SINIS detectors and tasks of space and ground-based radio astronomy

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We consider the possibilities of using SINIS bolometer and SQUID amplifier matrices for the tasks of the Millimetron project

And for measurements at high-altitude telescopes BTA and SUFFA

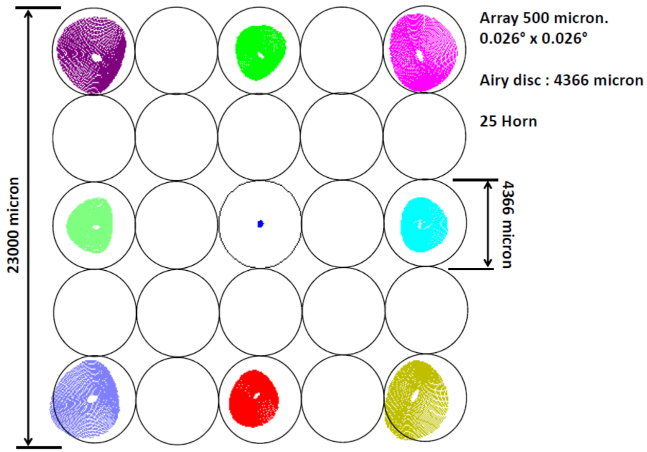
High frequency low spectral resolution instrument

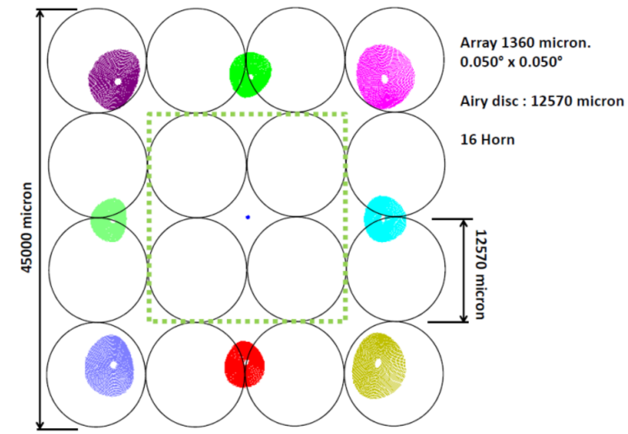
- Photometer-polarimeter for sky survey
- Matrix of 100x100 elements
- NEP=10^{-18} – 10^{-19} W/$Hz^{1/2}$ at 0.1 K
- Spectral resolution R=3 in 0.1-15 THz range
- Polarization resolution 0.1%

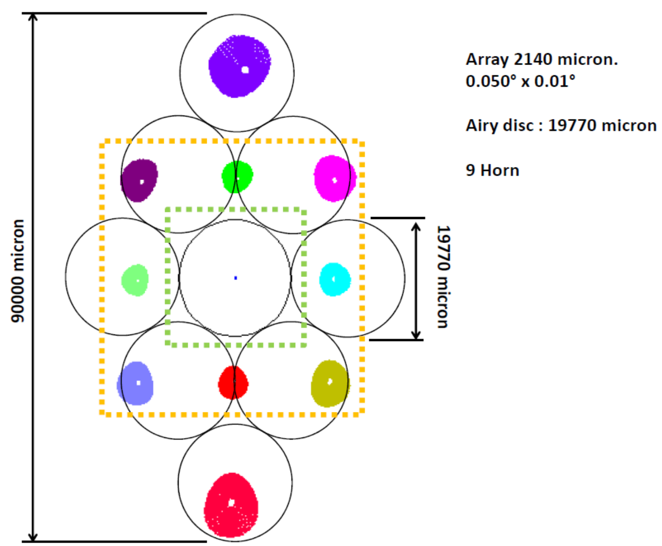
Millimetron low-frequency receiver:

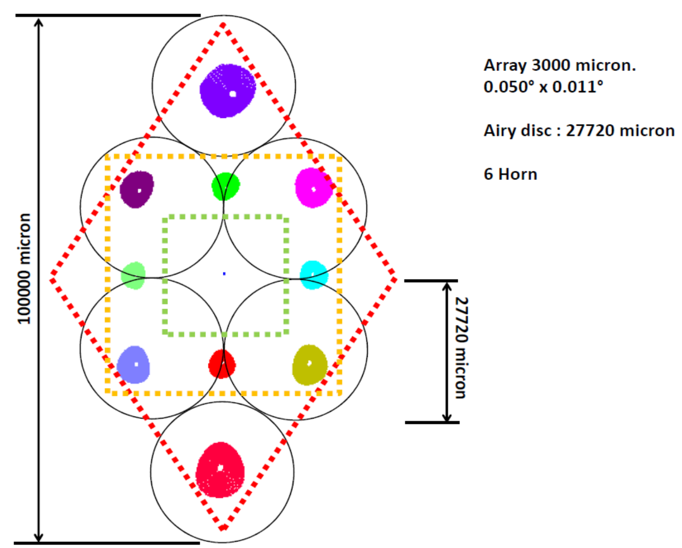
	Band 1	Band 2	Band 3	Band 4
Frequency range (GHz)	100 – 200	130 – 350	350 – 700	**700 – 1000**
FWHM (arcsec)	1.3	1.0	0.36	**0.18**
# of independent pixels	6	9	25	**36**
Background (pW)	5.4	8.2	9.7	**7.8**
Detector NEP (aW $s^{1/2}$)	53	87	97	**94**
Spectral Resolution (GHz)	1.25	1.25	1.25	**1.25**
Spectral Sensitivity (fW $s^{1/2}$ /GHz)	**26**	**43**	**47**	**46**

Matrices for bands 1-4









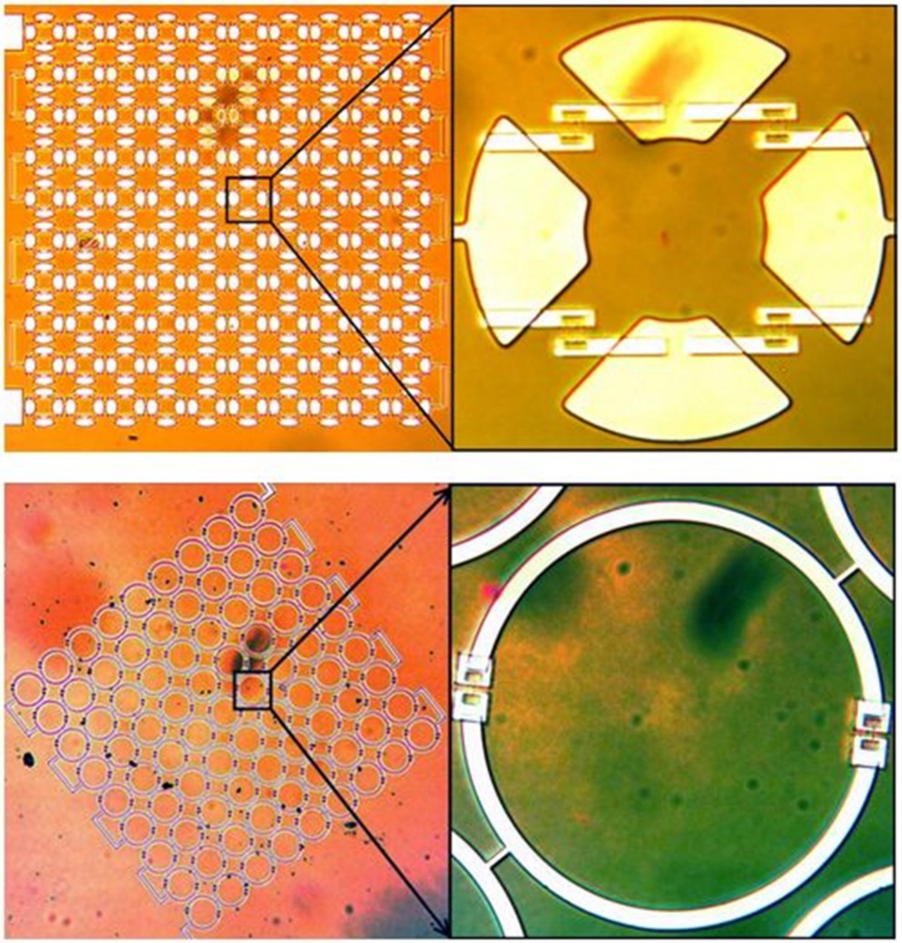
For few-pixel array both parallel matrix with SQUID readout and series matrix with JFET or MOSFET readout is suitable

Frequency selective surface and distributed absorber approaches

Broadband operation requires uniform spectral response, high sensitivity, and large dynamic range. This corresponds to a distributed absorber model in the form of a large array of electrically small antennas [1] and feedhorn with bandpass filters at the input. Increasing the number of array elements increases saturation power and significantly expands the dynamic range.

1. M. Tarasov, A. Sobolev, A. Gunbina, et. al. /Annular Antenna Array Metamaterial with SINIS bolometers //Journal of Applied Physics, V. 125, Issue 17, 2019

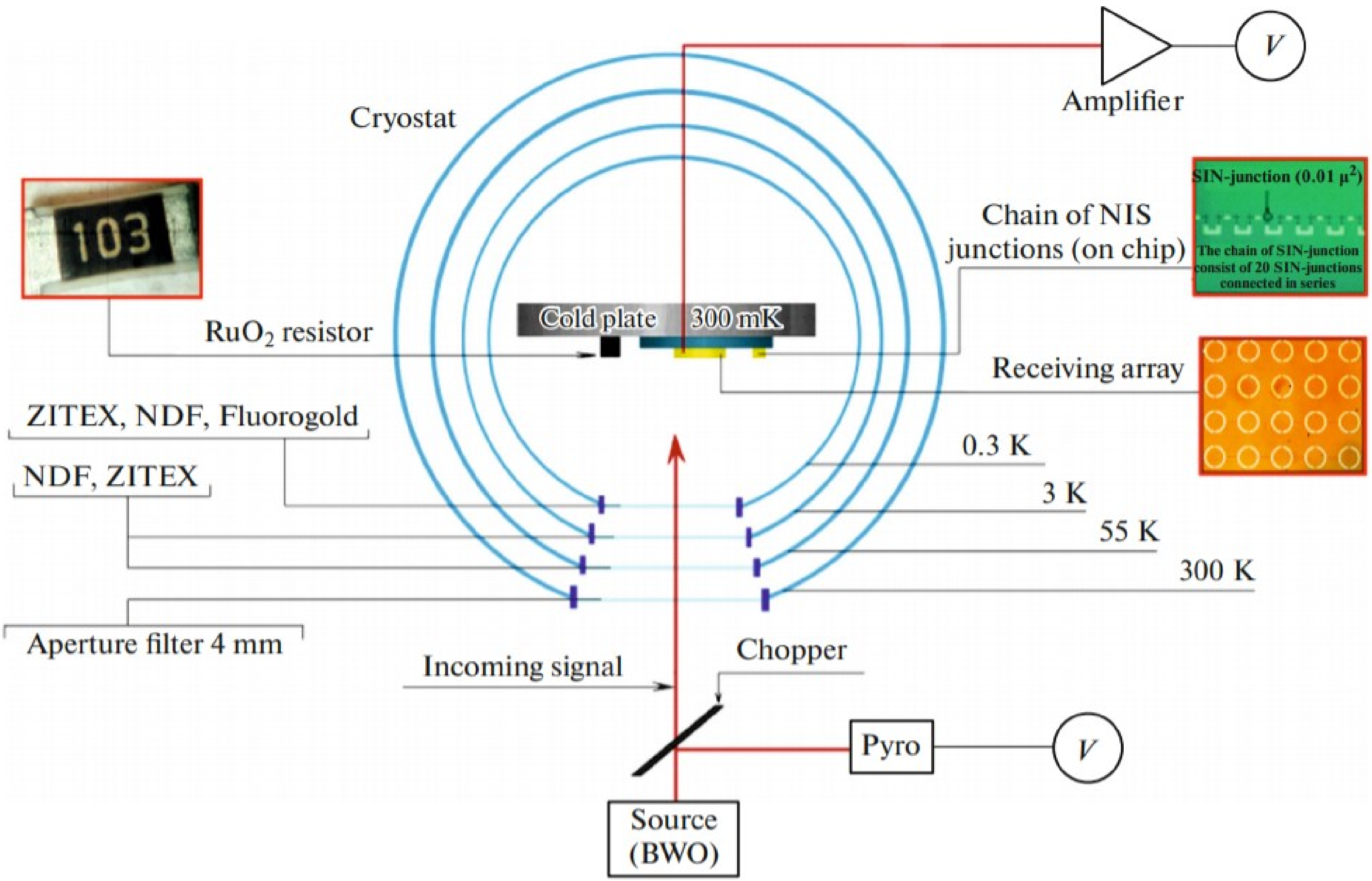
Matrices of electrically small antennas



Initial design is obtained by scaling of half-wavelength antennas below 1/20 of wavelength.

Antennas in the best samples are made of superconducting aluminum to reduce losses and improve cooling of superconducting electrodes of SINIS elements. Array consists of 100 annular antennas

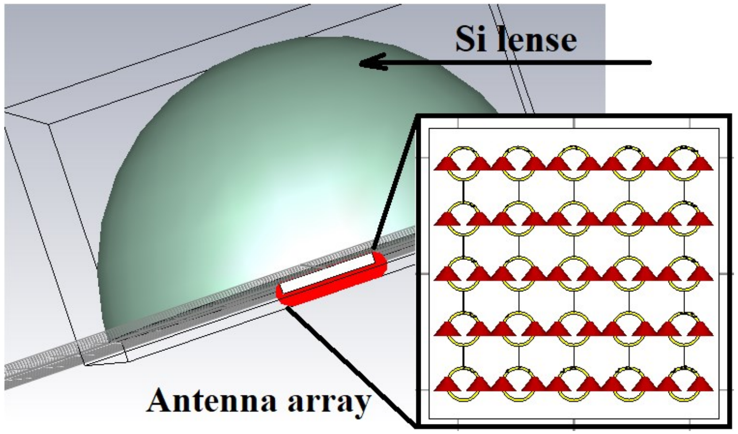
Experimental setup for spectral evaluation with three calibration channels

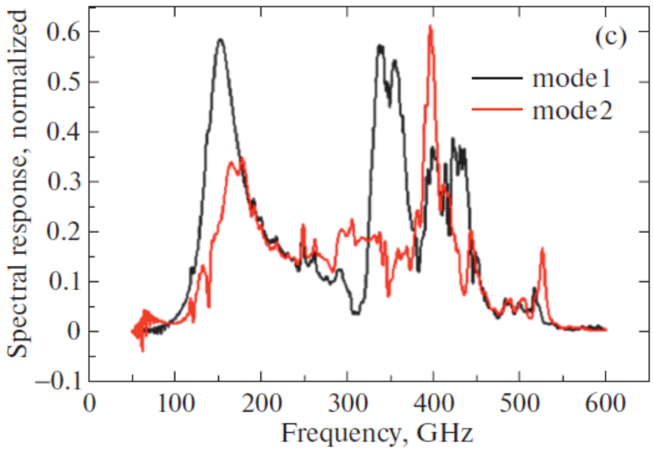


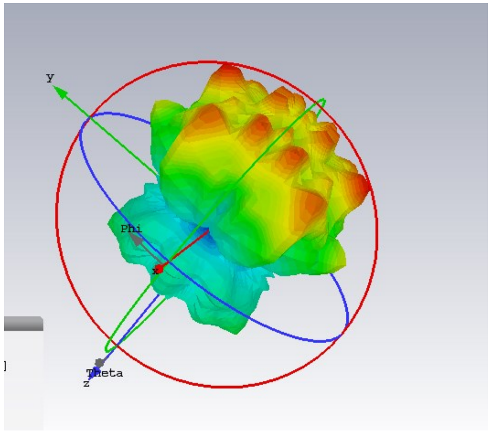
A. A. Gunbina, M. A. Tarasov, S. A. Lemzyakov, et. al. /Spectral Response of Arrays of Half-wave and Electrically Small Antennas with SINIS Bolometers //Physics of the Solid State, 2020, Vol. 62, No. 9, pp. 1604–1611

Two approaches in modelling and numerical simulations

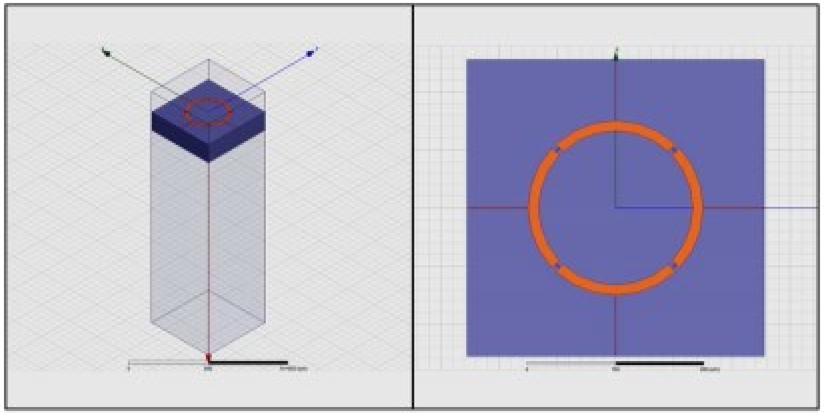
Model and simulation for the whole array with **half wavelength** antennas

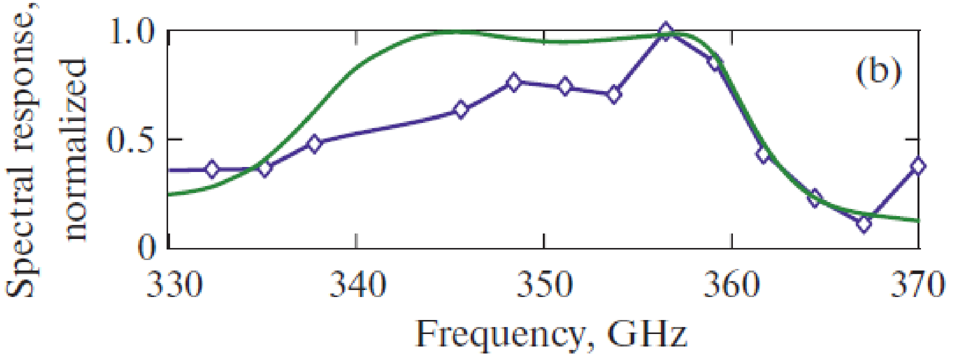






Modeling of unit cell

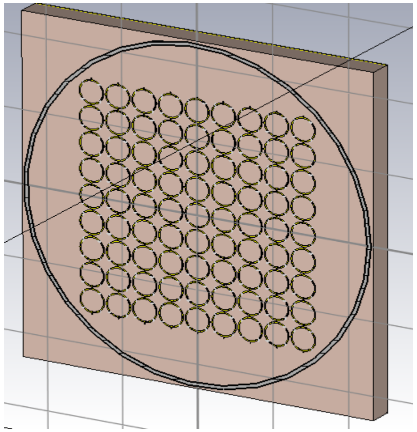


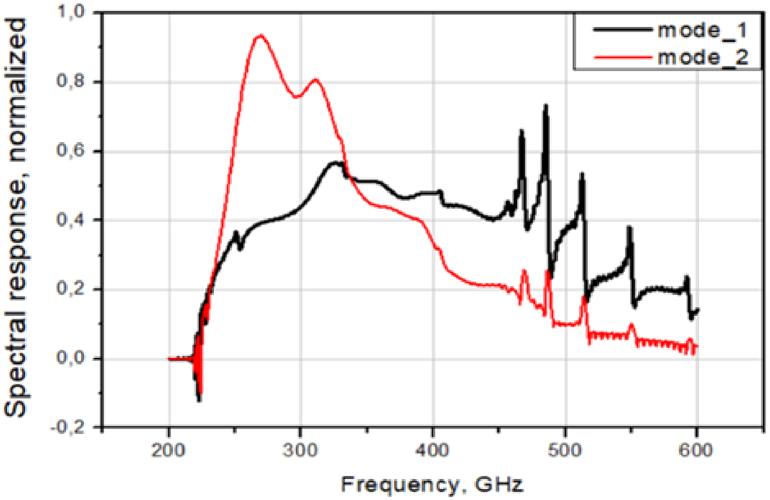


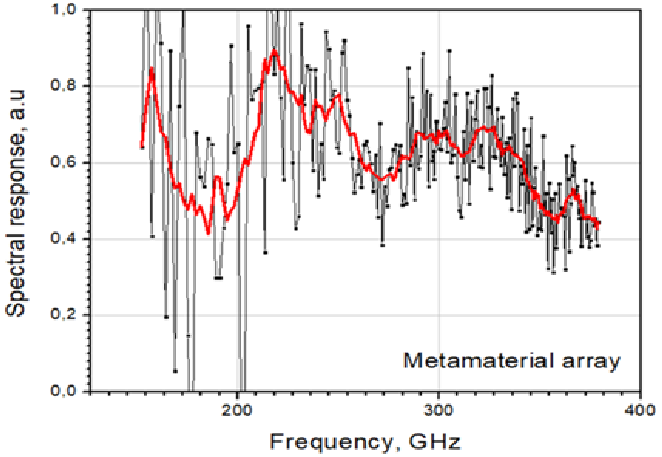
S. Mahashabde, A. Sobolev, A. Bengtsson, D. Andren, M. A. Tarasov, M. Salatino, P. de Bernardis, S. Masi, and L. S. Kuzmin, IEEE Trans. Terahertz Sci. Technol.**5**, 145 (2015)

Two approaches in modelling and numerical simulations

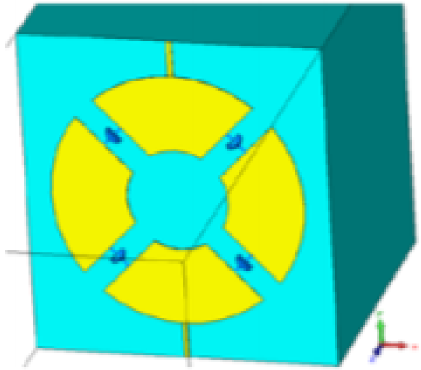
Model and simulation for the whole array with **electrically small antennas**

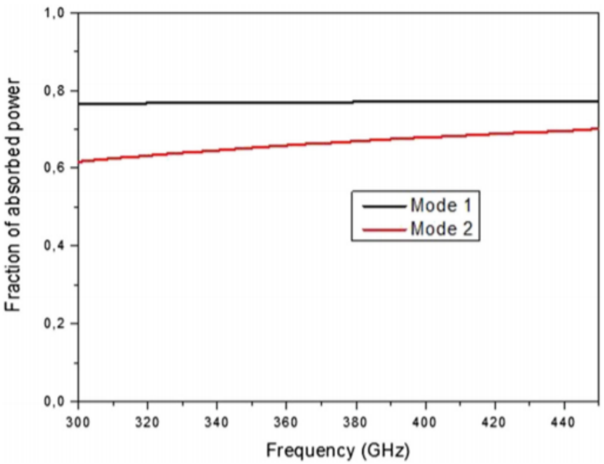






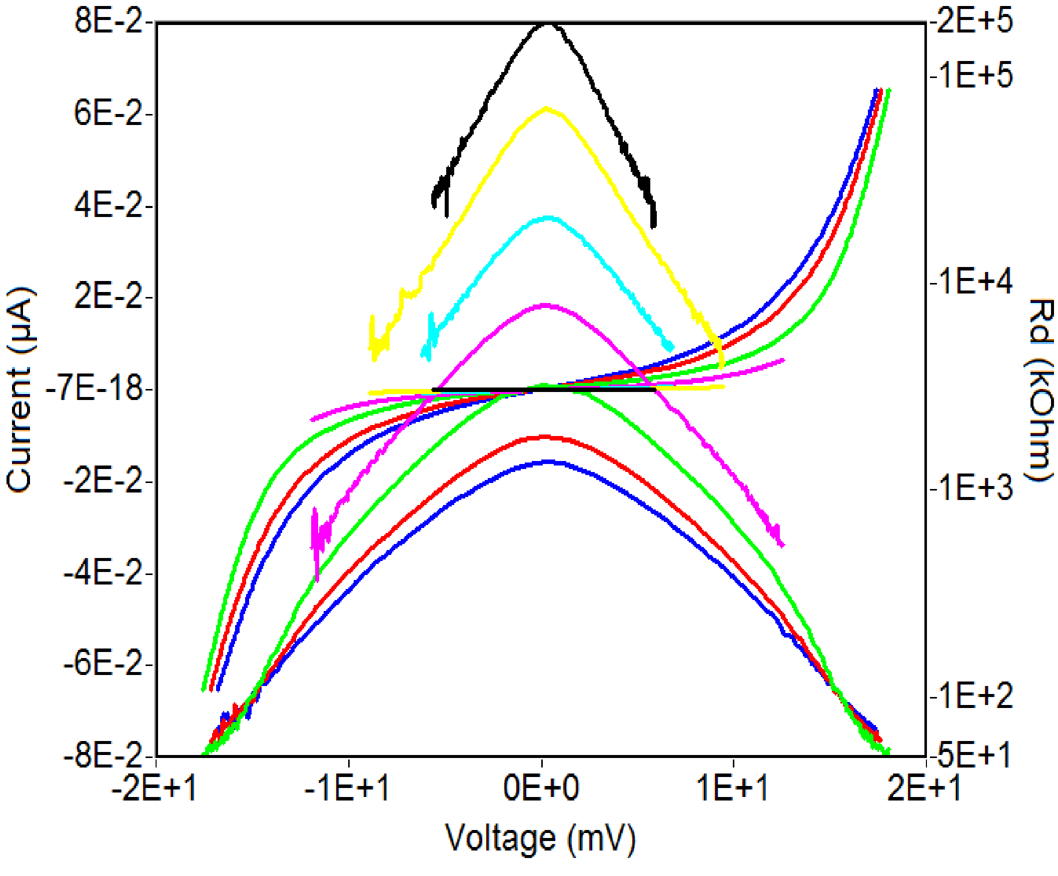
Modeling of unit cell





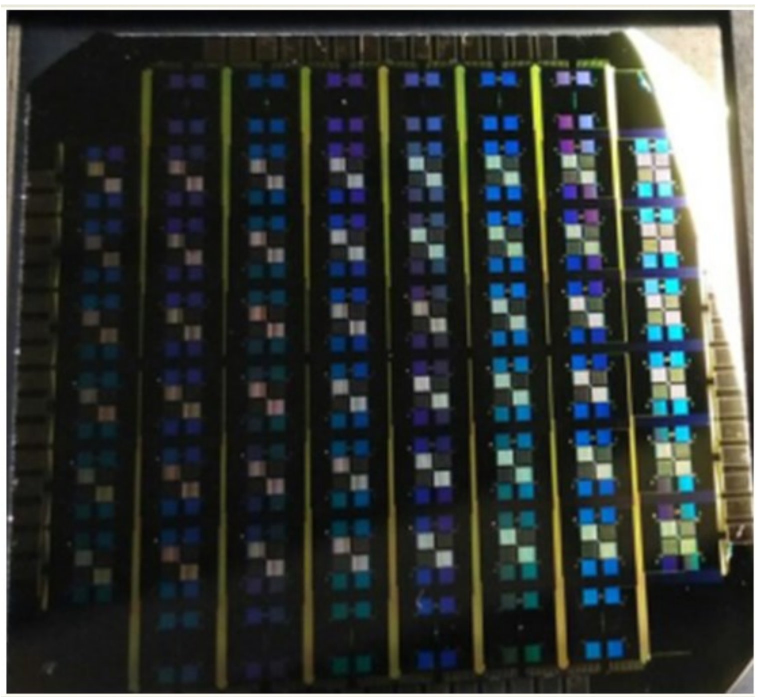
1. A.S. Sobolev, B. Beiranvand, A.M. Chekushkin, et. al., “Wideband metamaterial-based array of SINIS bolometers”, *in TERA 2018,* EPJ Web of Conferences 195*,* 05009-1 – 05009-2 (2018).
2. M. Tarasov, A. Sobolev, A. Gunbina, et. al., Journal of Applied Physics 125, 174501-1 - 174501-6 (2019).
3. A.A. Gunbina, M.A. Tarasov, S.A. Lemzyakov, et. al., Physics of the Solid State 62, 1604-1611 (2020).

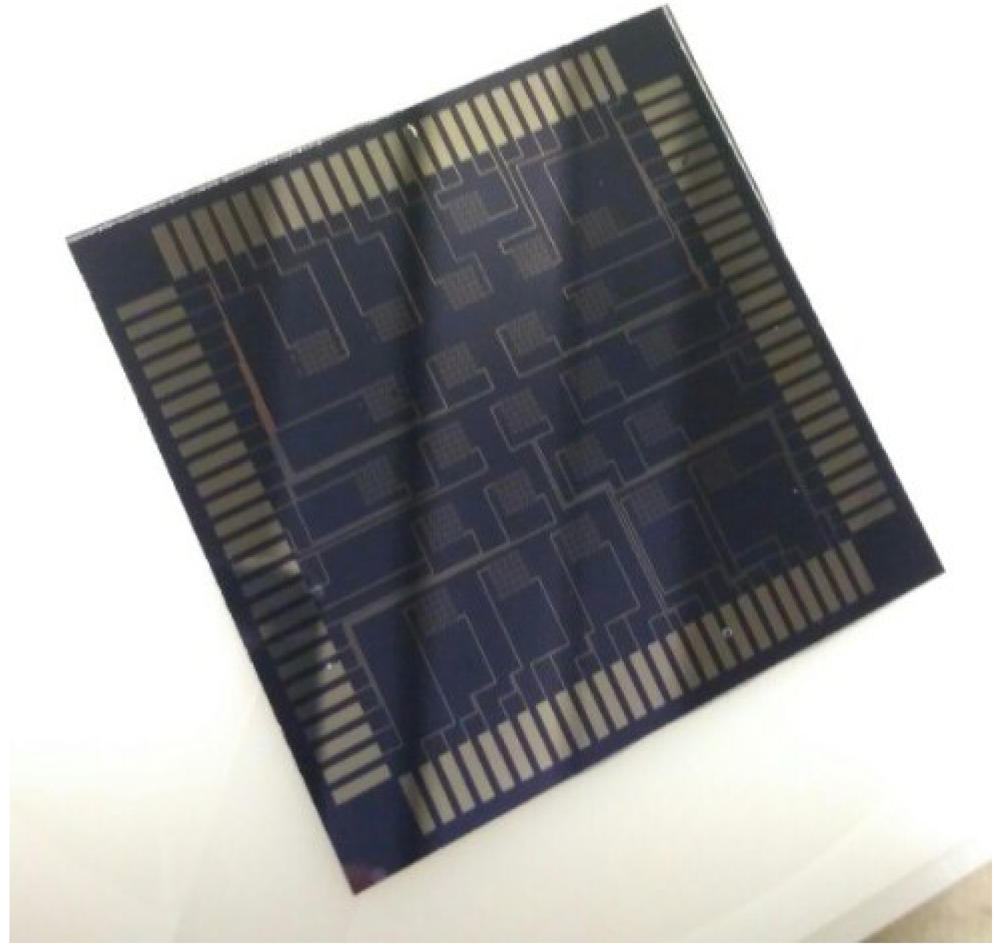
Electrically small superconducting antenna array



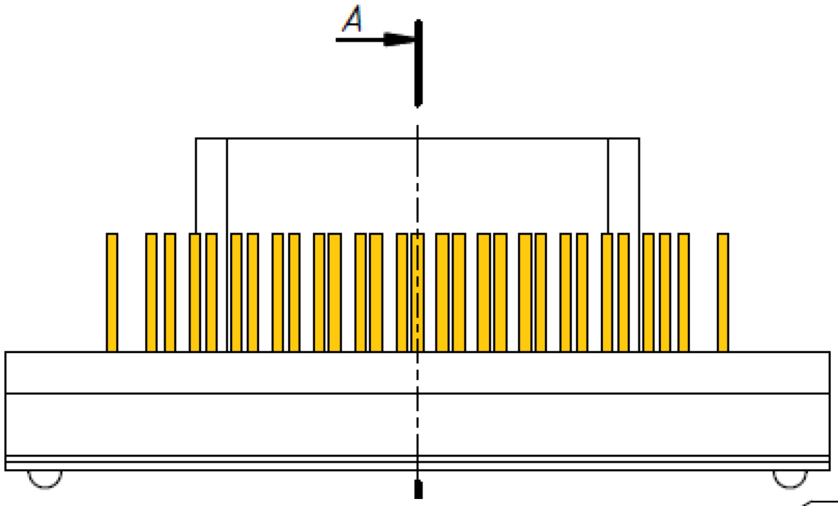
At 300 мК and low superconducting electrode area the resistance ratio is about 100, and for similar with **superconducting antenna** it approaches 1000. At 100 мК RR>10000.

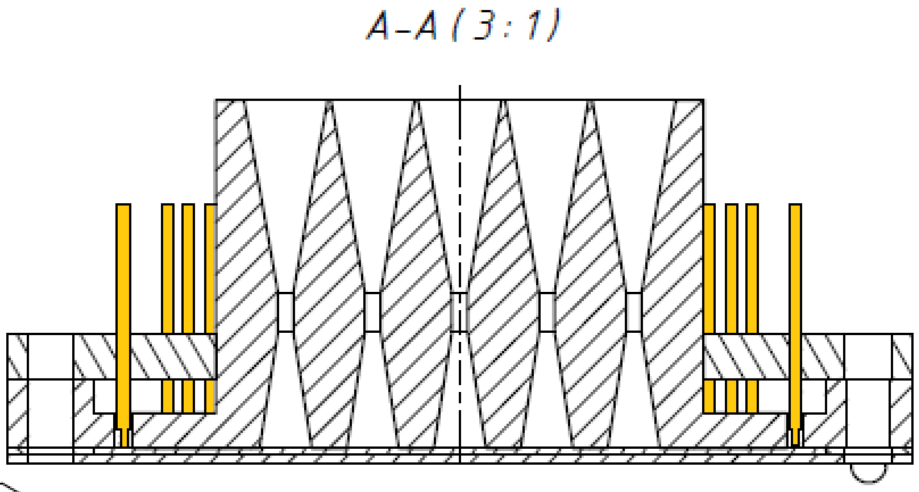
23 pixel matrix

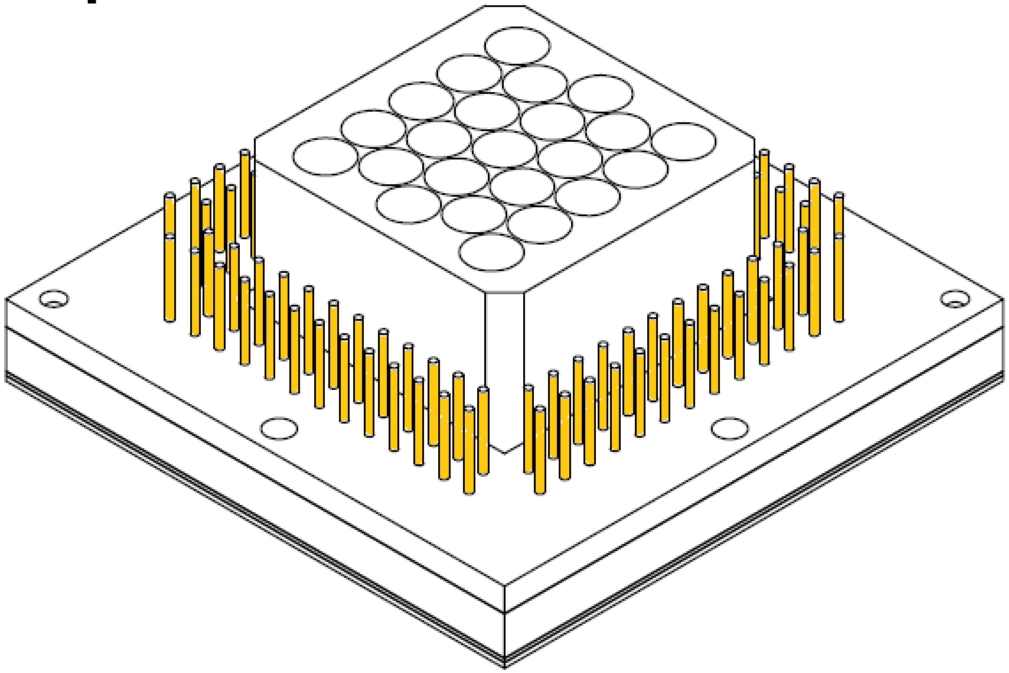




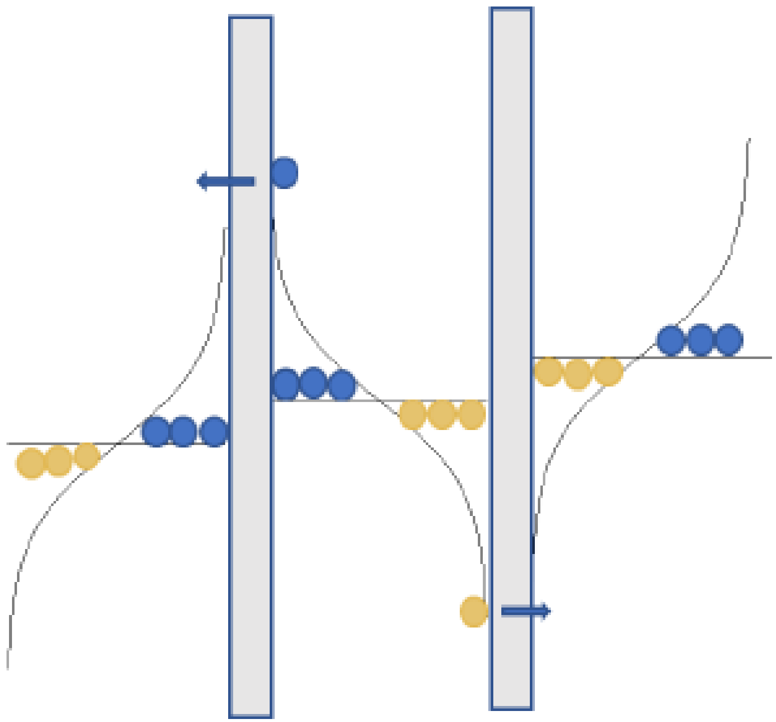
Sample holder with irradiation from antenna side

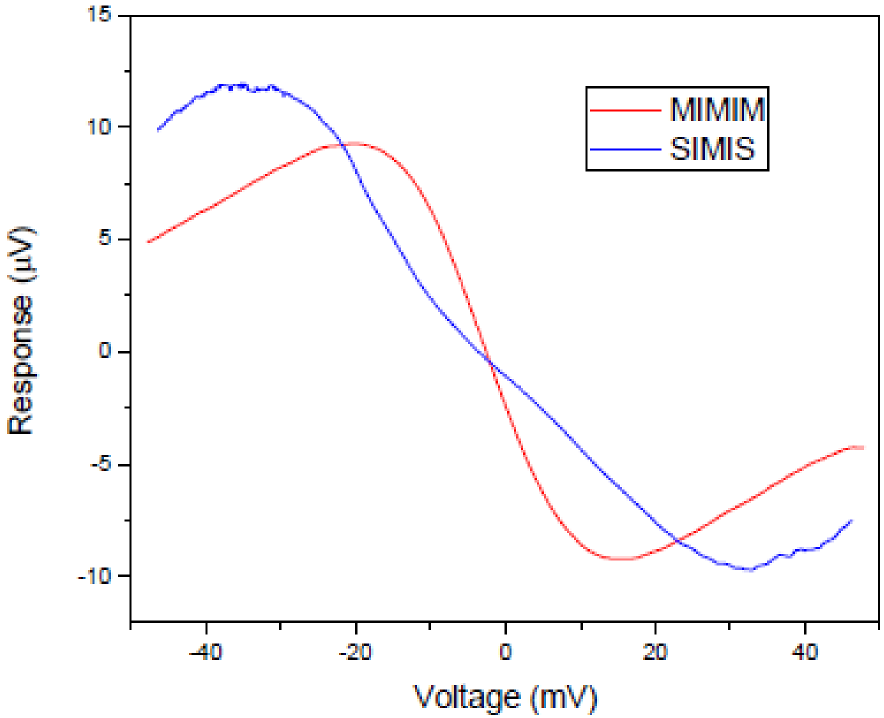






NININ detector





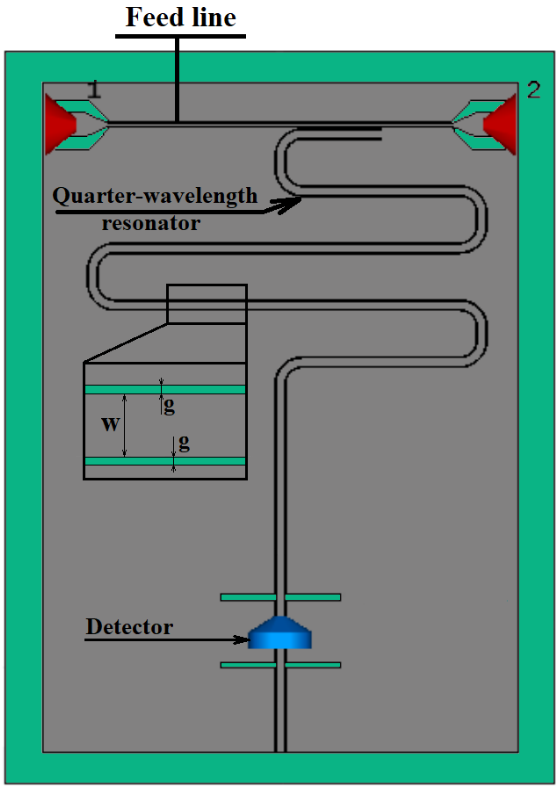
At T>1.2 K our SINIS device is converted into MIMIM that is still sensitive to radiation
Its responsivity drops down by 2 orders of magnitude but it still can detect radiation

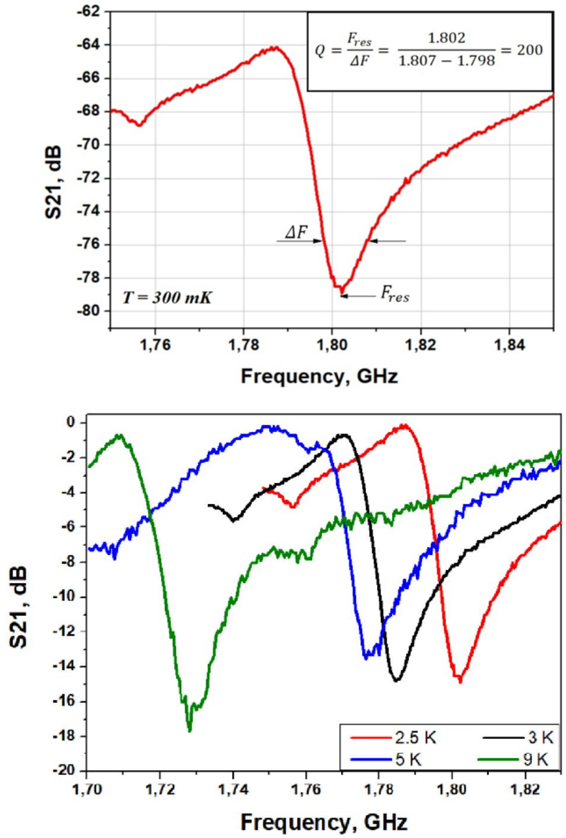
M.A. Tarasov, V.S. Edelman, S.A. Lemzyakov, et. al. /Cryogenic MIMIM and SIMIS Microwave Detectors//2020 7th All-Russian Microwave Conference (RMC), 2021

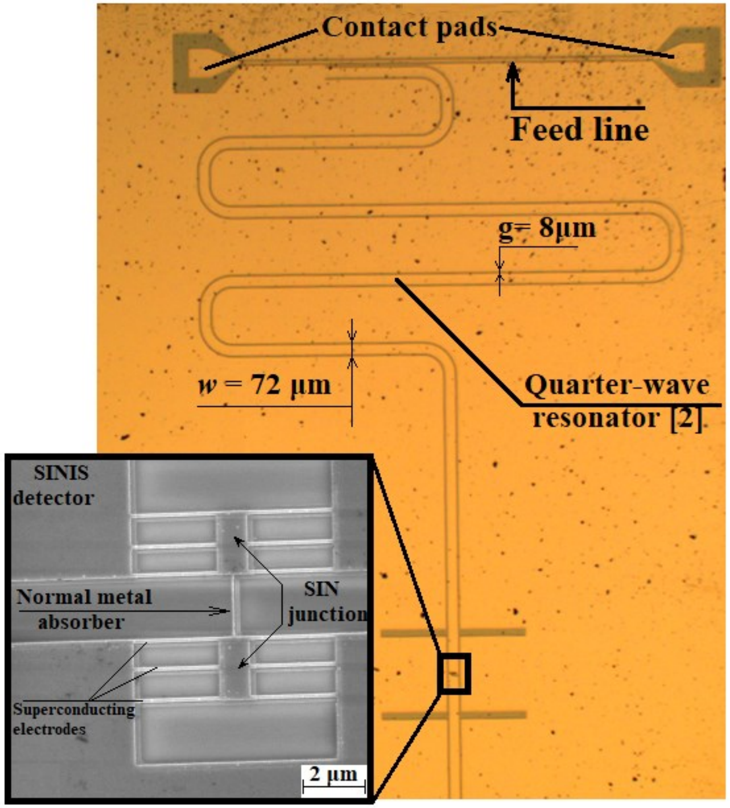
Multipixel imaging array

- For HF LRPP required to read out 10000 channels. Assuming that the mass of one semiconductor readout amplifier is 10 g, the mass for all channels will be above 100 kg and the cryostat must be connected with 20000 wires, which disable traditional readout even for ground systems. The solution is based on frequency-domain multiplexing, microwave readout and just one coaxial cable.
- For LF LRPP with the number of channels less than 100, it is possible to use relatively low-frequency megahertz bandwidth systems with SQUID amplifiers. Such readout is favorable for parallel connected arrays with output resistance of few Ohms.

Microwave readout



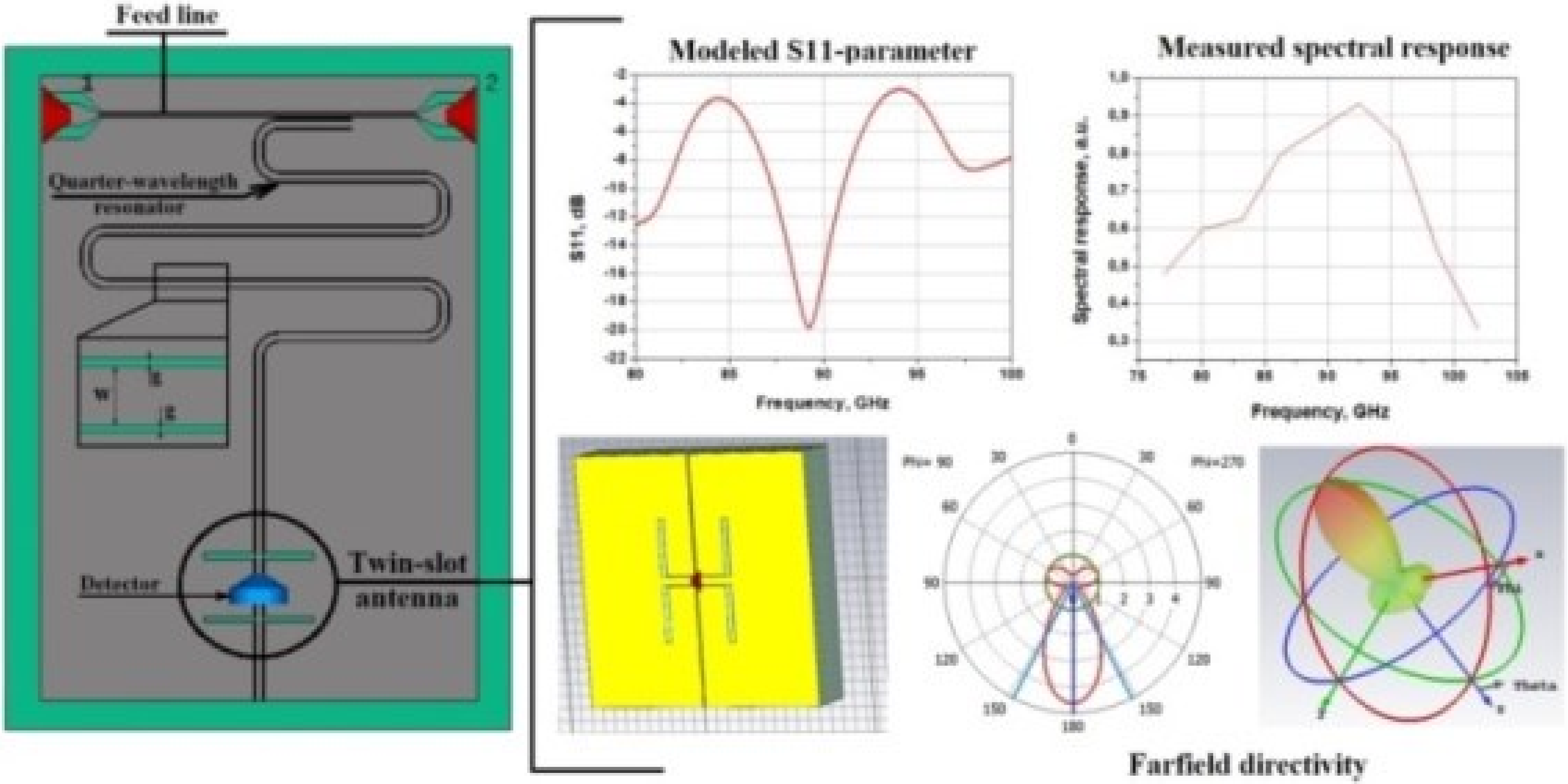




Microwave signal readout allows to use one coaxial cable to transmit the output signal from hundreds of channels and arrange frequency multiplexing

A.A. Gunbina, S. Mahashabde, M.A. Tarasov, et. al. /A 90 GHz SINIS detector with 2 GHz readout //Applied Superconductivity Conference 2020

Spectral response

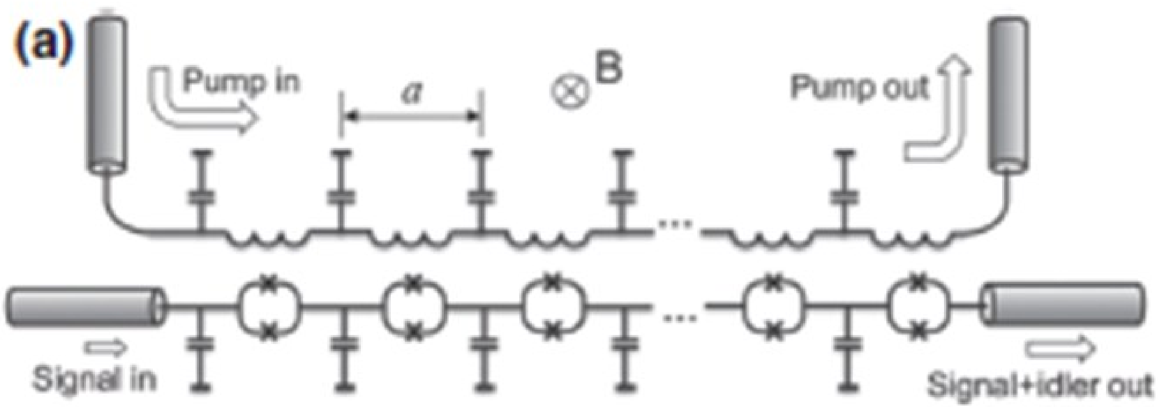


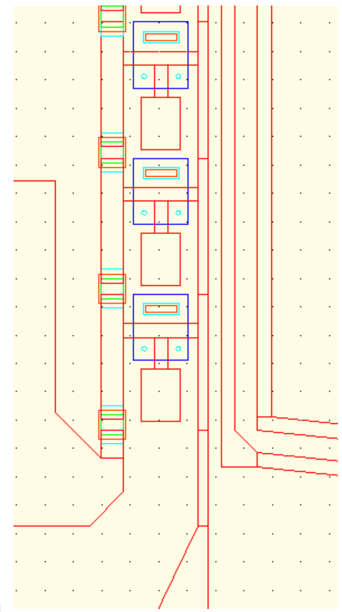
Readout electronics (TR)

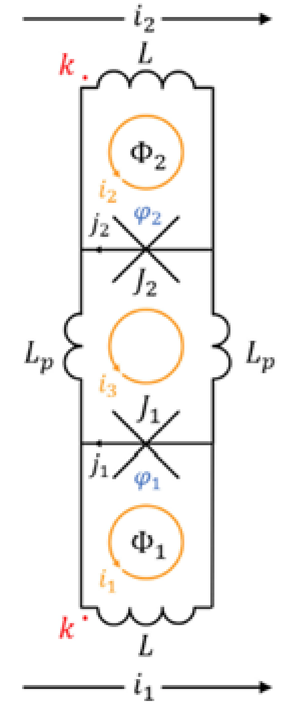
- *Depending on the selected technology, a suitable readout system must be selected. Given the limited total number of detectors, multiplexing is welcome, but not mandatory. Both KIDs and TESs require the use of FPGAs to efficiently control the multiplexing and the readout. CEBs require an array of analog amplifiers*. Actually do not require!

Josephson travelling wave parametric amplifier (PTB & HYPRES)

RF SQUID
dc SQUID
Different options

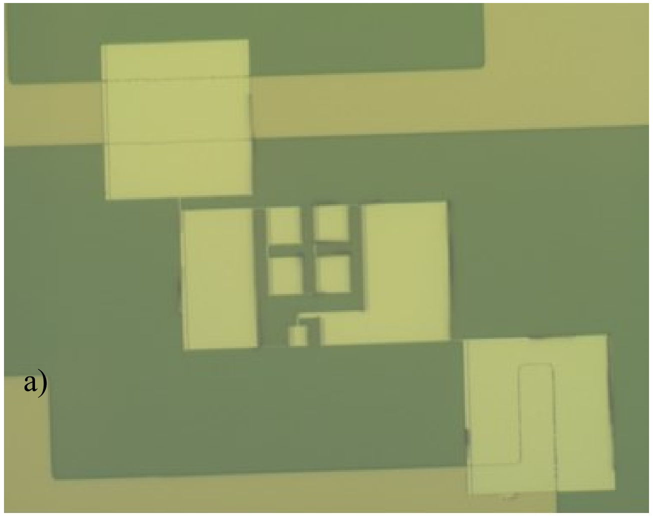




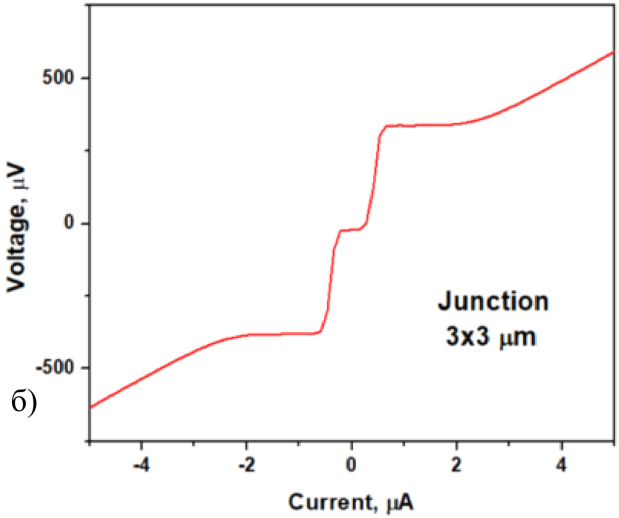


A.B. Zorin, Travelling wave parametric amplifier with three-wave mixing, // Phys. Rev. Appl., V. 6, 034006 (2016).
A.Miano, O.Mukhanov, Symmetric travelling wave parametric amplifier, IEEE Trans. Appl. Supercond., 29 (5), 1501706 (2019)

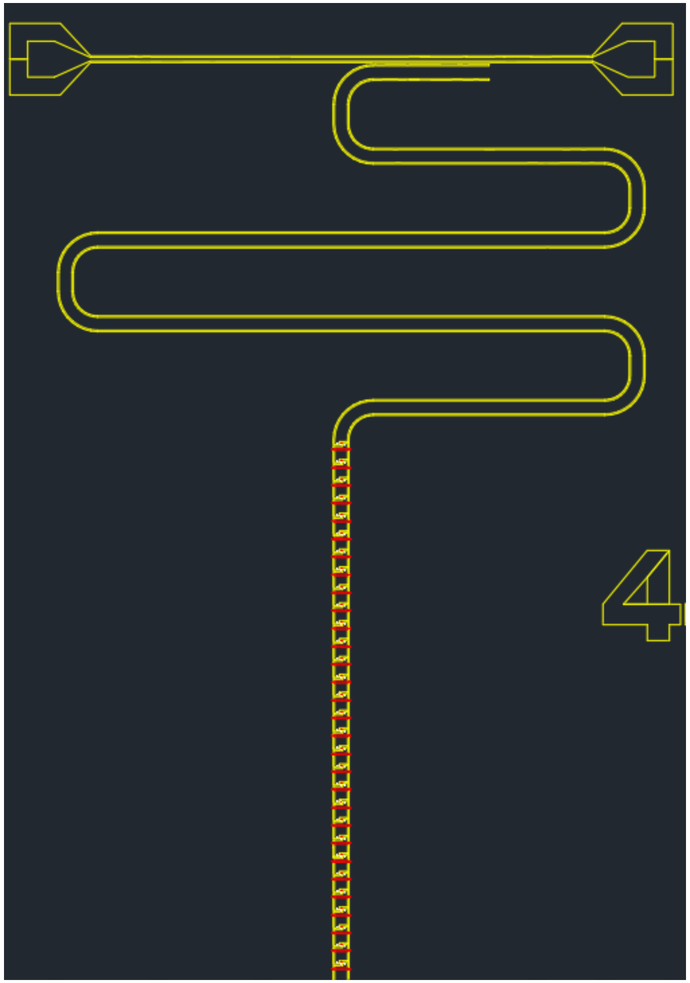
JTWPA by shadow evaporation



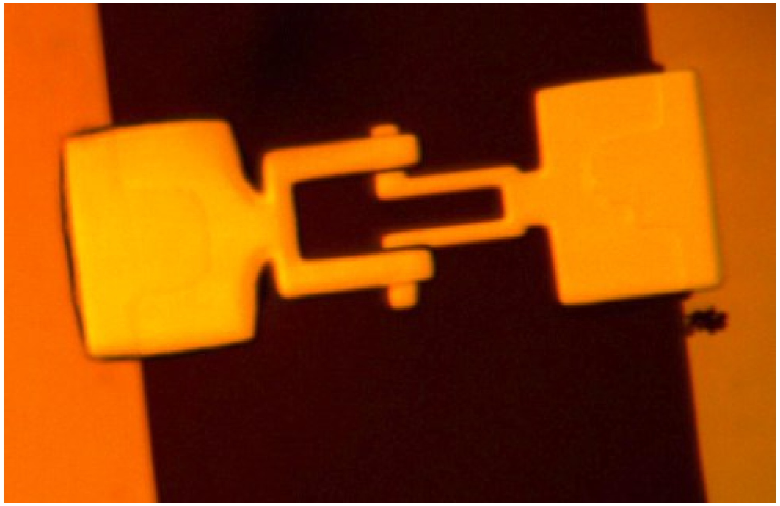
a)

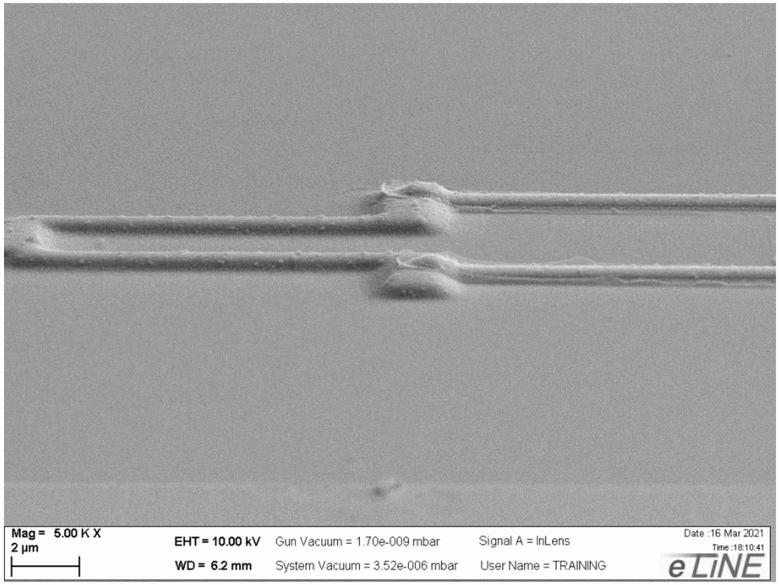


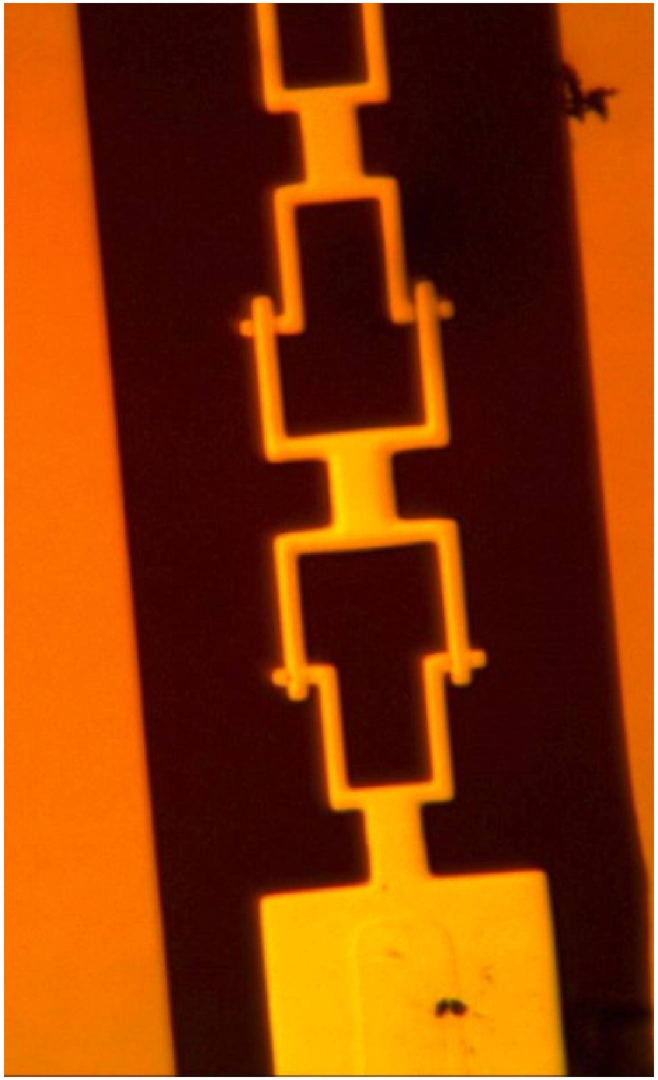
б)



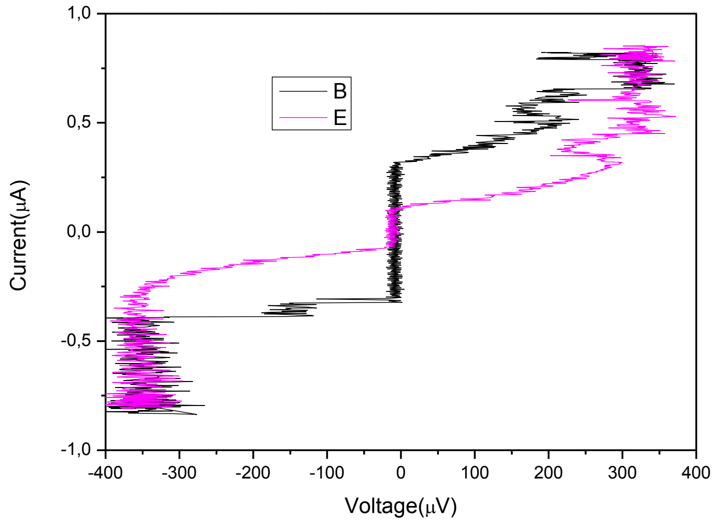
Magnetron sputtering and e-beam lithography

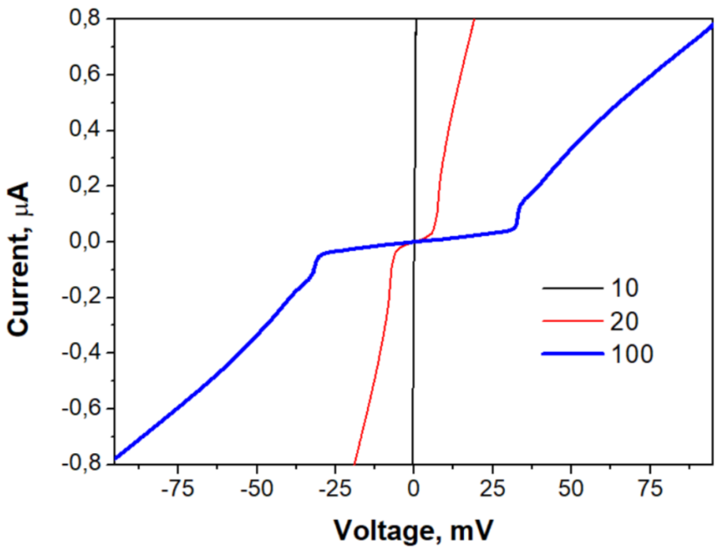






SIS junctions with thick Al films 300 nm





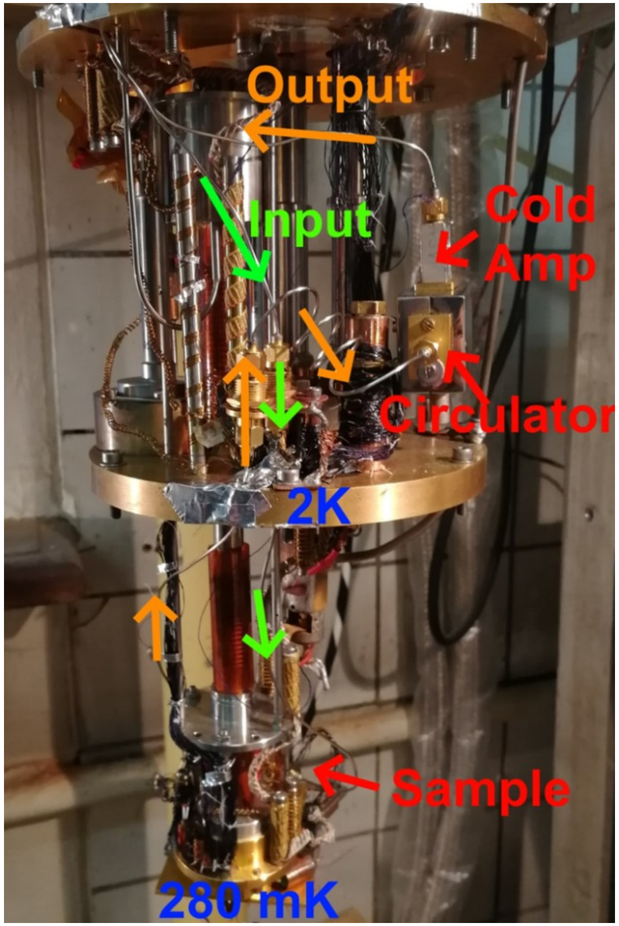
Arrays of 1-10-100-350 SQUIDs:

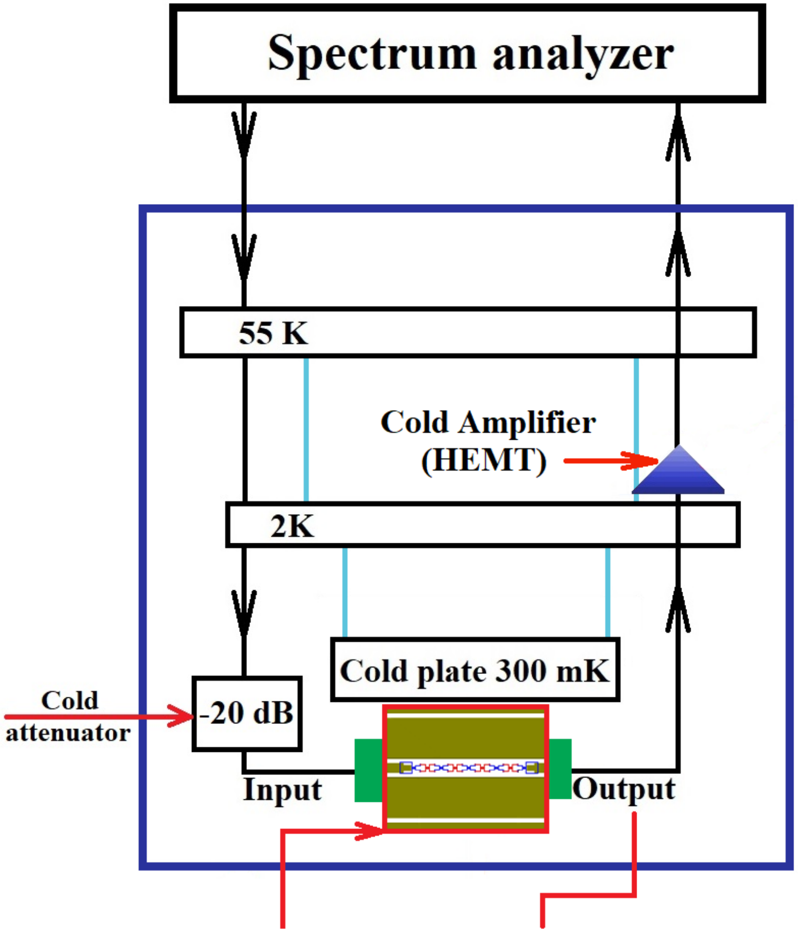
Junctions from 1x1 to2x2 μm^2
Critical currents 0.3-1.2 μA
SQUID loop from 50 to 260 μm^2

Asymptotic resistances:
Junction 2x2 μm – 360 Ω
Junction 1x1 μm– 600 Ω,

Arrays:
10 – 6 kΩ,
20 – 12 kΩ ,
100 – 58 kΩ.

Measurement setup for JTWPA





Expected performance

- For photometer array with JTWPA microwave multiplexer readout at T=0.1 K down to NEP=10^{-19} W/Hz$^{1/2}$
- For medium resolution spectrometer with dc SQUID readout at 0.1 K down to NEP=10^{-18} W/Hz$^{1/2}$
- JTWPA readout with quantum limited noise temperature down to 0.3 K at 3-8 GHz band

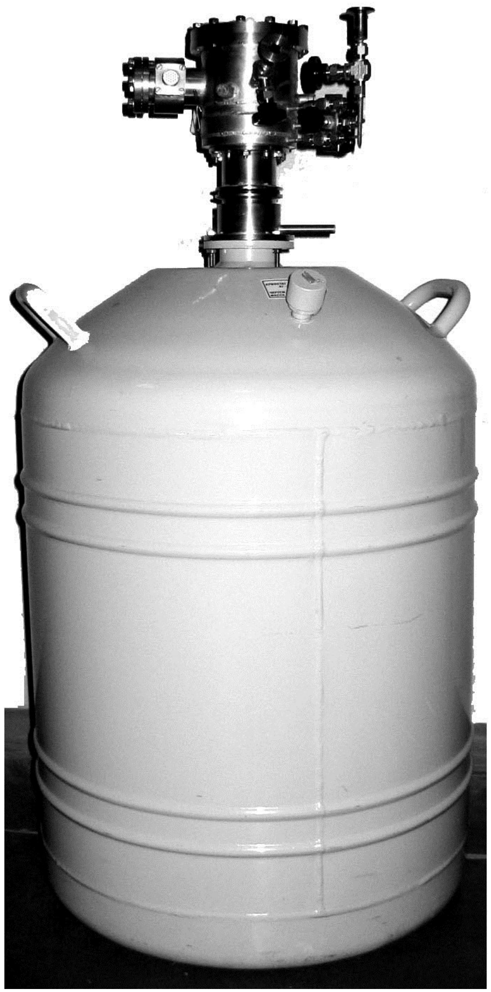
Conclusion - planning

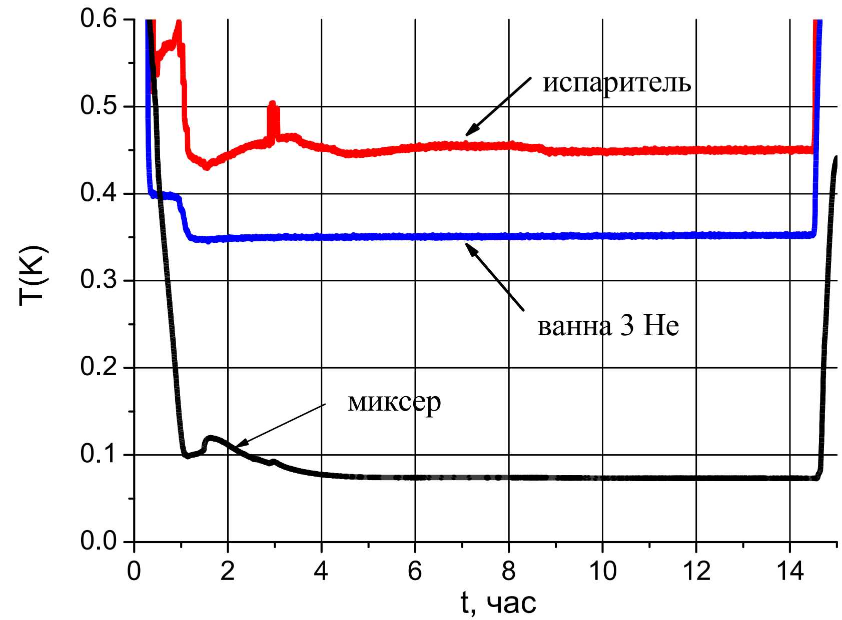
- Wideband matrix of parallel SINIS detectors in superconducting electrically small antenna (distributed absorber) for SQUID readout in LF MRPP
- Matrix 100x100 pixels with FDM readout for imaging array multipixel HF MRPP
- Josephson traveling wave parametric amplifier 3-8 GHz for FDM readout
- Magnetron sputtering and direct-write e-beam lithography for SINIS and JTWPA aluminum based technology

Support: RSCF № 21-42-04421 , state task AAAA-A19-119041990058-5, state defense order 1921730201662217000241851 TSNIIMASH

Dilution microcryostat for temperatures down to 50 mK.

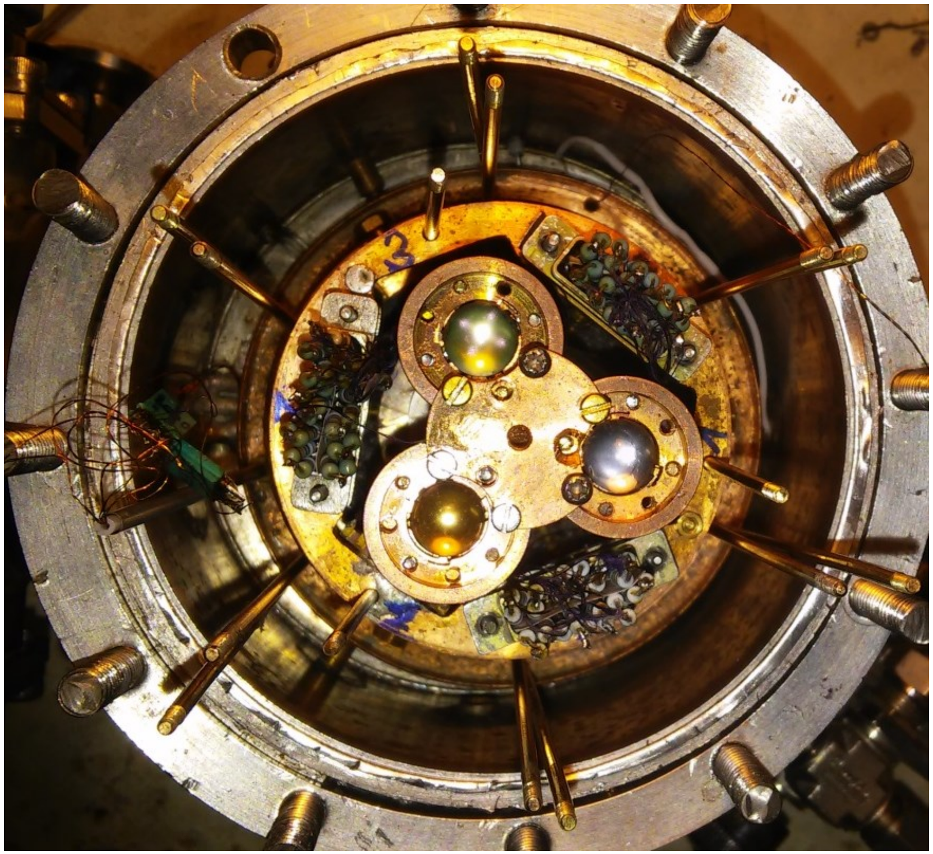
V.Edelman, Instr.Exp.Techn., №2, p. 159, 2009





At 0.1 K cooling power is about 1 μW. For low-temperature detectors power load about nanoWatt. Regeneration time 1 hour. In wide-neck 35 liter transport dewar it can operate 5-6 days.

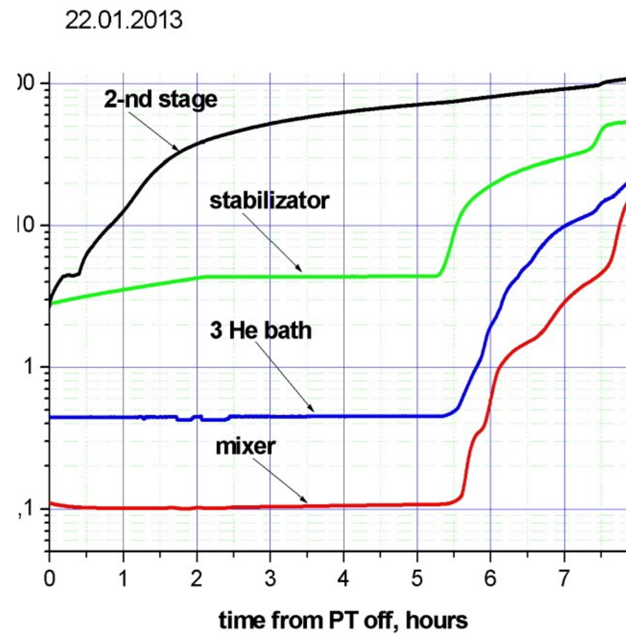
Sample chamber



Top view at 3 sapphire lenses that focus radiation at SINIS detectors. Radiation for calibrating sensitivity is provided by variable temperature black-body source placed at 0.4 K radiation shield and equipped with bandpass filters.

Dilution microcryostat below 0,1K with He recondensation by pulse tube.

V.Edelman, G.Yakopov, InstrExpTech №5, p. 129, 2013



Cooling down to operation temperature during night. About 2 hours need for dilution unit to cool below 100 mK. After that pulse tube is switched off and low temperature provided by condensed LHe in stabilizer.

From Millimetron Technical Project Book 4

- *Coupling of the detectors through few-mode feedhorns..*
- *Three technologies for the wide band multimode detector arrays. All these technologies can produce photon noise limited detectors in the loading conditions of the DFTS.*
- *TES (Transition Edge Sensors) are superconducting bolometers, already operated at ground and balloon-borne telescopes in large arrays (ACT, SPT, EBEX). They can be multiplexed both in time domain and in frequency domain. They require cold SQUID amplifiers with a complex readout electronics, and careful control of magnetic fields in the instrument.*
- *KIDs (Kinetic Inductance Detectors) are superconducting resonator detectors, intrinsically multiplexable. They reduce the heat load on the cold part of the instrument because can be read using only two coaxial cables for the whole system. They need a cryogenic HEMT or equivalent wide-band parametric amplifier. They have been operated at the telescope only once (NIKA).*
- *CEB (Cold Electron Bolometers) or SINIS are cryogenic detectors potentially very suitable for space applications (they are very much immune to cosmic rays hits since the sensitive volume is extremely small). A multiplexing technique has not been developed yet. They have never been used at the telescope yet. Cold JFET*