Linewidth of submillimeter wave flux-flow oscillators

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A reliable technique for wide band measurements of the spectral linewidth of superconducting oscillators integrated on-chip with superconductor-insulator-superconductor (SIS) detectors has been developed. The spectral linewidth of flux-flow oscillators (FFO) based on the unidirectional and viscous flow of magnetic vortices in a long overdamped Josephson tunnel junction was measured in the frequency range 250–580 GHz, and a linewidth as low as 200 kHz was obtained at 450 GHz. Also stable frequency locking of a FFO to very high (⩽60th) harmonics of an external microwave reference source has been demonstrated. The proposed technique may improve the sensitivity, frequency resolution, and stability of the fully superconducting integrated submillimeter wave receiver. © *1996 American Institute of Physics.* [S0003-6951(96)03131-2]

Recently the unidirectional and viscous flow of magnetic vortices in a long Josephson tunnel junction with high damping1,2 has been successfully used in the development of local oscillators (LO) for fully superconducting integrated submillimeter wave receivers.[3,4] The frequency and the power of this so-called flux-flow oscillator (FFO) can be continuously tuned over a wide frequency range only limited by the gap frequency of the superconductor. The FFO has been thoroughly tested from 100 up to 800 GHz.[2–6] A complete all-superconducting quasioptical receiver for operational frequencies in the range 360–530 GHz has been realized.[7] Integrated on a single chip it includes a planar double dipole antenna, a superconductor-insulator-superconductor (SIS) mixer, and as LO a superconducting FFO with matching circuits. The receiver noise temperature (DSB) was as low as 470 K and the wide tuning range exceeds 100 GHz.

Preliminary FFO spectral linewidth measurements[2,3,5,6,8] have demonstrated encouraging low values (130 kHz at 70 GHz,[5] about 1 MHz at 280 GHz,[6,8] and 2.1 MHz at 320 GHz[2]). The spectral linewidth of a FFO at high frequencies ($f>300$ GHz) has been measured either by mixing the emitted signal with the signal from another FFO integrated on the chip,[2,6,8] or with the nth harmonic (n=4–7) of an external Gunn oscillator ($f\approx 70$ GHz).[6,8] In both cases linewidth measurements can only be done in narrow frequency ranges. Furthermore, the linewidth of the second source adds considerably to the observed total linewidth.

In order to overcome these problems we have developed a new simple and reliable technique for linewidth measurements of, in principle, *any* superconducting oscillator operated in conjunction with a SIS mixer. Due to the strong nonlinearity of the SIS array it can be utilized as a high-number harmonic mixer in which the signal under investigation beats with, say, the 50th harmonic of an applied reference signal ($f\sim 10$ GHz) fed to the SIS mixer via the existing IF coaxial cable from a high-quality synthesized signal generator. The proposed method resembles the use of external harmonic semiconductor mixers (traditionally pumped by a low frequency LO) for mm-wave upgrade of microwave spectrum analyzers.

A special integrated test circuit was designed[9] for our wide band FFO linewidth measurements. The layout and a simplified equivalent diagram of the on-chip integrated circuit is shown in Fig. 1. The circuit comprises a two-junction SIS array mixer with capacitance tune-out circuit ''1'' (SIS junction area $S\approx 1-1.5\ \mu m^2$), three-stage impedance matching transformer ''5,'' the long Josephson junction (FFO) ''6'' (length $L=450\ \mu m$, width $W=3\ \mu m$). The transformer and capacitance compensation circuit are designed for a center frequency of 450 GHz. The base electrode of the long junction is employed as a control line to produce the magnetic field applied to the FFO.

The millimeter-wave signal coming from the FFO is mixed in the SIS array with the nth harmonic of the external reference oscillator. To prevent the external oscillator signal (as well as its harmonics) from reaching the FFO a high-pass microstrip filter ''3'' is employed. The filter, situated in the 4 μm wide microstrip line ($Z_0\approx 12\ \Omega$), consists of seven $\lambda/4$ microstrip stubs shorted at dc. The stubs are separated by $\lambda/4$

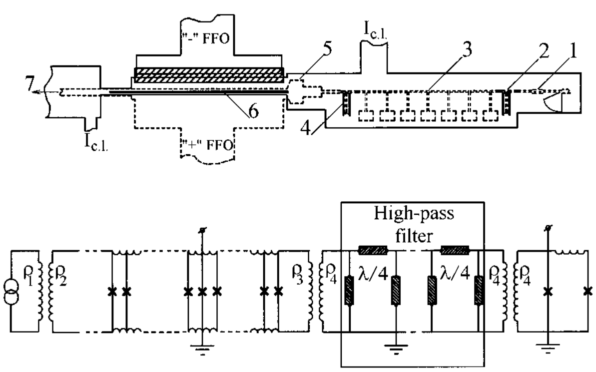

FIG. 1. Layout and simplified equivalent diagram of the test circuit for linewidth measurements. ''1''-SIS mixer; ''2,'' ''4''-dc bloc; ''3''-high-pass filter; ''5''-Chebyshev impedance matching transformer; ''6''-FFO; ''7''-connection to the input transformer and fine-line antenna. In the equivalent diagram $\rho_i:\rho_j$ indicates an impedance transformer, the discrete short junction (marked by $\times$) model is used for the long Josephson junction.

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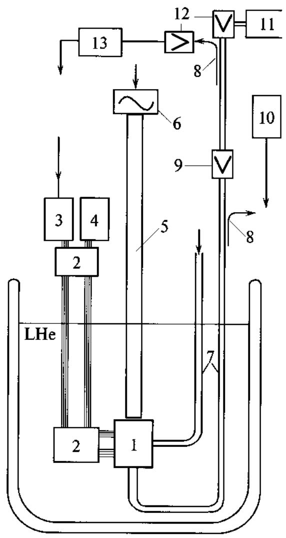

FIG. 2. Schematic drawing of the experimental setup for linewidth measurements: ''1''–test chip, ''2''-low-pass filter, ''3''-dc bias supplies, ''4''-voltage monitor, ''5''-60–90 GHz waveguide, ''6''-Gunn oscillator, ''7''-semirigid coaxial cables, ''8''-16 dB directional coupler, ''9''-1–2 GHz HEMT amplifier, ''10''-synthesized signal generator, ''11''-spectrum analyzer, ''12''-FET amplifier, ''13''-source locking microwave counter.

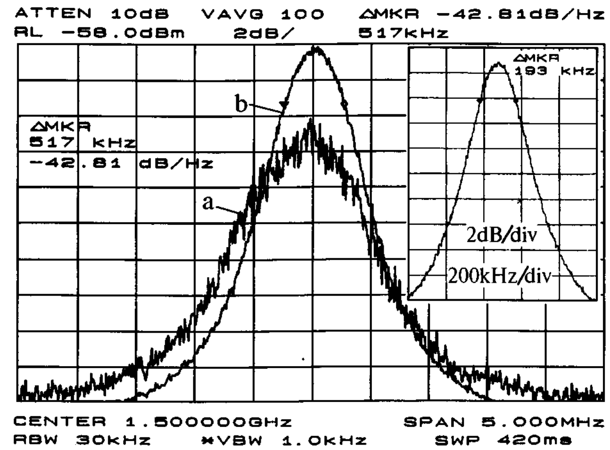

FIG. 3. IF power spectra recorded at $T=4.2$ K when the signal from the FFO ($f=435$ GHz) is mixed (lower sideband) with 45th harmonic of the synthesizer signal ($f=9.7$ GHz) for the case of (a) an autonomous FFO and (b) frequency locked by the source locking microwave counter. All spectrum analyzer settings are the same for both curves, except the curve (a) was measured with a video bandwidth (VBW) of 10 kHz, sweep time (SWP) of 50 ms and averaged 35 times. The inset shows the IF power spectrum recorded at $T=2$ K for the frequency locked FFO at 450 GHz.

microstrip sections (the calculated cutoff frequency is about 200 GHz). Two dc blocks ''2'', ''4'' are inserted in the microstrip line to prevent the filter from shortening the SIS mixer and the FFO at dc and IF. The special design of the dc blocks permit us to use only two superconducting layers in the circuit.

The integrated circuit is fabricated on a glass substrate with a technique developed earlier for producing high quality Nb–AlO_x–Nb SIS junctions and RSFQ digital devices.[10] To simplify the fabrication procedure both SIS and FFO junctions are made simultaneously from the same trilayer. The value of the critical current density, j_c, is about 8 kA/cm^2 ($\lambda_j=4$ μm), corresponding to a specific resistivity $R_n \times S$ ~ 25 Ω μm^2.

A block diagram of the setup is shown in Fig. 2. The output IF signal can be optimized by tuning the synthesizer power and the SIS bias point without detectable influence on the FFO under investigation. The proposed method permits us to measure the FFO linewidth at all frequencies, where sufficient pumping of the SIS mixer by the FFO takes place (from 200 up to 580 GHz). The results obtained by this technique (see Fig. 3) are in agreement with measurements obtained by mixing (at frequencies where the comparison was possible) of the FFO signal with harmonics of an external ($\sim$70 GHz) frequency stabilized Gunn oscillator. The signal from the Gunn oscillator is fed via the fin-line antenna and the input transformer (connection to which can be seen in Fig. 1, ''7'') to the FFO which was used as a harmonic multiplier.[6,8]

For precision linewidth measurements ($\Delta f < 1$ MHz) the IF spectra must be averaged with a sufficiently small ($\sim$1 kHz) video bandwidth. Even a relatively small drift of the control line or bias currents will result in considerable smearing of the averaging linewidth ($\delta f/\delta I \sim 5$ MHz/μA). A source locking microwave counter has been used for measuring the IF signal and frequency locking the FFO to the 10 GHz synthesizer (see Fig. 2). The analog output (locking signal) from the microwave counter can be used for fine adjustment of the FFO dc magnetic field or the bias current. In both cases frequency locking of the FFO has been successfully realized. The FFO IF spectra measured by the novel technique for both (a) autonomous and (b) frequency locked FFO are shown in Fig. 3. The linewidth of the frequency locked FFO was stable and repeatable. In fact it was possible to average the IF spectra for about 1 h without any noticeable change in the linewidth. At 450 GHz a linewidth as low as 200 kHz has been measured at $T=2$ K (see inset in Fig. 3).

Precision measurements of the FFO frequency can be used to reconstruct its IV curve with a resolution of less than 10 nV. A fine structure superimposed on the flux-flow steps was found; this structure results in a complicated dependence of the FFO linewidth on the magnetic field and bias current. Similar fine structure has been found previously[11–14] in connection with Fiske steps and zero field steps in the IV-curve of long Josephson junctions. The structure was ascribed to the resonance between the fluxons and excited plasma waves. The plasma waves may be generated during the fluxon propagation in the presence of spatially inhomogeneous regions which perturb its motion. Probably similar effects may be responsible for the observed fine structure of the flux-flow steps. It should be noted that the narrowest FFO linewidth were actually measured on one of these steps having an extremely small dynamic resistance, R_d. This means that in future investigations of the dependence of the FFO linewidth on R_d and subsequent comparison with a theory one has to derive the correct dynamic resistance in the operation point from the ''reconstructed'' IV curve.

The bandwidth of the servoloop used for frequency locking of the FFO is limited by low-pass filters in the dc bias supplies (see ''2'' in Fig. 2) with a cutoff frequency below 1 kHz. With direct connection of the output of the source locking microwave counter to the FFO bias (via the coaxial cable, see Fig. 2) it was possible to further decrease the FFO linewidth (by reducing the low frequency drift). In this case the bandwidth ($B = 10$ kHz) of the locking loop is determined by the slew rate of the source locking microwave counter.

The stability of the FFO frequency and power is crucial for most applications. As described above, the FFO may be frequency locked (or even phase locked) to the reference signal. This can be utilized to improve the performance of the submillimeter integrated receiver.[4,7] In the future, more advanced integrated receiver designs with two SIS mixers independently pumped by the same FFO, one SIS mixer may be used to stabilize the LO while the other serves as the low noise detector. With the proper choice of frequency bands and appropriate filtering the same IF cable may be used for both SIS mixers.

The FFO linewidth was also measured in the case where an external ~70 GHz microwave signal was applied to the FFO (via the fine-line antenna and impedance transformer, ''7'' in Fig. 1). In this experiment there is a direct mixing of the *n*th harmonic reference signal from the Gunn oscillator ($m = 5-7$) with the *n*th harmonic reference signal from the synthesizer. A large ($\geqslant 10$ dB) increase of the mixed signal was found when biasing the FFO on the *m*th Shapiro step in the IV curve. This effect may be explained by (partial) phase locking of the FFO by harmonic injection locking.

In conclusion, a new reliable technique for measuring the spectral linewidth of oscillators integrated with SIS mixers has been proposed and realized, and frequency locking of a FFO to an external microwave source has been demonstrated. The spectral linewidth of a FFO was measured in the frequency range 250–580 GHz; a linewidth as low as 200 kHz has been obtained at 450 GHz.

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