Superconducting integrated THz receivers: development and applications

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ABSTRACT

A Superconducting Integrated Receiver (SIR) comprises on one chip all elements needed for heterodyne detection: a low-noise SIS mixer with quasioptical antenna, a Flux-Flow Oscillator (FFO) acting as a Local Oscillator (LO) and a second SIS harmonic mixer (HM) for the FFO phase locking. Light weight and low power consumption combined with nearly quantum limited sensitivity and a wide tuning range of the FFO make SIR a perfect candidate for many practical applications. In particular, the SIR developed for novel balloon borne instrument TELIS (TErahertz and submillimeter LImb Sounder) covers frequency range 480 - 650 GHz. As a result of recent receiver's optimization the DSB noise temperature was measured as low as 120 K for the SIR with intermediate frequency (IF) band 4 – 8 GHz. The capability of the SIR for high resolution atmospheric spectroscopy has been successfully proven with scientific balloon flights from Kiruna, North Sweden. Diurnal cycles of ClO and BrO has been observed with BrO line level of only about 0.5 K. Possibility to use the SIRs for analysis of the breathed out air at medical survey has been demonstrated.

Keywords: Superconducting Integrated Receiver, Terahertz SIS mixers, superconducting local oscillators, integrated circuit technology

1. INTRODUCTION

A Superconducting Integrated Receiver (SIR)[1, 2] was proposed more than 10 years ago and has since then been developed up to the point of practical applications[3 - 5]. Our approach consists in developing a *single chip* heterodyne receiver, which is smaller and less complex than traditional devices. Typically, such a receiver consists of a number of main components (local oscillator, mixer, antenna structure, phase-lock circuit etc.) which are usually built as separate units and are complex (and thus costly). According to our concept (see Fig. 1) we have integrated all these components onto one single chip reducing overall system complexity in change for increased on-chip and lithographic fabrication complexity. A SIR comprises on one chip all key elements needed for heterodyne detection: a low-noise SIS mixer with quasi-optical antenna, a Flux-Flow Oscillator (FFO)[6] acting as a Local Oscillator (LO) and a second SIS harmonic mixer (HM) for the FFO phase locking. Continuous tuning of the phase-locked frequency has been experimentally demonstrated at any frequency in the range 350-750 GHz. The FFO free-running linewidth has been measured between 1 and 5 MHz, which allows to phase-lock up to 97 % of the emitted FFO power. The output power of the FFO is sufficient to pump the matched SIS mixer. The concept of the SIR is very attractive for many practical applications because of the compactness and the wide tuning range of the FFO[7]. Presently, the frequency range of most practical heterodyne receivers is limited by the tuning range of the local oscillator, typically 10-15% for a solid-state multiplier chain[8]. In the SIR the bandwidth is determined by the SIS mixer tuning structure and the matching circuitry between the SIS and the FFO. A bandwidth up to 30 – 40% may be achieved with a twin-junction SIS mixer design. Another potential advantage is the use of arrays of SIR channels within a single cryostat that could operate at the same or different LO frequencies.

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Infrared, Millimeter Wave, and Terahertz Technologies, edited by Cunlin Zhang,
Xi-Cheng Zhang, Peter H. Siegel, Li He, Sheng-Cai Shi, Proc. of SPIE Vol. 7854, 78540J
 · doi: 10.1117/12.868916

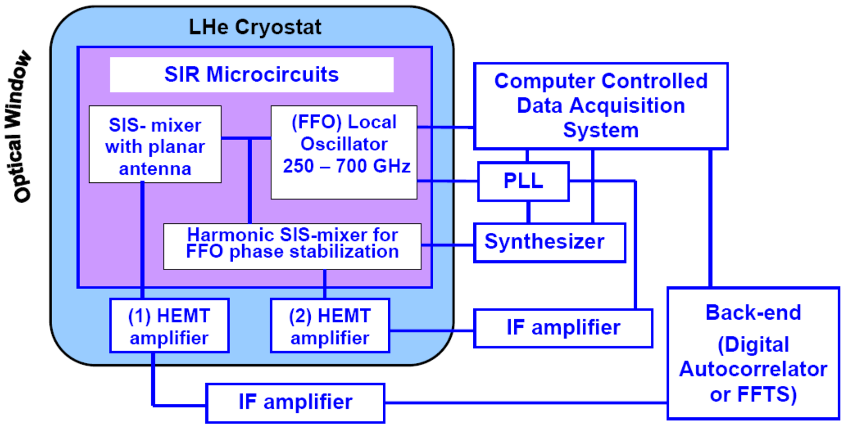

Figure 1. Block-diagram of the superconducting integrated receiver.

One of the important practical application of the SIR is TELIS (TErahertz and submillimeter LImb Sounder)[5, 9, 10] - a three-channel balloon-borne heterodyne spectrometer for atmospheric research developed in a collaboration of four institutes: Deutsches Zentrum für Luft- und Raumfahrt (DLR), Germany, Rutherford Appleton Laboratories (RAL), United Kingdom, and SRON – Netherlands Institute for Space Research, the Netherlands (in tight collaboration with Kotel'nikov Institute of Radio Engineering and Electronics, IREE, Moscow). All three receivers utilize state-of-the-art superconducting heterodyne technology and operate at 500 GHz (by RAL), at 480 – 650 GHz (by SRON + IREE), and at 1.8 THz (by DLR). TELIS is a compact, lightweight instrument capable of providing broad spectral coverage, high spectral resolution and long flight duration. The TELIS instrument serves also as a test bed for many novel cryogenic technologies and as a pathfinder for satellite based instrumentation.

TELIS is mounted on the same balloon platform as the Fourier transform spectrometer MIPAS-B[11], developed by IMK (Institute of Meteorology and Climate research of the University of Karlsruhe, Germany) and is operated in the mid-infrared (680 to 2400 cm^{-1}). Both instruments observe simultaneously the same air mass, and together they yield an extensive set of stratospheric constituents that can be used for detailed analysis of atmospheric chemical models, such as ozone destruction cycles. In particular, the 480 – 650 GHz TELIS channel is able to measure vertical profiles of ClO, BrO, O_3 and its rare isotopologues, O_2, HCl, HOCl, H_2O and 3 rare isotopologues, HO_2, NO, N_2O, NO_2, HNO_3, CH_3Cl, and HCN. In this paper the design and technology for the 480 – 650 GHz channel as used in the flight configuration are presented in conjunction with test results and the first preliminary scientific results.

Capability of the SIR for high resolution spectroscopy has been successfully proven also in a laboratory environment by gas cell measurements. The possibility to use SIR devices for the medical analysis of exhaled air will be discussed. Many medically relevant gases have spectral lines in the sub-terahertz range and can be detected by a SIR-based spectrometer. The Superconducting Integrated Receiver can be considered as an operational device, ready for many applications.

2. JOSEPHSON FLUX FLOW OSCILLATOR FOR INTEGRATED RECEIVER

A Josephson Flux Flow Oscillator (FFO)[6] has proven[4, 5, 7] to be the most developed superconducting local oscillator for integration with an SIS mixer in a single-chip submm-wave Superconducting Integrated Receiver[1 - 5]. The FFO is a long Josephson tunnel junction of the overlap geometry in which an applied dc magnetic field and a dc bias current, I_B, drive a unidirectional flow of fluxons, each containing one magnetic flux quantum, $\Phi_0 = h/2e \approx 2 \cdot 10^{-15}$ Wb (h is Planck's constant and e is the elementary charge). An integrated control line with current I_{CL} is used to generate the dc magnetic field applied to the FFO. According to the Josephson relation the junction oscillates with a frequency $f = (1/\Phi_0) \cdot V$ (about 483.6 GHz/mV) if it is biased at voltage V. The velocity and density of the fluxon chain and thus the power and frequency of the submm-wave signal emitted from the exit end of the junction may be adjusted independently by proper settings of I_B and I_{CL}.

There are a number of important requirements on the FFO properties to make it suitable for application in the phase-locked SIR. Obviously the FFO should emit enough power to pump an SIS mixer, taking into account a specially designed mismatch of about 5-7 dB between the FFO and the SIS mixer, introduced to avoid leakage of the input signal to the LO path. It is a challenge to realize the ultimate performance of the separate superconducting elements after their integration in a single-chip device. Implementation of the improved matching circuits and the submicron junctions for both the SIS and the HM allows delivering optimal FFO power for their operation.

Even for ultra wideband room-temperature PLL systems the effective regulation bandwidth is limited by the length of the cables in the loop (about 10 MHz for typical loop length of two meters). It means that the free-running FFO linewidth has to be well below 10 MHz to ensure stable FFO phase locking with a reasonably good spectral ratio (SR) - the ratio between the carrier and total power emitted by the FFO[7]. For example, only about 50 % of the FFO power can be phase-locked by the present PLL system at a free-running FFO linewidth of 5 MHz. A low spectral ratio results in a considerable error at resolving the complicated spectral line shape[12]. The "unlocked" rest of the total FFO power increases the phase noise and the calibration error. Thus a sufficiently small free-running FFO linewidth is vitally important for the realization of the phase-locked SIR for the TELIS.

2.1 Nb-AlN-NbN Flux Flow Oscillator

Earlier the Nb-AlOx-Nb or Nb-AlN-Nb trilayers were successfully used for the FFO fabrication. Traditional all-Nb circuits are being constantly optimized but there seems to be a limit for linewidth optimizations at certain boundary frequencies due to Josephson self-coupling (JSC) effect[13]. The JSC effect is the absorption of the FFO-emitted radiation by the quasi-particles in the cavity of the long junction. It considerably modifies the FFO properties at the voltages $V \approx V_{JSC} = 1/3*Vg$. For a Nb-AlOx-Nb FFO the transition corresponding *to* $V_{JSC} = Vg/3$ occurs around 450 GHz. Just above this voltage, the differential resistance increases considerably; that results in an FFO-linewidth broadening just above this point. This, in turn, makes it difficult or impossible to phase-lock the FFO in that region. We reported on development of the high quality Nb-AlN-NbN junction production technology[14]. The implementation of an AlN tunnel barrier in combination with an NbN top superconducting electrode provides also a significant improvement in SIS junction quality. The gap voltage of the junction Vg = 3.7 mV. From this value, and the gap voltage of the Nb film $\Delta_{Nb}/e = 1.4$ mV, we have estimated the gap voltage of our NbN film as $\Delta_{NbN}/e = 2.3$ mV[15]. So, by using the Nb-AlN-NbN FFOs we can cover important for TELIS the frequency range from 450 to 550 GHz imposed by the gap value of all-Nb junctions (V_{JSC} corresponds to 620 GHz for the Nb-AlN-NbN FFO).

We experimentally investigated a large number of the FFO designs. The length, *L*, and the width, *W,* of the FFO selected for TELIS project are 400 μm and 12 - 16 μm, respectively. The value of the critical current density, J_C, is in the range 4 - 8 kA/cm^2 giving a Josephson penetration depth, $\lambda_J \sim$ 6 - 4 μm. The corresponding value of the specific resistance is $Rn*L*W$ *is* ~ 50 - 25 Ohm*μm^2. For the numerical calculations we use a typical value of the London penetration depth, $\lambda_L \approx 90$ nm for all-Nb junctions, and a junction specific capacitance, $Cs \approx 0.08$ pF/ μm^2. The active area of the FFO (i. e. the AlO_x or the AlN tunnel barrier) is usually formed as a long window in the relatively thick (200-250 nm) SiO_2 insulation layer sandwiched between the two superconducting films (base and wiring electrodes). The so-called "idle" region consists of the thick SiO_2 layer adjacent to the junction (on both sides of the tunnel region) between the overlapping electrodes. It forms a transmission line parallel to the FFO. The width of the idle region (W_I = 8 - 10 μm) is comparable to the junction width. The idle region must be taken into account when designing an FFO with the desired properties. In our design it is practical to use the flat bottom electrode of the FFO as a control line in which the current I_{CL} produces the magnetic field, which mainly is applied perpendicular to the long side of the junction.

In Fig. 2 the typical current-voltage characteristics (IVCs) of a Nb-AlN-NbN SIS junction of an area of about 1 μm^2 is given, both the unpumped IVC (solid line) and the IVC when pumped by a Nb-AlN-NbN FFO at different frequencies (dotted lines). One can see that the FFO provides more than enough power for the mixer pumping. In this experiment we use the test circuits with low-loss matching circuits tuned between 400 and 700 GHz. Even with the specially introduced 5 dB FFO/SIS mismatch (required for the SIR operation) the FFO delivers enough power for the SIS mixer operation in the TELIS frequency range of 480-650 GHz[7]. An important issue for the SIR operation is a possibility to tune the FFO power, while keeping the FFO frequency constant. The dependence of the SIS pump current on the FFO bias current demonstrated that the FFO power can be tuned more than 15 dB, while keeping the same frequency by proper adjustment of the control line current.

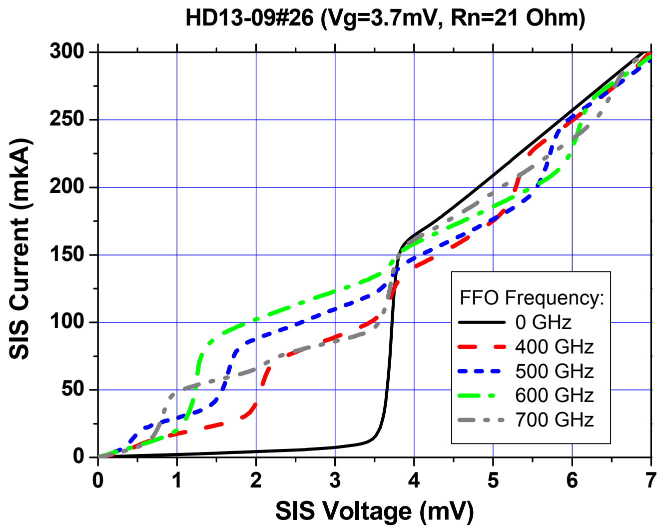

Figure 2. IVCs of the SIS mixer: unpumped – solid curve, pumped at different frequencies – dashed and dotted lines[15].

Continuous frequency tuning at frequencies below 600 GHz for the Nb-AlN-NbN FFOs of moderate length is possible, although the damping is not sufficient to completely suppress the Fiske resonant structure at frequencies below Vg/3. For short junctions with a small α (wave attenuation factor) the distance between the steps in this resonant regime can be as large, that it is only possible to tune the FFO at the certain set of frequencies. For a 400 µm long Nb-AlN-NbN junction this is not the case – the quality factor of the resonator formed by a long Nb-AlN-NbN Josephson junction is not so high at frequencies > 350 GHz. Therefore, the resonance steps are slanting and the distance between them is not so big. This allows us to set any voltage (and any frequency) below V_{JSC}, but for each voltage only a certain set of currents should be used. So, in this case we have the regions of forbidden bias-current values, specific for each voltage below V_{JSC}, instead of the forbidden voltage regions for the Fiske regime in Nb-AlOx-Nb FFO[15]. Special algorithms have been developed for automatic working point selection in flight.

2.2 Spectral Properties of the Flux Flow Oscillator

The FFO linewidth (LW) has been measured in a wide frequency range from 300 GHz up to 750 GHz using a well-developed experimental technique[16]. A specially designed integrated circuit incorporates the FFO junction, the SIS harmonic mixer and the microwave matching circuits. Generally, both junctions are fabricated from the same Nb/AlN/NbN or Nb/AlOx/Nb trilayer. The FFO signal is fed to the SIS harmonic mixer (HM) together with a 17 – 22 GHz reference signal from a stable synthesizer. The required power level depends on the parameters of the HM; it is about of 1 µW for a typical junction area of 1 µm^2. The intermediate frequency (IF) mixer product ($f_{IF} = \pm (f_{FFO} - n{\cdot}f_{SYN})$ at ~ *400 MHz* is first boosted by a cooled HEMT amplifier (T_n ~ 5 K, gain = 30 dB) and then by a high-gain room-temperature amplifier.

In order to accurately measure the FFO line shape the IF signal must be time-averaged by the spectrum analyzer. To remove low-frequency drift and interference from the bias supplies, temperature drift, etc. we use a narrow bandwidth (< 10 kHz) Frequency Discriminator (FD) system with relatively low loop gain for *frequency locking* of the FFO. With the FD narrow-band feedback system that stabilizes the mean frequency of the FFO (but does not affect FFO line shape) we can accurately measure the free-running FFO linewidth, which is determined by the much faster internal ('natural") fluctuations (see Fig. 3). The resulting IF signal is supplied also to the Phase-Locking Loop (PLL) system. The phase-difference signal of the PLL is fed to the FFO control line current. Wideband operation of the PLL (10-15 MHz full width) is obtained by minimizing the cable loop length. A part of the IF signal is delivered to the spectrum analyzer via a power splitter (see Fig. 3). All instruments are synchronized to harmonics of a common 10 MHz reference oscillator.

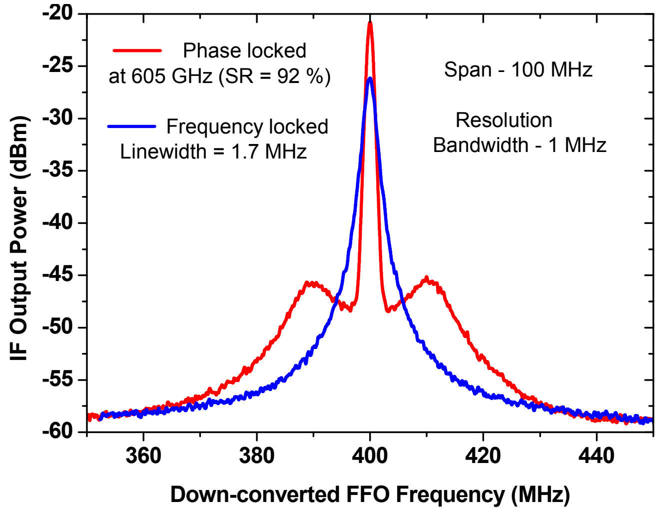

Figure 3. Spectra of the Nb-AlN-NbN FFO operating at 515.2605 GHz (blue curve – frequency locked by FD; red curve – phase-locked). Linewidth = 1.7 MHz; Spectral Ratio = 92 %.

This section can be summarized as follows. Continuous tuning of the frequency is possible for Nb-AlN-NbN FFOs due to bending and overlapping of the Fiske steps, so that any desirable frequency can be realized. A possibility to phase lock the Nb-AlN-NbN FFO at any frequency in the range 350-750 GHz has been experimentally demonstrated; an optimized design of the FFO for TELIS has been developed and tested. A free-running linewidth value from 5 to 1 MHz has been measured in the frequency range 300 – 750 GHz. As a result, the spectral ratio of the phased-locked FFO varies from 50 to 97 % correspondingly. To ensure remote operation of the phase-locked SIR several procedures for its automatic computer control have been developed and tested. New designs of the FFO intended for further improvement of its parameters are under development, but even at the present state the Nb-AlN-NbN FFOs are mature enough for practical applications. These achievements enabled the development of a 480 - 650 GHz integrated receiver for the atmospheric-research instrument TELIS (TErahertz and submillimeter LImb Sounder).

3. TELIS (TERAHERTZ AND SUBMILLIMETER LIMB SOUNDER)

3.1 TELIS Instrument Design

The front-end of the ballon-borne TELIS instrument for atmospheric research is common for the three channels on board. It consists of the pointing telescope, a calibration blackbody, relay and band-separating optics. Details of the optical design can be found in[17 - 19]. The three mirrors of the dual offset Cassegrain telescope are mounted on a common frame, rotatable around the optical axis of the output beam. Limb scanning is performed between the upper troposphere (8-10 km in the Arctic) to flight altitude (typically 32 km) in 1 to 2 km steps. At the tangent point of the line of sight, the vertical (elevation) resolution is about 2 km for an observational frequency of 500 GHz, scaling inversely proportional with frequency. In horizontal (azimuth) direction the spatial resolution is about a factor of 2 less due to the anamorphicity of the telescope. This is allowed as the atmospheric properties within the beam hardly depend on the azimuth. The radiometric gain of the spectrometers is calibrated once or twice in every Limb scan using a conical blackbody reference source and a measurement of the cold sky. For this, a small flip mirror is included between the telescope and the beam-separating optics. By measuring at two up-looking telescope positions, the impact of the remaining air above the gondola can be assessed.

Simultaneous observation by the receivers is achieved by quasi-optical beam splitting. First a wire-grid based polarizing beam splitter is employed to reflect one linear polarization to the 500 GHz channel, the other linear polarization is split by a dichroic filter between the SIR channel and the THz channel. Subsequently, off-set mirrors shape and direct the three beams to the cryogenic channels. Inside the custom designed liquid-helium cooled cryostat, each receiver has dedicated cold optics, a superconducting mixing element and intermediate-frequency (IF) amplifiers.

The warm optics couples to the SIR channel with a beam that has a waist radius ranging from 2 to 3 mm, located at the cryostat window. The system-pupil is imaged by two additional mirrors on the silicon elliptical lens; on the back surface of this lens the SIR chip is located. The SIR-channel cold-optics is also frequency independent to fully exploit the wide-band operation of the SIR device. The beam waist is measured to be 2.25 mm, which is within 1% of the designed value. The measured Gaussisity of the beam is 92.4%.

The IF processor (located on the main frame of TELIS) converts the amplified IF output signals of the three receivers to the input frequency range of the digital autocorrelator. The digital autocorrelator has a bandwidth of 2x2 GHz with 2048 spectral channels. Both the IF processor and the digital autocorrelator are developed by Omnisys Instruments AB[20].

The SIR channel is controlled with a battery-operated ultra low-noise biasing system. Since noise on the bias lines of the FFO translates in a wider FFO linewidth, several precautions, like decoupling of digital control lines and extensive filtering and shielding, are implemented. The SIR bias unit is digitally controlled by the on-board DLR PC-104 computer, that also interfaces with the other channels, the digital autocorrelator, and with the host instrument MIPAS. A radio link provides real-time two-way contact with the ground segment consisting of a server computer with three dedicated client computers, coupled through TCP/IP socket connections. The complete system is dimensioned to have sufficient cooling liquids and battery power for a 24 hour flight.

3.2 SIR Channel Design

A key element of the 480 – 650 GHz channel is the SIR[1-5] that comprises in one chip (size of 4 mm*4 mm*0.5 mm) a low-noise SIS mixer with quasioptical antenna, a superconducting Flux Flow Oscillator (FFO) [6] acting as a Local Oscillator (LO) and a second SIS harmonic mixer (HM) for FFO phase locking. Since the free-running linewidth of the FFO can be up to 10 MHz, for spectral applications the FFO has to be locked to an external reference oscillator employing a phase lock loop system. The concept of the SIR is very attractive for TELIS due to a wide tuning range of the FFO. In the SIR the bandwidth is basically determined by the SIS mixer tuning structure and matching circuitry between the SIS and FFO; bandwidth up to 30 - 40 % may be achieved with a twin-junction SIS mixer design (both for double-slot and double-dipole antennas). To achieve the required instantaneous bandwidth of 480-650 GHz a twin-SIS mixer with 0.8 μm^2 junctions and new design of the FFO/SIS matching circuitry were implemented. A microscope photograph of the central part of the SIR chip with double-dipole antenna is presented in Fig. 4.

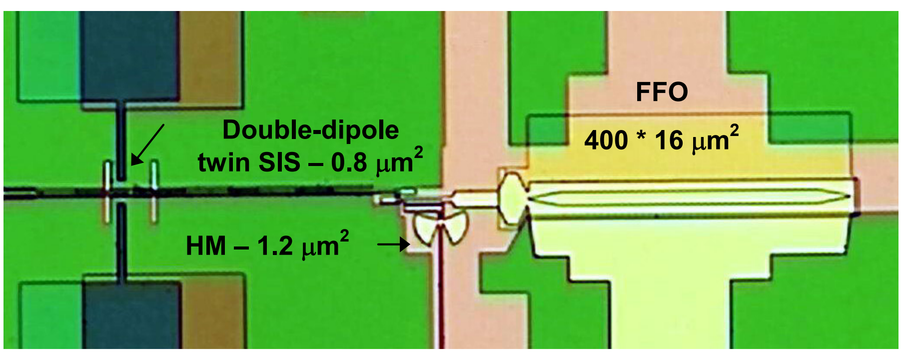

Figure 4. Central part of the SIR chip with double-dipole antenna, twin SIS-mixer and harmonic mixer for FFO phase locking.

The resolution of the TELIS back-end spectrometer is 2.160 MHz, sufficient to resolve the exact shape of atmospheric lines. The FFO line shape and spectral stability should ideally be much better than this. However, the free-running linewidth of the FFO can be up to 10 MHz and therefore a Phase Lock Loop (PLL) has been developed to phase lock the FFO to an external reference oscillator[6, 14]. For this, a small fraction of the FFO power is first directed to a so-called Harmonic Mixer (HM), placed on the SIR chip. The HM is pumped by an off-chip Local oscillator Source Unit (LSU) which is a tunable reference frequency in the range of 19-21 GHz. The frequency of the LSU is chosen such that the difference frequency of the n^{th} harmonic of the LSU, generated by the HM, and the FFO is about 4 GHz. This difference signal is then amplified by a cryogenic low-noise HEMT amplifier and down-converted to 400 MHz by using a second reference at 3.6 GHz. Finally, the frequency and phase of this 400 MHz signal is compared against yet another reference frequency of 400 MHz and the resulting error signal is fed back to the FFO. The LSU and the reference signals at 3.6 GHz and at 400 MHz are all phase-locked to an internal ultra stable 10 MHz Master Oscillator.

All components of the SIR microcircuits are fabricated in a high quality Nb-AlN/NbN tri-layer on a Si substrate[13]. The receiver chip is placed on the flat back surface of the elliptical silicon lens (forming an integrated lens-antenna) with accuracy 10 µm, determined by the tolerance analysis of the optical system. As the FFO is very sensitive for external electromagnetic interferences the SIR chip is shielded by two concentric cylinders: the outer cylinder is made of cryo-perm and the inner one of copper with a 100 µm coating of superconducting lead. All SIR channel components (including input optical elements) are mounted on a single plate inside a 240 mm x 180 mm x 80 mm box cooled by the thermo-straps to the temperature of about 4.2 K.

3.3 TELIS-SIR Channel Performance

The TELIS-SIR channel has been characterized in eight micro-windows that have been selected for the flight in (Sweden). These micro-windows have the following LO frequencies:

- 495.04 GHz for $H_2{}^{18}O$
- 496.88 GHz for HDO
- 505.60 GHz for BrO
- 507.27 GHz for ClO
- 515.25 GHz for O_2, pointing, and temperature
- 519.25 GHz for BrO and NO_2
- 607.70 GHz for ozone isotopes
- 619.10 GHz for HCl, ClO and HOCl.

Initial flight values for the parameters for the FFO, SIS and HM mixers have been determined for each micro-window. Dedicated algorithms allowing for fast switching between LO frequencies and for in-flight optimization of the SIR, have been developed (see below). It takes about 1 minute of stabilization and optimization to switch between two LO settings. All experimental results discussed here have been obtained with the SIR flight device. After optimization of the FFO design the free-running linewidth between 7 and 0.5 MHz has been measured in the frequency range 350 – 750 GHz, which allows to phase-lock from 35 to 95 % of the emitted FFO.

The measured double sideband (DSB) receiver noise temperature T_R, uncorrected for any loss, is presented in Fig. 5 as a function of LO frequency. As can be seen, the noise is well below 200 K at all frequencies of interest, with a minimum of 120 K at 500 and 600 GHz. The noise peak around 540-575 GHz is partially spurious, caused by absorption of water vapor in the path between calibration sources and the cryostat, and partially real - due to properties of the SIS-mixer tuning circuitry. The relatively high noise in this band is of no concern for science observations, since this part of the atmospheric spectrum is obscured by a highly saturated water-vapor line rendering it virtually useless for atmospheric science. The noise as a function of IF is fairly flat in the frequency range 4-8 GHz, as can be seen in Fig. 6. The dependence of the receiver noise temperature on the SIS bias voltage is very flat; for Nb-AlN/NbN circuits there is very wide range of SIS bias voltages where T_R is almost constant.

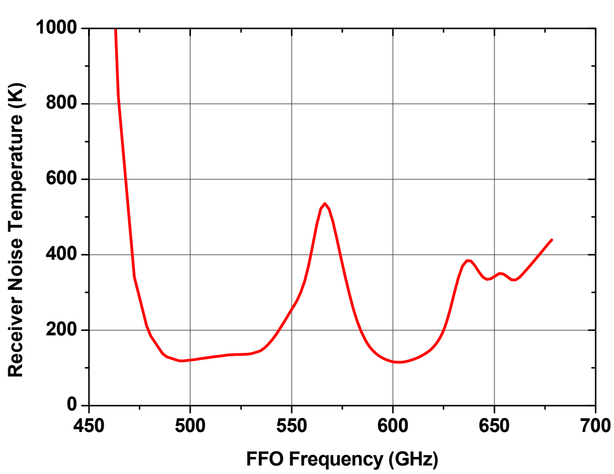

Figure 5. Measured DSB receiver noise temperature of the SIR for the flight device at IF frequency 8 GHz.

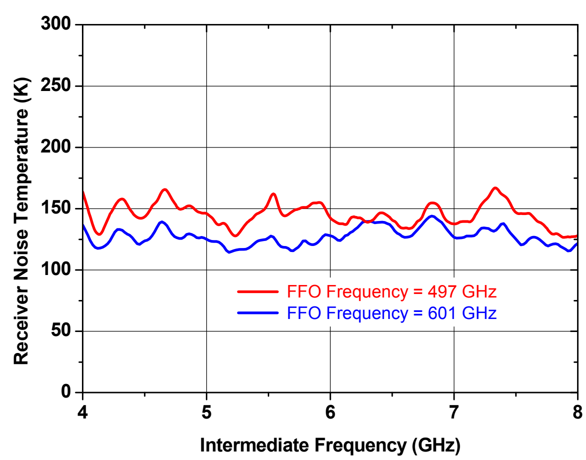

Figure 6. DSB receiver noise temperature as a function of the IF frequency, taken at two FFO frequencies: 497 and 601 GHz.

For the TELIS measurement strategy it is important to know whether the timing of limb sounding should depend on the stability of the complete receiver chain. The stability determines the optimum achievable measurement time for a single integration, and thus the required frequency of the calibration cycle. The stability of the complete TELIS-SIR system has been determined with a noise-fluctuation bandwidth of 17 MHz[10]. For the two IF channels that are used to determine the Allan variance it is found that the Allan stability time is about 13.5 seconds. When the difference of the two channels is taken to determine the Allan variance (this is the so-called spectroscopic, or differential, mode), the Allan stability time of 20 seconds is found. This is comparable to stabilities measured for astronomical receivers.

Within TELIS a 1.5 s integration time per tangent height is used. This is mainly driven by the required integrated signal levels at the autocorrelator input. The stability of the SIR channel therefore poses no constraints on the observing strategy. The SIR is a complicated device as it contains multiple interactive superconducting elements: a SIS mixer, an FFO, and an HM for the FFO phase locking. Special algorithms and procedures have been developed and tested to facilitate characterization of the SIR at reasonable time scales and for the SIR control during the flight.

3.4 Kiruna Campaigns and Preliminary Science Results

TELIS had two successful scientific campaigns from Kiruna, North-Sweden in March 2009 and in January 2010. The instrument was launched together with the MIPAS instrument on the MIPAS-B2 gondola (see Fig. 7). Scenario of both flights was quite similar. During ascent the SIR channel behaved nominally and already after 30 minutes the first spectra were recorded. After 3 hours the first flight ceiling was reached around 35 km. Several night recordings were taken, necessary for background measurements for species with a diurnal cycle and for instrument calibration. The instrument proved to be stable against the strong temperature variations of the atmosphere during ascent (with ambient temperatures as low as minus 90°C) and during sun-rise. The wind direction changed to south east, resulting in a long flight over Finland (total flight time was about 12 hours for both campaigns). During the whole morning the diurnal cycle of various species was monitored until the very end of the flight. In total several hundred limb sequences have been recorded. The MIPAS-TELIS balloon system performed nominally during the flight. After parachute landing and recovery the instruments were found to be undamaged, allowing for extra post-flight calibration measurements.

Figure 7. TELIS-MIPAS launch at Esrange, Sweden; March 2009. Balloon size: 400 000 m3; Payload weight: 1 200 kg

The science goals of the campaign from Kiruna, North Sweden, were threefold: investigation of the stratospheric hydrological cycle by measurements of isotopic water, catalytic ozone destruction by chlorine chemistry, and the bromine content of the stratosphere. Data presented in Fig. 8 prove the capabilities of the TELIS-SIR channel for high resolution spectroscopy. The width of the ozone line is measured to be about 10 MHz, as expected (see Fig. 8).

The data reduction is on-going, but the first preliminary science results are quite encouraging. Chlorine ozone destruction peaks in the arctic winter and/or spring when the so-called polar vortex breaks up. During this event the ClO radical, responsible for catalytic ozone destruction, becomes available in huge amounts. However, chlorine is also stored in non-reactive reservoir species of which HCl is an important member. The amount of HCl in the stratosphere is a measure of the total non-active Cl content and is as such an important species to monitor in ozone chemistry studies. Diurnal cycles of ClO and BrO has been observed with BrO line level of only about 0.5 K. Some preliminary results measured for HCl and ClO lines are presented in Fig. 9 and 10 respectively.

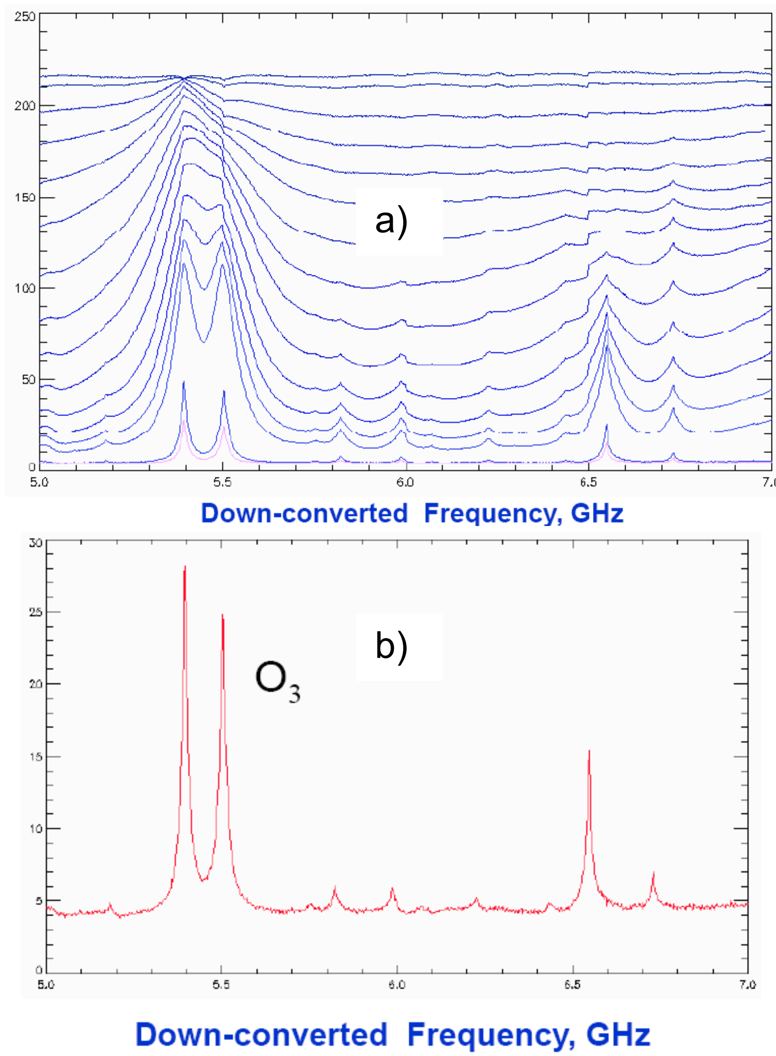

Figure 8. Spectra measured by Integrated Receiver (FFO frequency = 495 GHz) at the gondola altitude 30 km for the limb scanning in the range 10.5 – 30 km with 1.5 km increment (from top to bottom). The bottom curve is measured at telescope looking 45 degree up; this curve is re-plotted in Fig. 8.b. Intensity of the received signal in Kelvin is plotted as ordinate of the graphs.

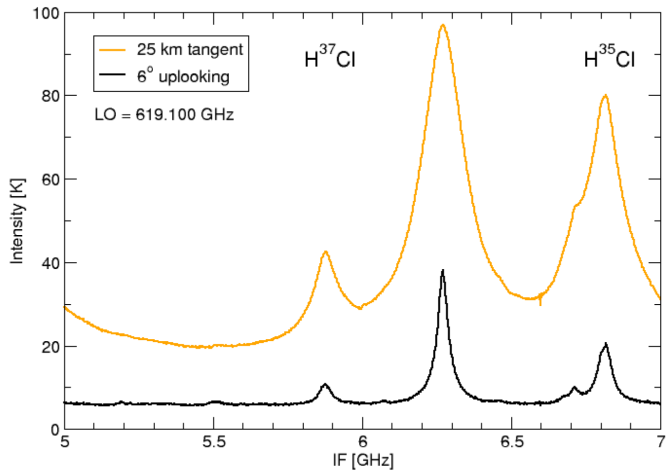

Figure 9. Spectra measured by the SIR (FFO frequency = 619.1 GHz) at the gondola altitude 30 km for two scanning directions: 25 km tangent and at telescope looking 6 degree up; these data demonstrate two HCl isotopes.

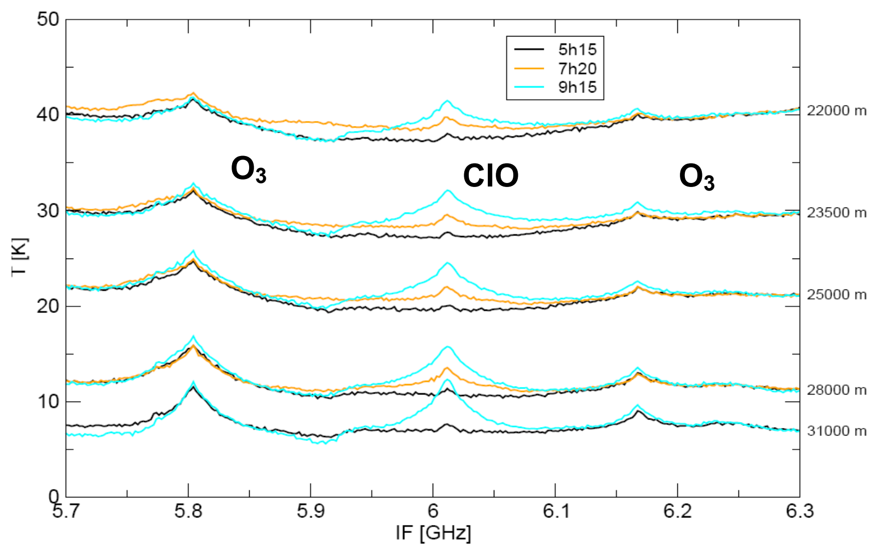

Figure 10. Variation of the ClO line over time (FFO = 495 GHz), measured by the SIR channel.

4. SIR FOR NON-INVASIVE MEDICAL DIAGNOSTICS

High sensitivity and spectral resolution of the integrated spectrometer enables the analysis of multi-component gas mixtures. Exhaled air of human includes about 400 gases, of which some can be indicators of various diseases and pathology. For example, nitric oxide, NO, was detected in the exhaled air of patients suffering from bronchial asthma, pneumonia and others chronic inflammatory diseases of upper airways. Besides, nitric oxide may have an effect on the reaction of tumors and healthy tissues on radiation therapy. Another example may concern the opportunity of non-invasive diagnostics of gastritis or peptic ulcer of the stomach by measuring the concentration of ammonia in exhaled air. Nowadays urease respiratory tests (application of urea with C^{13}) are mainly used to detect the diseases. However the method is quite expensive and its sensitivity is restricted by natural variations of C^{13} in exhaled air during the procedure. Natural concentrations of ammonia instead are quite low, so, the measurement of the ammonia concentration could be a good alternative. Another important application concerns the non-invasive diagnostics of diabetes, where exhaled acetone is an indicator.

A laboratory setup for spectral analysis of the exhalted air has been developed at IREE (input frequency range 480 – 630 GHz, noise temperature below 200 K over the range, spectral resolution below 1 MHz), based on the integrated spectrometer for atmosphere monitoring. The instrument parameters allow us to measure the spectral lines of the rotational transitions for most of the substances in the exhalted air. The laboratory setup has been developed and demonstrated using the gases OCS and NH_3 in the laboratory gas cell. Clear and well-defined response has been measured at the expected frequencies of spectral lines for pressures down to 10^{-3} mBar. Examples of the NH_3 spectra recorded by the SIR with the Fast Fourier Transform Spectrometer (FFTS) as a back-end, and by the novel technique based on application of the additional oscillator are presented in Fig. 11 and 12 respectively. The possibility to measure the spectral response in a few seconds has been demonstrated experimentally. This allows carrying on the real time medical survey. First spectral measurements by the integrated receiver of exhalted air in the subTHz range have demonstrated good selectivity and speed of the analysis as well as high sensitivity. For example, we have measured ammonia concentration with sensitivity on the order of 10^{-9} (1 ppb).

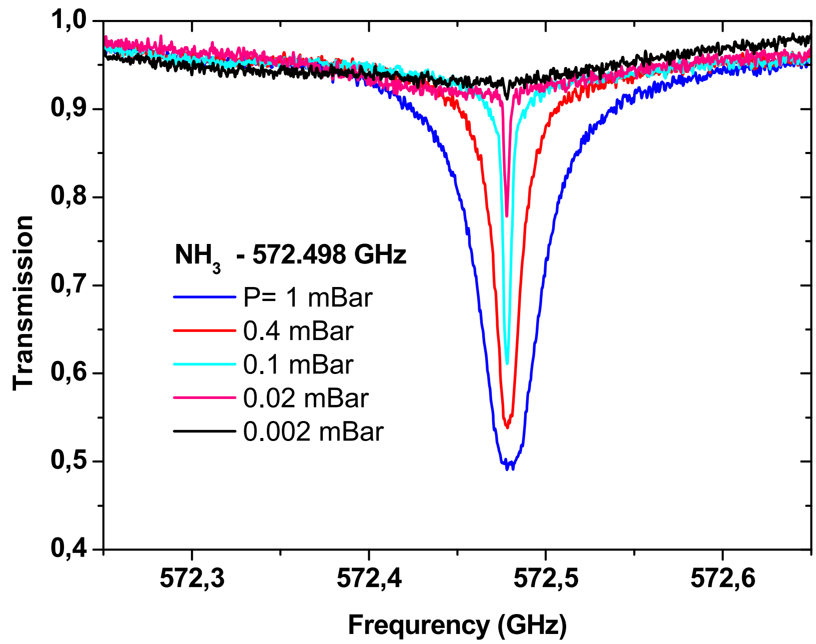

Figure 11. NH_3 spectra measured by the SIR with FFTS back-end at different pressures.

5. SUMMARY

The capability of the Superconducting Integrated Receiver for high resolution atmospheric spectroscopy has been successfully proven with scientific balloon flights from Kiruna, North Sweden. During the two 12-hours missions, phase–locked SIR operation and frequency switching in the 480 – 650 GHz frequency range has been realized. An intrinsic spectral resolution of the SIR well below 1 MHz has been confirmed by CW signal measurements in the laboratory. An uncorrected double sideband noise temperature below 120 K has been measured for the SIR when operated with a phase-locked FFO at an intermediate frequency bandwidth of 4 – 8 GHz. To ensure remote operation of the phase-locked SIR several software procedures for automatic control have been developed and tested. The first tentative HCl profile has been presented and its quality looks promising for future data reduction. Diurnal cycles of ClO and BrO has been observed at different viewing configurations (altitude), with BrO line level of only about 0.5 K. Possibilities to use the SIR devices for analysis of the breathed out air at medical survey have been demonstrated. The Superconducting Integrated Receiver can be considered as an operational device, ready for many applications.

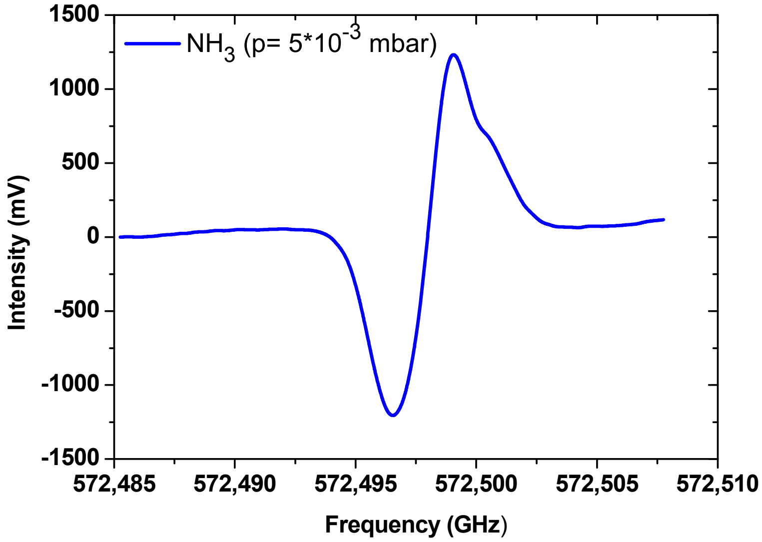

Figure 12. Response (derivative of the spectral line), measured for NH_3 gas by the integrated receiver with implementation of novel technique (details will be published elsewhere).

ACKNOWLEDGEMENTS

The authors thank colleagues at DLR, IPM, IREE and SRON for help and assistance in the SIR channel design and characterization: A Baryshev, D Boersma, J Dercksen, P Dmitriev, H Golstein, L de Jong, A Khudchenko, J Kooi, B van Kuik, A Pankratov, D Paveliev O Pylypenko, J van Rantwijk, S Shitov, A Sobolev, and E de Vrie; as well as M Birk, T de Graauw, R Hoogeveen, A Selig and W Wild are acknowledged for their support of this work.

The work was supported in parts by RFBR projects 09-02-00246, 09-02-12172-ofi-m, Grant for Leading Scientific School 5423.2010.2 and State contract № 02.740.11.0795.

REFERENCES

[1] Koshelets, V. P., Shitov, S. V., Filippenko, L. V., Baryshev, A. M., Golstein, H., de Graauw, T., Luinge, W., Schaeffer, H. and van de Stadt, H., "First Implementation of a Superconducting Integrated Receiver at 450 GHz", Appl. Phys. Lett. 68, No 9, 1273 (1996).

[2] Koshelets, V. P. and Shitov, S. V., “Integrated Superconducting Receivers”, Supercond. Sci. Technol. 13, R53 (2000).

[3] Yagoubov, P., Hoogeveen, R., Torgashin, M., Khudchenko, A., Koshelets, V., Suttiwong, N., Wagner, G. and Birk, M., “550-650 GHz spectrometer development for TELIS”, Proc. ISSTT, 338 (2006).

[4] Koshelets, V.P., Ermakov, A.B., Filippenko, L.V., Khudchenko, A.V., Kiselev,O.S., Sobolev,A.S., Torgashin, M.Yu., Yagoubov, P.A., Hoogeveen, R. W. M. and Wild,W., “Iintegrated Submillimeter Receiver for TELIS”, IEEE Trans. on Appl. Supercond., 17, 336 (2007).

[5] De Lange, G., Boersma, D., Dercksen, J., Dmitriev, P., Ermakov, A., Filippenko, L., Golstein, H., Hoogeveen, R., de Jong, L., Khudchenko, A., Kinev, N., Kiselev, O., van Kuik, B., de Lange, A., van Rantwijk, J., Sobolev, A., Torgashin, M., de Vries, E., Yagoubov, P. and Koshelets, V., “Development and Characterization of the Superconducting Integrated Receiver Channel of the TELIS Atmospheric Sounder”, Supercond. Sci. Technol. 23, No 4, 045016, (2010).

[6] Nagatsuma, T., Enpuku, K., Irie, F. and Yoshida, K., "Flux-flow type Josephson oscillator for millimeter and submillimeter wave region", J. Appl. Phys., 54, 3302, (1983).

[7] Koshelets, V.P., Dmitriev, P. N., Ermakov, A. B., Sobolev, A. S., Torgashin, M. Yu., Kurin, V. V., Pankratov, A. L. and Mygind J. "Optimization of the Phase-Locked Flux-Flow Oscillator for the Submm Integrated Receiver", IEEE Trans. on Appl. Supercond., 15, 964-967 (2005).

[8] Mehdi, I., "THz local oscillator technology", Proc. of SPIE, 5498, 103 (2004).

[9] Hoogeveen, R. W. M., Yagoubov, P. A., de Lange, A., Selig, A. M., Koshelets, V. P., Ellison, B. N. and Birk, M., Proc. SPIE, 5978, 440 (2005).

[10] Hoogeveen, R. W. M., Yagoubov, P. A., de Lange, G., de Lange, A., Koshelets, V., Birk, M. and Ellison, B., Proc. SPIE, 6744, (2007).

[11] Friedl-Vallon, F., Maucher, G., Seefeldner, M., Trieschmann, O., Kleinert, A., Lengel, A., Keim, C., Oelhaf, H. and Fischer, H., Appl. Opt., 43, 3335 (2004).

[12] Koshelets, V. P., Shitov, S. V., Ermakov, A. B., Koryukin, O. V., Filippenko, L. V., Khudchenko, A. V., Torgashin, M. Yu., Yagoubov, P., Hoogeveen, R. and Pylypenko, O. M., "Superconducting Integrated Receiver for TELIS", IEEE Trans. on Appl. Supercond., 15, 960-963 (2005).

[13] Koshelets, V. P., Shitov, S. V., Shchukin, A. V., Filippenko, L.V., Mygind, J. and Ustinov, A. V., "Self-Pumping Effects and Radiation Linewidth of Josephson Flux Flow Oscillators", Phys Rev B, 56, 5572-5577 (1997).

[14] Dmitriev, P. N., Lapitskaya, I. L., Filippenko, L. V., Ermakov, A. B., Shitov, S. V., Prokopenko, G. V., Kovtonyuk, S. A. and Koshelets, V. P., "High Quality Nb-based Integrated Circuits for High Frequency and Digital Applications", IEEE Trans. on Appl. Supercond.", 13, No 2, 107-110 (2003).

[15] Torgashin, M. Yu., Koshelets, V. P., Dmitriev, P. N., Ermakov, A. B., Filippenko, L. V. and Yagoubov, P. A., "Superconducting Integrated Receivers based on Nb-AlN-NbN circuits",.IEEE Trans. on Appl. Supercond., 17, 379-382 (2007).

[16] Koshelets, V. P., Shitov, S. V., Shchukin, A. V., Filippenko, L. V. and Mygind, J., "Linewidth of Submillimeter Wave Flux-Flow Oscillators", Appl. Phys. Lett., 69, 699-701 (1996).

[17] Yagoubov, P., van de Stadt, H., Hoogeveen, R., Koshelets, V., Birk, M. and Murk A., "Optical Design of sub-Millimeter Spectrometer for Limb Sounder", Proc. of the 28th ESA Antenna Workshop on Space Antenna Systems and Technologies (Noordwijk,) vol. 2, 763 (2005).

[18] Yagoubov, P. A., Vreeling, W-J., van de Stadt, H., Hoogeveen, R. W. M., Koryukin, O. V., Koshelets, V. P., Pylypenko, O. M. and Murk, A., "550-650 GHz spectrometer development for TELIS", Proc. of the 16th Intern. Conf. on Space Terahertz Technology (Gothenburg), 438 (2005).

[19] Murk, A., Yagoubov, P., Mair, U., Birk M., Wagner, G., van de Stadt, H., Hoogeveen, R. and Kämpfer, N., Proc. of the 28th ESA Antenna Workshop on Space Antenna Systems and Technologies (Noordwijk), 757 (2005).

[20] Emrich, A., Andersson, S. and Knis, M., Proc. of the joint 31st International Conference on Infrared Millimeter Waves and 14th International Conference on Terahertz Electronics (Shanghai), 314 (2006).