Balloon-Borne Superconducting Integrated Receiver for Atmospheric Research

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***Abstract*—A Superconducting Integrated Receiver (SIR) was proposed more than 10 years ago and has since then been developed up to the point of practical applications. We have demonstrated for the first time the capabilities of the SIR technology for heterodyne spectroscopy both in the laboratory and at remote operation under harsh environmental conditions for atmospheric research. Within a SIR the main components needed for a superconducting heterodyne receiver such as an SIS-mixer with quasi-optical antenna, a Flux-Flow oscillator (FFO) as the local oscillator, and a harmonic mixer to phase-lock the FFO are integrated on a single chip. Light weight and low power consumption combined with broadband operation and nearly quantum limited sensitivity make the SIR a perfect candidate for future airborne and space-borne missions. The noise temperature of the SIR was measured to be as low as 85 K, with an intermediate frequency band of 4–8 GHz in double sideband operation; the spectral resolution is well below 1 MHz. The SIR was implemented in the three-channel balloon-borne instrument TELIS (TErahertz and submillimeter LImb Sounder) that detects spectral emission lines of stratospheric trace gases (like ClO and BrO). These gases even in small quantities can have a significant impact on the atmosphere because they speed up certain chemical processes, such as ozone depletion.**

***Index Terms*—Data acquisition, Josephson junctions, phase locked oscillators, submillimeter wave receivers, superconducting devices, superconducting integrated circuits.**

I. Introduction

A SUPERCONDUCTING Integrated Receiver (SIR) [1], [2] is a complete heterodyne receiver comprising in one microcircuit a low-noise SIS mixer with quasi-optical antenna, a Flux-Flow Oscillator (FFO) [3]–[6] acting as a Local Oscillator (LO) and a second SIS harmonic mixer (HM) for the FFO phase locking. Our approach consists in reducing overall system complexity in change for increased on-chip and lithographic fabrication complexity. The SIR is smaller, has light weight and low power consumption combined with broadband operation and nearly quantum limited sensitivity. Because of all these advantages, the instruments using the SIR are very attractive for space-borne and airborne missions.

One of the important practical application of the SIR is TELIS (TErahertz and submillimeter LImb Sounder) [7]–[9]—a three-channel balloon-borne heterodyne spectrometer for atmospheric research developed jointly by four institutes: the Deutsches Zentrum für Luft- und Raumfahrt (DLR), Germany, the Rutherford Appleton Laboratories (RAL), United Kingdom, and the SRON—Netherlands Institute for Space Research, the Netherlands (in close collaboration with the Kotel'nikov Institute of Radio Engineering and Electronics, IREE, Moscow). All the 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). The TELIS is a compact, lightweight instrument capable of providing broad spectral coverage, high spectral resolution and long flight duration.

The TELIS is mounted on the same balloon platform as the Fourier transform spectrometer MIPAS-B [10], developed by the IMK (the Institute of Meteorology and Climate research of the University of Karlsruhe, Germany) and is operated in the mid-infrared range (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, during the Kiruna launch campaigns (March 2009 and January 2010) [7] the 480–650 GHz SIR TELIS channel was used to measure vertical profiles of ClO, BrO, O_3 and its rare isotopologues, O_2, HCl, HOCl, H_2O and 3 rare isotopologues, NO_2 and HCN.

In this paper the design, operating and testing algorithms of 480–650 GHz channel as used in the flight configuration are presented in conjunction with the preliminary scientific results of Kiruna 2010 launch campaign.

II. Superconducting Integrated Receiver for the TELIS Project

Diagram of the SIR is presented in Fig. 1; all SIR elements such as FFO, SIS and HM mixer are fabricated in a high quality Nb-AlN/NbN tri-layer [11] on a Si substrate; to combine these elements with appropriate matching circuits in complete receiver an Nb wiring layer is implemented.

In experimental setup the SIR chip is placed on the flat back surface of a Si lens that is fixed in special holder inside double magnetic shield. This assembly together with low-noise HEMT IF amplifier and DC filters is placed on a liquid helium temperature cold plate of the cryostat with optical window. Double

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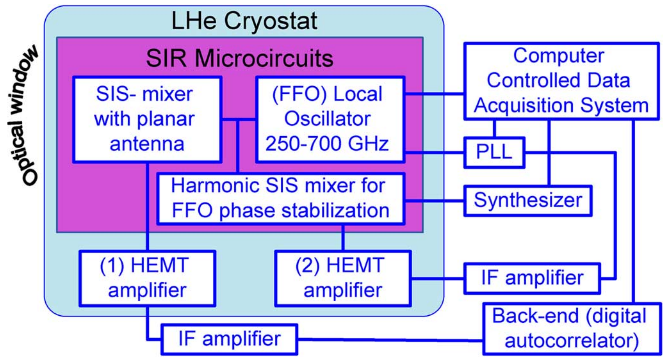

Fig. 1. Block-diagram of the superconducting integrated receiver.

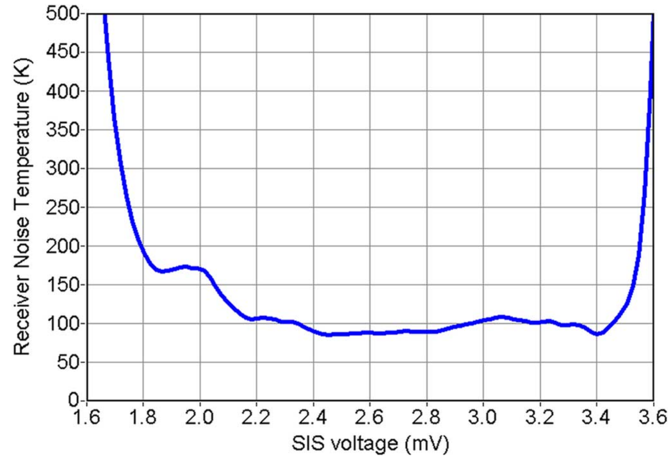

Fig. 2. Receiver noise temperature as a function of the SIS bias voltage measured at the LO frequency 507 GHz in the full 4–8 GHz IF range.

magnetic shielding is necessary because the FFO is very sensitive to external electromagnetic interference.

The Flux Flow Oscillator [3]–[6] has been proven [7], [12], [13] to be the most developed superconducting local oscillator for integration with an SIS mixer in a single-chip submm-wave SIR [1], [2], [7], [11]–[13]. 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. Thus the FFO frequency and power of emitted radiation can be tuned independently by changing control line (CL) and dc bias currents. Frequency tuning range of the whole instrument depends not only on the FFO properties, but also on design of all tuning and matching elements of the SIR; intrinsic FFO frequency range is much wider than 480–650 GHz finally realized in the flight TELIS device.

The resolution of the Digital Auto Correlator (DAC) used as 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 [3]–[6], [14].

One of the main advantages of superconducting receivers is low noise temperature of the device. The measured double sideband (DSB) receiver noise temperature T_R of the flight device, uncorrected for any loss is well below 400 K in the range of 470–630 GHz (except the noise peak around 575 GHz, which is of no concern for science observations due to a highly saturated water-vapor line at that frequency), with a minimum of 120 K at 500 and 600 GHz [7]. The noise as a function of IF is fairly flat in the frequency range 4–8 GHz [7]. The dependence of the receiver noise temperature on the SIS bias voltage is shown in Fig. 2; one can see that for Nb-AlN/NbN circuits there is a very wide range of SIS bias voltages where T_R is almost constant. Furthermore, this figure demonstrates not only T_R as low as 85 K (measured by novel IF amplifier without input isolator), but also complete suppression of the Josephson effect by the SIS integrated control line.

III. SIR Tests and Control Algorithms

A. Main Purposes of the Controlling System

As it was mentioned before, the Superconducting Integrated Receiver is a complex circuit, which contains a few mutually interacting elements (SIS, HM, FFO). The Integrated Receiver Test and CONtrol (IRTECON) [15], [16] system has been developed for thorough ground testing of all SIR elements as well as for evaluation of the whole instrument performance. All tests and flight control of the SIR channel were performed using flight measurement setup—specially built battery-operated ultra low-noise biasing system. At the next step the main operational parameters were optimized with the flight electronics and under the flight conditions. These parameters were written to the database and later on were used to control the SIR during the flight. To realize all these goals we developed effective test tools and flight algorithms for the SIR control, which include the following tasks:

)1 Preliminary tests of the device: measurements of the SIR IVCs, the FFO linewidth, the SIR noise temperature.
)2 Search of the optimal operational point for each selected frequency.
)3 Remote setting of the SIR to the optimized state; monitoring and maintaining of the SIR parameters during the flight.

For flight remote operation and controlling the SIR a special light version housekeeping software was developed. Operating algorithms were developed and tested by IRTECON, then adapted for remote operating and implemented into a flight software and hardware in form of executable scripts.

B. Optimization of the FFO Operation Point in the Fiske Step Regime

As an example let us describe the FFO tuning procedure in the Fiske step regime. At first, one should define operational range of the FFO bias and CL currents. At high current density the Fiske steps [11] do not last till the end of the I-V curve—at high currents the FFO went to chaotic (noise) oscillations regime. Presumably it related to the fact that at the end of the steps Josephson vortexes (fluxons) are moving with the speed approaching the Swihart velocity, which is the maximum velocity of fluxons in the junction. Due to Lorentz constriction fluxons become much shorter than distance between fluxons and an excitation of the internal oscillation modes in the fluxon chain becomes possible; that results in the wide-band chaotic oscillations. On the other hand, at low bias currents the differential re-

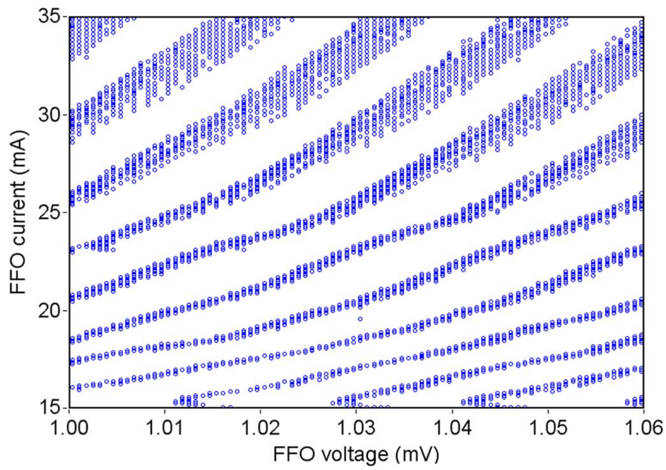

Fig. 3. Enlarged part of the FFO IVCs measured at different CL currents, measured for flight device (increment 0.1 mA), $I_b\ \mathrm{step} = 0.1\ \mathrm{mA}$.

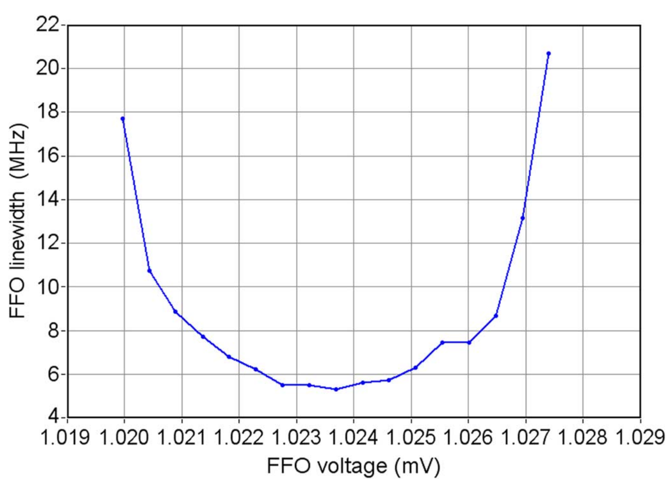

Fig. 4. Dependence of the FFO line width measured over Fiske step (FS) at $I_b = 30\ \mathrm{mA}$; importance of operation in the centre of FS is clear from this figure.

sistance R_d (and therefore the FFO linewidth) becomes higher [17]; also emitted by the FFO power might be not sufficient for pumping of the SIS junctions at low I_b.

Due to discontinuous FFO structure (see Fig. 3) there are only a few possible current ranges (usually 3–5) for each selected frequency. To realize the minimum possible linewidth and the widest operational margins, one has to set the FFO CL and the FFO bias to be in the center of the step at the maximum available bias current (corresponding to lower R_d)—see Fig. 4.

C. SIR Parameters Reproducibility and Flight Operation

The SIR is very sensitive to external electromagnetic interference and temperature variations, but specially developed shielding, novel design of the SIR itself and sophisticated operating algorithms provide stable operation of the device. Stability of all SIR parameters and reproducibility of the operating point were tested using thermal cycling in the laboratory. Perfect reproducibility of parameters gave us possibility to use in flight previously tuned and optimized operating parameters. Note that no degrading of performance for all selected devices was found after more than 2 years of tests. During the flight

Fig. 5. TELIS-MIPAS launch at Esrange, Sweden; March 2009. Balloon size: 400 000 m^3; Payload weight: 1 200 kg.

the SIR should perform extremely stable and reliable—some measurements last about an hour. The changing of the LO frequency for next measurement should be as fast as possible (about 1 min). In Fiske step region the search of the Fiske step center and full optimization lasted about 40–50 seconds; required time in the flux-flow regime was 20–25 s. Even relatively small change in temperature (due to pressure variations in the cryostat with constant pressure regulator) results in changing of the FFO operating point and requires fine tuning of the FFO. Fast changes are tracked by the PLL system; slow changes could be compensated by operator via radio link.

IV. Kiruna Campaigns and Preliminary Science Results

The TELIS had two successful scientific campaigns from Kiruna, North-Sweden in March 2009 [7] and in January 2010. The instrument was launched together with the MIPAS instrument on the MIPAS-B2 gondola (see Fig. 5). The science goals of both campaigns 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. Furthermore, validation of satellite measurements MIPAS + SCIMACHY/Envisat, MLS Aura and SMILES are carried out.

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 has been proven 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; 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 were recorded. After parachute landing and recovery the instruments were found to be undamaged, allowing for extra post-flight calibration measurements.

In the 2010 Kiruna campaign the launch pad of the balloon was just in the center of cold Arctic vortex and during the entire flight balloon stayed at this area. Such good weather conditions gave possibility to measure detailed dependence of ClO concentration to altitude and time during sunrise (see Fig. 6). One of the major achievements of the TELIS 2010 campaign is measurements of diurnal cycle of BrO with line intensity of only about

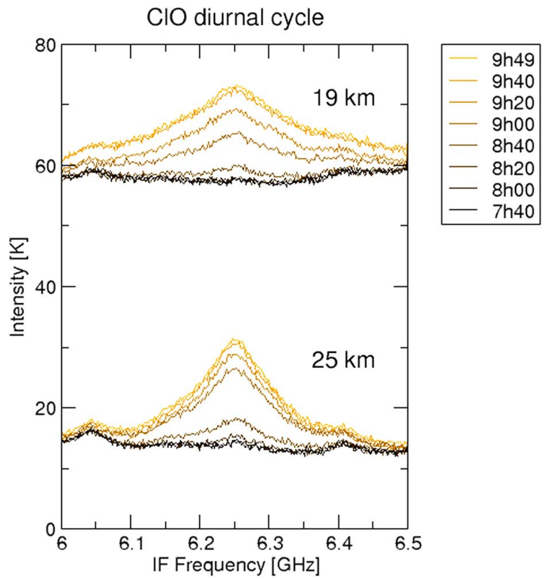

Fig. 6. Spectra measured by SIR show growth of ClO concentration after sunrise. LO frequency 495 GHz. On graph spectra for two different viewing configuration (corresponding to 19 and 25 km) are presented.

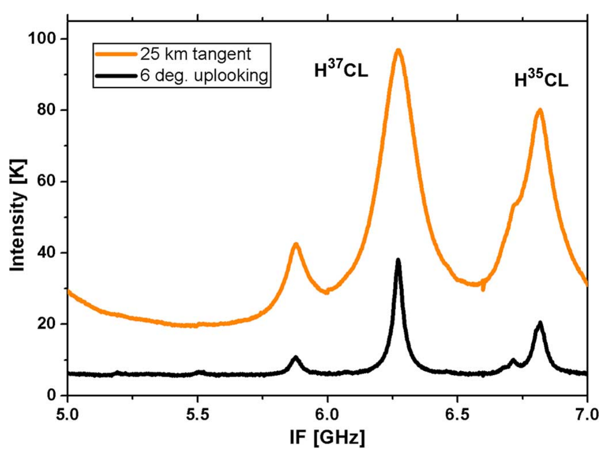

Fig. 7. Spectra of two HCl isotopes. LO frequency 619.1 GHz. On graph spectra for two different viewing configurations (corresponding to 25 km and 6 deg. uplooking) are presented.

0.3 K. In Fig. 7 spectra of two HCl isotopes are shown. Spectra were measured for two different directions corresponding to 25 km and 6 degrees up-looking.

V. Conclusion

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. To ensure remote operation of the phase-locked SIR several software procedures for automatic control have been developed and tested. Unique scientific results are obtained. The Superconducting Integrated Receiver can be considered as an operational device, ready for many applications including atmosphere monitoring, medical and security survey.

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