A Broadband Low Noise Heterodyne Receiver at 2.5 THz

K. Huber, H. Brand, L.-P. Schmidt

Abstract—**A 2.5 THz low noise heterodyne receiver with an IF bandwidth of about 7 GHz operating at room temperature is presented. Its main component is an open structure Schottky diode mixer with a substrateless Schottky diode designed and fabricated at the IHFT Darmstadt. The weak IF-signals are amplified by a noise-matched IF-amplifier in a frequency range from 6 to 13 GHz, covering the emission lines of several important molecules involved in the stratospheric ozone chemistry. The local oscillator signal (provided by a CO_2-laser-pumped methanol FIR-laser) is fed to the mixer together with the received signals via a Fabry-Perot type diplexer, which allows for significantly reduced signal loss compared to commonly used Martin-Puplett diplexers especially at the band edges. System noise temperatures as low as 16000 K (DSB) have been achieved up to the moment.**

I. Introduction

The 2.5 THz heterodyne receiver setup is depicted schematically in Fig. 1. It consists of a local oscillator subsystem, quasi-optical circuitry for calibration and diplexing and an open structure Schottky mixer combined with a noise matched IF-amplifier.

The local oscillator laser described previously [1] is capable of delivering a maximum output power of about 50 mW at 2522.8 GHz when powered by a 20 W CO_2-laser beam ($\lambda \approx 9\mu m$).

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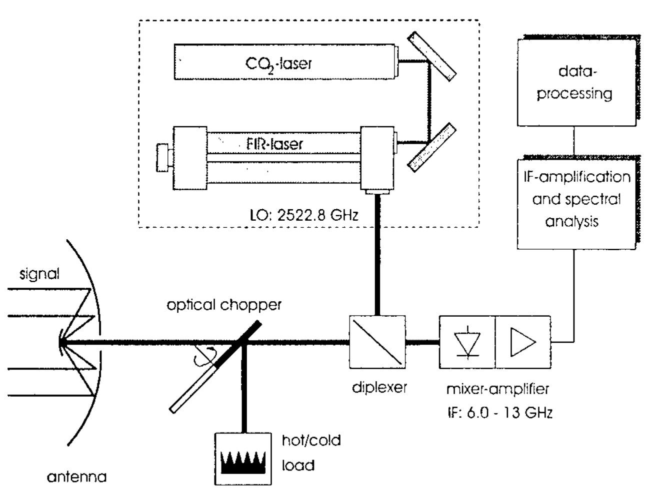

Fig. 1. Simplified schematic view of the radiometer

The main objectives of the radiometer are broadband imaging radiometry as well as spectroscopy of molecules involved in the stratospheric ozone chemistry. Both areas of application mentioned above benefit from a large IF-bandwidth, by a shorter measurement time in the broadband case and by a larger amount of specific emissions detectable in the spectroscopy application (for example OH, H_2O and O_3).

Thus, special care has been taken on broadband noise match of the first amplifier as well as on broadband operation of the diplexer.

II. Diplexer

Fig. 2 shows a photograph of the Fabry-Perot diplexer. It consists of two total reflectors, one of them being a refocusing mirror, and two partial reflectors. As most of the dielectric materials commonly used as beamsplitters in millimeter wave systems are quite lossy at 2.5 THz, wire grids have been used as partially reflecting mirrors. The tungsten wires have a diameter of 10 μm and a grid spacing of 50 μm and were fabricated at the mechanical workshop of the "Lehrstuhl für Hochfrequenztechnik" (LHFT).

The free spectral range (FSR) of the diplexer has been chosen to be approximately 1.88 GHz, thus the receiver IF bandwidth limited by the mixer-amplifier chain is split

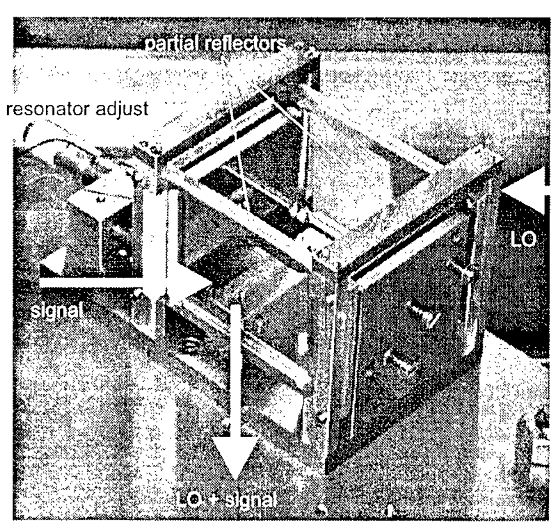

Fig. 2. Photograph of the 2.5 THz Fabry-Perot diplexer

into four subbands with center frequencies of 6.6, 8.4, 10.3 and 12.2 GHz, covering the emission spectra of various molecules involved in the stratospheric ozone chemistry [2]. For continuous covering of the entire receiver band, as desirable in broadband radiometry applications, the FSR of the Fabry-Perot would have to be increased (i. e. the dimensions of the diplexer have to be decreased) or a Martin-Puplett type diplexer must be used.

The LO-path loss has been measured to be about 4 dB whereas the signal-path loss is only about 0.5 dB. These values are slightly worse than predicted by theory, which is assumed to be due to the preceding transformation of the LO-beam and the resulting beam distortions and due to non-ideal adjustment of the diplexer.

III. Mixer-Amplifier Combination

At frequencies in the Terahertz or far infrared (FIR) regime the junction capacitance of mixer diodes has to be kept well below 1 fF in order to provide a good conversion efficiency. This means anode diameters of 0.5 μm or even less have to be realized. As the bias current necessary for optimum conversion is not affected by the diode area, the current density inside the junction rises with decreasing anode diameters and reaches values of several thousand A/mm^2. Measurements of the noise contribution of small area Schottky diodes have proven that the available noise power of forward biased diodes exceeds the value predicted by the classical formula by far [3]. The so called excess noise is assumed to be mainly due to hot electrons and interfacial traps [4]. Fig. 3 shows the noise temperature of an 0.5 μm substrateless Schottky diode compared with the noise temperatures of an ideal Schottky diode without series resistance and with a series resistance of 30 Ω, respectively.

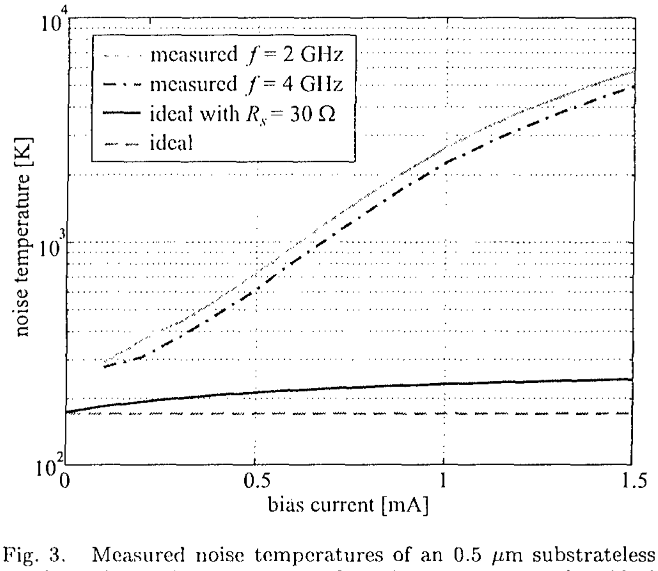

Fig. 3. Measured noise temperatures of an 0.5 μm substrateless Schottky diode compared to the noise temperature of an ideal Schottky diode without and with a series resistance of 30 Ω, respectively

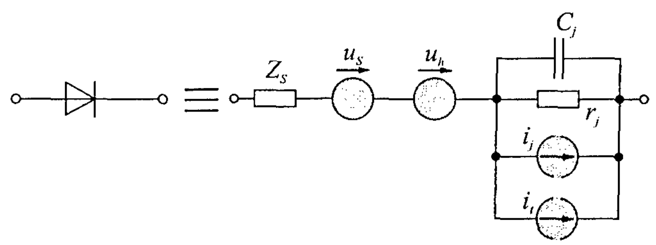

Fig. 4. Modified equivalent circuit of the Schottky diode

Based on the measurement results, a modified model for the Schottky diode according to Fig. 4 has been derived and implemented in a harmonic balance simulation of the mixer (with HP microwave design system). In the equivalent circuit Z_S is the complex impedance of the diode substrate, C_j is the bias dependent capacitance and r_j the dynamic resistance of the junction. The noise sources u_S, u_h, i_j and i_t represent the thermal noise of the series resistance, the hot electron noise, the shot noise and the trap noise, respectively. The values of the unknown quantities u_h and i_t have been derived by least squares fits of various noise power measurements of substrateless diodes with anode diameters of 0.5μm and epi-layer doping concentrations of $3 \cdot 10^{17}$ cm^{-3}.

It has been found, that the optimum diode bias current ranges between 150 μA and 300 μA depending on both the available LO power and the diode noise parameters.

The mixer diode, a substrateless Schottky diode fabricated by the IHFT in Darmstadt, has been soldered directly to the mixer block. The 4λ antenna is connected to the amplifier via a 90° bend and a 1.5 mm horizontal wire section (see Fig. 5).

The resulting IF path of this configuration is extremely short and thus eases a broadband noise match of diode and amplifier.

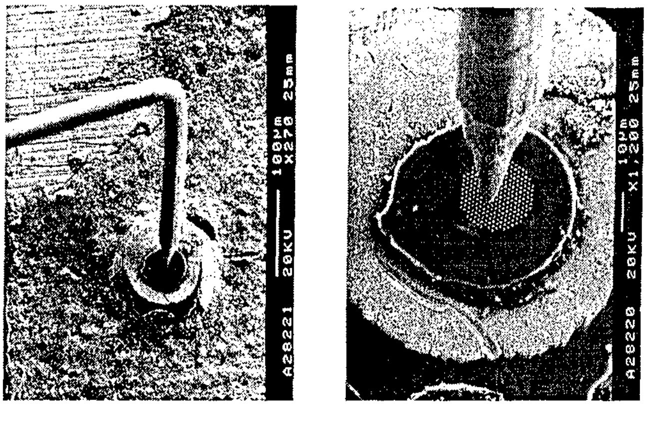

Fig. 5. SEM photographs of a contacted diode

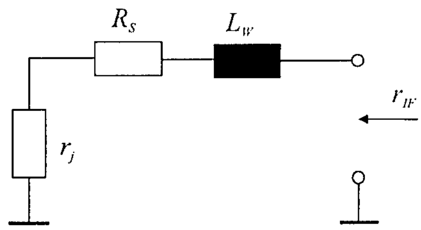

Fig. 6. Equivalent circuit of diode and whisker antenna at IF frequencies

In Fig. 6, the equivalent circuit of the diode including the whisker antenna at IF frequencies is depicted. The element values are:

- diode and whisker series resistance $R_S = 30\,\Omega$
- junction resistance at optimum operating point $r_j = 300\,\Omega$
- whisker inductance $L_W = 1.5$ nH

As the resulting IF-impedance of the whiskered diode is far from a value of 50 Ω, the noise contribution of commercially available 50 Ω amplifiers exceeds the value given in their datasheets when connected directly to the mixer. Instead of adding a passive IF-transformer between the mixer and a commercial 50 Ω amplifier, a noise-matched, two stage, uncooled HEMT-amplifier with FHX45X chips (Fujitsu) with an integrated bias supply for the mixer diode has been designed. Fig. 7 shows a photograph of the mixer-amplifier combination with the adjustable rooftop of the mixer's corner cube antenna and the integrated bias supply circuit.

In Fig. 8 the simulated and measured effective noise temperatures of the amplifier are shown. As it is difficult to measure the noise figure of the amplifier connected to the mixer, the amplifier noise for a source impedance r_S of 50 Ω has been simulated and compared to the measured

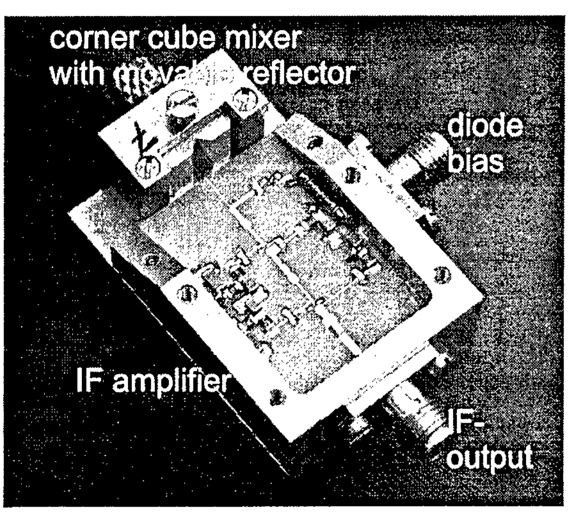

Fig. 7. Photograph of the mixer-amplifier combination

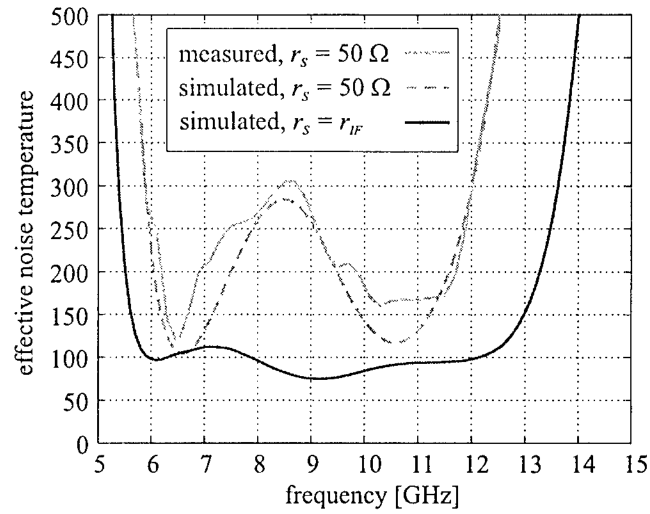

Fig. 8. Noise temperature of the IF-amplifier

values for this source impedance. The simulation of the actual noise temperatures of the amplifier connected to a source with $r_S = r_{IF}$ indicates values of about 100 K within a frequency range of 6 to 12.5 GHz.

IV. System performance

In Fig. 9 the measurement setup for the determination of the DSB noise temperature of the system is displayed. The LO passes a variable attenuator and the Fabry-Perot diplexer and is then focused on the corner cube antenna of the mixer. The signal path is continuously switched between a hot and a cold load, the resulting IF-signal is then amplified, filtered and rectified by a diode detector. From the ratio between dc voltage V_{dc} and ac voltage $\hat{V}$ and the corrected effective noise temperatures of the hot and cold load at 2.5 THz (T_h^*, T_c^*) the system noise temperature is calculated.

$$T_{sys} = (T_h^* - T_c^*) \cdot \frac{V_{dc}}{2 \cdot \hat{V}} - \frac{T_h^* + T_c^*}{2} \qquad (1)$$

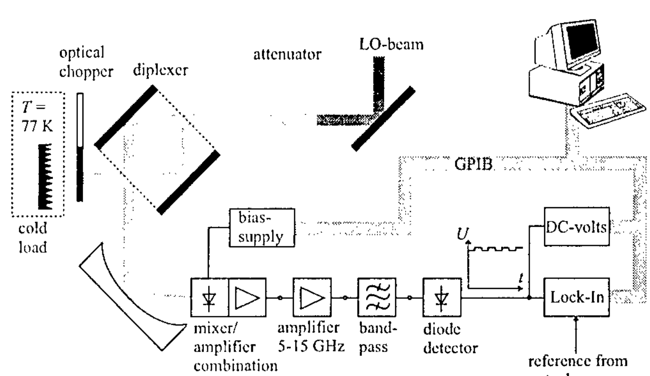

Fig. 9. Schematic view of the system noise temperature measurement setup

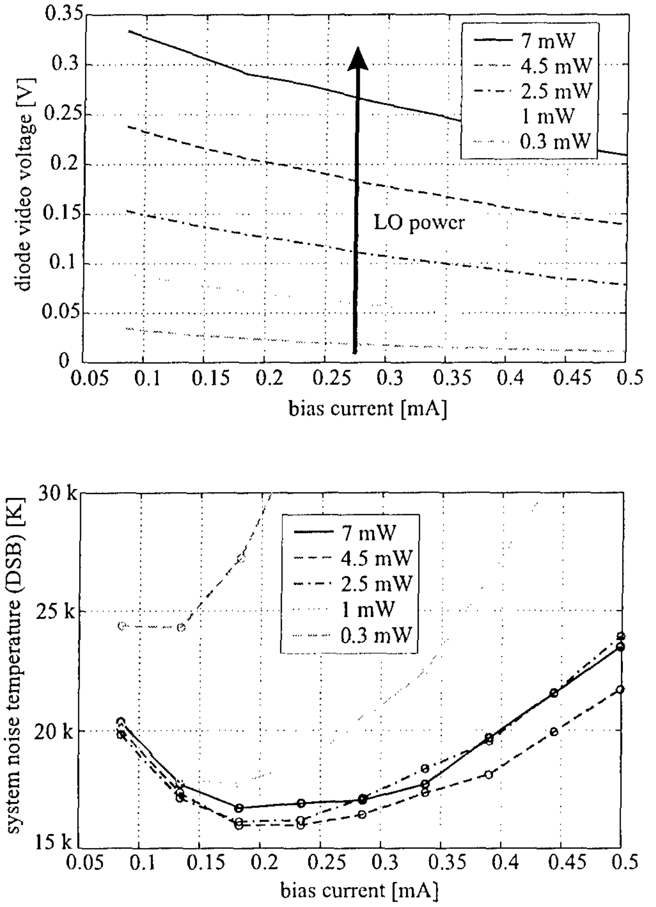

Fig. 10. Video voltage and DSB system noise temperature versus bias current for different LO power levels

Fig. 10 shows the results for the 8.5 ± 0.5 GHz channel of the receiver for different LO power levels which have been adjusted by various attenuators brought into the LO path. In the upper viewgraph the mixer diode video voltage is displayed, in the viewgraph below the DSB system noise temperature is shown.

The best noise temperature of about 16000 K could be achieved for a bias current of 0.2 mA just as expected from the harmonic balance simulation results. Another important result is that the optimum system performance is not achieved at the maximum LO power of about 7 mW (measured after the diplexer) but at a level of about 3-4 mW.

V. Conclusions

A 2.5 THz heterodyne receiver with a large IF bandwidth and a system noise temperature of 16000 K (DSB) has been presented. Key to the low noise operation at room temperature is the combination of an open structure mixer with a substrateless Schottky diode and a noise matched HEMT amplifier with an effective noise temperature as low as 100 K.

Diode improvement as well as optimization of the passive receiver components will certainly lead to a further decrease in system noise temperature.

Acknowledgments

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References

[1] M. Raum and K. Huber, "Standard design of SMMW laser ring resonators with optical pump beam guiding," in *Proceedings of the 6th IEEE International Conference on Terahertz Electronics*, (Leeds, United Kingdom), September 1998.

[2] S. Miller, M. Birk, F. Schreier, and D. Hausamann, "Airborne far-infrared heterodyne remote sensing of stratospheric OH: A feasibility study," *International Journal of Infrared and Millimeter Waves*, vol. 13, no. 9, pp. 1241 - 1268, 1992.

[3] G. Rehm, K. Huber, and S. Martius, "Excess noise in Schottky diodes for THz applications," in *Proceedings of the 6th IEEE International Conference on Terahertz Electronics*, (Leeds, United Kingdom), September 1998.

[4] A. Jelenski, A. Grüb, V. Krozer, and H. L. Hartnagel, "New approach to the design and the fabrication of THz Schottky barrier diodes," *IEEE Transactions on Microwave Theory and Techniques*, vol. 41, pp. 549 - 557, April 1993.

[5] C. I. Lin, A. Simon, and H. L. Hartnagel, "Fabrication of substrateless Schottky diodes for THz applications," in *Proceedings of the 4th International Workshop on Terahertz Electronics*, (Erlangen, Germany), September 1996.

[6] K. Huber, R. Hillermeier, H. Brand, C. I. Lin, A. Simon, M. Rodriguez-Girones, and H. L. Hartnagel, "2.5 THz corner cube mixer with substrateless Schottky diodes," in *Proceedings of the 5th International Workshop on Terahertz Electronics*, (Grenoble, France), September 1997.

[7] K. Huber, R. Engelbrecht, R. Hocke, M. Raum, H. Brand, S. Martius, and L.-P. Schmidt, "A broadband, low noise heterodyne receiver for stratospheric measurements at 2.5 THz," in *Proceedings of IGARSS 99*, (Hamburg), June 1999.

[8] K. Huber, G. Rehm, and N. Richt, "Numerical simulation of the base impedance of long wire whisker antennas," *International Journal of Infrared and Millimeter Waves*, vol. 20, pp. 265 - 278, February 1999.