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Externally phase locked sub-mm flux flow oscillator for integrated receiver

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ABSTRACT: The feasibility of phase locking a Josephson Flux Flow Oscillator (FFO) to an external reference oscillator is demonstrated experimentally. A FFO linewidth as low as 1 Hz (determined by the resolution bandwidth of the spectrum analyzer) has been measured relatively to 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 concept of the single-chip fully superconductive integrated receiver with phase-locked loop for spectral radio astronomy and aeronomy applications is discussed.

1. INTRODUCTION

Flux flow oscillator (Nagatsuma et al. 1984, 1985, 1987, 1988) 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 (Koshelets et al, 1997a). A noise temperature (DSB) as low as 100 K has been achieved by Shitov et al (1998) for an integrated receiver with the FFO operating around 500 GHz. The antenna beam, approximately f/10 with sidelobes of about - 17 dB, makes the integrated receiver suitable for coupling to the real telescope. For spectral radio-astronomy applications besides a low noise temperature and a good antenna beam pattern a high frequency resolution of a receiver is required. It is determined by both the instant linewidth of the local oscillator and its long-time stability and should be much less than 1 ppm of the center frequency. Recently a reliable technique for linewidth measurements has been developed by Koshelets et al (1996) and an autonomous FFO linewidth of a few hundred kHz was measured (Koshelets et al, 1996, 1997b), this value should be decreased considerably to met the requirements of real applications. In this report a dependence of a microwave linewidth of Nb-AlO$_x$-Nb FFOs on the junction parameters has been measured in the frequency range 250 - 550 GHz. The linewidth were measured both for autonomous FFO and FFO locked to an external synthesizer via a wideband feedback loop.

2. EXPERIMENTAL DETAILS AND RESULTS

FFO is a long Josephson tunnel junction in which an applied dc magnetic field and a bias current I_B drive a unidirectional flow of fluxons. An integrated control line with current I_{CL} is used to generate the dc magnetic field applied to the FFO. The velocity and density of the fluxons and thus the power and frequency of the emitted mm-wave signal may be easily tuned by either of the two external parameters. According to Josephson relation the junction biased at voltage V_{FFO}

oscillates with a frequency $f = (2\pi/\Phi_0)\,V_{FFO}$), where Φ_0 is the magnetic flux quantum = 2 10^{-15} Wb (that corresponds to 483.6 GHz/mV). Experimentally measured current-voltage characteristics (IVCs) of the Nb-AlO$_x$-Nb FFO are shown in Fig. 1. One can see that FFO IVCs are considerably modified at some threshold voltage of about 930 µV (which is 1/3 of the superconductor gap voltage for Nb-AlO$_x$-Nb tunnel junctions). A simple model based on Josephson radiation self-coupling (JSC) - Hasselberg et al (1974) - was introduced by Koshelets et al (1997b) to explain the experimentally measured FFO IVCs. The JSC caused by the absorption of the internal *ac* Josephson radiation photons by the quasiparticles results in current "bumps" at the voltage $V_{JSC} = V_g/(2n + 1)$, which gives $V_{JSC} = V_g/3$ for n = 1. The effect of self-pumping explains the abrupt vanishing of the Fiske steps (FS) at $V \approx V_g/3$ due to the strongly increased damping. This changing results in essential broadening of the FFO linewidth due to considerable increase of the FFO differential resistance (both for bias, $R_d^B = \partial V_{FFO}/\partial I_B$ and control line current, $R_d^{CL} = \partial V_{FFO}/\partial I_{CL}$).

A FFO linewidth is measured in the frequency range from 250 to 550 GHz by a new original experimental technique (Koshelets et al, 1996). The submm-wave signal coming from a FFO is mixed in a SIS mixer with n-th harmonic of an external reference synthesizer frequency f_{SYN} (≈10 GHz, n = 26 - 55). A photo of the integrated circuit for linewidth measurements is shown in Fig. 2. In order to prevent the external reference oscillator from reaching the FFO a high-pass microstrip filter with a cut-off frequency of about 200 GHz is used. The intermediate frequency (IF) signal, $f_{IF} = \pm(f_{FFO} - n\,f_{SYN})$ is amplified in a cooled amplifier. After additional amplification the signal enters a PLL system. A small part of the signal is applied via a directional coupler to a spectrum analyzer, which is also phase locked to the synthesizer by a common 10 MHz reference signal. By using this technique a down-converted FFO spectrum is measured. The recorded spectrum is the difference between the FFO signal and the n-th harmonic of the synthesizer, and thus a FFO phase noise is measured relative to an appropriate synthesizer harmonic. In the PLL unit the signal is compared with a 100 MHz reference signal that is also phase locked to the main 10 GHz synthesizer. The output signal proportional to the phase difference is returned via a Loop Bandwidth Regulator (maximum bandwidth about 10 MHz) to the FFO current bias through a coaxial cable and a cold 50 Ω resistor mounted on a bias plate.

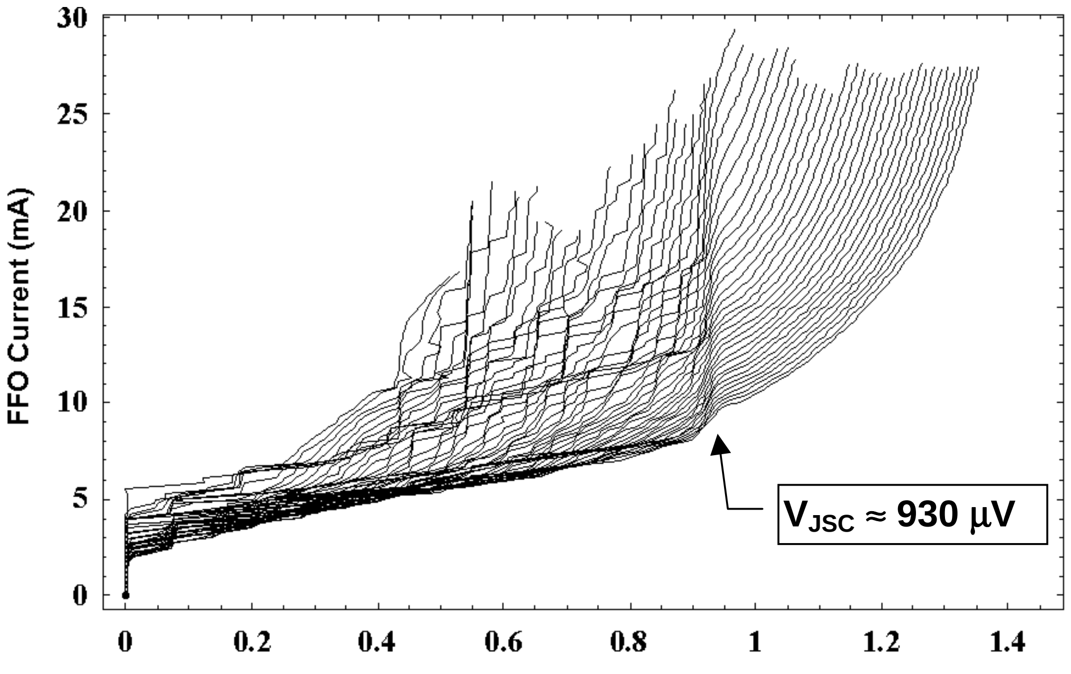

Fig. 1. IVCs of the Nb-AlO$_x$-Nb FFO recorded at different magnetic fields produced by integrated control line. Note an abrupt changing of the FFO behavior at boundary voltage $V_{JSC} \approx 930$ µV.

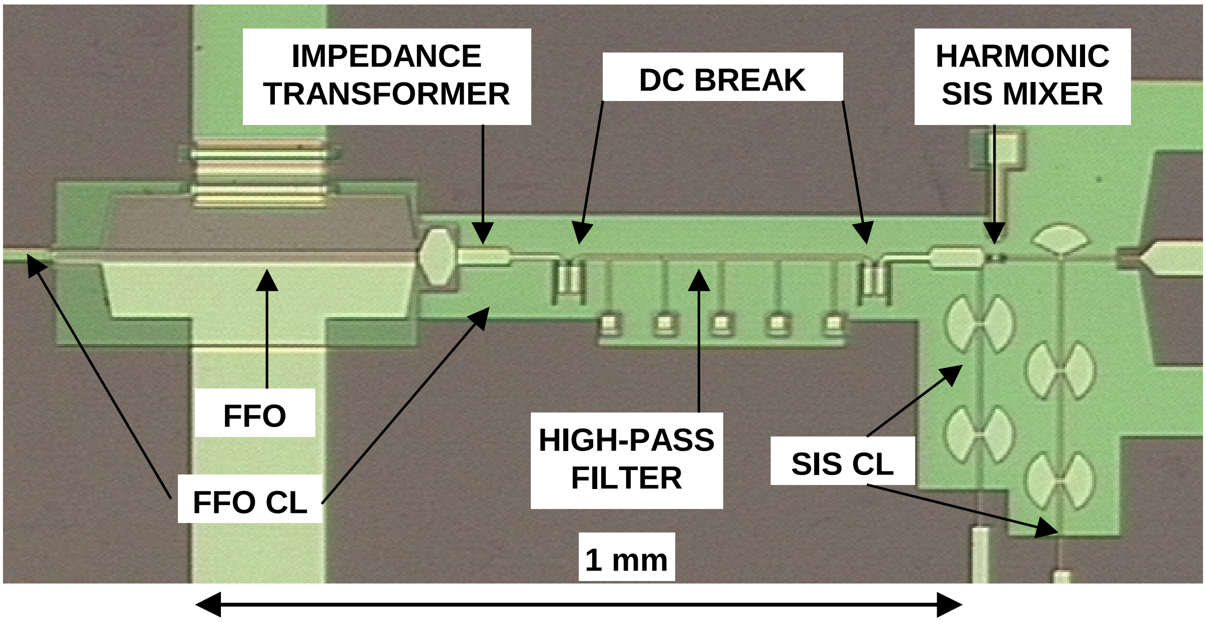

Fig. 2. Microphotograph of the central part of the microcircuits for FFO linewidth measurements.

The PLL system with a relatively low loop gain and a narrow bandwidth setting (< 10 kHz) was used for *frequency locking* of the FFO to the synthesizer in order to measure an autonomous FFO linewidth, Δf_{AUT}. In this case a spectral shape of the measured linewidth is unchanged and is equal to linewidth of the free-running FFO Δf_{AUT} (see Fig. 3a, where a spectrum of frequency locked FFO is shown by dash-dotted line). It was experimentally found by Koshelets et al (1998) and Mygind et al (1999) that a PLL system can considerably narrow a FFO linewidth if Δf_{AUT} at the 3 dB level is smaller than the PLL regulation bandwidth B_{PLL}. In our experiment full phase locking takes place for $\Delta f_{AUT} < 2.5$ MHz. Fig. 3 shows IF power spectra of the phase locked FFO measured at $f_{FFO} = 439$ GHz for different settings of the spectrum analyzer. A FFO linewidth as low as 1 Hz (determined by the resolution bandwidth of the spectrum analyzer) is presented in Fig. 3b. It means that the FFO linewidth can be reduced below the value determined by the fundamental shot and thermal fluctuations of a free-running tunnel junction. A consequence of the phase locking is the appearance of a vertical step in the FFO IVC ($R_d^B = 0$). The position of this step is also insensitive to small changes in the control line current, and accordingly also $Rd^{CL} = 0$. The low linewidth $\Delta f_{AUT} \leq 2.5$ MHz could be realized only in the resonant regime at $f_{FFO} < 450$ GHz where values of both R_d^B and R_d^{CL} do not exceed 0.01 Ω

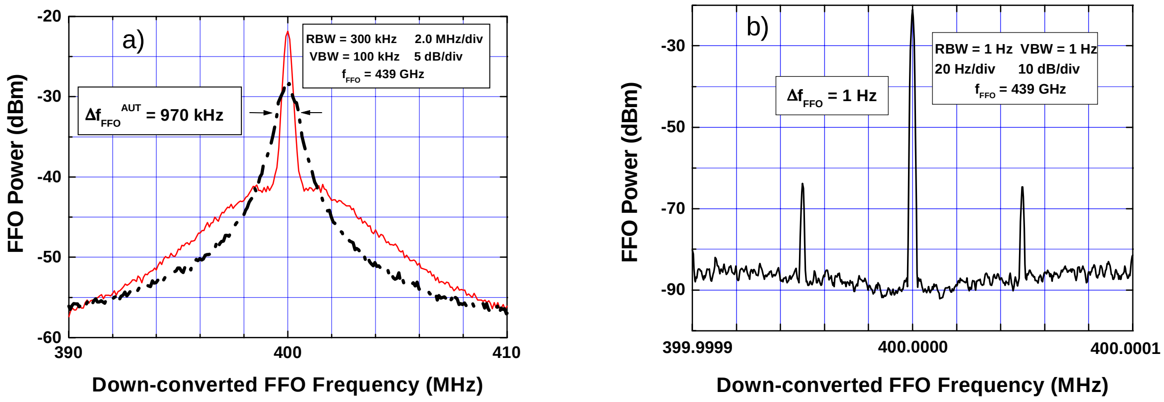

Fig. 3 IF power spectra of the FFO operating at 439 GHz for different settings of spectrum analyzer. Solid and dash-dotted lines in Fig. 3a show data for the optimal and the minimal B^{PLL}, respectively.

A Phase Locked Integrated all-superconducting receiver based on the developed technique for phase locking of the FFO has been proposed by Koshelets et al (1998). In this concept two separate SIS mixers are placed on one chip and connected to the same FFO. One SIS mixer serves as a heterodyne detector in the receiver while the other is used for phase locking of the FFO. Along with this concept an integrated superconducting heterodyne receiver for a frequency of about 350 GHz containing a phase-locked flux-flow oscillator has been designed and fabricated (Shitov et al, 1999). An alternative concept based on an already proven design of integrated receiver could be introduced. At this approach a submm signal from an external harmonic multiplier driven by 10-20 GHz synthesizer is applied to integrated receiver via beamsplitter. A small portion of the IF band (of about 100 MHz) will be used for monitoring of the mixing product between n-th harmonic of the synthesizer and FFO signal. This downconverted signal after narrow band filter will control the PLL system while the rest IF band will be used for analyzing an input signal.

3. CONCLUSION

The results given above demonstrate our ability to narrow the intrinsic linewidth of a Josephson oscillator using an external electronic PLL system, provided that the PLL bandwidth is larger than the linewidth of the autonomous oscillator. The combination of narrow linewidth and wide band tunability makes FFO a perfect on-chip local oscillator for integrated submm wave receiver intended for spectral radio astronomy aeronomy applications.

4. ACKNOWLEDGEMENTS

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