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PHYSICAL PROCESSES IN ELECTRON DEVICES

Analysis of Spectral Characteristics of a Superconducting Integrated Receiver

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Abstract—Frequency down-conversion of a received signal in an integrated receiver with a superconducting heterodyne oscillator is simulated. The effect of the nonideal heterodyne spectrum on the transformation is assessed. The possibility of elimination of distortions introduced by the heterodyne in the course of the input spectrum reconstruction is investigated. A new method for signal spectrum reconstruction is proposed and studied. The effect of noise at the receiver output on the reconstructed spectrum of the original signal is studied. The requirements for the heterodyne spectral parameters providing for the necessary accuracy of reconstruction are determined.

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INTRODUCTION

Receivers based on superconductor/insulator/superconductor (SIS) tunnel junctions exhibit the minimum noise temperature in the range 100–1200 GHz. Their sensitivity is bounded by the quantum limit $hf/2k$, where h is Planck's constant, k is the Boltzmann constant, and f is frequency [1, 2]. The reasons for this phenomenon are an extremely high nonlinearity of the superconducting element together with an ultimately low intrinsic noise that is related to the nature of the elements and the cryogenic working temperature. The integration time needed for detection of ultraweak signals and for measurements of ultralow concentrations is proportional to the squared noise temperature of the receiver. Therefore, SIS receivers make it possible to significantly shorten the observation time.

At a measured frequency higher than 300 GHz, the signal is strongly absorbed by atmospheric water vapor. Therefore, all submillimeter receivers and radio telescopes are located at relatively high altitudes or on board airplanes or satellites. Note that large sizes and weights and the high prices of heterodyne oscillators that work in the submillimeter range are the key factors that impede wide application of submillimeter receivers. A superconducting heterodyne oscillator can be integrated with an SIS mixer and placed in the same cryostat. This allows a substantial decrease in the size, weight, and power consumption of the receiver.

One of the achievements of modern cryoelectronics is the creation of a superconducting integrated receiver (SIR) of the submillimeter range [3, 4] with a widely tunable heterodyne based on the unidirectional flow of magnetic fluxes in a long Josephson junction (flux–flow oscillator (FFO)). A new integrated superconducting spectrometer operating in the range 550–650 GHz is being developed in cooperation with the Netherlands Institute for Space Research (SRON). This SIR-based spectrometer mounted on board a high-altitude balloon will be used for investigations of the Earth's atmosphere by means of oblique-incidence sounding in the framework of the Terahertz Limb Sounder (TELIS) project [5]. The test mission is scheduled late in 2006. The SIR will also be employed for space radio astronomy.

1. A SUPERCONDUCTING INTEGRATED RECEIVER

The superconducting integrated spectrometer for the TELIS project contains a 4 × 4 × 0.5 mm chip (Fig. 1 demonstrates the central part of the chip) that incorporates low-noise SIS mixer *1* with a quasi-optical antenna, superconducting heterodyne oscillator (FFO) *2*, and harmonic mixer (HM) *3* for phase locking of the FFO frequency. In the presence of only a dc supply voltage from batteries, this chip works as a superheterodyne receiver in the submillimeter wavelength range and requires no auxiliary microwave equipment.

Figure 2 demonstrates a simplified SIR circuit with a system for FFO frequency locking. The FFO signal and the signal from an external source received by the antenna are fed to the SIS mixer. The signals are multiplied, and the intermediate-frequency (IF) signal is delivered, first, to the cryogenic HEMT amplifier and, then, to the IF amplifiers located outside the cryostat. Thus, the output signal of the receiver is generated. A part of the FFO power is sent to the harmonic SIS mixer to be mixed with the mth harmonic of the reference synthesizer (20–22 GHz). This mixing yields the second IF signal with the frequency $f_{IF2} = \pm(f_{FFO} - mf_{synth})$. The signal is used by the phase-locked loop (PLL) system developed and created at the Institute of Microstructure Physics, Russian Academy of Sciences (Nizhni

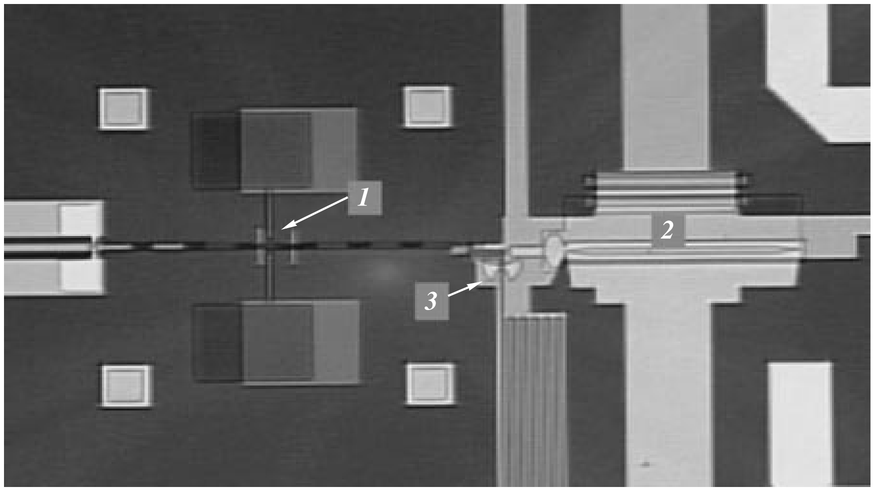

Fig. 1. Microphotograph of the central part of the SIR chip. The size of the area presented is about 1.5 × 1.0 mm.

Novgorod). The PLL system has two parallel circuits: a frequency-locking system and a phase-locking system. These systems have different lock-in and holding ranges and allow both simultaneous and individual operation.

The FFO oscillation frequency is related one-to-one to the FFO voltage by the Josephson relationship: $f_{\text{FFO}} = 2eV/h$ = (483.6 GHz/mV)V, where e is the electron charge. The dc bias current and the magnetic field generated by the current of the control line govern this frequency. In the autonomous operating mode, the FFO frequency stability is determined by low-frequency interferences and slow drifts in the power supply. In the frequency-locking mode, these fluctuations are compensated owing to the feedback circuit. The radiation spectrum of the frequency-locked (FL) FFO (Fig. 3a, dashed line) is determined by a nonlinear superposition of the thermal and shot noises. This spectrum can be approximated well by a Lorentzian line [6].

When the phase-locking system is activated, the FFO radiation spectrum has a shape shown by the solid line in Fig. 3a. One of the most important characteristics of this spectrum is the fraction of power concentrated in the central peak (spectral ratio (SR)). The spectral components lying outside the central peak are interpreted as the phase noise. It is demonstrated in [7] that the peak width is extremely small and determined by the characteristics of the reference synthesizer. The experimental values measured relative to the reference synthesizer are as low as 1 Hz, and the limit is determined by the resolution of the spectrum analyzer (Fig. 3b).

The narrower the FL FFO linewidth, the higher the fraction of power that corresponds to the PLL holding range. Note that, for the given PLL system, in the presence of phase locking, the SR value is related one-to-one to the width of the FFO intrinsic radiation line [8]. In the frequency range 500–700 GHz, the frequency-locking mode makes it possible to realize an FFO linewidth of 2–9 MHz. This provides concentration of 35–90% of the power in the central peak upon phase locking (Fig. 4). Note that a significant (from 2 to 9 MHz) broadening of the line with a decrease of the frequency of the FFO based on the Nb/AlO$_x$/Nb junctions results from the quantum effect of the self-detection of the Josephson oscillation in a tunnel junction [9].

2. DIRECT PROBLEM OF THE SIGNAL SPECTRUM TRANSFORMATION IN THE RECEIVER

2.1. Model and Data Employed

In an ideal receiver, the heterodyne spectrum should be close to the delta function. The FFO spectrum differs from the delta function substantially. The direct problem lies in simulation of transformation of the measured signal in the integrated receiver and determination of the effect of the nonideal FFO spectrum on the spectrum of the transformed signal. Finally, we should

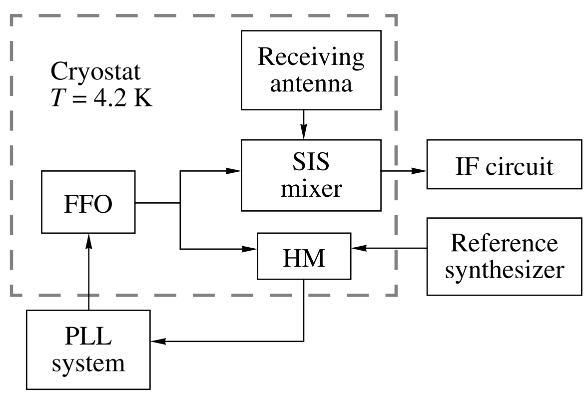

Fig. 2. Simplified block diagram of the receiver.

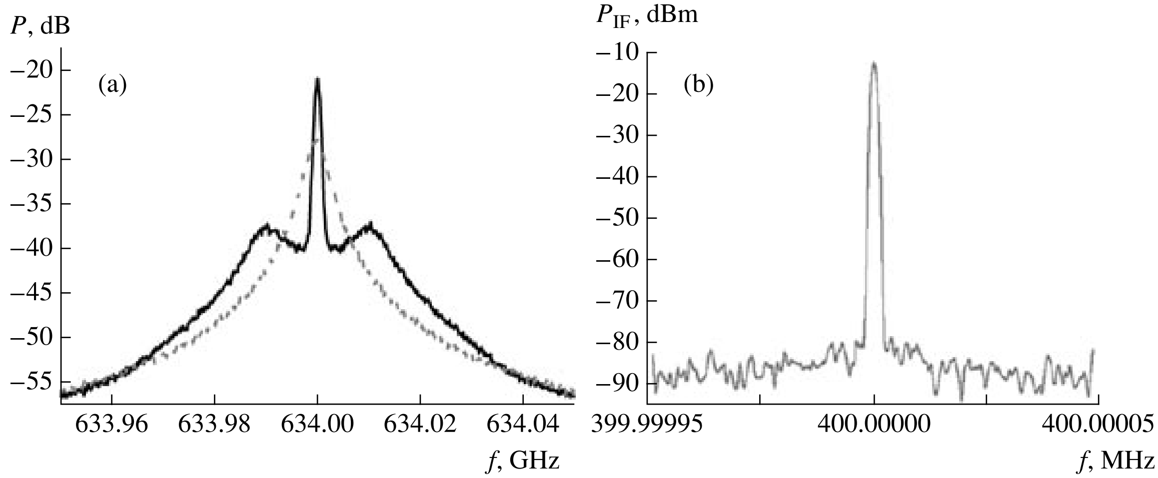

Fig. 3. (a) Experimentally measured (with a resolution of 1 MHz) distribution of power spectral density P of the PL and FL FFOs and (b) the PL FFO spectrum measured with a resolution of 1 Hz relative to the reference synthesizer in a range of 100 Hz and converted to lower frequencies.

work out the requirements for the parameters of the FFO spectrum (linewidth or SR) that provide for the needed accuracy of signal transformation.

The simulated emission line of HCl (625.9 GHz) calculated for various conditions (Fig. 5) is used as a source. The calculation conditions correspond to various altitudes of the balloon with the receiver during horizontal scanning of Earth's atmosphere. The altitudes are chosen in accordance with the real flight conditions. These spectra were calculated at SRON. The HCl emission lines serve as a good example for estimation of the spectral parameters of the receiver applied to measure the atmospheric spectra in the framework of the TELIS project, since these lines have complex shapes and contain narrow peaks. The spectra are specified with a resolution of 1 MHz.

The experimentally measured spectra of the FL FFO and phase-locked (PL) FFO (Fig. 3) are employed as the heterodyne spectra. For the FL FFO, the width of the radiation line ranges from 1.6 to 9.4 MHz. The corresponding SR of the PL FFO ranges from 89.4 to 25.3%. In the phase-locking mode, the intrinsic width of the central peak of the FFO radiation is relatively small [7]. In the spectra used for the calculations, this width (1 MHz) is equal to the resolution of the spectrum analyzer that is involved in spectral measurements. Note that the ratio of the peak power to the power of the phase noise remains unchanged. This is important because all heterodyne spectra are normalized in the further analysis. In the direct problem, the normalization to unity makes it possible to assess the distortions of the received spectrum related to the nonideal character of the FFO spectrum.

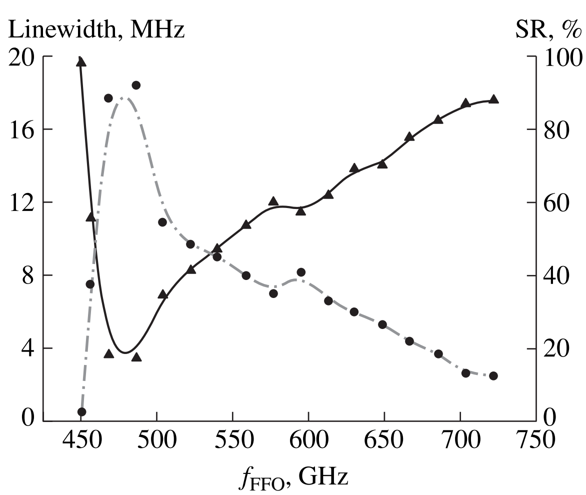

Fig. 4. Plots of (circles) the FL FFO linewidth and (triangles) the SR of the corresponding PL FFO vs. the FFO oscillation frequency.

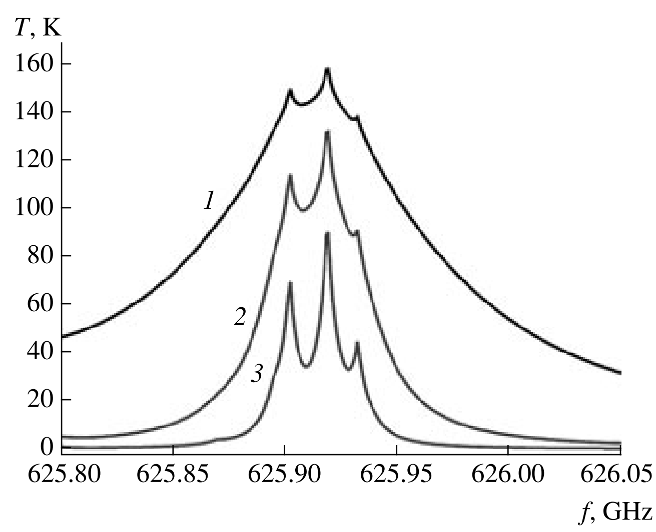

Fig. 5. Calculated spectra of HCl corresponding to altitudes of (*1*) 25, (*2*) 35, and (*3*) 40 km.

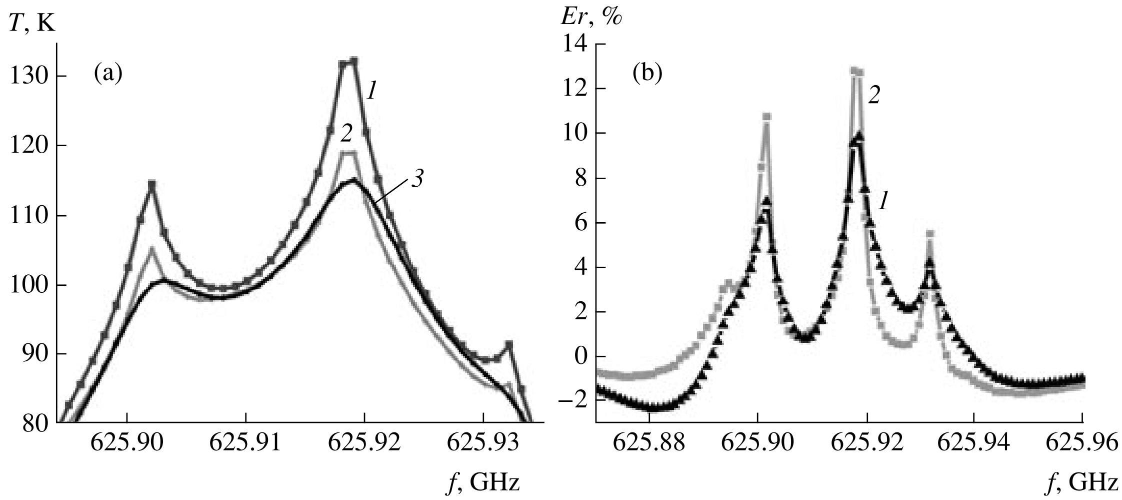

Fig. 6. (a) (*1*) Output spectrum of an ideal receiver that coincides with the input spectrum and the calculated output spectra of (*2*) the PL FFO and (*3*) the FL FFO (scaled-up central parts of the spectra are presented for clearness). (b) Plots of relative error *Er* vs. frequency for (*1*) the PL FFO and (*2*) the FL FFO (maximum errors are 10 and 13%, respectively).

It is known [1, 2] that the SIS mixer is a highly effective multiplier owing to relatively high nonlinearity. The output IF signal is equal to the product of the input signals. Using the convolution theorem, we derive the following expression:

$$I(f) = \int_{-\infty}^{+\infty} S(x-f)O(x)dx,$$

where $S(f)$, $O(f)$, and $I(f)$ are the power spectra of the source, heterodyne (local oscillator), and output signal, respectively, and f is frequency. Thus, we can calculate the power spectrum of the output signal $I(f)$ as a convolution of the source and heterodyne power spectra.

To estimate the error related to the nonideal character of the heterodyne spectrum, we employ the maximum difference between the input and output spectra. Usually, the maximum difference corresponds to the peak region. The peak heights in the source spectra are different; therefore, a relative error is used. It is equal to the maximum difference divided by the peak value (the spectral maximum), is measured in percent, and is used as a measure of the transformation error related to the nonideal character of the FFO spectrum.

2.2. A Solution to the Direct Problem

Figure 6a shows the output SIR spectra calculated in the framework of the above model for the FL and PL FFOs in comparison with the spectrum of the input signal. The linewidth of the FL FFO used as a heterodyne is 4 MHz and the SR of the corresponding PL FFO is 66.8%. The HCl spectral line at an altitude of 35 km serves as a source. It is seen that, in the case of the FL FFO, the peaks are smoothed more significantly than in the case of the PL FFO, thereby resulting in a larger error (Fig. 6b). Note that the spectral shape of the output signal is similar to the spectral shape of the input signal owing to the specific character of the PL FFO spectrum (a narrow central peak and a wide pedestal corresponding to the phase noise). This phenomenon is realized to a lesser extent in the FL FFO.

Figure 7 demonstrates the dependence of maximum relative error *Er* on the FFO spectral parameters. The PL FFO exhibits a linear decrease in the error with an increase in the SR of the heterodyne spectrum. The greater error of the FL FFO indicates the advantage of the phase-locking system.

On the basis of the results obtained for the HCl line at an altitude of 35 km, we can state that an error of no

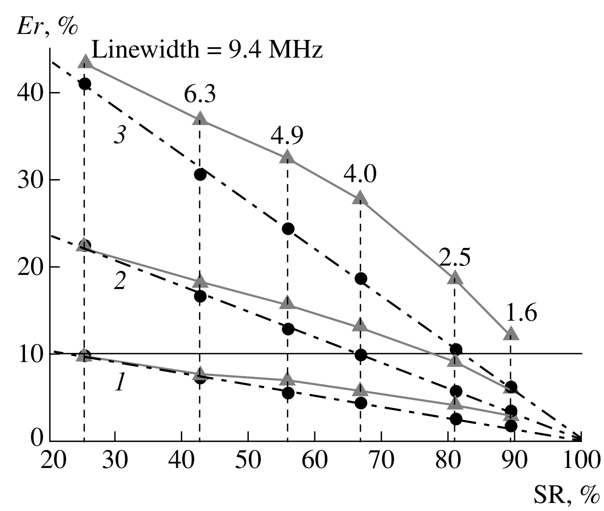

Fig. 7. Plot of the maximum relative error *Er* vs. the SR for (circles) the PL FFO and (triangles) the corresponding FL FFO spectra for the HCl line at altitudes of (*1*) 25, (*2*) 35, and (*3*) 40 km.

greater than 10% can be obtained using the FL FFO with a linewidth narrower than 3 MHz. The same result can be realized using the PL FFO with an SR higher than 67%. This result is attained by means of phase-locking of the FL FFO with a linewidth of 4 MHz. When the measurement altitude increases, the peaks in the spectrum of the HCl line become narrower and more developed. Therefore, the error increases and the requirements of the FFO parameters become more demanding. For an error of no greater than 1%, the FFO SR should be greater than 94%. Such an SR can be realized if the FFO linewidth is less than 0.7 MHz.

3. INVERSE PROBLEM OF SIGNAL SPECTRUM CONVERSION IN THE RECEIVER

3.1. Model and Data Employed

Normally, in the experiments, the spectral shape of the input signal should be reconstructed with allowance for the data regarding the spectra of the output signal and of the heterodyne. Therefore, the problem lies in working out the requirements of the FFO spectral parameters that provide for the needed accuracy of the signal spectrum reconstruction.

Let us assume that the signal spectrum at the receiver output and the heterodyne spectrum are known. Various spectra of the FL and PL FFOs are used as the heterodyne spectrum. The heterodyne spectra are normalized to unity. The same profiles of the HCl line as in the direct problem (Fig. 5) are used as a source. In all spectra, the resolution is 1 MHz. The output signal of the receiver is simulated as the convolution of the source and heterodyne spectra. Two methods for the reconstruction are considered: (i) deconvolution and (ii) an original iterative procedure that can be used in the case of the PL FFO at an SR greater than 50%.

In practice, the output signal of the receiver contains noise components that are independently manifested in the spectral channels. In the calculations, we take into account noise in the following way. The receiver's output signal is simulated and a normal noise is added to it. The noisy spectrum is employed in the reconstruction procedure. The result of the reconstruction is compared with the spectrum of the input signal, and the difference is used to characterize the effect of the level of the added noise on the resulting error. The noise at the receiver output is related to the single-sideband noise temperature [10] as follows:

$$T_n^{out} = \frac{1}{\sqrt{\Delta f \tau}} T_n^{SIR}.$$

Here, τ is the integration time and Δf is the width of the spectral channel of the receiver. For the typical parameters ($\tau = 1$ s and $\Delta f = 1$ MHz) and the realized noise temperature of SIR (200 K in the double-sideband mode [11], which corresponds to $T_n^{SIR} = 400$ K), the output noise temperature is $T_n^{out} = 0.4$ K.

Under real conditions, it is hardly possible to accurately determine the FFO spectrum. The TELIS project employs methods that allow determination of the SR for the PL FFO based on the signal measurement at the special output of the PLL system during the balloon flight. For the known SR, the PL FFO spectral shape can be obtained with a sufficiently high accuracy [8]. Therefore, it is important to estimate the accuracy of the SR value. To estimate the errors related to this accuracy, we employ different FFO spectra in the direct and inverse problems.

3.2. Reconstruction Procedures

Deconvolution. In the calculations, we use the deconvolution procedure known as the direct Fourier method.

Consider power spectrum $I(f)$ of the output signal of the receiver that corresponds to spectrum $S(f)$ of the input signal. The relationship between these spectra is written as

$$I(f) = \int_{-\infty}^{\infty} S(x-f)O(x)dx + N(f),$$

where $N(f)$ is the noise spectrum.

In the Fourier space, this equation takes the form

$$\hat{I}(x) = \hat{S}(x)\hat{O}(x) + \hat{N}(x).$$

The purpose of deconvolution is to find $S(f)$ using known functions $O(f)$ and $I(f)$. A solution can be obtained by calculating the inverse Fourier transform of function $\hat{\hat{S}}(x)$:

$$\hat{\hat{S}}(x) = \frac{\hat{I}(x)}{\hat{O}(x)} = \hat{S}(x) + \frac{\hat{N}(x)}{\hat{O}(x)}. \qquad (1)$$

Iterative procedure. This method has been proposed by us and is based on the specific shape of the PL FFO spectrum that can be represented as the sum $O(f) = O_1(f) + O_2(f)$, where $O_1(f)$ is the central narrow peak and $O_2(f)$ is the pedestal of the phase noise. In this case, the SR equals the ratio of the power corresponding to component O_1 to the total power $O_1 + O_2$ in the entire spectrum.

The heterodyne action on the spectrum of the received signal can be written in the operator representation: $\hat{O} \circ S(f) = I(f)$. Here, $S(f)$ is the source spectrum, $I(f)$ is the spectrum of the output signal, and

$\hat{O}$ is the operator that corresponds to the convolution with the spectrum of the local oscillator. Using the convolution linearity, we obtain $\hat{O} = \hat{O}_1 + \hat{O}_2$.

In the calculations, the heterodyne spectrum is normalized to unity. It can be represented as

$$O(f) = k_1 o_1(f) + k_2 o_2(f),$$

where $k_1 o_1 = O_1$, $k_2 o_2 = O_2$, and spectra o_1 and o_2 are normalized to unity; hence, $k_1 + k_2 = 1$. In this case, we obtain $\mathrm{SR} = k_1 \times 100\%$.

With allowance for the aforesaid facts, we have

$$I(f) = (k_1 \hat{o}_1 + k_2 \hat{o}_2) \circ S(f).$$

Operators $\hat{o}_1$ and $\hat{o}_2$ are known since the heterodyne spectrum is known. Output spectrum $I(f)$ is also known. Note that operator $\hat{o}_1$ corresponds to the convolution with spectrum o_1, which is a narrow peak with a unit area (δ function). We may assume that $\hat{o}_1 \equiv \hat{E}$, where $\hat{E}$ is the unit operator, which does not change the signal spectrum.

The action of the operator $k_1 \hat{o}_1 - k_2 \hat{o}_2$ upon $I(f)$ is represented as

$$\begin{aligned} &(k_1 \hat{o}_1 - k_2 \hat{o}_2) \circ I(f) \\ &= (k_1 \hat{o}_1 - k_2 \hat{o}_2) \circ (k_1 \hat{o}_1 + k_2 \hat{o}_2) \circ S(f) \\ &= (k_1^2 \hat{o}_1^2 - k_2^2 \hat{o}_2^2) \circ S(f). \end{aligned}$$

The action of the operator $k_1^2 \hat{o}_1^2 + k_2^2 \hat{o}_2^2$ upon the resulting expression yields

$$(k_1^4 \hat{o}_1^4 - k_2^4 \hat{o}_2^4) \circ S(f).$$

Being repeated, the aforementioned actions (multiplications by the conjugate expressions) result in the following formula:

$$(k_1^n \hat{o}_1^n - k_2^n \hat{o}_2^n) \circ S(f) = k_1^n \left(\hat{o}_1^n - \left(\frac{k_2}{k_1} \right)^n \hat{o}_2^n \right) \circ S(f). \quad (2)$$

If $k_2/k_1 < 1$ (SR is greater than 50%), the coefficient of the second term tends toward zero at $n \longrightarrow \infty$. Thus, since $\hat{o}_1 \equiv \hat{E}$, expression (2) contains only desired signal spectrum $S(f)$. In the calculations carried out at an SR of about 75%, it suffices to perform four or five iterations ($n = 2^4$–2^5).

In comparison with the deconvolution procedure, the main disadvantage of the iterative approach is related to the following limitation: the SR of the PL FFO should be greater than 50%. However, the advantage of the iterative method lies in the fact that it does not lead to ill-posed problems. An alternative scenario is realized for the deconvolution in the case of Eq. (1) since it may involve division by zero.

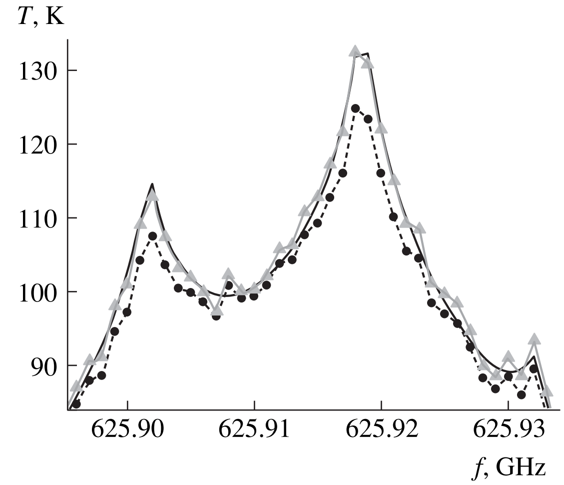

Fig. 8. Result of the HCl line reconstruction: (solid line) the input spectrum (central part of the HCl emission line corresponding to an altitude of 35 km), (circles) the simulated input spectrum (sum of the convolution of the input signal with the PL FFO spectrum with an SR of 80.4% and the additional normal noise T_n^{out} = 1 K), and (triangles) the reconstructed input spectrum.

3.3. Results of the Solution of the Reconstruction Problem

Effect of noise in the case when a single heterodyne spectrum is used for both direct and inverse problems. First, we perform calculations for the FL FFO spectra. Generally, Eq. (1) corresponds to an ill-posed problem because it may yield a nonunique unstable solution. In particular, this phenomenon leads to an increase in the noise level after the reconstruction procedure is applied [12]. Such a result is manifested most clearly in the case of the FL FFO spectra. The calculations show that the direct deconvolution results in a strong increase in the noise level and the procedure becomes inapplicable at $T_n^{out} \approx 1$ K (corresponding to a double-sideband noise temperature of the receiver of 500 K).

Subsequently, we use the PL FFO spectra and apply both reconstruction procedures (the original iterative procedure and deconvolution). Figure 8 demonstrates the spectrum transformed during the reconstruction. On the scale presented, the results obtained with both procedures are virtually identical for the above values of the parameters.

In the case of the iterative reconstruction, the noise level increases by a factor of 1/SR (Fig. 9), a result that follows from the algorithm. For an SR greater than 50% (the domain of applicability), the noise level increases

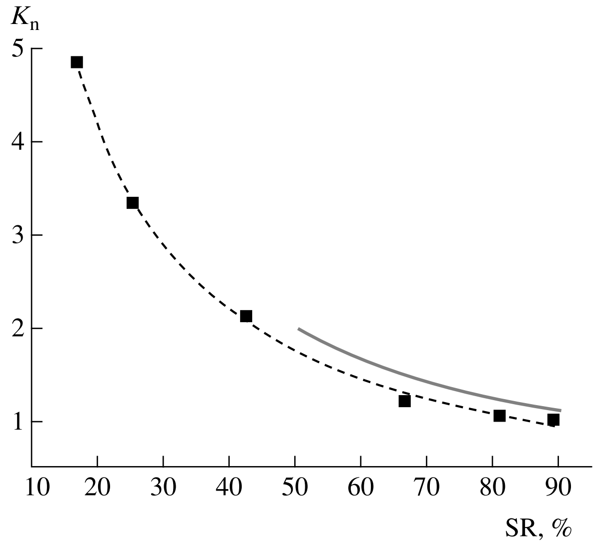

Fig. 9. Plots of noise gain K_n that characterizes the variation in the noise intensity for the reconstruction with (solid line) the iterative procedure and (squares) deconvolution vs. the SR of the PL FFO.

by a factor less than 2. Similar results are obtained for the reconstruction with the deconvolution method (Fig. 9). A decrease in the SR leads to a hyperbolic increase in the noise level. For the working range of the existing PLL system, the reconstruction with the direct deconvolution yields an increase in the noise level by a factor less than 5. The calculations show that, in the case when a single heterodyne spectrum is used for both the direct and inverse problems, the noise gain does not depend on the noise intensity (noise temperature) and remains unchanged when the spectra of HCl that correspond to different altitudes are used as sources.

Application of different heterodyne spectra for the direct and inverse problems with allowance for the effect of noise. To simulate the output spectrum of the receiver, we employ the PL FFO spectra with an SR ranging from 80.4 to 85.6%. This range is significantly greater than the expected experimental accuracy of the SR determination. The reconstruction is performed for the PL FFO spectrum with an SR of 80.4%. The maximum relative error is equal to the maximum difference between the calculated spectrum and the source spectrum divided by the maximum temperature of the corresponding HCl line. Figure 10 shows the results obtained. In all cases, an SR error of 1.5% (at an SR of about 80%) yields an error of less than 1%.

Two spectra with equal SRs may have slightly different shapes. An error emerges if one of them is used for the direct problem and the other is used for the inverse problem. However, it is demonstrated that the FL FFO spectrum can be approximated well by the Lorentzian curve. If the FFO with a predetermined intrinsic linewidth is locked with a specific PLL system, we obtain similar spectra of the PL FFO with close SRs [8]. Insignificant deviations of the curves shown in Fig. 10 from linear dependences are related to minor differences in the frequency distribution of the phase noise in the experimentally measured spectra. Addition of noise in the case when different heterodyne spectra

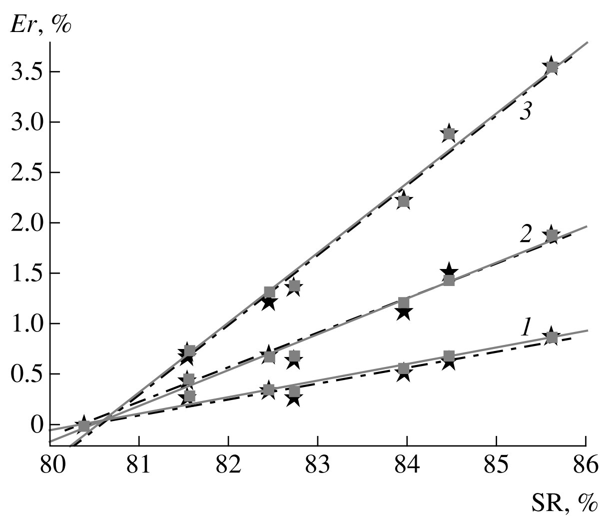

Fig. 10. Plots of reconstruction error Er emerging upon application of different heterodyne spectra for the direct and inverse problems vs. the SR of the PL FFO spectra used for simulation of the direct problem: (stars) results of deconvolution and (squares) results of the iterative procedure. The HCl lines at altitudes of (*1*) 25, (*2*) 35, and (*3*) 40 km serve as sources. The calculations are performed with neglect of the noise effect.

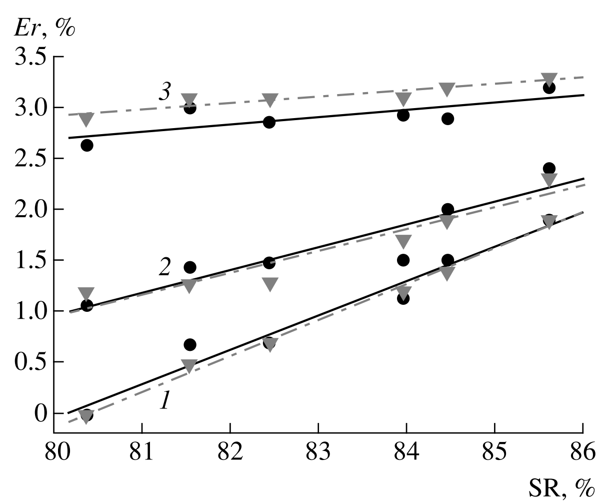

Fig. 11. Result of reconstruction of the HCl line at an altitude of 35 km via (triangles) direct deconvolution and (circles) the iterative procedure using the experimentally measured spectrum of the PL FFO (SR = 80.4%). Noise with T_n^{out} = (*1*) 0, (*2*) 0.4, and (*3*) 1 K is added. In the direct problem, we employ the experimental spectra of the PL FFO with the SR ranging from 80.4 to 85.6%.

are applied for the direct and reconstruction problems yields an additional error (Fig. 11). The resulting error is calculated as the square root of the sum of the squared errors. It follows from the linear approximation of the results obtained that an SR error of 2% leads to an error less than 2% for a realistic level of the added noise of $T_n^{out} = 0.4$ K.

CONCLUSIONS

The effect of the heterodyne spectrum and the output noise of the receiver on the reconstructed input spectrum has been studied. The requirements of the spectral ratio of the PL FFO have been worked out: the ratio should be determined with an error of about 1%. The results obtained show that the existing SIR satisfies the requirements of the TELIS (atmospheric sounding) project [5, 11]. In addition, this project employs alternative methods for signal reconstruction that are based on the a priori data regarding the source spectra, thereby substantially softening requirements of the heterodyne parameters. A relatively high (up to 100 kHz) spectral resolution needed for certain problems of radio astronomy (e.g., analysis of planetary spectra) can also be realized with the existing SIR.

The extension of the working range of the receiver to a frequency higher than 1 THz is an important problem for radio astronomy and aeronomy. An SIR based on niobium nitride with an FFO working frequency as high as 1 THz is being developed. In such SIRs, the FFO intrinsic linewidth can be significantly greater (even up to tens of megahertz). Therefore, an ultrabroadband (more than 50 MHz) PLL system should be created for the realization of the desired SR. To decrease the signal delay in the PLL system, the cryogenic PLL located in the immediate vicinity of the SIR can be employed.

ACKNOWLEDGMENTS

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