Microwave-assisted Measurement of the Frequency Response of Terahertz HEB mixers with a Fourier Transform Spectrometer

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***Abstract*— We describe a novel method of operation of the HEB direct detector for use with a Fourier Transform Spectrometer. Instead of elevating the bath temperature, we have measured the RF response of waveguide HEB mixers by applying microwave radiation to select appropriate bias conditions. In our experiment, a microwave signal is injected into the HEB mixer via its IF port. By choosing an appropriate injection level, the device can be operated close to the desired operating point. Furthermore, we have shown that both thermal biasing and microwave injection can reproduce the same spectral response of the HEB mixer. However, with the use of microwave injection, there is no need to wait for the mixer to reach thermal equilibrium, so characterisation can be done in less time. Also, the liquid helium consumption for our wet cryostat is also reduced. We have demonstrated that the signal-to-noise ratio of the FTS measurements can be improved with microwave injection.**

I. Introduction

The Fourier Transform Spectrometer (FTS) is widely used to characterize the frequency response of Hot Electron Bolometer (HEB) mixers operating in the Terahertz frequency range [1]-[4]. In such measurements, the HEB mixer is operated as a direct detector of the thermal source which powers the FTS. Appropriate operating conditions (i.e. bias voltage and current) are typically set by heating the HEB device to an elevated temperature around its critical temperature, Tc. This eliminates the need of a THz source to pump the HEB mixer.

It has previously been demonstrated that the injection of microwave radiation can be used to replace some of the required LO power in a THz HEB mixer [5]-[6]. This opens the possibility of performing FTS measurements of an HEB mixer operating at liquid helium temperature by applying microwave radiation. Given that a large number of scans and long integration time are needed for high spectral resolution measurements, the microwave injection method allows us to avoid the effects of any long term thermal instability associated with raising the bath temperature with a heater. In addition, there is no need to wait for the mixer to reach thermal equilibrium and liquid helium consumption in our wet cryostat is also reduced.

Our experiments show that the I-V characteristics of an HEB mixer pumped with microwave radiation differ significantly from those obtained with thermal biasing. This is in line with prior observations which have shown that the NbN film responds differently to microwave radiation [7]. In spite of the differences, we will show in this paper that the FTS data sets obtained when microwave radiation is applied compare very well to the spectra obtained when the device is heated.

In addition, we report on the observed families of current-voltage characteristics obtained when various amounts of heat, microwave, or terahertz radiation are applied to the mixer.

II. Experimental Setup

The FTS used in our experiments is based on the Martin-Puplett interferometer and is housed in a vacuum chamber to avoid any atmospheric losses, as is shown in Fig. 1.

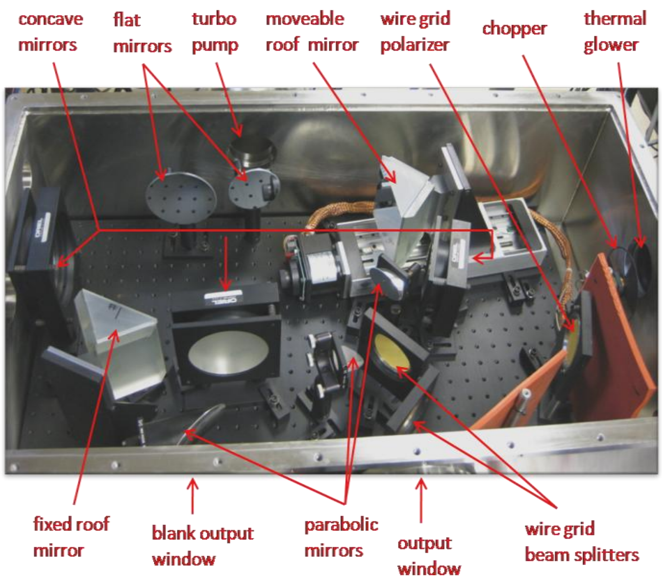

Fig. 1 A photograph of the FTS instrument

Details of the FTS instrument have been described previously [8]. A thermal glower acts as a broadband thermal source. Its radiation is chopped at a frequency of 37 Hz and divided by a wire grid polarizer made from 25 µm gold plated tungsten wires into two beams. The translation stage on which the movable roof-top mirror of the FTS is mounted provides a maximum displacement of 15 cm that produces spectral resolution of about 1 GHz. However, in our experiments, we generally limit our scan length to ~2 cm, corresponding to a spectral resolution of about 8 GHz.

As shown in Fig. 2, the cryostat housing the HEB mixer is positioned in front of the FTS chamber, with its anti-reflection coated crystalline quartz window facing the 0.5 mm Teflon output window of the FTS. This Teflon window imposes a small frequency dependent attenuation over the target frequency range of 0.5 – 1.5 THz.

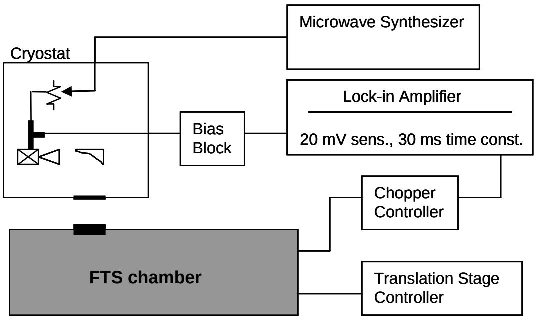

Fig. 2 Schematic diagram of the experimental setup

In these experiments, the HEB mixer measured was mounted in a 0.8 THz mixer block equipped with a corrugated horn feed [9]-[10]. A resistive heater and a diode thermometer, attached to the mixer block, allowed us to vary and measure the temperature of the block. Fig. 3 shows the layout inside the cryostat.

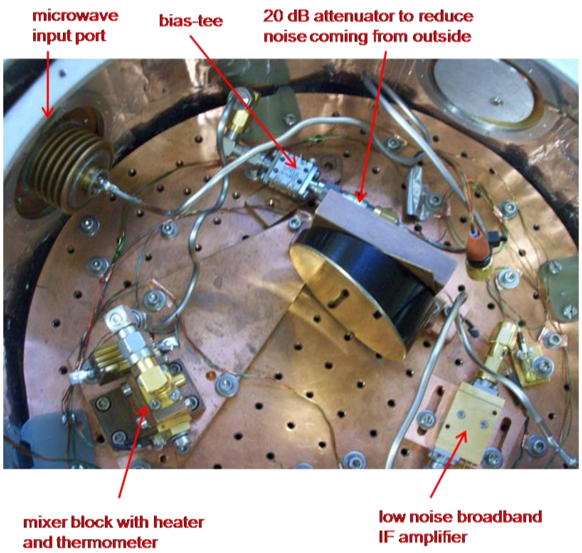

Fig. 3 Cryostat layout

The mixer block was connected to a bias-tee through which DC bias was applied. This was followed either by a low noise cryogenic amplifier for Y-factor characterization or by a 20 dB attenuator, which limits broadband noise, and a stainless steel semi-rigid cable is used to connect to the microwave input port of the cryostat.

An Agilent analog signal generator (Agilent Technology, E8257D) was used to produce a microwave tone up to 40 GHz for microwave injection.

III. I-V Curves of HEB Mixers

In our experiments, we used 800 GHz waveguide HEB mixers produced by the technological group of the MSPU. These mixers employ a ~3.5 nm thick NbN film produced by standard methods of photo- and e-beam lithography. Basic properties of the devices are presented in Table I. Devices #1 and #2 belong to two different batches and although their processing was similar, they differ in some features such as I-V and R(T) characteristics.

TABLE I
Basic Properties of the HEB Mixers Used for Experiments

Device	Characteristics of the misers			
	Size of the active element	**Critical temperature**	**Critical current**	R_N
#1	0.13×1.2 μm	10 K	220 μA	~130 Ω
#2	0.12×1.5 μm	11 K	210 μA	~60 Ω

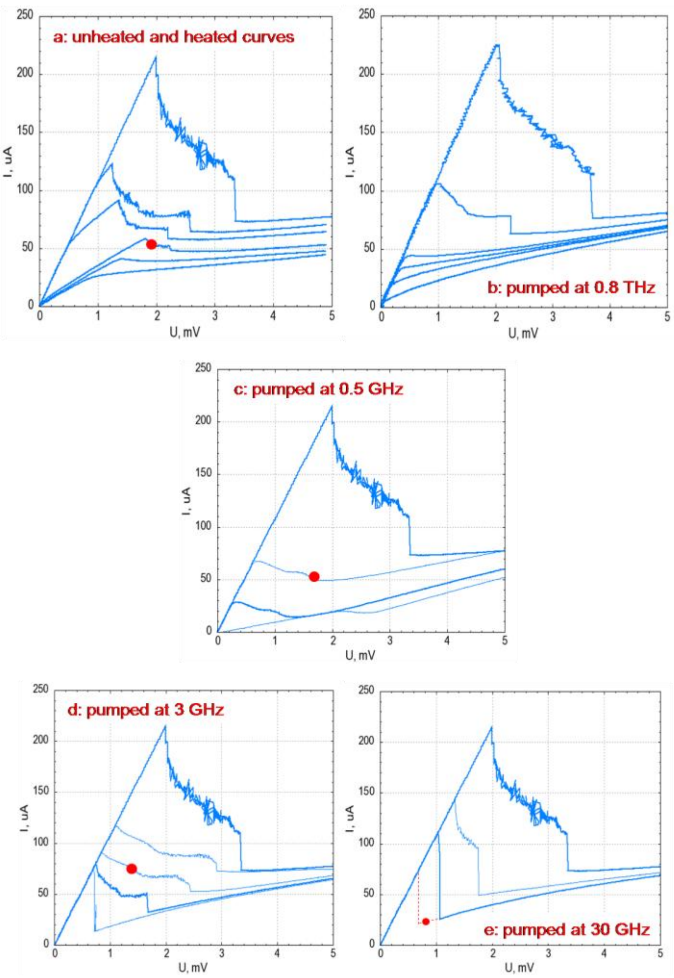

Fig. 4 Families of I-V curves of the HEB mixer (device #1): (a) unheated and heated curves; unpumped and pumped curves for incident radiation of (b) 0.8 THz; (c) 0.5 GHz; (d) 3 GHz; and (e) 30 GHz.

Red dots (•) represent bias points at which the FTS measurements were made. Dashed (----) line shows hysteresis when I-V curve was recorded.

We have studied the I-V characteristics of the two mixers measured with varying amounts of applied heat, terahertz radiation or microwave radiation. Four families of curves are plotted in Fig. 4.

It can be seen that the I-V curves produced by increasing the temperature of the mixer block (Fig. 4-a) most resemble those obtained by pumping the HEB mixer with 0.8 THz radiation that is above the gap frequency of the NbN film (Fig. 4-b). This explains why FTS measurement with thermal biasing can be used to derive the frequency response of HEB mixers. The curves produced by microwave injection (Fig. 4-c – Fig. 4-e) are marked by current switching between the superconducting state and the normal state of the NbN film. At the low end of the frequency range, the switching occurs at the much lower bias voltages. This phenomenon will be reported elsewhere [11].

IV. FTS Measurement Results and Discussion

For each family of curves shown in Fig. 4-a, 4-c – 4-e, we have selected bias points marked by red dots in the figure, at which FTS measurements were performed. These bias conditions were chosen to generate the maximum signal-to-noise ratio (SNR) in the interferograms. Fig. 5 shows interferograms obtained after averaging 4 scans at each of the bias points. It should be noted that for injection at 30 GHz the best bias point is found to be on a hysteretic branch of the I-V curve close to a current switching bias setting (shown with the red dashed (----) line in the figure).

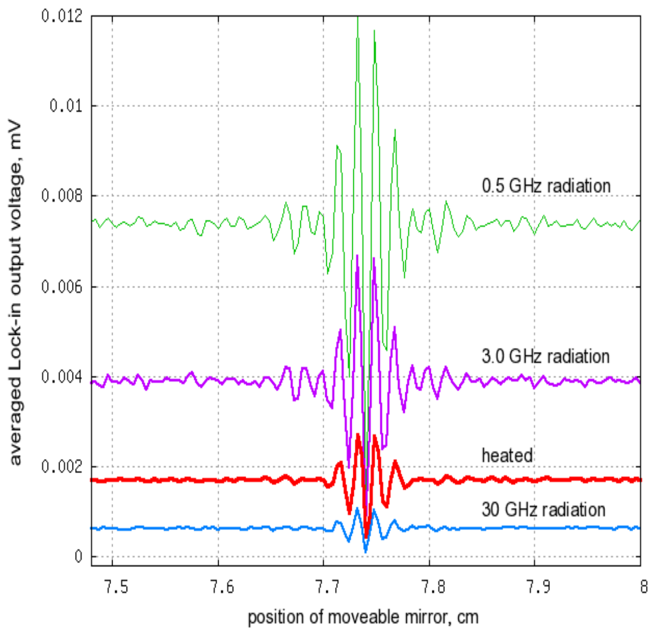

Fig. 5 Interferograms, each an average of 4 scans, for HEB mixer #1. The 4 interferograms from top to bottom were obtained when the device was pumped at 0.5 GHz, pumped at 3.0 GHz, heated, and pumped at 30 GHz respectively.

We noted that the higher direct responsivities associated with these optimal bias settings are related to regions of negative differential resistance around the bias points. However, in some negative resistive regions, the intrinsic noise of direct detection tends to be higher, especially near current switching regions exhibited with high frequency microwave pumping.

Referring to Fig. 5, the best SNR was obtained when a low frequency microwave radiation was used to pump the HEB mixer. The application of heat produced SNR that was intermediate between radiation injected at 3 GHz and 30 GHz. In spite of the difference in sensitivity the central fringes of the four interferograms are largely identical when normalized. In Fig. 6, we display a pair of normalized interferograms for comparison.

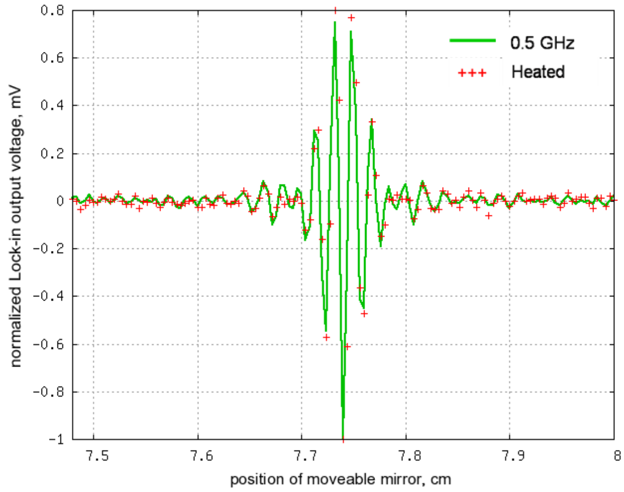

Fig. 6 Normalized response of the FTS when 0.5 GHz microwave radiation is applied (green line ——) or when heated (red marks + + +).

Standard techniques [12] of data apodization of the interferograms with a Hann window followed by a discrete Fourier Transform were used to derive the frequency response of the HEB mixers. In Fig. 7, we compare the normalized power spectra, or frequency response, of HEB mixer #1, obtained when heat or microwave radiation was applied.

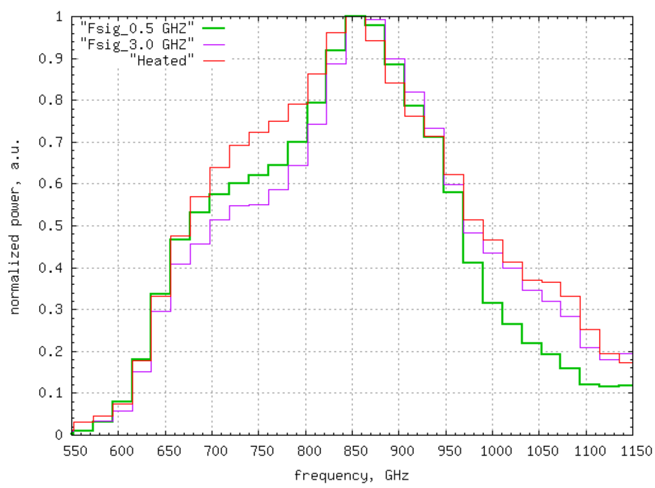

Fig. 7 Normalized power spectra for HEB mixer #1, obtained either through application of 0.5 GHz, or 3 GHz radiation or by heating the device.

In each curve, the spectral resolution is ~8 GHz, and the spectral response is centered at about 820 GHz. Furthermore, the shape of the spectral response obtained under different conditions remains constant. Fig. 8 displays a pair of normalized power spectra for mixer #2. Here the responses are a little different, but both show a significant dip at 760 GHz, which we attribute to attenuation from an atmospheric water line. Again, the mixer response to 33 GHz radiation agrees quite well to that obtained by mixer heating.

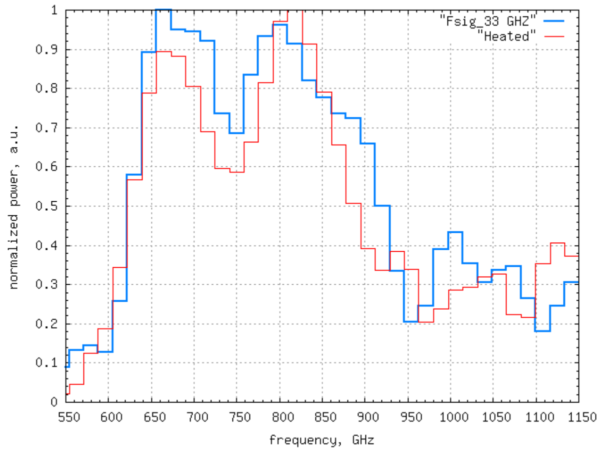

Fig. 8 Normalized power spectra for HEB mixer #2, obtained either through application of 30 GHz radiation or by heating the device.

V. Conclusions

We have successfully used microwave radiation to study the input bandwidth of HEB mixers with the help of an FTS. Our experiments demonstrate a certain equivalency between applying heat and microwave radiation for setting an appropriate pumping level of the HEB mixer in an FTS measurement.

We have carefully compared FTS data observed when microwave radiation or heating was used and found that microwave pumping can also reproduce the normalized power spectra derived from heating the device. In particular, we have shown that by lowering the injected microwave frequency, a higher responsivity can be achieved for certain bias points, usually associated with noticeable negative differential resistance.

Finally, we have compared I-V curves of HEB mixers pumped by a 0.8 THz LO source or applying heat to those obtained under different amounts of applied microwave radiation. We notice that in the microwave regime below the superconducting gap frequency, the I-V curves are marked by current switching between the superconducting and normal states.

Acknowledgment

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