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The stability of a terahertz receiver based on a superconducting integrated receiver

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Abstract
We present the results of stability testing of a terahertz radiometer based on a superconducting receiver with a SIS tunnel junction as the mixer and a flux-flow oscillator as the local oscillator. In the continuum mode, the receiver with a noise temperature of 95 K at 510 GHz measured over the intermediate frequency (IF) passband of 4–8 GHz offered a noise equivalent temperature difference of 10 ± 1 mK at an integration time of 1 s. We offer a method to significantly increase the integration time without the use of complex measurement equipment. The receiver observed a strong signal over a final detection bandwidth of 4 GHz and offered an Allan time of 5 s.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

The rapid development of terahertz technologies has prompted research into the possibility of using terahertz receivers in areas other than purely scientific ones. Among these, of great interest is the feasibility of building terahertz imaging systems for security applications. As of this writing, the systems actively in use are based on acoustic, magnetic, and electromagnetic principles, for example an acoustic detector of hard substances or a magnetic detector of metal objects. However, these are ineffective for the detection and recognition of potentially dangerous nonmetallic objects hidden by clothing or in the mail, such as plastic weapons, explosives, and drugs. The terahertz region of the spectrum could provide safe, fast imaging technologies that can detect objects hidden by clothing no matter what material they are made from.

Currently there are a great number of imaging systems that differ from each other mainly in their frequency range, which determines the quality of the images and also the feasibility of recognition of hidden objects. For example, infrared (IR) imaging systems are ineffective in some cases because of strong absorption of IR radiation by clothing, human tissue, and the atmosphere. At radio frequencies, penetration is much better, but in this case the spatial resolution, determined by the wavelength, is much worse. The solution lies in the middle, at terahertz frequencies, where good penetration combined with good spatial resolution allows recognition of hidden objects, including weapons, explosives, and drugs.

Currently there are several commercial terahertz imaging systems [1, 2]. When describing the capabilities of modern imaging systems it is necessary to formulate the basic requirements they should meet: remote imaging and passive imaging (this is especially important in systems where, firstly, the observer must not be visible and, secondly, the use of active imaging may cause health problems), the possibility of detecting objects hidden by clothing or luggage, and the possibility of determining the material the studied object is made of. It should be noted that all modern commercial imaging systems meet only some of the above requirements. Heterodyne receivers have great potential to become the receivers of choice in imaging systems because they not only meet all the aforementioned requirements but also have excellent spatial and temporal resolution.

At the heart of our heterodyne receiver is a superconducting integrated receiver (SIR) comprising, on a $4 \times 4 \times 0.5$ mm^3 chip, a low-noise superconductor–insulator–superconductor (SIS) mixer with double-dipole or twin-slot antennas integrated with a flux-flow oscillator (FFO), used as a local oscillator (LO), and a harmonic mixer for phase-locking the LO [3–5]. A schematic of the SIR is shown in figure 1. The SIR does not

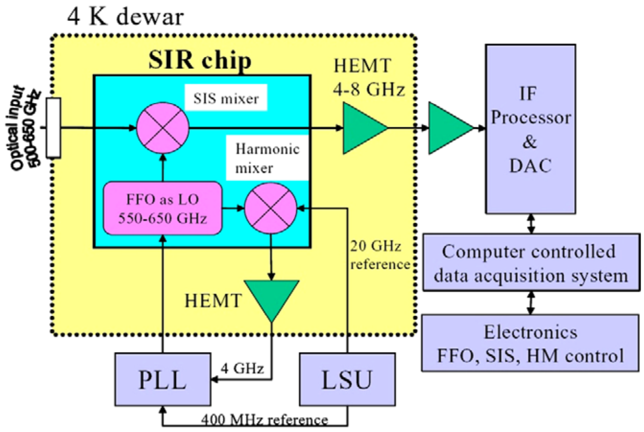

Figure 1. A schematic of an SIR-based receiver. The chip carries an SIS mixer coupled with a double-dipole or twin-slot antenna, a FFO made as a long Josephson junction, and a harmonic mixer for phase-locking the LO. A local oscillator source unit (LSU) based on a quartz frequency standard is used as in [5]. The SIS output signal passes through the IF chain to the data acquisition system.

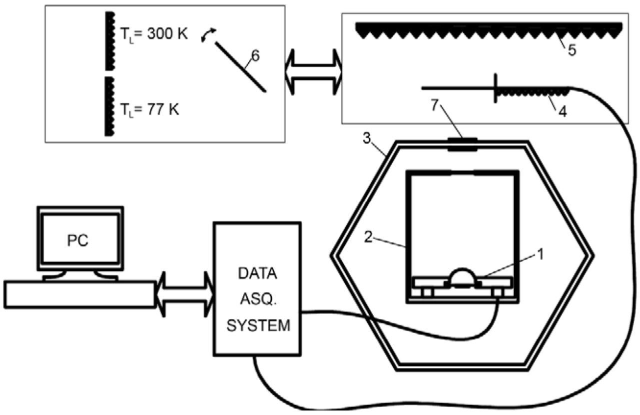

Figure 2. A schematic of the experimental setup: 1, mixer block; 2, magnetic shield; 3, cryostat; 4, chopper with blades at 295 K; 5, blackbody load with a variable temperature; 6, nutating mirror; 7, optical window of the cryostat.

require any sophisticated equipment and can run on a battery. Currently, the best SIRs have a noise temperature that does not exceed 100 K at LO frequencies of 500–700 GHz, and FFOs can be swept in the range 300–800 GHz with the autonomous linewidth no greater than 1 MHz.

In this work we use an FFO with a phase-locked loop (PLL), in which case one can say that the LO frequency is stable and there is no jitter in the usual understanding of the term. To characterize the FFO's stability one might speak about phase noise, as studied in detail in [6, 7]. When detecting a line from a synthesizer after multiplication we see a line with a width of less than 100 kHz [8]. If we speak about an autonomous FFO, then its stability is determined by the fluctuations in the power supply and external noise. In this paper we do not describe the fabrication process of superconducting integrated receivers in much detail. For more detail you may consult [9–11].

Employing a SIR in an imaging system means building an entirely new instrument with many advantages over traditional systems: high temperature resolution comparable to the best results for incoherent receivers; high spectral resolution allowing spectral analysis of various substances; the LO frequency can be swept to obtain images at various frequencies, effectively providing 'colour' images; since a heterodyne receiver preserves the phase of the radiation, it is potentially possible to construct 3D images.

2. Noise equivalent temperature difference of SIR

One of the main parameters that characterizes the noise performance of a receiver operating in the passive image mode is the noise equivalent temperature difference (NETD). The minimum NETD for the case when the receiver noise temperature is comparable with the antenna temperature can be determined from [12]:

$$\mathrm{NETD} = \alpha T_{\mathrm{N}} \sqrt{1 + \frac{T_{\mathrm{A}}}{T_{\mathrm{N}}} + \frac{3}{8}\left(\frac{T_{\mathrm{A}}}{T_{\mathrm{N}}}\right)^2} \frac{1}{\sqrt{B_H \Delta t}}, \qquad (1)$$

where T_{N} is the receiver noise temperature, T_{A} is the antenna temperature associated with the object, B_H is the intermediate frequency (IF) bandwidth, and Δt is the integration time. The factor α depends on the receiver type and is of order unity.

A schematic of the experimental setup used to measure the NETD is shown in figure 2. The SIR is mounted at the focus of an elliptical lens which is installed into a mixer block carrying two magnetic screens. The screens are made of permalloy and lead and protect the SIR from external magnetic fields. Such isolation is necessary because the FFO is extremely sensitive to the slightest variations of a magnetic field. The mixer block is mounted on the cold plate of a liquid helium cryostat. The SIR is remotely controlled. The SIS output was amplified by the IF chain with a passband of 4–8 GHz and registered by a square-law detector. The NETD was measured at 510 GHz, where the receiver had a noise temperature of 95 K within the IF range of 4–8 GHz. The cryostat window was made of Mylar. Using a chopper we switched the receiver input at a rate of 400 Hz between a blackbody load with a variable temperature and a room-temperature load (the blades of the chopper are at 295 K); both loads were made of Eccosorb® [13]. The output signal was fed to a lock-in amplifier remotely controlled by a PC.

The receiver output signal versus time is shown in figure 3. As the temperature difference between the loads decreases, the variance of the output signal decreases as well and reaches a minimum at $\Delta T_{\mathrm{load}} \sim 3$ K. The NETD in this case was found to be 10 ± 1 mK at an integration time of the lock-in amplifier of 1 s. Such behaviour of the NETD is due to IF chain gain fluctuations, instabilities of the SIR operating point and the FFO, and other factors that are published elsewhere [14].

As of this writing, the presented values of the NETD for the heterodyne receiver are the best available and comparable to the values of obtained for the best incoherent terahertz receivers [15].

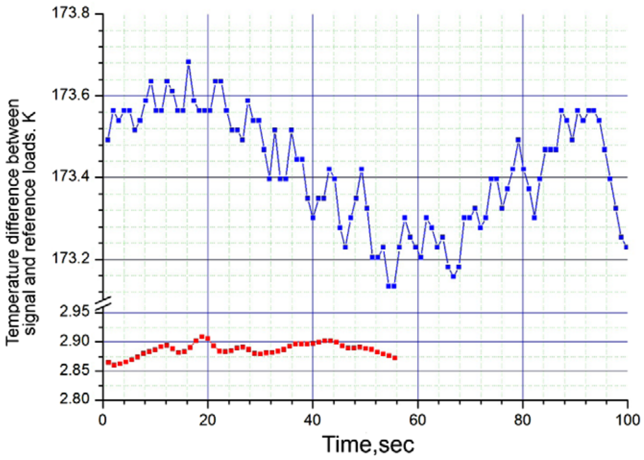

Figure 3. Time dependence of the difference between the temperatures of signal load and the chopper blades. In the case of a large difference (top line) NETD = 143 ± 14 mK, and for a small difference (bottom line) NETD = 10 ± 1 mK. In both cases the integration time of the lock-in amplifier was 1 s.

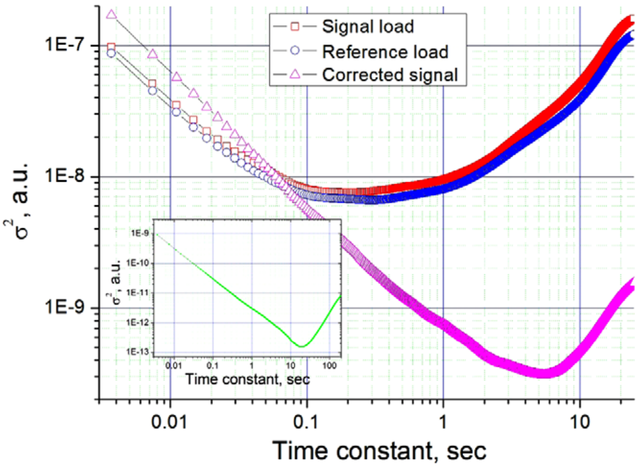

Figure 4. System stability of the SIR at the IF bandwidth of 4 GHz. The Allan variance of the SIR output signal when the receiver is looking towards the reference load with a fixed temperature (circle) or the room-temperature load (square) simulating the signal source. The triangle curve corresponds to the signal corrected according to (2). The inset shows the plot of the corrected signal for the case when the detection bandwidth is 40 MHz.

3. Time stability of a superconducting integrated receiver

The standard procedure to describe receiver instabilities is the computation of the Allan variance. Unlike the white noise which does not depend on the input signal, the $1/f$ noise and drift decrease in proportion to it [14]. These two factors result in an increase of the Allan time and for a low input signal the NETD reaches a minimum at an integration time of 1 s (figure 3).

For radio astronomy, where the receiver stability is of great importance, quite sophisticated stabilization schemes have been developed. The main principle is to stabilize the parameters of the IF chain components (which makes the whole scheme very expensive), decreasing the final detection bandwidth, which results not only in the increase of the Allan time but also the degradation of the NETD.

To use a SIR in a commercial system it is necessary to come up with a simple method of increasing the receiver Allan time. Our method consists of switching the receiver input between the object and a matched reference load at a known temperature.

To realize this method we did the following. Instead of the chopper we used a nutating mirror that could be remotely controlled (figure 2). The switching time between two successive positions of the mirror was ∼1.8 ms. During the experiment the mirror could be switched between two positions: OFF, with the receiver looking towards the reference load with a fixed temperature, and ON, with the receiver looking towards the room-temperature load that was simulating the signal source. Both loads were made of Eccosorb®. The IF signal was fed to the data acquisition system (DAS) which also controlled the position of the mirror. The DAS successively measured two values of the IF signal corresponding to the reference load and the signal.

Monitoring the reference load signal is necessary in order to compensate for the fluctuations of the IF gain caused by fluctuations in the power supply and temperature. The IF signal is used to compute the instantaneous value of the IF gain, which allows us to correct the signal from the observed source.

The increase in the Allan time was the result of the processing of the IF signal. For real time measurements one can correct the IF signal in the following way:

$$S'_{\mathrm{out_i}} = \frac{S_{\mathrm{out}_i}}{S_{\mathrm{ref}_i}} S_{\mathrm{ref}_0} \qquad (2)$$

where S_{ref_0} is the output signal at the initial moment when the receiver is looking towards the reference load, S_{out_i} and S_{ref_i} are outputs at a given moment of the receiver looking towards the signal and reference, respectively, and S'_{out_i} is the corrected output. The DAS software correct the output signal in real time.

Figure 4 shows three Allan variance plots: the reference signal, the source signal and the corrected signal (2). Naturally, the fluctuations of the corrected signal are higher at shorter integration times and are in general equal to $\sqrt{\sigma^2_{\mathrm{ref}} + \sigma^2_{\mathrm{out}}}$. By inspecting the Allan variance plots we see that the levels of the $1/f$ noise and drift are lower by one order of magnitude for the corrected signal, which allows us to increase the Allan time of the receiver. The inset in figure 4 shows the Allan plot for the case of a narrow final detection bandwidth (40 MHz). This plot shows the potential of the method, and in this case the Allan time equals ∼20 s. We would like to stress again that the above values of the Allan time were achieved without the use of any complicated schemes to stabilize the gain of the IF chain or the mixer conversion efficiency.

The advantages of our method are best seen in comparison with the results presented in [5]. The authors of that work used a stabilized receiver with an IF bandwidth of 17 MHz. The Allan time of their receiver was slightly lower than ours (see the inset in figure 4). The departure from the straight line given by the radiometer equation began at integration times of the order of a few seconds. In our case, despite a wider bandwidth (40 MHz), the Allan time was 20 s.

The results of stability tests of the terahertz radiometer based on a superconducting receiver with an SIS tunnel junction as a mixer and flux-flow oscillator as a local oscillator are the best for the receivers of this type. The obtained values of the NETD $= 10 \pm 1$ mK and the Allan time of 5 s for the receiver with a bandwidth of 4 GHz allow building a terahertz imaging system with a frame acquisition time of 2–3 s.The method described above allows real time correction of the receiver output in a terahertz imaging system.

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References

[1] http://www.thruvision.com
[2] http://www.teraview.co.uk
[3] Koshelets V P *et al* 1996 *Appl. Phys. Lett.* **68** 1273
[4] Koshelets V P and Shitov S V 2000 *Supercond. Sci. Technol.* **13** R53
[5] de Lange G *et al* 2010 Development and characterization of the superconducting integrated receiver channel of the TELIS atmospheric sounder *Supercond. Sci. Technol.* **23** 045016
[6] Koshelets V P, Dmitriev P N, Sobolev A S, Pankratov A L, Khodos V V, Vaks V L, Baryshev A M, Wesselius P R and Mygind J 2002 Linewidth of Josephson flux flow oscillators *Physica* C **372–376** 316–21
[7] Koshelets V P, Ermakov A B, Dmitriev P N, Filippenko L V, Khudchenko A V, Kinev N V, Kiselev O S, Sobolev A S and Torgashin M Yu 2008 Phase-locked local oscillator for superconducting integrated receiver *ISSTT08: The 19th Int. Symp. on Space Terahertz Technology (Groningen, April 2008)* pp 211–220 published in the Proceedings of the ISSTT-08
[8] Koshelets V P, Dmitriev P N, Ermakov A B, Sobolev A S, Torgashin M Yu, Khodos V V, Vaks V L, Wesselius P R, Mahaini C and Mygind J 2002 Superconducting phase-locked local oscillator for submm integrated receiver *Proc. 13th Int. Symp. on Space Terahertz Technology (Harvard University, March)* pp 473–82
[9] Filippenko L V, Shitov S V, Dmitriev P N, Ermakov A B, Koshelets V P and Gao J R 2001 Integrated superconducting receiver: fabrication and yield *Appl. Supercond. Conf. ASC2000 (Sept. 2000, Report 4EA01)*; *IEEE Trans. Appl. Supercond.* **11** 816–9
[10] Dmitriev P N, Lapitskaya I L, Filippenko L V, Ermakov A B, Shitov S V, Prokopenko G V, Kovtonyuk S A and Koshelets V P 2003 High quality Nb-based integrated circuits for high frequency and digital applications *IEEE Trans. Appl. Supercond.* **13** 107–10
[11] Torgashin M Yu, Koshelets V P, Dmitriev P N, Ermakov A B, Filippenko L V and Yagoubov P A 2007 Superconducting integrated receivers based on Nb–AlN–NbN circuits *IEEE Trans. Appl. Supercond.* **17** 379–82
[12] Esepkina N A, Korol'kov D V and Pariyskiy Yu N 1973 Radiotelescopes and radiometers (in Russian) (Moscow: Nauka)
[13] http://www.eccosorb.com
[14] Ozhegov R V, Okunev O V, Gol'tsman G N, Filippenko L V and Koshelets V P 2009 Noise equivalent temperature difference of a superconducting integrated terahertz receiver *J. Commun. Technol. Electron.* **54** 716–21
[15] Luukanen A, Grnberg L, Haarnoja T, Helistö P, Leivo M, Rautiainen A, Penttilä J, Bjarnason J E, Dietlein C R and Grossman E 2008 Passive broadband terahertz camera for stand-off concealed threat identification using superconducting antenna-coupled microbolometers *38th Eur. Microw. Conf. (Amsterdam, Oct. 2008); Proc. 38th Eur. Microw. Conf.* pp 943–6