INTEGRATED SUPERCONDUCTING RECEIVER AS A TESTER FOR SUB-MILLIMETER DEVICES AT 400-600 GHz

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ABSTRACT

We report on design and first application of a laboratory-purpose tester which can *in situ* detect spectrum of sub-millimeter wave emission within frequency range of 400-600 GHz from virtually any compact low-power source working within temperature range below 100 K. Both the receiver and the sample are placed in vacuum inside a laboratory test stick of diameter 50 mm, which is cooled down in a standard transport vessel for liquid helium. The sensor of the tester is designed on a base of the superconducting integrated receiver (SIR) chip working below 5 K. The chip sensor, beside the quasi-optical SIS mixer, contains an internal electronically tuned superconducting local oscillator, that provide low-noise operation at the level below 300 K DSB at central frequencies of 480-520 GHz as measured with a black body at the position of the test source. The signal detected by the SIS mixer is boosted by a helum-cold low-noise amplifier (G=20 dB, T_N=10 K) within frequency range 1-2 GHz and then by a second room temperature amplifier (G=53 dB, T_N=90 K) both mounted within the same test stick. The output level is sufficient for direct application to most of standard RF recorders, e. g. for a spectrum analyzer. To detect weak signals, a compact chopper-wing has been designed and placed at the input of the receiver module. Details of design and main test data measured at DC and RF are reported.

INTRODUCTION

The main goal of the project was development of a sensitive laboratory-purpose heterodyne receiver for detection and spectral study of radiation from variety of superconducting oscillators such as a 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 (quasi-optical) scheme is the most natural choice. A SIS mixer with integrated planar antenna can be a solution for the front-end of the 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 expenses of a regular (room temperature) submm local oscillator along with necessity of use a cryostat with optical window are that serious limitations for extensive use of the SIS receivers in laboratories. To overcome these drawbacks, the concept of a superconducting local oscillator that can be integrated with the SIS mixer has been proposed [5]. Such an oscillator based on FFO has been developed and tested experimentally showing promising performance. Both frequency and phase locking of the FFO to a reference source has been recently demonstrated [6-8]

The operation of the quasioptical superconducting integrated receiver (SIR) [8] at the frequency 500 GHz with the noise temperature of about 100 K, which is just 6 times exceeds the quantum limit, has been demonstrated [10]. 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 band of about 100 GHz. The estimated cost of the microcircuit can be of the order of $1,000 which is much lower if compare to that minimum of about $25,000, - price of a conventional set for the equivalent submm oscillator which may consist of BWO, powerful magnet and high voltage power supply, but the cryostat with SIS mixer is not included! Use of SIR chip, which is that ”two-in-one” device with low power consumption, seems very promising for laboratory scale instrumentation. For all these reasons the superconducting integrated receiver was chosen as a heterodyne sensor for laboratory-purpose research on sub-mm emission from a coolable sources which can be mounted at short distance from the sensor in the compact cold environment, e.g. within laboratory test stick.

EXPERIMENTAL DETAILS

A. Design of the stick receiver

Simplified drawing of the tester receiver cooled down 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 1200 mm long, which fits into a standard

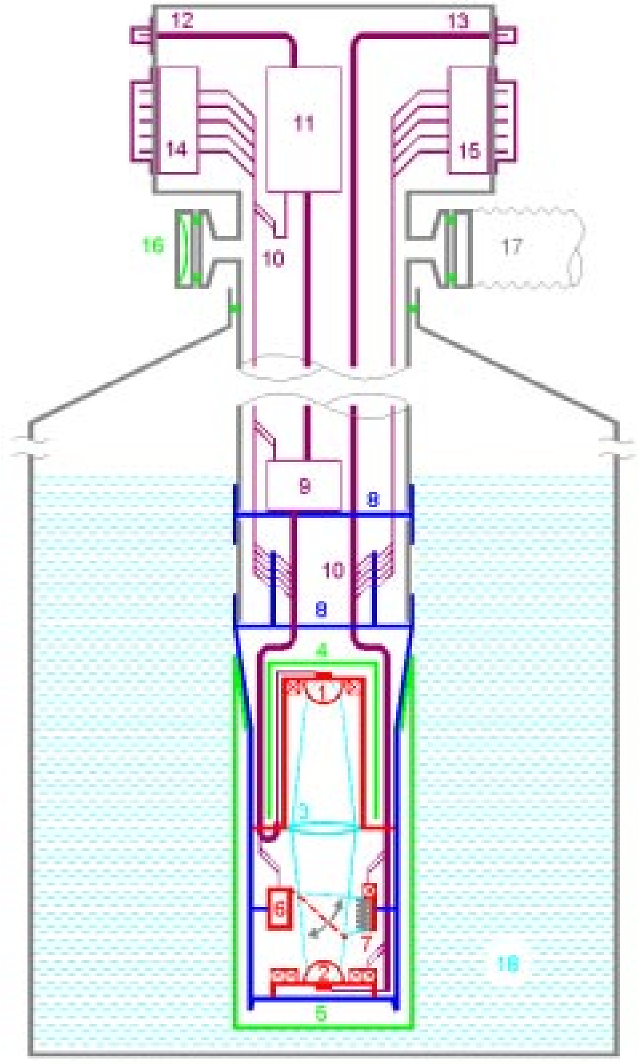

Fig. 1. Simplified drawing of a laboratory-purpose tester which can *in situ* detect spectrum of sub-millimeter wave emission from coolable sources within frequency range of about 400-600 GHz: (1) – receiving chip on silicon lens; (2) – emitting sample on silicon lens; (3) – focusing lens/infrared filter; (4) – magnetic shielding for 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) – cold IF amplifier; (10) – signal coaxial cables and bias wiring; (11) – buster IF amplifier; (12) and (13) – receiver output and coaxial cable for sample; (14) and (15) – dc connectors for bias of receiving head and sample; (16) and (17) – safety valve and vacuum pump connector; (18) – dewar with liquid helium.

vessel for liquid helium. To protect magnetic-sensitive samples from unwanted interference, the vacuumed permalloy shield is installed at the end of the stick using a precise cone connection. The sample shelf is equipped with a heater, thermometer, magnetic coil, rf coaxial cable and 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) was put at the position of the sample. A compact chopper-wing 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.

The exchangeable receiving head, which is presented in Fig. 2(a), has its own double-layer magnetic shielding from led (internal layer) and from permalloy (external one). The SIR sensor (1) 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 [10]. Being combined with the focusing lens, the double dipole antenna SIS mixer [2, 10] provides the beam of about 10 degrees wide pointed to the sample source (2) which can be also 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

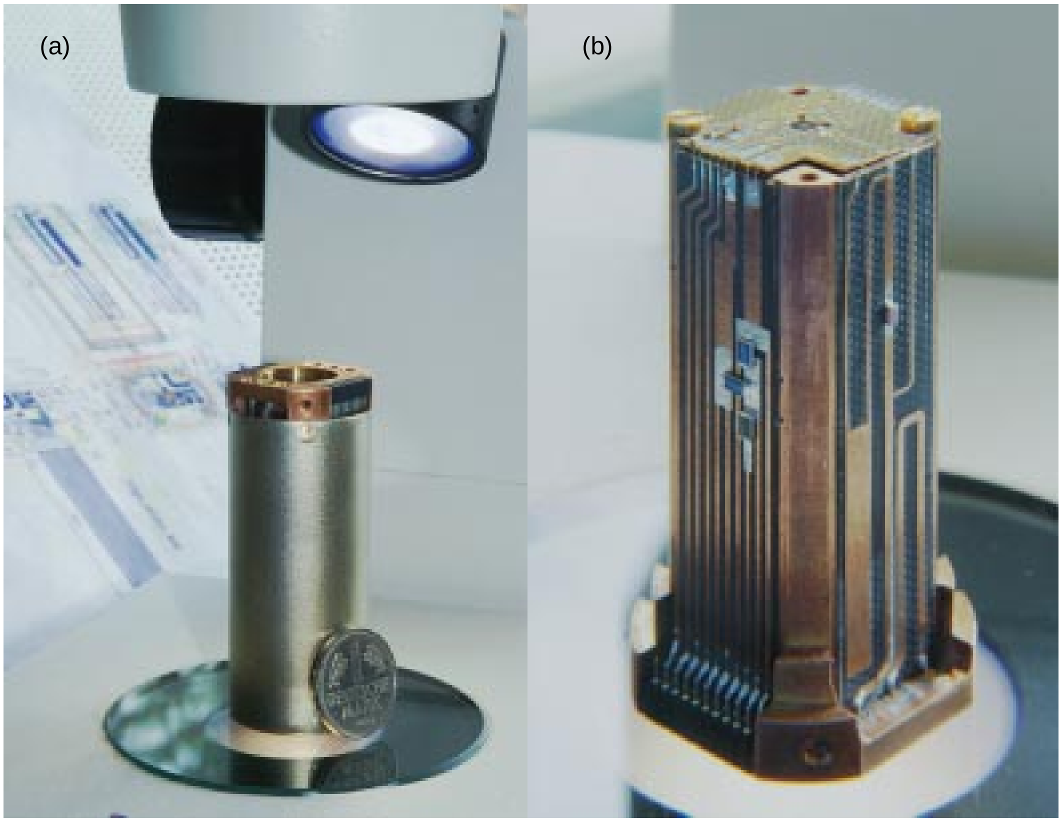

Fig. 2. Photographs of exchangeable receiving head (length 76 mm and diameter 32 mm): (a) magnetic shield is mounted; the input aperture and connectors are seen on the top; (b) magnetic shield is dismounted; the bias circuit and IF filters, including dual directional coupler (-23 dB), are mounted on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

receiving head. The bias circuit contains an IF filter and a printed dual directional coupler (-23 dB) which are mounted inside the shield of the receiving head as shown in Fig. 2(b). Three semirigid coaxial 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 compact as 32 mm in diameter and 76 mm in length; it can be installed not only in a dipstick 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.

To prevent the receiving head from the excessive heat provided by the first balanced IF amplifier (G=20 dB, T_N=10 K [11]), this amplifier is installed at a separate shelf, which has its own thermal contact to the LHe bath. All dc wires coming to both the receiver and the sample are mounted to a special heat sink PCB. The second IF amplifier (G=53 dB, T_N=90 K [11]) 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 [10], which electronically controls both the SIS mixer and the FFO. IV-curves of the SIS mixer obtained during the self-test procedure are presented in Fig. 3. The IV-curves of the local oscillator (FFO) are presented in Fig. 4 as it is being tuned with magnetic field (each IV-curve is swept at a constant magnetic field). The quasi-color (in gray scale here) is indicating the pump level provided for the SIS mixer. Processed data on the pump level can reveal the frequency response (about equal to instantaneous bandwidth) of the SIS mixer since the coupling circuit of the FFO is much more broadband. Note, that the useful frequency range of the receiver can be essentially wider, than the -3 dB band of the mixer pump (about 420-510 GHz from Fig. 3), because spectral density of a weak narrow-band signal can easily exceed the spectral density of the noise signal of a few thousand Kelvin. Since the noise temperature of the receiver measured with the calibration load is below 300 K (DSB), it is easy to estimate, that a narrow-band signal as weak as 0.1 pW can be detected at IF assuming the signal spectrum to be narrower than 10 MHz.

The spectral resolution of the receiver is about 1-10 MHz, that is defined by the linewidth (LW) 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 integrating signal within complete IF band. To get the coarse spectral information “on-the-fly”, the IRTECON controlling system is being modified. Presence of a signal can be then detected “by eye” using a graph in quasi-color, which shows amplitude of IF power

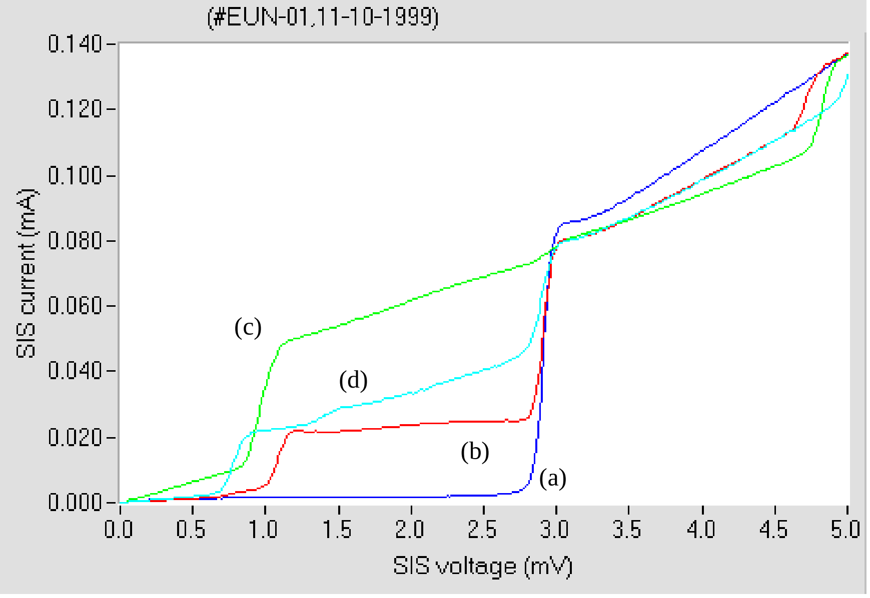

Fig. 3. IV-curves of SIS mixer: unpumped (a) and pumped by FFO at 428 GHz (b), 461 GHz (c), and 500 GHz (d).

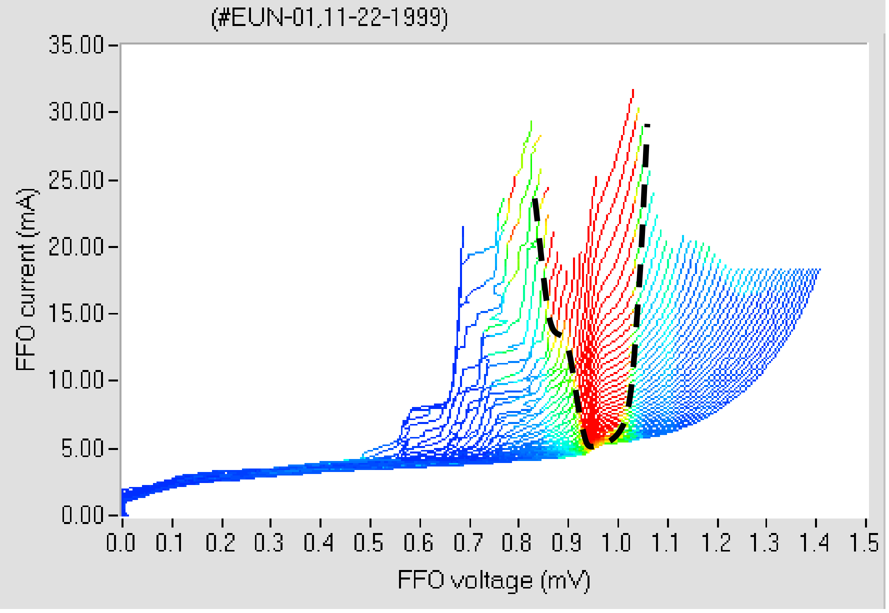

Fig. 4. IV-curves of FFO tuned by magnetic field. The frequency of this Josepson-type local oscillator in proportional to *bias voltage* (about 484 GHz per each mV), while delivered power is proportional to the *bias current*. The dashed curve indicates the region of sufficient pump level.

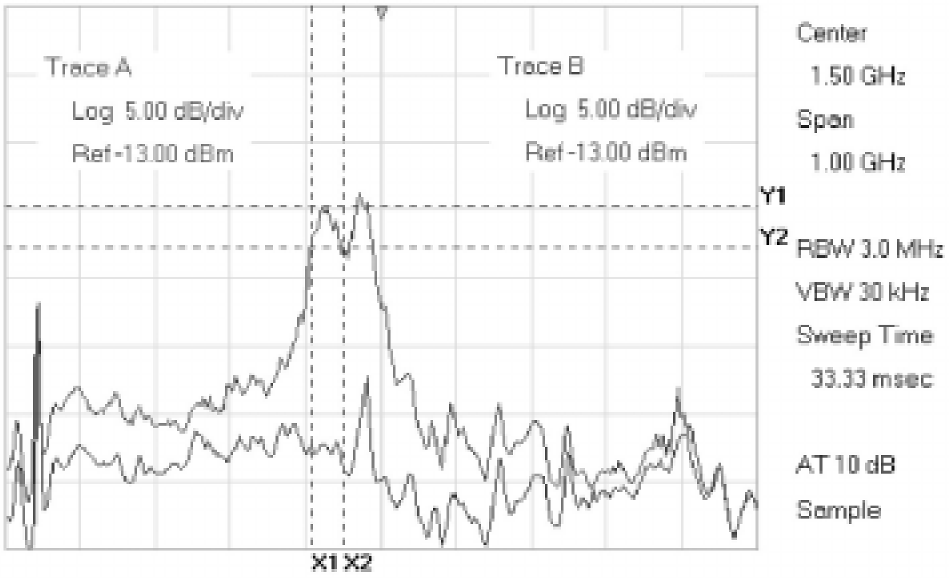

Fig. 5. Response at IF detected for relatively strong emission from a spare receiver chip (i.e. from second FFO) installed at the place of the test device (see Fig. 1).

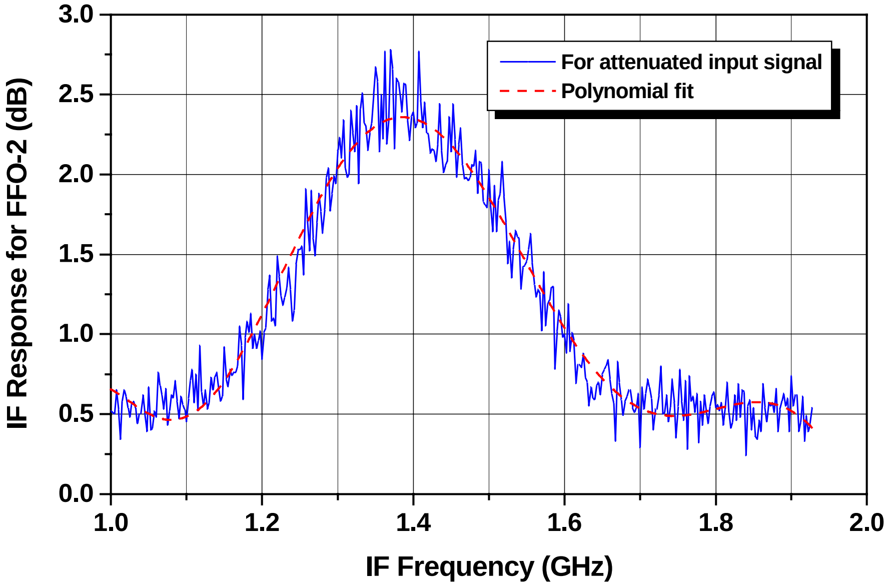

Fig. 6. Relatively wide IF spectrum from weak (attenuated) test source (second FFO) which was tuned for broad-band emission (see text and [12]).

vs. FFO frequency similar to pump level of the SIS mixer as in Fig. 4. Note, that 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 mixer pump can be used.

The spare chip receiver (SIR) on the elliptical lens was used as a specimen of the emitting source, as shown in Fig. 1. The fact, that some LO power is leaking from the SIS mixer towards antennas and eventually emitted [10], was used in this experiment. The measured spectrum of the FFO is presented in Fig. 5 showing mutual instability of two oscillators [6] which is mainly due to unwanted EMI. Since the possibility of frequency/phase locking of the FFO is experimentally proven [6-8], it can be introduced for the stick receiver in the future to resolve finest spectra. The example of a wide and low intensity spectrum is presented in Fig. 6. This spectrum is obtained from the sample SIR with its FFO biased at higher dynamic resistance producing emission of wider linewidth [12]. An absorbing film mounted at the aperture of the receiving head introduced extra attenuation.

CONCLUSION

A new submillimeter quasioptical laboratory-purpose heterodyne SIS receiver has been developed and tested successfully within frequency range 400-600 GHz. This receiver does not need a separate submillimeter local oscillator since uses ultra-compact Superconducting Integrated Receiver (SIR) 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 dipstick 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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