Design, fabrication and measurement of a membrane based quasi-optical THz HEB mixer

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***Abstract*—In this paper we present our recent development in quasi-optical membrane based superconducting hot electron bolometer (HEB) mixers at 0.6 THz. The phonon-cooled Niobium Nitride (NbN) HEB coupled to a double slot antenna is processed on a 1.4 µm thick stress-less Si_3N_4/SiO_2 membrane. The mixer block uses an off-axes mirror to focus the terahertz (THz) signal to the antenna and a back-short is placed behind the membrane to increase the gain of the antenna.**

We have simulated the input impedance of the membrane based double slot antenna and the radiation properties of the quasi-optical mixer with the aid of the full wave electromagnetic solver CST Microwave Studio. Measurements have been performed to obtain the double sideband receiver noise temperature and IF bandwidth. The measurement results will be discussed and compared with those of a thick substrate based HEB mixer.

***Index Terms*—Heterodyne detection, hot electron bolometer, quasi-optical, membrane based HEB.**

I. INTRODUCTION

THE phonon-cooled Niobium Nitride (NbN) HEB coupled with an integrated lens-antenna on thick dielectric substrate have demonstrated a high sensitivity for the THz heterodyne detection [1] – [3]. However, some losses remain inherent with this type of quasi-optical structure. The signal must pass through the dielectric material of the lens and the substrate which causes reflection and substrate modes losses. One way to avoid these problems is to use a metallic mirror to focus the signal to the antenna and reduce the substrate under the planar antenna. For a slot antenna it was shown that a dielectric thickness less than 0.04 λ_d [4] (with λ_d the wavelength into the dielectric) allows to consider the antenna as suspended in free-space, so without dielectric losses. For this reason, the antenna is deposited on a 1.4 µm thick membrane made of Si_3N_4/SiO_2 allowing a double slot antenna up to about 4 THz [5].

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This paper will begin by presenting the concept of our quasi-optical mixer block using a mirror and a planar antenna on the stress-less membrane. Then the design of the planar antenna with CST Microwave Studio (CST MWS) will be presented. Afterward, the measurements setup employed to characterize the mixer's sensitivity and the IF gain bandwidth will be detailed. Finally, the results obtained with the membrane based structure will be discussed and compared with a HEB coupled to a double slot antenna on a thick substrate and integrated on a silicon lens in the same measurement conditions.

II. CONCEPT AND DESIGN

A. Mixer block

The quasi-optical mixer block uses an off-axis parabolic mirror to focus the radiation to the antenna (Fig. 20). The mirror has a focal length of 12.7 mm, a diameter of 25.4 mm and focuses incident signal at 90°. Under the membrane, a back-short is placed at a quarter of the wavelength to increase the gain of the planar antenna. The Back-short is a metallic plane reflector made on a silicon substrate that has been thinned to allow the reflector at the good distance behind the membrane. The intermediate frequency (IF) signal produced by the HEB is transmitted to the SMA connector by a microstrip line of 50 Ω. The NbN HEB is fabricated on the membrane made of 600 nm thick of silicon nitride (Si_3N_4) and of 800 nm thick of silicon dioxide (SiO_2). All the details of the fabrication process of the membrane based HEB were explained in two previous papers [6], [7].

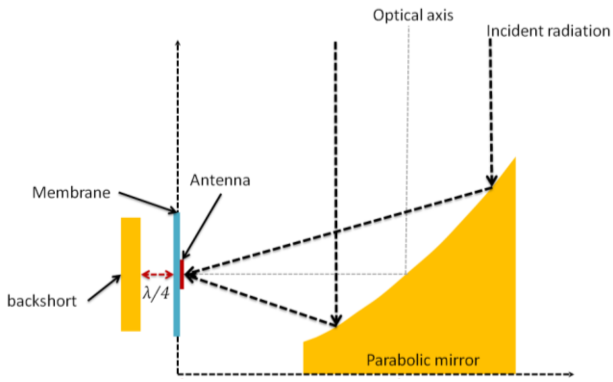

Fig. 20. Schematic view of the quasi-optical mixer block. The parabolic mirror focuses the THz signal to the antenna. The back-short placed behind the membrane increases the gain of the antenna.

B. Antenna design

Different kind of planar antennas may be selected to detect the THz radiation [8] – [11]. In this work, we have chosen a planar antenna widely used for THz heterodyne receivers: the double slot antenna (DSA). The DSA has linear polarization, good frequency selectivity and high directivity. Another advantage in our case is that the DSA can have an impedance around 75 Ω [12], which is the impedance of our HEB. We used a full wave electromagnetic solver, CST Microwave Studio to simulate the impedance of the DSA on membrane and its radiation pattern.

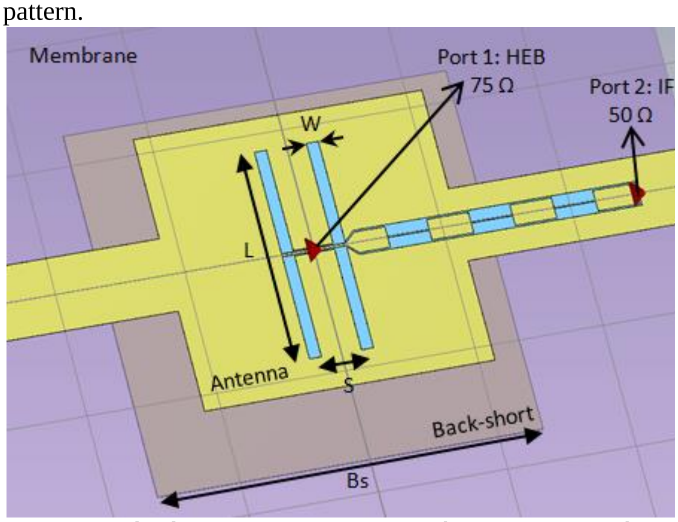

Fig. 21. Simulated structure in CST MWS. The antenna is on the membrane and the back-short is placed at a quarter of the wavelength behind the HEB. The HEB is a discrete port of 75 Ω and the IF output is a discrete port of 50 Ω.

A DSA can be determined by 3 parameters, the length and the width (*L* and *W*) of the slots and the separation (*S*) between the two slots. In a typical case the DSA is on a thick dielectric substrate and the length *L* is governed by the wavelength of the radiation and the material dielectric constant. In this case, the length can be written [13]:

$$L = 0.8A\lambda_0 \tag{1}$$

Here, λ_0 is the wavelength in vacuum and *A* is a factor that depends on the effective dielectric constant (ε_{eff}) and on the *W/L* ratio [14].

$$A = \frac{1}{\sqrt{\varepsilon_{eff}\left(1+\frac{W}{L}\right)}} \tag{2}$$

In our case, the membrane is thin enough (less than 0.04 λ_d) to consider the antenna as suspended in free-space, so ε_{eff} tends to 1. The ratio W/L is typically chosen to be between 0.02 and 0.07. Finally, L is around 0.75 λ_0 when the DSA is on a membrane, whereas it is around 0.3 λ_0 for a DSA on a thick silicon substrate. This means that the DSA is larger on thin membrane, which allows an easier fabrication process for higher frequencies. Concerning the separation between the slots, S is generally chosen to be around 0.17 λ_0. These parameter values (L, W and S) are chosen as point of departure for the design of the membrane based antenna. The entire structure of the device including the DSA, the RF choker filter, the membrane and the back-short is modeled with CST MWS (

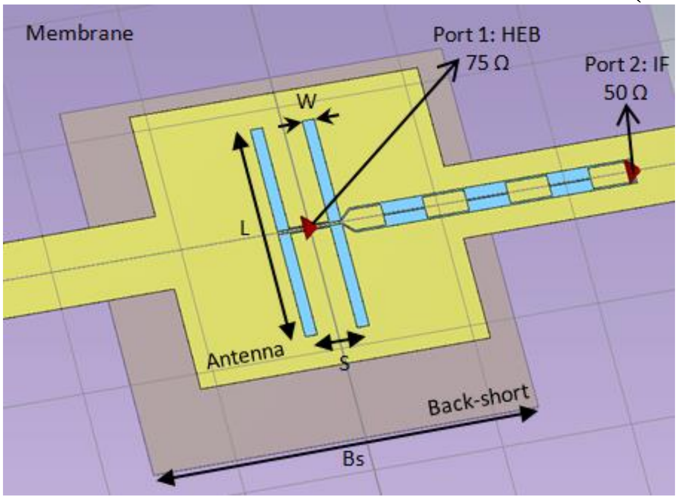

Fig. 21). For the simulation, the HEB is replaced by a discrete port of 75 Ω and the IF output is represented by a port of 50 Ω. Optimizations of the parameters L, W and S have been performed to minimize the return loss at the desired frequency, here 618 GHz and also to have an impedance of the antenna close to 75 Ω. The size of the back-short (named Bs on the picture) has also been optimized in order to have the best radiation pattern. The optimal size was found to be 600x600 µm² resulting an antenna directivity of 9.2 dBi. The optimized parameters are listed in the table 1 and the impedance of the DSA is plotted in Fig. 22. We can notice that the antenna has an impedance very close to 75 Ω near 618 GHz, allowing a good adaptation with the HEB.

TABLE 1. Parameters of the DSA and the back-short

L (µm)	**S (µm)**	**W (µm)**	**Bs (µm²)**
343 (0.71 λ_0)	80 (0.17 λ_0)	18.7 (0.05 L)	600x600

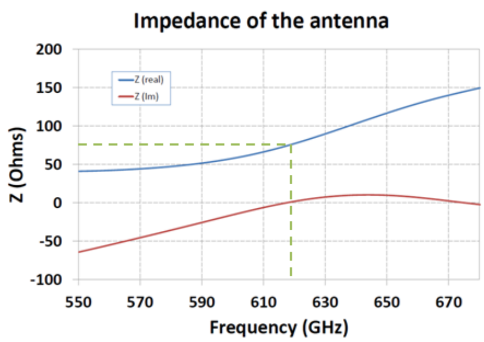

Fig. 22. Simulated impedance of the DSA. Around 618 GHz, the imaginary part (red line) is close to 0 and the real part (blue line) is very close to 75 Ohms.

The beam pattern of the membrane based DSA with the back-short has been calculated by the transient solver of

CST MWS. This method is well adapted to calculate the electromagnetic field near the antenna but is not suitable for the calculation of large structures such as the mixer block with the parabolic mirror. We thus used the Multi Level Fast Multipole Method (MLFMM) in CST MWS to simulate the beam pattern of the entire mixer block. The off-axis parabolic mirror has been modeled and the beam pattern of the membrane based antenna previously calculated has been placed in the focal plane of the mirror as an input source for the solver (Fig. 23). The result of the simulation is shown in Fig. 24. The main lobe has a magnitude of 36.5 dBi, an angular width of 1.3° at -3 dB and the side lobe level does not exceed -24.8 dB.

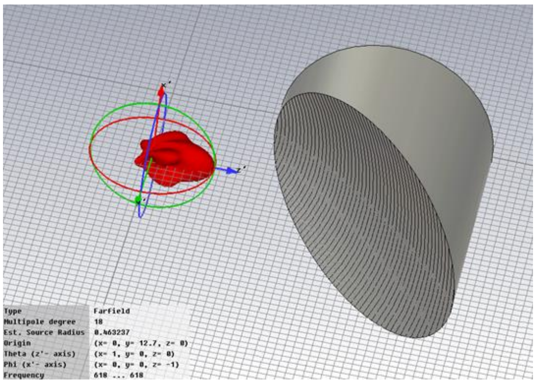

Fig. 23. The off-axis parabolic mirror is modeled to simulate the beam pattern of the entire mixer block.

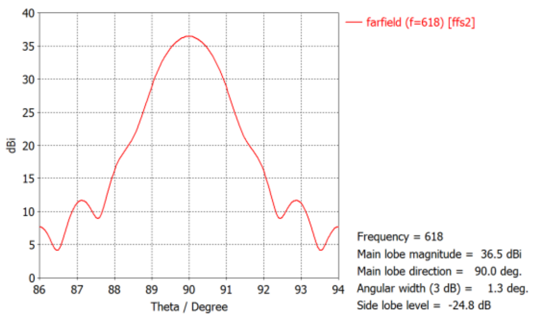

Fig. 24. Beam pattern of the mixer block.

III. MEASUREMENTS SETUP

The mixer's performance has been investigated around 600 GHz. The double side band (DSB) noise temperature and the IF gain bandwidth measurement has been performed by using two different setup.

A. *DSB noise temperature measurement setup*

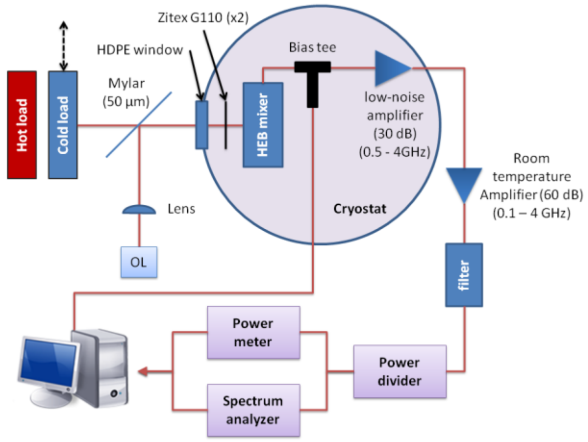

Fig. 25. Illustration of the measurement setup. The hot and cold loads are placed in front of the window of the cryostat for the Y-factor measurement.

The mixer block is mounted on the cold plate of an Infrared Labs cryostat. The RF and LO signals are sent into the cryostat by an optical access through a 1 mm thick HDPE window at room temperature. Two layers of Zitex® G110 block the infrared radiation [14], one is glued on the 4 K shield and the other one is mounted on the cold plate in front of the mixer block. A bias tee is used to feed the bias to the mixer and to transmit the IF signal to the cooled low noise amplifier (noise temperature 8 K, gain 30dB), which is a Caltech amplifier operating between 0.5 and 4 GHz. The IF signal comes out of the cryostat and is amplified by two amplifiers (2x 30 dB) at room temperature operating between 0.1 to 4 GHz. Then the output signal is filtered at 650 MHz with a bandwidth of 250 MHz.

The DSB noise temperature of the receiver is evaluated by using the Y-factor method. The LO signal, fixed at 618 GHz, is provided by an electronic source driven by a synthesizer. The LO source is placed in the focal plane of a lens to collimate the signal into the cryostat. Two black bodies made from Eccosorb are used as the hot and cold load with a temperature of 295 and 77 K respectively. The optical path between the LO source, the loads and the cryostat was not air evacuated and a 50 µm thick mylar was used as the beam splitter to combine the radiation from the hot/cold load and the LO source.

B. *IF gain bandwidth measurement setup*

The measurement setup is quite similar to that of the noise temperature measurement but we've taken care to suppress all the elements that could limit the IF bandwidth. The cooled low noise amplifier with a bandwidth from 0.5 to 4 GHz is removed and we don't use any filter outside the cryostat. Since the IF signal is very weak at the output of the cryostat, we amplify it with two wide band room temperature amplifiers (0.1 to 4 GHz). The output signal is read with a spectrum analyzer.

The IF signal is generated inside the HEB by mixing signals from two electronic sources, one as the LO and the other one as the RF. We start to pump the HEB with the LO around its optimal level which has been determined during the DSB noise measurement. After what, we place the second source, with a frequency very close to the LO frequency, in front of the cryostat and we adjust carefully the RF power in order to not over pump the HEB. The RF power transmitted to the receiver is maintained unchanged all along the measurement. The scanning along the IF band is made by tuning the frequency of the LO and for each point the power is adjusted in order to keep the same pumping level of the HEB.

IV. RESULTS AND DISCUSSION

A. *DSB noise temperature receiver*

We measured the DSB noise temperature of the membrane based HEB in the off-axis mixer block. The HEB consist of a 2 µm wide, 0.2 µm long and 5 nm thick NbN bridge between the electrodes of the DSA designed for 618 GHz. The HEB have a room temperature resistance of 90 Ω and a critical current of 240 µA at 4.2 K (**Ошибка! Источник ссылки не найден.**). Different pumping levels have been tried to find the best region to have the minimum noise temperature of the receiver.

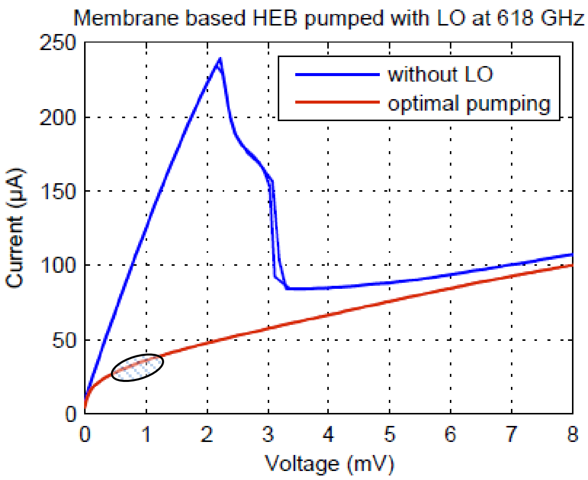

Fig. 26. I-V curves recorded at 4.2 K of the membrane based HEB without LO (blue line) and at the optimal pumping of the HEB (red line). In the circle, the optimal pumping region for the heterodyne measurement.

The IF output power of the HEB responding to the hot and cold load is recorded as a function of the bias voltage. Then, the Y-factor is calculated with: $Y = P_{hot}/P_{cold}$, and the DSB noise temperature (T_{DSB}) of the receiver can be obtained by:

$$T_{DSB} = \frac{295-77Y}{Y-1} \quad (3)$$

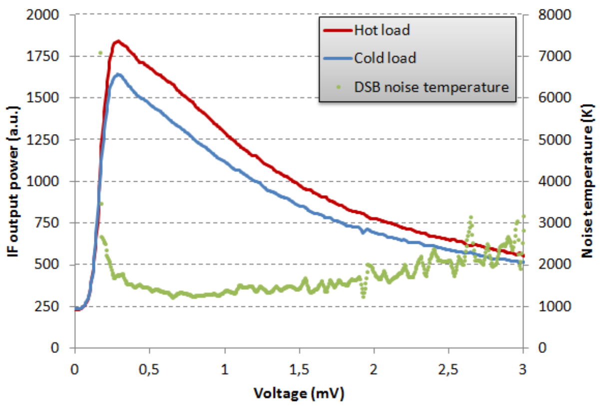

Fig. 27. DSB noise temperature measured with the membrane based mixer block. The blue and red lines represent the IF output power provided by the HEB with the cold and hot loads as a function of the bias voltage.

An uncorrected noise temperature around 1200 K was measured with the membrane based HEB (Fig. 27). In order to compare this result with a HEB on thick substrate, we used strictly the same measurement setup, only the mixer block is replaced by the one with an integrated lens-antenna and a HEB on a thick silicon substrate. This device on thick substrate is chosen for its similarity with the measured membrane based device. The HEB consist of a 2 µm wide, 0.2 µm long and 5 nm thick NbN bridge on a 350 µm thick silicon substrate. The HEB is coupled with the DSA designed for 600 GHz. It has a room temperature resistance of 83 Ω and a critical current of 210 µA at 4.2 K. With this device we measured an uncorrected noise temperature of 800 K. The measurement includes the optical losses between the beam splitter and the input of the mixer. As summarized in the table 2, the losses are estimated to be 2.85 dB. So, with an improvement of the optical path, we could hope a noise temperature below 600 K for the membrane based HEB and below 400 K for the HEB on a thick substrate.

TABLE 2. Losses in the optical elements

element	Loss (dB)
Beam splitter	1.5
HDPE window	0.45
Zitex filter (x2)	0.45 (x2)

B. *IF gain bandwidth*

Both membrane and thick substrate based HEB mixers are measured in the same conditions (described above) to obtain the IF gain bandwidth. As explained in the previous chapter, we tune the LO frequency to sweep the IF band between 0.2 and 5 GHz. The resulting beat signal is recorded by a spectrum analyzer for each frequency. The normalized IF output powers are presented in Fig. 28. The HEB on thick silicon substrate has an IF bandwidth at -3 dB around 3 GHz as expected and the membrane based HEB reveals an IF bandwidth much lower: around 0.9 GHz. That could be explained by the difference between the lattice parameters of the NbN film and the substrate. In the case of the membrane based HEB, the lattice parameters of the Si_3N_4 and the NbN are quite different [15], which causes an acoustic mismatch between the NbN film and the substrate, so the relaxation time of the electron inside the superconducting film is slowed [17] while in the case of HEB on the silicon substrate, the lattice parameters of the Si and the NbN are very close [15].

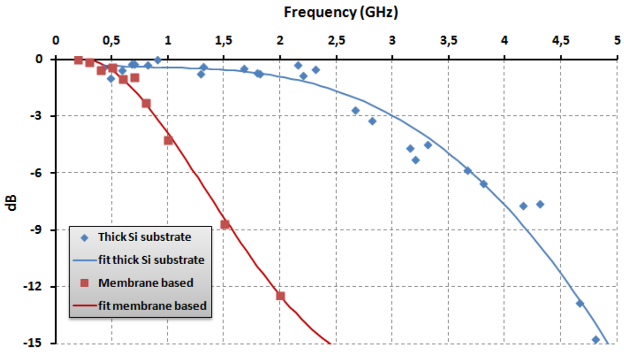

Fig. 28. IF gain bandwidth measured for a membrane based HEB (red dots) and a HEB on a thick silicon substrate (blue dots).

C. *Discussion*

The heterodyne measurements at 0.6 THz of the quasi-optical membrane based mixer have demonstrated promising results. Though the noise temperature is about 30% higher than that of the mixer with a HEB on a thick Si substrate which has been fabricated with the very similar process and measured in the same conditions, this work has demonstrated the feasibility of the membrane mixer concept and the fabrication process. Further improvements are needed to increase the coupling efficiency between the mirror, the antenna and the HEB. The IF gain bandwidth of the membrane based mixer seemed quite limited compared to the device on a thick silicon substrate revealing the need of a better understanding of the thermal transfer at the interface of the HEB and the Si_3N_4/SiO_2 membrane. Changing the layer material or adding a buffer layer could be a solution to increase the IF bandwidth.

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