Towards a parametric amplifier for millimeter wave Astrophysics

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Towards a parametric amplifier for millimeter wave Astrophysics

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Outline

• Astrophysics Motivation
• Operating principles
• Microwave Paramp
• Designs for millimeter wave devices
Astrophysical Motivation

• High spatial resolution Spectroscopy (ALMA)
• Low spatial resolution spectroscopy for Intensity mapping (e.g. CO)
• Spectroscopy for CMB foreground studies
• VLBI
Astrophysical Motivation

- Front end for heterodyne receiver
Low noise microwave/ millimeter wave amplifiers

- Transistor amplifiers: HEMT, SiGe BPT
  - Broad band, high dynamic range
  - 77K
  - Added noise > ~ 5 $h\nu$/ second / Hz
    (Quantum limit = $\frac{1}{2} h\nu$/ second / Hz)
Low noise microwave/millimeter wave amplifiers

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- Superconducting Junction Parametric Amplifiers
  - Quantum limited
  - Narrow band (resonant)
  - Low dynamic range
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Can we make a paramp with transistor amp- like bandwidth and dynamic range?

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Parametric Amplifiers

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Parametric Amplifiers

- Fiber optic paramps at visible frequencies
  - Based on Kerr nonlinearity, four-wave mixing
  - Traveling wave design
  - Broadband

from Hansryd et al. (2002)
Parametric Amplifiers

Frequency

signal

Pump 1

Pump 2

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Diagram:
- Signal
- Pump 1
- Pump 2
- Beat

Frequency
Parametric Amplifiers
Parametric Amplifiers

$$\omega_{p2} \pm (\omega_{p1} - \omega_s)$$
Parametric Amplifiers

signal

Pump 1

Pump 2

beat

Frequency
Parametric Amplifiers
Parametric Amplifiers

**Diagram:**

- Signal
- Pump 1
- Pump 2
- Beat
- Phase modulate
- Side-bands:
  \[ \omega_{p1} \pm (\omega_{p2} - \omega_s) \]
Parametric Amplifiers

- Signal
- Pump 1
- Pump 2
- Idler

Frequency
Parametric Amplifiers

- Degenerate amplification $\omega_{p1} \approx \omega_{p2}$
Kinetic Inductance Nonlinearity

- Superconducting Transmission line is a Kerr medium
  - Nonlinear kinetic inductance
  - $\Delta L_s = L_s(0)(1 + I^2 / I_*^2)$

![Diagram of NbTiN CPW line and phase shift at 4 GHz](image)

- 0.8 m NbTiN CPW line
- Bias Tee
- \( \Delta \theta \) (rad.)
- \( \Delta \) Transmission (dB)
- 4.7 radians!
Nonlinear dispersion

• Need to maintain phase relation between signal, pump, idler to achieve exponential gain
• Dispersion causes phase slippage
• The non-linearity itself has a dispersive effect dispersive
  – Self Phase Modulation (SPM), Cross Phase Modulation (XPM)
  – in the fiber paramp, nonlinear dispersion is compensated with intrinsic dispersion
  – operate in anomalous dispersion regime

**Graphs:**

- Dispersion in Silica
- Fiber paramp gain curve
Harmonic Generation

• Superconducting TRL is nearly dispersionless
  – Third Harmonic Generation (THG) is phase matched and efficient
  – Not a problem in fiber paramps due to large dispersion
  – Higher harmonic processes leads to “shock formation”

(From R. Landauer, 1960)

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New Idea: Dispersion Engineering

- Periodic loading to produce bandgap at $3\omega_p$
Achieving phase match

- Also use dispersion to cancel nonlinear phase slippage
Achieving phase match

- Also use dispersion to cancel nonlinear phase slippage
Impedance matching

- Long tapers transform 50Ω to paramp’s internal impedance
- Dispersion at pump frequency is phased in to avoid fringing from finite periodic structure
Microwave traveling wave amp

- ~0.8m CPW line – 1um line width, 35nm film thickness
Paramp gain

- Dynamic range limited by pump saturation (0.1mW)
Paramp gain

NIST 2-stage paramp (JPL-inspired design)
(courtesy of J. Gao)

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Y-factor noise measurement

- Noise referred to paramp input
  - HEMT noise subtracted
- Noise measured with continuous pump ~ 3.5 photons at 8.7 GHz
- Pulsed pump (5% duty cycle)
  - Excess noise reduced to ~2 photons noise
- Thermal effect
  - Testing better heat sinking, so far no improvement
Onset of dissipation

- Nonlinearity / Dissipation probed using resonators
  - mechanism for dissipation onset not yet understood
  - defects? Grain boundaries?...
- Nanowire results indicate large dissipationless nonlinearity achievable
- See Aditya Kher’s talk

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Extension to higher frequency

- Reduce distance between perturbations to scale frequency upward
- Practical to ~1 THz

![Predicted gain and predicted noise vs. operating temperature graphs](image)

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Ground straps

- Connect CPW ground planes to prevent slot mode excitation
- Air gap to avoid problems with amorphous dielectrics

Also investigating wafer vias and micro-machined structures to connect grounds

Aluminum ground strap using resist reflow process

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Coupling to Waveguide
Coupling to Waveguide
Waveguide setup

split block device housing

1K cooler
isolators

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Paramp gain

- Measured gain of a prototype device ($f_{\text{pump}} = 8.5$ GHz)

- Compare to cavity paramp with $\sim 1$ - 10MHz bandwidth

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Paramp gain ripple

- Measured gain of a prototype device ($f_{pump} = 8.5$ GHz)

- Compare to cavity paramp with ~1 - 10MHz bandwidth

One way gain:

$$S_{21} = Ge^{-i\beta \ell} \frac{T^2}{1 + \Gamma^2 Ge^{-2i\beta \ell}}$$
Reflectionless filters

- absorb out of band power to prevent parametric self oscillation
Summary

• Demonstrated a wideband parametric amplifier design suitable for detector applications

• 2-4 photons added noise
  – Expect quantum limited sensitivity can be reached
  – Thermal contribution to excess noise
  – Control through better thermal management
  – Lower gap materials, eg. TiN, WSi – lower pump lower
  – Defects in films?

• 80-116 GHz amp, $T_N \sim 5K$ .... higher frequencies

• Gain ripples
  – Improve with better matching, isolators

Coupled mode gain prediction

Prediction for 3 radian phase shift
Dynamic range

- Theoretically limited by pump depletion when $P_{\text{out}} \sim P_{\text{pump}} (\sim -10 \text{ dBm})$
Measurement setup