Development of the Flux-Flow Oscillators for Submm Integrated Receiver

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***Abstract* — A comprehensive experimental study of the Flux Flow Oscillator (FFO) linewidth on its parameters has been carried out in order to obtain free-running FFO linewidth well below 10 MHz and ensure phase-locked operation of a Superconducting Integrated Receiver (SIR). Essential dependence of the FFO linewidth on its width and idle region dimension has been found. A free-running linewidth between 10 and 2 MHz has been achieved in the frequency range 500 – 700 GHz. As a result the spectral ratio of the phased-locked FFO varies from 30 to 90 % correspondingly. First measurements of the free-running FFO linewidth for the FFOs of different length and comparison of the obtained results with existing theoretical models demonstrate significant dependence of the fitting parameter on the FFO length.**

I. Introduction

THE Superconducting Integrated Receiver (SIR) [1], [2] comprises in one chip a planar antenna integrated with an SIS mixer, a superconducting Flux Flow Oscillator (FFO) [3] acting as Local Oscillator (LO) and a second SIS harmonic mixer (HM) for FFO phase locking. In order to obtain frequency resolution required for practical application of a heterodyne spectrometer (of at least one part per million) an integrated local oscillator (LO) must be phase-locked to an external reference. Successful tests of the phase-locked FFO [2], [4] enabled the development of a 550-650 GHz integrated receiver for the Terahertz Limb Sounder (TELIS) [5] intended for measuring a variety of atmospheric constituents and scheduled to fly on a balloon in 2006.

Even for ultra wideband PLL system an effective regulation bandwidth is limited mainly by the cable length (about 7 MHz for typical PL loop length of two meters). It means that free-running FFO linewidth has to be well below 10 MHz to ensure stable FFO phase locking with reasonably good spectral ratio (SR) - the ratio between the carrier and total power emitted by FFO, determines quality of FFO phase locking. For example, only about 50 % of the FFO power can be phase-locked by the present PLL system at the free-running FFO linewidth of 7 MHz. Low spectral ratio results in considerable error in resolving the complicated line shape [6]. Thus sufficiently small free-running FFO linewidth is vitally important for realization of the phase-locked SIR for TELIS.

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II. Dependence of the FFO Linewidth on its Width

Previous measurements have demonstrated very prominent dependence of the FFO linewidth on FFO voltage (frequency) and considerable increase of the FFO linewidth with FFO current density [7]. Recently it was shown [8] that for all frequencies of interest the linewidth considerably decreases with increasing FFO width, W, (consequently, the spectral ratio is getting much higher). We have further explored this approach by increasing the FFO width up to 28 μm (that corresponds to more than 5 times Josephson penetration depth λ_J). A number of FFOs with the same electrodes layout, but different width of FFO junction (W = 4, 8, 12, 16, 20 and 28 μm) were fabricated using the same technological procedure with similar parameters (RnS =30 Ω*μm^2). The results of the LW measurements of these circuits at three FFO frequencies are presented in Fig. 1.

Even for the largest tested width (W = 28 μm) there is no evidence of deterioration of the FFO behavior. Furthermore, power delivered to mixer is getting higher and linewidth lower at all frequencies. Decreasing of the FFO linewidth with increasing FFO width is quite explainable according to existing theoretical models. The differential resistance on bias current, R_d^B, decreases more or less inversely proportional to bias current, I_b (in contrast to the case of changing of the FFO current density). Since the FFO linewidth is proportional to $R_d^2 * I_b$, it has to go down linearly with an increase of the FFO width. Of course, one can expect saturation of the linewidth decrease and deterioration of the FFO behavior at further width increase (for example, due to appearance of transversal modes). Since there is no reliable theory the optimal value of the FFO width has to be determined experimentally. Note that for a wide FFO there is a shift of the FFO centerline from the edge of control line that results in considerable decrease of the noise coming via magnetic field. Furthermore, wider FFO provides, presumably, more uniform bias current distribution [8] – due to much smaller inductance of the overlapping electrodes.

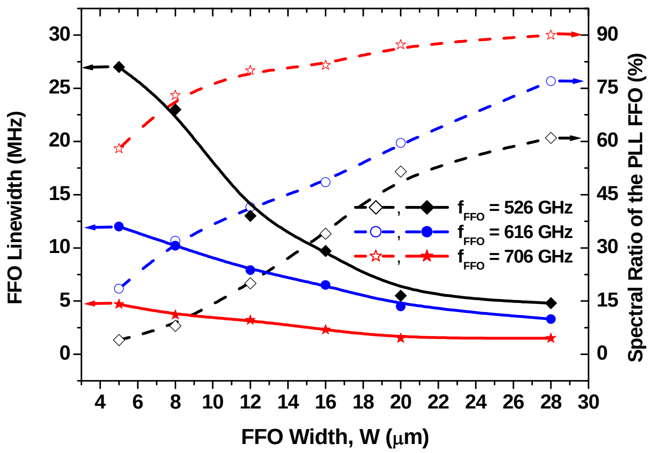

Fig. 1. Linewidth of free-running FFOs (left axis) and according Spectral Ratio for the phase-locked FFO (right axis) measured at different FFO frequencies as a function of FFO width. All circuits are fabricated using the same technological procedure with similar parameters (RnS =30 Ω*μm^2)..

III. Dependence of the FFO Linewidth on Length

Detailed measurements of the FFO linewidth [4], [9] demonstrate Lorentzian shape of the FFO line in a wide frequency range up to 700 GHz, both at higher voltages on the flux flow step (FFS) and at lower voltages in the resonant regime on the Fiske steps (FS's). It means that the free-running ("natural") FFO linewidth in all operational regimes is determined by the wideband thermal fluctuations and the shot noise (this is different from most traditional microwave oscillators) To explain the experimentally measured dependence of the free-running FFO linewidth, δf, an additional term proportional to differential resistance on control line current, R_d^{CL}, (control line produces magnetic field for FFO operation) has been introduced to the noise model of FFO [4], [9]. Actually at fixed bias current R_d^{CL} and R_d^B are unambiguously related R_d^{CL} = A*R_d^B [7] (A is ranged from 1 to 3 and depends only on bias current and FFO design). It means that experimental dependencies of the FFO linewidth can be well described by expression:

$$\delta f = (2\pi/\Phi_0^2)\,(K^*R_d^B)^2\, S_i(0); \qquad (1)$$

where $S_i(0)$ is the power density of low frequency current fluctuations.

According to existing theoretical models there should not be any significant dependence of the FFO linewidth on its length, *L*. We have measured linewidth in the frequency range 300 – 700 GHz for FFOs which are identical except for their length that is varied in the range 100 – 450 μm. Our measurements demonstrated that for short FFO even at $V > V_{JSC}$ [10] (V_{JSC} = 950 μV for Nb-AlOx-Nb junctions) Fiske steps considerably modified the FFO IV-curve; as a result dependence of the FFO linewidth on FFO voltage became non-monotonic. Nevertheless, dependence of the FFO linewidth on differential resistance R_d^B is smooth, but the fitting parameter K in formula (1) varies considerably with FFO length for tested FFOs. Dependence of the fitting parameter K on the FFO length is shown in Fig. 2. Data presented by the open symbols obtained if for fitting in (1) the following expression for *Si(0)* [11] is used:

$S_i(0) = (e/2\pi)\,\{I_{qp}\coth(v) + 2\,I_s\coth(2v)\},\ v = (eV_{dc})/(2\,k_B\,T).$

Here superconducting and quasiparticle parts of bias current are accounted separately, while the solid symbols are for the case if bias current treated entirely as normal. Note that K value appears to be below unity at L < 150 μm for "traditional" approach [11]. Additional study is required to clarify which expression is more adequate for long Josephson junctions.

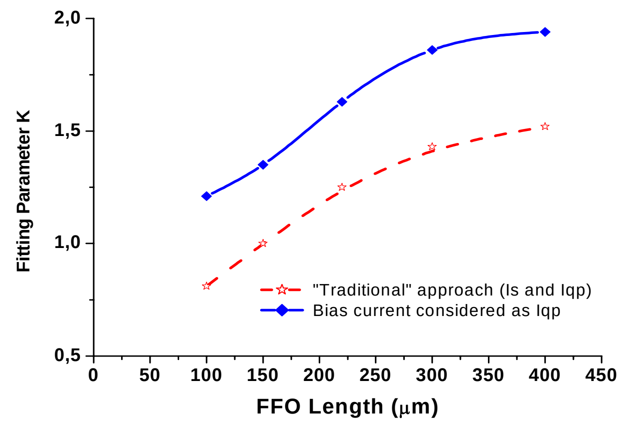

Fig. 2. Dependence of the fitting parameter K in formula (1) on FFO length for 2 different expressions for Si(0) - the power density of low frequency current fluctuations.. Open symbols - both superconducting and quasiparticle parts of bias current are accounted separately [11]; solid symbols – all bias current is treated as quasiparticle.

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