A SUPERCONDUCTING SPECTROMETER WITH PHASE-LOCKED JOSEPHSON OSCILLATOR

S. V. Shitov[1,2], V. P. Koshelets[1,2], P. N. Dmitriev[1], L. V. Filippenko[1], An. B. Ermakov[1,2], V. V. Khodos[3], V. L. Vaks[3]

[1]Institute of Radio Engineering and Electronics, Russian Academy of Sciences (IREE RAS), Moscow, Russia

[2]National Institute for Space Research (SRON), Groningen, the Netherlands

[3]Institute for Physics of Microstructures, Russian Academy of Sciences (IPM RAS), Nizhny Novgorod, Russia

Abstract

A sensitive heterodyne spectrometer employing a superconducting local oscillator is demonstrated experimentally for the first time at 327 GHz. The research is continuation of the study on a superconducting submillimeter integrated receiver. The sensor of the phase-locked receiver comprises a quasioptical double-dipole antenna SIS mixer ($T_{RX} \approx 250$ K, DSB), a Josephson-type flux-flow oscillator (FFO) and a twin-SIS harmonic mixer, all integrated on the same silicon chip of size 4 mm by 4 mm. An elliptical silicon lens is the only optical element focusing the beam. Room temperature PLL electronics is used along with a synthesized reference source at about 10 GHz. The effective bandwidth of the PLL circuit of about ± 10 MHz and the hold range of ± 2.5 GHz are estimated experimentally while locking at 32-th harmonic of the reference source. It was found that the optimum pump current of the SIS mixer can be adjusted within the range of 14…42 μA simply via change of the bias current of the FFO while it stays locked. The signal from a room temperature semiconductor harmonic multiplier driven by a second synthesizer is used to test the spectrometer; the spectral resolution as low as 10 kHz is estimated. The effect of broadening of a spectral line of SO_2 gas at 326867 MHz is measured for a laboratory gas cell at 300 K within the pressure range of 0.03-0.3 mbar demonstrating the resolution bandwidth better than 1 MHz.

Introduction

Sub-millimeter wave spectrometers are currently of great interest for radio astronomy and for earth study by monitoring the atmosphere chemistry. Most of advanced spectrometers nowadays employ ultra-low noise SIS mixers at the temperature of liquid helium. A sensor of the SIS mixer is a thin-film integrated circuit fabricated with micron accuracy so the tiny circuit may contain many SIS junctions. In contrast, conventional local oscillators used with SIS mixers are room temperature semiconductor devices (usually a Gunn oscillators in combination with multipliers). This fact makes impossible integral packaging of the whole receiving system.

There is a 1-microWatt level (moderate-power) type of Josephson junction oscillators, flux-flow oscillator (FFO), which is proven to be suitable for integration with a low-noise SIS mixer as a local oscillator (LO). Among the Josephson devices FFO has also an advantage of good tuneability in combination with relatively narrow free-running linewidth. Recent experimental study on phase-locking FFO up to 700 GHz [1] is the good support for the development of practicable submillimeter spectrometer. This paper deals with recent progress on experimental study of superconducting integrated receiver (SIR) with phase-locked (PL) FFO.

1. Chip design and measuring system

The microphotograph of the PLL SIR chip for 320-370 GHz band is presented in Figure 1. The equivalent scheme of the experimental chip containing the double-dipole single-junction SIS mixer, PLL feedback FFO and harmonic mixer (x35) is presented elsewhere [2,3]. A twin-SIS junction is used for the harmonic mixer and there is no magnetic field supply, so the harmonic mixer is operating in the Josephson mixing mode. Figure 2 presents the general view of the pixel with three coaxial cables mounted. The microwave lens from silicon with antireflection coating is clearly seen. The chip mount is placed inside a magnetic shield as described in [4]. The block scheme of the experimental setup is described elsewhere [5]. We note here only that the phase detector system and the reference source are room temperature devices outside the cryostat.

2. Experimental results and discussion

The experimental devices are produced using our standard procedure developed for integrated receivers and described elsewhere [6]. The preliminary test of device at dc is performed using computer control measurement system IRTECON [7]. The test results are presented in Figure 3 as a quasi-3D graph of the mixer pump on all possible regimes of the FFO. Similar graphs are created for both SIS mixer and HM. The fact that the largest pump is achieved for SIS mixer and HM at a bit different frequencies, may mean some imbalance in the power split. This is possible for our microstrip T-junction splitter due to deviations in the fabrication process. Another important feature of the device is absence of Fiske steps within certain region below the boundary voltage of $V_g/3$. The permanent tuning is available in this region. This unusual behavior, which would mean normally high damping of the FFO caused by losses, can be explained here by complete disappearance of the reflections at the end of the long junction provided by a perfectly matched output circuit. The phase-locking within such region of high damping is known to be difficult due to the wide initial linewidth associated with relatively high dynamic resistance [5].

The IV-characteristics of the twin-SIS harmonic mixer (HM) are presented in Figure 4. To obtain the optimal performance of the HM, it has to be pumped heavily that turns its IV-curve almost into a straight line. The IV-characteristic of the single-junction SIS mixer demonstrates no essential influence of the reference source at 10.1 GHz. The only effects seen when the reference source is switched on and off are partial suppression of the critical current (when FFO is off) and negligible change of the quasi-particle current (when pumped).

The Fourier transform spectrum (FTS) of the SIS mixer is obtained using Michelson interferometer and presented in Figure 5. The main peak of coupling is essentially narrower and higher in frequency than one predicted [2]. Careful calculations demonstrate that this effect can be explained by thinner insulation (190 nm instead of 250 nm). The inverse values of experimental heterodyne data (T_{rx}^{-1}) are plotted at the same graph demonstrating good fit to the FTS.

The heterodyne data were measured using standard hot/cold technique. The heterodyne response of the receiver is presented in Figure 6. Note that peak of the best sensitivity is within the region of high dynamic resistance of FFO that was discussed above. The spectrum of the FFO measured at this frequency is quite wide being affected by the fine resonant structure that is typical for a rectangular-end FFO [8]. For this reason the left peak of FTS from Figure 5 was used. The IV-curve of FFO phase-locked at 325.5 GHz is presented in Figure 7. The oscillator is locked at 32-th harmonic of the reference source (f_{REF} = 10158.35917 MHz) assuming that the spectral line (f_2 = 326867.5 MHz) will be present at upper sideband (USB) relative to the frequency of the LO. The part of the IVC is magnified and presented in the inset demonstrating loosing and restoring of the locking regime. To obtain these data the bias current was changed manually within wide range while the feedback loop remained closed. The vertical portion of the curve presents the regime of nearly fixed frequency. The real PLL regime remains within the bias current range of 37…43 mA while the frequency lock is possible within range of 27.5…43 mA. The PLL regime initial parameters are: the control line current 25.2 mA, the bias current 40 mA, the bias voltage of FFO about 673 µV, PLL IF = 401 MHz, the dynamic resistance of the IVC, R_d = 0.0015 Ω. The hold range of ± 2.5 GHz can be estimated from the experimental data. The IV-curves of the SIS mixer pumped at 325.5 GHz by the phase-locked FFO are presented in Figure 8. The data are demonstrating possibility of adjustment of LO power to its optimum value via changing the bias current of the FFO while it stays phase-locked. To estimate the stability of the spectrometer, the external signal source was used. The signal from synthesizer was applied to an external Schottky diode harmonic mixer, which worked as a multiplier producing a stable CW signal. The width of such spectrum, which has to include all system instabilities, was found below 10 kHz similar to [5].

The photograph of our experimental setup for the spectral line detection is presented in Figure 9. The 1-meter gas cell was filled initially with SO_2 gas at pressure of a few mbar. Then the cell was pumping down to desired pressure within range of 0.03-1mbar. To be sure that the system is tuned properly, the test with the external harmonic mixer was performed prior to the gas line detection. The example of a SO_2 gas spectrum obtained using AOS is presented in Figure 10. The experimental data taken for different pressure were processed using Lorenz fit similar to [5]. The effect of the linewidth broadening is presented in Figure 11.

Conclusions

The superconducting spectrometer on the base of an externally phase-locked superconducting Josephson oscillator has been developed and demonstrated the capability of detection of low-pressure atmosphere contaminant like the SO_2 gas, which is the side product of metallurgy industry. The resolution of the spectrometer, according to the gas cell measurements, is not less than 1 MHz and can be as good as 10 kHz, as it is demonstrated with CW source. To realize full potential of the new device, further improvements on both design and operation of FFO and coupling circuits are necessary.

This study provides an important input for future development of a balloon-based 500-650 GHz integrated receiver for the Terahertz Limb Sounder (TELIS) scheduled to fly in 2004-2005.

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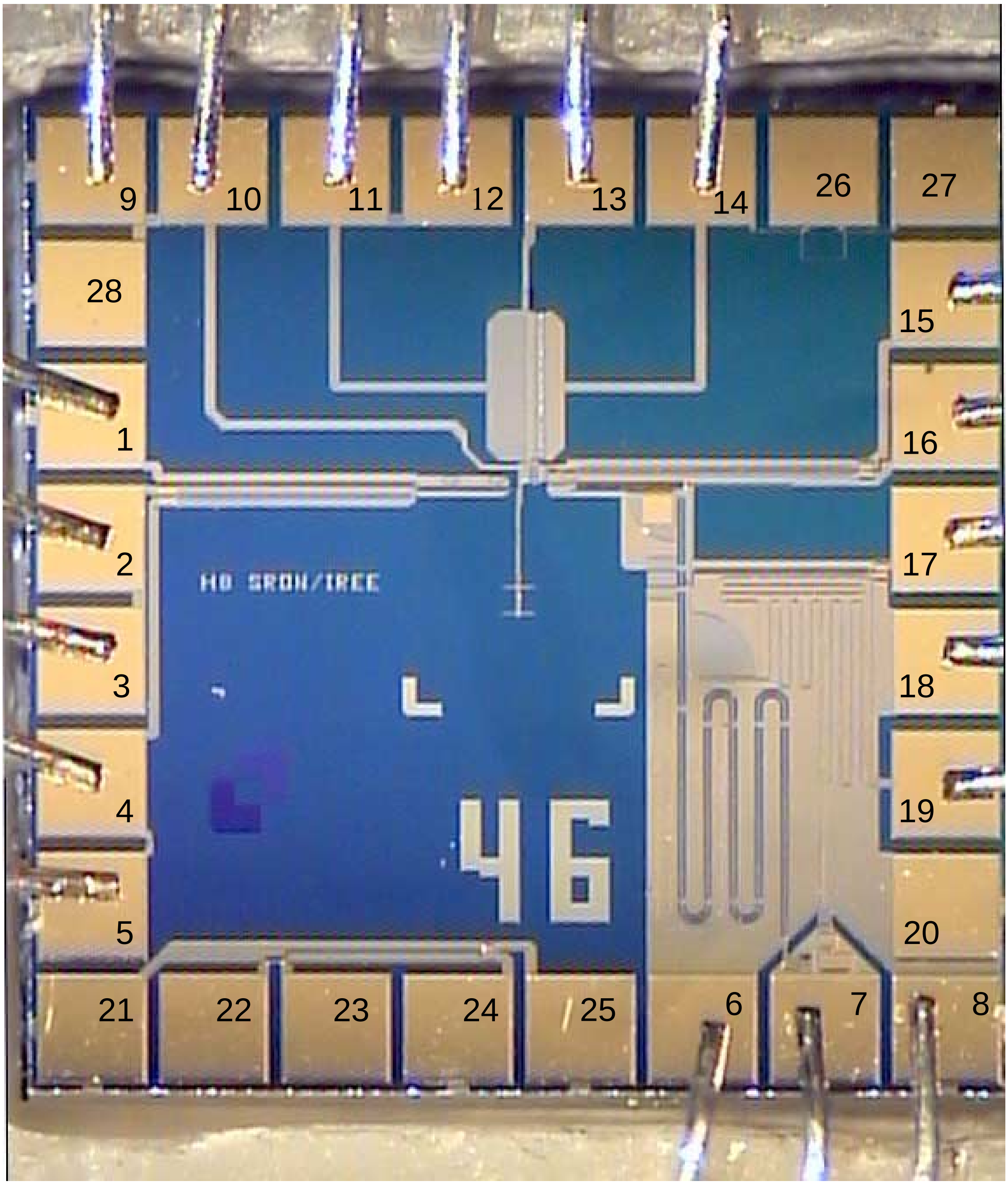

Fig. 1 Micro-photograph of the chip of the superconducting integrated receiver with phase-locked Josephson oscillator. The chip size is 4 mm by 4 mm. Contact pad destinations: (1), (2) SIS mixer bias / IF out; (3), (4) SIS control line; (5) bias for balanced mixer (optional); (6)-(8) reference signal input and bias input for harmonic mixer; (9), (11), (12), (14) FFO bias; (10), (13) FFO control line; (15)-(16) harmonic mixer control line; (17)-(18) SIS multiplier control line (optional); (19)-(20) SIS multiplier bias (optional); (21)-(27) test structures; (28) spare FFO grounding.

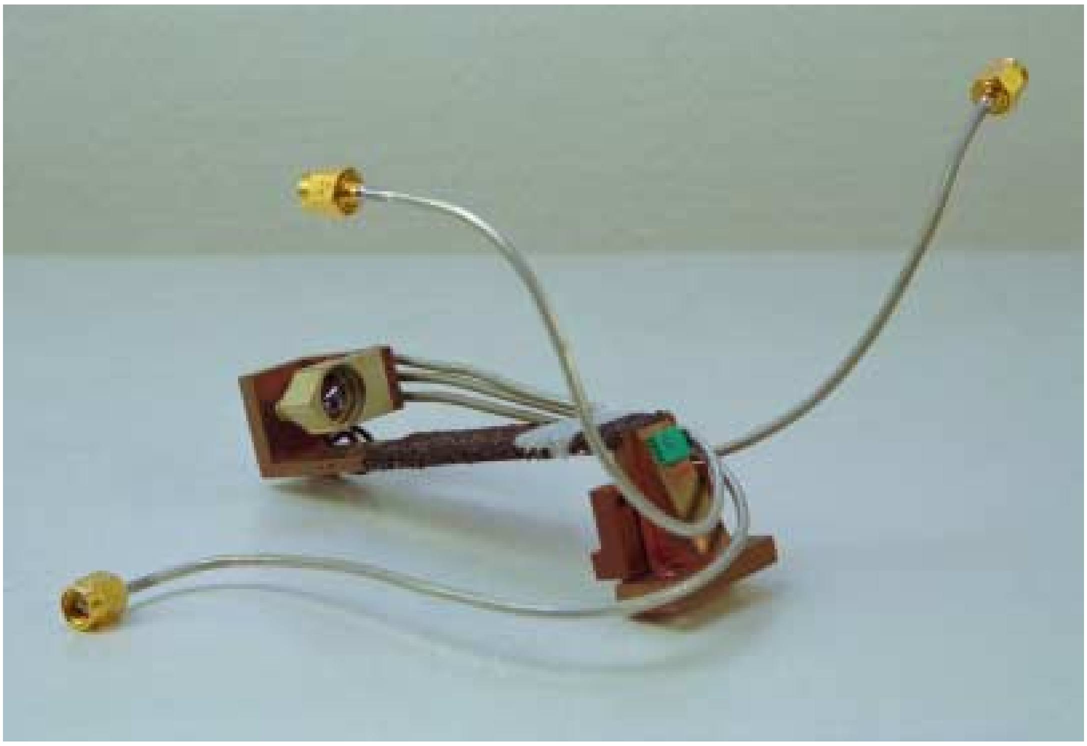

Fig. 2 General view of PLL SIR pixel. The mount of the imaging array is adapted. Three cables are connected to i) SIS mixer for IF/dc-bias, ii) FFO for PLL feedback, iii) harmonic SIS mixer for reference/PLL-IF/dc-bias.

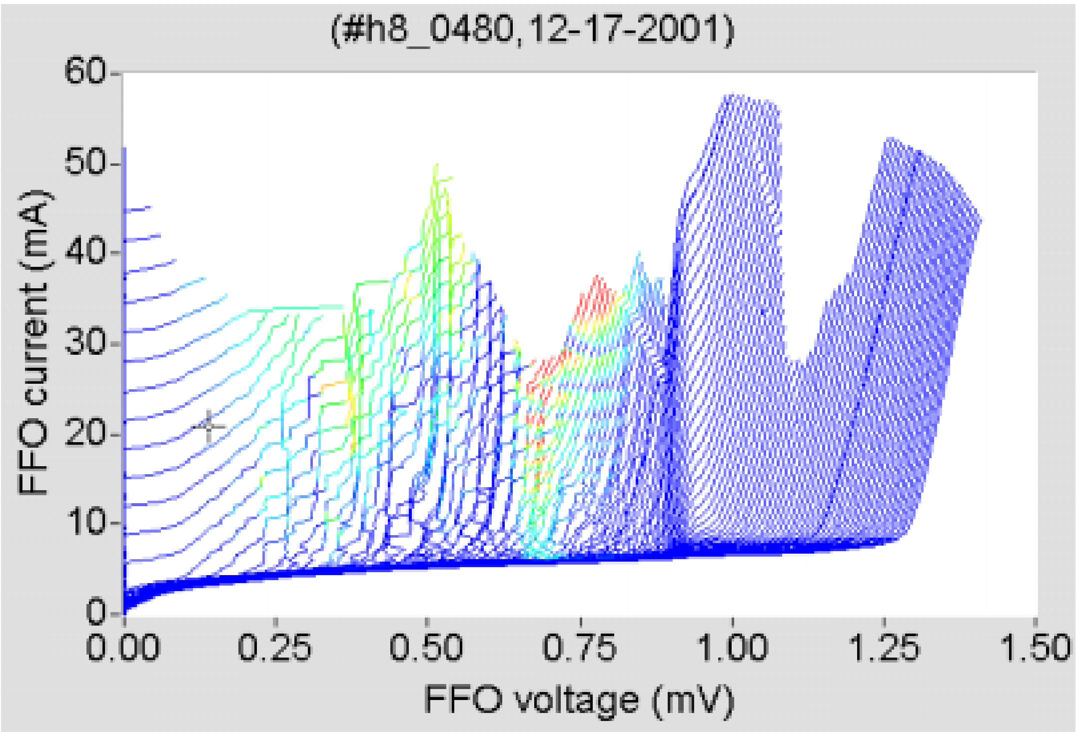

Fig. 3 Quasi-3D graph of the mixer pump on all possible regimes of the FFO.

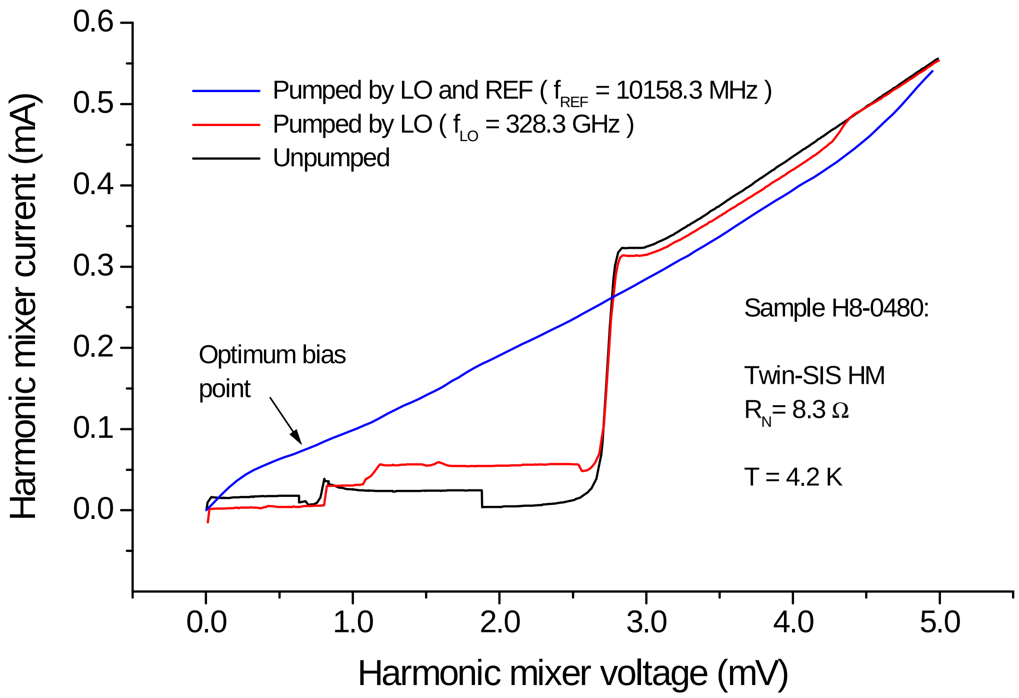

Fig. 4 IV-curves of harmonic mixer pumped with both FFO and reference source.

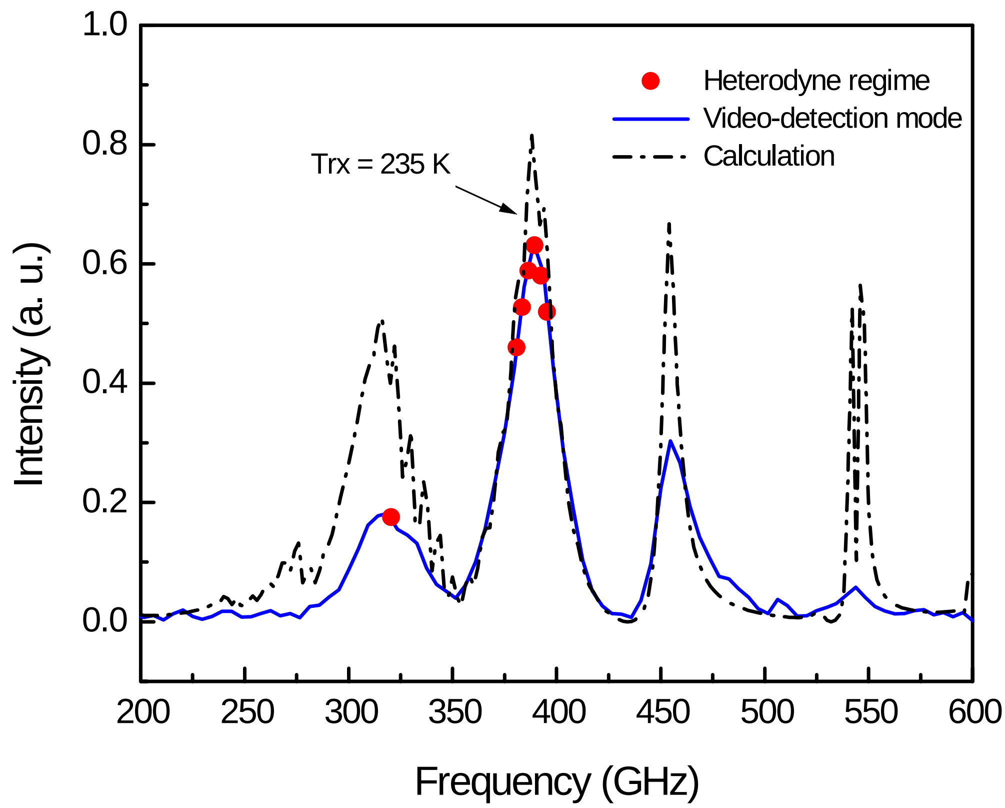

Fig. 5 Experimental FTS and heterodyne data along with best fit of calculated coupling between the antenna and the detector SIS junction.

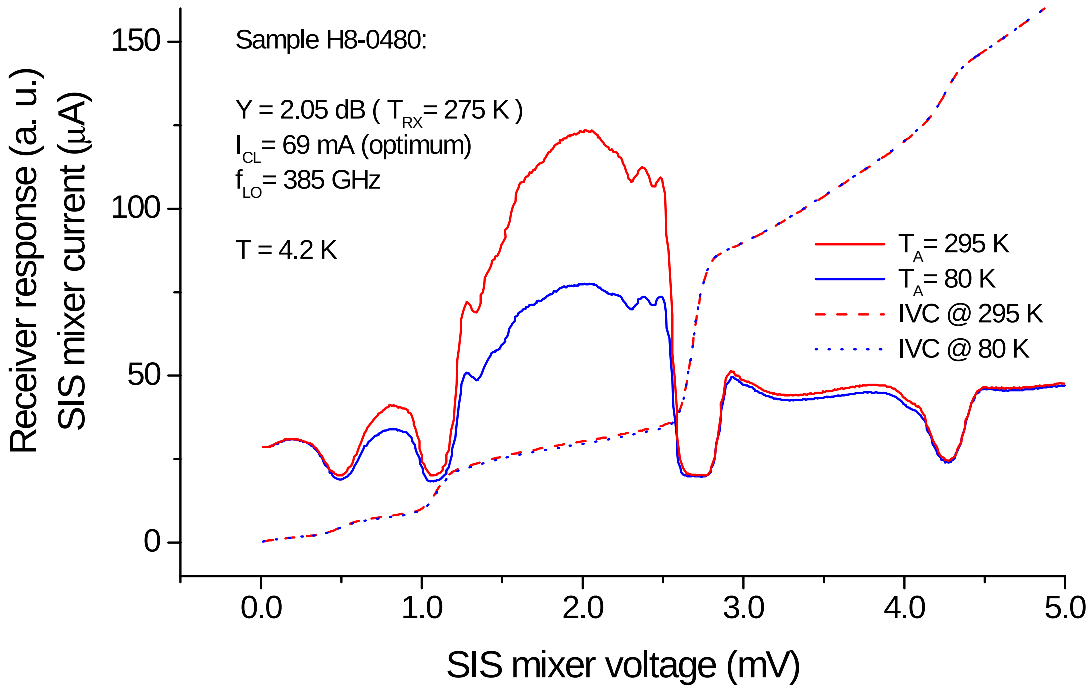

Fig. 6 Receiver heterodyne response at IF = 1.4 GHz and IV-curves of SIS mixer pumped by free-running FFO at about 385 GHz.

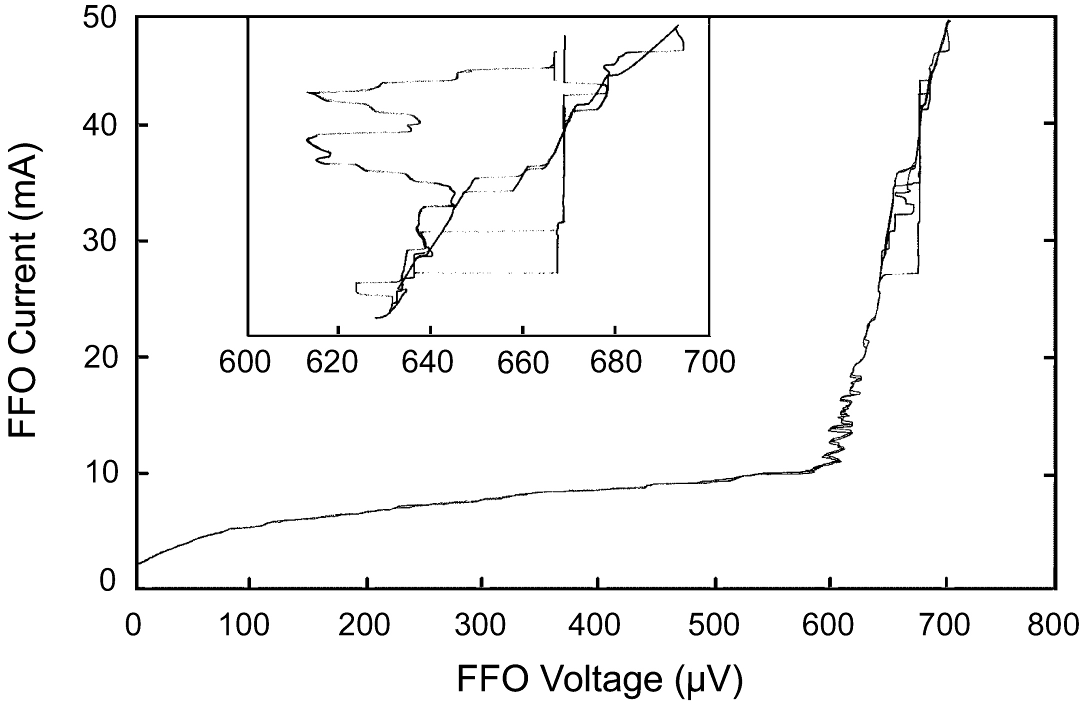

Fig. 7 IV-characteristic of FFO phase-locked at 325.5 GHz. The part of the IVC is magnified and presented in the inset demonstrating loosing and restoring of the locking regime for the PLL loop remains closed.

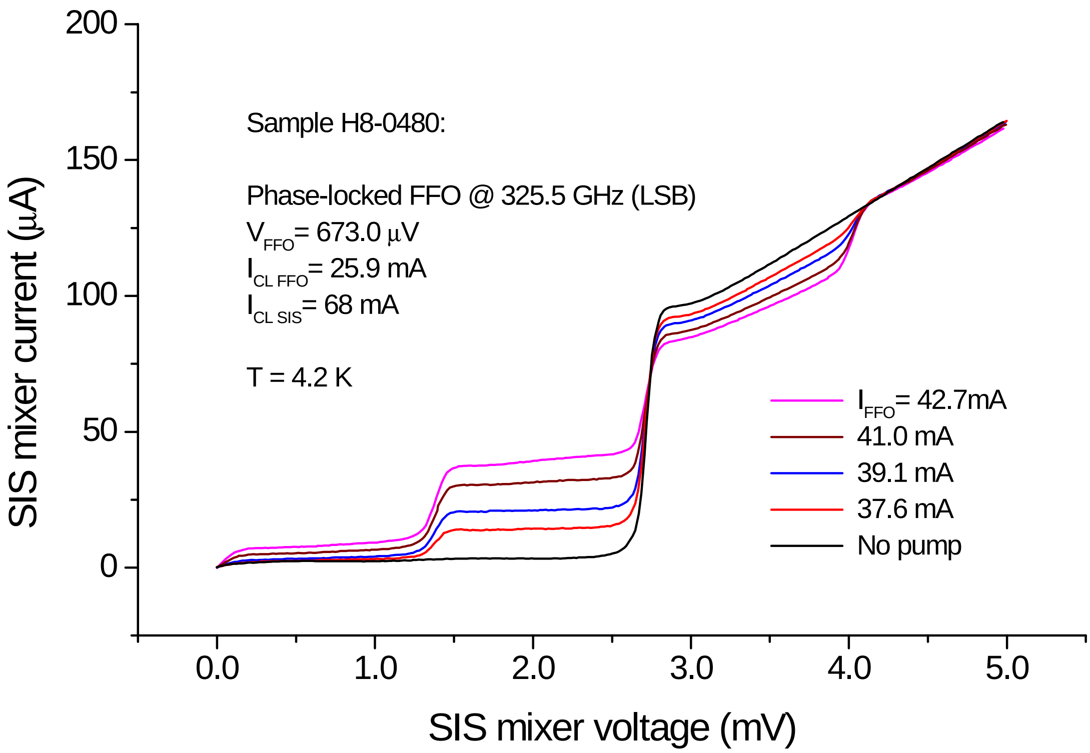

Fig. 8 IV-curves of SIS mixer pumped by phase-locked FFO. The pump level is being adjusted via simply changing the bias current of FFO while it stays phase-locked.

Fig. 9 General view of the gas cell setup.

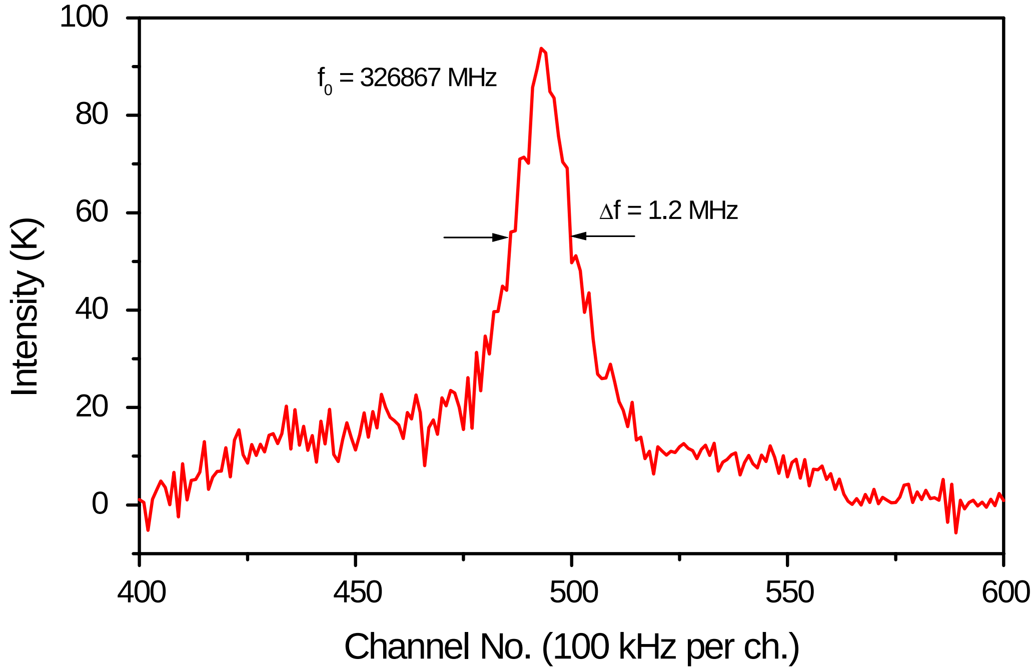

Fig. 10 Spectral line of SO_2 gas at pressure 0.03 mBar detected by superconducting integrated receiver with phase-locked Josephson oscillator (FFO). The data are processed using acousto-optical spectrometer.

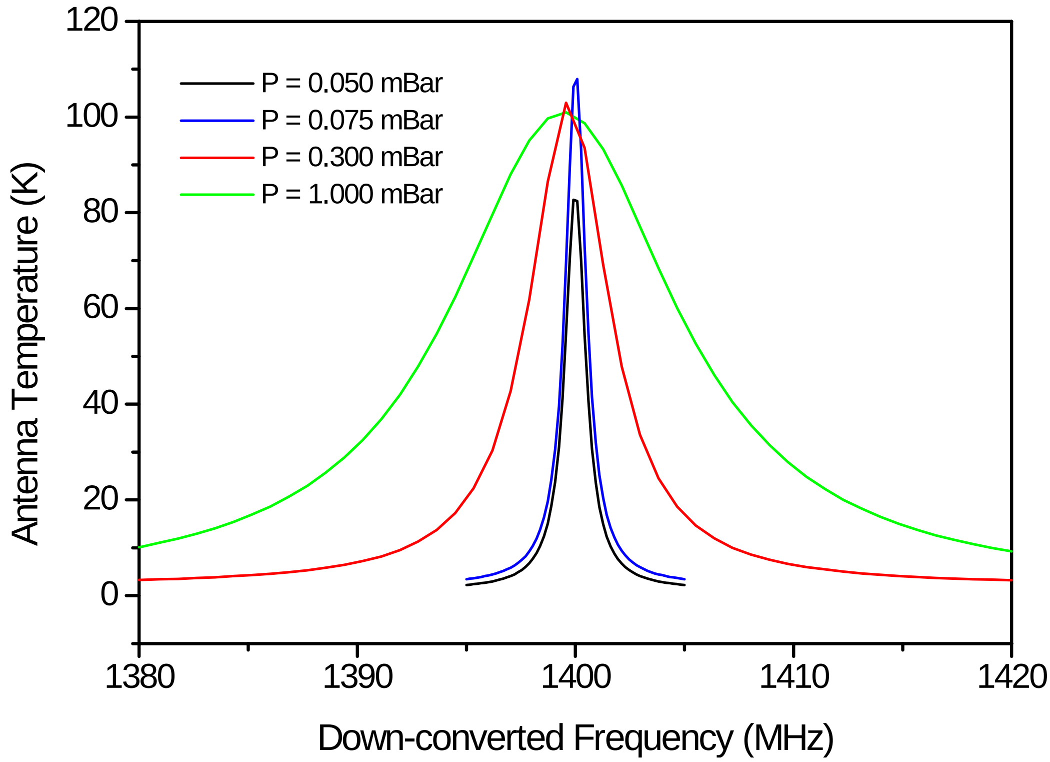

Fig. 11 Effect of broadening of SO_2 gas spectrum at 326.867 GHz measured by PLL superconducting integrated receiver.