Experimental Investigation of Cherenkov Flux-Flow Oscillators

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`Abstract`— **This paper is devoted to the experimental investigation of a new class of superconducting microwave oscillators based on Cherenkov radiation from Josephson vortices. Samples consisting of a long Josephson junction embedded in a dispersive transmission line with space-periodical inhomogeneities were fabricated and tested. We report observation of new resonances on the I–V curve of the system and present the first radiation measurements in the $80 - 120$ GHz frequency range.**

I. Introduction

The aim of this paper is an experimental investigation of a new class of Josephson oscillators proposed in [1] and based on Cherenkov radiation from Josephson vortices. To use the Cherenkov radiation is a promising way of improving the existing Josephson Flux-Flow Oscillators (FFO) [2]–[5] and making them competitive in the frequency range 200–600 GHz with the conventional non-superconducting electronic sources, such as electronic traveling wave tubes (TWT) and backward wave tubes (BWT). It seems that Cherenkov Josephson oscillators are also good candidates to fill the frequency gap 0.5–5 THz between microwave and far infrared radiation.

Nowadays, the power and the noise characteristics of the radiation from the conventional FFO are not as good as required by applications and have to be improved. The drawback of the currently used FFO based on a long Josephson junction (LJJ) is a low efficiency of interaction between solitons and plasma waves, since plasma waves are radiated only at the edge of the junction where it is attached to the radiation pick-up line, *e.g.* a fin-line antenna.

The Cherenkov FFO is a new kind of the FFO in which radiation of electromagnetic waves occurs along the entire junction. The operation principle of the Cherenkov FFO is similar to that of the TWT or BWT and is based on the well-known analogy between a Josephson vortex (fluxon) and a charged particle. The fluxons moving due to the bias current along the Josephson transmission line with dispersion, excite an electromagnetic wave by means of the Cherenkov effect. Further, through interaction with the radiation field the vortices bunch in the decelerating phase of the wave, providing the coherent contribution of a large number of solitons to the radiation.

The fluxons moving along a LJJ can emit electromagnetic radiation due to the Cherenkov effect (see, *e.g.*, Ref. [1] and references therein) when the fluxon velocity is equal to the phase velocity of the emitted electromagnetic wave. Therefore, Cherenkov radiation can not be excited in a conventional LJJ, described by the 1-D sine-Gordon equation, since the sine-Gordon equation leads to a dispersion of plasma waves $\omega^2(k) = \omega_p^2 + k^2 v_s^2$, *i.e.* the minimum phase velocity $v_{\min} = v_s$, while the velocity of fluxon $v < v_s$.

To provide a possibility of Cherenkov radiation by moving Josephson vortices, the dispersion of a Josephson transmission line should be distorted so that acceleration of solitons above the minimum phase velocity of plasma waves would become possible. There are several ways to form a Josephson transmission line with the proper dispersion. For example, a LJJ can be coupled to a passive waveguide system, which distorts the dispersion of plasma waves. We propose a space-periodical strip-line with LJJ embedded in it as a possible choice for a waveguide system with proper dispersion. It is a commonly used slow-wave system in conventional TWT and BWT. The general theory of Cherenkov radiation from Josephson vortices in such a system was developed in [1]. Another possibility is to use an annular Josephson junction with a finite width [6] or a slot-line Josephson junction [7], where the requested dispersion occurs due to geometrical factors.

II. Design

Here we report the results of the experiments with linear and annular Cherenkov FFO designed as shown in Figs. 1 and 2, respectively. The samples of a linear geometry consist of a LJJ embedded in a space-periodical

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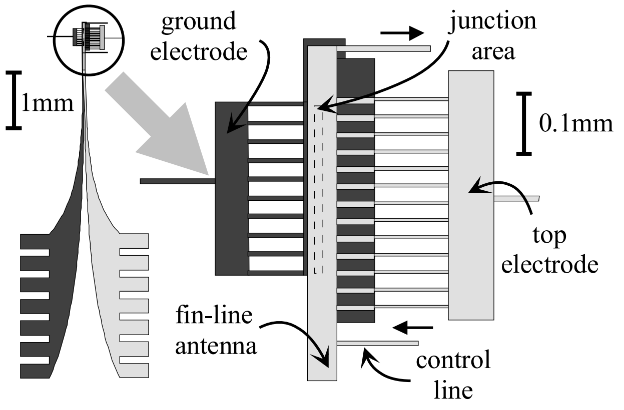

Fig. 1. Top view of the linear Cherenkov FFO layout: LJJ embedded in a periodic transmission line with a fin-line antenna connected to one edge.

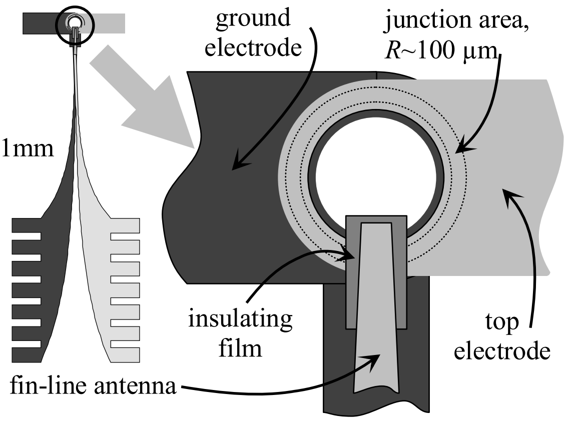

Fig. 2. Top view of the annular Cherenkov FFO layout: a conventional annular LJJ with a fin-line antenna attached to it either via an insulating film (shown) or directly (not shown).

slow-wave system (a set of side stubs), which smoothly turns into a fin-line antenna connected via a rectangular waveguide to a room-temperature receiver operating in the frequency range 80–120 GHz with a 1 GHz bandwidth. Annular samples consist of an annular LJJ with a fin-line antenna connected to it as shown in Fig. 2.

The parameters of the samples were chosen so as to fit the frequency of the anticipated radiation in the operating range of the receiver. The frequency is defined by the condition of the Cherenkov emission $v = v_{\rm ph}$, which for the case of a linear junction geometry can be written as

$$\omega(k) = v\left(k + \frac{2\pi n}{a}\right) \quad , \tag{1}$$

where $\omega(k)$ is the frequency of the emitted wave, v is the soliton velocity, a is the space period of the waveguide system, and n is an arbitrary integer number of spatial harmonics.

The Cherenkov condition for an annular system is

$$\omega(m) = \frac{v}{2\pi a} m \quad , \tag{2}$$

where $\omega(m)$ is the radiation frequency, m is the angular wave number, v is the fluxon velocity. Using the theory

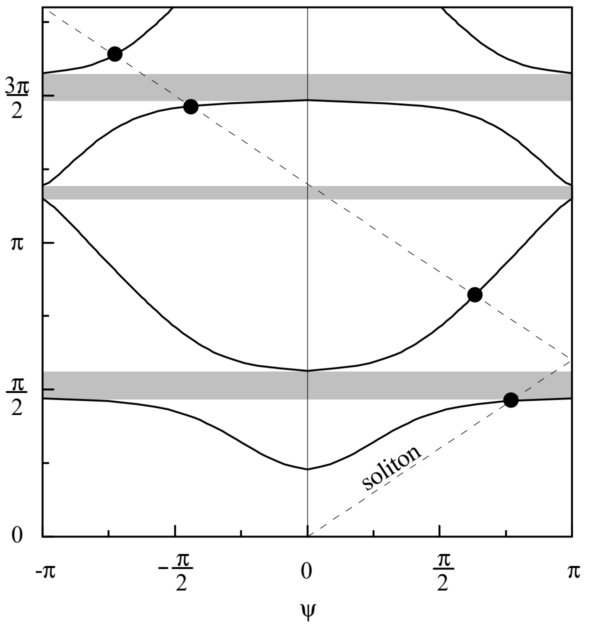

Fig. 3. Typical dispersion curves of LJJ embedded in a space-periodical transmission line with stubs. $\phi = \omega l_{st}/v_{st}$, $\psi = ka$, where l_{st} is the stub length, v_{st} is the velocity of wave in the stub, a is the spatial period of the transmission line.

of Cherenkov radiation in the space-periodical and annular structures developed in [1], [6], we can estimate the frequency of the anticipated radiation. We developed a computer program which allows to calculate the dispersion diagram of space-periodical and annular structures and, therefore, to predict the power and frequency of radiation. A typical set of the dispersion curves calculated by this program is shown in Fig. 3. The possible Cherenkov radiation frequencies correspond to the points of intersection of the soliton straight lines with the dispersion curves [see Eq. (1)] as shown in Fig. 3.

III. SAMPLE FABRICATION

The linear and annular LJJ's were fabricated using the standard Nb-Al-AlO$_x$-Nb technology. As a first step, we formed a Nb-Al-AlO$_x$-Nb trilayer using a mask for the ground electrode of the Josephson junctions, transmission line and fin-line antenna, and then etched it down to the ground electrode to form the junction. We used a Nb$_2$O$_5$ film produced by anodic oxidation as an insulating layer between the top and bottom electrodes of the transmission line and fin-line antenna. On top of this structure we sputtered a Nb counter-electrode of the fin-line antenna. To investigate the influence of the coupling between the fin-line antenna and the oscillator, we fabricated the samples with two different conjunctions between the fin-line antenna and LJJ: a) the counter-electrode of the fin-line antenna was connected to LJJ through the Nb$_2$O$_5$ insulating film, which plays the role of transition capacitance, as shown in Fig. 2 or b) directly via the ohmic contact *i.e.* without an insulating film. The shape of the annular LJJ

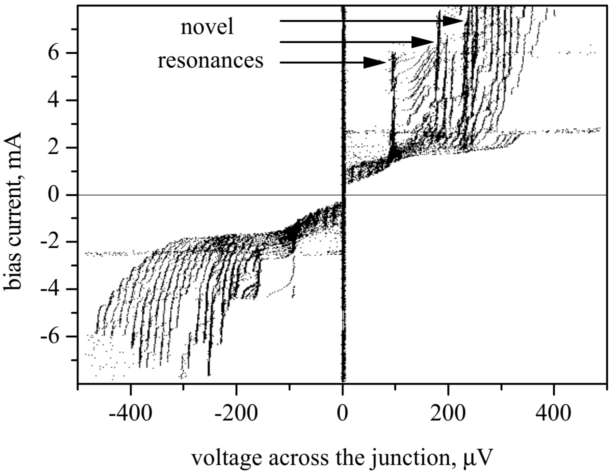

Fig. 4. Typical family of I–V curves of LJJ embedded in the periodical strip-line structure, at different values of external magnetic field measured at $T = 4.2\,\mathrm{K}$ using storage oscilloscope.

under investigation is the same as suggested in Ref. [8]. We measured the I–V curves (IVC) and radiation power for a set of linear and annular samples of different sizes.

IV. Experimental Results

A. Linear FFO with periodical slow-wave system

A typical family of IVC at $T = 4.2\,\mathrm{K}$ for different values of an external magnetic field applied in the plane of the sample perpendicular to its longer dimension, is shown in Fig. 4. The magnetic field was generated by the current passing along the control line (see Fig. 1). In comparison with the conventional LJJ, the IVC's exhibit several novel resonances marked by arrows in Fig. 4. The positions of these resonances depend on the length and space period of the side stubs. A computer simulation of the dispersive properties of the system shows that these resonances are related to the edges of the Brillouin zone (see Fig. 3), where the density of states has a maximum. Measurements of the I–V families at higher temperatures showed that these resonances survived even at $T \approx 7\,\mathrm{K}$, while the Fiske resonances were considerably suppressed. The power dissipated when the system is biased on one of these steps may be estimated as $P = V\Delta I$, where V and ΔI are the voltage and the amplitude of the step, respectively. This yields the following estimation for the emitted power: $P \approx 0.2\,\mathrm{mV} \times 1\,\mathrm{mA} \approx 200\,\mathrm{nW}$.

During the radiation measurements both the frequency of the receiver and the magnetic field were fixed and dependences the $P(I)$ and $V(I)$ were taken simultaneously. Typical results are presented in Fig. 5. The power of the radiation measured at the input of the waveguide (just at the edge of the fin-line antenna), was about 5 nW. The receiver was calibrated using standard technique, applying thermal blackbody radiation at the liquid nitrogen temperature to the input of the receiver and measuring its response.

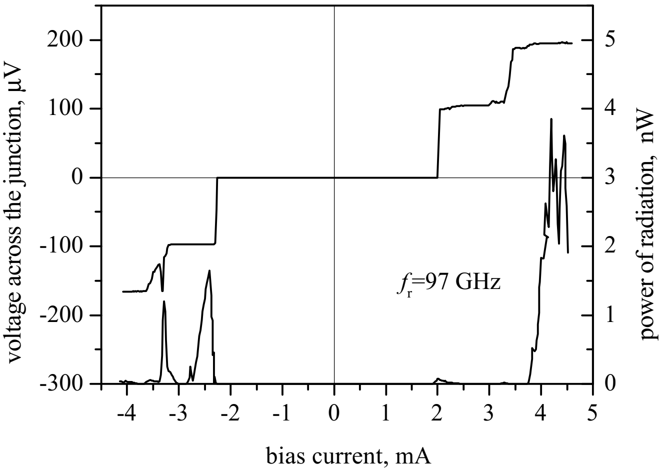

Fig. 5. The power of radiation P and the voltage V across LJJ *vs.* bias current I.

The results of the radiation measurements may be summarized as follows. There are radiation peaks at the frequencies: (a) close to the Josephson frequency $\omega = \omega_j$, (b) close to the second harmonic of the Josephson frequency $\omega = 2\omega_j$, (c) given by the ratio of integers like $\omega = \frac{3}{2}\omega_j$, $\omega = \frac{4}{3}\omega_j$. The direction of maximum radiation may either coincide with or be opposite to the direction of the fluxon motion, depending on the sample and on the frequency. For example, in Fig. 5 one can see that radiation with frequencies $\omega = \omega_j$ and $\omega = 2\omega_j$ corresponds to different polarities of the bias current. Checking the polarities of the bias and the control line current, we conclude that for this case the direction of the first harmonic radiation coincides with the direction of the vortex motion and is opposite for the second harmonic. This result may be naturally interpreted as the Cherenkov radiation of a backward wave, which exists in space-periodical structures.

B. Annular FFO

The IVC of the annular Josephson junction, with the internal and external radii $r = 90\,\mu\mathrm{m}$ and $R = 105\,\mu\mathrm{m}$ and without trapped fluxons is shown in Fig. 6. The critical current of the junction was about 17mA and the estimated Josephson penetration length is $\lambda_j = 25\,\mu\mathrm{m}$.

To trap the fluxons in an annular LJJ, a sample was cooled below $T_c \approx 9.2\,\mathrm{K}$ in the presence of a small bias current. The IVC's for the junction with trapped fluxons demonstrate quite unusual behavior. Two steps shown in Fig. 7 were observed. Interpreting the step at $V \approx 31\,\mu\mathrm{V}$ as the one corresponding to one running vortex, we estimate the Swihart velocity which was found to be $0.03c_0$, where c_0 is the speed of light in vacuum and is close to the theoretically calculated value. The second step at $V \approx 122\,\mu\mathrm{V}$ has the voltage four times as high as the voltage of the first step. This ratio of the step voltages has not been clear so far and is probably caused by mutual interaction of vortices affected by the inhomogeneity, introduced by the fin-line antenna.

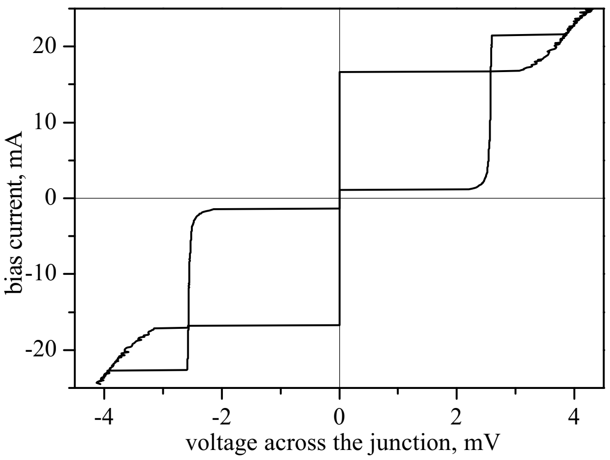

Fig. 6. *I–V* characteristic of annular junction with fin-line antenna

At high magnification one can see that the second step has a fine structure shown in the inset in Fig.7. In our opinion, the fine structure is related to the interaction of moving fluxons with different traveling/standing plasma modes pumped by means of the Cherenkov mechanism. Similar steps were observed by Goldobin *et al.* [9] in a system of two inductively coupled LJJs.

For measurement of the radiation from the annular LJJ we used the same technique as for the linear junction. We found that the emitted radiation has the frequency which does not obligatory coincides with the n-th harmonic of the Josephson frequency but can also be *e.g.* $\frac{3}{2}\omega_j$. As an example, in Fig. 7 we show the response of the receiver tuned at 91 GHz. The radiation at 91 GHz occurs at all steps. Analysis of the relations between the voltage and the receiver frequency yields $\omega_r = 6\omega_j$ for the first step and $\omega_r = \frac{3}{2}\omega_j$ for the second . The power of the radiation (*e.g.* at $\frac{3}{2}\omega_j$) was quite low, typically 50 pW for the annular junction while the typical radiation power obtained for the linear Cherenkov FFO was about 1.6 nW.

V. Conclusion

The *I–V* curves and radiation measurements can be explained in terms of Cherenkov radiation of the direct and backward plasma waves in a space-periodical structure and annular structures. The theoretical predictions for the radiation frequencies, based on the Cherenkov radiation concept, agree with the experimental data.

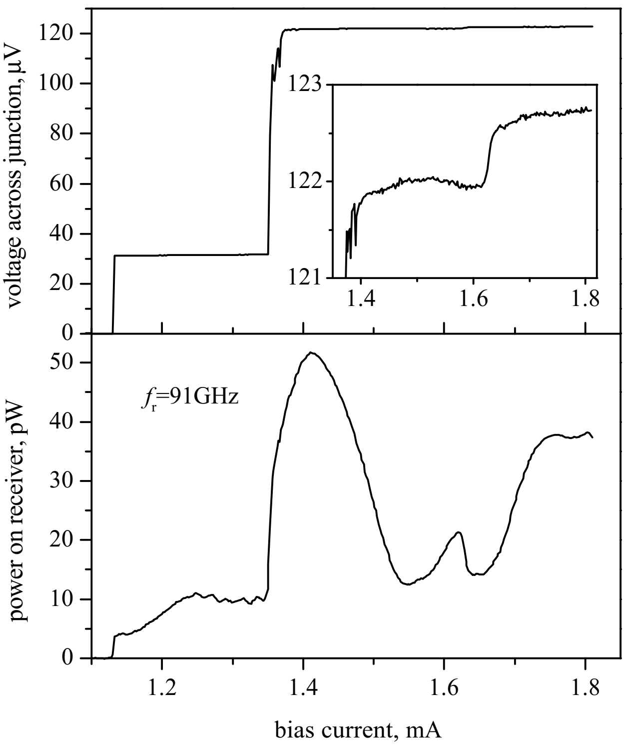

Fig. 7. Voltage V and the power of radiation P *vs.* bias current I for annular junction with fin-line antenna.

The results presented in this article stimulate further use of the theoretical results [1], [6] for development of novel Cherenkov FFO with enhanced characteristics.

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