

A 1.5 THz Hot-Electron Bolometer Mixer Operated by a Planar Diode Based Local Oscillator

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Abstract — We have developed a 1.5 THz superconducting NbN Hot-Electron Bolometer mixer. It is operated by an all-solid-state Local Oscillator comprising of a cascade of 4 planar doublers following an MMIC based W-band power amplifier. The threshold available pump power is estimated to be 1 μ W.

I. INTRODUCTION

In recent years, there has been a growing interest in the radio astronomy and remote-sensing communities to develop low-noise heterodyne receivers for the 1.5 THz frequency band. These receivers are needed for spaceborne, aircraft-based, and ground-based observations of molecular and atomic transitions. Above 1 THz, the superconducting Hot-Electron Bolometer (HEB) mixer is the element of choice for low-noise receiver development. A number of receivers have been developed [1-3]. However, in all these reports a Far-Infrared Laser is used to provide Local Oscillator (LO) drive. Solid-State LO units based on whisker contacted Schottky diodes have also been employed to operate HEB mixers up to 1.26 THz [4]. In both cases, however, it is difficult, if not impossible, to vary the LO frequency.

With the advent of millimeter-wave power amplifiers and planar diode technology for sub-millimeter multipliers, power output in excess of 1 μ W has been obtained above 1 THz using a cascade of planar diode multipliers [5], pumped by MMIC based power amplifiers in W-band [6]. In this paper, we report the first successful operation of a 1.5 THz HEB mixer pumped by such an LO unit.

II. NBN HOT-ELECTRON BOLOMETER MIXER

The heart of our low-noise heterodyne receiver is a mixer based on a 3.5 (± 0.5) nm thick Niobium Nitride (NbN) film deposited on a crystalline quartz substrate. A

200 nm thick Magnesium Oxide buffer layer is used to provide a better acoustic match between the NbN film and the quartz substrate. This increases the Intermediate Frequency (IF) bandwidth of the mixer to about 3.7 GHz [7]. The critical temperature of the film is about 9.7 K and the transition width is about 0.9 K.

The mixer element: a micro-bridge measuring 100 nm long and 1 μ m wide, is formed between 2 normal electrodes defined by electron-beam lithography. These dimensions have been chosen so that the mixer can be operated with limited LO power.

After fabrication in a clean room, the wafer is lapped and diced to give individual chips, which measure 72 μ m wide, 18 μ m thick and 1.1 mm long. The mixer chip is mounted into a suspended microstrip channel in a waveguide mixer block. The waveguide measures 168 x 42 μ m. The mixer block is a scaled version of other fixed-tuned waveguide mixers developed at the Harvard-Smithsonian Center for Astrophysics (CfA) [4].

III. RECEIVER LAYOUT

A schematic of the receiver layout is shown in Fig. 1. The mixer block, equipped with an integral corrugated feed horn, is installed in a liquid helium cryostat. The beam from the feed horn illuminates an off-axis parabolic mirror and passes through several layers of porous Teflon infrared filters before exiting the cryostat through a high-density polyethylene vacuum window. A Martin-Puplett polarizing interferometer is placed in front of the window for LO/signal diplexing. The polarizers are made from 10 μ m thick freestanding wire grids, and are efficient up to ~ 2 THz. This optical setup has previously been shown to provide good optical coupling to the mixer [8], and has an estimated insertion loss of about 1 dB.

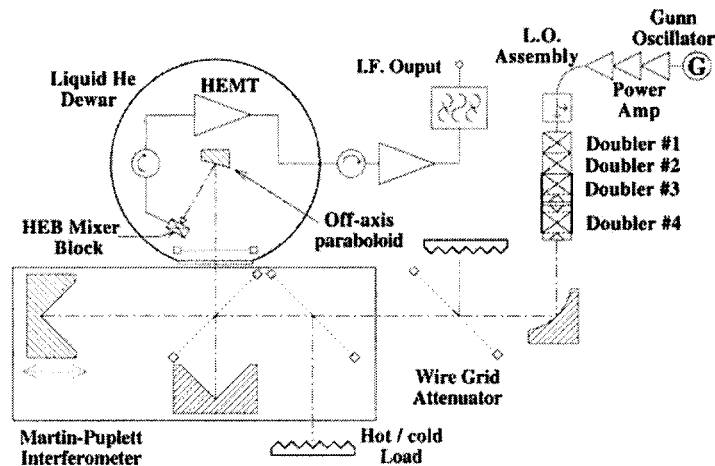


Fig. 1 Layout of our measurement setup showing the liquid helium cooled superconducting HEB receiver and the LO assembly. Note that the 3rd stage and 4th stage coupler are coupled through a horn-to-horn interface.

The mixer is connected to a 3 GHz cryogenic HEMT amplifier through a circulator. After further room temperature amplification, the IF signal passes through a 1.2 GHz wide filter, centered at 3 GHz, to a power meter which is used to measure the IF output. The total noise temperature at the input of the IF system is about 3.5 K.

IV. LOCAL OSCILLATOR

The LO source uses a cascaded chain of four passive fixed-tuned doublers (net $\times 16$ multiplication). The primary oscillator is a 90-98 GHz Gunn oscillator, and is followed by 3 stages of power amplification with a resultant power output of 130-150 mW. The power amplifiers are GaAs MMIC's fabricated at TRW, and assembled into waveguide housings at the Jet Propulsion Laboratory (JPL). The bias voltage of the amplifier cascade is used to control its output level.

Each of the four doublers is of balanced design using planar GaAs Schottky diode arrays made at JPL [9]. They are fabricated with integral matching and bias circuitry on thin GaAs, much of which has been removed to reduce problems with higher order modes. Each of the first 3 stages utilizes a 'substrate-less' chip: the entire circuit consisting mostly of suspended metal with beam leads for mounting and grounding. The diodes are mounted in series across the input waveguide of these 3 doublers and the center of each array is connected to an integral probe extending into an output waveguide. The final stage utilizes a 'membrane'-based chip. Details of the design and fabrication have been presented elsewhere [5,10].

The diodes use an epitaxial layer doping ranging from $1 \times 10^{17}/\text{cm}^3$ for the first doubler to $5 \times 10^{17}/\text{cm}^3$ for the last doubler. The lower doping levels of the lower frequency

doublers offer a significant increase in carrier mobility at low temperature. This allows the doublers to produce higher power output at cryogenic temperatures. The higher doping level is needed in the higher frequency doubler to avoid velocity saturation. In this initial experiment, the LO is operated at room temperature.

The first stage doubler uses a 6-diode array, the second stage doubler uses a 4-anode array and the third stage uses a simple diode pair. The center frequencies of the 3 stages are: 195, 390 and 770 GHz, and their room temperature efficiencies at mid-band are 25%, 16% and 10% respectively. In our experiment, the first 2 stages are passively biased with zener diode loads. This slightly reduces the output power and bandwidth but makes the operation easier. The third stage is operated with a bias voltage of around -2 V. The final stage is a resistive doubler with a maximum efficiency of $\sim 1\%$. The diodes are supported by a $3 \mu\text{m}$ thick membrane held by a $50 \mu\text{m}$ thick frame. They are mounted in series in the output waveguide. This doubler is forward biased by a current source of $0.2 - 0.5$ mA. With no pump power, the bias voltage across the 2 diodes is 1.5 V, and with the maximum available pump power, it drops to 1.2 V.

The first 3 stages of the cascade are coupled via their waveguide inputs and outputs. For developmental reasons, the last stage is coupled to the third stage via similar feed horns integral to the blocks. The two stages are rigidly bolted together. In Fig. 2, we plot the measured output power of a similar unit as a function of frequency. In this measurement, the first 2 stages are actively biased. Large ripples are observed, primarily because of the number of stages and the horn-to-horn coupling of the last stage. Nevertheless, for room temperature operation, output power in excess of $1 \mu\text{W}$ has been recorded over many

frequency points between 1.45 and 1.55 THz. This frequency response can be improved by using a more suitable waveguide interface between the third and last stage. As expected, when the assembly is cooled to 60 K, the output power significantly increases.

The final doubler also incorporates an integral diagonal horn, with a rhombic output aperture measuring 1.5 mm on a side. The emergent beam is collimated by an off-axis parabolic mirror, placed at the LO port of the Martin-Puplett diplexer. A wire grid attenuator is inserted to adjust the available LO power. We estimate the cross polarization component of the radiation from the diagonal horn to be about 10%, and the efficiency of the LO coupling scheme is estimated to be 70%.

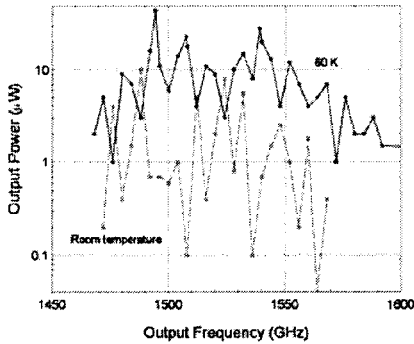


Fig. 2 Measured output power of a similar LO unit for both operation at room temperature and at 60 K. In this measurement, the first two doublers are actively biased. This yields a wider bandwidth and about 25% more output power.

V. RECEIVER PERFORMANCE

The sensitivity of the receiver was measured using the standard Y-factor method, with ambient (295 K) and cold (77 K) loads placed at about 1 m away from the cryostat window. The current-voltage characteristics of the HEB device are shown in Fig. 3, together with the receiver output in response to hot and cold loads at an LO frequency of 1.476 THz. The critical current of the device is 105 μ A and its normal-state resistance is 115 Ω . At this frequency, the output power of the LO unit is measured to be 7.5 μ W. As shown in the figure, the device is nearly driven into the normal-state at this power level.

Optimum sensitivity is achieved at a bias voltage of 0.7 mV and a bias current of 27 μ A. At this operating point, a Y-factor of 1.075 has been measured, corresponding to a receiver noise temperature of about 2800 K. The conversion loss of the receiver is estimated to be about -19 dB. The relatively low conversion efficiency is

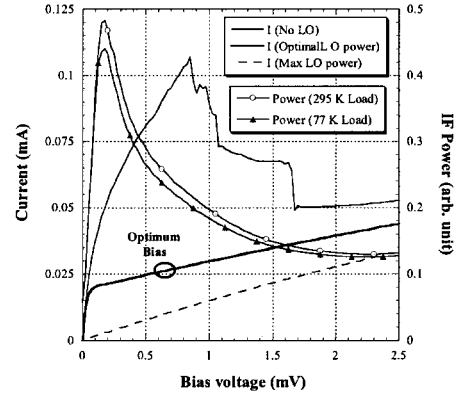


Fig. 3 Current-Voltage Characteristics of the HEB mixer at different LO power levels at 1.476 THz. Also shown is the IF output power in response to hot (295 K) and cold (77K) loads. The optimal bias point is marked on the optimally pumped I-V curve, where the measured Y-factor is 1.075 at that point.

probably due to the wide transition width of the NbN film. We expect that this can be improved.

By noting the attenuation introduced by the wire grid attenuator, we infer that the LO is able to optimally pump the HEB mixer at frequencies where the available LO power is above 1 μ W, typically at the peaks of the power spikes shown in Fig. 2. Around these peaks, the LO can be tuned over a bandwidth of \sim 2 GHz. We can also derive the LO power “absorbed” by the HEB element from the current-voltage curves in Fig. 3 using the isotherm method [11]. This yields an absorbed power of \sim 70 nW. Taking into account the various optical coupling losses discussed above, this translates to an available pump power of \sim 120 nW, which is about an order of magnitude below the inferred threshold pump power of 1 μ W. We believe that the isotherm method underestimates the required LO drive. The low conversion efficiency could also have reduced the LO coupling efficiency. Referring to Fig. 2, this 1 μ W threshold suggests that if the LO were operated at low temperatures, the LO would be potentially usable up to 1.6 THz, and with nearly complete frequency coverage between 1.45 and 1.6 THz.

Fig. 4 gives the measured Y-factor as a function of LO frequency. Also shown is the spectral response of the mixer as measured by a Fourier Transform Spectrometer. In this case, the mixer is operated in direct detection mode at an elevated bath temperature. It can be seen that the input bandwidth of the receiver is about 500 GHz. The peak response of the mixer is around 1.25 THz, but it clearly has reasonable sensitivity up to 1.5 THz. At higher frequencies, the response rolls off and the Y-factor degrades.

In spite of the small device size, direct detection effects were not observed to influence the mixer: the bias current change in passing from a cold to an ambient input load is only 40 nA, or less than 0.2%. This shows that the size of the device is not excessively small for saturation to be a problem. Our experiment demonstrates that this is the appropriate size for operation with a 1 μ W solid-state LO source.

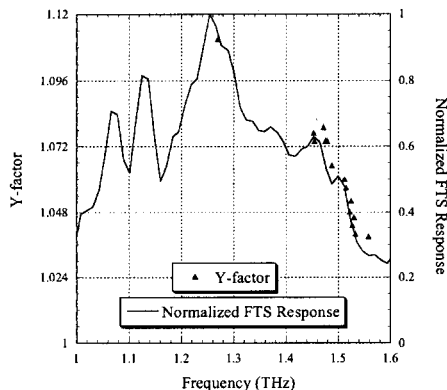


Fig. 4 Measured Y-factor of the receiver as a function of LO frequency. The Y-factor given at 1.27 THz was measured with another LO which employs whisker-contacted Schottky multiplier [4]. Also shown is the spectral response of the mixer measured by a Fourier Transform Spectrometer (FTS) using the HEB device in direct detection mode.

V. CONCLUSION

We have successfully operated a 1.5 THz Hot-Electron Bolometer mixer with an all solid-state LO unit comprising of a cascade of 4 planar diode doublers pumped by a W-band power amplifier. Operating at room temperature, the LO assembly is able to provide output power in excess of 1 μ W at a number of frequencies between 1.45 and 1.55 THz, which is sufficient to optimally pump the 100 x 1000 x 3.5 nm NbN mixer element. Finally, a Y-factor of 1.075 has been recorded for the receiver operating at a frequency of 1.476 THz.

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