Superconducting Travelling Wave Parametric Amplifier: reaching quantum noise limit

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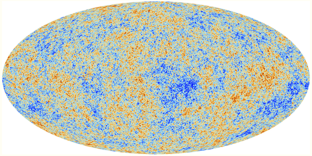
Projects

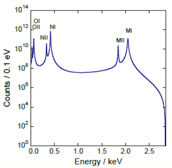
QUBIC

Objetive: detect CMB radiation[1]



ECHo

Objetive: study neutrino mass[2]



Read-out System

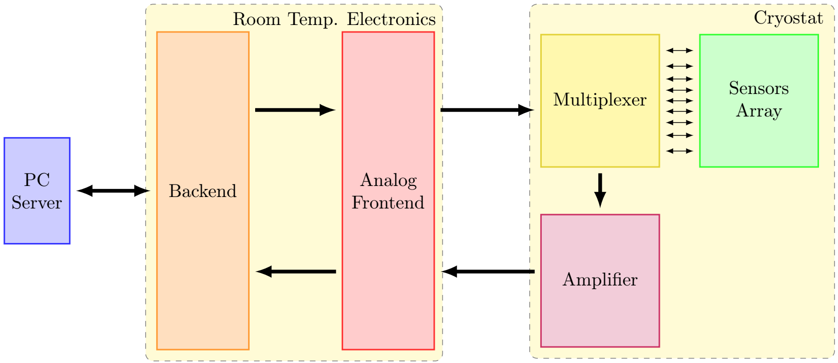
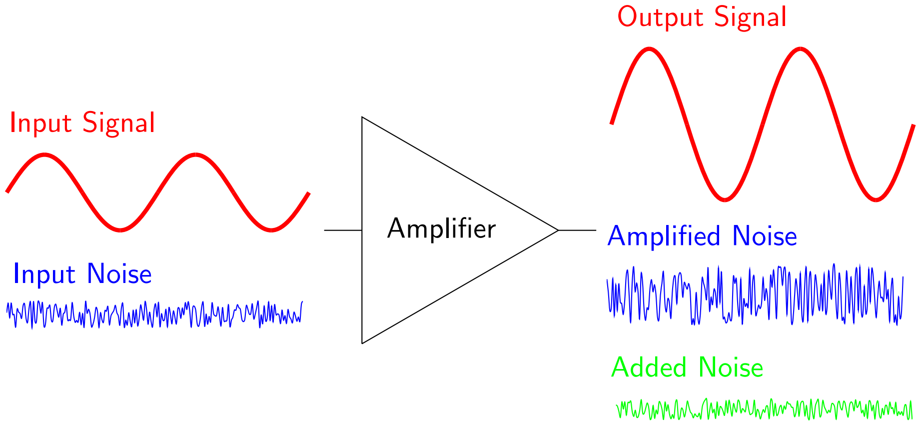


Figure 1: Proposal read-out system

Amplifiers: state of the art

Technology	Gain [dB]	Bandwidth [GHz]
InP-InGaAs DHBT	17	50
SiGe (130nm)	36	23
CMOS (90nm)	28	22
Parametric	20	8

Amplifiers



$$SNRi = \frac{InputSignal}{InputNoise} \qquad SNRo = \frac{OutputSignal}{AmpifiedNoise + AddedNoise}$$

$$F = \frac{SNRi}{SNRo}$$

Noise

Friss Formula

$$FT = F1 + \frac{F2 - 1}{G1} + \frac{F3 - 1}{G1G2} + ...$$

Parametric Amplifier can work at cryogenic temperature (mK).

It doesn´t use resistive elements that add noise.

Parametric Amplifier: Concept

Transfer energy from the pump signal to the input signal to be amplified.

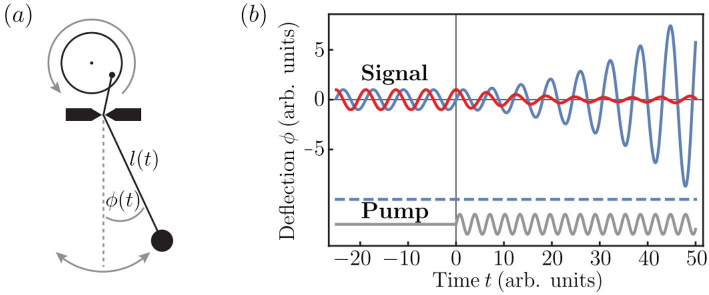


Figure 2: Parametric Amplifier

Parametric Amplifier: Characteristics

Advantages

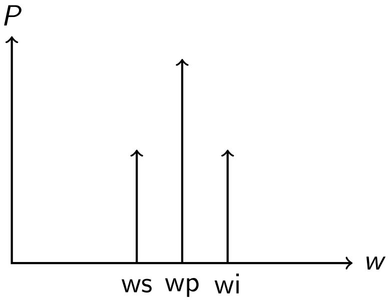
- Doesn´t need transistors
- Use non-dissipative elements
- Can achieve quantum noise limit

Disadvantages

- Less gain and bandwidth than transistors based amplifiers

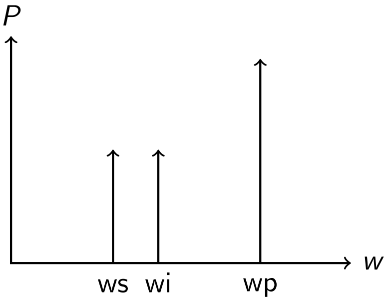
Parametric Amplifier: Modes

4 Wave Mixing



$$2wp = ws + wi$$

3 Wave Mixing



$$wp = ws + wi$$

Travelling Wave Principle

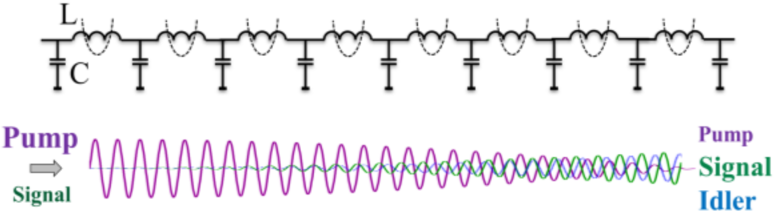


Figure 3: Input signal amplification through a travelling wave line

Long interaction between pump and input signal→DISPERSION.
Dispersion engineering is necessary.

Josephson Junction

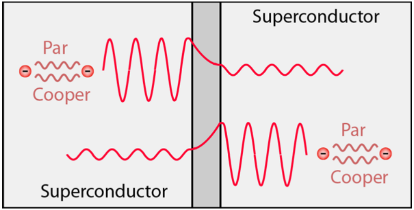


Figure 4: Josephson junction (JJ)

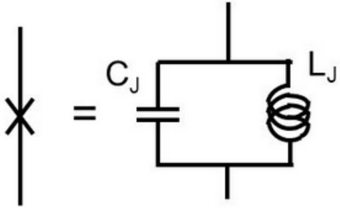


Figure 5: JJ symbol and electrical model

Discovered by Brian Josephson in 1962.
Has many application such as SQUIDs, superconducting qubits, and amplifiers.

Josephson TWPA

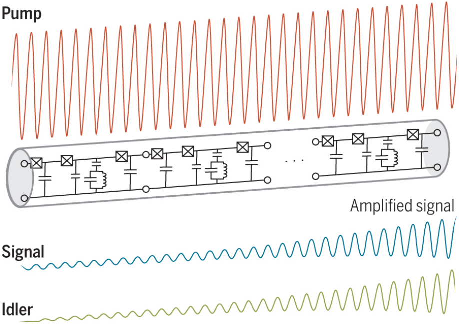


Figure 6: JTWPA [3]

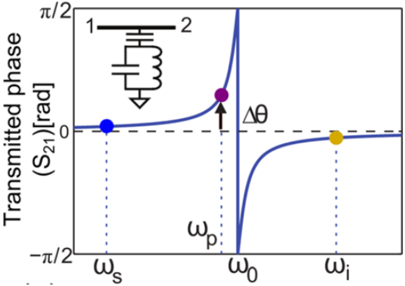


Figure 7: Resonant phase matching [4]

Kinetic Inductance

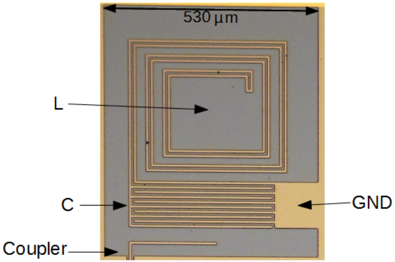


Figure 8: Microwave kinetic inductance detector

- Related with the kinetic energy
- Becomes relevant at
  - High frequency
  - Low temperature
- NbTiN

Kinetic Inductance TWPA

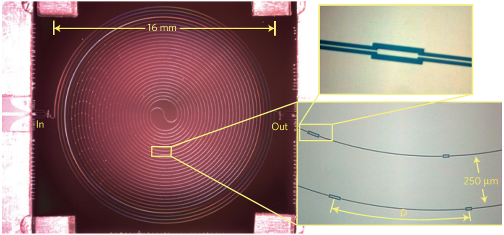


Figure 9: KITWPA [5]

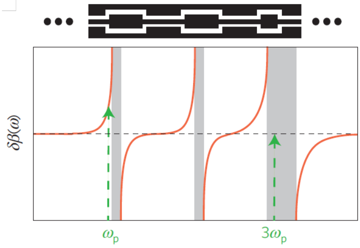


Figure 10: Phase matching

Josephson Junction vs Kinetic Inductance

Similarities

- Both are superconductors
- Working modes
- Gain between 10 and 20 dB
- Bandwidth between 4 to 8 GHz
- Noise quantum limit

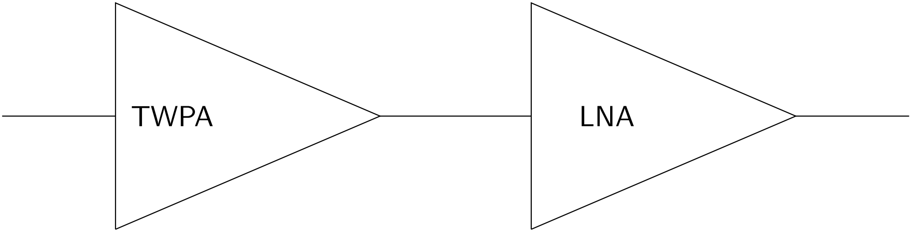
Differences

- Size
- Pump power
- Dynamic range
- Design

Proposal Amplifier Stage

Projects Requirements:

- At least 35dB of gain
- Dynamic Range until -20dBm



1st Amp Stage: Kinetic Inductance TWPA
2nd Amp Stage: Low Noise Amplifier (HEMT)

Future Work

- Study the kinetic inductances behavior of some materials.
- See which of these materials can be manufactured in our institutes (ITeDA, KIT).
- Study the behavior of the TWPA with multitonal signals.
- Design and simulation of a TWPA.

References

- The QUBIC collaboration; “QUBIC, the Q&U Bolometric Interferometer for Cosmology”. *Astroparticle Physics*,Volume 34, Issue 9, p. 705-716 (2010).
- Sander 0., Karcher N., Krömer O., Weber M., Kempf S., Wegner M. & Enss C.; “Software-defined Radio Readout System for the ECHo Experiment”. *Physics-Instrumentation and Detectors*, (2018).
- DOI: 10.1126/science.aad0858, (2015)
- APPLIED PHYSICS LETTERS 106, 242601 (2015)
- DOI: 10.1038/NPHYS2356, (2012)

THANKS

Dispersion

Change in phase velocity.
Self-phase and cross-phase modulation.

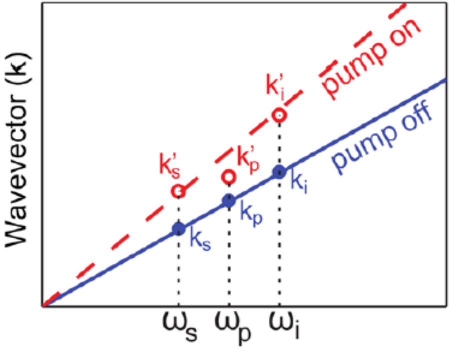


Figure 11: Dispersion[1]

[1] APPLIED PHYSICS LETTERS 106, 242601 (2015)

Gain and Phase

$$g = \sqrt{\frac{k_s k_i}{k_p^2}(\gamma k_p)^2 - (\kappa/2)^2}$$

Figure 12: Gain

$$\kappa = 2\gamma k_p + k_s + k_i - 2k_p$$

Figure 13: Phase conservation

$$G_s = \cosh^2(\gamma k_p z)$$

Figure 14: Exponential gain

Dynamic Range

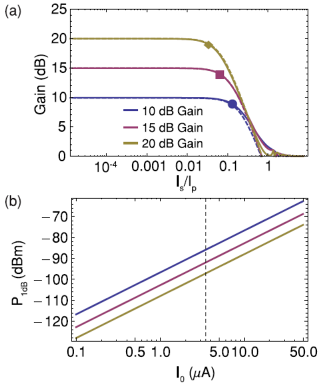


Figure 15: JTWPA dynamic range [2]

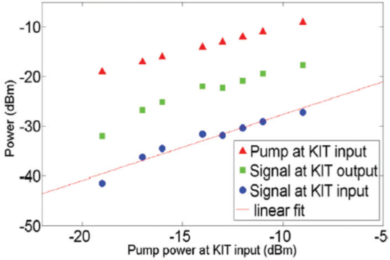


Figure 16: KITWPA dynamic range [3]

[2] PRL 113, 157001 (2014)
[3] Appl. Phys. Lett. 108, 012601 (2016)