An Integrated Receiver With Phase-Locked Superconducting Oscillator

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Abstract—A submillimeter heterodyne spectrometer employing a superconducting local oscillator is demonstrated for the first time. The sensor chip comprises a quasioptical double-dipole lens-antenna SIS mixer ($T_{\mathrm{RX}} = 250$ K at 380 GHz), a Josephson flux-flow oscillator and a SIS harmonic mixer. Room temperature PLL electronics is used with a reference source at 10 GHz. The PLL bandwidth of 10 MHz and the hold range of 3 GHz are estimated for locking at 32-th harmonic of the reference source. The spectral resolution better than 1 MHz and broadening effect of a spectral line of SO_2 gas at 326867 MHz are measured with a laboratory gas cell at 300 K at pressure 0.03 – 0.3 mbar using acousto-optical spectrometer.

Index Terms—Heterodyne spectrometer, Josephson flux-flow oscillator, phase-locked oscillator, quasioptical SIS receiver.

I. INTRODUCTION

SUB-MILLIMETER wave spectrometers are currently of great interest for radio astronomy and for Earth atmosphere study. Most of advanced spectrometers nowadays employ ultra-low noise SIS mixers at the temperature of liquid helium. The sensor of a SIS mixer is a thin-film circuit fabricated with micron accuracy so this technology is naturally applicable for integrated circuits. In contrast, conventional local oscillators used with SIS mixers are room temperature semiconductor devices (usually a Gunn oscillators in combination with multipliers). This approach makes difficult integration of the whole receiving system.

A superconducting Josephson flux-flow oscillator (FFO) is proven to be suitable for integration with a low-noise SIS mixer as a local oscillator (LO). Among Josephson devices the FFO has an advantage of good tuneability in combination with a relatively narrow free-running linewidth. Recent experimental study on FFO demonstrated possibility of phase-locking up to 700 GHz [1]; this is a good basis for development of a practicable submillimeter spectrometer [2]. Present paper deals with
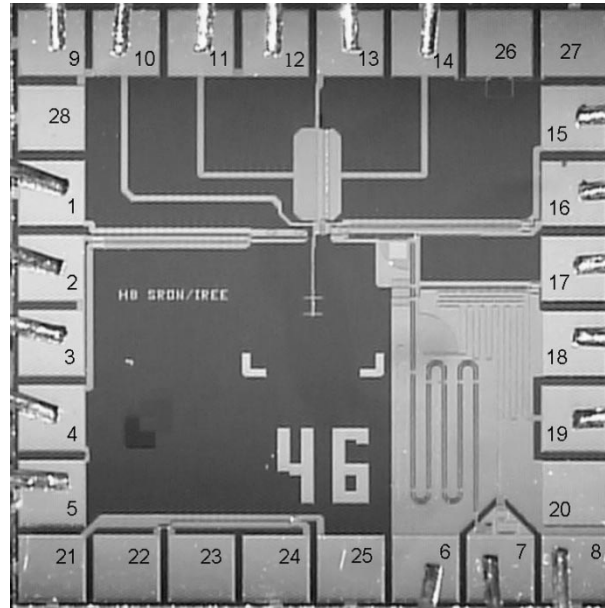
Fig. 1. Chip of superconducting integrated receiver with phase-locked Josephson oscillator (4 mm by 4 mm). Connections shown: 1, 2 contact pads of SIS mixer; 3, 4 SIS control line; 5 bias for balanced mixer (optional); 6-8 reference input and bias for harmonic mixer; 9, 11, 12, 14 FFO bias; 10, 13 FFO 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.

study of a superconducting integrated receiver (SIR) containing the phase-locked FFO as a local oscillator and a quasioptical lens-antenna SIS mixer.

II. EXPERIMENTAL DETAILS

A. Chip Design and Measuring System

The microphotograph of the PLL SIR chip for 320–370 GHz band is presented in Fig. 1. The equivalent scheme of the experimental chip containing the double-dipole single-junction SIS mixer, PLL feedback FFO and harmonic mixer is presented elsewhere [3], [4]. A twin-SIS junction used for the harmonic mixer is operating without magnetic field supply. Fig. 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 [5]. The block scheme of the experimental setup is described elsewhere [6]. We note only that, to reduce length of the PLL loop, the phase detector system is mounted to the wall of the cryostat.
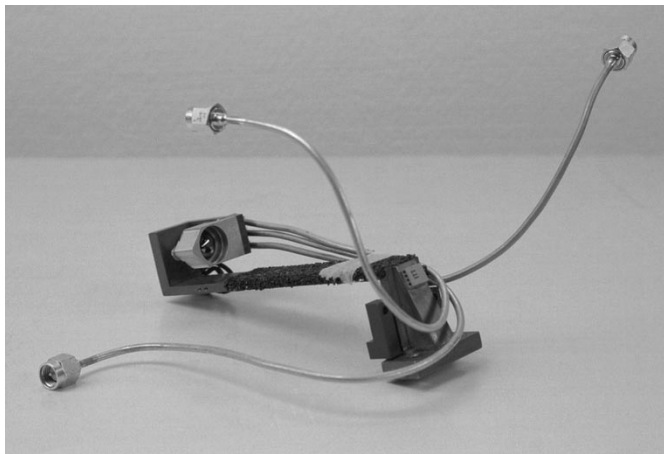
Fig. 2.   General view of PLL SIR pixel. The mount of the imaging array is adapted. Three cables are connected to i) SIS mixer for IF/dc-bias, ii) FFO for PLL feedback, iii) harmonic SIS mixer for reference/PLL-IF/dc-bias.
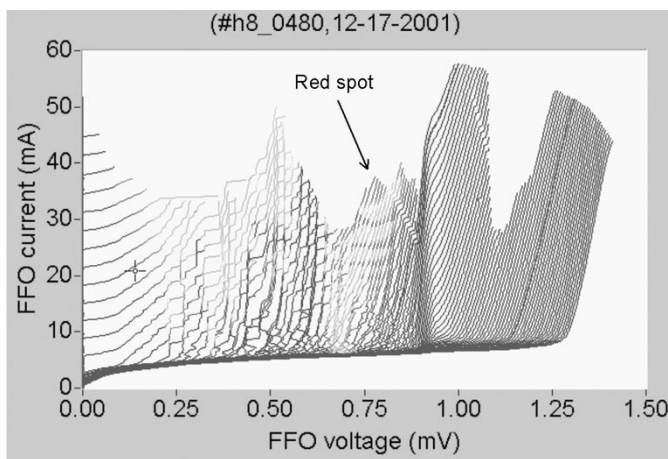

Fig. 3.   Test graph of mixer pump on regimes of FFO tuned by magnetic field.

B. Experimental Results and Discussion

The experimental devices are produced using our standard procedure developed for integrated receivers and described elsewhere [7]. The preliminary test of a device at dc is performed using the computer control measurement system IRTECON [8]. Fig. 3 presents a family of IV-curves of FFO for different strength of magnetic field provided by an integrated control line. The data points of each IV-curve get different color from blue to red indicating strength of SIS mixer pump. The red 'spot' level corresponds to regimes of FFO suitable to operate the SIS mixer. Similar graph is used for indicating pump level of the harmonic mixer (HM). An important feature of the device is absence of Fiske steps within certain region below the boundary voltage of $V_g/3$ [2]. The permanent tuning is available in this region. This unusual behavior, which would mean normally high damping of the free-running FFO caused by losses, can be explained here by complete disappearance of reflection 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 [6].
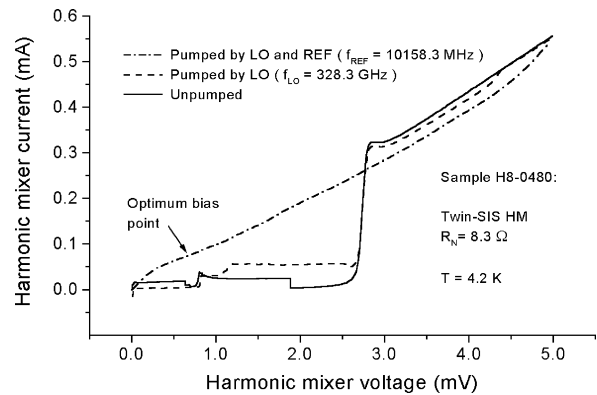

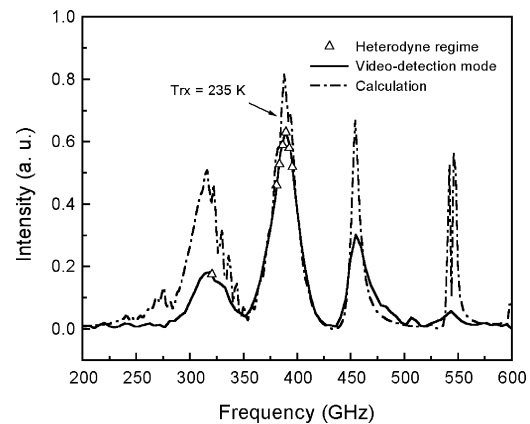Fig. 4. IV-curves of harmonic mixer pumped with FFO and reference source.

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

The IV-characteristics of the twin-SIS harmonic mixer (HM) are presented in Fig. 4. To obtain the optimal performance of the HM, it has to be pumped strongly by the reference source at about 10 GHz that turns IV-curve of HM almost into a straight line. The IV-characteristic of the detector SIS junction demonstrates no essential influence of the reference source at 10.1 GHz that mean proper rf isolation. 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 in the quasiparticle current (when the FFO is on).

The Fourier transform spectrum (FTS) of the SIS mixer is obtained using Michelson interferometer as shown in Fig. 5. It was found that the main peak of sensitivity at 380 GHz is essentially narrower and a bit higher in frequency than it was predicted initially by design, 50 GHz and 345 GHz respectively [3], [4]. The result of numerical analysis is also presented in Fig. 5 as the best fit to the experimental data. The fit demonstrates that present results 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 noise temperature of the receiver was measured using the standard hot/cold technique. The heterodyne response of the receiver at $IF = 1.4$ GHz is presented in Fig. 6. Note that the peak of highest sensitivity of the detector from Fig. 5 is, unfortunately, within the region of high dynamic resistance, R_d,
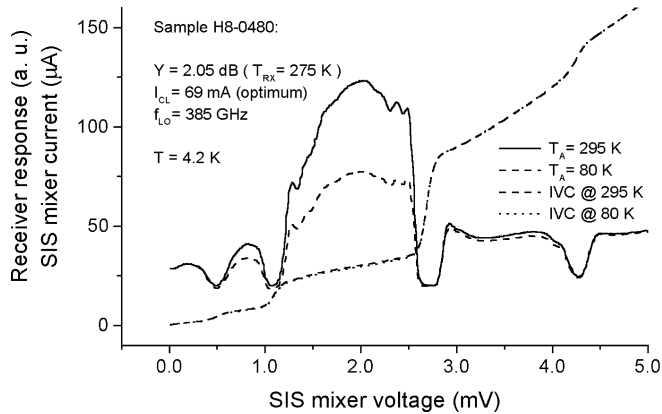
Fig. 6. Receiver heterodyne response at $IF = 1.4$ GHz and IV-curves of SIS mixer pumped by free-running FFO at 385 GHz.

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.

of the FFO (see Fig. 3). It is known that for higher R_d spectrum of a free-running FFO is affected more by the noise current. In our case the spectrum appeared as a multi-peak fine resonant structure, which is typical for a rectangular-end FFO [9], so the frequency region of the best sensitivity could not be used for the locking of the FFO. For this reason the left (less sensitive) peak of the detector response (at about 320 GHz) was used for testing the spectrometer.

A spectral line of SO_2 gas at 326 867.5 MHz was chosen and thus the frequency that FFO has to be tuned to is defined as 325.5 GHz. To be sure that the LO is tuned properly, a test with a synthesized CW signal was performed prior to the gas line detection. The fundamental CW signal of about 20 GHz was applied to a room temperature Schottky diode mixer to produce a harmonic exactly at the frequency of the spectral line. A beam of the open waveguide of the Schottky mixer was then coupled to the quasioptical input of the receiver.

To phase-lock the FFO at the required frequency of 325.5 GHz, the reference PLL signal from main synthesizer was applied at $f_{\mathrm{REF}} = 10\,158.359\,17$ MHz. It was assumed that 32-th harmonic of f_{REF} is separated from the required frequency of FFO by PLL $IF = 401$ MHz and that the spectral line has to be present at upper sideband (USB) relative to the frequency of the LO. The spectral width of the test CW signal was found below 10 kHz similar to [6].

The IV-curve of FFO phase-locked at 325.5 GHz is presented in Fig. 7. The part of the IVC is magnified in the horizontal direction (see inset) demonstrating loosing and restoring of the locking regime. To obtain these data, the bias current was changed manually within wide range whereas the feedback loop remained closed. The vertical portion of the curve presents the regime of nearly fixed frequency. The real PLL regime remained within the bias current range of 37–43 mA whereas the frequency lock was possible within range of 27.5–43 mA. The PLL regime initial parameters were as following: the control line current 25.2 mA, the bias current 40 mA, the bias voltage of FFO about 673 μV, the dynamic resistance of the FFO, $R_d = 0.0015\ \Omega$. The hold range of ± 2.5 GHz is 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 Fig. 8. The data are demonstrating possibility of adjustment of LO power
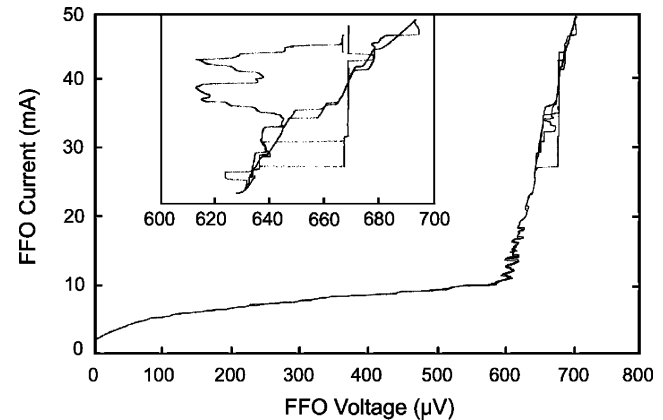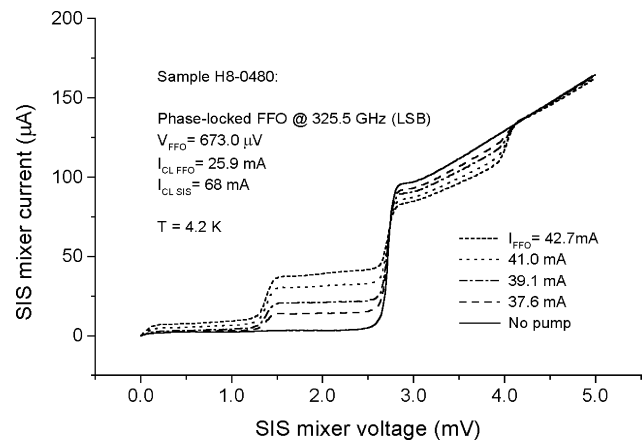

Fig. 8. IV-curves of SIS mixer pumped by phase-locked FFO. The pump level is being adjusted via simply changing the bias current of FFO whereas the superconducting oscillator stays phase-locked.

Fig. 9. General view of the gas cell setup.

to its optimum value via changing the bias current whereas the FFO stays phase-locked.

The photograph of our experimental setup for detection of a gas spectral line is presented in Fig. 9. The 1-meter gas cell was
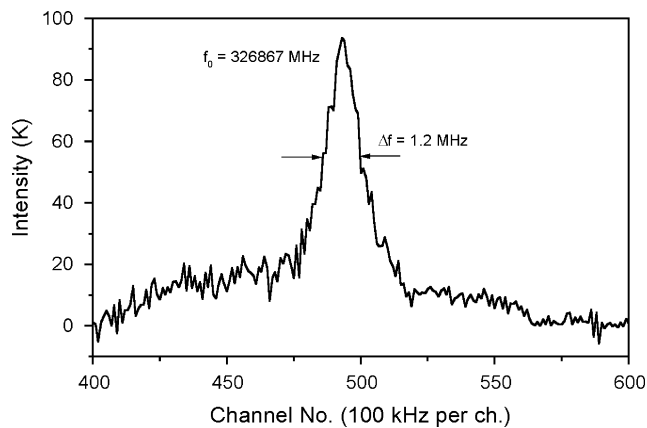
Fig. 10. Spectral line of SO_2 gas at pressure 0.03 mbar detected by superconducting integrated receiver with phase-locked Josephson oscillator (FFO). The data obtained using acousto-optical spectrometer.
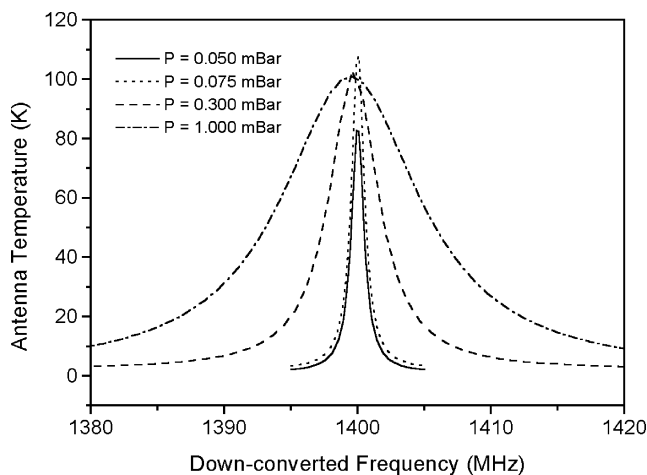

Fig. 11. Effect of broadening of SO_2 gas absorption spectrum at 326 867 MHz measured by PLL superconducting integrated receiver. The Lorencian fit to experimental data is used.

filled initially with SO_2 gas at pressure of a few mbar. Then the cell was pumping down to desired pressure within range of 0.03–1 mbar. The example of a SO_2 gas spectrum obtained with acousto-optical spectrometer (AOS) is presented in Fig. 10. The experimental data taken for different pressure were processed using the Lorenz fit similar to [5]. The effect of the linewidth broadening was clearly detected that is presented in Fig. 11.

III. CONCLUSION

A sensitive superconducting spectrometer on the base of an integrated externally phase-locked superconducting Josephson-type Flux Flow Oscillator (FFO) is developed for the first time. The spectrometer demonstrated capability of detection of low-pressure atmosphere contaminants like SO_2 gas, which is a by-product of the metallurgy industry. The resolution of the spectrometer, as tested with a gas cell using a back-end acousto-optical spectrometer, is better than 1 MHz and can be as good as 10 kHz that is demonstrated with CW source. To realize full potential of this new technology and reach the quantum noise limit of modern SIS receivers, further improvements of the chip are still necessary both in operation of the FFO and in design of the coupling circuit. 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 2005. The new technology has also good potentials in distant detection of different atmosphere contaminants including Chemical Warfare Agents (CWA).

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