DARTWARS: development of Kinetic Inductance TWPAs with DARTWARS

MARIE CURIE ACTIONS
GA: 101027746

INFN
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

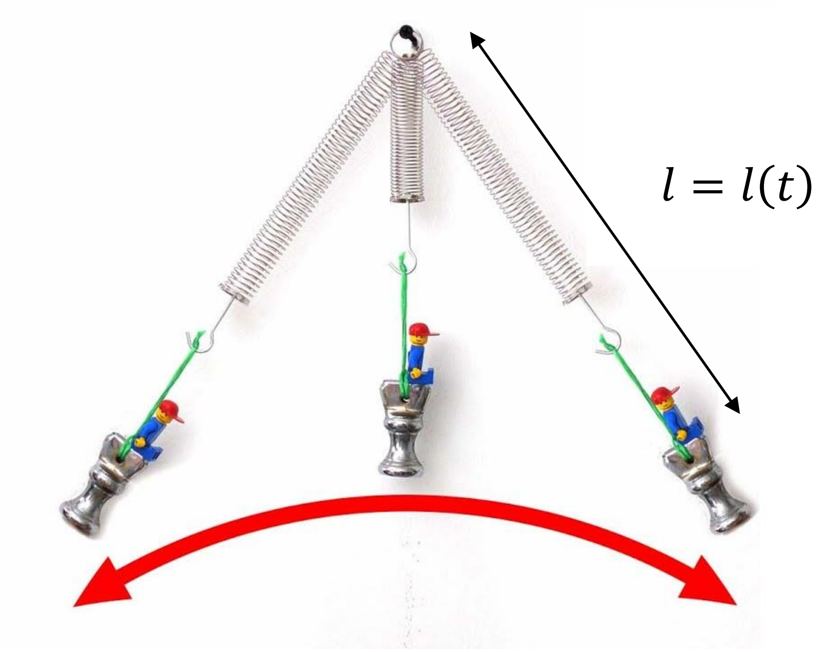
Parametric amplification for dummies

Resonance if:

1) sinusoidal driving force ($f_d = f_r \rightarrow$ linear gain with time)
2) one parameter periodically varied ($f_d = 2f_r \rightarrow$ exponential growth)

e.g., the pendulum: $\ddot{\theta} \cong \frac{g}{l}\theta$, $\omega = \sqrt{g/l}$

if $l = l(t) = l_0 \sin(2\omega t) \rightarrow \frac{dE(t)}{dt} \propto E(t)$



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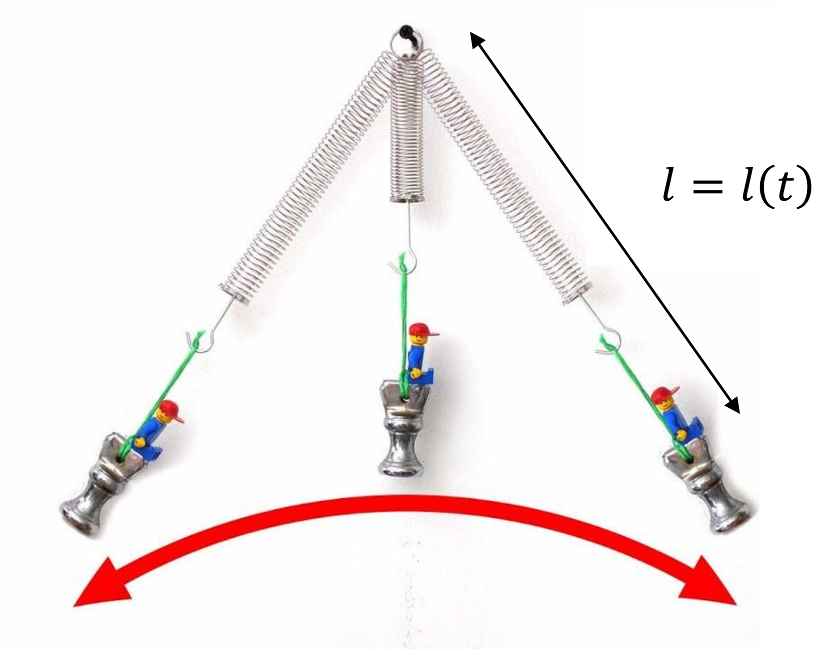

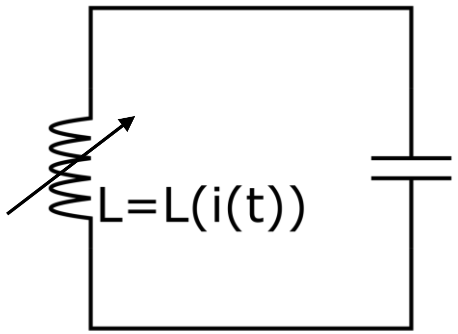

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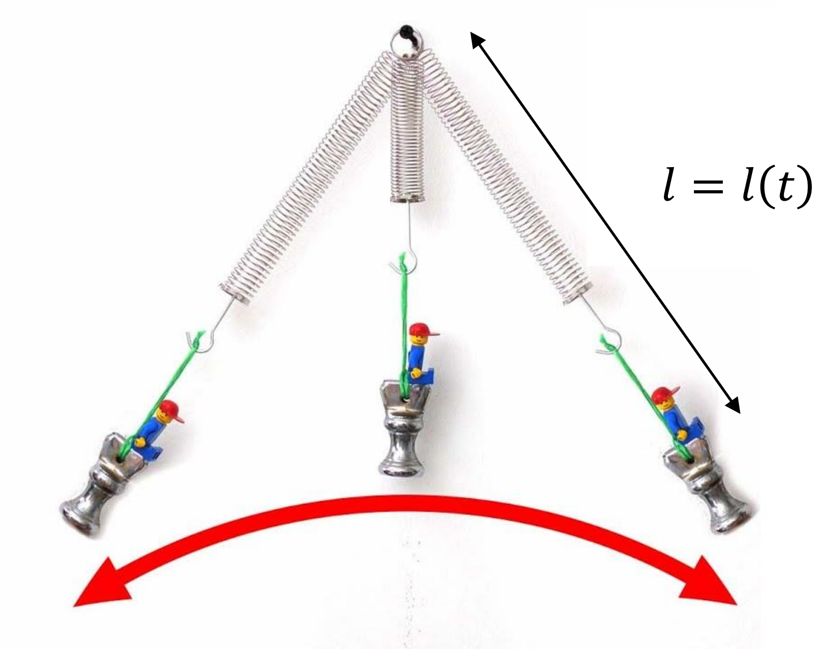
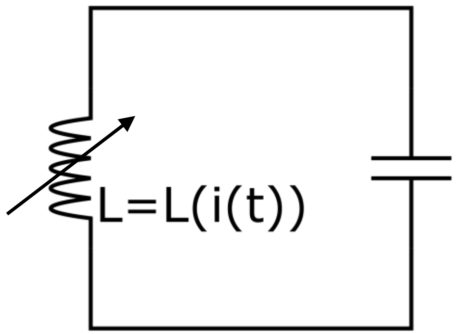
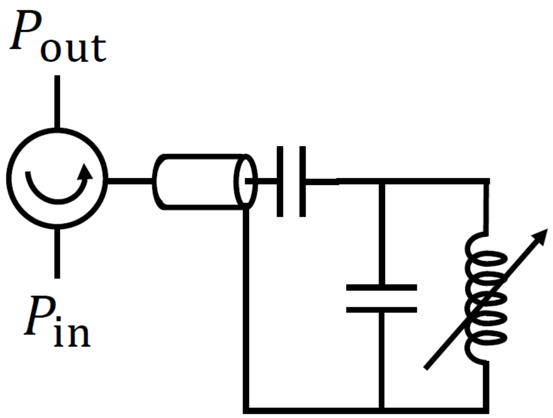




resonator-based parametric amplifiers (JPA, JPC, etc.)



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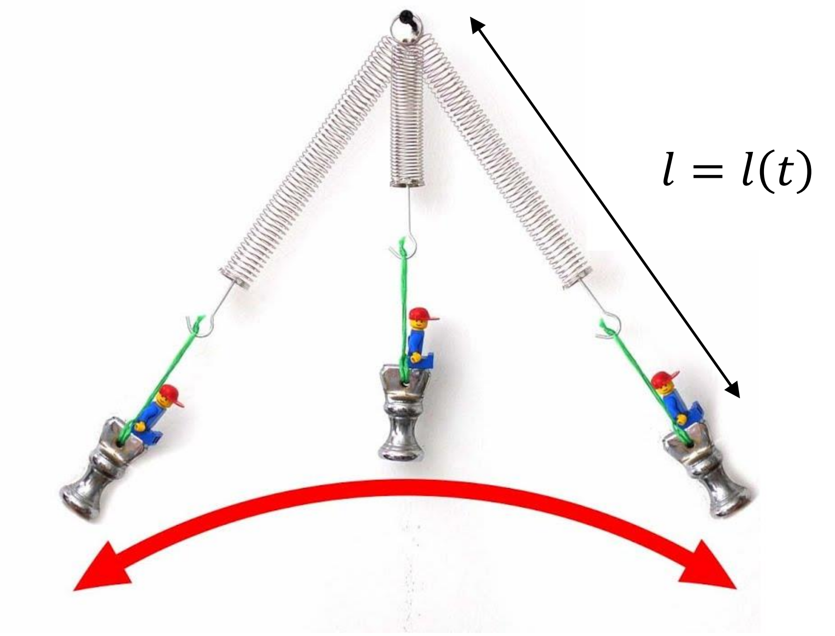
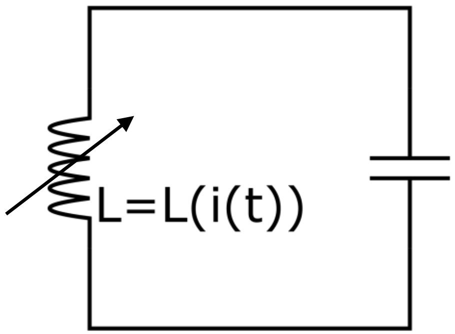
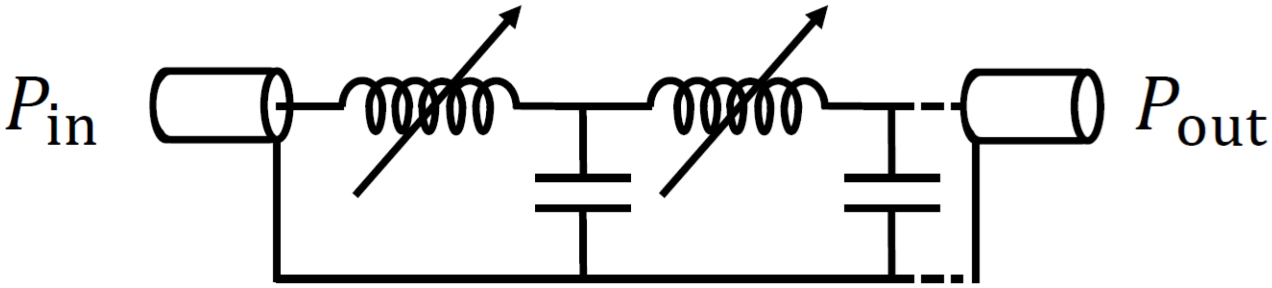
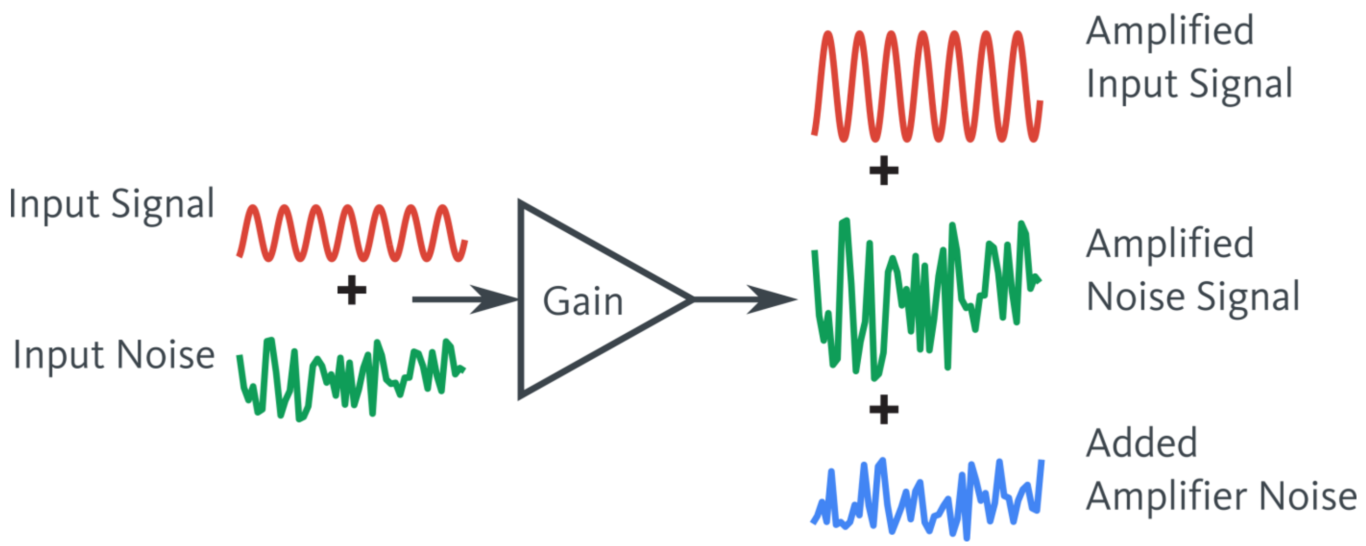




Traveling wave parametric amplifiers
(J-TWPA, KI-TWPA)

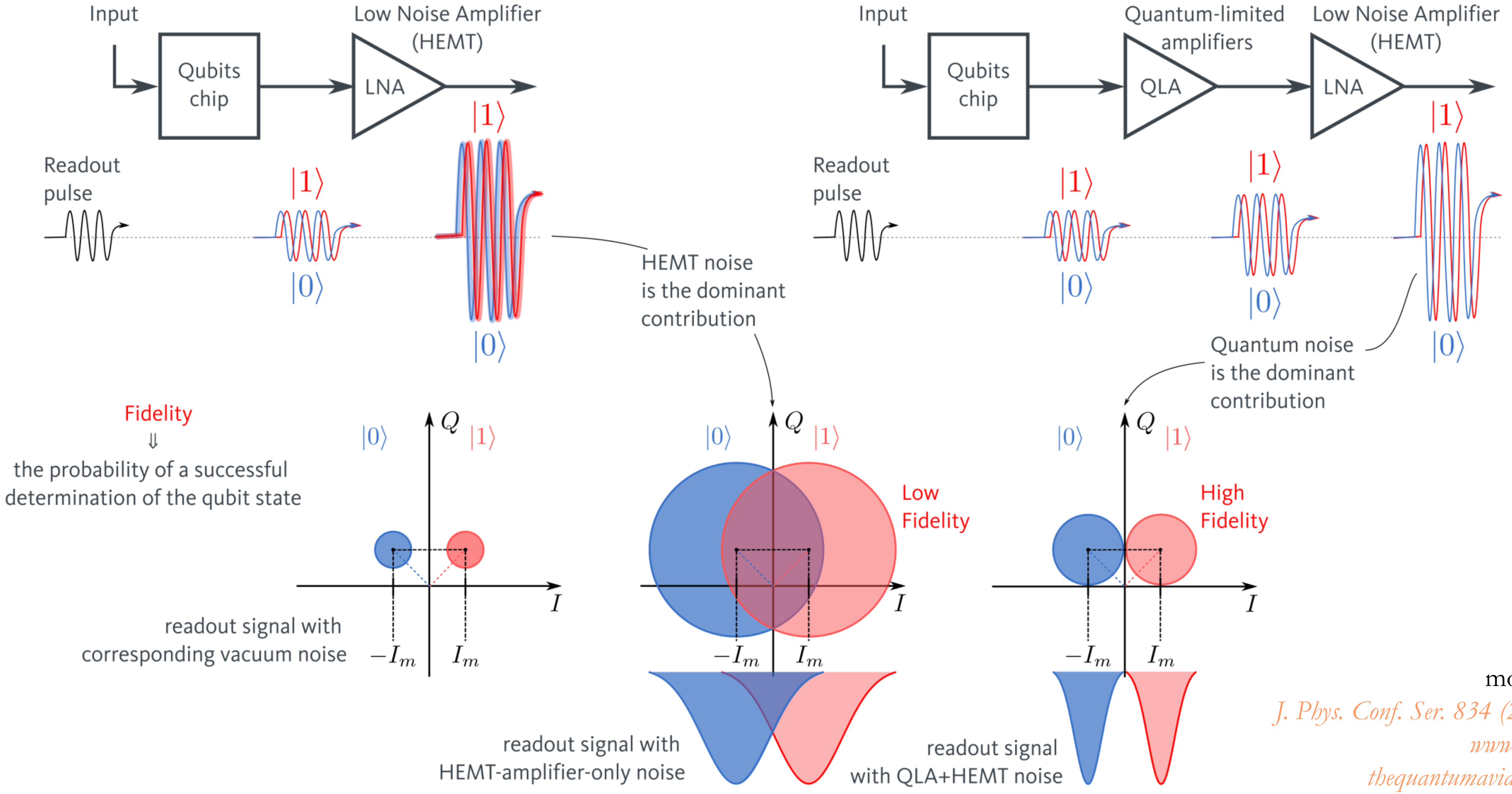


Low noise readout



- 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

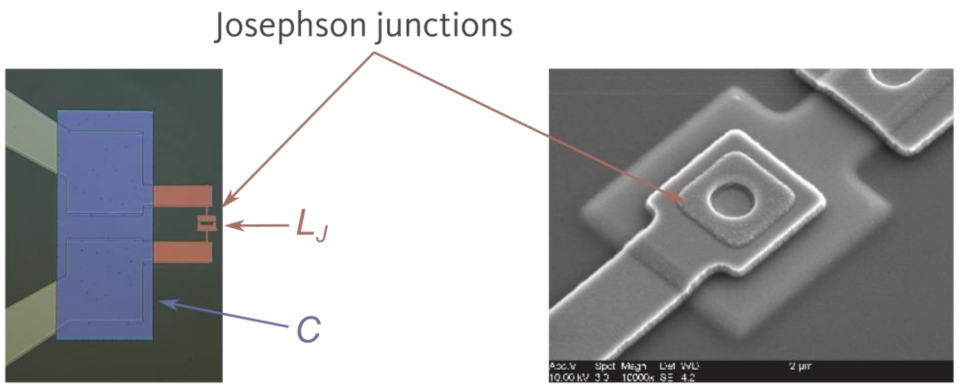
High fidelity qubits readout

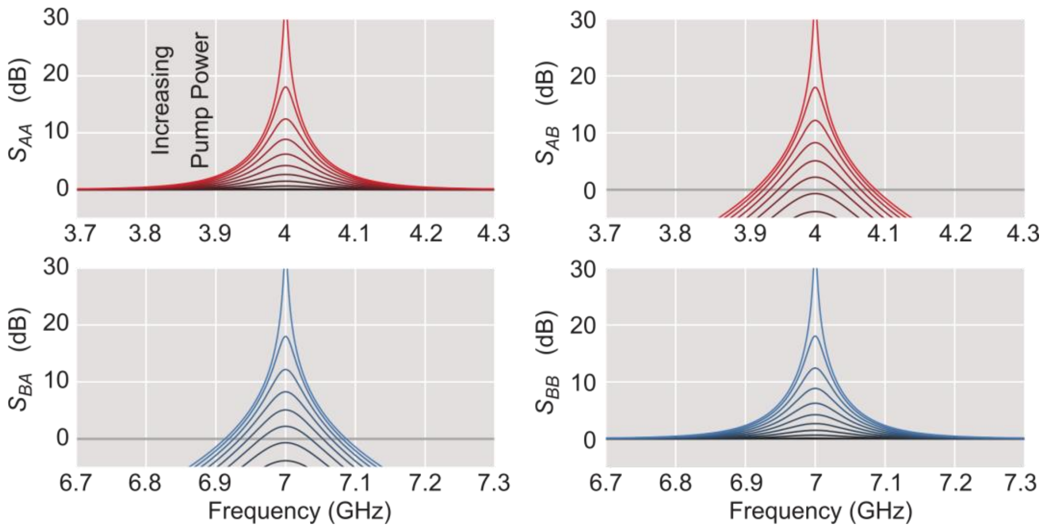


more details on
J. Phys. Conf. Ser. 834 (2017) 012003
www.ibm.com/blogs
thequantumaviary.blogspot.com

Josephson Parametric Amplifiers (JPA)

- signal to be amplified mixed with a strong pump through a non-linear element
- in JPAs, non-linearity provided by the Josephson junction
- demonstrated noise level close to the quantum limit
- very narrow bandwidth < 100 MHz
  - ➢ few detectors/qubits per line
  - ➢ product gain-BW is fixed
- very small saturation power < -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)

- transmission line with embedded non-linear elements

Phys. Rev. B 87, 144301

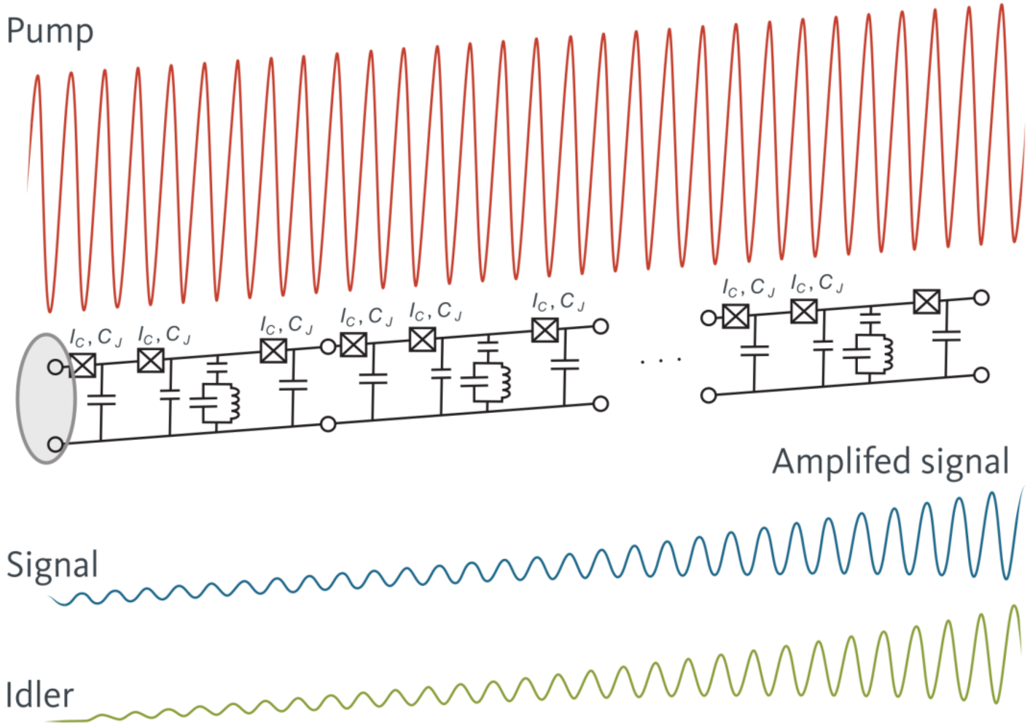
- non-linearity provided by Josephson Junction or intrinsic (non-linear) Kinetic Inductance of a superconductor. At the first order:

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

where I_* is material-dependent, expected to be close to I_c

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

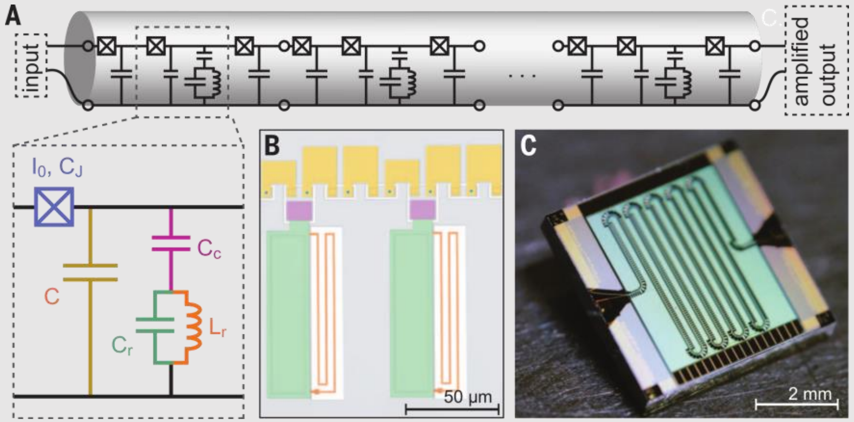
3-Wave Mixing (3WM):
$f_P = f_s + f_i$
biased transmission line



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

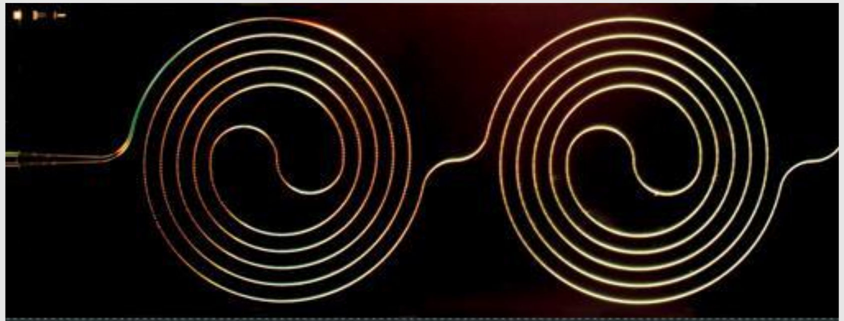
Traveling Wave Josephson Parametric Amplifiers



Science 350, 6258 (2015) 307-310

- TWJPAs: 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 saturation power < -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): 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 saturation power: from -50 to -45 dBm

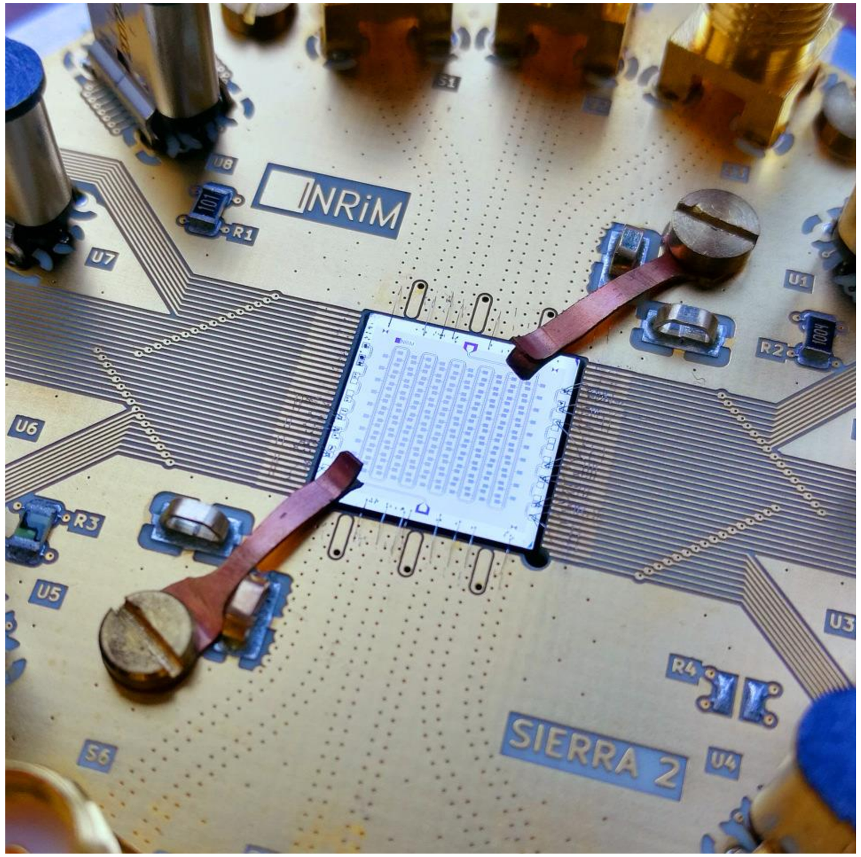
DARTWARS: Detector Array Readout with Traveling Wave AmplifieRS

The main aims of DARTWARS are:

1. development of high-performance amplifiers – both KIT and TWJPA - optimizing design, new materials and fabrication processes

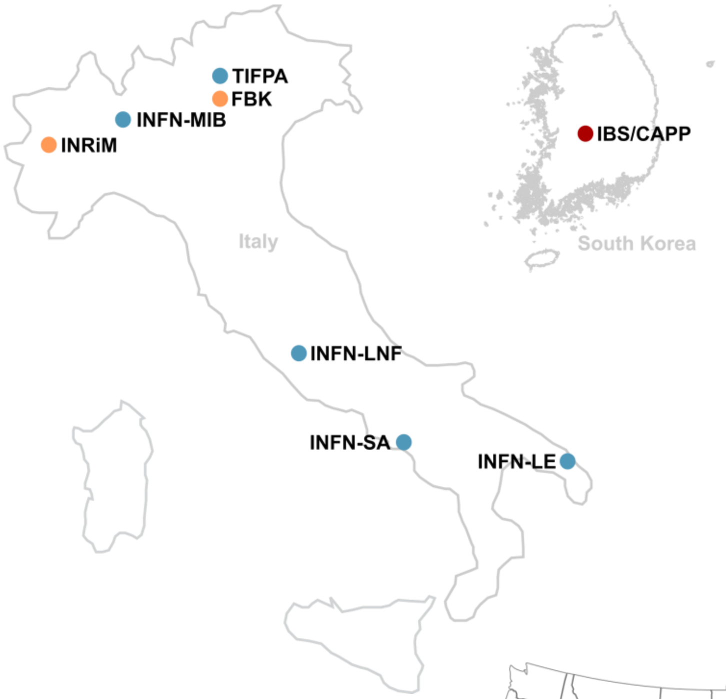
    - high gain ~ 20 dB
    - large saturation power ~ 50 dBm
    - (nearly) quantum limited noise T_N < 600 mK
    - reduced gain ripple
    - yield improvement

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

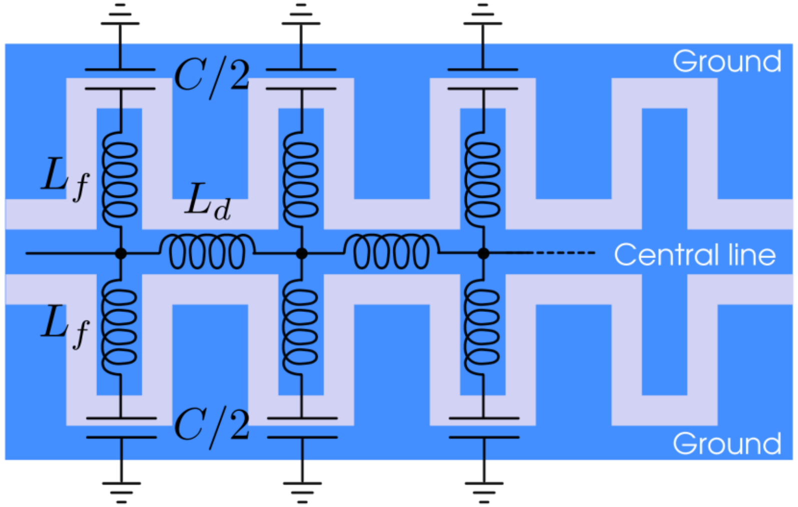
KITWPA within DARTWARS

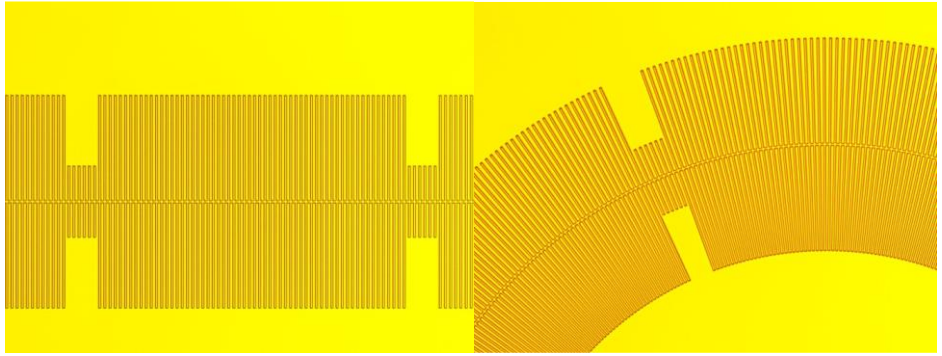
- CPW:
  - ➢ first implementation of KI-TWPA — *B. Eom et. al., Nature Phys. 8 (2012) 623–627*
  - ➢ ease of fabrication
  - ➢ good gains, BW and noise
  - ➢ 2 m long CPW for +15 dB gain
  - ➢ high impedance (200 Ω) → match to 50 Ω required

- Artificial transmission line:
  - ➢ small sections of a CPW recreate a transmission line of lumped-elements
  - ➢ 20 cm long transmission line for +15 dB gain
  - ➢ near-quantum-limited noise demonstrated in the 3.5-5.5 GHz

M. Malnou et al., PRX Quantum 2 (2021) 010302

Artificial transmission line

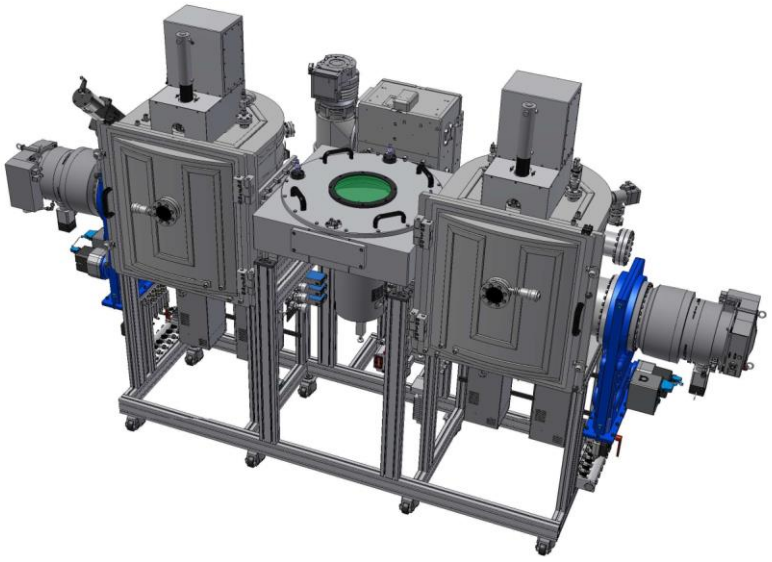


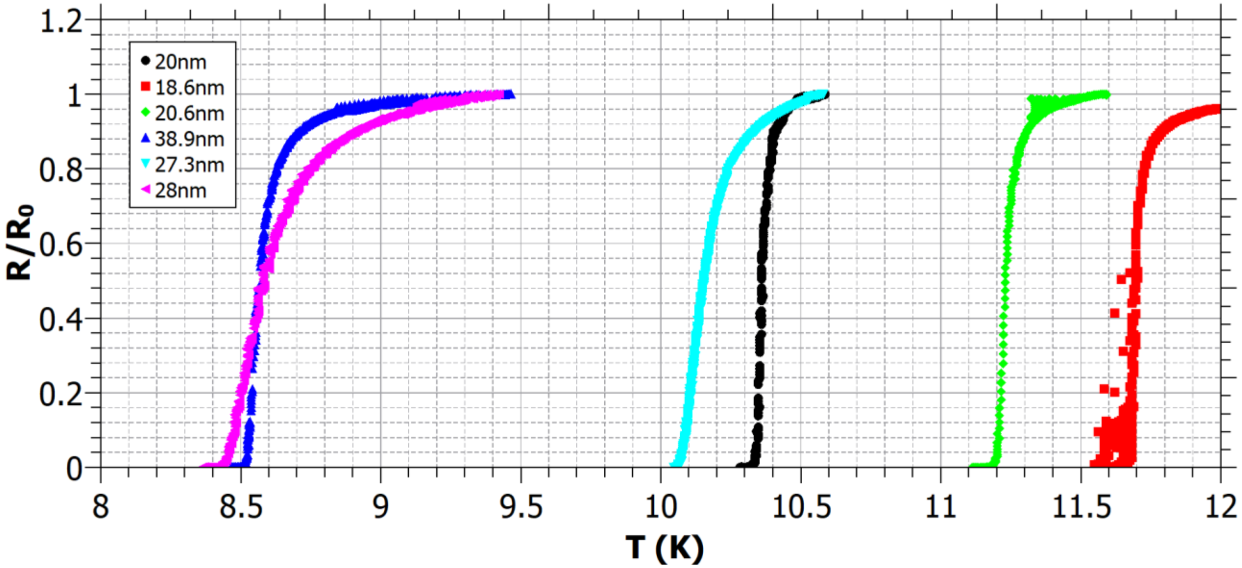


first DARTWARS prototype produced @ FBK Aug 2022

KITWPA: film optimization

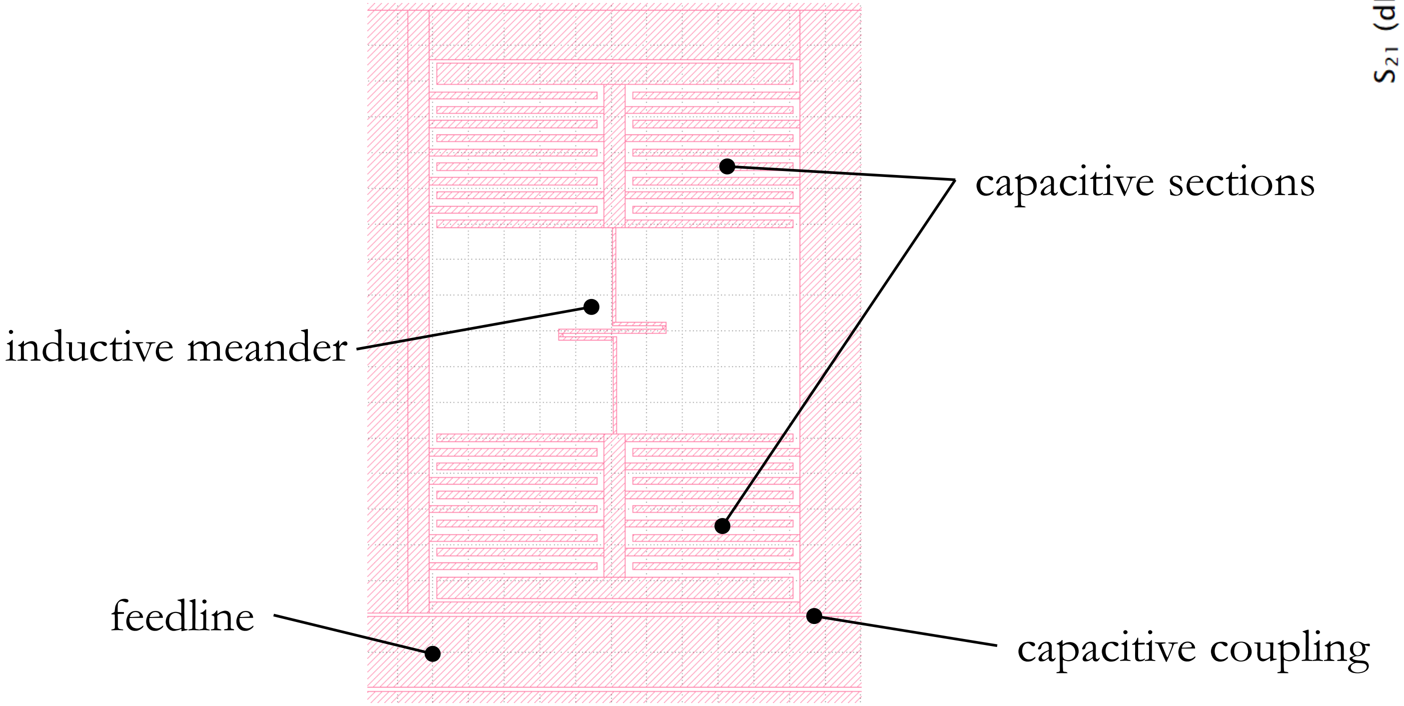
- <u>Goal: deposition of a 20 nm thick NbTiN film</u>
- depositions of Nb and NbN @FBK to test the new sputter (KS 800 cluster)
- T_c and *RRR* compatible with literature
- NbTiN deposited with $Nb_{0.66}Ti_{0.34}$ sputter target
  - obtained T_c=(10-11.5) K (literature 13-15 K)
- new sputter target $Nb_{0.80}Ti_{0.20}$
- Nb dry etch with SF_6 and Ar (new recipe)
- Several miroresonators produced in 2021-22, first prototype of KI-TWPA produced during summer 2022

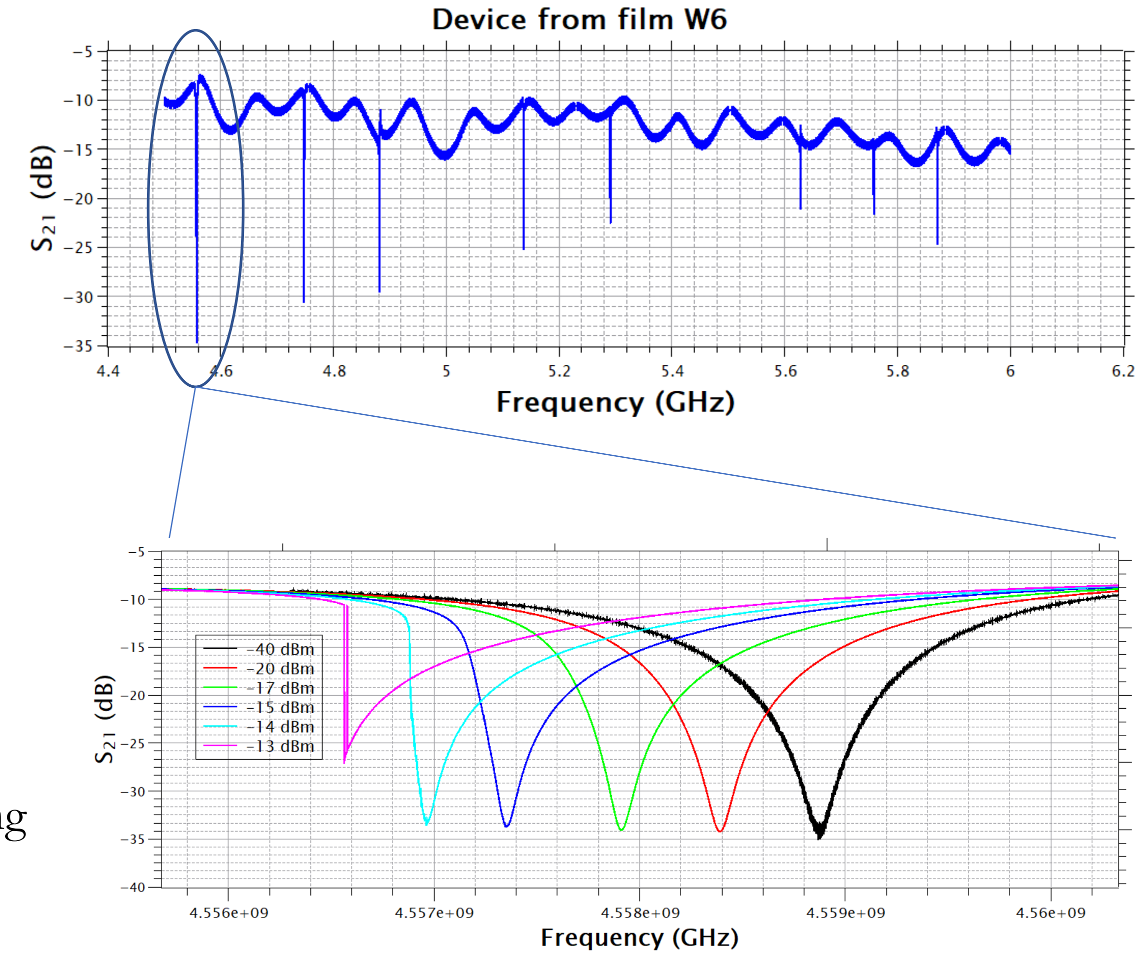




KITWPA: material characterization @FBK/TIFPA

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



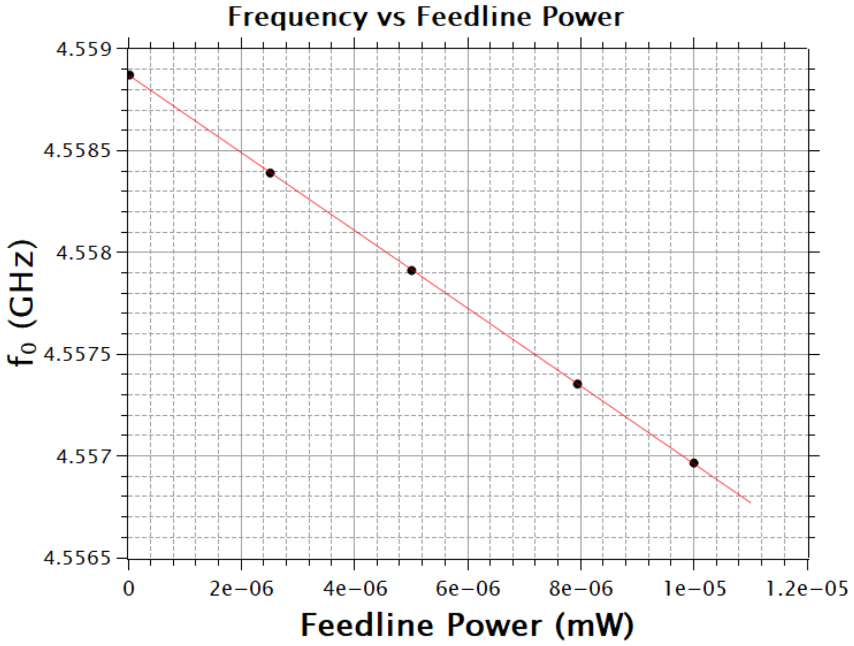


Quality factors in the range (0.2 - 1) · 10^5

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

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

M. Borghesi et. al., arXiv:2208.10101 [quant-ph]



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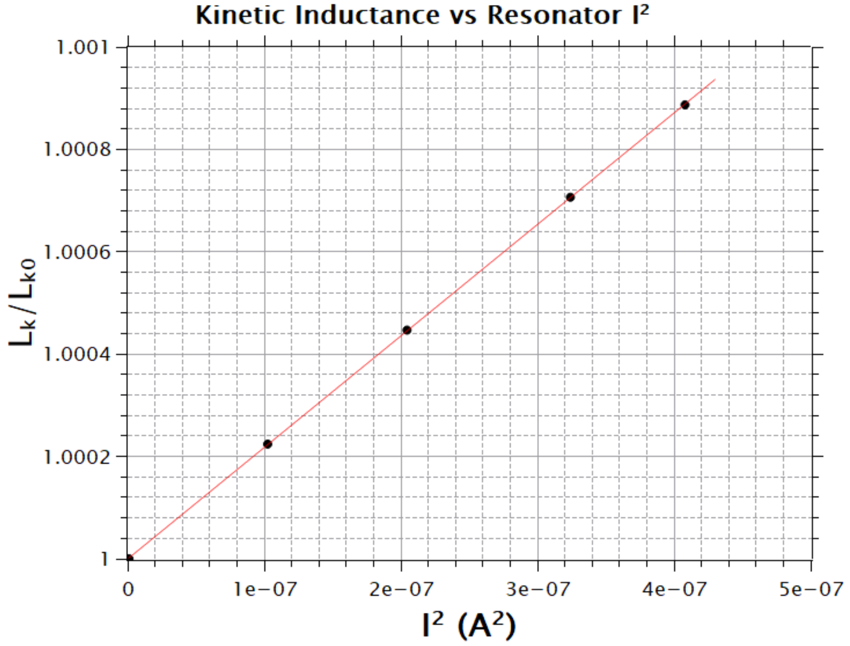


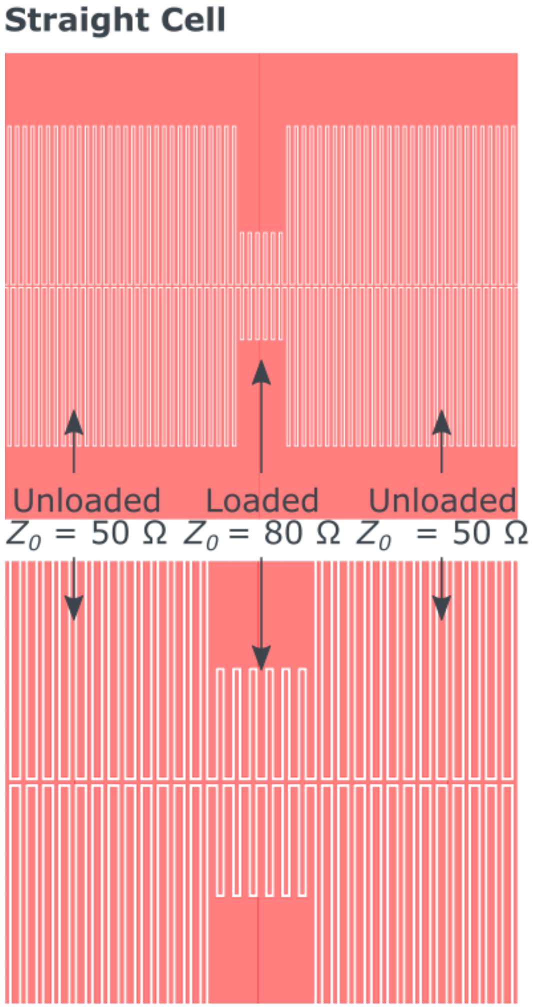
need to:

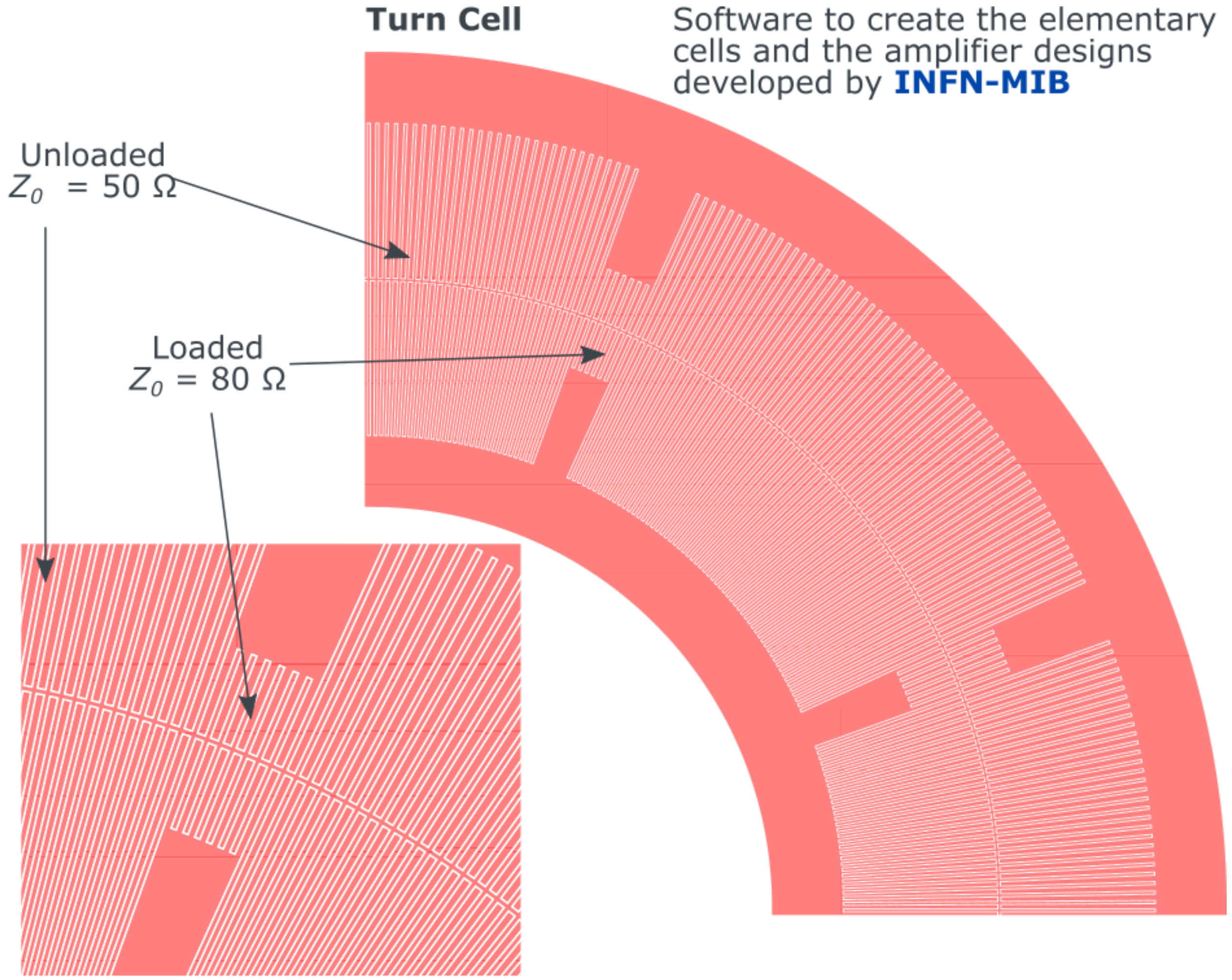
- relate L_k to f_{res} → Sonnet simulation: $(f_{res})^{-2} \propto (L_k + L_g)C$
- relate I^2 to $P_{feedline}$ → estimated C and L from Sonnet
  → circuit simulator (QUCS)
- estimate I_* from $L_k(f_{res})$ (Sonnet)

L_s measured between ~ 4 and 50 pH/sq
I_* (18 – 20) mA
I_c (2.2 – 2.4) mA

max non-linearity $I_c/I_* = 0.25$

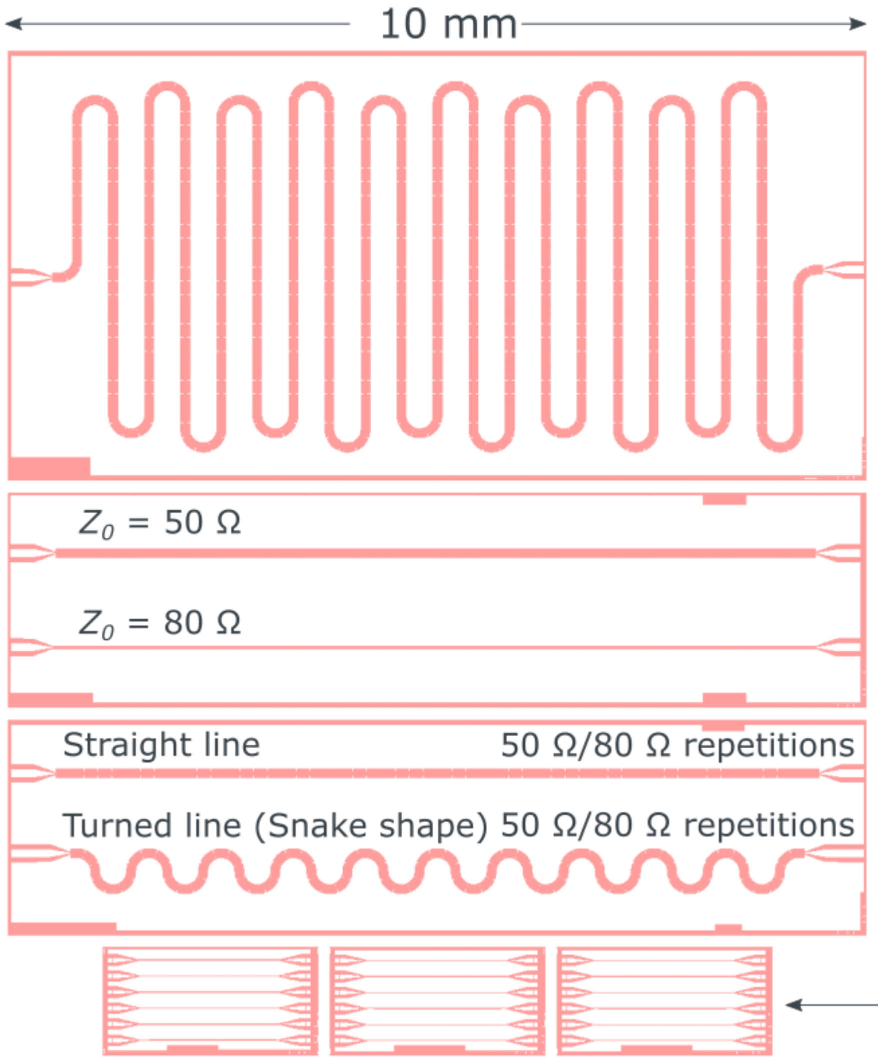
KITWPA – Design





Software to create the elementary cells and the amplifier designs developed by **INFN-MIB**

KITWPA – Design



Design developed in collaboration between **INFN-MIB**, **INFN-TIFPA** and FBK

KIT amplifier, shorter version (foreseen gain ~ 8-10 dB)
Unloaded cell: 60 cells, 50 Ω/cell
Loaded cell: 6 cells, 80 Ω/cell

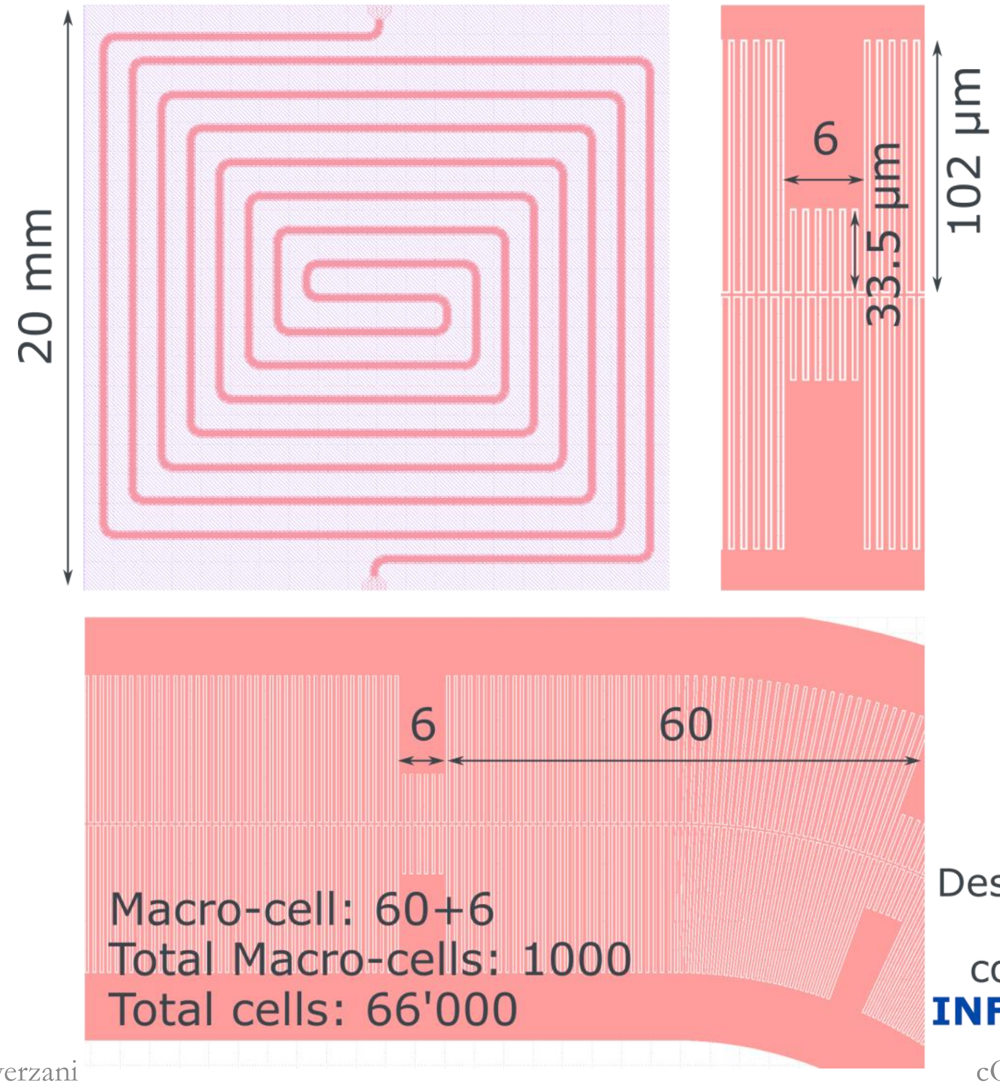
Fishbone line with fixed characteristic impedance for RF characterizations: I_c, I_*, L_k

Fishbone line with unloaded and loaded repetitions for further RF characterizations

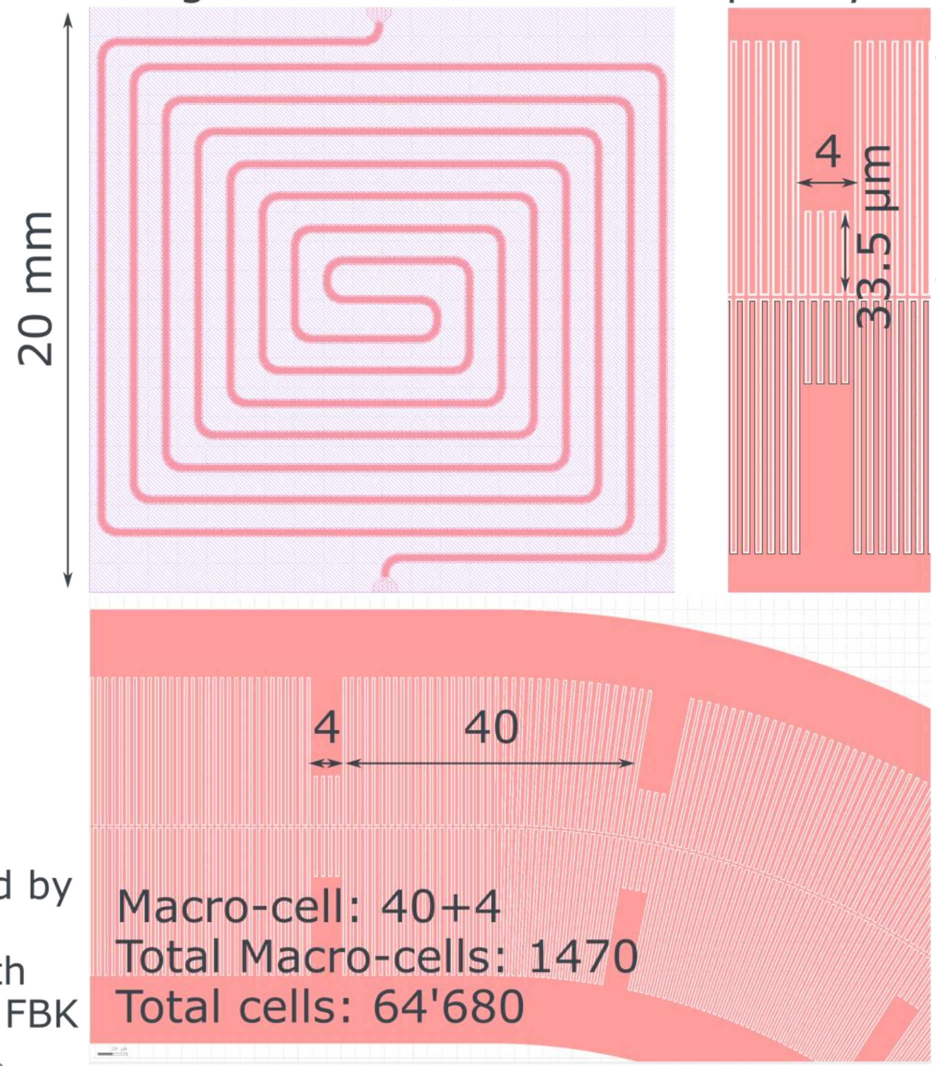
Wires with different size for DC characterizations: T_c, R_n, L_k

KITWPA – Design

Version 60-6
[PRX Quantum 2, 010302 (2021)]



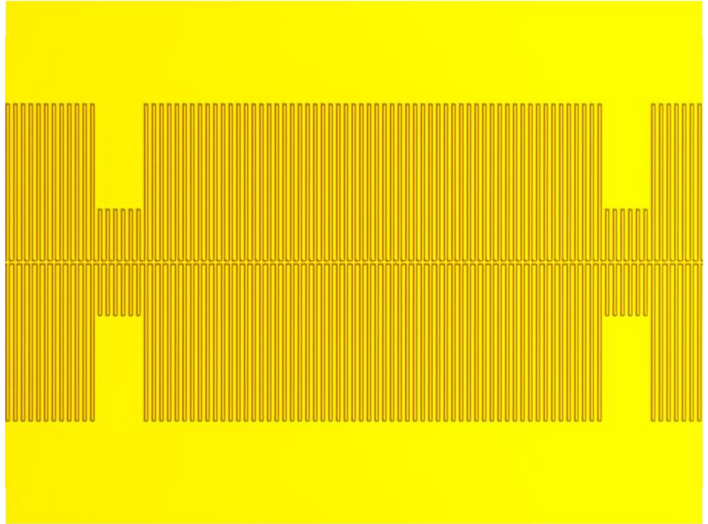
Version 40-4
designed for the C-band frequency range

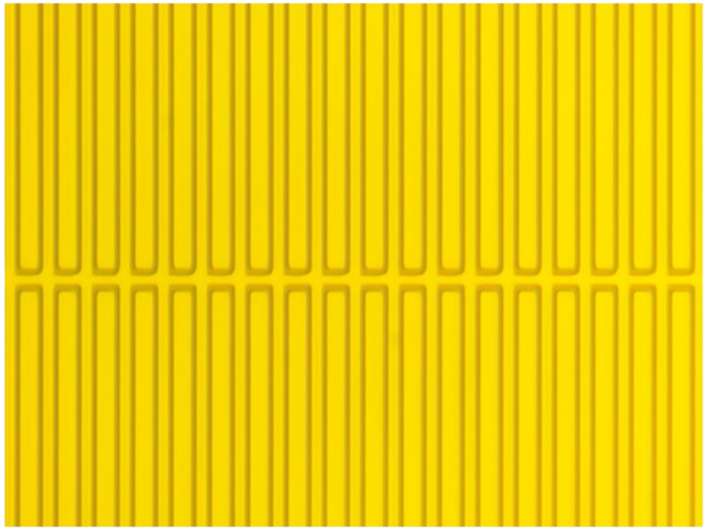


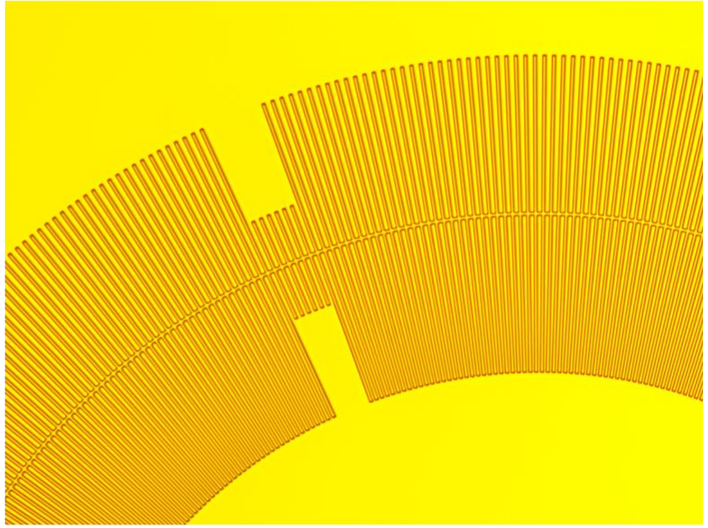
Designs developed by **INFN-MIB** in collaboration with **INFN-TIFPA** and FBK

KITWPA – Production

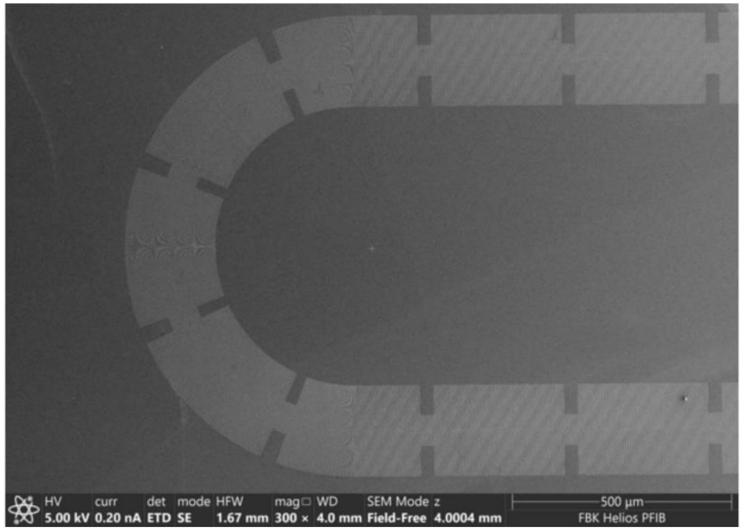
Optical Microscopy Images

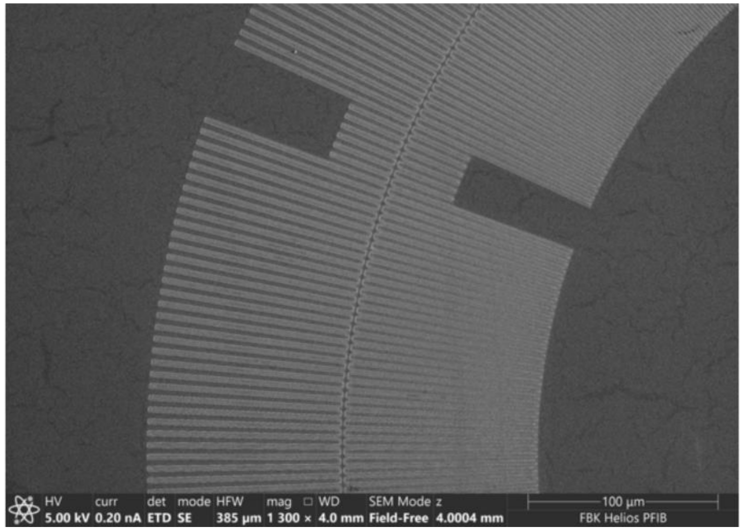




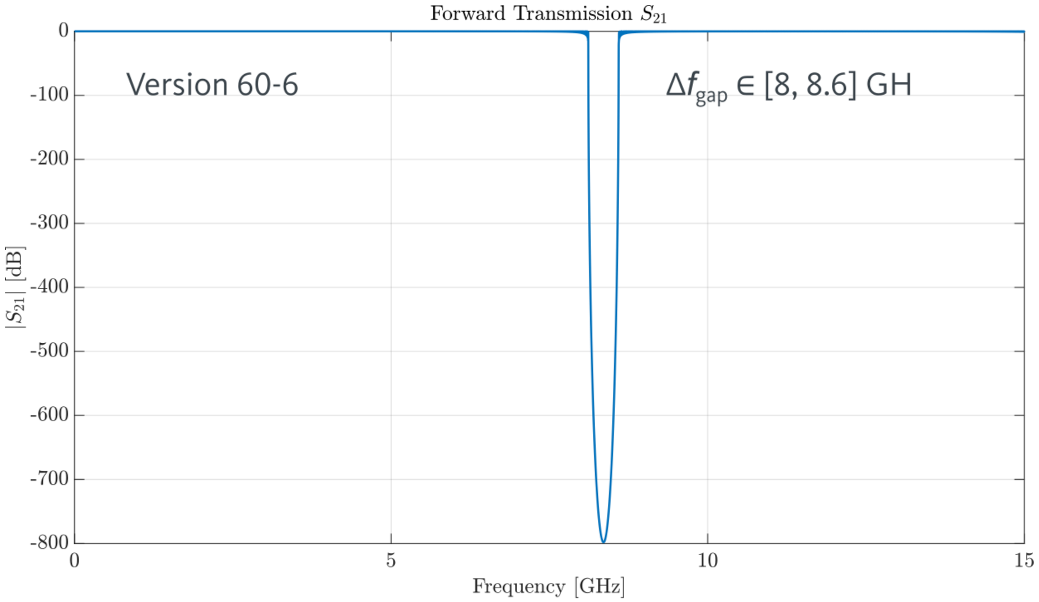


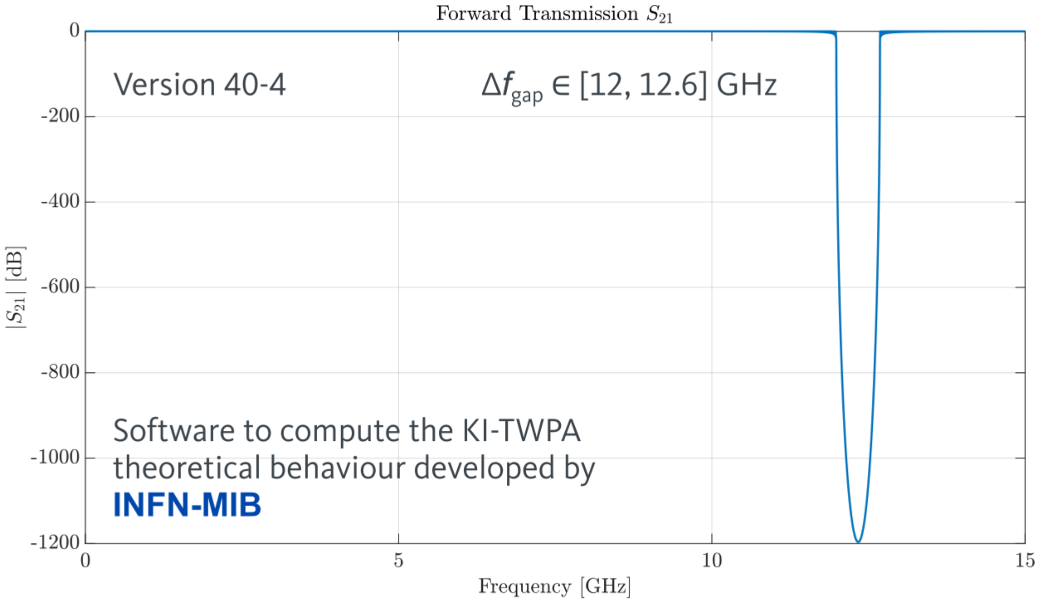
Scanning Electron Microscopy Images

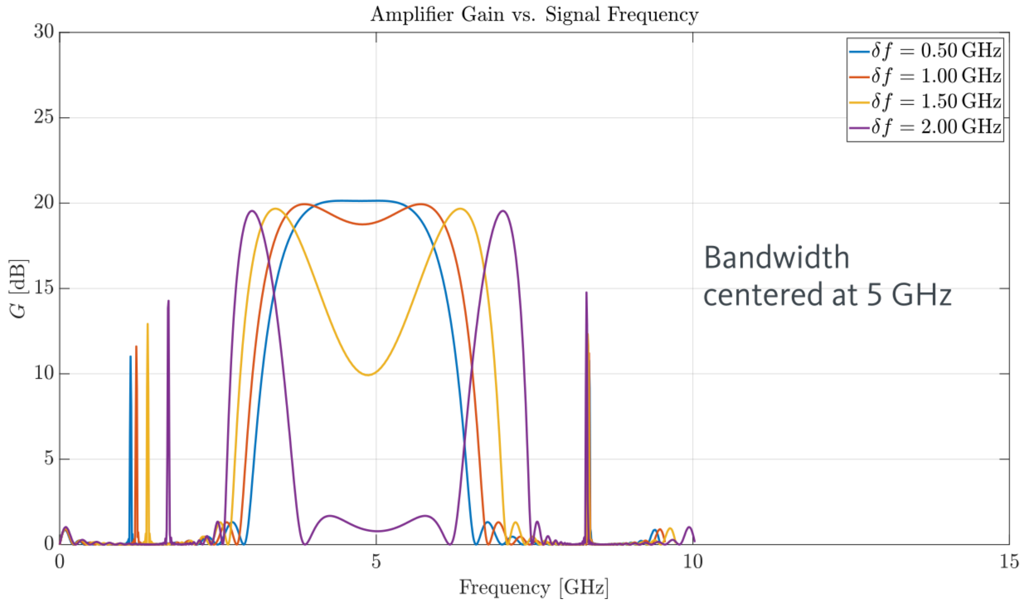


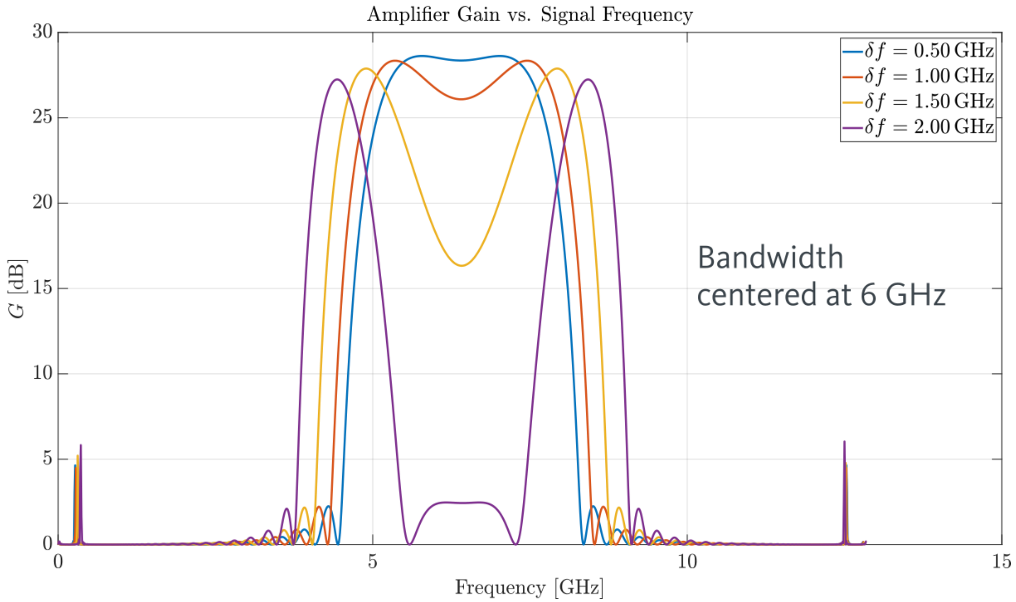


KITWPA – Expected performance



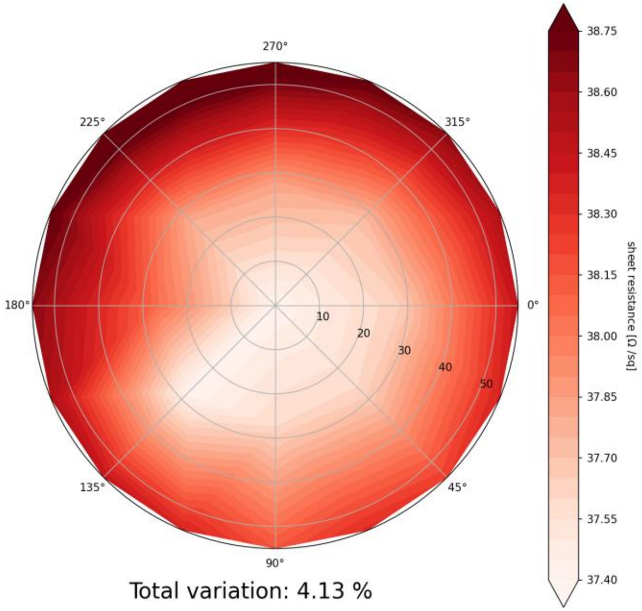


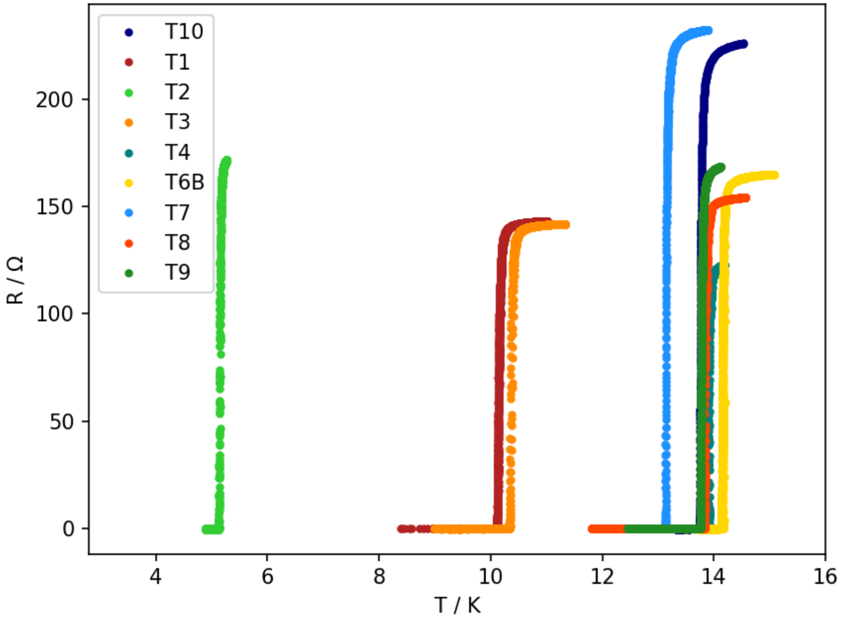


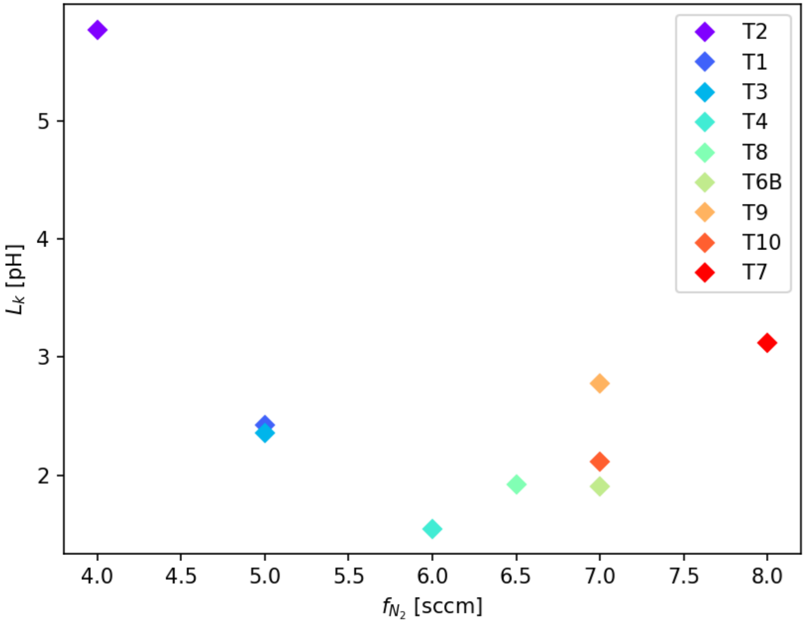


KITWPA: film optimization (cont'd)

- tests with $Nb_{0.80}Ti_{0.20}$ sputter target
- optimization of recipe: **N_2 flow**, power and pressure
- wafer cut in strips → T_c, *RRR*, R_n → L_s
- T_c = (5-14) K (literature 13-15 K)
- thickness disuniformity down to few %







Conclusions

- the demand for high gain/wide bandwidth with low noise amplifiers is driven by the readout of superconducting qubits, cryo detectors, RF cavities, …

- design of DARTWARS KI-TWPA started in 2021 and the first material characterizations have been performed across 2021 and 2022. The first devices has been produced during summer; next production with new target expected soon

- demonstration of detectors/qubits readout is expected for 2023

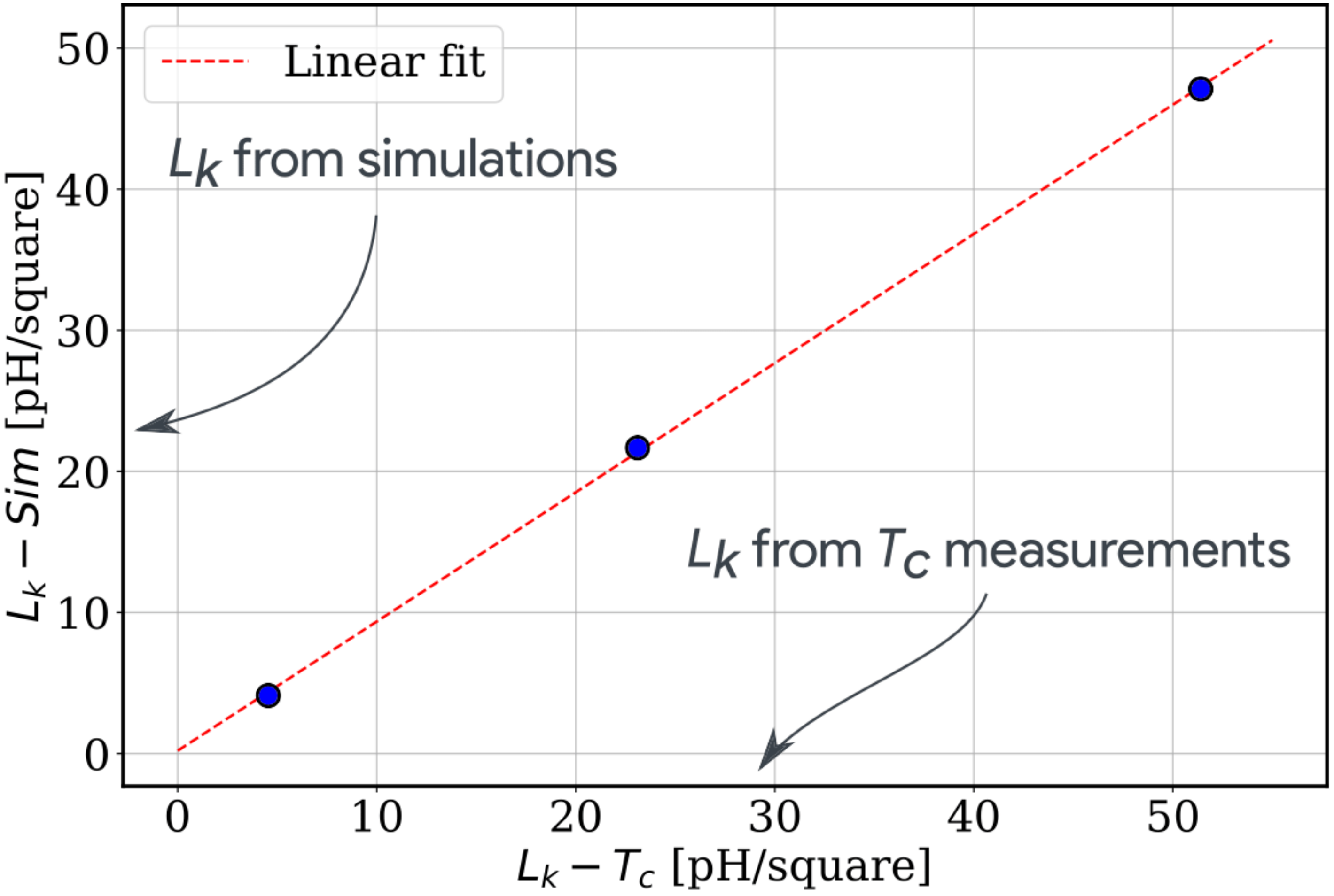
- DARTWARS will allow to build the expertise within INFN in designing and developing innovative quantum devices

- the results of DARTWARS 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/

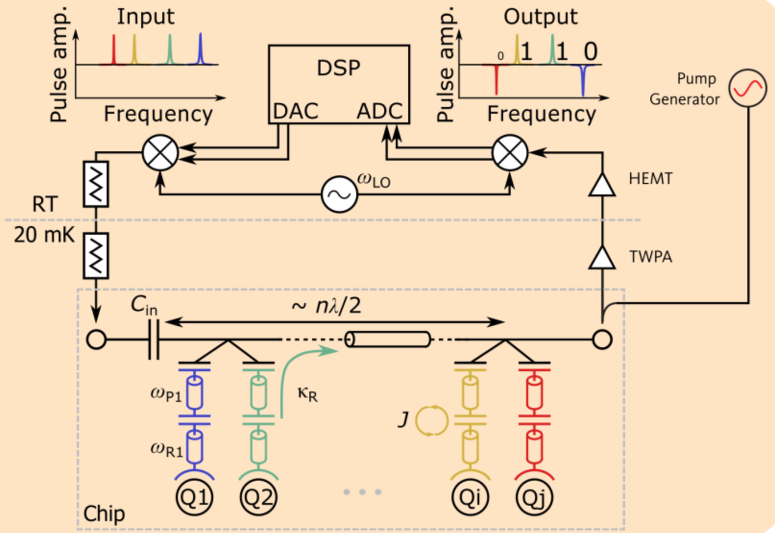
Backup slides

L_s comparison

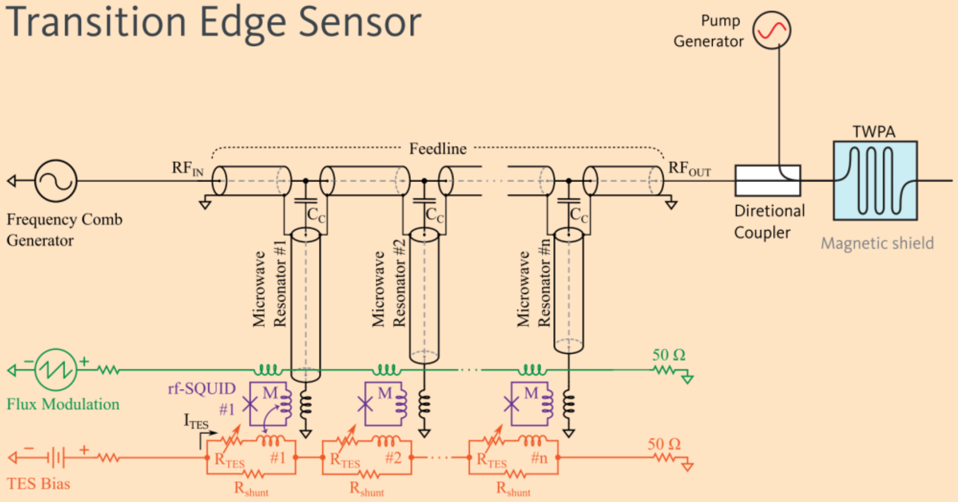


DARTWARS: readout of superconducting devices

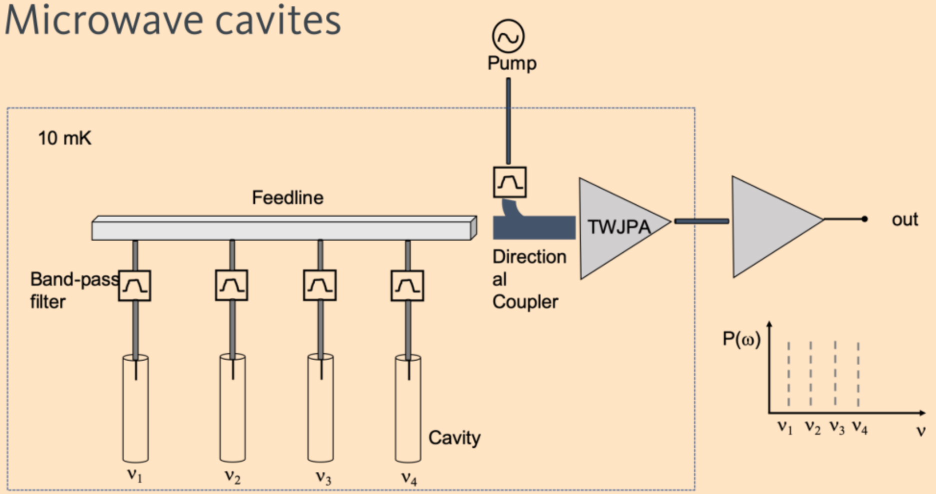
Qubit



Transition Edge Sensor



Microwave cavites



Quantum Sensing of Magnons

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