Superconducting Integrated Submm Wave Receiver

Valery Koshelets, Andrey Ermakov, Pavel Dmitriev, Lyudmila Filippenko, Andrey Khudchenko, Nickolay Kinev, Oleg Kiselev, Alexander Sobolev, Mikhail Torgashin
Institute of Radio Engineering and Electronics (IREE), Moscow, Russia

Pavel Yagoubov, Ruud Hoogeveen, and Wolfgang Wild
SRON Netherlands Institute for Space Research, the Netherlands
Superconducting Integrated Submm Wave Receiver

Outline

• Superconducting Integrated Receiver (SIR)
• Flux Flow Oscillator (FFO) for SIR
• Nb-AlN-NbN FFO – first implementation
• TErahertz Li mb Sounder (TELIS) project
• TELIS SIR channel design
• SIR channel performance
• Future applications
• Conclusion
Superconducting Integrated Receiver (SIR) with phase-locked FFO

- **SIR chip**
  - SIS mixer
  - Harmonic mixer
  - FFO as LO: 550-650 GHz

- **4 K dewar**
- **HEMT**
  - 4-8 GHz

- **Optical input**: 50-650 GHz

- **PLL**
  - 4 GHz

- **LSU**
  - 400 MHz reference

- **IF Processor & DAC**
- **Computer controlled data acquisition system**
- **Electronics**
  - FFO, SIS, HM control

September 23-28, 2007
Superconducting Integrated Receiver, Palinuro, FJPN-07
STATE OF THE ART (2002)

- Single chip Nb-AlOx-Nb SIS receivers with superconducting FFO have been studied at frequencies from 100 to 700 GHz;
- A DSB receiver noise temperature as low as 90 K has been achieved at 500 GHz;
- 9-pixel Imaging Array Receiver has been successfully tested;
- FFO Phase Locking (PLL) up to 700 GHz.

APPLICATIONS

- Airborne Receiver for Atmospheric Research and Environmental Monitoring; Radio Astronomy
- Focal Plane Array Receivers;
- Laboratory submm wave Spectrometers.
Internal part of the SIR Microcircuit

Double-slot twin SIS – 0.8 \( \mu m^2 \)

FFO
400*16 \( \mu m^2 \)

HM – 1.0 \( \mu m^2 \)

Nb-AlOx-Nb or Nb-AlN-NbN; \( Jc = 5 - 10 \) kA/cm\(^2\)

Optionally: SIS – \( Jc = 8 \) kA/cm\(^2\); FFO + HM = 4 kA/cm\(^2\)
IVCs of the FFO measured at different magnetic fields

International Conference on Nonlinear Superconducting Devices and HTc Materials, Capri-94
Nb-AIN-NbN FFO for SIR; new features

JSC, $V_B = V_g/3$
Quality of the AlOx and AlN tunnel barriers on the current density

The graph shows the relationship between the current density ($J_c$, kA/cm$^2$) and $R_n S$, $\Omega \mu^2$. The data points are compared for three different tunnel barrier materials:

- **Nb-AlOx-Nb**
- **Nb-AlN-Nb**
- **Nb-AlN-NbN**

The graph indicates that the $R_n S$ value decreases as the current density increases, with different materials showing distinct trends in this relationship.
Nb-AlN-NbN SIS pumped by FFO; FFO frequency tuning

HD13-09#26 (Vg=3.7mV, Rn=21 Ohm)
A set of the SIS IV-curves, pumped by FFO at 500 GHz

(#HD13-09#26,06-08-2006)(R_n=20.92 R_j/R_n=22.6 V_g,mV=3.70)
SIS mixer pumping at different Nb-AlN-NbN FFO bias (output power) setting

(#HD13-09#26, 06-08-2006) NbN; pumping at 500 GHz
Circuit for FFO Linewidth Study & PL

- IMPEDANCE TRANSFORMER
- FFO
- FFO CL
- DC BLOCK
- HIGH-PASS FILTER
- SIS CL
- HARMONIC SIS MIXER
- 1 mm
Example of FFO Spectrum

![Graph showing FFO Spectrum]
FFO Linewidth

\[ \Delta f = (Rd_B + K \cdot Rd_{CL})^2 \left( \frac{2e}{\hbar} \right)^2 \left[ \frac{e* I_{qp}}{2\pi} \coth\left( \frac{eV}{2kT} \right) + \frac{e* I_S}{\pi} \coth\left( \frac{eV}{kT} \right) \right] \]
\[ \Delta f := \left( \frac{2e}{h} \right)^2 \cdot \left( R_d + K \cdot R_{dCL} \right)^2 \cdot \left[ \frac{e \cdot (l_{qp})}{2 \cdot \pi \cdot \coth \left( \frac{e \cdot V}{2 \cdot k_B \cdot T} \right)} + \frac{2 \cdot e \cdot (l_s)}{2 \cdot \pi \cdot \coth \left( \frac{e \cdot V}{k_B \cdot T} \right)} \right] + \frac{1}{\pi} \left( \frac{2e}{h} \right) \left( R_d + R_{dCL} \right) \cdot I_{lf} \]
FL and PL spectra of the Nb-AlN-NbN FFO: frequency 605 GHz; LW = 1.7 MHz; SR = 92%
Down-converted spectra of the FFO operating at 671 GHz. Span – 100 Hz.
FFO linewidth and Spectral Ratio PL FFO on its oscillation frequency.
Linewidth of free-running FFOs and SR for the PLL FFO as a function of FFO width (RnS = 30 Ω*μm²)
A close-up of FFO IVC in Fiske steps region

(#HD13-09#26,08-25-2006) Color scale: 34.3 μA
Frequency dependence of the FFO: Nb-AlOx-Nb and Nb-AlN-NbN circuits

![Graph showing frequency dependence of FFO](image)
TELIS - TErahertz LIimb Sounder

TELIS Objectives:

• Measure many species for atmospheric science (ClO, BrO, O₃, HCl, HOCl, etc);
  - Chemistry, Transport, Climate
• Serve as a test platform for new sensors
• Serve as validation tool for future satellite missions

Three independent frequency channels, cryogenic heterodyne receivers:

- 500 GHz by RAL
- 600-650 GHz by SRON-IREE
- 1.8 THz by DLR (PI)
Simulated spectra for **Ozone** and **HCl** at 625 GHz

HCl spectrum, 2 km intervals, total atmosphere to 60 km

- **Ozone**
- **HCl**
Simulated atmospheric spectra (DSB) at 619 GHz

Orbit = 40 km / tangent = 27 km / FFO width = 9 MHz

Intensity [K]

IF (GHz)
## TELIS-SIR Main Parameters

<table>
<thead>
<tr>
<th>#</th>
<th>Description</th>
<th>Value (Spec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Input frequency range, GHz</td>
<td>500 – 650 (550 – 650)</td>
</tr>
<tr>
<td>2</td>
<td>Minimum noise temperature in the range (DSB), K</td>
<td>150 (250)</td>
</tr>
<tr>
<td>3</td>
<td>Output IF range, GHz</td>
<td>4 - 8 (5 - 7)</td>
</tr>
<tr>
<td>4</td>
<td>Spectral resolution (width of the spectral channel), MHz</td>
<td>&lt; 1 (2)</td>
</tr>
<tr>
<td>5</td>
<td>LO frequency net, MHz</td>
<td>&lt; 300</td>
</tr>
<tr>
<td>6</td>
<td>Dissipated power at 4.2 K stage (including IF amplifiers chain), mW</td>
<td>100</td>
</tr>
<tr>
<td>7</td>
<td>Operation temperature, K</td>
<td>&lt; 4.5</td>
</tr>
</tbody>
</table>
Wire grid polarizer and dichroic plate are used to separate this receiver from the two other frequency channels (not shown). The cold optics and mixer element are located inside the cryostat at the ambient temperature 4.2 K
Layout of SIR cold channel

Integrated lens-antenna (L6)

Magnetic shield

Parabola (L5)  Hyperbola (L4)

Ellipse (L3)  Wire grid

Flat

Window (L2)

Parabola (L1)

Cryostat

Termination load

SSB
Photo of the SIR-TELIS channel

September 23-28, 2007
Superconducting Integrated Receiver,
Palinuro, FJPN-07
SIR Mixer Block with Shields

September 23-28, 2007
Superconducting Integrated Receiver,
Palinuro, FJPN-07
Silicon (Si); 4 x 4 x 0.5 mm$^3$
Nb-AlO$_x$-Nb or Nb-AlN-NbN;
Uncorrected Receiver Noise Temperature (DSB)

Water line 557 GHz
SIR Noise Temperature on Intermediate Frequency and SIS Bias

![Graph showing SIR Noise Temperature on Intermediate Frequency and SIS Bias.](image-url)
SIR Stability: Allan variance test

Phase-locked SIR

Graph showing Allan variance test results with data points for different time scales (t, sec). The diagram includes symbols for FFO, IF amp, BP filter, and Power meter.
Antenna-Lens Beam Pattern of the SIR at 625 GHz
Amplitude and phase APB of the SIR with cold optics

Amplitude

Phase
Deconvolved spectrum of two OCS emission lines (gas pressure 1.2 mBar; FFO frequency 625.24 GHz)
Gas cell measurements; resolution determined by DAC

OCS gas, P=2mB
Phase locked FFO; spectral resolution < 1 MHz

Synthesizer Frequency = 644.8 GHz
Remote optimization of the PLL SIR operation (3-D)
ESPRIT – Exploratory Submm Space Radio-Interferometric Telescope

- Telescope sizes ~ 3.5 meter; off-axis
- Number of elements \( N = 6 \) (15 baselines)
- Projected baselines 200 - 1000 meter
- Frequencies:
  - Spots in the range 0.5 – 6 THz
- Front Ends -
  - (0.5 – 1.5 THz) SIS mixers, multiplier LO /
    \( SIR = FFO + SIS + HM \)
  - (1.5 – 6 THz) HEB mixers, QCL as LO
- System temperature < 1000 K
- IF bandwidth > 4 GHz (goal 8 GHz)
“Millimetron” – Russian Space Agency (2017)
12 m cryogenic mirror; $\lambda = 0.01$ - 20 mm.
Conclusion

- Concept of the Phase-locked SIR is developed and tested.
- Nb-AlN-NbN FFO and SIR have been successfully implemented.
- Improved design of the FFO for TELIS has been developed and optimized; free-running linewidth from 1 to 10 MHz recorded in the frequency range 350 – 740 GHz that allows to phase lock from 35 up to 95% of the FFO power.
- 3-rd generation of the PL SIR for TELIS has been developed showing a possibility to realize TELIS requirements: Frequency range 500 – 650 GHz; Noise Temperature 150 K; IF bandwidth 4 - 8 GHz; Spectral resolution better 1 MHz; Beam Pattern - FWHM = 3 deg, with sidelobes < - 17 dB. Procedure for remote optimization of the PL SIR operation has been developed and experimentally proven.
- First TELIS flight is scheduled on April 2008.
- Future space missions are under consideration.