

# Generation of the electromagnetic radiation by superconducting films.

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## Abstract

Coherent microwave radiation has been directly detected from superconducting Nb films in the frequency range up to 600 MHz. The mixed state in the films has been influenced by a superposition of two alternating magnetic fields directed perpendicular to film surface. First of them, which slowly varies in time, sets up a vortex structure in the film, while the second high-frequency electromagnetic field provides a synchronization of Abrikosov vortex motion. The simultaneous action of the fields results in either the amplification or generation of electromagnetic radiation. Harmonic mixing of the radiation is also detected.

*Key words:* vortex; pinning; microwave radiation;

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## 1. Introduction

An interesting problem in modern superconductivity is the creation of microwave oscillator. This was predicted by Josephson [1]. A novel approach was proposed in [2] to designing superconducting microwave oscillator. A superconducting film was placed in a low-frequency oscillating magnetic field directed perpendicular to the film surface. The field sets up a vortex structure in the film. The interaction of the vortices with planar pinning centres can lead to a metastable mixed state. The key feature of the approach is magnetic coupling between the film and a resonant circuit, mounted in such a way that the inductive coil is located in the vicinity of the film and creates an additional high-frequency oscillating magnetic field directed transverse to the film surface. The transition of the metastable vortex lattice into its ground state causes the vortex jumps. Under a change in the applied magnetic field, the high-frequency field periodically helps to the vortices to overcome energy barriers and to escape from the pinning centre. Thus this field

can synchronize the jumps of the vortices in the superconductor. In turn, every vortex jump induces an electromagnetic pulse in the coil of the circuit, and can increase the energy of the electromagnetic oscillation in the circuit. Thus a positive feedback effect arises. A change in the magnetic field per the period of high-frequency oscillation gives new critical condition for jumping of the pinned vortices, and, thus, a new fraction of the trapped vortices are included in the process. Coherent microwave radiation has been directly detected from Nb [2] and  $\text{GdBa}_2\text{Cu}_3\text{O}_7$  films [3] in the frequency range up to 600 MHz at 4.2 K and 10 MHz at 77.4 K, respectively.

Evidently, the vortex jumps in the superconducting films can be stimulated by external high-frequency electromagnetic field as well, because the probability of the vortices, or their bunches, to jump from a pinning center to an adjacent center depends on the applied electromagnetic field. It should result in the amplification of the signal. The amplification of the electromagnetic radiation by the superconducting films was detected in the frequency range of 0.15 - 4 MHz [4]. It is worth noting that the amplification proves the possibility of the realization of the positive feedback when the superconducting films are used to generate coherent

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electromagnetic radiation. The purpose of the present work is to investigate nonlinear properties of the oscillator.

## 2. Experimental Details

The experimental technique used for investigating of the electromagnetic radiation emitted by the superconducting films was described in [2]. The measurements were carried out using Nb films at 4.2 K. The films were prepared by electron-beam evaporation in a high-vacuum system. The low-frequency oscillating magnetic field, directed perpendicular to the film surface, varies in time ( $t$ ) according to the law  $H_{\perp} = H_{\perp 0} \sin(2\pi f_{exc} t)$ , where the amplitude of the oscillation  $H_{\perp 0}$  reaches 1 kOe, and the frequency  $f_{exc}$  is within 17 Hz to 1 kHz. The field produced by a transport current flowing through a coil causes the motion of Abrikosov vortices. For synchronization of the vortex jumps, the inductance of a LC-resonant circuit is mounted near the film. The radiation power spectra emitted by superconducting films are measured by a selective microvoltmeters (SMV) in the range of 0.2 - 600 MHz.

## 3. Result and Discussion

In [2], the radiation frequency was found to be equal to the resonant frequency of the LC circuit ( $f_{LC}$ ), and the power emitted proportionally increased with increasing in the amplitude and frequency of an exciting magnetic field. In this study, the results of the detailed investigation of the radiation spectra are presented in the case of their high power. A spectrum of the coherent radiation emitted by superconducting films is shown in Fig 1. As is seen, in addition to the main peak at the  $f_{LC}$ , there appear a number of new maxima. The positions of the maxima are  $f_n = n f_{LC}$ , where  $n$  is an integer. The origin of the harmonics of the radiation is dependence of the inductance value on the oscillating current in the LC-circuit because the coil is located in the vicinity of the superconducting film. And magnetic properties of superconductors depend on the field produced by the coil when the amplitude of the current oscillation is large enough. It is known [for example, 5] that the harmonics of the radiation can arise in LC-oscillating systems with nonlinear inductance.

Moreover, it is found that the radiation depresses the noise radiation, so that low-frequency noise transforms into a generated signal at the  $f_{LC}$ . This result is explained by the fact that the electromagnetic field emitted provides a decrease in the hysteresis formed in

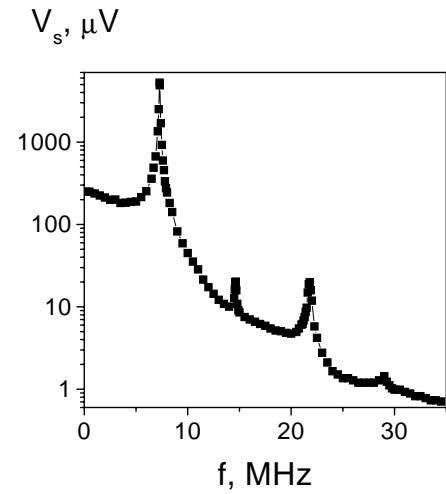


Fig. 1. An example of the frequency dependence of the rf signal.

the magnetisation curve of the superconducting films, and the energy source of the electromagnetic field, both coherent and noise, is the hysteresis.

Thus, the new nonlinear properties of the oscillator using LC-circuit for the synchronization of the vortex jumps in the superconducting films are found. It offers new possibilities for applying superconductors in electronics.

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