Development of a 1.8-THz Hot-Electron-Bolometer Mixer for TELIS

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***Abstract*— We report on the further development of the superconducting NbN hot-electron bolometer mixer for the 1.8 THz channel of the Terahertz and susbmillimeter Limb Sounder that has resulted in an extension of the intermediate frequency band and a decrease in the mixer noise temperature.**

I. INTRODUCTION

Terahertz and susbmillimeter Limb Sounder (TELIS) is a new balloon borne three channel (0.5, 0.6, and 1.8 THz) cryogenic heterodyne spectrometer, which will allow limb sounding of the Earth's atmosphere within the submillimeter and far-infrared spectral range [1]. The instrument is being developed by a consortium that includes the Space Research Organization of the Netherlands (SRON), the Rutherford Appleton Laboratory (RAL) in the United Kingdom and the German Aerospace Center (DLR, leading institute). TELIS will utilize the state-of-the-art superconducting heterodyne technology and is designed to be compact and lightweight, while providing broad spectral coverage, high spectral resolution and an operation time larger than the typical flight duration (≈24 hours) in a single campaign. The combination of high sensitivity and extensive flight duration will allow investigation of the diurnal variation of key atmospheric short-lived radicals such as OH, HO_2, ClO, and BrO together with stable constituents such as O_3, HCl and HOCl. In the present flight configuration the 1.8 THz channel is equipped with the replica of the mixer that has been developed for the 6H-band (coverage 1410-1910 GHz) of the Heterodyne Instrument for the Far Infrared (HIFI) [2] onboard of the Hershel Space Observatory. The HIFI mixer [3] is a phonon cooled hot electron bolometer (HEB) fabricated from a NbN film that has been grown on a high resistivity silicon substrate at the Physical Department of the State Pedagogical University (Moscow). The bolometer is integrated with a planar double-slot antenna and a 5-mm diameter elliptical lens.
The DSB noise temperature of the TELIS receiver with the HIFI mixer measured in the lab at 1.8 THz was slightly larger than 3000 K at the intermediate frequency 4 GHz and raised to 5000 K at the upper edge (6 GHz) of the usable IF band. The noise temperature corrected for optical losses was 1700 k at 4 THz [4]. Although this performance complies with the baseline figures of merit of the TELIS 1.8-THz channel, an improvement of the noise temperature and a decrease of the required local oscillator power would ease the instrument operation and increase the throughput of scientific date during the flight time.

II. THE HEB MIXER

Hot-electron bolometers were made from NbN films with a nominal thickness of 5.5 nm deposited by magnetron sputtering on highly resistive 340 μm thick Si optically polished substrates with native oxide (Films were provided by he Physical Department of the State Pedagogical University in Moscow, B. Voronov and G. Gol'tsman). The films typically had a superconducting transition temperature of 9.5 K and a square resistance of approximately 600 Ω at room temperature. To define the film thickness, a few micrometers thick slice of a similar film made at right angles to the film surface was studied by means of high resolution transmission electron microscopy (HRTEM). The image obtained with HRTEM is shown in Fig. 1. The native oxide layer (SiO_2) clearly seen in the picture makes a poorly defined interface between the film and the substrate. There is also a niobium oxide layer on the top of the film which causes additional resistance at the interface between the film and the planar antenna. Results of the HRTEM study show a consistency with the previously reported data [5].

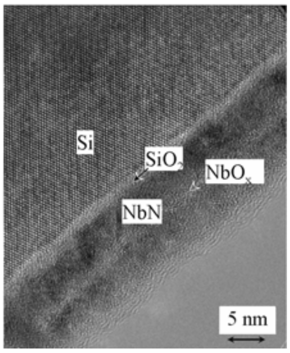

Fig. 2 HRTEM image of a typical NbN film on silicon substrate. Courtesy R. Schneider and D. Gerthsen, University of Karlsruhe.

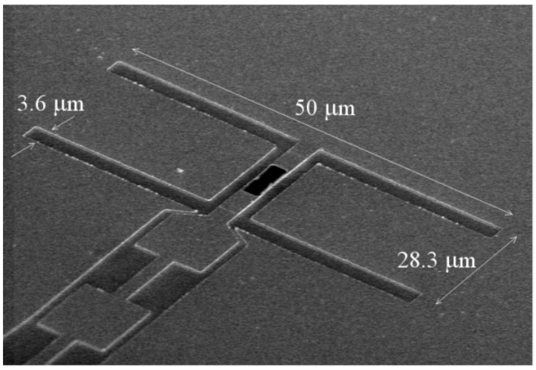

Fig. 3 Picture made with scanning electron microscopy shows the layout of the twin-slot antenna with the HEB mixer and a part of the filter structure [5].

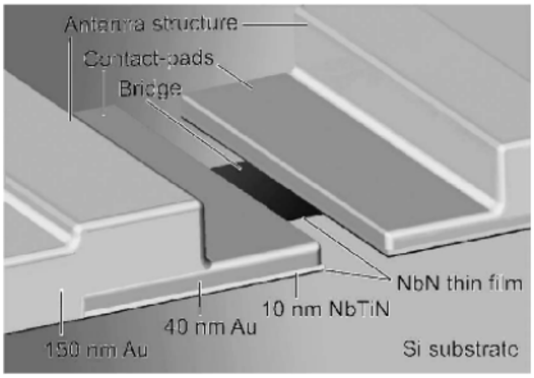

Fig. 4 Schematics of the contact pads fabricated between the NbN film and the gold antenna layer in order to minimize the contact resistance and thus improve the noise temperature of the HEB mixer [5].

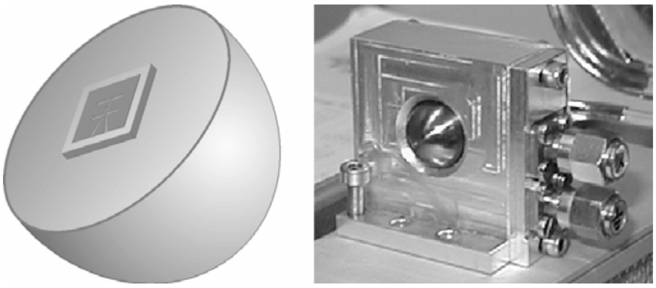

Fig. 5 Mixer chip on the rear side of the silicon elliptical lens (left) and the photo of the mixer block (right).

The HEB and the planar twin-slot antenna are made by a few deposition and lithographic steps from the multiplayer system including NbN film, matching getter film and a gold layer. Details of the technological approach have been described elsewhere [6]. The HEB is located in the middle of a co-planar waveguide (CPW) connecting two slots of a twin-slot antenna. The quasioptical twin-slot antenna was designed for a center frequency of 1.8 THz. The dimensions of the important antenna defining the center frequency are shown in Fig.2. The CPW transformer has a central line width of 2.8 µm and a gap of 1.4 µm, yielding a characteristic waveguide impedance of 51 Ω. The HEB is connected to CPW via gold contact pads consisting of 10 nm NbTiN and 40 nm Au on top. Fig. 3 shows schematically the sequence of contact layers. The contact pads are fabricated by cleaning the NbN surface that is followed by in situ sputter deposition of the metal layers. The precise contacting to the NbN film by the contact pads turns out to be essential for the mixer performance of HEBs. The antenna is defined by lift-off using a negative e-beam resist mask and in situ evaporation of 5 nm Ti for adhesion, 150 nm Au, and on top 10 nm Ti to avoid redepositing Au during later etches steps. As a last step, the bridge width is defined between the contact pads by a negative e-beam resist etch mask and subsequent reactive ion etching. The final HEB dimensions were 1.5 x 0.2 μm^2. It was covered with a passivating SiO_2 layer.

The 2×2 mm^2 substrate with the planar antenna and the HEB was glued to the rear side of a silicon elliptical lens (Fig. 4). The planar antenna appeared at the second geometric foci (looking along the propagation vector of the incident radiation) of the lens ellipse with the elliptical axes $a = 6.27$ mm and $= 6.0$ mm. The lens had an antireflection coating from Paryhlene-C optimized for 1.8 THz. The positioning accuracy of the HEB with respect to the lens center was better than 20 micrometers limiting the deviation of the mixer beam from the geometrical axis of the lens to 0.55°.

III. LABORATORY TEST

The mixer was characterized in the laboratory test receiver [7] shown schematically in Fig.5. The mixer with the lens was mounted in a mixer block (Fig. 4) that was thermally anchored to the cold plate in the vacuum chamber of an IRlabs HDL-5 dewar. The mixer operation temperature was 6.5 K at which the critical current of the HEB was 113 µA. The HEB was dc voltage biased through the bias chip designed to cover the IF band from 1 to 7.5 GHz. The radiation was coupled through a 2-mm thick wedged TPX window and a blocking quartz filter with diamond powder. The filter (C-45; IRlabs) cut off the radiation with a wavelength smaller than 45 µm. The LO radiation was provided by an infrared gas laser at the frequency 1.89 THz. A diplexer was used to match the LO polarization to the polarization of the twin-slot antenna. The LO and signal radiation were superimposed wit a 6-µm thick Mylar beam splitter in the p-polarization. The IF signal was enlarged with a cooled low-noise microwave amplifier (30 dB gain, 1-12 GHz bandwidth, 4 K noise temperature) and guided out of the dewar with a coaxial cable. The spectrum of the IF signal was recorded by a power meter in the bandwidth 50 MHz that was defined by the microwave filter with electrically controlled center frequency. The system noise temperature was computed in the Collen-Welton formulation (quantum noise theory) from the Y-factor that was measured in the common way by alternating the cold (77 K) and hot (297 K, chopper wheel) black body (Eccosorb) covering the field of view of the mixer. The 3-dB IF bandwidth of the mixer was measured using the signal produced by alternating loads [7]. The optical path between the loads and the dewar window was 70 cm. Optical losses associated with the setup are summarized in Table I. The directional beam pattern of the mixer antenna was measured with a high-pressure metal-halide lamp having a diameter of 5 mm. The lamp was moved in the far field of the antenna, typically at a distance from 1.5 m to 2 m from the feed. The corresponding angular resolution was better than 0.2 degree. The signal at the intermediate frequency was recorded as a function of the lamp position [8].

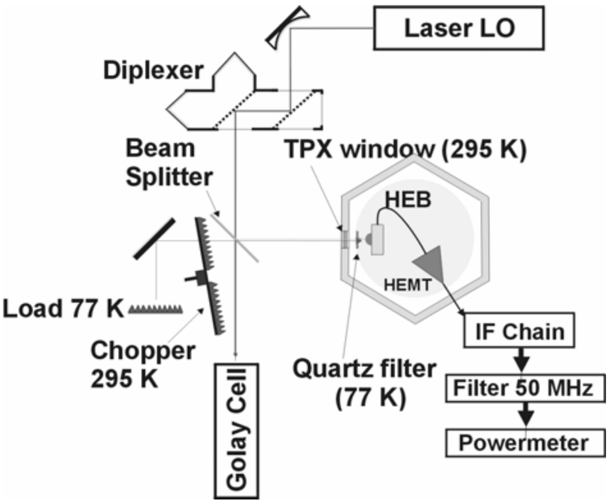

Fig. 6 Schematics of the laboratory test setup. HEMT denotes the amplifier.

TABLE III
SUMMARY OF THE OPTICAL LOSSES AT 1.89 THz

Element Los	ses, dB	Method
Signal path (35% humidity)	0.9	Computed
Mirror	0.46	Measured
Beam-splitter	0.06	Computed
TPX window	0.67	Computed
Filter at 77 K	1.3	IRlabs specs
Si lens with Paryhlene	2.1	Measured

IV. MIXER PERFORMANCE

The major mixer parameters measured with the lab receiver are collected in Table II. The measured system noise temperature, as well as the noise temperature corrected for optical losses (see Fig. 6), increases with IF frequency. This observation rules out possible shrinking of the usable mixer bandwidth due to optics. According to the conventional mixer model, the rate of the noise temperature increase is controlled by the zero-frequency ratio of the thermal fluctuation noise to the Johnson noise. The ratio is directly connected with the steepness of the superconducting transition of the NbN film. Excluding film degradation during device manufacturing, one should expect the same rate of the noise temperature increase for all devices made from films with the same quality. However, the IF wiring and microwave lines guiding the signal to the amplifier may introduce resonances directly affecting the measured noise temperature. Thus a better design of the IF mixer readout can extend the usable bandwidth. Doing that we achieved the IF coverage from 1 to 7.5 GHz with less that 2 dB ripples in the measured noise temperature.

TABLE IV
MIXER PERFORMANCE IN THE LAB RECEIVER

Measured DSB noise temperature	1500 K @ 1.5 GHz 3050 K @ 4.0 GHz 4400 K @ 6.0 GHz 5400 K @ 7.0 GHz
Corrected for optical losses noise temperature (at the tip of the lens)	690 K @ 1.5 GHz 1390 K @ 4.0 GHz
T_n variations in the 4-6 GHz band	Less than 2 dB
HEB conversion gain @ 1.5 GHz	-9.8 dB
Gain bandwidth (3 dB)	2.7 GHz
LO power in front of the window	0.6 µW
Directional beam pattern: Waist (ω_0) Width (θ_0) Side-lobes	3.3 mm 0.88 degree Less than -14 dB

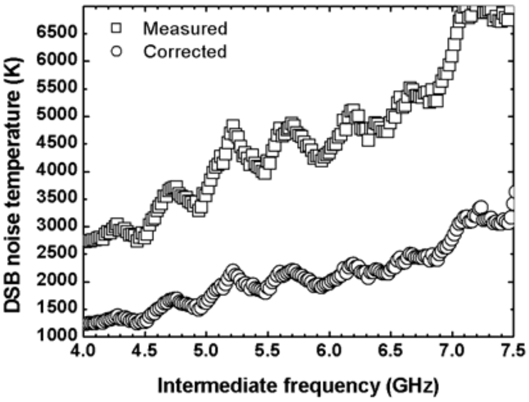

Fig. 7 Measured and corrected noise temperature in the 4 to 7.5 GHz band.

The directional pattern of the antenna beam shows an almost perfect coincidence with the pattern modeled by means of the physical optics and ray tracing technique [8]. The modeled pattern is shown in Fig. 7 along with the experimental E-field cut of the beam. The noise of the setup limited the lowest available level to –17 dB, just sufficient to confirm that the first side lobes appear below –14 dB. Fitting of the measured pattern with the Gaussian profile returned the position and the size of the beam waist along with the angle of divergence. The beam waist is located in front of the lens at a distance of approximately 6 mm from the tip of the lens.

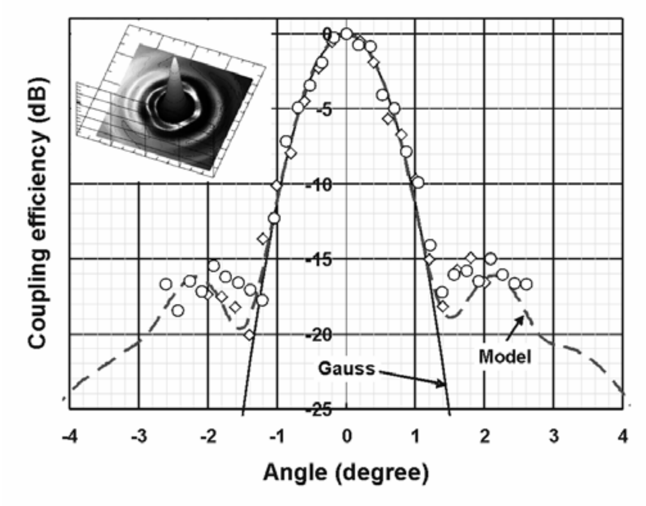

Fig. 8 Directional pattern in the E-plane (symbols) and the best fit with the Gaussian profile. Also shown is the E-plane cut of the modeled beam profile. Inset shows the modeled 3-dimentional directional beam pattern.

In conclusion, we have demonstrated the superconducting hot-electron bolometer mixer satisfying the goal performance of the TELIS 1.8 THz channel and having slightly better noise temperature and an extended IF coverage as compared to the mixer of the present flight configuration.

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REFERENCES

[1] M Birk, U. Mair, M. Krocka, G. Wagner, P. Yagoubov, R. Hoogeveen, T. de Graauw, H. van de Stadt, A. Selig, H.-W. Hübers, H. Richter, A. Semenov, V. Koshelets, S. Shitov, B. Ellison, D. Matheson, B. Alderman, M. Harman, B. Kerridge, R. Siddans, J. Reburn, A. Duric, A. Murk, A. Magun, N. Kämpfer, D. Murtagh, "TELIS – development of a new balloon borne THz/submm heterodyne limb sounder," Digest of the 35th COSPAR Scientific Assembly, Paris, France, 18-25.7.2004, p. 352, 2004.

[2] S. Cherednichenko, V. Drakinskiy, T. Berg, P. Khosropanah, E. L. Kollberg, "Hot-electron bolometer terahertz mixers for the Herschel Space Observatory," *Review of Scientific Instruments*, Vol. 79, pp. 034501-(1-10), 2008. Digital Object Identifier: 10.1063/1.2890099

[3] T. de Graauw, E. Caux, R. Gusten, W. Jellema, W. Luinge, J. Pearson, T. Phillips, R. Schieder, J. Stutzki, K. Wafelbakker, N. Whyborn, K. Wildeman, "The Herschel-Heterodyne Instrument for the Far-Infrared (HIFI)," Conference Digest of the Joint 29th International Conference on Infrared and Millimeter Waves, and 12th International Conference on Terahertz Electronics, pp. 579-580, October 2004. Digital Object Identifier: 10.1109/ICIMW.2004.1422223

[4] M. Birk, private communication.

[5] J. R. Gao, M. Hajenius, F. D. Tichelaar, T. M. Klapwijk, B. Voronov, E. Grishin, G. Gol'tsman, C. A. Zorman and M. Mehregany, "Monocrystalline NbN nanofilms on a 3C-SiC/Si substrate," *Applied Physics Letters*, Vol. 91, pp. 062504 (1-3), (2007).

[6] M. Hajenius, J. J. A. Baselmans, A. Baryshev, T. M. Klapwijk, J. W. Kooi, W. Jellema and Z. Q. Yang, "Full characterization and analysis of a terahertz heterodyne receiver based on a NbN hot electron bolometer," *Journal of Applied Physics*, Vol. 100, pp. 074507 (1-10), 2006.

[7] A. D. Semenov, K. Ilin, M. Siegel, A. Smirnov, S. Pavlov, H. Richter and H.-W. Hübers, "Evidence of non-bolometric mixing in the bandwidth of a hot-electron bolometer," *Supercond. Sci. Technol.*, Vol. 19 pp. 1051–1056, September 2006.

[8] A. Semenov, H. Richter, H.-W. Hübers, B. Günther, A. Smirnov, K. Ilin, M. Siegel and J. Karamarkovic, "Terahertz performance of integrated lens antennas with a hot-electron bolometer," *IEEE Transactions on Microwave Theory and Technique*, vol. 55, pp. 239-247, February 2007