Flux Flow Oscillators for Sub-mm Wave Integrated Receivers

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Abstract - The results of a detailed study of the microwave linewidth of Nb-AlOₓ-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 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-AlOₓ-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 $V = V_g/3$ caused by the increase of the damping [5]. The geometric resonances (or FSs) exist for low normalized damping $\alpha/\lambda < 1$, where $l = L/\lambda$ is the junction length normalized to the Josephson penetration length $\lambda$. If the damping is sufficiently low (say, $\alpha < 0.01$, this condition can be satisfied even for large normalized junction lengths, $l = L/\lambda \geq 60$. The FSs smear out (transition into the so-called Eck peak) when the damping increases to a value of about $\alpha/\lambda \geq 2$. This happens at $V_g/3 \approx V > 950$ 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.

II. FFO LINEWIDTH

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

$$\Delta f = \frac{2\pi\Phi_0}{h} R^2_S S(0),$$

where $\Phi_0$ is the magnetic flux quantum, $S(0)$ is the density of the low frequency current fluctuations, and $R_S$ is the dc differential resistance which transforms the current fluctuations to voltage (and phase) noise. For a lumped tunnel junction [8]

$$S(0) = \frac{e^2}{2\pi} I_d(V_d) \coth(v), \quad v = (eV_d)/(2k_B T_{th}),$$

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where \(e\) is the electron charge, \(k_B\) is the Boltzmann’s constant, \(I_{\text{dc}}\) and \(V_{\text{dc}}\) are the averaged normal current and voltage, and \(T_{\text{eff}}\) 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 \(I_S\). 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 supercurrent is adsorbed both in the external circuitry and in the tunnel junction itself. The random absorption of the supercurrent is adsorbed both in the external circuitry and in the tunnel junction itself.

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 \(T_{\text{eff}}\) 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 \(\Delta f\) 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 \((\Delta f \propto R_d^{-1})\) mainly determines the value of \(\Delta f\) at high \(R_d\). The level of the external interference becomes dominant \((\Delta f \propto R_d)\) at small \(R_d\) (below 0.01 \(\Omega\) 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 \(R_{d,\text{CL}} = dV_{\text{FFO}}/dI\). 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 \(R_{d,\text{CL}}\) determines \(\Delta f\) at \(R_{d,\text{CL}} > R_d\), and a plateau appears in the \(\Delta f(R_d)\) dependence. The \(R_{d,\text{CL}}\) value is very low when biased on Fiske steps (about 0.005 \(\Omega\)) and increases considerably between steps. At \(V > V_b\) in the “pure” flux-flow regime \(R_{d,\text{CL}}\) is about 0.1 \(\Omega\) and does not depend noticeably on voltage. The noise contribution caused by \(R_{d,\text{CL}}\) 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 \(R_{d,\text{CL}}\) above and below \(V_b\). The value of the external low frequency interference corresponding to a current fluctuation \(I_{\Delta} = 0.08 \mu A\) is used in the calculations.

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 \(T_{\text{eff}} = 25 K\). 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 \(T_{\text{eff}} = 60 K\). According to our numerical calculations the level of self-pumping \(eV_{\text{RF}}/hf\) is decreasing with the FFO voltage, so we cannot 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 \(Z_{\text{sh}}(f) > Z_{\text{FFO}}\) 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 > \(\Delta f\).

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

An integrated circuit comprising FFO, SIS mixer and matching elements is used to measure the FFO linewidth. Overlap Nb-AlOₓ-Nb junctions (length L 500 µm, width W about 3 µm, current density 5-8 kA/cm²) 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 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 \( \Delta f_{AUT} \). 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 $\Delta f_{\text{AUT}}$ at the 3 dB level is initially lower than the PLL regulation bandwidth $B_{\text{PLL}}$. In the opposite case where $\Delta f_{\text{AUT}} > B_{\text{PLL}}$ 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 $B_{\text{PLL}}$ at different initial $\Delta f_{\text{AUT}}$ (FFO frequency 270 - 420 GHz). At a $\Delta f_{\text{AUT}}$ of about $B_{\text{PLL}}$ (Fig. 3a, $\Delta f_{\text{AUT}} \approx 7.5$ 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 $\Delta f_{\text{AUT}}$ (different values of $R_d$ and $R_{d_{\text{CL}}}$ were used). The real phase locking takes place at $\Delta f_{\text{AUT}} = 2.5$ 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 $R_{d_{\text{CL}}} = 0$ as well. A regulation range in the FFO bias voltage as large as 1.5 V has been experimentally measured. This corresponds to a PLL regulation band of about 750 MHz.

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.

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### References


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