WP1: Design and Simulation

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Motivation of the work

Ultralow-noise microwave amplification and detection plays a central role in different applications, going from **fundamental physics experiments** to the deployment of **quantum technologies**.

Good examples are detection of **Dark Matter, Axion, Dark Photons, neutrinos, Cosmic Microwave Background radiation, Magnons, Qubit readout and Quantum Computing**.

In many of these applications the necessity of reading **weak microwave signals** from **multiple** detectors, or cavities or qubits, calls for **large bandwidth amplifiers with the lowest possible noise.**

Amplifiers based on **High Electron Mobility Transistors** have good bandwidth and high dynamic range but too much noise (equivalent noise temperature from 2 to 5 K). They operate at few K and dissipate mW

Model	Bandwidth [GHz]	Gain [dB]	Noise [K]
LNF-LNC4_8C	4 to 8	42	1.5
LNF-LNC2_6A	2 to 4	42	1.9
LNF-LNC4_16B	4 to 16	36	3.6
LNF-LNC4_23A	4 to 23	29	5.8

data from the Low Noise Factory website

Quantum limited superconducting amplifiers are good alternatives.

Josephson Parametric Amplifiers (JPA), widely used to read qubits, have very good noise performances but limited bandwidth.

Superconducting **Traveling Wave Parametric Amplifiers** (TWPAs) have the potential of offering **quantum limited noise and large bandwidth**.

Traveling Wave Parametric Amplifiers (TWPAs)

Microwaves travel along a transmission line **with embedded non-linear elements**
O. Yaakobi, L. Friedland, C. Macklin, and I. Siddiqi, Phys. Rev. B 87, 144301 (2013)

The nonlinear reactive element can be implemented by the Kinetic Inductance (**KI**) of superconductors or by the inductance of a Josephson Junction (**JJ**).

The Inductance is, in both cases and to the lowest order, given by

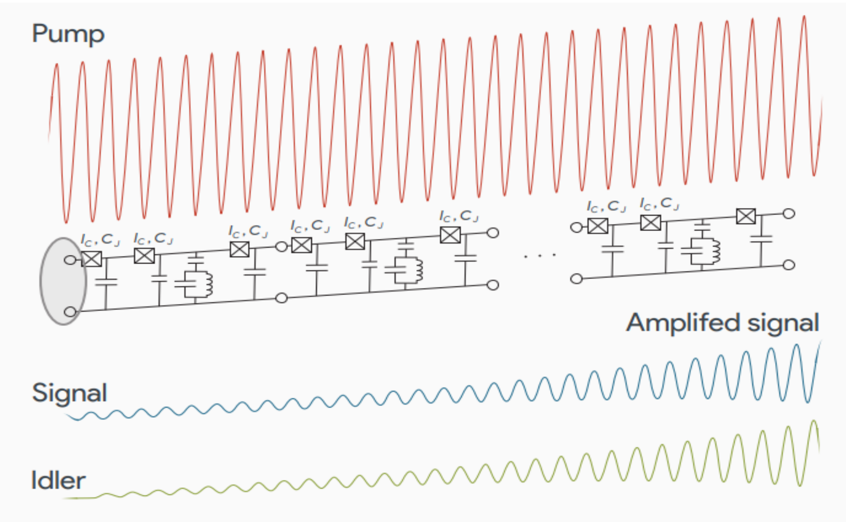
$$L(I) = L_0 \left[1 + \left(\frac{I}{I_c}\right)^2\right]$$

Ic is the superconductor critical current for KI or the junction critical current for JJ
At I < Ic junctions are dissipationless and act as a nonlinear inductor

I is the total current flowing and, in general, is made of Irf + Idc

Idc adds a 3rd order term in energy allowing 3-wave mixing (which is better since the pump frequency is outside the amplification band)

Overall TWPAs perform well in terms of **Noise**, **Bandwidth** and **Integrability**, but are limited in terms of **Gain** and **Saturation Power**



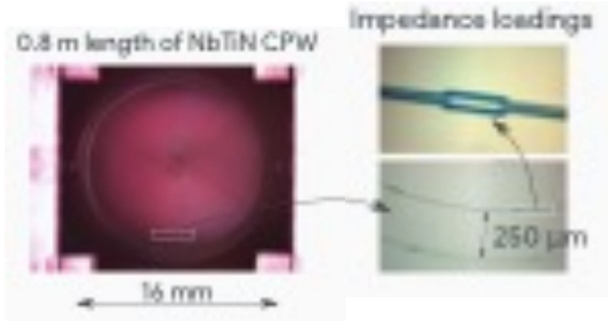
A large pump tone modulates this inductance, coupling the pump (fp) to a signal (fs) and idler (fi) tone via frequency mixing;

3-wave mixing **3WM**
fp = fs + fi

4-wave mixing **4WM**
fp+fp = fs + fi

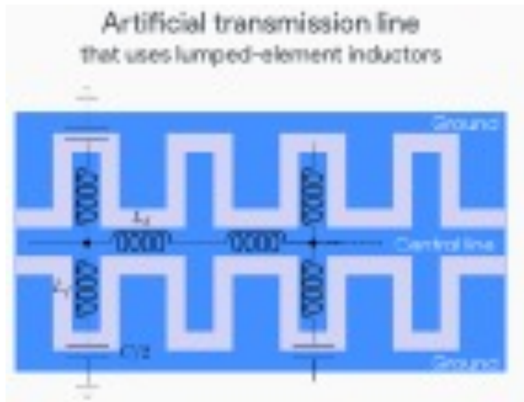
KI-TWPA

The KI-TWPAs use nonlinear kinetic inductance of a superconductor, constructed as transmission line, to produce parametric amplication;



- CP transmission line was selected for the first implementation of a KI-TWPA amplier
  (B. Eom et. al., Nature Phys. 8 (2012) 623–627)

👍 relatively easy to fabricate;
👍 promising results in term of gain, bandwidth, noise level;
👎 to achieve 15 dB gain, a CPW over 2 m long is used → low fabrication yield;
👎 characteristic impedance Z0 = 200 Ω ⇒ an impedance transformer to match 50 Ω is required;

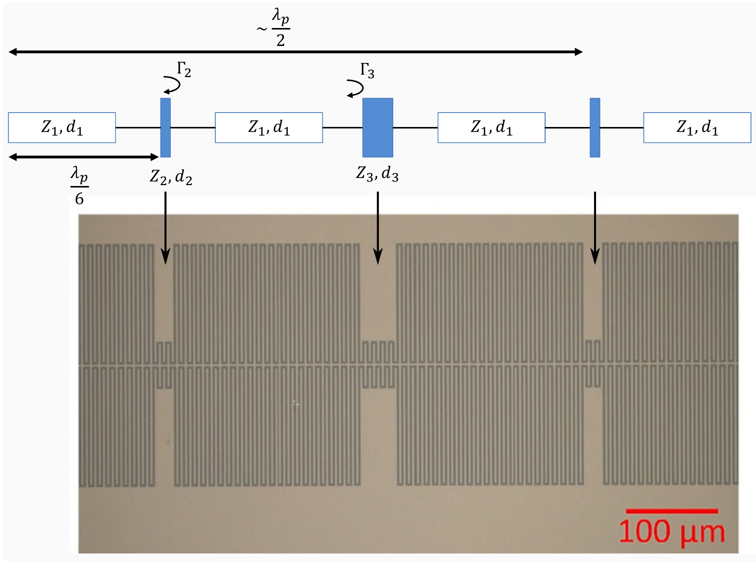


- One way to reduce the impedance, but maintaining the use of CPW lines, is to construct them in the form of artificial transmission lines
  (S. Chaudhuri et al., Appl. Phys. Lett. 110 (2017) 152601)
- small sections of a CPW are used to recreate a transmission line made of lumped-elements;

👍 15 dB gain achievable with shorter transmission line (20 cm vs 2 m);
👍 Near-Quantum-Limited Noise Performance over between 3.5 and 5.5 GHz
  (M. Malnou et al., PRX Quantum 2 (2021) 010302)

The Design

• A lumped-element transmission line cell possesses a characteristic impedance of $Z_0 = \sqrt{L/C}$ and a low-pass cutoff frequency $\omega_c = 1/\sqrt{LC}$;
• At $\omega < \omega_c$ an artificial transmission line behaves like a conventional transmission line with the same characteristic impedance Z_0;
• A $Z_0 = 50\ \Omega$ artificial transmission line may readily be made by appropriately tuning the unit-cell inductance and capacitance;



Dispersion engineering: modified design to improve gain and performance
• The characteristic impedance is ”periodically” modified every one-sixth of a wavelength at a frequency slightly above the pump frequency f_p to form a wide stopband at $3f_p$
• Every third loading is modified in length (longer or shorter relative to the first two) to create a narrow stopband near f_p;
• In this way the pump tone picks up additional phase shift to fulfill the **phase-matching condition**, while its **third harmonic is suppressed** by the $3\ f_p$ stopband;
• As a results an **exponential gain** can be achieved over a **broad bandwidth** of more than one-half of the pump frequency

Goal: design of a periodically-loaded NbTiN” fishbone” parametric amplifier

Material Issues

- A perfect knowledge of the materials is needed as input to design the transmission line:
  - Film resistivity ρ_n;
  - Film kinetic inductance: L_k;
  - Film critical temperature: T_c;
  - Substrate dielectric constant: ε_r
- Deposition and characterization runs are in progress (more details in WP2 and WP3 status reports);
- Simulation by cascading the ABCD matrices to compute the theoretical dispersion relations and the signal power gain;

⇒ a custom python code is being developed at the moment

- Development of amplier design and model validation by commercial EM simulators (HFSS and Sonnet);
- Preparation of the gds file and production at FBK

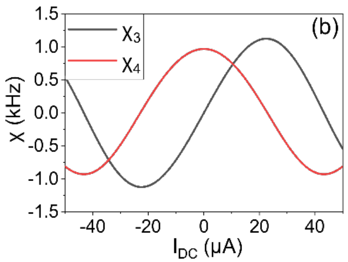
Preliminary depositions of Niobium (Nb) and Niobium nitride (NbN) were made at FBK to test the co-sputtering system obtaining Critical temperatures (Tc) and Residual-resistance ratios (RRR) compatible with literature;
More recent results on NiTi and NbTiN films made at FBK (see next presentations)

TWJPA

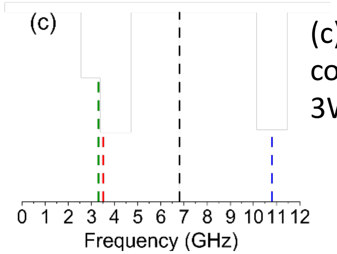
TWJPA: the nonlinear element is a Josephson junction

In order to achieve a better control of nonlinearity an rf- SQUID configuration is considered

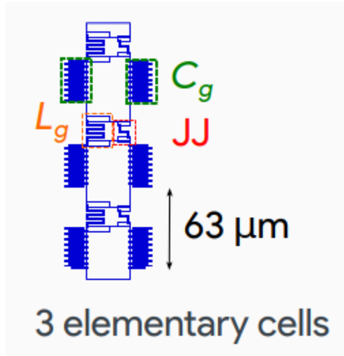
There is the possibility to control the magnetic flux through the SQUID by a DC current and therefore modify the response of the amplifier

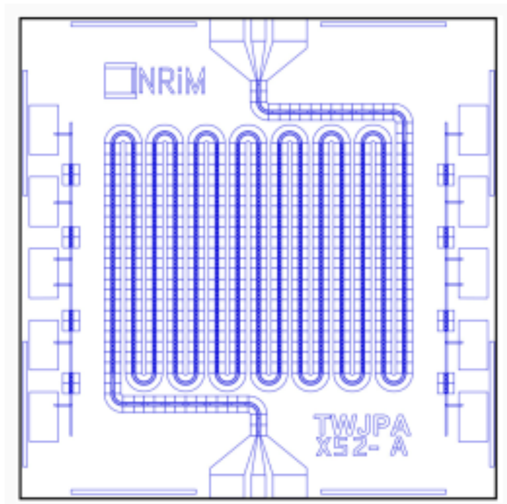


(b) Computed quadratic χ3 and cubic χ4 nonlinear coefficients that modulate the intensity of respectively the 3WM and 4WM idlers



(c) The dashed lines represent the frequencies corresponding to the pump (black), signal (green), 3WM idler (red) and 4WM idler (blue).





The initial realization of a TWJPA by INRiM

Preliminary tests at LNF and IBS show encouraging results (see later presentations)

TWJPA

New design with added periodic loading to realize phase matching conditions, and achieve large gain

- 3WM TWJPA based on microwave transmission line formed by a serial array of non-hysteretic one-junction RF-SQUIDs and periodic loading;

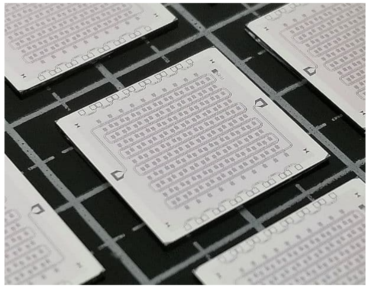
In this way the phase matching condition is achieved at a specified frequency (about 19 GHz in this case)

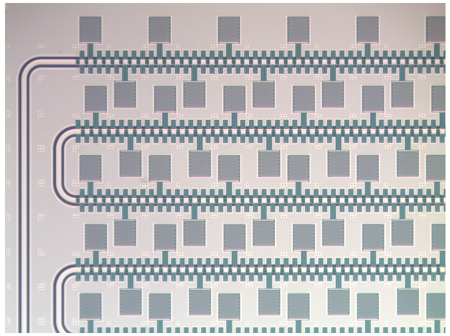
Still there is the possibility to control the magnetic flux through the SQUIDs by a DC current

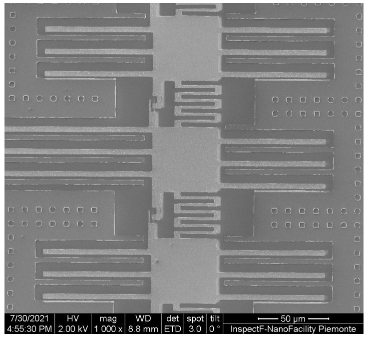
- JJs realized as Al/Al-Ox/Al tri-layers exploiting the Niemeyer-Dolan technique (shadow evaporation);

- Design and production by INRiM

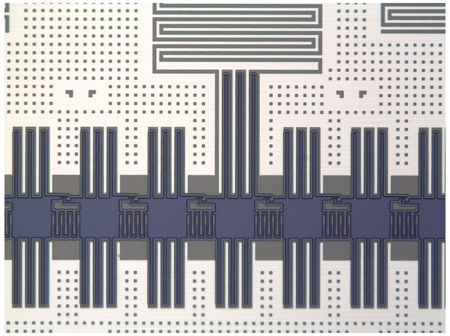
Details in Emanuele Enrico’s presentation







The JJ cell forming the RF-SQUID



The TWJPA with periodic lumped elements

WP1: Design and Simulation

Work Package Number:	1	**Start Date or Starting Event**			Project start	
WP Package Title:	Design, Optimization and Simulation					
Participant short name:	LNF	LE	MIB	SA		
Person/month per participant	6	6	10	32		
WP Leader	Sergio Pagano (SA)					

Objectives: **the goal of this WP is to improve the current parametric amplifiers design with new layouts and simulations**

Description of work
For both amplifier solutions the designs will match **a gain of >20 dB** over different bandwidths: C-band (4-8 GHz, TESs and MKIDs), and X-band (8-12 GHz, for microwave cavities and qubit, L+S band (1-4 GHz for the cavities designed at the IBS-CAPP (Korea). Numerical simulation for the amplifier behavior will exploit the experience of the Unisa group in parallel GPU computing.

Tasks Description
T1.1: Development of theoretical models for describing the TWPAs behavior (M1-M9);
T1.2: Simulation and design of the TWPAs, considering new and innovative solution (M1-M24, M28-M32);
T1.3: Analysis of experimental results in terms of device model and results of simulations (M10-36)

Milestones
M1.1: Design of TWJPA and DTWKI operating in different bands (M10)
M1.2: Improved design of TWJPA and DTWKI operating in in different bands (M24)
M1.3: Second improved design of TWJPA and DTWKI operating in different bands (if needed) (M32)

Role of participants
- INFN-SA and the WP2 leader will coordinate and supervise the design and simulation for theTWJPA amplifiers;
- INFN-MIB and the WP2 leader will coordinate and supervise the design and simulation for the DTWKI amplifiers;
- Results from simulation and experimental measurements will be analyzed by INFN-SA and INFN-MIB with the coordination of the WP2 leader.

Deliverables
D1.1: Optimized models and code for simulation of DTWKI/TWJPA (M12)
D1.2: Design of first generation of DTWKI/TWJPA operating in different bands (M10)
D1.3: Design of improved DTWKI/TWJPA after feedback from testing and field runs (M22/M30) **D1.4:** Report on performances obtained and expected improvements (M12/M24/M36)

T1.1: Development of theoretical models for describing the TWPAs behavior (M1-M9)
The theoretical classical models of TWPA are well defined, new «quantum» model have been proposed

T1.2: Simulation and design of the TWPAs, considering new and innovative solution (M1-M24, M28-M32)
KI-TWPA the design is still at a initial stage while the activity is concentrated on the realization of high quality superconducting materials
TWJPA the design is more advanced, already at second generation.
There are issues on bandwidth for 1st generation devices that need redesign, possibly solved with 2nd generation.
We want to develop a simulation system that could explore physical and geometrical parameters variation of the TWPA in order to optimize the performances. This activity is still at initial phase.
We need input on physical and design parameters from partners

M1.1: Design of TWJPA and DTWKI operating in different bands (M10)
We are a bit late on DTWKI but are confident to be able to achieve it in next 4 months

D1.1: Optimized models and code for simulation of DTWKI/TWJPA (M12)
As above, a delay of 4 months is foreseen.