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Superconducting Integrated Submm Wave Receivers

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Abstract

The concept of the fully Superconducting Integrated Receiver (SIR) has been developed and experimentally demonstrated. The single-chip submm wave receiver includes a planar antenna integrated with a SIS mixer, which is pumped by an internal superconducting Flux Flow Oscillator (FFO) as local oscillator (LO). A DSB noise temperature below 100 K has been demonstrated around 500 GHz. Heterodyne measurements have shown that the instantaneous bandwidth of the receiver is 15 – 20 % which meets the requirements of practical applications. The double-dipole lens-antenna SIS mixer has an antenna beam ≈ f/9 with sidelobes below - 16 dB. This enables an efficient coupling of the SIR to the telescope antenna. With the FFO phase locked in the frequency range 270 - 440 GHz a linewidth as low as 1 Hz has been measured relative to a reference oscillator. A compact array of 9 SIRs has been developed and tested. Each pixel contains an *internally pumped* receiver chip, which is mounted on the back of an elliptical silicon lens. A noise temperature of about 150 K has been measured at 500 GHz using the internal FFO for the imaging array of Integrated Receivers.

Introduction

Lightweight and compact ultra sensitive submm Superconducting Integrated Receivers (SIRs) with low power consumption are very attractive for both radio-astronomical research and distant monitoring of the Earth atmosphere[1,2]. The new ambitious radio-astronomy multi-dish projects (e.g. ALMA) would gain considerably by using single-chip SIRs due to their lower price and better serviceability as compared to conventional approaches. A distant study of the atmospheric pollution is possible using air- or satellite borne SIRs for detection of the spectrum lines of ozone, chlorine and other elements in the submm wave range. Presently the SIR chip comprises a SIS-mixer with quasioptical antenna and a superconducting FFO as local oscillator. In the future chip designs an intermediate frequency SQUID amplifier and superconducting circuits for digitization of the down converted signals and their real time processing may be integrated. In this report we review the latest results of the SIR study.

Integrated Receiver Design

SIS heterodyne receivers are successfully used in radio astronomy for observation of spectra in the mm and sub-mm wave range. The noise temperature of a SIS mixer is ultimately limited only by the fundamental quantum value hf/k. The lack of cheap, compact, and easily tunable submm oscillators motivates the direct integration of a superconducting LO with the SIS mixer. In the past few years the FFO [1] has proven to be a reliable wideband and easy tunable local oscillator suitable for integration with a SIS-mixer in a single-chip sub-mm wave receiver [2]. The FFO is a long Josephson tunnel junction in which an applied *dc* magnetic field and a *dc* bias current drive a unidirectional flow of magnetic flux quanta (fluxons). A *dc* current in an integrated control line is used to generate the applied magnetic field. The density of the fluxons and thus the power and frequency of the emitted mm-wave signal may be easily tuned by either of the two external parameters. According to the Josephson relation the junction biased at voltage V oscillates with the frequency $f = (2\pi/\Phi_0)V$, where $\Phi_0 = 2\ 10^{-15}$ Wb is the magnetic flux quantum (corresponding to 483.6 THz/V).

The SIR microcircuits are fabricated on a crystalline Si substrate on the base of a high quality Nb-AlO_x-Nb trilayer. Each individual chip with size 4 mm × 4 mm × 0.5 mm contains a SIS mixer incorporated in double-dipole antenna and a FFO with matching circuits. As shown in Fig. 1 the micron size SIS junction ($R_N = 15 – 25\ \Omega$) placed in the center of the mixer makes the shared load of the two dipole antennas. The receiver chip is placed on the flat back surface of an elliptical silicon lens. To achieve a beam with high efficiency and good rotational symmetry a back reflector is installed behind the double-dipole antenna. The elliptical silicon lenses and their anti-reflection coating are manufactured using precision diamond turning. The mixer block is mounted on the cold plate of a liquid helium cryostat equipped with a thin Mylar or Capton window at 300 K and a crystalline quartz IR filter at 80 K. A black polyethylene film at 4.2 K is used as a heat shield. All windows as well as their anti-reflection coating are optimized for a center frequency of 500 GHz. A cryoperm shield enclosing the mixer block reduces the influence of external magnetic interference.

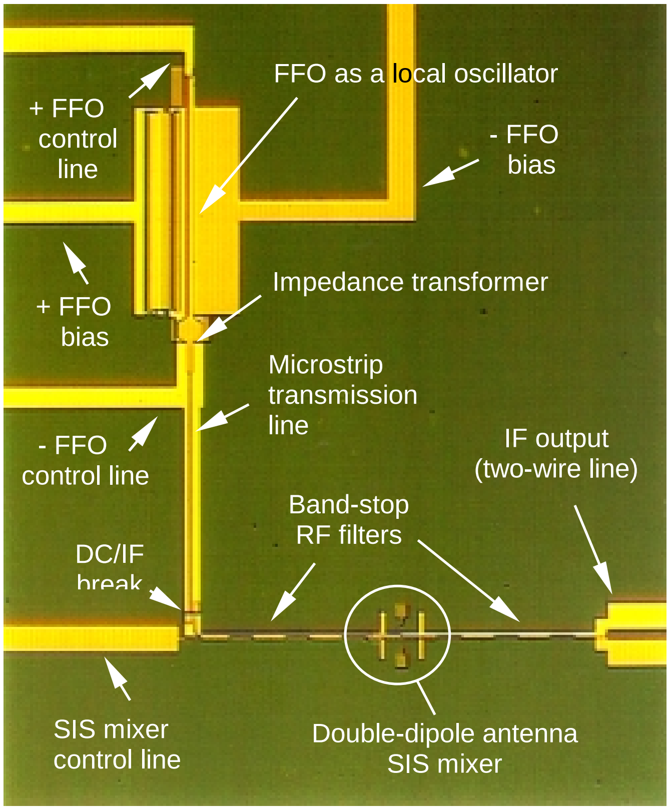

Fig.1 Photo of central part of the Integrated Receiver chip

Experimental Results

A receiver DSB noise temperature about 100 K (few times the quantum limit) has been achieved for the *single* SIS junction SIR with the internal FFO operated over the frequency range 460 - 500 GHz. An instantaneous bandwidth of about 20 % has been observed by heterodyne measurements. The antenna beam, approximately f/9 with sidelobes below - 16 dB [2], makes the integrated receiver suitable for coupling to the telescope. A noise analysis was performed in order to identify the contributions from the different receiver components to the noise temperature of the system. This analysis enabled us to reduce the receiver noise temperature at 475 GHz of a particular prototype mixer to below 40 K, the lowest value achieved worldwide so far. Also a *balanced mixer* SIR concept has been tested. In this configuration in principle no FFO power is directed to the antenna and no signal is coupled back to the FFO. The preliminary results show noise temperatures below 100 K over the frequency range 480 - 510 GHz.

For spectral radio-astronomy applications besides the noise temperature and the antenna beam pattern also the frequency resolution of the receiver is a major parameter. The resolution which is determined by both the instant linewidth of the local oscillator and its long-time stability should be much less than 1 ppm of the receiver center frequency. The feasibility of phase locking the Josephson FFO to an external reference oscillator has been demonstrated experimentally [3]. With the FFO phase locked a linewidth as low as 1 Hz was measured relative to a reference oscillator in the frequency range 270 - 440 GHz. This linewidth is far below the “fundamental” level given by shot and thermal noise of the free-running tunnel junction. The combination of narrow linewidth and wide band tunability makes the FFO a perfect on-chip local oscillator for integrated submm wave receiver intended for spectral radio astronomy applications.

An array of nine single mixer SIRs has been developed and tested. The so-called “fly’s eye” optical configuration is used for the Imaging Array. This reduces both the inequality of the beams as well as the *rf* and magnetic cross-talk between the nine pixels. An elliptical lens can be matched directly to a telescope simply by choosing a lens diameter that matches the telescope f-number, and no extra optical components are needed. The imaging array consists of 9 elliptical silicon lenses 10 mm diameter and a center to center separation of 13 mm, which corresponds to an undersampling of about 4. Each lens carries its own individual receiver chip with a double-dipole antenna and a backing reflector. No interaction between the modules has been observed within the experimental accuracy for both *dc* and *rf* fields. No malfunction of the SIR has been found under extensive irradiation with a cobalt source. It is also important that no degradation of the noise temperature has been observed for integrated receiver chips fabricated more than two years ago.

In order to simplify the SIR operation the data acquisition system IRTECON was developed for the ***I***ntegrated ***R***eceiver ***Te***st and ***Con***trol. The program which is written under LabWindows collects *dc* and *rf* data automatically. One of the routines of IRTECON finds the optimum bias for the SIS mixer at a particular frequency by minimizing the receiver noise temperature. For the whole SIR imaging array a noise temperature of about 150 K has been measured at 500 GHz using the internal FFO.

Acknowledgments

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References

[1]. V. P. Koshelets, S. V. Shitov, L. V. Filippenko, A. M. Baryshev, H. Golstein, T. de Graauw, W. Luinge, H. Schaeffer, H. van de Stadt, “First Implementation of a Superconducting Integrated Receiver at 450 GHz,” *Appl. Phys. Lett.*, vol. 68 (9), pp. 1273-1275, 1996.

[2]. V. P. Koshelets, S. V. Shitov, L. V. Filippenko, A. M. Baryshev, W. Luinge, H. Golstein, H. van de Stadt, J.-R. Gao, T. de Graauw, “An Integrated 500 GHz Receiver with Superconducting Local Oscillator”, *IEEE Trans. on Appl. Supercond*., vol. 7, p. 3589, 1997.

[3]. V. P. Koshelets, S. V. Shitov, A. V. Shchukin, L. V. Filippenko, P. N. Dmitriev, V. L. Vaks, J. Mygind, A. B. Baryshev, W. Luinge, H. Golstein, "Flux Flow Oscillators for Sub-mm Wave Integrated Receivers", ASC-98, EQB-04, *IEEE Trans. on Appl. Supercond.* 1999, in press.