Towards Detection of OH Line at 3.5 THz Using a HEB Mixer and a Distributed Feedback Quantum Cascade Laser

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***Abstract*—We report the demonstration of a heterodyne receiver for detection of OH lines at 3.5 THz. The receiver uses a superconducting NbN hot electron bolometer integrated with a tight winding spiral antenna as mixer and a THz distributed feedback quantum cascade laser operating at 3.42 THz as local oscillator. We measured a double sideband receiver noise temperature of 2100 K at the optimum local oscillator power of 290 nW. This noise temperature can be further reduced to 1000 K if we correct the loss due to the use of an uncoated lens, and the losses of the window and the air. We also demonstrate that the improved, single spot beam of the THz QCL can easily pump the HEB mixer. Therefore, the combination of a HEB and such a DFB QCL can in principle be used to detect an OH line at 3.5 THz. However, a high input power of several watts needed to operate the QCL at an L-He cryostat poses a big challenge to the receiver stability.**

I. Introduction

Problems related to the Earth's atmosphere such as global warming and ozone destruction can be monitored and better understood by observations in the far-infrared regime. This regime holds the most important spectral signatures of the relevant molecules. Among them hydroxyl (OH) radical, which has emission lines at frequencies such as 1.8, 2.5 and 3.5 THz, has been identified as being crucial probes [1]. OH is the dominant oxidizing chemical in the atmosphere. It destroys most air pollutants and many gases involved in ozone depletion and the greenhouse effect. To detect them and resolve the line spectrum, it is desirable to have a sensitive heterodyne receiver operated in a balloon-borne or a space-borne observatory. The key components of such a receiver are a mixer (where the mixing process takes place) and a THz coherent source as local oscillator (LO). Several space-borne or balloon-borne instruments have been constructed to detect OH lines. For example, NASA's Earth Observing System Microwave Limb Sounder (EOS-MLS) [2] based on a room-temperature Schottky-diode as mixer and an
optically pumped gas laser as LO [3] is now operated to detect an OH line at 2.5 THz. TErahertz and submm LImb Sounder (TELIS) is a three-channel balloon-borne heterodyne spectrometer for atmospheric research [4]. The 1.8 THz channel based on a superconducting NbN hot electron bolometer (HEB) mixer and a solid state, multipliers based LO will focus on the OH lines at 1.8 THz..

Figure 1 shows a predicted spectrum of OH lines at 3.5 THz. The OH line at 3.551 THz is ideal for monitoring and retrieval [5] since it not only has the highest intensity among different OH lines but also is well isolated from other molecular lines. However, OH lines at 3.5 THz have never been studied by high-resolution heterodyne spectroscopy because of lack of suitable local oscillators at this particular frequency. Solid state LOs based on multipliers have demonstrated up to 2 THz, but are unlikely to generate sufficient output power at such a high frequency. Optically-pumped gas lasers can be operated at much high frequencies. However, they have no strong lasing lines very close to 3.5 THz OH lines.

Solid-state THz quantum cascade lasers (QCLs) [6] become an appearing choice of LO for this specific frequency because of their compactness, high output power, linear polarization, narrow linewidth, and phase locking ability. THz QCLs have been successfully demonstrated as LOs in laboratory using either a double-metal waveguide [7] or a surface plasmon waveguide structure [8], [9]. But they all employ a Fabry-Pérot cavity to achieve a single mode lasing. In general, a Fabry-Pérot cavity is impossible to control the operating frequency precisely, e.g, not within an accuracy of a few GHz. Therefore, for the detection of OH line at 3.551 THz, an additional mode control mechanism should be introduced to THz QCLs. Currently a distributed feedback (DFB) structure is known to achieve the single-mode operation at a designed frequency [10].

Here we report the measurement of a heterodyne receiver which combines a superconducting NbN HEB mixer and a THz DFB QCL at 3.42 THz, and demonstrate low noise performance of the receiver. To overcome the problem caused by high input power of the QCL, which results in a draft of LO power, we applied a different characterization method for the receiver sensitivity [11].

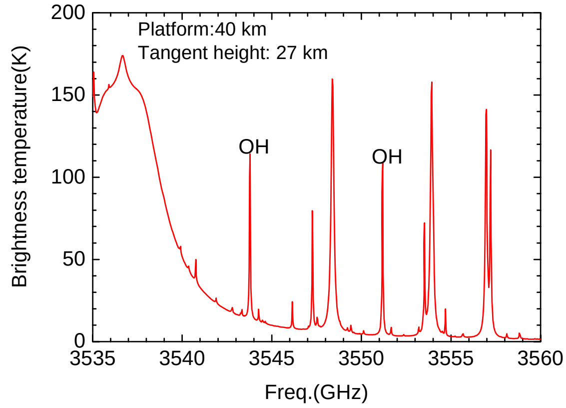

Fig.1 Simulated emission spectrum of OH lines in the atmosphere for an instrument at 40 km in limb geometry. The tangent height is 27 km.

II. THz DFB QCL AND THE BEAM PATTERN

The QCL used in our experiment is developed by ETH-Zürich, Switzerland. The active region, based on a bound-to-continuum design [12], is a GaAs/AlGaAs materials system on a semi-insulating GaAs substrate grown by molecular beam epitaxy (MBE), while the DFB structure is based on strongly coupled surface grating fabricated with wet chemical etching and metal coverage [13]. All side "facets" of the laser ridge are fully covered by the metal layer. The periodicity (Λ) of the first-order Bragg gratings determines the emission frequency as follows: $\Lambda=\lambda_{wg}/2n_g$, where λ_{wg} and n_g are the designed wavelength and effective refractive index, respectively. Lasing spectrum of a THz DFB QCL with a ridge width of 200 μm and length of 1.25 mm has been measured by FTS and the result shows a single-mode or monochromatic emission at 3.42 THz. Although it is not exactly at our targeting frequency of 3.551 THz, it should be appropriate to demonstrate a receiver for the OH line detection because the difference in frequency is so small that makes virtually no difference in the sensitivity.

Such a THz DFB QCL is expected to have a diffraction-limited single-spot beam, which should be reasonable for coupling the radiation to a mixer. However, in practice, the beam contains highly dense interference fringes in the far-field pattern (see Fig.2a) although the envelope of the beam is determined by the effective area of the facet and the wavelength and thus follows the diffraction-limited. Despite of an output power of 3 mW in CW, it is unable to pump an NbN HEB mixer, namely not enough THz power to bring the HEB in the optimal operating condition. The HEB itself requires only about a few hundred of nanoWatts power. The reason is the highly dense interference fringes in the far-field beam (see Fig.2a). However, by adding cardboard papers as THz absorbers on the top of laser bar and also on the metal plate under the laser, the interference fringes have been eliminated experimentally. This was achieved in a different, but a very similar DFB QCL. Now the far-field beam pattern shows a single-spot beam, as illustrated in Fig. 2b. Although the physical origin is still under study, it is believed that due to the absorbers, all the parasitical radiations are decoupled from the radiation emitted from the front facet. The details of the beam study have been reported in [14] and will be summarized in a separated publication. The new DFB QCL with an improved beam pattern has actually a maximum output power of 2 mW in CW mode, measured at about 10-20 K of the bath temperature for the QCL. We found that such a single spot beam allows for an efficient coupling to an NbN HEB mixer in a heterodyne measurement. The laser can overpump the HEB (namely bring the HEB to a normal state) even using a thin Mylar beam splitter of 3.5 μm. The input DC power of the THz DFB QCL is about 5 W. As it will be discussed, the high input power unfortunately makes the QCL, which is mounted in an L-He vacuum cryostat, difficult to stabilize its temperature and thus its output power.

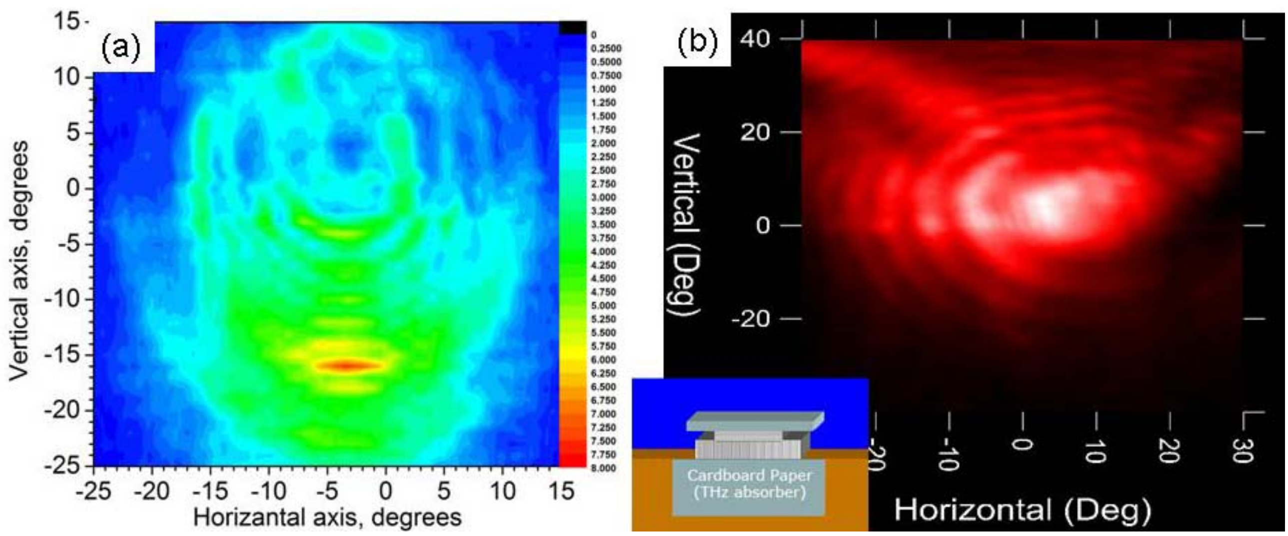

Fig.2 Measured 2D far-field beam patterns of two very similar THz DFB QCLs. Original beam pattern for one DFB QCL in (a); improved beam by adding cardboard papers as THz absorbers for another DFB QCL in (b).

III. HEB MIXER

The HEB mixer used is shown in Fig.3. It consists of a 2 µm wide, 0.2 µm long, and 5.5 nm thick NbN bridge on a highly resistive, natively oxide Si substrate [15]. The bridge is connected to the antenna by NbTiN (10 nm)/Au (50 nm) bilayer contact pads. The antenna is an on-chip spiral one made of a 170 nm thick Au layer. It has a tight winding design with inner diameter of 6.6 µm close to the NbN bridge (see Fig.3). Based on the study in [16] and our previous results using a design with a diameter of 15 µm, an expected upper cutoff frequency of this antenna is 6 THz. The HEB has a room temperature resistance of 80 Ω and a critical current of 275 µA at 4.2 K. This HEB has demonstrated an extremely low (DSB) receiver noise temperature of 1300 K at 4.3 THz using a FIR gas laser as local oscillator and a vacuum measurement setup [11].

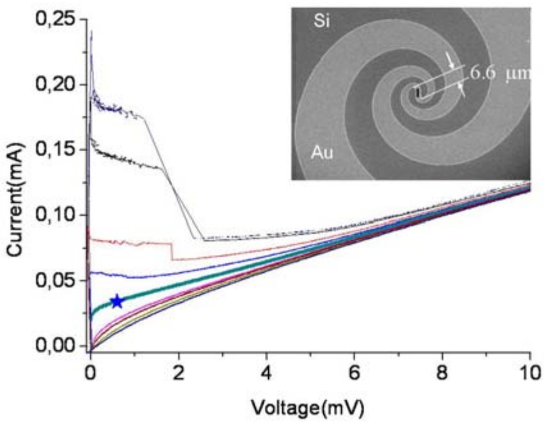

Fig.3 A set of current-voltage curves of an NbN HEB mixer at 4.2 K at different LO power from a 3.42 THz DFB QCL, where the center of the optimum operating region is indicated by a star. The inset shows a SEM micrograph of an HEB integrated with a spiral antenna with an inner diameter of 6.6 µm.

IV. HETERODYNE MEASUREMENT SETUP

Figure 4 shows a schematic view of the heterodyne measurement setup. We use two cryostats, in which the QCL and the HEB are mounted separately. A vacuum liquid helium cryostat which contains more helium than the cryostat for a HEB and thus has a high cooling capacity was used to operate the QCL. To apply the QCL as LO, we operate it in CW mode. The output power of the QCL is coupled to the HEB antenna using a standard quasi-optical technique: the Si chip with the HEB is glued to the backside of an elliptical Si lens (Φ=12 mm) without anti-reflection coating, which is placed in a metal mixer block, thermally anchored to the 4.2 K cold plate of the HEB cryostat. The beam from the QCL passes through a high-density polyethylene (HDPE) window of the QCL cryostat and is collimated with a HDPE lens (f=50 mm), combined with the radiation of 295 K (hot)/77 K (cold) load by the 3.5 µm thick beam splitter, then passes through a HDPE vacuum window (1 mm thick) at room temperature, and a QMC low-pass (or heat) filter [17], mounted on the 4 K shield of the HEB cryostat. A wire grid, inserted into the LO path between the HDPE lens and the beam splitter and controlled by computer, is used to regulate LO power (actual power absorbed by the HEB).

The intermediate frequency (IF) signal, resulting from the mixing of the LO and the hot/cold load signal, is amplified first using a cryogenic low noise amplifier operated at 4.2 K and then followed by room-temperature amplifiers. This signal is filtered at 1.4 GHz in a band of 80 MHz. The entire IF chain has a gain of about 80 dB and a noise temperature of 7 K.

To obtain the DSB receiver noise temperature ($T_{N,rec}$), we measured the receiver output noise power, $P_{out,hot}$ and $P_{out,cold}$, responding to the hot load and cold load. So $T_{N,rec}$ can be easily expressed by Y-factor ($Y=P_{out,hot}/P_{out,cold}$)

$$T_{N,rec} = \frac{T_{eff,hot} - YT_{eff,cold}}{Y-1}$$

where $T_{eff,hot}$ and $T_{eff,cold}$ are the equivalent temperatures of a blackbody at 295 and 77 K, respectively, which are 302.7 K and 104.6 K at 3.42 THz according to the Callen-Wellton definition [18].

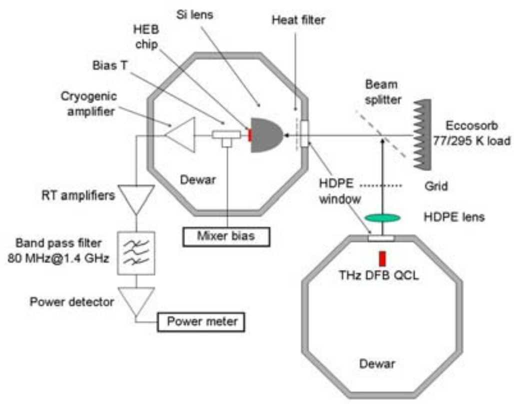

Fig.4 Schematic view of the heterodyne measurement setup, where a NbN HEB mixer and a THz DFB QCL are separately mounted in two vacuum L-He4 cryostats.

V. MEASUREMENT RESULTS

Figure 3 shows a typical set of current-voltage (*I-V)* curves of the HEB pumped by the QCL from zero power to a fully pumped power level. Around the optimum operating point indicated by a star, where the LO power in the HEB is about 290 nW, the bias voltage 0.6 mV, and bias current 30 µA, the best sensitivity is obtained.

Due to the LO power drifting, we are unable to obtain reliable sensitivity data using a standard method for a HEB, in which LO power is fixed, but the bias voltage is varied. We now apply a different characterization method as introduced in [11] to measure the DSB receiver noise temperature. In this case we measure the receiver output noise power as a function of bias current, under a fixed bias voltage, while continuously varying the LO power by the wire grid. Note that the current follows exactly the change of

LO power. This will move the bias point from the fully pumped to the unpumped region or vice versa, vertically on the I-V curves. Two such data sets are recorded, one, $P_{out,hot}(I)$, responding to the hot load and the other, $P_{out,cold}(I)$, to the cold load, so the Y factor can be easily obtained by $Y(I)= P_{out,hot}(I)/P_{out,cold}(I)$ at the exactly same current for a fixed voltage. Fig. 5 shows measured receiver output noise power data, $P_{out,hot}(I)$ and $P_{out,cold}(I)$, as a function of current and fitted curves at several bias voltages. Using the fitted curves, we derive the DSB receiver noise temperature as a function of current at different voltages.

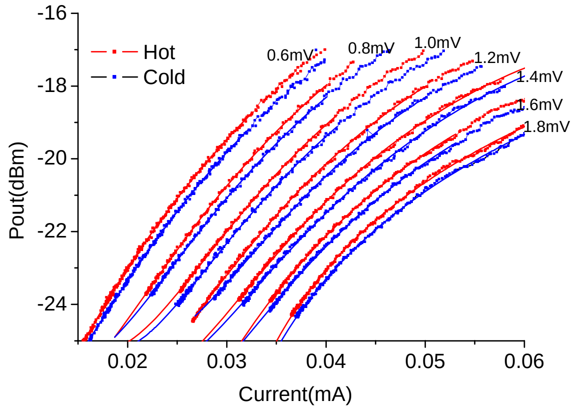

Fig. 5. Receiver output noise power of a HEB mixer as a function of bias current for different bias voltages from 0.6 mV to 1.8 mV. The current follows directly the change of LO power. The data points and curve in red correspond to the hot load, while the ones in blue to the cold load.

The lowest receiver noise temperatures are found in the data taken at 0.6 mV. The $T_{N,rec}$ versus current, together with measured output noise power data points and fitted curves, is shown in Fig. 6. The lowest $T_{N,rec}$ is 2100 ±50 K, occurred at a bias current of 30 μA. In fact, the ultimate receiver noise temperature can be a factor of two lower if we reduce the loss in the bare Si lens and in the window, and the loss due to water absorption in the air. A receiver noise temperature of 1000 K is expected at this frequency if we use an anti-reflection coated Si lens (~1 dB reflection loss), and we perform the measurement in a vacuum hot/cold setup [11] (removing 1.2 dB cryostat window loss and 0.8 dB air loss at this frequency). We emphasize that this is the first measurement of the noise temperature of a HEB receiver at a frequency in the vicinity of 3.5 THz OH line. Since the difference between two frequencies is so small, we can assume that an equal sensitivity can be achieved at the OH line frequency. Furthermore, the measured or expected receiver noise temperature at 3.42 THz is in a good agreement with the sensitivity obtained at 4.3 THz [11] if we take into account an empirical frequency dependence of the sensitivity.

We now turn to the issue of the instability of LO power and thus the instability of the receiver. As reported earlier, a THz QCL can offer an extremely stable output power [7]. However, for the present QCL it requires about 5 W DC input power when it is operated in CW mode. Whenever such a DC power is applied to the laser, the temperature monitored at the metal-holder for the QCL, which is mounted directly on the cold plate of the L-He cryostat, and thus the temperature of the laser itself, starts to increase and eventually reaches an operating region, where the temperature gets relatively stable, but still has a drift. As a consequence, the output power of the QCL shows a quick decrease and then drifts slowly. This will obviously affect the stability of the complete receiver. To demonstrate this instability, we simultaneously measured the receiver output noise power and bias current as a function of time over a period of 3 minutes immediately after turning the QCL on. As shown in Fig. 7, the receiver output noise power as well as the current of the HEB increases dramatically as QCL heats up until that the temperature of THz DFB QCL is stabilized in about 1.5 minutes. Even after that the receiver output noise power and bias current remains drifting due to the instability of QCL output power.

In the same experiment, we also demonstrate the effect of direct detection in the HEB due to wideband hot/cold radiation [19]. Because of a combination of our tight winding spiral antenna, which has a wide RF bandwidth, and the relatively small HEB, amount of the power from the hot and cold load coupled into the HEB is no longer negligible in comparison with the required LO power. As suggested in both power and current curve in Fig. 7, there are additional small periodic jumps during switching between hot and cold load. In this case a change of ~0.5 μA in the bias current of the HEB was observed, indicating an evident direct detection. In principle, such a direct detection effect can be eliminated by adding a narrow bandpass filter between the mixer and hot/cold loads, which in turn limits coupled hot/cold load power. In practice, because we are using a different characterization method to determine the Y-factor, as discussed before and shown in figure 5&6, the obtained receiver noise temperature in our case is unaffected by the direct detection effect.

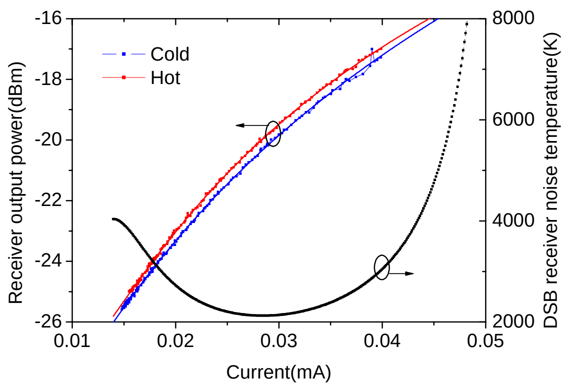

Fig. 6 Measured receiver output noise power of a HEB mixer at the optimum bias voltage of 0.6 mV (dots) and the polynomial fit (lines) responding to hot and cold loads as a function of the bias current of the HEB, which follows the change of the LO power (left axis). The resulted DSB receiver noise temperature curve as a function of the bias current of the HEB (right axis).

CONCLUSIONS

In summary, we have characterized a heterodyne receiver using a HEB as mixer and a THz DFB QCL emitting at 3.42 THz as local oscillator in order to demonstrate a system for the detection of the OH line at 3.5 THz. We have shown that the far-field beam pattern of a THz DFB QCL after introducing the absorbers around the laser becomes a single-spot beam, which makes the QCL to pump a HEB mixer easily in the heterodyne setup even with a thin beam splitter of 3.5 µm. We obtained a DSB receiver noise temperature of 2100 K at 3.42 THz. The sensitivity can be reduced to 1000 K if a coated Si lens and vacuum hot/cold setup are used. These values are the first establishment of heterodyne sensitivity in the vicinity of 3.5 THz OH line. Furthermore, the expected receiver noise temperature at this frequency confirms that the THz DFB QCL has a pure, single mode emission line. However, we also find that a too high input power needed to operate the QCL is still an issue and causes instability of the receiver, that makes other measurements than the Y-factor, such as a spectroscopic measurement, impossible.

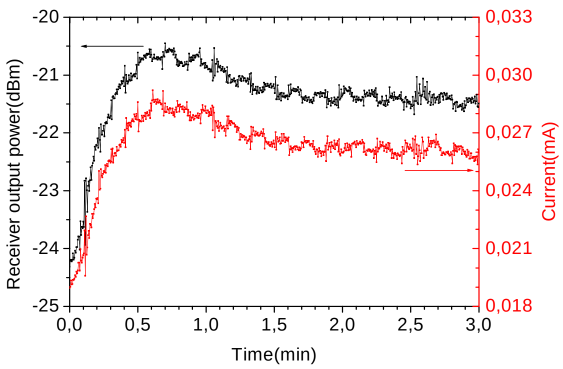

Fig.7. Measured receiver output noise power (left axis) and bias current of the HEB (right axis) as a function of time over the period of 3 minutes after turning the THz DFB QCL on and heating up. The small periodic jumps in both power and current curves are due to switching between hot and cold load, which is done manually.

To realize a practical heterodyne receiver for the detection of 3.5 THz OH line, which can be employed in a balloon-borne, like TELIS, or a space borne telescope, due to the availability of cryo-coolers and limited electrical power in both cases we foresee several technique challenges with regard to the use of THz QCLs as LO. First, the input DC power has to be far below 100 mW if it is operated around 5-10 K. An alternative is to have a THz QCL operated at a relatively high temperature, e.g., 70 K or higher. In the latter case the input power becomes less demanding and can have as much as ~1 Watt [20]. In principle, low input power [21] and high operating temperature [22] THz QCLs have been demonstrated in literature. Second, one needs to develop a frequency or phase locking technique for the QCL. A usual way to stabilize a LO is to lock the THz line to a reference signal up converted from a microwave source. However, due to lack of a solid state reference sources at such a high frequency, one needs to explore different phase locking schemes.

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REFERENCES

[1] R.G. Prinn, J. Huang, R.F. Weiss, D.M. Cunnold, P.J. Fraser, P.G. Simmonds, A. McCulloch, C. Harth, P. Salameh, S. O'Doherty, R.H.J. Wang, L. Porter, and B.R. Miller, "Evidence for substantial variations of atmospheric hydroxyl radicals in the past two decades," *Science*, vol.292, pp.1882-1888, 2001.

[2] M.C. Gaidis , H.M. Pickett, C.D. Smith, S.C. Martin, R.P. Smith, and P.H. Siegel, "A 2.5-THz receiver front end for spaceborne applications," *IEEE trans. Microwave Theory and Techniques*, vol.48, no.4, pp.733-739, 2000.S. Zhang, C. Zhu, J. K. O. Sin, and P. K. T. Mok, "A novel ultrathin elevated channel low-temperature poly-Si TFT," *IEEE Electron Device Lett.*, vol. 20, pp. 569–571, Nov. 1999.

[3] E.R. Mueller, W.E. Pobotham, Jr.,R.P. Meisner, R.A. Hart, J. Kennedy, and L.A. Newman, "2.5 THz laser local oscillator for the EOS chem 1 satellite," *in Proc. 9th Int. Space Terahertz Technol. Symp.*, Pasadena, CA, pp.563-572, 1998.

[4] P.L. Yagoubov, R.W.M. Hoogeveen, A.M. Maurellis, U. Mair, M. Krocka, G. Wagner, M. Birk, H.-W. Hübers, H. Richter, A. Semenov, G. Gol'tsman, B. Voronov, V. Koshelets, S. Shitov, B. Ellison, B. Kerridge, D. Matheson, B. Alderman, M. Harman, R. Siddans, and J. Reburn, "TELIS-development of a new balloon borne THz/sum heterodyne limb sounder," *In Proc. 14th International Symposium on Space Terahertz technology*, 22-24 April, Tucson, Arizona, pp.204-214, 2003.

[5] A. de Lange, "TELIS and OH," SRON internal report, 2005.

[6] R. Köhler, A. Tredicucci, F. Beltram, H.E. Beere, E.H. Linfield, A.G. Davies, D.A. Ritchie, R.C. Iotti, and F. Rossi, "Terahertz semiconductor-heterostructure laser," *Nature*, London, vol.417, pp.156-159, 2002.

[7] J.R. Gao, J.N. Hovenier, Z.Q. Yang, J.J.A. Baselmans, A. Baryshev, M. Hajenius, T.M. Klapwijk, A.J.L. Adam, T.O. Klaassen, B.S. Williams, S. Kumar, Q.Hu, and J.L. Reno, "Terahertz heterodyne receiver based on a quantum cascade laser and a superconducting bolometer," *Applied physics letters*, 86, 244104, 2005.

[8] H.-W. Hübers, S.G. Pavlov, A.D. Semenov, R. Köhler, L. Mahler, A. Tredicucci, H.E. Beere, D.A. Ritchie, and E.H. Linfield, "Terahertz quantum cascade laser as local oscillator in a heterodyne receiver," *Optics express*, vol.13, no.15, pp.5890-5896, 2005.

[9] M. Hajenius, P. Khosropanah, J.N. Hovenier, J.R. Gao, T.M. Klapwijk, S. Barbieri, S. Dhillon, P. Filloux, C. Sirtori, D.A. Ritchie, and H.E. Beere, "Surface Plasmon quantum cascade lasers as a terahertz local oscillators," *Optics letters*, vol. 33, no. 4, pp.312-314, 2008.

[10] L. Mahler, R. Köhler, A. Tredicucci, F. Beltram, H.E. Beere, E.H. Linfield, D.A. Ritchie, and A.G. Davies, "Single-mode operation of terahertz quantum cascade lasers with distributed feedback resonators," *Appl. Phys. Lett.*, vol. 84, no. 26, pp.5446-5448, 2004.

[11] P. Khosropanah, J.R. Gao, W.M. Laauwen, M. Hajenius and T.M. Klapwijk, "Low noise NbN hot-electron bolometer mixer at 4.3 THz," *Appl. Phys. Lett.*, 91, 221111, 2007.

[12] J. Faist, M. Beck, T. Aellen, E. Gini, "Quantum cascade lasers based on a bound-to-continuum transition," *Appl. Phys. Lett.*, vol.78, no. 2, pp.147-149, 2001.

[13] L. Ajili, J. Faist, H. Beere, D. Ritchie, G. Davies, and E. Linfield, "Loss-coupled distributed feedback far-infrared quantum cascade lasers," *Electronics letters*, vol.41, no.7, pp.419-420, 2005.

[14] J.N. Hovenier, S. Paprotskiy, J.R. Gao, P. Khosropanah, T.M. Klapwijk, L. Ajili, M.A. Ines, and J. Faist, Abstract, ISSTT 2007.

[15] A standard film provided by Moscow State Pedagogical University, Moscow, Russia.

[16] A.D. Semenov, H. Richter, H.-W. Hübers, B. Günther, A. Smirnov, K.S. Il'in, M. Siegel, and J.P. Karamarkovic, "Terahertz performance of integrated lens antennas with a hot-electron bolometer," IEEE Trans. Microwave theory and techniques, vol.55, no.2, pp.239-247, 2007.

[17] The heat filter has an upper cutoff frequency of 5 THz and 0.22 dB loss at 3.42 THz and is made by QMC Ltd.

[18] A.R. Kerr, "Suggestions for revised definitions of noise quantities, including quantum effects," *IEEE Trans. Microwave Theory Tech.* vol.47, no.3, pp.325-329, 1999.

[19] J.J.A. Baselmans, A. Baryshev, S.F. Reker, M. Hajenius, J.R. Gao, T.M. Klapwijk, Yu. Vachtomin, S. Maslennikov, S. Antipov, B. Voronov, and G. Gol'tsman, "Direct detection effect in small volume hot electron bolometer mixers," *Appl. Phys. Lett.*, vol.86, 163503, 2005.

[20] W. Wild, Th. de Graauw, A. Baryshev, J. Baselmans, J.R. Gao, F. Helmich, B.D. Jackson, V.P. Koshelets, P. Roelfsema, N.D. Whyborn, and P. Yagoubov, "Terahertz Technology for ESPRIT – A Far-Infrared Space Interferometer", *In Proc. 16th Int. Symposium on Space Terahertz Technology*, Göteborg, Sweden, May 2-4, 2005, pages 68-73.

[21] S. S. Dhillon, J. Alton, S. Barbieri, A. de Rossi, M. Calligaro, H. E. Beere, E. H. Linfield, D. A. Ritchie, and C. Sirtori, "Ultralow threshold current terahertz quantum cascade lasers based on double-metal buried strip waveguides", *Appl. Phys. Lett*. 87, 071107, 2005.

[22] B. S. Williams, S. Kumar, and Q. Hu, "Operation of THz Quantum cascade lasers at 164K in pulsed mode and at 117K in continuous-wave mode," *Opt. Express 13*, 3331, 2005.