DARTWARS: Design of TWPA amplifiers based on high kinetic inductance materials

Andrea Giachero

University & INFN of Milano-Bicocca

DARTWARS

Detector Array Readout with Traveling Wave AmplifieRS

UNIVERSITA' DEGLI STUDI DI MILANO BICOCCA

MARIE CURIE ACTIONS

INFN Istituto Nazionale di Fisica Nucleare

CSN5 Technological research

Parametric amplifiers

- Parametric amplification $\Rightarrow$ periodic variation of a parameter generates amplification

- Tunable element $\Rightarrow$ inductance $\Rightarrow$

$$\begin{cases} \text{Josephson junction (JJ):} & L_J(I) = L_{J_0} \dfrac{\arcsin(I/I_c)}{I/I_c} \\ \text{Kinetic inductance (KI):} & L_K(I) = L_{K_0} \left(1 + \dfrac{I^2}{I_*^2}\right) \end{cases}$$

There are two types of parametric amplifiers

Resonator-based amplifier	Transmission line-based amplifier (traveling-wave)
• They needs circulator (lossy, bulky)	• Harder to build (very long transmission line)
• Limited bandwidth (few hundred of MHz), Appl. Phys. Lett. 122, 014001 (2023)	• Large bandwidth (> 1 GHz), Science 350(6258), 307-310 (2015) and Nature Phys 8, 623–627 (2012)
• JJ-based: JPC, JPA, SPA;	• JJ-based: JTWPA;
• KI-based: KIPA	• KI-based: KI-TWPA (also known as KIT or DTWKI)

DARTWARS has the goal of developing transmission line-based amplifiers: JTWPA, KI-TWPA

Designing a TWPA amplifier based on kinetic inductance non-linearity typically involves the following steps:

1. Selecting the appropriate material $\Rightarrow$ low dissipation and high non-linearity;
   $\Rightarrow$ Highly resistive superconductors such as NbTiN can have L_k that exceeds 90% of the total inductance;

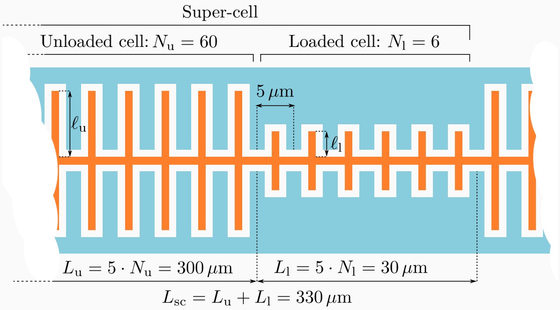
2. Determining all the material characteristics that have an impact on the amplifier design:
   $\Rightarrow$ Critical temperature T_c, normal resistivity ρ_n, kinetic inductance L_k, scaling current I_*, signal loss δ
   Federica and Andrea's talks will cover this part

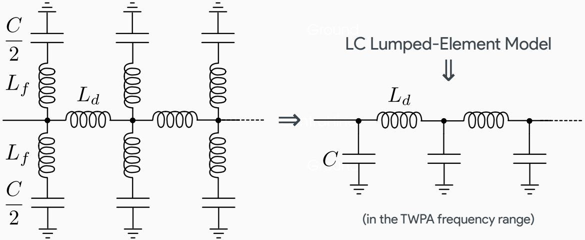
3. Choosing the geometry of the transmission line:
   $\Rightarrow$ two possible solution: CPW (PRX Quantum 2 (2021) 010302) and (inverted) microstrip (Phys. Rev. Research 3 (2021) 023184)

4. For the chosen geometry determining the line characteristic parameters (Z_0, L and C per unit length) starting from EM simulations and material characterizations;

5. Developing a theoretical model that describes the chosen transmission line geometry starting from the measured/simulated characteristic parameters;

6. By using the developed model, simulating the performance of the amplifier (operating frequency range and gain).



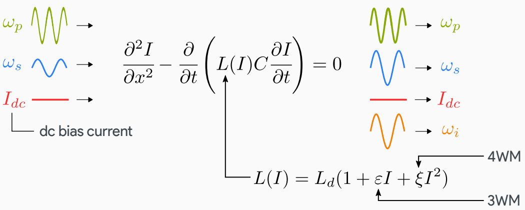


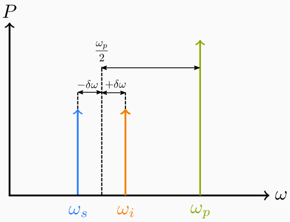
- Series of coplanar waveguide (CPW) sections (cells) with inductance L_d;
- Two interdigitated capacitor (IDC) fingers that form the capacitance to ground C;
- Characteristic impedance $Z_0 = \sqrt{L_d/C}$ tuned by the finger length;
- N_{sc} super-cell composed by N_u unloaded-cell with $Z_0 = 50\,\Omega$ and N_l loaded-cell with $Z_0 > 50\,\Omega$ to create a weakly dispersive line.

- NbTiN film with a thickness around (10-30) nm shows a kinetic inductance around $L_k = (7 - 10)$ pH/sq (depending on the fabrication process);
- From EM simulations the chosen geometry provide L_d and C such that $Z_0 = 50\,\Omega$ with finger length $\ell \sim 100\,\mu$m and $Z_0 = 80\,\Omega$ with finger length $\ell \sim 35\,\mu$m;

Coupled mode equations (CME)

- Waves propagation in the transmission line $\Rightarrow$ non-linear kinetic inductance introduced in the Telegrapher's equations
- Pump and signal 4-way-mix (4WM), producing an idler such that $2f_p = f_s + f_i$;
- If the a DC bias is applied to the line pump and signal 3-way-mix (3WM), producing an idler such that $f_p = f_s + f_i$;





CMEs:

$$
\begin{cases}
\dfrac{\mathrm{d}I_p}{\mathrm{d}x} = \dfrac{j\varepsilon}{4}k_p I_s I_i\, e^{-j\Delta k x} + \dfrac{j\xi}{8}k_p I_p\left(|I_p|^2 + 2|I_s|^2 + 2|I_i|^2\right) \\
\dfrac{\mathrm{d}I_s}{\mathrm{d}x} = \dfrac{j\varepsilon}{4}k_s I_p \overline{I_i}\, e^{j\Delta k x} + \dfrac{j\xi}{8}k_s I_s\left(2|I_p|^2 + |I_s|^2 + 2|I_i|^2\right) \\
\dfrac{\mathrm{d}I_i}{\mathrm{d}x} = \dfrac{j\varepsilon}{4}k_i I_p \overline{I_s}\, e^{j\Delta k x} + \dfrac{j\xi}{8}k_i I_i\left(2|I_p|^2 + 2|I_s|^2 + |I_i|^2\right)
\end{cases}
$$

where:

$$\Delta k = k_p - k_s - k_i$$

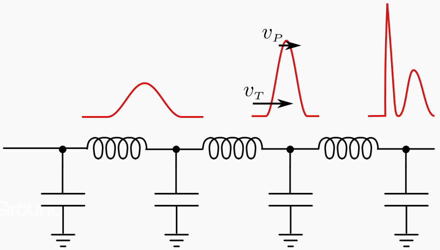
$$\xi = \frac{1}{I_*^2 + I_{dc}^2}$$

$$\varepsilon = \frac{2I_{dc}}{I_*^2 + I_{dc}^2} = 2I_{dc}\xi$$

Propagation in a dispersionless line $\Rightarrow$ all the cells with $Z_0 = 50\,\Omega$

- Velocity decreases at high current;
- Tail of the pulse moves faster than peak;
- Generation of shock waves:

  solving the CMEs $\Rightarrow$ low (quadratic) gain limited to few dB;

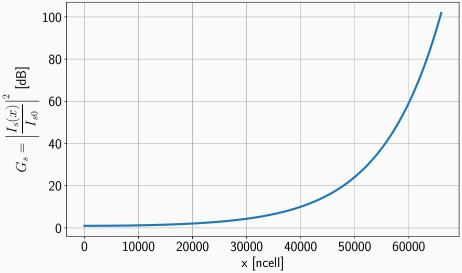


Periodic loading with $Z_0 > 50\,\Omega$ along the transmission line provides:

- Dispersive line $\Rightarrow$ modified phase velocities
- Extra delay at the pump frequency to create phase-matching:

$$\Delta\beta = \Delta k + \frac{\xi}{8} I_{p0} (k_p - 2k_s - 2k_i) = 0$$

- Suppression of shock waves via stop-band;
- Exponential gain: $G_s = \left| \frac{I_s(x = L_{KIT})}{I_s(0)} \right|^2 = \cosh^2 \left(\frac{\delta_L \, k_p \, L_{KIT}}{8} \right)$



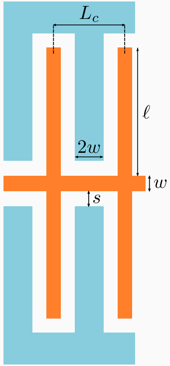
Goal: bandwidth centered at 5/6 GHz and gain around $G = 20$ dB

Unloaded cell with $Z_0 = 50\,\Omega$

Kinetic inductance : $L_k = 10$ pH/sq (target value from fabrication)
Characteristic impedance per cell: $Z_0 = 50\,\Omega$ (wanted value from design)
Capacitance per cell: $C \sim 20$ fF (from EM simulation)
Inductance per cell: $L_d \sim 50$ pH (from EM simulation)
Finger length: $\ell \sim 102\ \mu$m (from EM simulation)
Number of cell per super-cell: $N_u = 60$

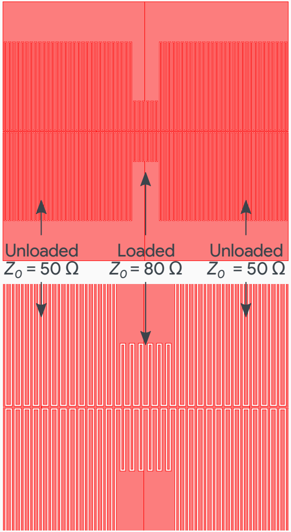
Loaded cell with $Z_0 = 80\,\Omega$

Kinetic inductance : $L_k = 10$ pH/sq (target value from fabrication)
Characteristic impedance per cell: $Z_0 = 80\,\Omega$ (wanted value from design)
Capacitance per cell: $C \sim 7$ fF (from EM simulation)
Inductance per cell: $L_d \sim 50$ pH (from EM simulation)
Finger length: $\ell \sim 34\ \mu$m (from EM simulation)
Number of cell per super-cell: $N_l = 6$



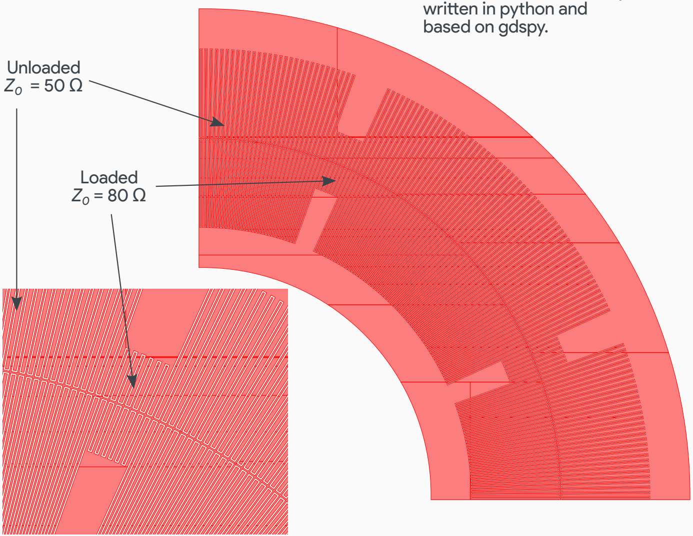
Finger width : $w = 1\ \mu$m
Spacing : $s = 1\ \mu$m
Cell length : $L_c = 5\ \mu$m
Cells per super-cell : $N_c = N_u + N_l = 66$
Number of super-cell : $N_{sc} = 1000 \cdot N_c = 66000$
Total length : $L_{\mathrm{KIT}} = N_{sc} \cdot L_c \sim 33$ cm

Straight Cell



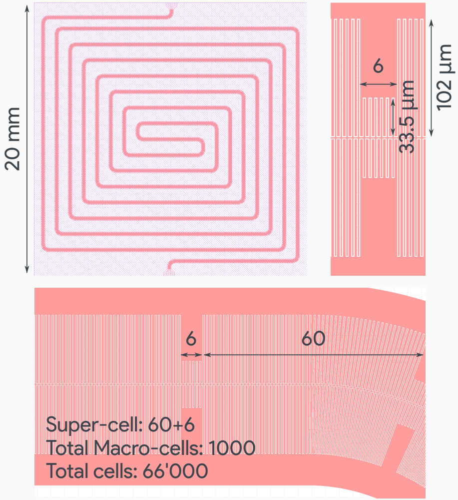
Turn Cell

Software to create the super-cells written in python and based on gdspy.



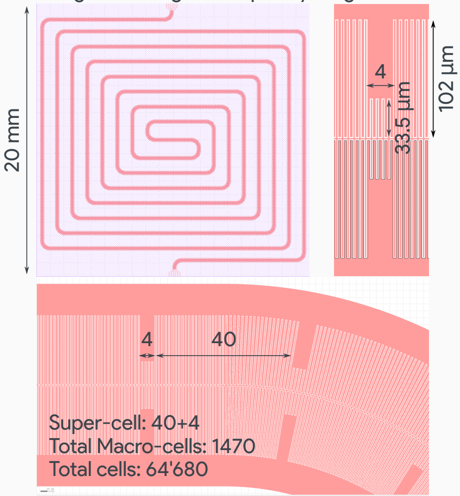
Version 60-6

[PRX Quantum 2, 010302 (2021)]

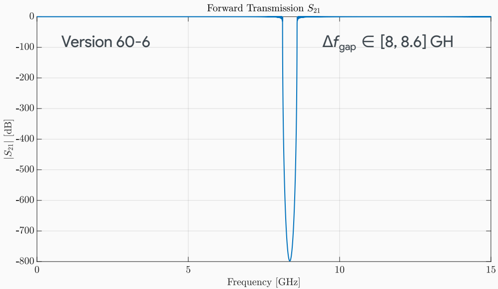


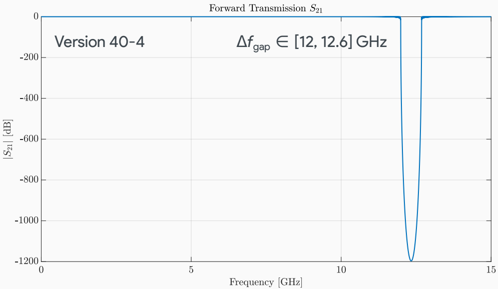
Version 40-4

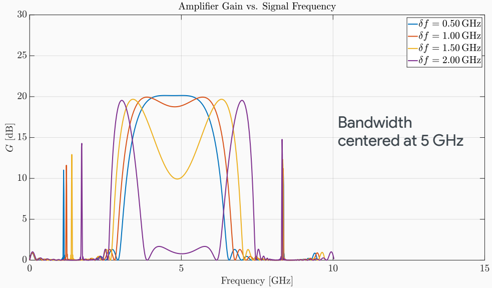
designed for higher frequency range

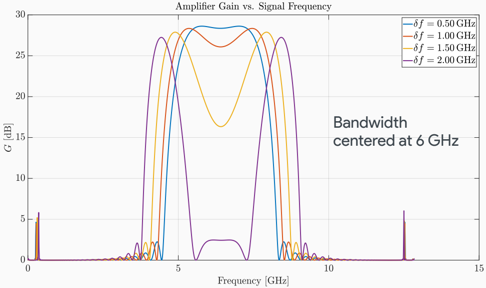


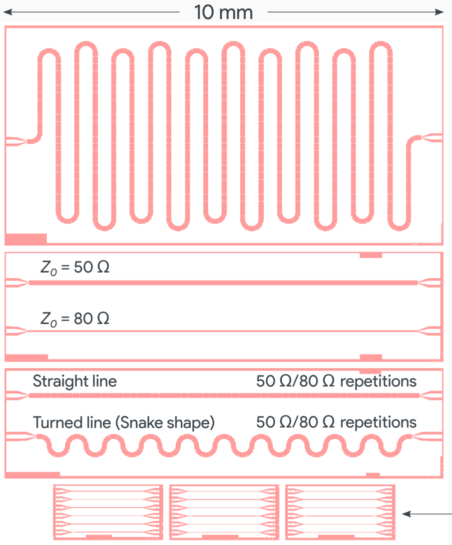
Foreseen bandwidths











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

Production DWD1

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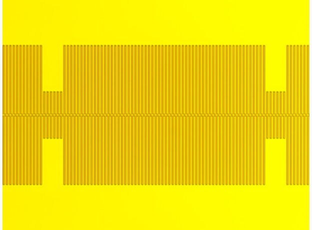
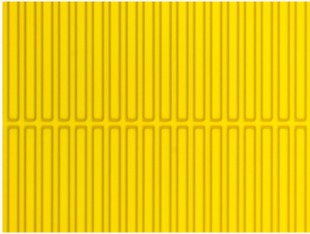
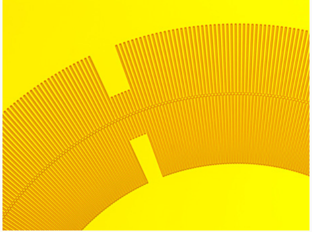
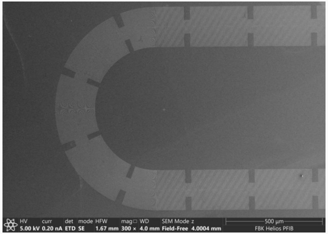
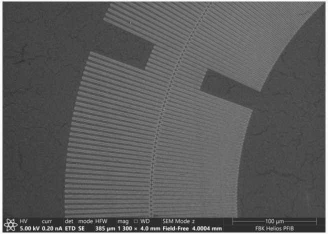
Optical Microscopy Images

Scanning Electron Microscopy Images





Conclusion

- Completed a study and tuning of the NbTiN production process to achieve a desired kinetic inductance
  more details in the Federica's talks
- Conducted EM on the chosen CPW transmission line to determine the optimal finger length to match the desired impedance;
- Developed Python software to solve the Coupled-Mode Equations (CME) system and evaluate the behavior of the amplifier;
- Designed the macrocell and entire amplifier using a custom Python software;
- Fabricated a first prototype of the amplifier with a shorter length for testing purposes;
- Currently undergoing characterization measurements on the first prototype;
  more details in the Andrea's talks