Superconducting Integrated Receiver for TELIS

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Abstract— **TELIS (Terahertz and submm Limb Sounder) is a cooperative European project to develop a three-channel heterodyne balloon-based spectrometer for measuring a variety of atmospheric constituents within the lower stratosphere. The 600 - 650 GHz channel is based on a phase-locked Superconducting Integrated Receiver (SIR). SIR is the on-chip combination of a low-noise SIS mixer with quasioptical antenna, a superconducting Flux Flow Oscillator (FFO) acting as Local Oscillator (LO) and an SIS harmonic mixer (HM) for FFO phase locking. A number of new solutions was implemented in the new generation of SIR chips. To achieve the wide-band performance of the spectrometer, a side-feed twin-SIS mixer with 0.8 μm² junctions integrated with a double-dipole (or double-slot) antenna is used. A Fourier transform spectrometer (FTS) test demonstrated a possibility to obtain the required instantaneous bandwidth for the SIS mixer. To ensure the autonomous operation of the phase-locked SIR on the balloon a number of approaches for the PLL SIR automatic control have been developed.**

Index Terms—**Submillimeter wave integrated receivers, phase-locked oscillators, superconducting devices.**

I. Introduction

TELIS (Terahertz and submm Limb Sounder) [1] contains three independent receiver channels, selected to yield the maximum science output and to provide the most complete map of atmospheric species ever measured from one platform. The channels with the common front-end optics are located inside one helium-cooled cryostat and operate at 500 GHz, 600–650 GHz and at 1.8 THz. These channels employ correspondingly a superconductor-insulator-superconductor (SIS) mixer, a Superconducting Integrated Receiver (SIR) and a hot electron bolometer (HEB) mixer. Inside the cryostat each of the receivers has dedicated cold optics and intermediate frequency (IF) amplifier. All three channels will be operated simultaneously providing IF signals for digital auto correlators (two of 2 GHz and one of 4 GHz bandwidth). 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 concept of SIR [2] looks very attractive for TELIS due to a wide tuning range of the FFO [3]. 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. In the baseline of TELIS concept the SIR channel will operate from 600 to 650 GHz, eventually aiming at a larger coverage, 500 to 650 GHz. The goal is to achieve the single side band receiver noise temperature below 400 K within this band.

II. SIR Channel Design

A key element of the 650 GHz channel is an SIR [2], [4] that comprises in one chip (size of 4 mm*4 mm*0.5 mm) a low-noise SIS mixer with quasioptical antenna and a superconducting Flux Flow Oscillator (FFO) acting as an LO [5], [6], [7]. The FFO is a long Josephson tunnel junction in which an applied dc magnetic field and a bias current drive a unidirectional flow of fluxons. The velocity and density of the fluxons and thus the power and frequency of the emitted signal may be adjusted independently by joint action of bias current and magnetic field. The SIR microcircuits for quasioptical mixers are 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. To reduce the magnetic field interference to the FFO, a folded control line feeder of the SIS mixer is placed opposite to the FFO, resulting in a 10^{-3} suppression coefficient.

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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 500-650 GHz with emphasis on 600-650 GHz frequency range, a side-feed twin-SIS mixer with 0.8 μm^2 junctions is implemented.

The input signal is fed to the receiver through the IR filter and passes through a Single Side-Band (SSB) filter based on Martin-Puplett polarization rotating interferometer. The unwanted sideband of the mixer is reflected by two wire grids and terminated by a 4.2 K cold load. In order to reduce external magnetic interference to the sensitive FFO, the mixer block is shielded by two coaxial cans. The external can is made of cryo-perm and the internal one is of copper covered with 100 µm of superconducting lead. 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. All receiver components will be mounted on a single 4.2 K plate. The complete SIR receiver with a size of 240x180x80 mm^3 will be pre-aligned and fully tested before mounting into a TELIS system.

Initially FFO is not a very stable frequency source with typical intrinsic free-running linewidth of a few MHz, thereby limiting the ultimate spectral resolution of the receiver. However, the FFO is a voltage-controlled oscillator and its frequency can be stabilized by locking it to an external reference oscillator using a Phase-Lock Loop (PLL) system [5], [6], [7]. Two concepts of PLL SIR are implemented in the current design of the spectrometer and SIR chip itself. In the first (the simplest) approach a submm-wave signal from an external harmonic generator (HG), driven by a 19-21 GHz synthesizer, can be applied directly to the receiving mixer. The intermediate frequency of the mixer is then amplified by a wideband, 4-8 GHz, low-noise cryogenic HEMT amplifier ("SIR IF amplifier"). A small part of the IF band at 4 GHz is used to monitor the mixing product between the n-th harmonic of the synthesizer signal and the FFO signal. This down-converted signal, after narrow-band filtering, controls the phase-locking loop (PLL) system while the rest of the IF band is used to analyze the down converted "sky" signal. In a second approach the chip receiver contains an additional harmonic mixer (HM), which is used to mix a part of the FFO signal with the n-th harmonic of the synthesizer. In this case one more IF amplifier ("PLL IF amplifier") is needed. In both concepts the 4 GHz PLL signal is then down converted to 400 MHz in a PLL system. In the PLL the frequency and phase of the mixing product are compared with the reference 400 MHz. Finally, the PLL generates feedback current added to FFO control line (providing magnetic field for FFO) to compensate for the phase error. The PLL electronics is placed close to the cryostat to minimize the total PLL loop length.

4-8 GHz cryogenic HEMT low noise amplifiers (LNA) are developed by "Iceberg" (Kyiv, Ukraine) in a framework of TELIS project. LNA has two stages and is based on InP transistors. Flight model amplifiers are integrated with Pamtech isolators. Figure 1 shows the measured gain and noise temperature of the amplifier at 4.5 K bath temperature. Noise performance of cryogenic amplifiers was tested using Y-factor technique with a 50 Ω load at the amplifier input. Temperature of the load was varied in a range from 6.5 to 15 K. An output was further amplified by a room temperature TELIS amplifier (total gain 67 dB, $T_N < 150$ K) and registered by a spectrum analyzer. Both gain and noise of the LNA were measured at a bath temperature of 4.5 K during one cooling cycle using a cryogenic switch to connect LNA to either external signal for gain measurements or internal 50 Ohm load for noise measurements. Gain is corrected for the loss in the dewar cables; noise temperature is corrected only for the 0.2 dB cable loss.

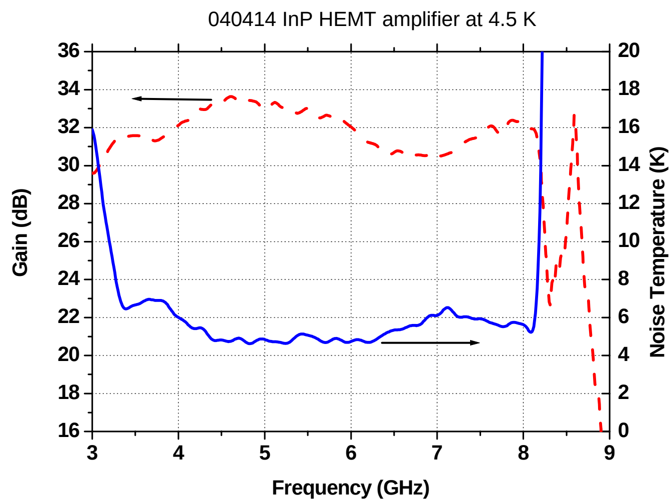

Fig. 1. Gain and noise of the LNA #040414 measured at 4.5 K. Power consumption of the InP LNA is of about 5–7 mW A peak in the noise temperature at 7 GHz corresponds to the extra loss measured in the isolator

III. Experimental Results

A. DC and FTS Tests of the SIR Microcircuits

A few batches of Nb-AlOx-Nb receivers were produced in IREE and preliminary tested at SRON. By extensive DC tests several chips with "good" dc IVC of SIS junctions and FFO and sufficient HM pump in the required band were selected for further FTS and noise temperature measurements. As it is seen from Fig. 2a, the integrated FFO provides enough power to the SIS mixer and harmonic mixer in the TELIS-specified frequency range (for the SIS-mixer the optimal normalized pump level is of about 0.2). It was shown [8] that for efficient operation of the PLL system the HM pumping above 5 µA is sufficient (that corresponds to the normalized level 0.03 in the graph). The FTS test results presented in Fig. 2b demonstrate a possibility to obtain the required instantaneous bandwidth for the twin SIS mixer. The thorough heterodyne experiment is under preparation; preliminary tests give the uncorrected double side band (DSB) noise temperature of about 200 K measured with FFO phase-locked at 667 GHz.

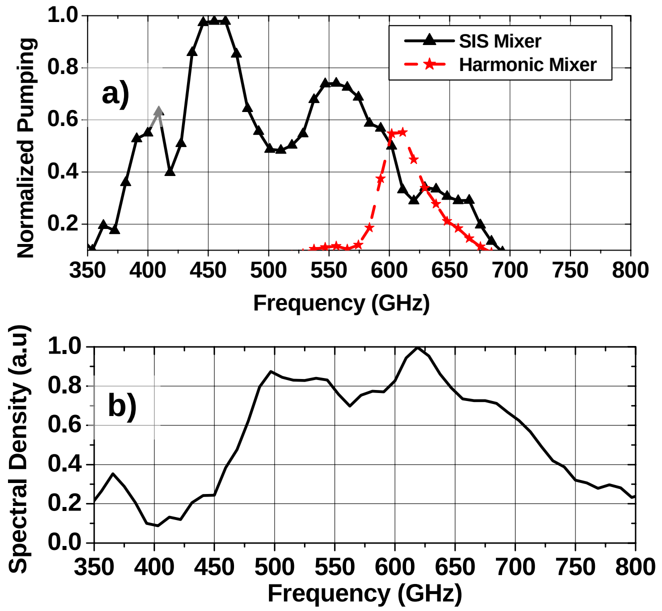

Fig. 2. Frequency characteristics of new SIR chip: a) Pumping current of SIS and HM at a certain frequency normalized at the current rise at the gap voltage for SIS and HM accordingly (Ig SIS = 100 μA, Ig HM = 172 μA).
b) FTS data of the double-dipole twin SIS mixer. A dip at 560 GHz corresponds to absorption line of water.

B. *Remote optimization of the PLL SIR operation*

It is important to ensure that a tuning of a phase-locked (PL) SIR can be provided distantly. For this purpose a computer controlled PLL system with a specially designed output has been developed. The dc signal at the "IF level output" is proportional to power measured by detector with 0.8 MHz band-pass filter at 400 MHz. It is possible to optimize the HM tuning by monitoring the "IF level output" in the PL regime while the HM bias voltage or the synthesizer power are being adjusted (see Fig. 3). It's clear from Fig. 3 that there is a number of closely spaced local maximums. 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. On the other hand the "valleys" between picks are quite deep and precise tuning of the parameters (HM bias voltage, synthesizer power) is required. The most favorable region of the parameters is around zero voltage at HM and synthesizer power about +13 dBm (note that power delivered to HM is about 1 μW). At lower values of synthesizer power (≤ 10dBm) the spacing between peaks became twice as small as compared to optimal – this corresponds to crossover from the quasiparticle to Josephson mode of HM operation.

As a matter of fact, no significant difference between these two regimes has been found at proper settings of the synthesizer power: almost the same signal to noise ratio (SNR) and Spectral Ratio (SR - the ratio between power of the carrier and total FFO power) can be realized. From Fig. 3 one can see that the tuning of the single-junction HM is quite smooth both for HM bias voltage and synthesizer power; tuning by the PLL gain level is even smoother. Note that all dependences are very well reproducible.

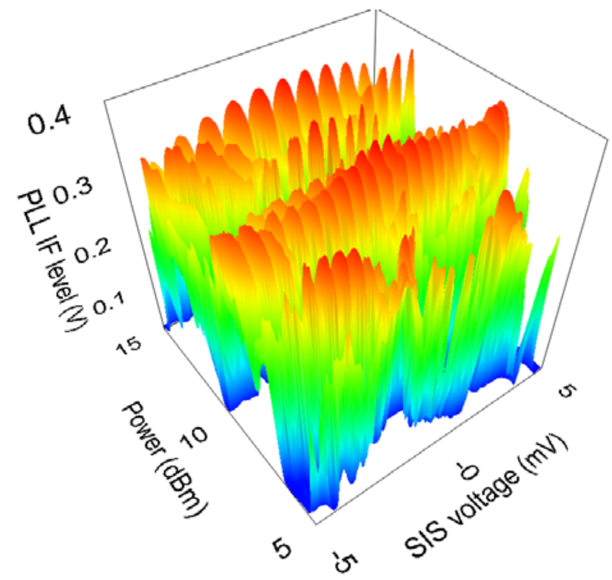

Fig. 3. 3-D diagram for HM operational parameters measured by PC controlled PLL. The level of IF-out PLL signal is represented by color scale; note that normal PL operation is possible at IF levels larger than 250 mV.

It is also important to determine the quality of FFO phase locking (SR value at the selected frequency [8]) distantly without complicated spectrum measurements. To realize this possibility mentioned above "IF level output" of the PLL system can be used. The DC signal at this output is proportional to the PL FFO spectral ratio (see Fig. 4), providing that the power level is kept constant. Furthermore, the constant of proportionality does not depend on FFO bias current and is the same for FFOs of quite different design (see Fig. 4). In a flight version of the PLL system the bandwidth of the BPF before the detector will be switchable; this provides a possibility of keeping the IF power level constant. 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 regime can be automatically restored if the HM mode is adjusted to one of the optimal peaks.

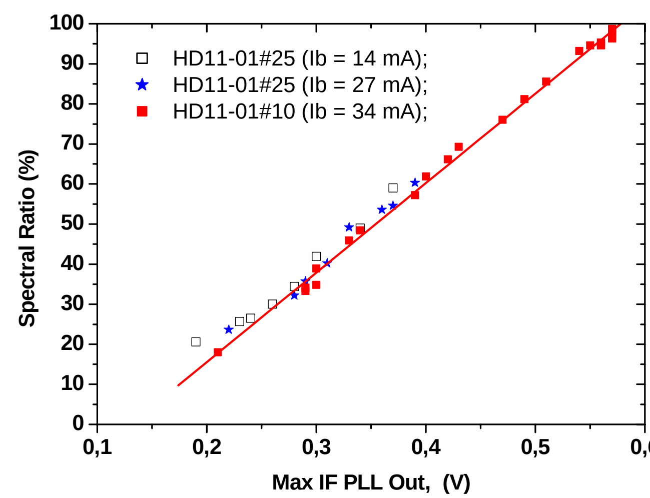

Fig. 4. Spectral ratio of the PL FFO on IF level output of the PLL system measured for the FFOs of different design.

C. *Reconstruction of the Complicated Line Profile*

Spectral ratio of the FFO obviously determines the quality of the output signal. We have made estimations of errors due to non-ideal shape of the phase-locked FFO line (Fig. 5a). As a signal we took computer-simulated spectrum of one of HCl lines at a very low pressure of 0.1 mbar (Fig. 5b) and as a local oscillator (LO) signal we took experimental FFO spectra with different autonomous linewidth. Assuming linear multiplication in the mixer and taking into account "Convolution Theorem" (saying that Fourier transform of a convolution gives a product of Fourier transforms of initial functions) we calculated the spectra of the output signal for different LO signals and compared them to the initial spectrum (Fig. 6). One can see how output signal quality degrades with the increase of initial FFO linewidth. Zero noise level outside the signal bandwidth causes steep slopes on the side peaks. This slightly increases error on the "boundaries" of the signal.

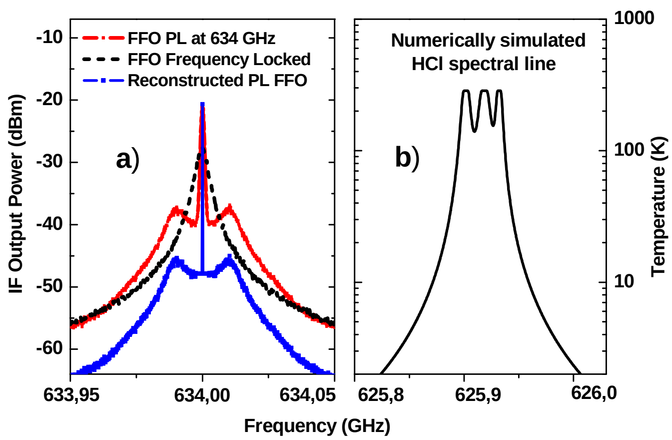

Fig. 5. a) Spectra of the phase-locked and frequency locked FFO; reconstructed spectra: of the PL FFO used for calculations is also shown.
b) Computer-simulated spectrum of one of HCl lines.

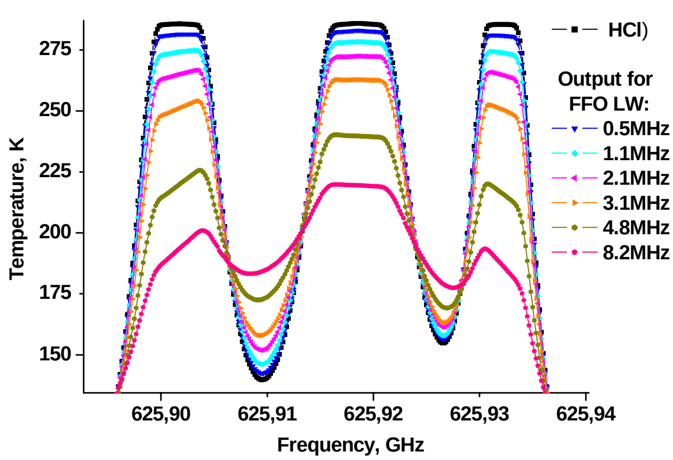

Fig. 6. The form of the output spectra at conversion of the HCl line for phase locked FFO with various free-running linewidth compared to the "ideal" spectrum (when LO spectrum is a δ-function).

Relative error for phase locked and frequency locked FFO as a function of free-running FFO is shown in Fig. 7. Note that free-running FFO linewidth and SR are unambiguously related [8]. From Fig. 7 one can see that free-running linewidth below 1 MHz is required for discrepancies below 1% and 2.5 MHz is the upper limit for 10% error. In case of adjacent narrow peaks it's impossible to discern them with FL FFO, while phase locking allows to see the peaks. Thus FFO phase locking is necessary while free running linewidth exceeds the desired spectral resolution of the device. Since atmospheric lines to be measured by TELIS (altitudes < 40km) are pressure broadened they can be measured with required accuracy by already developed FFO with free-running linewidth below 10 MHz.

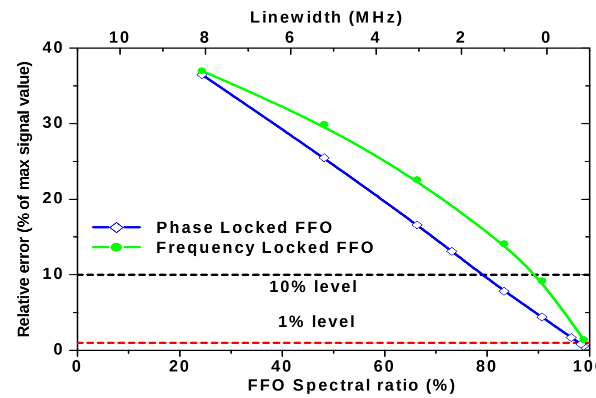

Fig. 7. Relative error of conversion of the HCl line for phase locked and frequency locked FFO. Appropriate linewidth scale is given at the top.

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