Externally Phase-Locked Flux Flow Oscillator for Submm Integrated Receivers: Achievements and Limitations

Valery P. Koshelets, Sergey V. Shitov, Pavel N. Dmitriev, Andrey B. Ermakov, Alexander S. Sobolev, Mikhail Yu. Torgashin, Victor V. Khodos, Vladimir L. Vaks, Paul R. Wesselius, Pavel A. Yagoubov, Carsten Mahaini, and Jesper Mygind

***Abstract*—A Josephson Flux Flow Oscillator (FFO) is the most developed superconducting local oscillator for integration with an SIS mixer in a single-chip submm-wave receiver. Recently, using a new FFO design, a free-running linewidth ≤ 10 MHz has been measured in the frequency range up to 712 GHz, limited only by the gap frequency of Nb. This enabled us to phase lock the FFO in the frequency range 500–712 GHz where continuous frequency tuning is possible; resulting in an absolute FFO phase noise as low as -80 dBc at 707 GHz. Comprehensive measurements of the FFO radiation linewidth have been performed using an integrated SIS harmonic mixer. The influence of FFO parameters on radiation linewidth, particularly the effect of the differential resistances associated both with the bias current and the applied magnetic field has been studied in order to further optimize the FFO design. A new approach with a self-shielded FFO has been developed and experimentally tested.**

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

I. Introduction

SUBMM Superconducting Integrated Receivers (SIR) [1], [2] are very suitable for both radio-astronomical research and remote monitoring of the Earth atmosphere due to their ultimate sensitivity, compactness and low power consumption. The SIR is a single-chip device, which comprises an SIS-mixer with a quasioptical antenna and a superconducting local oscillator. Presently, a Flux Flow Oscillator (FFO) [3] based on unidirectional flow of magnetic vortices (fluxons) in a long Josephson tunnel junction is the best choice for integration with an SIS mixer. Nb-AlO$_x$-Nb FFO's have been successfully tested as local oscillators from 120 to 700 GHz (the 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 [2], [4]. A receiver double side band (DSB) noise temperature below 100 K has been achieved for a SIR with the FFO operated at 520 GHz [2], [5].

The frequency resolution of a receiver is one of the major parameters in spectral radio astronomy. To obtain the required frequency resolution the local oscillator must be phase-locked to an external reference. 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 [6]. An unexplained superfine resonance structure in the FFO IV-curves (IVC's) was resolved by this technique [7]. This structure considerably complicates FFO phase locking. In order to avoid this structure and to realize continuous in-lock frequency tuning we have developed a new design of the FFO [8], [9]. 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. 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 simplifies the impedance matching to the microwave circuits.

II. FFO Line Shape and Autonomous Linewidth

The absence of the resonance structure enables detailed analysis of the shape of the free-running FFO spectrum in different regimes of FFO operation. A frequency locking system with very narrow bandwidth (a so called frequency detector) is used. This eliminates very low-frequency noise and drift, and allows us to measure the "natural" linewidth, determined by the much faster fluctuations. 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. The line shape is Lorentzian for wide-band fluctuations [10], [11], whereas the profile is Gaussian for narrow-band external electromagnetic interference, e.g., electro-magnetic interference (EMI) with frequencies smaller than the free-running FFO linewidth δf_{AUT}. A Lorentzian shape of the FFO line has been observed at higher voltages on the flux flow step (FFS) [9] as well as at smaller voltages on the Fiske steps (FS's) [8] in the resonant regime. This means that the free-running FFO linewidth in all operational regimes

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V. P. Koshelets, S. V. Shitov, P. N. Dmitriev, A. B. Ermakov, A. S. Sobolev, and M. Yu. Torgashin are with Institute of Radio Engineering and Electronics, Russian Academy of Science, Mokhovaya 11, 101999, Moscow, Russia (e-mail: valery@hitech.cplire.ru).

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

P. R. Wesselius and P. A. Yagoubov are with the Space Research Organization of the Netherlands (SRON), 9700 AV Groningen, The Netherlands (e-mail: P.A.Yagoubov@sron.rug.nl).

C. Mahaini and J. Mygind are with the Department of Physics, Technical University of Denmark, B 309, DK-2800 Lyngby, Denmark (e-mail: myg@fysik.dtu.dk).

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is determined by wideband thermal and shot noise fluctuations. This is different from many traditional microwave oscillators where the "natural" linewidth is very small and the observed linewidth can be attributed mainly to external fluctuations.

According to theory [10], [11] the radiation linewidth of a small (lumped) Josephson oscillator can be accounted for by including current fluctuations with spectral power density, $S_i(0)$. This noise spectral density $S_i(0)$ is a nonlinear superposition of wide-band thermal and shot noise converted by the Josephson junction to low frequencies $0 < f < \delta f_{\mathrm{AUT}}$ [10], [12]. 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. In a long Josephson junction with flux flow, fluctuations in the moving fluxons chain may also result in additional FFO linewidth broadening [13], [14]. Nevertheless, as stated in [15], the expression for the lumped junction linewidth similar to [10], [12] might be valid also for the long distributed Josephson junction. The experimental values of the FFO linewidth [4], [8], [16], however, are considerably larger than predicted by the short tunnel junction model (TJM) [10], [12], [15]. Furthermore, the dependence of the measured linewidth on the differential resistance does not follow a square law $(R_d^B)^2$ in the whole range of experimental parameters [4], [8]. At low R_d^B values at Fiske steps there is a plateau where the linewidth does not decrease below a few hundred kilohertz. To explain such behavior an additional noise contribution is needed. Furthermore since the FFO line shape remains Lorentzian at FS's with small R_d^B [8] 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 of distributed long Josephson junction.

Recently, an additional noise term, which accounts for the influence of the wideband noise associated with the magnetic field control line (CL), has been added to form a phenomenological FFO model [8] (see also [17]):

$$\delta f = \left(2\pi/\Phi_0^2\right)\left(R_d^B + K R_d^H\right)^2 S_i(0), \tag{1}$$

where $R_d^H = \partial V_{\mathrm{FFO}}/\partial I_H$ is the differential resistance associated with the magnetic field, and K is a coefficient of the order of unity. Note that $R_d^H = R_d\mathrm{CL}/M$, where $R_d^{\mathrm{CL}} = \partial V_{\mathrm{FFO}}/\partial I_{\mathrm{CL}}, M$ 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 solid line in Fig. 1). The calculated dependence of the linewidth of the lumped tunnel junction [10], [12] for the case of wide-band fluctuations only via I_B $(K = 0)$ is shown in Fig. 1 by the dashed line. The solid line is calculated for each experimental point taking into account all relevant parameters (I_B, V, R_d^B, R_d^H, 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 understood, and has to be further studied.

It should be noted that the measured linewidth depends on experimental parameters in a very similar way for different FFO designs. It means that radiation linewidth is fully determined by the easily measured dc FFO parameters taken from the I-V curves and may be estimated without complicated high frequency measurements. For our FFO designs, usually R_d^H is considerably larger than R_d^B and thus determines the linewidth value. Details of a systematic study of the dependence of R_d^H and R_d^B values on FFO design and electrical parameters will be presented elsewhere; here we only discuss some of the obtained results.

The dependence of R_d^B and R_d^H on the FFO voltage (measured from dc IVC) is shown in Fig. 2 for three different bias currents, I_B [19]. First of all both R_d^B and R_d^H appear to be almost independent on I_B in the wide range of bias currents which are optimal for FFO operation. R_d^B is small and almost independent on voltage for FFO frequencies in the range 500–700 GHz. On the other hand Fig. 2 shows a well-defined dependence of R_d^H on bias voltage (FFO frequency). The R_d^H value increases approximately 2.5 times when decreasing the FFO

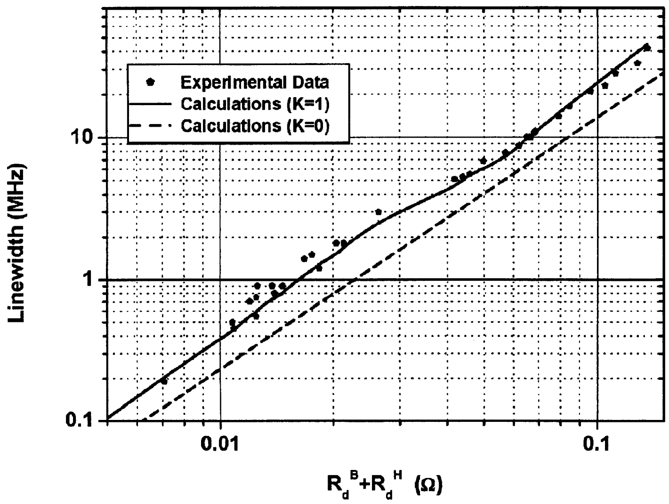

Fig. 1. Dependence of FFO radiation linewidth on the sum of differential resistances $R_d^B + R_d^H$.

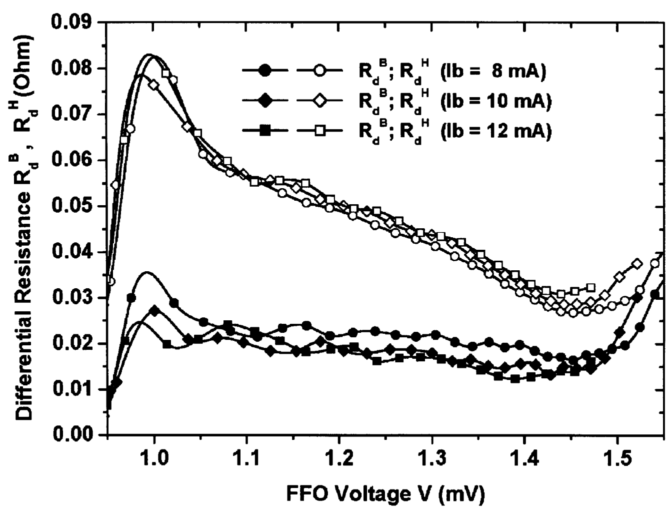

Fig. 2. Dependence of the differential resistances R_d^B and R_d^H on FFO voltage, measured at different bias currents, I_B. The lines are the guides to the eye.

voltage from 1.45 to 1 mV. Note that the Josephson self-coupling (JSC) effect considerably modifies the FFO IVC's at voltages $V \approx V_{\rm JSC} = 1/3 * V_{\rm gap}$ ($V_{\rm JSC}$ corresponds to 450 GHz for a Nb-AlO$_x$-Nb FFO) [16]. This is reflected in an abrupt change of both R_d^B and R_d^H in the range 0.9 mV $< V < 1.1$ mV. At lower voltages the smooth $R_d^H\ (V)$ dependence is disrupted by the Fiske steps, still with the tendency to increase R_d^H with decreasing voltage. This behavior has been observed for all tested FFO's of very different designs and may now be considered as typical. Presumably it reflects the fact that introduction of an additional fluxon in the junction requires a larger CL current as the fluxon chain gets denser.

$R_d^H(V)$ has a minimum at 1.45 mV corresponding to a FFO frequency of 700 GHz. The position of this minimum coincides with $V_g/2$ and changes with temperature as V_g. Apparently, an increase of R_d^H at $V > 1.45$ mV is due to a steep increase of the losses in the FFO electrodes at frequencies higher than the Nb gap. The R_d^H value strongly increases from 0.03 Ω (that results in a free-running linewidth of about 5 MHz) to 0.08 Ω at 500 GHz (1.03 mV). The free-running FFO linewidth correspondingly increases by more than a factor of 6, complicating the phase locking of a FFO.

For different batches of the same FFO design we observe a dependence of R_d^H on the critical current density. Almost a 50% increase of the minimum R_d^H value occurs as the critical current density decreases from 3 to 6 kA/cm^2 between batches. A possible explanation is that by increasing critical current density the Josephson penetration length λ_J is decreased (hence the spatial size of the fluxon and the density of fluxons in the junction are decreased as well), thus resulting in decreasing of the R_d^H.

It was found that R_d^H depends on the width of the upper electrode through which the bias current is injected. To check this a series of samples with different widths (40, 80, 120 and 160 μm) of the injector was fabricated. The results are presented in Fig. 3—where one can see, that R_d^H increases with the width of the upper electrode.

It is known that magnetic shielding is absolutely necessary for proper operation of FFO. In practice the size of a superconducting integrated receiver (SIR) is defined by the size of a shield (100 mm typically) [2], surrounding the tiny SIR chip. This is why the integration of the superconducting shield directly onto the chip may be a kind of breakthrough for further miniaturization of the SIR. The first step we made is placing the FFO on top of an "infinite" ground plane. The second step will be addition of a superconductor shield cover. The bias current is introduced to the top electrode of the FFO via resistors, which are placed at the equal distance of 50 μm along the FFO. The magnetic field control line is implemented in the counter electrode of the FFO. To avoid the leakage of FFO power each dc connection is provided with a RF band-stop filter.

Preliminary measurements show very stable IVC's with low R_d^B (0.005 Ω typically) and moderate R_d^H (from 0.055 to 0.02 Ω in the voltage range 1.05–1.45 mV) that are quite similar to data presented in Figs. 2–3. The performance of the shielded FFO at linewidth measurements has to be somewhat affected by the fact that the CL source cannot be grounded with either of its terminals that suggests some EMI is present. The first test results are quite encouraging and the advancement of the shielded FFO will be continued.

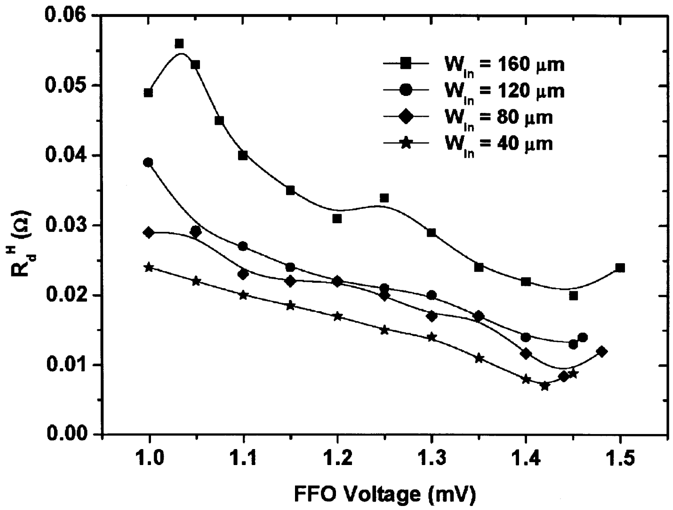

Fig. 3. Dependence of the differential resistance R_d^H on width of the injector electrode $W_{\rm in}$. The lines are the guides to the eye.

III. FFO Phase Locking: Towards Applications

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 applying a phase-locked loop (PLL) system with bandwidth larger than $\delta f_{\rm AUT}$. 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 [18]. After amplification the IF signal is compared to a 400 MHz reference signal in an analogue phase detector, the output of which is fed to the FFO bias supply. The PLL unit is optimized for operation with a low signal-to-noise ratio at a minimal time delay (a measured delay of about 5 ns corresponds to a regulation bandwidth of 50 MHz). The bandwidth of the complete PLL system, $\Delta f_{\rm PLL}$, is further limited to 15 MHz due to the delay in its 2 m long cables, but fortunately it does exceed the free-running linewidth of a FFO of new design.

Earlier, phase locking of a Josephson oscillator was demonstrated in the frequency range 250–450 GHz [18] 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 [4], [8], [9] results in a decrease of the free-running FFO linewidth in the flux flow regime for $V > V_{\rm JSC}$. Along with development of an improved wideband PLL system it enables us to phase lock the FFO in the frequency range from 490 to 712 GHz, limited only by the gap value of the Nb-AlO$_x$-Nb junction. Fig. 4 demonstrates spectra of the frequency and phase locked FFO operating at 707 GHz.

The PLL system, of course, cannot change the wide-band thermal and shot noise fluctuations $S_i(0)$, but it can effectively suppress the influence from external low frequency fluctuations and diminish both differential resistances R_d^B and R_d^H in the bias point (at frequencies $f < \Delta f_{\rm PLL}$) to nearly zero. This manifests itself as a constant-voltage step in the dc I-V curve of the FFO.

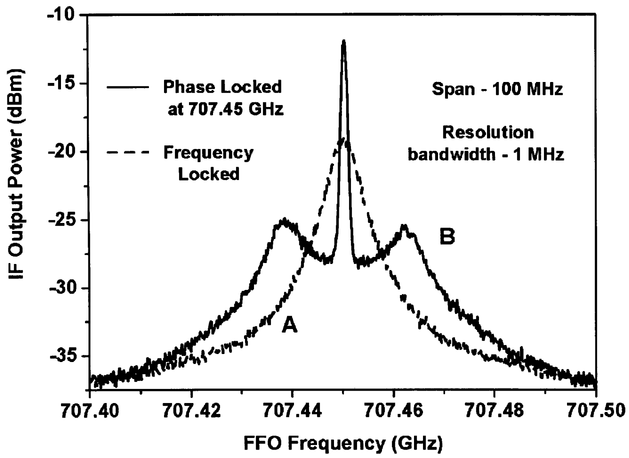

Fig. 4. Residual spectra of a FFO operating at 707.45 GHz: frequency locked FFO (A) and phase-locked FFO (B).

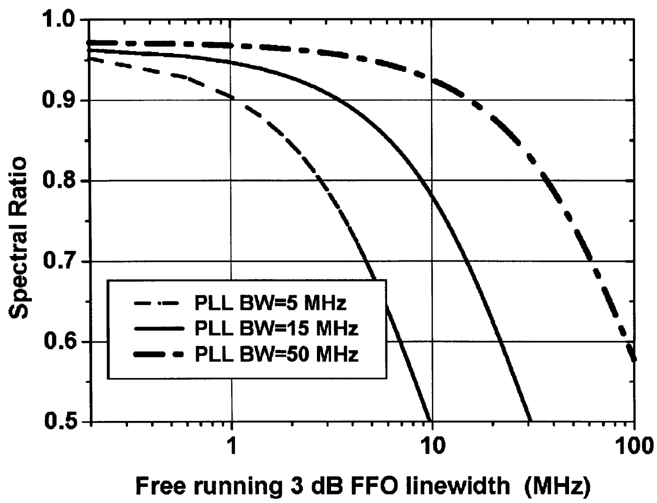

Fig. 5. Spectral Ratio (portion of the phase-locked FFO power) dependence on the free-running FFO linewidth for three values of PLL bandwidth.

According to (1) the zero dynamic resistance created by the PLL system results in an infinitely sharp spectral line. Indeed, a 1 Hz linewidth is measured at 707 GHz relative to the reference oscillator [19].

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 number used in the harmonic mixing. The absolute FFO phase noise is dominated [9], [19] 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. In order to resolve a weak signal adjacent to a strong line the PLL FFO must have a well-defined line-shape. The dynamic range of the spectrometer is closely related to the ratio between the carrier and the spectral power density (FFO phase noise) at a frequency offset equivalent to the channel spacing of the spectrometer. The phase noise of the phase-locked FFO is about -80 dBc/Hz at a 1 MHz offset from the carrier for $f_{\mathrm{FFO}} = 700$ GHz. For a 1 MHz channel this gives a dynamic range of 20 dB for the spectrometer.

Since the free-running FFO line shape is Lorentzian, the FFO power inside the effective PLL regulation bandwidth can be calculated, see Fig. 5. From this figure one can see that the initial FFO linewidth should not exceed 3.5 MHz (for an effective PLL bandwidth of about 15 MHz) to ensure that the phase-locked FFO oscillates with 90% of the total power. The "unlocked" rest of the total FFO power will increase both the phase noise and the calibration error. To overcome this problem an additional decrease of the FFO free-running linewidth (new designs with smaller R_d^B and R_d^H) and an increase of the PLL regulation bandwidth are required. In this respect the ongoing design of a new ultra-wideband PLL system that can operate at cryogenic temperature seems very promising.

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