

*The Australian Consortium for Interferometric
Gravitational wave Astronomy*

The Australian National University

**Interferometry and Squeezing:
Quantum Optics Research at the
ANU.**

David E. McClelland

Overview

- about ACIGA
- about the Quantum Optics Group

Quantum Noise

- Injection locking
- Squeezing in SHG
- making squeezed light robust

Advanced configurations

- Signal Recycling
- ~~Sagnac vs. Michelson~~
- ~~RSE on a Sagnac~~

Quantum noise and advanced configurations

- Squeezing and signal recycling



Welcome to the **Australian Consortium for Interferometric Gravitational Astronomy (ACIGA)**
web page.

Objectives

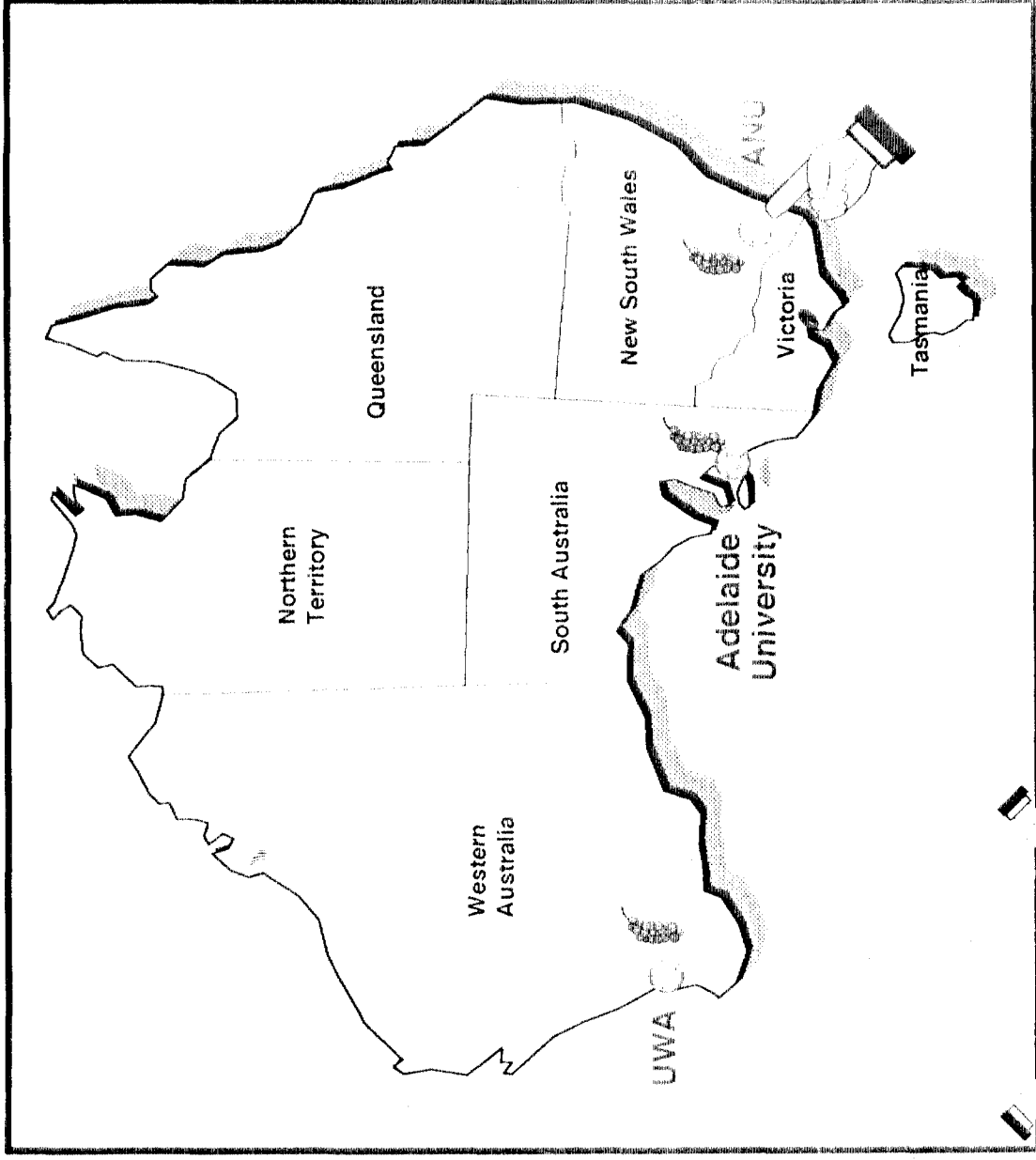
In collaboration with the world gravitational wave community to:

- Undertake research and development aimed at improving the performance of present laser interferometer gravitational wave detectors through advanced designs to ultimate limits set by mechanics, quantum mechanics, lasers and optics;
 - Transfer this R&D into practical designs for inclusion in existing and future detectors including the Australian International Gravitational Observatory as the Southern Hemisphere component of the world wide observational network;
 - Transfer the R&D where appropriate to the Industrial partners for the production of commercial products (see note below re intellectual property rights);
 - Arrange conferences, seminars and workshops as required to compliment and enhance the research of the members of the consortium.
-

Management Structure

www.gqu.edu.au /Physics/ACIGA/

ACIGA




 ANU : Optics

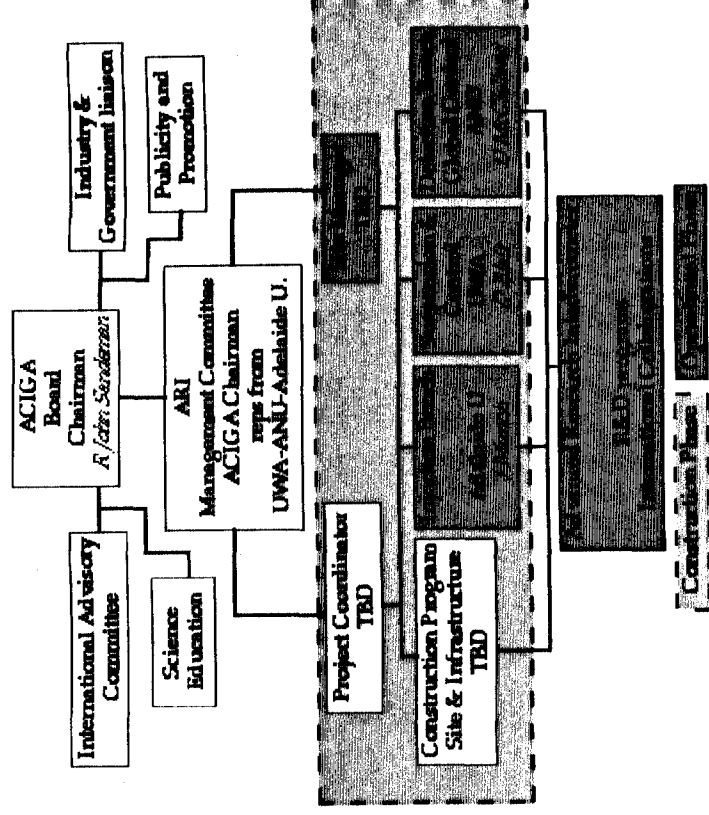
Interferometric configurations, control, signal extraction, quantum optics (squeezed states), laser injection locking

 UWA : Mechanics

Mirror suspensions, seismic/mechanical isolation, High-Q resonators, Sapphire transducers

 Adelaide : Lasers

Diode-pumped solid state lasers, Holographic beam splitters and beam correcting elements



ACIGA Board

Consists of the representatives of the ACIGA membership including all partners. Acts as an advisory board for all ACIGA operations including input from the International groups and Australian government and industry bodies.

ARI Management Committee

The committee which oversees the construction and operation of the ARI including its planning for as a corner station for an operational gw detector. It implements policy decisions of the ACIGA board. Oversees the coordination of the construction and operation of the ARI.

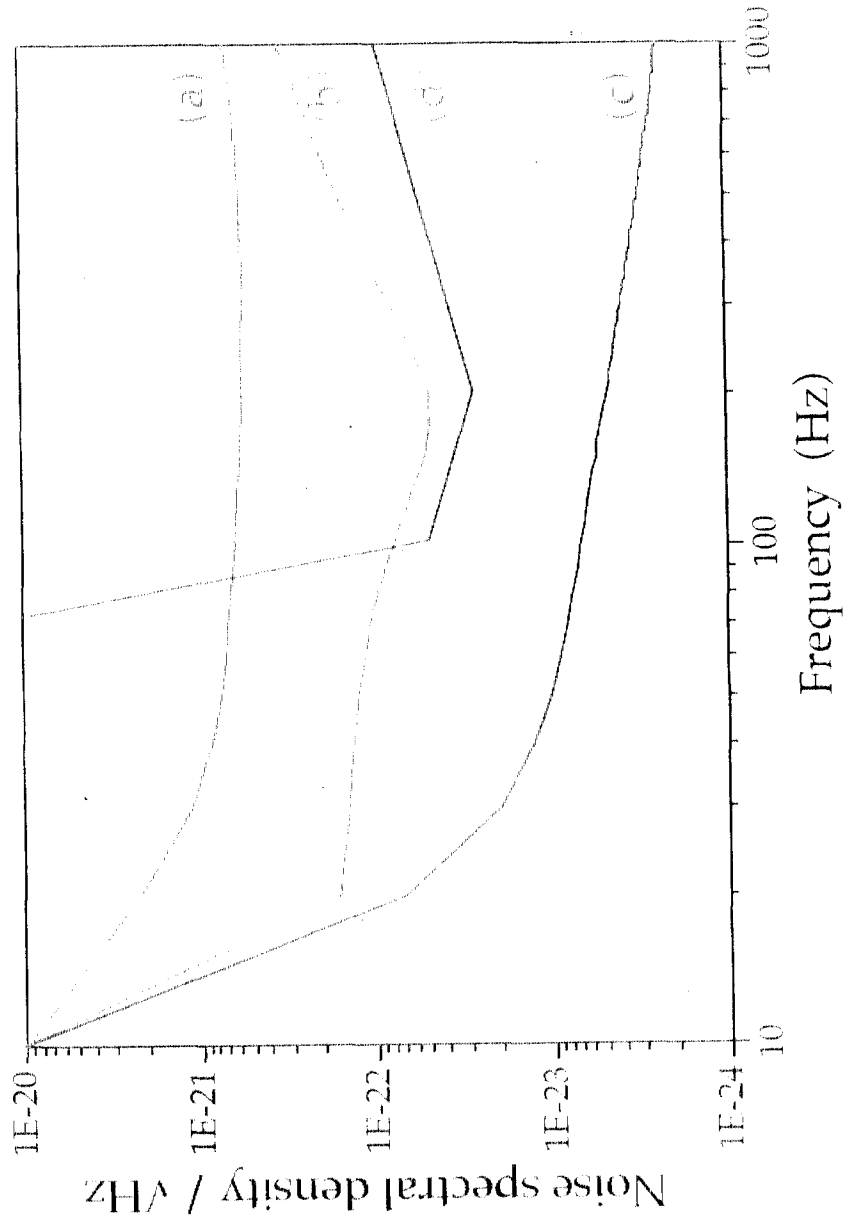
Chaired by the Chairman of ACIGA



Emeritus Professor R. John Sandeman

Representatives of

AIGO 400 TOTAL NOISE BUDGET



Stage 1 noise budget: laser power 5 W and assuming PR and SR
 frequencies of 100 Hz, 100 kg test masses, and $Q_s \sim 1005$ to 10 Hz

Stage 2 noise budget: PR ~ 1700, SR ~ 800; 100 kg masses; $Q_s \sim 1005$ to 10 Hz

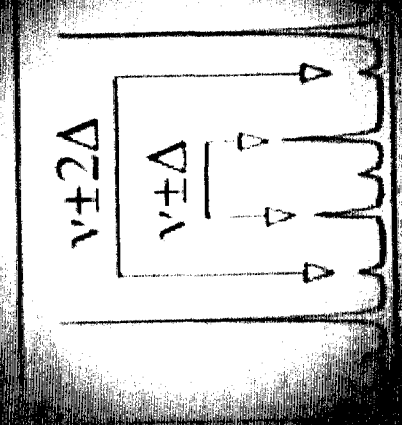
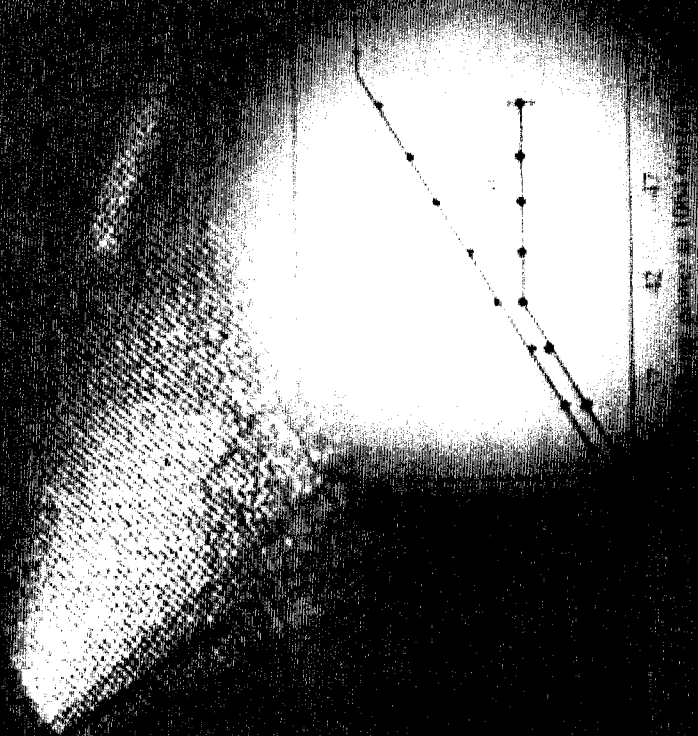
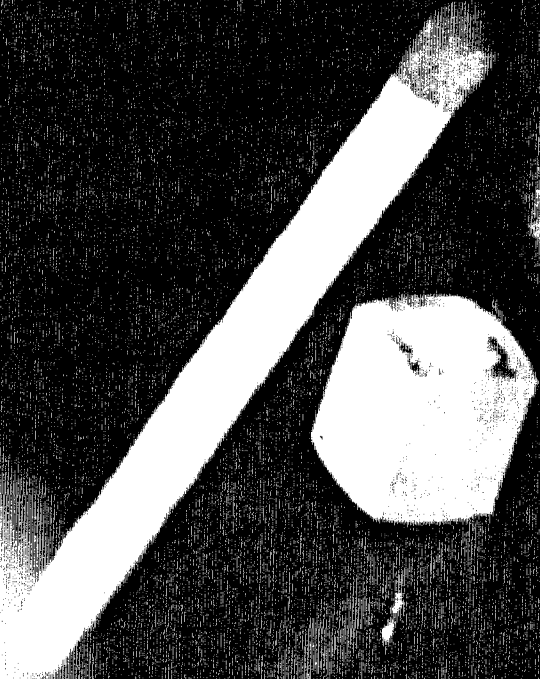
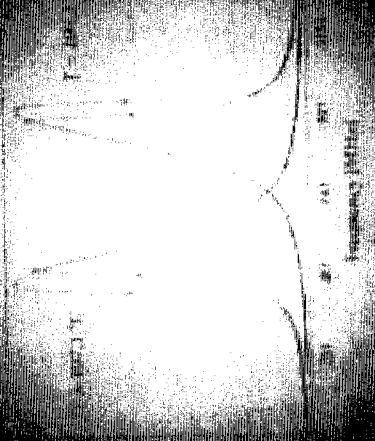
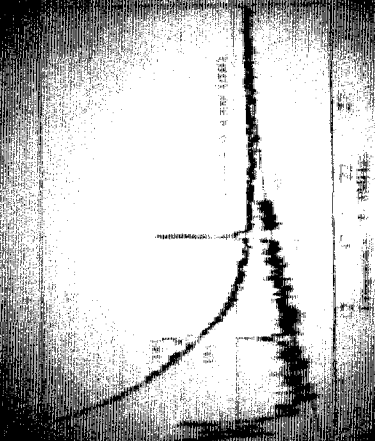
(a) thermal noise floor

(b) stage 1 noise budget

(c) stage 2 noise budget

(d) total noise budget

Quantum Optics 1996 Annual Report ANU



People

ACIGA:

Malcolm Gray
Boris Petrovichev
Dan Shaddock
Karl Baigent

Charles Harb

Elanor Huntington

Quantum Optics

Hans Bacher
Tim Ralph
Ping Koy Lam
Jinwei Wu

Matthew Taubman
Andrew White

Linearised model:

$$\hat{a} = \alpha + \delta \hat{a}$$

operator classical operator
value

**Scaled intensity noise
= amplitude quadrature noise**

$$\text{Var}(n) = n \text{ Var}(X1)$$

All Q-functions are 2 dim Gaussian.

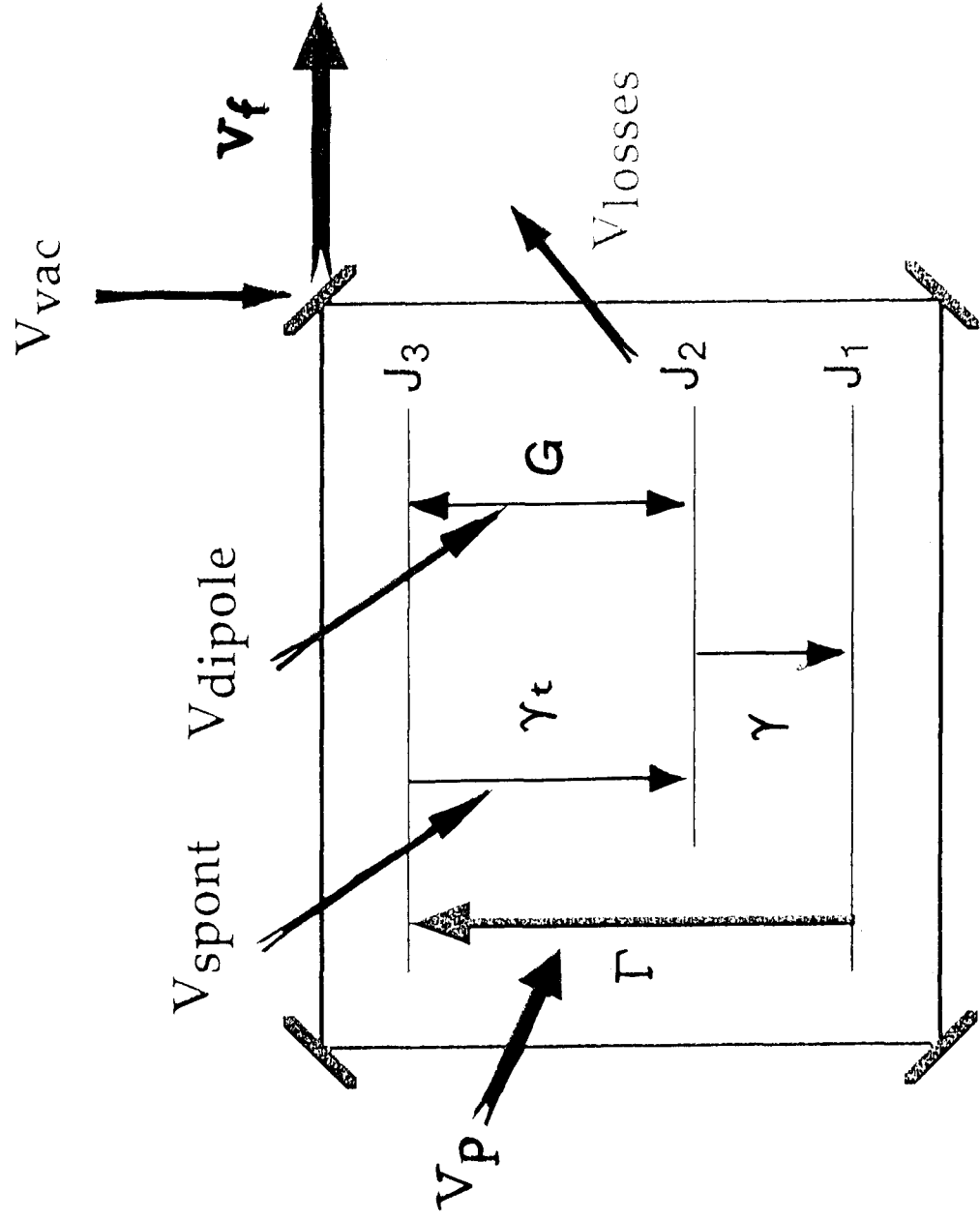
**V1(Ω) contains all necessary
information**

**Optical systems can be described by
noise transfer functions**

Theory + Exp. Tests: Tim Ralph et al

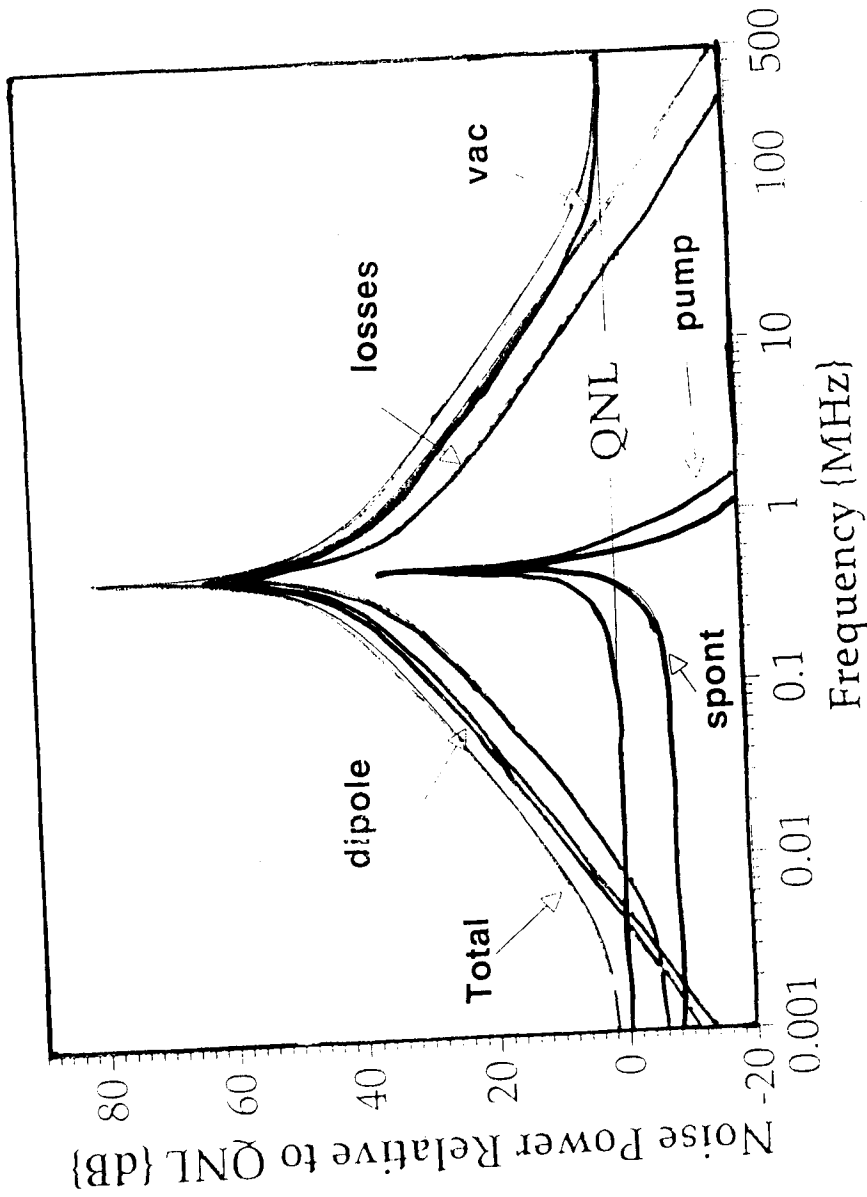
**See also : Squeezed state of light
C.Fabre Physics Report 219 (1992)**

Nd:YAG laser model:



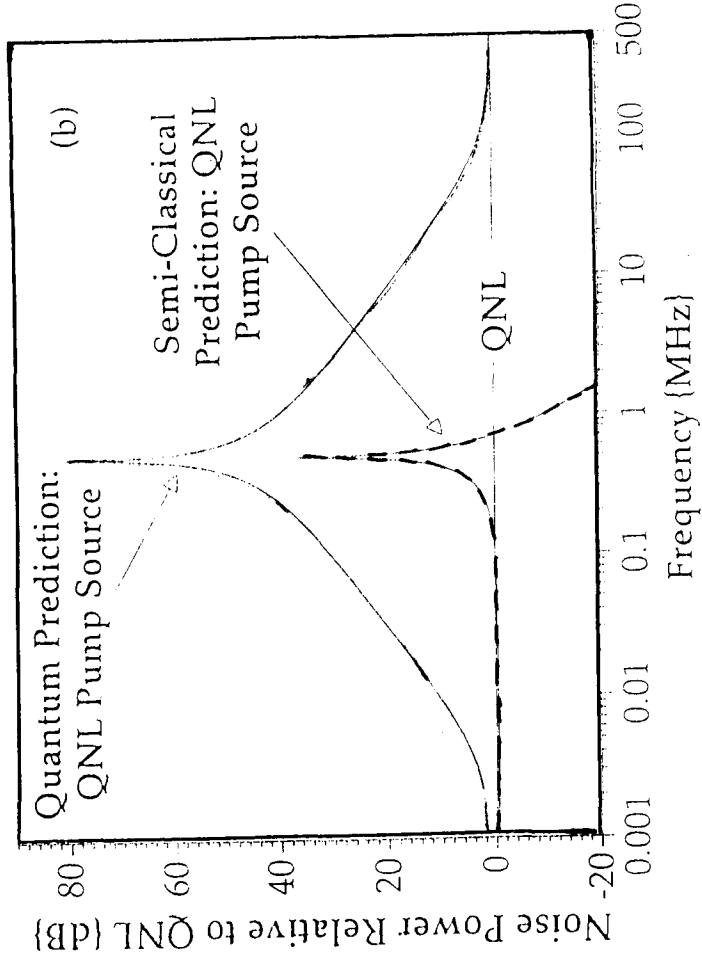
Noise contributions:

$$\begin{aligned}
 V_f = & \left\{ 1 + \frac{4\kappa_m(\omega^2 + \gamma_l^2) - 8\kappa_m\kappa G\alpha_f^2\gamma_l}{(\omega_f^2 - \omega^2)^2 + \omega^2\gamma_l^2} \right\} V_{vac} \\
 + & \left\{ \frac{2\kappa_m G^2 \alpha_f^2 \Gamma}{(\omega_f^2 - \omega^2)^2 + \omega^2\gamma_l^2} \right\} V_p \\
 + & \left\{ \frac{2\kappa_m G^2 \alpha_f^2 \gamma_l J_3}{(\omega_f^2 - \omega^2)^2 + \omega^2\gamma_l^2} \right\} V_{spont} \\
 + & \left\{ \frac{2\kappa_m G J_3 ((\gamma_l + \Gamma)^2 + \omega^2)}{(\omega_f^2 - \omega^2)^2 + \omega^2\gamma_l^2} \right\} V_{dipole} \\
 + & \left\{ \frac{4\kappa_m \kappa_l (\gamma_l^2 + \omega^2)}{(\omega_f^2 - \omega^2)^2 + \omega^2\gamma_l^2} \right\} V_{losses}
 \end{aligned}$$

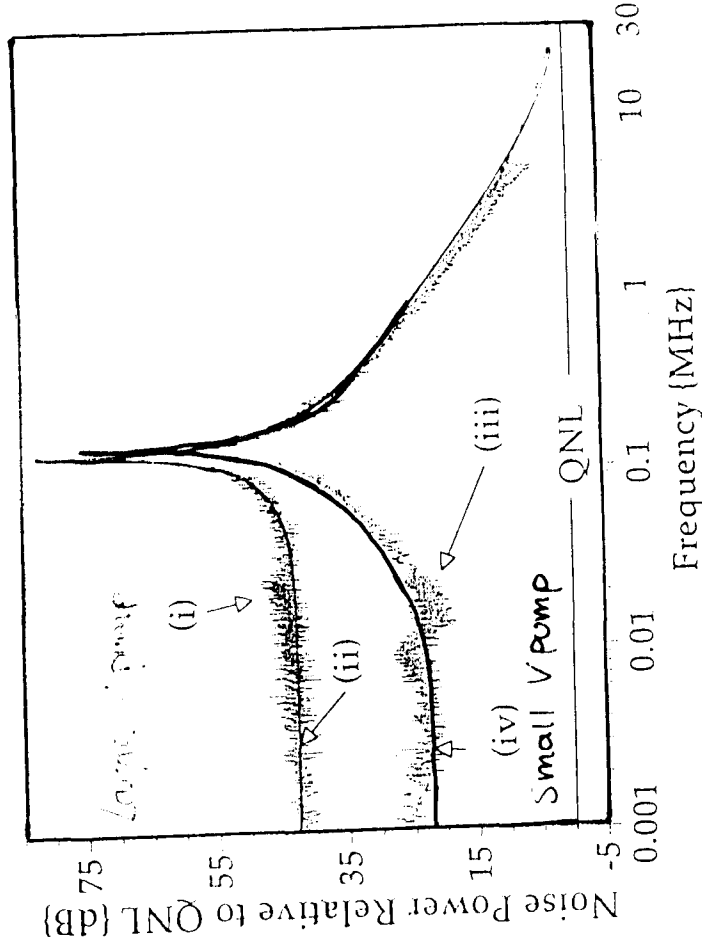


Intensity noise dependence of Nd:YAG lasers on their diode laser pump source C.C.Harb, T.T.Ralph, E.Huntington, D.E.McClelland, H-A.Bachor, I.Freitag submitted to J.Opt.Soc.Am. B (1997)

1. Experimental test : LASER

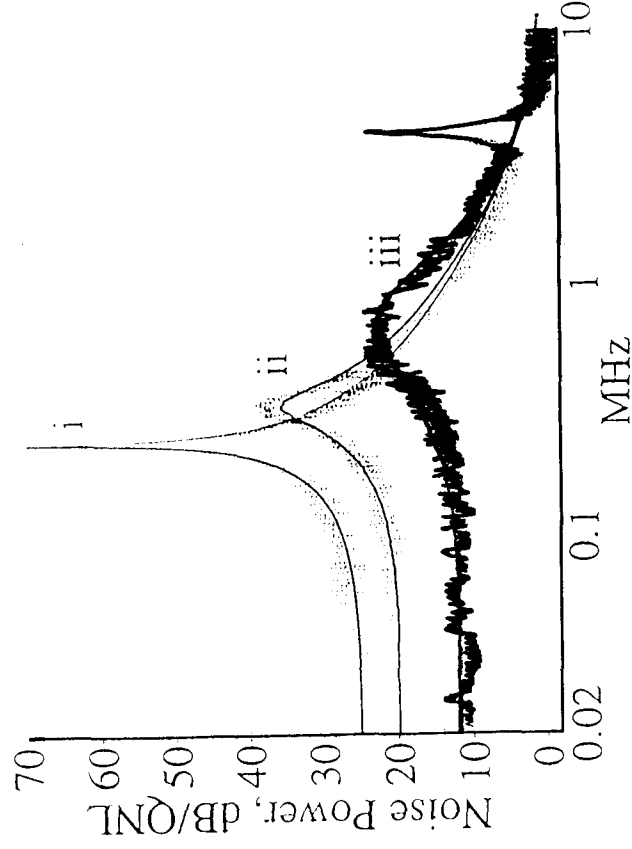
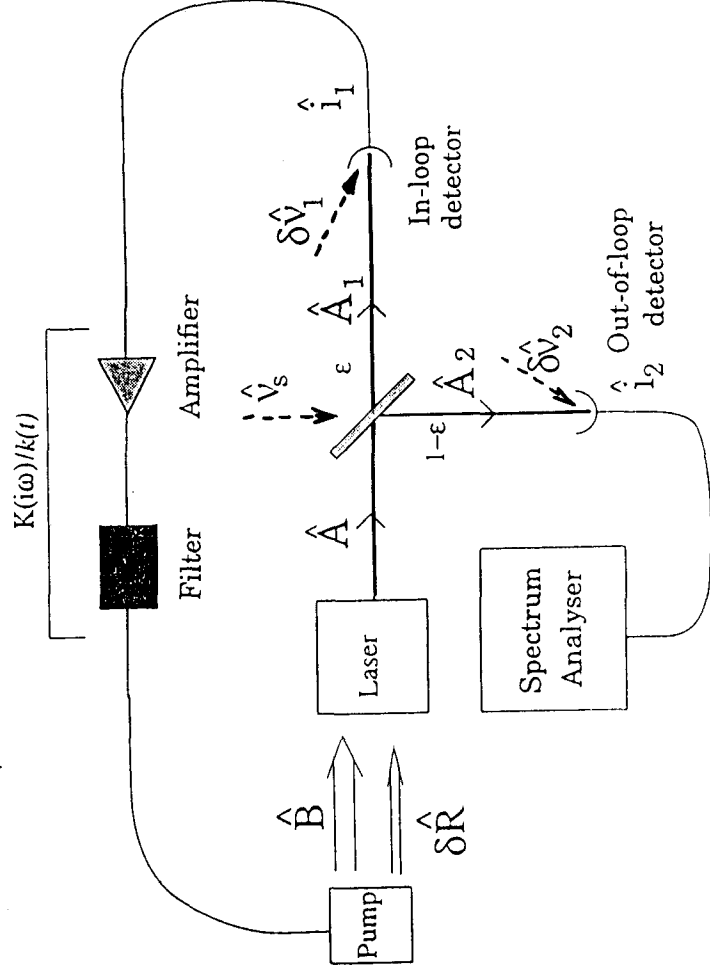


The quantum model is vastly different to semiclassical model



The experiments agree, once the noise of the pump is taken into account

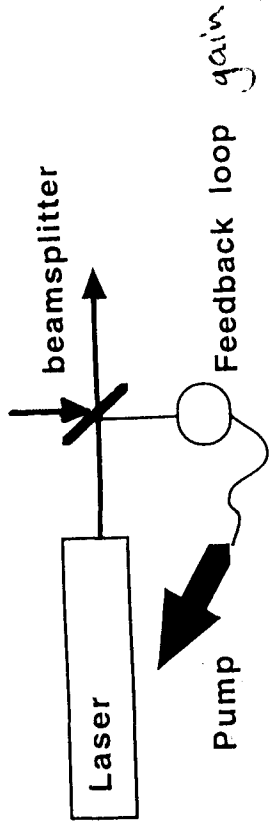
Experimental Test: Laser with Feedback



Modelling a Laser Noise Eater

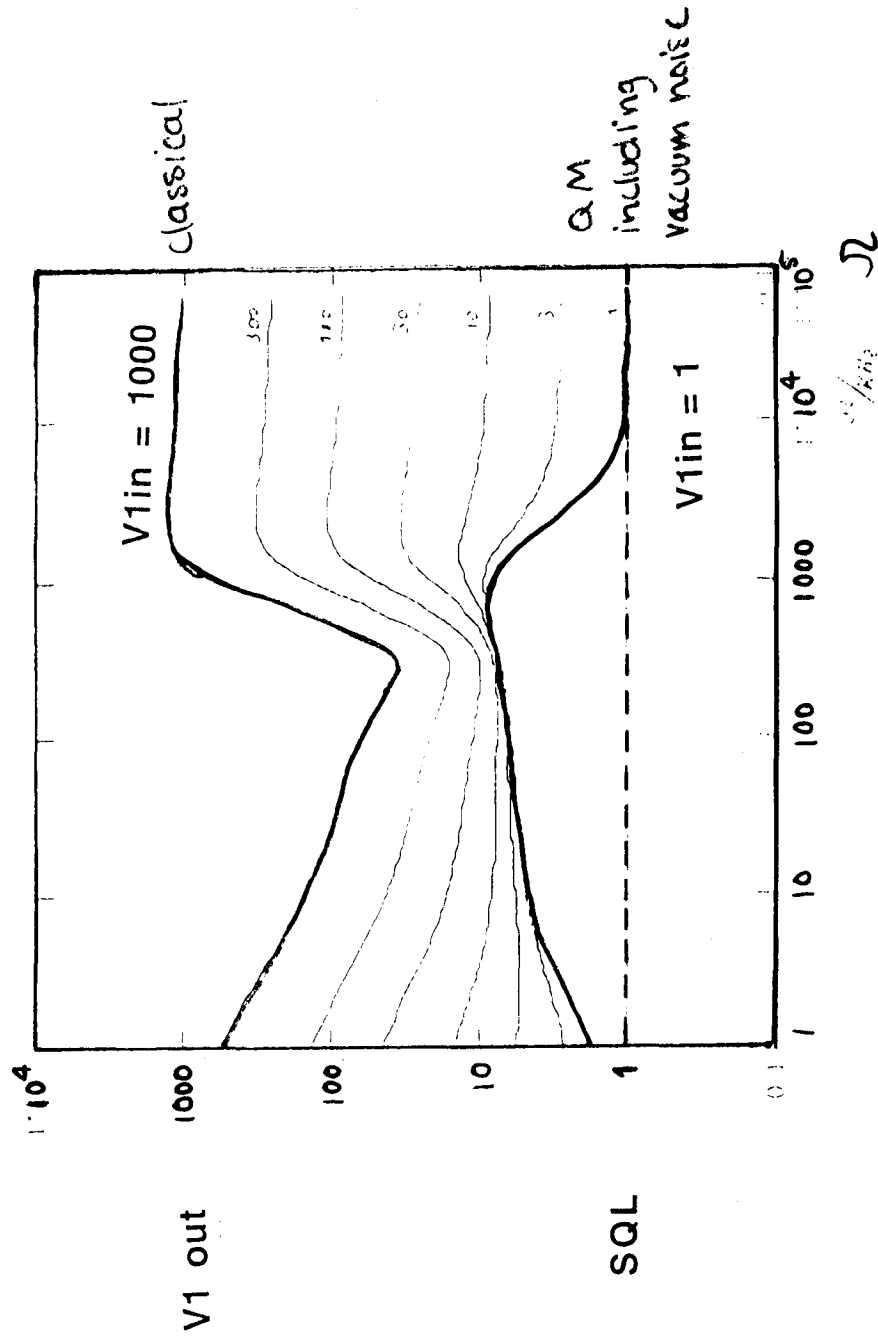
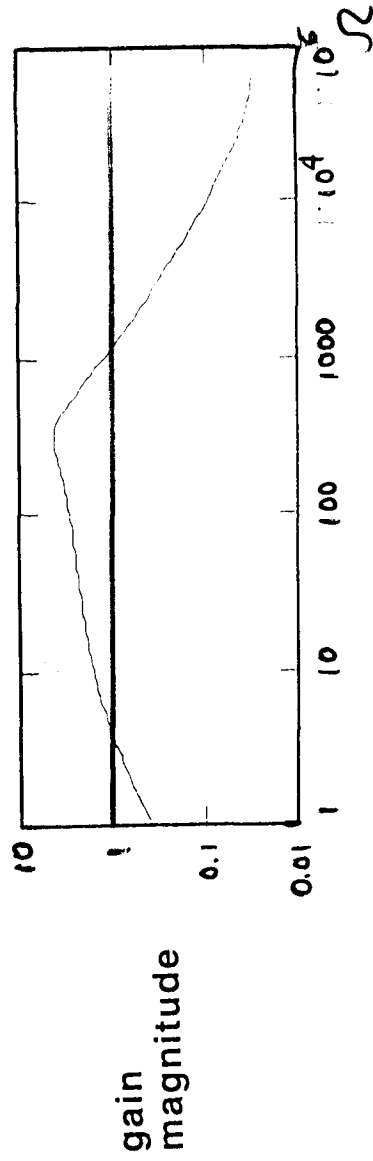
- i No Gain in Feedback Loop
- ii 0.01 X Maximum Gain in Feedback Loop
- iii Maximum gain in Feedback Loop

Electro Optic feedback

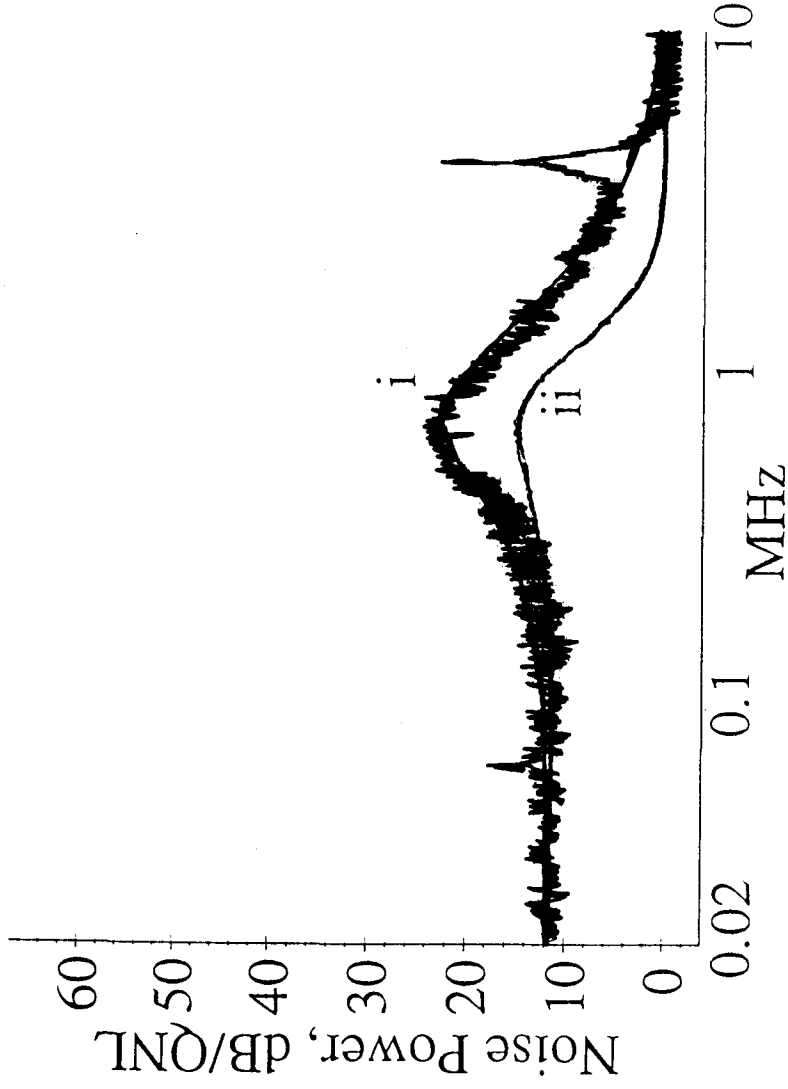


Feedback loop introduces extra noise.

The control is different at the quantum noise limit



Experimental Test



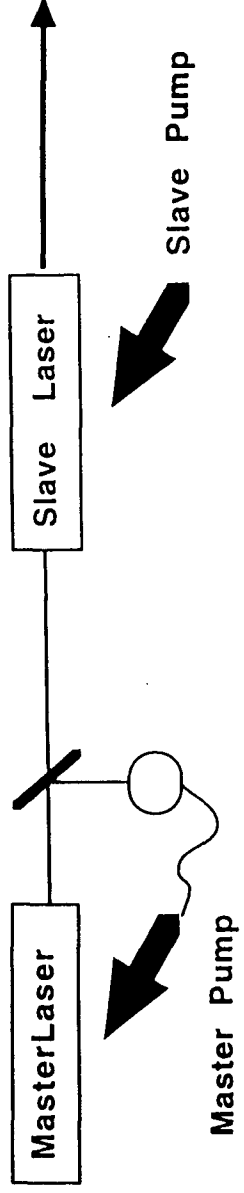
Modelling a Laser Noise Eater

with;

i Quantum Model.

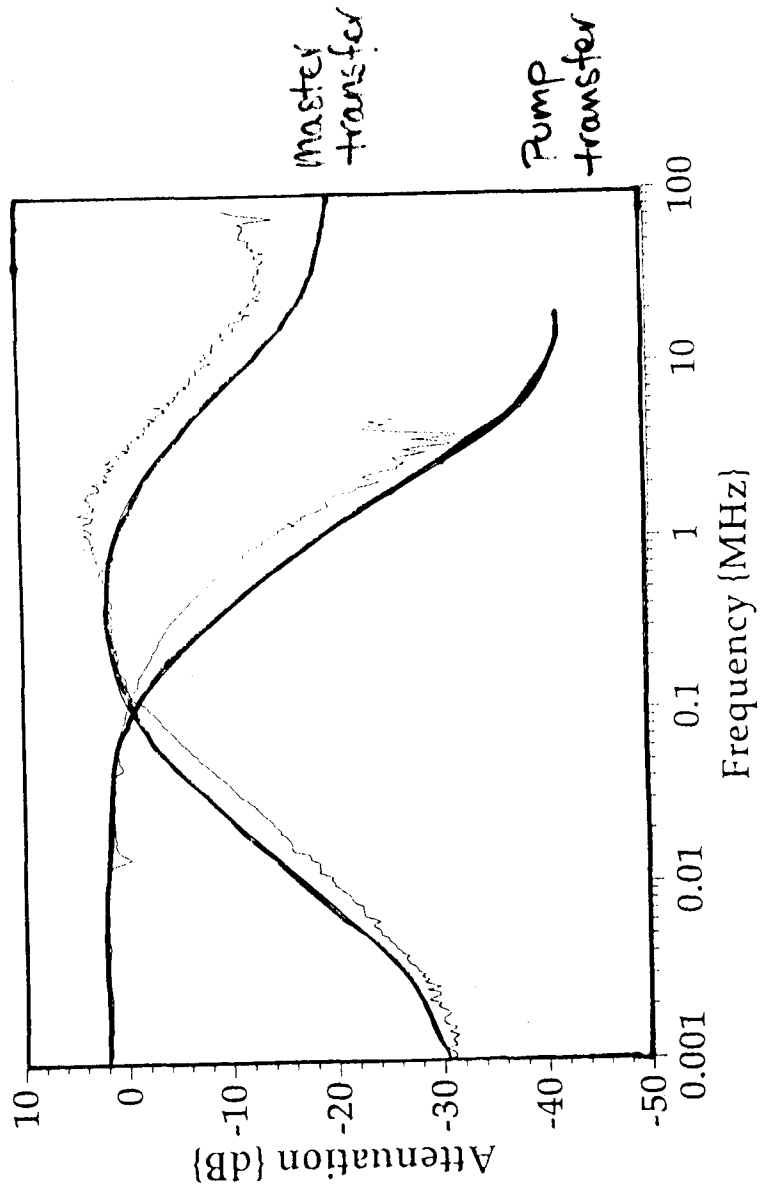
ii Classical Model.

Experimental test: Injection Locking

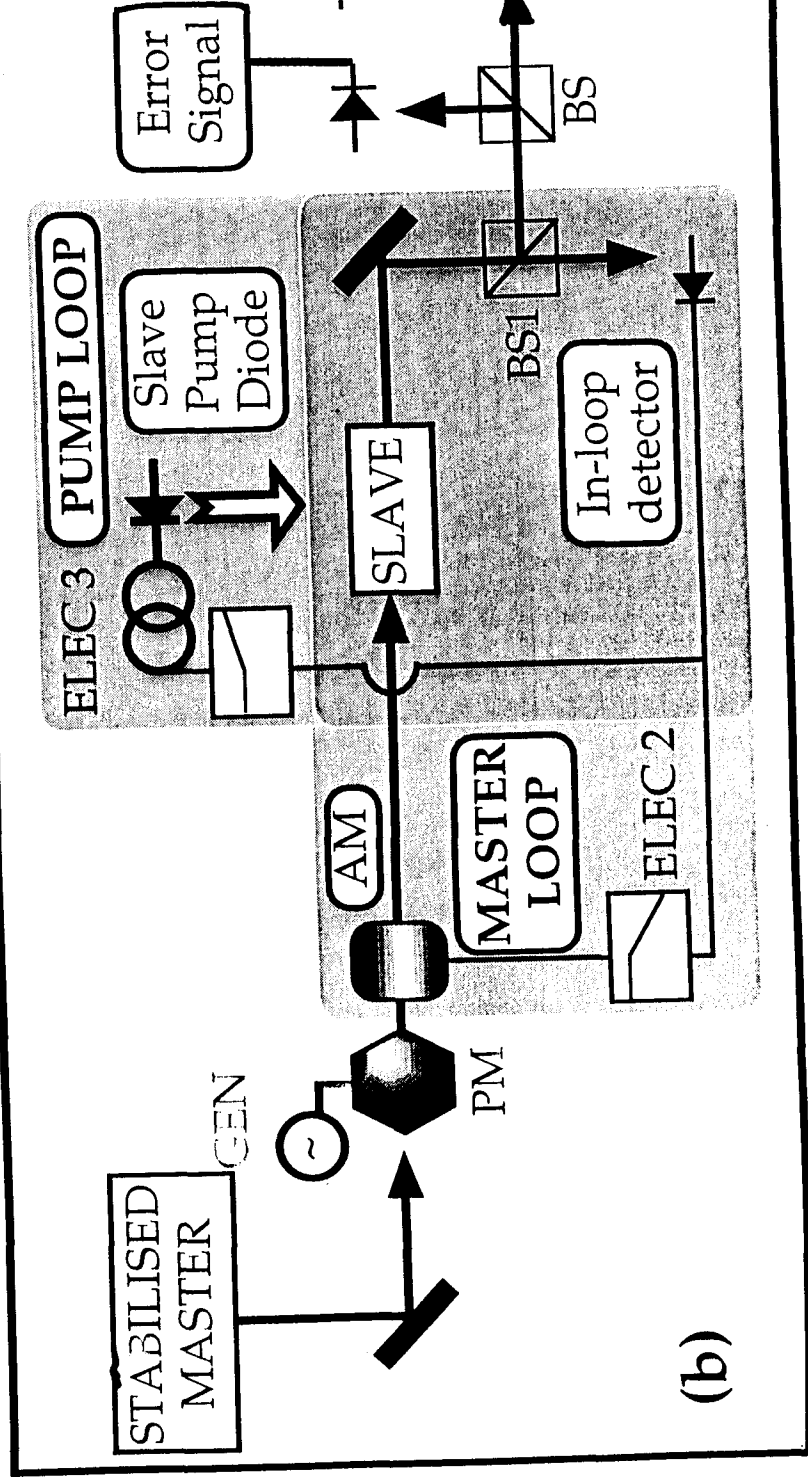
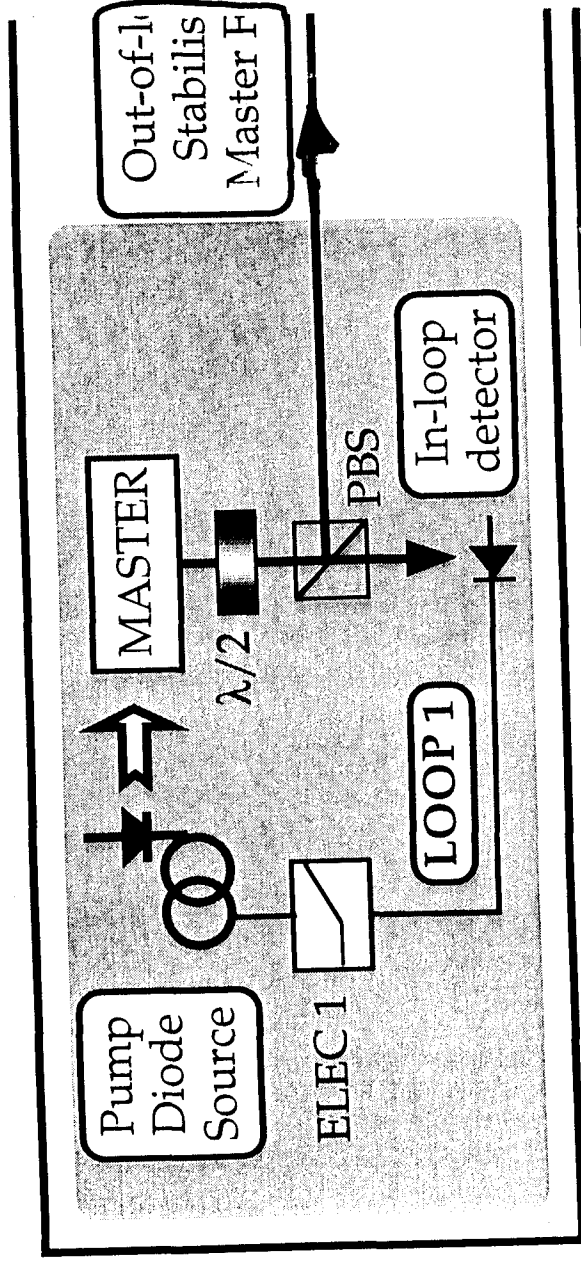


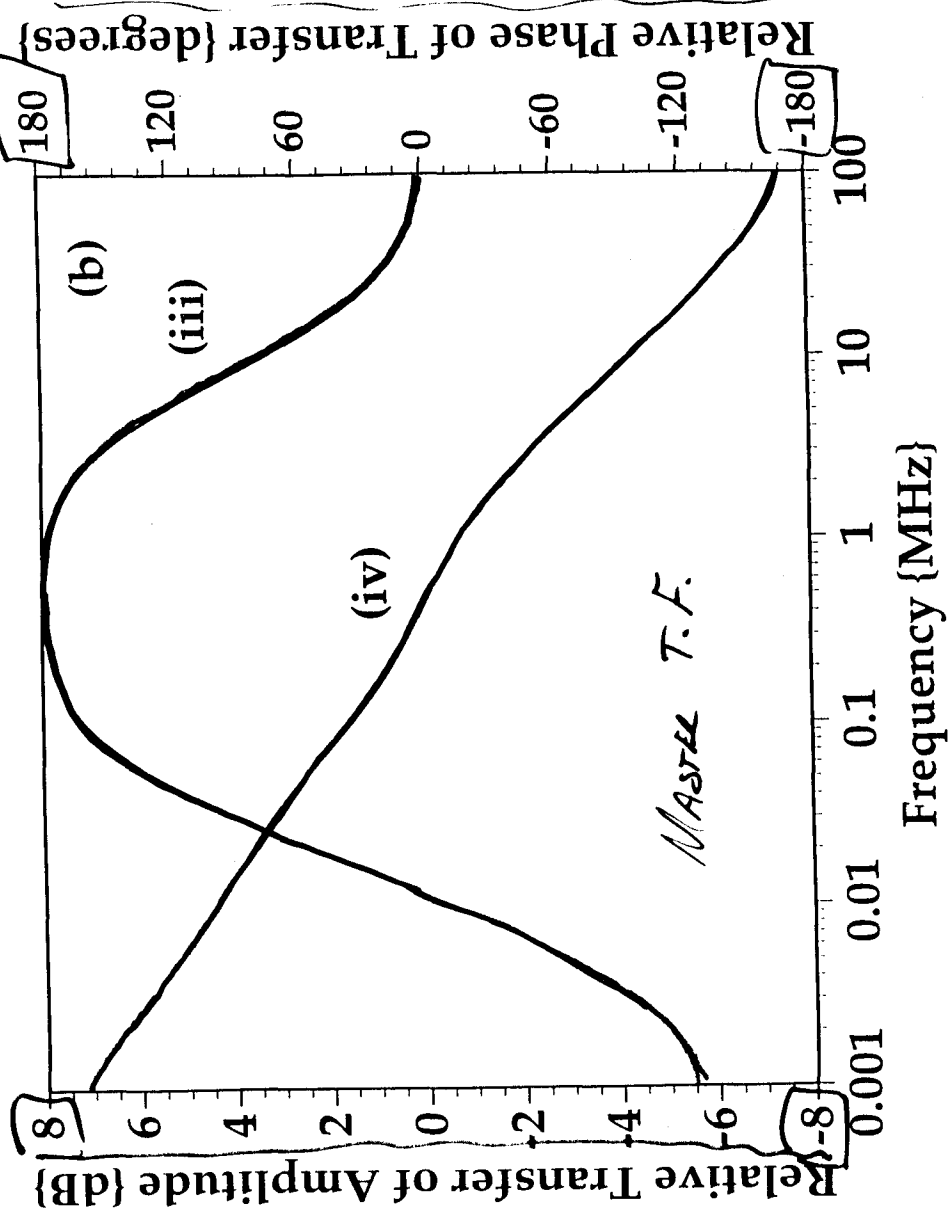
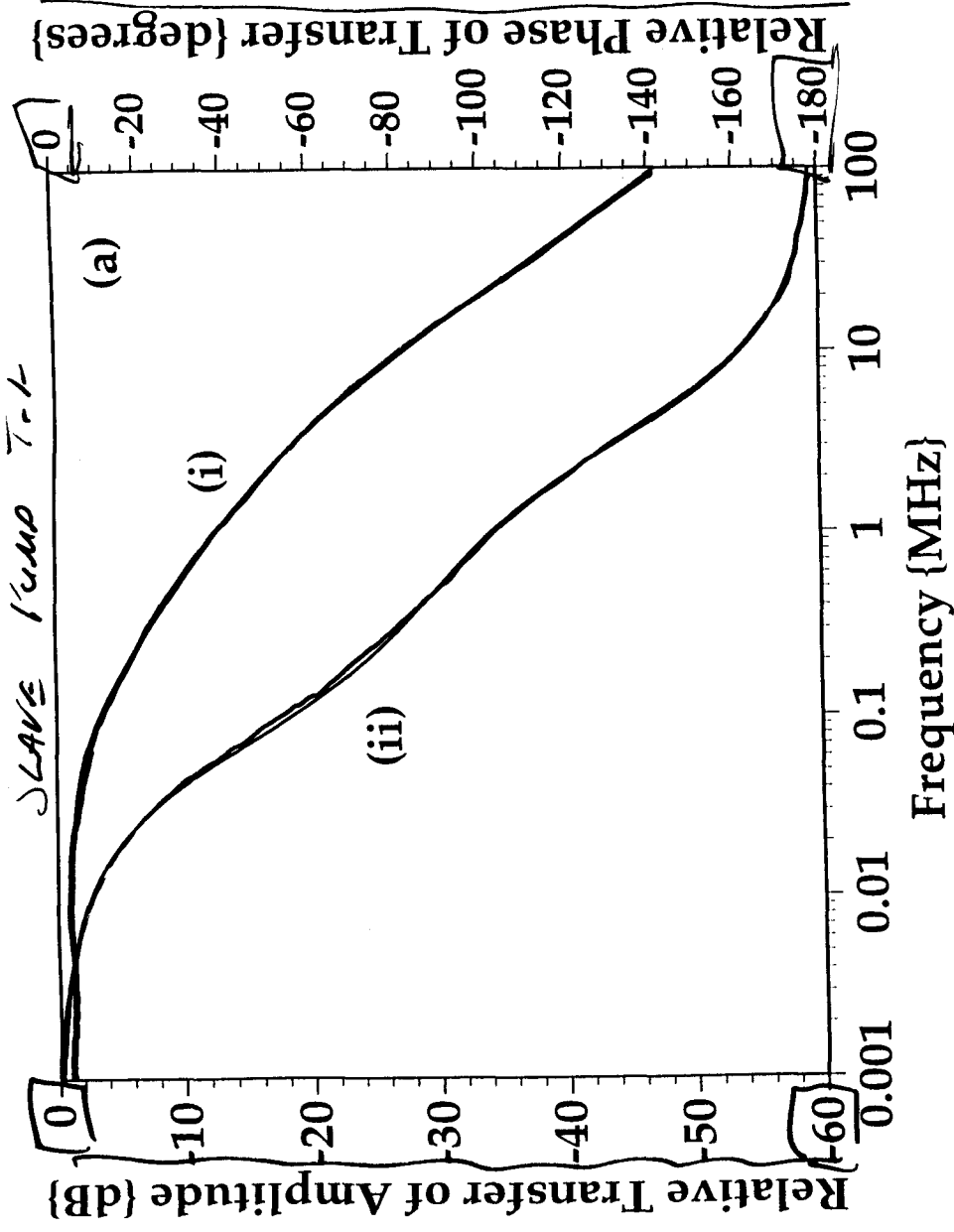
Slave laser (large power) is locked to Master laser (low noise)

I.Freitag, H. Welling App.Phys.B.58,537 (1994)
A.D.Farinas, E.K.Gustafson, R.L.Byer Opt.Lett. 19, 114 (1994)
R.Barillet, A.Brillet, R.Chiche, F.Clewa, L.Latrach, C.N.Man Meas.Sci and Tech. (1995)

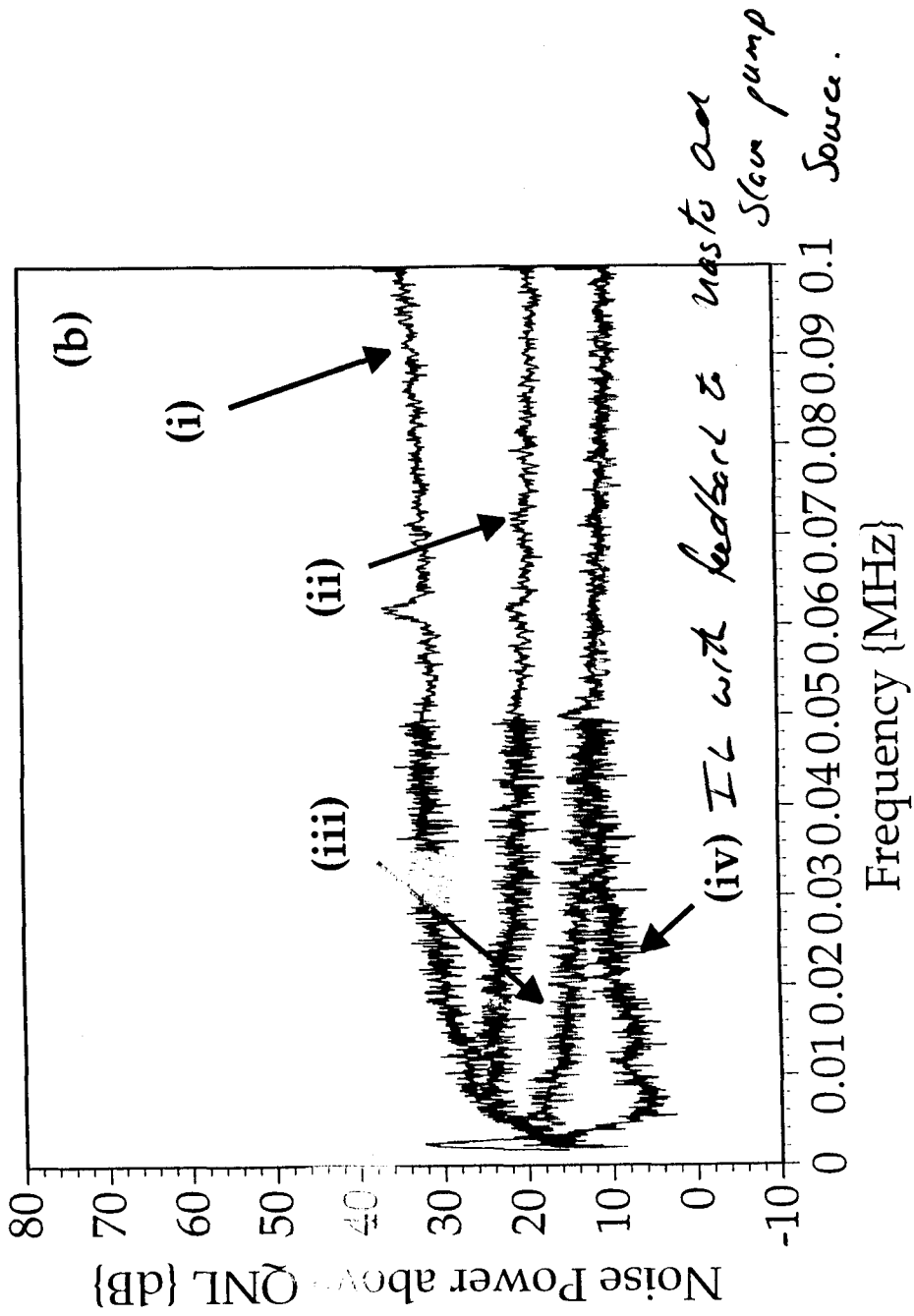
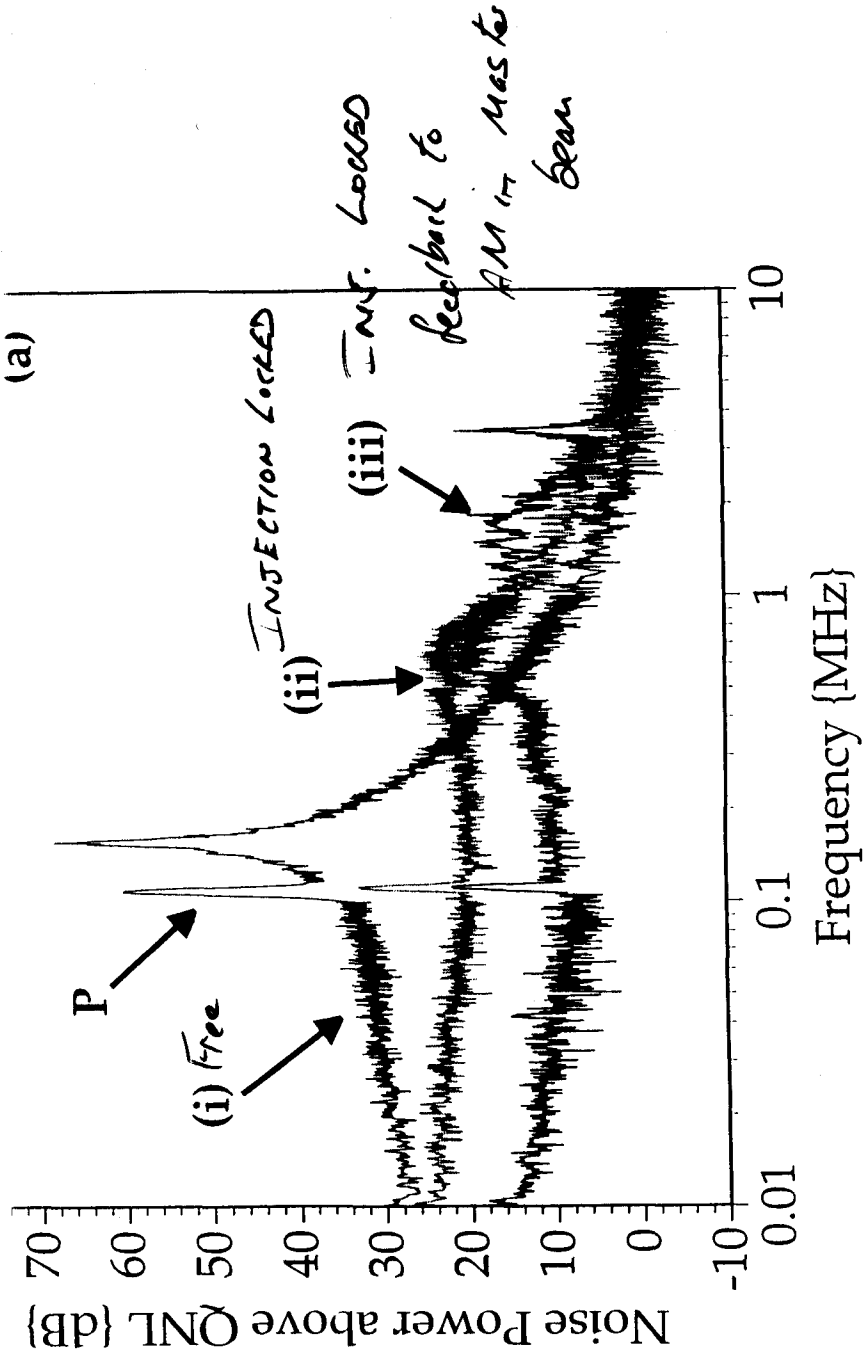


Low frequency: pump noise, medium: amplified master, high frequency : QNL master noise



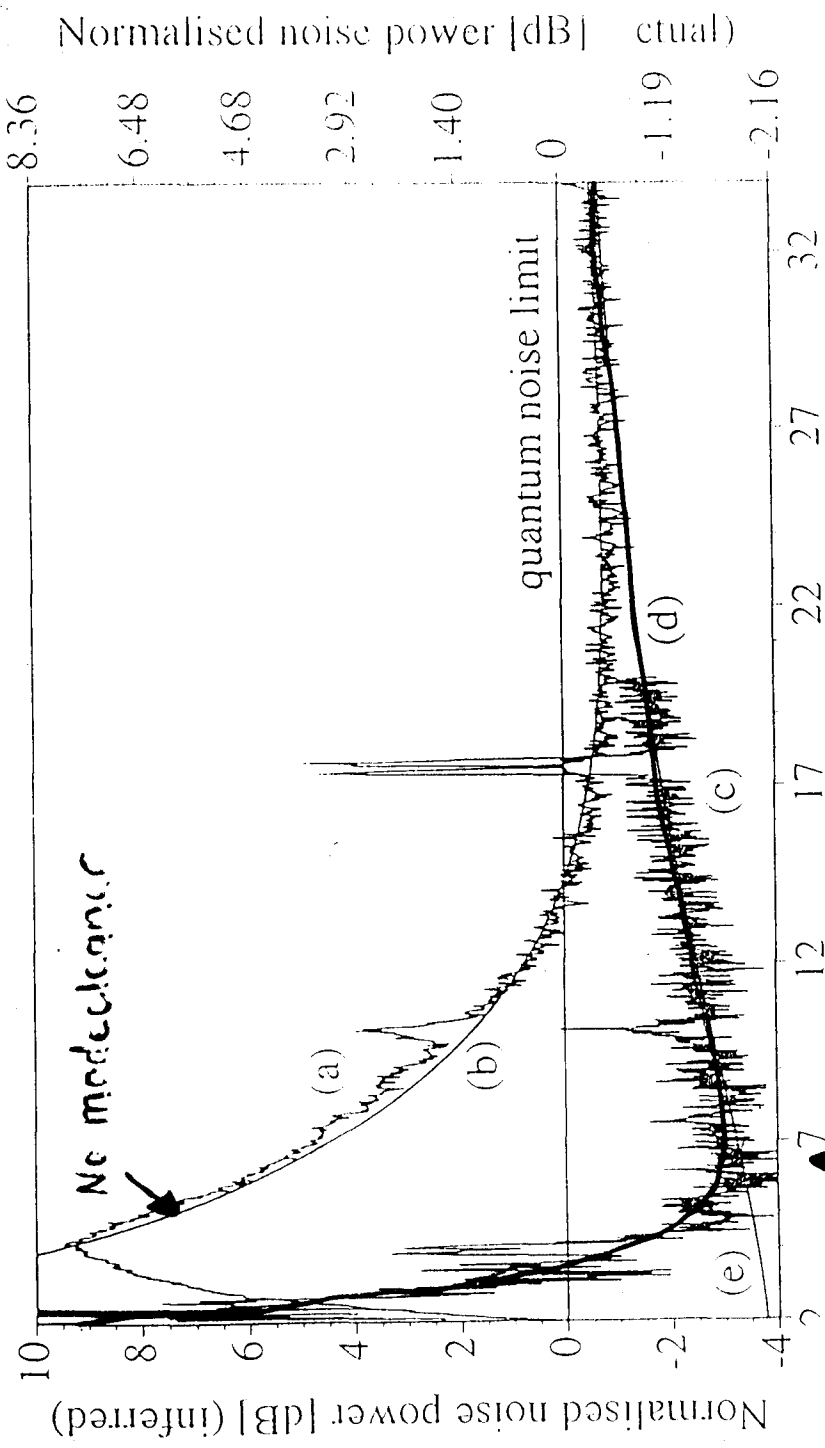
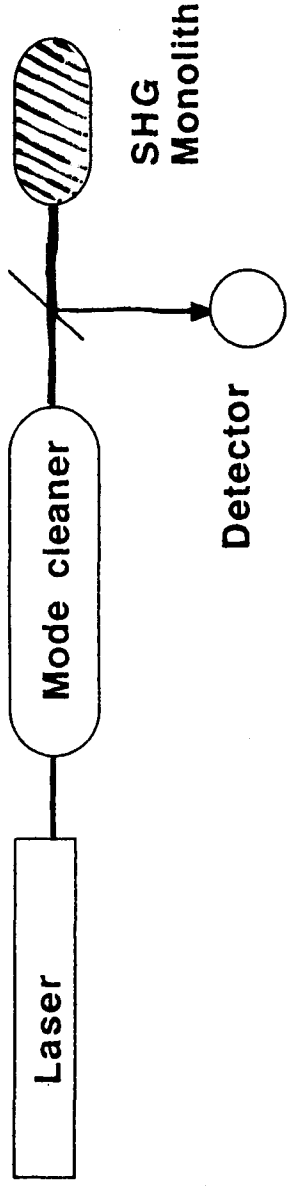


Huntington et al, Feedback Control..., Figure 2



Huntington et al, "Feedback Control ...", Figure 3

Experimental Test: Squeezing



Daylight Squeezing

Runs continuously for many hours

⇒ Reliable

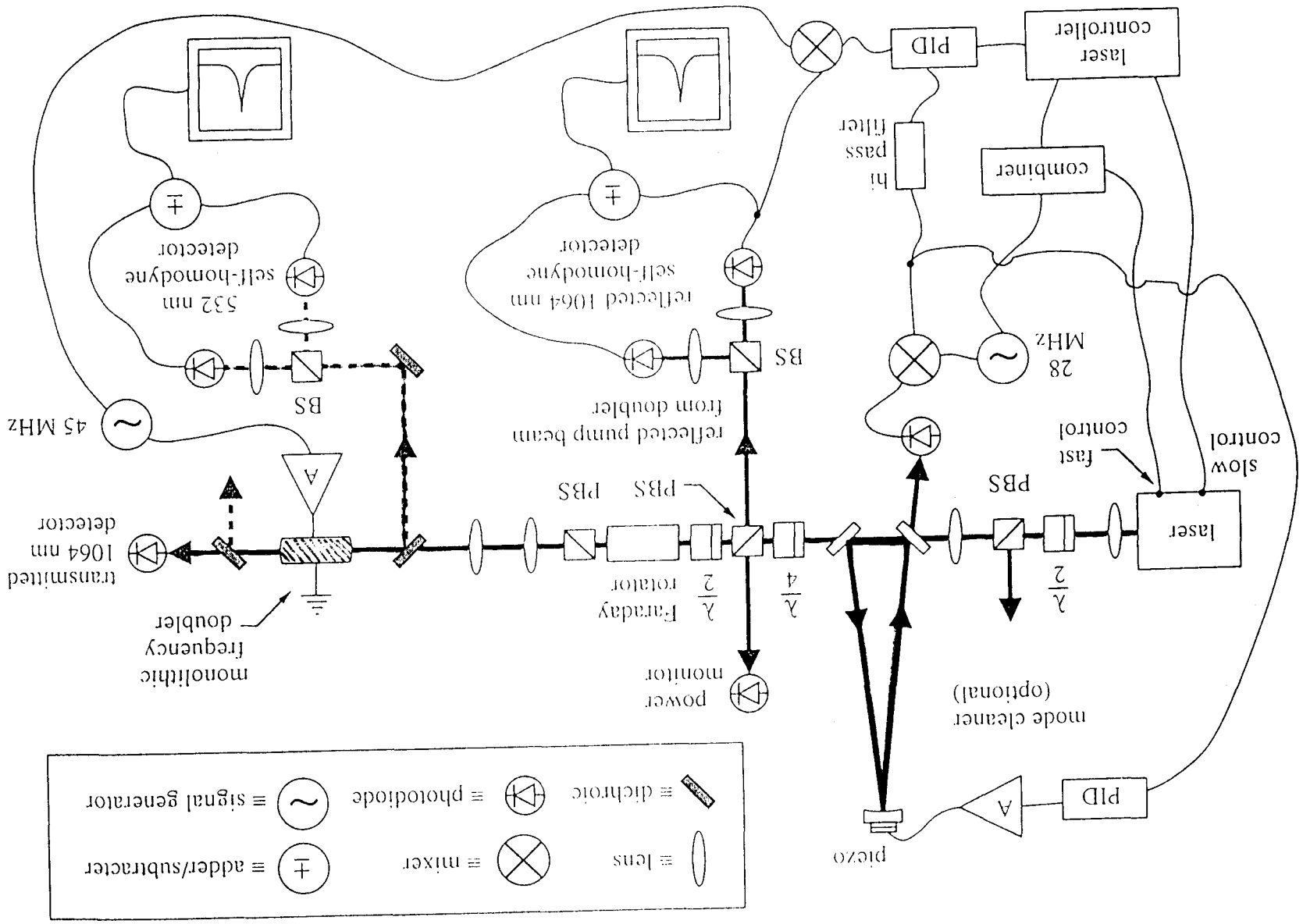
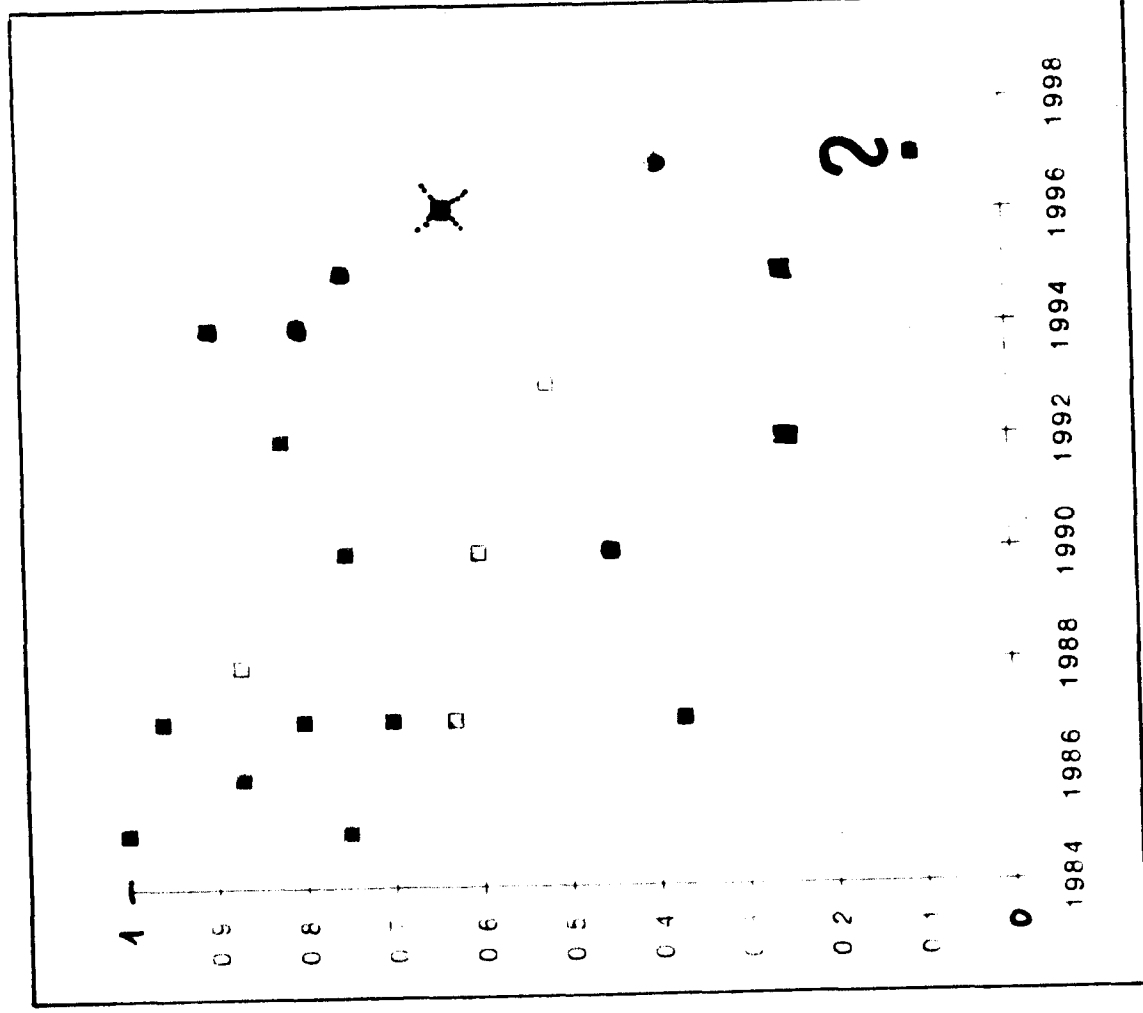


Figure 2

The last 10 Years

Experimental Results in Quadrature Squeezing



1 Hoover

□ Atomic systems and Kerr Effect

■ Sub-threshold OPO

■ SHG

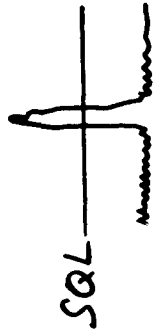
● Diode Laser (Lakhtin)

Open Questions:

How to use squeezed states ?

How to make squeezed light robust ?

How to build a noiseless amplifier ?



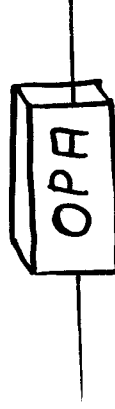
loss

SQL ~~Amplitude~~



Grangier et. al. PRL '71 (93)
 Karlsson et. al. PRL '71 (93)
 Edwards

no coherence

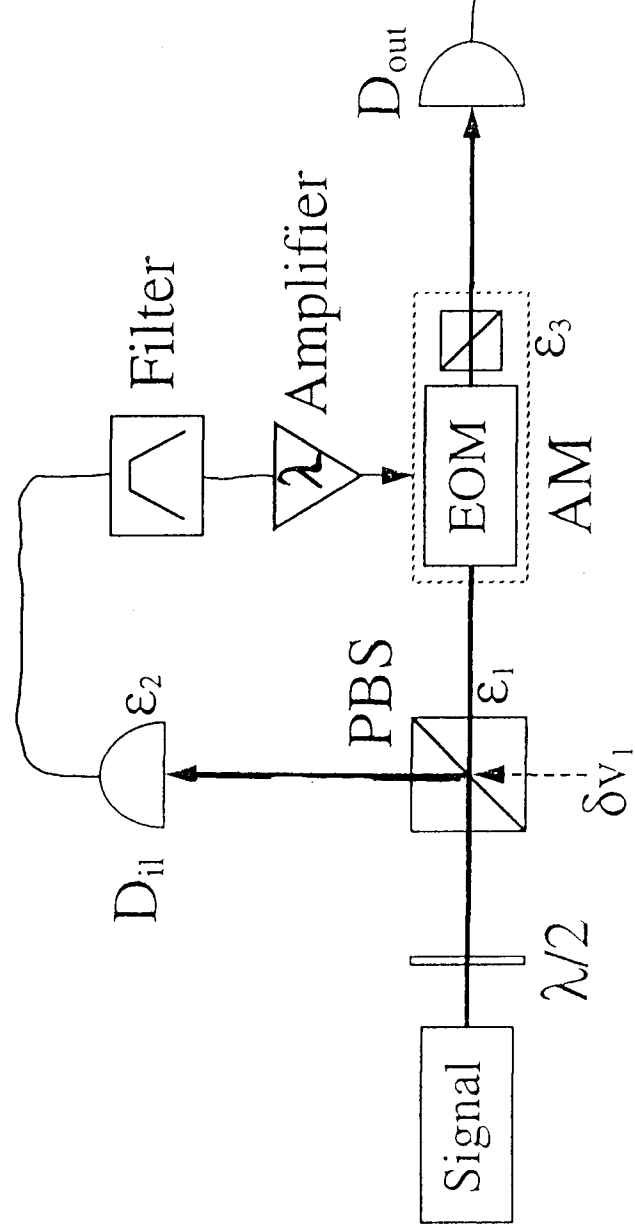


Bruck meier et. al. PRL '93

low gain

Making Squeezed light robust

electro-optic Feed Forward



Schematic layout

The Noise Spectrum of the Output of a Feedforward Loop has the general form:

Input
(Noise + Signal) Amplifier Detection

$$V_{out} = \underbrace{(A + \lambda B)^2}_{\text{Gain}} V_{in}$$

$\lambda \equiv$ feedforward gain
 $A, B, C, D, E \equiv$ positive, real

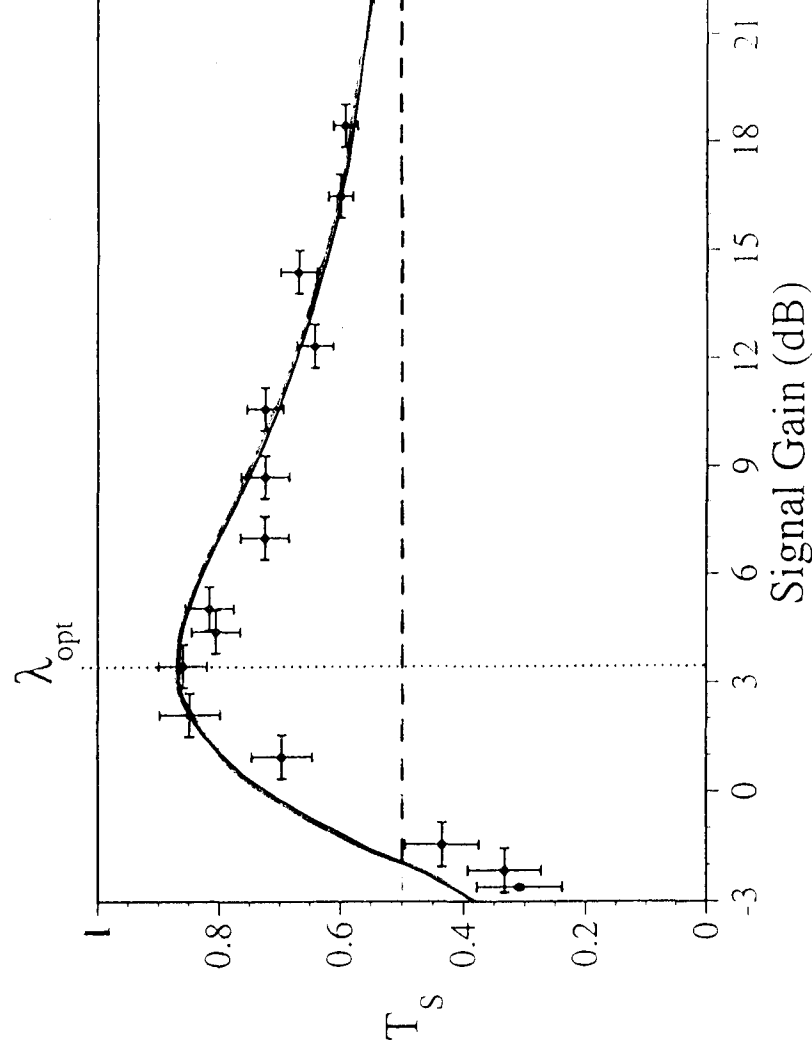
T_s = ratio ^{out} input SNR to ~~output~~ ⁱⁿ SNR

can be maintained

for normal large gain amplifier $T_s < 0.5$

$$T_s = \frac{SNR_{out}}{SNR_{in}}$$

$T_s = 1$ perfect amplifier

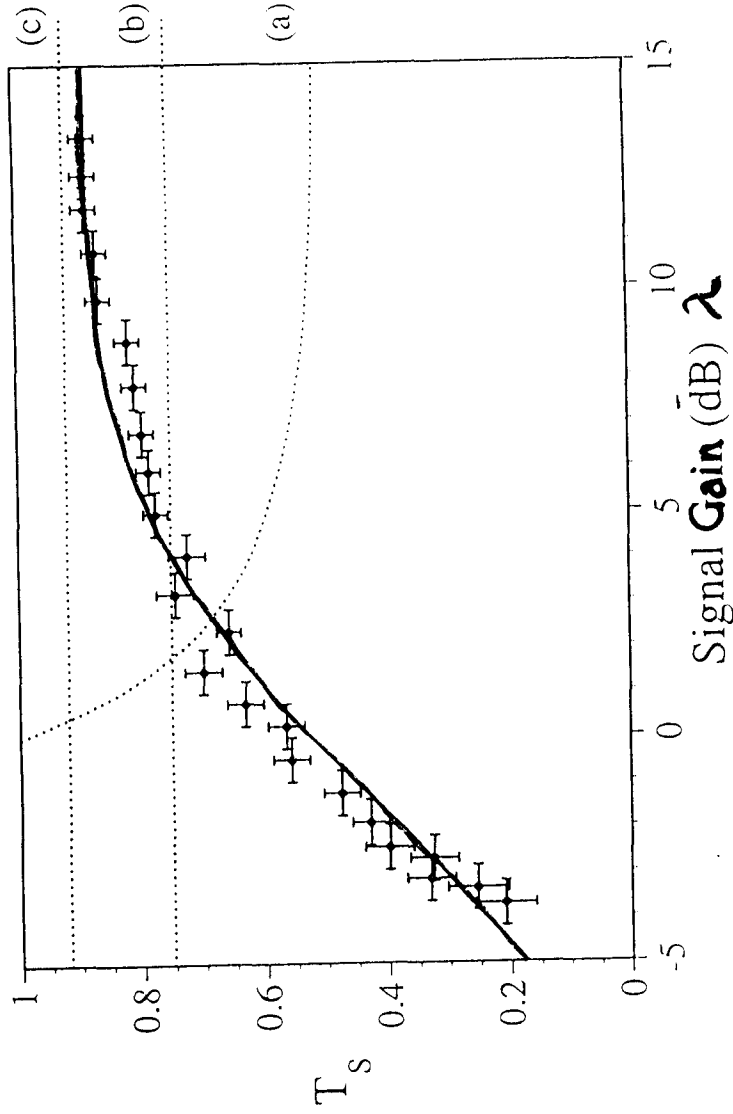


beam splitter = 50 %

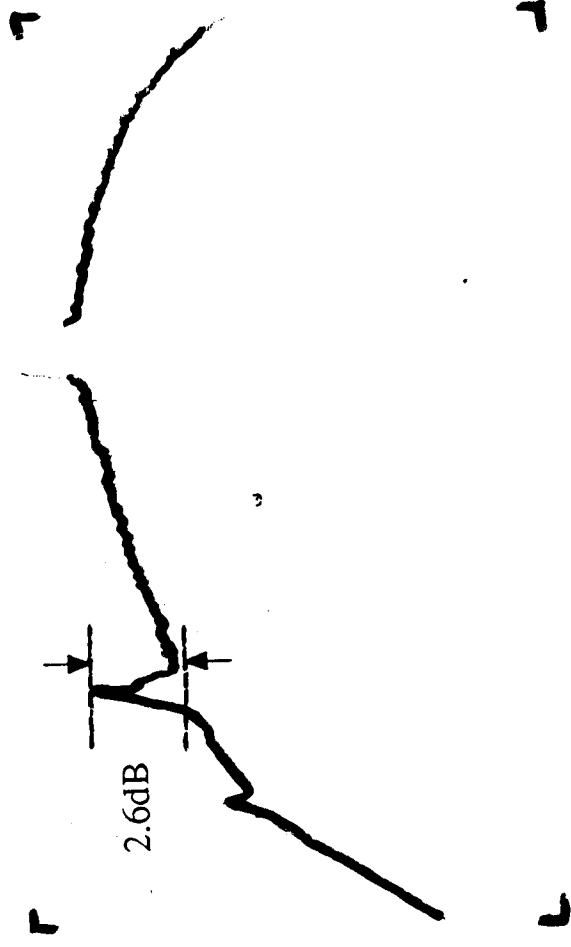
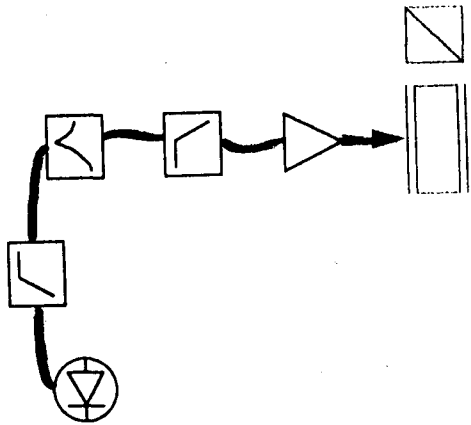
T_s = ratio input SNR to output SNR
can be maintained

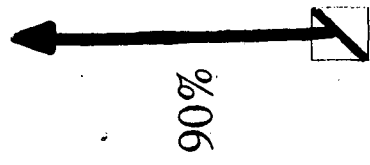
for normal large gain amplifier $T_s < 0.5$

$$T_s = \frac{SNR_{in}}{SNR_{out}}$$



beam splitter = 10 %





T

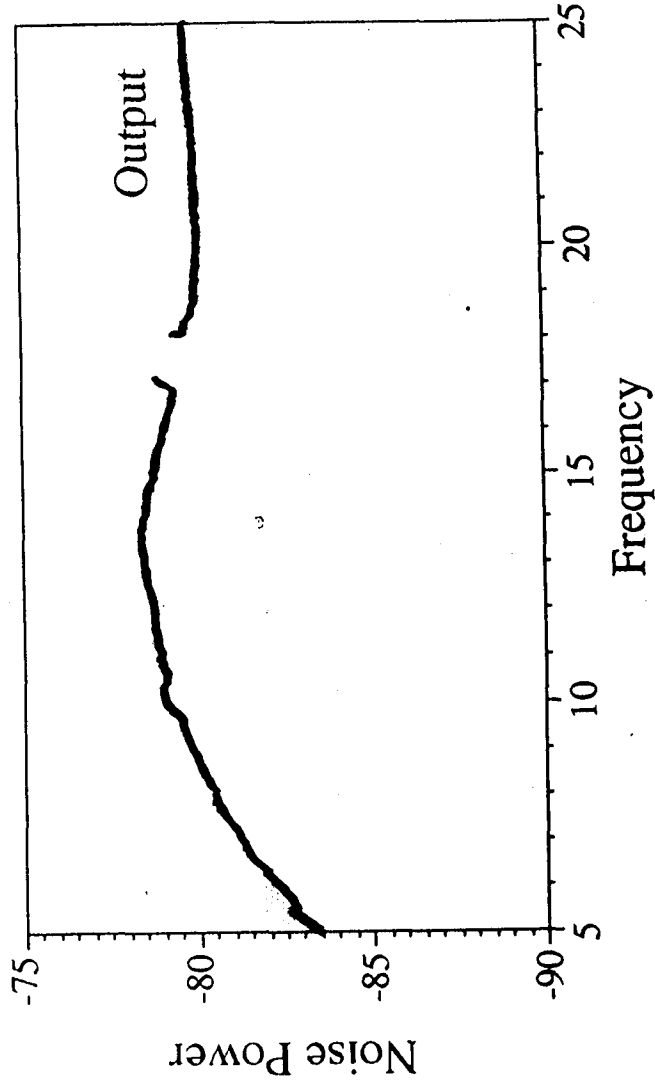
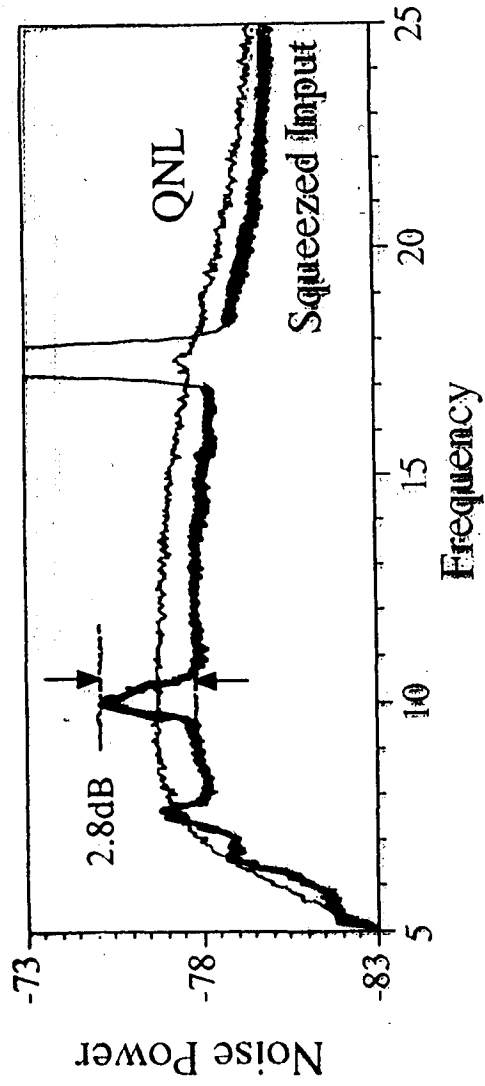
T

S

T

T

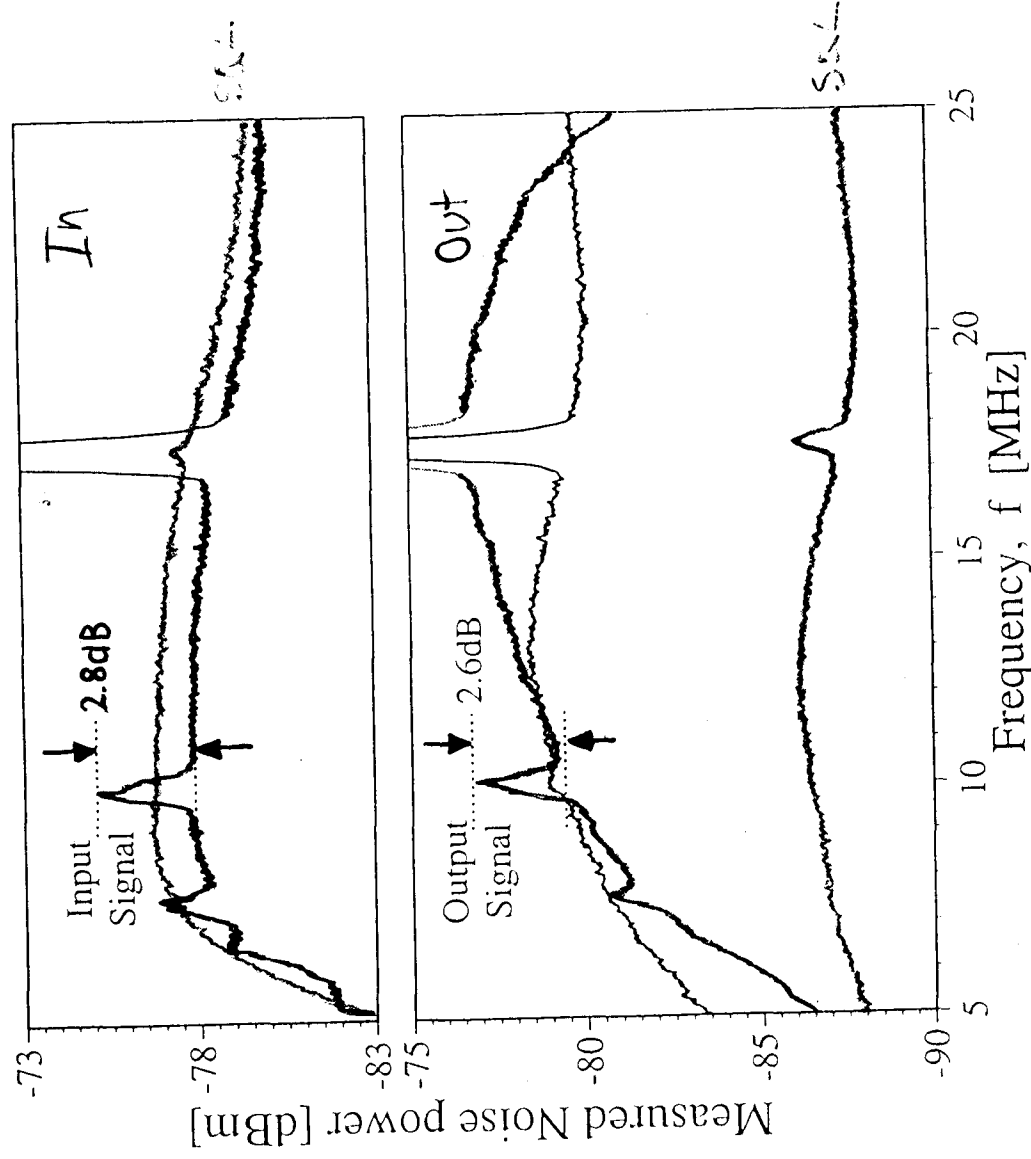




The crucial test:

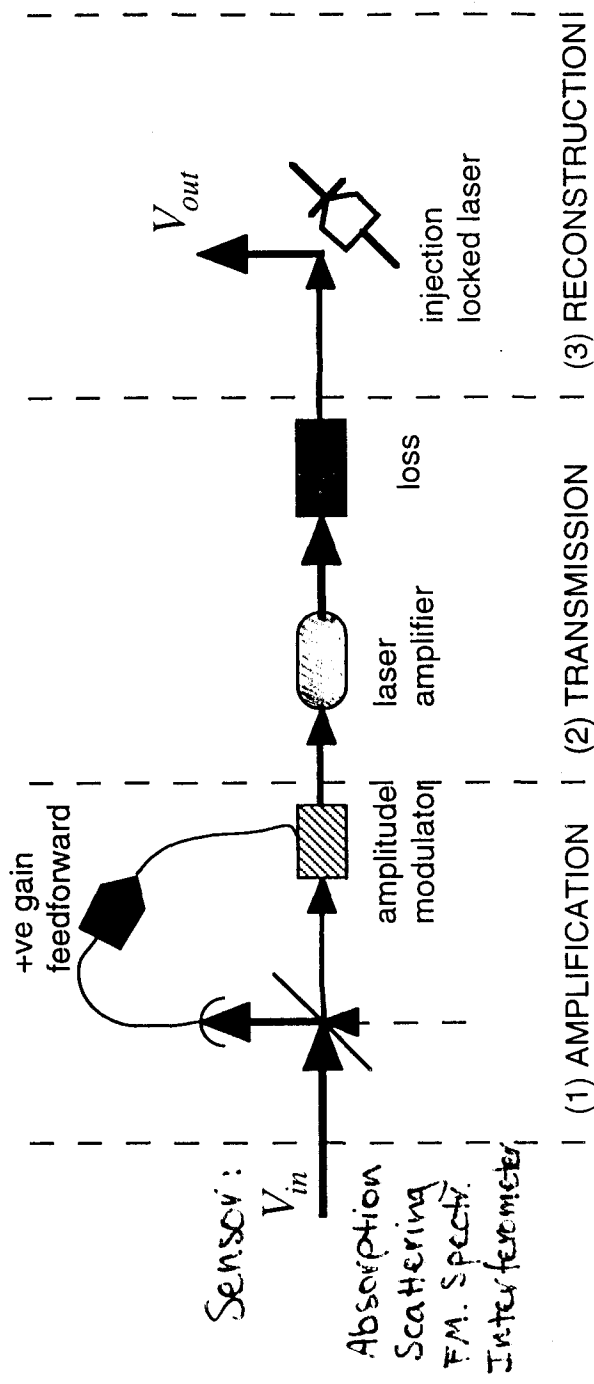
even with squeezed light the SNR

can be maintained



**Remaining technical problem:
get better in-loop photodetector**

Robust Transmission



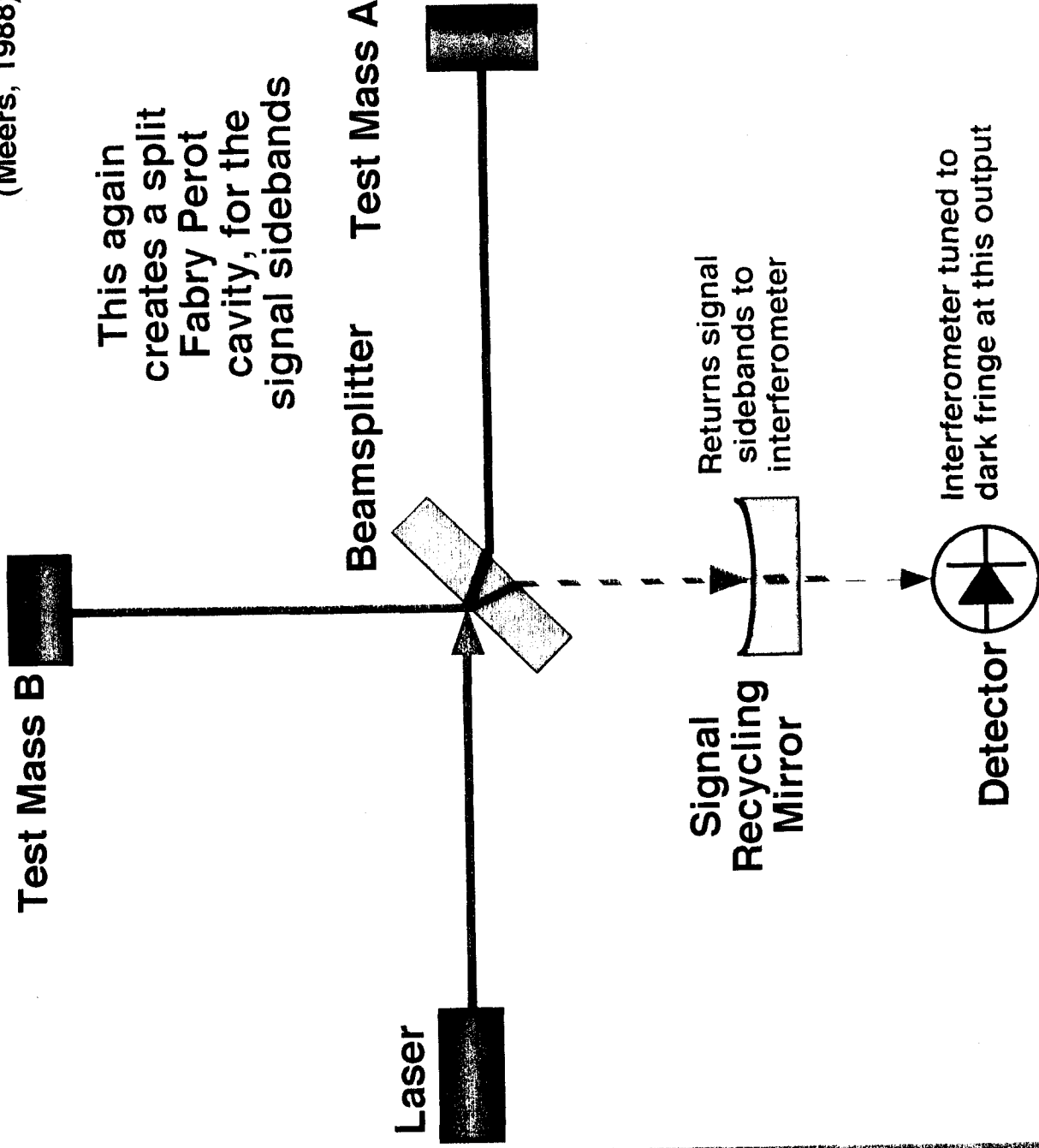
- (1) Feedforward loop amplifies signals whilst deamplifying carrier (only additional noise due to detector efficiency).
- (2) Laser amplifier compensates for transmission loss (signal well above QNL so small noise penalty)
- (3) Injection locking deamplifies signals whilst amplifying carrier (if pump noise suppressed only additional noise due to internal laser losses)

Satisfies criteria for QND

Signal Recycling



(Meers, 1988)



Resonant effect - increased GW sensitivity at frequencies of interest, lower sensitivity elsewhere.

Synchronises the coupling of signal sidebands into the output beam so that the resultant electric field builds up. Optimal response is obtained when the SRC is impedance matched for the signal sidebands.

SRC can be tuned to optical carrier (broadband) or one sideband (tuned) or both sidebands (doubly resonant).

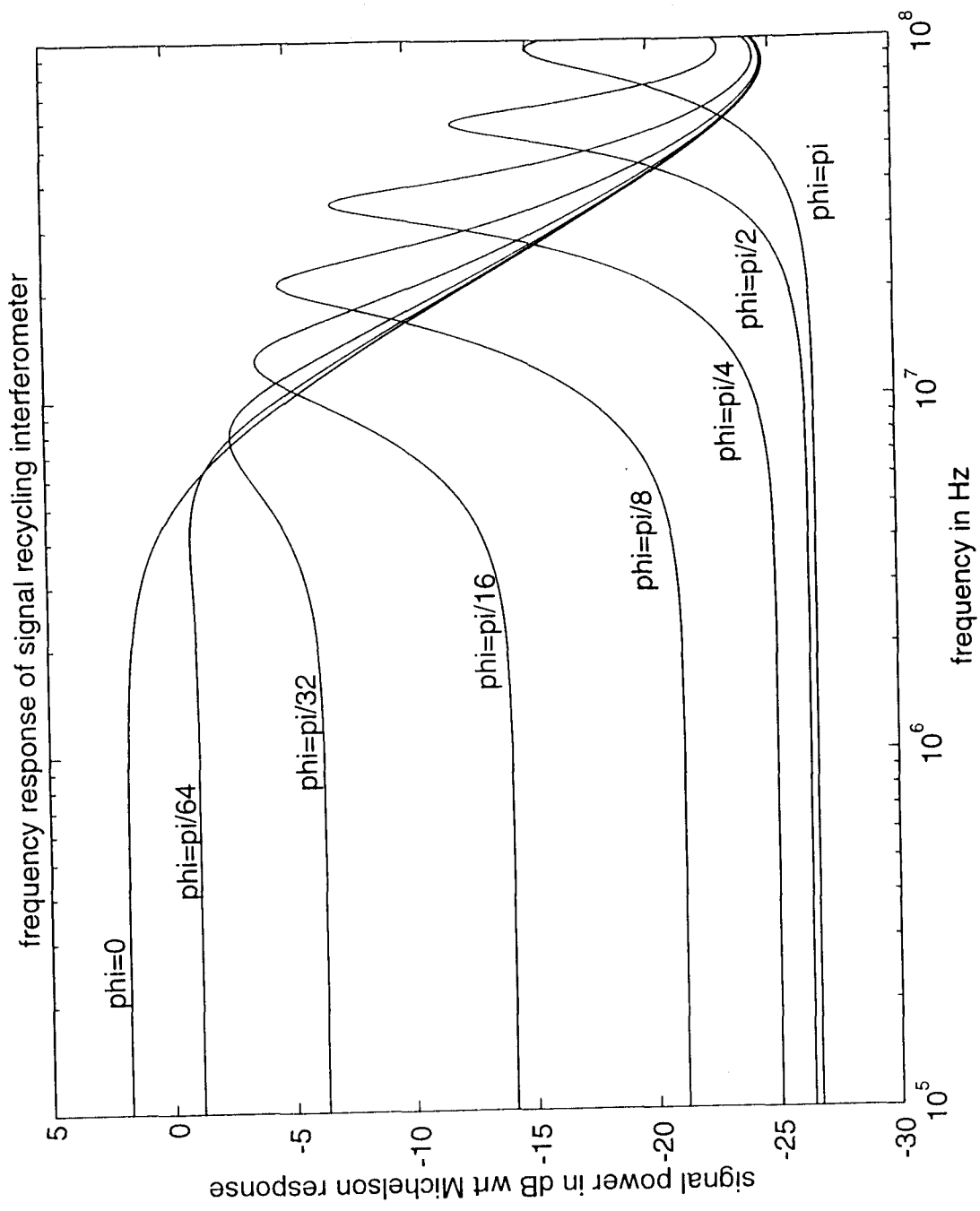
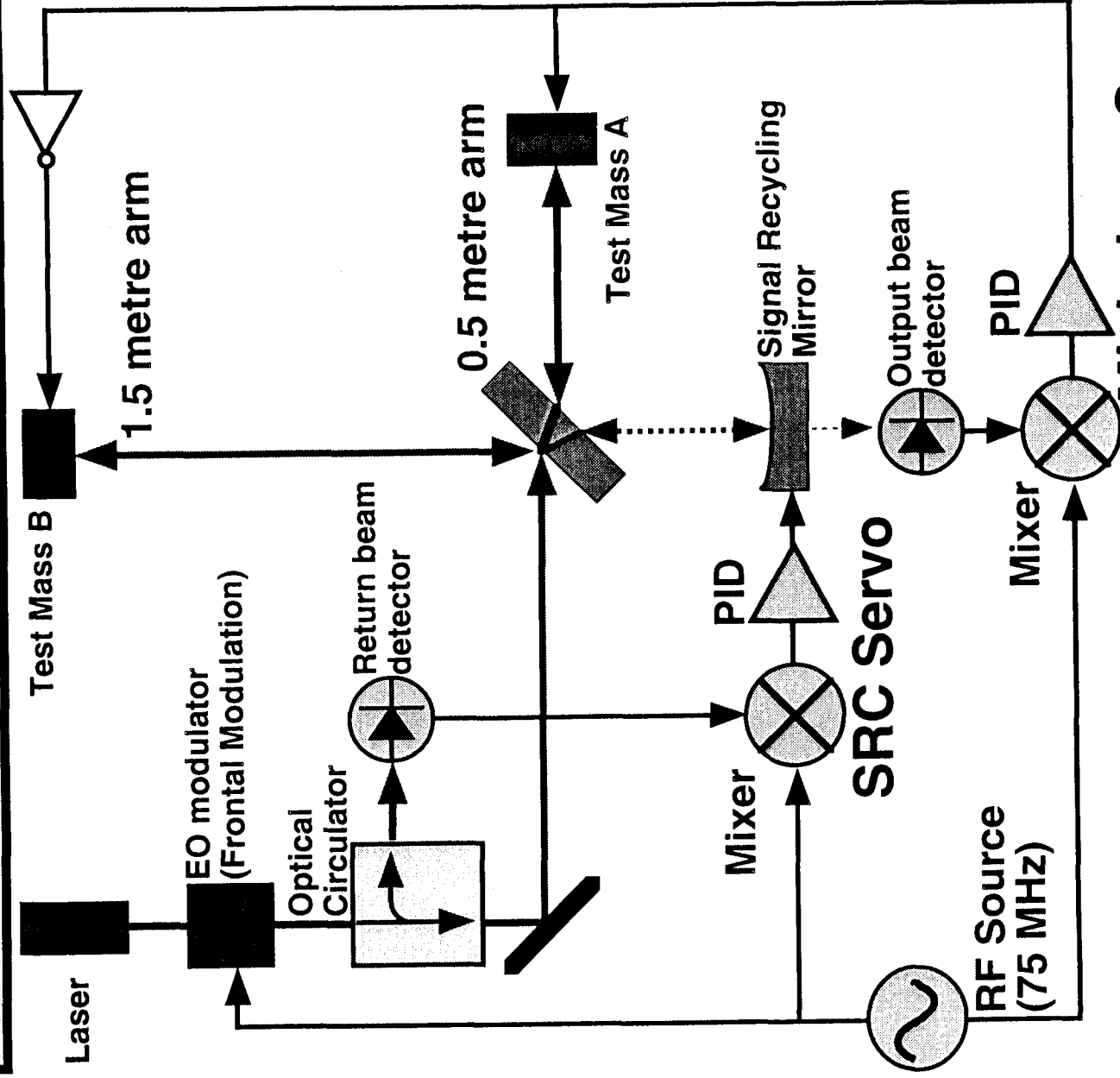
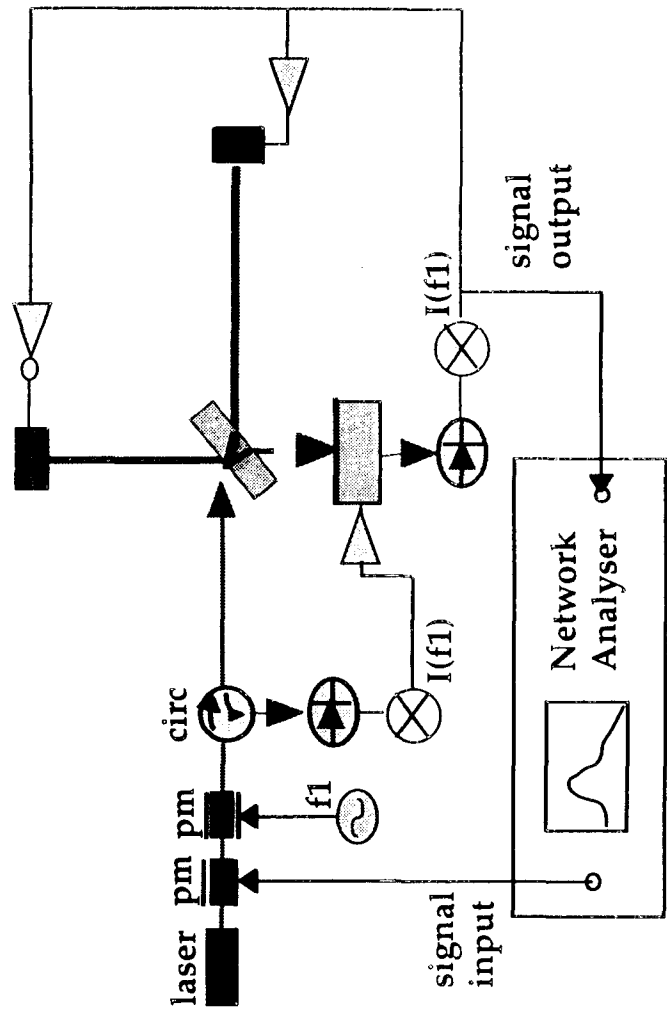


figure (3)

Orthogonalising two error signals



Michelson Servo
When the arm lengths differ by 1 metre, the two optical outputs provide orthogonal error signals to lock the SRC resonance and Michelson dark fringe independently.



signal recycling layout

Figure 4

Figure 6A

Raw Analyser data

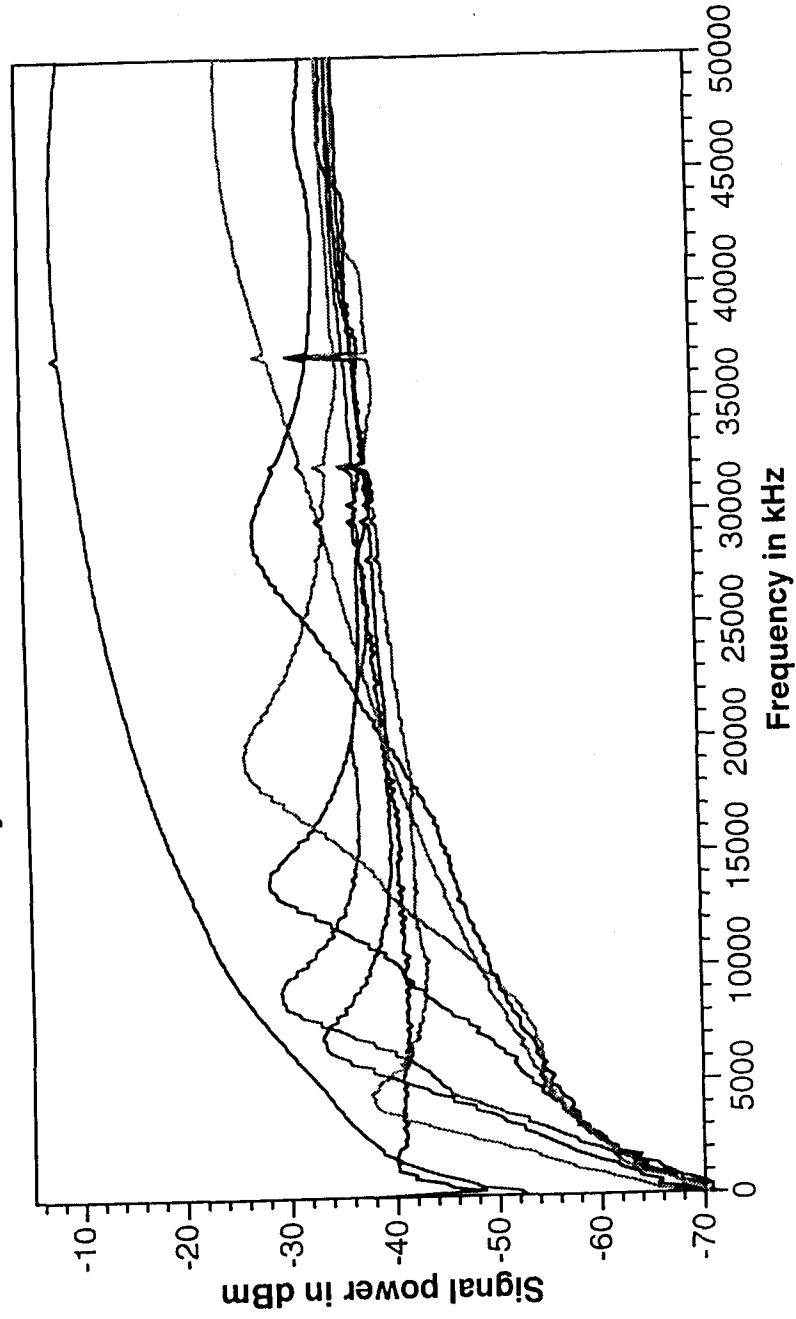
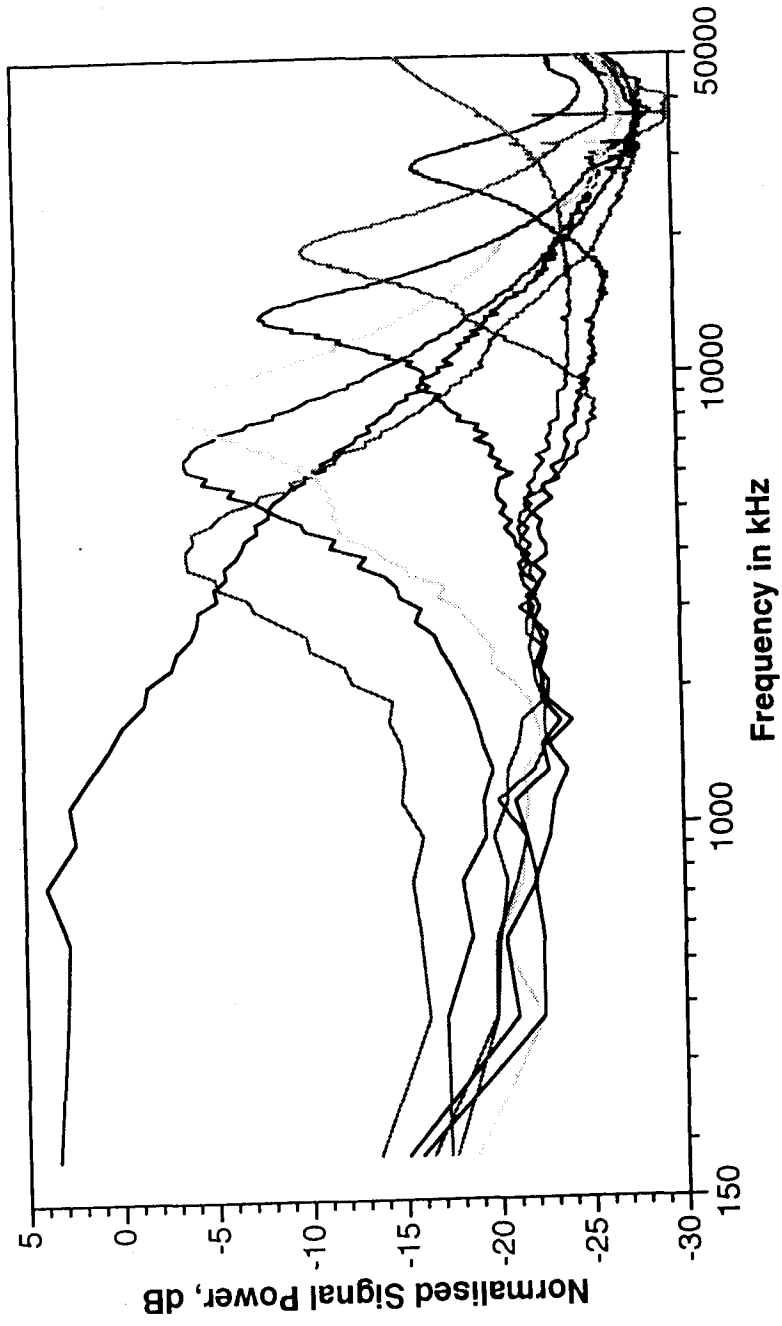


Figure 6B

Analyser Data normalised to the simple Michelson response



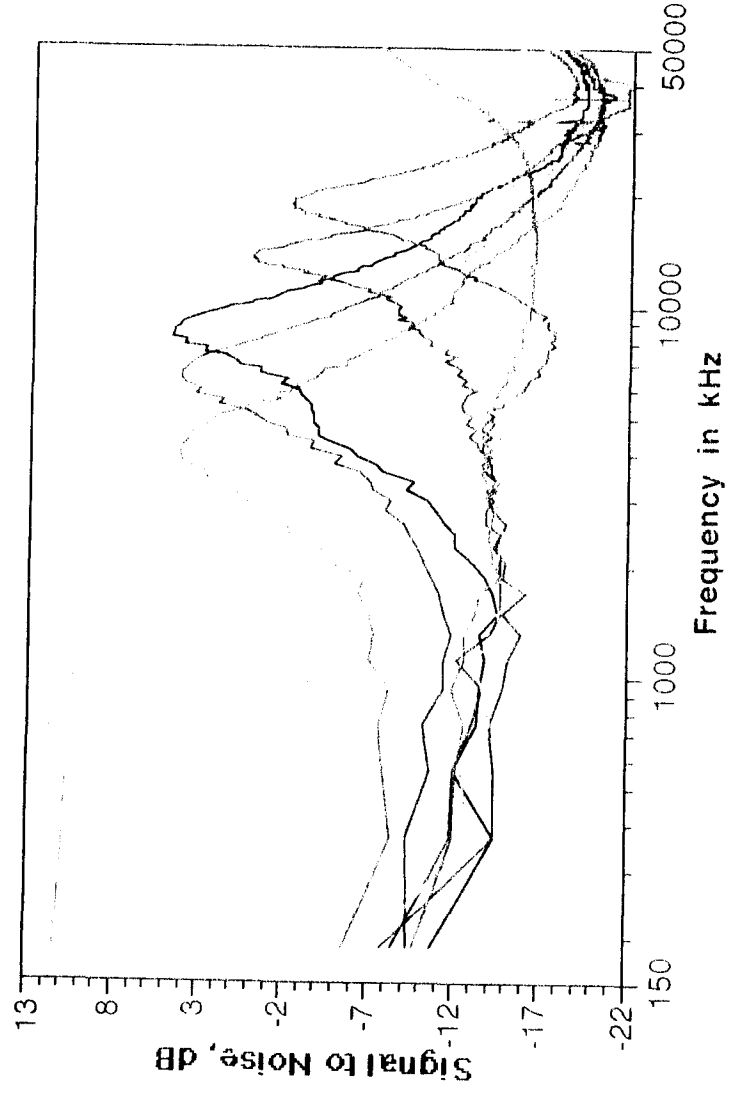
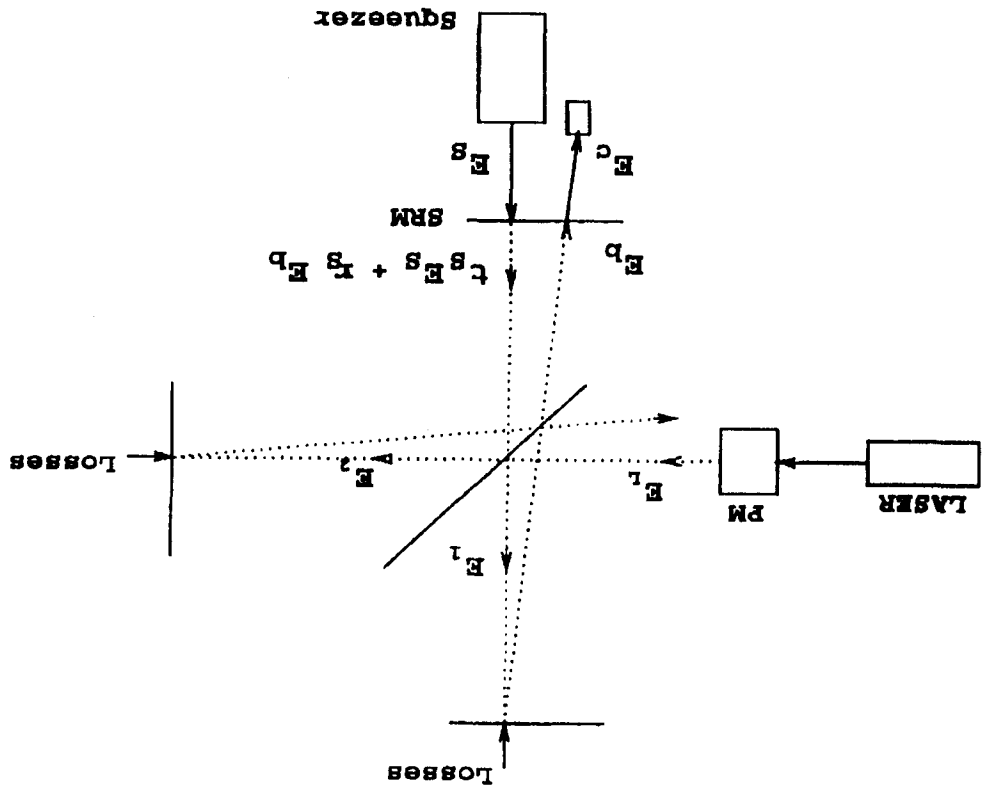


Figure 2B: The differential phase frequency response of the signal recycling interferometer for various detuning from broadband (trace (a)) to anti resonant (trace(h)).

WYOUT For ANALYSIS Signal Recycling



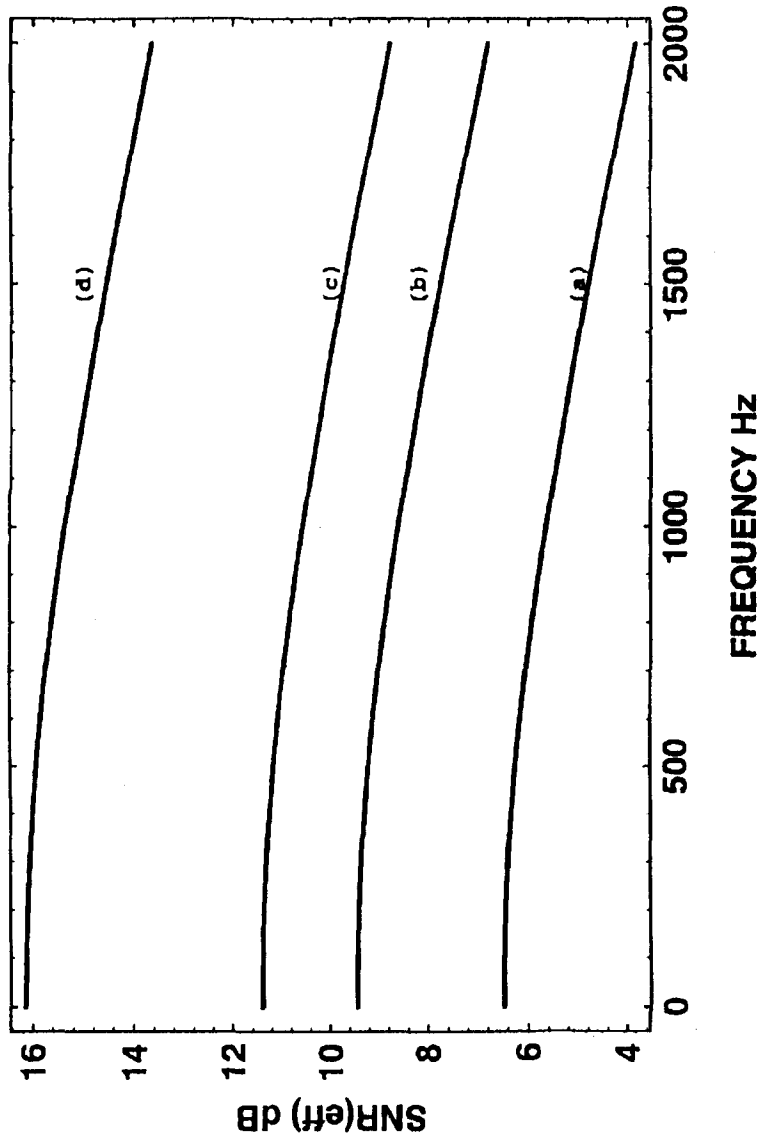
SQUEEZING IN A FABRY PEROT MODULATED SIGNAL RECYCLED LASER RESONATOR

Chakravartty et al, 1997

Fig 1

Fig 2

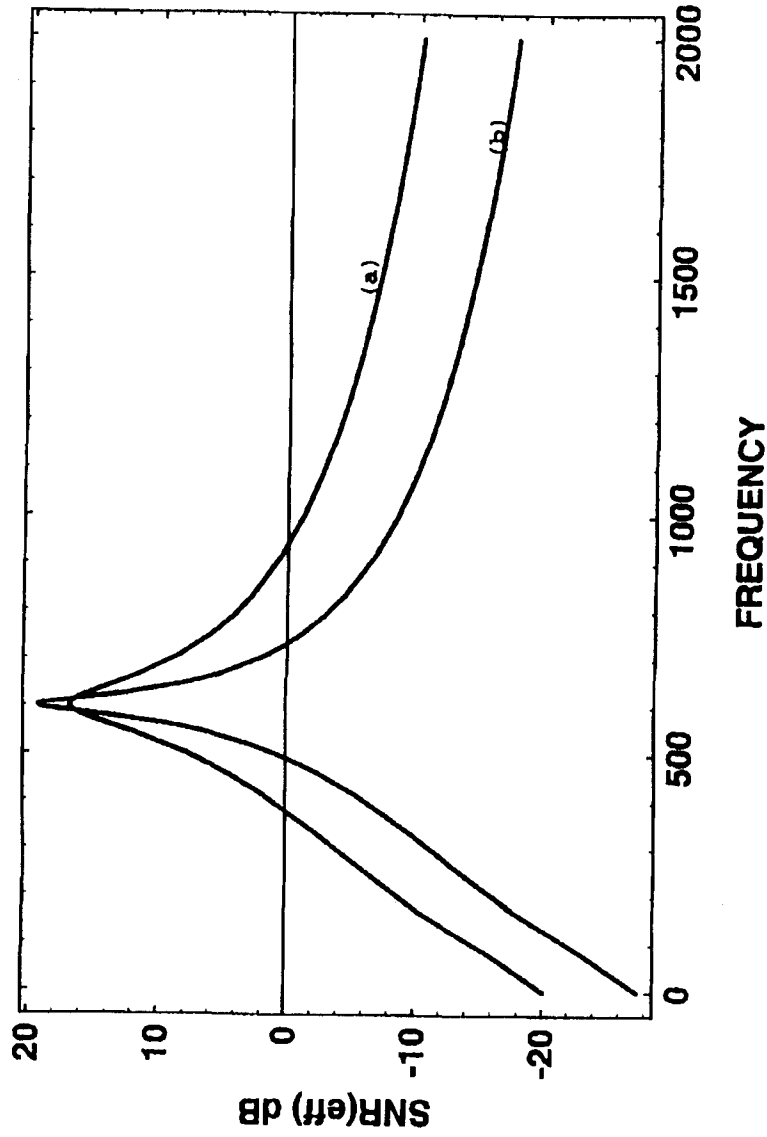
BROADBAND DUAL RECYCLING



- (a) Vacuum noise input $R_{SN} \ll R_{noise}$
- (b) 3dB squeezing overcomp loc
- (c) 5dB squeezing
- (d) 10dB squeezing

Fig 4

Narrow band (Tuned) Signal Recycling



(a) Vacuum input

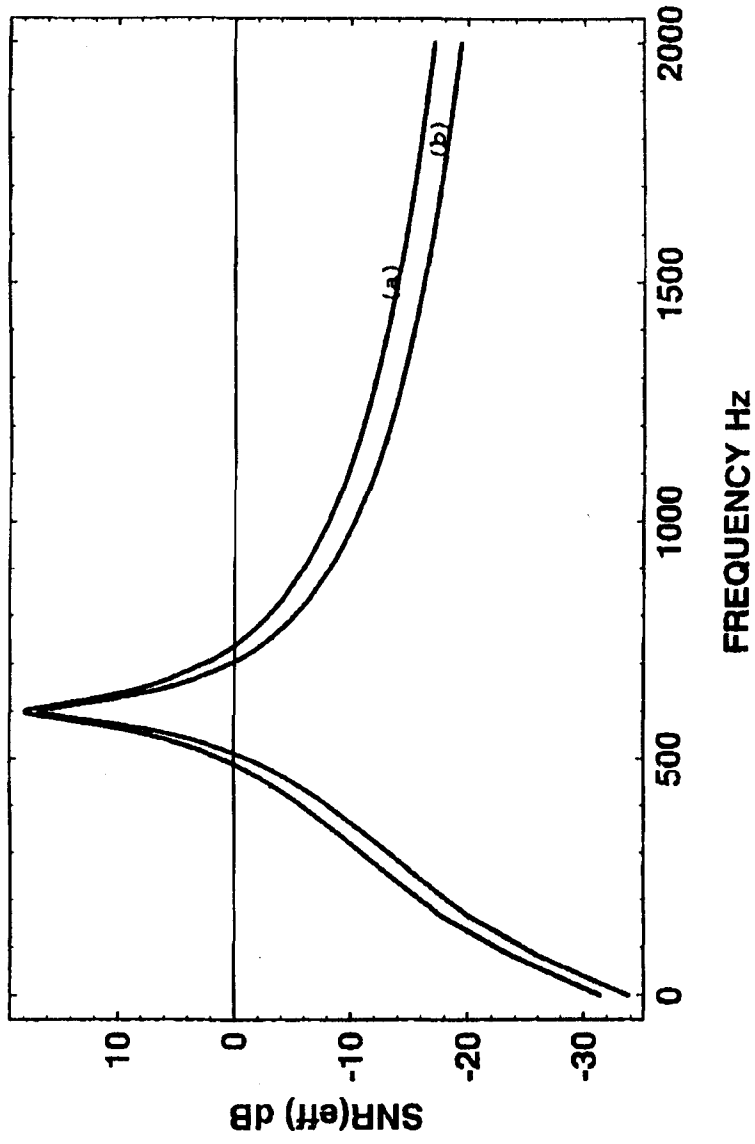
Overcoupled.

(b) 10 dB Squeezing, optimised at tuning peak

Note Reduction in SNR away from peak

Fig 7

Tuned Recycled Signal Reception



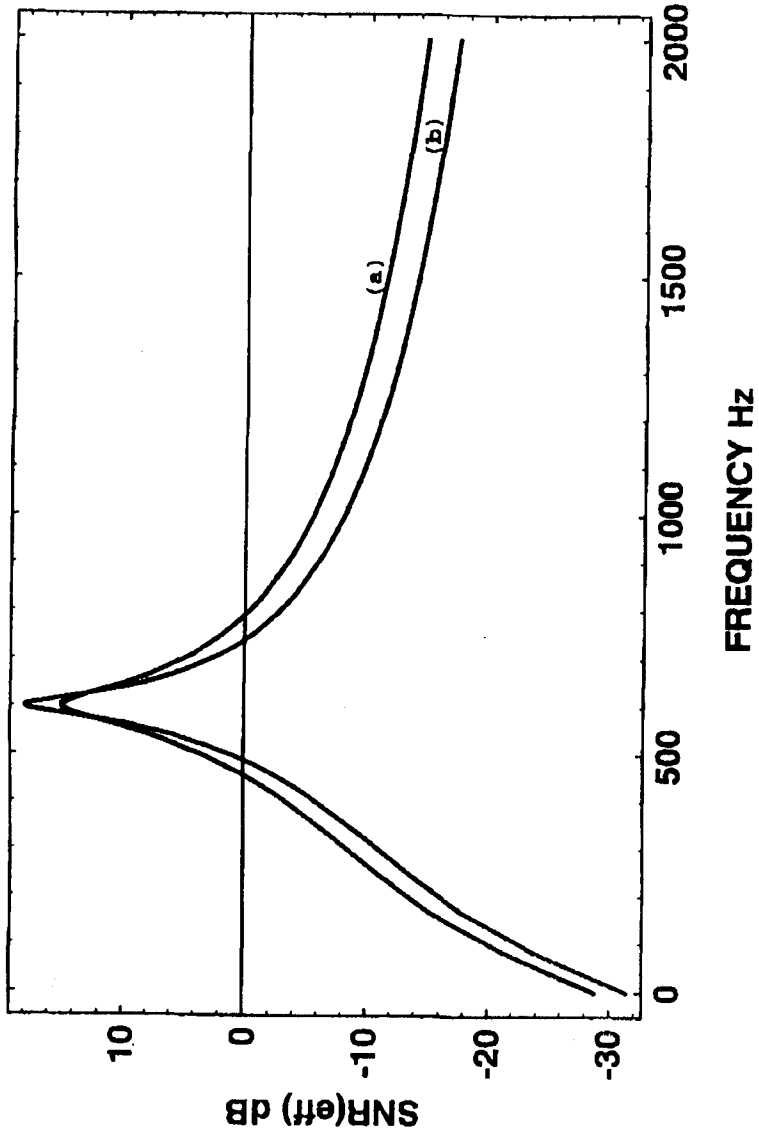
Impedance matched

(a) Vacuum

(b) 10dB Squared optimum at tuning peak.

Fig 8

Tuned Receiver



Impedance matched case

(a) 10 dB Squeezed optimised at 100 Hz

(b) vacuum
- Slight reduction at peak
- enhanced bandwidth.