DARTWARS: development of quantum limited superconducting amplifiers for advanced arrays read out

MARIE CURIE ACTIONS
GA: 101027746

Istituto Nazionale di Fisica Nucleare

CSN5 Technological research

UNIVERSITA' DEGLI STUDI DI MILANO BICOCCA

BIQUTE

DARTWARS
Detector Array Readout with Traveling Wave AmplifieRS

Marco Faverzani

University & INFN Milano - Bicocca

Ultra low noise amplification for microwave readout: why?

MKIDs

Microwave Kinetic Inductance Detectors multiplexed in the RF band

- Amplified by High-Electron-Mobility Transistor (HEMT)

👍 broad bandwidth ~ 4/5GHz
👎 energy resolution/NEP limited by the noise: T_N ~ 2-5 K

TESs/MMCs

Microwave multiplexed readout

- Amplified by High-Electron-Mobility Transistor (HEMT)

👍 broad bandwidth ~ 4/5GHz
👎 energy resolution/NEP limited by the noise: T_N ~ 2-5 K
👎 not suitable for threshold detection (e.g., dark matter)

RF cavities

RF signal from cavities (e.g., axion searches)

- Josephson parametric amplifier (JPA)

👍 quantum limited noise
👎 narrow bandwidth ~ 100 MHz
👎 one JPA per cavity

Qubits

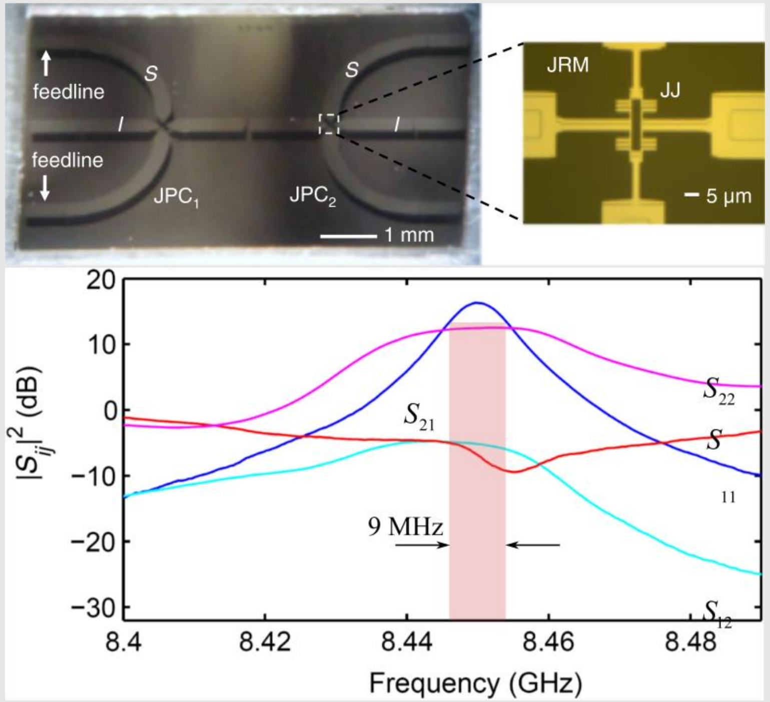
RF probe signal scattered by superconducting resonator coupled to the qubit circuit

- Josephson parametric amplifier (JPA)

👍 quantum limited noise → high fidelity
👎 narrow bandwidth ~ 100 MHz
👎 few qubits per readout line

IBM and Google qubit readout

IBM: Josephson Parametric Converter

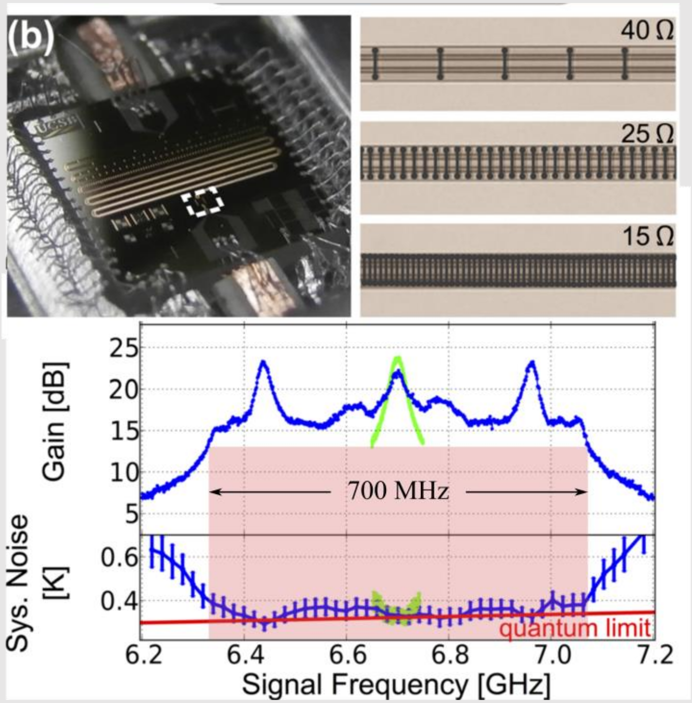


Phys. Rev. X 3 (2013) 031001

- gain ~ 15 dB
- narrow BW: 9MHz @ 8.45 GHz

👎 one qubit/readout chain

Google: Impedance-transformed Parametric Amplifier

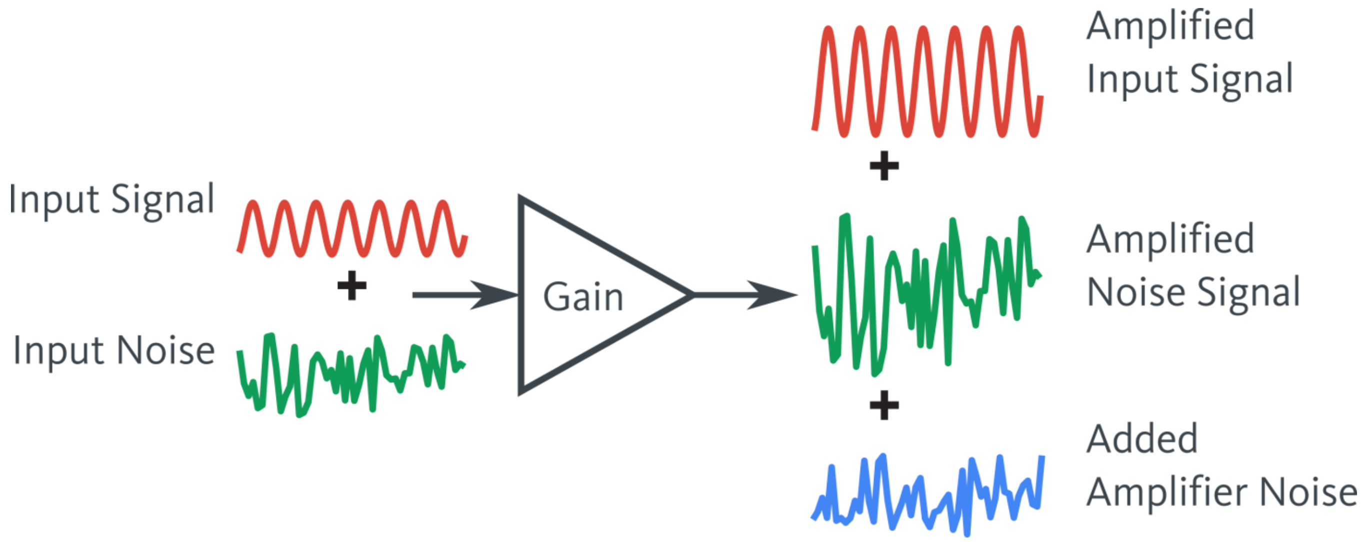


Appl. Phys. Lett. 104 (2014) 263513

- gain ~ 15 dB
- larger BW: 700MHz @ 6.7 GHz

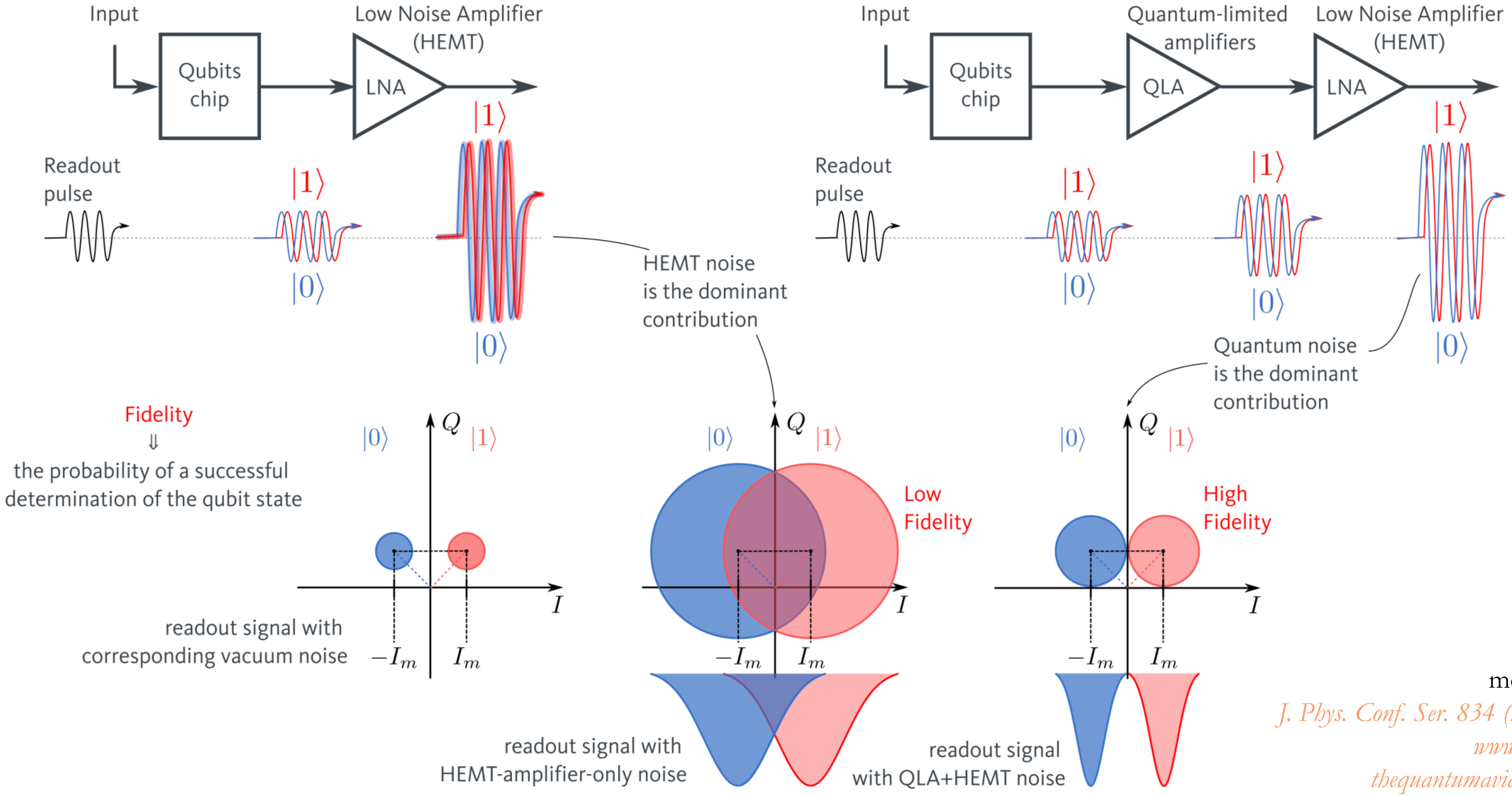
👉 six qubit/readout chain

Low noise readout



- the input of the amplifier is sensitive to both the noise and the signal at the input
- the amplifier adds noise to several sources (thermal fluctuations, e-h recombination in semiconductors, etc.)
- Heisenberg's uncertainty principle sets a lower limit to the added noise
- a quantum limited amplifier has an added (temperature) noise $T_N \sim hf/k_B \sim 50$ mK/GHz

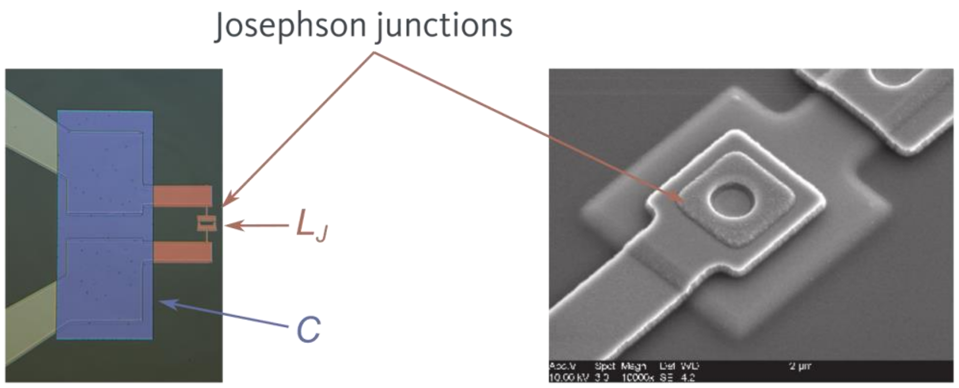
High fidelity qubits readout

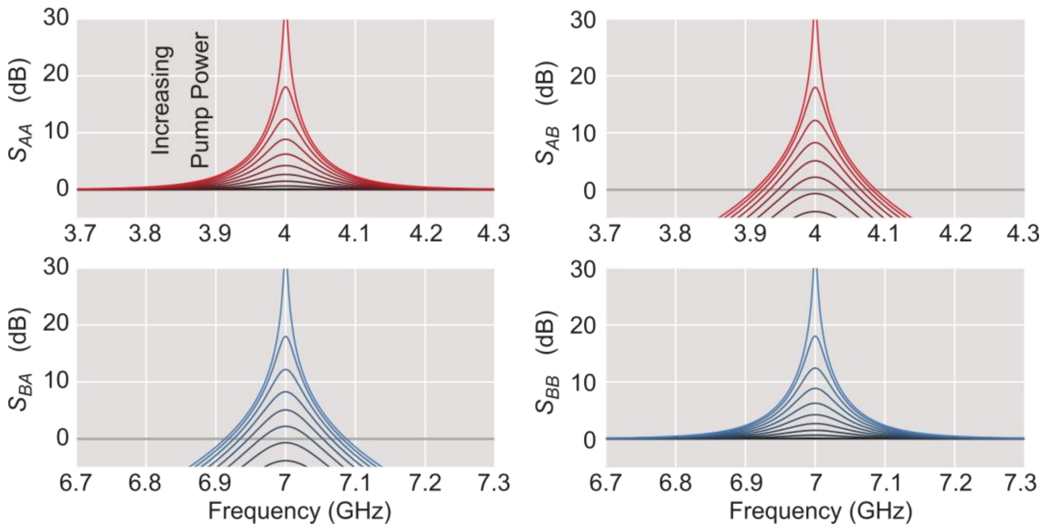


more details on
J. Phys. Conf. Ser. 834 (2017) 012003
www.ibm.com/ blogs
thequantumaviary.blogspot.com

Josephson Parametric Amplifiers (JPA)

- the weak signal to be amplified is mixed with a strong pump tone exploiting a non-linear element (capacitance or inductance)
- JPAs are weakly non-linear oscillators, where the non-linearity is provided by the Josephson junction
- **demonstrated noise level close to the quantum limit**
- very narrow bandwidth < 100 MHz
  - ➢ few detectors/qubits per line
- high gains are achievable, but **the product gain-BW is fixed**
- very small dynamic range < -100 dBm
  - ➢ few devices per line
- currently employed as a first stage of amplification in reading out superconducting qubits and RF cavities





IEEE Microwave Magazine 21, 8 (2020) 45

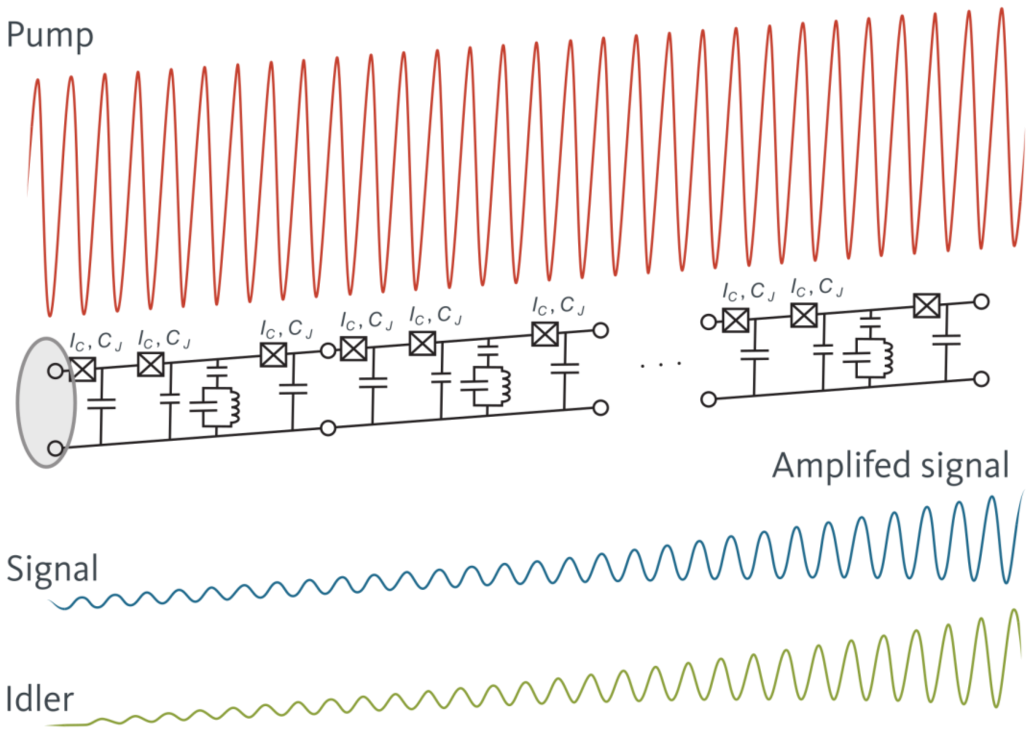
Traveling Wave Parametric Amplifiers (TWPAs)

- different approach respect to JPA: it is composed of a transmission line with embedded non-linear elements

- the non-linearity can be provided by Josephson Junction or the intrinsic (non-linear) dependance on the supercurrent of the Kinetic Inductance of a superconductor. At the first order, this dependance can be approximated as:

$$L(I) = L_0 \left(1 + \frac{I}{I_*}\right)^2$$

I_* is a material-dependent parameter expected to be close to the critical current of the superconductor



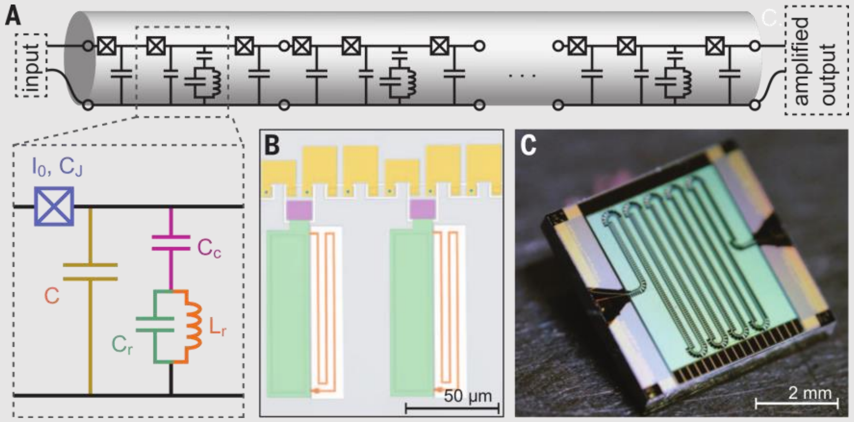
4-Wave Mixing (4WM):
$2f_P = f_s + f_i$
unbiased transmission line

3-Wave Mixing (3WM):
$f_P = f_s + f_i$
biased transmission line

A large pump tone (f_P) modulates the inductance, coupling the pump to a signal and an idler tone via frequency mixing

TWPAs: Josephson and Kinetic Inductance

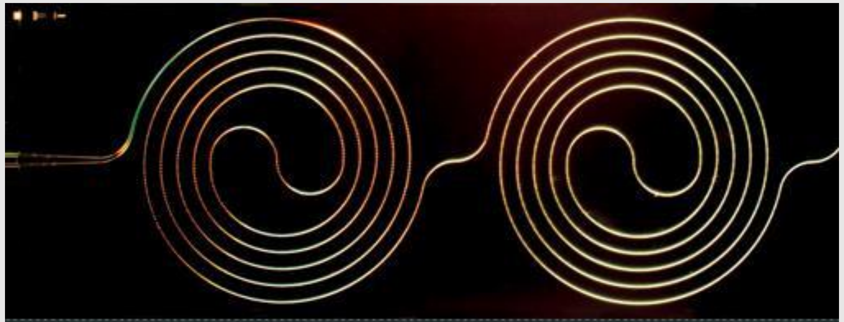
Traveling Wave Josephson Parametric Amplifiers



Science 350, 6258 (2015) 307-310

- TWJPAs consist of a non-linear lumped element transmission line
- one single cell consists of a Josephson Junction plus a capacitive shunt toward the ground
- demonstrated quantum-limited noise level
- wide BW > 4 GHz @ 5 GHz
- limited gain < 20 dB
- small dynamic range < -90 dBm

Kinetic Inductance Traveling Wave Parametric Amplifiers



Above: A section of a W-band traveling-wave kinetic inductance parametric (TKIP) amplifier. It consists of a 0.15 m length of NbTiN coplanar waveguide (CPW) line arranged in double spirals. The thickness of the line is 35 nm and the center conductor and gap widths are 1 micron.

Nature Physics 8 (2012) 623–627

- KI-TWPA (a.k.a. KIT) exploit the distributed non-linear kinetic inductance of TiN or NbTiN
- patterned into CPW or lumped element artificial transmission line
- noise close to quantum limit
- wide BW >4 GHz @ 5 GHz
- limited gain and gain profile with large ripple
- high dynamic range from -50 to -45 dBm

Microwave amplification: summary

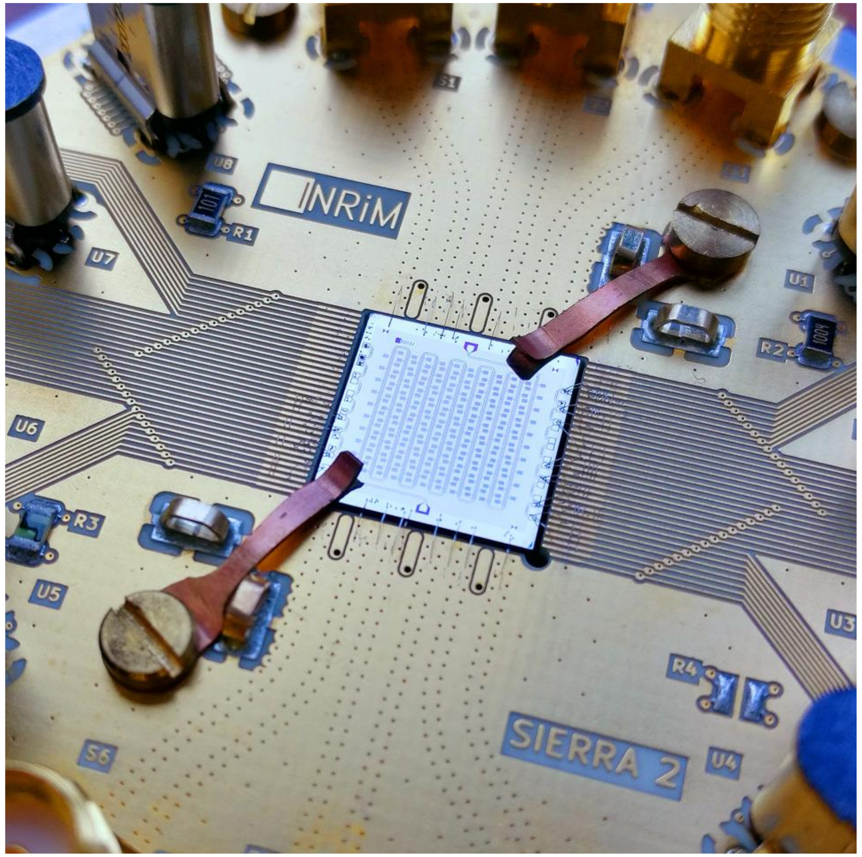
	HEMT	**JPA**	**TWPA**
technology	semiconductor	superconductor	superconductor
noise	👎	👍	👍
bandwidth	👍	👎	👍
gain	👍	👍	👍/👎
saturation power	👍	👎	👍/👎
integrability	👎	👍	👍

The main aims of DARTWARS are:

1. development of high-performance amplifiers following both the approaches of KIT and TWJPA optimizing the design and exploring new materials and fabrication processes

   - high gain ~ 20 dB
   - large saturation power ~ 50 dBm
   - (nearly) quantum limited noise T_N < 600 mK
   - reduced gain ripple

2. demonstration of readout of various detectors/devices (i.e., TESs, MKIDs, RF cavities and qubits) with improved performances thanks to the amplification with added noise at the quantum level



picture courtesy of INRiM

DARTWARS: the collaboration

INFN units:

- MIB: coordination of the whole project with a focus on the design and characterization of the devices (mainly DTWKI)
- LNF COLD (CryOgenic Laboratory for Detectors): supervision of the devices' fabrication and participation in the characterization (mainly TWJPA)
- LE: investigation of magnon-cavity polaritons applied to quantum computing and quantum sensing
- SA: coordination of design and simulation of TWPAs; packaging and testing of TWJPA
- TIFPA: supervision of production at FBK; participation in the characterization (mainly DTWKI)

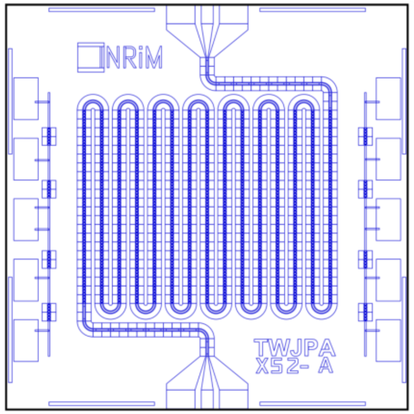
Other institutions:

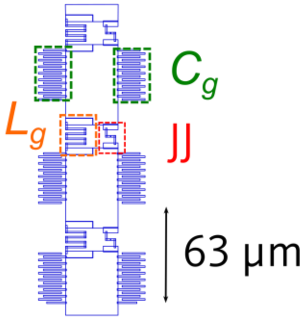
- Fondazione Bruno Kessler (FBK) Micro System Technology group (MST) of Centre for Materials and Microsystems (CMM): fabrication of DTWKI prototypes
- Istituto Nazionale di Ricerca Metrologica (INRiM): design and fabrication of TWJPA prototypes
- Institute for Basic Science Center for Axion and Precision Physics Research (IBS-CAPP): co-finances the production; participation in the characterization
- National Institute of Standards and Technology (NIST): participation in designing and testing of DTWKI

TWJPA within DARTWARS

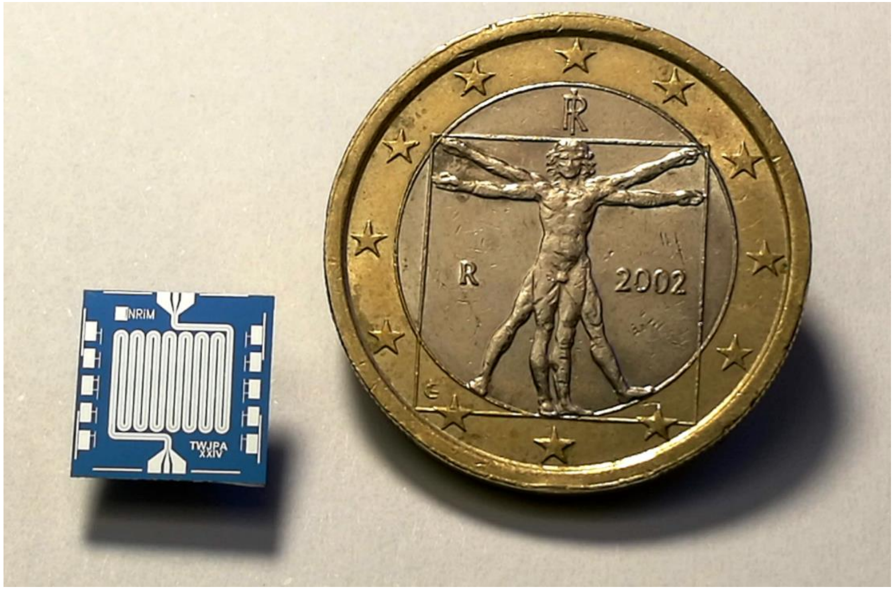
- recent studies suggest that TWJPA operated in the three-wave mixing (3WM) mode might increase the power handling, while decreasing the gain vs. frequency ripple
- new design 3WM TWJPA based on microwave transmission line composed of a serial array of non-hysteretic one-junction rf-SQUIDs
- mixing process due to the non-linear inductance of the JJs
- JJs created as Al/Al-Ox/Al tri-layer exploiting the Niemeyer-Dolan technique
- design and production made in collaboration with the Istituto Nazionale di Ricerca Metrologica (INRiM, Torino)

TWJPA chip fabricated at INRiM



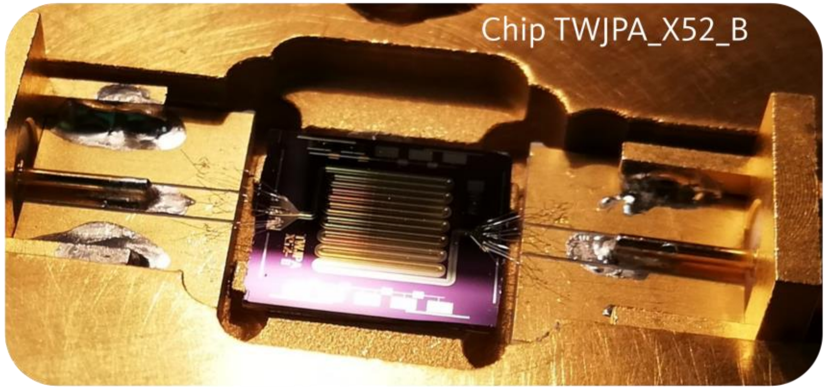


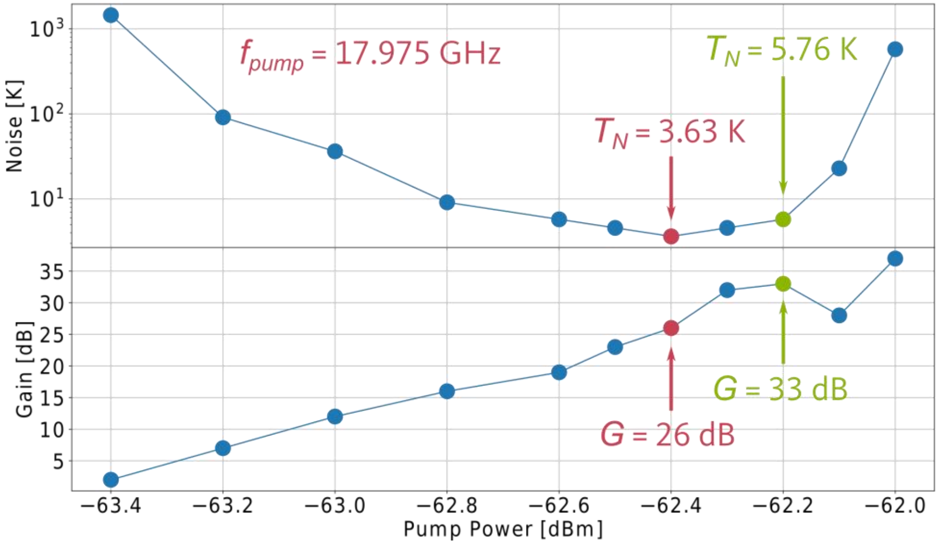
3 elementary cells



TWJPA within DARTWARS

- in the first semester of 2021 chips with TWJPA produced at INRiM were tested both at LNF and IBS-CAPP
- measurements showed clear evidence of parametric amplification but with a non-homogeneous behavior in frequency probably due to a non-homogeneous fabrication of the ~ 900 JJs of the device
- gain up to 30 dB was observed at particular frequencies and with a minimum noise temperature of 3.63 K
- new design with modified dispersion relation to reducing mismatch between the traveling tones, is in development
- production and characterization of JJs @ INRiM and MIB
- new production foreseen for first half of 2022

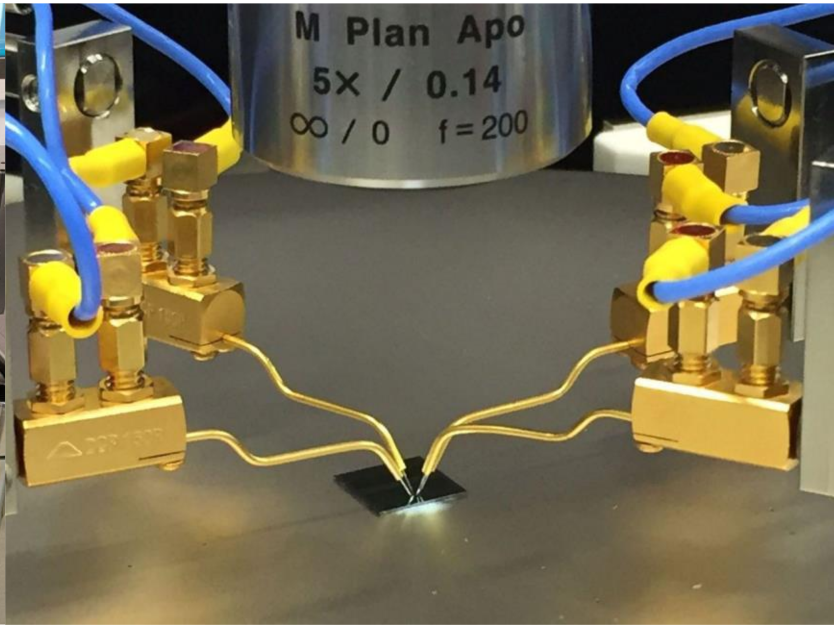




JJs production and characterization @INRiM and MIB

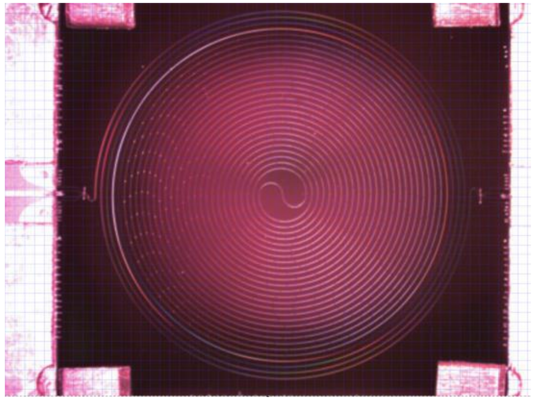
DART WARS

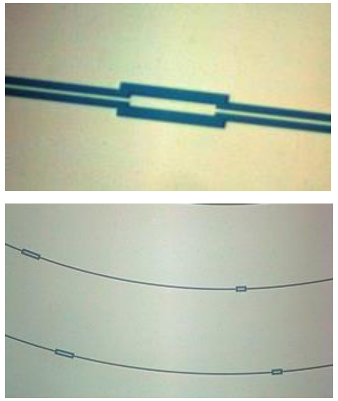
- JJs produced at INRiM with two oxidation processes (dynamic and static), but with fixed *time* × *pressure*$^{0.5}$
- JJs designed to have a $I_c = 4\ \mu A$
- expected normal resistance (from Ambegaokar-Baratoff) is $R_N \approx 80\ \Omega$
- normal resistance measured with 4-terminal probe station coupled to a Keithley 4200A Parameter Analyzer (current ramp 0.1 ÷ 10 μA)
- detected position dependent resistance around 2-4 Ω
- on average, the measured $R_N \approx 12\ \Omega$
- new production run is being characterized

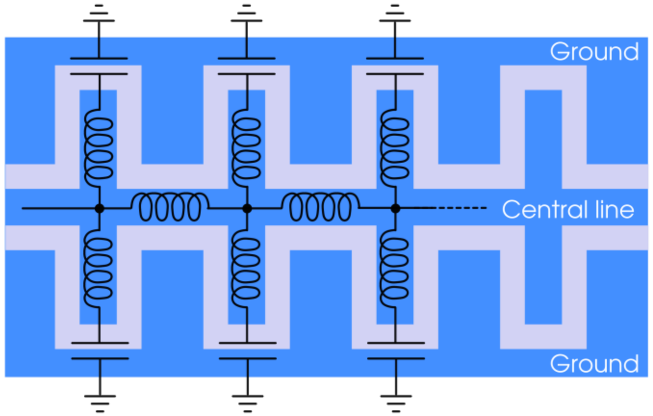


KITWPA within DARTWARS

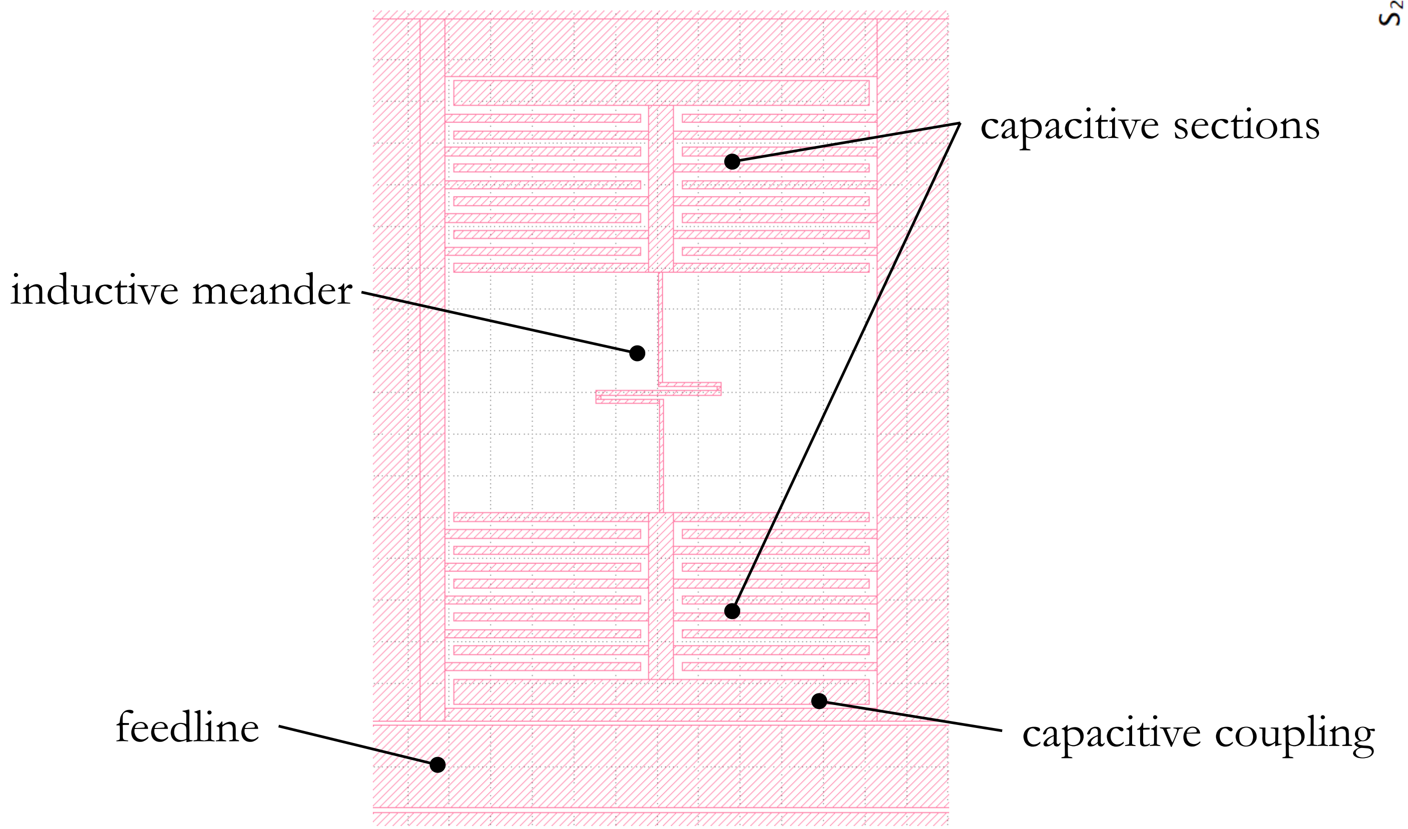
- two different approaches for the transmission line:
  - classical CPW
  - artificial transmission line with lumped elements
- the advantage of the lumped element approach a shorter transmission line: 20 cm vs. 1-2 m
- the goal is to lower the device heating with a consequent reduction of the gain ripple and yield improvement
- different materials will be considered to lower the T_c: multilayer of Titanium and Titanium Nitrate (Ti/TiN) and Tungsten Silicide (WSi)
- Transmissions implemented with a different layouts: microstrip transmission lines with ultra-low-loss single-crystal silicon dielectrics fabricated on a silicon-on-insulator (SOI) wafer
- Production in collaboration with the Fondazione Bruno Kessler (FBK, Trento).

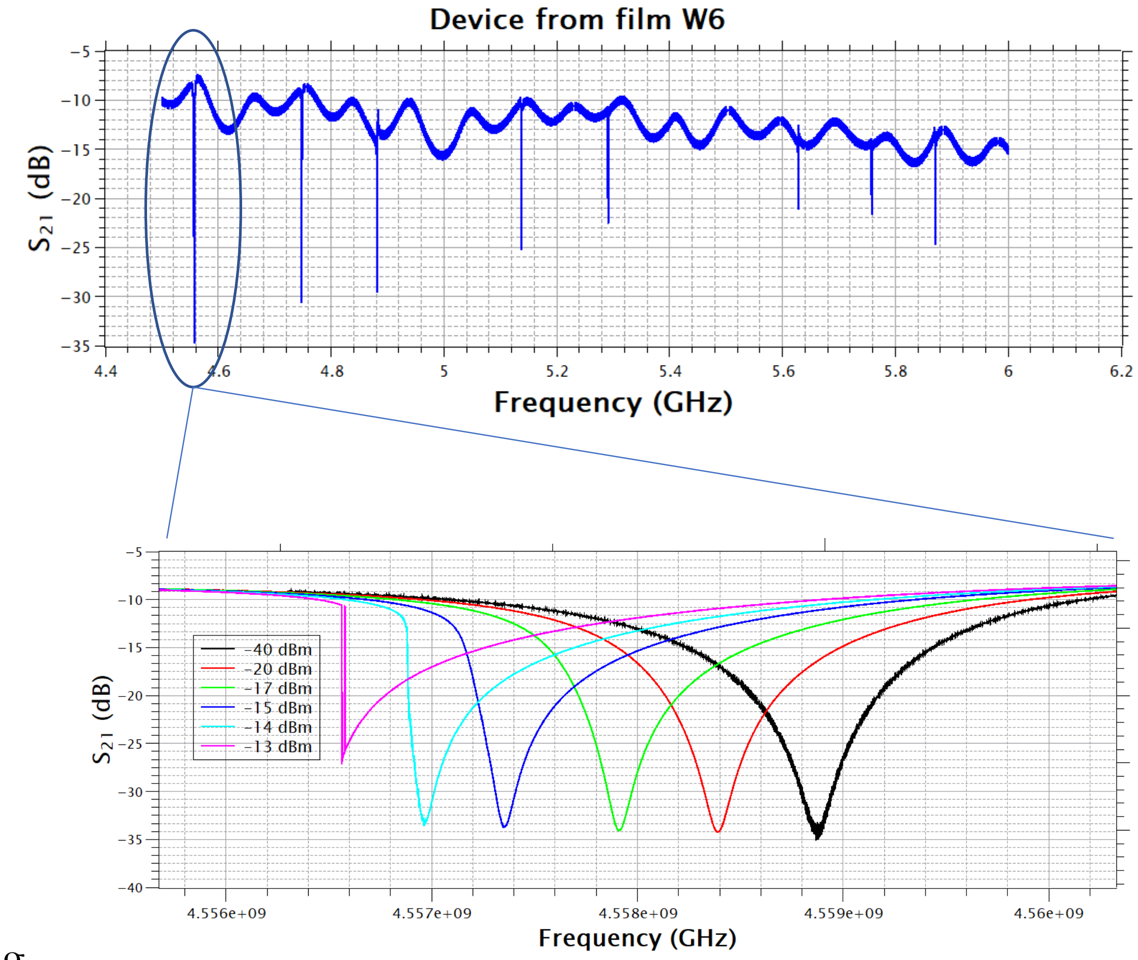






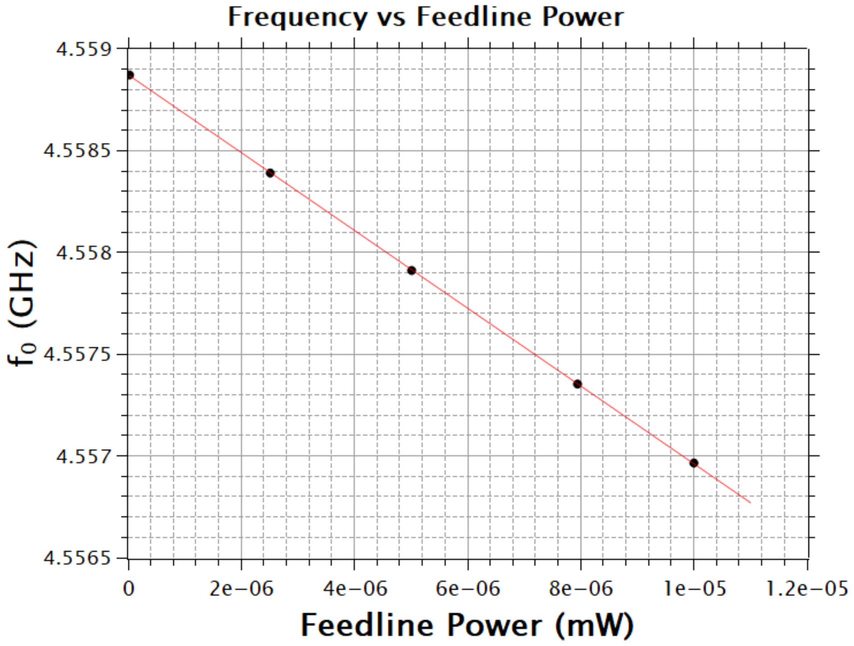
NbTiN patterned into micro-resonators (KIDs) to characterize the kinetic inductance (and its non-linearity)



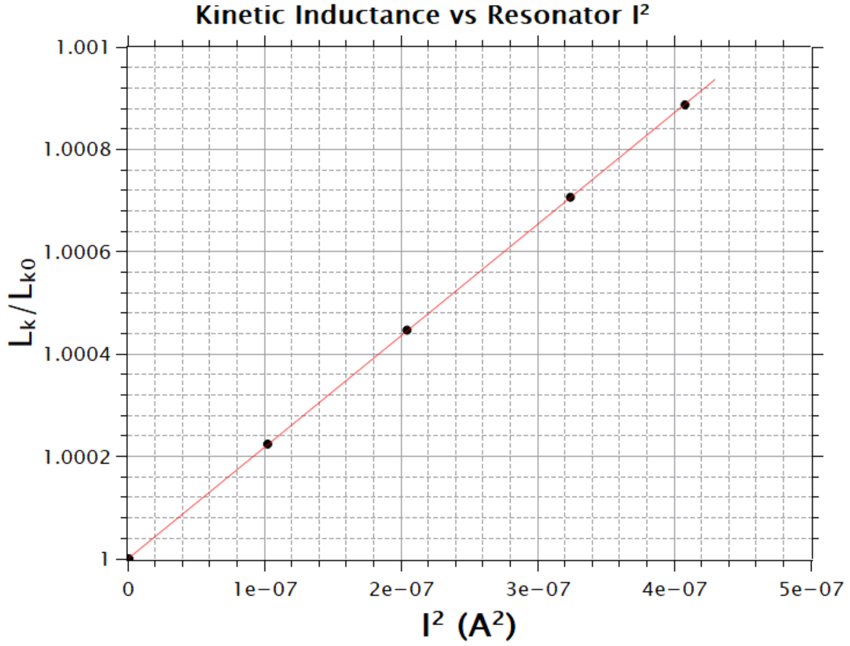


$$L_k = L_{k_0}\left[1 + \left(\frac{I}{I_*}\right)^2\right]$$

KITWPA: material characterization @FBK/TIFPA (cont'd)



$$L_k = L_{k_0}\left[1 + \left(\frac{I}{I_*}\right)^2\right]$$



need to:

- relate L_k to f_{res} → Sonnet simulation: $(f_{res})^{-2} \propto (L_k + L_g)C$
- relate I^2 to $P_{feedline}$ → estimated C and L from Sonnet
  → circuit simulator (QUCS)
- estimate I_* from $L_k(f_{res})$ (Sonnet)

L_k measured as high as ~50 pH/sq
I_* as high as 20 mA

KITWPA: material characterization @FBK/TIFPA (cont'd)

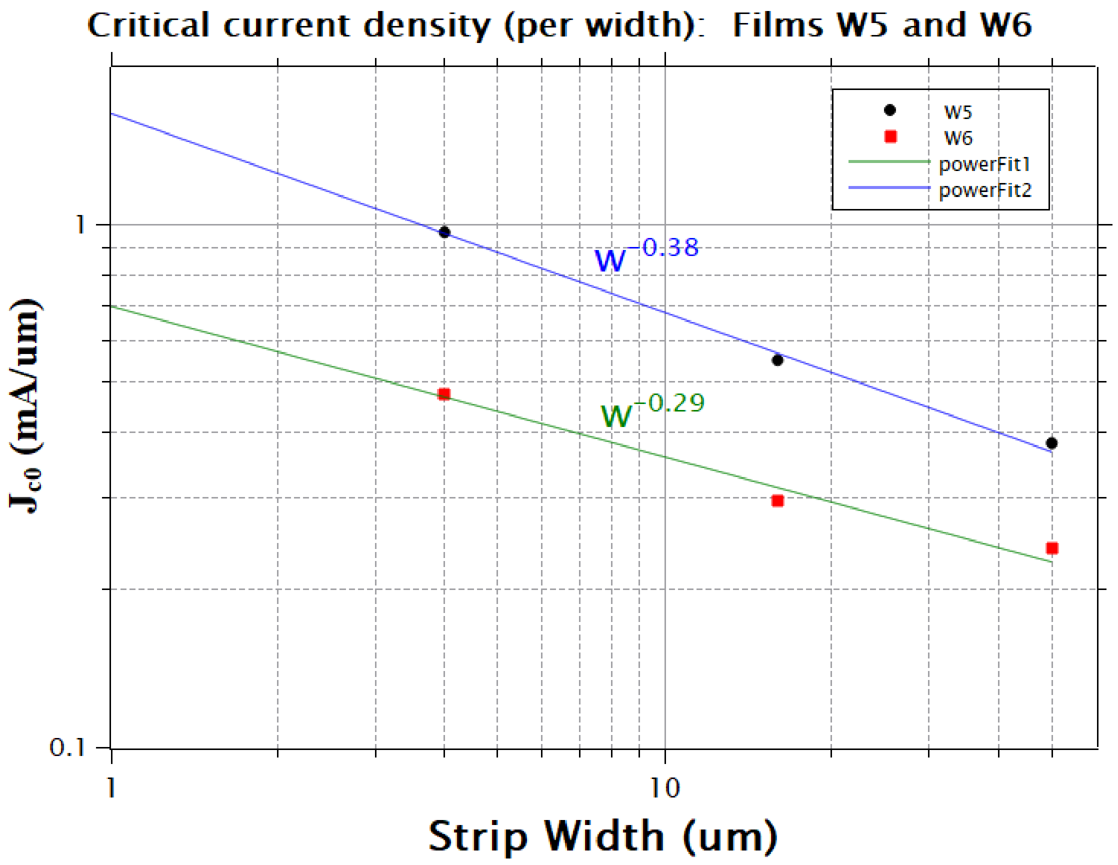
Critical current measurement:

- performed on strips of film immersed in LHe to minimize self-heating effects
- corrected to zero temperature according to Ginzburg-Landau predictions:

$$I_c = I_{c_0}(1-t^2)(1-t^4)^{1/2}$$
$$t = \frac{T}{T_{c_0}}$$

- J_c expected to increase for smaller widths (the current densities increases at the strip edges) as

$$J_c \propto w^{-\frac{1}{2}}$$

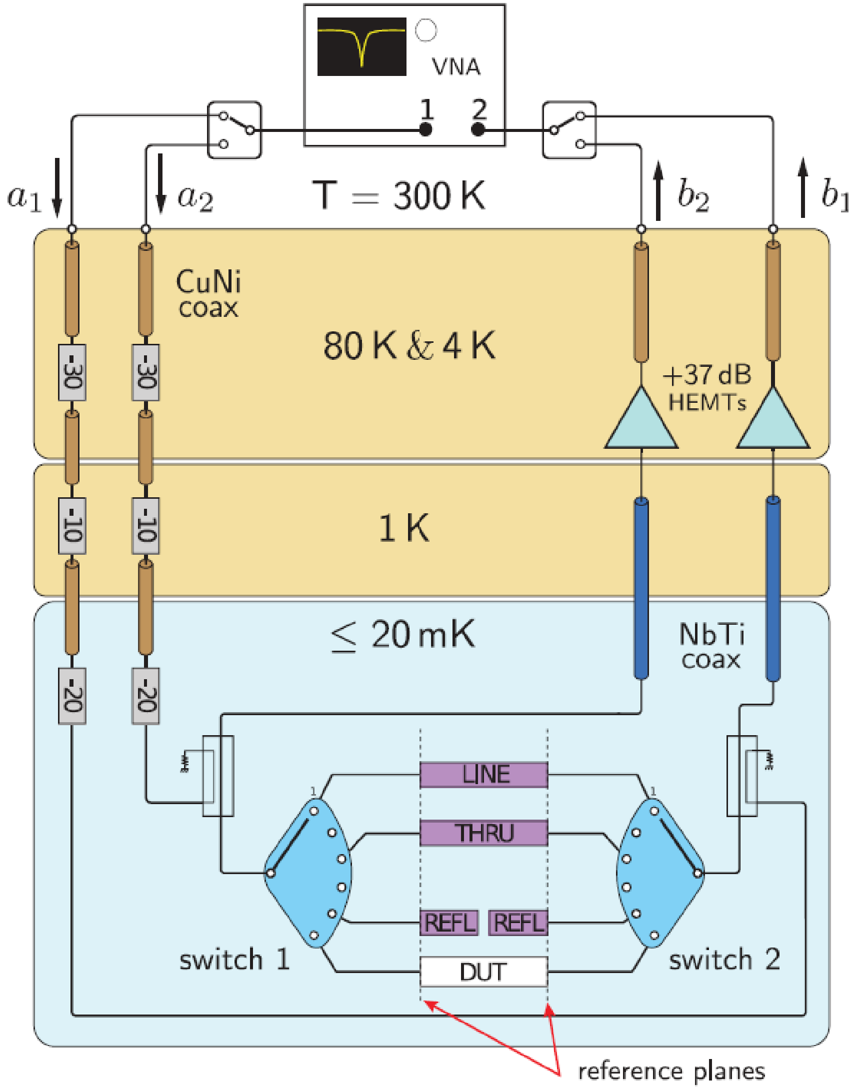


(I_c/I_*) sets the maximum non-linearity
In our films we measured a (I_c/I_*) as high as 0.24

Cryogenic Thru-Reflect-Line (TRL)

- necessary to precisely evaluate the S-parameters of the device excluding the effects of the readout line
- of great importance for DARTWARS, it will be developed in collaboration with the INRiM branch of SuperQuant (20FUN07 SUPERQUANT - Microwave Metrology for Superconducting Quantum Circuits, under the European Metrology Programme for Innovation and Research (EMPIR))
- technique of great utility also in the field of material characterization finalized to quantum computing

Rev. Sci. Instrum. 91 (2020) 091101



Rev. Sci. Instrum. 84 (2013) 034704

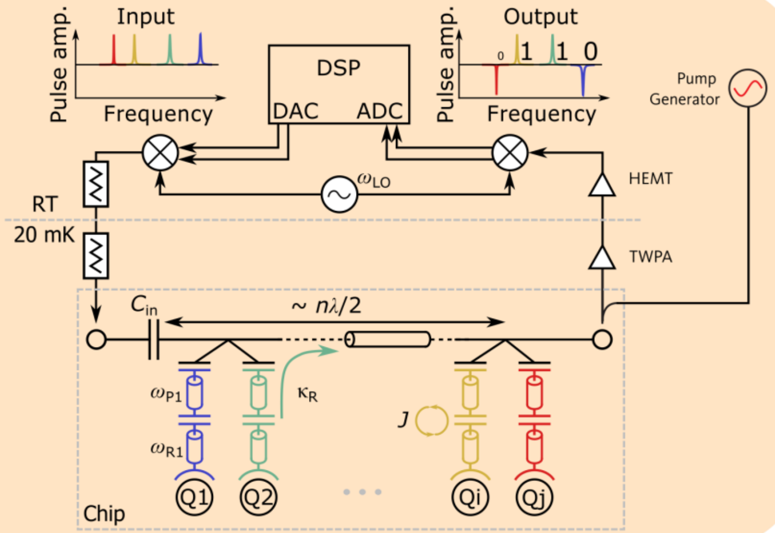
Conclusions

- DART WARS aims at
  - developing (nearly-)quantum limited noise Traveling Wave Parametric Amplifiers with two approaches: KI-TWPA and TWJPA, exploring new designs and materials
  - demonstrating the readout of several devices (TES/MKIDs/RF cavities/qubits) with improved performances
- the design started in 2021 and the first material characterization have been performed across 2021 and 2022. The first devices are expected to be produced within this year
- the demonstration of detectors/qubits readout is expected for 2023
- DART WAR will allow to build the expertise within INFN in designing and developing innovative quantum devices
- the results of DART WARS will potentially impact particle/astro-physics (such as m_ν measurement, dark matter, $0\nu\beta\beta$, coherent elastic neutrino-nucleus scattering, …) as much as fast-growing fields such as quantum computing/sensing, quantum squeezing, quantum radar, …
- more details available at https://dartwars.unimib.it/ and https://biqute.unimib.it/

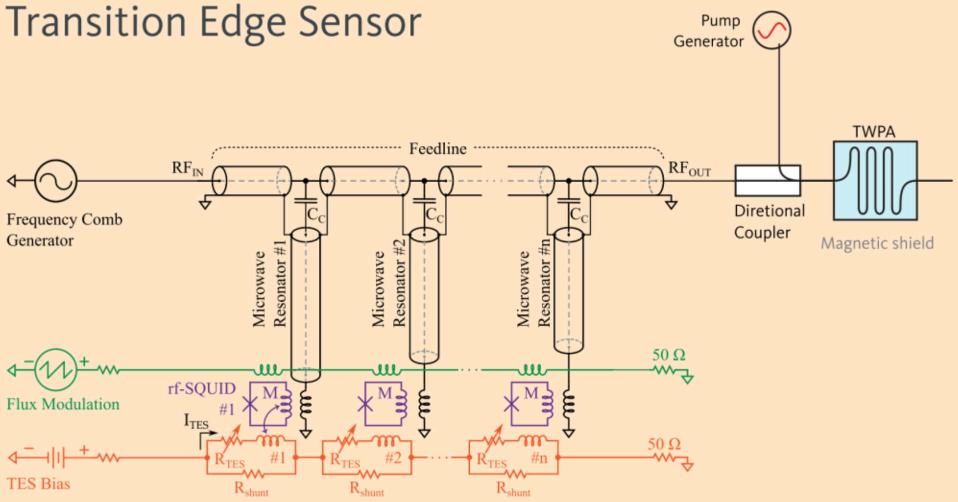
Backup slides

DARTWARS: readout of superconducting devices

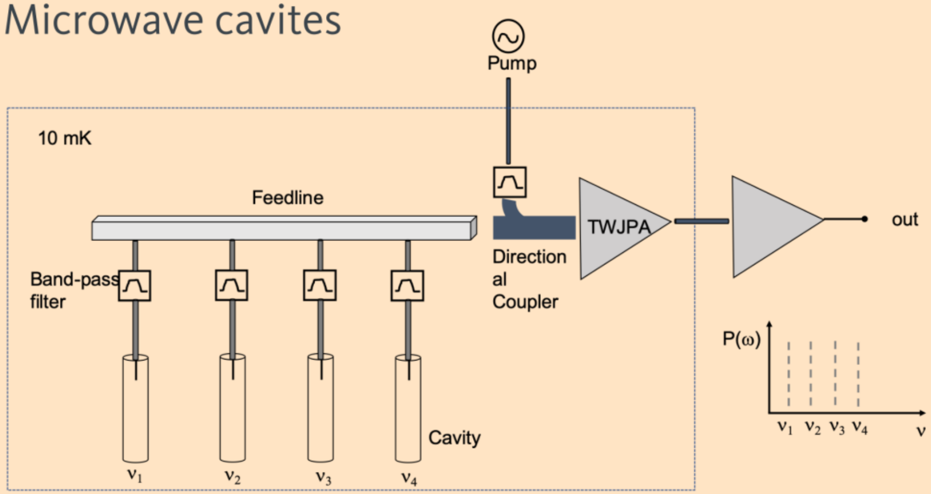
Qubit



Transition Edge Sensor



Microwave cavites



Quantum Sensing of Magnons

(with yttrium-iron-garnet (YIG) sphere)