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Performance of the Phonon-Cooled Hot-Electron Bolometric Mixer between 0.7 THz and 5.2 THz

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Abstract **– We report on the phonon cooled NbN hot electron bolometer as mixer in the terahertz frequency range. Its hybrid antenna consists of a hyperhemispheric silicon lens and a logarithmic-spiral feed antenna. Noise temperatures have been measured between 0.7 THz and 5.2 THz. A quarter wavelength layer of Parylene works as antireflection coating for the silicon lens and reduces the noise temperature by about 30%. It was found that the antenna pattern at 2.5 THz is determined by the feed antenna and not by the diameter of the lens.**

I. Introduction

A number of on-going astrophysical and atmospheric research programs are aimed to the Terahertz (THz) spectral region. Projects which involve THz heterodyne receivers are the Stratospheric Observatory for Infrared Astronomy (SOFIA) [1] and the Far-Infrared and Submillimetre Telescope FIRST [2]. Many important emission lines which will be observed with these observatories are between 1 THz and 5 THz. Examples are the CII fine structure line at 1.6 THz, the OH rotational transition at 2.5 THz and the OI fine structure line at 4.75 THz. These applications require a receiver with the noise temperature close to the quantum limit. Recent studies have shown that superconducting hot-electron bolometric (HEB) mixers are able to satisfy such requirement [3,4]. Since in a sufficiently small superconducting HEB mixer only the electrons are heated by the incoming radiation the response time of the HEB is of the order of the electron-phonon interaction time. This results in low noise temperatures, low local oscillator (LO) power requirement, and intermediate frequencies (IF) of several GHz. In this paper we present the design and performance of a NbN phonon-cooled HEB mixer in the frequency range from 0.7 THz up to 5.2 THz.

II. Mixer Design

Devices were fabricated from 3.5 nm thick NbN films which typically had a room temperature resistivity of 220 μΩ·cm and a superconducting transition temperature of about 10 K. Films were deposited in a nitrogen atmosphere by dc reactive magnetron sputtering of Nb on 350 μm thick optically polished substrates from pure silicon. Details of the process are described elsewhere [5]. A planar two-arm complementary logarithmic-spiral antenna was used to couple the signal and the LO radiation with the mixer. The log-spiral antenna belongs to a family of frequency independent antennas, i. e. impedance and beam pattern are to a large extent frequency independent. The winding of our antenna can be characterized by the angle $\phi = 70°$ at which a radial line from the origin of the antenna intersects a spiral arm. The central part of the antenna was patterned from a 250 nm thick gold film using electron beam lithography while the outer part was defined by conventional UV photolithography. The layout of the antenna is shown in Fig. 1. The circle inside which the antenna arms form inner terminals has a diameter of 2.2 μm. The diameter of the circle that circumscribes the spiral structure is 130 μm. Between these circles, the antenna arms inscribe 2.15 full turns. The spiral structure is terminated by a coplanar line, which was lithographed on the same substrate and had an impedance of 50 Ω. The substrate carrying the HEB, the planar antenna and the co-planar line, was glued with its rear surface onto the flat side of an extended hemispheric lens. The lens was cut off from an optically polished sphere that was made from high resistivity (>10 kΩ cm) silicon. Spheres of 6 mm and 12 mm diameter were used for this purpose. The extension of the lens together with the substrate yields a total extension length of 1.2 mm and 2.4 mm for the 6 mm and 12 mm lens, respectively. These values are very close to the extension length corresponding to the synthesised elliptic lens for which the beam pattern of the hybrid antenna is expected to be diffraction limited [6]. The mixer was mounted at the cold plate of a l-He cryostat. A cold quartz filter was used to block the 300 K background radiation.

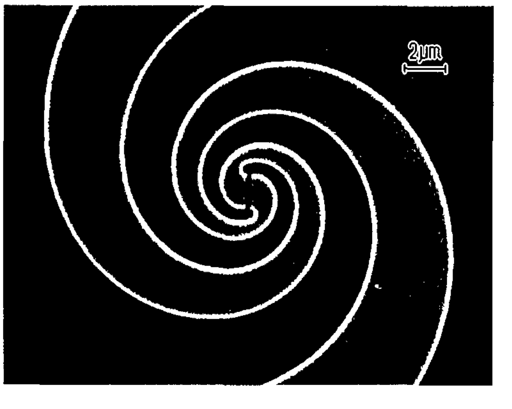

Fig. 1: Layout of the logarithmic spiral antenna. The gap in the center of the antenna has the height 1.7 μm and the width 0.2 μm. The width defines the length of the HEB.

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III. NOISE TEMPERATURE

The noise temperature was measured at several frequencies from 0.7 THz to 5.2 THz. The IF frequency was 1.5 GHz. An optically pumped far-infrared (FIR) ring laser and a transversely excited FIR laser were used as a local oscillator in the frequency ranges 0.7 THz to 2.5 THz and 2.5 THz to 5.2 THz, respectively. Results from measurements of the noise temperature at 2.5 THz were identical irrespective of which laser system was used. The double side-band (DSB) receiver noise temperature was determined by the Y-factor method making use of Eccosorb as the hot and cold load at temperatures of 293 K and 77 K, respectively. To derive the receiver noise temperature from the measured Y-factor the dissipation-fluctuation theorem in the form of Callen and Welton was used.

Table 1: DSB noise temperatures at THz frequencies.

Freq. [THz]	Device	Lens	T_{DSB} [K]	$T_{DSB,corr}$ [K]
0.623	A1	12 mm	1300	800
1.397	A1	12 mm	2000	1100
1.627	A1	12 mm	2100	1200
2.523	A1	12 mm	2600	1700
3.106	A3	6 mm	4000	2800
4.252	A3	6 mm	5600	3900
5.246	A3	6 mm	8800	6200

A major contribution to the noise temperature originates from losses in the optical elements. The main sources are the quartz filter with 1.1 dB to 1.9 dB loss and the reflection loss at the surface of the silicon lens (≈ 1.5 dB). At frequencies below 3 THz a filter made from Zitex has a lower loss than quartz [7]. The reflection loss of the lens can be reduced by an anti-reflection (AR) coating with Parylene (see section IV). The last column in Table 1 displays the DSB noise temperatures assuming a Zitex filter for the data below 3 THz and a AR coated silicon lens optimized for each frequency. Above 3 THz the improvement ist only due to the AR coating since Zitex and quartz have almost the same loss. Beside the losses in the optical components there is another mechanism which contributes to the increase of the noise temperature with higher frequencies. This additional loss is caused by an increasing impedance mismatch between the HEB itself and the antenna. Due to the skin effect the rf-current in the HEB is confined to the outer region of the bridge while the central part carries less and less current with increasing frequency. A detailed investigation of this mechanism can be found in Ref. [8].

IV. PARYLENE ANTI-REFLECTION COATING

Parylene C is a good candidate as AR coating. It is a polymer with a refractive index of about 1.62 that matches closely the required value $n_{Si}^{1/2} \approx 1.84$ for a quarter wavelength antireflection layer on silicon. Beside that Parylene C is chemically inert, has a high thermal stability and has practically no water absorption. It is deposited from the gas phase. This results in films of uniform thickness and high conformity. Two lenses each with a diameter of 6 mm were made from the same silicon crystal. One of the lenses was coated with a 18.5 – 20 μm thick Parylene C layer. The improvement of the noise temperature due to a lens with this AR coating was investigated for two HEB mixers at four different frequencies between 0.7 THz and 2.5 . A significant improvement of about 30% was achieved at 2.5 THz. The improvement decreases towards the smaller frequencies as expected because the thickness of the Parylene C layer corresponds to about a quarter wavelength at 2.5 THz. Fig. 2 illustrates the relative improvement, i.e. the difference in noise temperature measured with the uncoated and the coated lens divided by the noise temperature measured with the uncoated lens. Also shown (solid line) is the relative improvement as expected from transmittance measurements of plane parallel silicon samples [9]. In this case, the relative improvement is the difference in transmittance between the coated and the uncoated sample divided by the transmittance of the uncoated sample. However, the transmittance measurements have been performed at 300 K where the refractive index is 1.62. It is known that the refractive index of Parylene C decreases with temperature. The dashed line is the relative improvement of the transmittance calculated by assuming a refractive index of 1.5 for Parylene C at 4 K. It can be seen that the transmittance data and the noise temperature measurements are in excellent agreement. A detailed study of Parylene C as AR coating at THz frequencies can be found in Ref. [9].

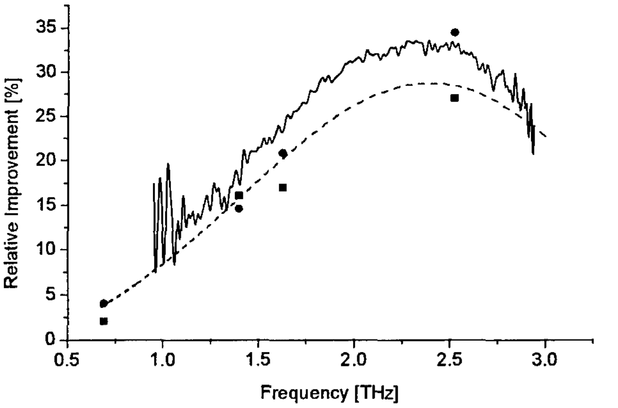
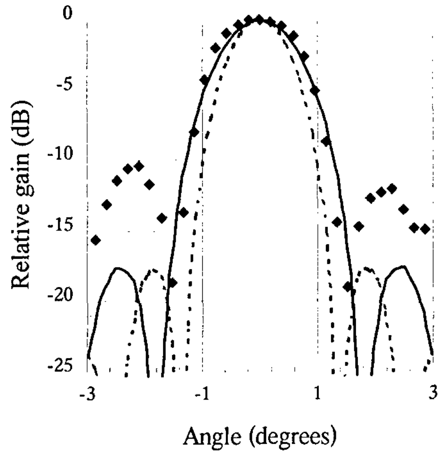


Fig. 2: Relative improvement of the noise temperature of two HEB mixers (circles and squares) due to a AR coating with Parylene C. The solid and the dashed line correspond to the relative improvement of the transmittance of a plane parallel silicon sample with the same coating at 300 K and 4 K, respectively.

V. ANTENNA PATTERN

Beam patterns of the hybrid antenna have been measured at 2.5 THz with the 6 mm and the 12 mm lens. Both lenses had no AR coating. Fig. 3 displays results for E-planes. The dashed lines represent the diffraction limited antenna patterns that were simulated for the physical diameter d of the lens according to the expression $(2J_1(\nu)/\nu)^2$, where $\nu=(\pi \tan(\theta)\, d)/\lambda$, θ is the angle and J_1 is the Bessel function of the first kind. The calculated full widths at half maximum (FWHM) are 1.19° and 0.59° while the measured profiles yield 1.65° and 0.75° for the 6 mm and the 12 mm lens, respectively. The solid lines are calculated according to the above given expression but the diameter of the aperture was set to yield the closest match with the measured antenna pattern. The resulting diameter of the effective aperture is 4.5 mm and 9.3 mm for the 6 mm lens and the 12 mm lens, respectively. These values correspond to a 70° beamwidth (FWHM) of the log-spiral feed antenna independent of the diameter of the lens. This is in good agreement with measurements of the antenna pattern of a log-spiral antenna with the same characteristic angle but at cm-wavelengths [10]. A less tightly wound spiral with smaller characteristic angle ϕ will yield a broader pattern of the feed antenna resulting in a narrower beam. However, the pattern will be less symmetric.



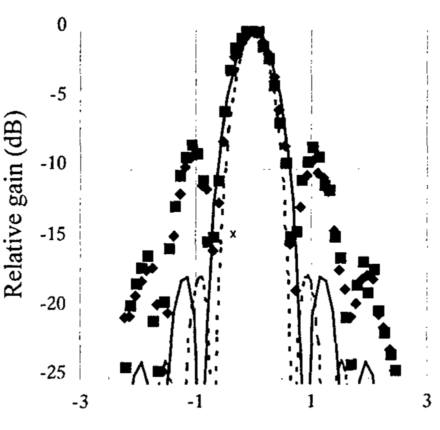


Fig. 3: Beam pattern at 2.5 THz of the hybrid antenna with a 6 mm lens (upper figure) and a 12 mm lens (lower figure). The solid lines display the closest match between theory and experiment while the dashed lines correspond to the pattern as expected from the lens diameter.

VI. Conclusion

We have investigated phonon-cooled NbN HEB mixers in the THz frequency range. The noise temperatures range from 1300 K at 0.7 THz to 8800 K at 5.2 THz. A major source of loss is the reflection at the surface of the silicon lens of the hybrid antenna. This can be overcome by a quarter wavelength AR coating with Parylene C. The noise temperature is decreased by about 30% due to this AR coating. It is shown that the beam pattern of the hybrid antenna is determined by the beam pattern of the feed antenna and not by the diameter of the lens.

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