Superconducting Submm Integrated Receiver for TELIS

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Abstract. In this report we present design and first experimental results for development of the submm superconducting integrated receiver spectrometer for Terahertz Limb Sounder (TELIS). TELIS is a collaborative European project to build up a three-channel heterodyne balloon-based spectrometer for measuring a variety of atmospheric constituents of the stratosphere. The 550 - 650 GHz channel of TELIS is based on a phase-locked Superconducting Integrated Receiver (SIR). SIR is an on-chip combination of a low-noise Superconductor-Insulator-Superconductor (SIS) mixer with quasioptical antenna, a superconducting Flux Flow Oscillator (FFO) acting as Local Oscillator (LO), and SIS harmonic mixer (HM) for FFO phase locking. A number of new solutions were implemented in the new generation of SIR chips. To achieve the wide-band performance of the spectrometer, a side-feed twin-SIS mixer and balanced SIS mixer with 0.8 μm^2 junctions integrated with a double-dipole (or double-slot) antenna is used. An improved design of the FFO for TELIS has been developed and optimized providing a free-running linewidth between 10 and 2 MHz in the frequency range 500 – 700 GHz. It is important to ensure that tuning of a phase-locked (PL) SIR can be performed remotely by telecommand. For this purpose a number of approaches for the PL SIR automatic computer control have been developed. All receiver components (including input optical elements and Martin-Puplett polarization rotating interferometer for single side band operation) will be mounted on a single 4.2 K plate inside a 240x180x80 mm^3 box. First measurements give an uncorrected double side band (DSB) noise temperature below 250 K measured with the phase-locked FFO; more detailed results are presented at the conference.

1. Introduction

TELIS (Terahertz and submm Limb Sounder) [1] is a collaborative European project that combines three independent receiver channels, selected to yield maximum science output and to provide the most complete map of atmospheric species ever measured from one platform. The channels sharing the same front-end optics are located inside one helium-cooled cryostat and operate at 500 GHz, 550–650 GHz and at 1.8 THz. TELIS will provide measurement of atmospheric constituents including OH, O_3, N_2O, CO, HCl, HOCl, ClO, and BrO that are associated with the depletion of atmospheric ozone and climate change. In addition, TELIS will serve as a test bed for a number of novel technologies in the field of low-noise cryogenic heterodyne detection. The first flight is foreseen in 2006.

The 550 - 650 GHz channel is based on a phase-locked Superconducting Integrated Receiver (SIR) [2]. SIR is an on-chip combination of a low-noise SIS mixer with quasioptical antenna, a superconducting Flux Flow Oscillator (FFO) [3] acting as a Local Oscillator (LO) and an SIS harmonic mixer (HM) for FFO phase locking. The velocity and density of the fluxons and thus the power and frequency of the FFO may be adjusted independently by joint action of bias current and magnetic field. The concept of SIR [2] looks very attractive for TELIS due to a wide tuning range of the FFO. Presently, the frequency range of most practical heterodyne receivers is limited by the tunability of the local oscillator (LO). For a solid-state multiplier chain the fractional input bandwidth typically does not exceed 10-15 %. In the SIR the bandwidth is basically determined by an 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. There is a number of important issues that have to be addressed to SIR design and its operation [4 –6]. First of all it is a challenge to realize the ultimate performance of separate superconducting elements after their integration in a single-chip device. Also it is important to ensure that operation and tuning of a phase-locked (PL) SIR can be provided distantly. The knowledge of exact parameter values of the frequency locked (FL) and phase-locked (PL) FFO is required for correct retrieval procedure.

2. SIR design

The SIR microcircuit (size of 4 mm*4 mm*0.5 mm) is fabricated from a high quality Nb-AlOx-Nb tri-layer on a Si substrate. The FFO is connected to the double-dipole or double-slot antenna/mixer with a microstrip transmission line, which contains a number of rf-coupling and dc-blocking elements. Both the SIS mixer and FFO are provided with local magnetic fields via integrated control lines. The receiver chip is placed on the flat back surface of the elliptical silicon lens. A quarter-wave back reflector chip is installed at the double-dipole antenna to obtain a beam of high efficiency and good symmetry. To achieve the required instantaneous bandwidth of 550-650 GHz a side-feed twin-SIS mixer with 0.8 μm^2 junctions is implemented. Microphotograph of the central part of the SIR chip with double dipole antenna is presented in figure 1.

One of the constraints implied by SIR is a requirement to place the receiver chip inside cylindrical magnetic shield, since FFO is very sensitive for the external interferences. The magnetic shield consists of two coaxial cans. The external layer is made from cryo-perm and the internal one is copper covered with 100 μm of superconducting led. The SIR chip is positioned far enough from the opening of the shielding cans, which is the only aperture for entering the signal beam and all electrical connections. The magnetic shield is 90 mm long and has an inner clear aperture of 25 mm. Thus the integrated lens-antenna configuration should be compatible with large f-number optics. This is realized by using an elliptical lens and locating the feed antenna at the more distant focus of the ellipse. The lens diameter of 10 mm is selected by optimizing for the minimum beam size at 100 mm from the integrated lens-antenna at 550-650 GHz, so that the shielding cylinder does not truncate the beam. To minimize the reflection loss at the lens-air interface, the curved surface of the lens is coated with a 74 micron thick Stycast antireflection coating, optimized for the center frequency 600 GHz.

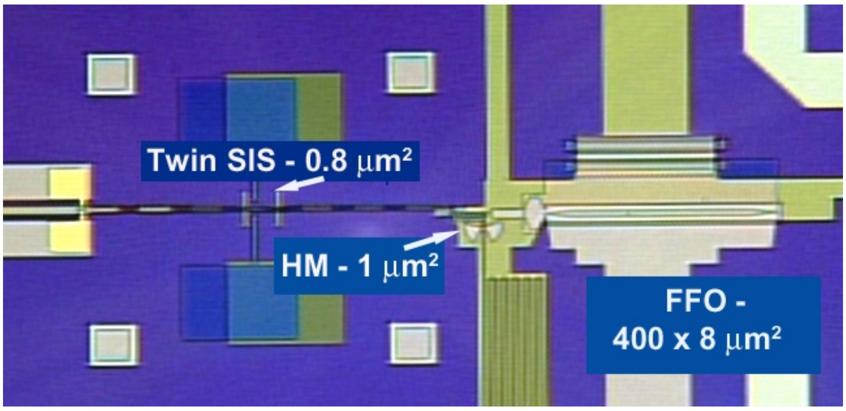

Figure 1. Central part of the SIR chip with double-dipole antenna, twin SIS-mixer and harmonic mixer for FFO phase locking.

SIR shall detect atmospheric lines with a spectral resolution of the order 5 MHz. To achieve this resolution, FFO is locked to an external reference oscillator using Phase Lock Loop (PLL) system. FFO is used as a 550-650 GHz LO for the SIS mixer. A small fraction of the FFO power is also directed towards the integrated on the same chip HM (see figure 1). The latter mixes the FFO with the n-th harmonic of the 19-21 GHz reference. The mixing product at 4 GHz is amplified by a cryogenic HEMT amplifier. In the PLL the mixing product is downconverted to 400 MHz, and its frequency and phase are compared with the reference 400 MHz. Finally, the phase difference signal generated by the PLL is used as a feedback to the FFO control line current to compensate for the phase error. To realize FFO phase-locking regulation bandwidth of the PLL system has to exceed FFO free-running linewidth. To obtain required PLL wideband operation (well above 10 MHz) a computer controlled PLL system has been developed by Institute for Physics of Microstructure (IPM), Nizhny Novgorod, Russia; this PLL system resides right outside the cryostat to minimize the total loop length.

3. Experimental results

The SIR microcircuits of the described above design have been tested as a receiver [4, 6] showing for the first time a possibility to realize the PL SIR concept at frequencies above the boundary [2, 5] where the FFO operates in a real Flux-Flow regime and continuous frequency tuning is possible (this boundary is about 450 GHz for Nb-AlOx-Nb tunnel junctions). Optimization of the FFO-SIS and FFO-HM matching circuits and implementation of submicron junctions for both mixers improved pumping of SIS and HM by the FFO. Both mixers have enough FFO power for optimum operation in the frequency range 500-650 GHz.

The SIR chip is mounted in a “flight” mixer block surrounded by an anti-magnetic shield. No other optical elements of the TELIS cold channel were installed for these measurements. Noise temperature measurements are done using the Y-factor technique by chopping between hot (295 K) and cold (80 K) loads in the signal path of the receiver. The IF response of the mixer is amplified by a “flight” IF chain configuration. It consists of a cryogenic InP based 4-8 GHz low noise amplifier (LNA) followed by a RT amplifier. The signal is detected by a fast power meter in a 40 MHz bandwidth, selected by a tunable YIG filter. Such procedure (for all frequencies of interest) takes usually about 20 minutes for a fixed SIS-mixer bias voltage. From these data the DSB receiver noise temperature can be calculated (see figure 2). It was also possible to optimize the bias voltage of the SIS mixer for each FFO bias point; in this case a complete scan requires 2-3 hours. We have also used the PLL system in “flight” configuration and were able to lock the FFO practically at any frequency in the 550-650 GHz range. The best noise performance of all tested SIRs does not completely satisfy TELIS specifications yet. It is obviously a challenge to optimize the performance of three interdependent superconducting elements on one chip in such wide frequency range. Further development of SIR microstrip coupling circuitry and experimental tests of different chip configurations are in progress.

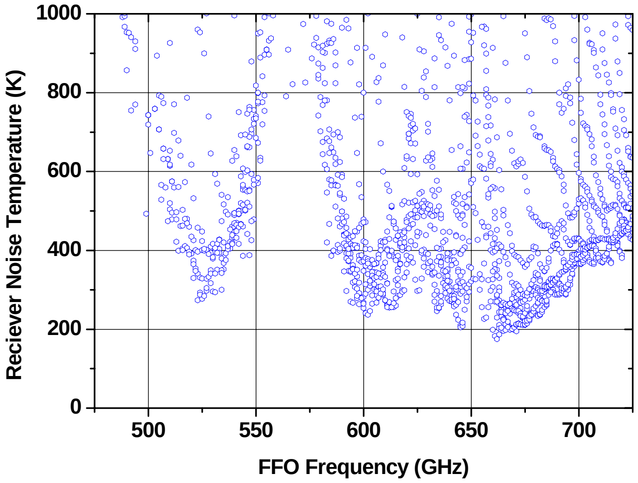

Figure 2. Uncorrected DSB noise temperature of the SIR as a function of FFO frequency measured at different FFO bias currents that results in various SIS pumping levels (T_{BATH} = 2.1 K, V_{SIS} = 2.2 mV, IF = 4.3 GHz).

3.1. Remote optimization of the PL SIR operation

It is important to ensure that tuning of a phase-locked SIR can be provided distantly. Equally important is to determine in flight the main parameters of the FFO at specific bias conditions (without complicated spectrum measurements). The knowledge of such parameters as “free-running” linewidth (FRL) for the frequency locked FFO and spectral ratio (SR) for the phase-locked FFO are required for correct retrieval of trace gas profiles. It was shown [5] that the SR value for the given PLL system is determined by the free-running FFO linewidth: these two quantities are unambiguously related. To adjust in flight the PL FFO operation (and to determine the resulted SR of the PL FFO) a computer controlled PLL system with a specially designed monitoring channel “IF level output” has been developed by IPM. The dc signal at this output of the PLL system is proportional to the PL FFO spectral ratio [4]; furthermore, the constant of proportionality does not depend on FFO bias current and is the same for FFOs of quite different design. It means that SR can be determined in flight.

Dedicated software (IRTECON) controls the SIR electronics and PLL settings, allowing automatic optimization and remote operation of the phase locked SIR. It is possible to optimize the HM tuning by monitoring the “IF level output” in the PL regime while the HM bias voltage and/or the synthesizer power are being adjusted. As it was shown in [4, 5] there is a number of closely spaced local maximums on this 3-D plot. The height of these maximums is almost equal in quite a large range of parameters, so any of these peaks can be used for PL SIR operation. Because the “valleys” between peaks are quite deep precise tuning of the parameters (HM bias voltage, synthesizer power) is required as phase locking can be lost. With reduced synthesizer power delivered to the HM the spacing between the peaks becomes twice as small compared to optimal. This corresponds to a transition from the quasiparticle to Josephson regime of HM operation. Since there is no significant difference between these regimes [4], low synthesizer power is used for the present PL SIR measurements to minimize cross talk between pumped HM and SIS-mixer. Thus it seems that fine-tuning of HM regimes may be accomplished during the flight remotely by simple algorithms. It is important that phase locking can be automatically restored if the HM is adjusted to one of the optimal peaks.

Acknowledgments

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