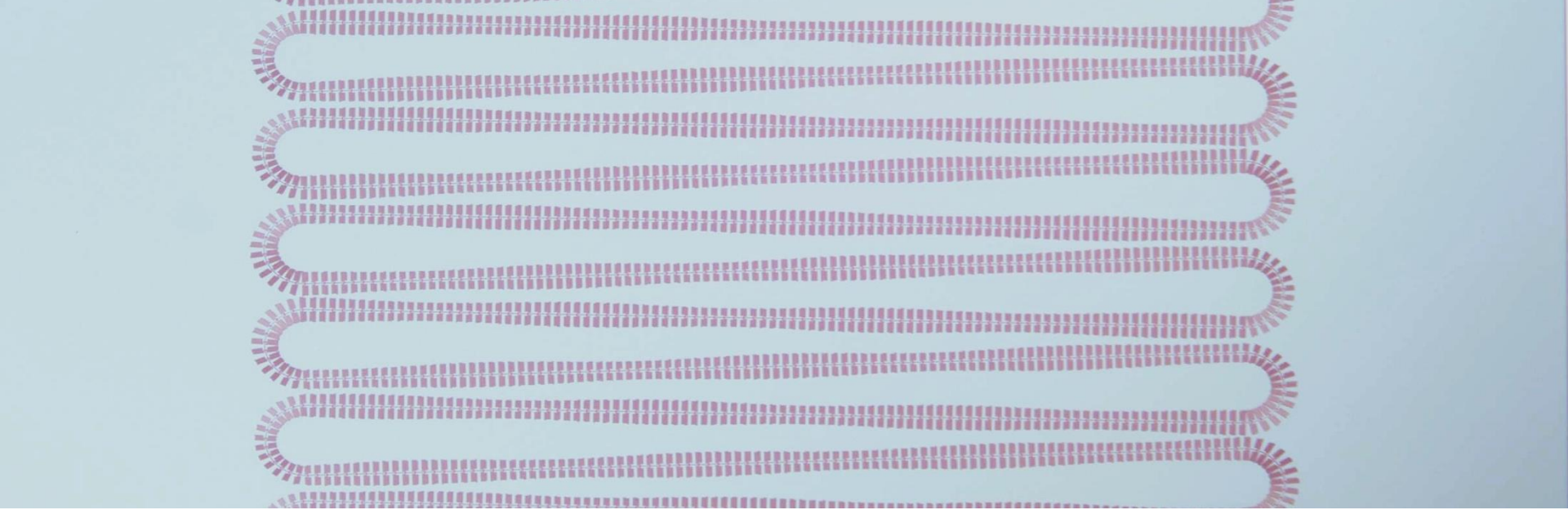

Kinetic Inductance Traveling Wave Parametric Amplifiers (KI-TWPAs)

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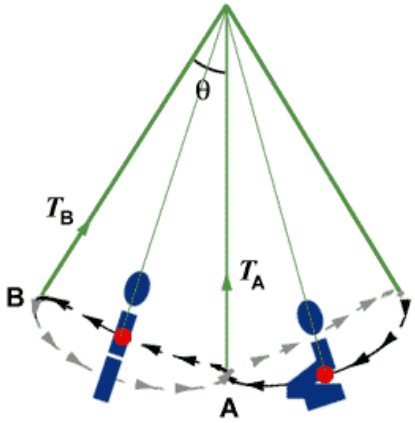
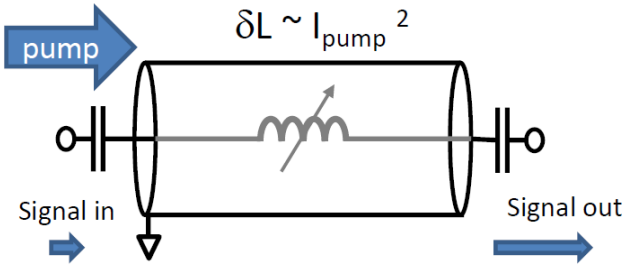
Jet Propulsion Laboratory
California Institute of Technology

Parametric Amplification

- Parameter of the system is varied with a strong “pump”
- $\delta L \sim I_{Pump}^2$ Nonlinearity in the resonant circuit
- *Nonlinearity* transfers power from pump to signal
- Purely reactive nonlinearity
  - Need not add noise beyond the QM limit
- E.g., Josephson parametric amplifiers
  - Narrow band

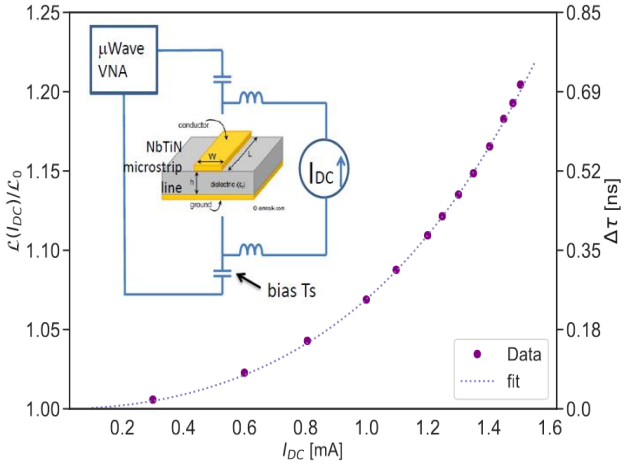




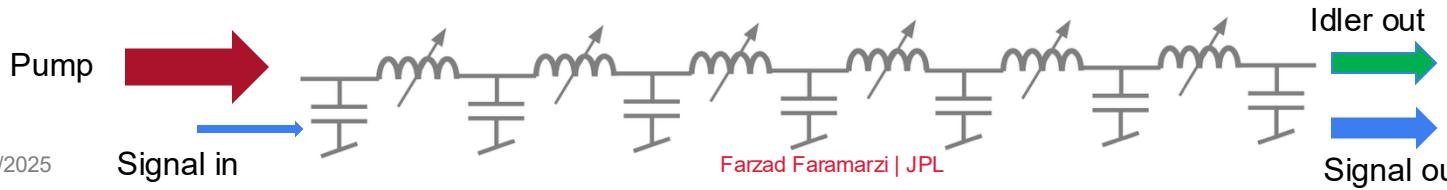
Kinetic Inductance – Traveling Wave Parametric Amplifier

KI Nonlinearity of a Microstrip Line

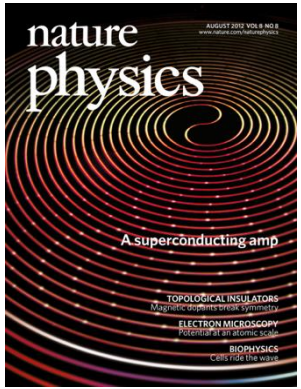
- Distributed geometry, e.g., non-linear transmission line
- Energy transfer along the length of the transmission line
- Near ideal nonlinearity $L_K(I) = L_K(0)\left(1 + \frac{I^2}{I_*^2} + \ldots\right)$
- Analogous to Kerr nonlinearity in optics (intensity dependent index n)
  - Supports 4-wave mixing (4WM) & other nonlinear processes



Shu et. al (2021)



Phase Matching & Dispersion Engineering

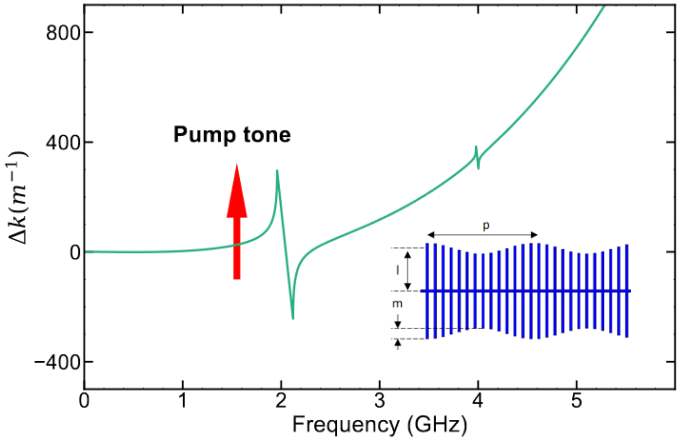


Peter Day et al.

- Maintain a phase relation between the signal, idler, and pump (Phase matching condition)
  - Controls power flow

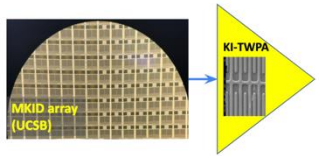
$$\Delta\phi_p = \frac{k_p |I_p|^2}{8 I_*^2}$$

  - Wideband gain + maximum gain
- Capacitive stubs
  - Impedance matching $Z = \sqrt{\frac{L}{C}}$
  - Mismatch unwanted nonlinear processes
  - Bandgap (band stop)

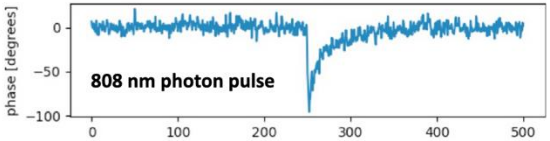


Motivation

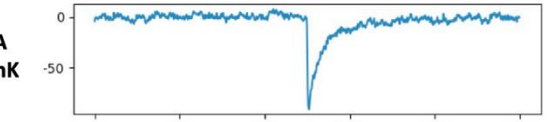
- Astronomical Instrumentation
  - Low Background, Photon Counting Mode
    - OUVIR MKIDs
    - μMUX readout of TESs, MMCs
  - RF or IF Amplifiers for the Heterodyne Receivers
    - Improve noise performance and bandwidth of receivers
  - Pre-amplifiers for radiometers & DSN
- QIS & Fundamental Physics
  - Readout of Cryogenic Qubits
    - Transmon, spin qubits, etc.
  - Quantum Sensing
    - Direct Dark Matter Searches



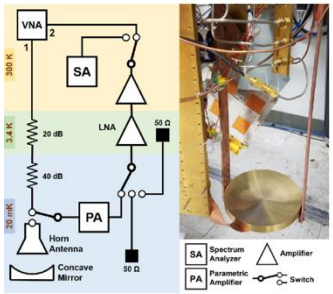
- HEMT only
- $T_{sys} \sim 5K$

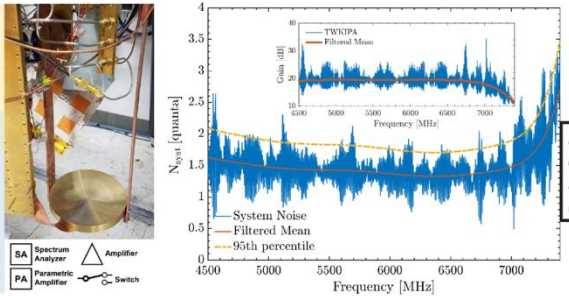


- with TWPA
- $T_{sys} \sim 430mK$



Zobrist et al., Applied Physics Letters 115, no. 4 (2019): 042601

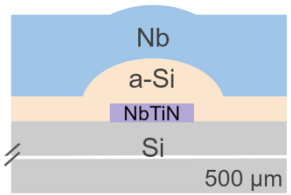




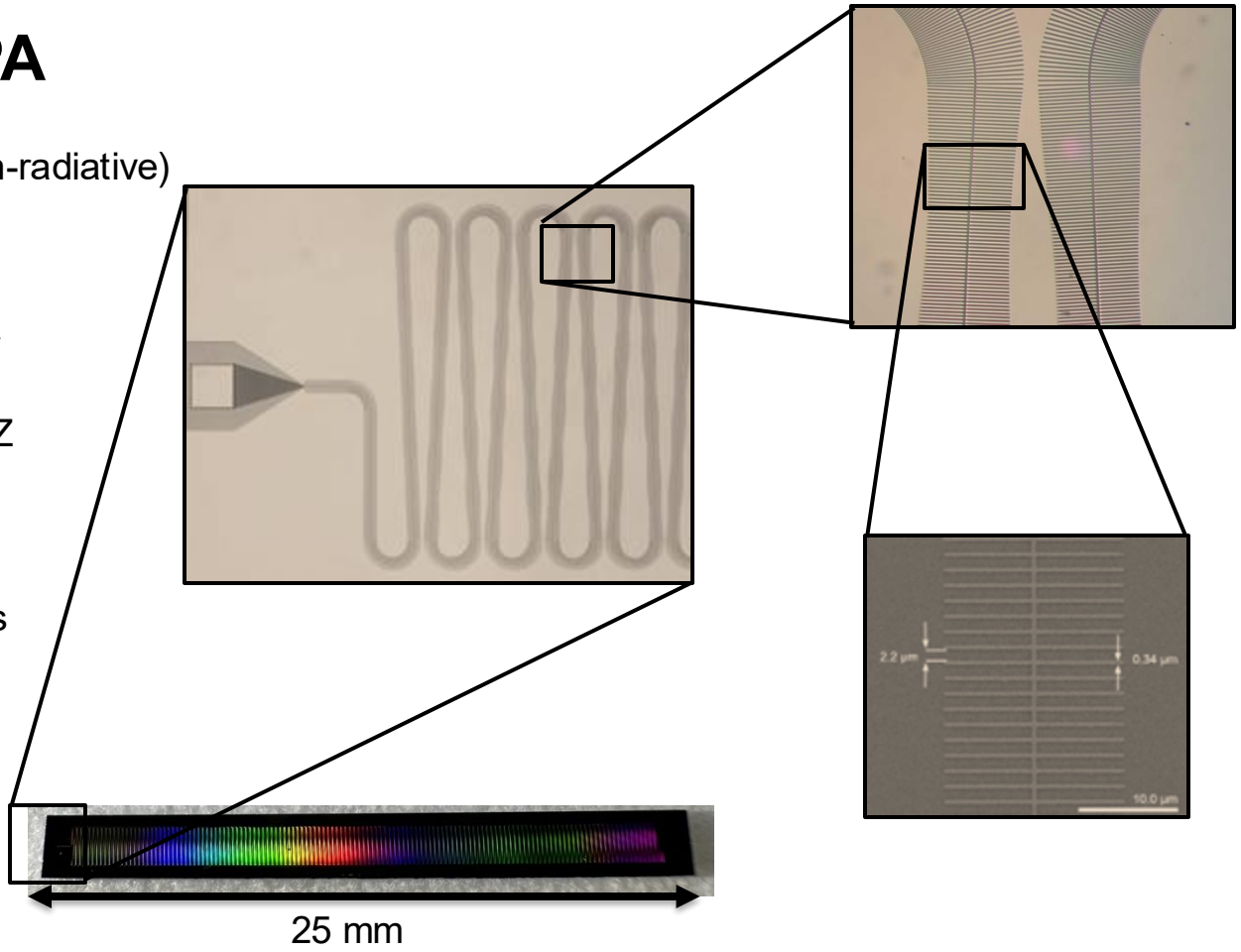
Ramanathan, K. et al. Physical Review Letters 130, no. 23 (2023): 231001

Microstrip KI-TWPA

- Continuous ground plane (Non-radiative)
- Fabrication robustness
- 0.25 - 0.35 μm wide conductor
- Add capacitive stubs to lower Z
- $v_{ph} \sim 0.005 \ - 0.01 \ c$
- Can meander for compactness
- Dispersion Engineering



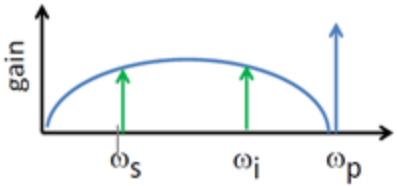
Fabrication stack



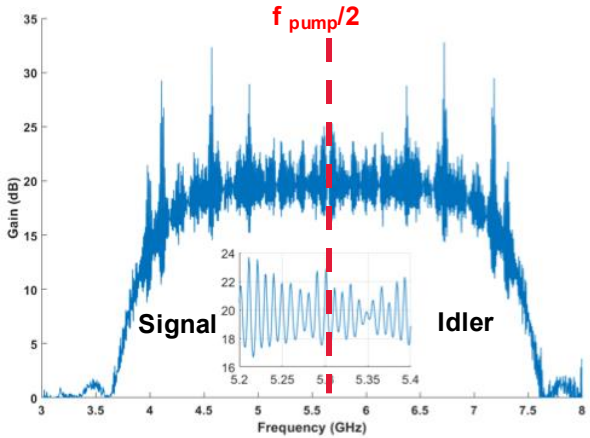
Three-Wave Mixing Devices

- Couple-mode equations for nonlinear transmission line $\frac{\partial^2 I}{\partial z^2} - \frac{\partial}{\partial t}\left[L(I)C\frac{\partial I}{\partial t}\right] = 0$
- Three-wave mixing 3 WM: $L(I) = L_0\left(1 + \frac{I^2 + 2II_{DC} + I_{DC}^2}{I_*^2}\right)$
- Signal & idler bands are symmetric around $f_{pump}/_2$

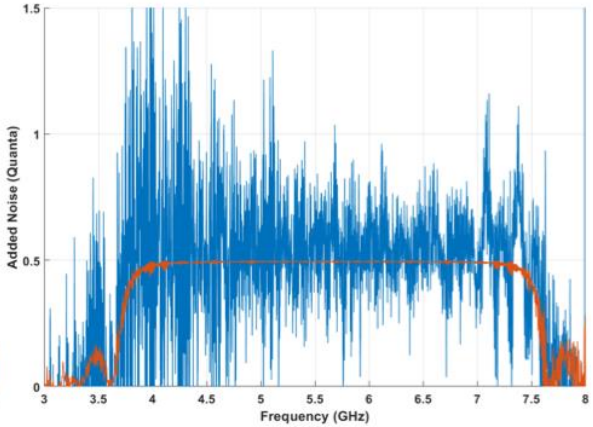
$\omega_p = \omega_s + \omega_i$



Three-Wave Mixing Process



Measured gain of a 3WM KI-TWPA.

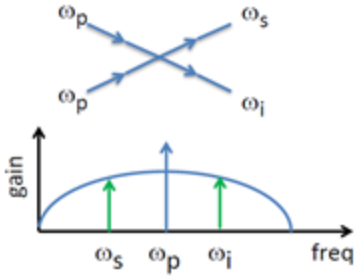


Measured noise of a 3WM KI-TWPA.

Klimovich, N. et al. (2023). arXiv:2306.11028

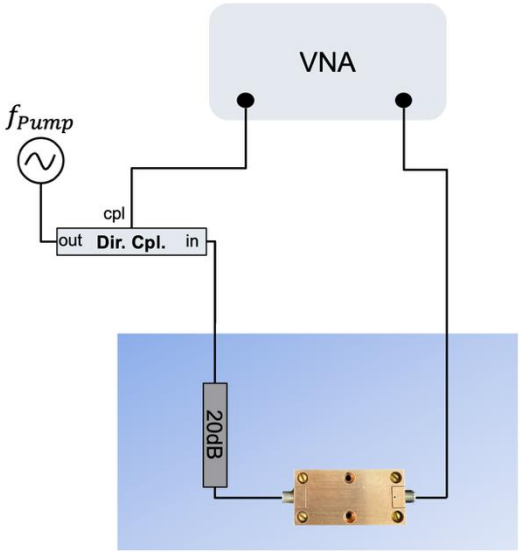
Four-Wave Mixing Devices

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

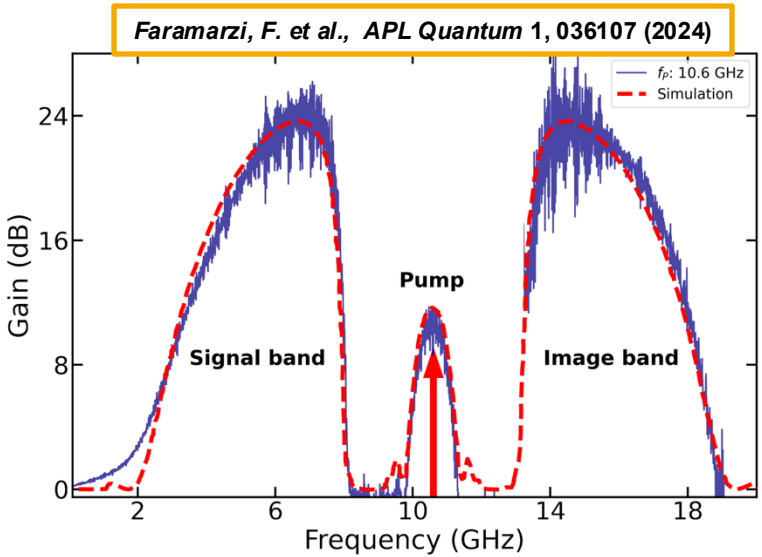


Four-Wave Mixing Process

- Four-wave mixing 4 WM: $L(I) = L_0\left(1 + \frac{I^2}{I_*^2}\right)$
- Signal & idler bands are symmetric around f_{pump}
- Separation of bands, no contamination from idler



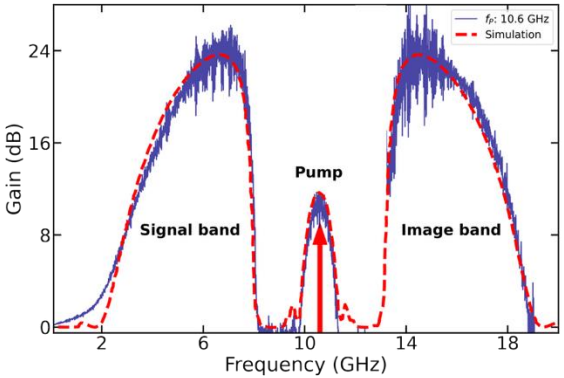
Test setup

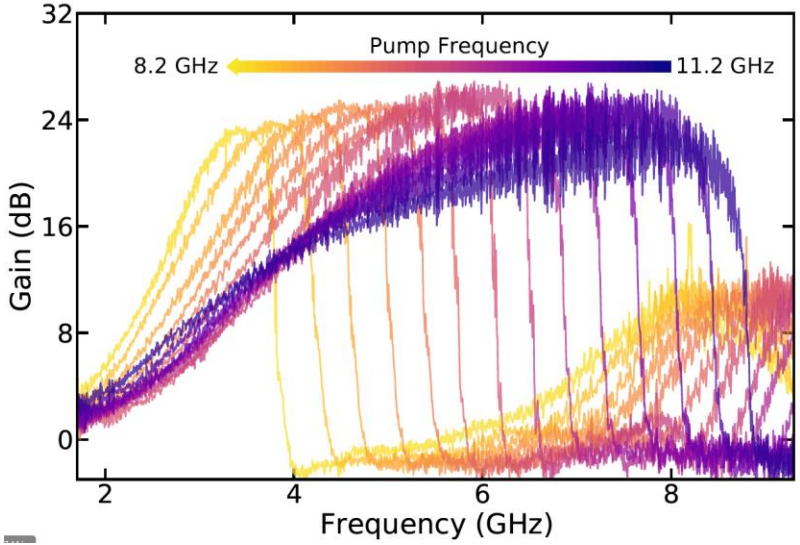


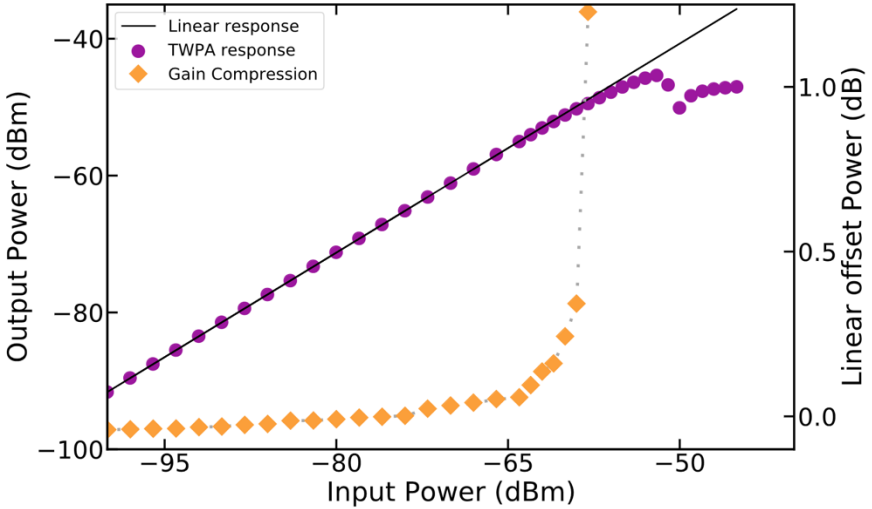
Measured gain of a 4WM KI-TWPA.

NbTiN Four-Wave Mixing Devices

- Band separation
- Tunable signal band gain and ***dual-band operation***
- High Dynamic Range (P1dB = -58 dBm @ 15 dB gain)
- $I_*^2 \propto T_c^2$ (T_c ~ 13 K) → Pump power ~ 10 μW

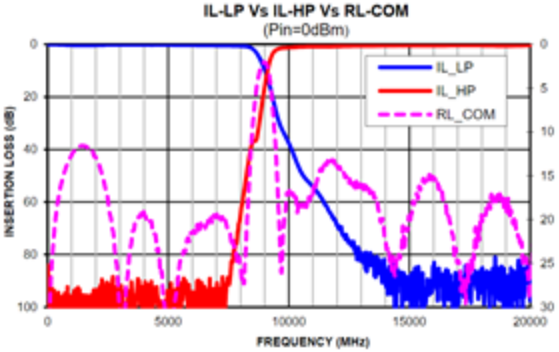




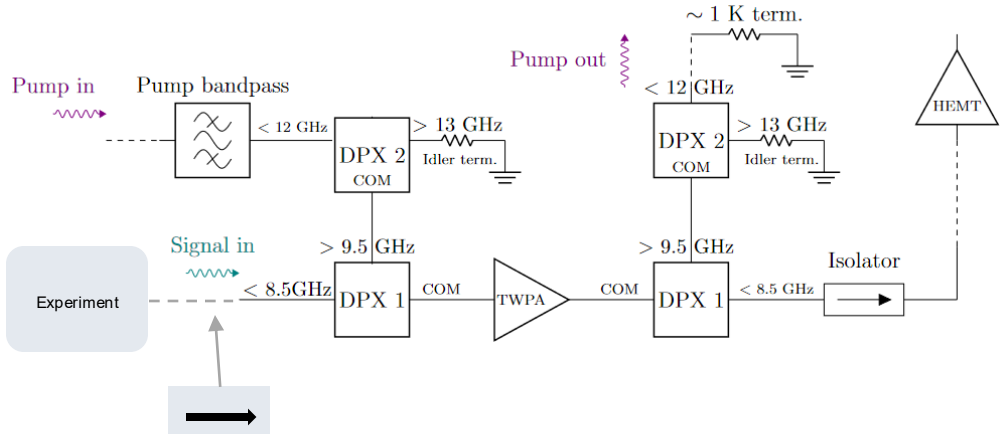


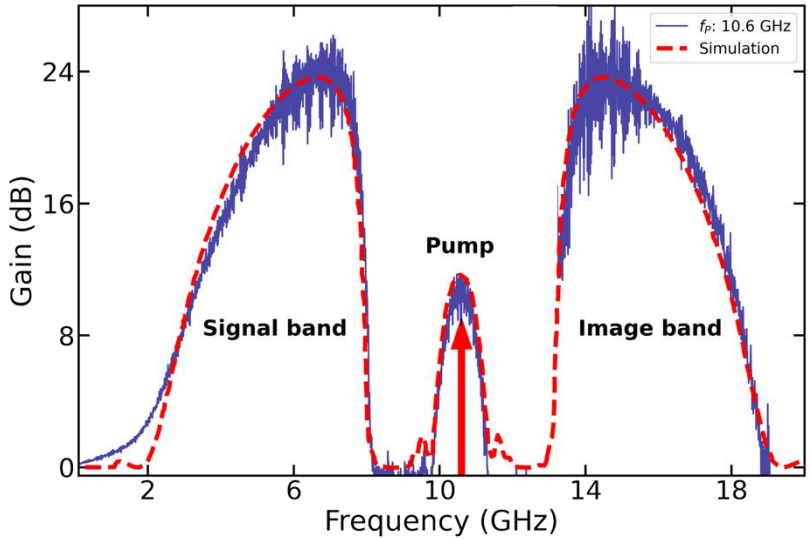
KI-TWPAs in Experimental Setup

- lack of I/O isolation
- Prevent TWPA from seeing in-band reflections
- Cold termination for idler freqs $T \ll hf_{idler}/k_B$
- Prevent the following amplifier from saturating
- Avoid pump heating & reflection
- Prevent noise from the HEMT



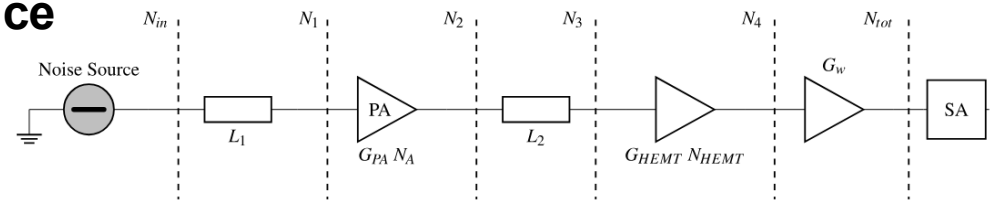
Minicircuits diplexer (fc= 9.5 GHz)

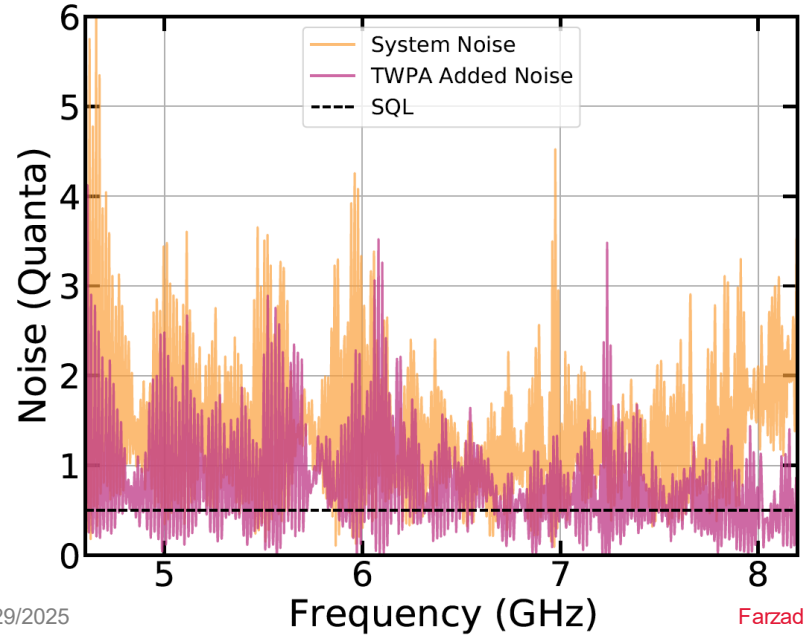


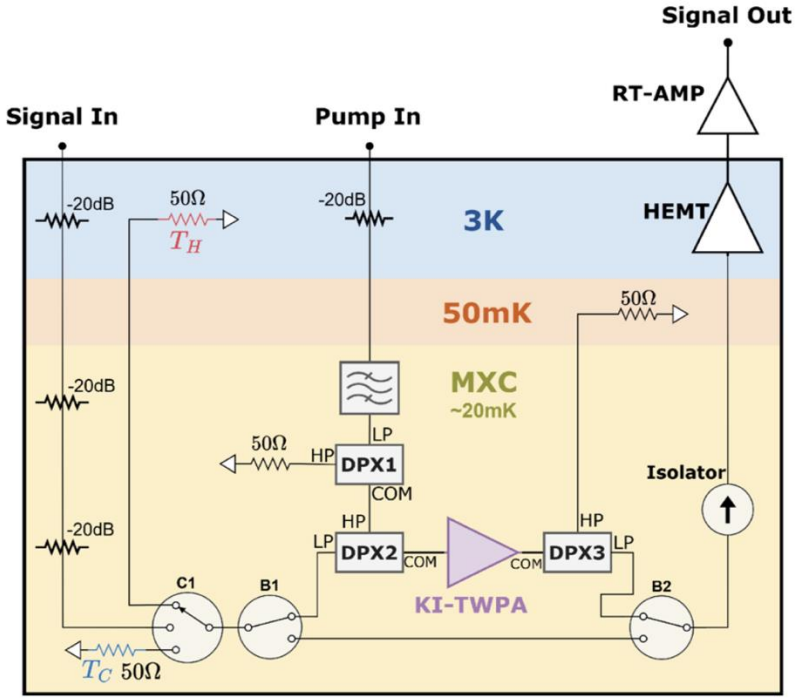


4 - 8 GHz 4WM TWPA Noise Performance

- Hot & cold termination or variable temp source
- Total system noise
- Amplifier added noise
- Near Quantum Limited performance





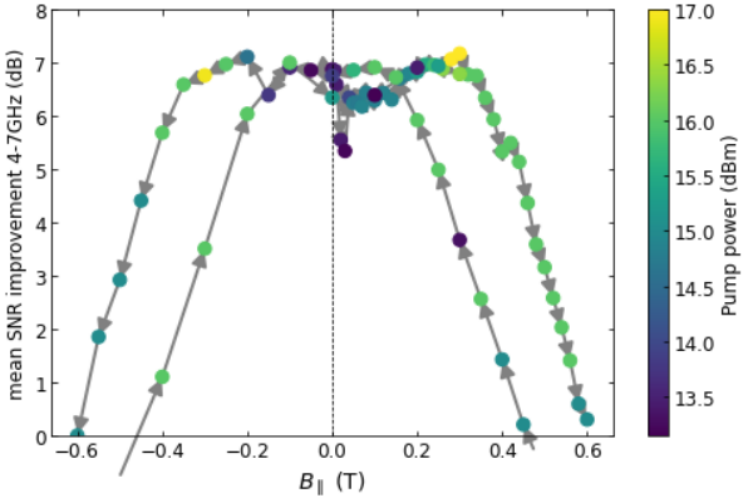


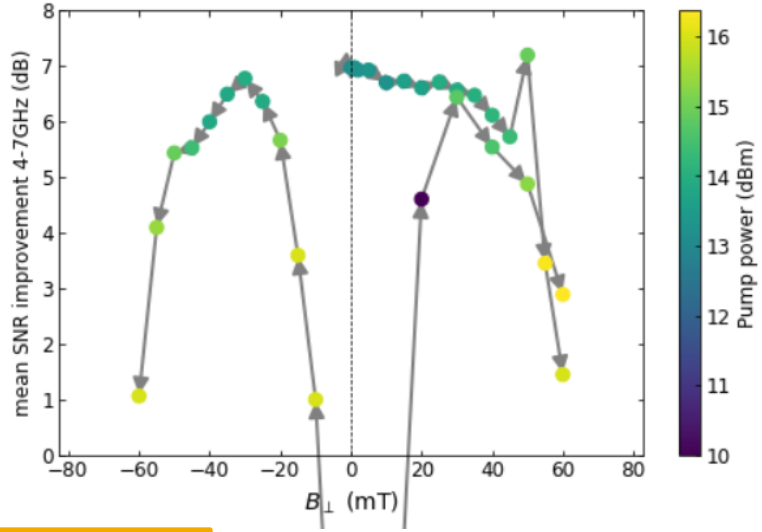
Y-factor noise setup.

Magnetic-Field Dependence

- Collaboration with Andolab at University of Cologne, Germany
- S21 and gain measurements vs $B_{\parallel}$ and $B_{\perp}$, pump settings optimized at each field

- Ultimately limited by thick Nb ground plane (Bc=1.5 T)
- SNR improvement can improve at intermediate $B_{\parallel}$ but not for $B_{\perp}$ - $B_{\perp}$ also shows stronger hysteresis
- ~10x better field compatibility than Josephson TWPA cf. Janssen et al. PR. Appl. 22, 054018 (2024)

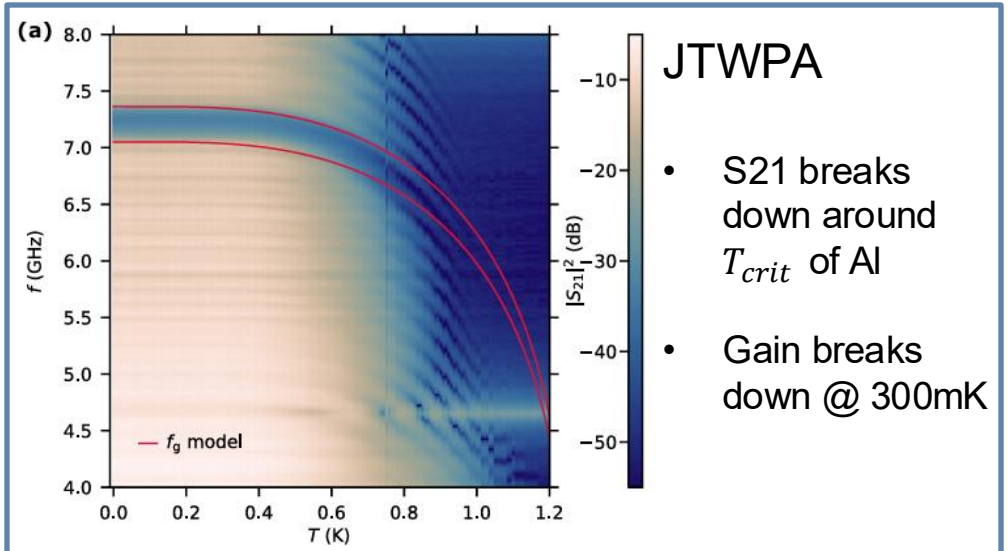




Janssen et al., arXiv preprint arXiv:2509.15043,(2025)

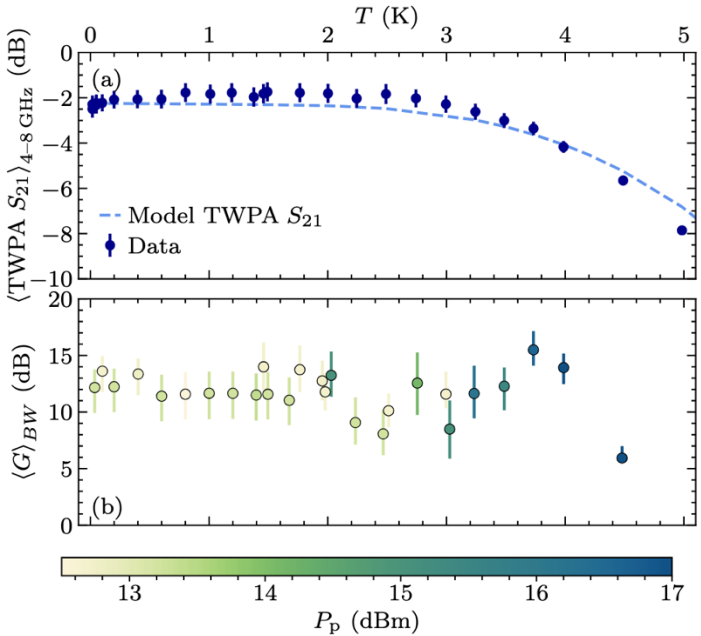
High-Temperature Operation

- measured in Cologne (fluctuations due to pump optimization)
- Device limited by T_{crit} of Nb ground plane
- Contrary to aluminum Josephson TWPA operation above 1K possible with SNR improvement over mK bypass configuration



JTWPA

- S21 breaks down around T_{crit} of Al
- Gain breaks down @ 300mK



Janssen et al., arXiv preprint arXiv:2509.15043,(2025)

Janssen et al. PR. Appl. 22, 054018(2024)

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