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METALS

A Microwave Photon Detector

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Abstract—The possibility of the implementation of a single-photon detector in the microwave range has been discussed. It has been shown that, for these purposes, it is possible to use an unshunted Josephson junction, which is switched from the superconducting state into a finite-voltage state at the presence of an external signal. The sensitivity of this detector is determined by the distribution of switchings in the absence of an external signal. It has been demonstrated that there is a Josephson junction with a noise temperature below 60 mK at a nominal external temperature of 10 mK. A specific detector intended for the measurement of external microwave signals has been proposed, designed, and fabricated. The first experimental results have been presented.

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1. INTRODUCTION

Currently, there are several strategies for the implementation of a quantum computer. One of these strategies is aimed at the implementation of an adiabatic quantum computer [1, 2], which, sometimes, is referred to as the quantum simulator. The production of efficient quantum switches is also in the focus of attention of researchers (see, for example, [3]). The realization of the ideas of quantum optics for the implementation of a photonic computer in the microwave range is an important problem. In this field of research, among other things, it has been demonstrated that there is a strong nonlinear interaction of macrowave photons with a system of Josephson junctions that play the role of a medium, the nonlinearity of which is described by the Kerr constant. The experimentally obtained large values of the Kerr constants indicate the fundamental possibility of the development of optical switches in the microwave range [4].

However, the absence of efficient single-photon detectors for low-energy photons fundamentally limits the experimental realization of the ideas of quantum optics and the development of a promising research direction such as microwave quantum engineering. It should be noted here that superconductors are very promising materials for use in the design and fabrication of scalable solid-state devices. First, the techniques used for manufacturing low-loss thin-film transmission lines, high-quality resonators [5], and microwave signal power dividers [6, 7] have been well known. Second, superconducting quantum bits (qubits), which have been actively investigated in recent years [8–10], can in principle play the role of two-level quantum systems for the generation and detection of photons. Moreover, the known elements of superconducting electronics, which employ a nonlinear behavior of Josephson junctions, can be used for the desired signal processing.

It should be noted that the creation of scalable solid-state devices for generation, transmission, and processing of microwave quantum signals (signals containing a small number of photons) requires low temperatures. For example, in order to minimize the probability of thermal (temperature T) excitation of a quantum oscillator (frequency ω), it is necessary to satisfy the condition $h\omega > k_BT$, where h is the Planck constant and k_B is the Boltzmann constant. Hence, it follows that the frequency of 21 GHz corresponds to the temperature of 1 K. Thus, the use of superconducting materials in microwave quantum engineering, where the main nonlinear element is a Josephson junction, seems to be quite natural.

2. JOSEPHSON JUNCTION AS A DETECTOR AT LOW FREQUENCIES

A typical current–voltage characteristic of the Josephson junction with niobium electrodes is shown in Fig. 1. As the applied current increases, the Josephson junction remains in the superconducting state until the critical current I_C is achieved. In the vicinity of the critical current I_C, there is a jump into the state with a finite voltage of approximately 3 mV for tunnel Josephson junctions based on niobium. This electromagnetic signal is easily detected by conventional devices.

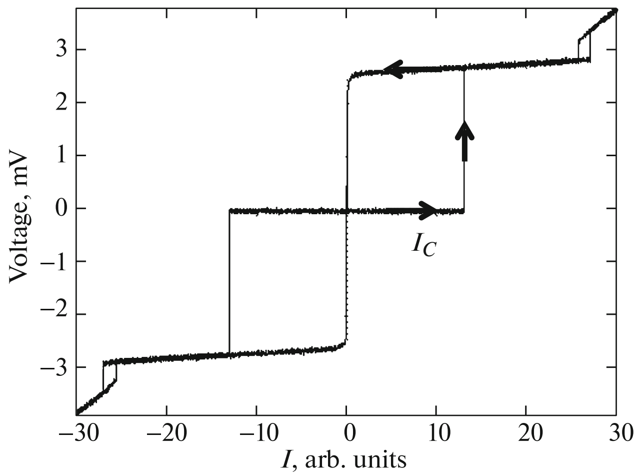

Fig. 1. An example of the current–voltage characteristic of the unshunted tunnel Josephson junction based on niobium at the voltage of ≈3 mV after the jump. The arrows indicate directions of the current sweep. The electric current is given in arbitrary units.

Thus, the idea of the detector is as follows: the electric current (referred to as the bias current I_B), which is close to the critical current I_C, is applied to a Josephson junction so that the voltage at the junction is equal to zero. The incoming electromagnetic signal effectively increases the bias current and, thus, induces the transition to the state with a finite voltage, which serves as the output signal.

In order to improve the sensitivity of such a detector, it is necessary to examine in detail the mechanisms of switching of the Josephson junction. The model used in this case is well known. It implies that the dynamics of the Josephson junction is described by the behavior of the Josephson phase. The phase, in turn, is simulated by a dimensionless particle in the field with a potential in the form of a washboard (see Fig. 2). The modulation of the height of the potential barrier or the presence of an exciting field can lead to the fact that the dimensionless particle escape from a potential well. As a result, the voltage is generated at the Josephson junction.

In the general case, the above-described switching of the voltage from the zero state to the final state can be caused both by thermal energy (a "jump" over the potential barrier, see Fig. 2) and by macroscopic phase tunneling (also see Fig. 2). At low temperatures, it is the latter regime that determines the intrinsic noise of the device.

These two processes, namely, thermal activation (TA) and macroscopic quantum tunneling (MQT), are characterized by their own activation probabilities per unit time, i.e., Γ_{TA} and Γ_{MQT}, respectively. These

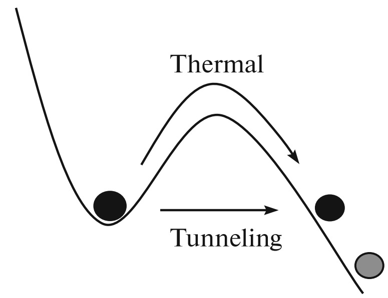

Fig. 2. Potential of the unshunted tunnel Josephson junction with the current. The arrows indicate possible (thermal and quantum) mechanisms of switching.

quantities (escape rates) are determined by the following expressions [11]:

$$\Gamma_{\mathrm{TA}} = \frac{\omega_0}{2\pi}\frac{4}{\left(\sqrt{1+\dfrac{Qk_{\mathrm{B}}T}{1.8\Delta U}}+1\right)^2}\exp\left(-\frac{\Delta U}{k_{\mathrm{B}}T}\right),$$
$$\Gamma_{\mathrm{MQT}} = \frac{\omega_0}{2\pi}\sqrt{\frac{B}{2\pi}}\exp(-B), \qquad (1)$$

where ω_0 is the frequency of phase oscillations in the potential well, which is equal to $\sqrt{2\pi I_C/\Phi_0 C_K}\,(1 - I^2)^{1/4}$; Φ_0 is the magnetic flux quantum; $I = I_B/I_C$ is the dimensionless current of the Josephson junction; ΔU is the potential barrier height determined by the Josephson energy E_J; $Q = \omega_0 R_N C_K$ is the quality factor of the device; R_N is the electrical resistance of the Josephson junction; C_K is the capacitance of the Josephson junction; $B = \dfrac{\Delta U}{\hbar\omega_0}\left[7.2 + \dfrac{8A}{Q}\right]$; and A is the parameter determining the dissipation.

From these expressions, it can be seen that the probability of thermal activation Γ_{TA} is a function of the temperature, whereas the probability of macroscopic quantum tunneling Γ_{MQT} does not depend on the temperature. Then, it is obvious that we can calculate the temperature of switching from one regime to another (see, for example, [11]):

$$T_{\mathrm{cr}} = \frac{\hbar\omega_0}{2\pi k_{\mathrm{B}}}\left[\sqrt{1+\left(\frac{1.2A}{2Q}\right)^2} - \frac{1.2A}{2Q}\right]. \qquad (2)$$

This expression determines the equivalent noise temperature of the detector. It should be noted that the equivalent noise temperature of the detector can be decreased by increasing the capacitance of the Josephson junction. However, a change in the capacitance of the Josephson junction will change the operating frequency range of the detector, and a decrease in the capacitance of the junction will also lead to a decrease in the operating frequency.

Based on the above considerations, the Nb/AlO/Nb Josephson junction with the following parameters was fabricated at the VTT Technical Research Centre of Finland: the critical current density was 30 A/cm^2, the capacitance was $C_K = 0.33$ pF, and the electrical resistance was $R_N = 0.44$ kΩ [11]. The sample was measured at the Leibniz Institute of Photonic Technology (Jena, Germany) in a dilution refrigerator at a nominal temperature of 10 mK. In order to minimize the external noise (which is of fundamental importance for solving our problem!), first, the sample was placed inside the magnetic and superconducting shields, and, second, the dependences of the voltage on the current were measured using filtered twisted pairs with *RC* filters at a cutoff frequency of 10 kHz at a temperature step of 4 K. Additionally, *LC* filters at the same cutoff frequency and copper-powder absorption filters were used at a step of 10 mK. The electric current was swept in accordance with the following law: it changed in steps of 0.1 nA/ms within 10 ms at a waiting time of 10 ms between the steps. The experimentally obtained width of the switching of this autonomous transition at a temperature of 10 mK amounted to only 4.5 nA, and the corresponding noise temperature was approximately equal to 60 mK [11].

For comparison, we estimated the amplitude of the electric current corresponding to a single photon at a frequency of 3 GHz. This amplitude is determined by the expression $I_A = \sqrt{\frac{\hbar\omega}{2\pi L_R}}$, where L_R is the inductance of the corresponding part of the transmission line. For a quarter-wavelength coplanar microwave resonator [12, 13], the amplitude of the electric current was estimated as $I_A \approx 20$ nA. Therefore, one-half of the spread in the switching of the value of 2.2 nA, which is a measure of the sensitivity of this device, is quite sufficient to detect a single photon in the microwave range.

Thus, we demonstrated that intrinsic fluctuations of the unshunted Josephson junction with specially chosen parameters are not very large. However, it is important to note here that all the measurements were performed at a low frequency. An analysis of the parameters of a possible photon detector requires the use of a model that would describe the interaction of a Josephson junction with a quantized electromagnetic field.

3. JOSEPHSON JUNCTION AS A PHOTON DETECTOR

Since we plan to work with a small number of photons, it is necessary to use the quantum description of the switching of a Josephson junction (the schematic diagram of the switching of a Josephson junction is shown in Fig. 2). In this case, the system is open. Therefore, we should use a rather cumbersome formalism of the density matrix. Our colleagues from Denmark have proposed an elegant approach to the solution of the problem, i.e., the use of the so-called imaginary potential for the description of the evolution of the phase of the Josephson junction [14].

As is known, the time evolution of a closed quantum system is described by the dynamics of the state vector of the system $|\Psi(t)\rangle$, which is subject to the Schrödinger equation

$$ih\frac{d}{dt}|\Psi(t)\rangle = \hat{H}(t)|\Psi(t)\rangle, \tag{3}$$

where $\hat{H}(t)$ is the Hamiltonian operator of the system (here, i is the imaginary unit). For the time-independent Hamiltonian $\hat{H}$, this equation is integrated, and the solution can be written in the form $|\Psi(t)\rangle = \exp\left(-\frac{i}{h}\hat{H}t\right)|\Psi(0)\rangle$. It is obvious that, if the Hamiltonian contains the imaginary part, then the amplitude $|\Psi(t)\rangle$ changes, and the problem ceases to be inverse. Generally speaking, in this case, the Hamiltonian $\hat{H}$ is not Hermitian. This calls into question the "legitimacy" of the aforementioned procedure. However, the verification has demonstrated that this description is adequate for specific problems [15]. In particular, the dynamics of the phase of the Josephson junction is well described in the framework of the above formalism [14].

Thus, in a potential well (before the tunneling), the Josephson junction is described by the Schrödinger equation (3) with the Hamiltonian

$$\hat{H}(t) = -\frac{\hbar^2}{2M}\frac{\partial^2}{\partial\varphi^2} - U(\varphi, t). \tag{4}$$

Here, $U(\varphi, t) = U_0 + U_{mv}$, where $U_0 = E_J(\cos\varphi + I\varphi)$ is the potential of a dc-current (I) biased Josephson junction, U_{mv} describes the influence of a microwave field on the potential, and $M = (\Phi_0/2\pi)^2 C_K$ is the "effective mass."

After the event of tunneling (outside the potential well, see Fig. 2), potential (4) is complemented by the imaginary part $iV_{im}(\varphi, t)$ calculated using the expression for the "running" states of the phase of the Josephson junction, which were obtained in [16]. The electrical resistance of the Josephson junction is described by the phase-nonlinear term (the last term in the Hamiltonian given below; for details, see [14]). The full Schrödinger equation can be written as

$$\begin{aligned} ih\frac{d}{dt}|\Psi(\varphi,t)\rangle &= \left(-\frac{\hbar^2}{2M}\frac{\partial^2}{\partial\varphi^2} - U(\varphi,t)\right)|\Psi(\varphi,t)\rangle \\ &+ iV_{im}(\varphi,t)|\Psi(\varphi,t)\rangle + i(\varphi - \langle\varphi\rangle)^2|\Psi(\varphi,t)\rangle. \end{aligned} \tag{5}$$

A comparison with other models demonstrates that the proposed approach has the right to exist; in particular, it well describes the dynamics of switchings of a Josephson junction [14]. However, this is not sufficient for the fabrication of a real photon detector,

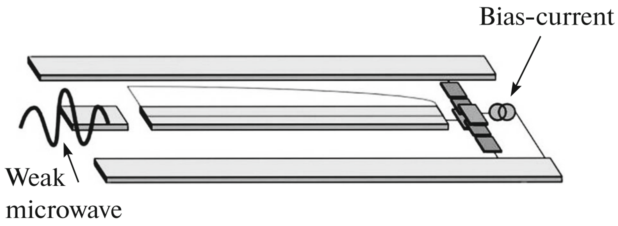

Fig. 3. Schematic diagram of the device for the detection of weak microwave signals. After the input capacitance, the central conductor of the resonator is short-circuited at the current-biased Josephson junction. Two side superconducting strips are grounded. The fundamental mode of the coplanar resonator is schematically shown above the central conductor.

because the coupling with the quantized electromagnetic field must necessarily take place.

4. DESIGN OF THE DETECTOR

In order to provide the coupling of a dc-current biased Josephson junction with the measured microwave signal, this Josephson junction is placed in a quarter-wavelength coplanar microwave resonator (Fig. 3). The basic idea is to use this structure as a microwave radiation detector. A photon (photons) trapped in the resonator switches the Josephson junction into a finite-voltage state, which serves as the output signal of the detector. The coplanar resonator can be represented as a structure composed of a series-connected *LC* circuits. The Hamiltonian of this system can be written as follows:

$$H_T = \sum_j \hbar\omega_j a_j^\dagger a_j, \quad (6)$$

where ω_j is the angular frequency of the oscillator and $a_j(a_j^\dagger)$ is the creation (annihilation) operator of photons in the *j*th mode. The Hamiltonian of the dc-current biased Josephson junction was written in the previous section. Thus, the problem is reduced to the determination of the total Hamiltonian of the Josephson junction–resonator system, which consists of the following components:

$$H = H_{T,s} + H_{\mathrm{JJ}} + H_{\mathrm{I}}, \quad (7)$$

where $H_{T,\,s} = \hbar\omega a^\dagger a$ is the single-mode Hamiltonian, H_{JJ} is Hamiltonian (4) with the potential $U(\varphi, t) = E_{\mathrm{J}}(\cos\varphi + I\varphi)$, and H_I is the Hamiltonian describing the coupling and the interaction between the Josephson junction and the resonator.

Omitting the details of the derivation of the total Hamiltonian of the "Josephson junction–coplanar resonator" system, it should be noted that, here, we used the standard formalism. First, from the equations of motion for the transmission line, we obtained the Lagrangian. Then, in the single-mode approximation, we derived the desired Hamiltonian in accordance with the standard rules (for details, see [17]).

The numerical analysis performed for the obtained equation demonstrated that the system is effective enough to detect even single microwave photons. It was established that, for the optimum value of the bias current $I = 0.92$, the quantum efficiency of the system was as high as 0.99 at the detection time of 82 ns. In this case, the operating frequency band of the detection was 100 MHz when the fundamental frequency of the pump signal was 2.45 GHz. It is assumed that the transition to the multimode regime will only slightly deteriorate the characteristics obtained in the present study. It should be noted that Josephson junctions with a high critical current $I_{\mathrm{C}} > 10$ μA are not appropriate to use in the structure of the detector because of the high switching energy, which will lead to a heating of the structure and to a decrease in the sensitivity of the device.

The first samples were fabricated in technological processes of the preparation of Nb/Al/Nb junctions and niobium films [18], which have been used in the clean room at the Leibniz Institute of Photonic Technology (Jena, Germany). The test measurements performed at a nominal temperature of 10 mK showed that the critical current was slightly higher than the desired current and amounted to 13 μA. The gap voltage at the junction (the voltage after the jump) was equal to 2.6 mV, the electrical resistance of the junction was $R_N = 130\ \Omega$, and the capacitance was 400 fF. The quality factor of the resonator short-circuited at the Josephson junction was 1100, and the inductance of the resonator was 3.5 nH.

Despite the slightly overestimated critical current, the sample demonstrated its efficiency and switched over in response to a high-frequency signal. At the moment, we cannot uniquely determine its sensitivity, because the experimental cycle is not finished yet.

5. CONCLUSIONS

Thus, first, the calculations have demonstrated that the proposed microwave photon detector can have a sensitivity that is close to the quantum limit. Second, this structure can be fabricated (and the first samples have already been prepared!) using the conventional superconducting technology and measured by standard methods at millikelvin temperatures.

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