Traveling Wave Parametric Amplifiers

(within DARTWARS)

MARIE CURIE ACTIONS
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INFN
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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?

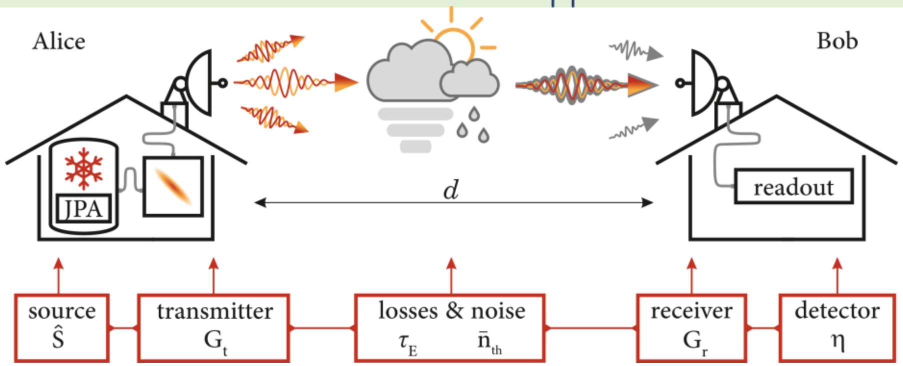
- **multiplexed readout of large detector/qubit array**
  N. Zobrist et al. Appl. Phys. Lett. 115 (2019) 042601
  L. Ranzani et al. Appl. Phys. Lett 113 (2018) 242602
  J. Heinsoo et al. Phys. Rev. Applied 10 (2018) 034040

- **readout for axionic dark matter detection**
  C. Braggio et al. Rev. Sci. Instrum. 93 (2022) 094701
  J.M. Navarro and B.K. Tan Proc.SPIE Int.Soc.Opt.Eng. 11881 (2021)

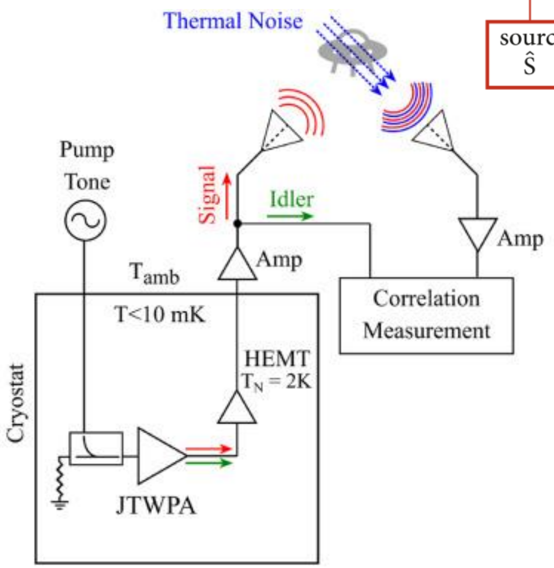
- **microwave quantum key distribution**
  F. Fesquet et al. arXiv:2203.05530v1 [quant-ph]

- **quantum radar**
  L. Fasolo et al. Measurement: Sensors 18 (2021) 100349

- **squeezed-state microwave radiation source**
  A.L. Grimsmo and A. Blais Npj Quantum Inf. 3 (2017) 20
  M. Esposito et al. Phys. Rev. Lett. 128 (2022) 153603



quantum communication
arXiv:2203.05530v1 [quant-ph]



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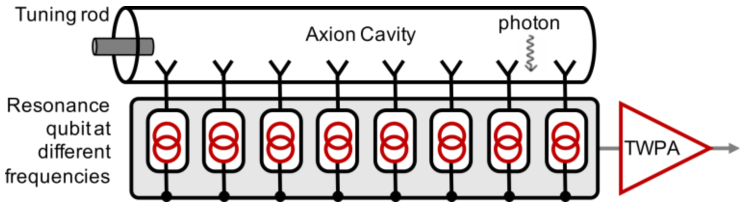
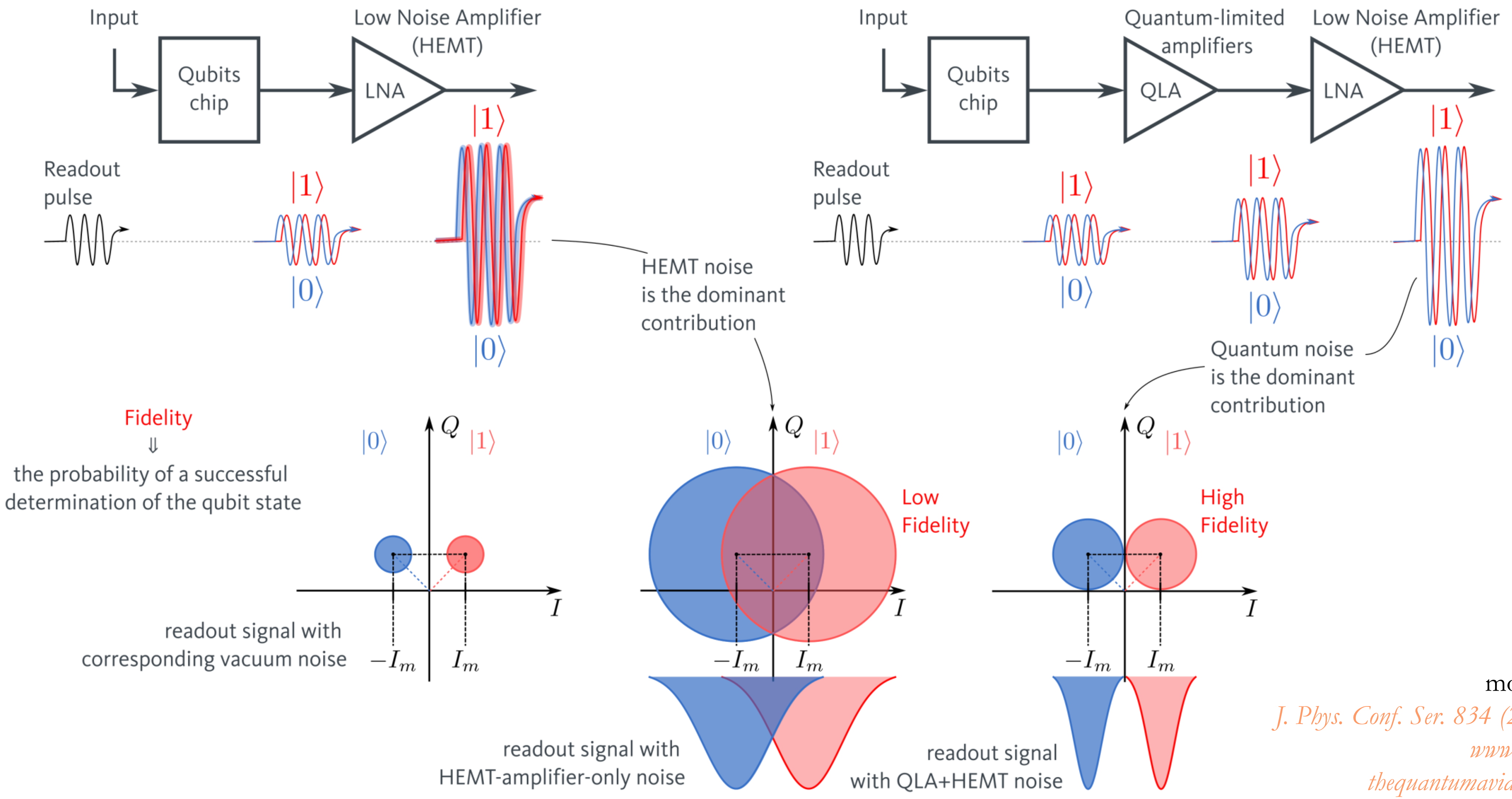
Measurement: Sensors 18 (2021) 100349



DM detection
Proc.SPIE Int.Soc.Opt.Eng. 11881 (2021) 139-148

all these applications require broadband amplification and minimum added noise (i.e. information preservation)
Travelling-Wave Parametric Amplifiers (TWPA) are (near) quantum limit amplifiers capable to match these requirements

High fidelity qubits readout



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

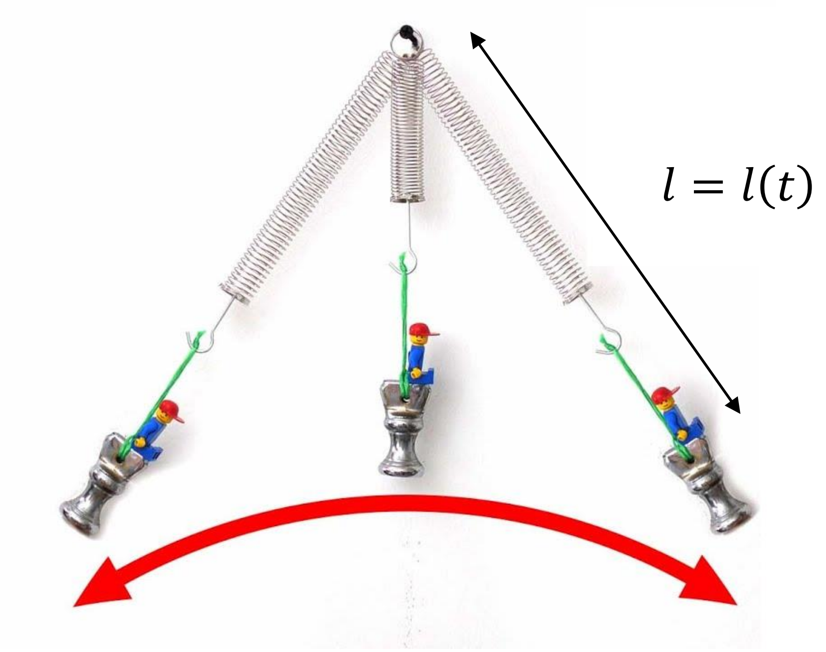
Parametric amplification for dummies

Resonance if:

1) sinusoidal driving force ($f_d = f_r$ → linear gain with time)
2) one parameter periodically varied ($f_d = 2f_r$ → 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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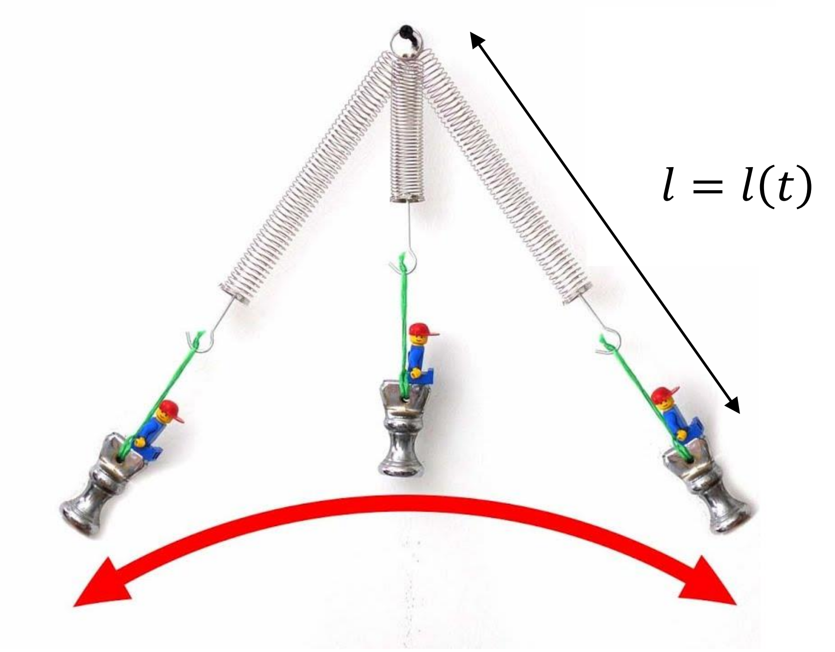

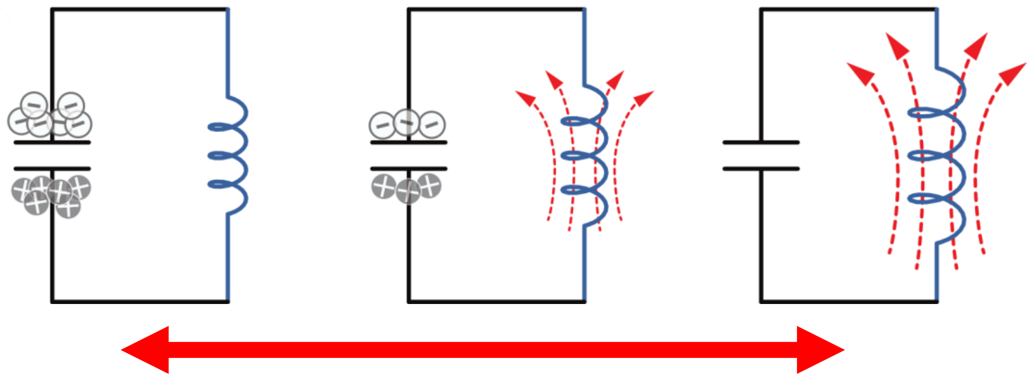

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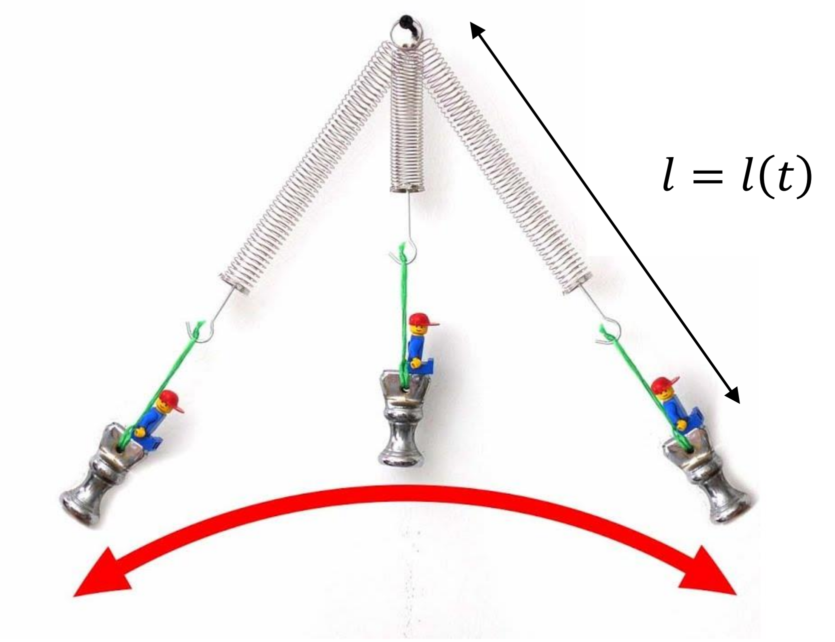

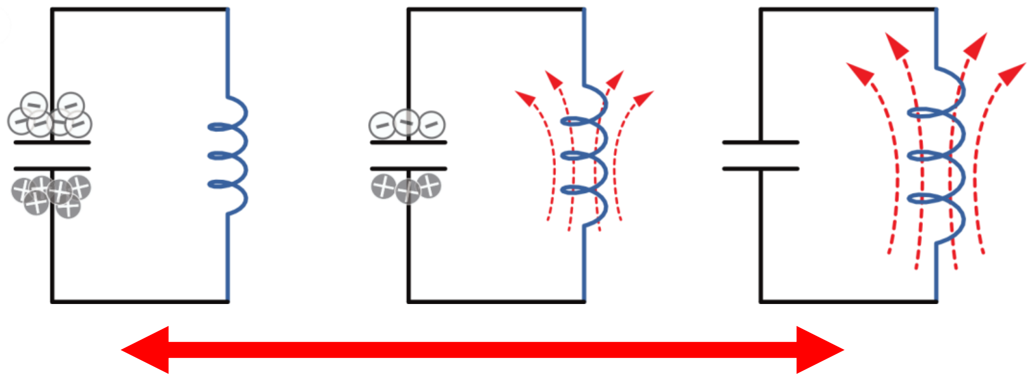

Josephson Junctions (JJ) → $L_J = L_{J0} \frac{\arcsin(I/I_c)}{I/I_c}$

Parametric amplification for dummies

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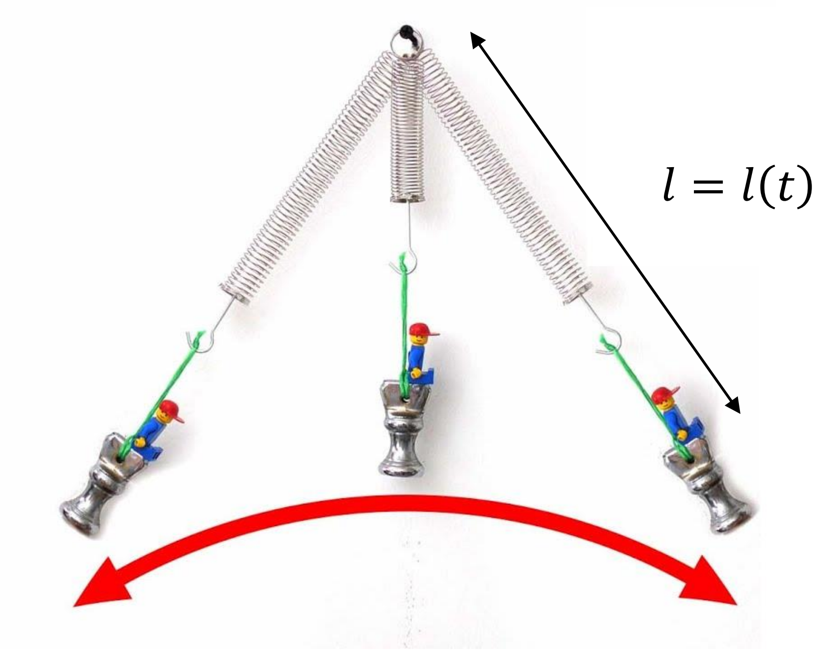

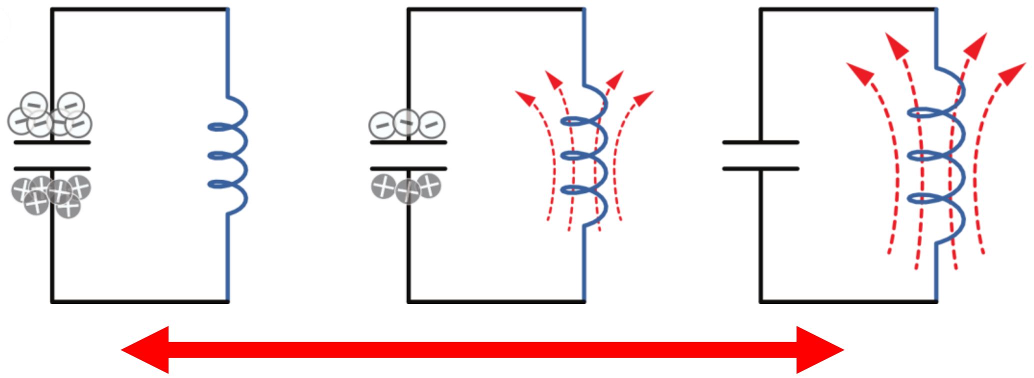

Kinetic Inductance (KI) → $L_K = L_{K0}\left(1 + \frac{I^2}{I_*^2}\right)$

Parametric amplification for dummies

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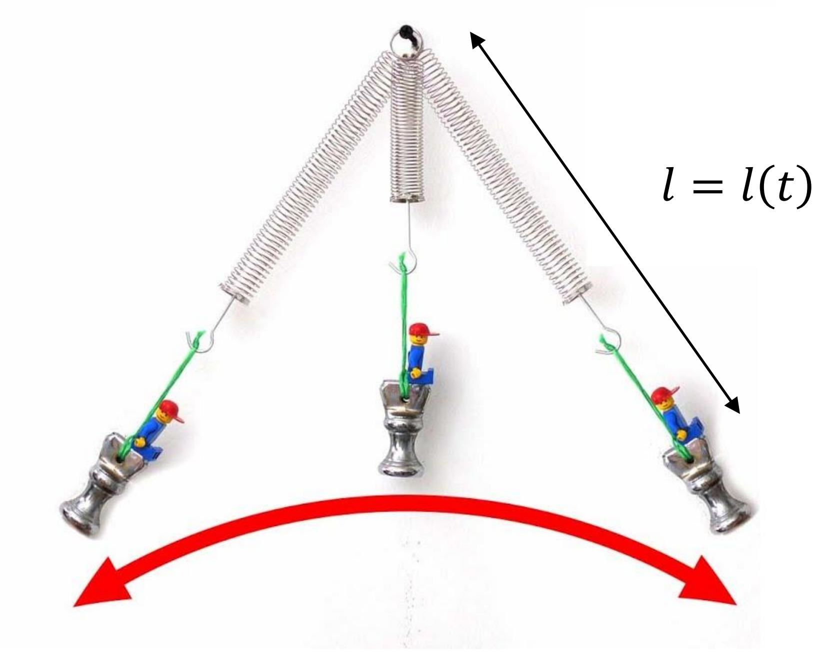
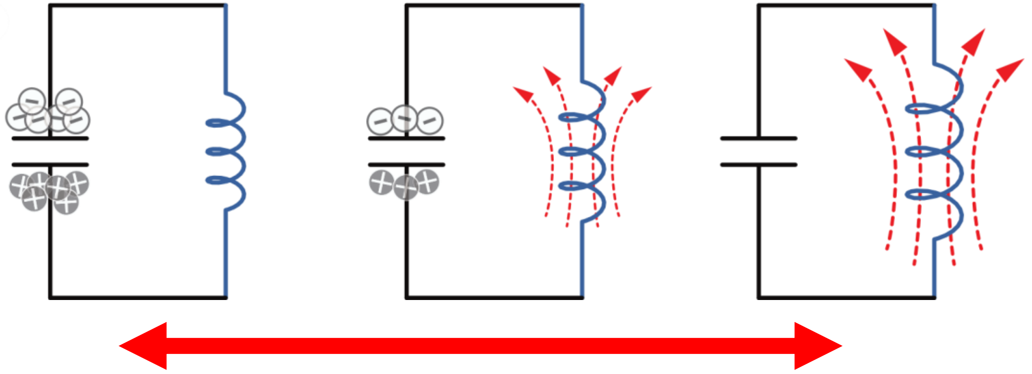
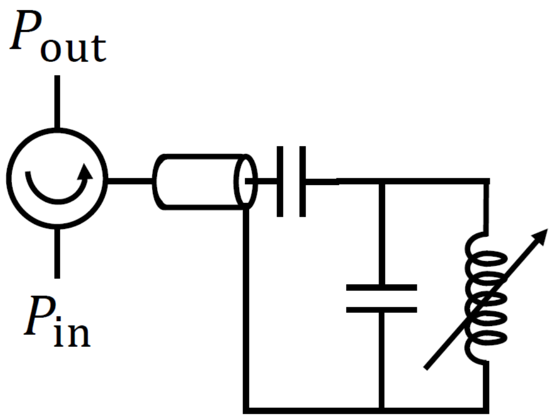




resonator-based parametric amplifiers (JPA, JPC, etc.)



Parametric amplification for dummies

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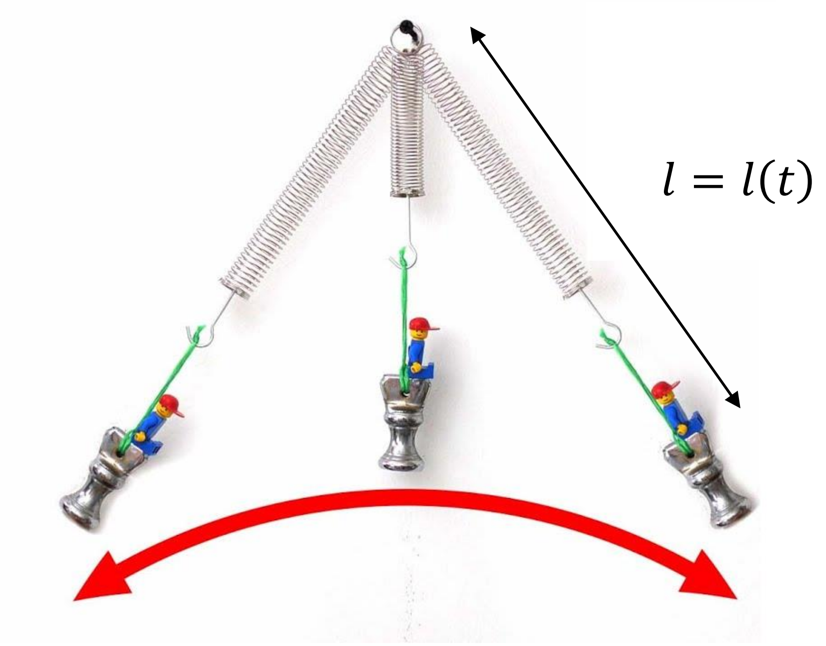
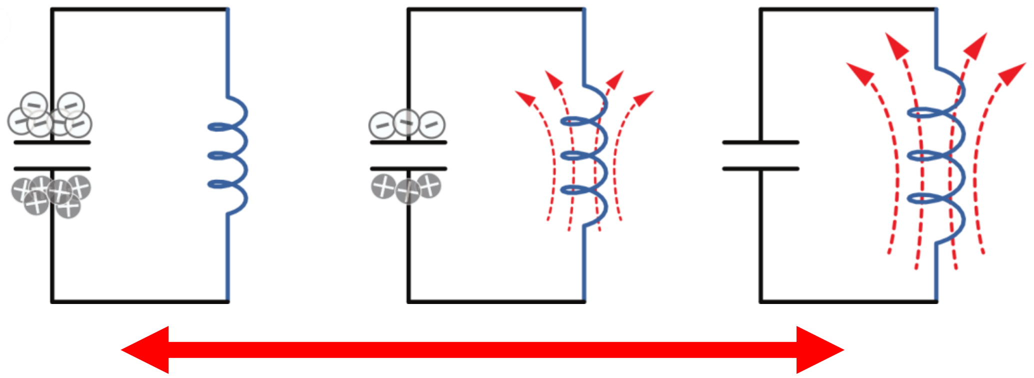
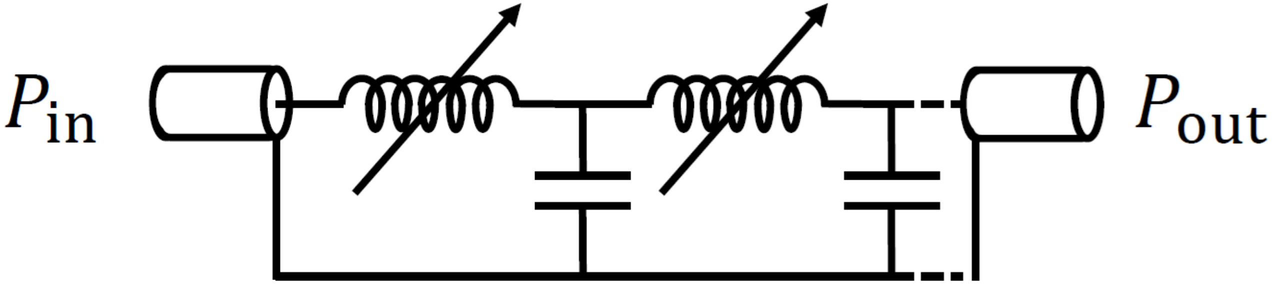
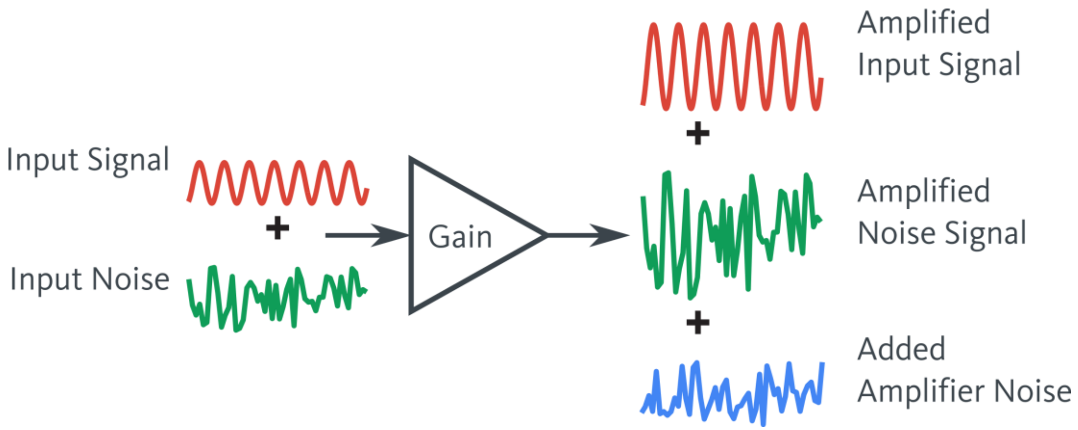




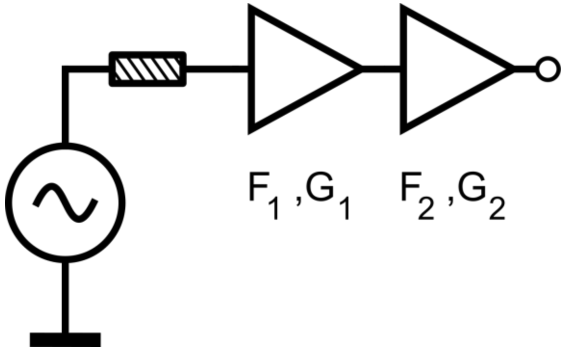
Traveling wave parametric amplifiers (J-TWPA, KI-TWPA)



Low noise readout



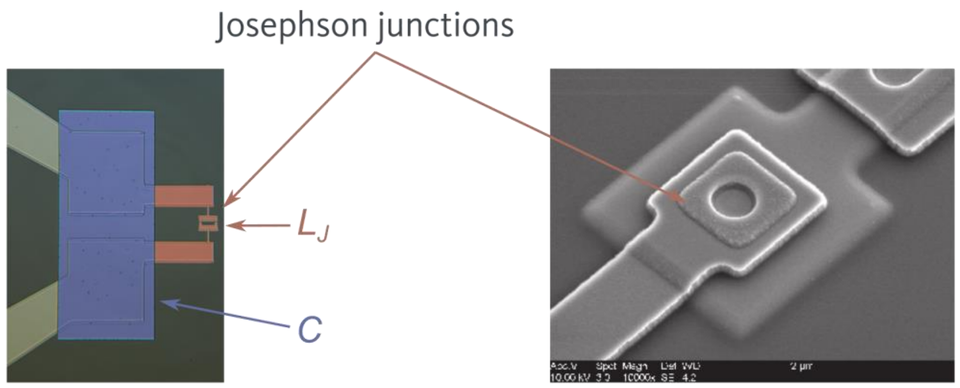
- the amplifier adds noise to several sources (thermal fluctuations, e-h recombination in semiconductors, etc.)
- a quantum limited amplifier has an added (temperature) noise $T_N/f \sim h/2k_B \sim 25$ mK/GHz
- in a two-stage amplification scheme, the first stage dominates the overall noise figure (if $G_1 \gg F_2$)

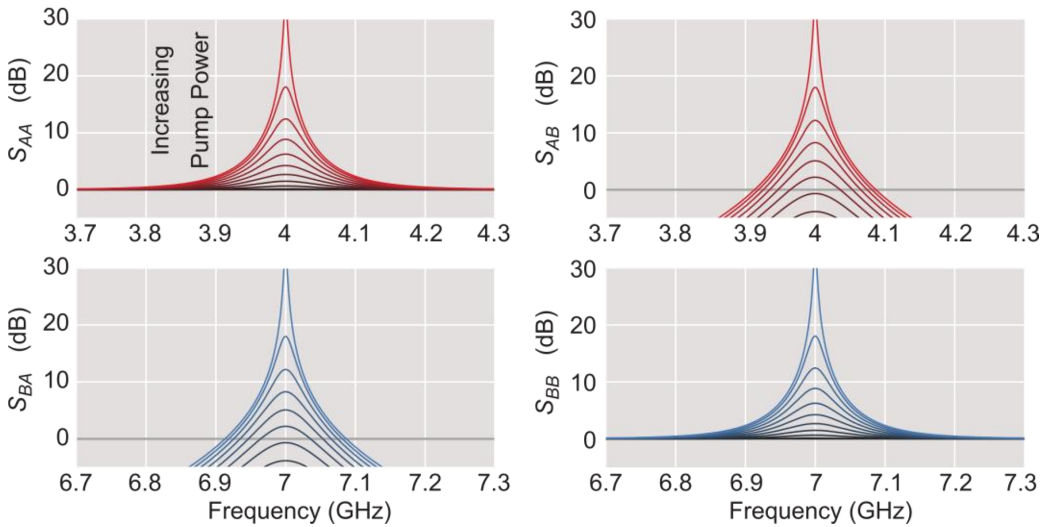


$$F_{TOT} = F_1 + \frac{F_2 - 1}{G_1}$$

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





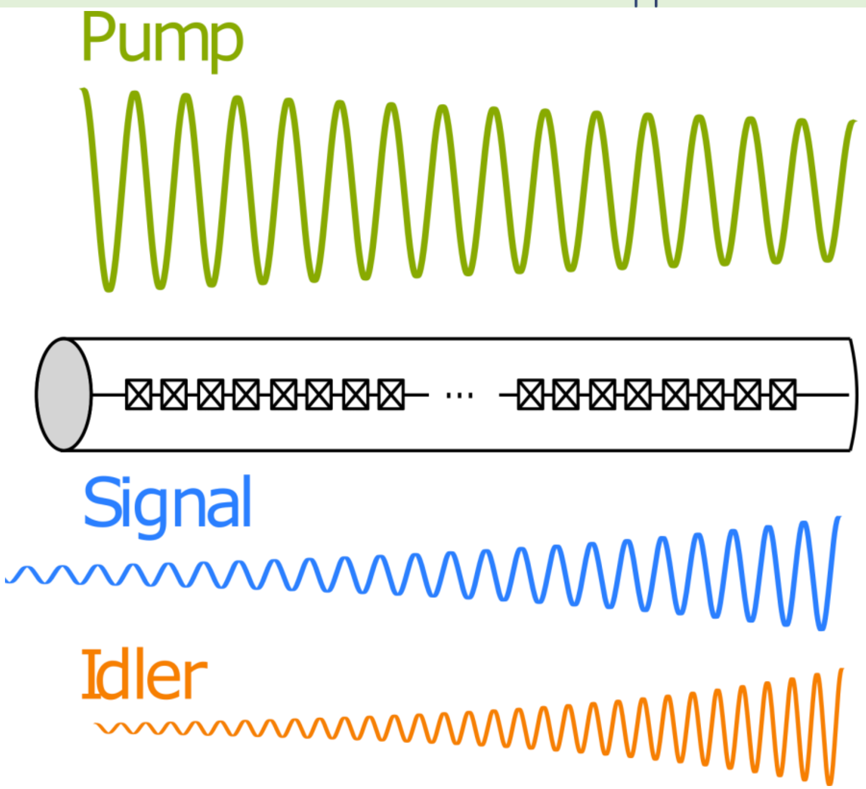
IEEE Microwave Magazine 21, 8 (2020) 45

Traveling Wave Parametric Amplifiers (TWPAs)

- transmission line with embedded non-linear elements

Phys. Rev. B 87, 144301

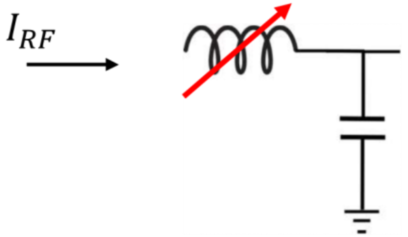
- non-linearity provided by Josephson Junction or intrinsic (non-linear) Kinetic Inductance of a superconductor



Unbiased transmission line:
4-wave mixing

$$\Delta\beta = k_s + k_i - 2k_p$$

$$2\omega_p = \omega_s + \omega_i$$

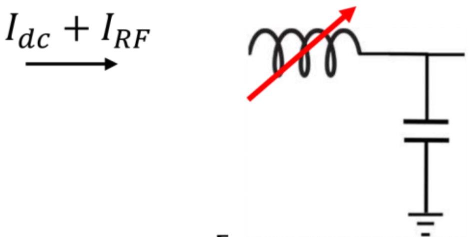


$$L(I) = L_o\left[1 + \left(\frac{I_{RF}}{I_*}\right)^2\right]$$

Biased transmission line:
3-wave mixing

$$\Delta\beta = k_s + k_i - k_p$$

$$\omega_p = \omega_s + \omega_i$$



$$L(I) \approx L_o\left[1 + \frac{I_{dc}^2}{I_*^2} + 2\frac{I_{RF}I_{dc}}{I_*^2}\right]$$

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

Periodic loading

- periodic loading along the transmission line creates the phase matching condition

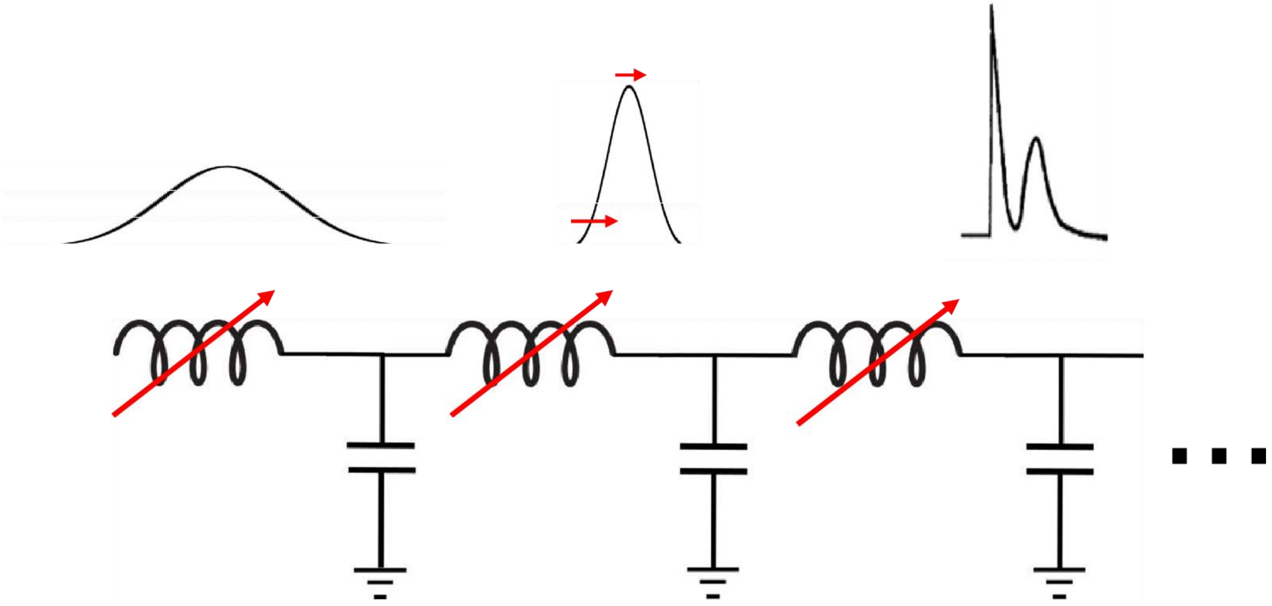
$$\Delta\beta = k_s + k_i - k_p = -\frac{k_p|A_p|^2}{I'^2_*}$$

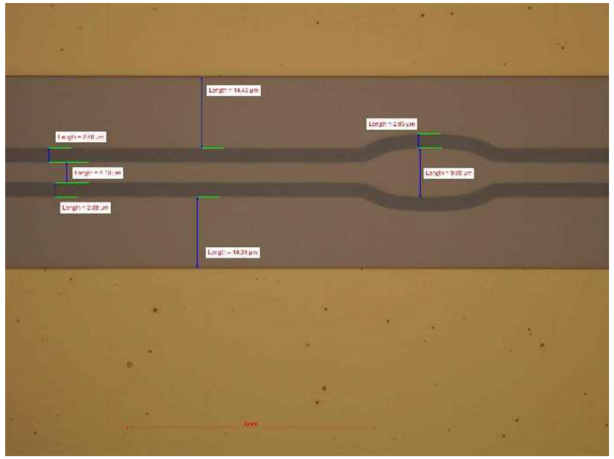
- prevents creation of shock waves
  - velocity decreases with current
  - tail of a pulse moves faster than peak
  - shock waves would limit the gain at 3 dB!

- avoids coupling with higher harmonics of the pump

➢ High (exponential) gain:

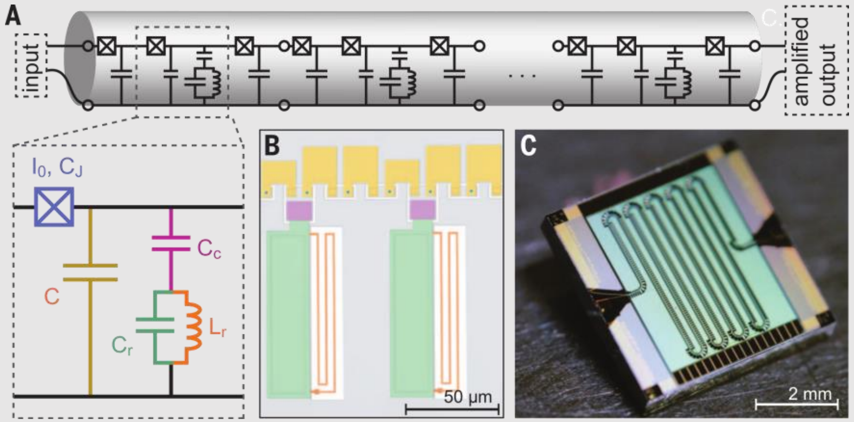
$$G = \frac{1}{4}\exp\left(2\frac{k_p|A_p|^2}{I'^2_*}\right)$$





TWPAs: Josephson and Kinetic Inductance

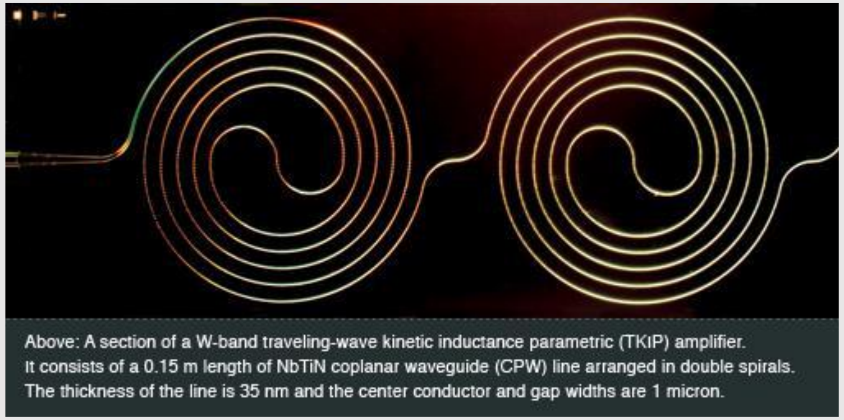
Traveling Wave Josephson Parametric Amplifiers



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



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

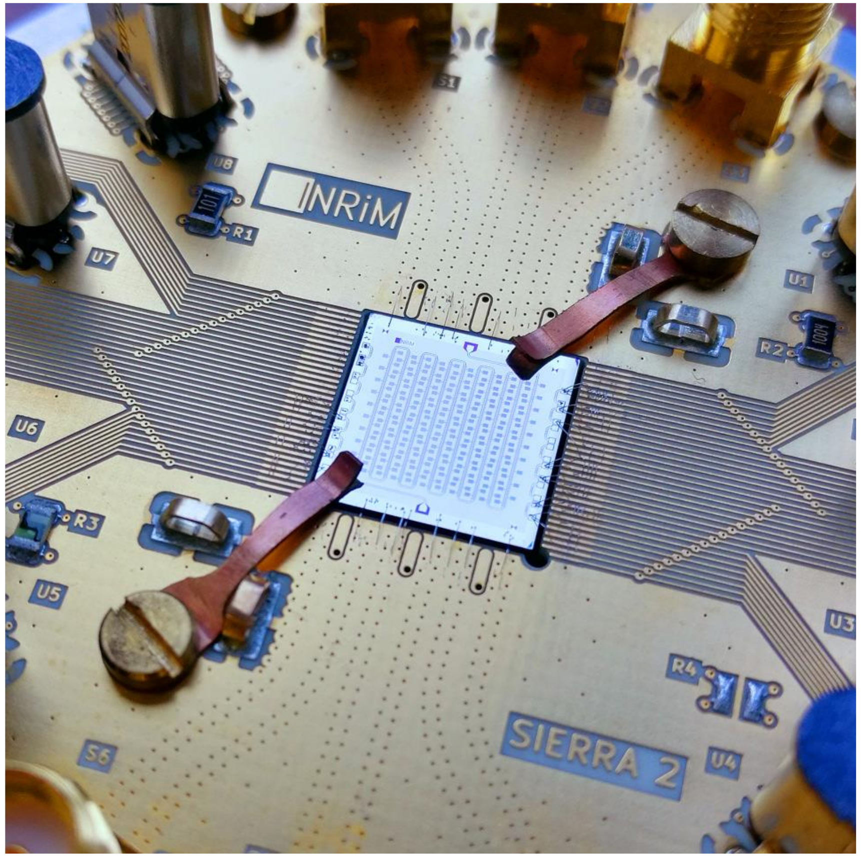
DARTWARS: Detector Array Readout with Traveling Wave AmplifieRS

The main aims of DARTWARS are:

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

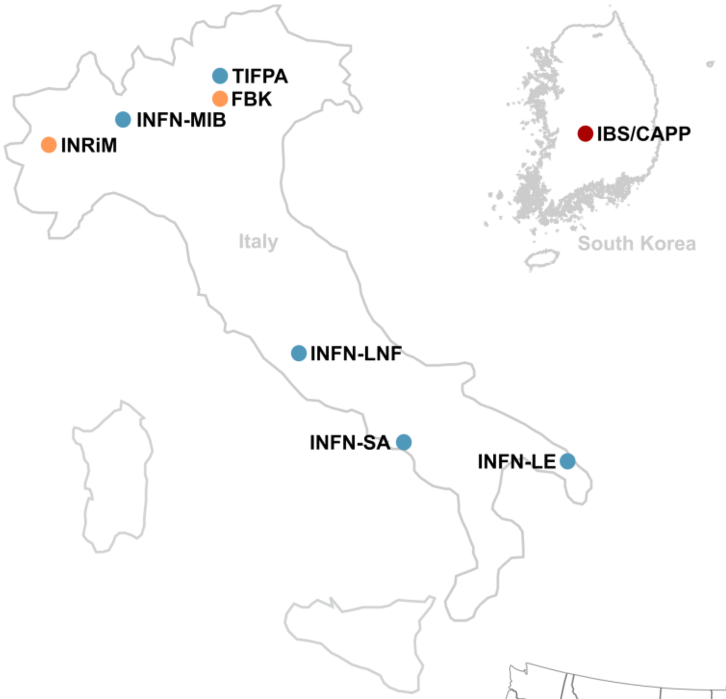
    - high gain ~ 20 dB
    - large saturation power ~ 50 dBm
    - (nearly) quantum limited noise T_N < 600 mK
    - reduced gain ripple
    - yield improvement

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

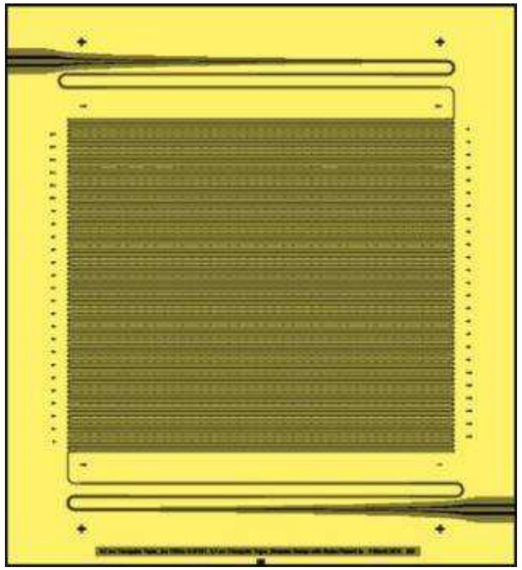
KITWPA within DARTWARS

- 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

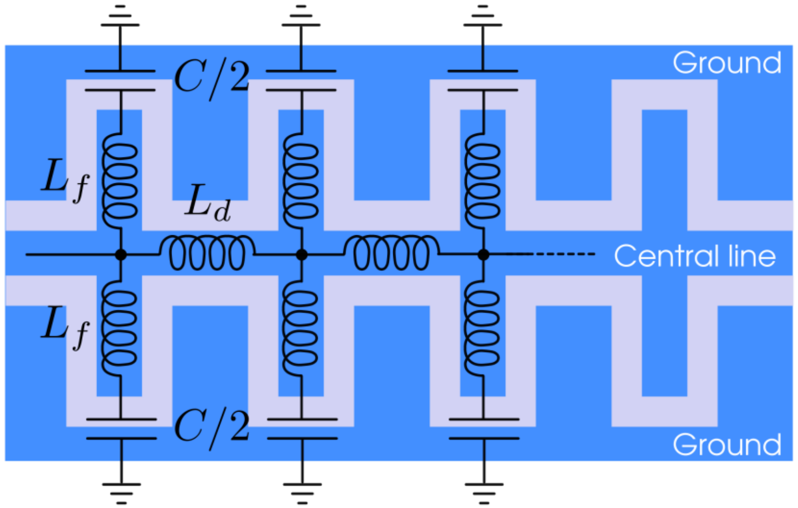
- Artificial transmission line:
  - small sections of a CPW recreate a transmission line of lumped-elements
  - 20 cm long transmission line for +15 dB gain
  - near-quantum-limited noise demonstrated in the 3.5-5.5 GHz

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

CPW

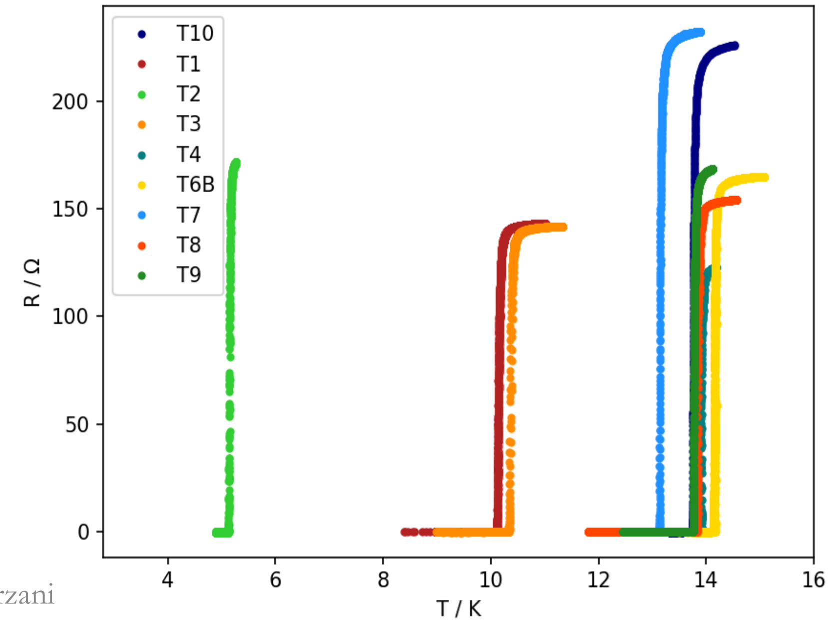


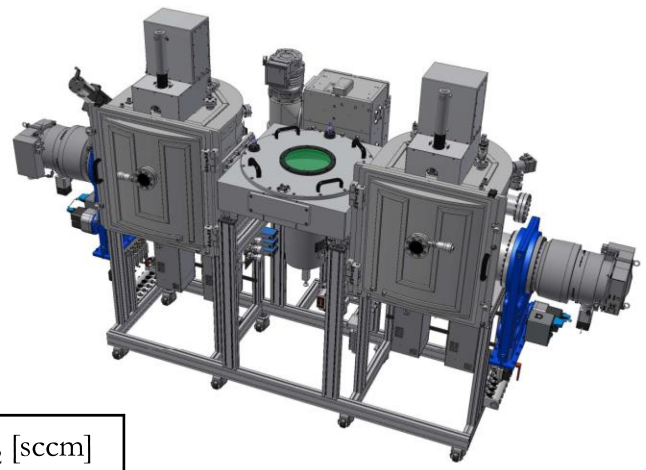
Artificial transmission line



KITWPA: film optimization @FBK

- Goal: 20 nm thick NbTiN film T_c ~ 14K, L_k ~ 10 pH/□
- new sputter (PVD Kenosistec 800 Cluster)
- sputter target $Nb_{0.80}Ti_{0.20}$
- Nb dry etch with SF_6 and Ar (new recipe)
- **how do (T_c , R_s , L_k) depend on sputtering parameters?**





Run DWT2

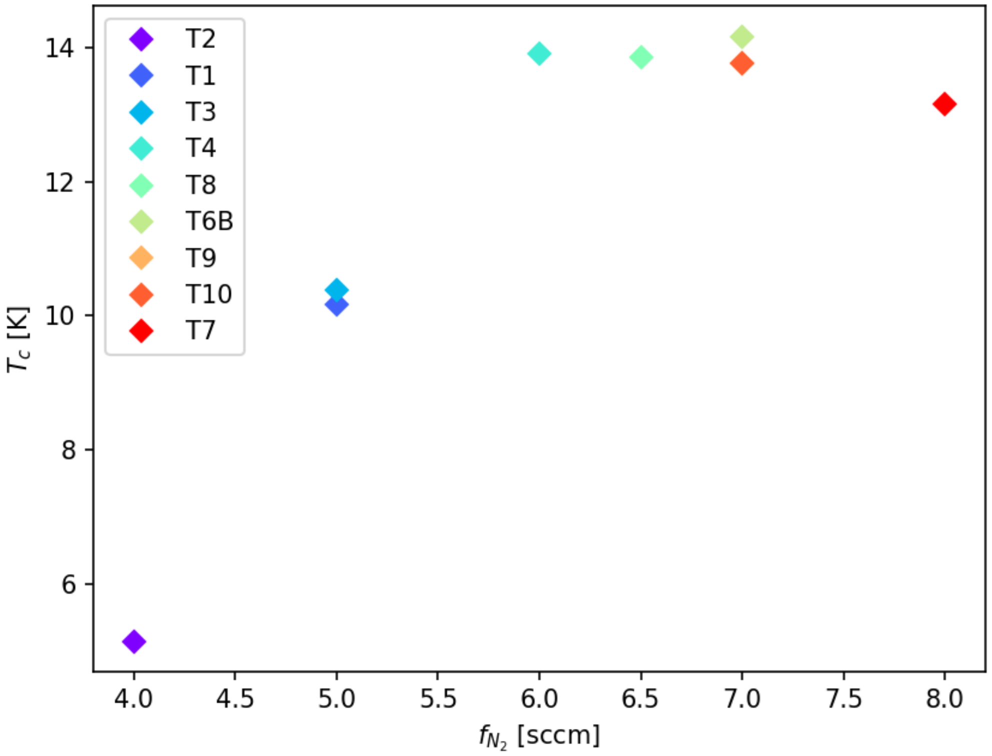
W	P [W]	p [mbar]	f_{N2} [sccm]
T1	700	2e-3	5
T2	700	3e-3	4
T3	700	3e-3	5
T4	700	3e-3	6
T5	1200	3e-3	5
T6	700	3e-3	7
T6B	700	3e-3	7
T7	700	3e-3	8
T8	700	3e-3	6.5
T9	700	3e-3	7
T10	600	3e-3	7

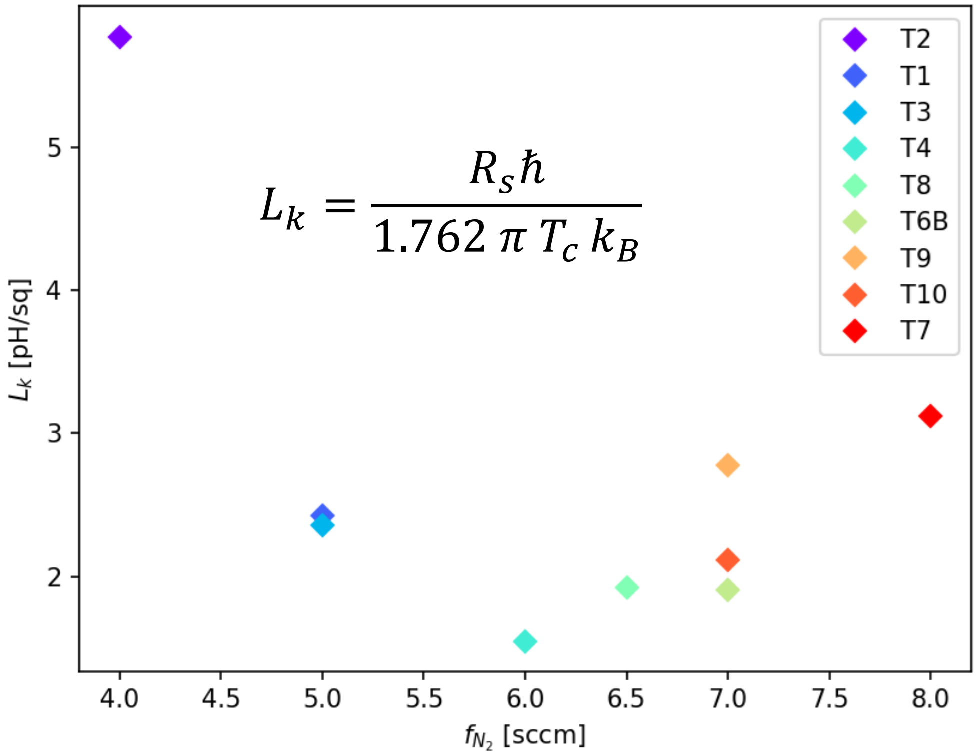
For all wafers:

Ar flow = 50 sccm
t = 6 minutes
T = 400 °C

KITWPA: film optimization @FBK

Run DWT2





$$L_k = \frac{R_s \hbar}{1.762\, \pi\, T_c\, k_B}$$

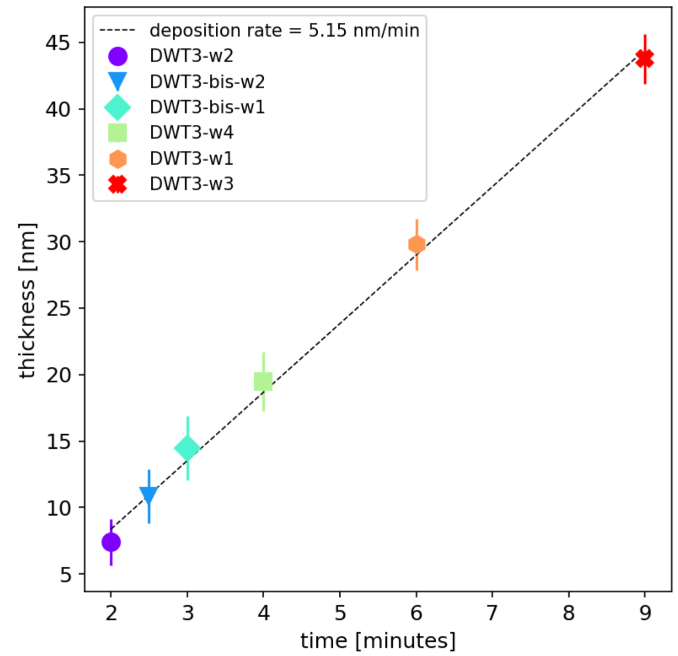
KITWPA: film optimization @FBK

Run DWT3

Wafer	t [minutes]
DWT3/w1	6
DWT3/w2	2
DWT3/w3	9
DWT3/w4	4
DWT3-bis/w1	3
DWT3-bis/w2	2.5

For all wafers:

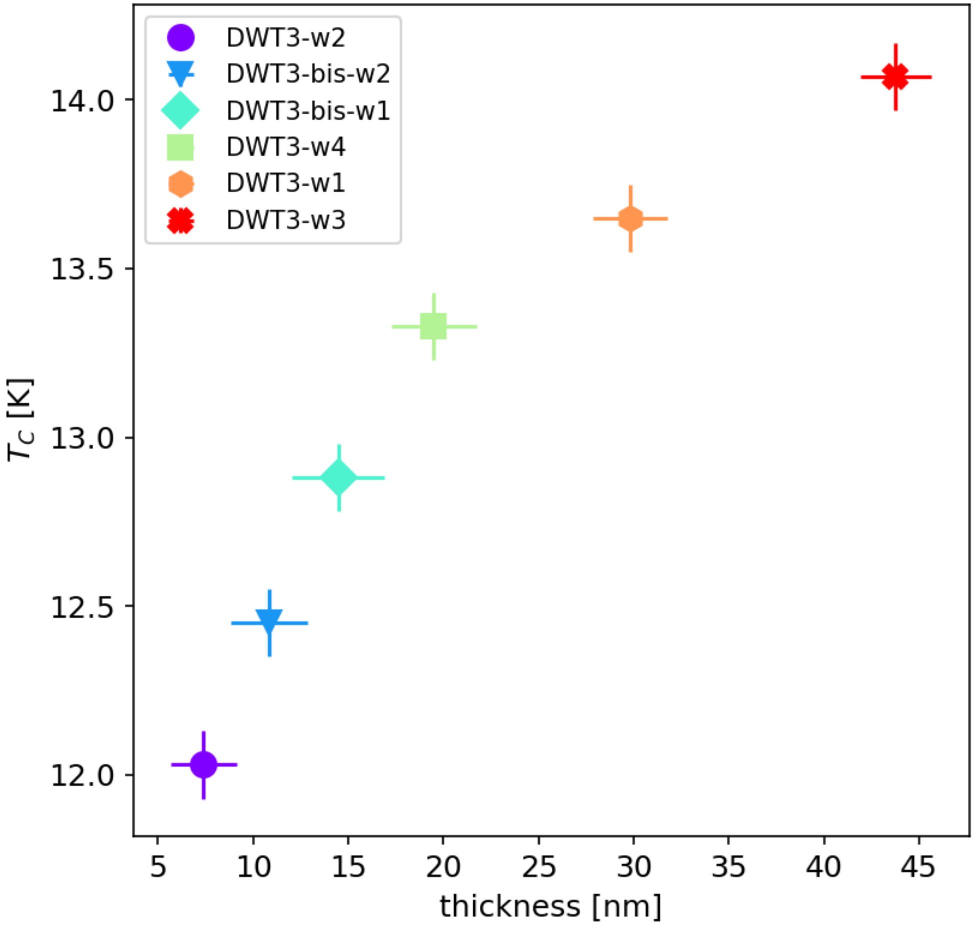
P = 600 W
p = 3e-3 mbar
Ar flux = 50 sccm
N_2 flux = 7 sccm
T = 400 °C

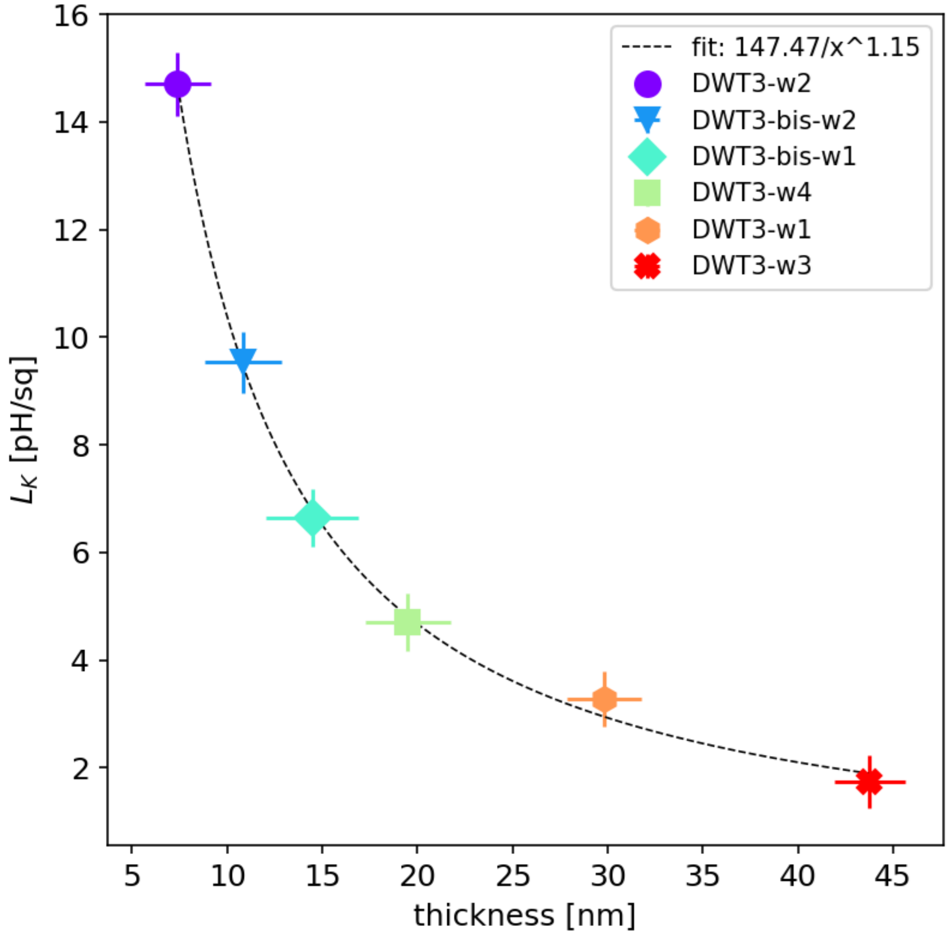


Lithography with KIDs mask → more precise measurement of thickness:

KITWPA: film optimization @FBK

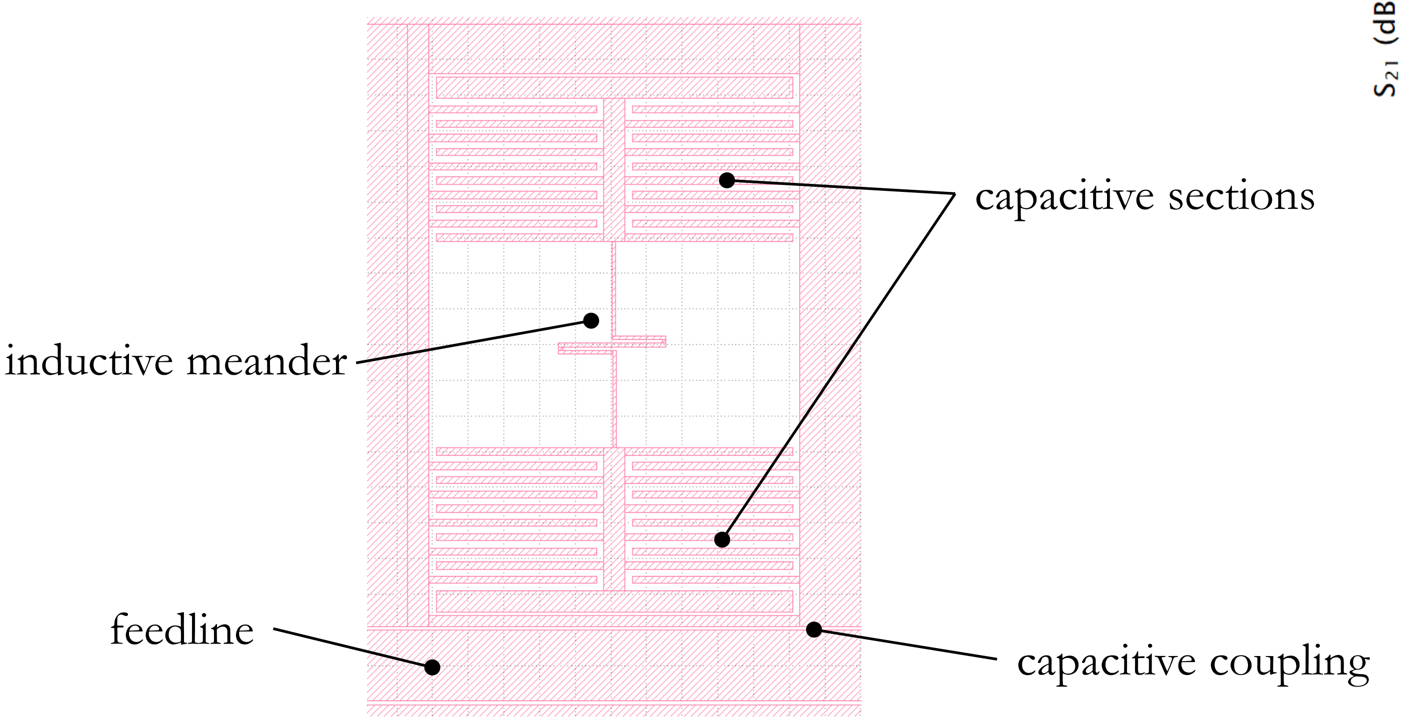
Results on Run DWT3

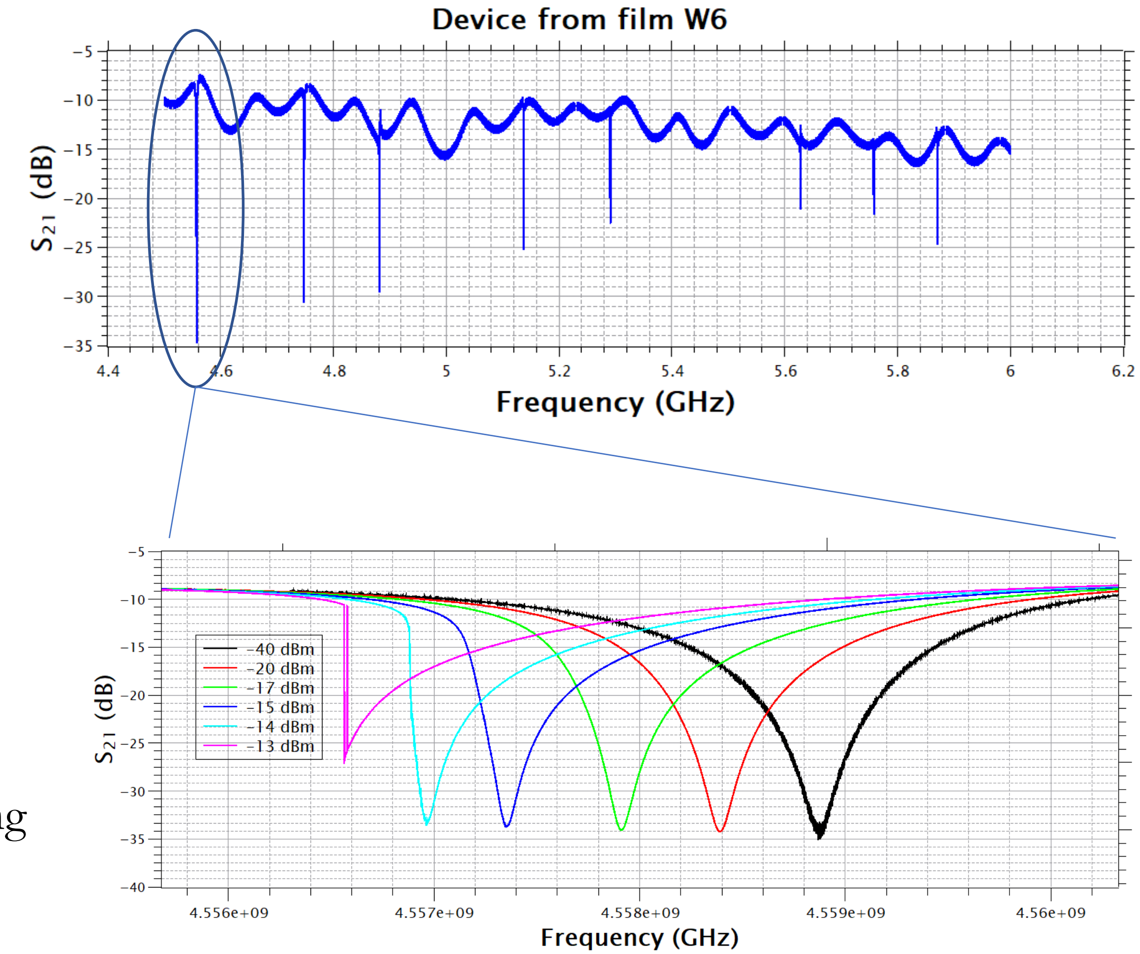




KITWPA: material characterization @FBK/TIFPA

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



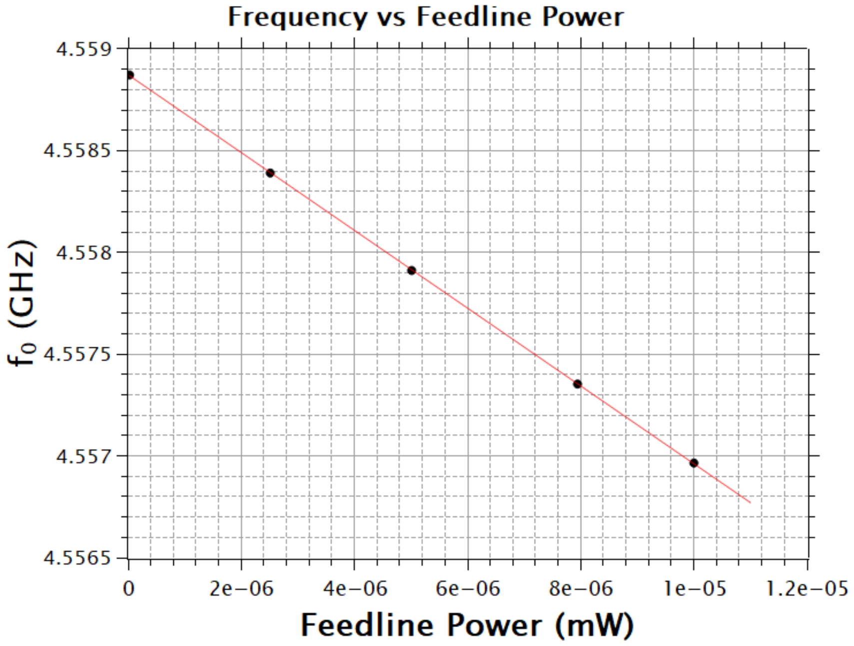


Quality factors in the range $(0.2 - 1) \cdot 10^5$

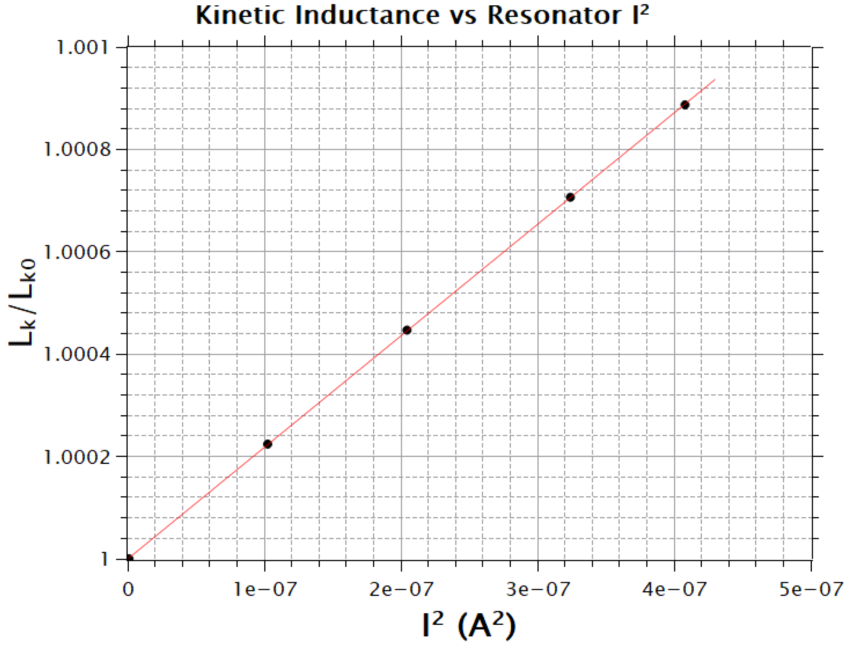
$$L_k = L_{k_0}\left[1 + \left(\frac{I}{I_*}\right)^2\right]$$

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

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



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



need to:

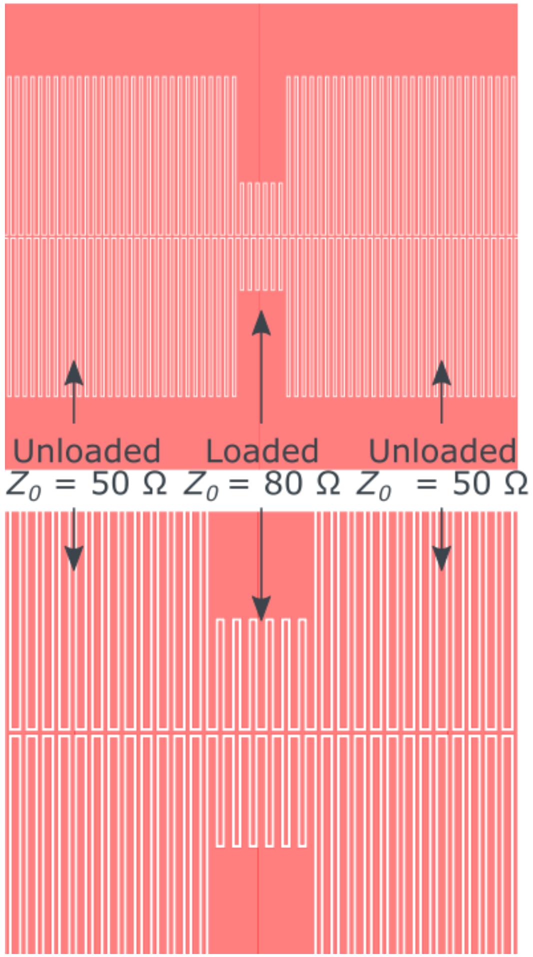
- relate L_k to f_{res} → Sonnet simulation: $(f_{res})^{-2} \propto (L_k + L_g)C$
- relate I^2 to $P_{feedline}$ → estimated C and L from Sonnet
  → circuit simulator (QUCS)
- estimate I_* from $L_k(f_{res})$ (Sonnet)

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

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

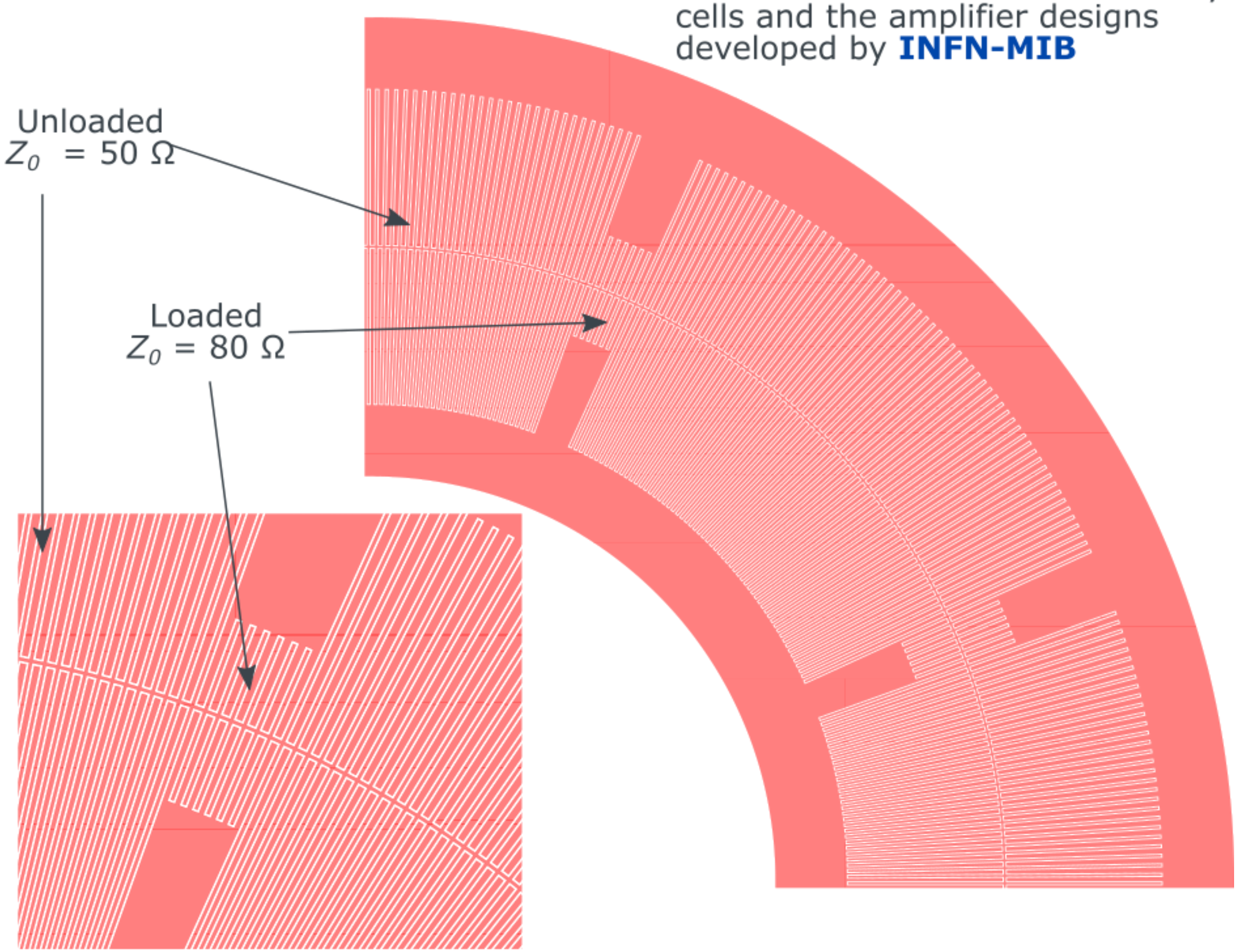
KITWPA – Design

Straight Cell

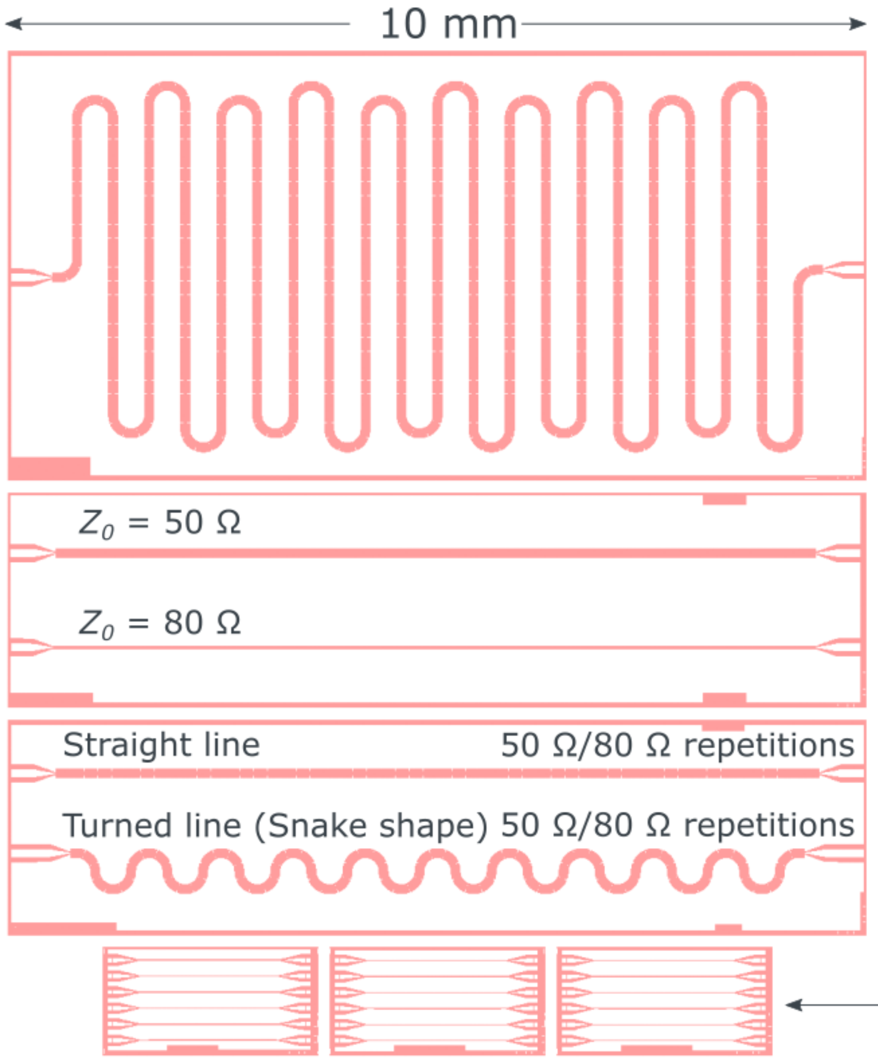


Turn Cell

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

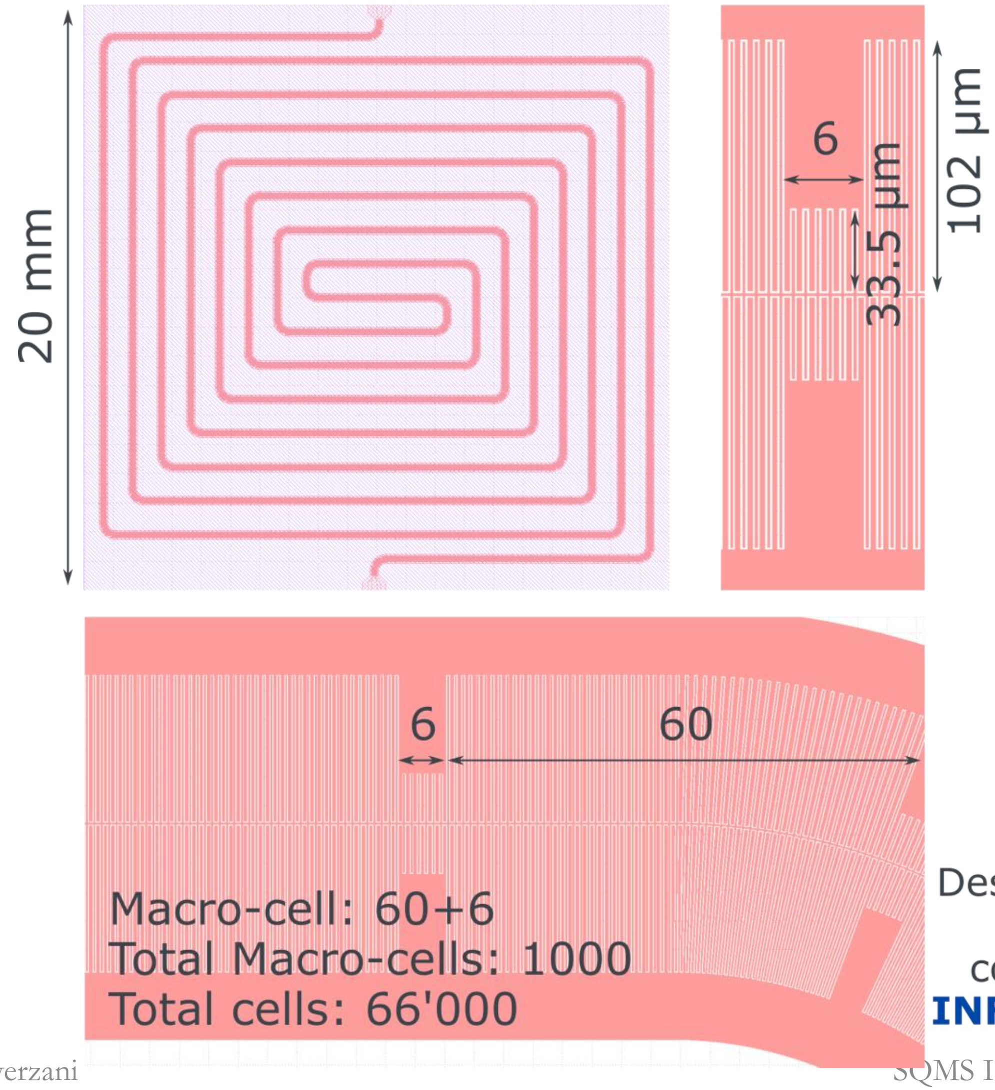
Wires with different size for DC characterizations: T_c, R_n, L_k

KITWPA – Design

DART WARS

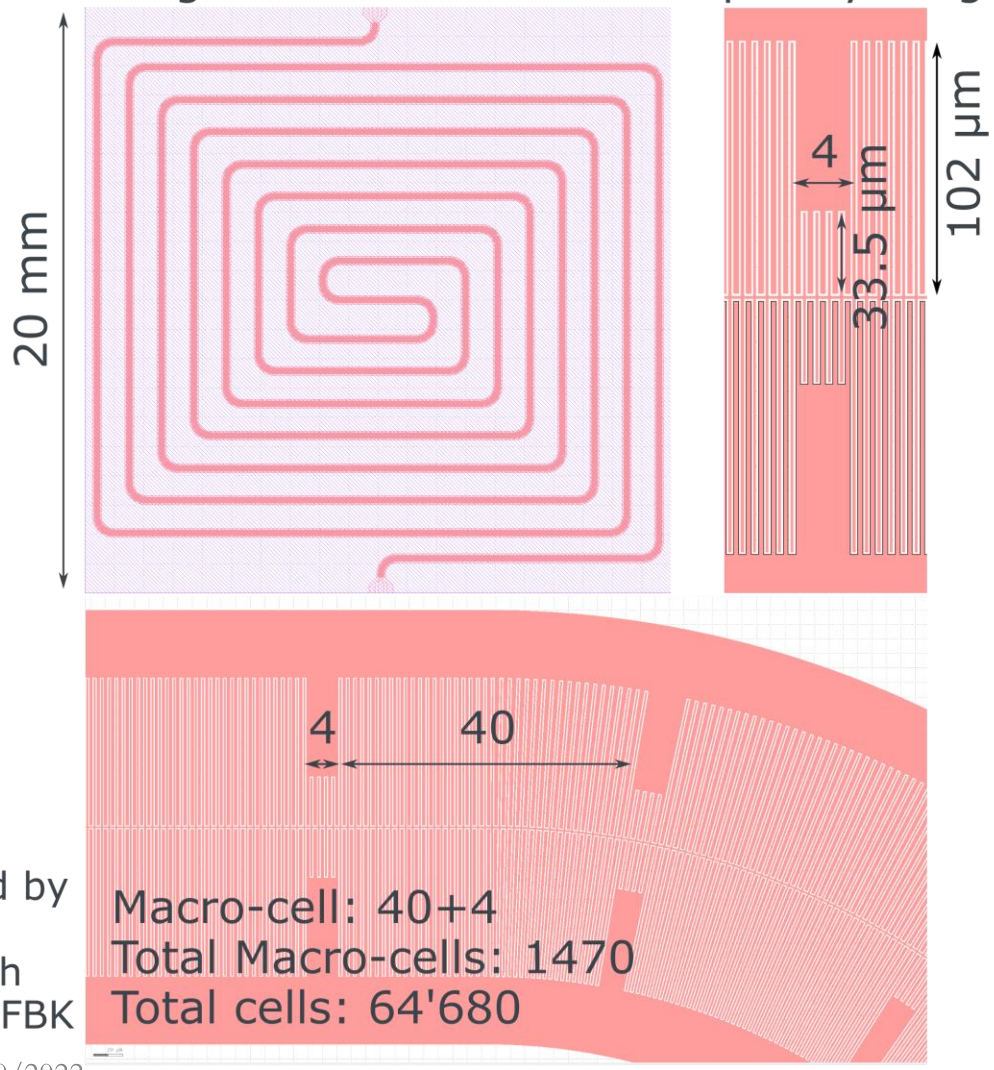
Version 60-6

[PRX Quantum 2, 010302 (2021)]



Version 40-4

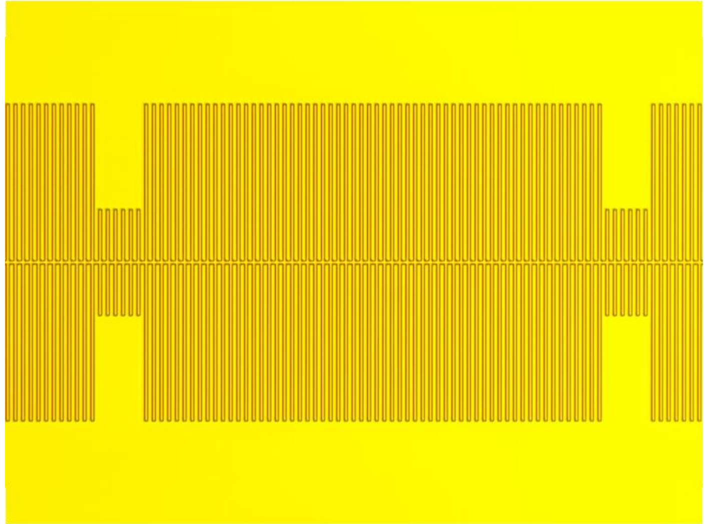
designed for the C-band frequency range

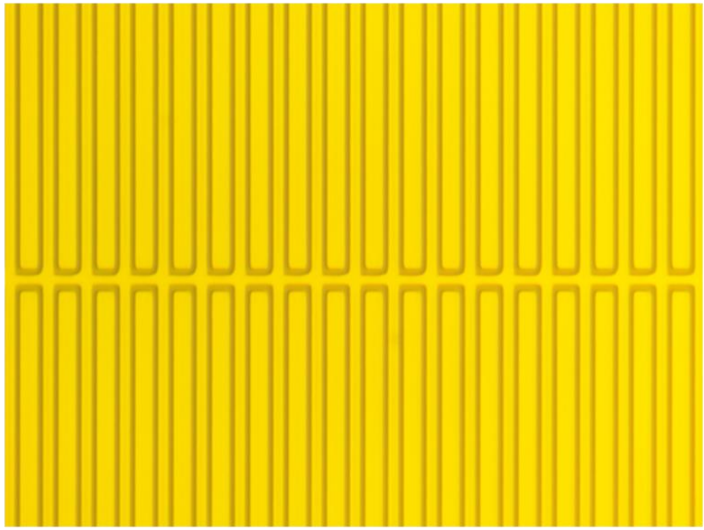


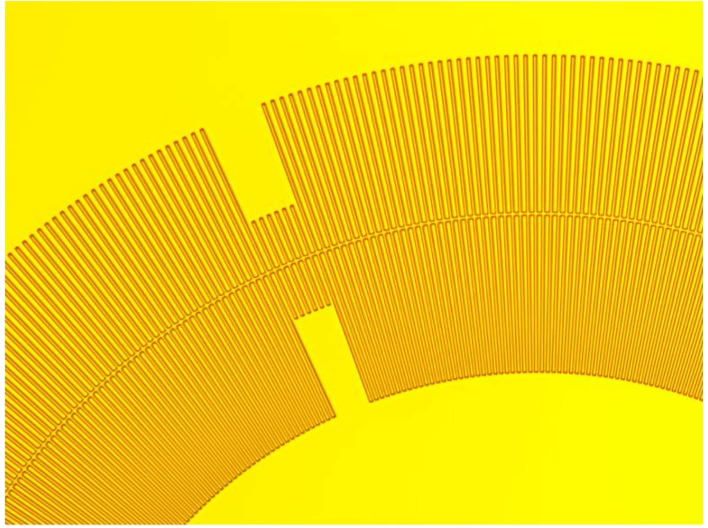
Designs developed by **INFN-MIB** in collaboration with **INFN-TIFPA** and FBK

KITWPA – Production

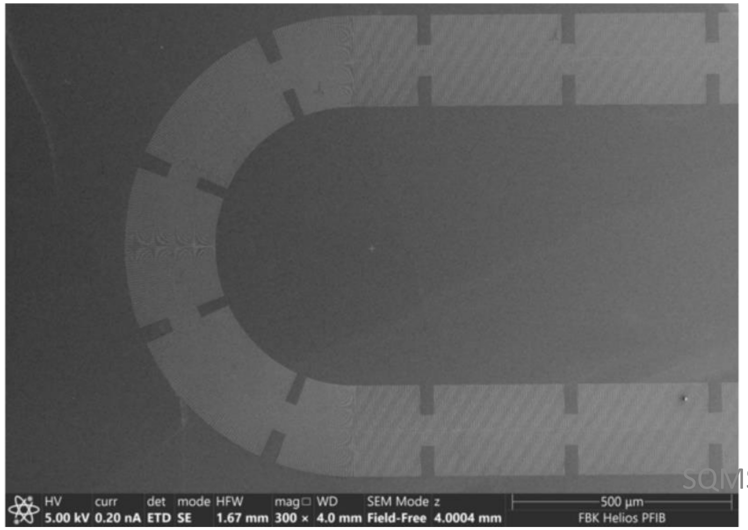
Optical Microscopy Images

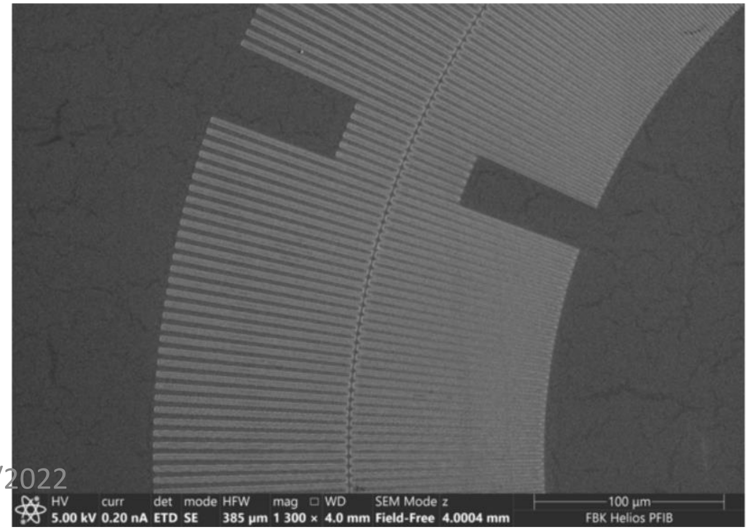




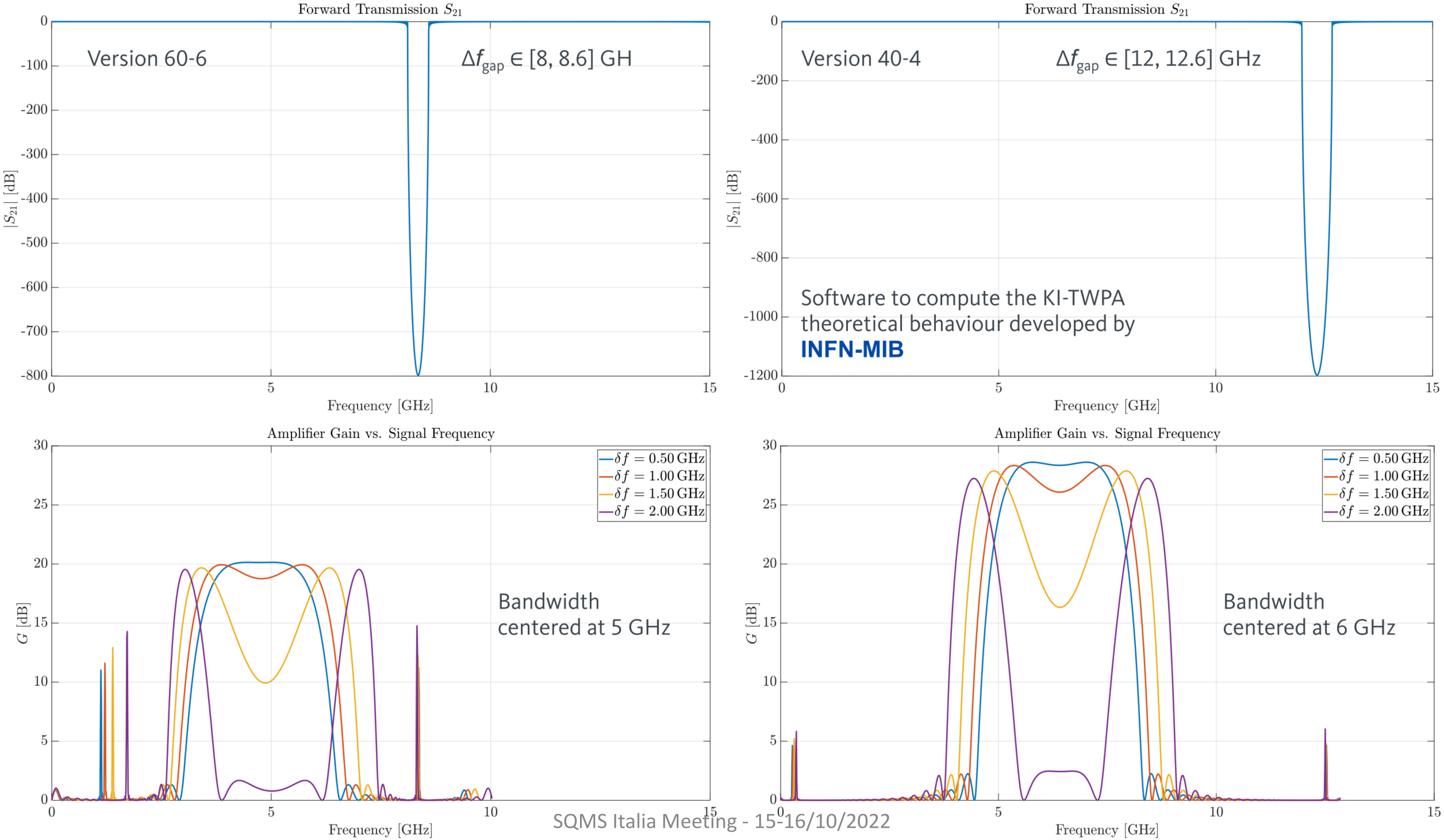


Scanning Electron Microscopy Images

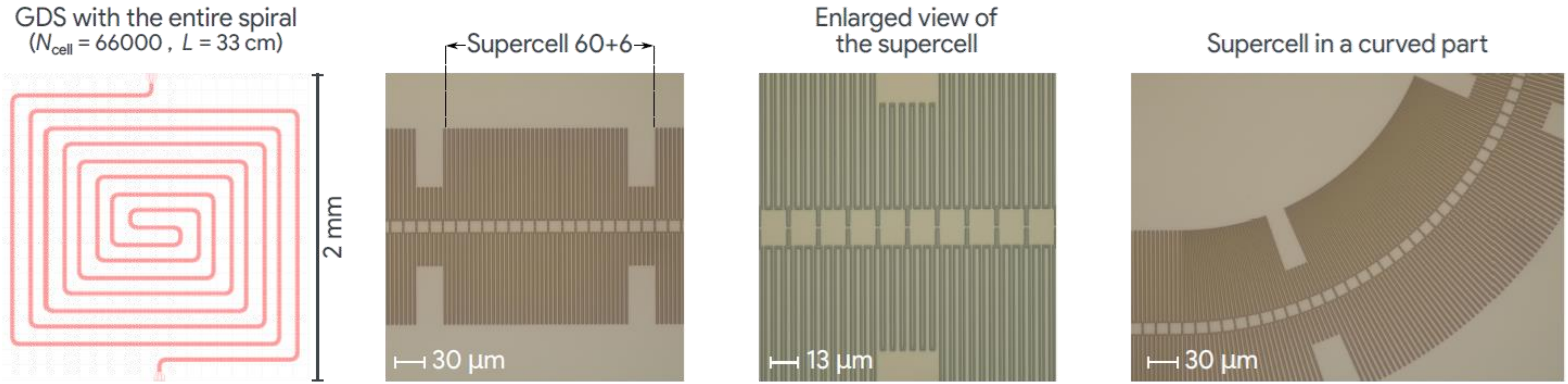




KITWPA – Expected performance



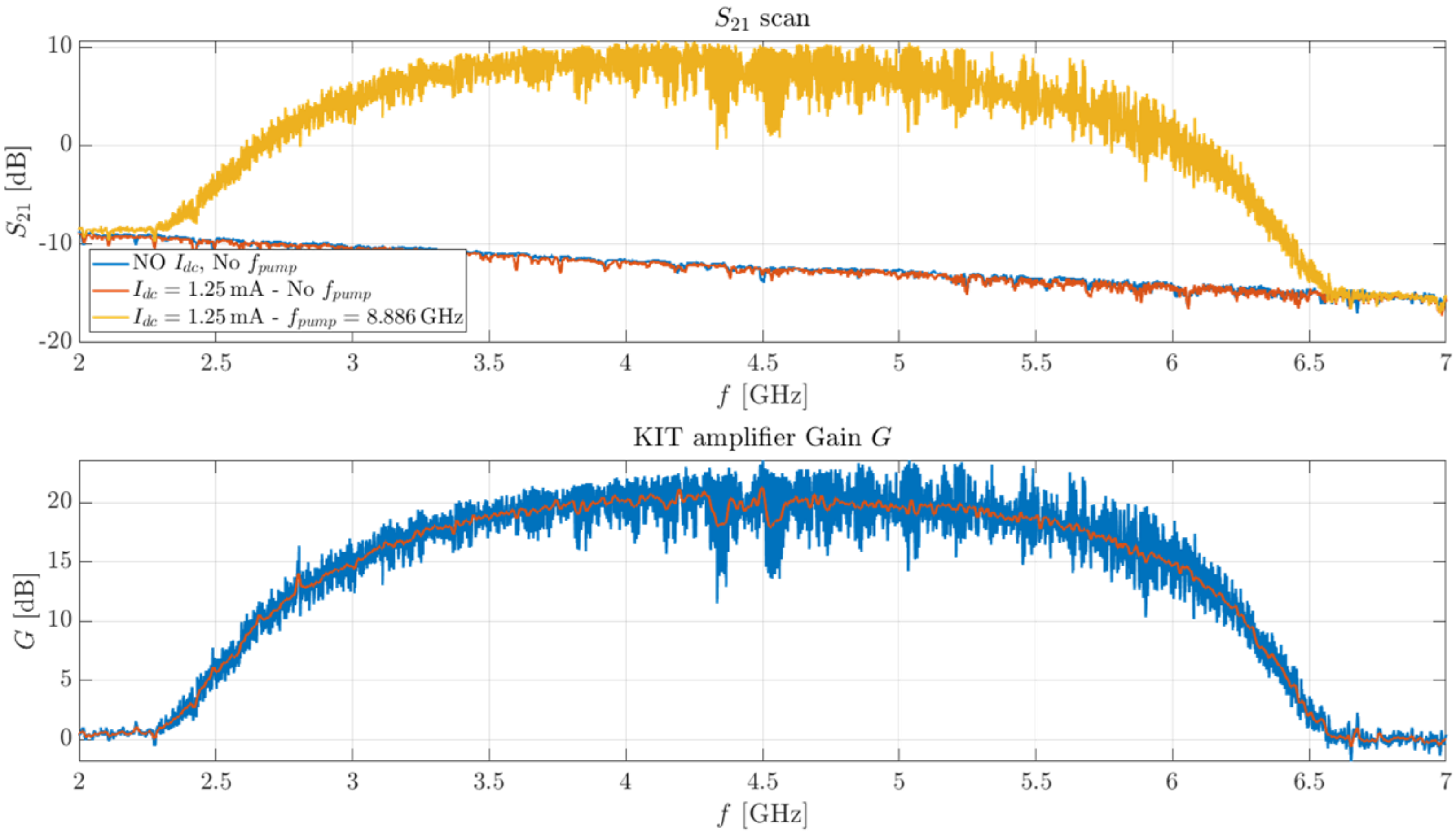
KITWPA @NIST



- NbTiN thickness 20
- first KI-TWPA prototypes with t = 10 nm produced at the end of October with two different unloaded/loaded cell repetition (60-6 and 42-6 for two different frequency range)
- characterization measurements in progress

KITWPA @NIST

Device characterization – NbTiN 20 nm



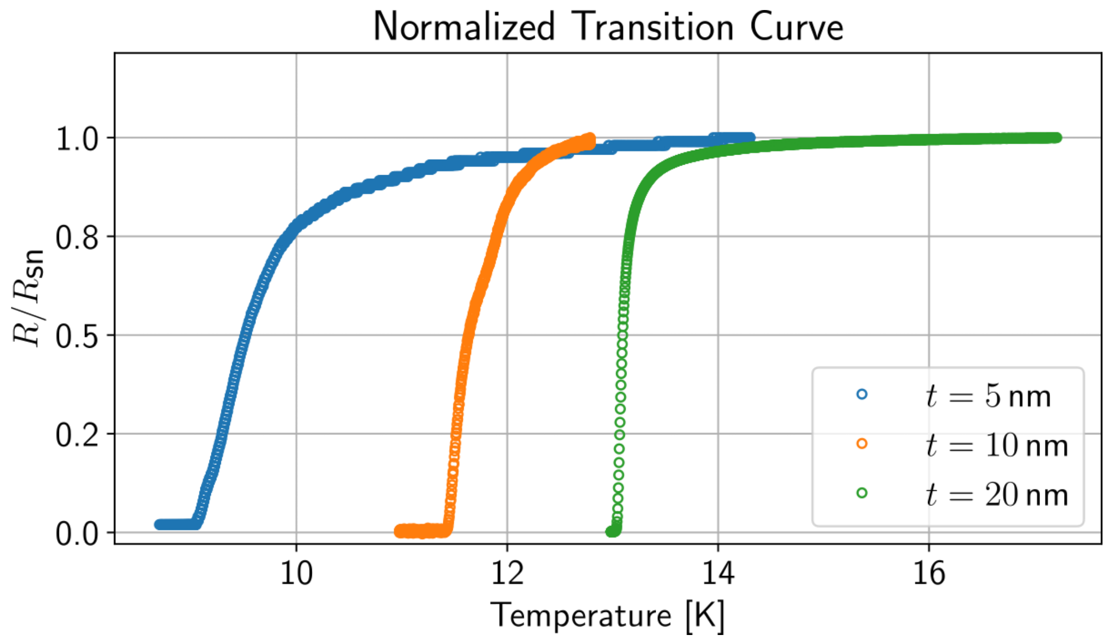
KITWPA @NIST

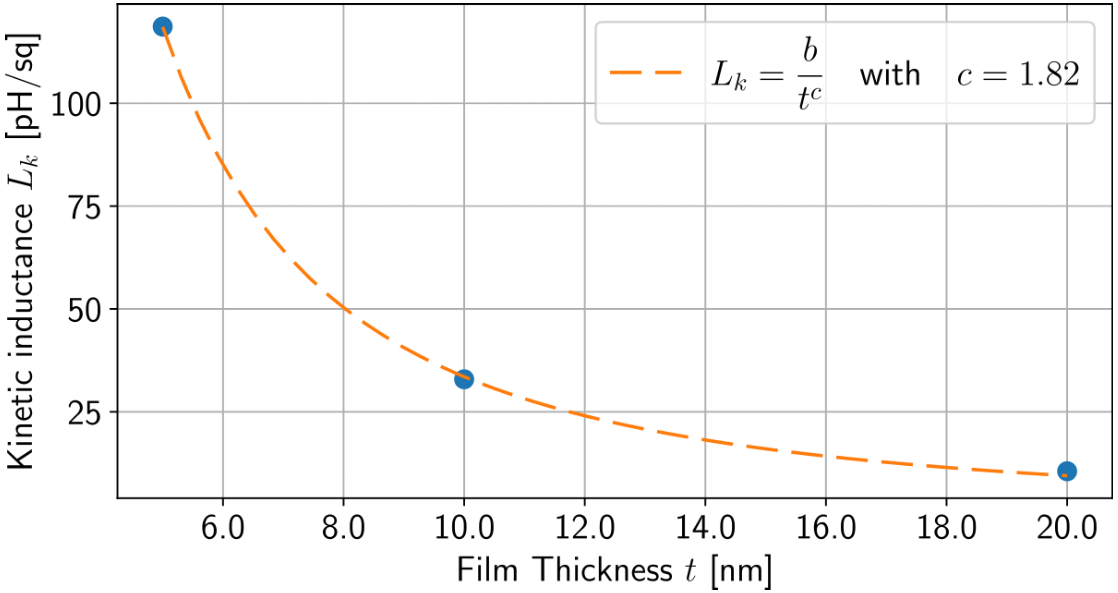
- want to reduce thickness of film

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

  - smaller thickness → larger L_0 → lower I to get same L
  - smaller power, meaning lower added noise

t [nm]	T_c [K]	L^0_k [pH/□]	L^{res}_k [pH/□]	Q_i
5	9.5	118.6	93.3	30k
10	11.6	32.9	31.5	50k
20	13.1	10.5	10.6	70k

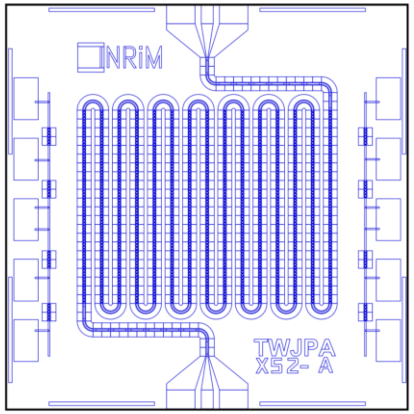


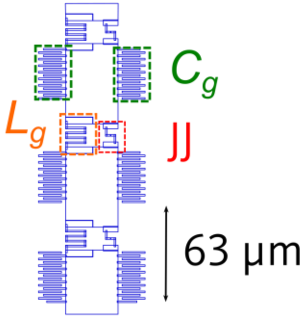


TWJPA within DARTWARS

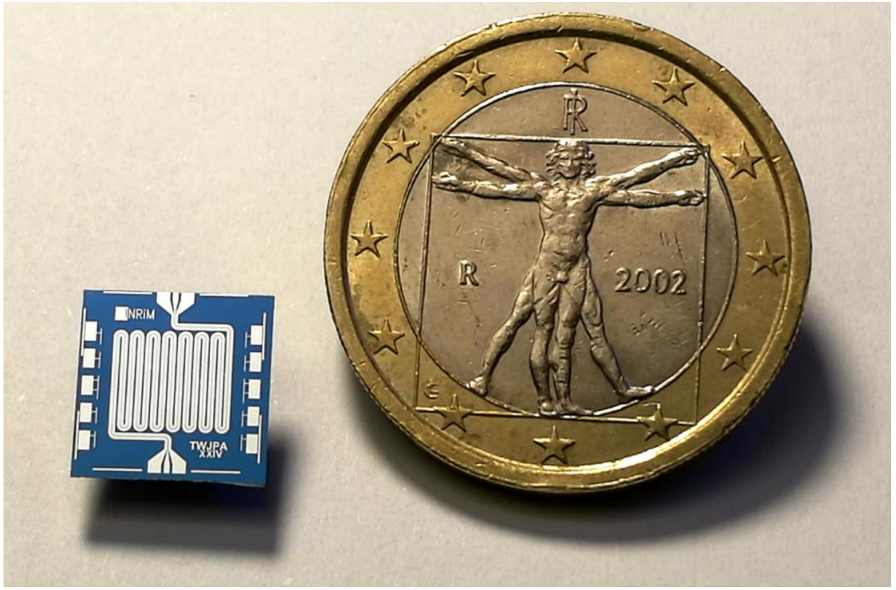
- recent studies suggest that TWJPA operated in the three-wave mixing (3WM) mode might increase the power handling, while decreasing the gain vs. frequency ripple
- new design 3WM TWJPA based on microwave transmission line composed of a serial array of non-hysteretic one-junction rf-SQUIDs
- mixing process 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

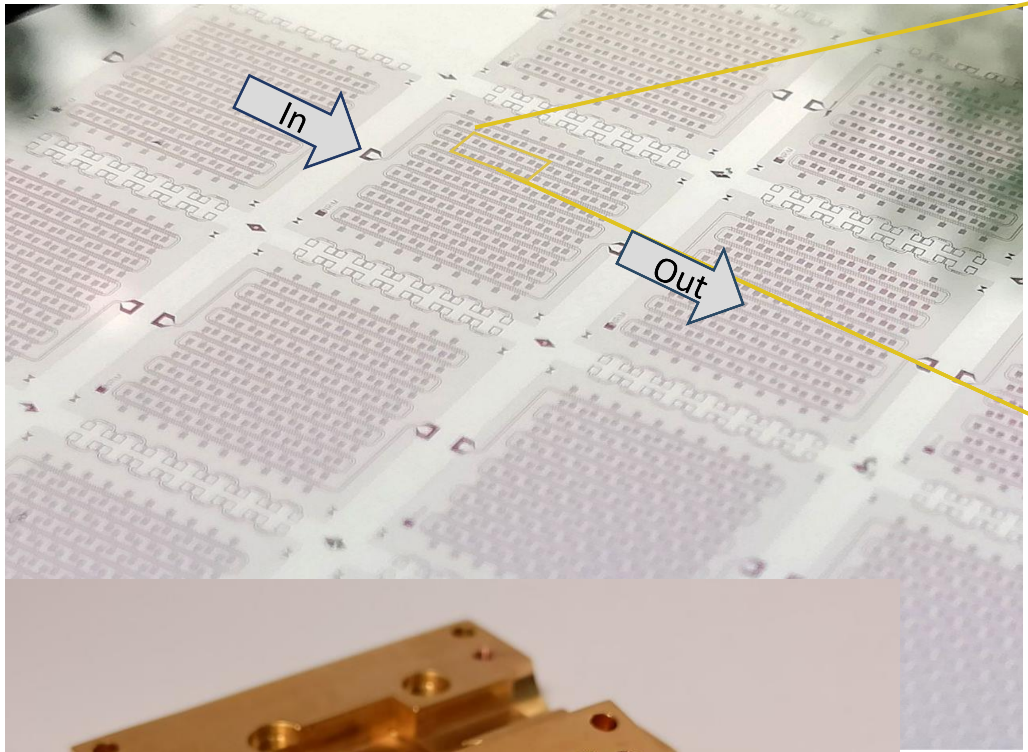


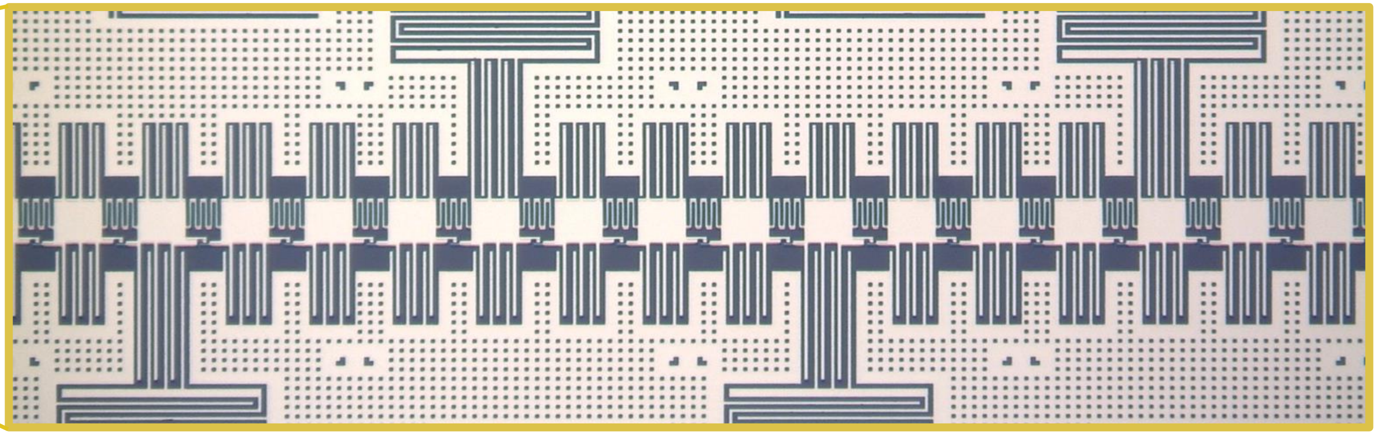


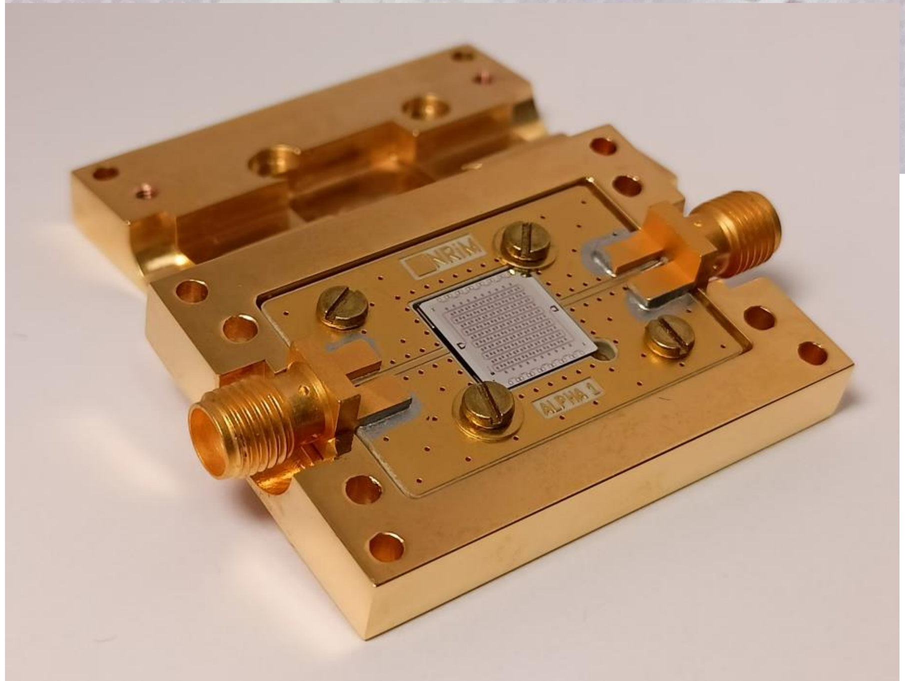
3 elementary cells



JTWPA





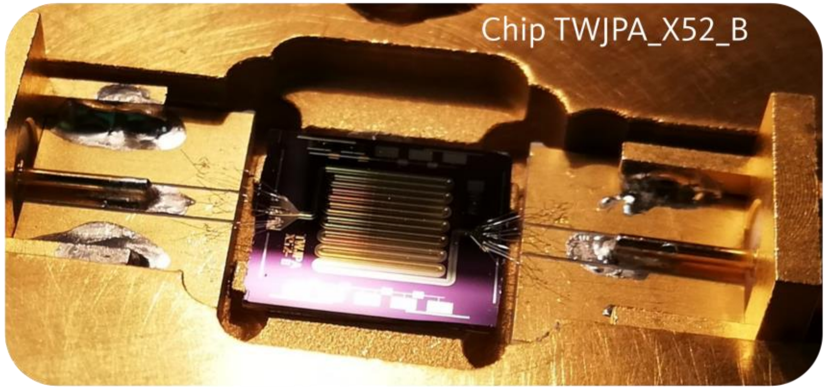


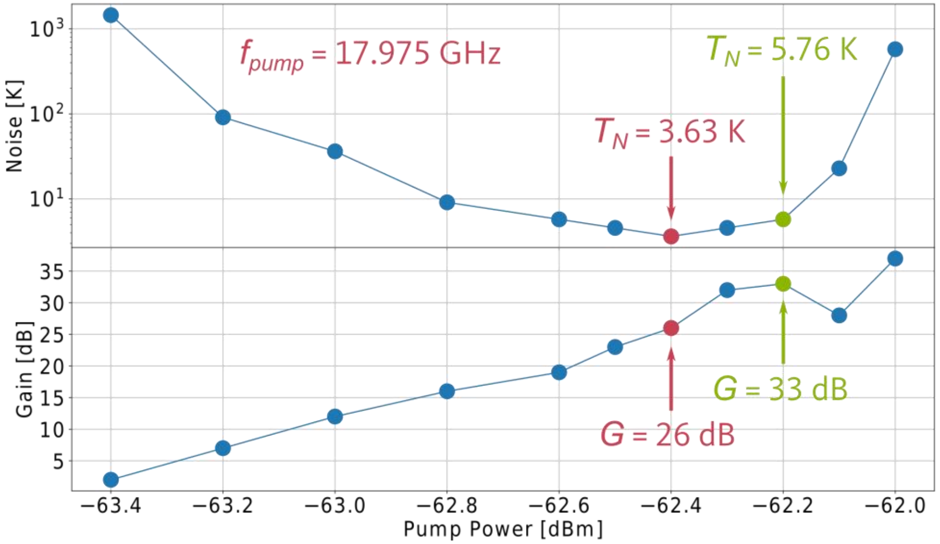
- Josephson Junction **spread** of parameters deeply affect the amplifiers performances (eg. gain)

- Due to the exponential dependence of its properties, Josephson tunnel junctions are the **bottleneck** of the whole JTWPAs operation

TWJPA within DARTWARS

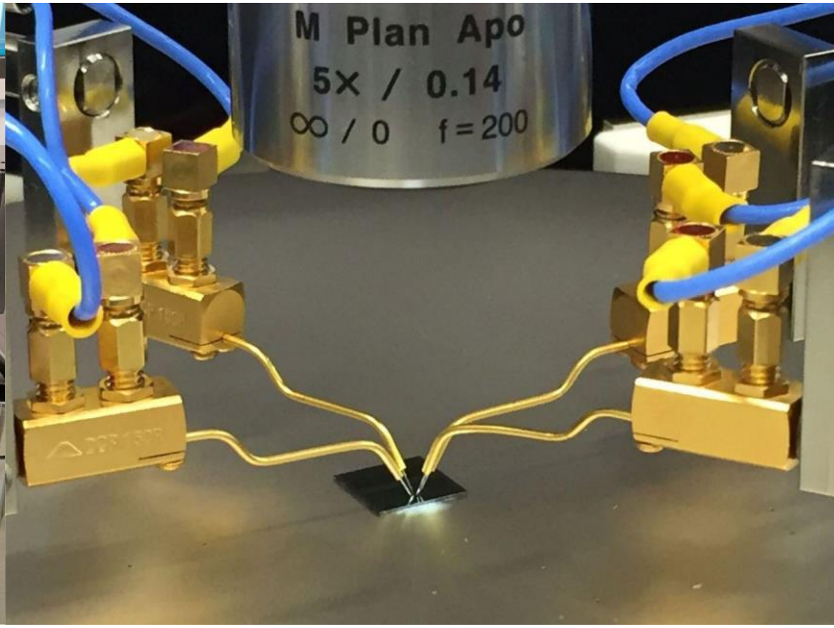
- chips with TWJPA produced at INRiM were tested both at LNF and IBS-CAPP
- measurements showed parametric amplification but with a non-homogeneous behavior in frequency: non-homogeneous fabrication of the ~ 900 JJs of the device
- gain up to 30 dB was observed at particular frequencies and with a minimum 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





JJs production and characterization @INRiM and MIB

- 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 µA
- 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)
- on average R_N is close to the target value
  - still to address spread in value (around 15%)

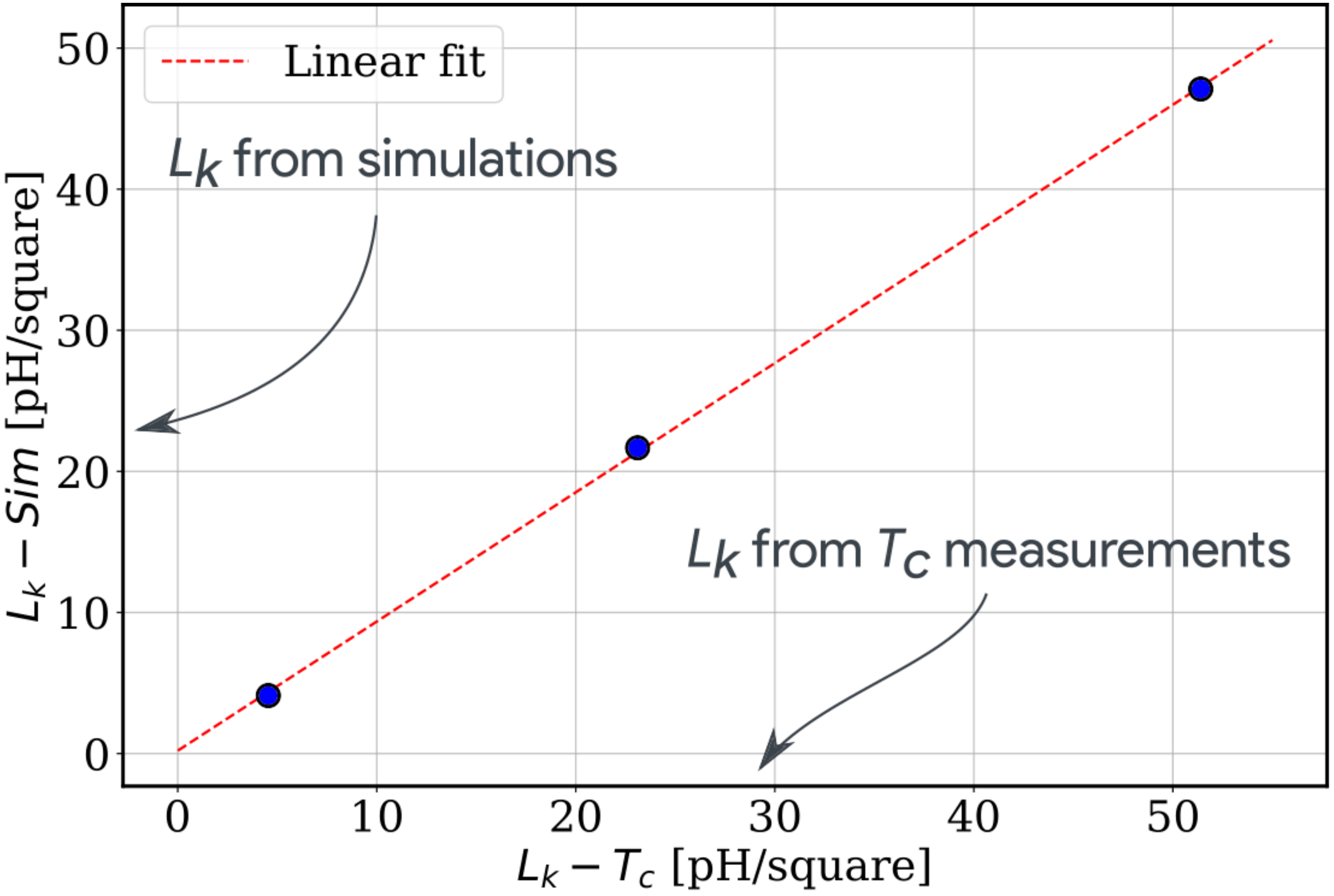


Conclusions

- 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/

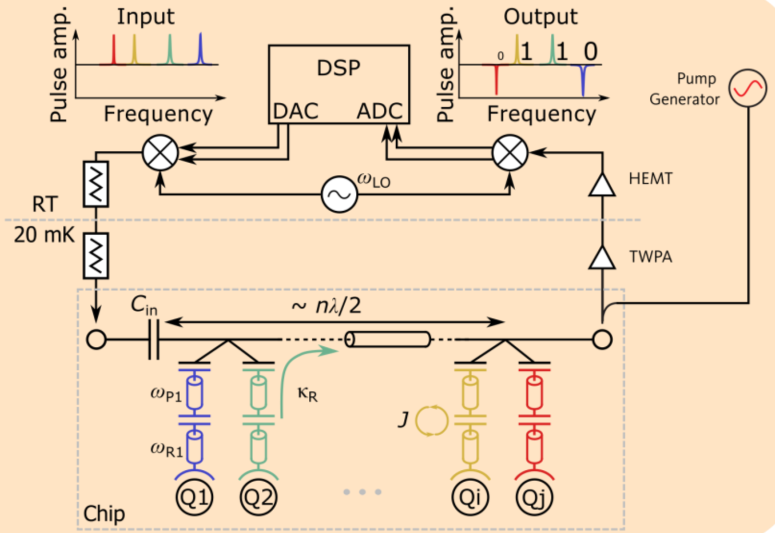
Backup slides

L_s comparison

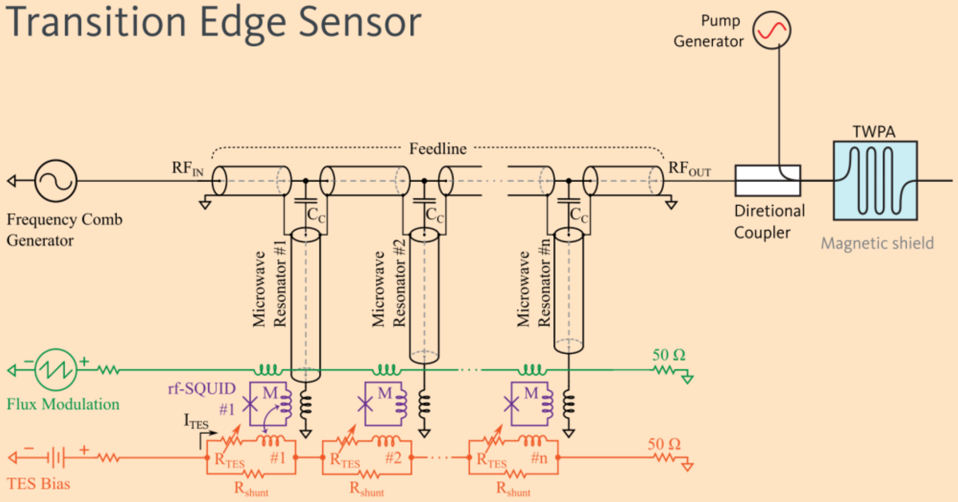


DARTWARS: readout of superconducting devices

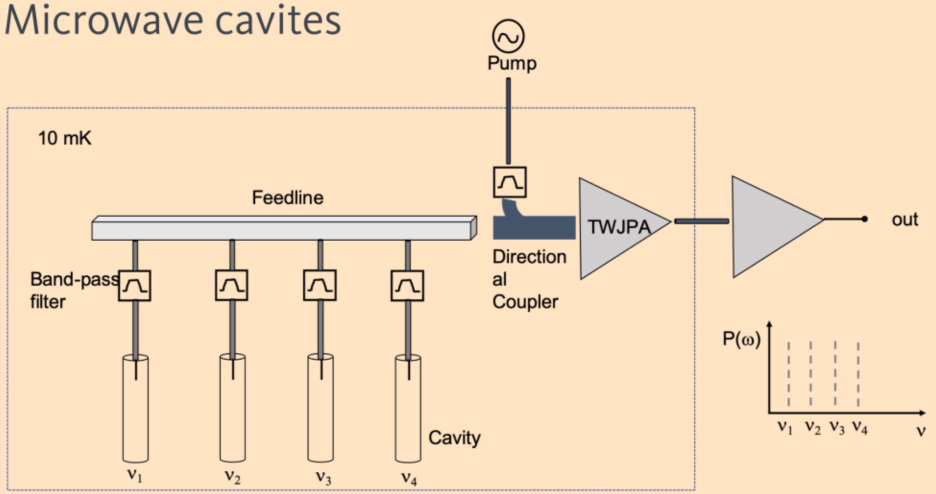
Qubit



Transition Edge Sensor

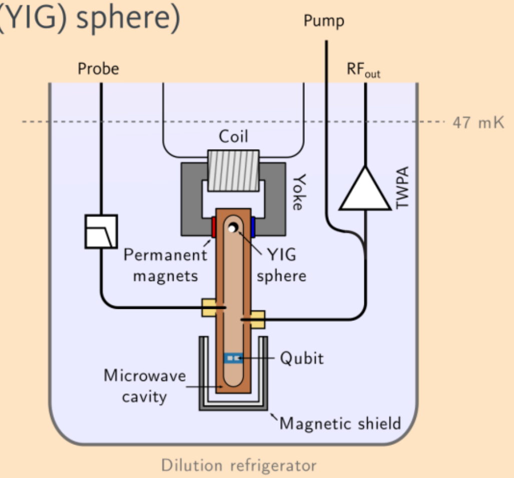


Microwave cavites



Quantum Sensing of Magnons

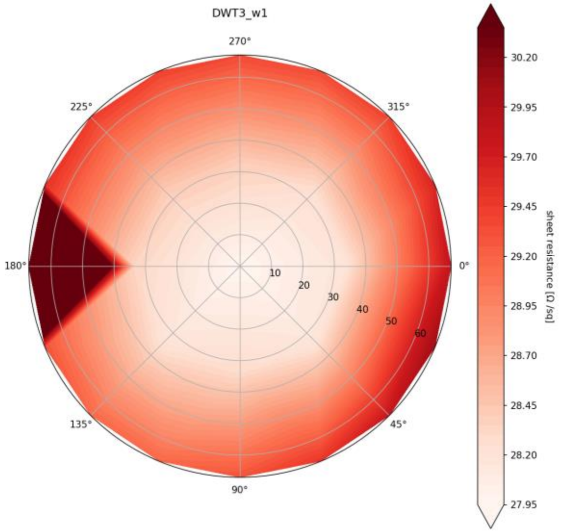
(with yttrium-iron-garnet (YIG) sphere)



KITWPA: film optimization @FBK

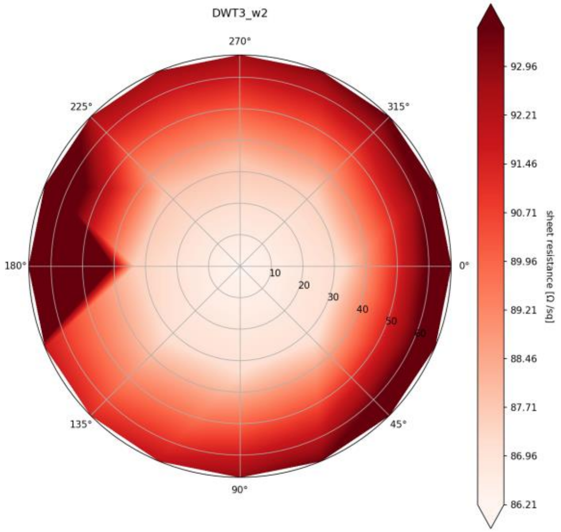
homogeneity test from sheet resistance measurement

6 minutes



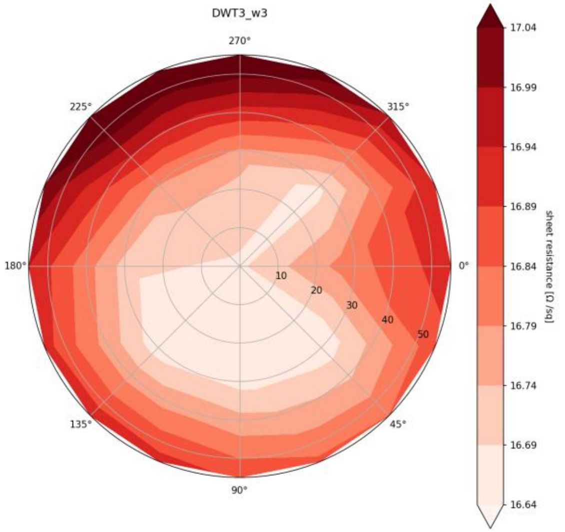
Total variation: 34.15 %
Variation excluding flat area: 6.54 %

2 minutes



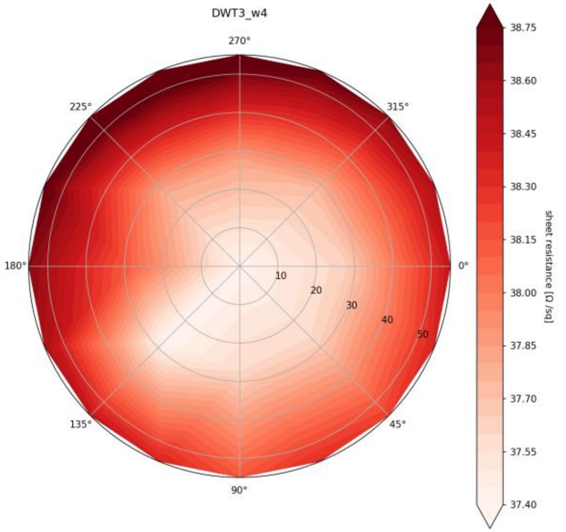
Total variation: 33.39 %
Variation excluding flat area: 8.9 %

9 minutes



Total variation: 2.96 %
Variation excluding flat area: 2.96 %

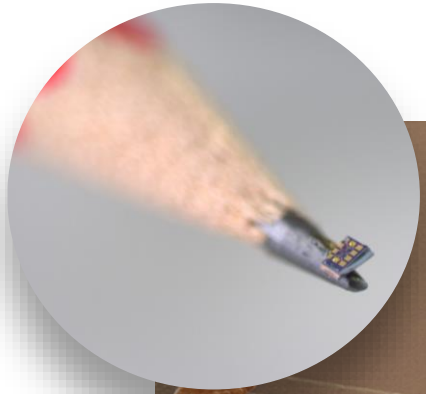
4 minutes

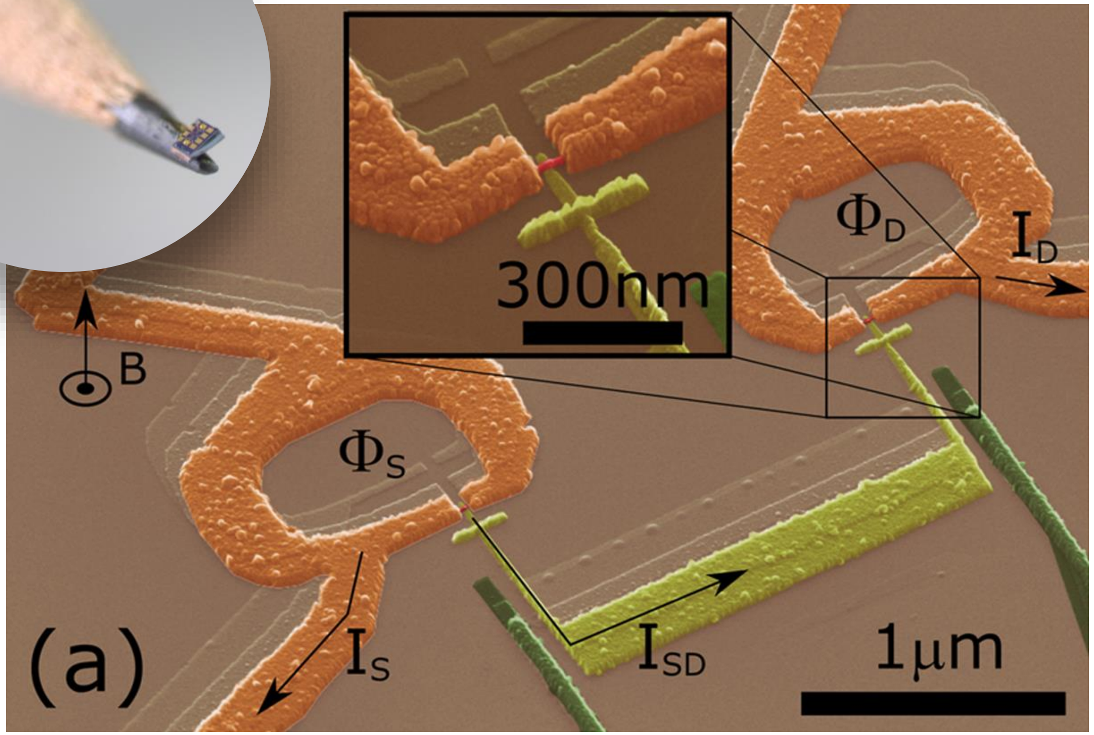


Total variation: 4.13 %
Variation excluding flat area: 4.13 %

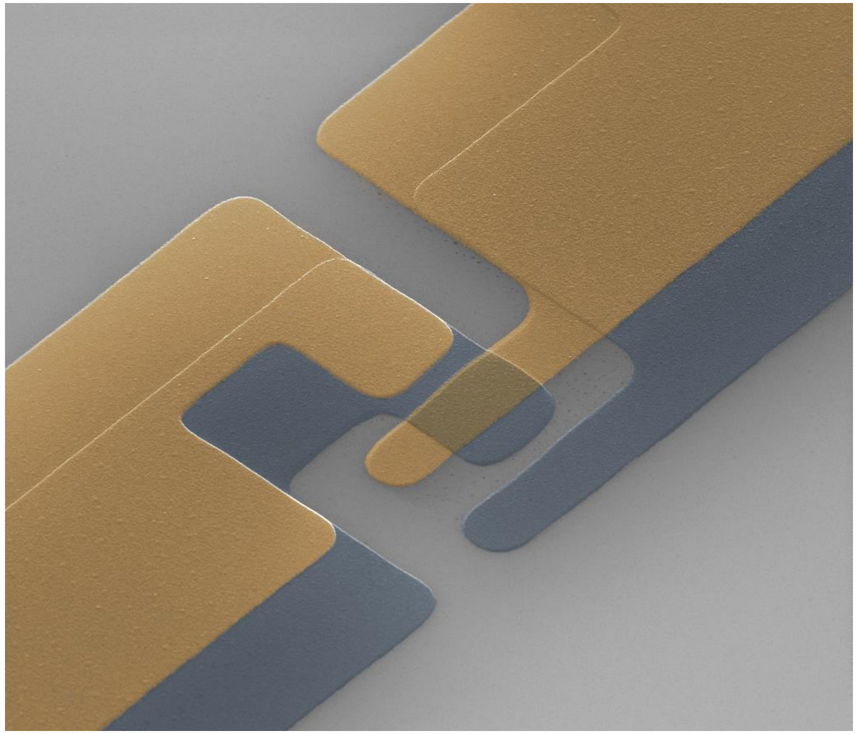
JTWPA – Technological challenge

Need for **reproducibility** and **stability** of Josephson Junctions on a large scale approach





E. Enrico, et al., *Single charge transport in a fully superconducting SQUISET locally tuned by self-inductance effects*, AIP Advances **12**, 055122 (2022)



UV shadow lithography based Josephson Junction

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

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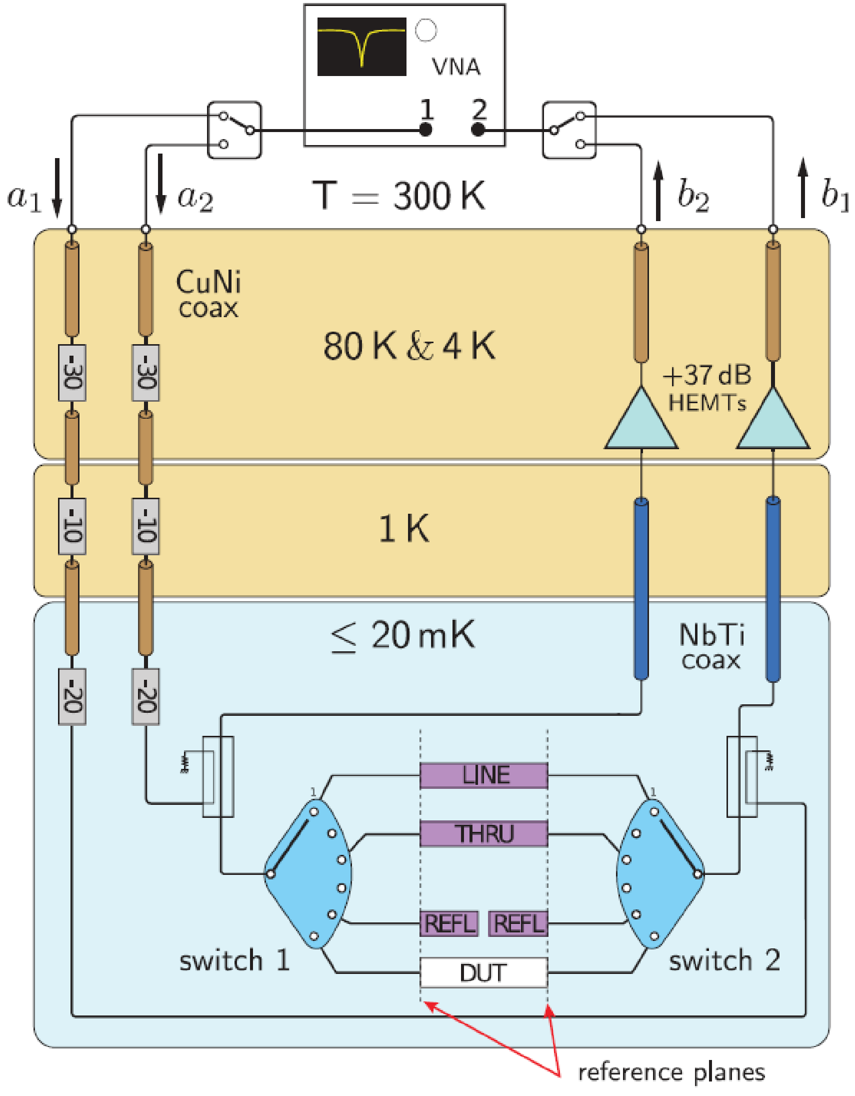

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