Superconducting Integrated Receiver as 400-600 GHz Tester for Coolable Devices

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***Abstract*—Laboratory-purpose submillimeter wavelength receiver is developed and tested. The device can *in situ* detect spectrum of an rf source working below 100 K within frequency range of 400-600 GHz. A sample is placed close to the receiver sensor; both are in vacuum inside the probe stick cooled by liquid helium in the standard transport dewar. The quasi-optical sensor is designed on a base of the superconducting integrated receiver chip; its noise temperature below 300K was measured with a variable-temperature black body at 520 GHz. The output level of the tester is suitable for the direct readout by a spectrum analyzer. Details of design and main test data are reported.**

***Index Terms*—Double-dipole antenna, flux-flow oscillator, Josephson oscillator, lens-antenna, microwave lens, planar antenna, quasi-optical mixer, quasi-optical receiver, SIS mixer, SIS receiver, spectral measurements, submillimeter receiver, superconducting integrated circuit.**

I. Introduction

Main goal of the project was development of a sensitive laboratory-purpose heterodyne receiver for the detection and spectral study of radiation from variety of superconducting oscillators such as flux-flow oscillators (FFOs), Josephson array oscillators or HTc structures and, possibly, from coolable semiconductor sources. To enable such a test for oscillators working at different temperatures, the non-contacting (quasioptical) scheme is the most natural choice. A SIS mixer with integrated planar antenna can be a good solution for the front-end of the test receiver [1], [2].

It is well-known that SIS mixers are the most sensitive devices for heterodyne reception in the frequency range of 100-1000 GHz with the noise temperature limited only by the quantum value hf/k [3], [4]. However, the large size, weight and expense of regular (room temperature) submillimeter local oscillators along with necessity of use a cryostat with optical window are the serious limitations for extensive use of SIS receivers in a laboratory. To overcome these drawbacks, the concept of a superconducting local oscillator that can be integrated with a SIS mixer has been proposed [5], [6]. Such an oscillator based on FFO has been developed and tested experimentally showing promising performance. Both frequency locking and phase locking of the FFO to a reference source has been recently demonstrated [7]-[11].

The operation of the quasi-optical superconducting integrated receiver (SIR) [12] at the frequency 500 GHz with the noise temperature of about 100 K, that is just 6 times the quantum limit, was demonstrated recently [13]. This chip-size heterodyne sensor can detect radiation as week as 10^{-13} W in the frequency range 300-700 GHz (with few exchangeable chips or sensor heads provided). Each set can cover the band of about 100 GHz. The estimated cost of the microcircuit [14] can be of the order of $1,000 that is much less if compare to that minimum of about $25,000, - price of a conventional set for the equivalent submillimeter oscillator which may consist of a BWO, a strong magnet and a high voltage power supply (the cryostat with the SIS mixer is not included!). In contrast to this bulky setup, the use of SIR sensor allows to mount the sample at a short distance within a compact cold environment, e.g. within laboratory test stick. That is why the SIR chip, which is ”two-in-one” device with low power consumption, was chosen as a heterodyne sensor for the laboratory-purpose research on submillimeter emission from coolable sources.

II. Experimental Details

A. Design of the probe receiver

Simplified drawing of the receiver inserted in a transport dewar with liquid helium is presented in Fig. 1. The device is designed as a stick made from stainless steel tube of diameter 50 mm and length of 1200 mm that fits into the standard vessel for liquid helium. To protect magnetic-sensitive samples from unwanted interference, the vacuumed cryoperm shield is installed at the end of the stick using a precise cone connection. The sample shelf is equipped with heater, thermometer, magnetic field coil, coaxial rf cable and rectangular waveguide (2.4 mm x 1.2 mm). To check the noise temperature of the receiver head, which is mounted at higher position, the variable-temperature load (black body)

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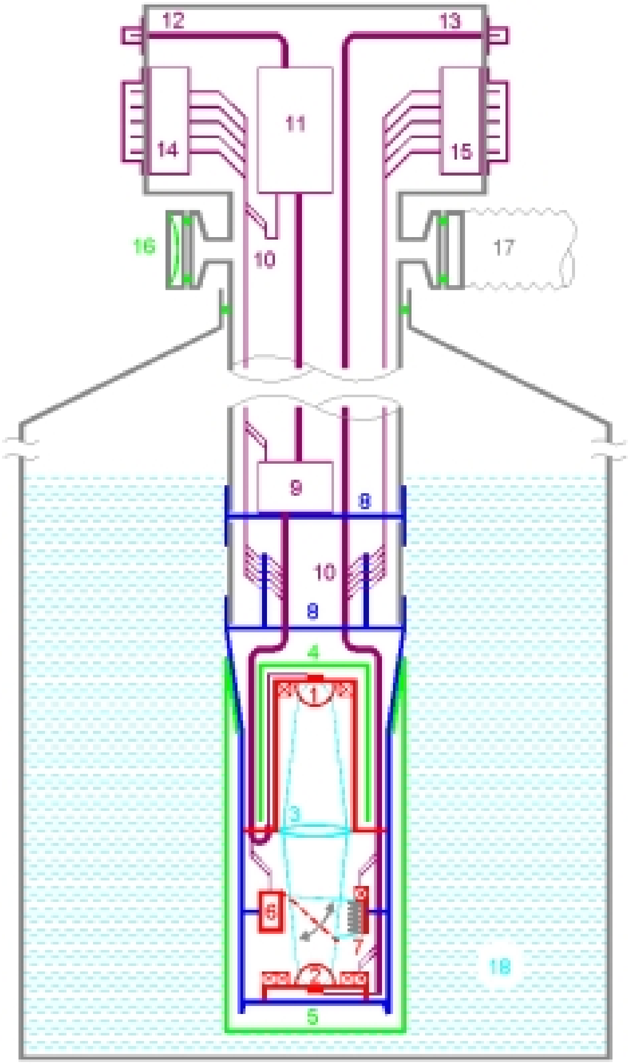

Fig. 1 Simplified drawing of laboratory-purpose tester which can *in situ* detect spectrum of submillimeter wave emission from coolable sources within frequency range of about 400-600 GHz: (1) receiving chip on silicon lens; (2) emitting sample on silicon lens; (3) focusing lens/infrared filter; (4) magnetic shielding of receiving chip; (5) vacuumed permalloy shield; (6) source switch/chopper; (7) calibration load; (8) heat sink chains for receiving head and for IF amplifier; (9) low-noise cold IF amplifier; (10) output coaxial cables and dc wiring; (11) buster IF amplifier; (12) and (13) IF output and sample cable; (14) and (15) dc connectors for receiving head and sample; (16) and (17) safety valve and vacuum pump connector; (18) dewar with liquid helium.

was put at the position of the sample. A compact chopper-wing (6) has been developed on the base of a mechanical relay, which can provide the switching rate of a few hertz. This chopper can switch the input of the receiving head between the sample and the calibration load as shown in Fig. 1.

The exchangeable receiving head is presented in Fig. 2(a). The head has its own double-layer magnetic shielding from led (internal layer) and from cryoperm (external one). The SIR sensor (1) [6], [14] is installed in the depth of the shield (4), as shown in Fig. 1, and mounted at the flat back of the silicon elliptical lens with antireflection coating [13]. Being combined with the focusing lens, the double dipole antenna SIS mixer [2], [13] provides the beam of about 10 degrees wide pointed to the sample source (2) which can also be equipped with its own lens. An additional focusing lens (3) and/or an infrared filter can be mounted at the adjustable aperture ring of the receiving head. The bias circuit contains an IF filter and a printed dual directional coupler (-23 dB) which are mounted inside the shield (4) of the receiving head as shown in Fig. 2(b). Three semirigid coaxial rf cables are connecting the receiver head: one cable for the cold IF amplifier and two others for the dual directional coupler, which is used for testing both the amplifier performance and the SIS mixer output reflection loss (not shown in Fig. 1). The receiving head is designed as a compact cylinder 32 mm in diameter and 76 mm in length; it can be installed not only inside a probe stick as shown in Fig. 1, but also in practically any cryostat or close-cycle cooler, which provides a cold flange with temperature of about 5 K or lower.

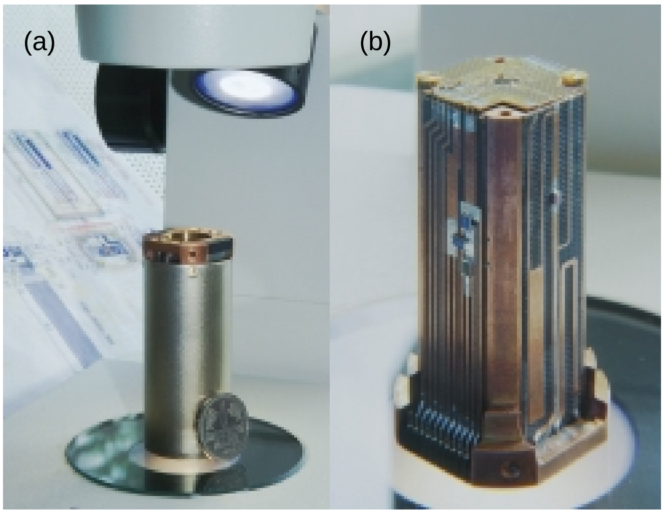

Fig. 2 Photographs of exchangeable receiving head (length 76 mm and diameter 32 mm): (a) magnetic shield is mounted; the input aperture and connectors are seen on the top; (b) magnetic shield is dismounted; the bias circuit and IF filters, including dual directional coupler (-23 dB), are mounted on the walls of the cooper block; the SIR chip of size 4 mm by 4 mm is seen on the top.

To prevent the receiving head from excessive heat produced by the first balanced IF amplifier (9) (G=20 dB, T_N=10 K [15]), this amplifier is installed at a separate shelf (8), which has its own thermal contact to the LHe bath (18). All dc wires (10) coming to both the receiver and the sample are mounted to a special heat sink PCB. The second IF amplifier (11) (G=53 dB, T_N=90 K [15]) is installed at the top of the stick at 300 K inside the connector box, also in vacuum. To avoid electrical chocks to the receiving chip during the connection procedure, a safety relay is used to short sensitive terminals of the device.

B. *Test results and discussion*

Performance of the receiver was tested using computer system IRTECON [13], [16], which electronically controls both the SIS mixer and the FFO. IV-curves of the SIS mixer obtained during the test procedure are presented in Fig. 3 as it

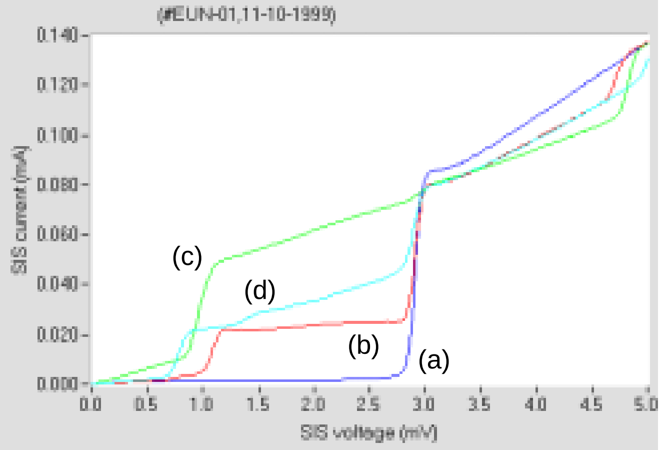

Fig. 3 IV-curves of SIS mixer: unpumped (a) and pumped by FFO at 428 GHz (b), 461 GHz (c), and 500 GHz (d).

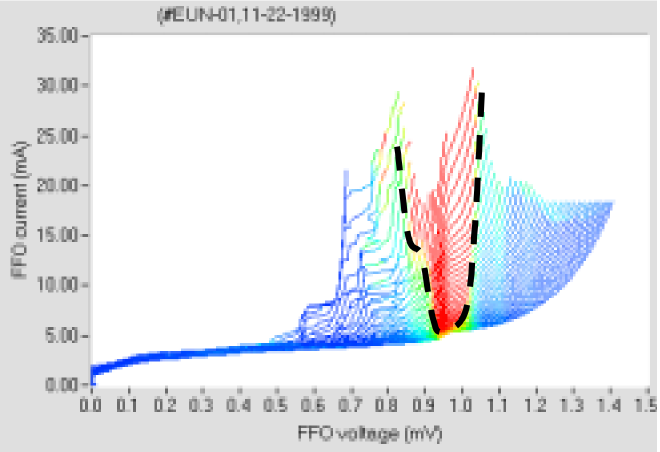

Fig. 4 IV-curves of FFO tuned by magnetic field. The frequency of this Josepson-type oscillator is proportional to *bias voltage* (about 484 GHz/mV), while delivered power is proportional to the *bias current*. Dashed curve indicates the region of sufficient pump level of SIS mixer.

appears at the monitor of controlling computer. The IV-curves of the local oscillator (FFO) are presented in Fig. 4. This is the result of tuning FFO by a magnetic field, i. e. each IV-curve is swept at the different magnetic field. The quasi-color (in the gray scale here) is indicating the pump level provided for the SIS mixer. Processed data on the pump level can reveal the frequency response of the SIS mixer (about equal to its instantaneous bandwidth) since the coupling circuit of the FFO is much more broadband.

The spectral resolution of the receiver is about 1-10 MHz, that is defined by the linewidth and stability of the free-running FFO. The spectra wider than IF band (from 1 GHz to 2 GHz in our case) can be measured by scanning LO frequency, i. e. in the FFO scan mode. Doing this, one can scan FFO in 1 GHz steps while integrating output signal within complete IF band. To get the coarse spectral information "on-the-fly", the IRTECON controlling system is being modified [16]. A signal can be then detected "by eye" using the quasi-color, which presents amplitude of IF output power vs. FFO frequency similar to pump level of the SIS mixer as shown in Fig. 4. To subtract the noise floor, at least one reference scan is necessary with signal source turned off. The detected spectra can be corrected to the frequency response of the receiver. For this purpose the data on the mixer pump can be used.

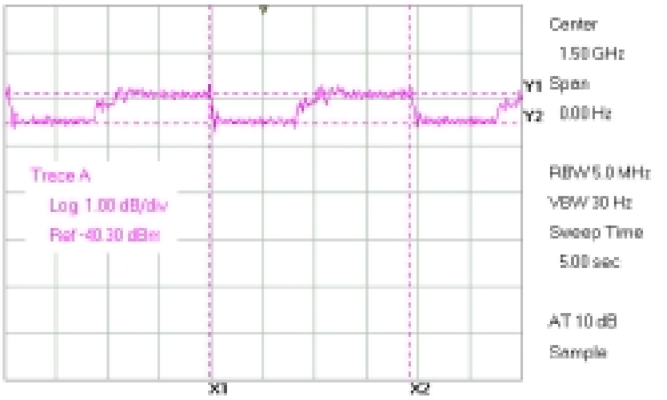

Fig. 5 Response measured at intermediate frequency, IF = 1.5 GHz with cold chopper, which switches input of the receiver between test loads at temperatures about 50 K and 4 K.

The noise temperature of the receiver measured with the calibration load (7) was below 300 K (DSB). The hot/cold response measured with cold mechanical chopper (6) from Fig. 1 is presented in Fig. 5. It is possible to estimate, that a narrow-band signal as weak as 0.1 pW can be detected at IF, assuming the spectrum of the signal narrower than 10 MHz. It worth to note here, that the useful frequency range of the receiver can be essentially wider, than the 3 dB band of the particular mixer from Fig. 3 (about 420-510 GHz), if the spectral density of a relatively weak but narrow-band signal exceeds a few thousand Kelvin.

To test the receiver, the spare SIR chip was used as a specimen of the emitting source (2), as shown in Fig. 1. The fact, that some LO power is leaking from the SIS mixer towards antennas and eventually emitted [6],[13], was used in this experiment. The measured spectrum of the FFO is presented in Fig. 6 as it appears at the monitor using the HP BenchLink software. The detected multi-peak spectrum

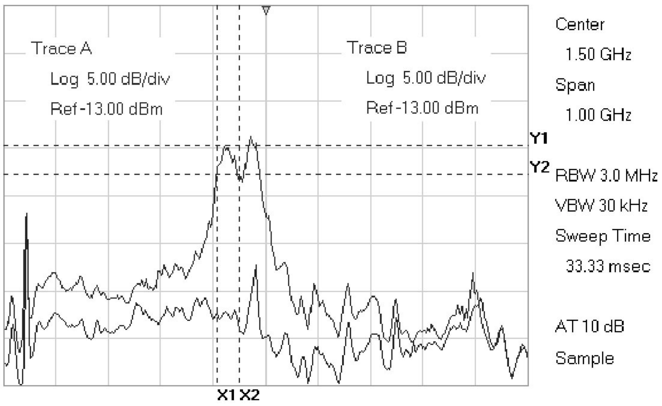

Fig. 6 Response at IF detected for relatively strong emission from a spare receiver chip (i.e. from second FFO) installed at the place of the test device (see Fig. 1).

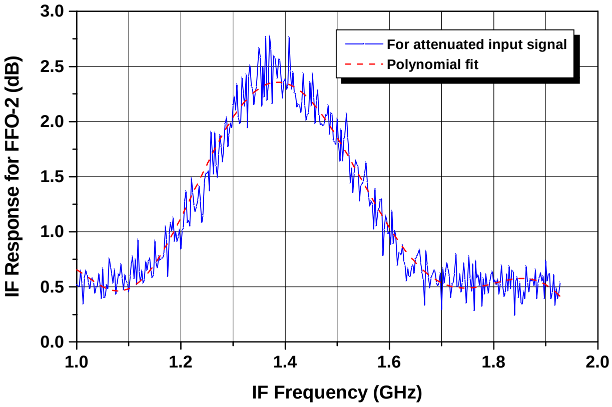

Fig. 7 Relatively wide IF spectrum from weak (attenuated) test source (second FFO), which was tuned for broadband emission.

can be explained with mutual instability of two oscillators [7], that is mainly due to unwanted 50 Hz EMI. This problem can be solved with frequency/phase locking of the FFO, that is experimentally proven [7]-[11]. To resolve finest spectra, we are looking forward to introduce PLL circuit for the probe receiver. The example of a wide and low intensity spectrum is presented in Fig. 7. This spectrum is obtained from the same sample SIR, but the FFO is biased at higher dynamic resistance producing emission of wider linewidth [10]. An absorbing film mounted at the aperture of the receiving head introduced extra attenuation.

III. CONCLUSION

A new quasi-optical submillimeter laboratory-purpose heterodyne SIS receiver is developed and tested within frequency range 400-600 GHz. This receiver does not need a separate local oscillator, since it uses ultra-compact Superconducting Integrated Receiver chip with its internal electronically controlled local oscillator. The receiving head is developed as a compact general-purpose device, which can be used in variety of setups including a probe stick or an optical cryostat. Authors hope that this development is a beneficial step towards wider use of superconducting receivers in laboratory studies.

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