Low Noise Amplification with HEMTs and PARAMPs

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Introduction

- Noise
  - Look at common sources of noise and quantum noise in particular
- Low noise amplifiers
  - Types
  - The HEMT
  - Techniques for lowering the noise temperature
  - Current state of the art and commercial options
- Parametric amplifiers
  - Examples
  - Four wave mixing
  - Kinetic Inductance
- Towards the quantum limit and noise squeezing
- Electron Paramagnetic Resonance

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Sources of Noise

- Thermal (Nyquist) Noise
  - Thermal vibrations of bound charges (Cooling)
- Quantum Noise
  - Due to quantized nature of particles (Squeezing)

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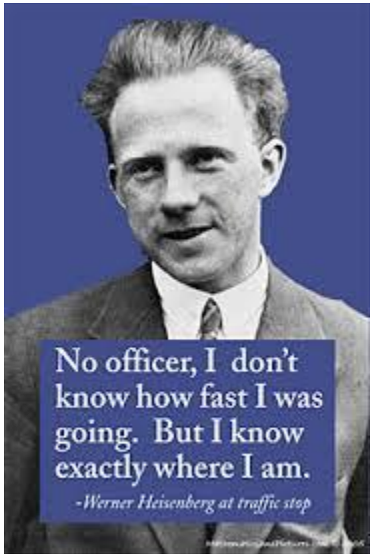
Quantum Noise

- The quantum noise limit: $T_n \sim hf/k_B$
  - ~50mK/GHz
- In escapable result (or is it) of quantum mechanics
  - Arises because, once detected by an antenna, the amplitude (and phase) of light's electric field is transduced into an amplitude (and phase) of a current, neither of which can be known simultaneously with complete accuracy



Quantum Noise

- Light: sinusoidal electric field E(t) can be expressed by: $E(t) = \frac{1}{2}[a(t) + a^*(t)]$
- a(t) are phasors that rotate in the complex plane: $a(t) \cdot e^{-i\omega t}$ where a is a complex amplitude $a = x + ip,\ a^* = x - ip,\ x = \frac{1}{2}(a + a^*),\ p = \frac{1}{2i}(a - a^*)$
- We can now express the field:

$$E(t) = x\cos \omega t + p\sin \omega t$$

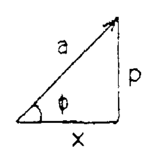


Figure 1. Phasor and quadrature-component representations of the electric field for monochromatic classical light.

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Quantum Noise

- **E(t), a(t), a*(t), x and p** can be viewed as quantum mechanical operators.
- a and a* are the bosonic annihilation and creation operators
- Commutation relation:

$$[a(t), a^{\dagger}(t)] = a(t)a^{\dagger}(t) - a^{\dagger}(t)a(t) = 1$$

- This also means that *x* and *p* do not commute

$$[x, p] = \frac{i}{2}$$

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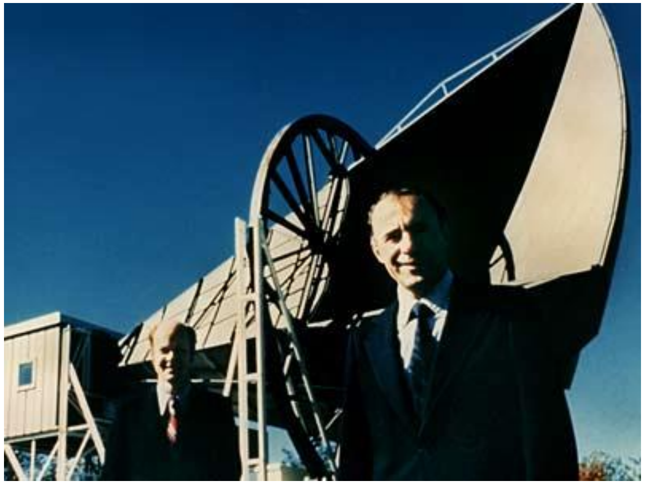
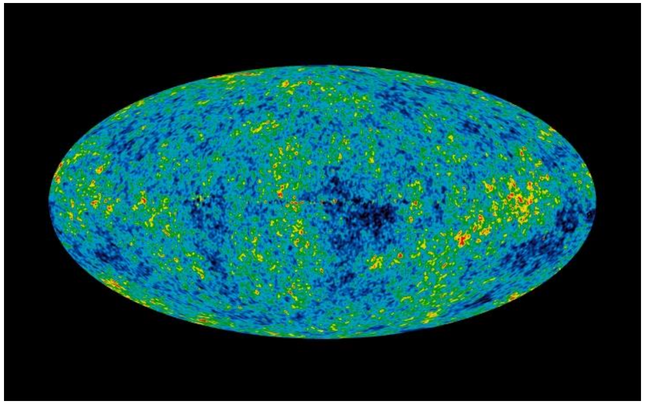
Low Noise Amplifiers

- To increase the amplitude with as little extra noise as possible.
- Key figures of merit:
  - Gain
  - Noise Figure = $\frac{S_i/N_i}{S_o/N_o}$
    - Noise Temperature = $T_{Ambient}(10^{NF/10}-1)$
- Examples
  - MASERs
    - Very low noise, narrow bandwidth
  - Transistors
    - BJTs, MOSFETs, MESFETs, HEMTs ….
    - Low noise and wide bandwidths are possible
  - Parametric Amplifiers
    - Reactance based, so very low noise temperatures are possible





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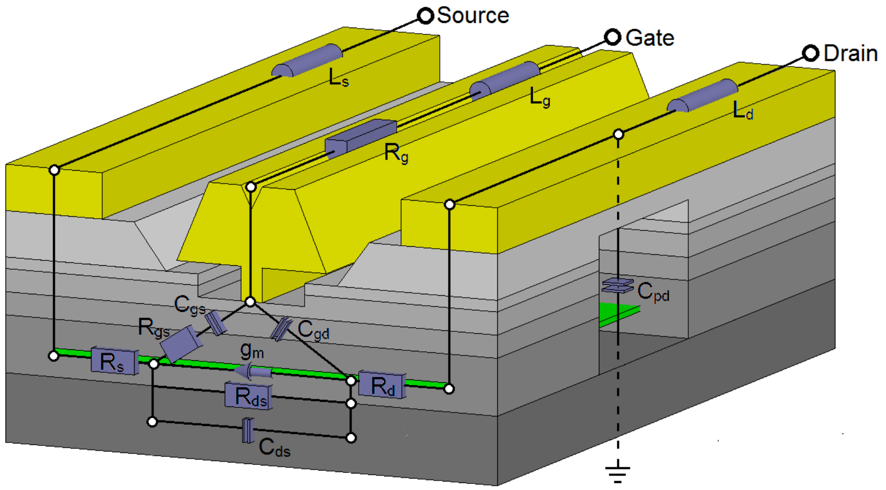
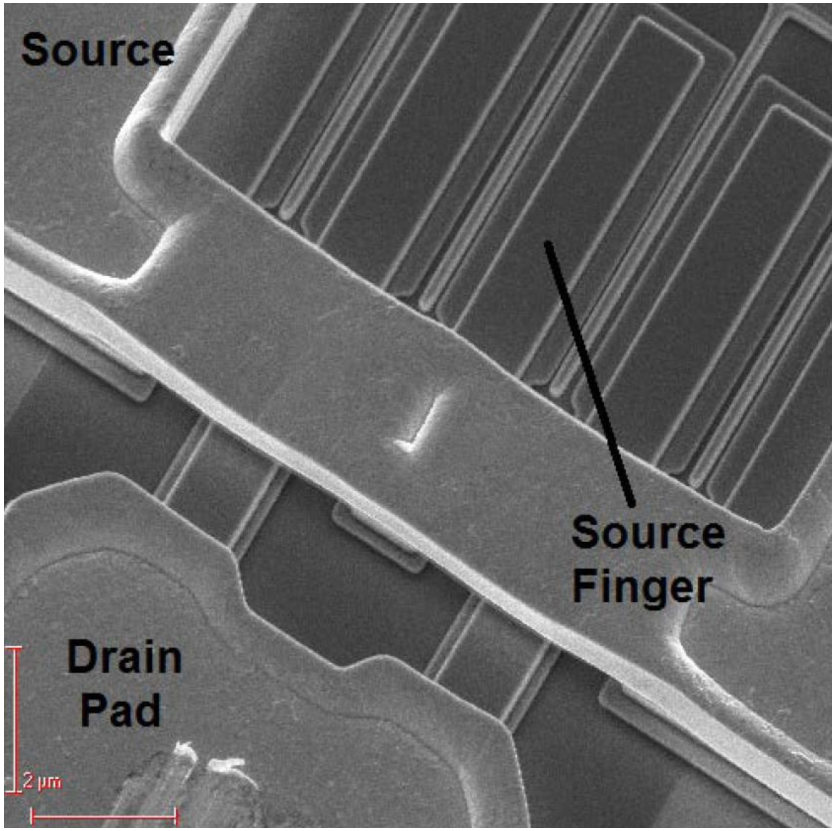
HEMTS





- Indium Phosphide substrate offers the lowest noise
- Electrons confined to a 2-dimensional conduction channel
- This channel is in an undoped semiconductor, which increases the mobility of the electrons

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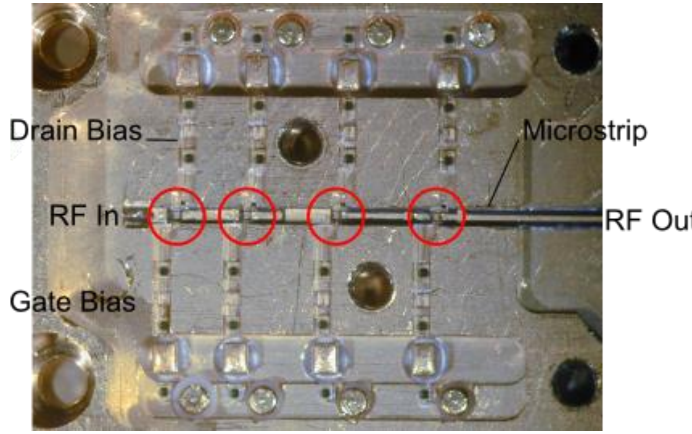
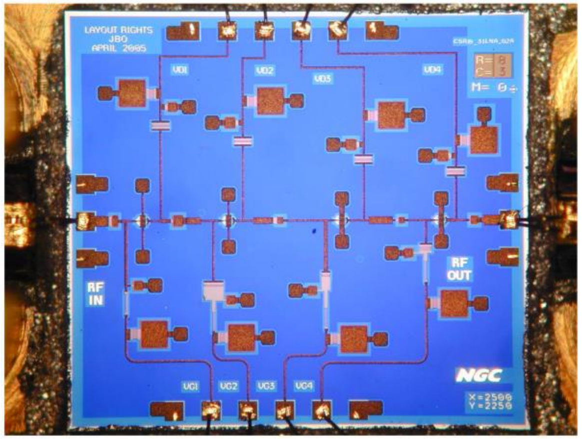
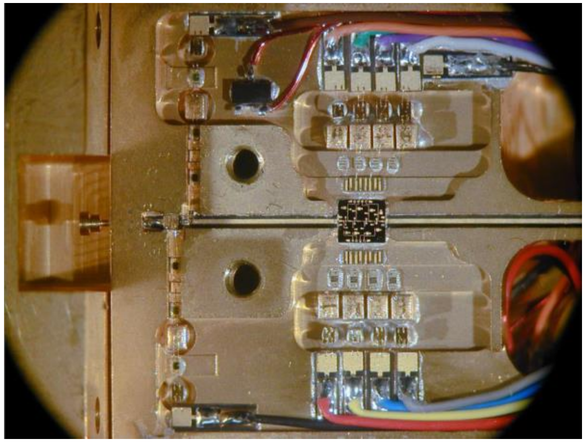
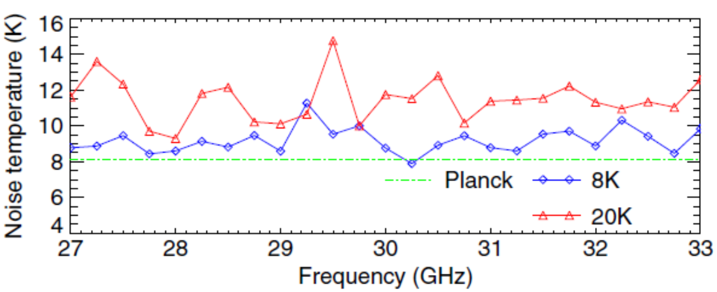
Technology





- MIC or Hybrid
  - Discrete components, time consuming to build, lowest noise
- MMIC
  - All components integrated onto a single chip, suitable for mass production, tuning options are restricted.
- T+MMIC
  - Discrete first stage (optimized for low noise) transistor followed by a MMIC (for gain)





McCulloch *et al* (2015)

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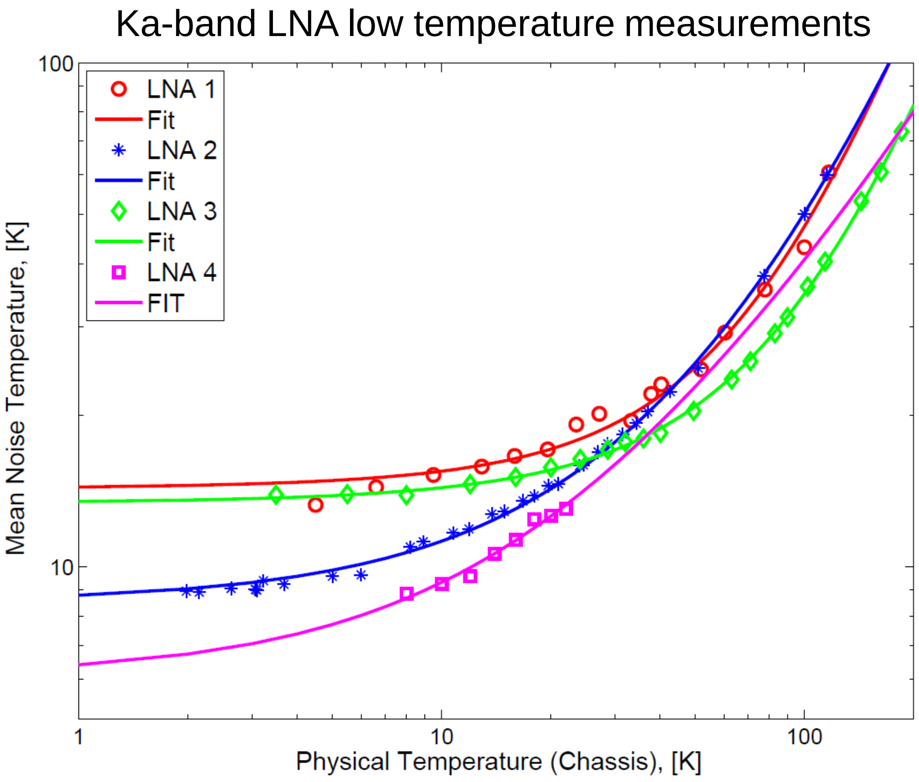
Cooling LNAs

- Cooling usually results in an order of magnitude decrease in the noise temperature
- Improvement in noise temperature becomes increasing negligible below 20-30K



McCulloch *et al* (2017)

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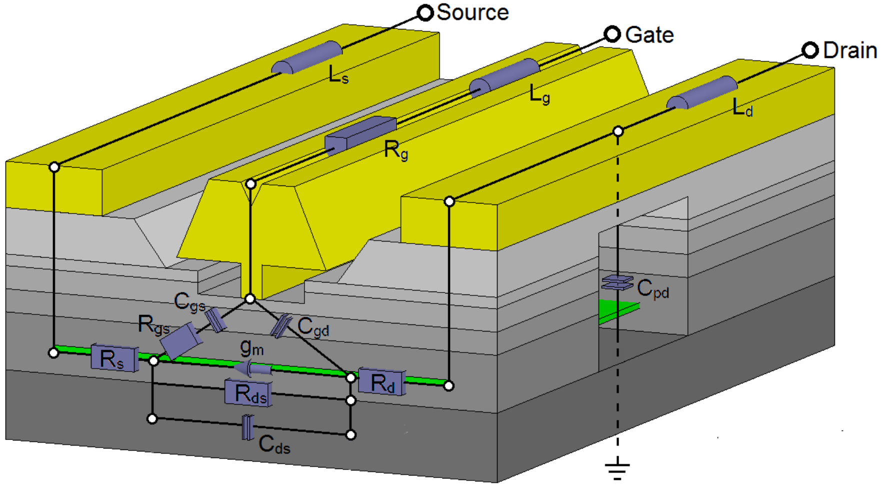
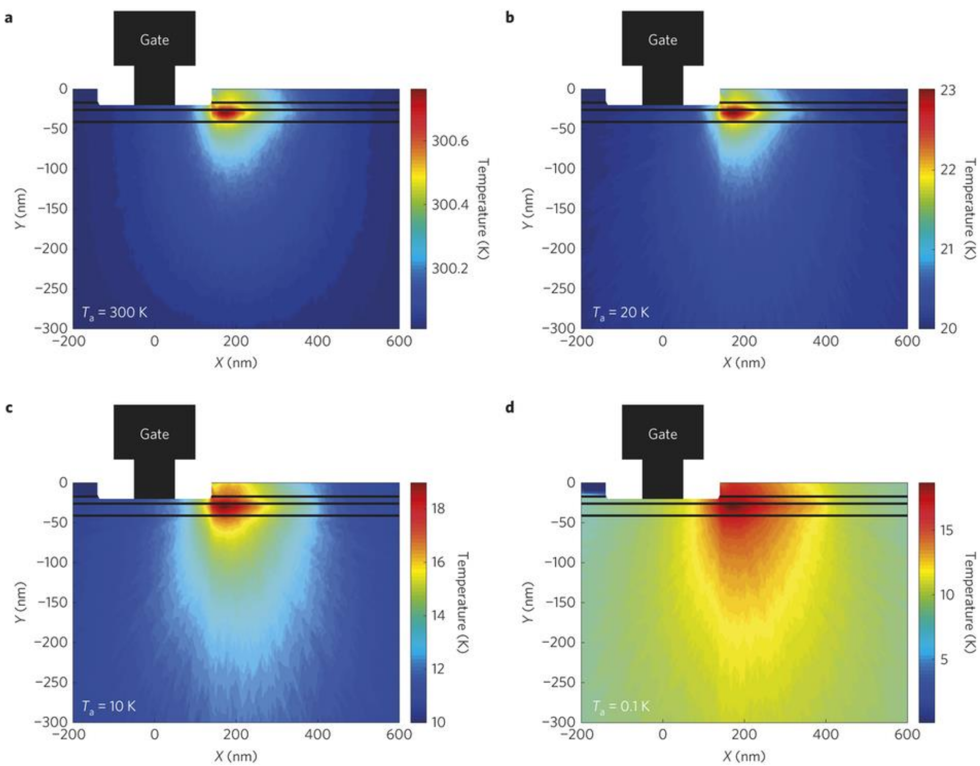
HEMT Limitations



- Below 30K, the conduction channel starts to remain hotter than its surroundings.
- This is because phonon blackbody radiation is no longer capable of transporting the heat away
- This limits the effectiveness of further cooling
- The drain temperature now remains substantially above ambient temperature
- Restricts HEMT based technologies to ~2-3 times the quantum limit



Schleeh *et al* (2015)

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Current State of the Art LNAs

Band	Substrate	Technology	Freq (GHz)	Noise Temp (K)	Year	Lead Author / Organisation
S	InP	MMIC	2	1.2 (0.09)	2017	LNF
C	InP	MMIC	7	3.0 (0.34)	2012	Schleeh
X	InP	MIC	8.4	4.0 (0.40)	2001	Bautista
Ka	InP	MIC	30	5.0 (1.44)	2009	PLANCK
W	InP	MMIC	85	22 (4.08)	2009	Bryerton

Quantum Noise Limit

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Commercial Options

- LNF in Sweden.
  - 0.3 to 115GHz
  - www.lownoisefactory.com/products

Model	Frequency (GHz)	Noise Temperature (K)
LNF-LNC0.6_2A	0.6 – 2	1.7
LNF-LNC4_16B	4 - 16	3.8
LNF-LNC23_42WB	26 - 40	9.0
LNF-LNC65_115WA	65 - 110	28

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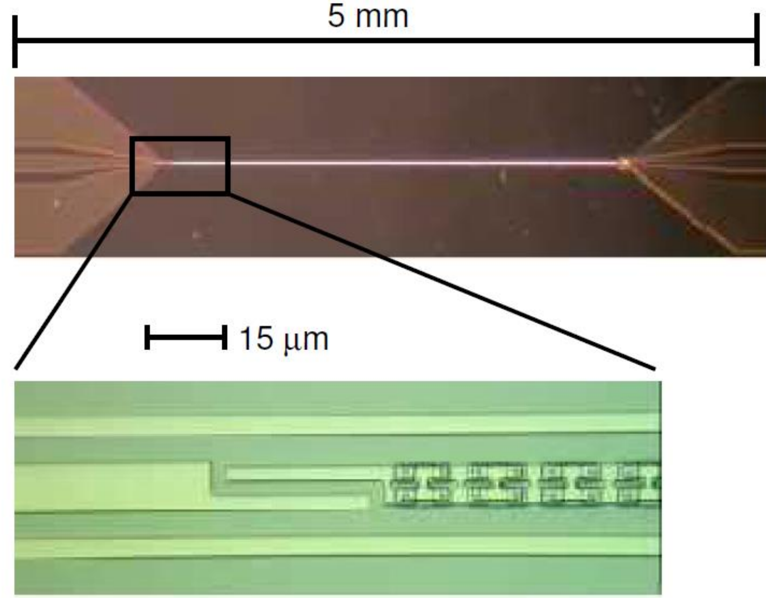
Parametric Amplifiers

- Early work
  - Electron-Beam Parametric Amplifier developed in 1958
  - Josephson Junctions began to be used in the 1970's
  - Typically they have been inherently narrowband
- Recently the travelling wave parametric amplifier has been developed. These utilise either arrays of Josephson Junctions or electrically long superconducting transmission lines



Above: A section of a W-band traveling-wave kinetic inductance parametric (TKIP) amplifier. It consists of a 0.15 m length of NbTiN coplanar waveguide (CPW) line arranged in double spirals. The thickness of the line is 35 nm and the center conductor and gap widths are 1 micron.

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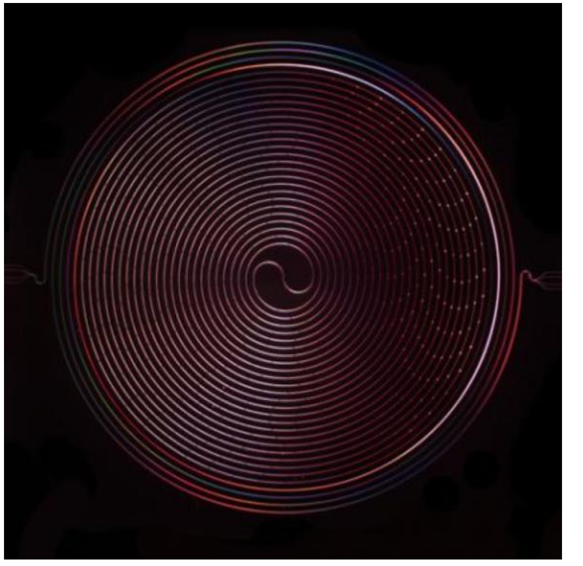
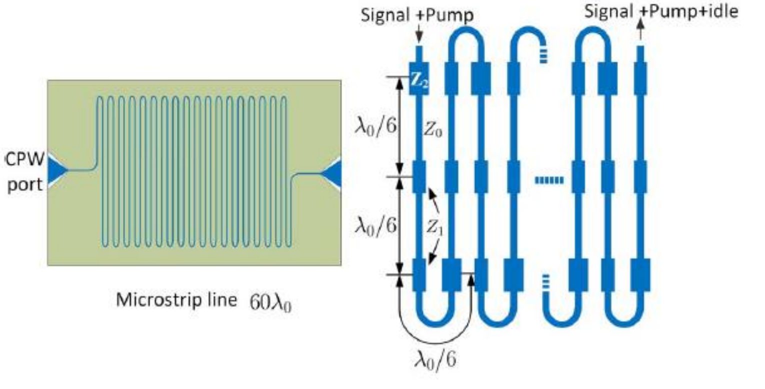
Parametric Amplifiers

- Electrically long ~60 – 400λ co-planar waveguide or microstrip superconducting transmission lines
- Examples
  - Eom (2012), Bockstiegel (2015),NASA Microdevices Laboratory (2012), Shan (2016)





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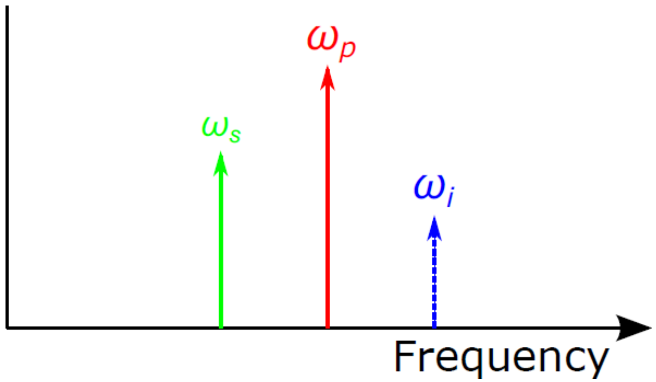
Four Wave Mixing



- Actually use non-degenerate four wave mixing with
  - 1 pump (ω_p)
  - 1 signal (ω_s)
  - 1 idler (ω_i)

Energy will be transferred from the pump to the signal (GAIN) and generated idler so long as

- Energy is conserved $2\omega_p = \omega_s + \omega_i$
- A phase matching condition is maintained

$$\Delta\beta = \beta(\omega_s) + \beta(\omega_i) - 2\beta(\omega_p) = 0$$

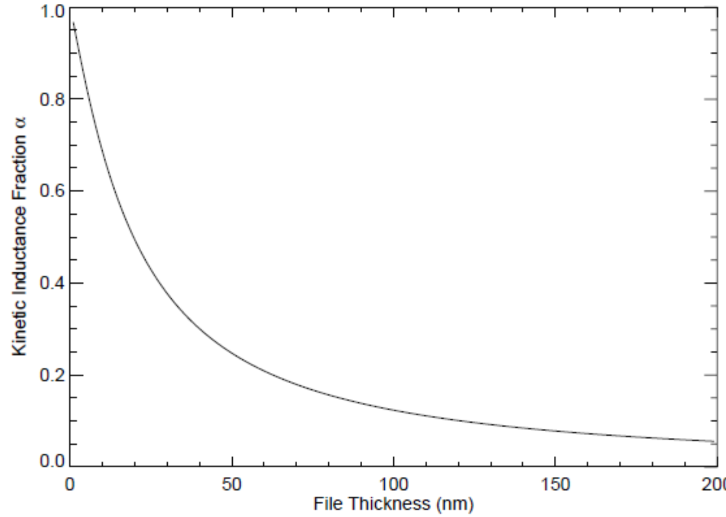
with β the propagation constant

- Dispersion engineering is used to prevent the formation of harmonic shock fronts and to control the phase matching

Kinetic Inductance

- FWM requires a non-linearity
- In optic parametric amplifier, this non-linearity is provided by the Kerr effect.
- In superconducting transmission line, the kinetic inductance (L_k) can also provide the necessary non-linearity.
  - $L_k(I) = L_k(0)\,[1 + (I/I_*)^2]$
    - With I_*, which is comparable to the critical current, setting the scale of the non-linearity
- From the Mattis Bardeen theory of superconductivity:
  - $L_k \propto R_n$
  - $I_* \propto 1/R_n$
    - Hence a superconductor's kinetic inductance and its non-linearity are enhanced by thin films with a high normal state resistivity (R_n)

Kinetic Inductance



Mazin 2004, Ch 3

- The film must be thin (~20nm), this ensures a uniform current density
-

Material	T_c (K)	Δ_0 (μeV)	ρ_n (μΩ cm)
Nb	9.2	1395	10
NbTi	8.5	1289	74
NbN	11.8	1790	240
NbSi	1.05	159	500
TiN	4.1	622	100
NbTiN	14.8	224	1700

Shim (2015)

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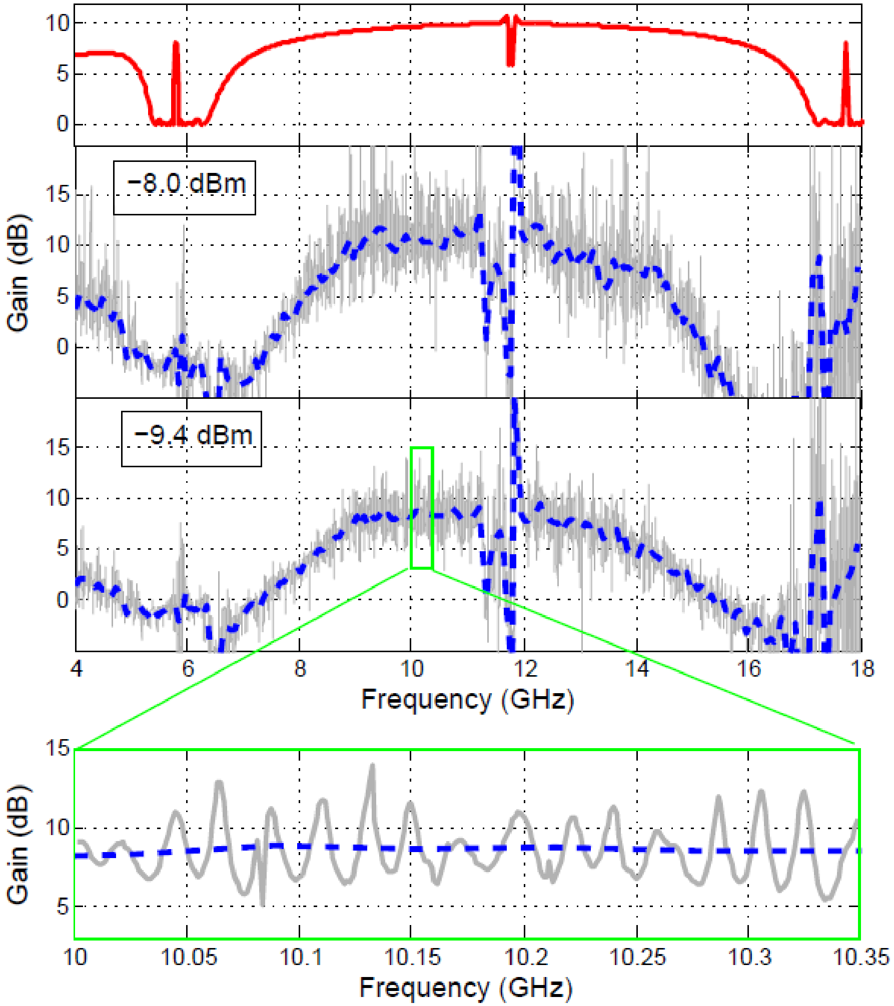
Drawbacks

- The Pump signal
- Gain “Jitter”
- Impedance mismatches at the input and output are the likely cause
- Still much development work required



Eom *et al* (2012) Fig. 3

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Towards and perhaps below the Quantum Limit

- Eom *et al* report an added noise of 3.4±0.2 photons at 9.4GHz
- Other groups investigating travelling wave parametric amplifiers also report noise temperatures approaching the quantum limit, e.g Macklin *et al* (2015)
- Can we go below???

Noise Squeezing

- Recalling the earlier idea that a sinusoidal electric field can be expressed as the sum of two quadratures

$$E(t) = x\cos \omega t + p\sin \omega t$$

- Caves (1982, 2012), expresses the quantum limit as an amplifier uncertainty principle

$$A_1 A_2 \geq \frac{1}{16}\left|1 - (G_1 G_2)^{-1/2}\right|^2$$

- Where G1 and G2 are the gains of each quadrature and A1 and A2 represent the noise added to each quadrature

Noise Squeezing

- For phase insensitive amplifiers (phase preserving) the uncertainty principle reduces to

$$A \geq \frac{1}{2}|1 - G^{-1}|$$

- Which in the high gain limit implies that the amplifier adds at least ½ a quantum of noise to the input (the quantum limit)
- HOWEVER, phase sensitive or non phase preserving amplifiers can respond differently to each of the quadratures

$$A_1 A_2 \geq \frac{1}{16}\left|1 - (G_1 G_2)^{-1/2}\right|^2$$

- Generally, if the noise added to one of this quadratures is reduced, the noise in the other must be increased.
- Except, if $G_1 G_2 = 1$ the amplifier need not add any noise to either quadrature
- Hence sub quantum noise amplification may be possible

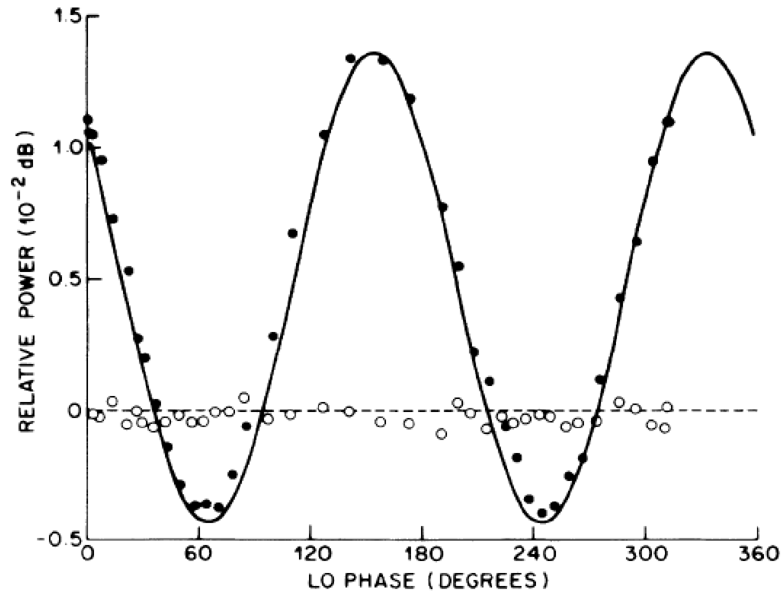

FIG. 3. Thermal-equilibrium-noise squeezing at 4.2 K. The open-circle data, taken with AT of Fig. 2 set for a maximum attenuation, establish the baseline. When pump power is delivered to the Josephson-parametric amplifier the noise (filled circles) drops below the baseline for certain settings of the relative phase between the LO and the pump. The smooth curve is a comparison of theory with experiment with no adjustable parameters.

Extract from Yurke, Phys Rev Lett, 60 (1988)
19.4GHz Josephson Parametric Amplifier
Minimum noise temperature 0.28K
Quantum limit @ 19.4K 0.47K

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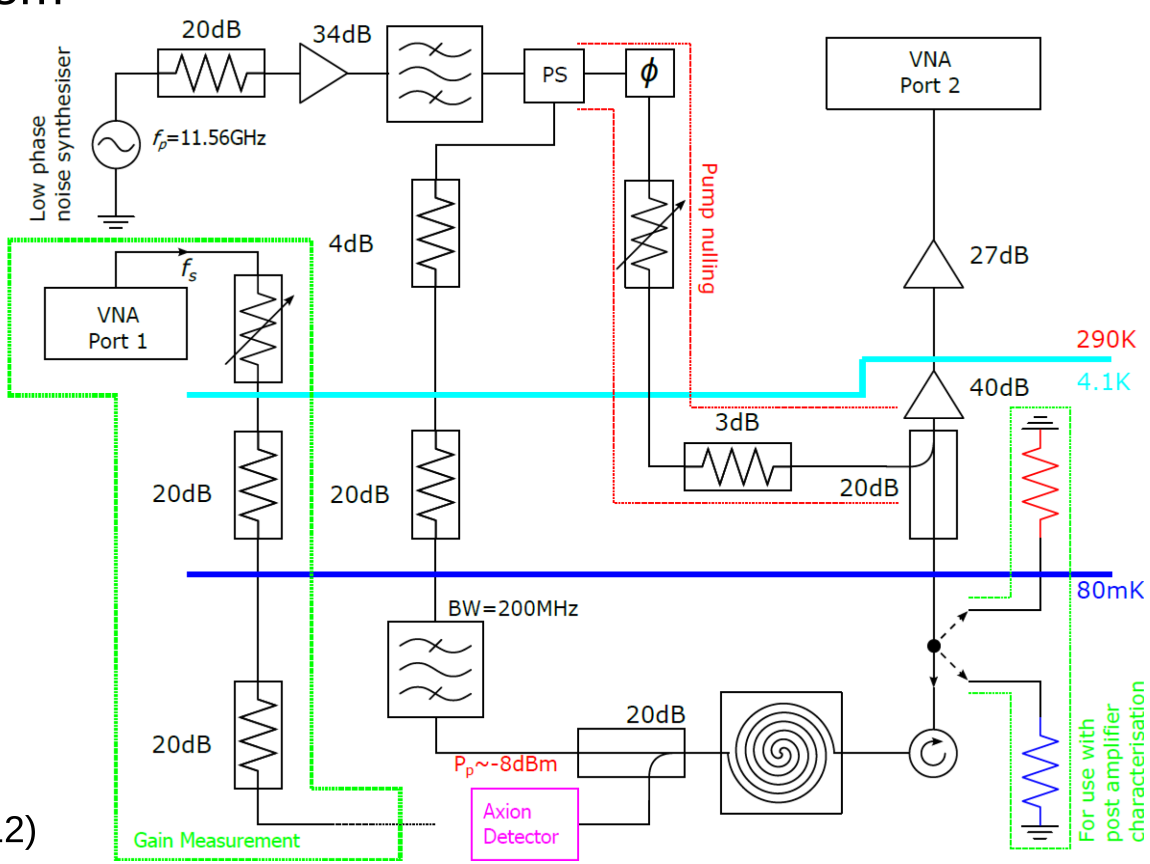
Applications

As an amplification system for an axion detection system



Adapted from Eom *et al* (2012)

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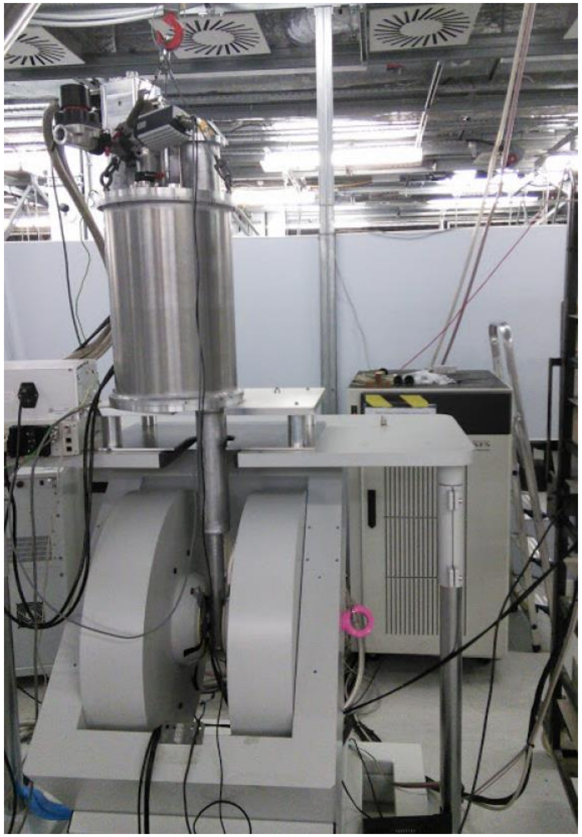
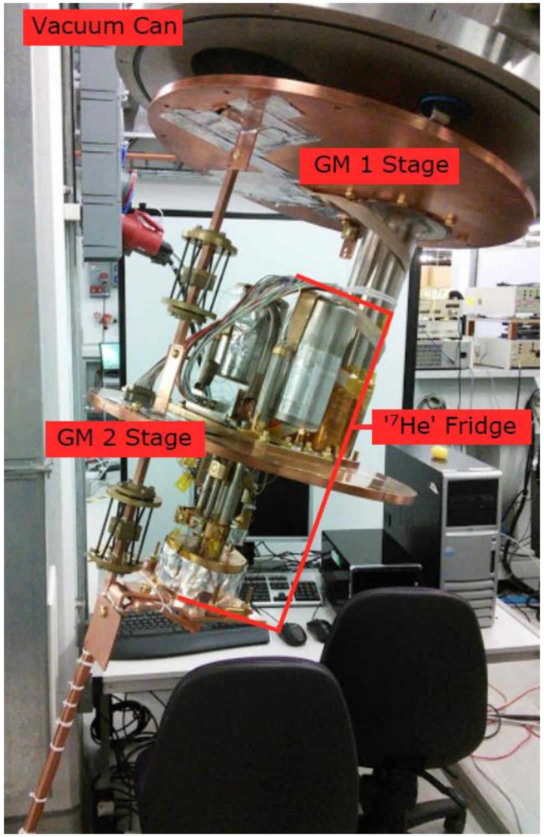
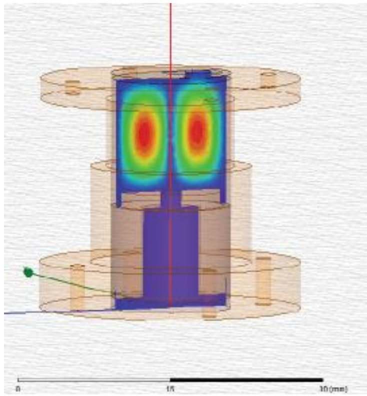
Applications

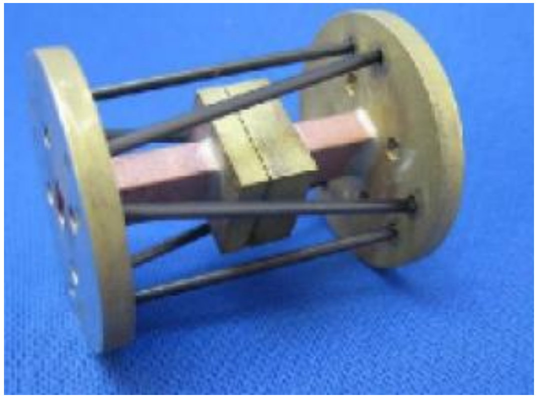
- There has been interest in using RF resonant cavities as axion detectors (Graham et al 2016, QUAX).





- We have developed a 300mK electron paramagnetic system (Melhuish *et al* 2017) that could be adapted for an axion experiment.
    - Resonant frequency ~34GHz
    - TE011 cavity
    - Q factor 24000
    - Magnetic field ~2T





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Conclusions

- Reviewed the current state of HEMT based LNA technology.
  - Shown that LNAs are possible with noise temperatures a few times the quantum limit.
- Outlined an exciting new technology, the travelling wave parametric amplifier
  - Discussed how it offers the potential for amplification with a noise temperature at or below the quantum limit
- Briefly commented on how this technology could be applied to axion detection.

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References and Further Reading

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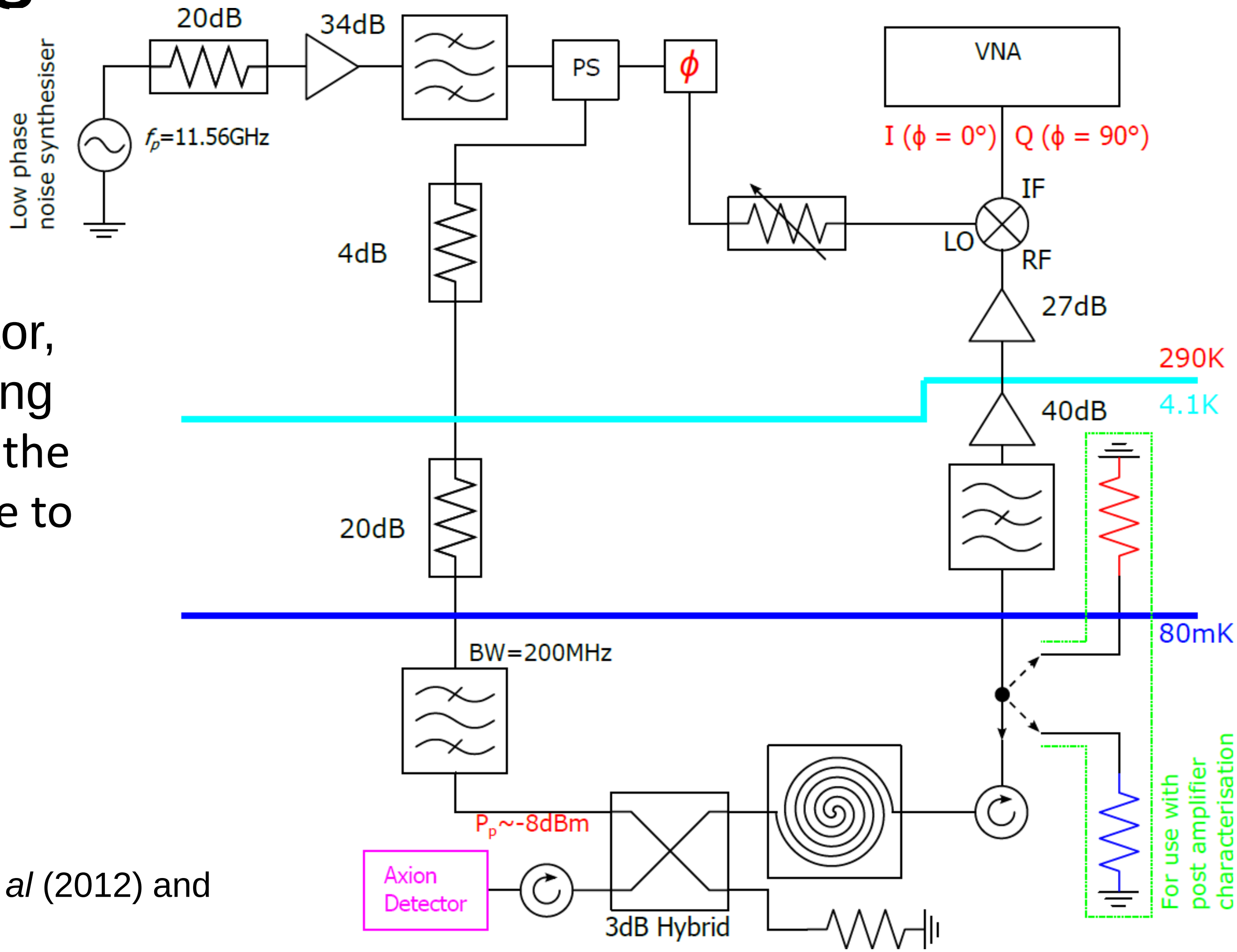
Applications



- As an axion detector, with noise squeezing
- Control of ϕ allows the squeezed quadrature to be accessed.

Adapted from Eom *et al* (2012) and Yurke *et al* 1988