ASC'98, Palm Desert. Report EQB-04

Flux Flow Oscillators for Sub-mm Wave Integrated Receivers

Valery P. Koshelets, Sergey V. Shitov, Alexey V. Shchukin, Lyudmila V. Filippenko, Pavel N. Dmitriev, Vladimir L. Vaks*
Institute of Radio Engineering and Electronics, Russian Academy of Sciences, Mokhovaya 11, 103907 Moscow, Russia
*Institute for Physics of Microstructure, Russian Academy of Sciences, GSP-105, 603600 Nizhny Novgorod, Russia

Jesper Mygind
Department of Physics, Technical University of Denmark, B309, DK-2800 Lyngby, Denmark

Andrey M. Baryshev, Willem Luinge, Hans Golstein
SRON-Groningen, P.O.Box 800, 9747 AV Groningen, the Netherlands

Abstract - **The results of a detailed study of the microwave linewidth of Nb-AlO$_x$-Nb flux flow oscillators (FFO) are presented. The dependence of the FFO linewidth on the junctions parameters has been measured by using an improved technique based on harmonic mixing in the frequency range 250 - 600 GHz. Experimental data are compared with theoretical estimates to evaluate the influence of the possible mechanisms responsible for the broadening of the FFO linewidth. The origins of the increased linewidth at the transition from the resonant to the "pure" flux-flow regime are discussed. The results of the linewidth measurements for the FFO locked via a wideband feedback loop are presented. The possibility of real phase locking of the Josephson oscillator has been demonstrated experimentally. A FFO linewidth as low as 3.3 kHz (determined by resolution bandwidth of spectrum analyzer) has been measured at 310 GHz; it is far below the fundamental level given by shot and thermal noise of the free-running tunnel junction.**

I. Introduction

The FFO [1] has proven to be a reliable wideband and easy tunable local oscillator suitable for integration with a SIS-mixer in a single-chip sub-mm wave receiver [2]. A DSB noise temperature below 100 K has been achieved for an integrated receiver with the FFO operating near 500 GHz [3]. For spectral radio-astronomy applications the frequency resolution of the receiver, which is determined by both the instant linewidth of the local oscillator and its long-time stability, should be better than 1 PPM of the center frequency. Recently a new simple and reliable technique for linewidth measurements has been developed [4] and a FFO linewidth of only few hundred kHz was measured. It was found [5] that the FFO linewidth appears to be about one magnitude larger than predicted by the theory for a lumped Josephson tunnel junction even at the resonant Fiske steps. Furthermore, an abrupt increase of the FFO linewidth at the voltages higher than the boundary voltage has been found experimentally [5]; this broadening accompanies the change in the damping in a tunnel junction. This boundary voltage V_b is about 1/3 of the gap voltage, 950 μV for Nb-AlO$_x$-Nb tunnel junctions. A simplified model based on Josephson radiation self-coupling [6] was introduced [5] to explain the experimentally measured FFO I-V curves. The effect of Josephson self-coupling (JSC) basically is absorption of *ac* Josephson radiation by the quasiparticles. This leads to the well-known phenomenon of photon assisted tunneling. The JSC results in current bumps at $V_{JSC} = V_g/(2n + 1)$, which gives $V_{JSC} = V_g/3$ for n = 1. The effect of self-pumping explains not only the FFO current bumps observed in the I-V curve, but also the abrupt transition of the Fiske steps (FS) at $V \approx V_g/3$ caused by the increase of the damping [5]. The geometric resonances (or FSs) exist for low normalized damping $\alpha l < 1$, where $l = L/\lambda_J$ is the junction length normalized to the Josephson penetration length λ_J. If the damping is sufficiently low (say, $\alpha \le 0.01$), this condition can be satisfied even for large normalized junction lengths, $l = L/\lambda_J \ge 60$. The FSs smear out (transition into the so-called Eck peak) when the damping increases to a value of about $\alpha l \ge 2$. This happens at $V_g/3 \propto V > 950$ μV where the FFO enters the "real" flux-flow regime.

In this report a numerical model of the FFO taking into account all known noise sources (both internal and external) has been developed and used for explanations of the FFO linewidth broadening. The decrease of the intrinsic FFO linewidth (determined by wide band thermal fluctuations) by using an electronic phase locked loop (PLL) has been demonstrated experimentally.

Manuscript received September 14, 1998

The work was supported in parts by the Russian Program for Basic Research, the Russian SSP "Superconductivity", the Danish Research Academy, the Danish Natural Science Foundation, the Netherlandse Organisatie voor Wetenshappelijk Onderzoek (NWO) grant and ESA TRP contract 11/653/95/NL/PB/SC.

E-mail: valery@hitech.cplire.ru

II. FFO linewidth

The oscillation linewidth Δf of a Josephson junction is mainly determined by low frequency current fluctuations. For white noise it can be written (see e.g. [7]) as:

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

where Φ_0 is the magnetic flux quantum, $S_i(0)$ is the density of the low frequency current fluctuations, and R_d is the dc differential resistance which transforms the current fluctuations to voltage (and phase) noise. For a lumped tunnel junction [8]

$$S_i(0) = (e/2\pi)\, I_{dc}(V_{dc}) \coth(v), \quad v = (eV_{dc})/(2\, k_B\, T_{eff}), \qquad (2)$$

where e is the electron charge, k_B is the Boltzmann's constant. I_{dc} and V_{dc} are the averaged normal current and voltage, and T_{eff} is the effective temperature of the quasiparticles in the junction electrodes. This formula describes a nonlinear superposition of thermal and shot noise. Expression (2) is modified for a distributed Josephson junction placed in a real experimental environment. First the supercurrent should be taken into account along with the normal current I_N. The power produced by the oscillating supercurrent is adsorbed both in the external circuitry and in the tunnel junction itself. The random absorption of the emitted photons leads to variations of the averaged supercurrent I_S. Consequently an additional term appears [7] in the spectral density (2):

$$S_i(0)_{FFO} = (e/2\pi)\ \{I_N \coth(v) + 2\ I_S \coth(2v)\}. \qquad (3)$$

The supercurrent itself can not be the source of fluctuations because of its reactive character; the additional term proportional to I_S appears due to the interaction of the supercurrent with the embedding circuit. It should be noted that the overall linewidth does not depend strongly on the used ratio between the super and normal current, especially at an increase of T_{eff} above 4.2 K.

Expression (1) should be modified to include the thermal noise in the biasing resistors, and external low frequency interference. The linewidth Δf has been calculated numerically taking into account all noise components including noise contributions from the bias and control line circuitry. The low frequency components of the current density $S_i(f)$ should be considered in this calculation. The cut-off frequency is determined by a resulting linewidth [7], this means that the linewidth has to be calculated self-consistently. The results of the calculations are shown in Fig. 1 for different experimental parameters. A superposition of shot and thermal noise of a tunnel junction ($\Delta f \propto R_d^2$) mainly determines the value of Δf at high R_d. The level of the external interference becomes dominant ($\Delta f \propto R_d$) at small R_d (below 0.01 Ω in our experiments). Furthermore the linewidth depends also on fluctuations in the external magnetic field described by the differential regulation resistance of the control line $R_d^{CL} = dV_{FFO}/dI_{CL}$. The integrated control line in the base or counter electrode is used for the adjustment of the magnetic field in the FFO. The value of R_d^{CL} determines Δf at $R_d^{CL} > R_d$, and a plateau appears in the $\Delta f(R_d)$ dependence. The R_d^{CL} value is very low when biased on Fiske steps (about 0.005 Ω) and increases considerably between steps. At $V > V_b$ in the "pure" flux-flow regime R_d^{CL} is about 0.1 Ω and does not depend noticeably on voltage. The noise contribution caused by R_d^{CL} becomes dominant at $V > V_b$ even at large R_d, see Fig. 1. The calculated FFO linewidth versus R_d is shown in Fig. 1 for two values of R_d^{CL} above and below V_b. The value of the external low frequency interference corresponding to a current fluctuation $I_{fl} = 0.08\ \mu A$ is used in the calculations.

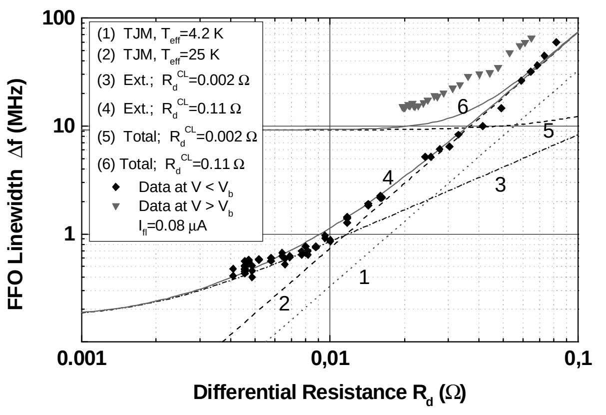

Fig. 1 Numerically calculated dependencies of FFO linewidth on differential resistance R_d: (1), (2) – Tunnel Junction Model for T_{eff} = 4.2 and 25 K correspondingly; (3), (5) – external interference and (4), (6) – resulting FFO linewidth at $I_{fl} = 0.08\ \mu A$ and R_d^{CL} = 0.002 and 0.11 Ω. Experimental data for $V < V_b$ and $V > V_b$ are shown by diamonds and triangular.

The experimental data from Ref. [5] measured in different regimes are also shown in Fig. 1 for comparison. One can see that the experimental data taken below V_b agree well with calculations at T_{eff} = 25 K. This large effective temperature may be due to absorption of the FFO Josephson radiation by quasiparticles in the Niobium electrodes. The quasiparticles could be heated above the bath temperature ("hot electrons") due to the finite electron-phonon interaction time. The data for $V > V_b$ deviate noticeably from the calculated. A fit is only possible with a 5 times increase of the calculated linewidth. This large linewidth broadening corresponds to T_{eff} = 60 K. According to our numerical calculations the level of self-pumping eV_{rf}/hf is decreasing with the FFO voltage, so we can not attribute this additional increase of the linewidth to further rise of the electron temperature.

The linewidth increase in the non-resonant regime may be explained by a model recently proposed by Golubov et al. [9]. This model accounts for the fluctuations in the inter-fluxon spacing in the moving fluxon chain under the influence of non-correlated spatially distributed thermal noise in the junction. According to the theory [9] the broadening is significant at large fluxon velocities and small normalized magnetic fields where the fluxon chain is "soft". The experimental broadening of the FFO linewidth, however, is much smaller than predicted by [9]. Probably on the FS in the resonant regime the standing electromagnetic waves "regulate" the fluxon motion and reduce their degree of freedom. Even at $V > V_b$ it is possible to suppress this broadening by additional resonant elements externally connected to the FFO [10].

According to [7] the radiation linewidth could be affected by changing the spectral density or differential resistance at considerably low frequencies $f < \Delta f$. This can be done by: i) appropriate shunting at low frequencies (provided that the impedance of the shunt $Z_{sh}(f) >> Z_{FFO}$ at high Josephson oscillation frequency); ii) modification of the high frequency imbedding impedance in such a way that R_d is decreased [10], [11]; iii) suppression of the current fluctuation by an external phase locking (PLL) system with bandwidth > Δf.

III. EXPERIMENTAL DETAILS AND RESULTS

An integrated circuit comprising FFO, SIS mixer and matching elements is used to measure the FFO linewidth. Overlap Nb-AlO_x-Nb junctions (length L 500 µm, width W about 3 µm, current density 5-8 kA/cm^2) are used for the FFO. The details of the circuit design are published elsewhere [4], [5]. A block diagram of the set-up for linewidth measurements is shown in Fig. 2. In order to measure the FFO linewidth in a wide frequency range up to 600 GHz a new experimental technique [4] was used. The mm-wave signal coming from the FFO is mixed in the harmonic SIS mixer with the n-th harmonic of the external reference synthesizer. In order to prevent the external oscillator signal (as well as its harmonics) from reaching the FFO a high-pass microstrip filter with cut-off frequency of about 200 GHz is employed. The intermediate frequency (IF) signal, $f_{IF} = \pm(f_{FFO} - n\, f_{SYN})$ is amplified in a cooled amplifier (T_n of about 20 K, gain 27 dB). After additional room temperature amplification the signal enters the PLL system. In this unit the signal frequency is divided by four and in a Frequency-Phase Discriminator compared with a 100 MHz reference signal. Via the Loop Bandwidth Regulator (maximum bandwidth 10 MHz) the output signal proportional to the phase difference is applied back to the FFO through the coaxial cable and the cold 50 Ω resistor mounted on the bias plate. The same coaxial cable entering the cryostat is used both for the 10 GHz synthesizer signal and the PLL control output. The couplers with microstrip filter are used to combine and split these signals. The PLL output signal can be connected both to the FFO bias and the magnetic field control line. In order to perform accurate linewidth measurement, the IF spectra have to be averaged with a sufficiently small video bandwidth (~ 10 kHz). Due to the high tuning coefficient even a relatively small low frequency drift of the control line and/or dc bias currents results in a significant shift of the FFO frequency leading to a smearing of the averaged linewidth. The PLL system with a relatively narrow bandwidth setting (< 10 kHz) was used for frequency locking of the FFO to the 10 GHz synthesizer in order to measure the autonomous FFO linewidth Δf^{AUT}. In this case the shape of the measured linewidth is unchanged, but the signal is stable in frequency. The measured FFO linewidth spectra in different operational regimes are shown in the Fig. 3.

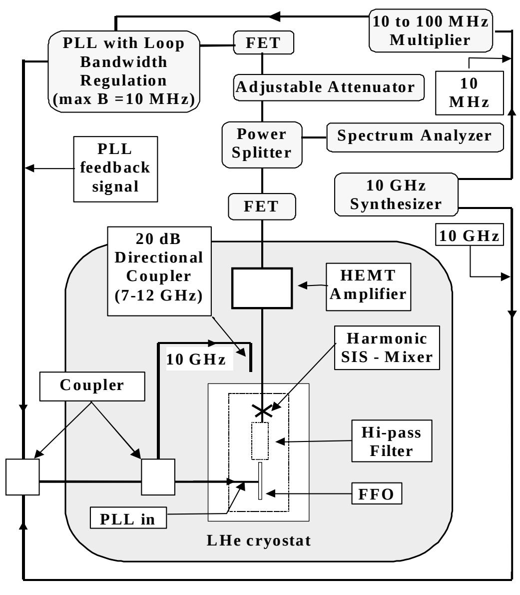

Fig. 2 Block-diagram of the set-up for linewidth measurements.

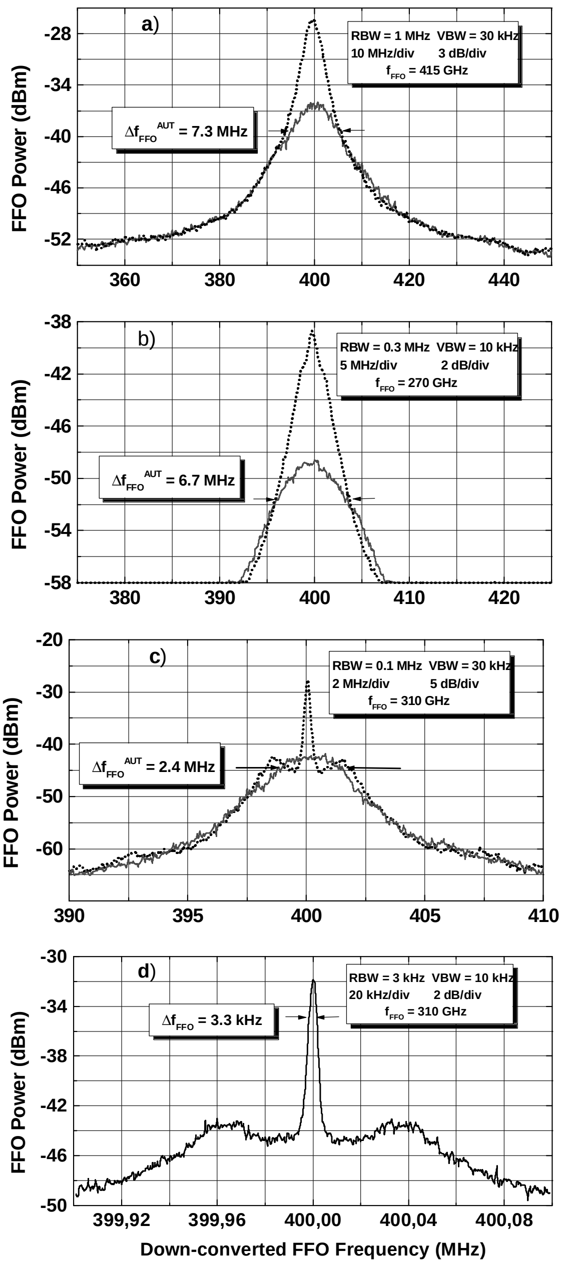

Fig. 3 IF power spectra of the FFO operating at different regimes.

It was experimentally found that the PLL system can considerably decrease the FFO linewidth if the Δf^{AUT} at the 3 dB level is initially lower than the PLL regulation bandwidth B^{PLL}. In the opposite case where $\Delta f^{AUT} > B^{PLL}$ only frequency locking without a noticeable linewidth change was possible. The FFO spectra are shown in Fig. 3a-c for the minimal and the optimal B^{PLL} at different initial Δf^{AUT} (FFO frequency 270 - 420 GHz). At a Δf^{AUT} of about B^{PLL} (Fig. 3a, $\Delta f^{AUT} \approx 7.5$ MHz) there is a 10 dB increase of the FFO power at the central frequency while the 3 dB FFO linewidth is reduced by 3 times. A sharp peak appears at the central frequency (Fig. 3b) with further decreasing of the Δf^{AUT} (different values of R_d and R_d^{CL} were used). The real phase locking takes place at $\Delta f^{AUT} \approx 2.5$ MHz (Fig. 3b, c), in this case 99% of FFO power initially present in a band of 25 MHz. A FFO linewidth as low as 3.3 kHz is presented in Fig. 3d. This value actually is determined by the resolution bandwidth of the spectrum analyzer. It means that the FFO linewidth can be reduced below the value determined by fundamental shot and thermal fluctuations of a tunnel junction.

It should be noted that a vertical step appears in the FFO IVC ($R_d = 0$) with the FFO locked. The position of this step is insensitive to small changes in the control line current, so that $R_d^{CL} = 0$ as well. A regulation range in the FFO bias voltage as large as 1.5 μV has been experimentally measured. This corresponds to a PLL regulation band of about 750 MHz.

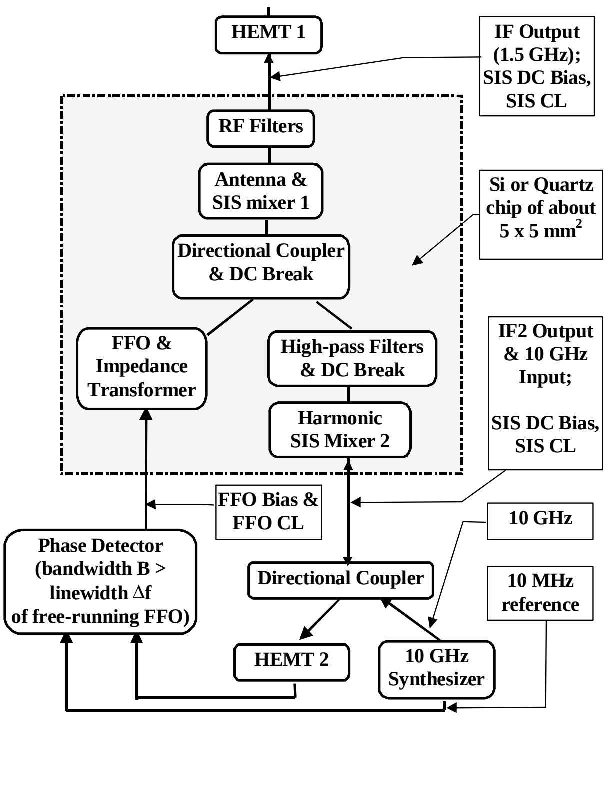

Fig. 4 Proposed block-diagram of the phase locked Integrated Receiver.

The developed technique for FFO phase locking could be used in the Integrated Receiver, a possible block diagram of such receiver is shown in Fig. 4. In this concept two separate SIS mixers are connected to the same FFO and placed on one chip-receiver. For operation at all FFO voltages including $V > V_b$ an additional shunt should be used to decrease the initial FFO linewidth. Also an ultra-wide band PLL system with sufficiently small phase noise is needed.

IV. Conclusion

A numerical model taking into account all known noise components of the FFO integrated in the real experimental circuit has been developed. This model was used for quantitative analysis of the FFO linewidth measurements. All the results listed above demonstrate our ability to decrease the intrinsic linewidth of a Josephson oscillator by an external electronic PLL system, provided that the PLL bandwidth is larger than the initial oscillator linewidth.

Authors thank Th. de Graauw and N. D. Whyborn for fruitful discussions.

References

[1] 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, pp. 3284, 1984; Pt. III, *J. Appl. Phys.*, vol. 58, pp. 441, 1985; Pt. IV, *J. Appl. Phys.*, vol. 63, pp. 1130, 1988.

[2] V.P. Koshelets, S.V. Shitov, L.V. Filippenko, A.M. Baryshev, W. Luinge, H. Golstein, H. van de Stadt, J.-R. Gao, T. de Graauw, "An Integrated 500 GHz Receiver with Superconducting Local Oscillator", *IEEE Trans. on Appl. Supercond.*, vol. 7, pp. 3589-3592, 1997.

[3] 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", this conference, report EMA-09.

[4] 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.

[5] 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.

[6] L.-E. Hasselberg, M.T. Levinsen, M.R. Samuelsen, "Theories of subharmonic gap structures in superconducting junctions," *Phys. Rev. B*, vol. 9, pp. 3757-3765, 1974.

[7] K.K. Likharev, Dynamics of Josephson junctions and circuits, Gordon and Brench Science Publichers, 1986.

[8] M.J. Stephen, "Noise in the ac Josephson effect," *Phys. Rev.*, vol. 182, pp. 531-538, 1969.

[9] A.A. Golubov, B.A. Malomed, and A.V. Ustinov, "Radiation linewidth of a long Josephson junction in the flux-flow regime," *Phys. Rev. B*, vol. 54, pp. 3047-3050, 1996.

[10] V.P. Koshelets, S.V. Shitov, S.V. Shchukin, I.V. Abramova, J. Mygind, A.V. Ustinov. "Self-Pumping Effects and Radiation Linewidth of FFO", Proceedings of the ISEC'97, Berlin, Germany, June 26-29, vol 3, pp 210-212, 1997.

[11] A.B. Baryshev, A.V. Yulin, V.V. Kurin, V.P. Koshelets, S.V. Shitov, A.V. Shchukin, P.N. Dmitriev, L.V. Filippenko, "Cherenkov Flux-Flow Oscillators: Output Power and Linewidth", this conference, report ELD-05.