FTS measurement of a 2.5 THz double-slot antenna on SiO_2/Si_3N_4 membrane

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Abstract— **Membrane-based NbN HEB mixers are being developed for new type of receivers. Taking advantage of the quasi-optic design allowed by the membrane, those detectors are expected to show numerous advantages and permit to easily design and process double-slot antennas up to several THz. This work presents the FTS measurements made with a membrane-based double-slot antenna, designed at 2.5 THz, and using an NbN HEB mixer.**

As HEB mixers on SiO2/Si3N4 membranes are recent innovative devices, new technological challenges are faced, which limit the overall processing yield to about 30%. In order to improve the processing yield, we have developed a new processing procedure, which we present also in this paper. The results collected allow us to have high expectations.

***Index Terms*— heterodyne receiver, HEB mixer, stress-less membrane, coupling efficiency, low-cost space applications, quasi-optic array design.**

I. INTRODUCTION

Receivers for astronomical observation above 1 THz have been developed the last years, such as the ground-based radio telescope in the south pole TREND, the airborne-based observatory SOFIA or the space-based Herschel observatory All these observatories use NbN Hot Electron Bolometer on bulk Silicon chips [1, 2], since it has been demonstrated to be the best mixing element at above 1.4 THz, showing better noise performances than SIS [3, 5], an intermediate frequency about 4 GHz [6, 7] and LO power requirement around a few hundreds of mW [8].

Detection of submillimeter lines of OH and HD at 2.5 and 2.7 THz presents a high interest for radioastronomers [9]. Observations of the 112µm ground-state rotational transition of the deuterated hydrogen molecule, HD, with SOFIA will allow the derivation of the abundance profile of deuterium across the Galactic disk and nearby galaxies, thereby providing critical information on the star formation history of these systems. The fundamental OH doublet at 119 µm [10] is of special interest. The hydroxyl radical is one of the most important molecules in interstellar chemistry. It is vital for understanding the water chemistry, since it is both a precursor of water production and a product of water destruction.

At those very high frequencies, the fabrication of waveguides becomes very difficult. In recent years, the micromachining technology has been proposed for the fabrication of millimeter wave circuits on very thin dielectric membranes [11]. We chose then a quasi-optic design, with a HEB mounted on a freestanding SiO2/Si3N4 membrane, for plethora of reasons: it allows us to use a mirror instead of a silicon lens (and anti-reflection coating), decreasing the overall noise temperature, the structure of the antenna is enlarged and the processing at very high frequencies is made easier, a back-short can be added at $\lambda/4$ to double the antenna gain.... such a device on a membrane has been studied already in a few papers [12, 14].

Planar antennas are usually used to couple the RF power to the bolometer and it is mandatory to experimentally determine the RF bandwidth of those antennas. Fourier Transform Spectrometer is usually used for this type of investigation [15].

II. SIMULATIONS

On silicon wafers, the dimensions of the double-slot antenna are defined by scaling method [16]. The slot length L is usually taken equals to $0.3\lambda_0$, the distance between slots S equals to $0.17\lambda_0$ and the width of the slots W equals to $0.02\,\lambda_0$.

At 2.5 THz, λ_0 equals 120 µm, and the slot length L_1 should then be equal to 40 µm on Silicon. Since the membrane thickness 1.4 µm < $0.04\lambda_0$ (4.8 µm), no influence is expected from the membrane [17]. From equation 1, we find a factor of 2.55 between the substrate and the membrane. Then, we should find from the simulations $L=L_1*2.55=102$ µm.

$$L/\lambda_0 = \frac{0.48.A}{\sqrt{\frac{\varepsilon_r + 1}{2}}} \qquad (1)$$

After simulation with CST microwave studio [18], the resonance has been found for a slot length equals to L=91 µm,

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which is smaller than the theory, but reflect the influence of the dielectric membrane.

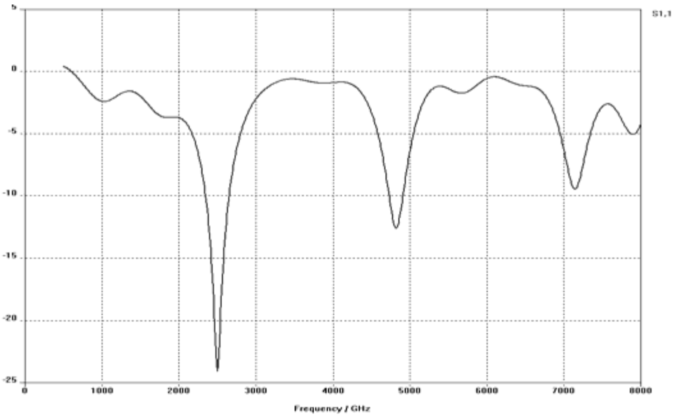

Fig. 1. S11 parameter from the Double-Slot antenna on membrane at 2.5 THz

III. MEASUREMENTS

3.1 Absorption

Atmosphere contains numerous gases which absorb microwave radiations coming from the sky. The absorption depends on the air pressure and humidity. Indeed, higher atmosphere suffer less from the absorption than low atmosphere. That's why submillimeter ground-based telescopes are located in high altitude and dry air environment. Our receiver will be placed on SOFIA Telescope flying at 14 km above the sea level, in the ionosphere.

But FTS measurement has to be made on ground. Around 2.5 THz, absorption is severe (Fig.2). One needs to design and build a vacuum chamber FTS. Still the air path from the vacuum chamber to the cryostat will attenuate the signal, according to the sea level atmospheric absorption, which is due to chemicals, such as CO and H_2O gases.

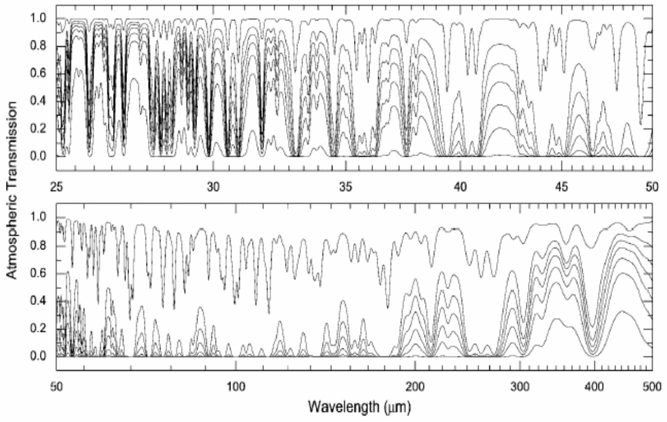

Fig. 2: Atmospheric absorption at 0 km and 14 km

3.2 Setup

We present in this paragraph the Fourier Transform Setup (Fig.3). All the system is placed under vacuum, to avoid to much absorption lines at those frequencies. An Hg lamp is chopped and illuminates with a large range of frequencies. A stepper motor moves the movable mirror. The cryostat is places in front of the FTS output and the biased signal is connected to a lock-in amplifier locked on the chopped signal frequency. The beam coming out is a Gaussian beam large enough to have a good coupling with the lens.

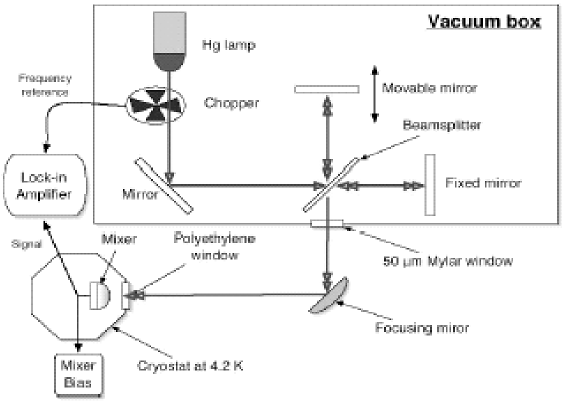

Fig. 3: FTS Setup

A Mylar beam splitter with a thickness of 50 µm was used in order to obtain sufficient signal-to-noise ratio at frequencies above 1 THz. For the spectral measurements, the HEB was constant-voltage biased.

The device temperature was set at the transition edge temperature at ~ 7 K, using a heater.

The mixer unit used for the measurement is quasi-optic (Fig.4). It uses a Silicon lens, and the chip is glued at the back of the lens. A pin is connected to the IF pad to take the IF signal out.

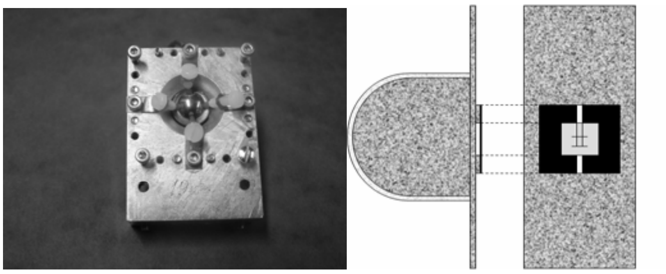

Fig. 4: Chip mounting in mixer unit

3.3 Measurements

The FTS is operated in a step and integration mode with an integration time of 1 s. The measured interferogram is then apodized by a cosine squared apodization function. Finally the Fourier transform of the apodized interferogram gives the spectrum response of the antenna at 2.5 THz (Fig.5).

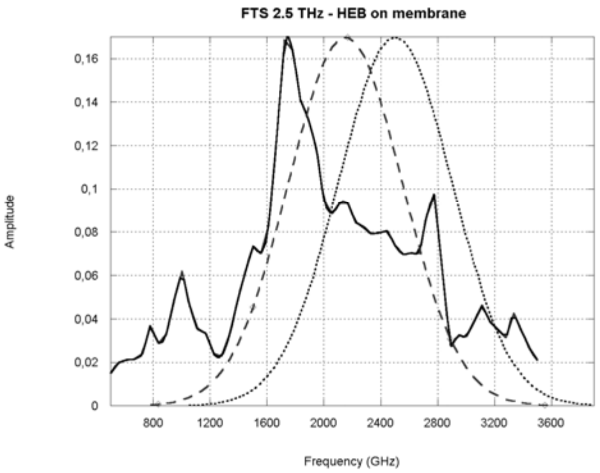

Fig. 5: 2.5 THz FTS response

The FTS maximum frequency measured was 6 THz, the number of step was 200 and the resolution was 2 cm^{-1} (60 GHz).

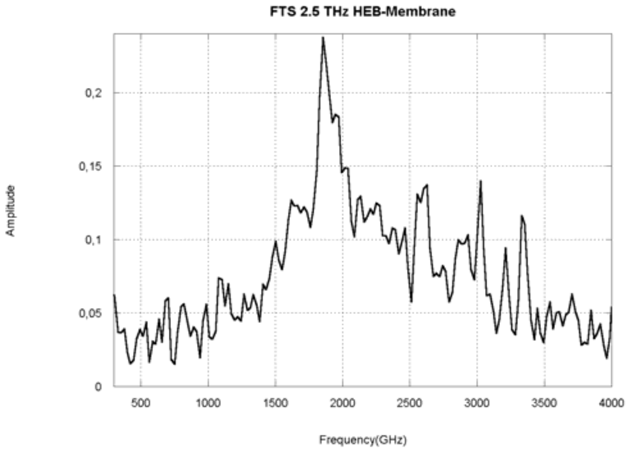

Fig. 6: 2.5 THz FTS response

Here is another FTS measurement of the same device, but the number of step was 1000 with a resolution of 0.4 cm^{-1} (12GHz). (Fig, 6)

From [10], we can compare the absorption lines contained in the air path between the vacuum chamber and the cryostat window. Table 1 summarizes the theoretical and observed absorption lines.

Ther.Freq.	1.66	1.93	2.41	2.50
Obs. Freq.	1.664	1.921	2.414	2.507
Ther.Freq.	2.67	2.77	2.88	3.00
Obs. Freq.	2.671	2.78	2.88	2.97

Table 1: Molecular transition lines comparaison

As we can see on fig. 5 and 6, the RF response of the double-slot antenna is not Gaussian as it should be in theory. We think the radiation encountered reflections in the air gap contained between the silicon lens and the double-slot antenna, as can be seen on Fig. 4. In order to confirm this explanation, we measured the FTS RF response of this antenna, taking exactly the same dimensions, but placing the antenna on a bulk Silicon substrate. In that way, we will be able to observe the shape of the RF response, but at lower frequencies. Result is shown in Fig.7.

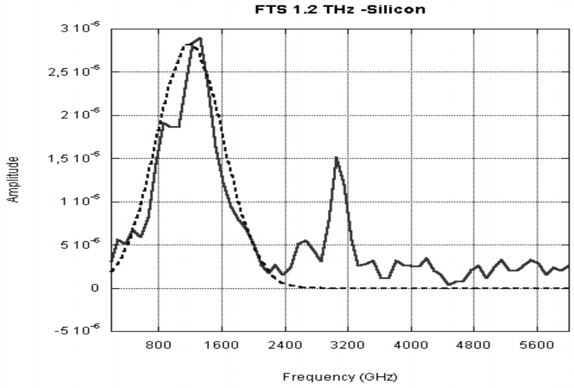

Fig. 7: FTS response on Silicon

The shape is very close to the one it should be in theory, which means that we encountered some reflections at 2.5 THz, due to the air gap between the Silicon lens and the dielectric membrane.

3.4 Discussion

We can now calculate the central frequency of the RF response at 2.5 THz (see Fig. 5), and compare it with the theoretical one. We find out a shift of 12 % (2.2 THz instead of 2.5 THz), which correspond to the shift of 15 % observed by Neto *et al* in [19] at same frequency. The simulations are then verified and the shift of 12 % remains unexplained. Another result is that the substrate is not the cause of this shift, since we observe it as well on a membrane-based antenna.

From the FTS measurement on Silicon, it is found out a central frequency of 1.2 THz. The central frequency observed on a membrane is 2.2 THz. If the membrane would not have influenced the RF response of the antenna, we would have found out a central frequency on Silicon of 1 THz. It means that the antenna responds to higher frequencies. The antenna structure on membrane is then smaller than it would be in free air. The simulations have then taken into account the action of the dielectric membrane on the antenna dimensions. Logically, the factor between RF response on Silicon and membrane should then be lower than 2.55 (from equation 1). Actually, it is found out a factor of 1.83. The membrane indeed acts as would do a semi-infinite bulk substrate of refraction index of 1.65.

IV. MEMBRANE PROCESS

4.1 *Membrane Process*

A SiO_2/Si_3N_4 1.4 µm thick membrane is deposited on both faces of a 4" wafer in Toulouse and sent to Chalmers. After NbN film deposition and HEB processing in Chalmers facilities, the membrane on the back face has to be removed (window opening). This step is done by Reactive Ion Etching (RIE). The next step is to remove the Silicon until reaching the SiO_2 membrane on the top face. This is achieved by using the patented "Bosh" process. Fig. 3 & 4 show the result on the top face without any pattern and the view from the back-side with the antenna patterns which are on the front side.

Fig. 3: front side

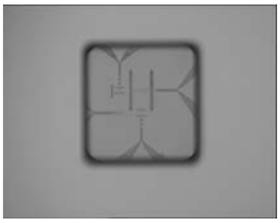

Fig. 4: back side

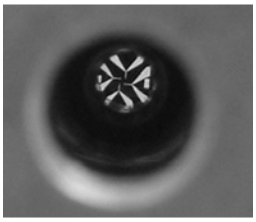

Fig. 5: chip in mixer unit

Fig. 5 shows the same antennas than figure 4, mounted into the quasi-optic mixer block. The view is from the back side where a back-short can be inserted. This mixer block design should avoid reflection or standing waves for future measurements.

5.2 *Process procedures*

It has been tried to deposit NbN films on chips with a membrane already etched, in order to expose the HEB to less process steps. T_c was not as good as a dummy sample placed in the same condition for comparison. It would be due to the temperature on the membrane which seems to be not as high as it is on a bulk silicon chip.

Almost 70% of the devices degrade or die during the membrane process, even if shorted. A solution has been found out and experimented. The last step of HEB process (NbN Ion etching) has been done after the membrane process. All devices successfully passed this procedure and show good I-Vs.

V. CONCLUSION

We have reported in this paper the FTS measurements of double-slot antennas designed at 2.5 THz on SiO_2/Si_3N_4 1.4 µm thick membrane, and on bulk Silicon substrate. A shift of 12 % from the expected central frequency has been observed and a factor of 1.83 has been found out between the two RF responses on the two different substrates. It means that the simulations are correct, but that the dielectric membrane influences the RF behaviour of the antenna. That will be taken into account to redesign the antenna dimensions.

Future investigation has to be made to confirm this factor of 1.83, by measuring FTS of double-slot antenna designed for 4.7 THz on membrane. Moreover, noise bandwidth measurement can be done with an antenna radiating at 2.5 THz on membrane.

REFERENCES

[1] E.M. Gershenzon, G.N. Goltsman, I.G. Godize, Y.P. Gusev, A.I. Elantev, B.S. Karasik, A.D. Semenov, "Millimeter and Submillimeter Range Mixer Based onElectronic Heating of Superconducting Films in the Resistive State," Superconductivity, 3, pp. 1582-1597, 1990

[2] D.E Prober, superconducting terahertz mixer using a transition-edge microbolometer, Appl. Phys. Letter 62(17), (1997), p2119.

[3] P. Yagoubov, M. Kroug, H. Merkel, E. Kollberg, G. Gol'tsman, A.Lipatov, S. Svechnikov and E. Gershenzon, "Quasioptical NbN phonon cooled hot electron bolometric mixers with low optimal local oscillator power", Proc. 9th Int. Symnp. on Space Terahertz Technology, Pasadena, CA, 131 (1998).

[4] P. Yagoubov, M. Kroug, H. Merkel, E. Kollberg, G. Gol'tsman, S. Svechnikov and E. Gershenzon, "Noise temperature and Lo power requirement of NbN phonon-cooled hot electron bolometric mixers at Terahenz frequencies", Submitted to Appl. Phys. Leu., 1998.

[5] A. Skalare, W.R. McGrath, B. Bumble and H. G. LeDuc, "Noise and RF bandwidth measurements of a 1.2 THz HEB heterodyne receiver", Proc. 8fh hit. Symp. on Space Terahertz Technology, Cambrige, MA, 47, (1997).

[6] P. Yagoubov, G. Gol'tsman, B. Voronov, L. Seidman, V. Siomash, S. Cherednichenko, and E. Gershenzon. "The Bandwidth of HEB Mixers Employing Ultrathin NbN films on Sapphire Substrate", Proc. 7th Int. Syrtzp. on Space Teruhertz Technology, Charlottesville. VA, 290, (1996).

[7] S. Cherednichenko, P. Yagoubov, K. n'in, G. Gol'tsman and E. Gershenzon, ''Large bandwidth of NbN phonon cooled hot-electrcin bolometer mixers on supphire substrates", Proc. 8th Inf. Sytnp. on Spuce Terahertz Technology, Cambrige, MA, 245, (1997).

[8] S.Cherednichenko et al. "Local oscillator power requirement and saturation effects in NbN mixers," 11th ISSTT, Ann Arbour, Michigan, May 2000, pp. 379-388

[9] www.sofia.usra.edu

[10] http://www.mpe.mpg.de/ir/ISO/linelists/Molecular.html

[11] J. Sor et al., Electronics letters, 36, p.1, 2000.

[12] A hot-spot model for membrane-based HEB mixer J. Baubert, H. Merkel, M. Salez Proceeding of 13th International Symposium on Space Terahertz Technology, 2002. Tucson, Arizona.

[13] Membrane-based HEB mixer for THz applications J. Baubert, M. Salez,Y. Delorme, P. Pons, G. Goltsman, H. Merkel, B. Lecomte Proceeding of the SPIE International Symposium on Microtechnologies for the New Millennium 2003. Maspalomas, Gran Canaria, Canary Islands, Spain. Proc. SPIE Int. Soc. Opt. Eng. 5116, 551 (2003)

[14] Millimeter wave HEB mixers on membrane: Theory - fabrication process - resultsJ. Baubert, M. Salez, Y. Delorme, P. Pons, G. Goltsman, H. Merkel, B. Lecomte Proceeding of MEMSRF 2003, Toulouse, France.

[15] P.F Goltsmith "Quasi optical systems", IEEE Press, 1998, p. 204

[16] Dipole and slot elements and arrays on semi-infinite substrates Kominami, M.; Pozar, D.; Schaubert, D. Antennas and Propagation, IEEE Transactions Volume 33, Issue 6, Jun 1985 Page(s):600 - 607

[17] D.F Filipovic, S.S. Gearhart, G.M Rebeiz, "Double-slot antennas on extended hemispherical and elliptical dielectric lenses", IEEE Trans. On Microw. Th. And Tech., Vol 41, n 10, Oct 1993

[18] CST & HFFS simulation for membrane-based HEBs in array configuration J. Baubert, M. Salez, Y. Delorme, P. Pons, G. Goltsman, H. Merkel, B. Lecomte SPIE "Astronomical Telescopes" June 2004.

[19] R.A Wyss, A. Neto, W.R Mc Grath, Submillimeter spectral response of twin-slot antennas coupled to HEB, Proc. Os 11th ISSTT, Ann Arbor, MI, May 1-3, 2000.