RADIOMETER AT A FREQUENCY OF 108-120 GHz FOR STUDY OF THE EARTH'S ATMOSPHERE

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ANNOTATION

The short millimeter wave range is of great interest to the physics of the atmosphere, radioastronomy and communications.

A superheterodyne radiometer at a frequency of 108-120 GHz is described in the work. Features of the receiver are intermediate frequency modulation and the use of a harmonic frequency converter, which simplified design of the system. The fluctuation sensitivity threshold of the radiometer is 1 K, with a 1 sec time constant.

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Introduction

The region of the electromagnetic spectrum with frequencies /3*
from 100 to 250 GHz is of considerable interest for study of the atmosphere of the Earth. Since the characteristic lines of the rotational spectrum of the oxygen molecule, water vapor and other gases are in this range, it seems possible to determine a number of atmospheric parameters: total mass of water vapor; altitude profiles of temperature and humidity; secondary gas content (CO, NO, O_3 and others), which is exceedingly important to the solution of a broad group of problems in geophysics (study of the hydrologic cycle, weather prediction, etc).

Radiometers are required for the solution of these problems, which, together with high sensitivity, would have the following operating characteristics: small size and weight; low energy consumption. Despite the rapid development of UHF range receiver technology, short millimeter wave radiometers are significantly inferior to centimeter wave radiometers in sensitivity and other characteristics. Since there are practically no low noise amplifiers in the millimeter range, receivers are built according to the superheterodyne scheme, with varistor frequency converter at the input. In view of the continuous improvement in quality of frequency converters, such /4
a radiometer design will evidently permit the development of

*Numbers in the margin indicate pagination in the foreign text.

devices down to 1 mm wavelength in the coming years, with a noise temperature on the order of 100 K or less [1-3].

A superheterodyne radiometer with harmonic frequency converter at the input and modulation at the intermediate frequency, for studies of the atmosphere at frequencies of 108-120 GHz, is described in the present work. The task of development of a sensitive device was set up in the design of this radiometer (with a fluctuation sensitivity threshold $\sim$1 K), with low weight, compactness and reliable operation.

1. Design Characteristics of Radiometer Circuit

A typical UHF range radiometer is a device with input modulation. However, a number of specific difficulties must be noted, in the way of increasing sensitivity of a short millimeter wave superheterodyne radiometer. The first is the increase in losses in the input circuit of the receiver (for example, losses in standard wave guides at 200 GHz reach 10 dB per meter). The second is deterioration of the transmission characteristics of the varistor frequency converters, due to the effect of the stray parameters of the nonlinear element. The third is the lack of reliable heterodyne oscillators which are convenient to operate. Although existing electromagnetic oscillation generators have overlapped the frequency region up to 1000 GHz and more (reverse wave tube), they are distinguished by low reliability, considerable weight and the necessity for high voltage power sources. There presently are solid state oscillators in the long wave part of the millimeter range, and shortening of their operating wavelengths is taking place continuously. Varistor designs, Schottky barrier diodes (DBSh), are being improved. Concerning losses in the input circuit, they always are present, because of /5 the presence of the modulator and bypass device. The magnitude of these losses can reach several decibels.

To overcome these difficulties, the 108-120 GHz superheterodyne radiometer was built, according to a scheme with modulation at the intermediate frequency [4,5] and with the frequency converter at the second harmonic of the variable conductivity of the varistor [6]. This design permits a decrease in losses in the input circuit and significant simplificiation of the design. Harmonic frequency converters were widely used in the 1960's [7,8]. However, there is the opinion that the conversion losses of such converters increase by an average of 6 dB, with an increase in harmonic number by one [9]. Therefore, subsequently, in connection with the development of shorter and shorter wave heterodyne oscillators, interest in harmonic frequency converters has flagged. However, a calculation, carried out by a method similar to that reported in work [10], showed that, for existing diode structure, DBSh, in distinction from the previously used point contact diodes, the conversion losses of the frequency converter in the second harmonic is only 1-2 dB poorer than in the case of conversion at the basic frequency. Therefore, DBSh harmonic frequency converters were used in the design described, and they permit the use of a relatively low frequency heterodyne.

A flow chart of the radiometer is presented in Fig. 1. The waveguide circuit from the antenna to the frequency converter was made in an oversize 7.3 mm x 3.4 mm cross section waveguide, with transition to a 0.8 mm x 1.6 mm cross section. The second harmonic frequency converter of the heterodyne (1) has the form of a four way waveguide piece. The signal waveguide has a 0.8 mm x 1.6 mm cross section and the heterodyne, 1.8 mm x 3.6 mm. A standard 5 mm range reflection oscillator (2) was used as the heterodyne. To decrease the losses in the input circuit, the signal from noise generator (4) is fed through the heterodyne waveguide, through a high frequency filter in the form of waveguide segment (3). The converted signal is fed to modulator (5) and further, through bypass circulator (7), to intermediate frequency amplifier $UPCh_1$ (8). Four channel voltage divider (9) is connected to the $UPCh_1$ output. Band filter (10) is connected to one of the splitter outputs. Further, the signal is amplified by UCh_2 (11) and is detected by detector (12). The low frequency signal is amplified by the low frequency preamplifier integrated with the detector and UCh_1. The amplified low frequency signal is fed to the second unit, where selective filter (14), UCh_2 (15), synchronous detector (16), reference voltage generator with power amplifier (17) and direct current amplifier (18) are located. The radiometer is assembled in the form of two units. Unit I is thermostatted and is located in the antenna. Unit II is located in a room next to the antenna. /6

2. Radiometer Characteristics

The measured radiometer fluctuation sensitivity ΔT with double band reception and a low frequency output filter, in the form of a RC circuit, time constant of 1 sec, is 1 K at the heterodyne frequency of 112.5 GHz. The UPCh transmission band was measured at 0.8 GHz (with a mean frequency of 1.5 GHz), which corresponds to a 19000 K noise temperature of the system. In tuning the heterodyne from 108 to 118 GHz, the noise temperature of the system changes by 3 dB, reaching 38000 K at the ends of the range (Fig. 2). Regulation of the transmission band from 200 MHz to 800 MHz is possible by changing filters. The voltage divider at the first UPCh output has three supplementary outputs, which permits connection of supplementary filters and reception in four channels in a 0.8 GHz band, as needed. Since instability of operation of the frequency converter in modulation at intermediate frequency can degrade the system sensitivity, the frequency converter is supplied with an optimum automatic bias resistor in the diode current rectifier circuit (see below). After two hours of heating, the uniform "zero" drift of the radiometer under laboratory conditions is not over 1/6 the width of the noise track in 2 hours of continuous operation. The change in gain was not over 3% in this time. A specimen of the calibration signal and noise track recordings is presented in Fig. 3. Data on the radiometer are presented in the Table, where the characteristics of existing analog devices with input modulation and frequency conversion at the basic harmonic of the heterodyne also are presented. /7

The dimensions of the radiometer antenna unit are 600 x 500 x 200, weight 15 kg, dimensions of power supply and control unit 500 x 400 x 250, weight 10 kg. A standard GZ-37 generator power pack is used for klystron power supply.

3. Second Harmonic Frequency Converter

The frequency converter is the most important element of the radiometer, which determines the system sensitivity and stability. Therefore, particular attention was given to the frequency converter design.

Calculation of the transmission and impedance characteristics

TABLE

a f /ГГц/	b $T_{шсист}$ /К/	c $f_{УПЧ}$ a /ГГц/	Коэфф. шума УПЧ /дБ/ d	e Тип УПЧ	Литерат. источник f
I08-I20	I9000	I,5	6	g транзисторный	
90-I00	5000*		3	h параметрический	[II]
I70-270	220000*	9			[I2]
* при однополосном приеме					

*With single band reception.
Key: a. GHz
b. $T_{system\ noise}$
c. f_{UPCh}
d. UPCh noise factor (dB)
e. UPCh type
f. Reference
g. Transistor
h. Parametric

of the second harmonic converter with variable varistor conductivity, with the use of a DBSh in it, was carried out in a manner similar to that in work [10]. In the calculation, the current-voltage characteristics of the diode were approximated linear-irregular, the capacitance of the nonlinear element barrier was assumed to be constant and a four frequency performance was considered: signal ω_c, image ω_z, intermediate ω_{pc} and combination $\omega_1=\omega_g+\omega_{pc}$ (ω_g is the heterodyne frequency), and the remaining combination frequencies were assumed to be closed on the nonlinear element terminals. The calculated minimum conversion loss, input and output impedances, as functions of the ratio ω_c/ω_{pr} (where $\omega_{pr}=(R_sC_\delta)^{-1}$, R_s is the series resistance, C_δ is the nonlinear element barrier capacitance),

are presented in Fig. 4. They give an idea of the possible frequency converter characteristics at given signal frequencies and stray parameters of the diode structure. Based on the calculation, the second harmonic frequency converter was constructed in a standard waveguide section. Measurements of the stray parameters, carried out by the method described in [13], gave the values: R_s=10 ohm; C_δ=0.022 pF, which corresponds to ω_{pr}=730 GHz and ω_c/ω_{pr}=0.15-0.16. The minimum conversion losses found from these data L_{min}=7.4 dB, the optimum signal generator resistance R_g=70 ohm, output resistance R_{out}=100 ohm, /9
and the optimum voltage cutoff angle of the heterodyne θ=30°.

Experimental study of the harmonic frequency converter was carried out by the method described in work [10]. The experimental conversion losses L_{out}, output KSV [standing wave ratio] and noise temperature at the converter output $T_{con.out}$ were determined, with the input load temperature equal to room temperature (T_0) and a heterodyne frequency, at which minimum conversion loss was observed. For comparison of theory with experiment, the rated conversion losses in single band reception,[1] were found,

$$L_{rated} = \frac{2 L_{out}(1-|\Gamma|^2)}{L_{in.cir}} \qquad (1)$$

where $|\Gamma|$ is the modulus of the voltage coefficient of reflection at the converter output, $L_{in.cir}$ is the losses in the passive UHF circuit and chamber.

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[1]In L_{out} measurements, double band reception is assumed.

Graphs of the rated conversion losses vs. rectified current and various direct bias voltages are presented in Fig. 5. Graphs of the output KSV are presented in Fig. 6. Graphs of the rated conversion losses are presented in Fig. 7, at three fixed values of the heterodyne power $P_{h1} > P_{h2} > P_{h3}$.

The experimentally determined rated output noise temperature of the frequency converter $T_{rated\ out\ noise}$ are presented in Fig. 8. For comparison, the noise temperature curve at $P_h = 0$ is presented in the figure.

The frequency converter described was made in a standard waveguide. Therefore, matching it with the signal generator /10
resistance was accomplished, by means of the contact needle inductance. For this purpose, the contact needle inductance was simulated in a 3 cm range waveguide. A graph of the needle impedance as a function of ratio ω/ω_{cr} (ω_{cr} is the critical frequency of the waveguide) is presented in Fig. 9. As follows from the experiment, matching of the impedance of a standard waveguide with a 30-70 ohm input resistance is possible for a typical contact spring shape, in the range ω/ω_{cr} $\sim$1.1-1.25. The observed dependence of the contact needle inductance on frequency leads to a narrow band frequency converter. (see Fig. 2). The relatively narrow band nature of the frequency converter makes it possible to attenuate or even suppress the image channel of the receiver at high intermediate frequency >3 GHz, which is important in spectral studies.

Comparison of theory with experiment demonstrates good agreement of the calculated and measured minimum conversion losses. However, there are some differences in the frequency converter characteristics. For example, in Fig. 7, the minimum conversion loss at three fixed values of P_h was reached at $\theta \sim 60°$ for a lower value of P_h, and at $\theta \sim 70°$, for higher heterodyne power.[2]

The excess noise temperature for some conditions is more than 100 K, in which, at some bias voltages and heterodyne powers, a noise reduction is possible, which is below the values obtained in T_{out} noise measurements at $P_h=0$. The phenomena noted can be explained by the effects of variable barrier capacitance. A calculation of the transmission and noise characteristics of a frequency converter at the first harmonic of the heterodyne is presented in works [14,15]. The results of these works are qualitatively consistent with the experimental data described above. Actually, as follows from [14], the conversion losses are close together for the cases of constant and variable barrier capacitance with a forward bias, while the graphical relations of the relative noise temperature (t_{noise}) of a millimeter wave frequency converter presented in [15] show that t_{noise} exceeds 1.6 in a number of cases, which was found experimentally. /11

Thus, to find the noise factor minimum of a millimeter wave frequency converter, the variable nature of the nonlinear element barrier capacitance must be taken into account.

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[2]The heterodyne voltage cutoff angle was found from the expression

$$\operatorname{tg} \theta - \theta_1 = \frac{I_0 \pi R_s}{\varphi - u_{cm}}, \qquad (2)$$

where I_0 is the constant component of the current through the diode, ϕ is the barrier height, u_{cm} is the bias voltage and $\phi=0.85$ V for the DMSh used.

4. Selection of Frequency Converter Operating Conditions in Modulation at Intermediate Frequency

In a radiometer with modulation at intermediate frequency, a more careful selection of the frequency converter operating conditions is required. Conditions were pointed out in [6], under which the sensitivity of a radiometer with modulation at intermediate frequency does not deteriorate

$$\delta T > \frac{1}{L^2}(T_{eq} - T_b)\Delta L + \left(1 - \frac{1}{L}\right)\Delta T_{eq} = \Delta T_{out}, \quad (3)$$

where δT is the UPCh temperature sensitivity, T_{eq} is the equivalent temperature of a frequency converter, represented by a resistive multipole in thermodynamic equilibrium at this temperature, T_b is the background temperature, ΔL, ΔT_{eq} is the change in corresponding values with heterodyne power oscillations, ΔT_{out} is the change in frequency converter output temperature.

It is evident that, at $T_{eq}=T_b$ and $L=1$, the frequency converter does not degrade the sensitivity of a radiometer with modulation at intermediate frequency. The same thing is achieved with the conditions $\partial T_{out}/\partial P_h=0$. In practice, this can be done, by selection of the resistance in the direct bias power source circuit. With small changes in heterodyne power, the current rectified by the diode changes. This results in bias voltage increments, at which T_{out} remains at a constant value.

We represent the output temperature as dependent on P_h and u_{cm}: $T_{out}=T_{out}(P_h, u_{cm})$; then,

$$\Delta T_{out} = \left(\frac{\partial T_{out}}{\partial P_r}\right)_u \Delta P_r + \left(\frac{\partial T_{out}}{\partial u_{cm}}\right)_P \Delta u_{cm} \tag{4}$$

Let $\Delta T_{out}=0$, i.e., compensation is accomplished by automatic bias. From (4), we obtain

$$\frac{\Delta u_{cm}}{\Delta P_r} = -\frac{\left(\partial T_{out}/\partial P_r\right)_u}{\left(\partial T_{out}/\partial u_{cm}\right)_P} \tag{5}$$

Since

$$\Delta u_{cm} = \Delta I_0 R_{cm}\,, \tag{6}$$

where R_{cm} is the internal resistance of the bias source, and

$$\Delta I_0 = \left(\frac{\partial I_0}{\partial P_r}\right)_u \Delta P_r + \left(\frac{\partial I_0}{\partial u_{cm}}\right)_P \Delta u_{cm}\,, \tag{7}$$

from (6) and (7), we find

$$\frac{\Delta u_{cm}}{\Delta P} = \frac{R_{cm}\left(\frac{\partial I_0}{\partial P_r}\right)_u}{1 - R_{cm}\left(\frac{\partial I_0}{\partial u_{cm}}\right)_P}\,. \tag{8}$$

By equating (8) and (5), after transformations, we obtain the desired automatic bias resistance /13

$$R_{cm} = \frac{\left(\frac{\partial T_{out}}{\partial P_r}\right)_u}{\left(\frac{\partial I_0}{\partial u_{cm}}\right)_P \left(\frac{\partial T_{out}}{\partial P_r}\right)_u - \left(\frac{\partial I_0}{\partial P_r}\right)_u \left(\frac{\partial T_{out}}{\partial u_{cm}}\right)_P}\,. \tag{9}$$

In the general case, exact calculation of R_{cm} by formula (9) is complicated, since both the variable nature of the barrier resistance and the parameters of the actual frequency converter circuit must be taken into account. They are the contact needle inductance, stray capacitances, heterodyne noise, the nature of the loads at the combined frequencies and harmonics of the heterodyne, losses in the chamber, effect of misalignment at the transformer input and output, etc. Therefore, the experimental way of determination of the derivatives was used below, for which the experimental $T_{out.ex}|_p$ and $T_{out.ex}|_u$ vs. rectified current were found. The corresponding family of curves is shown in Fig. 10. For simplification of the radiometer scheme, T_{out} was selected as the ambient temperature. For this purpose, function L_{ex}-$L(I_0,P_h)$ was recorded, at which $T_{out}=T_0$, from which the optimum values of u_{cm} and I_0 were found. They proved to be 0.8 V and 6.8 mA, respectively (Fig. 11). For this point, we define the point designated by the number 1 (see Fig. 10). With some change of Ph, if u_{cm}=const, T_{out} changes and shifts to point 2. However, with the new power value, a change of u_{cm} occurs, and T_{out} shifts to point 3, with the former output noise temperature. From the graphically found current changes $\Delta I_0^{(1,3)}$ and $\Delta u_{cm}^{(1,3)}$ between points 1 and 3, we find $R_{cm}=\Delta u_{cm}^{(1,3)}/\Delta I_0^{(1,3)}$. Besides this, the stability of the resulting value at nearby points must be estimated. Otherwise, conditions with different values of P_h and u_{cm} are necessary. For R_{cm} to be constant, it is sufficient for the slopes of the $T_{out.ex}|_p$ and $T_{out.ex}|_u$ as a function of rectified current to be retained in the vicinity where changes in heterodyne power are possible. Under these conditions, with the smallest conversion losses, it turns out that R_{cm}=-30 ohm. Therefore, the automatic bias resistance was chosen as small as possible. In this case, the necessary heterodyne power /14 stability for a given UPCh $\sim$ 1%, which is completely practicable. To achieve complete stabilization with positive active automatic bias resistance, conditions are necessary, under which the $T_{out.ex}|_p$ and $T_{out.ex}|_u$ curves have the same slopes, which follows from equality (5).

Conclusion

A study of a superheterodyne radiometer with modulation at intermediate frequency and harmonic frequency converter was conducted in the work. The fluctuation sensitivity threshold of the radiometer at τ=1 sec is 1 K. In two hours of continuous operation, the system sensitivity did not deteriorate.

It was shown that modulation at intermediate frequencies simplies the radiometer design, since there is no need for bypass devices, and the input circuit losses decrease.

A harmonic frequency converter assists in solution of the heterodyning problem. In an experimental study of the harmonic frequency converter, an effect of the variable capacitance of the nonlinear element barrier was found.

It should also be noted that the use of a lower noise UPCh and improvement in the diode structures results in a significant decrease in receiver system noise. The superheterodyne radiometer with modulation at intermediate frequency and harmonic frequency converter at the input turns out to be /15
a promising receiver, since, with increase in the limiting diode frequency, conversion losses of the harmonic frequency converter

will approximate the conversion losses at the basic frequency and, in this case, the conditions for achieving more stable operation of the device are simplified.

In conclusion, the author thanks V.S. Etkin and Yu.B. Khapin for continual interest and assistance in the work.

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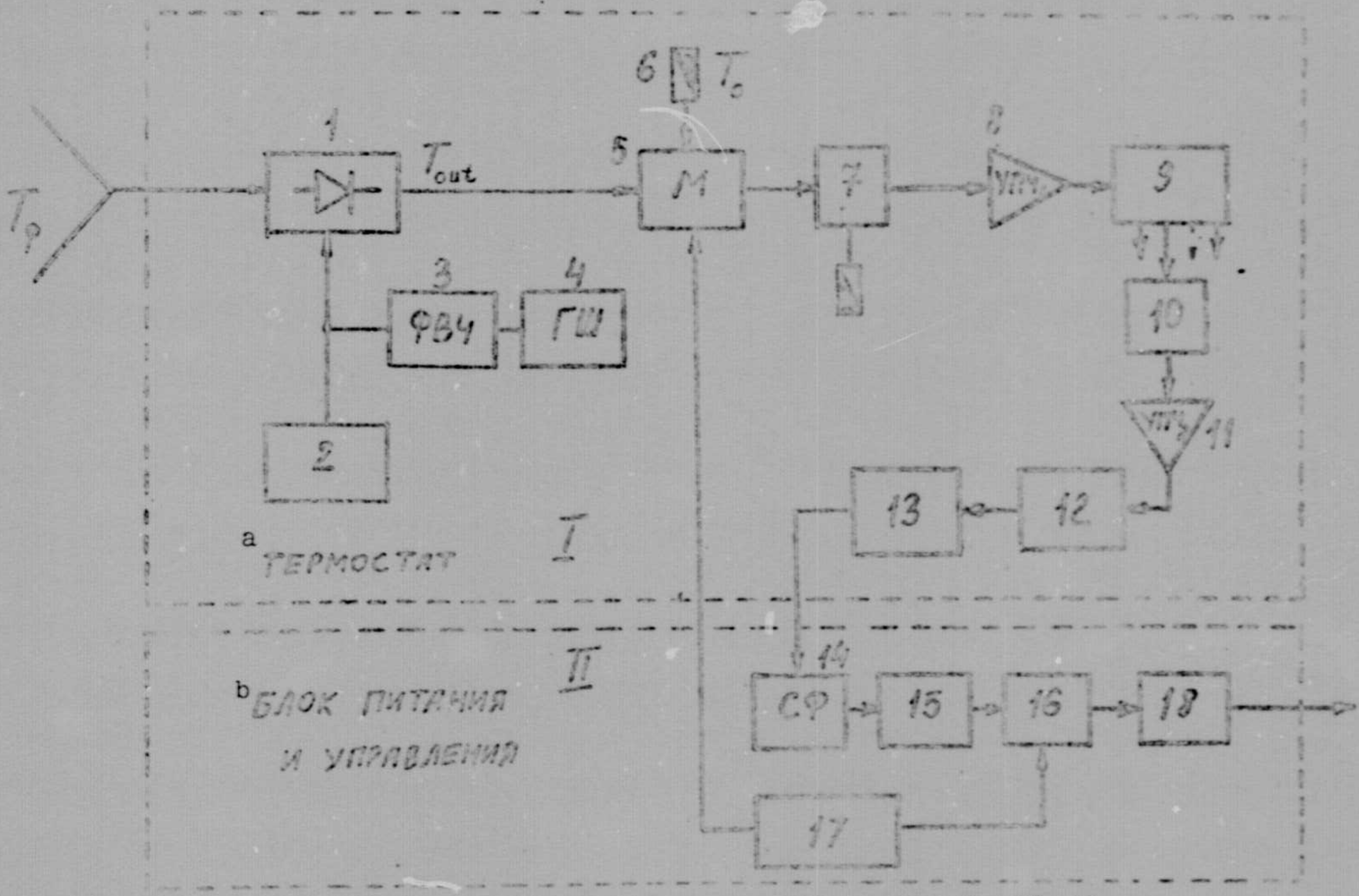

Fig. 1. Flow chart of radiometer at frequencies of 108-118 GHz.

Key:
a. Thermostat
b. Power supply and control unit
3. High frequency filter
4. Noise generator
8,11. Intermediate frequency amplifier
14. Selective filter

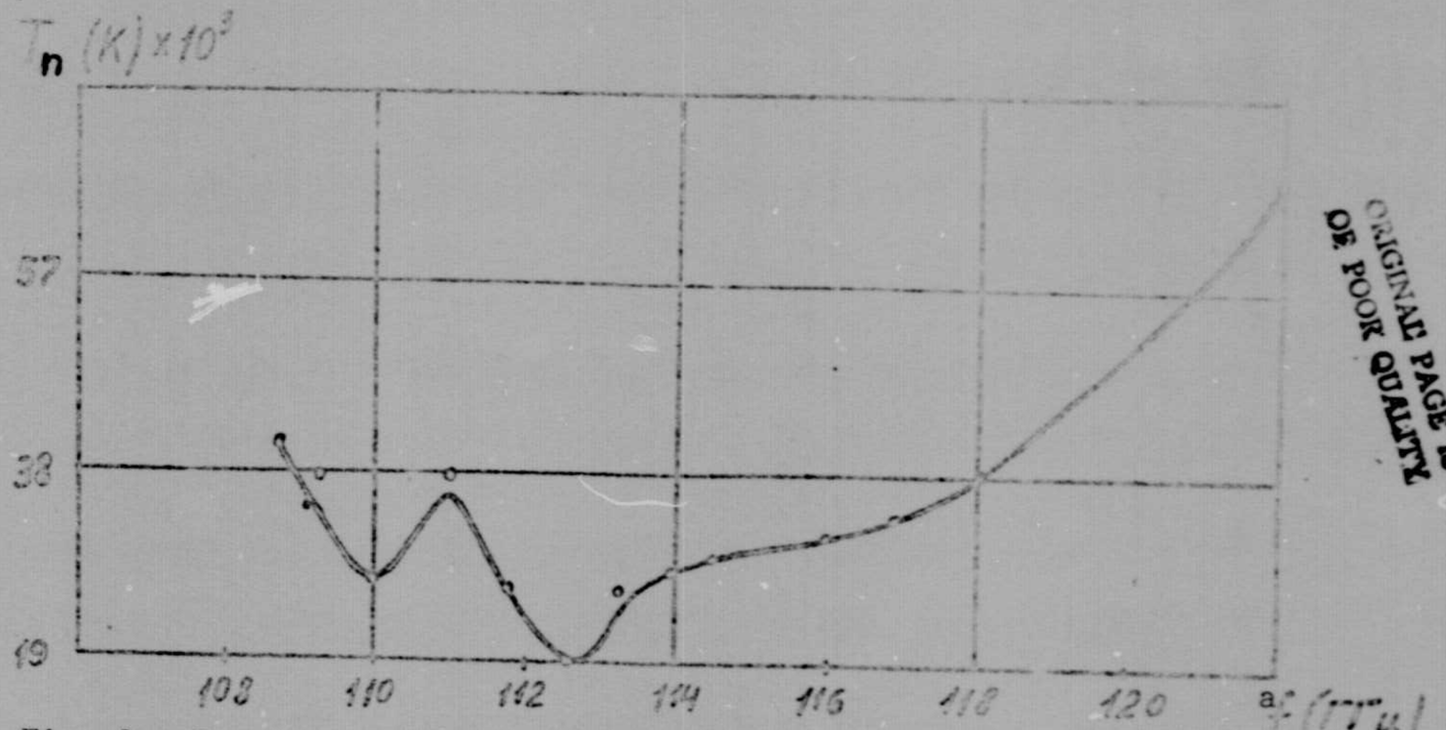

Fig. 2. Frequency variation of equivalent noise temperature of of system in double band reception.

Key: a. f(GHz)

f(GHz)

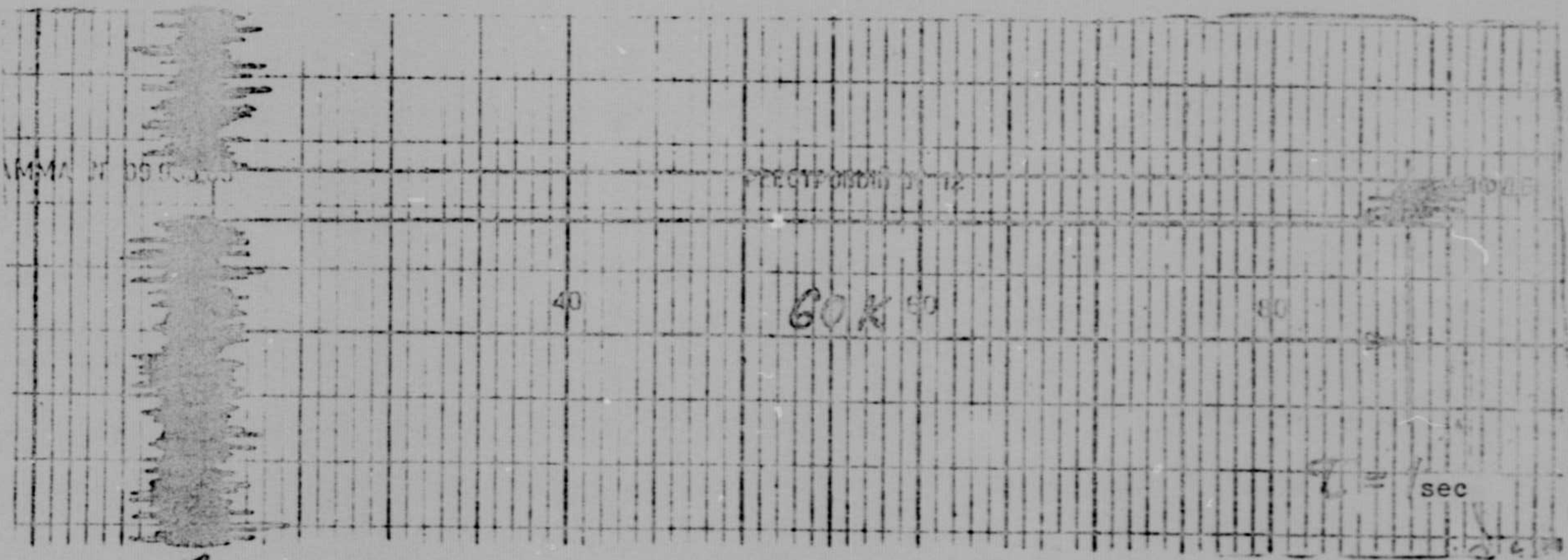

Fig. 3. Specimen of calibration signal recording.

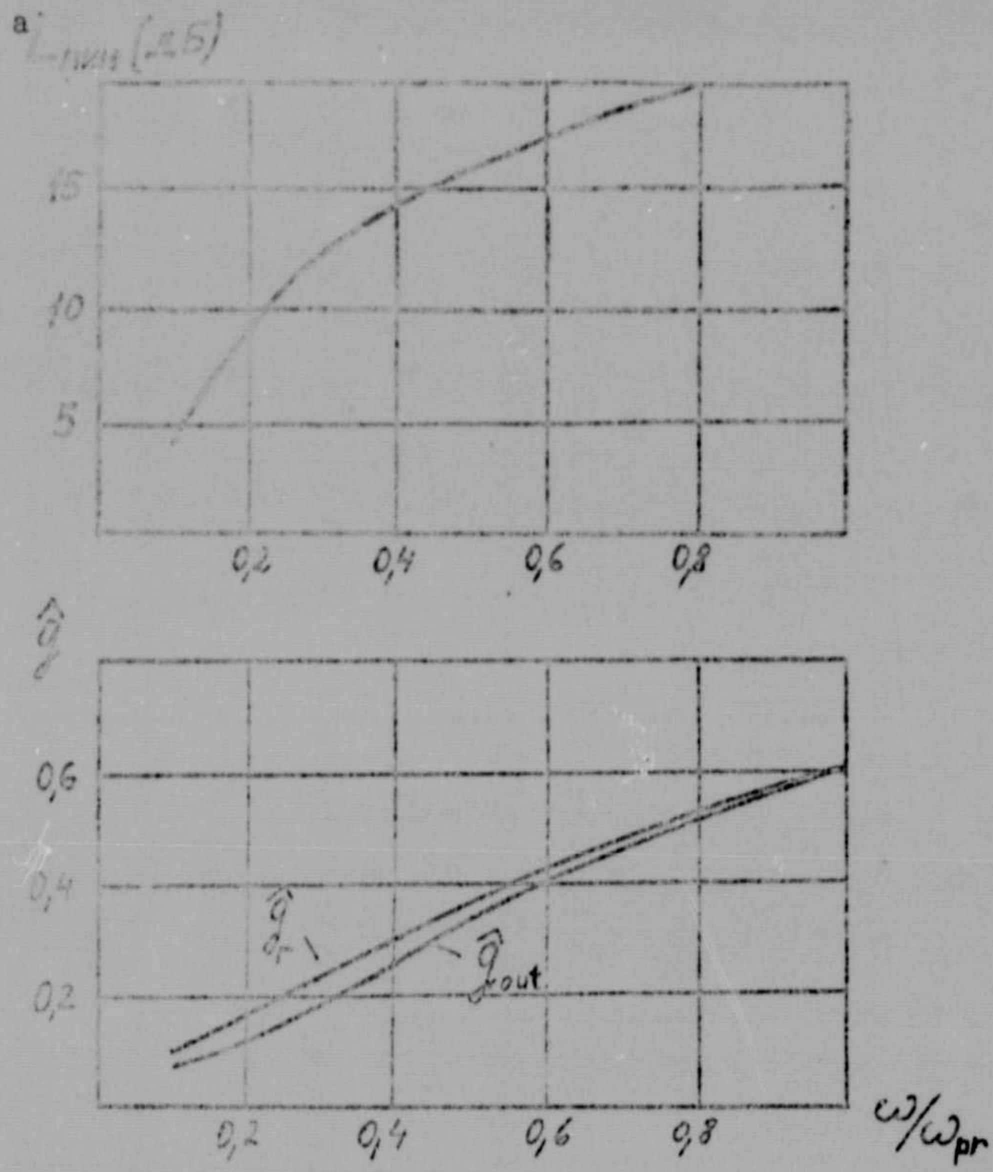

Fig. 4. Minimum conversion loss, normalized with optimum signal generator conductivity g_r/g_s and output conductivity g_{out}/g_s of second harmonic frequency converter vs. ratio ω/ω_{pr} in wide band image frequency mode ($g_s = R_s^{-1}$).

Key: a. Lmin(dB)

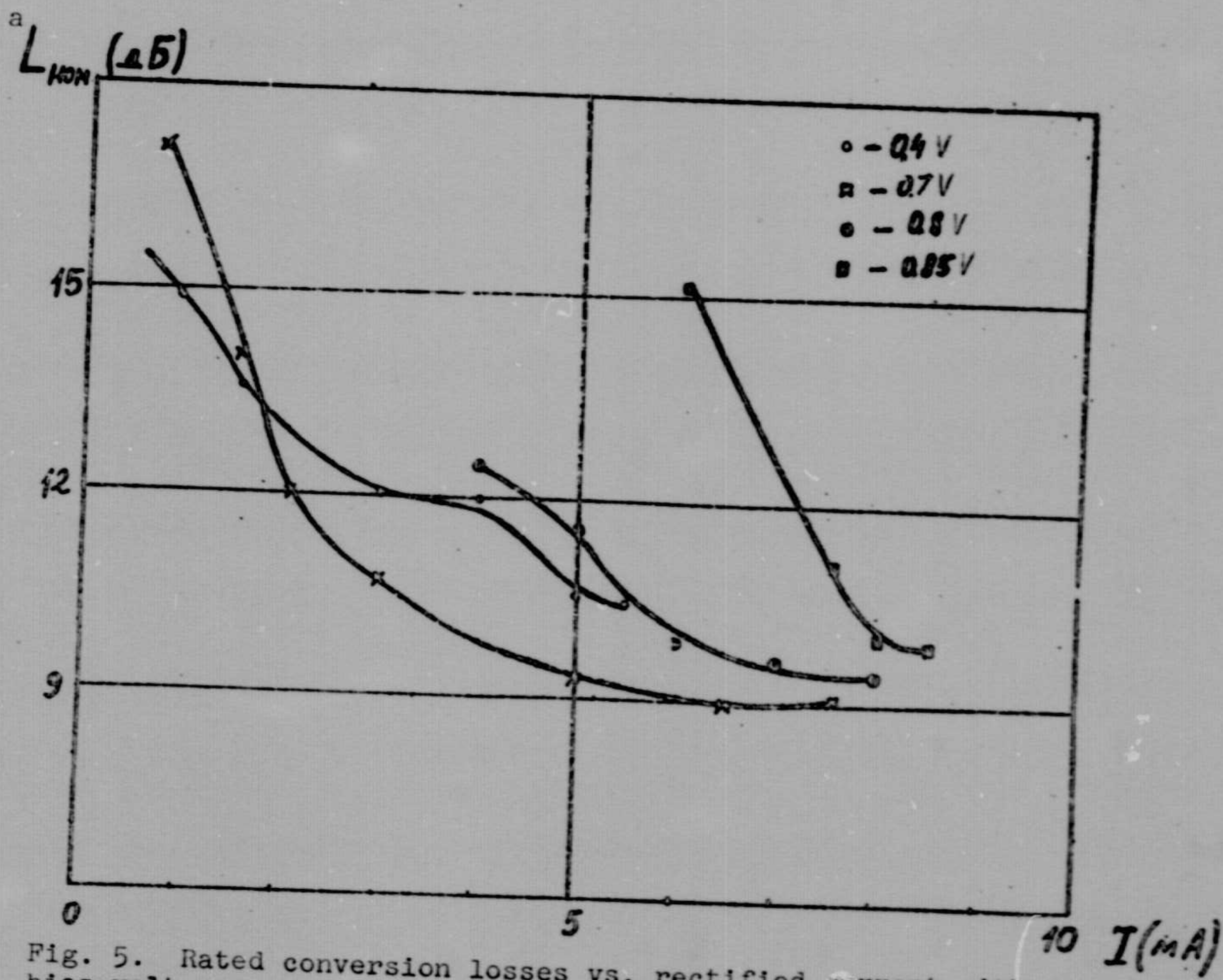

Fig. 5. Rated conversion losses vs. rectified current with various bias voltages on diode.

Key: a. L_{rated} (dB)

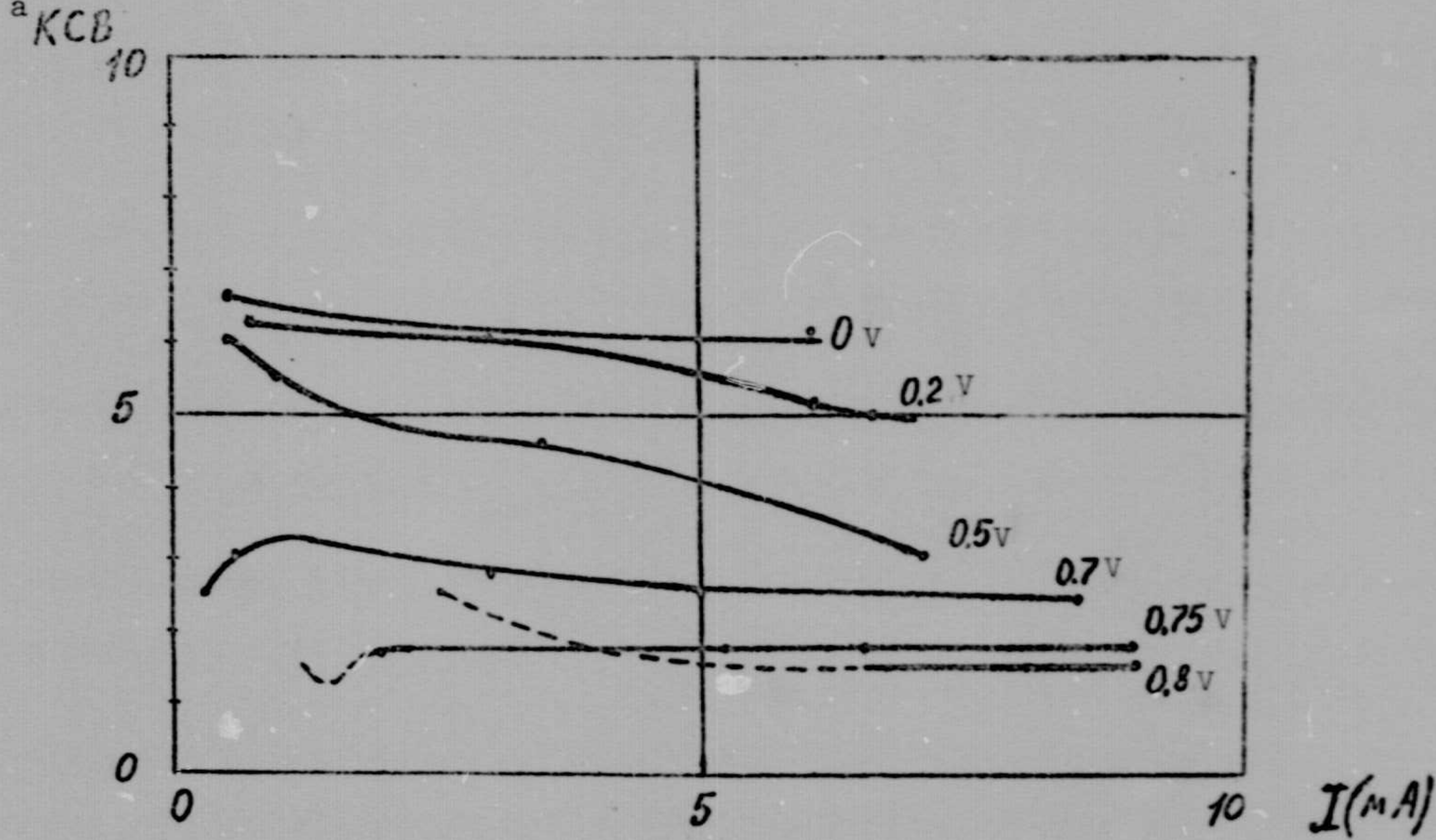

Fig. 6. Frequency converter output standing wave ratio vs. rectified current with various bias voltages on diode (dashed line corresponds to $R_{out}<Z_0$, solid, $R_{out}>Z_0$, $Z_0=50$ ohm).

Key: a. Standing wave ratio

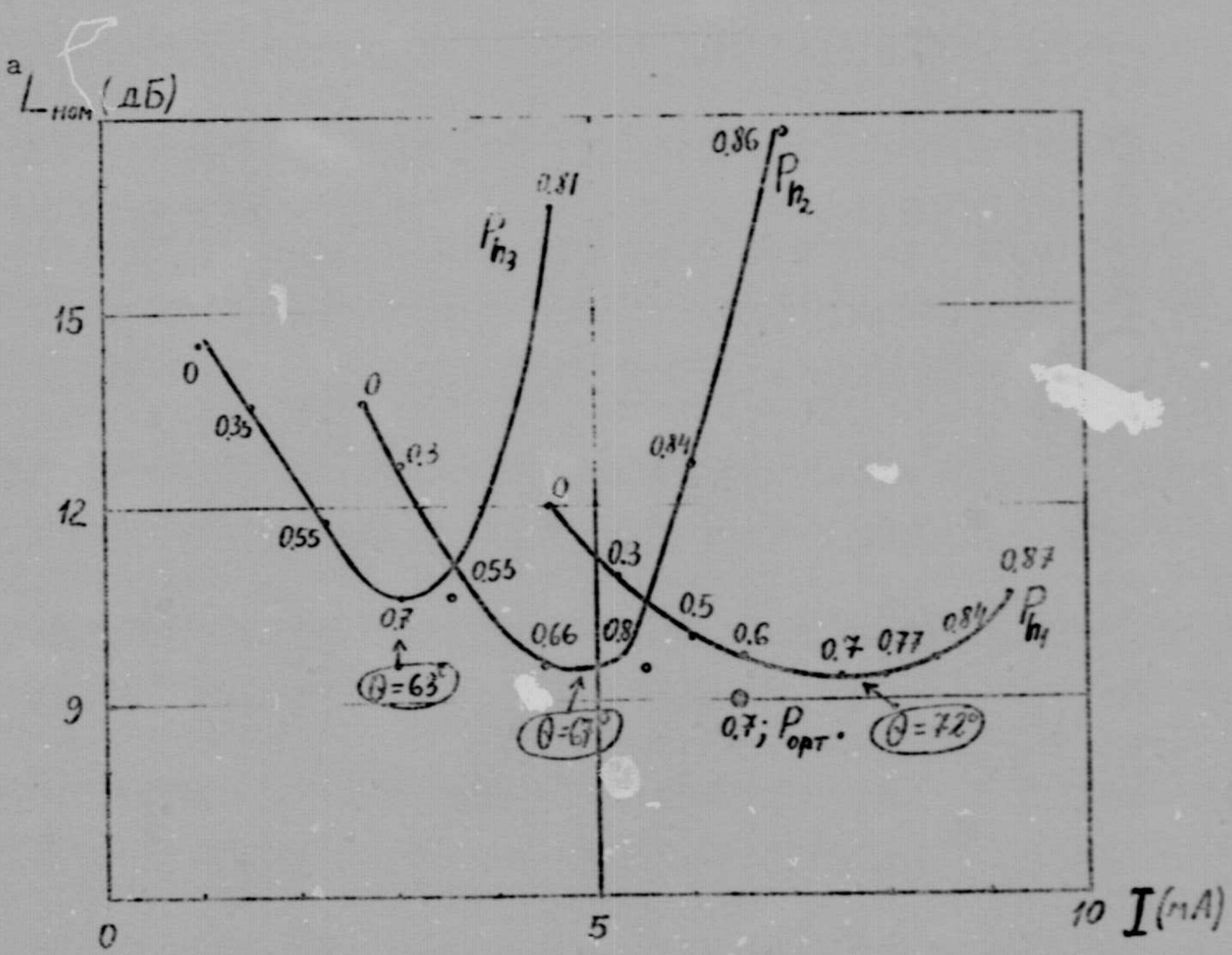

Fig. 7. Rated conversion losses vs. rectified current with fixed heterodyne power $P_{h1}>P_{h2}>P_{h3}$; forward bias voltage values designated by numbers; for points of minimum transformation loss, heterodyne voltage cutoff angles are presented.

Key: a. L_{rated} (dB)

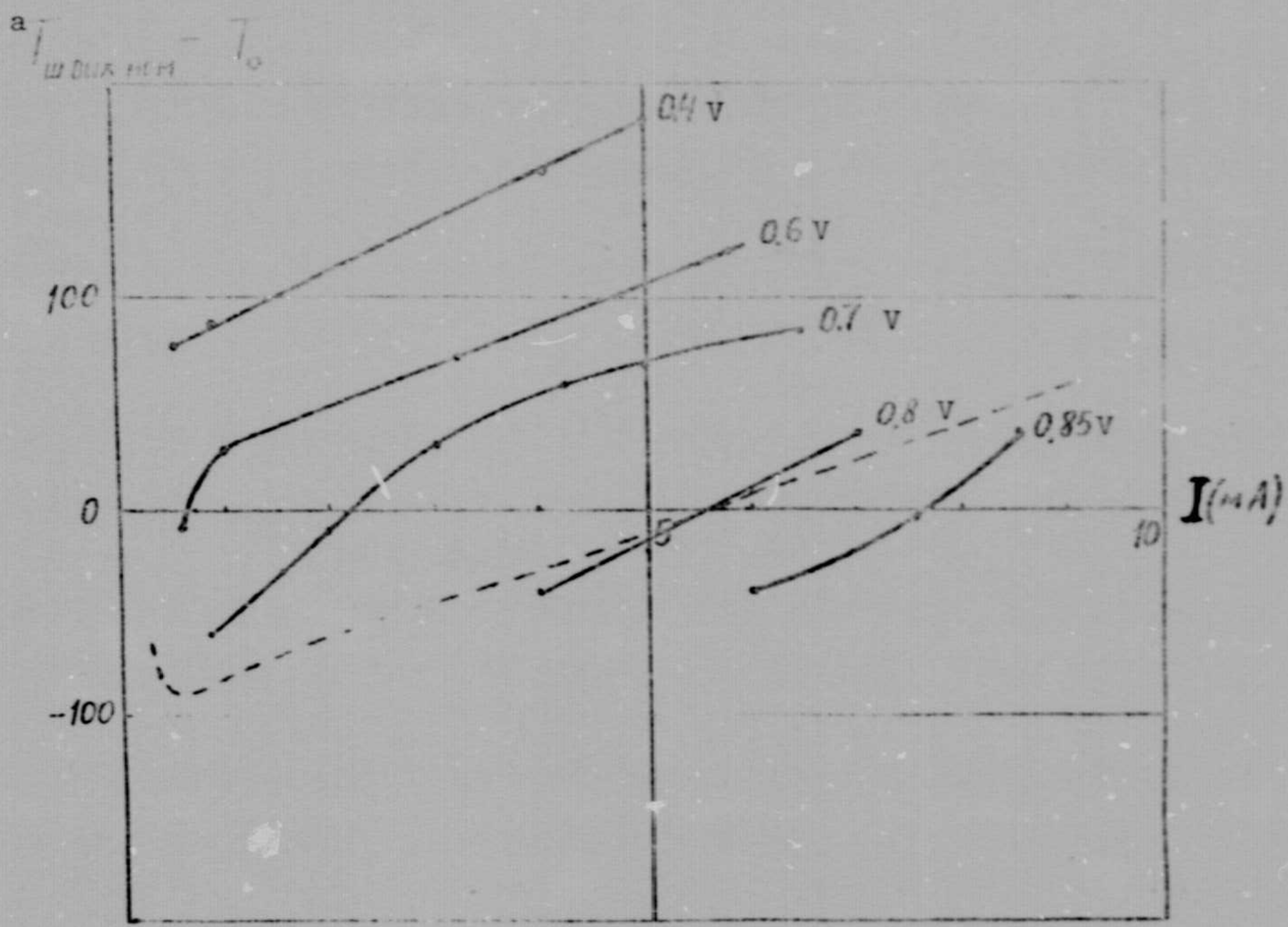

Fig. 8. Rated frequency converter output noise temperature vs. rectified current with various fixed bias voltages; dashed line, noise temperature at P_h=0.

Key: a. $T_{rated\ out.noise} - T_0$

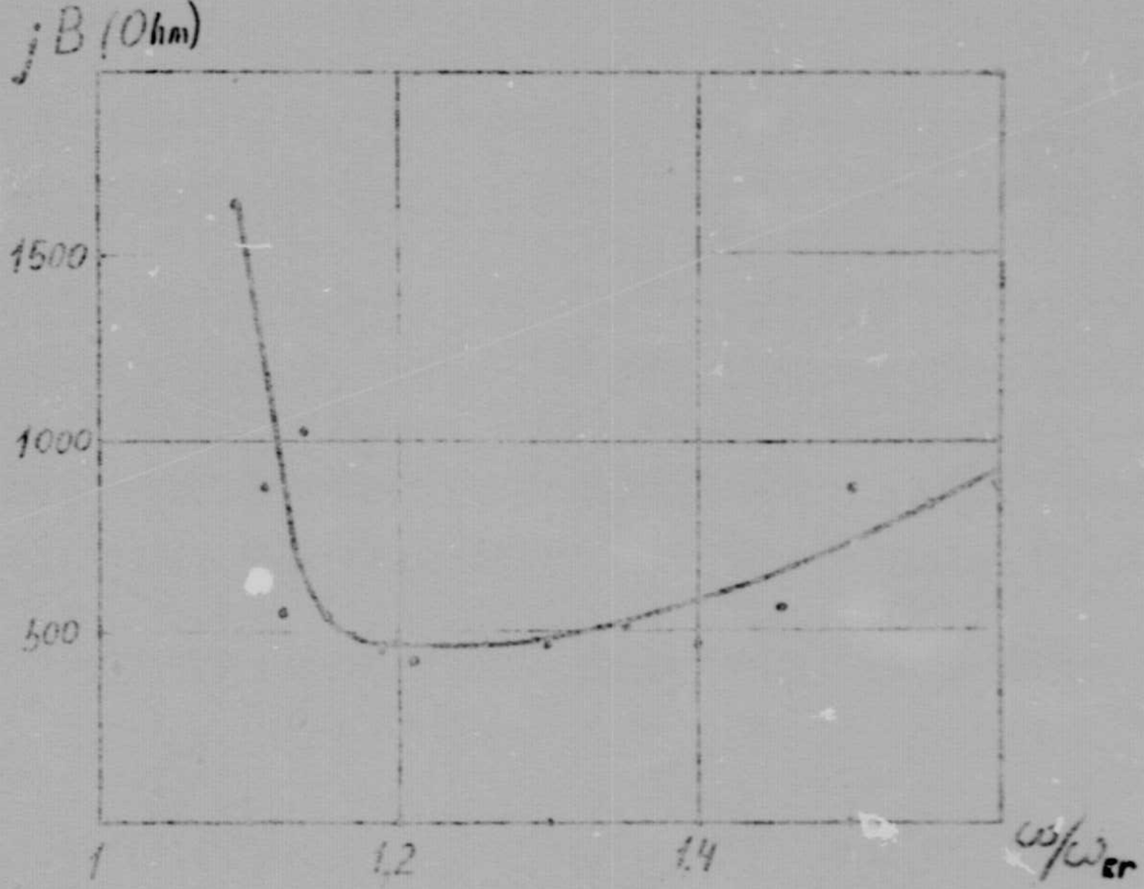

Fig. 9 Contact needle impedance in standard waveguide vs. ratio ω/ω_{cr}.

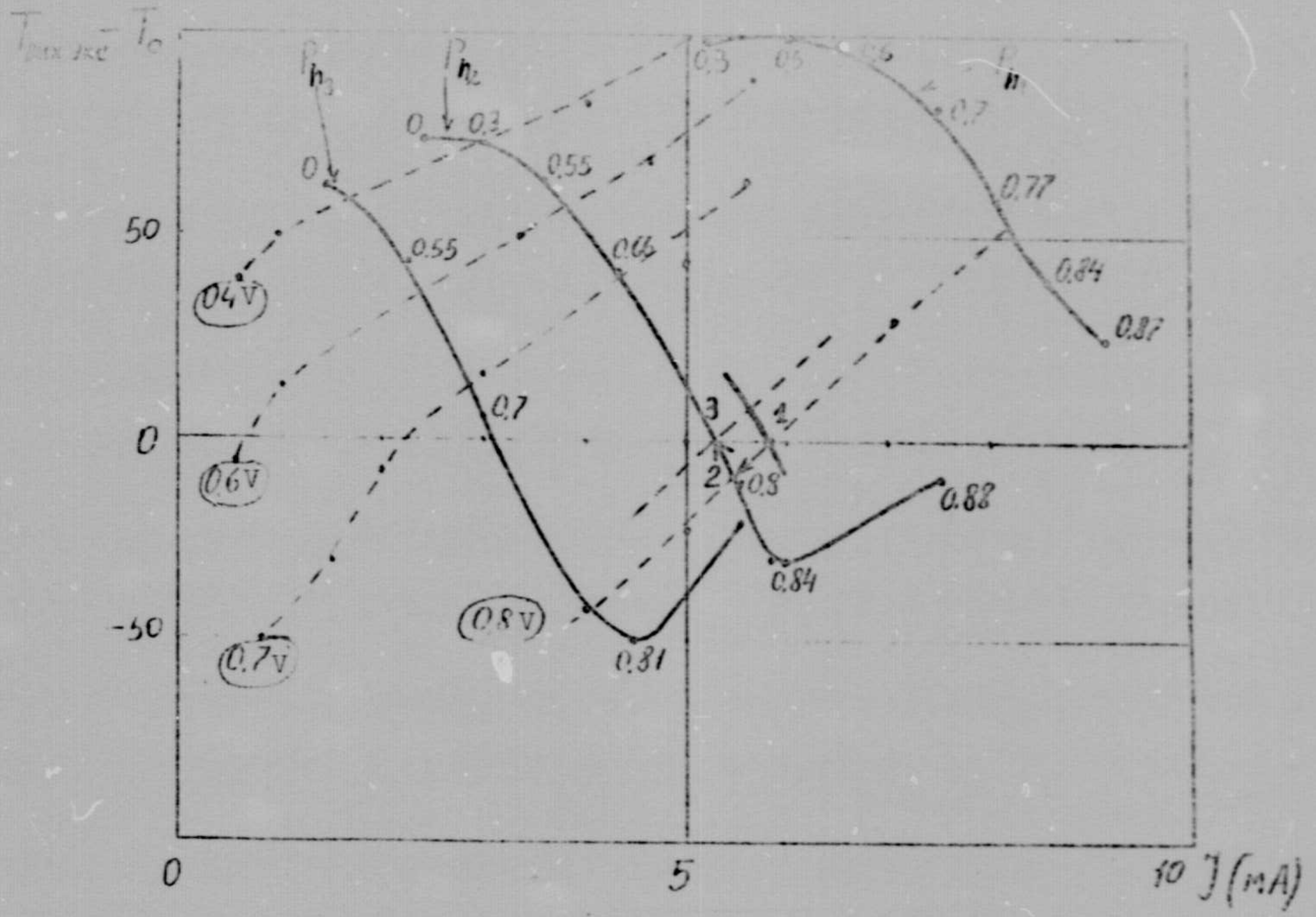

Fig. 10. Experimental output noise temperature of frequency converter vs. rectified current with fixed heterodyne power (solid line) and with fixed bias voltage on diode (dashed line).

Key: a. $T_{out.ex}-T_0$

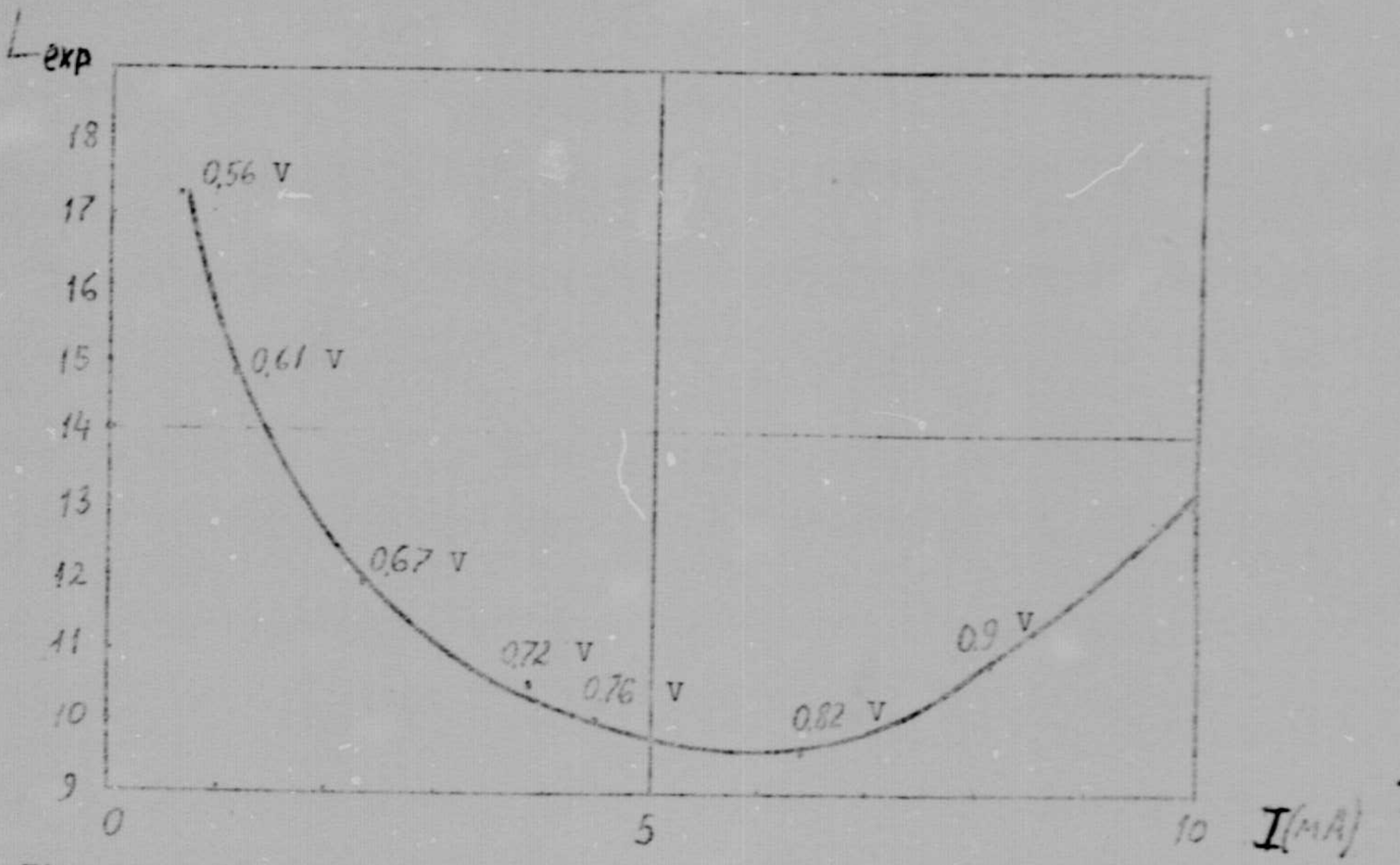

Fig. 11. Experimental conversion loss vs. rectified current under condition $T_{ex.out.noise} = T_0$.