SUPERCONDUCTING SUBMM INTEGRATED RECEIVER WITH PHASE-LOCKED LOCAL OSCILLATOR

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ABSTRACT

The Josephson Flux Flow Oscillator (FFO) has proven to be a perfect on-chip local oscillator for integrated submm receivers. Local oscillators based on Nb-AlO_x-Nb FFOs have been successfully tested from about 120 to 700 GHz (gap frequency of Nb) providing enough power to pump an SIS-mixer (about 1 μW at 450 GHz); both the frequency and the power of the FFO can be dc-tuned. Extensive measurements of the dependence of the free-running FFO linewidth on the differential resistances associated both with the bias current and the control-line current (applied magnetic field) have been performed. A profile of the FFO line was found to be Lorentzian both at Fiske steps (FS's) in the resonant regime and on the flux flow step (FFS) at high voltages. A phenomenological model of the FFO linewidth taking into account all known noise sources (both internal and external) is used to explain the FFO linewidth dependence on experimental parameters. The narrow enough free-running FFO linewidth in combination with the construction of a wide-band PLL system have enabled us to phase lock a FFO in the frequency range 490 – 712 GHz where continuous frequency tuning is possible.

The concept of a fully Superconducting Integrated Receiver (SIR) has been developed and experimentally realized. A single-chip submm wave receiver includes a planar antenna integrated with a SIS mixer, pumped by an internal superconducting Flux Flow Oscillator (FFO) as local oscillator (LO). A DSB noise temperature below 100 K has been demonstrated around 500 GHz. Heterodyne measurements have shown that the instantaneous bandwidth of the receiver is 15 – 20 %, which meets requirements for practical applications. The double-dipole lens-antenna SIS mixer has an antenna beam ≈ f/9 with sidelobes below - 16 dB. This enables an efficient coupling of the SIR to a telescope antenna. A compact array of 9 SIRs has been developed and tested. Each pixel contains an internally pumped receiver chip, which is mounted on the back of an elliptical silicon lens.

A breadboard of a superconducting integrated spectrometer with a phase-locked FFO has been tested showing that the frequency resolution of the full receiver is as low as 10 kHz at 364 GHz. The effect of broadening of a spectral line of SO_2 gas at 326,867 MHz is measured for a laboratory gas cell at 300 K within the pressure range of 30-300 mbar. 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.

Acknowledgements

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Introduction.

Lightweight and compact ultra-sensitive submm Superconducting Integrated Receivers (SIR) [1, 2] with low power consumption are very suitable for both radio-astronomical research and remote monitoring of the Earth atmosphere. The SIR is a single-chip device, which comprises an SIS-mixer with a quasioptical antenna and a superconducting local oscillator. Presently, the Flux Flow Oscillator (FFO) [3] based on unidirectional flow of magnetic vortices in a long Josephson tunnel junction is the best choice for integration with an SIS mixer. Nb-AlO_x-Nb FFO's can provide enough power to pump an SIS-mixer from 120 to 700 GHz. Both frequency and power of the FFO can be dc tuned [2, 4]. A receiver DSB noise temperature below 100 K has been achieved for a SIR with the FFO operated in the frequency range 480 - 520 GHz [2, 5]. An imaging array of nine SIRs has been developed and tested [2, 5].

The frequency resolution of a receiver is one of the major parameters in spectral radio astronomy. In order to obtain the required frequency resolution of at least one part per million and to allow interferometric measurements the local oscillator must be phase-locked to an external reference. Earlier, phase locking of a Josephson oscillator was demonstrated for a FFO, biased on resonant Fiske steps, in the frequency range 250 – 450 GHz [6]. In this case the initial free-running FFO linewidth (FWHP, full width, half power) is of about 1 MHz, significantly decreased by the geometric Fiske resonances. Obviously, these resonances make continuous frequency tuning difficult, but their influence can be almost completely diminished be proper design of the FFO and impedance matching circuits. An increase of the intrinsic linewidth at voltages $V > V_{JSC} = 1/3*V_{gap}$ (corresponds to frequency > 450 GHz for Nb-AlOx-Nb FFO) due to an abrupt increase of the internal damping [7] caused by Josephson self-coupling (JSC) considerably complicates phase locking of the FFO in this regime (V_{gap} is the superconducting gap voltage of the FFO).

FFO Linewidth

In order to study the conditions for phase locking of the FFO, its linewidth has been measured using a specially developed technique based on an integrated harmonic mixer [8]; see also [2, 4]. An unexplained superfine resonance structure on the FFO IVC was resolved by this technique [9]. This structure considerably complicates FFO phase locking. In order to avoid this structure and to realize permanent frequency tuning (at least along the Fiske steps) we have developed a new design of the FFO. The new FFO is tapered at both ends so that its width is decreased from 6 μm to 1.5 μm over a distance of 20 μm (see Fig. 1). As a result of this modification the resonant structure was almost suppressed. It should be noted that a tapered FFO has larger output impedance compared to the usual FFO of rectangular shape. This also simplifies the impedance matching to the microwave circuits.

The absence of the resonance structure enables detailed analysis of the free-running FFO spectrum. The FFO line profile has been measured in different regimes of FFO operation and compared to theoretical models. For this we use a frequency locking system with a relatively low loop gain (so called, frequency detector). Thus very low-frequency noise and drifts are eliminated by the narrow-band feedback and the "natural" linewidth, determined by much faster fluctuations, can be measured. The shape of the FFO spectrum provides important information about the relationship between internal and external fluctuations as well as the spectral distribution of these fluctuations. According to theory [10, 11] the line shape is Lorentzian for wideband fluctuations, whereas the profile will be Gaussian for narrow-band external electromagnetic interference, e.g. EMI with frequencies smaller than the free-running FFO linewidth δf_{AUT}. A Lorentzian shape of the FFO line has been observed both at higher voltages on the flux flow step (FFS) [12] and at Fiske steps (FS's) [13] in the resonant regime, see Fig. 2. This means that the free-running FFO linewidth in all operational regimes is determined by wideband thermal and shot noise fluctuations.

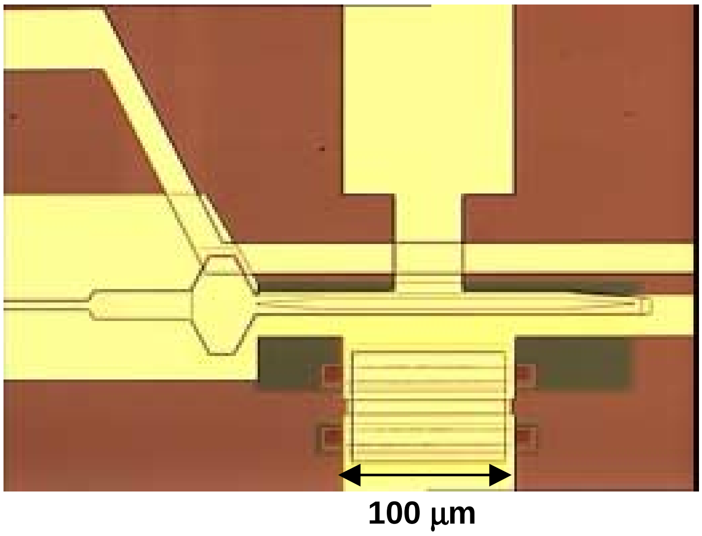

Fig. 1. Photo of the tapered FFO with separate control line for magnetic tuning.

According to theory [10, 11] the radiation linewidth of a small (lumped) Josephson oscillator is determined by the noise spectral power density, $S_I(0)$, of the bias current at low frequencies, $0 < f < \delta f_{AUT}$, where δf_{AUT} is the linewidth of the free-running junction. This noise spectral density is a nonlinear superposition of wide-band thermal and shot noise converted by the Josephson junction to low frequencies [10, 14]. The current noise is transformed into voltage (and consequently, frequency) fluctuations by the differential resistance, $R_d^B = \partial V/\partial I_B$, associated with the bias current I_B. The dependence of the calculate linewidth for the lumped tunnel junction is shown as curve 1 in Fig. 3. The experimental values of the FFO linewidth (asterisks in Fig. 3) are considerably larger than predicted [10, 14, 15]. Furthermore, there is a plateau where the linewidth does not decrease below a few hundreds of kilohertz while R_d^B decreasing below 0.003 Ω. To explain such behavior an additional noise contribution is needed; furthermore since the FFO line shape remains Lorentzian at FSs with small R_d^B we can conclude that this extra noise is wideband. Thus the standard noise model for lumped (short) tunnel junction is insufficient to explain the noise associated with the flux flow in the distributed long Josephson junction.

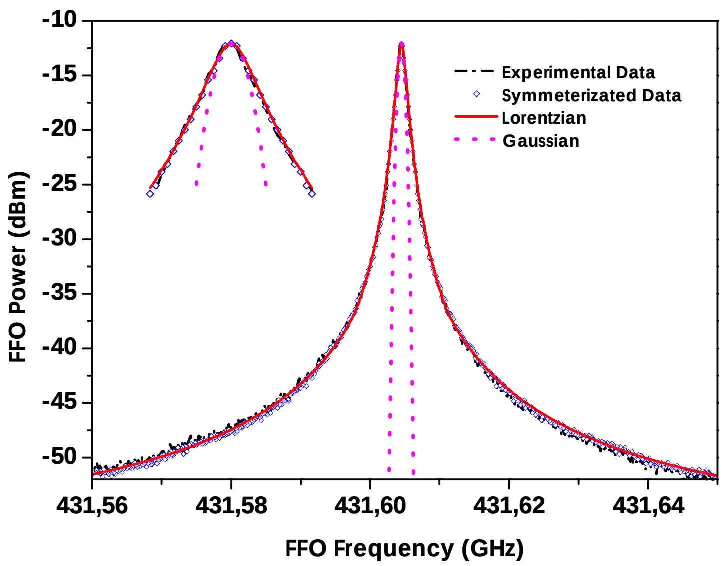

Fig. 2. FFO spectrum measured when biased on the Fiske step (V_{FFO} = 893 µV, R_d = 0.0033 Ω, R_d^{CL} = 0.00422 Ω, δf_{AUT} = 1.2 MHz) – dash-dotted line. The symmetrizated experimental data are shown by diamonds. Fitted theoretical Lorentzian and Gaussian profiles are shown by solid and dotted lines, respectively. The inset shows a zoom-in on the central peak with the frequency axis multiplied 5 times.

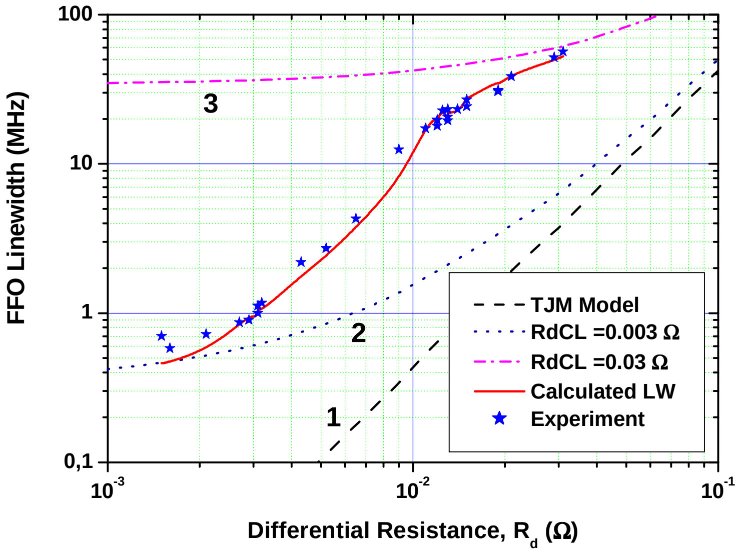

Fig. 3. Dependence of FFO radiation linewidth on the bias current differential resistance R_d^B. Curves 1 - 3 are calculated for the following parameters: V_{dc}= 1 mV, I_{qp}=3 mA, I_s=7 mA, T_{eff} = 4.2 K.

Recently an additional noise term, which accounts for the influence of the wideband noise in the bias current introduced via the magnetic field, has been added to form a phenomenological FFO model [12] (see also [16]):

$$\delta f = (2\pi/\Phi_0^2)\,(R_d^B + K^*R_d^H)^2\, S_i(0), \qquad (1)$$

where $R_d^H = \partial V_{FFO}/\partial I_H$ is the differential resistance associated with the magnetic field , and K is a coefficient of the order of unity. Note that $R_d^H = (\partial V_{FFO}/\partial I_{CL})/M$, where M is the mutual inductance between the control line and the FFO, I_{CL} is the current in the control line. This model allows us to calculate quantitatively the FFO linewidth in the whole operational range (see Fig. 3 – solid line). The calculated dependence of the linewidth of the lumped tunnel junction [10, 14] for the case of wide-band fluctuations only via I_B (K = 0) is shown in Fig. 3 by the dashed line 1), the dependence for fixed values of R_d^{CL} = 0.003 Ω and R_d^{CL} = 0.03 Ω are presented by the dotted and the dash-doted lines 2) and 3), respectively. The solid line is calculated for each experimental point taking into account all relevant parameters (I_B, V, R_d^B, R_d^{CL}, etc.). Indeed the calculations agree with the measured linewidth over the whole range of experimental parameters by using K =1 both on the Fiske steps and on the flux flow step. The fact that K =1 gives the best fit is not well understood yet, but it may relate to the geometry of the junction and the control line.

In order to phase lock the FFO one has to decrease the free running linewidth, which (in accordance to Eq. 1 and Fig. 3) is mainly determined by R_d^B and R_d^{CL}. New designs of the FFO have been developed to achieve this, one design is shown in Fig. 1. A typical set of the IVCs measured for a FFO with a new design is shown in Fig. 4. Data were recorded with incremented magnetic field. Each IVC was measured for a fixed control line current, I_{CL}, which is then incremented by $\Delta I_{CL} \approx$ 0.5 mA before the next IVC is recorded.

The FFO, as any Josephson junction, is a perfect voltage-controlled oscillator and hence its frequency can be stabilized and the FFO linewidth can be decreased by phase locking to an external reference source using a phase-lock loop (PLL) system with bandwidth larger than δf_{AUT}. Actually, a PLL system will effectively suppress the influence from external low frequency fluctuations and alter the differential resistances R_d^B and R_d^{CL} in the bias point. We have developed a special PLL unit utilizing an integrated SIS harmonic mixer to down-convert the FFO signal to a 400 MHz IF signal. After amplification the IF signal is compared to a 400 MHz reference signal in an analog phase detector, the output of which is fed to the FFO bias. All reference signals as well as the spectrum analyzer used to display the phase noise on the IF signal are phase-locked to a common 10 MHz reference oscillator. The PLL unit is optimized for operation with a low signal-to-noise ratio at a minimal time delay (measured delay of about 5 ns corresponds to a regulation bandwidth of 50 MHz). The bandwidth of the complete PLL system, Δf_{PLL}, is further limited to 15 MHz due to the delay in its 2 m long cables, but it still exceeds the free-running linewidth of the FFO with new design.

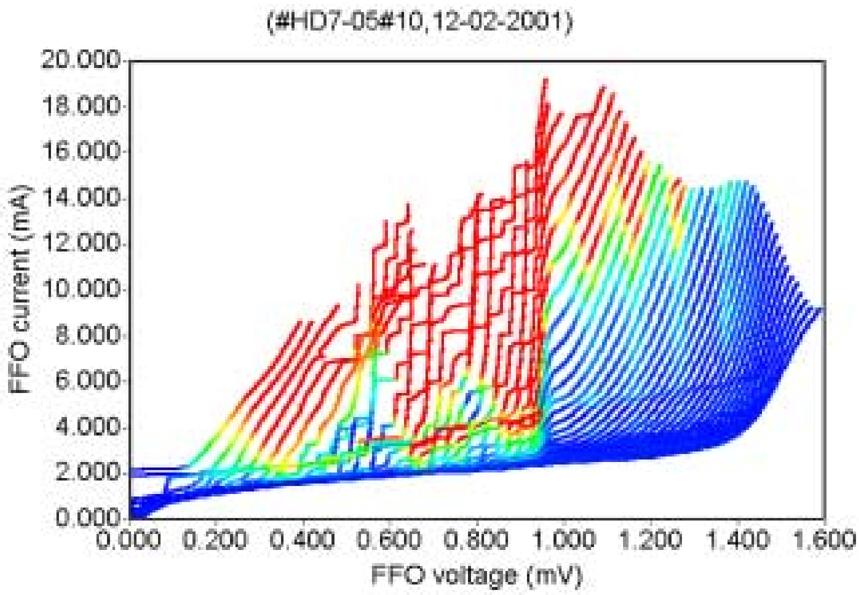

Fig. 43. IVCs of the FFO with new design, measured with incremented magnetic field (I_{CL} = 10–35 mA)

Earlier, phase locking of a Josephson oscillator was demonstrated in the frequency range 250 – 450 GHz [6] for a FFO biased on resonant Fiske steps. In this case the initial free-running FFO linewidth (FWHP, full width, half power) was only about 1 MHz due to the low dynamic resistance of the Fiske resonances. The new design of the FFO [12, 13] results in a decrease of the free-running FFO linewidth in the flux flow regime for $V > V_{JSC}$. Along with development of an improved wideband PLL system it enables us to phase lock FFO in the frequency range from 490 to 712 GHz, limited only by the gap value of the Nb-AlOx-Nb junction. Fig. 5 demonstrates the spectra of the frequency and phase locked FFO operating at 707 GHz. The “wings” at the curve "A" of Fig. 5a mark the frequency difference from the carrier at which the phase of the return signal from PLL system is shifted by π/2 that results in some increase of the phase noise.

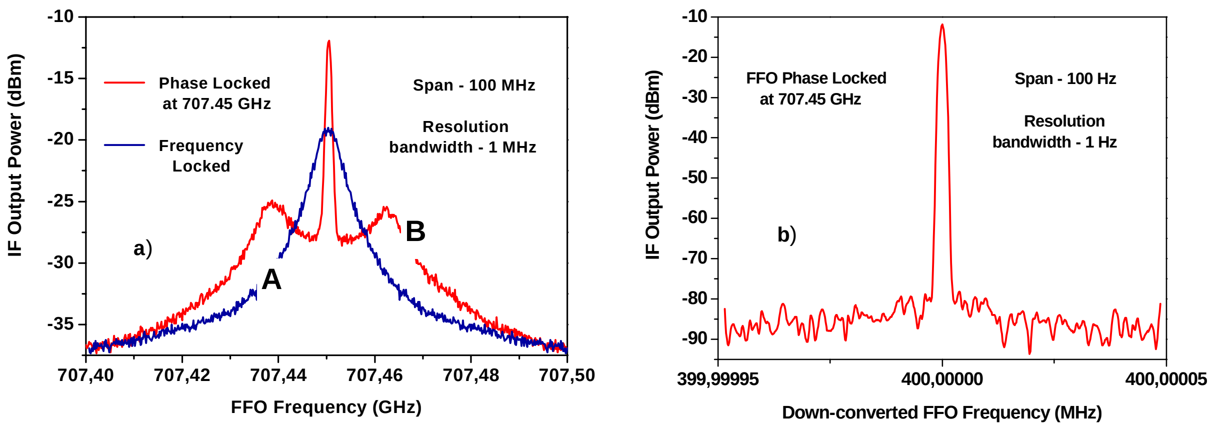

Fig. 5. Residual spectra of a FFO operating at 707.45 GHz. **(a)** Frequency locked FFO (A) and phase-locked FFO (B); the free-running linewidth is δf_{AUT} = 6.3 MHz, spectrum analyzer span 100 MHz. **(b)** Down-converted spectrum, span 100 Hz. T = 4.2 K

The PLL system, of course, cannot change the wide-band thermal and shot noise fluctuations, but it can diminish both differential resistances (at frequencies $f < \Delta f_{PLL}$) to zero. This manifests itself as a constant-voltage step in the dc I-V curve of the FFO. Note that a similar step with finite slope and larger voltage and current span appears when the FFO is frequency locked only. According to Eq. (1) the zero dynamic resistance created by the PLL system results in an infinitely sharp spectral line. Indeed, as seen in Fig. 5 b, a 1 Hz linewidth is measured at 707 GHz relative to the reference oscillator. The 1 Hz is an artifact caused by the limited frequency resolution of the spectrum analyzer. One can see that the residual phase noise is as low as 75 dB below the carrier. The dependence of the phase noise on the frequency offset from the carrier is shown with diamonds in Fig. 6. Even lower phase noise has been measured for a FFO in the resonant regime when biased on the steep Fiske steps, f = 450 GHz (see Fig. 6). In order to find the “absolute” (total) phase noise of the phase-locked FFO one should add the noise of the reference oscillator multiplied by n^2 where n is the harmonic number used in the harmonic mixing. The absolute FFO phase noise (solid lines in Fig. 6) is dominated by the reference oscillator noise for offsets < 1 MHz. Note that the measured phase noise already meets the requirements for single dish radio astronomy and atmospheric missions. It should be mentioned that the phase noise at large offsets probably is limited by the measuring system rather than by the FFO itself.

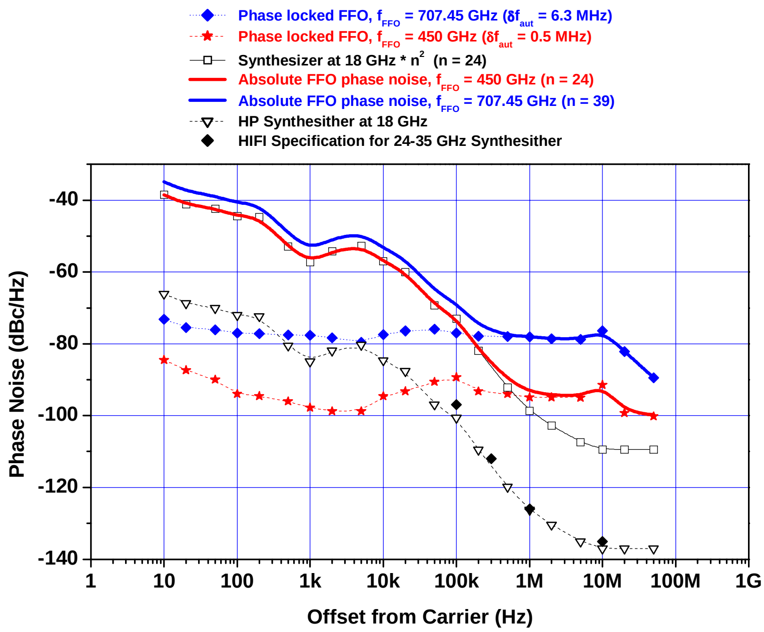

Fig. 6. **P**hase noise of a phase-locked FFO measured at different frequencies. Since the phase noise of the FFO is measured relative to the n^{th} harmonic of a synthesized oscillator, its noise, multiplied by a factor n^2, should be added to the residual FFO noise to get the total (absolute) FFO phase noise – solid and dash lines.

Integrated Receiver with Phase-Locked FFO.

Recent results on phase locking of a FFO to an external reference oscillator have been used to develop an integrated receiver with phase-locked loop [2, 4, 6]: a 350 GHz receiver chip containing a phase-locked flux flow oscillator, and two SIS mixers (a quasioptical SIS mixer, incorporated in a double-dipole antenna for signal detection, and a harmonic SIS mixer for FFO phase locking) has been designed [17], fabricated and successfully tested. The FFO is phase-locked to the n-th harmonic of a 10 GHz synthesizer source ($n \approx 30 - 35$). 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 ± 3 GHz are estimated experimentally while locking at 32-th harmonic of the reference source.

The microphotograph of the PLL SIR chip for 320-370 GHz band is presented in Fig. 7. The chip is mounted on the flat surface of the silicon microwave lens with antireflection coating. The chip mount is placed inside a magnetic shield. The block scheme of the experimental setup is described elsewhere [2, 4]. The signal from an external semiconductor harmonic multiplier driven by a different synthesizer has been used to test the integrated receiver with a spectral resolution as low as 10 kHz (see Fig. 8). Very recently a PLL integrated receiver has been tested successfully as a laboratory spectrometer using AOS as a back-end (see Fig. 9). Broadening of a SO_2 spectral line by increasing the gas pressure in a one-meter long gas cell has been measured in absorption at 326.867 GHz. This is the first demonstration of a spectrometer driven by a Josephson oscillator, which can be tuned precisely and locked at the frequency of a desired spectral line

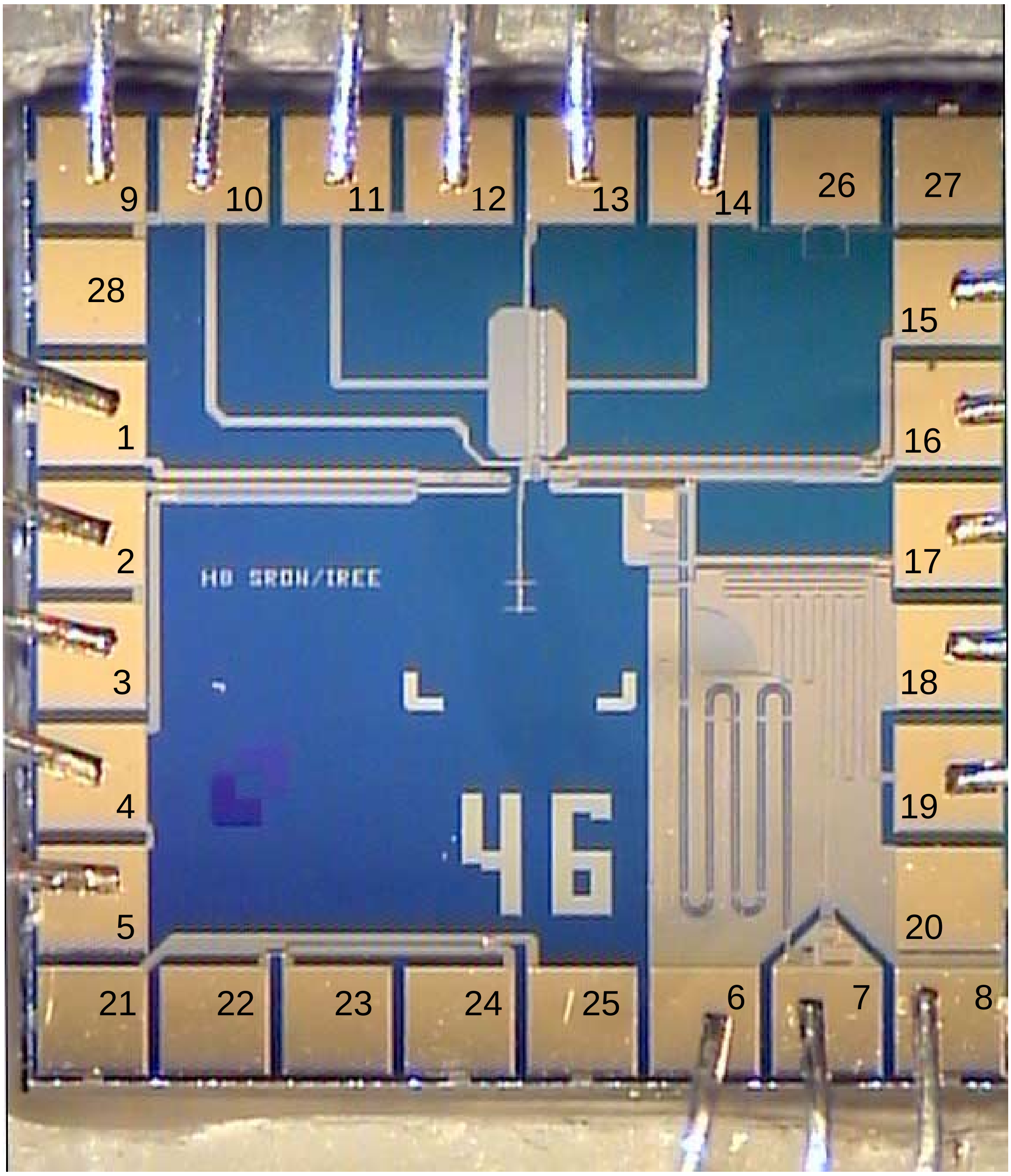

Fig. 7. Micro-photograph of the chip of the superconducting integrated receiver with phase-locked Josephson oscillator. The chip size is 4 mm by 4 mm. Contact pad destinations: (1), (2) SIS mixer bias / IF out; (3), (4) SIS control line; (5) bias for balanced mixer (optional); (6)-(8) reference signal 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.

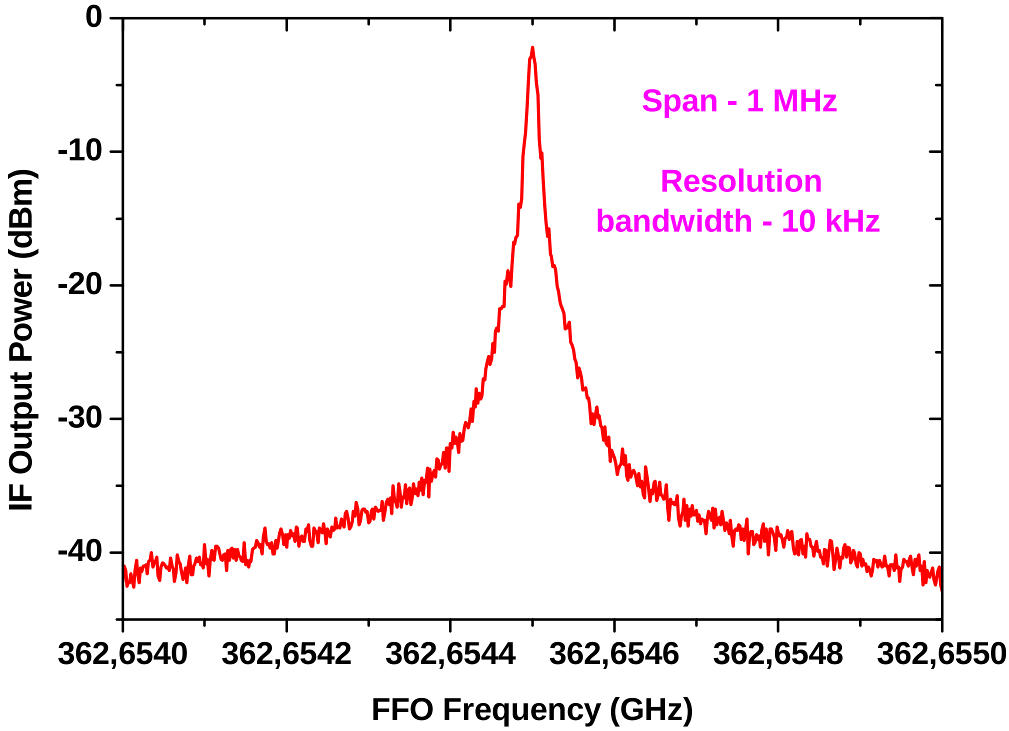

Fig. 8. The signal emitted by an external harmonic multiplier driven by synthesizer, the signal is measured by the integrated receiver with phase-locked FFO at 364.0545 GHz (IF = 1.4 GHz, low sideband).

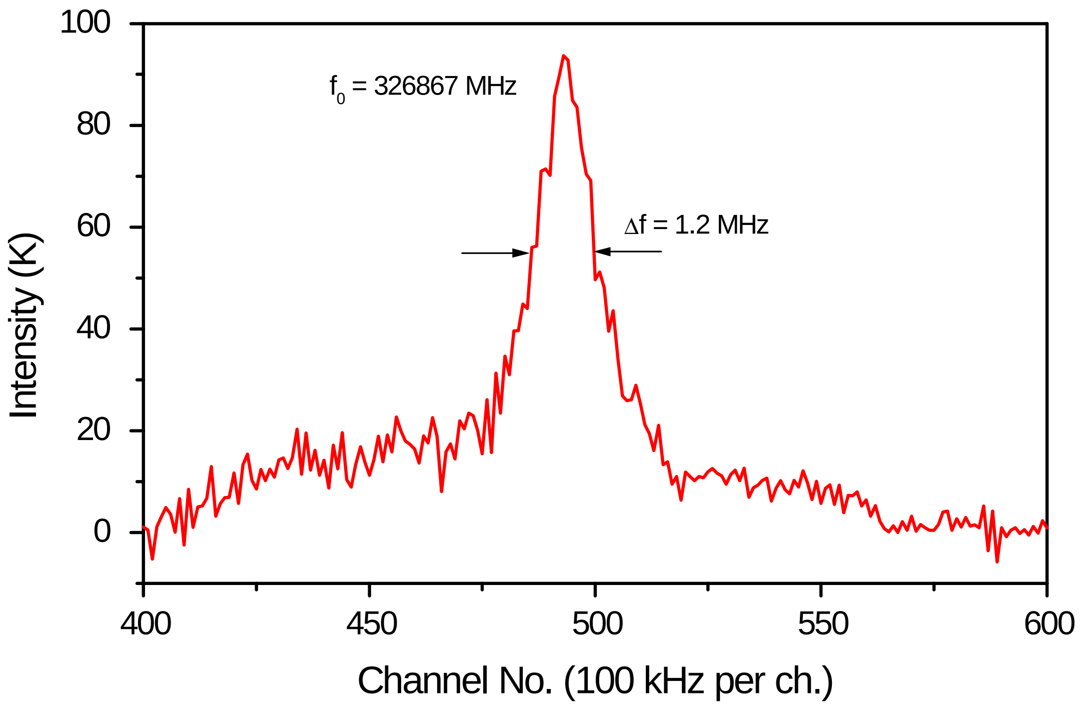

Fig. 9. Spectral line of SO_2 gas at pressure 0.03 mBar detected by superconducting integrated receiver with phase-locked Josephson oscillator (FFO). The data are processed using acousto-optical spectrometer.

A recent ESA study of observational requirements for future atmospheric chemistry missions concluded that improved observations from space of ClO, BrO and other trace gases would be required to understand how stratospheric ozone will respond to changing chlorine and bromine loadings and changing climate beyond 2008. A sub-millimetre wave limb-sounder with superconducting (SIS) receivers cooled to 4K could meet these requirements. These observations by 4K sub-mm and terahertz limb-sounders would be unique within the proposed timeframe as well as improving substantially on preceding satellite missions.

As a prelude to future spaceborne atmospheric sounding missions and in support of the above scientific rationale, funding has been secured by three European national institutes (DLR, SRON and RAL) to develop a high sensitivity, balloon borne atmospheric sounder that will allow simultaneous measurement of key molecular constituents within the stratosphere [18]. The instrument is called TELIS (TErahertz and submm LImb Sounder) and 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. The 650 GHz channel is being developed in cooperation between IREE and SRON and is based on a single-chip Superconducting Integrated Receiver (SIR). Tunability of the FFO shall allow for a wideband operation of this channel, with a goal to obtain 100 GHz instantaneous rf bandwidth or even more. The main parameters of this channel are listed in Table 1.

Table 1

##	Description	Base line	Goal
1	Input frequency range, GHz	600 - 650	500-650
2	Minimum noise temperature in the range (DSB), K	200	250
3	Output IF range, GHz	4 - 8	4 - 8
4	Spectral resolution (width of the spectral channel), MHz	1	1
5	Contribution to the nearest spectral channel by phased locked FFO (dynamic range of the spectrometer), dB	-20	-20
6	Contribution to a spectral channel by phased locked FFO at 4-6 GHz offset from the carrier, K	20	20
7	LO frequency net (distance between nearest settings of the PL FFO frequency), MHz	< 300	< 300
8	Dissipated power at 4.2 K stage (including IF amplifiers chain), mW	100	50
9	Operation temperature, K	< 4.5	< 4.5

Conclusion

A considerable narrowing of the free-running FFO linewidth (compared to all previous measurements) along with the construction of a wide-band PLL system have enabled us to phase lock a Nb-AlOx-Nb FFO in the frequency range 490 – 712 GHz where continuous frequency tuning is possible. An absolute FFO phase noise as low as –73 dBc and –69 dBc at 100 kHz offset from the carrier has been achieved at 450 and 707 GHz, respectively. This satisfies requirements for a single dish radio astronomy missions and atmospheric monitoring. The superconducting integrated receiver with phase-locked FFO has been tested in gas cell measurements and by external synthesizer, showing a frequency resolution better than 10 kHz at 364 GHz. 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 2005.

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