

Superconducting Submm Integrated Receiver with Phase-Locked Flux-Flow Oscillator for TELIS

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Abstract—We present results of a single-chip superconducting integrated receiver development for the Terahertz Limb Sounder (TELIS) balloon project. TELIS is a collaborative European project to build a three-channel heterodyne balloon-based spectrometer for measuring a variety of the stratosphere constituents. The Superconducting Integrated Receiver (SIR) comprises in one chip a planar antenna integrated with a superconductor-insulator-superconductor (SIS) mixer, a superconducting Flux Flow Oscillator (FFO) acting as Local Oscillator (LO) and a second SIS harmonic mixer (HM) for FFO phase locking. An improved design of the FFO for TELIS has been developed and optimized. A free-running linewidth between 9 and 2 MHz has been measured in the frequency range 500 – 710 GHz. As a result the spectral ratio of the phased-locked FFO varies from 35 to 90 % correspondingly, ensuring that at least half of the phase-locked FFO power in the primary frequency range for TELIS (550-650 GHz). The FFO performance required for successful TELIS operation is discussed. New generation of the SIR for TELIS with improved FFO performance has been developed and preliminary tested. 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. Preliminary measurements give an uncorrected double side band (DSB) noise temperature of about 200 K measured at 2.1 K with the FFO phase-locked at 660 GHz. The effect of FFO linewidth imperfections on retrieval procedure is discussed.

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

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I. 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. 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 FFO is a long Josephson tunnel junction with a unidirectional flow of fluxons caused by applied dc magnetic field and bias current. The velocity and density of the fluxons and thus the power and frequency of the emitted signal may be adjusted independently by tuning bias current and magnetic field. The SIR microcircuits are fabricated from a high quality Nb-AlO_x-Nb tri-layer on a Si substrate. The FFO is connected to a 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 the FFO are provided with local magnetic fields via integrated control lines.

In order to obtain frequency resolution required for practical application of a heterodyne spectrometer (of at least one part per million) an integrated local oscillator (LO) must be phase-locked to an external reference. To achieve this goal a concept of the integrated receiver with phase-locked loop (PLL) has been developed [4] and experimentally proven. Following this concept a 350 GHz single-chip receiver has been designed, fabricated and successfully tested [5], [6], showing the frequency resolution of the receiver as good as 10 kHz. The effect of SO₂ gas spectral line broadening as measured by this spectrometer for a laboratory gas cell demonstrated the feasibility of such device for practical applications [6], although this SIR could operate only at almost fixed frequencies on Fiske steps.

There is a number of important issues that have to be addressed to SIR design and its operation. 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. The last issue is related to the fact that FFO linewidth has Lorentzian shape both at higher voltages on the flux flow step (FFS) [5] and at lower voltages in the resonant regime on the Fiske steps (FS's) [7]. It means that the free-running ("natural") FFO linewidth in all operational regimes is determined by the wideband thermal fluctuations and the shot noise. This is different from most of traditional microwave oscillators where the "natural" linewidth is very small and the observed linewidth can be attributed mainly to external fluctuations. All these issues will be discussed in this report.

II. SIR DESIGN AND RESULTS OF THE FIRST RF TESTS

A key element of the 650 GHz channel is the SIR [2] that comprises in one chip (size of 4 mm*4 mm*0.5 mm) a low-noise SIS mixer with quasioptical antenna (double dipole or double slot) and a superconducting Flux Flow Oscillator (FFO) acting as LO. The receiver chip is placed on the flat back surface of the elliptical silicon lens. A quarter-wave back reflector chip is installed behind the double-dipole antenna to obtain a beam of high efficiency and good symmetry. To achieve the required instantaneous bandwidth of 550-650 GHz with emphasis on 600-650 GHz frequency range, a side-feed twin-SIS mixer with $0.8 \mu\text{m}^2$ junctions is implemented. Microphotograph of the central part of the SIR chip with double dipole antenna is presented in Fig. 1.

The SIR microcircuits of this design have been preliminary tested as a receiver [8] showing at the first time a possibility to realize the PL SIR concept at high frequencies above boundary [9] where FFO operates in a real Flux-Flow regime and continuous frequency tuning is possible (this boundary is of about 450 GHz for Nb-AlO_x-Nb tunnel junctions).

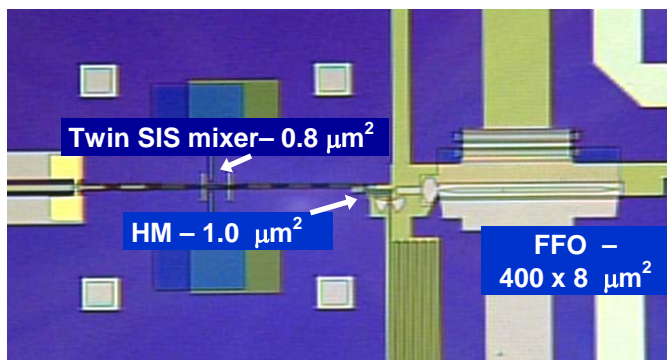


Fig. 1. Central part of the SIR chip with double-dipole antenna, twin SIS-mixer and harmonic mixer for FFO phase locking.

It was also found that due to insufficient coupling between FFO and SIS/HM the SIR phase-locking is possible only at some specific frequencies. For example, results presented in Fig. 2 - 4 have been measured at bath temperature of 2.1 K. In this case a reasonably good pumping for both SIS and HM was realized at FFO frequencies from 500 to 680 GHz. It was impossible to get a good pumping of the SIS mixer at bath temperature of 4.2 K at 670 GHz, where the best sensitivity was measured by FTS. The reason is losses in the SIR microstrip lines at frequencies close to the gap value of Nb (note that temperature of the SIR chip is usually a little higher than that of the bath).

Dependence of the experimentally measured Y-factor on the FFO frequency and FFO bias current is shown in Fig. 2. The data were measured by specially developed data acquisition system for Integrated Receiver TEST and CONTROL (IRTECON) [9]. We used a rotating hot/cold load chopper (frequency of about 11 Hz), tunable IF YIG filter (bandwidth of about 40 MHz) and fast power meter. Such procedure (for all frequencies of interest) takes usually of about 20 minutes for fixed SIS-mixer bias voltage (2.2 mV for data shown in Fig. 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. From the data presented in Fig. 2 DSB receiver noise temperature can be re-calculated (see Fig. 3). Note that there is a wide range of the FFO bias currents (i.e. FFO power) where Y-factor is close to maximum; it makes possible the selection of optimal conditions for HM operation.

To investigate frequency resolution of the receiver we have measured the signal of the synthesizer multiplied by superlattice structure developed by D. Paveliev from University of Nizhny Novgorod (see report at this conference). The results of these measurements are presented in Fig. 4; one can see that recorded signal is a convolution of the delta-function provided by synthesizer with phase-locked spectra of the FFO.

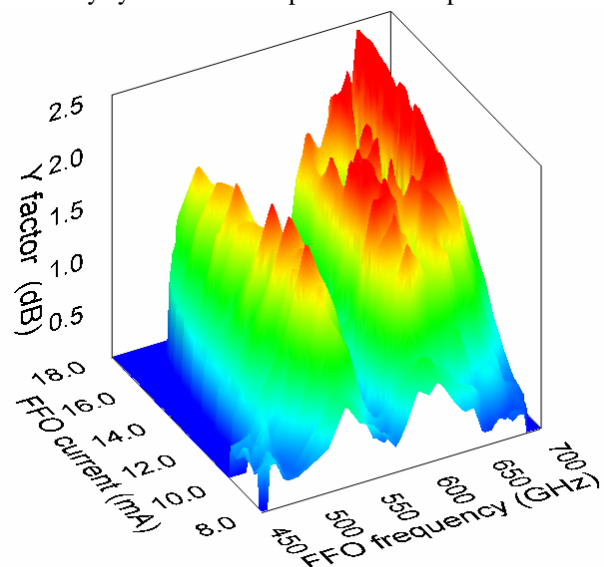


Fig. 2. Y-factor of the SIR as a function of FFO frequency and FFO bias current ($T = 2.1$ K, $V_{\text{SIS}} = 2.2$ mV, $IF = 4.3$ GHz).

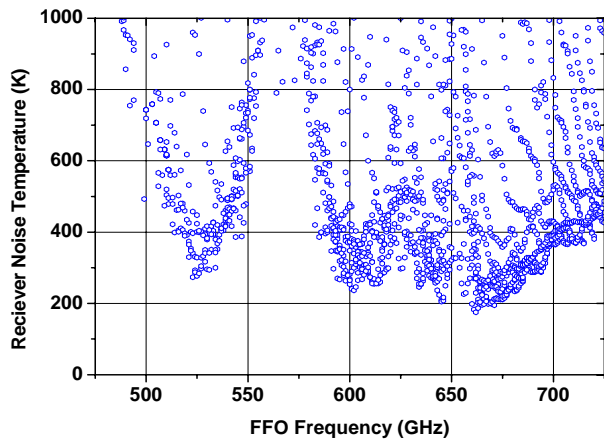


Fig. 3. Uncorrected DSB noise temperature of the SIR as a function of FFO frequency measured at different FFO bias currents that results in various SIS pumping level ($T_{BATH} = 2.1$ K, $V_{SIS} = 2.2$ mV, IF = 4.3 GHz).

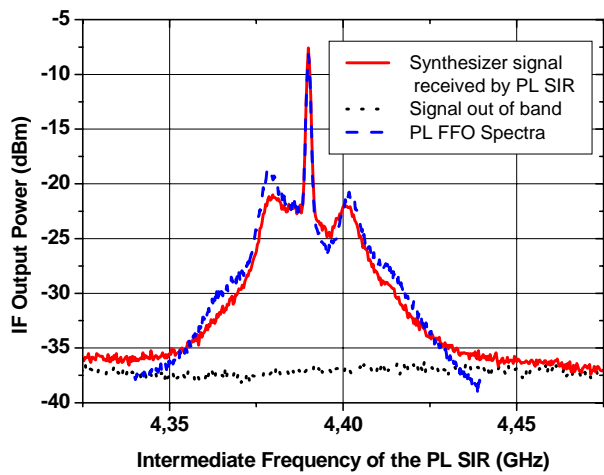


Fig. 4. Signal of multiplier driven by synthesizer (17.967 GHz \times $37 = 664.8$ GHz), measured by TELIS SIR with FFO phase-locked at 660.4 GHz – solid line. For the trace shown by dotted line the signal of the synthesizer is shifted by 5 MHz to be out of IF band. Dashed line – spectrum of the PL FFO, measured at HM IF output and frequency translated.

For the first SIR designs it was impossible to realize a PL SIR operation in the whole TELIS frequency range mainly because of two important problems: 1) insufficient pumping of the SIS-mixer and/or the HM at some frequencies; 2) influence of the 22-24 GHz synthesizer power, applied to HM on the SIS-mixer operation. The high harmonics (up to 30th) of the synthesizer is mixed in the HM with FFO signal and down-converted signal is used by the PLL system to stabilize FFO frequency. The synthesizer power required for HM operation is rather high; at some frequencies a part of that power “leaked” to the SIS-mixer that resulted in smearing of the SIS IVC and considerable deterioration of the SIR performance. To overcome these problems a new design of SIR microcircuit has been developed. The main features of the new design are: novel construction of the matching elements, decreased (submicron) area of SIS and HM junctions, etc. Results of the tests of these microcircuits at DC are presented below.

III. DC TESTS OF THE TELIS SIR OF THE NEW DESIGN

There is a number of important requirements for the FFO properties to make it suitable for application in the phase-locked SIR. Obviously an 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 SIS mixer, introduced to avoid leakage of the input signal to the LO path. Implementation of the improved matching circuits and submicron junctions both for SIS and HM allows to deliver enough FFO power for the optimal operation of these devices (see Fig. 5 – 7, where an SIS-mixer pumping is illustrated; that is the most important for low noise SIR operation). Note that the 22-24 GHz synthesizer provides pumping for HM while FFO power is a signal that should be down-converted, so even moderate HM pumping by FFO (5-10 % of the HM I_g , where I_g is a current jump at the gap voltage V_g) is enough [10] to ensure large enough signal to noise ratio (SNR) at the IF output and consequently efficient FFO phase locking.

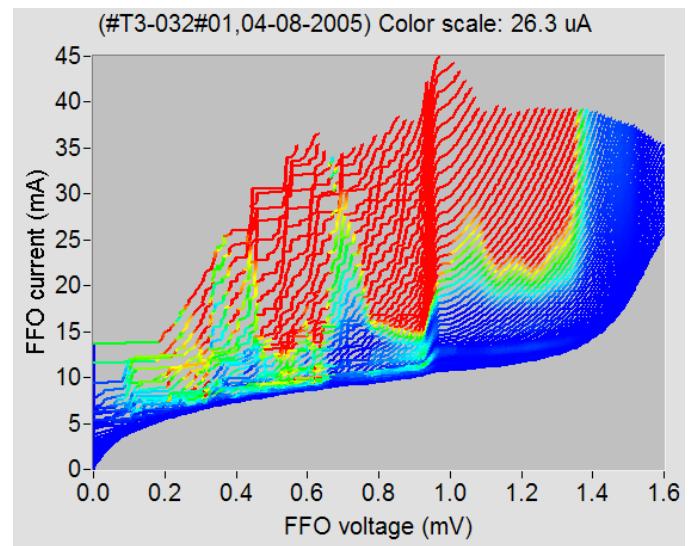


Fig. 5. IVCs of the FFO of T3 design measured at different CL currents; the pumping of the SIS-mixer is shown by color scale (red color corresponds to pumping level $> 25\%$ of SIS I_g), see Fig. 8, 9.

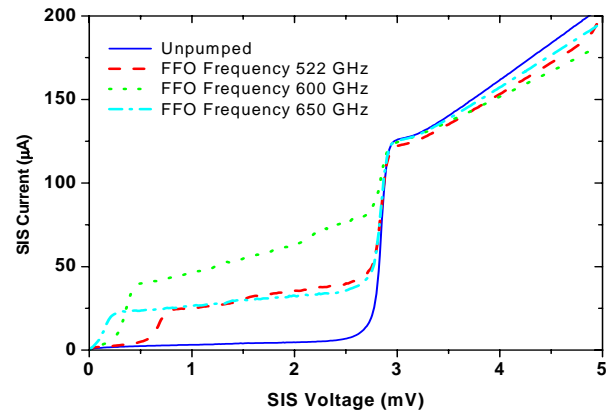


Fig. 6. IVCs of the SIS-mixer of T3 design: solid line - unpumped, dashed, dotted and dash-dotted – pumped by FFO at frequencies 522, 600 and 650 GHz correspondingly.

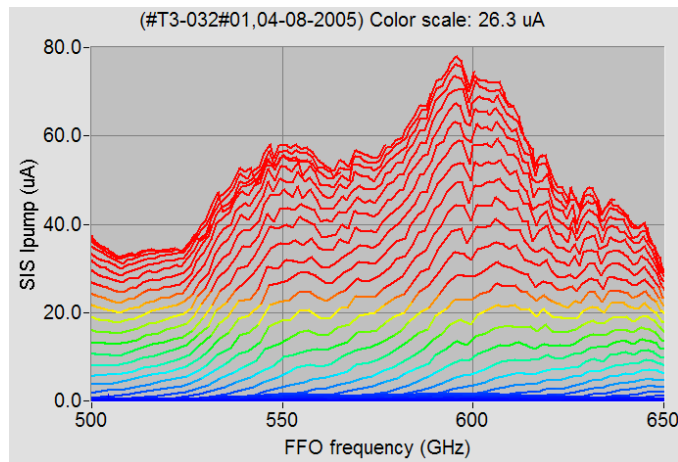


Fig. 7. Pumping of the SIS-mixer as a function of FFO frequency at different FFO CL currents. The pumping level $> 25\%$ of I_g ($> 26.3 \mu\text{A}$) is realized in the TELIS-SIR frequency range 500 - 650 GHz.

IV. DEPENDENCE OF THE FFO LINEWIDTH ON ITS PARAMETERS

Even for ultra wideband PLL system an effective regulation bandwidth is limited by the cable length (about 7 MHz for typical PL loop length of two meters). It means that free-running FFO linewidth has to be well below 10 MHz to ensure stable FFO phase locking with reasonably good spectral ratio (SR) - the ratio between the carrier and total power emitted by FFO, determines quality of FFO phase locking. For example, only about 50 % of the FFO power can be phase-locked by the present PLL system at the free-running FFO linewidth of 7 MHz. Low spectral ratio results in considerable error in resolving the complicated line shape [8]. Thus sufficiently small free-running FFO linewidth is vitally important for realization of the phase-locked SIR for TELIS.

Previous measurements [11] have demonstrated considerable increase of the FFO linewidth with FFO current density. It contradicts with the simplified consideration: the increase of the FFO current density should result in an increase of the total FFO bias current and a decrease of the FFO differential resistance. Since the FFO linewidth is proportional to $R_d^2 \cdot I_b$, the increase of the FFO current density has to be accompanied by the decrease of the measured FFO free-running linewidth. In reality the increase of the linewidth is caused by the fact that decrease of the differential resistance is smaller than expected [11]. High value of the current density ($J_c \geq 8 \text{ kA/cm}^2$) is important for wide-band operation of an SIS mixer at submm wave range. The discussed above increase of the FFO linewidth with current density creates serious problem in design and development of SIR chips. Implementation of two separate tri-layers with different current densities - one for the SIS mixer (high J_c) and the other for the FFO (lower J_c) might be a solution. We have successfully tested and verified this approach for SIR TELIS microcircuits.

Recently it was shown [10] that for all frequencies of interest the FFO linewidth considerably decreases with increasing FFO width (consequently, the spectral ratio is

getting much higher). Furthermore, there is no visible saturation of this effect in the studied range of FFO widths up to $28 \mu\text{m}$. In principle such behavior is quite explainable according to existing theoretical models: FFO linewidth, proportional to $R_d^2 \cdot I_b$, has to go down with an increase of the FFO width since it should result in an increase of total FFO bias current and in decrease of the FFO differential resistance. Fortunately, in contrast to the case of changing of the FFO current density, the R_d value indeed decreases more or less inversely proportional to I_b . Of course, one can expect saturation of the linewidth decrease and deterioration of the FFO behavior at further width increase (for example, due to appearance of the transversal modes). Since there is no reliable theory the optimal value of the FFO width has to be determined experimentally.

Dependences of the free-running FFO linewidth and SR of the phase-locked FFO on the FFO frequency measured at constant bias current of 32 mA for FFO as wide as $28 \mu\text{m}$ are presented in Fig. 8. Abrupt increase of the linewidth at the FFO frequency of about 450 GHz is caused by the effect of Josephson self-coupling (JSC) [12]. The JSC considerably modifies FFO properties at voltages $V \approx V_{JSC} = 1/3 \cdot V_g$ (V_{JSC} corresponds to 450 GHz for a Nb-AlO_x-Nb FFO) and results in larger internal damping at voltages $V > V_{JSC}$ that significantly complicates phase locking of the FFO at frequencies just above V_{JSC} .

Note that for the wide FFO its centerline is shifted from the edge of the bottom electrode that results in considerable decrease of the R_d^{CL} value. Furthermore, larger overlapping of the electrodes for wider FFO presumably provides more uniform bias current distribution - due to much smaller inductance of the overlapping electrodes. Presented results are very encouraging and these modifications of the FFO have been already implemented in the TELIS SIR chips.

In conclusion, an improved design of the FFO for TELIS has been developed and optimized. Free-running linewidth value from 9 to 2 MHz has been measured in the frequency range 500 - 710 GHz. As a result the spectral ratio of the phase-locked FFO varies from 35 to 90 % correspondingly, ensuring that at least half of FFO power is phase-locked in the primary frequency range for TELIS 550-650 GHz.

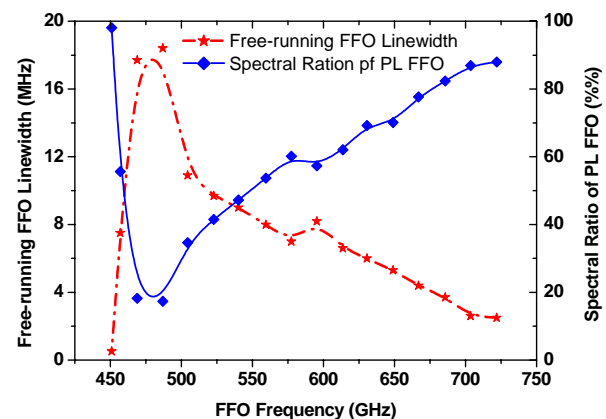


Fig. 8. Free-running linewidth and SR of PL FFO of a new design as a function of FFO frequency (FFO width = $28 \mu\text{m}$; $R_n S = 30 \text{ Ohm} \cdot \mu\text{m}^2$).

V. 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 procedure. It was shown [10] that the SR value for the given PLL system is determined by the free-running FFO linewidth: these two quantities are unambiguously related. So only one value (SR or FRL) has to be measured in flight to ensure retrieval procedure.

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 Institute for Physics of Microstructure, Russian Academy of Science (Nizhny Novgorod, Russia). The dc signal at this output of the PLL system is proportional to the power measured by a detector with 0.8 MHz band-pass filter at 400 MHz. This DC signal is proportional to the PL FFO spectral ratio (see Fig. 9) [8]. Furthermore, the constant of proportionality does not depend on FFO bias current and is the same for FFOs of quite different design (see Fig. 9). It means that SR can be determined in flight if the power level is kept constant.

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 (see Fig. 10) [8]. It is clear from Fig. 10 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 peaks are quite deep and precise tuning of the parameters (HM bias voltage, synthesizer power) is required. At the synthesizer power of about 10dBm (power delivered to HM is of about 1 μ W) the spacing between peaks became twice as small 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; almost the same signal to noise ratio (SNR) and consequently Spectral Ratio can be realized. On the other hand the requirement to minimize cross talk between pumped HM and SIS-mixer forced us to use mainly the Josephson mode of HM operation for present PL SIR measurements.

From Fig. 10 one can see that tuning of the single-junction HM is reasonably smooth for both HM bias voltage and synthesizer power; tuning by the PLL gain level is even smoother. Note that all dependences are very well reproducible. 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.

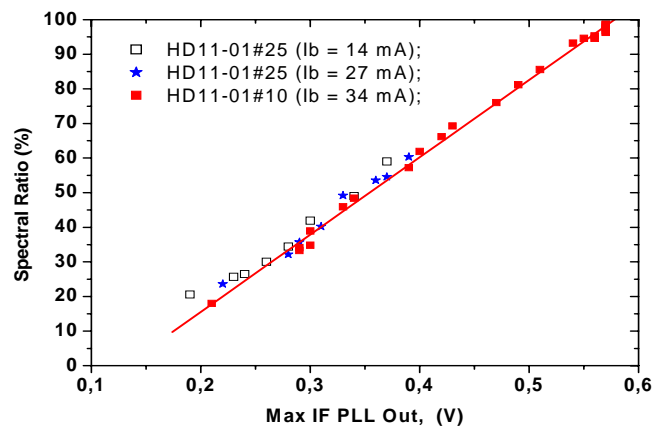


Fig. 9. Spectral ratio of the PL FFO on IF level output of the PLL system measured for the FFOs of different design.

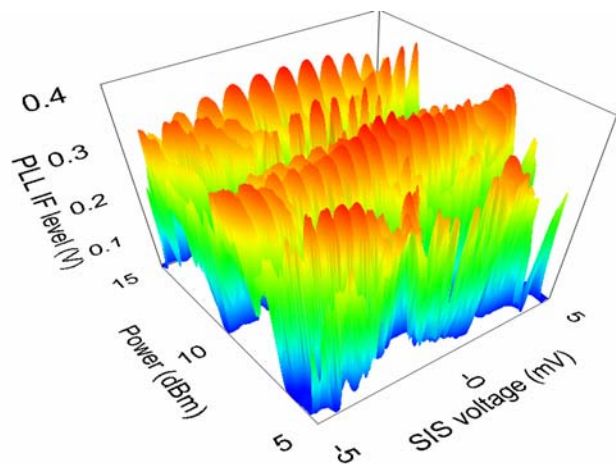


Fig. 10. 3-D diagram for HM operational parameters measured by PC controlled PLL. The level of IF-out PLL signal is represented by color scale; note that normal PL operation is possible at IF levels larger than 250 mV.

VI. RETRIEVAL: INFLUENCE OF FFO SPECTRUM IMPERFECTION

The output mixer product depends on FFO spectral properties. Initial source spectrum is distorted due to FFO spectrum imperfections. To assess the impact of an imperfect FFO spectrum on trace gas profile retrieval in TELIS a model based on the SMART retrieval code (Sub Mm Atmospheric Retrieval of Trace gases) is used. The basic of the SMART is as follows: a database contains spectroscopic information of many trace gases present in the atmosphere. When the value of density or volume-mixing ratio is given, as well as temperature, pressure and viewing geometry a synthetic spectrum can be calculated [13]. This so-called forward model has been verified and validated in the ASUR (Airborne Sub-millimeter SIS Radiometer) project. Retrieval simulations are performed by “creating” a SMART spectrum and its comparison with a measured one. So in this retrieval model the good prior knowledge is used.

In the case when the prior knowledge about measured spectrum is absent different deconvolution methods can be used. We tested one of them (Fourier-quotient method). This

method often leads to an ill-posed problem [14]. For example this method cannot be used for present frequency locked FFO, because of strong noise amplification after deconvolution. However our calculations show, that all retrieval methods work well enough in the case of PL FFO spectra with $SR > 50\%$. Noise is “amplified” by approximately a factor of two (see Fig. 11); for these calculations we added Gaussian noise at the SIR output ($T_{Add} = 1$ K). This added noise corresponds to SSB noise temperature of the SIR = 1000 K, 1 MHz band and integration time of 1 sec. In flight FFO spectrum is not exactly known. To simulate this situation different PL FFO spectra are used for the forward convolution while retrieval calculations are made for one spectrum with $SR = 80.4\%$ (see Fig. 12). For the realistic added noise $T_{Add} = 0.4$ K the 2% uncertainty in the SR value results in less than 2% error after deconvolution.

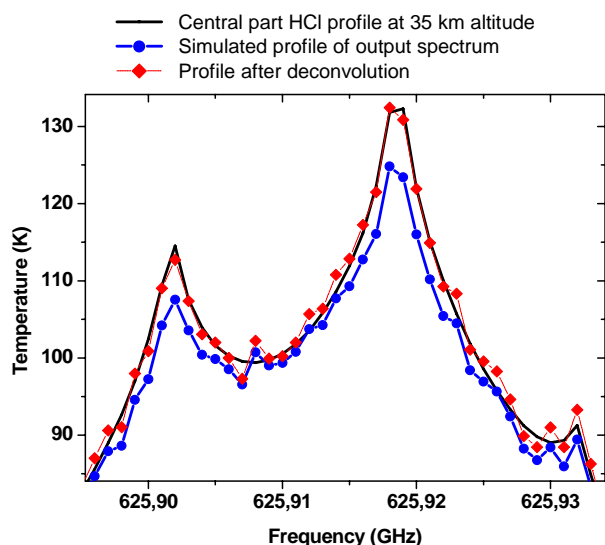


Fig. 11 Results of deconvolution of HCl line. Solid line - input spectrum (central part of HCl spectrum at altitude 35 km). Circles - simulated output spectrum (convolution of the input spectrum with spectrum of PL FFO, $SR=80.4\%$, plus added gaussian noise $T = 1$ K). Diamonds - result of deconvolution of simulated output spectrum with spectrum of PL FFO.

VII. CONCLUSION

The concept of the PL SIR for TELIS has been experimentally proven. New generation of the SIR microcircuits for TELIS has been developed and preliminary tested, showing a performance approaching to TELIS requirements.

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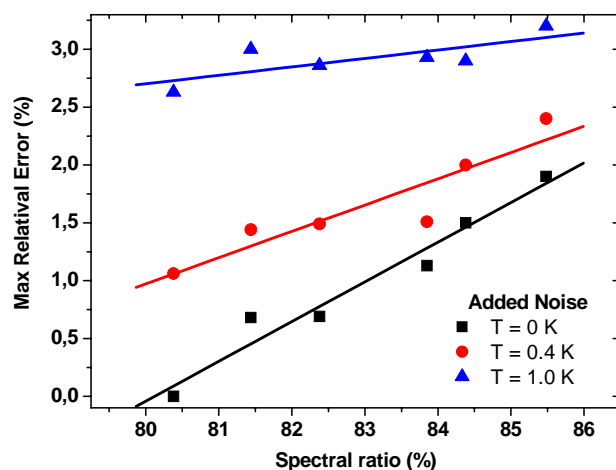


Fig. 12. Results of deconvolution (retrieval model) of the HCL line with experimentally measured PL FFO spectrum ($SR=80.4\%$) for three different temperature of added noise. In forward model the experimental PL FFO spectra with SR from 80.4% to 85.5% are used.

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