Superfine Resonant Structure on IVC of Long Josephson Junctions and Its Influence on Flux Flow Oscillator Linewidth

Valery P. Koshelets, Andrey B. Ermakov, Sergey V. Shitov, Pavel N. Dmitriev, Lyudmila V. Filippenko, Andrey M. Baryshev, Willem Luinge, Jesper Mygind, Vladimir L. Vaks, Dimitry G. Pavel'ev

***Abstract*—The Josephson Flux Flow Oscillator (FFO) has proven to be a perfect on-chip local oscillator for integrated submm receivers; a noise temperature (DSB) below 100 K has been achieved at 500 GHz. Recently a FFO linewidth as low as 1 Hz has been measured in the frequency range 270 - 440 GHz. A new technique for both linewidth measurements and phase locking of the FFO is developed; this method employs an off-chip harmonic multiplier. By measuring the frequency of the FFO radiation emission, its IV-curve can be reconstructed with an accuracy better than 1 nV. A superfine resonant structure with a voltage spacing of about 20 nV and extremely low differential resistance has been observed in the FFO IVCs. This resonant structure modifies the performance of the FFO compared to the one expected from the "averaged IV-curve". The influence of this resonant structure on phase locking is discussed. Also results of FFO phase noise measurements are presented.**

***Index Terms*—Josephson junctions, phase locked oscillators, submillimeter wave integrated circuits, superconducting devices**

I. INTRODUCTION

Light-weight and compact ultra sensitive submm-wave superconducting integrated receivers (SIR) with low power consumption [1], [2] are very attractive for both radio-astronomical research and remote monitoring of the Earth atmosphere. Presently, a Flux Flow Oscillator (FFO) based on unidirectional flow of magnetic vortices in a long Josephson tunnel junction [3] looks most promising as LO for on-chip integration with a SIS mixer. Nb-AlO$_x$-Nb FFOs, which have been successfully tested from about 120 GHz to 700 GHz – the gap frequency of Nb - deliver sufficient power (≈ 1 μW at 450 GHz) to pump a SIS mixer. Both frequency and power of the FFO can be tuned electronically [2]. A receiver noise temperature below 100 K (DSB) has been achieved for a SIR with an internal FFO operated in the frequency range 480 - 520 GHz [1], [2]. A FFO can be fabricated on the same trilayer - and by the same technological procedure - as a SIS mixer. Further, the complexity of a FFO circuit is much lower than known Josephson junction array oscillators. The most important issue to be proven before real FFO application, is the possibility of FFO phase locking at all frequencies of interest.

In this report we present a new technique for linewidth measurements and FFO phase locking, as well as the latest FFO linewidth measurements - including FFO phase noise.

Manuscript received September 18, 2000. This work was supported in part by the Russian SSP "Superconductivity", the RFBR projects 00-02-16090 and 00-02-16270, INTAS project 97-1712, ISTC project 1199, the Netherlandse Organisatie voor Wetenshappelijk Onderzoek (NWO) and the Danish Natural Science Foundation.

V. P. Koshelets, A. B. Ermakov, S. V. Shitov, P. N. Dmitriev, and L. V. Filippenko are with Institute of Radio Engineering and Electronics, Russian Academy of Science, Mokhovaya 11, 103907, Moscow, Russia, (telephone: 7-095-203-2784, e-mail: valery@hitech.cplire.ru)

A. M. Baryshev is with the Space Research Organization of the Netherlands (SRON), P.O. Box 800, 9700 AV Groningen, the Netherlands, on leave from Institute of Radio Engineering and Electronics, Moscow, Russia, (telephone: 31 (0)50 3634074, e-mail: andrey@)sron.rug.nl)

W. Luinge is with the Space Research Organization of the Netherlands (SRON), P.O. Box 800, 9700 AV Groningen, the Netherlands, (telephone: 31 (0)50 3634074, e-mail: W.Luinge@sron.rug.nl)

J. Mygind is with the Department of Physics, Technical University of Denmark, B 309, DK-2800 Lyngby, Denmark, (telephone: +45 4525 3268, e-mail: myg@fysik.dtu.dk)

V.L. Vaks is with Institute for Physics of Microstructure, Russian Academy of Sciences,GSP-105, 603600, Nizhny Novgorod, Russia (telephone: 7-8312-607648, e-mail: vax@ipm.sci-nnov.ru)

D. G. Pavel'ev is with Nizhny Novgorod State University, Gagarin Avenue 23, 603600 Nizhny Novgorod, Russia (telephone: 7-8312-656032, e-mail: pavelev@rf.unn.runnet.ru)

II. FFO LINEWIDTH MEASUREMENTS.

For spectral radio-astronomy applications besides the noise temperature and the antenna beam pattern also the frequency resolution of the receiver is a major parameter. The resolution, which is determined by both the instant linewidth of the local oscillator and its long-time stability should be much less than 1 ppm of the receiver center frequency. Previous measurements on linewidth of FFOs [4] - [10] have demonstrated the following values; 130 kHz at 70 GHz [4], about 1 MHz at 280 GHz [5], and 2.1 MHz at 320 GHz [6]. Unique time resolved measurements of FFO radiation were performed by using an Acousto-Optical Spectrometer (AOS) with an integration time of 1 μs; the linewidth of free-running FFO was less than 1 MHz at 350 GHz [7].

A reliable technique for linewidth measurements based on an integrated Josephson harmonic multiplier has been developed [8] and a free-running FFO linewidth of a few hundred kHz was measured in the submillimeter range. However, the observed FFO linewidth is almost one order of magnitude wider [8], [9] than predicted by the theory for a lumped Josephson tunnel junction. A simple model based on Josephson radiation self-coupling was introduced [9] to explain the experimental FFO linewidth.

The feasibility of phase locking the Josephson FFO to an external reference oscillator has been demonstrated experimentally [10]. With the FFO phase locked a linewidth as low as 1 Hz was measured relative to a reference oscillator in the frequency range 270 - 440 GHz. This linewidth is far below the "fundamental" level given by shot and thermal noise of the free-running tunnel junction.

The linewidth, Δf, of a Josephson junction is mainly determined by value of current fluctuations at low frequency. For white noise it can be written as:

$$\Delta f = (2\pi/\Phi_0^2)\,(R_d^B)^2\, S_i(0), \qquad (1)$$

where $S_i(0)$ is the density of the low frequency current fluctuations, $R_d^B = \partial V/\partial I_B$ is the dc differential resistance which transforms the current fluctuations to voltage (and phase) noise. Fluctuations in the external magnetic field can be accounted for by the differential tuning resistance of the control line $R_d^{CL} = \partial V_{FFO}/\partial I_{CL}$ for fixed dc bias current I_B. In the case of an *external interference* both the "usual" differential resistance R_d^B and R_d^{CL} "convert" low frequency external noise currents, $I_{lf}^{(B,\ CL)}$, to frequency fluctuations following the same relations:

$$\Delta f \propto R_d^{(B,CL)} * I_{lf}^{(B,CL)} \qquad (2)$$

A consequence of the phase locking is the appearance of a vertical step ($R_d^B = 0$) in the dc current-voltage characteristic (IVC) of the FFO at the voltage corresponding to the frequency f_{FFO} where the FFO is locked. The position of this step is insensitive to small changes in the control line current, that means also $R_d^{CL} = 0$. It results in zero radiation linewidth (see Eq. 1, 2) even at finite density of white current fluctuations and external interference.

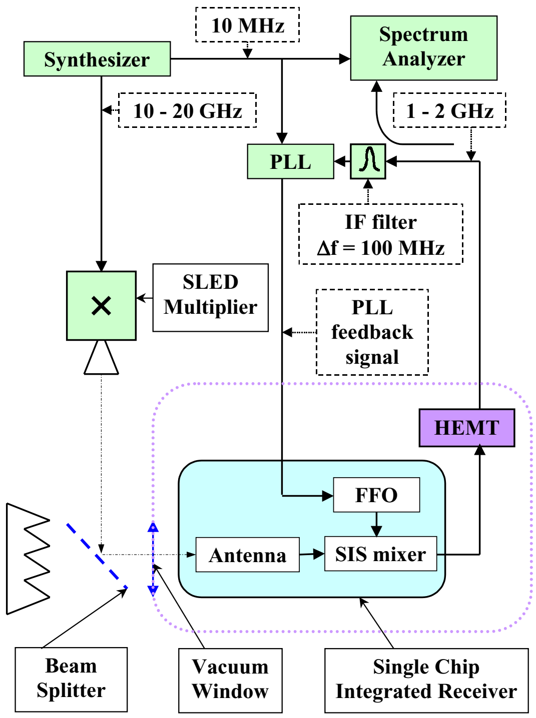

Fig. 1. Block Diagram of the Integrated Receiver (SIR) with Phase Locked FFO and External Harmonic Multiplier.

A. External Harmonic Multiplier

Previous FFO linewidth measurements [9], [11] have demonstrated at certain conditions the existence of a structure of closely spaced steps in the IVC of long Josephson junctions. The voltage spacing is about 20 nV, corresponding to a frequency separation of 10 MHz, that cannot be recorded by usual dc technique. This structure manifests itself as a nonlinear relation between the measured FFO frequency and the bias or/and control-line currents. In order to exclude that the recorded resonance structure could be due to the integrated harmonic mixer technique, an external harmonic multiplier based on a quasi-planar superlattice electronic device (SLED) [12] has been developed and tested. The SLED was mounted in a circular waveguide (with a cut-off frequency of about 400 GHz) followed by a conical horn with an output diameter of 6 mm. A constant-voltage bias and the pump signal from the synthesizer (frequency 5 - 22 GHz) are applied to the SLED. The signal of multiplier is fed to an integrated receiver of standard design [1], [2] via a vacuum window (see Fig. 1). Heterodyne mixing with the FFO local oscillator signal can be measured up to 500 GHz that corresponds to the 27-th harmonic of the input signal from the synthesizer ($f_S \approx 18$ GHz). Fig. 2 shows the down-converted FFO signals measured by this technique with the frequency locked - curve A- and phase locked – curve B).

The external harmonic multiplier enables us to check an alternative concept of the Phase Locked Integrated Receiver. This concept is based on an already proven design of the integrated receiver chip [1], [2]. In this approach a submm-wave signal from an external harmonic multiplier driven by a 10 - 20 GHz synthesizer is applied to the integrated receiver via a beam splitter. A small portion of the IF band (about 50 MHz) 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 PLL system while the rest of the IF band is used to analyze the down-converted signal. Here the development of a cryogenic multiplier looks very promising. The output power would be increased according to theoretical expectations, and a much thicker beam splitter can be used at cryogenic temperatures due to reduced losses.

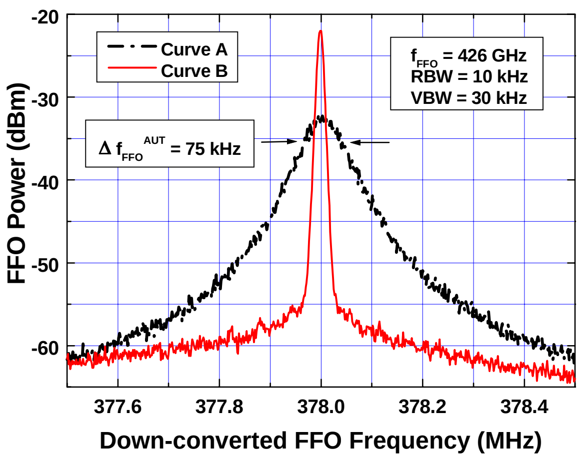

Fig. 2. Down-converted spectra of the FFO operated at 426 GHz; frequency locked (curve A) and phase locked (curve B).

III. SUPERFINE RESONANT STRUCTURE.

The superfine resonance structure is present also in the measurements done by the external multiplier, and thus the resonances can be attributed to properties of the FFO rather than to the measuring method. Generally an FFO can irradiate only in a specific range near the corresponding "resonance" frequencies, f_r, while the oscillator is unstable between these values. This behavior is clearly demonstrated in Fig. 3 (f_{synt} = 17.05 GHz, n = 25, Lower Side Band). Traces A and B are recorded at constant bias current: I_b = 17 782 µA and 17 779 µA, respectively (number of averages, N_{av} = 100). Point A is stable while an attempt to bias at point B fails due to small fluctuations which force the FFO to jump between stable states, spending on the average almost equal time in both states (see curve B).

Trace "C" in Fig. 3 illustrates this phenomenon in a different way; it is recorded when fine-tuning the FFO bias (from 18 710 µA to 18 770 µA) in the regime "max-hold". In this regime the spectrum analyzer takes the maximum signal amplitude from many measurements at each frequency point. One can see that FFO frequency can be permanently tuned only in a range of about 5 MHz, while frequencies between these stable regions cannot be obtained. Even a small change of the bias current near the edge of the stable region, the frequency (voltage) of the FFO "jumps" to the next stable region.

Using the Josephson equation the FFO IVC can be reconstructed in detail by measuring the bias current dependence of the FFO output frequency. The accuracy of the frequency (and correspondingly, voltage) measurement is determined by the spectrum analyzer resolution used for the specific span. For the data presented in Fig. 3, 4 the resolution bandwidth, RBW, was 300 kHz corresponding to a voltage accuracy of about 0.6 nV. By using a special measuring procedure the frequency reading from the spectrum analyzer was recorded simultaneously with adjusting I_b and I_{CL}. From these data the exact shape of the FFO can be reconstructed; the "recovered" FFO IVCs demonstrate the existence of a well-defined superfine structure (see Fig. 4). Up to now there is no reliable theoretical explanation of this superfine resonant structure. The exact geometry of the FFO influences the resonant structure, in particular, the results reported in [10] were measured for a tapered FFO where the resonance effect was less pronounced. The results depicted in Figs. 3, 4 are from an FFO with a standard rectangular overlap geometry.

From Fig. 4 one can see that the FFO IVC (at low levels of external interference) consists of a set of separate steps rather than being a continuous curve. The differential resistance on these steps is extremely low, R_d^B(res) = 0.00037 Ω. Important to note is, that this value is considerably lower than the average value (R_d^B = 0.0016 Ω) recorded using the traditional technique. An even more dramatic reduction has been measured for the control-line differential resistance, $R_d^{CL} = \partial V_{FFO}/\partial I_{CL}$ (0.0009 Ω and 0.0073 Ω respectively).

Note the extremely narrow linewidth ≈75 kHz (Fig. 2, curve A) was measured at a FFO frequency of 426 GHz due to extremely low differential resistance. Actually, this is the linewidth of the free-running FFO since it was recorded with a very narrow (< 10 kHz) PLL regulation bandwidth that only suppresses low-frequency external interference without changing the FFO linewidth (frequency locking).

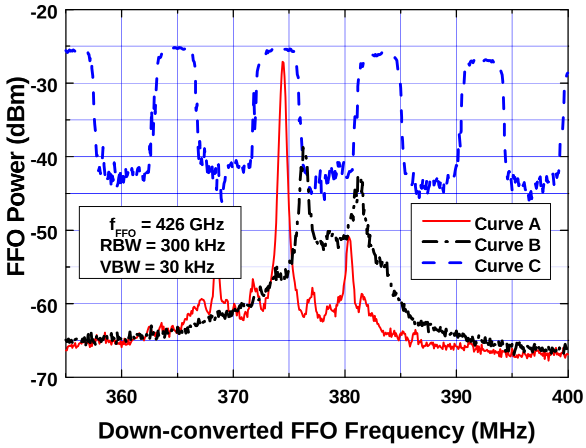

Fig. 3. Down-converted FFO signal recorded at constant bias current adjusted inside one of the resonances (curve A) and in between two resonances (curve B). Curve C is recorded with the FFO bias tuned in the "max hold" regime.

Since the frequency separation between adjacent resonances is comparable with the maximum PLL system bandwidth, jumps between adjacent resonances create considerable difficulties for phase locking of the FFO. Nevertheless full phase locking can be realized even in the presence of the resonance structures, but only at specific frequencies (see Fig. 2).

IV. FFO PHASE NOISE.

The residual phase noise of the phase locked FFO - measured relative to the reference synthesizer - is plotted in Fig. 5 for three different FFO frequencies as function of the offset from the 400 MHz carrier. One can see that there is no pronounced dependence of the phase noise on the frequency of the locked FFO. It means that the noise is mainly controlled by the measuring technique and the PLL system. To get the total FFO phase noise, one should add the synthesizer noise multiplied by n^2 to residual phase noise of

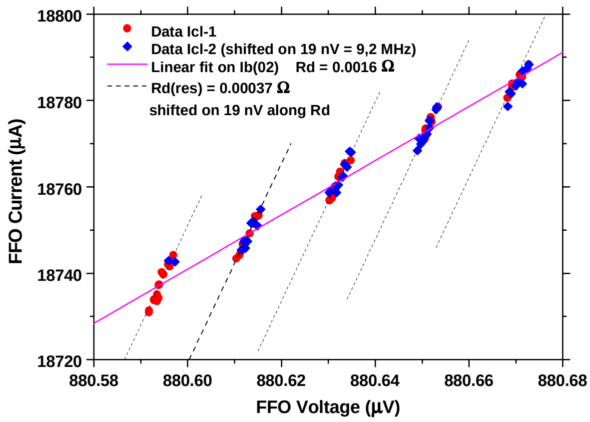

Fig. 4. Reconstructed IVC of the FFO. Data marked "I_{CL}-2" are measured at a slightly different I_{CL} value and corresponds to an adjacent resonance. These data are shifted by 19 nV along the Fiske step with slope $1/R_d^B$

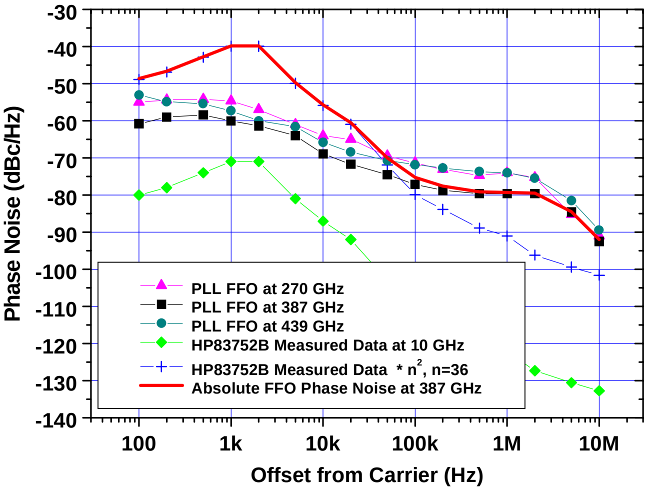

Fig. 5. Experimental phase noise of a phase locked FFO at different frequencies. Since the phase noise of the FFO, e.g., at 387 GHz is measured relative to the 36th harmonic of the synthesizer, the synthesizer noise, multiplied by a factor 36^2 = 1296, should be added to the residual FFO noise to get the total (absolute) FFO phase noise – solid line.

the FFO. The measured data for the synthesizer (HP83752B) are also presented in Fig. 5. In this measurement where the FFO, operating at 387 GHz, is locked to the 36-th harmonic of the synthesizer, n^2 = 1296. The total FFO phase noise (solid line in Fig. 5) is dominated by the synthesizer noise for offsets < 100 kHz. The origin of the noise at larger frequency offset is under investigation.

It should be noted that phase locking of a FFO has been realized only on the steep Fiske steps (FSs), where the free-running FFO linewidth is about 1 MHz corresponding to small values of R_d^B and especially R_d^{CL}, where $R_d^B = \partial V_{FFO}/\partial I_b$ and $R_d^{CL} = \partial V_{FFO}/\partial I_{CL}$ are the differential resistances associated with the bias current, I_b, and the control-line current, I_{CL}, respectively. The linewidth increases at voltages above the boundary voltage, V_{JSC}, [9] where R_d^B and R_d^{CL} are considerably larger than on the FSs (as a result of the abrupt increase of internal damping due to Josephson self-coupling [9]). It is still an experimental challenge to obtain phase locked operation in the "true" flux flow regime where the normalized damping is large, $\alpha L/\lambda_J \geq \pi$, and correspondingly, the initial FFO linewidth exceeds ≈ 10 MHz.

V. Conclusions

Preliminary tests demonstrate that there is no fundamental difference between results obtained by using either an integrated harmonic mixer or an external multiplier. The proper choice is a matter of convenience and relevance for the different applications. Phase locking of the FFO to an external reference oscillator is demonstrated experimentally using both measurement schemes. A FFO linewidth as low as 1 Hz (determined by the resolution bandwidth of the spectrum analyzer) has been obtained by both techniques in the frequency range 270 - 440 GHz relative to a reference oscillator. To our knowledge it is the first time that the spectral linewidth of any Josephson device has been reduced so much by means of an electronic system. The observed superfine resonance structure in the FFO IVC reduces the FFO linewidth due to smaller differential resistance, but complicates phase locking of the FFO.

Implementation of the single-chip Superconducting Integrated Receiver (SIR) with phase-lock-loop facilities is especially advantageous for new radio-astronomy projects based on an imaging array or multi-receiver approach (e. g., ALMA). The PLL Integrated Receiver is ready to be tested in the nearest future for practical spectral radio-astronomy in the frequency range 350 - 450 GHz.

Acknowledgment

Authors thank Thijs de Graauw, Hans Golstein Vladislav V. Kurin Mogens R. Samuelsen, Herman van de Stadt, Alexey V. Ustinov, Paul R. Wesselius, and Nick Whyborn for fruitful and stimulating discussions

References

[1] S.V. Shitov, A.B. Ermakov, L.V. Filippenko, V.P. Koshelets, A.B. Baryshev, W. Luinge, Jian-Rong Gao, "Superconducting Chip Receiver for Imaging Applications", *IEEE Trans. on Appl. Supercond.*, vol. 9, No 2, pp. 3773-3776, 1999.

[2] V.P. Koshelets, S.V. Shitov, "Integrated Superconducting Receivers", *Superconductor Science and Technology*, vol. 13, pp. R53-R69, 2000.

[3] T. Nagatsuma, K. Enpuku, F. Irie, and K. Yoshida, Flux-Flow type Josephson oscillator for millimeter and submillimeter wave region, *J. Appl. Phys.* vol. 54, pp. 3302-3309, 1983; see also Pt. II: *J. Appl. Phys.* vol. 56, p 3284; 1984; Pt. III: *J. Appl. Phys.* vol. 58, p. 441; 1985, Pt. IV: *J. Appl. Phys.* **63**, 1130, 1988.

[4] A.V. Ustinov, T. Doderer, R.P. Huebener, J. Mygind, V.A. Oboznov, and N.F. Pedersen, Multi-Fluxon effects in long Josephson junctions, *IEEE Trans. on Appl. Supercond.*, vol. 3, pp. 2287-2294, 1993.

[5] V.P. Koshelets, A.V. Shchukin, I.L. Lapytskaya, J. Mygind, Spectral linewidth of autonomous and injection-locked flux-flow oscillators, *Phys. Rev. B.* vol. 51, pp. 6536-6341, 1995.

[6] Y.M. Zhang, D. Winkler, and T Claeson, Linewidth measurements of Josephson flux-flow oscillators in the band 280-330 GHz, *Appl. Phys. Lett.* vol. 62, pp. 3195-3197, 1993.

[7] U. Muller, K. Jacobs, Proceeding of the 10th International *Symp. on Space Terahertz Techn*, Clarlottesville, USA, 1999 , pp. 13-28.

[8] V.P. Koshelets, S.V. Shitov, A.V. Shchukin, L.V. Filippenko, and J. Mygind, "Linewidth of submillimeter wave flux flow oscillators", *Appl. Phys. Lett.*, vol. 69, pp. 699-701, July 1996.

[9] V.P. Koshelets, S.V. Shitov, A.V. Shchukin, L.V. Filippenko, J. Mygind and A.V. Ustinov, "Self-pumping effects and radiation linewidth of FFO," *Phys. Rev. B*, vol. 56, pp. 5572- 5577, Sept. 1997.

[10] V.P. Koshelets, S.V. Shitov, L.V. Filippenko, V.L. Vaks, J. Mygind, A.B. Baryshev, W. Luinge, N. Whyborn, "Phase Locking of 270-440 GHz Josephson Flux Flow Oscillator", *Rev. of Sci. Instr.*, vol. 71, No 1, pp. 289-293, 2000.

[11] A.V. Ustinov, Physics Institute III, University of Erlangen-Nuernberg, D-91058, Germany, personal communication, 1992.

[12] E. Schomburg, R. Scheuerer, S. Brandl, K.F. Renk, D.G. Paveliev, Yu. Koschurinov, V. Ustinov, A. Zhukov, A. Kovsh, P.S. Kop`ev, *Electronics Letters*, vol.35, No.17, 1999.