Development of the High-resolution Spectrometer of the Millimetron Space Observatory

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***Abstract*—The study of the origin and transport of water in the universe is an important part of the scientific program of the Millimetron space observatory. This will be made possible by observations conducted in single-dish mode using an onboard instrument - the High Resolution Spectrometer (HRS). This instrument incorporates heterodyne array receivers operating within the range $0.5-2.7$ THz, comprising 3-pixel arrays of superconductor-insulator-superconductor (SIS) mixers operating at frequencies below 1.3 THz and 7-pixel matrix receivers based on NbN HEB mixers observing above 1.3 THz. This paper presents the current status of development for all the mixers used in the HRS instrument of the Millimetron space observatory.**

***Index Terms*—Heterodyne receiver, THz range, matrix of detectors, NbN thin film.**

I. INTROLDUCTION

THE study of cosmic objects and processes in the Universe carried out from the surface of the Earth is limited by the atmosphere of the planet. In the submillimeter range $0.02-1$ mm absorption is due to molecules of water vapor H_2O, carbon dioxide CO_2 and oxygen O_2. The H_2O molecule is the most important molecule for studying the evolution of life in the Universe. Atmospheric water vapor makes it difficult to ground-based observations of the H_2O emission from space objects. The use of space observatories with broadband and sensitive receivers makes it possible to increase the number of directly observed water lines tens of times, which will ultimately make it possible to study the entire chain of its transformations in the interstellar medium from dense clouds to protoplanetary disks. The study of the origin and transport of water in the Universe is an important part of the scientific program of the Millimetron space observatory [1]–[3] - space telescope with a cooled 10-meters mirror designed to study various objects in the Universe in the millimeter and sub-mm bands. The goal of the "water" program is to determine the water content in various space objects from galaxies to comets, to study the mechanisms of water transfer between space objects of different types and the connection of interstellar water molecules with the emergence of life on Earth, as well as to study the ways of water formation in the gas and solid phases of interstellar matter [4].

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II. HIGH-RESOLUTION SPECTROMETER GENERAL DESCRIPTION

As part of Millimetron "water" program, observations will be made in single-dish mode in the following frequency ranges: 500–600 GHz, 740–900 GHz, 1080–1230 GHz, $1300-1400$ GHz, $1890-1910$ GHz, $2390-2410$ GHz and $2660-2680$ GHz using heterodyne instrument "High-resolution spectrometer". The spectral lines located within these frequency bands, along with the scientific rationale for their observation, are described in details in [4]. The main technical parameters of the spectrometer are presented in TableI. For the first three bands it is planed to use 3 pixel receivers based on superconductor-insulator-superconductor (SIS) mixers. The intermediate frequency band is assumed to be $4-12$ GHz. At the same time, it can be reduced to $4-8$ GHz to save onboard resources; such a reduction will not have a critical impact on scientific tasks. At frequencies above 1300 GHz, it is proposed to use a 7 pixels DSB receivers with H/V polarisation based on Hot-electron bolometers (HEB) [5]. The expected single-sideband noise temperature is presented in the penultimate column. Further in this paper we will discuss in depth technical details regarding the mixers, with a view to elucidating the rationale behind the selected sensitivity.

The preliminary design of the High Resolution Spectrometer for Millimetron space observatory [6] is a logical continuation of the HiFi instrument [7]. The difference is in focus on facilitating mapping capabilities through the configuration of compact arrays and the modification of the instrument's pick-up mirror M3 from a fixed mode to a scanning regime.

III. SIS MIXER-BASED HETERODYNE RECEIVERS

Terahertz receivers based on SIS mixers are known to be the most sensitive heterodyne instruments for frequency range roughly 200–1300 GHz [8]. To operate the SIS mixer, the strong nonlinearity of the tunnel current in the current-voltage characteristic (IVC) of the SIS junction is used; under the influence of a local oscillator, quasiparticle current steps appear on the current-voltage characteristics of the SIS [9]; this process is called photon assisted tunneling. By their nature, SIS mixers can provide conversion gain. Important advantages of SIS mixers are low local oscillator power requirements and extremely low intrinsic noise. The noise temperature of the mixer in double sideband (DSB) mode is limited by the quantum value $hf/2k_B$ [10], where h and k_B are the Planck and Boltzmann constants, respectively. This is why SIS mixers are already successfully used both for ground-based radio telescopes [11]–[15], and for space missions [7], [16].

A. 500-600 GHz channel

This frequency range is well developed; SIS receivers have been implemented in space [7], [17] and at largest ground based multi-element interferometer ALMA [18]. The new SEPIA Instrument was installed and commissioned at the Atacama Pathfinder Experiment telescope (APEX) [19]. This range typical waveguide or quasioptical receivers are based on SIS junction incorporated into Nb thin film structures been manufactured on silicon or quartz substrates. The used Nb films are good superconductors at cryogenic temperatures with the energy gap above the frequency range. This Nb wiring delivers high and intermediate frequencies to and from the tunnel junction on the chips. Implementation of the SIS junctions with a high current density makes it possible to increase the operating frequency of SIS receivers and expand the bandwidth. However, there is a limit to increasing barrier transparency for SIS junctions with Al_2O_3 barrier. This limit is on the order of 10-15 kA/cm^2; with a further increase in current density, a sharp deterioration in the quality of SIS junctions occurs. In order to overcome this limitation, a technology was developed for the fabrication of Nb-Al/AlN-Nb tunnel SIS junctions with extremely high tunnel barrier transparency, made by nitridization of the Al surface in an RF plasma discharge. Implementation of the SIS junctions with AlN barrier allows not only realize DSB noise temperature well below 100 K at frequencies up to 650 GHz, but also provide a very flat Intermediate Frequency (IF) response from 4 to 12 GHz with heterodyne waveguide receiver [18]. Based on the achieved sensitivities we put in the TableI expected single-sideband noise temperature of 200 K. Furthermore, we propose the utilisation of a sideband-separating SIS mixer [20], [21] to facilitate in-flight sideband calibration, with the objective of populating at least one pixel.

TABLE I
FREQUENCY RANGES AND MAIN PARAMETERS OF HRS INSTRUMENT RECEIVERS.

Chanal	*Band* (GHz)	*Pixel*	*Technology*	T_n (K)	*Res.* (")
$M1$	500–600	3	SIS	200	14
$M2$	740–900	3	SIS	400	9
$M3$	1080–1230	3	SIS	1000	7
$M4$	1300 – 1400	7	HEB	1000	6
$M5$	1890 – 1910	7	HEB	1200	4
$M6$	2390 – 2410	7	HEB	1400	3
$M7$	2660 – 2680	7	HEB	1400	3

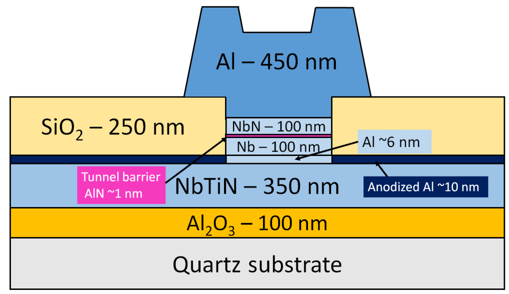

Fig. 1. Structure of the technological layers near $Nb/Al - AlN/NbN$ junction embedded into NbTiN/Al microstrip line in the SIS-receiver.

B. 740-900 GHz channel

Further improvement in the parameters of SIS mixers was achieved by development of Nb-AlN-NbN junctions, where niobium nitride is used as the top electrode instead of niobium. The utilisation of such structures enables not only an increase in the tunneling current density, but also a substantial elevation the total gap voltage of the junction V_g from 2.8 to 3.7 mV. This significantly enhances the potential for operation of such structures at high frequencies (above 700 GHz), when the size of the photonic step is hf/e exceeds V_g. In addition, at high current densities for Nb-AlN-NbN junctions, the quality parameter, determined by the ratio of the sub-gap resistance to the normal one, R_j/R_n, turns out to be noticeably higher than for purely niobium junctions. The R_j/R_n value reaches 20 at a tunnel current density of 70 kA/cm^2, which indicates the high quality of the tunnel barrier [22]. However, to ensure good matching between such high current density junctions and the antenna, submicron SIS junctions are required.

The operating frequency of SIS receivers based on niobium films is limited by the frequency of the Nb energy gap (approximately 700 GHz). A solution to this problem was found in the development of devices with microstrip lines based on Nb compounds with higher energy gap frequencies, in particular NbTiN. The top electrode of the line is usually made of a normal metal at these temperatures (typically Al), to avoid overheating of the SIS junction [23], [24]. We developed an SIS mixer based on high critical current density Nb-AlN-NbN tunnel junctions embedded in a microstrip line consisting of a 320 nm thick NbTiN bottom electrode (ground plane) and a 500 nm thick Al top electrode [25], [26]. Microstrip electrodes are separated by an insulating layer of SiO_2 250 nm thick. The SIS junction is located on the NbTiN film, and the top NbN layer is in contact with the top Al electrode (see cross-section in Fig.1).

For the frequency range 740-900 GHz we plan to build our instrument based on heritage gained during developed of the

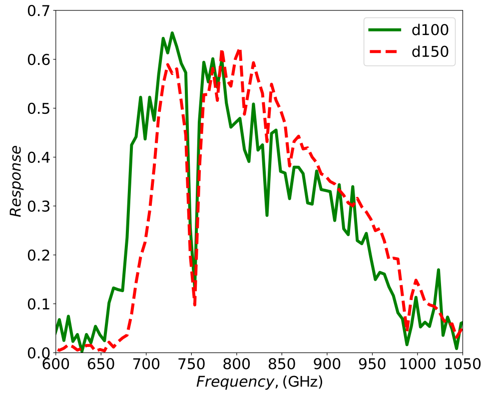

Fig. 2. The frequency response of SIS mixers for design ”d100” and ”d150” measured using a Fourier transform spectrometer.

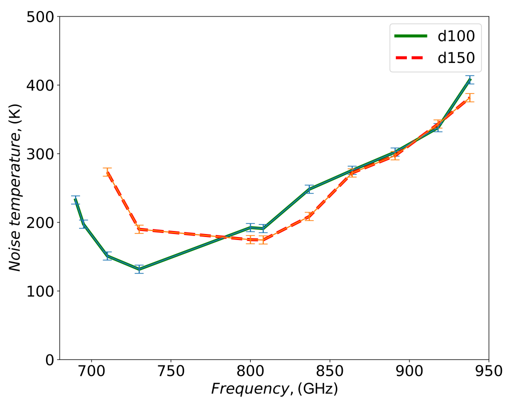

Fig. 3. The noise temperature of SIS mixers for design ”d100” and ”d150” measured by standard two-load (77K/300K) technique. The data is corrected for the 88% transparent 12 μm mylar beam splitter used for LO injection.

SIS mixer for CHAMP+ instrument for APEX telescope [25], [26]. The intended frequency range for this mixer was within the $787 - 950\ GHz$ atmospheric window, however, the mixer response is high also at frequencies down to 700 GHz for a few of the designs, see Fig.2 The DSB noise temperature for SIS mixers has been demonstrated as low as $3hf/k_B$ [26]. As illustrated in Fig. 3, the noise temperature of the dual-sideband mixer in the target frequency range is approximately 200 K. Similar to the $500 - 600\ GHz$ instrument we plan to use here at least one sideband-separating pixel. This will be based on the experience gained in the development of $800 - 950\ GHz$ two-sideband SIS mixer [27] .

C. 1080-1230 GHz channel

This is the highest frequency band in HPS instrument based on SIS mixer technology. In the past it was successfully proven for HiFi Band 4 and Band 5 [7], [28]. The DSB noise temperature for HiFi Band 4 was below 400 K for frequencies up to 1120 GHz. This indicates that it may be possible to reach the SSB noise temperature of approximately 1000 K with this receiver.

We plan to build our SIS mixer using the same technology as for the band 740-900 GHz, i.e. based on Nb-AlN-NbN junctions and with NbTiN ground electrode. To ensure the feasibility of superconducting mixer based on NbTiN within the specified frequency range, we have addressed separately the question on the quality of the produced NbTiN films at frequencies up to 1300 GHz.

We have already started the work on studying the superconducting NbTiN films which would allow us to manufacture the devices with operating frequency range up to 1.2 THz [29], [30] and to be published soon. The films fabricated were measured using terahertz time-domain spectrometer Menlo Systems Tera K15. In [29] we have found the optimal pressure of nitrogen in magnetron for obtaining the NbTiN film on silicon substrate with high energy gap Δ, critical temperature T_c and low normal-state resistivity near T_c. In [30] we studied the impact of the layers which are necessary for technological processes (buffer 100 nm-thick Al_2O_3 layer at the substrate for the surface protection in RIE-processes; 10 nm-thick anodized Al layer for protection of the bottom electrode during etching in CF_4 when SIS-junctions are formed). Only slight deterioration of the NbTiN film properties was observed for all the buffer layers. In [F3, to be published] we studied the properties of NbTiN films sputtered on quartz substrates.

Our results show that NbTiN film with gap frequency as high as 40 cm^{-1} or 1200 GHz can be obtained which corresponds to $hf_{gap} = 2\Delta = 4.82$ meV. Fig.4 depicts the spectra of transmission coefficient (a), permittivity (b) and real part of conductivity (c) for the NbTiN film on quartz substrate with Al_2O_3 buffer layer and anodized Al on the film surface. This is exactly the film that forms bottom electrode in superconductor microstrip line in receiver (see Fig.1).

The results obtained thus far instill confidence that the embedding circuit for the future $1080 - 1230$ GHz SIS mixer will exhibit acceptable losses, thereby enabling the desired receiver noise temperature to be achieved.

IV. HEB MIXER-BASED HETERODYNE RECEIVERS

The high sensitivity of HEB mixers ensured their application in astronomical projects of the European Space Agency: SOFIA airborne observatory with a 2.5-meter mirror capable of observing at frequencies from 1 to 5 THz. [31] and TELIS [32] for operation in the range 1.76-1.86 THz. In the HERSCHEL space observatory, the $1.4 - 1.9$ THz channel also used HEB mixers [7]. Among the SOFIA instruments, the 1.4, 1.9 and 2.5 THz channels of the GREAT instrument are based on single waveguide NbN HEB mixers [33]. The upGREAT tool, the successor to GREAT, is already a multi-pixel heterodyne matrix [34]. The upGREAT Low Frequency Array (LFA) consists of 2×7 pixel waveguide HEBs, two sets needed to separate polarizations at 1.9–2.5 THz. The upGREAT High Frequency Array (HFA) consists of 7 waveguide HEBs tuned to operate at $4.745\ THz$. The hexagonal configuration is chosen for maximum display efficiency. An LFA with a noise temperature of $600\ K$ at the center of the frequency range was successfully commissioned to observe the [C II] line at 1.905 THz. Direct detection of atomic oxygen on

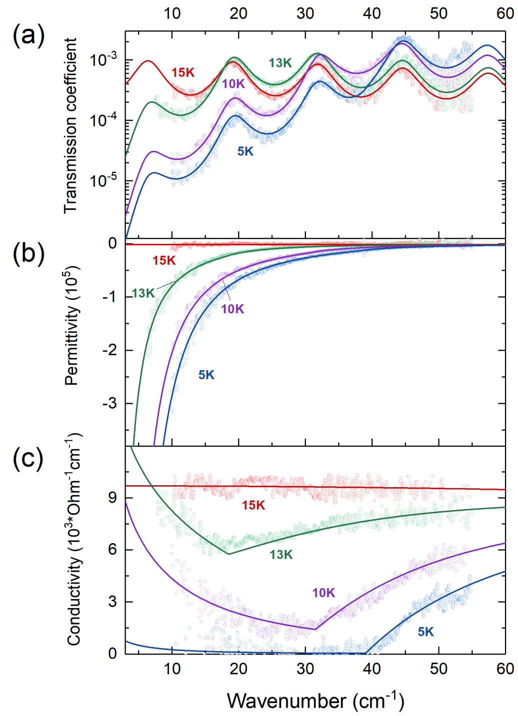

Fig. 4. Measured spectra of the transmission coefficient (a), permittivity (b) and conductivity (c) of the superconducting $NbTiN$ film on quartz substrate with 100 nm Al_2O_3 buffer layer and anodized aluminum on surface.

the dayside and nightside of Venus [35] was demonstrated by HFA. The DOME A observatory, being developed by the Purple Mountain Observatory of the Chinese Academy of Sciences, may become the most promising ground-based observation platform for THz astronomy [36]. It is planned to build a 5-meter THz telescope, DATE5, equipped with a dual-band heterodyne receiver for atmospheric window frequencies of 0.85 THz and 1.4 THz based on an HEB mixers.

Disordered ultra thin (3.5 − 4 nm) superconducting NbN film is used as a sensitive element in these terahertz range HEB mixers. Due to the physical principle of the HEB mixer operation, this "ingredient" is the most crucial, the combination of extremely low film thickness and its superconducting properties determines the characteristics of the final receiver.

Modern NbN HEBs as heterodyne detectors have almost reached their sensitivity limit [33], [37], however, they have a conversion band (IF band) not exceeding 3 − 4 GHz [38]. Further reduction of the noise temperature, an increase in the IF band as well as reduction of the required local oscillator (LO) power has a significant practical interest. Currently, each pixel of the heterodyne matrix – HEB mixer – is considered as a separate detector, requiring individual adjustment of the bias voltage and the LO power. With a matrix size of at least a ten pixels, such an individual approach is difficulty applicable. The solution of the problem could be the fabrication of an unified HEB mixers that do not require individual settings. To meet the issue we improve the technology for deposition of NbN films and the NbN HEB mixers fabrication processes to fabricate mixers with as close as possible R(T) characteristics

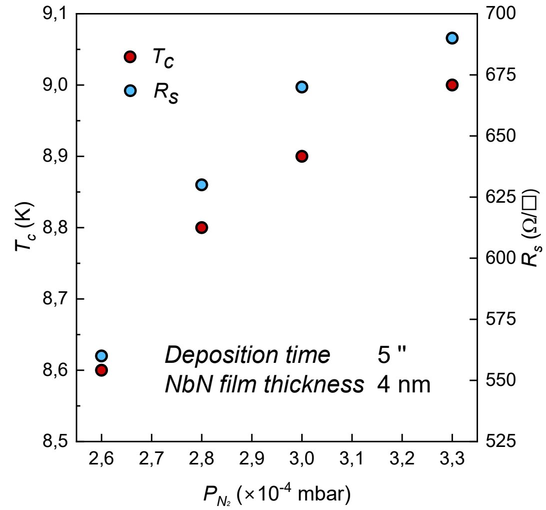

Fig. 5. Dependence of the T_c and R_s of the NbN films on the N_2 partial pressure during deposition process, each deposition took 5 sec.

and a minimum spread of normal resistances R_{300} for devices with same geometry within the one batch.

A. NbN HEB mixers fabrication and DC test

HEB mixers were fabricated from a bilayer $NbN - Au$ structure with a thickness of NbN film of $3.5 - 4$ nm and Au $20 - 25$ nm deposited *in-situ* using reactive magnetron sputtering onto the surface of a high-resistivity Si substrate. The substrate temperature could vary up to 900 $°C$. Before film deposition, the substrate surface was cleaned in oxygen plasma, followed by treatment in a hydrofluoric acid solution. This, along with speed optimization by reducing the discharge current to 300 μA, made it possible to achieve high uniformity of the superconducting properties (film thickness, T_c and surface resistance R_s) of the NbN film over the Si substrate surface.

The dependence of the critical temperature and surface resistance of NbN films at a deposition time of 5 seconds is presented in Fig.5. The optimal values of the critical temperature T_c and critical current density j_c were obtained with the following parameters of the NbN film deposition process: substrate temperature 800 $°C$, partial pressures of Ar and N_2 were 5×10^{-3} $mbar$ and $3 - 3.3 \times 10^{-4}$ $mbar$, current and discharge voltage were 300 μA and 300 V. NbN deposition was followed by *in-situ* deposition of an Au layer after cooling the Si substrate down to 400 $°C$. Long time cooling of the Si substrate made it possible to anneal the fabricated NbN film to improve its superconducting properties and its distribution over the substrate. The NbN film deposition rate, for given process characteristics, was determined by test the dependence of film thickness on sputtering time. Same to the NbN films, the Au layer thickness was controlled over the deposition process time based on the obtained deposition rates. The thickness of the deposited films was measured using an atomic force microscope AFM.

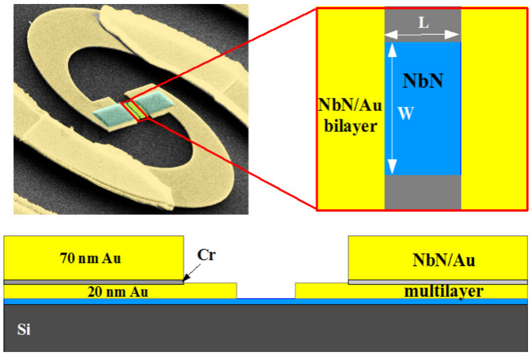

Fig. 6. False color SEM photo and crosssection sketch of central part of a typical NbN HEB device, showing the active material of NbN (blue). The yellow parts made of gold (Au) serve as ports of THz spiral antenna.

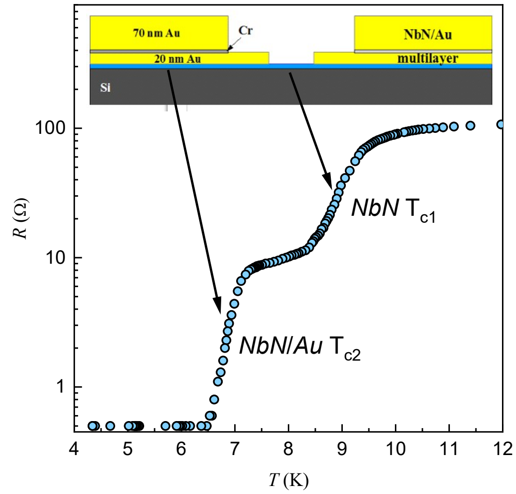

Fig. 7. Temperature dependence of the NbN HEB mixer resistance R. The appearance of the second superconducting transition at T_{c2} is caused by the proximity effect in the NbN film under $in-situ\ Au$. The value of the mixer resistance after the first transition is determined by the width NbN of the bridge and the coherence length ξ in the NbN film. Resistance appears in a superconducting NbN film due to the process of conversion of normal electrons into Cooper pairs. The conversion region is determined by the coherence length of the resulting Cooper pairs.

In the process of an HEB mixer fabrication, electron and photo lithography methods, chemical and ion etching processes, thermal metal deposition and electron beam evaporation deposition, as well as the lift off process in acetone are used. For photo and electron lithography processes, Ti/Au alignment marks are made on top of Au surface of the NbN/Au two-layer structure. This is followed by the fabrication of the spiral THz antenna and setting the width W of the future NbN mixer bridge using electron lithography and liquid and plasma-chemical etching processes. The photolithography method, thermal deposition of Ti and Au layers and the lift off process are used to form the outer part of the antenna and the mixer bond pads. At the final step of the fabrication, the length L of the NbN bridge of the mixer is set; for this purpose, electron lithography, ion and liquid etching methods are used. Central part of the mixer is covered with a layer of SiO_2 to prevent the external undesirable environment influence.

Typical sizes of superconducting bridges of HEB mixers ranged from 0.1–0.4 μm in length L, and 1–4 μm in width W. SEM photo and crosssection of the central part of the THz antenna, shown in Fig.6. With a normal resistance per square NbN film $R = 650 - 700\ \Omega/\square$ (with a NbN thickness of $4\ nm$), the ratio of the bolometer length to its width L/W is kept constant to achieve a 65 Ω resistance in the normal state for optimal RF and IF coupling.

Optimized sequence of the HEB mixers fabrication processes, the sensitive element - the NbN bridge of the mixer - during the fabrication had been coated with $in-situ\ Au$ layer, made it possible to minimize the spread of normal resistances R_{300} of the mixer; along with the optimized process of NbN film deposition, it also allowed to minimize the spread in T_c down to 0.1 K for mixers fabricated within the same process. The dependence of the NbN HEB mixers resistance R as function of the temperature is presented in Fig.7. A conventional HEB device consists of 2 main parts. The central, bare NbN film with critical temperature T_{c1}, connected to a superconducting $NbN - Au$ layer, with critical temperature T_{c2}, which serves as THz antenna. The appearance of the second superconducting transition at T_{c2} is caused by the suppression of superconductivity in the NbN film under thin $in-situ\ Au$ due to the proximity effect. The remaining NbN film under the shunt Au antenna is in a normal state at temperatures above 4.2 K. The difference in T_c between the NbN bridge and NbN/Au bilayer for our NbN films exceeds 2K, this indirectly indicates the quality of the electrical contact, as well as the thickness of the NbN film. The proximity effect appears at sizes on the order of the coherence length ξ in a superconductor, which is on the order of 3 nm for thin NbN films.

B. NbN HEB mixers noise temperature

Double side band noise temperature ${T_n}^{DSB}$ measurements were carried out at a local oscillator frequency of 2.52 THz using the “cold” / “hot” (77K/300K) blackbody technique. A quantum cascade laser QCL was used as a local oscillator source. QCL had an output power of about 5 mW, frequency tuning of about 10 GHz, power dissipation of 1 W at a physical temperature of 17 K. To couple the mixer with the radiation, we used an elliptical Si lens. Using a 3.5 μm - thick Mylar beamsplitter, the local oscillator was combined with the blackbody. The transmittance of the beamsplitter was no less than 0.97 at a frequency of 2.52 THz. The optical window of the cryostat was made of high-density polyethylene HDPE. To prevent the direct detection effect, we used a cooled to 4 K narrow-band interference filter with a transmittance of 0.9. A cold amplifier with a gain of 35 dB had a T_n of no higher than 10 K in the $1 - 8\ GHz$ band. The estimated contribution of the optical path to the measured ${T_n}^{DSB}$ value did not exceed 100 K. Fig.8 shows the experimental results of measuring ${T_n}^{DSB}$ for mixers from three different batches. Red circles indicate the results

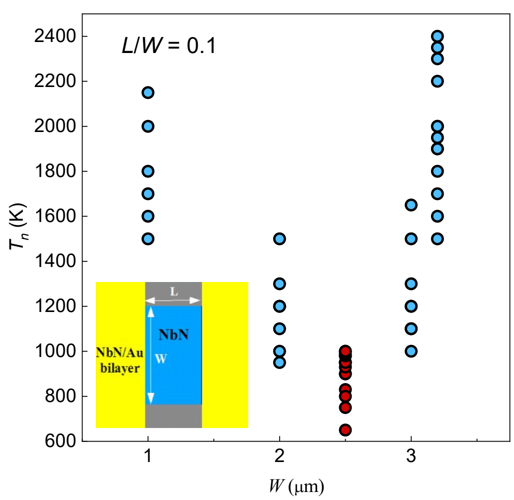

Fig. 8. NbN HEB mixer double side band noise temperature T_n as function of the NbN bridge width W measured at 2.52 THz LO frequency.

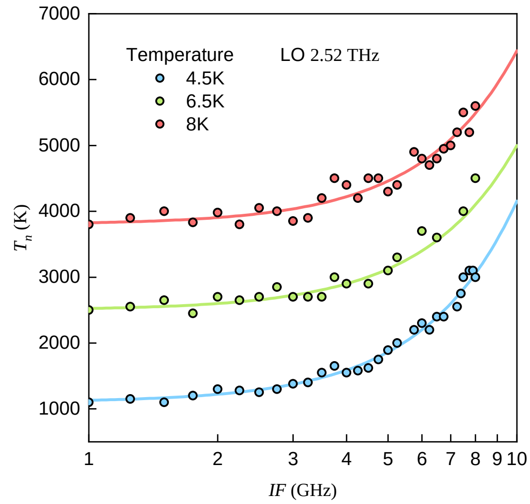

Fig. 9. NbN HEB mixer double side band T_n@2.52 THz as function of the intermediate frequency IF measured on different bath temperature T.

for mixers fabricated using optimized NbN film deposition and mixer fabrication routes. Blue circles indicate mixers fabricated using "old" non-optimized $in-situ$ and $ex-situ$ technology. The spread in ${T_n}^{DSB}$ for mixers fabricated using optimized technology does not exceed 200 K with an average level of 800 K. This value well meets the design requirements and has a margin for losses in the future optical path of the instrument. Fig.9 shows the experimental results of ${T_n}^{DSB}$ in the intermediate frequency IF band. The measurements were carried out for three temperatures 4 K, 6.5 K and 8.5 K. Since the measurements were limited to the band of the cooled amplifier, the experimental points were approximated by a curve of the form ${T_n}^{DSB}(f) = [1 + (f/\Delta f)]^2$ to determine the frequency Δf at which ${T_n}^{DSB}$ will double. During the work, it was determined that as the temperature of the NbN HEB mixer increases, ${T_n}^{DSB}$ naturally increases, but at the same time Δf also increases. This effect is caused by the design of the mixer, namely the presence in the mixer NbN bridge regions near the normal metal contacts of the antenna with suppressed superconductivity due to the proximity effect. Electron conversion regions at temperatures below T_{c2} block the diffusion of "hot" electrons into cold metal contacts.

V. Conclusion

The development of mixer, which can be used to built receivers for the High Resolution Spectrometer for Millimwtron space observatory gives us confidence to formulate the expected sensitivity levels for all the bands within the the range 0.5 -2.6 THz. For channel M1 the Nb base SIS mixers with AlN tunnel barrier will be utilised. For channels M2 and M3 SIS mixers with NbTiN wiring will be built. To implement channels $M4 - M7$ the NbN HEB mixers will be used; the achieved unification of the parameters of the fabricated mixers will make it possible to create a heterodyne matrix of 7 pixels with parameters that meet the requirements of the instrument. Since the mixers use a helical antenna that works well in the $1 - 5$ THz band, it will be possible to use a pair (H/V polarization) of such matrices for sequential observation in channels $M4 - M7$.

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