

# *Advanced Interferometer Topologies*

**A series of 3 ‘tutorials’.**

**by**

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## *Advanced Interferometer Topologies 1*

- Introduction and background
- Light recycling: increasing the signal

## *Advanced Interferometer Topologies 2*

- Recycling continued

## *Advanced Interferometer Topologies 3*

- The Sagnac alternative
- Interferometer control and choice of configuration

Ref.: D. McClelland, Aust.J.Phys**48**, 953 (1995) and refs. therein  
J. Mizuno, A. Rüdiger, R. Schilling, W. Winkler and K.  
Danzmann, Opt.Comm.**138**, 383 (1997) and refs. therein.

## *Advanced Interferometer Topologies 1*

- 1.1 Basic Noise Sources in an interferometer
- 1.2 What is Photon Noise?
- 1.3 Dark Fringe Operation and Modulation
- 1.4 Power Recycling
- 1.5 Narrowbanding
- 1.6 Resonant or Synchronous Recycling
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## *Advanced Interferometer Topologies 2*

2.1 Distortions in Dual Recycling

2.2 Compound Doubly Resonant Recycling

2.3 Resonant Sideband Extraction (RSE)

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3.1 The Sagnac Configuration

3.2 Length Sensing and Alignment sensing Issues

3.3 Sensitivity Theorem

3.4 Choice of Configuration

# *Advanced Interferometer Topologies 1*

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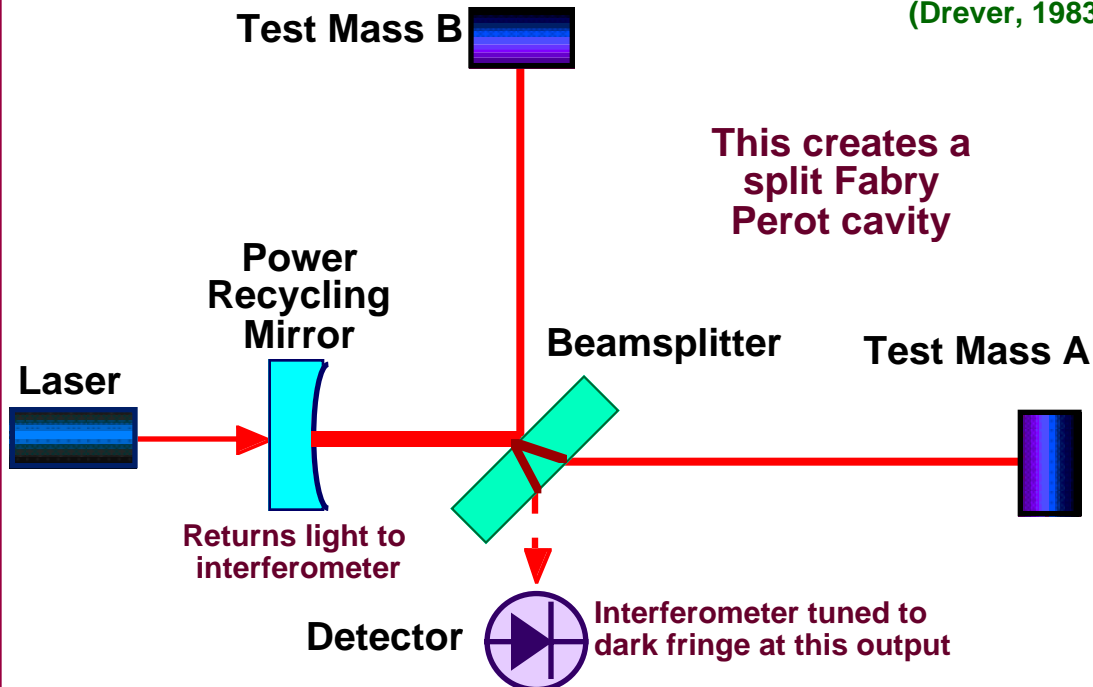
## **1.1 Basic Noise Sources in an interferometer**

- seismic  
pendulum thermal  
mirror thermal  
violin  
PHOTON
- Assume there is some interesting frequency band in which the dominant noise is photon, or shot, noise
- Standard Layout

# Power Recycling



(Drever, 1983)



By proper choice of mirror reflectivity and position, light is impedance matched into the cavity.  
Optical power builds up by a factor  $\sim 1 / \text{Loss}$ .

Signal sidebands at detector increase in proportion to the field amplitude, and sensitivity is thereby improved.

Broadband effect - equivalent to a simple increase in input laser power. (Largest factor to date  $\sim 300$ )

Requirements: Stabilise laser relative to Power Recycling Cavity (PRC)

Superpolished low loss mirrors, low distortion substrates

Match arm lengths and mirror curvatures

Control mirror tilt (all mirrors); Laser mode-cleaning

**Beware thermal lensing in beamsplitter !**

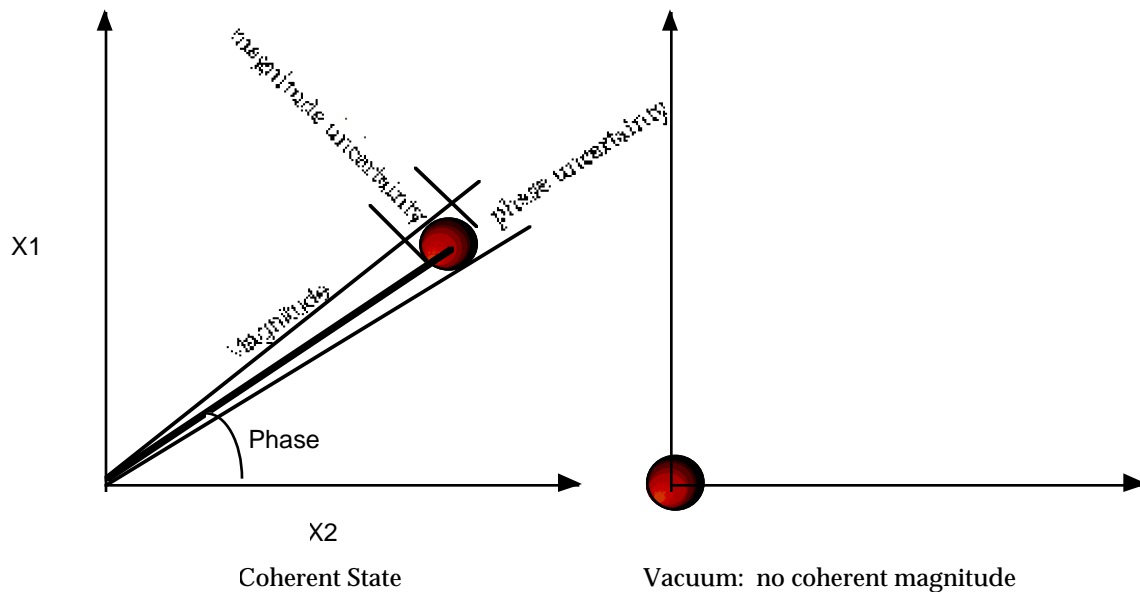
Arm length and arm storage

## 1.2 What is Photon Noise?

- arises from the application of the Heisenberg Uncertainty Principle to light
- wave picture: amplitude - phase uncertainty

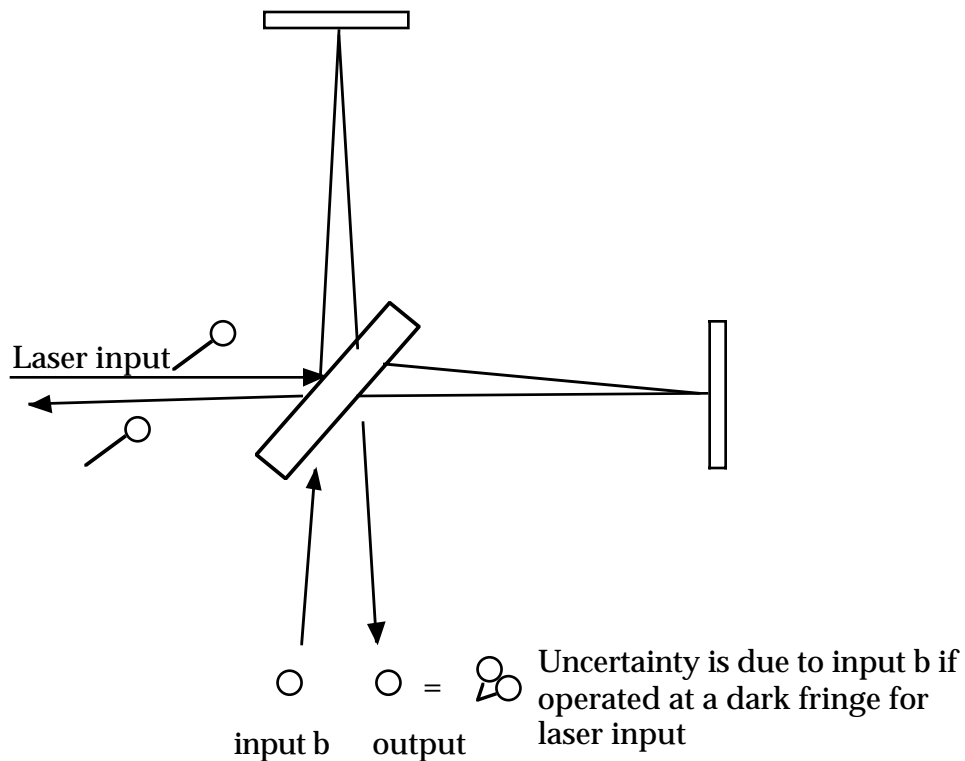
particle picture - coherent state and Poissonian statistics

fluctuation in the measurement of  $N$  photons is given by  $\sqrt{N}$ .



$$\Delta X1 \Delta X2 \geq 1/4$$

- Interferometers and vacuum noise



- Caves (1981) PRL, PRD

$$\Delta x_{pc} = c / (2b\omega\sqrt{N} \cos(\phi/2))$$

$$h_{pc} = (1/4\pi bL) (2\pi h c\lambda/I_o)^{1/2}$$

- frequency distribution of this noise  
amp. spectral density is white.

- Accompanied by Radiation pressure fluctuations
  - fluctuation in photon number in interferometer arm leads fluctuating radiation pressure on end mirrors
  - fluctuating pressure is anticorrelated between the arms producing momentum and hence position uncertainty
  - $\sim \sqrt{N}$
  - rolls off as  $1/f$

$$h_{rp} = 2\pi h(b/mL) (I_o / hc\lambda)^{1/2} (\Delta f_{bw})^{-1}$$

- minimum uncertainty, equivalent to the standard quantum limit, is reached at an optimum power

## 1.3 Dark Fringe Operation and Modulation

- operation on a dark fringe allows common mode cancellation of noise on the input beam
- also minimises the signal BUT maximises signal to noise ratio
- in fact, need some light to overcome electronic noise --> slight offset from dark fringe or use a phase modulation technique.
- Phase modulation methods:
  - internal
  - frontal or in-line or Schnupp
  - external (Mann et al, Phys.Lett.A.)



## Essentially:

- phase modulate at an rf frequency at which the laser is photon noise limited
- modulation sidebands are then incident on photodetector along with interferometer output
- detector output is demodulated at the rf frequency
- signal then consists of:
  - (a) dc output beating with the noise (audio sidebands) on the rf frequency
  - (b) the constant rf component beating with noise (audio sidebands) on the carrier and any gw signal present
- operation close to a dark fringe for the carrier minimises both the carrier (suppressing (a)) and its audio sidebands revealing the gw signal.
- Required intensity in the rf sidebands depends on:
  - level of waist light hitting photodetector
  - level of electronic noise.

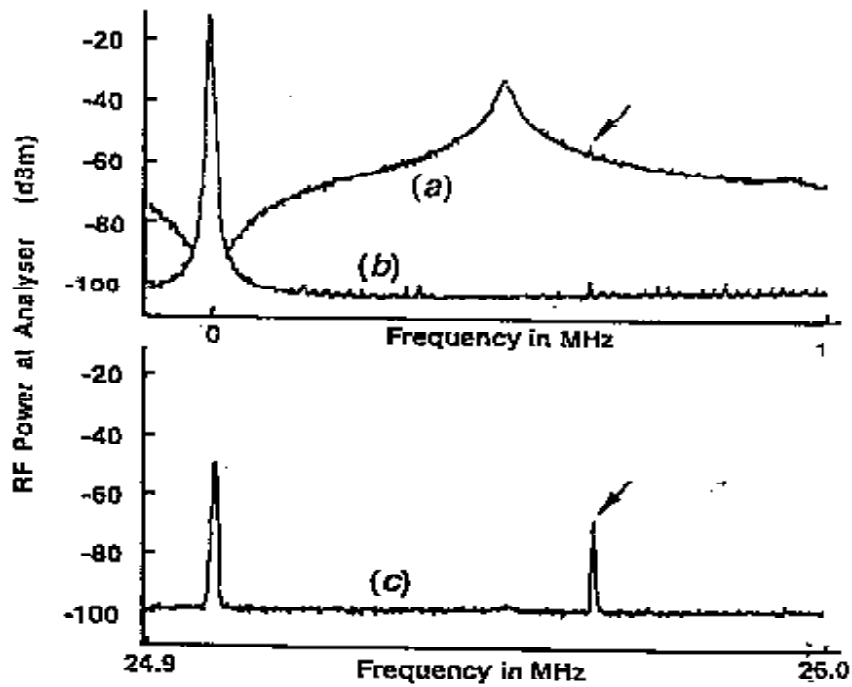


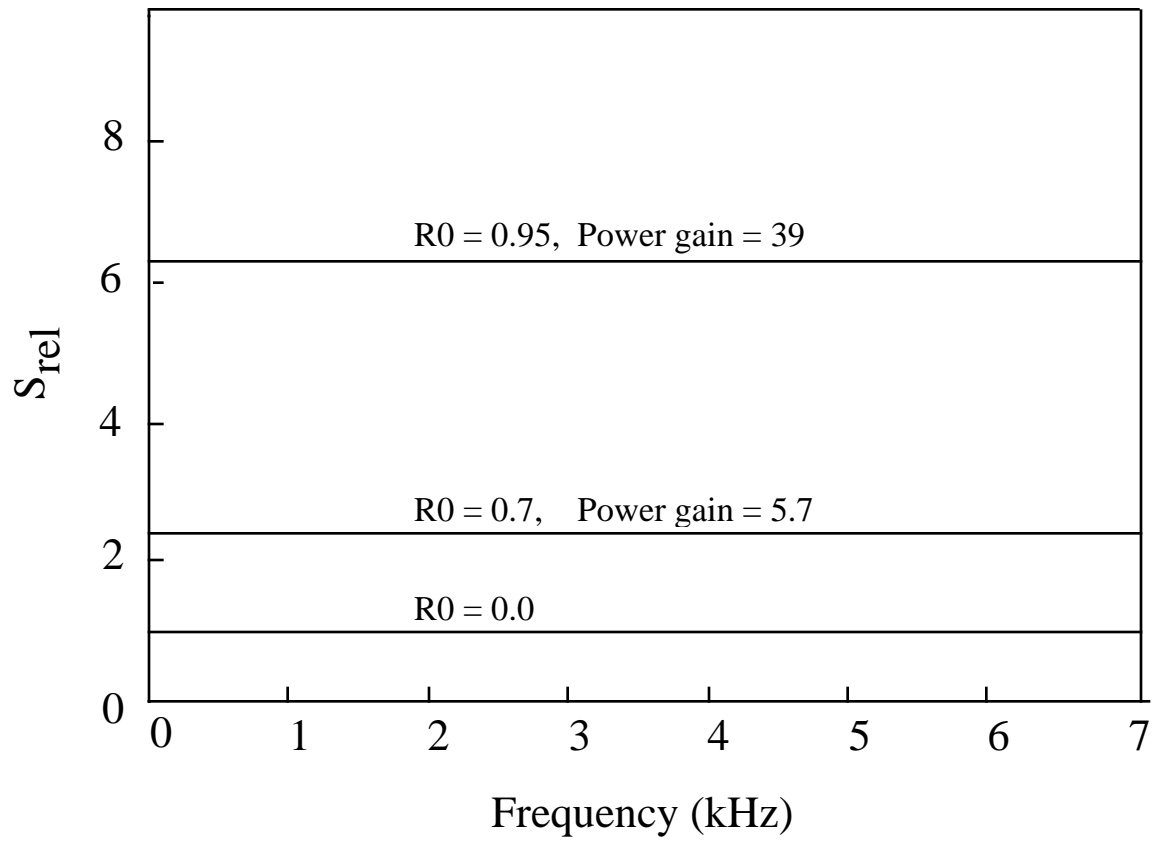
Fig. 6.

Top: signal barely visible against classical noise  
Bottom: internal modulation exhumes signal from noise  
(from Stevenson, Gray, Bachor, McClelland, Appl. Opt)

## 1.4 Power Recycling

- With dark fringe operation, energy conservation requires that the incident light power at carrier frequency is either absorbed/scattered in the interferometer OR reflected back toward the laser and wasted.
- Drever (1983) realised that this waist light could be recycled: insert a mirror to re-reflect the waist light back into the interferometer.
- This technique, coined Power Recycling, is now standard

See Fig.7 layout; Fig.8 - power  
buildup and improvement in response



- Experimental results to date:

First: Garching (1988); recycling factor of

Best: MIT (1997); recycling factor of 460

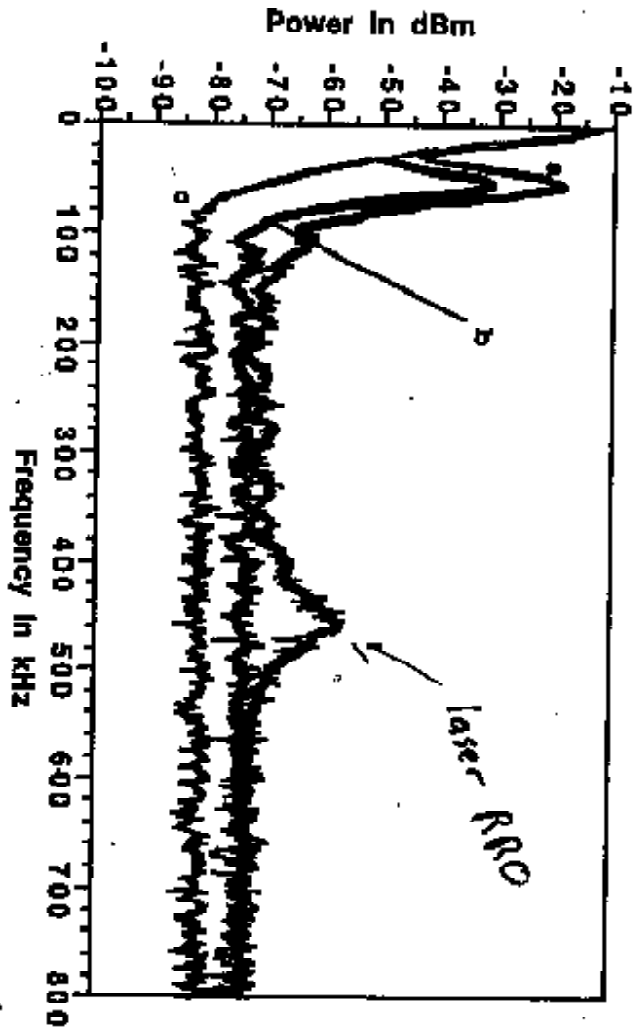
- Maximum buildup occurs when the input is ‘impedance matched’ into the interferometer. ie transmission of the power recycling mirror is set equal to the losses inside the instrument.

If the same buildup can be achieved without arm cavities, similar sensitivity is reached.

LIGO/Virgo/TAMA choose to employ both arm cavities with power recycling to reduce the thermal loading on the main beam splitter.

GEO600, ACIGA opt to impedance match without arm cavities (see later).

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~ spectrum with power recycling (power build up  $\approx 35$ )

~ spectrum with simple Michelson

~ Electronic noise floor

Signal power at 50kHz increased by  $\approx 6$  (16dB)

E:

## 1.5 Narrowbanding

- Standard layout, detector bandwidth is determined by arm cavity pole ( $\sim 1/\text{storage time}$ ) which is the same for the carrier and the signal sidebands.
- Typically 500 - 1000 Hz.
- Proposed PR factors ( $\sim 20 - 100$ ) have no impact on this.
- Narrowbanding techniques trade off bandwidth to achieve better sensitivity
- Techniques include:
  - resonant recycling (Drever, 1983)
  - detuned recycling (Vinet et al, 1988)
  - signal (dual) recycling (Meers, 1988)

## 1.6 Resonant or Synchronous Recycling

- because the gw strain reverses sign every half period, light should be stored in an interferometer arm for no longer than this, else imposed phase shift begins to decrease.
- Standard configuration: choose maximum gw frequency to be detected and set arm storage appropriately.
- Drever (1983) proposed that if the light leaving 1 arm after this time was directed into the perpendicular arm, the imposed phase shift would continue to increase.
- If this is done for 1 bounce before interference  $\implies$  Sagnac response
- Resonant recycling, as shown in Fig. 10, effectively forms a coupling cavity between the 2 arms, with the output extracted at BS1, now acting as a semi reflecting mirror.

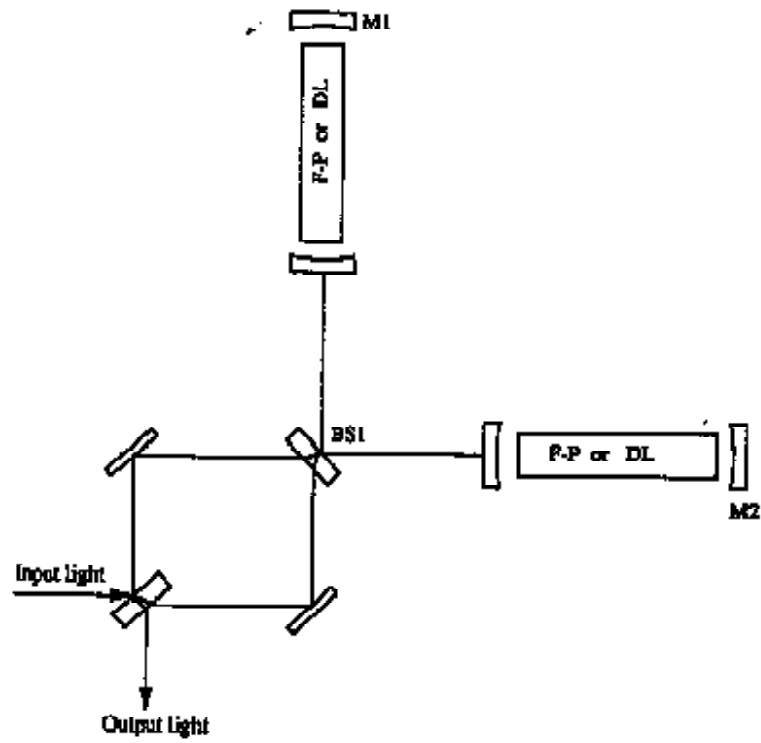


Fig. 4. Optical arrangement for resonant recycling.

Fig 10.

- optimum for a only 1 gw frequency with a cavity type response around this peak --> tuned or narrow banded instrument.
- Peak response can only be altered by changing arm cavity storage.
- Exhibits ‘wavefront healing’ as any spatial distortions, manifested by light scattered into higher order spatial modes, are resonantly suppressed (see Dual recycling)
- No experiments have been performed.

## 1.7 Signal (Dual) Recycling

- Meers in 1988 suggested recycling the signal exiting the interferometer.

see Fig. Mirror Ms reflects the signal back into the interferometer, where it adds coherently. As such, it forms a split optical cavity, known as the signal recycling cavity (SRC), with the reflecting elements in the interferometer arms

- Peak response occurs at the frequency to which the SRC is tuned, with response rolling off approx. with the bandwidth of the SRC.

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- Dual Recycling Interferometer

