Radiation linewidth of the flux-flow oscillator with integrated self-field coil

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Abstract. The FFO is a long Josephson junction in which the flow of magnetic flux quanta, and thus the oscillator frequency is controlled by the DC bias current I_B, and the DC current I_{CL} producing the magnetic field at the junction ends. We have experimentally studied the properties of the *Nb/AlOx/Nb* and *Nb/AlN/Nb* trilayer FFOs when I_B also contributes to the magnetic field. A number of samples were fabricated, each containing an FFO integrated with a bias current loop designed so that the bias current can generate approximately the same positive or negative contribution to the magnetic fields at both ends of the FFO. The magnetic field is proportional to $I_{CL} + Lp*I_B$, where Lp is given by the loop design. We have made a study of both the DC parameters and the radiation linewidth for FFOs with different integrated loops and compared our results to that for the FFO without any loop. It was found that loops with positive contribution ($Lp > 0$) make the FFO linewidth smaller (although the differential resistance of the FFO on the bias current becomes larger), while loops with negative contribution ($Lp < 0$) result in broadening of the FFO radiation linewidth. The magnitude of this effect strongly depends on the critical current density, the $Rn*S$ product, which was varied in our experiments from 13 to 35 Ohm*μm^2. We propose a possible explanation of this effect.

1. Introduction

During the last decade the flux-flow oscillator (FFO) has been considered as the most promising local oscillator in superconducting integrated sub-millimeter receivers (SIRs). The SIR comprises on one chip a planar antenna integrated with a Superconductor Insulator Superconductor (SIS) mixer, pumped by an internal FFO as a local oscillator (LO). Presently SIRs are planned to be used in a collaborative European project TELIS – a balloon mission on environmental monitoring [1], where the receiver will operate in the 550 - 650 GHz band. In order to obtain the resolution required for practical applications the FFO must be phase-locked to an external reference oscillator.

The free-running FFO linewidth determines the Spectral Ratio (SR) of the SIR - the ratio between the phase-locked and the total FFO power [2]. Finally, SR is one of the parameters, which define overall SIR performance and the need to have a required SR value over the whole operational frequency band transfers into the need to have an FFO with an autonomous linewidth in this band less than some technically determined value. Previous studies [3] revealed that the linewidth Δf of the long Josephson junction can be described by the formula (1), containing both differential resistance on the bias current I_B and the control line current, I_{CL}:

$$\Delta f = 2\pi e\left(\frac{1}{\Phi_0}\right)^2 \left(Rd + K\cdot Rd_{CL}\right)^2 \cdot \left[I_{QP}\coth\frac{eV}{2k_B T} + 2I_S\coth\frac{eV}{k_B T}\right] \qquad (1)$$

which includes a nonlinear superposition of thermal and shot noise down-converted by the Josephson junction to low frequencies. I_{QP} and I_S are the quasi-particle and superconducting pair components of I_B, respectively. K - is a fitting parameter, depending mainly on the geometry of FFO electrodes. From the mathematical point of view the term $K*Rd_{CL}$ in Eq (1) has a meaning of the correlated noise transfer from the channel of the FFO bias current to the magnetic field at the junction's ends. We have studied experimentally a number of FFOs designed so that the I_B also contributes to the magnetic field at the both FFO ends.

2. Samples layout and experimental background

For comparative study of both DC properties and FFO radiation linewidth we fabricated a few batches with junctions having RnS values (the product of the normal state resistance and the junction area) from 13 to 35 $\Omega*\mu\text{m}^2$. Each batch was containing samples with FFOs of three different layouts represented in figure 1. The basic (reference) configuration (figure 1a) was compared to the designs, where the current I_B due to integration of a loop in the wiring electrodes makes a positive (figure 1b) or a negative contribution (figure 1c) to the magnetic field H at the FFO ends. In this case $H \sim I_{CL}+Lp*I_B$, where Lp is a loop parameter. The sign of Lp depends on the loop orientation. If the DC voltage of the reference FFO is a function of I_B and I_{CL}: $V_{ref}=V_{ref}(I_B,I_{CL})$ then in the presence of a loop it will take the form $V_{loop}=V_{ref}(I_B,I_{CL}+Lp\ I_B)$ and the dynamic resistance on the bias current for the FFO with a loop can be expressed via the "reference" Rd in the form

$$Rd\big|_{loop} = \partial V_{loop} / \partial I_B = Rd\big|_{ref} + Lp\cdot Rd_{CL} \qquad (2)$$

Positive loops giving $Lp > 0$ increase the slope of the FFO IV-curves and result in larger Rd values. Negative loops reduce Rd and may even cause the so called "back banding" of the IV-curves when Rd is negative. The reference FFO also has a part of a loop disconnected from the electrodes to provide the same conditions for magnetic flux quanta moving inside the junction for all three FFO geometries under comparative study. The absolute value of Lp can be found from $I_C(H)$ measurements or comparison of Rd/Rd_{CL} ratio for two opposite loop orientations. For samples with the distance D between the loop and the edge of the FFO control line equal to 14 μm the parameter Lp was found to be approximately 0.2, while for D = 7 μm Lp becomes equal to 0.3. The results presented below were obtained for the FFOs having D = 14 μm.

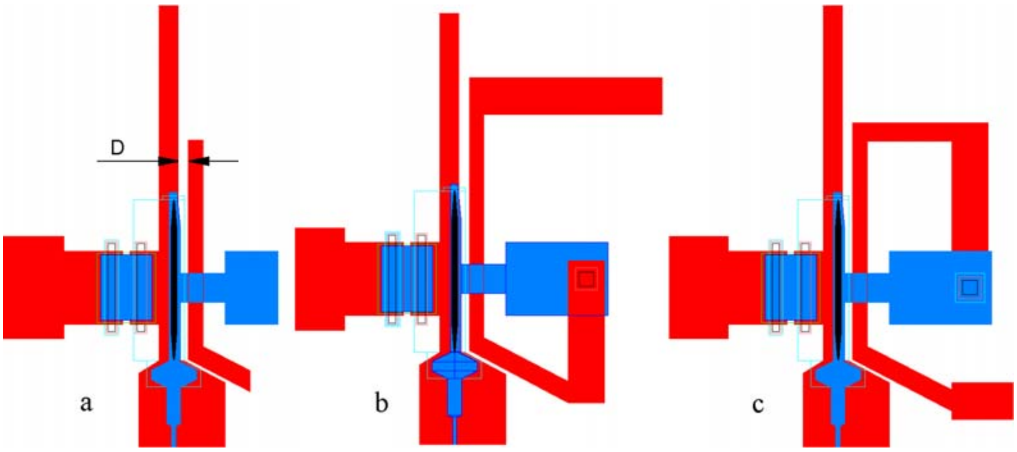

Figure 1. FFO layouts. (a) - neutral (reference) configuration Lp = 0; (b) - the loop provides positive contribution to the magnetic field by I_B ($Lp > 0$); (c) – the current I_B makes negative contribution to the magnetic field ($Lp < 0$).

Recently the FFO radiation linewidth has been measured for the FFO without a loop, but biased in a way so that I_B was also contributing to the magnetic field only at on of the junctions's ends [4]. In the present study the integrated loop allows I_B to contribute to the field at both FFO ends without any significant change in the profile of I_B distribution along the junction

3. Experimental results for *Nb/AlO$_x$/Nb* and *Nb/AlN/Nb* FFOs

In figure 2 the differential resistances Rd and Rd_{CL} are presented as functions of the FFO DC voltage measured at the constant value of I_B=18 mA for the FFOs with $Rn*S$ = 27 $\Omega*\mu m^2$. Circles correspond to the data for the reference FFO ($Lp \approx 0$), squares represent the sample with the positive loop ($Lp \approx 0.2$). The coincidence of the $Rd_{CL}(V)$ dependences for the FFOs with the loop and without it implicitly indicates that fluxons dynamics as well as the bias current injection profile was not significantly influenced by the presence of the loop. At the same time it is clearly seen from figure 2b that the dependence $Rd(V)$ is considerably modified by the positive loop in accordance with Eq (2).

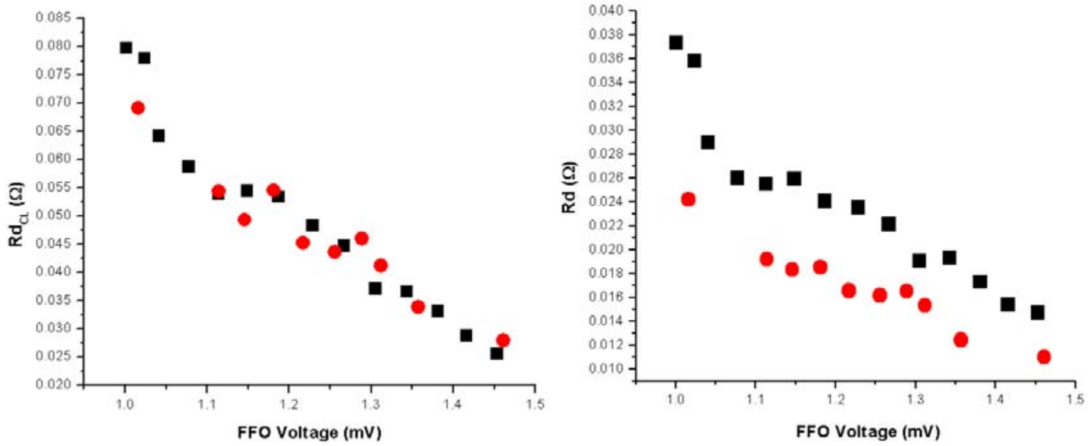

Figure 2. Rd and Rd_{CL} as functions of the DC FFO voltage. Circles represent data for the reference sample without a loop. Squares represent the FFO with the positive loop.

In figure 3 the linewidth data are presented for the *Nb/AlO$_x$/Nb* and *Nb/AlN/Nb* FFOs with $Rn*S$ values 27 $\Omega*\mu m^2$ (figure 3a) and 13 $\Omega*\mu m^2$ (figure 3b) correspondingly. According to this study positive loops reduce the linewidth (squares), while negative ones increase it (triangles) compare to the "reference" FFO (circles). In Figure 3b the data points of the reference FFO lay between the data points for the FFOs with loops, but close to the local minimum at the voltage 1.4 mV (the gap voltage for Nb) the linewidth data merge together into a single dependence for all three FFOs. The difference between the linewidth values for the reference FFO and the FFO with a loop is 5 to 10 MHz and almost independent on the critical current density of the junction (which is inversely proportional to the $Rn*S$ value). Probably, this effect may be accounted for by some changes in the I_B distribution profile due to the presence of the external magnetic field created by the loop. Also the FFO may induce small AC currents in the I_B channel, which can convert via the loop internal FFO bias current fluctuations into correlated external magnetic field noise.

It should be noted that the loop did not influence the FFO linewidth dependency in our experiments with FFOs having $Rn*S$ values more than 30 $\Omega*\mu m^2$. In this case the linewidth data measured as a function of the FFO voltage at constant I_B for the reference FFO did not differ from the similar data obtained for the FFO with a loop. In this situation the K-factor from Eq (1) is equal to $-Lp$, which is the case described by the theory [4]. At higher current density (lower $Rn*S$ values) the situation drastically changes and because of the presented above effect the K-factor absolute value exceeds the absolute value of Lp. The possibility to reduce the FFO linewidth using an integrated loop may have an important practical application in SIRs, where both an SIS-mixer (which has to have low *Rn*S* value) and the FFO are integrated on a single chip and can be fabricated from a single trilayer.

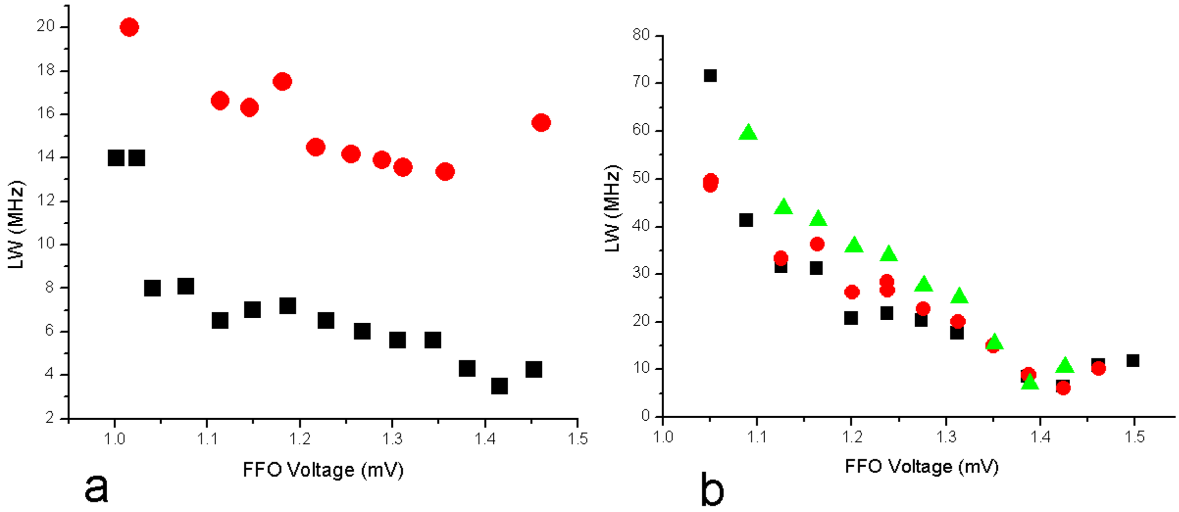

Figure 3. The linewidth data for *Nb/AlO$_x$/Nb* FFO with *Rn*S* value about 27 Ω∗μm^2 (a) and for *Nb/AlN/Nb* FFO with *Rn*S* = 13 Ω∗μm^2 (b). circles - reference FFO, squares - FFO with the positive loop, triangles - FFO with the negative loop.

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References

[1] Hoogeveen R, Yagoubov P, Kleipool Q, Koshelets V, Shitov S, Ellison B and Birk M 2004 TELIS: a novel three-channel cryogenic heterodyne receiver for stratospheric research *IRMMW2004/THz2004 Conference* digest, Karlsruhe Germany, September 2004, 581

[2] Koshelets V, Dmitriev P, Ermakov A, Sobolev A, Torgashin M, Kurin V, Pankratov A and Mygind J 2005 Optimization of the Phase-Locked Flux-Flow Oscillator for the Submm Integrated Receiver *IEEE Trans. on Appl. Supercond.* **15** 964-967

[3] Koshelets V, Ermakov A, Dmitriev P, Sobolev A, Baryshev A, Wesselius P, Mygind J 2001 *Supercond. Sci. Technol.* **14** 1040

[4] Mygind J, Koshelets V, Samuelsen M and Sobolev A 2005 *IEEE Trans. on Appl. Supercond.* **15** 968-970