10.7 THz HEB Heterodyne Mixer Designs

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Abstract— **We report on the development of a 10.7 THz Hot Electron Bolometer (HEB) mixer. The NbN HEB is fabricated on a 9µm silicon membrane with an integrated gold planar antenna which is attached to the backside of a silicon lens to couple to free space. The mixer designs encompass both narrow-band and broadband antennas. Direct response measurements of two HEB-devices are presented.**

Keywords—HEB mixer, Archimedean spiral antenna, double-slot antenna

I. Introduction

We are currently developing a Hot Electron Bolometer (HEB) mixer for the high resolution observation of molecular hydrogen at 10.7 THz. The observation of the weak emission feature of the electric quadrupole transition of H_2 at 10.7 THz (28 µm) requires high spectral resolution which only a heterodyne system can supply. The mixer uses a Niobium Nitride (NbN) HEB microbridge as the mixing element. This microbridge is integrated with a gold antenna on a high resistivity silicon substrate that is subsequently glued on a silicon lens. The mixer was initially intended to fly on the Stratospheric Observatory for Infrared Astronomy (SOFIA) [1] whose operational time was recently shortened to the end of September of 2022.

II. Design

The receiver is based on a concept with integrated lens-antenna. A 9µm thick, high resistivity silicon membrane with an integrated planar antenna is directly attached to the flat backside of a silicon (Si) lens to couple to free space. The Si lens consists of an extended hemisphere with a radius of 0.5mm and a cylindrical extension of 164µm. The RF components are integrated in a tellurium copper housing with IF-board (see Fig.1). The front of the block has an about 14° slope to avoid reflections of a possibly not perfectly matched local oscillator (LO) beam, which would lead to standing waves in the LO path negatively influencing the stability of the receiver. The copper mixer housing is the reference towards the further receiver optics.

To enable a very accurate positioning of the antenna relative to the center of the lens and to the copper mixer housing the silicon membrane contains additional markers. With respect to both, the block-assembly and the lens-assembly markers, the antenna is referenced with an accuracy of approximately 1µm.

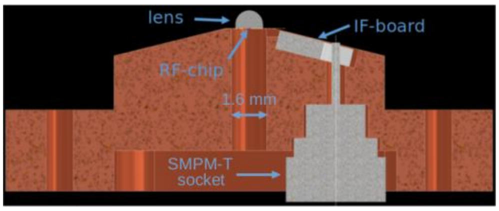
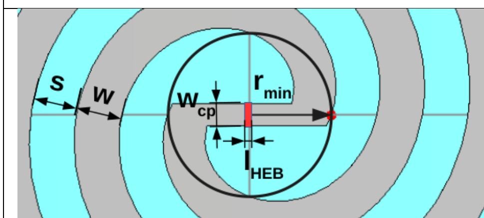


Fig. 1: Sketch trough the cut of the copper receiver housing.

The broadband and narrow-band RF-circuits presented here are based on a double-slot antenna with RF-choke and an Archimedean spiral antenna. They are composed of a 70nm thick gold layer. A main challenge of the RF-circuit designs is to allow a good power transfer at the HEB-antenna interface within the constraints given by the high HEB layer resistivity and the natural limitation in the dimensions of the RF-structures given by the fabrication technique. The high frequency requires a smaller feed than can be reliable fabricated which leads to a non-vanishing imaginary part in the port-impedance for the Archimedean spiral antenna. The geometric specifications of the spiral antenna are given in Tab.I. The reflection at the HEB-antenna interface is depicted in Fig. 2 for different resistance values for the HEB microbridge in the center of the Archimedean spiral antenna.

Five different versions of a double-slot antenna have been fabricated to account for potential uncertainties for instance given by fabrication tolerances and uncertainties of the material properties (silicon at operating frequency and cryogenic temperatures[2], SiO_2 (bridge substrate), Au resistivity). The full-wavelength slots are between 9 to 10.3µm long, with slot-distances between 5 and 5.6µm. The RF-choke is directly attached to the antenna as shown in Fig.3. It blocks the RF-signal and presents a short circuit at the antenna side at the operating frequency. It consists of 7 lambda-quarter high and low impedance CPW lines. There are fabricated versions where the CPW line at the antenna interface partly is shortened/elongated to study the effect of the filter on the antenna resonance. The effect of the filter on the input impedance at the antenna terminal is exemplarily depicted in Fig.4 for the maximum and minimum value which is assumed to be obtained for the given resistivity and aspect ratio of the HEB microbridge integrated at the antenna terminal.

TABLE I.

Geometrical specifications	
	
w	1 µm
s	1 µm
w_{cp}	0.5 µm
l_{HEB}	120 nm
r_{min}	1.74 µm
Number of turns	1.75

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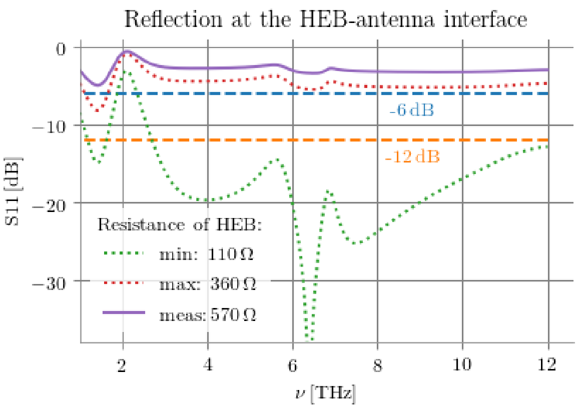


Fig. 2: S11-parameters at the HEB-antenna interface of the Archimedean spiral antenna for different resistance values of the HEB.

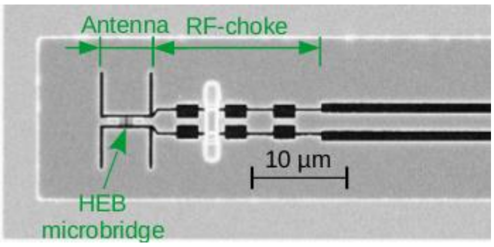


Fig. 3: SEM picture of fabricated double-slot antenna with RF-choke.

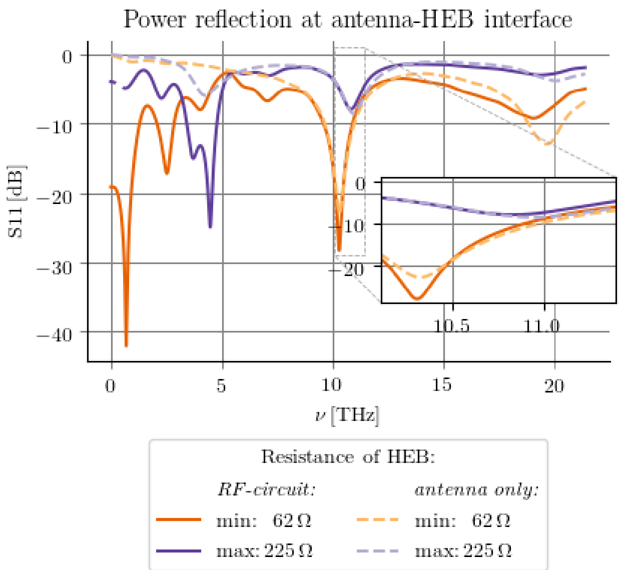
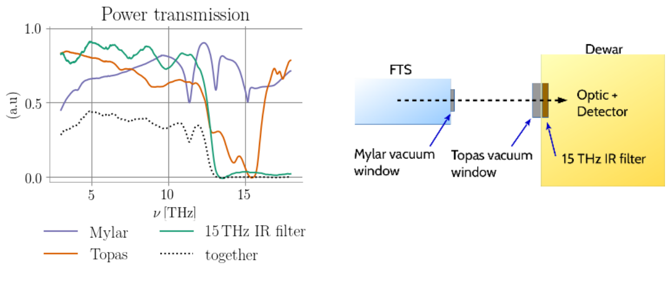


Fig. 4: S11-parameters at the antenna-HEB interface of the double-slot antenna for different resistance values of the HEB.

III. Measurements

First batches with different mixer designs have been fabricated using a combination of E-beam and UV lithography. The local oscillator for the Heterodyne measurement is still pending. Therefore first investigations of the fabricated devices are done using the mixers as direct detectors of a Fourier Transform Spectrometer (FTS) as sketched in Fig.5. The measurement frequency range is restricted by the optical components in the setup to 3 - 12 THz (see Fig.5). The HEB-devices are operated around their critical temperatures and are DC-biased in the constant current mode via a Bias-T, with a stable bias point in the IV curve of the HEB set as indicated as black dot in Fig.6. The spectra have been measured with the maximum FTS resolution of 0.08 cm^{-1} as an average over 5 to 12 spectra.



(a) (b)

Fig. 5: (a) Transmission characteristics of different optical components used in the Fourier Transform Spectrometer setup and (b) their location in the FTS setup.

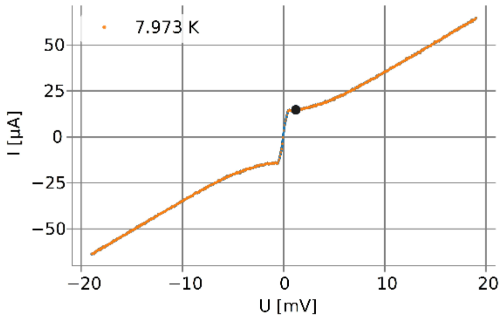


Fig. 6: IV curve of an HEB-device operated around its critical temperature. The black dot indicates the typical location of the bias point chosen for operation.

IV. Results

From a batch with in total 80 RF-chips so far two HEB-devices have been characterized, which are based on one double-slot antenna and one Archimedean spiral antenna, respectively. The raw and calibrated response spectra are depicted in Fig. 7 and Fig .8. The calibration takes into account the transmission characteristic of the FTS and dewar vacuum windows, the IR-filter and the transmission spectrum of the empty FTS, which is measured with the internal detector of the FTS and mainly depicts the spectral transmission of the FTS-beamsplitter. The very large attenuation of the FTS-signal contributed by the sum of all optical components at 11.4 THz does not allow a reasonable assessment of the measured spectrum around that frequency and yields an artefact in the calibrated spectra.

The Archimedean spiral antenna based HEB-device shows a slightly wavy steady response signal over the whole measurement frequency range of the setup as to be expected from simulation results (see Fig .7). For the HEB-device with the double-slot antenna (see Fig. 8) a distinct linearly polarization-dependent response behavior could be shown by means of a grid placed in the optical pathway between FTS and dewar window. The device exhibited maximum response in the dedicated linear polarization direction of the antenna and no response for the respective cross-polarized radiation. The response spectrum (see Fig. 8) exhibits a response peak around 10 THz and one pronounced peak around 7.5 THz. The response peak around 10 THz corresponds to the full-wavelength resonance of the antenna. Based on simulation results carried out with CST Microwave studio[3], the response peak around 7.5 THz likely corresponds to a resonance, where the double slot antenna behaves as four, in-phase driven lambda-quarter slot pieces.

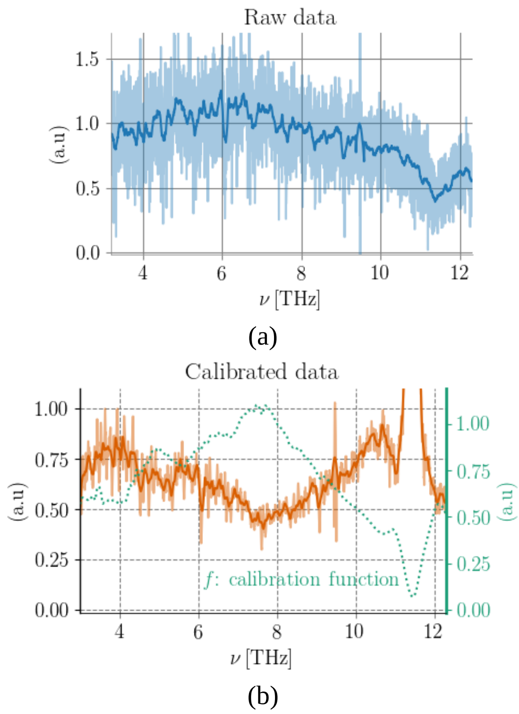


Fig. 7: Spectral direct response ((a) raw and (b) calibrated data) of HEB-device based on the Archimedean spiral antenna.

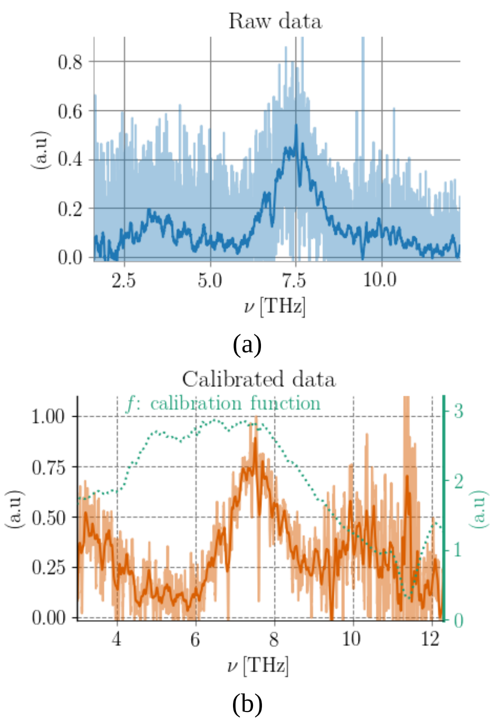


Fig. 8: Spectral direct response ((a) raw and (b) calibrated data) of HEB-device based on the double-slot antenna with RF-choke (*Antenna*: slot-length: 9µm, slot-distance: 5.6µm, slot-width: 0.3µm, *CPW between slots*: inner conductor width: 0.8µm, slot width: 0.3µm).

V. Conslusion

Direct response of HEB-devices based on a narrow-band and a broadband antenna have successfully been measured within a frequency range from 3 - 12 THz. Measurements of further HEB-devices including double-slot antennas, Archimedean spiral antennas and logarithmic spiral antennas will follow soon with an improved FTS-setup with a better signal-to-noise-ratio around 11.4 THz.

References

[1] J. Böhm, et al., "Development of a HEB mixer for the observation of molecular hydrogen on SOFIA." *ISSTT 2019: 30th International Symposium on Space Terahertz Technology*, 2019.

[2] J. Böhm, et al., "Cryogenic temperature-dependence of HRFZ Silicon refractive index from Mid-to Far-IR down to 5 K." *2021 46th International Conference on Infrared, Millimeter and Terahertz Waves (IRMMW-THz). IEEE*, 2021

[3] Computer Simulation Technology GmbH. CST - Computer Simulation Technology.