Broadband Fourier Transform Spectrometer (FTS) Measurements of Spiral and Double-Slot Planar Antennas at THz Frequencies

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Abstract

The direct responses of NbN phonon-cooled hot electron bolometer (HEB) mixers, integrated with different planar antennas, are measured, using Fourier Transform Spectrometer (FTS). One spiral antenna and several double slot antennas, designed for 0.6, 1.4, 1.6, 1.8 and 2.5 THz central frequencies, are investigated. The Optimization of the measurement set-up is discussed in terms of the beam splitter and the FTS-to-HEB coupling. The result shows that the spiral antenna is circular polarized and has a bandwidth of about 2 THz. The frequency bands of double slot antennas show some shift from the design values and their relative bandwidth increases by increasing the design frequency. The antenna responses do not depend on the HEB bias point and temperature, as long as the device is in the resistive state.

I. Introduction

Hot electron bolometer (HEB) mixers currently have better performance as heterodyne receivers at THz frequencies, where SIS and Schottky mixers have worse sensitivity. It has been shown that NbN HEB mixers have noise temperature about $10h\nu/k$ [1,2], an intermediate frequency bandwidth close to 4 GHz [1,2], and require few hundreds of nW local oscillator power [3]. Among many factors, which affect the performance of mixers, the RF coupling is obviously crucial.

In order to couple the RF radiation to HEB, it is usually integrated with a planar antenna, which is specifically designed for the frequency of interest. Theoretically, this type of mixer is expected to operate up to 10 THz and even above. However, as the design frequency increases, the size of the antenna decreases and it becomes difficult to estimate the antenna performance. Therefore it is inevitable to study the antenna frequency band experimentally. Fourier Transform Spectrometer (FTS) is usually used for this type of investigation in sub-millimeter range [4,5].

Log periodic spiral and double slot antennas are among the most commonly used planar antennas in sub-millimeter technology today. In order to characterize these antennas in THz range, we fabricated a set of NbN HEB mixers integrated with a spiral antenna and also with different double slot antennas, designed for 0.6 up to 2.5 THz. This paper presents the measured direct RF response of NbN HEB mixers, integrated with these antennas, using FTS.

II. Fourier Transform Spectrometer

The Fourier Transform Spectrometer (made by SPECAC LTD.) consists of a Michelson interferometer in vacuum chamber with a chopped Hg arc lamp and 50 μm Mylar output window. The source provides broadband radiation with the maximum intensity in the visible region, which is blocked by a black 0.2 mm thick polyethylene. The movable mirror has a maximum span of 200 mm with a minimum step size of 1.25 μm. The FTS is operated in a step-and-integration mode with an integration time of 1 sec. The measured interferogram is then apodized by cosine squared apodization function. Finally the Fourier transform of the apodized interferogram gives the spectrum of the response. The size and the number of steps determine the resolution and the maximum frequency of the spectrum. By choosing 200 steps with step size 7.5 μm one can achieve 90 GHz resolution up to 10 THz maximum frequency. Figure 1 shows the normalized measured spectrums, using 10 and 20 μm thick Polyethylene beam splitters. In both cases, Golay cell was used as a detector. The normalized calculated spectrums are depicted in the same figure. In this calculation, only the Fresnel's equations are used and the multiple reflections inside the beam splitter are taken in to account [6].

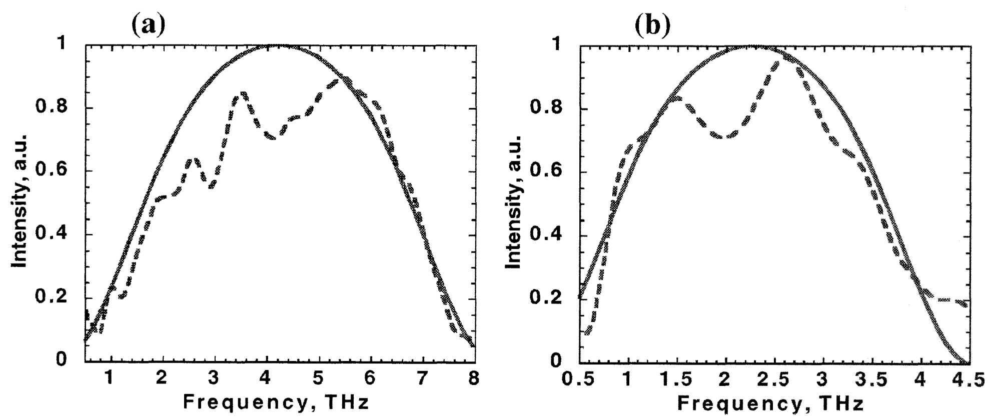


Figure 1. Measured (dashed lines) and calculated (solid lines) spectrums of the output signal from FTS, using (a) 10 μm polyethylene (b) 20 μm polyethylene beam splitters. A Golay cell was used as a detector.

The 10 μm thick polyethylene beam splitter can be used to study transmission properties of different materials up to 7.5 THz. For example, figure 2 shows the transmission spectrum of 1mm thick Teflon film. We can see that it is almost opaque for frequencies above 6 THz.

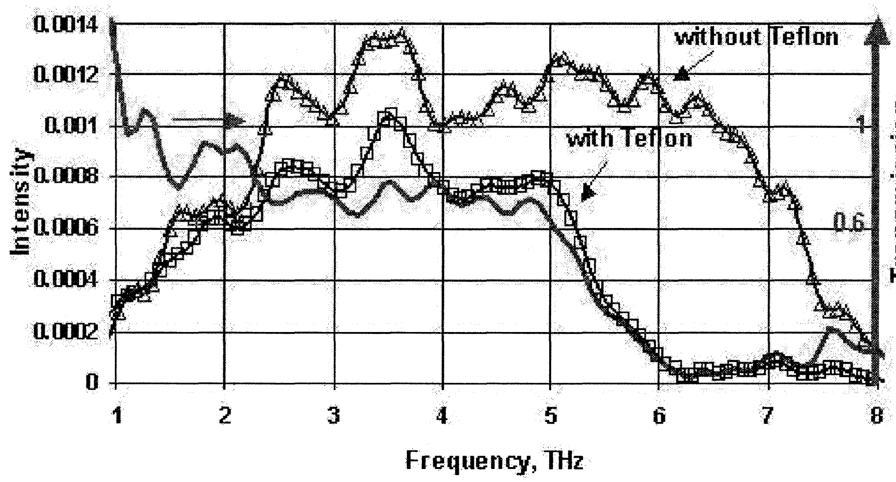


Figure 2. Study of transmission property of a 1 mm thick Teflon sheet. The triangle line is the response without the Teflon. The rectangle line in the response with Teflon. The solid line shows the Teflon transmission.

The 20 μm thick polyethylene beam splitter was used to measure the direct responses of the HEB mixers integrated with different planar antennas up to 4 THz.

III. Beam coupling

Characterizing the FTS output beam using a Golay cell indicates that it is divergent and quite wide (a few cm in diameter at the FTS output window). On the contrary, the main lobe of the receiver's radiation pattern is just few degrees wide [7,8,9] (for detailed description of the receiver see next section). Therefore, when the FTS output beam was directly coupled to the receiver, the response signal was very weak and noisy. In order to enhance the coupling, a parabolic off-axis mirror and a Teflon lense were tested between the FTS output and the receiver. Golay cell was used as a detector to investigate the effect of these two focusing tools. As it is shown in figure 3, better coupling was achieved via the mirror compared to the Teflon lense. By normalizing the curves (insertion in figure 3), we see that the Golay responses, with and without using the mirror, have the same spectra. The losses in Teflon cause attenuation above 2 THz. This indicates that the mirror is more suitable choice for wideband measurements.

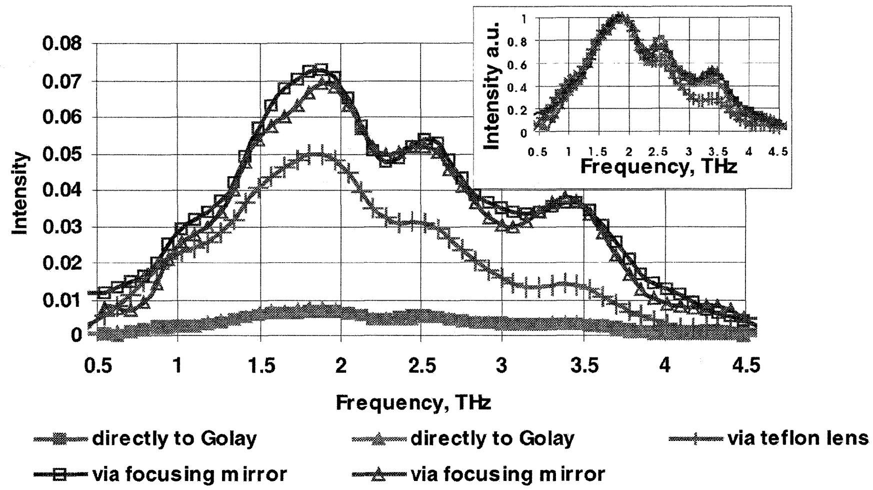
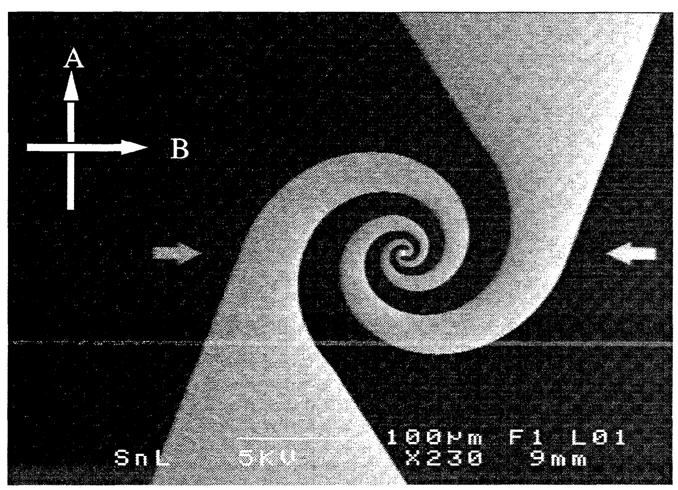


Figure 3. Study of a parabolic off axis mirror and a Teflon lens for collimating the FTS output beam. In these measurements, Golay cell was used as a detector. The insertion shows the normalized curves.

IV. Planar Antennas Measurements

The direct responses of NbN hot electron bolometers, integrated with different planar antennas have been measured. All the devices are made from 3.5 nm thick NbN films, sputtered on high resistive silicon substrates. The bolometers are 0.4 μm long and 4 μm wide. The chips were placed on a holder with 12 mm diameter silicon lens and mounted in a liquid Helium cryostat. The operating point of the device was controlled by DC bias and heating the mixer holder at the same time. A parabolic off-axis mirror was placed between the FTS output window and the cryostat. 20 μm thick Polyethylene film was used as a beam splitter in the FTS. All antenna measurements were done with 400 steps and a step size of 12.5 μm for movable mirror. This setting gives 30 GHz spectrum resolution (before apodization) and 6 THz maximum frequency.

Figure 4. SEM picture of the log periodic spiral antenna.



Two different types of planar antennas have been measured. One is log periodic spiral antenna and the other double slot antenna. Figure 4 shows a SEM picture of the spiral antenna. The spiral has inner and outer radii of 10 and 100 μm, respectively. The total antenna arm length is about 300 μm, which is calculated from its radii and the expansion rate (3.2 per turn) [10].

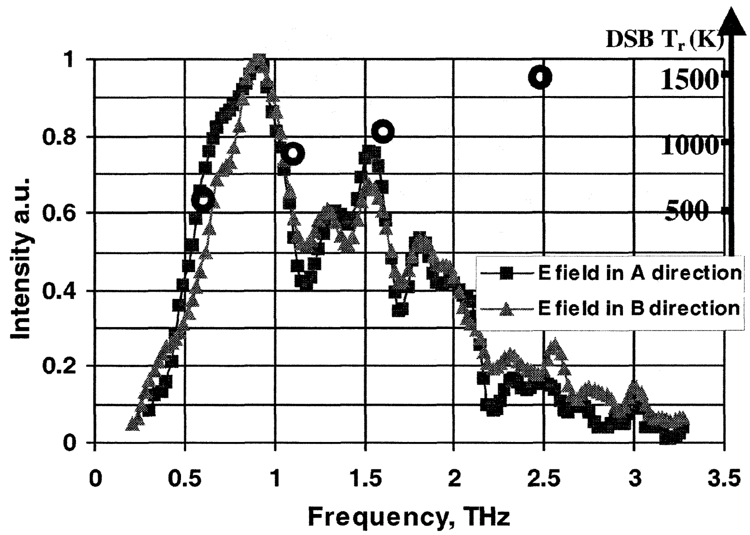


Figure 5. Normalized direct responses of the HEB, integrated with the spiral antenna. Direction A and B are shown in figure 4. Small circles show the measured double side band receiver noise temperatures at different LO frequencies.

The direct responses of the HEB integrated with the spiral antenna were measured with two different polarization of the incident beam. As we see in figure 5, the response spectrum of the spiral antenna did not show any polarization dependence. The bandwidth was about 2 THz, which is in agreement with estimated bandwidth of this type of Antenna in [11].

Figure 6 shows a SEM picture of a HEB, integrated with a double slot antenna, designed for 1.6 THz. Similar antennas have been fabricated for 0.6, 1.4, 1.8 and 2.5 THz. In all designs, the slot length (L) is $0.3\lambda_0$, the distance between slots (S) is $0.17\lambda_0$ and the width of the slots (W) is $0.02\lambda_0$, where λ_0 is the wavelength at design frequency in vacuum. The design rule was adopted from [12]. The dimensions of these antennas are summarized in Table 1. Note that the width of the coplanar line in the middle of the antenna is 4 μm and the same for all antennas.

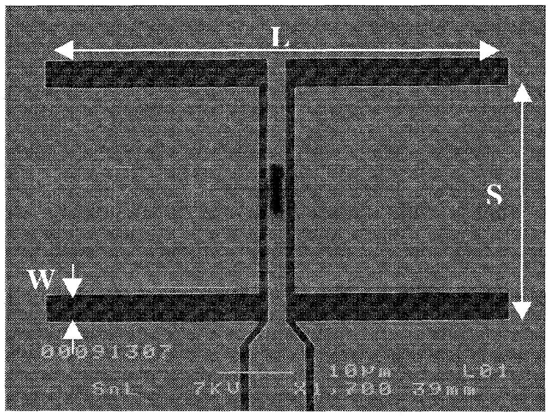


Figure 6. SEM picture of double slot antenna

	L (µm)	S (µm)	W (µm)
0.6 THZ	155	84	10,5
1.4 THz	64	36	4,6
1.6 THz	56	32	4
1.8 THz	50	28	3,6
2.5 THz	38,4	19,2	2,4

Table 1. Dimensions of the double slot antennas

The direct responses of the HEBs integrated with different double slot antennas are shown in Figure 7. The frequencies at which the local maximums and minimums occur are almost the same for all double slot antennas and also coincide with the strongest water absorption lines. We observe shifts between the bands of the antennas, designed for different frequencies. The higher is the design frequency, the wider is the relative bandwidth. This can be due to the fact that the width of the center coplanar line is the same in the middle of all the antennas and it is getting more comparable with the antenna size as design frequency increases (See table 1).

These results give important information about the optical losses in noise temperature measurements, which are usually done in air. For example in Figure 7(a), we see that although the antenna is designed for 2.5 THz, the response at 2.5 THz and 1.6 THz is almost the same. This can be the reason that the double side band receiver noise temperature of this mixer was measured 1700K, at both 1.6 and 2.5 THz LO frequencies.

Although it is difficult to see the center frequency of the antenna band directly, it can be estimated by fitting a parabola to the measured curve. Figure 8 shows the measured curves (solid line with squares) and the fitted parabolas (solid line) for 1.6 and 2.5 THz antennas. The calculated transmission of 30 cm air at 22°C and 30% humidity with 70 GHz resolution is depicted by the dashed line. Multiplying the parabolas with the atmosphere transmission factor gives a close approximation to our measured data (solid line with triangle). The conclusion is that the antenna responses are close to those parabolas mentioned above. We see that the response is down shifted from the design frequency, which has also been reported for antennas, integrated with Nb HEBs [4,5].

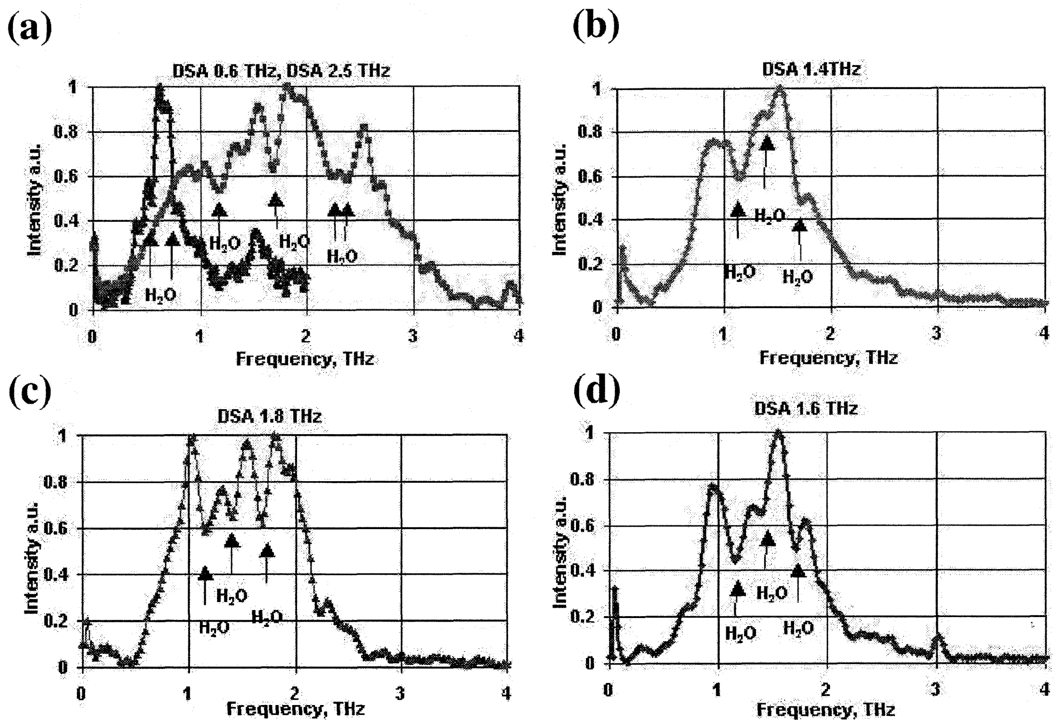


Figure 7. Direct responses of the HEBs integrated with different double slot antennas (DSA).

The direct responses were also measured at different operating conditions of the bolometers. The bias voltage was changed between 1 to 4 mV. We also changed the temperature of the mixer, within the range that the devices are stable and the DC characteristics of the bolometers were close to when they are used as mixers and pumped by a local oscillator. For all measured devices, the spectra did not change by varying either the bias voltage or the ambient temperature. This indicates that the direct responses are determined by the antenna structures and not by the bolometer operating condition, as long as it stays within the resistive state.

V. Conclusion

We have succeeded to extend the FTS frequency band up to 7.5 THz by using 10 μm polyethylene as a beam splitter. This set up can be used to study the optical property of material in THz range. For instance the transmission coefficient of 1mm thick Teflon sheet is measured. We see that it is almost opaque above 6 THz.

Our measurements show that the RF bandwidth of the spiral antennas is not strongly dependent on the radiation polarisation. The direct response of HEB integrated with different double slot antennas shows that the frequency bands of all antennas are down-shifted from their design values. Besides, the antenna bandwidth increases with increasing the design frequency.

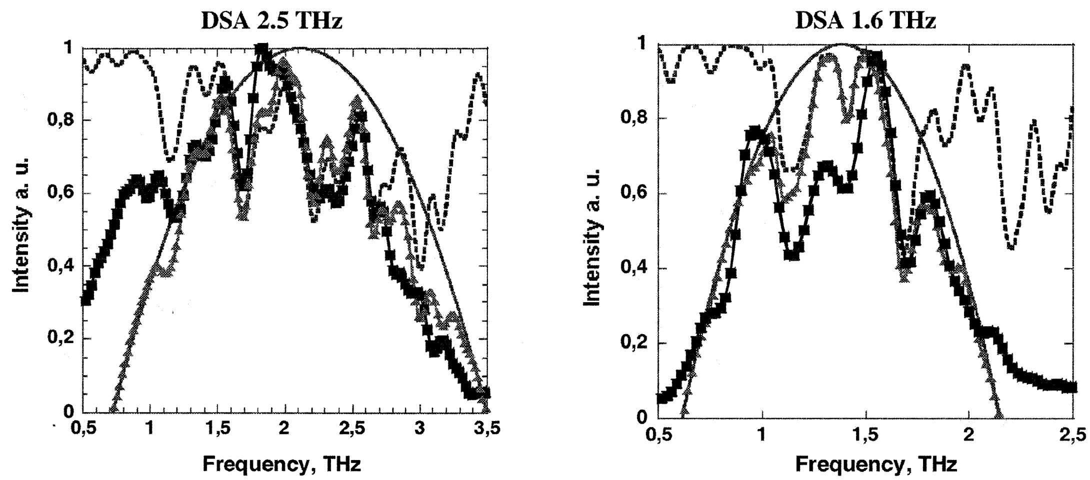


Figure 8. Calculated (solid line with triangles) and measured (solid line with squares) results for 1.6 and 2.5 THz antennas. The dashed lines show the air transmission coefficient. The parabolas (solid lines) are fitted to the measured curves.

For all measured mixers, changing the bias and temperature of the device, within resistive state, does not affect the result. This indicates that the measured spectrum is determined by the antenna response and not the intrinsic response of the bolometer. However, this might not be the case when the device is heated by a local oscillator (LO) instead of a heater. The temperature of the bolometer is not uniform when it is pumped by the LO. Therefore the response of the device might depend on the bias point and the absorbed LO power.

The interpretation of the antenna RF bandwidth from measurements is strongly affected by the water absorption. Vacuum measurements are required to characterise the planar antennas accurately. However, since the noise temperature measurements are usually done in air, the presented results are very informative.

VI. Acknowledgements

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