Forward and Backward Wave in Cherenkov Flux-Flow Oscillators

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***Abstract*—Josephson Flux-Flow Oscillators (FFO) have been used as an on chip local oscillator at frequencies up to 650 GHz. An autonomous FFO linewidth of about 1 MHz was measured in the resonant regime at $V_b < 950$ μV for niobium – aluminum oxide – niobium tunnel junctions, while considerably larger values were reported at higher voltages. To overcome this fundamental linewidth broadening we propose an on chip Cherenkov radiation flux-flow oscillator (CRFFO). It consists of a long Josephson junction and a superconducting slow wave transmission line that modifies essentially the junction dispersion relation. Two superconductor insulator-superconductor junction detectors are connected both to the long Josephson junction and the slow wave line to determine the available microwave power. The power is measured at different CRFFO biasing conditions. Both a forward wave and a backward wave oscillation regime are observed. A FFO and a CRFFO with the same junction parameters are compared.**

A FFO has been used as a local oscillator at frequencies up to 650 GHz. An Integrated Receiver including an SIS mixer and a FFO as LO has shown a receiver noise temperature below 100 K in the 500 GHz band [1]. The FFO linewidth has been carefully investigated [2]. It was shown that with a free running FFO a linewidth below 1 MHz could be achieved in the resonant regime [2]. The possibility to decrease the FFO linewidth by an external phase lock system (PLL) has been demonstrated recently [4]. The free running FFO linewidth should be small enough in order to reduce the linewidth by means of a PLL. At bias points above the boundary voltage $V_b = 950$ μV for $NbAlO_xNb$ junctions it is observed that both R_d and linewidth increase. This can be explained by the increase of the rf loss in a long Josephson junction (LJJ) due to the self-pumping effect [2], [3].

The FFO performance could be improved if the mutual interaction between vortices and waves takes place in the whole junction. To achieve this the velocities of the vortices and the excited wave must be the same. The maximum vortex velocity never exceeds the linear waves velocity in the plain FFO and a resonant interaction is impossible. The dispersion characteristic of the waves in a LJJ can be modified by the addition of an external system. The resonant Cherenkov radiation conditions can be met if there are waves with low phase velocity. Then the interaction between vortices and waves occurs in whole junction and can significantly increase the output power of the flux-flow device. This effect has been discussed in theoretical papers [5]-[9] as well as in experimental ones [10]-[12].

The other advantage of devices based on Cherenkov radiation effect is the possibility to make the radiation spectrum narrower. The linewidth ΔF is proportional to R_d^2 in a conventional FFO. Cherenkov radiation has a resonant nature and it would lead to a decrease in R_d and a narrower radiation spectrum.

A modification of I-V characteristics has been observed by the authors for half annular junctions embedded with slow wave structure. [12]

In this work measurement results for a long linear junction with the same slow wave structure as in [12] and a modified design of detector circuits are presented. A clear indication of backward and forward wave is found from an experimental data.

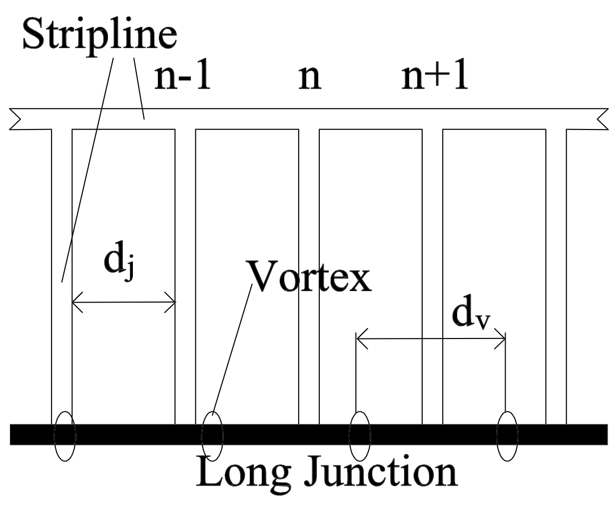

Fig. 1. Operation principle schematics.

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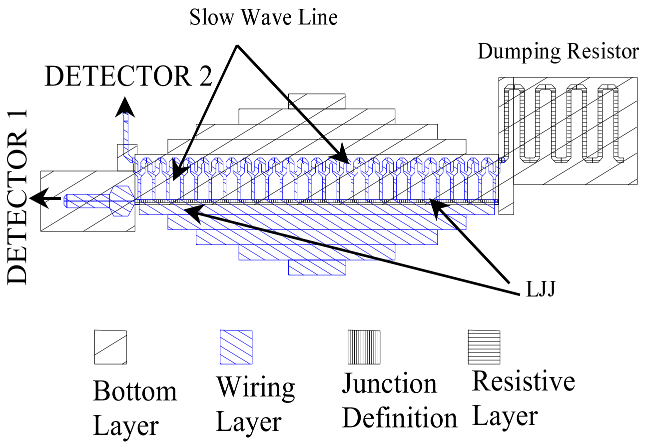

Fig. 2. CRFFO Layout.

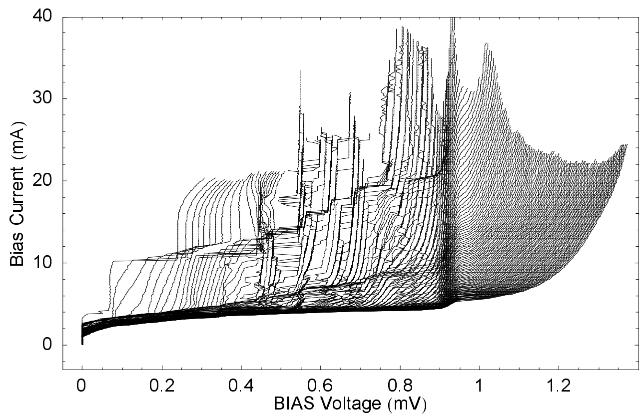

Fig. 3. Set of I-V curves for a LLJ without slow wave structure. Curves were recorded with the magnetic field across LLJ as parameter.

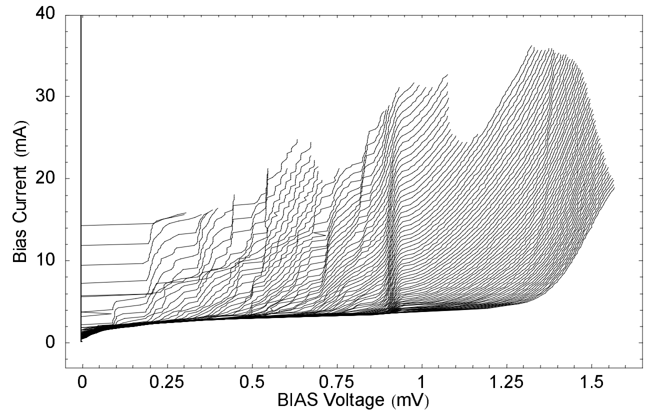

Fig. 4. Set of CRFFO I-V Characteristics recorded with the magnetic field control line current as parameter.

The LJJ is connected to the periodical stripline structure shown in Fig. 1. Radiation appears when vortices move along the junction and scatter on the all strip line ends. Let the vortex scatter on n-th node of the system at time $t = t_n$ and the radiation enters the strip line. The same vortex scatters on $n+1$ -th node at a time $t_{n+1} = t + \tau$ where $\tau = \frac{d_j}{v_v}$ is the delay time needed for the vortex to run from n-th to $n+1$ -th node, d_j is the junction length between nodes, v_v is vortex velocity. The waves emitted due to the vortex scattering on the different nodes should be added with proper phase. In order to get effective wave excitation the following condition must be satisfied $kd_l \pm \omega(k)\tau = 2\pi l$ where k is wave number, $\omega(k)$ is dispersion of waves in strip line, l is any integer. The frequency of the radiation of a single vortex can be found from last equation.

In case of a moving vortex chain the radiation from all vortices should be added in phase. To achieve it the condition $kd_v = 2\pi m$ where d_v is the distance between vortices and m is an integer must be satisfied. This condition could be achieved in practice by changing the distance between fluxons varying the magnetic field across the LJJ. It is possible to excite a strong wave by a large number of vortices scattering on the strip line ends using one with small dissipation. The radiation amplitude can be controlled by adjusting the fluxons density.

The layout of the experimental chip is shown in Fig. 2. The CRFFO consists of a 510 μm long and 3.5 μm wide LJJ and the periodical slow wave line. The period of the line along the LJJ is 20 μm. The $\frac{\lambda}{4}$ length of the parts of the slow wave system, perpendicular to the LJJ, has been chosen in order to provide a good impedance match between the 20 Ω impedance line and the low impedance (≈ 0.5 Ω) of the LJJ at around 450 GHz. The needed delay in the line is realized by additional sections along the LJJ. The external magnetic fileld has been applied to the LJJ by means of the integrated magnetic field control line in the top electrode of the LJJ. Most of the *dc* control line current follows the low-inductance part on top of the LJJ. The LJJ critical current density was $\approx 8\ kA/cm^2$. A normal metal stripline load is connected to the end of the slow wave line to prevent possible reflection.

Two detector chains are attached to the experimental structure as shown in Fig. 2. Detector 2 is connected to the slow wave line and detector 1 is connected directly to the LJJ. Each detector has a band pass filter and *dc*-breaks. A twin SIS junction circuit is used as the wide band microwave detector. The operating range of this circuit is 300-650 GHz. The detector chain design is described in detail in [2].

LLJ of the same size and with the same detector 1 chain has also been made for comparison.

The experiment has been carried out on a dipstick at 4.2 K physical temperature. The power from both detectors has been measured simultaneously with the I-V characteristics of the LLJ. Each detector junction has a normal resistance of 14 Ω. The microwave power is estimated by measuring the increase of the SIS junction bias current at a fixed bias voltage in the first photon step. This current is propotional to the absorbed rf power in the range of experimental parameters.

The measured I-V characteristics of LLJ without slow

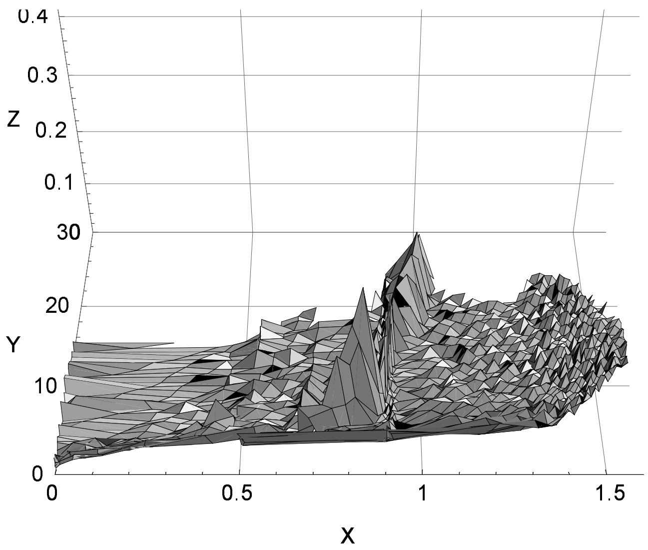

Fig. 5. Set of CRFFO I-V characteristics with detector 2 output signal shown in Z coordinate. Flux-flow is directed towards detector 2. X coordinate is CRFFO bias voltage in mV. Y-coordinate is CRFFO bias current in mA. Z-coordinate is detector power a.u.

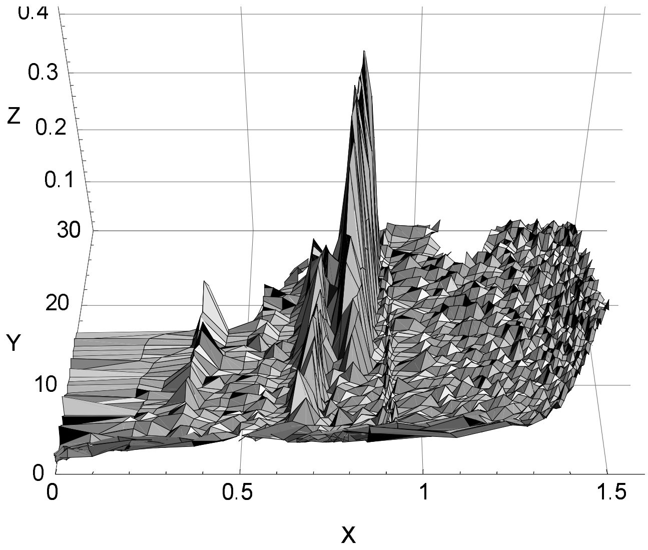

Fig. 6. Set of CRFFO I-V characteristics with detector 2 output signal shown in Z coordinate. Flux-flow is directed from detector 2. X coordinate is CRFFO bias voltage in mV. Y-coordinate is CRFFO bias current in mA. Z-coordinate is detector power a.u.

wave structure is presented in Fig. 3. Fiske steps are clearly visible at voltages below 0.95 mV. The measured I-V characteristics of the CRFFO are presented in Fig. 4. It shows the set of resonances around 0.8 mV bias voltage at different bias currents and magnetic fields. These resonances correspond to the different modes of operation of the CRFFO and confirmes that R_d of the LJJ can be reduced by the slow wave line. It is possible to tune the voltage of the resonances by adjusting the external magnetic field, while the position of Fiske steps in Fig. 3 is fixed.

The CRFFO I-V characteristics with power received by the detector 2 are presented in Fig. 5, 6. In Fig. 5 fluxons are moving towards detector 2. The peak of output power in this figure reperesents a forward wave mode of operation. In Fig. 6 fluxons are moving from detector 2 and a backward wave mode of operation is shown. Both modes can be continuously tuned by changing the bias current and the external magnetic field across the structure. The power scale for both figures is the same.

We conclude that the Cherenkov Flux-Flow Oscillator with microstrip loops type slow wave system has been designed fabricated and measured. The measurement shows induced resonances on the CRFFOs I-V curves with tunable frequency. The positions of resonances and it's magnetic field dependance suggest the Cherenkov mode of interaction between vortices and electromagnetic waves in the system. Both forward and backward wave type of resonances have been observed by changing the direction of flux-flow. The microwave power of order 0.8 μW has been measured both in the LJJ and in the slow wave system.

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