to suppress the super-current, the responsivity and the sensitivity of the device are still competitive and are both ~20% below the peak values obtained with lower drive and active bias.

IV. Relaxation-Oscillation-Based Detection

While the technique presented above works for black body radiation with incident power levels amounting to fractions of nW, it is not suitable for use at much higher input power levels, for example at power levels delivered by CW sources. Here we present a different detection technique based on relaxation oscillations. In this case, the injected microwave signal no longer pumps the HEB device but acts as a probe for the relaxation oscillation.

It is well known that HEB devices exhibit relaxation oscillations [8] when biased at intermediate voltages between the superconducting and normal state. We find that this type of spontaneous switching phenomenon persists even in the presence of low level of incident THz radiation. In Fig. 4 we plot a series of I-V curves corresponding to different levels of pump power at 0.8 THz. Referring to the figure, as the incident pump power increases, the device goes through a bi-stable region, which is characterized by negative differential resistance. Compared to the I-V curves shown in Fig. 2, no distinct switching is observed. This is because the incident photons have an energy which is above the gap superconducting of the NbN thin film [7].

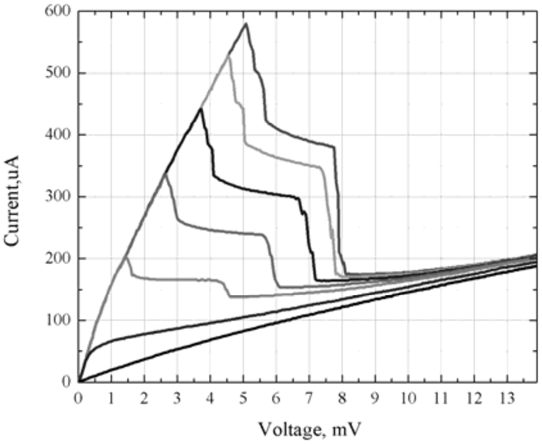

Fig. 4 Current-voltage curves of a typical HEB device pumped by THz radiation.

A schematic of the experimental set-up is given in Fig. 5. As in the small signal detector, the injection frequency was chosen to be within the band of the LNA. However, the injected microwave power was kept low, typically about 10 nW at the device, compared to 10 μW used for the small-signal experiments. After amplification by the cryogenic LNA and a room temperature amplifier, a spectrum analyzer was used to examine the reflected wave from the device. At the same time, this signal was demodulated using the homodyne detection scheme described above. After filtering and further amplification, an oscilloscope captured the time domain signal carrying information regarding the state of the device.

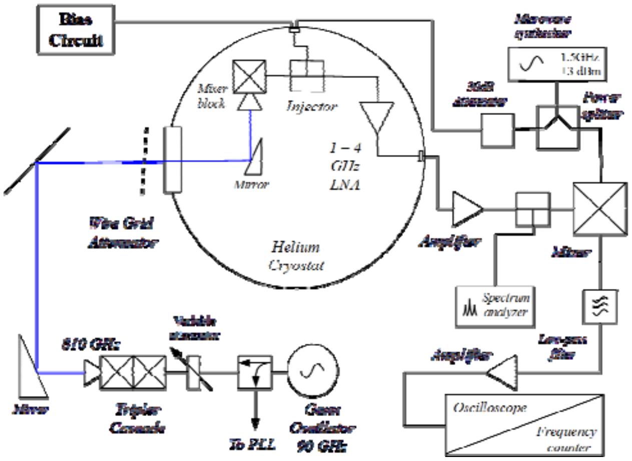

Fig. 5 Experimental setup of the relaxation-oscillation-based power detection system.

Spectra of the reflected microwave probe signal showed the carrier together with multiple sidebands spaced regularly about the carrier. This is consistent with a modulation by the relaxation oscillation. We found that the modulation frequency increases as the incident THz power level is increased. In addition, this modulation frequency is very stable for any given input power setting. Fig. 6 shows the relaxation oscillations recorded by the oscilloscope. The oscillations appear as a train of pulses. With increasing incident THz radiation, the frequency of the pulses increases, while the shape of the pulses remains the same. The pulse width, in particular, remains constant, independent of the amount of incident power.

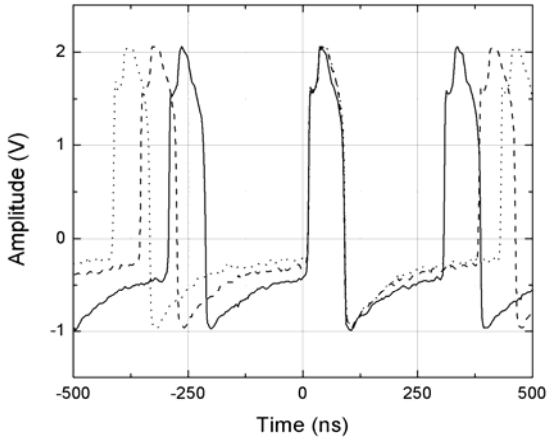

Fig. 6 Time-domain relaxation oscillations captured by the oscilloscope for 3 different bias points in the bi-stable region. The pulse rates are: 2.35 MHz (dotted line), 2.73 MHz (dashed line), and 3.27 MHz (solid line). Note that they all have the same pulse width.

V. DIGITAL POWER MEASUREMENT

The fact that the recorded pulse shape is fairly square reveals an internal spontaneous switching in the device, between the superconducting and normal state. Since higher incident radiation leads to more heating of the device, a higher pulse rate at a constant pulse width indicates that the device is spending proportionally more time in the normal state. If one assumes that a certain amount of energy is required to push the device from the superconducting state into the normal state, and this energy is supplied in part by the incident radiation, then a measurement of the switching rate should be a good measure of the incident power.

In order to verify the above hypothesis, we used a frequency counter to record the pulse rate at the output of the homodyne detection scheme. The frequency counts were generally stable for a fixed incident power. Scattering of counts was typically a few kHz (~0.1%). A wire grid attenuator was installed in front of the cryostat window to vary the incident power; and in Fig. 7 we plot both the frequency count and the bias current of the HEB device as a function of the relative incident power as the wire grid is rotated. The data show that the frequency count forms an excellent linear fit with respect to incident power. The bias current also shows a reasonable fit but over a 10-fold change in incident power, a few percent of deviation from linearity is noted. Clearly, the digital frequency count is an excellent proxy of the incident power level.

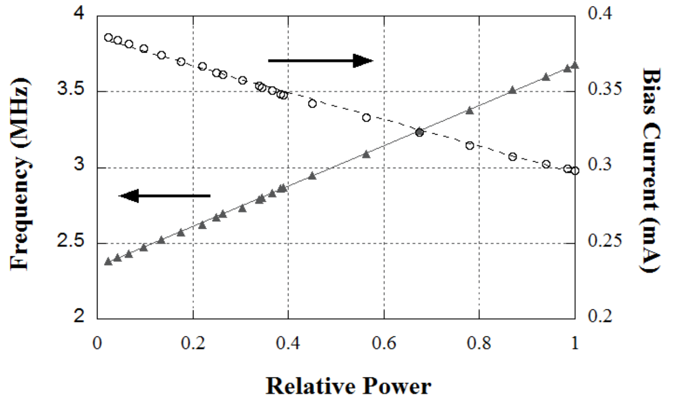

Fig. 7 Variation of frequency count and bias current as the incident THz power level is varied using the wire grid attenuator. The lines on the plot represent the best linear fit to the data points.

With the wire grid set at the minimum attenuation we estimated the maximum incident THz power level to be ~70 nW In Fig. 8 we plot the frequency shift in relaxation oscillation $\Delta f = f\,(P_{\text{incident}}) - f\,(0)$ as a function of relative incident power in a log-log plot. The figure shows that the linearity range of the measurement is about 15 dB. The linearity measurement was probably limited by the leakage of the wire grid polarizer and the polarization purity of the source and detector.

For this particular device, measuring 5 x 0.5 μm, the linear measurement range runs from 3 to 70 nW. A device with larger volume would allow higher power to be measured. Currently, most THz power meters operate above 1 μW, so this technique represents a potential unique application for the HEB mixer element. Accurate calibration of power levels can be achieved by running the detector in the small-signal mode and black body radiation sources can be used for calibration.

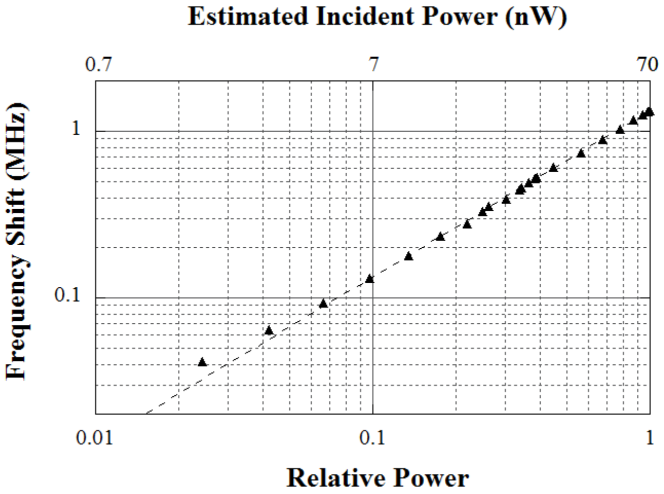

Fig. 8 Log-log plot of the measured frequency shift as a function of the incident THz power. The horizontal scale above the plot gives the estimated incident power. The solid line is the best linear fit of the data points, and shows a linearity range of about 15 dB, from 3 to 70 nW.

VI. CONCLUSION

By injecting microwaves to an NbN hot-electron bolometer mixer, we were able to use the reflected microwave power from the device to measure the power level of the incident THz radiation. Two modes of operation have been developed. In the small-signal detector, the impedance modulation induced by the chopper was demodulated in a homodyne scheme and measured by a lock-in amplifier. The detector could be operated at zero bias when the microwave power was just high enough to suppress the super-current. At higher incident power levels, frequency counting of the relaxation oscillation pulses provided a digital readout of the incident power. This mode of detection is suitable for power levels in the range of 1 nW - 1 μW; and, with a linearity range of >15 dB, offers the possibility of accurate power measurement of weak THz signals.

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REFERENCES

[1] W.F.M. Ganzelves, L.R. Stewart, J.R. Gao, P.A.J. de Korte, and T.M. Klapwijk, “Direct response of twin-slot antenna-coupled hot-electron bolometer mixers designed for 2.5 THz radiation detection,” *Appl. Phys. Lett.*, vol. 76, pp. 3304-3306, May 2000.

[2] Y. Ren, D.J. Hayton, J.N. Hovenier, M. Cui, J.R. Gao, T.M. Klapwijk, S.-C. Shi, t.-Y. Kao, Q. Hu, and J.L. Reno, “Stabilized HEB-QCL heterodyne spectrometer at super-terahertz,” *Proc. SPIE,* vol. 8452, p. 845210, Sept. 2012.

[3] Yu.P. Gousev, G.N. Gol’tsman, B.S. Karasik, E.M. Gershenzon, A.D. Semenov, H.S. Barowski, R.S. Nebosis, and K.F. Renk, “Quasioptical superconducting hot electron bolometer for submillimeter waves,” *Infrared & MM Waves.*, vol. 17, no. 2, pp. 317-331, 1996.

IEEE/CSC SUPERCONDUCTIVITY NEWS FORUM (global edition) January 2015.
ASC 2014 manuscript 2EPo1E-06 published online in *IEEE Trans. Appl. Supercond.*
(IEEE XPLORE) DOI: 10.1109/TASC.2014.2377670, on December 18, 2014.

[4] Y. Lobanov, C.E. Tong, A. Hedden, R. Blundell, and G. Gol'tsman, "Microwave-assisted measurement of the frequency response of terahertz HEB mixers with a Fourier transform spectrometer," in *Proc. 21st Int. Symp. Space THz Tech.,* pp. 428-432, Oxford Univ., Oxford, U.K., Mar. 2010.

[5] P.K. Day, H.G. LeDuc, B.A. Mazin, A. Vayonakis, and J. Zmuidzinas, "A braoadband superconducting detector suitable for use in large arrays," *Nature,* vol. 425, pp. 817-821, Sept. 2003.

[6] S. Ryabchun, C.-Y. E. Tong, R.Blundell, and G. Gol'tsman, "Stabilization scheme for hot-electron bolometer receivers using microwave radiation," *IEEE Trans. Applied Supercond*., vol. 19, no. 1, pp. 14-19, Feb. 2009.

[7] Y. Lobanov, E. Tong, R. Blundell, A. Hedden, B. Voronov, and G. Gol'tsman, "Large-signal frequency response of an HEB mixer from 300 MHz to Terahertz," *IEEE Trans. Appl. Supercond*., vol. 21, pp. 628-631, June 2011.

[8] Y. Zhuang, D. Gu, and S. Yngvesson, "Bistability in NbN HEB mixer devices," *Proc. 14th Int. Symp. Space THz Tech.,* pp. 289-298, Tucson, AZ, April 2003.

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