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Towards a Phase-Locked Superconducting Integrated Receiver: Prospects and Limitations

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Abstract. Presently a Josephson Flux Flow Oscillator (FFO) appears to be the most developed superconducting on-chip local oscillator for integrated submm-wave SIS receivers. The feasibility of phase locking the FFO to an external reference oscillator at all frequencies of interest has to be proven for practical FFO implementation in radio astronomy and other spectral applications. A linewidth of a phase-locked FFO as low as 1 Hz has been measured relative to an external reference oscillator in the frequency range 270 – 440 GHz on steep Fiske steps in the low damping regime. The increase of the intrinsic linewidth at higher voltages due to an abrupt increase of the internal damping considerably complicates phase locking of the FFO. Comprehensive measurements of the FFO radiation linewidth have been performed using an integrated harmonic SIS mixer. Results on FFO linewidth and spectral line profile have been compared to theory in order to optimize the FFO design. 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. Two integrated receiver concepts with phase-lock loop have been developed and experimentally tested.

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I. Introduction

Superconducting Integrated Receiver (SIR) [1, 2] is a single-chip device, which comprises a SIS-mixer with a quasioptical antenna and a superconducting local oscillator. Lightweight and compact ultra-sensitive submm SIRs with low power consumption are very attractive for both radio-astronomical research and remote monitoring of the Earth atmosphere. At the moment a Flux Flow Oscillator (FFO) based on the unidirectional flow of magnetic vortices in a long Josephson tunnel junction [3] is the best choice for integration with an SIS mixer. Local oscillators based on Nb-AlO_x-Nb FFOs, which have been successfully tested from about 120 to 700 GHz (gap frequency of Nb) provide power enough to pump an SIS-mixer (about 1 μW at 450 GHz). Both the frequency and the power of the FFO can be dc tuned [4, 5]. A front-end noise temperature of 85 K has been achieved at 140 GHz for a waveguide integrated receiver with a FFO [6]. Recent progress in the development of the quasi-optical integrated receiver with a FFO was presented in the review [2].

A few important points are worth to be mentioned. i) A receiver DSB noise temperature below 100 K has been achieved for SIR with the internal FFO operated in the frequency range 480 - 520 GHz [7]; it means that the performance of the SIS mixer is close to the quantum limit. ii) A free-running FFO linewidth considerably below 1 MHz has been measured near 450 GHz [8, 9]. Furthermore, phase locking the Josephson FFO to an external oscillator has recently been demonstrated experimentally [9]. A FFO linewidth as low as 1 Hz (determined by the resolution bandwidth of the spectrum analyzer) was measured relative to a reference oscillator in the frequency range 270 - 440 GHz. iii) The FFO can be fabricated with the same trilayer (and using the same technological procedure) as the SIS mixer. Further more the complexity of the FFO circuit is much lower as compared to the JJ array oscillator.

The frequency resolution of a receiver (along with the noise temperature and the antenna beam pattern) is one of the major parameters in spectral radio astronomy. The resolution, which is determined by both the instantaneous linewidth of the local oscillator and its long-time stability, should be much less than 1 ppm of the center frequency. Previous measurements of the linewidth of the FFO have demonstrated that the intrinsic linewidth increases considerably at voltages above a boundary voltage of the order of 1/3 of the gap voltage as a result of the abrupt increase of the internal damping due to Josephson self-coupling [10]. Note that the observed FFO linewidth is almost one order of magnitude wider [4, 10] than predicted by the theory for a *lumped* Josephson tunnel junction [11, 12]. The FFO linewidth was measured in a wide frequency range up to 600 GHz using a novel experimental technique [8]. A specially designed integrated circuit comprising the FFO, the SIS mixer, and the microwave circuit elements needed for the rf coupling is used for linewidth measurements. In this paper the results of extensive measurements of the radiation linewidth as well as a profile of the FFO emission are presented and compared to the theoretical models. Also included are the latest results for the phase locking of the FFO to an external reference oscillator.

2. FFO Line Shape and Linewidth Measurements.

Accurate linewidth measurements [13] for an FFO of standard design have allowed us to detect a superfine structure of closely spaced “resonances” with a frequency separation of ≈10 MHz. The fine structure manifests itself as a highly nonlinear relation between the measured FFO frequency and the bias or/and control-line currents. Using the Josephson equation the current-voltage curve (IVC) can be reconstructed in detail by measuring the dependence of the FFO output frequency on the bias current. The ”recovered” FFO IVCs demonstrate the existence of a well-defined superfine structure. The voltage spacing is about 20 nV, which is somewhat below the resolution of usual dc technique. The differential resistance $R_d^B = \partial V/\partial I_B$ on these steps is extremely low, much below 0.001 Ω. It is important to note that this value is considerably lower than the average value R_d^B measured with the traditional dc technique. An even more dramatic reduction has been measured for the control-line differential resistance, $R_d^{CL} = \partial V_{FFO}/\partial I_{CL}$. As a result the very narrow linewidth ≈75 kHz was measured at a FFO frequency of 426 GHz in a bias point with such extremely low differential resistance [13].

Since the frequency separation between adjacent resonances is comparable to the maximum bandwidth of the PLL system, switching between adjacent resonances create considerable difficulties for phase locking of the FFO. Complete phase locking can be realized only in certain frequency ranges near the center of resonance. Obviously, even a small external interference may cause switching between adjacent resonances and thus prevent phase locking.

Up to now no theoretical explanation of this superfine resonant structure has been given. The exact geometry of the FFO influences the resonant structure. In particular, the results reported in [9] were measured for a FFO with variable width where the resonance effect was less pronounced. The results presented in [13] are from an FFO with standard rectangular overlap geometry. In order to avoid the fine resonance structure we have developed a new design of the FFO. In this design the FFO is tapered from both sides so that its width is decreased from 6 μm to 1.5 μm over a distance of 20 μm (see Fig. 1). As a result of this modification the resonant structure was almost totally suppressed, see Fig. 2. In this figure continuous frequency tuning is demonstrated by curve B. This curve is recorded providing a fine-tuning of the FFO bias while the spectrum analyzer being in “max-hold” regime. One can see that the FFO frequency can be continuously adjusted (in the figure the FFO frequency tuning range is limited by the spectrum analyzer span of 100 MHz). The small variation of the maximum level is due to non-ideal coupling between the SIS mixer and the coolable IF amplifier (standing waves). It should be noted that a tapered FFO has larger output impedance compared to a standard FFO of rectangular shape. This considerably simplifies the matching to the following microwave circuits. At the left end of the FFO one can see the first section of the impedance transformer, which loads the FFO output.

The absence of the resonance structure makes it possible to provide a detailed analysis of the free-running FFO spectrum, which has been measured using the integrated harmonic mixer technique [8]. A frequency detector system with a relatively low loop gain has been used to frequency lock the FFO. In this case it is assumed that only very low frequency noise and drift are eliminated by the narrow-band feedback. Thus the linewidth, determined by much faster fluctuations, which are assumed to be the “natural” ones, can be carefully measured. The shape of the FFO spectrum provides us with important information about the internal and external fluctuations and their parameters. According to the theory [12, 14] the shape is Lorentzian for white noise fluctuations, while for narrow-band interference (at frequencies smaller than the autonomous FFO linewidth δf_{AUT}) the profile will be Gaussian. An example of the FFO spectrum measured on the Flux Flow Step (FFS) is presented in Fig. 3 by the dash-dotted line. The measured data, symmetrizated relative to the center frequency are shown by diamonds. The theoretical curves are also shown in Fig. 3 for comparison. The calculated theoretical expressions providing the best fit at the top of the peak are shown by dash-dot and dotted lines for Lorentzian and Gaussian distributions, respectively.

The coincidence between the calculated Lorentzian curve and the symmetrizated experimental data is excellent, actually better than 5% of the emitted power if a minor amplifier’s nonlinearity of about 0.4 dB is taken into account. This agrees with theoretical expectations [12, 14] for the pure flux-flow regime on the FFS with large differential (bias current) resistance R_d^B [10]. The profile of the FFO line recorded when biased at the steep Fiske step (FS), where the differential resistance is extremely small, can be different [10] from the one measured on the smooth FFS. Nevertheless, very recently it was shown [15] that the FFO spectrum measured at the Fiske step is also very well described by a Lorentzian. It means that the low frequency external fluctuations can be almost fully suppressed by appropriate filtering and shielding in combination with frequency stabilization system.

The data presented in [15] demonstrate that the profile of the FFO emission line is Lorentzian even at the "plateau", which is observed in the dependence of the FFO linewidth on differential resistance [10, 16] at $R_d < 0.01\,\Omega$. This fact is very important for linewidth calculations. It gives us the experimental evidence that the wide-band fluctuations are present in the magnetic field, because according to [16] at small R_d the FFO linewidth is mainly determined by fluctuations of the magnetic field. Since an influence of the wide-band fluctuations in the bias resistors feeding the control line (CL) is negligibly small [16], it means that there is a channel for transfer of the wide-band fluctuations from the bias current I_B to the FFO via the magnetic field. Partially, it can be associated with a self-field effect (part of the bias current is flowing along the FFO electrodes creating a magnetic field proportional to I_B). Under these circumstances the role of the differential resistance of the CL, $R_d^{CL} = \partial V_{FFO}/\partial I_{CL}$, appears to be very important. This has never been taken into account in the theoretical considerations. If we include the wide-band fluctuations via the CL in the numerical model [16] by an empirical coefficient K (as a multiplier to the measured value of R_d^{CL}), this allows us to fit the experimental linewidth data to the calculated both on the Fiske steps and on the flux flow step [15]. This empiric approach seems to be very similar to that derived recently by A. Pankratov [17] on the base of the same assumption concerning the influence of wide-band fluctuations via magnetic filed.

3. Superconducting Integrated Receiver with Phase Locked FFO

Detailed analyses of the measured dependence of the radiation linewidth [10, 15, 16] on the FFO parameters provides us with information and knowledge for further optimization of the FFO design. In order to reduce both the bias and control line differential resistances a new design of the FFO electrodes has been made. As a result of these modifications a free-running FFO radiation linewidth of about 10 MHz has been measured in the whole flux flow regime: from 490 to 715 GHz, (see Fig. 3, for example). This considerable linewidth decrease (compared to all previous measurements) along with a development of the wide-band Phase Locking Loop (PLL) system provides the possibility for phase locking the FFO also in Flux Flow Regime where continuous frequency tuning is possible; these results will be published elsewhere [18].

Recent results on phase locking of an FFO to an external reference oscillator have been used to develop the practical concept of the integrated receiver with phase-locked loop [9, 16, 19] presented schematically in Fig 4. Following this concept a 350 GHz receiver chip containing a quasioptical SIS mixer, a phase-locked flux flow oscillator, a harmonic SIS mixer and an SIS multiplier as a source for the harmonic mixer (optional) has been designed, fabricated and successfully tested. The FFO is phase-locked to the *n*-th harmonic of a 10 GHz synthesized source ($n \approx 30 - 35$) using room temperature electronics with a PLL loop bandwidth of about 20 MHz. The signal from an external harmonic multiplier driven by another synthesizer is used to test the integrated receiver with phase locked FFO. The down-converted IF signal of the phase locked SIR is presented in Fig.5. The resolution bandwidth of the spectrum analyzer is 100 kHz; which satisfies all needs for spectral application of the submillimeter receiver. In this experiments we used the FFO of the traditional rectangular design, which only allowed phase locking in specific frequency ranges. These results will be published elsewhere [18].

The present state of development of the PLL Integrated Receiver for practical spectral radio astronomy is, so far, quite encouraging. The receiver contains well-understood elements and devices and is under test in the frequency range 350-450 GHz. In this frequency range the Fiske steps (FS) of the Nb-AlO_x-Nb FFO are closely spaced and almost overlapping due to the low losses and the dispersion in the long Josephson tunnel junction. The frequency gaps between the available LO bands corresponding to the voltage difference between subsequent FS's, where FFO phase locking is possible; do not exceed 5 GHz for the chosen FFO length. One may overcome these gaps by using a wide-band IF amplifier with wide enough bandwidth (2-4 GHz) to allow continuous frequency coverage while the FFO is biased and locked on adjacent FSs.

Very recently the PLL integrated receiver has been tested successfully as a laboratory spectrometer. The effect of broadening of the SO_2 gas spectral line at 326.867 GHz has been demonstrated using a one-meter long gas cell. These results will be published elsewhere. The results on FFO phase locking in the Flux Flow regime [18] make possible a development of a superconducting integrated receiver with phase locked local oscillator having extremely wide and continuous frequency coverage from 500 to 700 GHz.

The implementation of an external harmonic multiplier [13] has enabled us to check an alternative concept of the Phase Locked Integrated Receiver. This concept is based on an already proven design of the integrated receiver chip [1, 2]. A submm-wave signal from an external harmonic multiplier driven by a 10 - 20 GHz synthesizer is applied to the integrated receiver via a beam splitter (see figure 8 for details). A small portion of the IF band (about 50 MHz) is used to monitor the mixing product between the n-th harmonic of the synthesizer signal and the FFO signal. The down-converted signal after narrow-band filtering controls the phase locking loop (PLL) system while the rest of the IF band is used to analyze the down-converted signal. Here the development of a cryogenic multiplier looks very promising. The output power may be increased according to theoretical expectations, and a much thicker beam splitter can be used at cryogenic temperatures due to the reduced contribution to the receiver noise temperature.

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Figure Captions

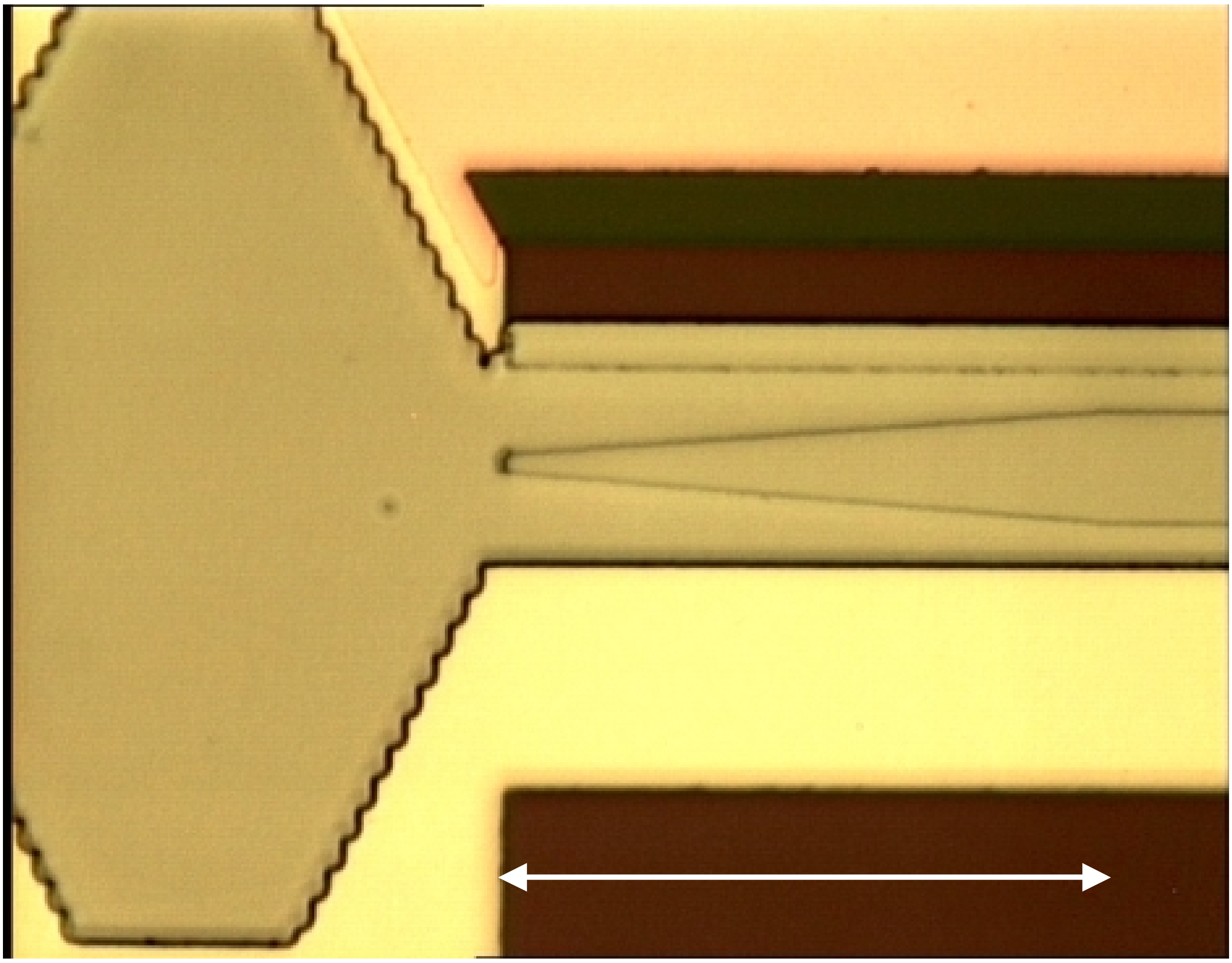
Fig. 1. Photo of the central part of the superconducting integrated circuit for linewidth measurements, showing one end of the tapered FFO and the first stage of the impedance transformer.

Fig. 2. Down-converted signal emitted by a frequency locked FFO at constant bias current (curve A). Curve B is recorded with the FFO bias tuned in the "max-hold" regime.

Fig. 3. Down-converted spectra of the FFO frequency locked at 576 GHz– dash-dotted line. The symmetrizated experimental data are shown by diamonds. Fitted theoretical Lorentzian and Gaussian profiles are shown by solid and dotted lines, respectively.

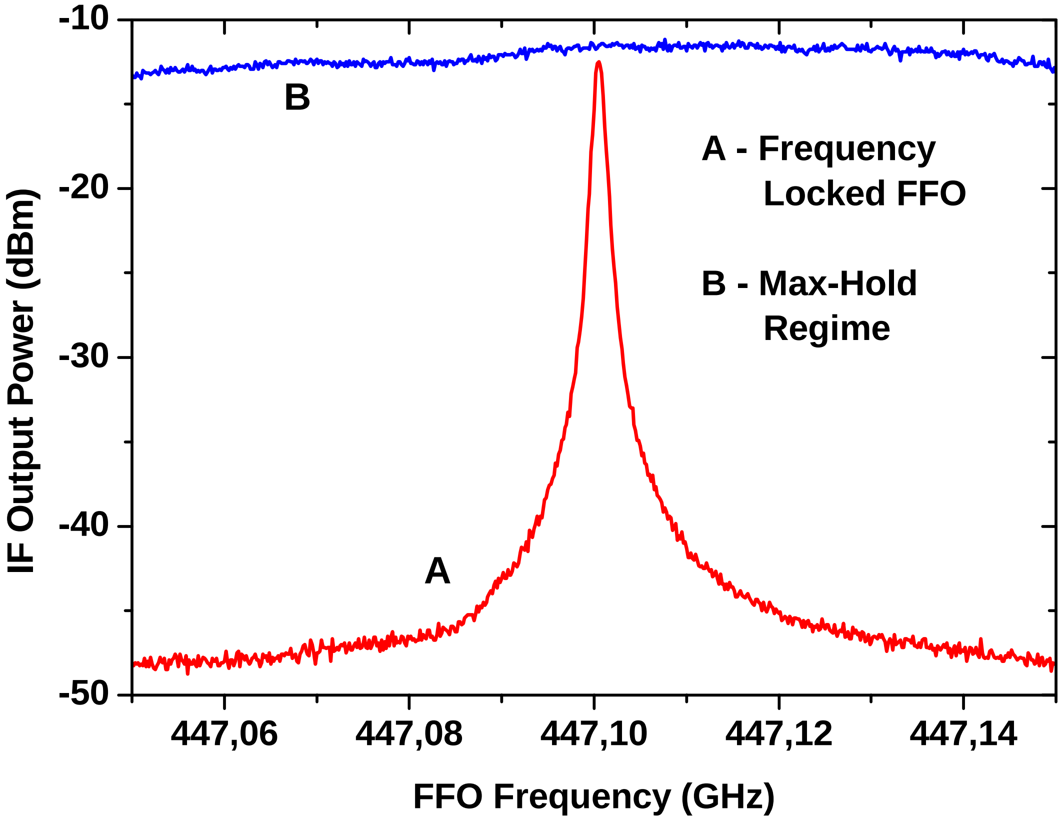
Fig. 4. Block-diagram of the sub-millimeter all-superconducting phase locked single-chip Integrated Receiver. The common FFO pumps two SIS mixers, one serves as the detector/mixer, and the other facilitates the phase locking of the FFO.

Fig. 5. Down-converted IF signal of the integrated receiver with FFO phase locked at 342.7555 GHz. The signal is emitted by external harmonic multiplier driven by synthesizer.

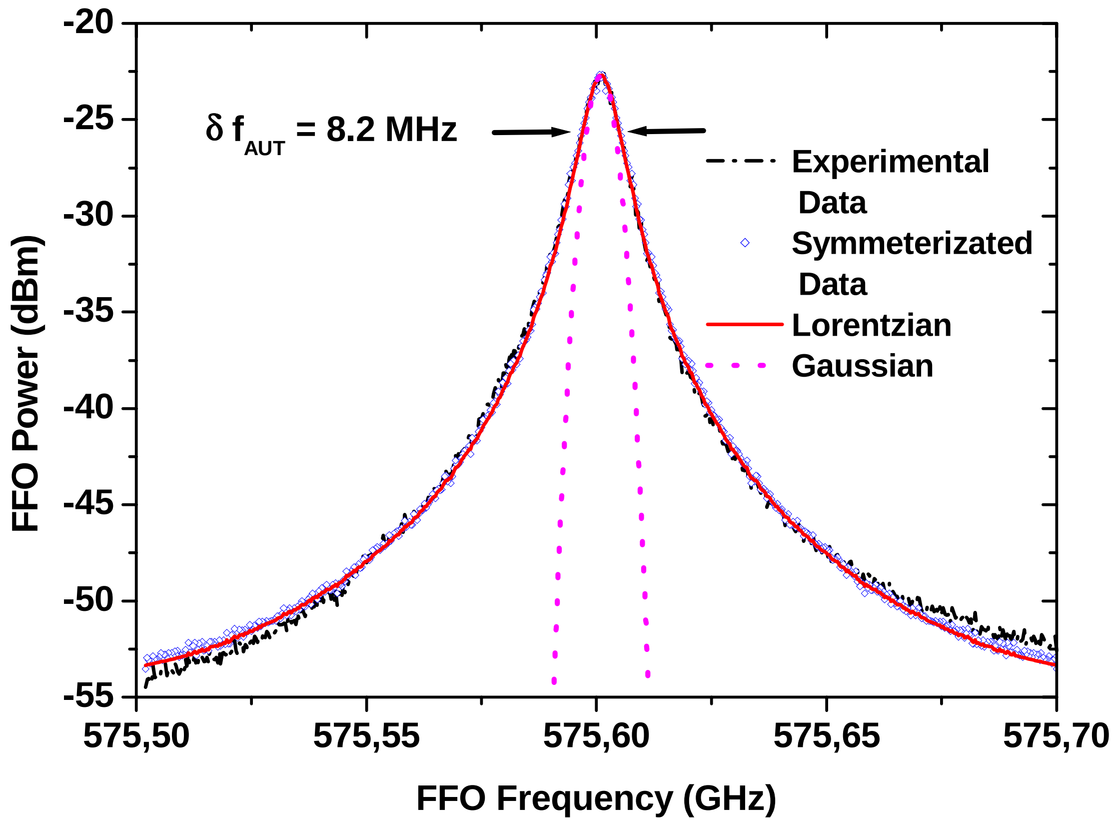


20 μm

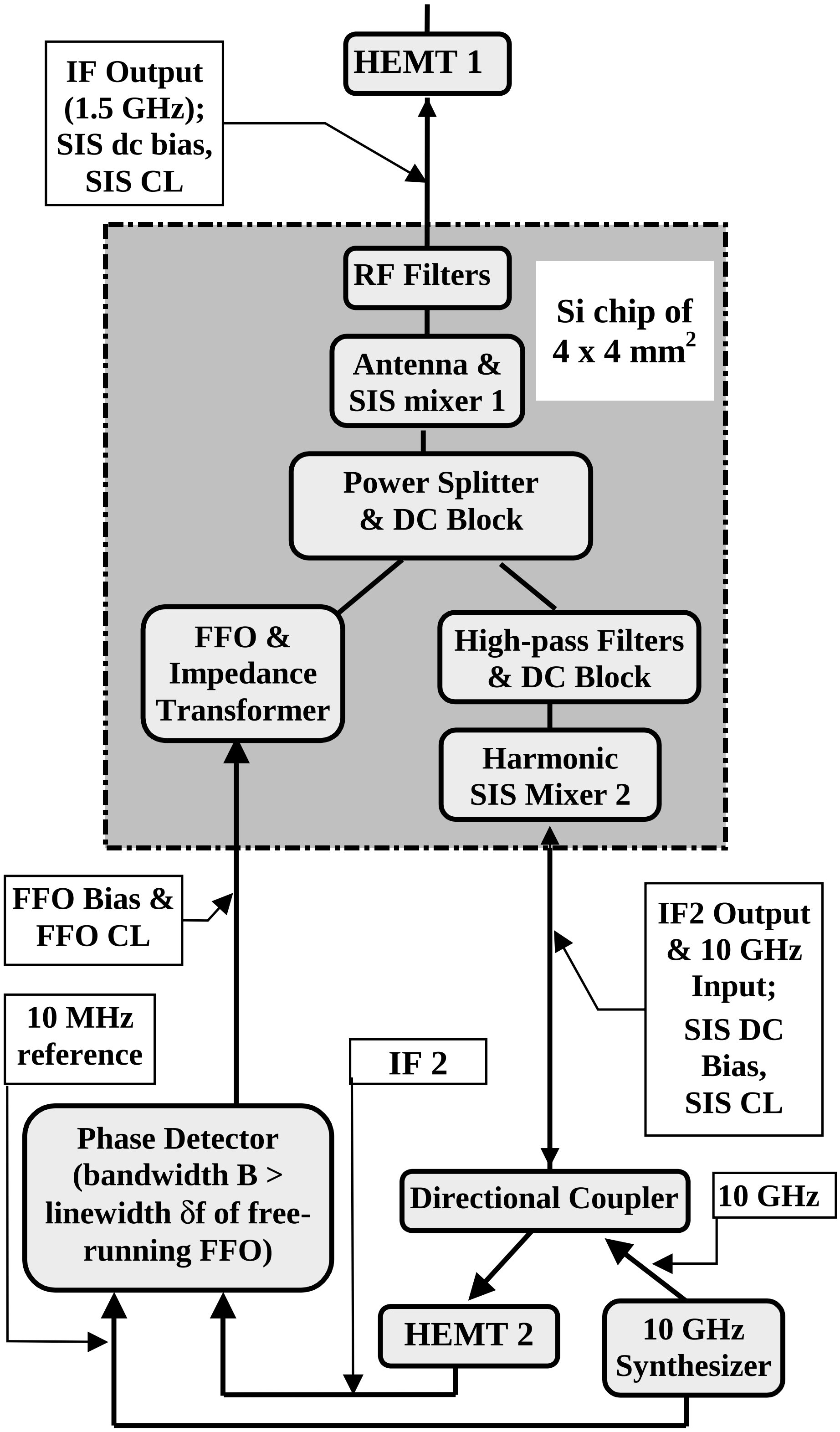
V. Koshelets, et al.; **FIG. 1**



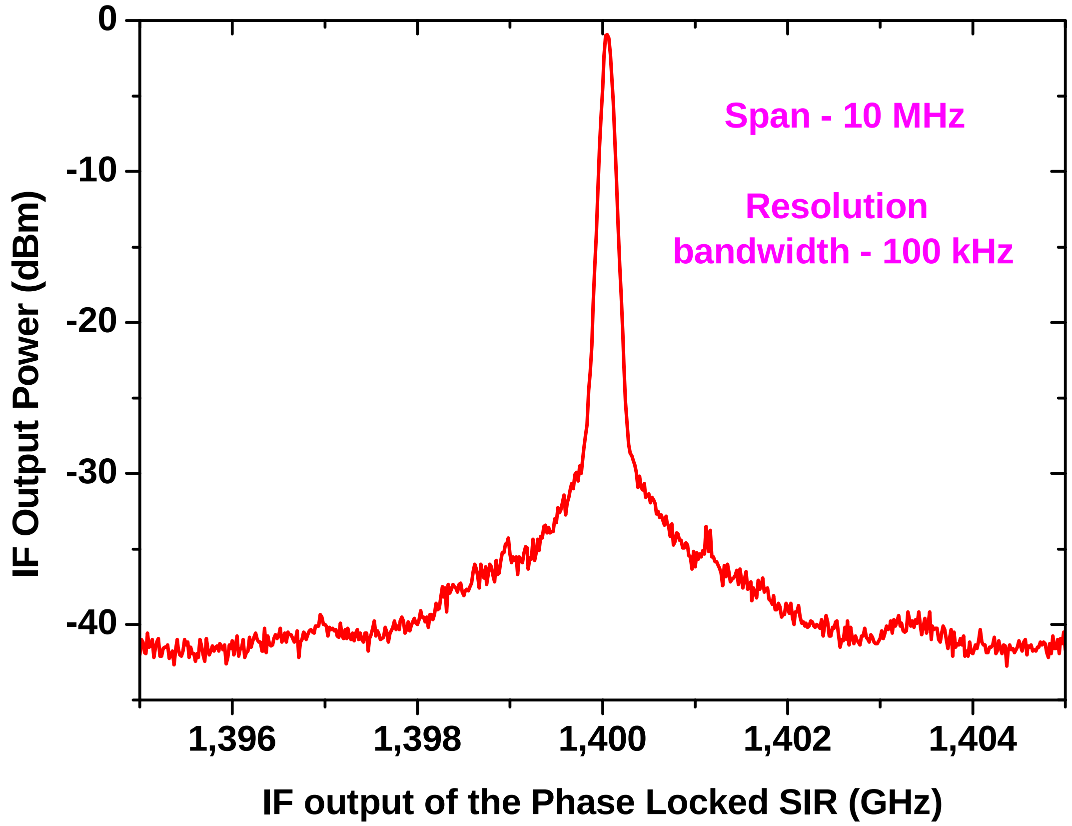
V. Koshelets, et al.; **FIG. 2**



V. Koshelets, et al.; **FIG. 3**



V. Koshelets, et al.; **FIG. 4**



V. Koshelets, et al.; **FIG. 5**