PERFORMANCE OF TERAHERTZ HETERODYNE RECEIVER WITH A SUPERCONDUCTING HOT-ELECTRON MIXER

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Introduction

During the past decade major advances have been made regarding low noise mixers for terahertz heterodyne receivers. State of the art hot-electron-bolometer (HEB) mixers have noise temperatures close to the quantum limit and require less than a microwatt power from the local oscillator (LO). The technology is now at a point where the performance of a practical receiver employing such mixer, rather than the figures of merit of the mixer itself, is of major concern. We have incorporated a phonon-cooled NbN HEB mixer in a 2.5 THz heterodyne receiver and investigated its performance. This yields important information for future development of heterodyne receivers such as GREAT (German receiver for astronomy at THz frequencies aboard SOFIA) [1] and TELIS (Terahertz limb sounder), a balloon borne heterodyne receiver for atmospheric research [2]. Both are currently under development at DLR.

Mixer Design

The HEB was manufactured from a superconducting NbN film with a nominal thickness of 3.5 nm. The film was deposited by dc reactive magnetron sputtering on a 350 μm thick Si or MgO substrate [3]. The bolometer having a width of 2.4 μm and a length of 0.2 μm was located in the center of a planar feed antenna. Two types of feed antenna have been tested: logarithmic-spiral and double-slot. The logarithmic-spiral antenna was designed to cover the frequency range from about 0.5 THz to 6 THz, while the double-slot antenna was optimized for 1.8 THz. Due to processing the transition temperature (9 K) of the bolometer was lower than the transition temperature (10 K) of the film while the transition width and the square resistance slightly increased. The substrate with the HEB was glued onto the flat side of an extended hemispherical 12 mm diameter silicon lens with a Parylene antireflection coating, which was optimized for 2.5 THz [4]. The lens with the HEB was mounted in an Infrared Labs helium dewar with a wedged TPX pressure window and a cold

(77 K) quartz filter. The intermediate frequency (IF) signal was guided out of the mixer via the 50 Ω coplanar line. A circulator was used to feed the bias to the mixer and to transmit the IF signal to a 2 K low noise HEMT amplifier. The IF signal was filtered at 1.5 GHz with a bandwidth of 75 MHz, further amplified and rectified with a crystal detector.

Receiver Performance

Noise temperature and IF bandwidth

An optically pumped FIR ring laser [5] was used as a local oscillator. Signal radiation and LO radiation were superimposed by a 6 μm thick Mylar beam splitter. The double sideband (DSB) noise temperature of the receiver was measured by the Y-factor method. Hot and cold loads (Eccosorb) at 293 K and 77 K alternatively covered the receiver beam. Output signals due to hot and cold loads were continuously readout by a computer, which performed statistical analysis of the signal and computed the noise temperature. Fig. 1 shows typical current-voltage (I-V) characteristics of the mixer recorded at different LO power. Minimal noise temperature is achieved in the vicinity of the operation point A. Applying an isothermal technique we estimated 100 nW power absorbed by the HEB at this optimal operation point. The best DSB noise temperature was about 2200 K at 2.5 THz frequency. We found that this figure does not noticeably decrease in the IF frequency range up to 2 GHz. This finding correlates with the expected 6 GHz noise temperature roll-off frequency for our HEB mixers [6].

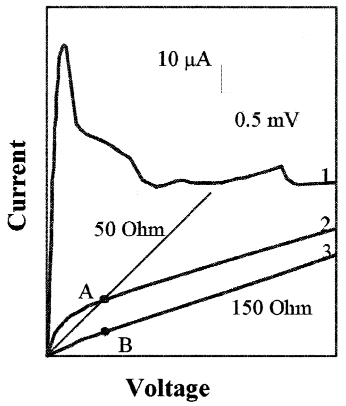

Figure 1 *IV-curve of the mixer (1: unpumped, 2: optimally pumped, 3 driven in the normal state) The lowest noise temperature is achieved in the point A.*

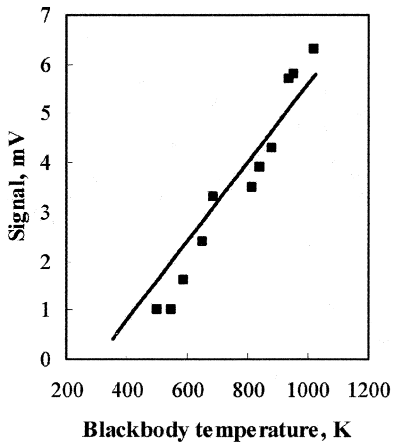

Figure 2 *Heterodyne signal as a function of the black body temperature.*

Dynamic range and conversion losses

In order to evaluate the dynamic range of the mixer we measured the heterodyne response to black body radiation at 2.5 THz. We varied the black body temperature while keeping its aperture fixed. The receiver response (Fig. 1) was linear up to the black body temperature 1050 K. The beam-filling factor by the black body aperture was 10% [7]. This suggests a maximum non-saturating background temperature of ≈ 400 K at the receiver input. Since the signal shows no signs of saturation even at the largest black body temperature, we expect that the 3 dB compression would occur at a load temperature significantly larger than 400 K. The slope of the straight line in Fig. 2 corresponds to a conversion efficiency of -17 ± 1 dB. This figure includes optical coupling losses, conversion efficiency of the mixer, and losses in the IF chain from the mixer output to the input of the cold amplifier. The optical losses at 2.5 THz are 4 ± 0.5 dB [3]. The IF losses were estimated comparing the noise signals originating from a 50 Ω resistor and the mixer driven into the normal state (point B in Fig. 1). This yields 4 ± 0.5 dB IF losses (for details see Ref. 7). The remaining 9 ± 1 dB loss are due to the conversion efficiency of the mixer. This is in agreement with the conversion efficiency calculated [7] in the framework of the uniform large signal model.

Beam pattern

The beam pattern of our hybrid antenna with a double-slot and a logarithmic-spiral feed is shown in Fig. 3. Patterns were measured at a LO frequency of 1.6 THz and 2.5 THz by moving a hot point like source in the far field of the receiver. The output heterodyne signal was registered as a function of the position of source. The solid lines represent Gaussian fit to the profile of the main lobe. At 1.6 THz a 3 dB beam width of 1.1° and 1.3° was found for the double-slot and logarithmic-spiral feed antenna, respectively. The side lobes were at -10 dB and at -6 dB, indicating that at this frequency the double-slot feed antenna is the better choice. However, this changes at higher frequencies where the dimensions of the double-slot antenna become comparable to the size of the HEB and the IF embedding circuitry. At 2.5 THz, we found higher side lobes and wider beam pattern for the double-slot feed.

Noise stability

Instantaneous noise of the output signal sets the minimum contrast of the source (source versus background) that can be distinguished by the receiver. If the output noise is completely uncorrelated (i.e. white) the radiometer equation states that the noise drops down as square root of the integration time. However, in practice the total noise of a receiver is a combination of white noise, $1/f$ noise and low frequency drift noise. The latter two do not integrate down. To choose the best observation strategy with particular

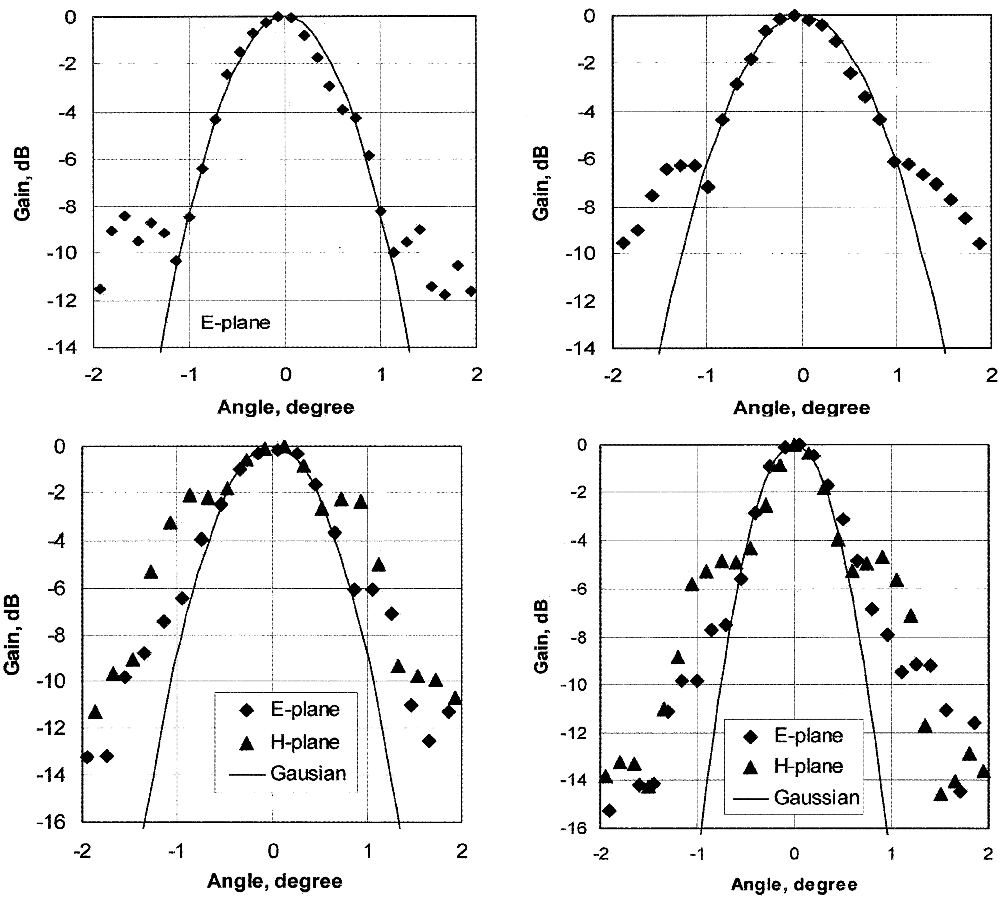

***Figure 3** 1.6 THz (top row) and 2.5 THz (bottom row) gain pattern of hybrid antennas with double-slot (left) and logarithmic-spiral (right) feed on the 12 mm lens.*

receiver, it is useful to consider the “Allan” variance, σ_A, given by $\sigma_A(t)^2 = \sigma(t)^2/2$, where σ is the standard deviation of the signal [8] from the root mean square value. For a noise spectrum that contains white noise, 1/f and drift noise the “Allan” variance takes the form $\sigma_A(t)^2 = at^\beta + b/t + c$, where a, b, c and $\beta > 1$ are constants showing relative contribution of different noise types. They define an optimum integration time (“Allan” stability time), which is the crossover from the $1/t$ behavior due to the white noise to a plateau or an increase of σ_A caused by $1/f$ or drift noise, respectively. Fig. 4 displays the mean square output noise (σ_A) of our receiver as a function of integration time for two different bias regimes. For an operation regime in the linear part of the I-V characteristic (regime 1) the “Allan” time is 5 sec and the DSB noise temperature is 5500 K while in the nonlinear part (regime 2) this time is only 0.1 sec although the DSB noise temperature is much lower (1500 K). Indeed, the spectrum of the output noise in the regime 2 (Fig. 4, right panel) shows excess low frequency noise that is a mixture of the $1/f$ noise and drift noise.

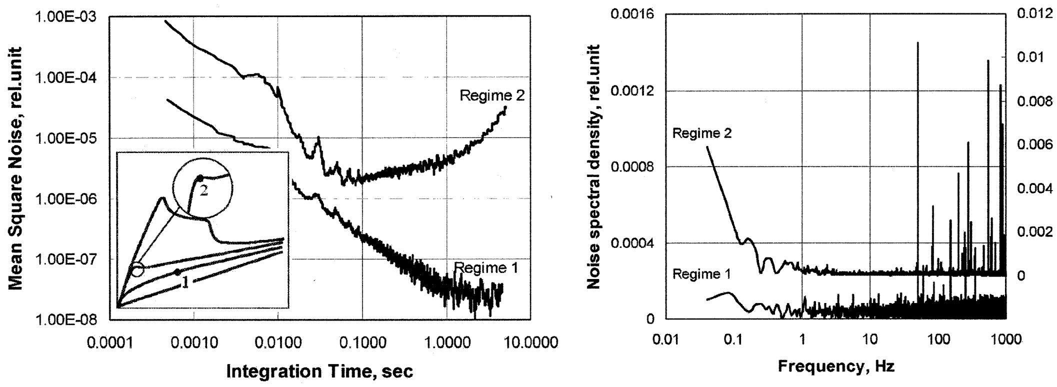

Figure 4 *"Allan" variance as a function of time (left panel) and spectrum of the output receiver noise (right panel) for two different operation points (see inset).*

Spectroscopy Test

As an overall receiver test we recorded a methanol emission line using a gas cell with 50 cm absorption length. The line was located in the upper sideband and was separated by 1.6 GHz from the 2.52278 THz methanol LO laser line. The gas was kept at ambient temperature. Behind the cell a 77 K blackbody was placed. An acousto-optical spectrometer was used as backend spectrometer. Fig. 5 shows spectra measured at two different gas pressures. The vertical scale corresponds to single sideband noise temperatures. The line was opaque in the center. Thus the signal should not be larger than 296 K. Larger experimental values may be due to the sideband ratio deviating from one or due to misalignment. The smooth line is a Voigt fit with a linear background. The line

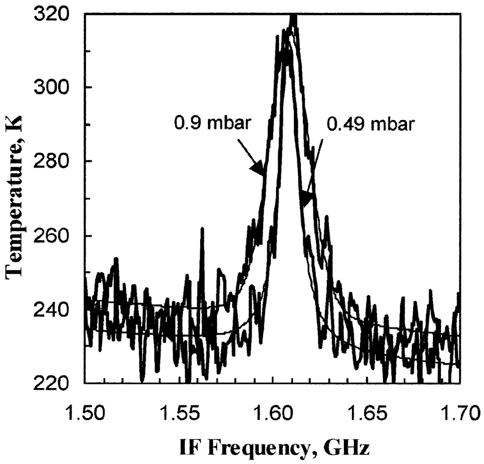

***Figure 5 Methanol** emission line measured at the gas pressure 0.49 mbar and 0.90 mbar*

full width at half maximum was 13 MHz at 0.49 mbar and 26 MHz at 0.90mbar that corresponds to the expected line width deduced from pressure broadening measurements at millimeter wavelengths.

Conclusion

We have demonstrated the practical usability of the terahertz heterodyne receiver with the NbN HEB mixer performing spectroscopy of a methanol emission line. The dynamic range of the receiver is large enough for applications in astronomy and atmospheric research. Both the noise temperature and noise stability of the receiver are strongly dependent of the operating point of the mixer. Thus, statistical analysis of the receiver noise, not only the noise temperature, is required for full performance characterization.

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