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Switching of superconducting nanowires from NbN to the normal state and back at high frequency in two-layer structures due to local heating

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The work of a single element of the device consisting of two galvanically isolated superconducting NbN nanowires in different layers, into one of which a resistance of $\sim 1.2\,\mathrm{k\Omega}$ is integrated at the point of their intersection, is demonstrated. The device actuation (output voltage generation) occurs due to contactless local heating of the superconductor by heat released in the resistive section of the nanowire in the adjacent layer through the separating dielectric layer. In liquid helium (4.2 K), pulse and sinusoidal RF signals, as well as sinusoidal microwave signals at frequencies of 1, 4 and 9 GHz, were fed to the device. It was found that when a pulse RF signal is fed, the response speed of the contactless inverter corresponds to a frequency of ~ 0.83 GHz; when a sinusoidal signal of 100 MHz is fed, a periodic signal of double frequency appears at the output; When a microwave signal is applied, peaks at double the frequency (2, 8 and 18 GHz) are observed on the frequency spectrum, which indicates the possibility of the device operating at frequencies up to 18 GHz.

Keywords: NbN nanowire, superconductivity, microwave, contactless inverter, cryotron, „Y-tron“, „h-tron“.

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Introduction

In modern semiconductor processors, an increase in the number of transistors leads to a dramatic increase in the total length and density of connecting wires, limiting performance at the level of GHz units due to the emergence of parasitic RC circuits [1,2]. Since the connecting wires are conductors that emit heat during the flow of current, an increase in the number of transistors is accompanied by an increase in parasitic energy release in the metallization layer. Thus, the total energy consumption of American data centers in 2018 amounted to 205 TWh of electricity [3].

It follows from this that a further increase in the computing power of semiconductor computers (including supercomputers) is possible mainly due to quantitative growth.

These limitations of semiconductor electronics force the development of alternative computing technologies, including those based on the superconductivity effect. At the moment, both quantum computing technologies and technologies with classical computing architecture, as well as cryogenic semiconductor technologies, are developed [4].

The most developed superconducting field with classical architecture is fast single-quantum logic (RSFQ — Rapid Single Flux Quantum). Modern RSFQ logic devices have a clock frequency of up to 50 GHz, as well as extremely low power consumption of a single switch (120 aJ versus 10^5 aJ for CMOS technology). The RSFQ technology also has various modifications: ERSFQ (Enchanted RFSQ), LV-RSFQ (Low-Voltage RSFQ), AQFP (Asymmetric Qubit Flux Parametron), RQL (Resonant-Tunneling Quantum Logic), which allow to achieve even lower power consumption (up to 0.086 aJ for switching) [5]. HYPRES uses this technology to manufacture commercial devices [6], and the development of RSFQ logic is included in the international roadmap for Devices and Systems (IRDS) as the cutting edge of microelectronics in the post-Moore era [7].

An alternative direction in the development of superconducting logic is to use the effect of controlling the state of a superconductor section using an external source. The cryotron of D. Buck was the first device of this kind in which a section of a cylindrical superconductor is switched between a normal and superconducting state by means of a gate that creates a magnetic field above the critical field [8]. Later, IBM created a thin-film version of the cryotron, which also uses the magnetic field to control the superconducting state [9] . Despite the fact that the characteristic size of the element is approximately 1 mm, it is noted in Ref. [10] that when scaling this device to the characteristic size of 100 nm, it is possible to achieve the switching time of ~ 1 ps (corresponds to the switching frequency of ~ 1 THz) and switching energy of $\sim 10^{-19}$ J/bit. These parameters are comparable in speed and energy efficiency to modern RSFQ circuits.

Work is also currently underway to control the superconducting state using local heating. Thus, SRC „Kurchatov Institute“ has created and develops a direction aimed at manufacturing the element base of superconducting logic devices based on thin-film nanowires. The principle of operation of the devices is based on switching a section of a superconducting nanowire between normal and superconducting states under the influence of local heating. Another superconducting nanowire with an integrated section with a metallic type of conductivity is used as a heater [11].

The integration of resistance is carried out using the technology of selective modification of the atomic composition of thin-film materials, also developed in SRC „Kurchatov Institute“. Within the framework of this technology, a thin-film material consisting of several atoms with different masses (for example, metal oxides and nitrides) is irradiated with low-energy ions (~ 1 keV). In particular, when a superconducting NbN film is irradiated with a mixed proton-oxygen beam, a gradual selective substitution of nitrogen atoms for oxygen atoms occurs.

It should be noted that other authors are also developing devices for controlling the state of a superconductor using local heating. For example, thin-film cryotrons with galvanic coupling were created in Ref. [12], in which the superconductor is heated in the created narrowing of the gate connected to the superconductor. Later, they manufactured devices for reading information „Y-tron“ [13], devices for controlling the superconducting state without galvanic coupling „h-tron“ [14], as well as memory cells on based on [15].

Let's take a closer look at the „h-tron“ device known from the literature, which also uses the heat generated in a metal gate to transfer a superconducting nanowire in an adjacent layer to a normal state. It should be emphasized here that, despite the similar method of contactless switching of a superconductor to a normal state in the „h-tron“ device and in the devices we create, the method used in them to transfer a section of a superconductor to a normal state due to local heating was patented by us earlier in the Russian Federation [11].

Fig. 1 shows a diagram of the „h-tron“ device on a thin-film NbN. A thin titanium electrode with a thickness of 30 nm acts as a gate. The gate is separated from the controlled NbN wire by 20 nm of silicon oxide SiO_2. The thickness of the controlled nanowire is 20 nm. When current flows through a gate with a metallic type of conductivity, heat is generated in it according to the Joule-Lenz law, which heats a section of the superconductor above a critical temperature, bringing it to a normal state.

It should be noted that the authors of Ref. [14] do not evaluate the performance of this device. It is known that the time of heat propagation over a certain distance from the heater, which is necessary to warm up the body to a certain temperature, is proportional to the square of this distance. It follows from this that reducing the thickness of the dielectric between the gate and the heated wire will increase the speed of the device (for example, reducing the thickness of the dielectric by 2 times should increase the switching frequency by 4 times). An additional limitation of the device's performance may be the thickness of the gate itself and the heated nanowire, since heating a superconductor of greater thickness will require more energy and more time to warm up. At the same time, the authors of Ref. [14] rightly point out that the actual performance of the device also strongly depends on the conditions of heat removal.

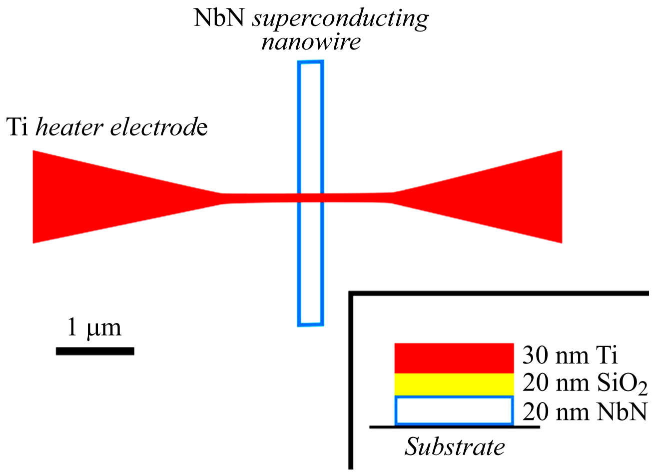

Figure 1. Schematic diagram (*a*) and colored SEM image (*b*) of the logic device „h-tron“ [14].

Despite the similar operating principle of the „h-tron“ device from Ref. [14] and the contactless switching device we are studying, the latter has several advantages in the expected higher switching frequencies and lower power consumption. This is attributable to the following structural differences between our devices.

Firstly, the method of selective change of atomic composition used by us allows the integration of resistances into ready-made superconducting nanowires. This makes it possible to form sections with a metallic type of conductivity only in the section of the nanowire that is intended for local heating, i.e. without excessive heat dissipation on the supply wires. This technology also makes it possible to combine superconducting sections with metallic-type sections with a smooth interface between the metallic and superconducting parts of the nanowire (in contrast to the „sharp“ interface that occurs when using the „lift-off“ technology when inserting a metal section into a superconducting nanowire). This is especially true for multi-stage logic devices, in which one stage may contain a superconducting section controlled by an external gate and a resistive section serving as a gate for the next stage.

Secondly, the integration of resistances by mixed ion irradiation through a mask makes it possible to produce all integrated resistances in one technological irradiation operation.

Thirdly, by varying the dose of mixed ion irradiation, as well as the geometry of the irradiated area, it is possible to adjust the nominal value of the integrated resistance, or, with a decrease in dose, to create areas with suppressed superconductivity with reduced critical properties [16].

Fourth, the smaller thicknesses of the separation dielectric we use make it possible to achieve the heating required for switching a superconducting nanowire to a critical temperature faster than in the glqqh-tron“ devices.

Previously, we studied the behavior of NbN exposed to the mixed ion irradiation, which is necessary for the manufacture of elements of superconducting electronics. Thus, when irradiating NbN films with a thickness of 5 nm with a mixed proton-oxygen beam in the dose range of 1.8–9 dpa (displacements per atom), a change in the nature of conductivity from superconducting to metallic is observed. The film becomes dielectric at a temperature of 4.2 K when exposed to doses of 9–12.6 dpa, while the change in the nature of the conductivity is due to a change in the chemical composition of the film [16].

The main purpose of this work is to experimentally demonstrate the switching of a small section of a superconducting NbN nanowire from a superconducting state to a normal state and back at high frequencies due to local heating by heat released by a section of normal metal (gate) located in an adjacent layer.

1. Experiment description

The object of the study is a two-layer NbN structure on a sapphire substrate, which is a pair of NbN nanowires located in different layers. The nanowires are arranged perpendicular to each other and are separated by an Al_2O_3 12.5 nm thick dielectric (Fig. 2).

The control resistance R_1 is integrated into the nanowire in the second layer at the intersection with the other nanowire. This nanowire will be referred to as a gate. The second nanowire in the intersection region remains superconducting and is converted to a normal state by exceeding T_c as a result of heat transfer from R_1 at the gate, located at a distance equal to the thickness of the interlayer dielectric. We will call this nanowire the main nanowire. The width of the gate and the main wire in our experiments was the same and was 400 nm, the thickness of the nanowires (corresponding to the thickness of the NbN film) was 6.5 nm for the main wire (first layer) and 5.5 nm for the gate (second layer).

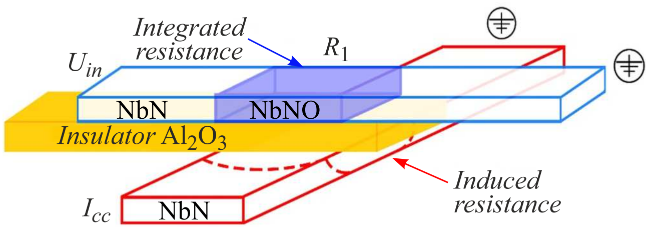

Figure 2. Diagram of a single logical device.

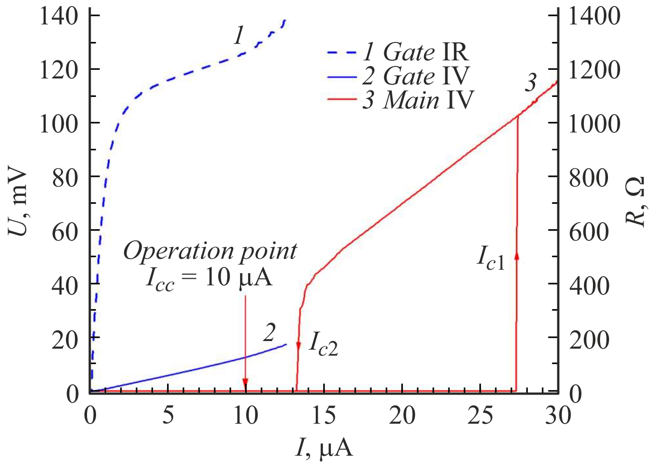

Figure 3. Current-voltage curve of the gate (Gate IV) and the main wire (Main IV) with the dependence of the differential resistance on the current through the gate (Gate IR).

The resistance R_1 in a superconducting NbN gate is a square region 400 × 400 nm of niobium oxynitride NbNO created from the initial niobium nitride under the action of mixed ion irradiation. This region has a metallic type of conductivity at a temperature of 4.2 K and is made by selectively replacing nitrogen atoms with oxygen atoms using radiation technology developed in SRC „Kurchatov Institute“ [17]. Within the framework of this technology, a nanowire was irradiated through a mask with a mixed ion beam consisting of 99 % protons and 1 % oxygen ions. The energy of the mixed ion beam during irradiation was 1 keV, ion current density was 0.849 A/m^2. The radiation fluence was $\sim 10^{17}$ cm^{-2}. Stabilizing annealing was performed at a temperature of 200 °C after irradiation. The electrical resistance of the irradiated material per square was ∼ 1.2 kΩ/sq as a result of irradiation and annealing.

Fig. 3 shows the current-voltage curve (CVC) of the gate (Gate IV) and the main wire (Main IV), as well as a graph of the dependence of electrical resistance on the current through the gate (Gate IR).

It should be noted that there is hysteresis on the CVC of the main wire 3, i.e., the difference between the critical transition current from the superconducting state to the normal I_{c1} and the critical transition current from the normal state to the superconducting I_{c2}. This difference is explained by the fact that, when in the normal state, the superconductor is subject to Joule self-heating, which keeps it from transitioning to the superconducting state [18]. In connection with this fact, the operating value of the current I_{cc} applied to the main wire is a value lower than I_{c1} and I_{c2}, i.e., corresponding to the presence of the main wire in a superconducting state. The operating current value I_{cc} is selected so that $I_{cc} > I_{c1}$, and there will be no return of the main wire to the superconducting state after a single switch, and, as a result, disruption of the correct operation of the device. Thus, the value $I_{cc} = 10\,\mu$A is selected as the operating value of the current on the main wire.

The curves *2* and *1* (Fig. 3) respectively represent the CVC and the differential resistance of the gate in the operating region of the integrated resistance (i.e., before the transition to the normal state of the superconducting sections of the gate). A non-linearity is observed for the integrated resistance value: the integrated resistance value increases with increasing current.

Let's take a closer look at the curve *1*. The sharp increase in the nominal resistance in the current range of $0 - 5\,\mu$A is presumably associated with the transition to the normal state of the remnants of the superconducting phase in the resistance formation zone. A slow increase in resistance in the current range of $5 - 10\,\mu$A may be due to a change in resistance per square of the irradiated area as it heats up in case of current sweeping during CVC recording.

Further bending of the curve with increasing current through the gate may be associated with the transition of the superconducting portion of the gate to a „resistive“ state. It is explained by the formation and movement of Abrikosov vortices when the current approaches the critical transition current to the normal state (not shown in curves *1* and *2*, since the transition of the superconducting part of the gate to the normal state is beyond its operating range). The resistive state is described in more detail in Ref. [19]. Thus, the differential resistance in the region of more than $10\,\mu$A is the sum of the nominal integrated resistance and the additional series resistance of the superconducting gate region.

By comparing the curve *1* with the curve *2*, it can be noted that for the device to work correctly, the gate must have a resistance of $1-1.3\,\mathrm{k}\Omega$, which corresponds to the minimum input voltage of $\sim 3\,$mV. The maximum input voltage is limited to $\sim 18\,$mV, because when this value is exceeded, an undesirable transition to the normal state of the superconducting part of the gate occurs. It should be noted that with a fixed NbN film thickness, the integrated resistance value depends on the radiation dose (the dose determines the resistance per square film), as well as on the shape of the irradiated area.

Two types of experiments were performed in this study. In the first type of experiment, a gate pair was investigated for the gate's ability to switch the main wire from a superconducting state to a normal one at high frequencies. To do this, an alternating voltage Uin was applied to the gate using an external RF signal generator, which serves as an input signal. A supply direct current I_{cc} was applied to the main wire using an external current source, the value of which was chosen less than the critical reverse transition current (I_{c2}) of the main wire (the current of transition from the normal state to the superconducting state). The limitation of the supply current of the main wire to the value of the reverse junction current ($I_{cc} < I_{c2}$) was due to the need to ensure that the main wire returns to the superconducting state after removing the gate signal. When the main wire is switched

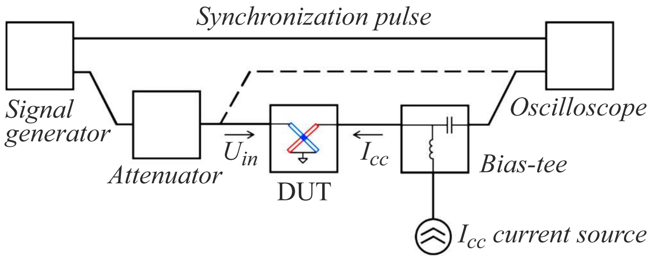

Figure 4. Measurement circuit of the tested device with the recording of the input and output signals by an oscilloscope.

to a normal state, a voltage is generated on it, which is recorded by the oscilloscope. The studied device operates in the repeater mode in this configuration, i.e., applying voltage to the input leads to voltage at the output of the device.

The setup of experiments of the first type is shown in Fig. 4. A synchronization pulse signal from an oscillator was applied to the first channel of the oscilloscope. A signal from the generator output is sent directly to the second channel of the oscilloscope along with a synchronization pulse for recording the input signal (dashed line in Fig. 4). Then the signal from the generator output is already sent to the tested device, while the synchronization pulse continues to be sent to the first channel of the oscilloscope. This measurement setup allows approaching the correct synchronization of the input and output signals on the device, but it does not save you from a possible phase delay of the output signal during passage through the device and the cryogenic RF path.

An RF signal of two types was applied to the input: a rectangular unipolar pulse and a sinusoidal signal. The repetition rate of the rectangular pulses was 50 MHz, the minimum rise time of the front of the input rectangular pulse used was 1.2 ns, which formally corresponds to a frequency of 0.83 GHz. Therefore, special attention was paid to the study of the area of the output signal front, the steepness of which reflects the speed of the device.

The input of a sinusoidal signal with a frequency of 100 MHz was used to demonstrate the correct operation of the device: a periodic signal with twice the frequency was expected at the output. This is due to the fact that local heating, which causes the operation of the device, is generated in the resistive section of the gate, regardless of the direction of current (voltage sign) through the gate. The output voltage depends only on the absolute value of the amplitude of the input signal and must occur on both the positive and negative half-cycles of the incoming sine wave.

The limitations of the frequency experiments described above were due to the limited capabilities of the oscilloscope for recording signals in time: the maximum frequency for the device used was 1 GHz.

In the second type of experiment, a sinusoidal microwave signal at frequencies of 1, 4, and 9 GHz was applied to the input of the device using an external microwave generator. Due to the lack of an oscilloscope for the

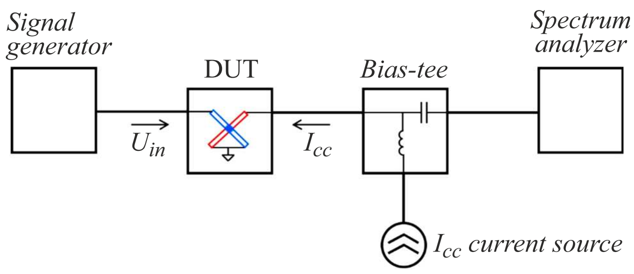

Figure 5. Measurement circuit of the tested device with the recording of the output signal by the spectrum analyzer.

specified frequency range, the output signal was recorded on a spectrum analyzer in the double frequency range (2, 8 and 18 GHz, respectively). When a sinusoidal signal is applied to the spectrum analyzer, even with the power off, a peak may occur due to the transmitted signal and its harmonics. Therefore, the measurements were carried out with I_{cc} on and off. The measurement circuit is shown in Fig. 5.

Platinum contacts with an intermediate nickel sublayer were sputtered onto the NbN layer to ensure ohmic contact of the superconducting nanowires with the measuring stand. The contact between the sample and the stand is ensured by gluing a gold hair to the sample using indium. The measuring stand is placed in a vessel with liquid helium and cooled to a temperature of 4.2 K.

2. Results and discussion

During the experiments of the first type, it was found that when the amplitude of the rectangular unipolar pulse signal of the inverter actuation voltage is exceeded, rectangular pulses are observed on the second wire, the duration and frequency of which correspond to the duration and frequency of the input pulses (50 MHz). The rise time of the leading edge of the output signal was also ~ 1.2 ns, which corresponds to the rise time of the leading edge of the input signal. If the amplitude of the input pulse signal is below the operation threshold of the inverter, then no pulses were observed on the second nanowire, i.e. the main nanowire did not switch to the normal state.

Fig. 6 shows the dependences of the input voltage at the gate (curve *1*) and the output voltage at the superconducting nanowire (curve *2*). As can be seen from Fig. 6, the rate of rise of the output signal along the leading edge corresponds to the rate of rise of the input signal and is ~ 1.2 ns.

For the sinusoidal input signal, as soon as the voltage entered the operating range of the inverter, a signal with twice the frequency compared to the frequency of the input signal was observed on the second nanowire. This frequency doubling effect is explained by the fact that the inverter operates on both the positive and negative branches of the sine wave. This is because local heating, which is the reason for the operation of the inverter, is generated in the resistive

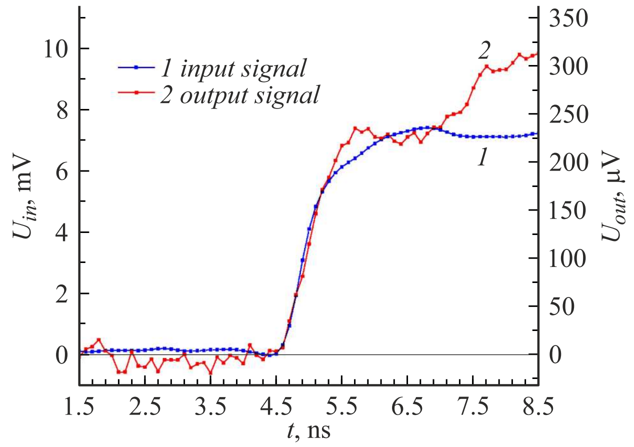

Figure 6. The leading edge of the input signal at the gate (*1*) and the output signal (*2*) on the main nanowire due to its switching to the normal state by a rectangular unipolar pulse.

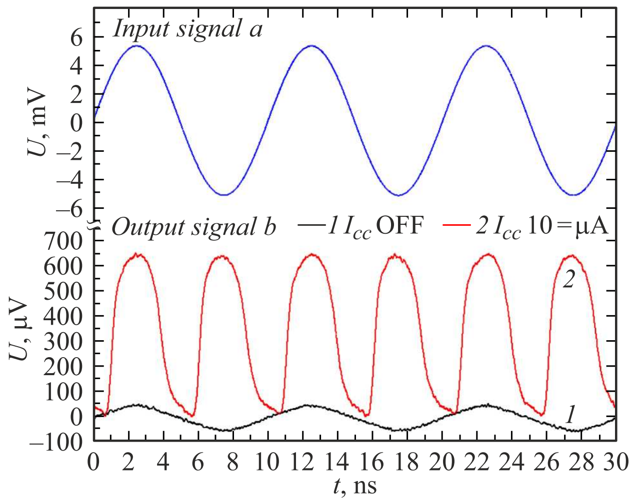

Figure 7. Switching of the superconducting nanowire with a sinusoidal signal: *a* — input signal on the gate; *b* — output signal on the superconducting nanowire.

section of the first nanowire, regardless of the direction of current (voltage sign) through the first nanowire.

Fig. 7 shows the waveforms of the sinusoidal input signal a and the output signal *b* with the power on ($I_{cc} = 10\,\mu$A) and off (I_{cc} OFF).

The analysis of Fig. 7 shows that the periodic peaks of the output signal are characterized by the shape of the upper part of the sine wave, repeating the upper part of the input signal. At this time, the output nanowire is in a normal state and, according to Ohm's law, a voltage arises on it proportional to the magnitude of the resulting resistance.

The transition of a superconducting nanowire to a normal state occurs when the input voltage level exceeds a certain threshold level (~ 3 mV). The reverse transition of the nanowire from the normal state to the superconducting state

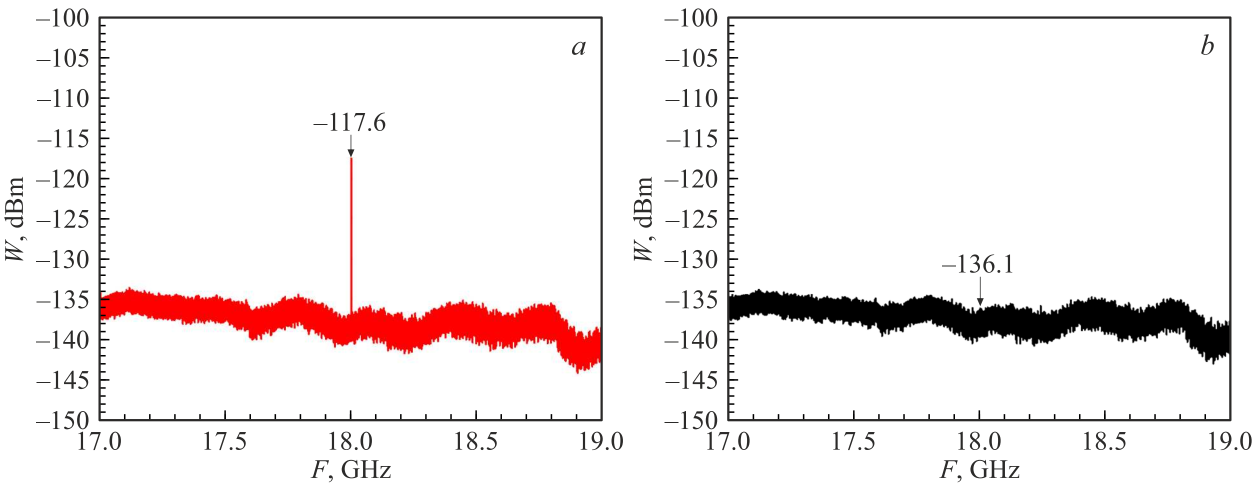

Figure 8. The spectrum of the output signal at a frequency of 18 GHz when switching a superconducting nanowire with an input sinusoidal signal at a frequency of 9 GHz: *a* — when the power is turned on at the output nanowire; *b* — when the power is turned off at the output nanowire.

occurs at the moment when the input voltage drops below the threshold level ($\sim$ 3 mV).

The value of the output signal is close to zero between the maxima (i.e., the output nanowire is in a superconducting state at this moment). Despite the alternating nature of the input signal, the output signal always has a positive polarity. The frequency of the output signal is twice as high as the frequency of the input signal (frequency doubling effect).

Measurements of switchings in the microwave frequency range were carried out using a spectrum analyzer. Fig. 8 shows the spectra of the output signal at a frequency of 18 GHz when switching a superconducting nanowire with an input sinusoidal signal at a frequency of 9 GHz. Fig. 8, *a* shows the spectrum with the power on at the output nanowire, and Fig. 8, *b* — with the power off at the output nanowire.

An analysis of Fig. 8 shows that when using an input signal with a frequency of 9 GHz at a doubled frequency of 18 GHz, there is a strong peak in intensity (Fig. 8, *a*) of the high-frequency signal, which disappears when power is removed from the output stage (Fig. 8, *b*). It should also be noted that at the frequency of the input signal, the peak is observed with I_{cc} turned off (the passing signal), and when I_{cc} is turned on, the peak intensity increases (the passing signal and, presumably, the harmonic of the output signal).

A similar effect of doubling the frequency of the signal at the output of the device compared to the frequency at the input was experimentally obtained for the following frequencies of incoming signals: 1, 4, and 9 GHz, i.e., peaks were observed at the output at frequencies of 2, 8, and 18 GHz in the operating range of the inverter amplitude.

Conclusion

The results obtained for the first time on the experimental observation of frequency doubling effects during operation of a two-layer cryogenic logic device based on NbN superconducting nanowires using the local heating effect are presented.

Switching of a superconducting wire from a superconducting state to a normal one has been experimentally demonstrated when a rectangular pulse is applied while maintaining the leading edge duration up to 1.2 ns (corresponds to the switching frequency $\sim$ 0.83 GHz and the minimum parameters of the currently available equipment).

It has been experimentally shown that switching of a superconducting nanowire to a normal state when a sinusoidal RF signal is applied to the gate occurs when the input signal level exceeds the threshold value $\sim$ 3 mV; the polarity of the output signal is positive and does not depend on the sign of the input signal; the frequency of the output signal is twice the frequency of the input sinusoidal signal.

The effect of doubling the frequency of the microwave signal at the output (2, 8 and 18 GHz) compared with the frequency of the input signal 1, 4 and 9 GHz has been experimentally demonstrated.

The results obtained prove the potential of using the manufactured samples to create logic devices with high clock frequencies.

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Conflict of interest

The authors declare that they have no conflict of interest.

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