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Ministero dell'Università e della Ricerca

Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

NQSTI National Quantum Science and Technology Institute

Kinetic Inductance Traveling Wave Parametric Amplifiers for Practical Microwave Readout

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INFN - Milano-Bicocca

Bicocca Quantum Technologies (BiQuTe) Centre

UNIVERSITA' DEGLI STUDI DI MILANO BICOCCA

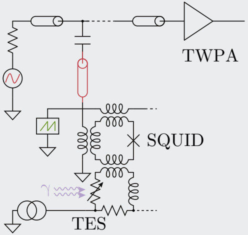
BIQUTE

MARIE CURIE ACTIONS

INFN Istituto Nazionale di Fisica Nucleare

Broadband quantum limited amplifiers and their applications

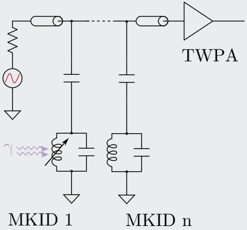
TES and MMC detectors



rf-SQUID multiplexing of TES/MMC microcalorimeter arrays for x-ray and gamma-ray spectroscopy.

Appl. Phys. Lett. 122, 214001 (2023)

MKIDs detectors

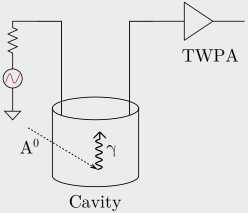


Optical or Phonon-Mediated MKIDs are naturally frequency domain multiplexed detectors

Appl. Phys. Lett. 115, 042601 (2019)

arXiv:2402.05419 [physics.ins-det]

Resonant microwave cavity

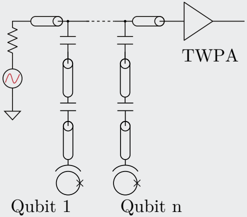


Resonant cavity haloscope readout to perform broadband axion searches

Rev. Sci. Instrum. 94, 044703 (2023)

Phys. Rev. D 108, 062005

Quantum bit

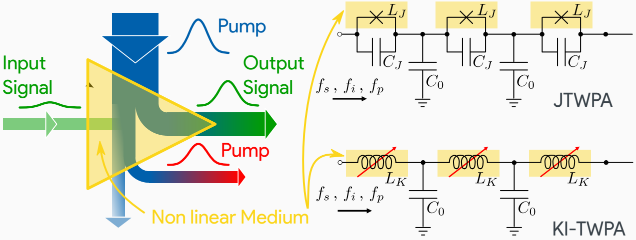


Fast and high-fidelity readout of simultaneous superconducting qubits

Appl. Phys. Lett. 113, 242602 (2018)

Phys. Rev. Applied 10, 034040 (2018)

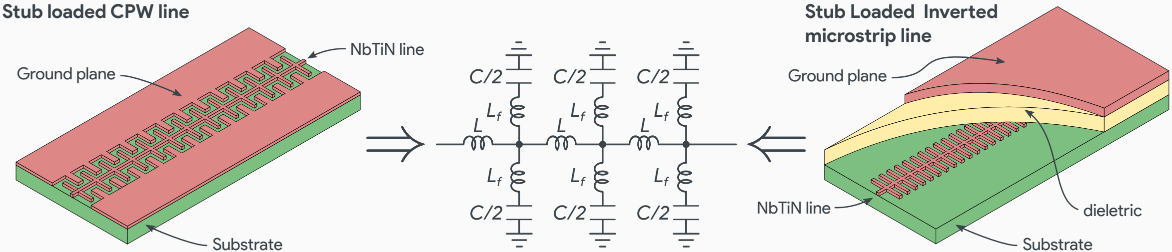
- TWPA: non linear transmission line;
- The nonlinear element can be implemented by Josephson Junction (JJ) or Kinetic Inductance (KI) of superconductors;
- A large pump tone modulates this element, coupling the pump (f_p) to a signal (f_s) and idler (f_i) tones via frequency mixing;



JTWPAs have become important for superconducting-circuit experiments such as multiplexed qubit readouts and sensing.

... however, the development of Kinetic Inductance TWPA (KI-TWPA or KIT) is particularly significant because they

- are simple to fabricate and require only few lithography and etching steps, without overlapping structures;
- provide a high dynamic range, high gain, and operate near the SQL;
- can operated also at higher temperatures, from millikelvin to 4 K (space application, spin-qubit, ...);
- are resilient to high magnetic fields (spin-qubit, axion search, ...);



Stub-loaded CPW:

- Originally proposed by NIST in 2017;
- Capacitance (C) due to the stub length and to the gap between the ground plane and the central line:
  $\Rightarrow$ Ideal for modest kinetic inductance values ($L_k \sim 10$ pH/sq);
- The central line and ground plane are very close ($\sim 1\ \mu$m)
  $\Rightarrow$ High probability of a short to ground
  $\Rightarrow$ Very low fabrication yield (10%);

Stub-loaded IMS:

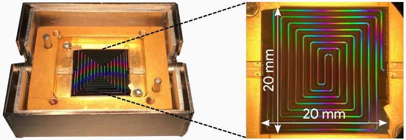
- Capacitance (C) due to the stub-lenght, to the dielectric permittivity and thickness:
  $\Rightarrow$ More degree of freedom having a C to match a high L
  $\Rightarrow$ Ideal for high kinetic inductance values ($L_k > 30$ pH/sq);
- Shorter elementary cell $\Rightarrow$ compact design;
- Ground plane and central line are totally isolated
  $\Rightarrow$ Very low fabrication yield (>90%);
- Dieletric could introduce losses;

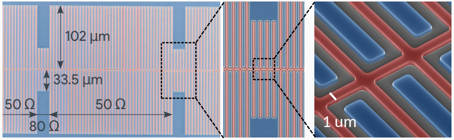
KI-TWPA based on 20 nm thick NbTiN film have shown promising noise performances ⇒ near-quantum-limited amplifier

- Series of coplanar waveguide (CPW) sections (cells) with inductance $\mathcal{L}$ and capacitance to ground $\mathcal{C}$ tuned by the finger length: $Z_0 = \sqrt{\mathcal{L}/\mathcal{C}}$
- Super-cell composed by $N_u = 60$ with $Z_0 = 50\,\Omega$ and $N_l = 6$ with $Z_0 = 80\,\Omega$ to create a weakly dispersive line.
- Good performance at 30 mK
  M. Malnou *et al.* PRX Quantum 2, 010302 (2021)
- Good performance at 4 K
  M. Malnou *et al.* Phys. Rev. Applied 17, 044009 (2022)
- Readout demonstration with rf-SQUID and TESs
  M. Malnou *et al.* Appl. Phys. Lett. 122, 214001 (2023)

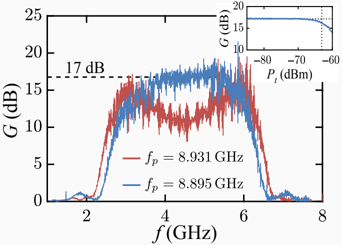
... but...

- very high pump power to operate;
- very low fabrication yield (<10%);





Good gain, bandwidth, high power handling



Material: NbTiN
Thickness: 20 nm
L_k: 10 pH/sq
T_c: 15 K
Gain: 17 dB
Bandwidth: 3.5-5.5 GHz
Noise: 3.1 quanta
Pump Power: −28 dBm
I_{dc}: 1.5 mA
I_*: 7 mA

DARTWARS-INFN (2021-2024)

INFN Istituto Nazionale di Fisica Nucleare · CSN5 Technological research · Università degli Studi di Milano Bicocca · Fondazione Bruno Kessler

DARTWARS-MSCA (2022-2024)

Università degli Studi di Milano Bicocca · University of Colorado Boulder · NIST · Marie Curie Actions

GA: 101027746

MiSS (2024-2027)

MiSS – Microwave Squeezing with Superconducting (meta) materials

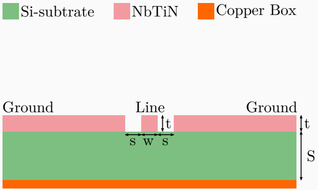
GA: 101135868

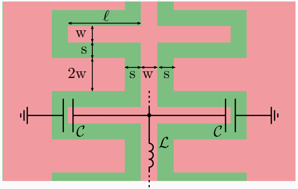
Fondazione Bruno Kessler · Università degli Studi di Milano Bicocca

2021 · 2022 · 2023 · 2024 · 2025 · 2026 · 2027

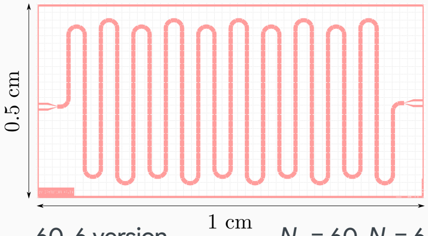
NQSTI National Quantum Science and Technology Institute · Università degli Studi di Milano Bicocca · INFN Istituto Nazionale di Fisica Nucleare · Fondazione Bruno Kessler

KI-TWPA in collaboration with INFN and FBK: design





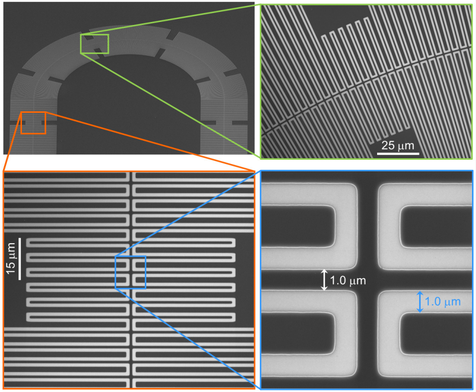
- NbTiN line with kinetic inductance $L_k = 8.5\,\mathrm{pH/sq}$ produced in collaboration with FBK;
- Conservative stub-loaded CPW line (inspired by PRX Quantum 2 (2021) 010302)

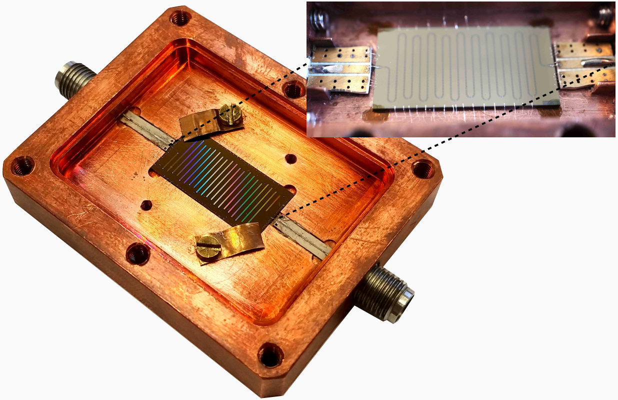


60-6 version $N_u = 60, N_l = 6$

- Meander-shaped line to simplify the design
- Each supercell composed by: $N_u = 60$ unloaded cells and $N_l = 6$ loaded cells;
- Total number of supercells: $N_{sc} = 523 \Rightarrow$ *half-size*;
- Total number of cells: $N_c = 34518 \Rightarrow$ Total line length: $L_{tot} \sim 17.3\,\mathrm{cm}$;
- Chip sizes: $0.5 \times 1\,\mathrm{cm}^2$;
- Expected gain: $G \sim 10\,\mathrm{dB}$, centered at 6 GHz;
- Expected pump frequency: $f_p \sim 12\,\mathrm{GHz}$;

Production of the *half-size* amplifier



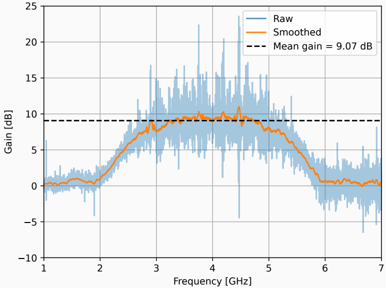


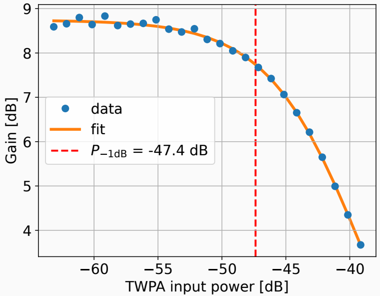
Design, production and characterization published in:

- Phys. Scripta 98 (2023) 12, 125921
- IEEE Trans. Appl. Supercond. 34,3 (2024) 1700605
- J. Low Temp.Phys. 216 (2024) 1-2, 156-164

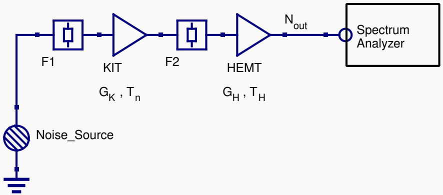
Gain measurements

- Amplification bandwidth centered around 4 GHz (lower than expected);
- Maximum gain measured around 9 dB in the 3 dB bandwidth, which aligns with the expected value;
- Critical current of $I_c = (1.41 \pm 0.01)$ mA and a scaling current of $I^* = (6.72 \pm 0.03)$ mA, as expected and compatible with literature;
- 1 dB compression point estimated at $P_{-1dB} = -47.4$ dB;
- Higher pump power yields higher gain, but it also introduces larger ripples in the gain curve:
  $\Rightarrow$ not optimized box, local heating on the chip (hot-spots) not optimized grounding, etc
- Very encouraging performances for this first prototypes production

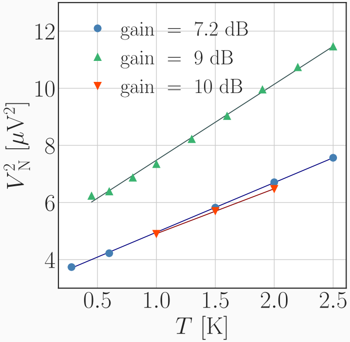




- Measurement of noise using the Y-factor method ⇒ Johnson-Nyquist noise of a 50 Ω resistor at various known temperatures;
- Noise source with an adjustable temperature range between 0.28 and 2.5 Kelvin.
- Noise measurements at three different gain settings: 7 dB, 9.2 dB, and 10 dB;
- Previous calibration of all system attenuation (including the line and RF components) and gains (HEMT and warm amplifiers) during dedicated cooling cycles.



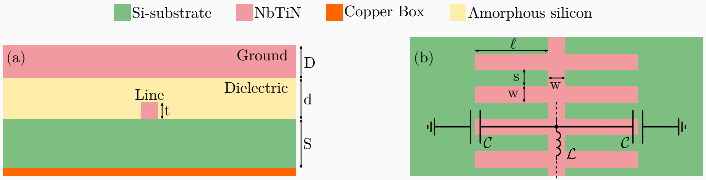
Noise measurements results @ 4 GHz			
G_K (dB)	7.2	9.0	10
T_{sys} (K)	1.78	1.72	2.06
T_n (K)	0.5	0.7	1.0
N_q	2.5	3.4	4.9



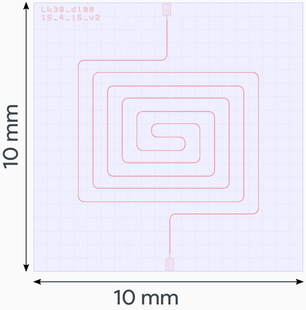
Noise temperature $T_n \leq$ 600 mK

DARTWARS goal accomplished in the first prototype

KI-TWPA in collaboration with NIST: High Kinetic Inductance TWPA



- NbTiN line with higher kinetic inductance $L_k = 30$ pH/sq (instead of 10 pH/sq) IEEE Trans. Appl. Supercond. 33,5 (2023) 1700905;
- Inverted-microstrip lines provide higher capacitance due to the amorphous silicon (a-Si) dielectric;

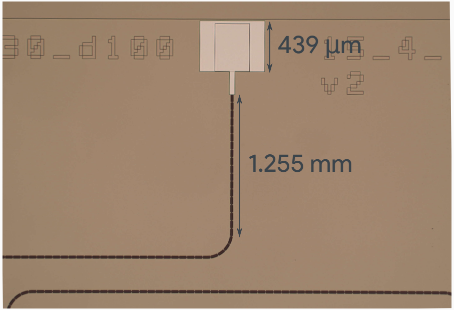


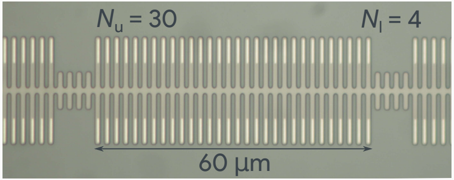
30-4 version

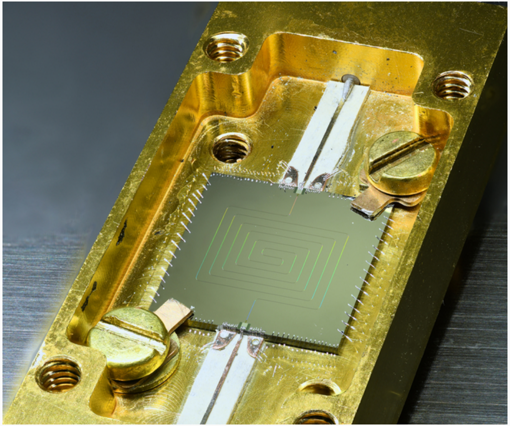
$N_u = 30$
$N_l = 4$

- Two-arm spiral layout to optimize the chip size;
- Each supercell composed by: $N_u = 30$ unloaded cells and $N_l = 6$ loaded cells;
- Total number of supercells: $N_{sc} = 1200$;
- Total number of cells: $N_c = 40800 \Rightarrow$ Total line length: $L_{tot} \sim 8.2$ cm (for the previous CPW version: $L_{tot} \sim 33$ cm);
- Chip sizes: $1 \times 1\,\text{cm}^2$ (for the previous CPW version: $2 \times 2\,\text{cm}^2$);
- Expected gain: $G > 25$ dB, centered at 6 GHz;
- Expected pump frequency: $f_p \sim 12$ GHz;

Devices production at NIST microfabrication facilities (Version v2)







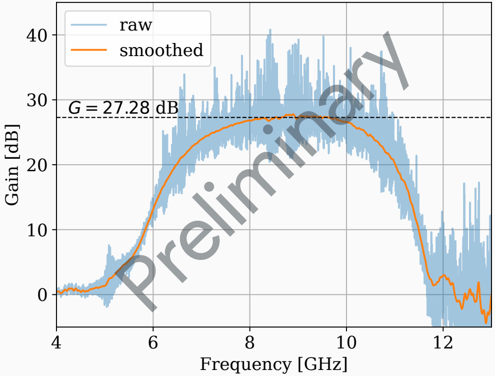
- Version v1 produced in Summer 2024 and published in J.Low Temp.Phys. 215 (2024) 3-4, 152-160;
- Version v2 produced in Fall 2023;

Version v2: 12 prototypes tested:

- 10/12 amplifiers showed a gain $G > 20$ dB;
- Fabrication yield: 83% (2 not working devices)
- $G = (20 - 27)$ dB ✔ ☺;

For the best devices:

NbTiN thickness :	$t = 10$ nm	lower than CPW	✔ ☺
Kinetic Inductance:	$L_0 \sim 30$ pH/sq	higher than CPW	✔ ☺
Critical current:	$I_c \sim 0.8$ mA	lower than CPW	✔ ☺
Scaling current :	$I_* \sim 2.8$ mA	lower than CPW	✔ ☺
Bias current :	$I_{dc} \sim 0.5$ mA	lower than CPW	✔ ☺
Pump power:	$P_p \sim -40$ dBm	lower than CPW	✔ ☺
1 dB compression point:	$P_{1dB} \sim -70$ dBm	compatible CPW	✔ ☺
3 dB bandwidth:	$B = 3.2$ GHz	compatible CPW	✔ ☺

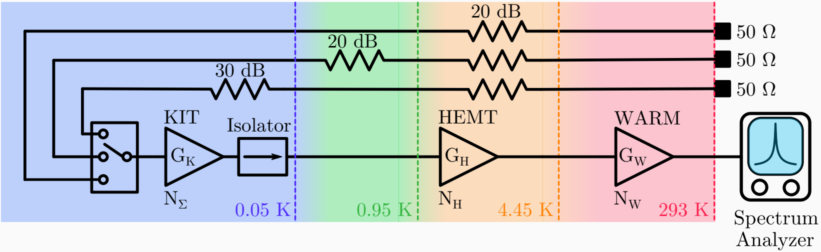


... but ...

- Line impedance lower than expected $Z_0 \sim 40\,\Omega$ ☹
- Gain centered at higher frequency: $f_{center} = 8.3$ GHz ☹

Fabrication issues

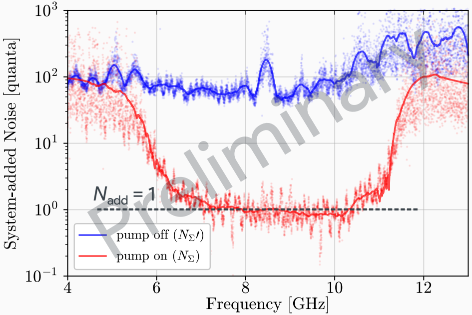
- Lower kinetic inductance: $L_k = 25$ pH/sq 😠
- Lower dielectric constant: $\varepsilon_r = 8.6$ 😠



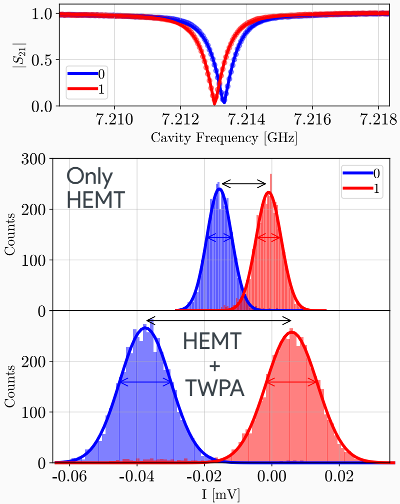
- Modified y-factor (hot/cold) method for measuring the noise;
- Full loss characterization of each component (all at base temperatures);
- KI-TWPA performance creeping up on the SQL ✔☺:

$$N_{add} \simeq 1\,\text{quanta} \Rightarrow T_N = 400\,\text{mK @ 8 GHz}$$

- Equivalent results with a shot-noise tunnel junction (SNTJ) source;

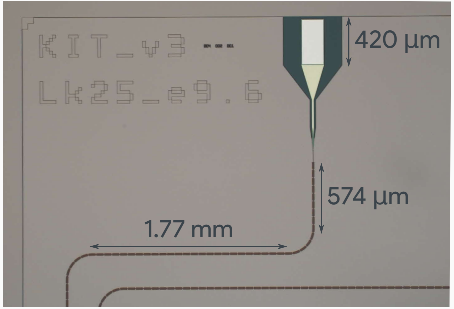


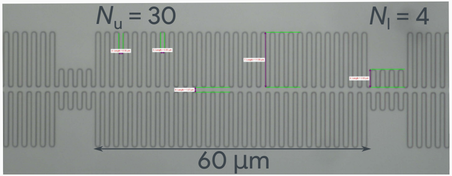
- Readout of an 8-qubit array with cavities in the range from 5.8 to 7.2 GHz;
- TWPA gain centered at 8.2 GHz ⇒ cavities fall in the lower cutoff;
- Pump tone properly filtered to minimize any leakage in the qubit array;
- Only 10-15 dB of on-off gain is available in that region (probably less considering a line loss of around 3 dB);
- Inside the bandwidth maximum improvement in the state measurement SNR by a factor of 1.45, and increase the fidelity from 96.2% to 97.8%;
- Encouraging results despite the mismatch between TWPA bandwidth and qubit frequencies;
- A new qubit array optimized for fast readout and a new TWPA will be used to perform better measurements;

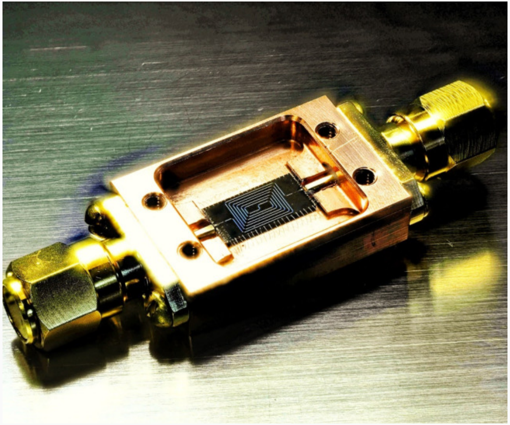


IEEE Trans. Appl. Supercond. 35 (2025) 5, 1500305

Production of the Version v3 at NIST



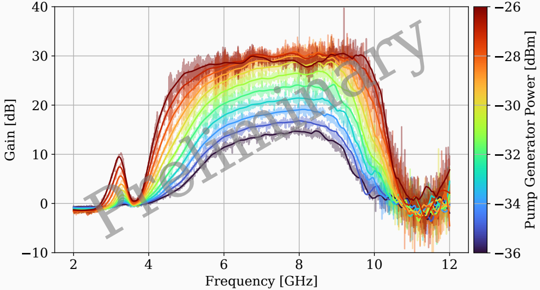




Version v3 produced in Summer 2024

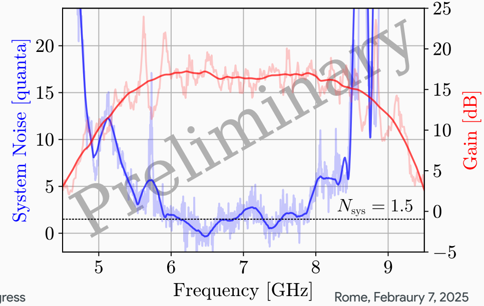
Paper ready to be submitted on PRX Quantum

- Optimized stub lengths for covering different kinetic inductance L_k and permittivity ε_r combinations;
- Optimized transitions from stub-loaded microstrip to standard microstrip to CPW ports;
- Optimized copper box with spring-loaded pogo pins to avoid bonds;



Preliminary results

- Tunable gain up to $G = 30$ dB;
- Very low gain ripple $r < 1.5\ \text{dB}_{\text{rms}}$ over 3 GHz of bandwidth;
- Transmission line with characteristic impedance around $Z_0 = 49\ \Omega$ (that reach 50 Ω by applying the bias);
- System noise around $N_{syst} = 1.5$ (measurement with improved configuration in progress);



- For Italian Developments:
  - Transition from a stub-loaded CPW line to an inverted microstrip line, following the NIST solution;
  - Design of test structures for extracting the dielectric and superconducting characteristic parameters;
  - Design and production of the first inverted microstrip TWPA amplifier before June (Q2);
- For the Development in Collaboration with NIST:
  - Versions v2 and v3 of the amplifier have shown highly competitive performance in terms of gain, ripple, and noise;
  - Version v2 has been successfully used for qubit array readout;
  - Version v3 currently under chracterication and optimization;
  - A new qubit array, optimized for fast readout, is in development for readout demonstration with Version V3;
  - Optimization of a new version with on-chip bias tees and directional couplers/diplexers;
  - Optimization of new versions for sub-GHz applications (MKIDs) and high-frequency applications (>20 GHz, hot qubits, and cavities).

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