The polarization RSE tabletop interferometer

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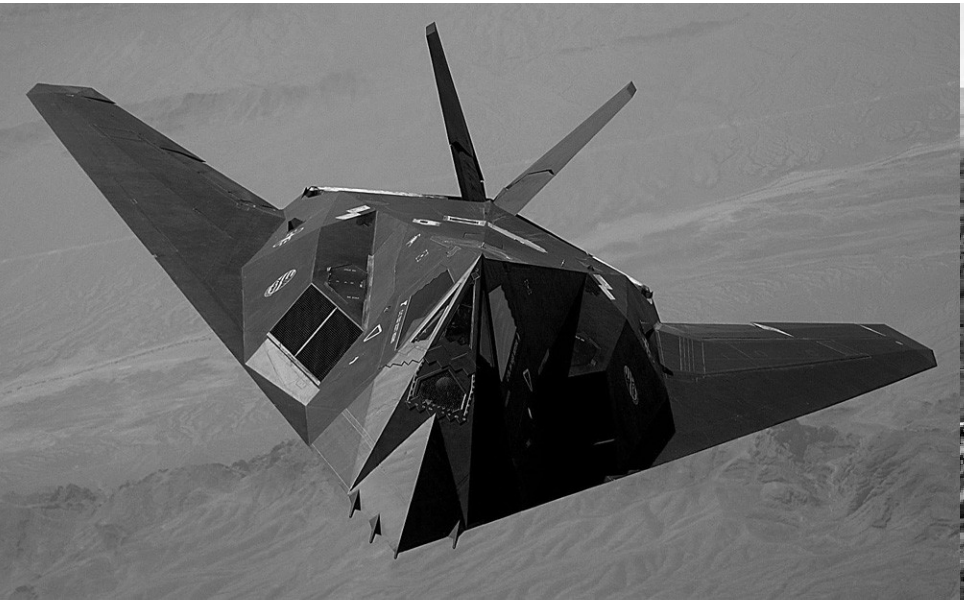
First, a teaser…



Q: What do these things have in common?

Polarization RSE is a frequency tunable (RSE) interferometer configuration that uses the control and readout schemes of first generation (non-RSE) detectors.

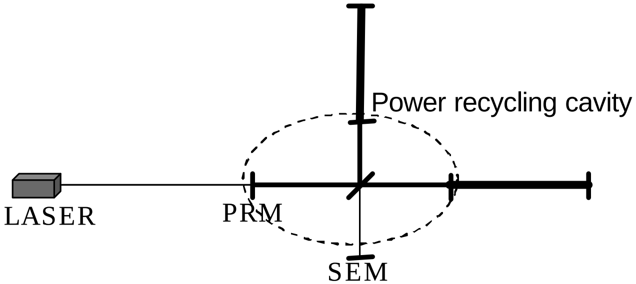
- Why is this important?
- How does it work?
- Results from the prototype
- Conclusion

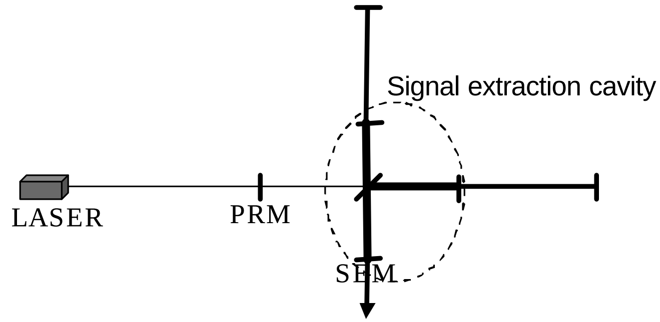
Motivation

- Resonant Sideband Extraction (RSE) will be used in second generation detectors
  - Reduces thermal load on the beamsplitter
  - Allows frequency tuning of the interferometer
  - Can beat the standard quantum limit at certain frequencies
- Control schemes and signal readout used with 1st generation detectors are inadequate for conventional RSE configurations.
  - More cross-coupling of length degrees of freedom in RSE configurations
  - Modified control schemes use extra RF sidebands which greatly increase detector bandwidth requirements
  - Imbalance of RF sidebands in detuned configurations make RF readout susceptible to excess technical noise (although may allow reduction in quantum noise)
  - detuning requires reoptimizing demodulation phases
- Goal: create and demonstrate a frequency tunable (RSE) configuration compatible with the readout and control schemes of first generation detectors.

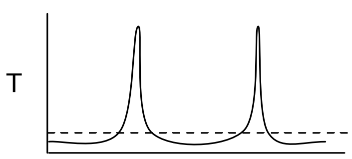
RSE overview

- High-finesse arm cavities increase the circulating power in the arms, thereby increasing the sensitivity and decreasing the detector bandwidth.
- “Power” exits the beamsplitter at the bright port
- “Signals” exit the beamsplitter at the dark port
- The signal extraction mirror (SEM) causes a resonant buildup for signals in the signal extraction cavity, which makes the arm cavities’ near mirrors look transparent to the signal sidebands in the arms allowing them to exit the interferometer before being averaged out during the long storage time of the arm cavities.
- The signal extraction cavity length determines the SEC resonant frequency and hence the peak frequency of the detectors response.
- The reflectivity of the signal extraction mirror sets the bandwidth of the resonance and hence the bandwidth of the detectors response.
- BONUS The optical feedback produced by the signal extraction mirror couples radiation pressure and shot noise allowing the standard quantum limit to be exceeded in a narrow frequency band.





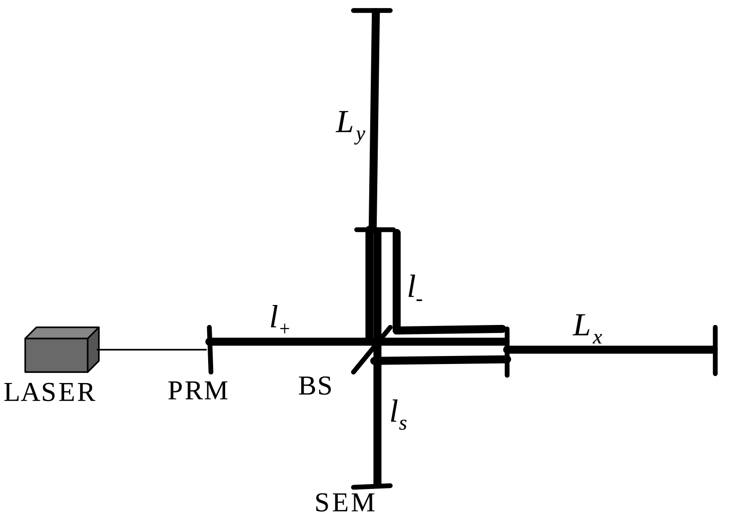
SEC transmission is increased on resonance



Cavity tuning $f = 2wl / c$

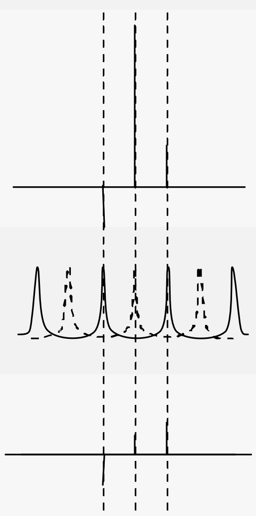
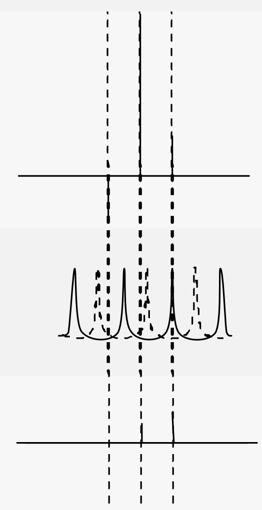
Challenges of (other) RSE configurations

- RSE requires 5 lengths to be controlled vs 4 for 1st generation detectors.
  - Complicates lock acquisition: requiring several intermediate steps with the parameters of the control scheme reoptimized at each step
  - Degrades the control matrix: The control signals for the first 4 degrees of freedom have a sensitivity to the additional 5th degree of freedom
  - This requires an extra modulation frequency, and greatly increases bandwidth requirements for the photodetector



Challenges of (previous) RSE configurations

- Sideband imbalance at dark port
  - Allows noise from phase modulation to couple to the output signal

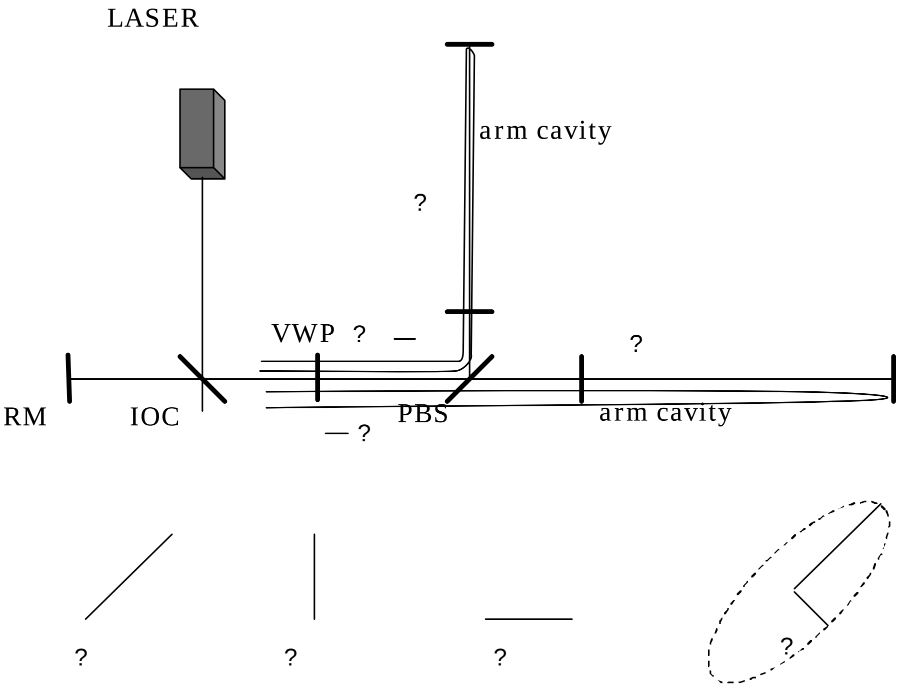
	Non-RSE or broadband RSE configuration	Detuned configuration
Input spectrum: Carrier with phase modulated RF sidebands		
Transmission of signal extraction cavity to dark port		
Spectrum at dark port:	excess carrier light produces only harmless phase noise	excess carrier light produces amplitude noise because of sideband imbalance

Addressing the challenges of RSE

- Conventional RSE
  - Various control schemes have been developed and tested on table-top experiments
  - Development of high-power, high-frequency photodetectors for RSE is proceeding
  - DC readout to avoid excess noise in RF readout has been proposed
  - various tuning mechanism that can tune the interferometer to a discrete set of frequencies have been shown
- Polarization RSE

Polarization RSE interferometer

- The light in the arms is split by polarization.
- All of the light (power and signal) exits the polarizing beam splitter through the same port.
- A differential signal causes a change in the polarization state of the output light
- The output power is in the “bright polarization” the output signal is in the “dark polarization”
- A single recycling mirror recycles both the power and the signal
- A variable waveplate in the recycling cavity shifts the resonant frequency for the signal relative to the power.
- An off-axis input-output coupler provides polarization-dependant coupling to the recycling cavity so the power and signal cavity finesse can be different
- RSE is realized in an interferometer with only 4 degrees of freedom



Mathematical model of the interferometer

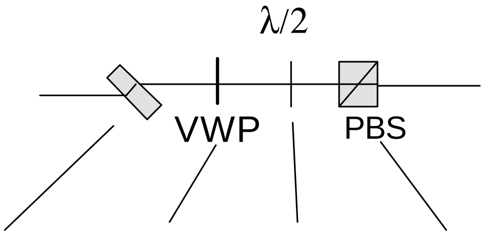
- Use Jones calculus to describe the round-trip operator for the recycling cavity
- Expand the steady-state solution for cavity buildup with respect to length deviations to calculate the length sensing signals
- Investigate the static response with imperfect polarizing optics to determine if they can couple noise to the output port
- Calculate the gravitational wave response from the product of the carrier buildup in the arms, the Michelson transfer function, and the sideband buildup in the recycling cavity.

Mathematical model of the interferometer

- Use Jones calculus to describe the round-trip operator for the recycling cavity
  - Represent polarized light as a vector
  - Represent optical elements as 2x2 matrices
  - Multiply matrices to compute Jones matrix for a round-trip in the recycling cavity

$$\hat{s} = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \quad \hat{p} = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} \quad \begin{bmatrix} -1 & 0 \\ 0 & 1 \end{bmatrix}$$



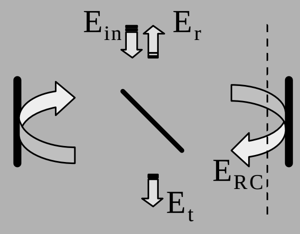
$$RT = \begin{bmatrix} it_p & 0 \\ 0 & it_s \end{bmatrix} \begin{bmatrix} e^{if} & 0 \\ 0 & 1 \end{bmatrix} \frac{1}{\sqrt{2}} \begin{bmatrix} -1 & 1 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}$$

Mathematical model of the interferometer

- Expand the steady-state solution for cavity buildup with respect to length deviations to calculate the length sensing signals
- Results illuminate the choice of signals for length sensing

$$\frac{\vec{E}_r}{E_0} \approx \begin{bmatrix} p_0 + p_1 \\ s_0 + s_1 \end{bmatrix} \qquad \frac{\vec{E}_t}{E_0} \approx t_{IOC}^{-1} \begin{bmatrix} -ip_0 - ip_1 \\ c_0 + c_1 + c_2 - is_0 - is_1 \end{bmatrix}$$

steady-state cavity model



$$\vec{E}_{RC} = RT\,\vec{E}_{RC} + r_{IOC}\,\vec{E}_{in}$$

$$\vec{E}_r \approx r_{IOC}\vec{E}_{RC}$$

$$\vec{E}_t \approx i\,t_{IOC}\,\vec{E}_{in} - i\,t_{IOC}\vec{E}_{RC}$$

	dark polarization	bright polarization
carrier	$p_0 \equiv \frac{it_{IOC,s}t_{IOC,p}e^{i2b}}{\left(1+t_{IOC,p}^2 e^{i2b}\right)r_{IOC,s}^2}\left[\left(\frac{1+r_{nm}}{1-r_{nm}}\right)kL\,d\Phi_- + df_-\right]$	$s_0 \equiv \frac{1}{r_{IOC,s}^2} + \frac{i}{r_{IOC,s}^2}\left[\left(\frac{1+r_{nm}}{1-r_{nm}}\right)kL\,d\Phi_+ + df_+\right]$
1^{st} order sidebands	$p_1 \equiv \frac{it_{IOC,s}t_{IOC,p}e^{i2b}df_-}{\left(1+t_{IOC,p}^2 e^{i2b}\right)r_{IOC,s}^2}$	$s_1 \equiv \frac{1}{r_{IOC,s}^2} + \frac{idf_+}{r_{IOC,s}^2}$

Length sensing

- Polarization RSE length sensing signals are analogous to those of a (non-RSE) power-recycled Fabry-Perot Michelson interferometer
- A control scheme analogous to that of TAMA300 can be used

Polarization RSE field amplitudes

	dark polarization	bright polarization
carrier	$p_0 \equiv \frac{it_{IOC,s}t_{IOC,p}e^{i2b}}{\left(1+t_{IOC,p}^2 e^{i2b}\right)r_{IOC,s}^2}\left[\left(\frac{1+r_{nm}}{1-r_{nm}}\right)kLd\Phi_- + df_-\right]$	$s_0 \equiv \frac{1}{r_{IOC,s}^2} + \frac{i}{r_{IOC,s}^2}\left[\left(\frac{1+r_{nm}}{1-r_{nm}}\right)kLd\Phi_+ + df_+\right]$
1st order sidebands	$p_1 \equiv \frac{it_{IOC,s}t_{IOC,p}e^{i2b}df_-}{\left(1+t_{IOC,p}^2 e^{i2b}\right)r_{IOC,s}^2}$	$s_1 \equiv \frac{1}{r_{IOC,s}^2} + \frac{idf_+}{r_{IOC,s}^2}$

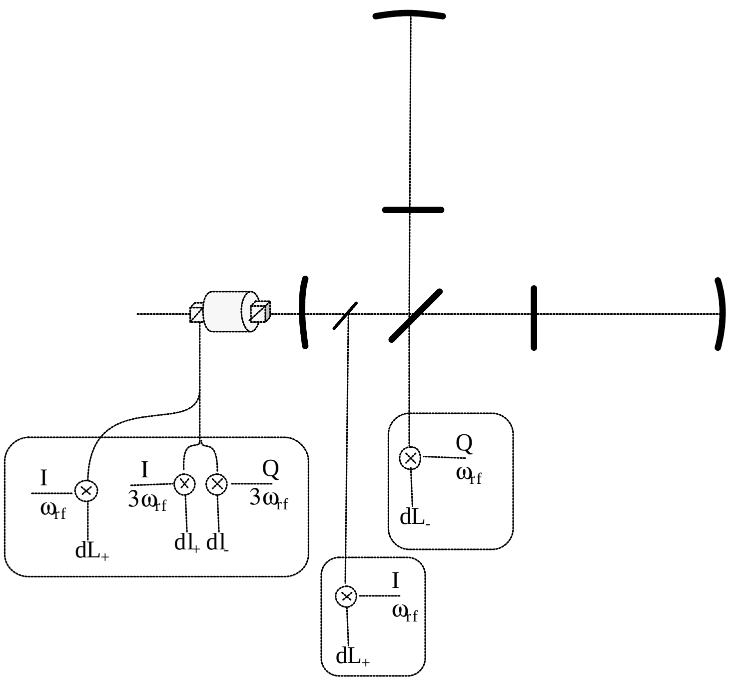
TAMA300 field amplitudes

	dark port	bright port
carrier	$E_0 \equiv \frac{it_{PRM}}{\left(1-r_{PRM}^2\right)}\left[\left(\frac{1+r_{nm}}{1-r_{nm}}\right)kLd\Phi_- + df_-\right]$	$E_0 \equiv r_{PRM} - \frac{t_{PRM}^2}{\left(1-r_{PRM}\right)^2}\left[\left(\frac{1+r_{nm}}{1-r_{nm}}\right)kLdF_+ + df_+\right]$
1st order sidebands	$E_1 \equiv \frac{it_{PRM}df_-}{\left(1-r_{PRM}\right)^2}\cos a - \frac{it_{PRM}\left(1+idf_+\right)}{\left(1-r_{PRM}\right)^2}\sin a$	$E_1 \equiv r_{PRM} - \frac{t_{PRM}^2\left(1+idf_+\right)}{\left(1-r_{PRM}\right)^2}\cos a + \frac{t_{PRM}^2 df_-}{\left(1-r_{PRM}\right)^2}\sin a$

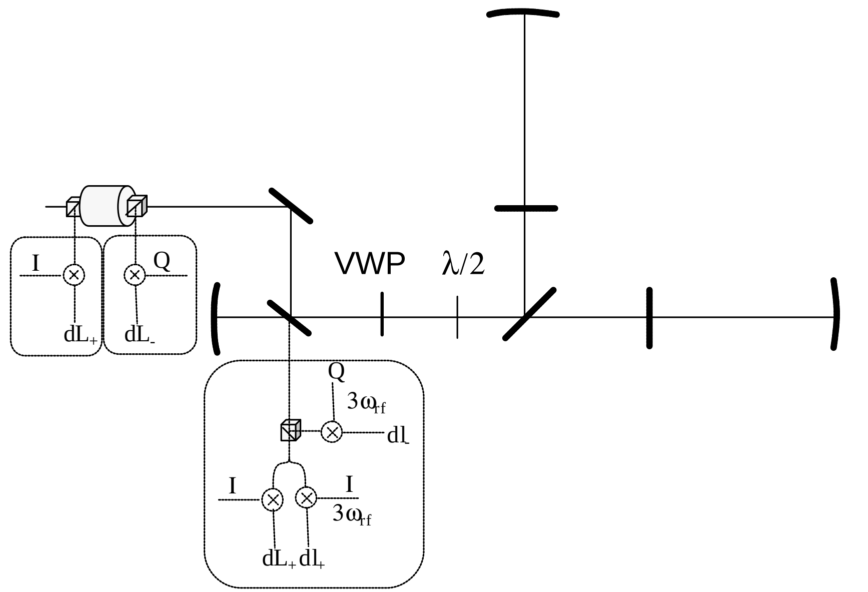
Length sensing

- Signal detection ports are analogous to those of first generation detectors

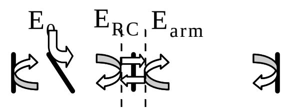
TAMA300

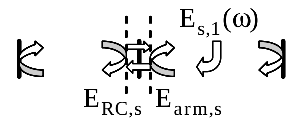


polarization RSE



Theoretical response (to GWs)

- Calculate the gravitational wave response from the product of
  - Carrier build in arms 

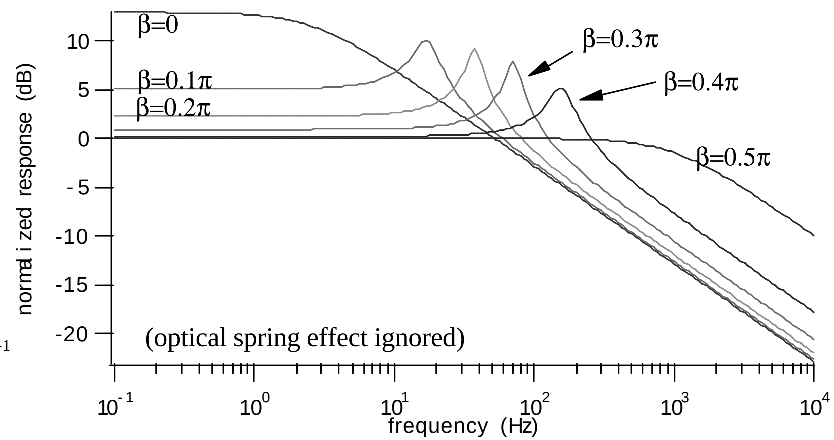
  - Conversion from carrier to sidebands by a GW $c_1(w) \equiv \frac{E_{s,1}(w)}{E_{cav}}$
  - Buildup of sidebands from arms in recycling cavity 

- Response is that of RSE

$$c_{PRSE}(w) = -r_{IOC}^2\, i(1+r_{nm})\frac{w_0}{w}\sin(wL/c)\,e^{iwL/c}\begin{bmatrix}0 & B\\ C & 0\end{bmatrix}$$

$$C = \left\{\frac{t_{nm}^2}{r_{nm}}e^{i2kLw/w_0} + \left[1 - e^{2iklw/w_0}\left(r_{nm} - \frac{t_{nm}^2}{e^{i2kLw/w_0} - r_{nm}}\right)\right.\right.$$

$$\left.\left.\times\ t_{IOC,s}^2\right]\left[1 - \left(r_{nm} + \frac{t_{nm}^2}{r_{nm}}\right)e^{i2kLw/w_0}\right]\right\}^{-1} \times \left(1 + \frac{1}{r_{nm}}e^{i2b}\,t_{IOC,p}^2\right)^{-1}$$



Theoretical response (to noise)

- Investigate the static response with imperfect polarizing optics to determine if they can couple noise to the output port
  - one round trip in the interferometer recycling cavity is described by

$$\begin{bmatrix} p' & s' \end{bmatrix} = \begin{bmatrix} RT_{11} & RT_{21} \\ RT_{12} & RT_{22} \end{bmatrix} \begin{bmatrix} p \\ s \end{bmatrix}$$

  - for deviation of parameters (wave plate angles, birefringence, etc.) about their nominal values, the resulting spurious signal has only 1 first order dependence, which is a static quantity

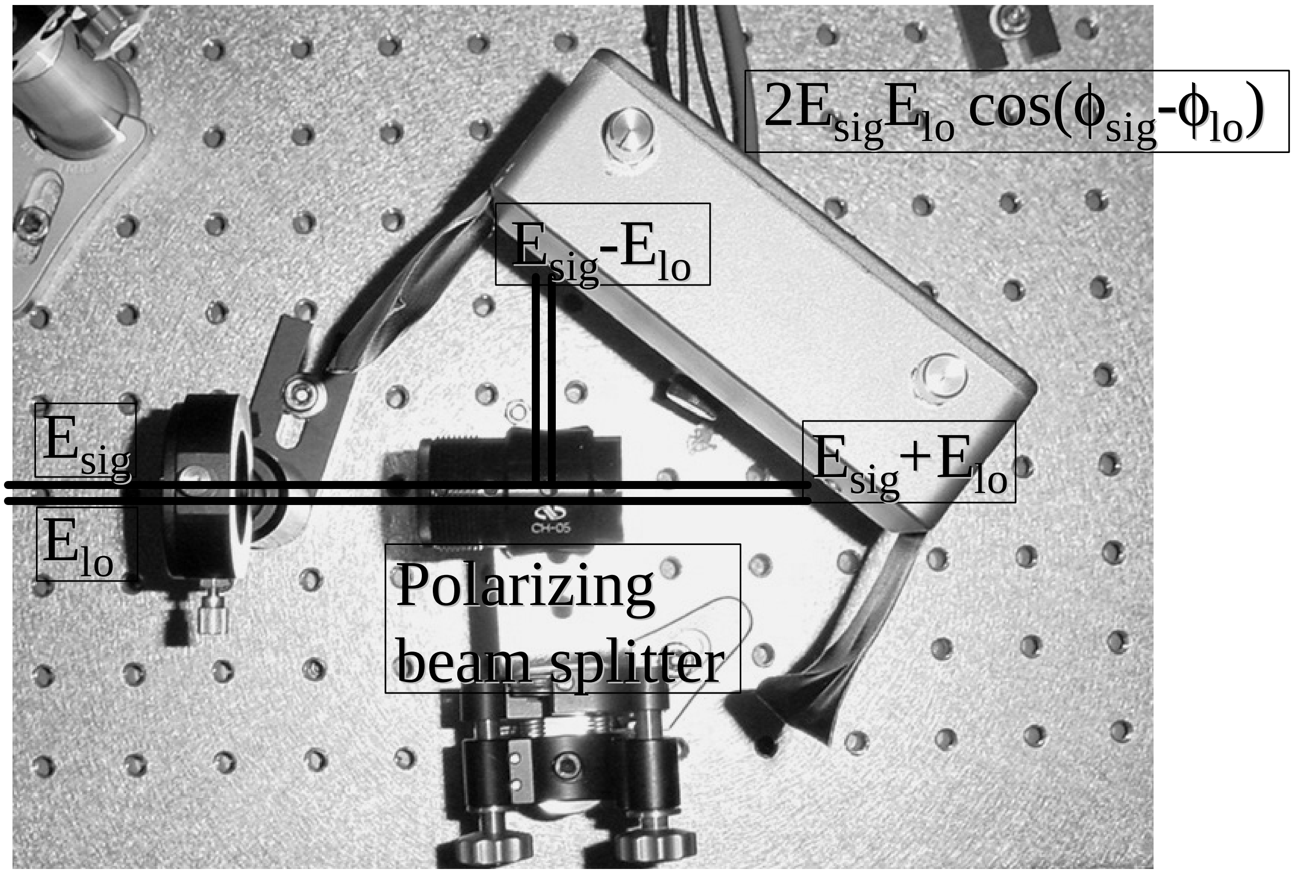
$$RT_{21} = \underbrace{14\Delta\Gamma_{HWP} + \Delta\Gamma_{HWP}}_{\text{birefringence of half waveplate}}\Big(\underbrace{0.5\Delta q_{HWP} - 1.7\Delta q_{VWP}}_{\text{angular misalignment of waveplates}} + \underbrace{5.9A_{PBS,p} - 35A_{PRB,s}}_{\text{leakage of s,p polarizations through the polarizing beamsplitter}}\Big) - \Delta b \Delta q_{VWP} + J(3)$$

- Noise due to polarizing optics seems manageable

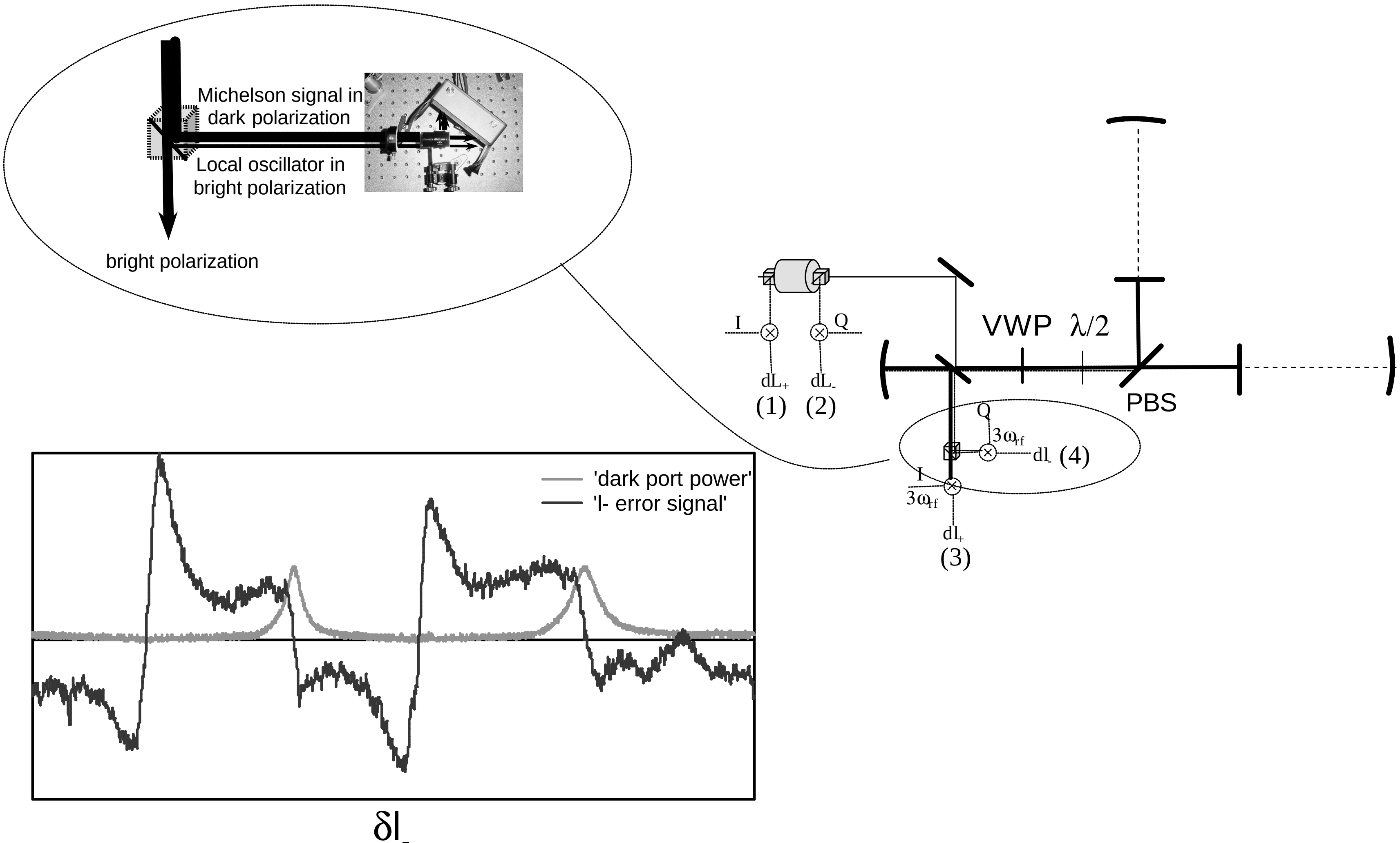
Unique aspects of the polarization RSE operation

- The use of an orthogonally polarized local oscillator for generating control signals
- Control of a Michelson without asymmetry
  - not necessary, but can reduce coupling of laser frequency noise to signal
- Differential tuning of a birefringent cavity
- Creating polarization sensitive finesse for a linear cavity

Balanced detection with an orthogonally polarized local oscillator

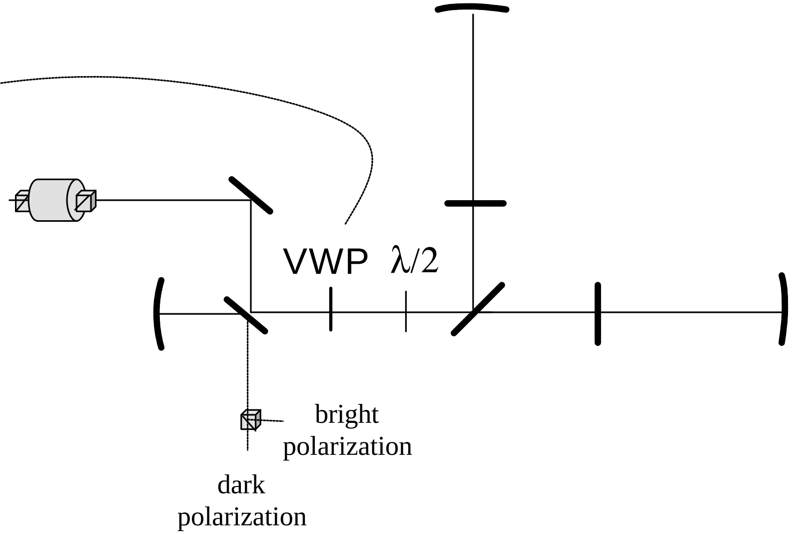


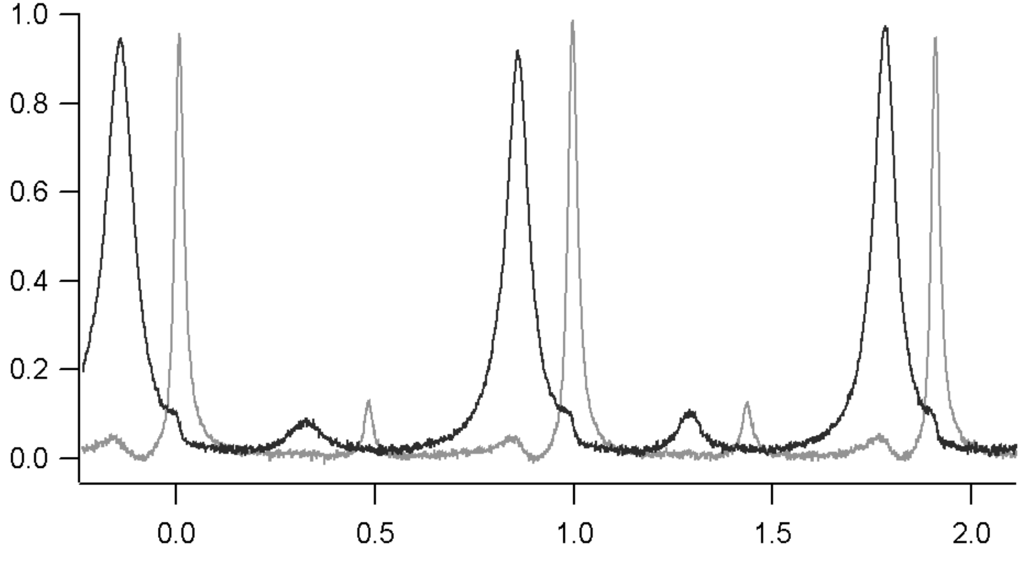
Control of a Michelson without asymmetry



Differential tuning of a birefringent cavity

As the birefringence of this waveplate is varied, the transmission spectra for the two polarization states become detuned

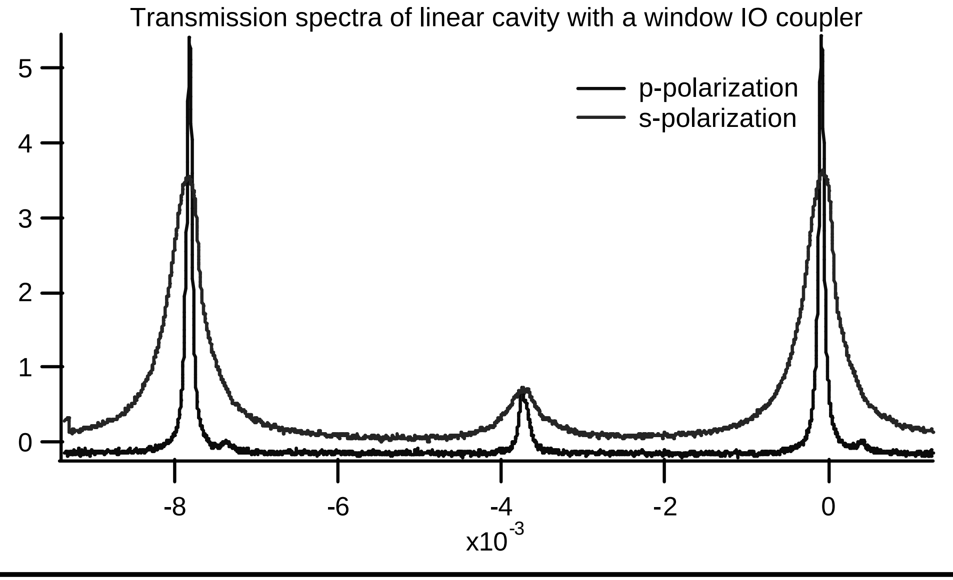


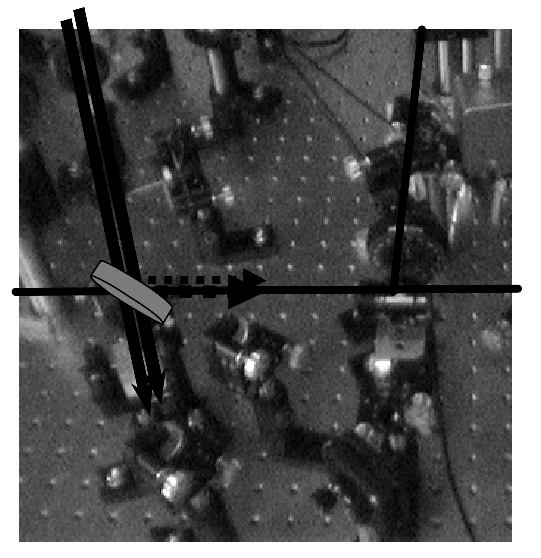


Transmission spectrum of recycling cavity showing both polarization states

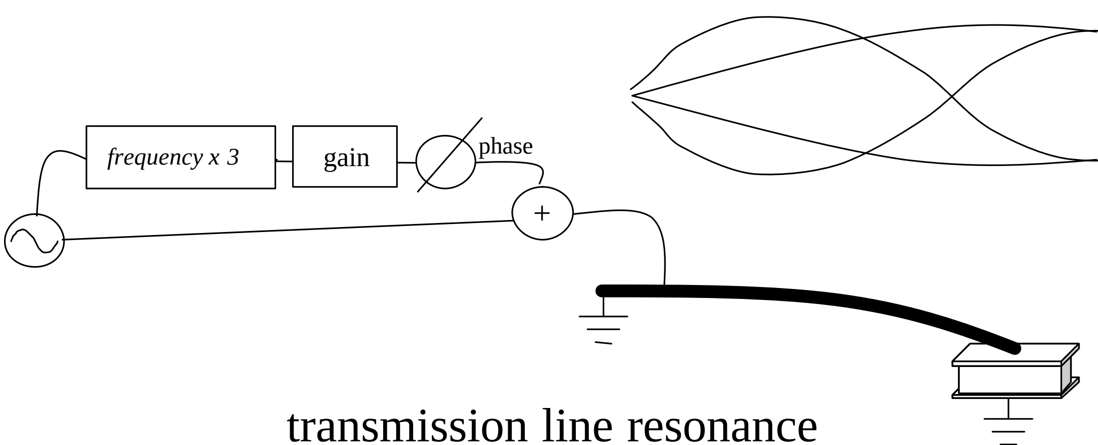
Creating polarization sensitive finesse for a linear cavity.

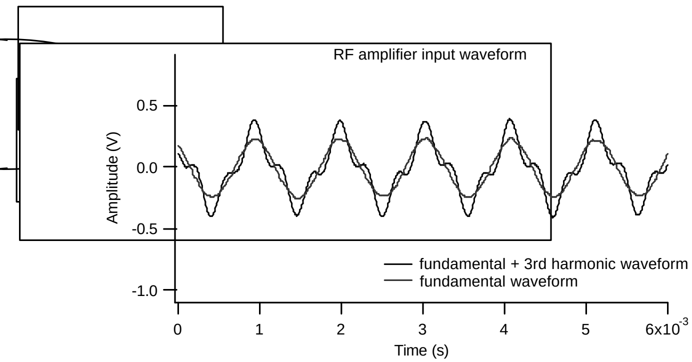
A non-normal incident window provides different coupling for the s and p polarization into the recycling cavity

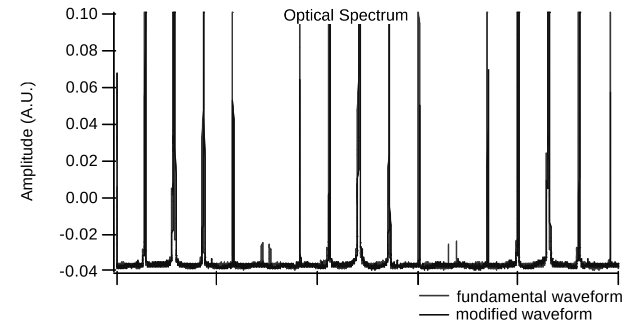




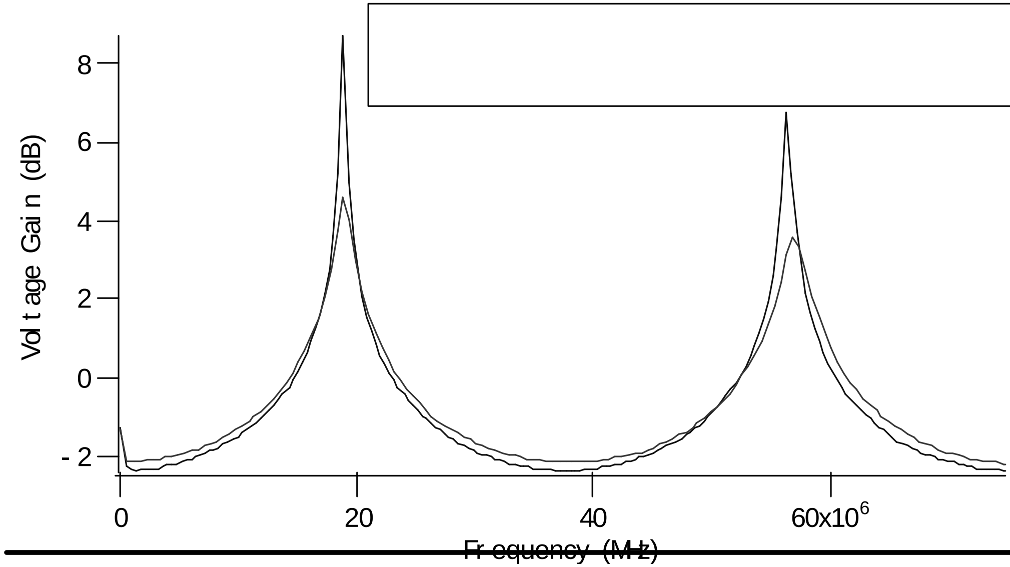
Elimination of 3rd order sidebands

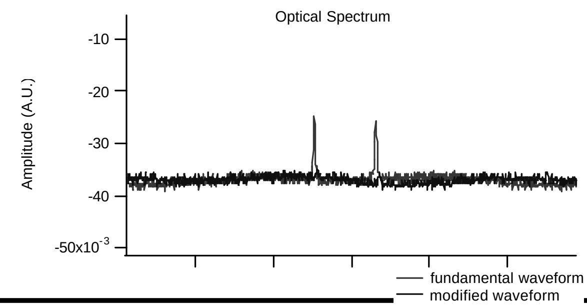




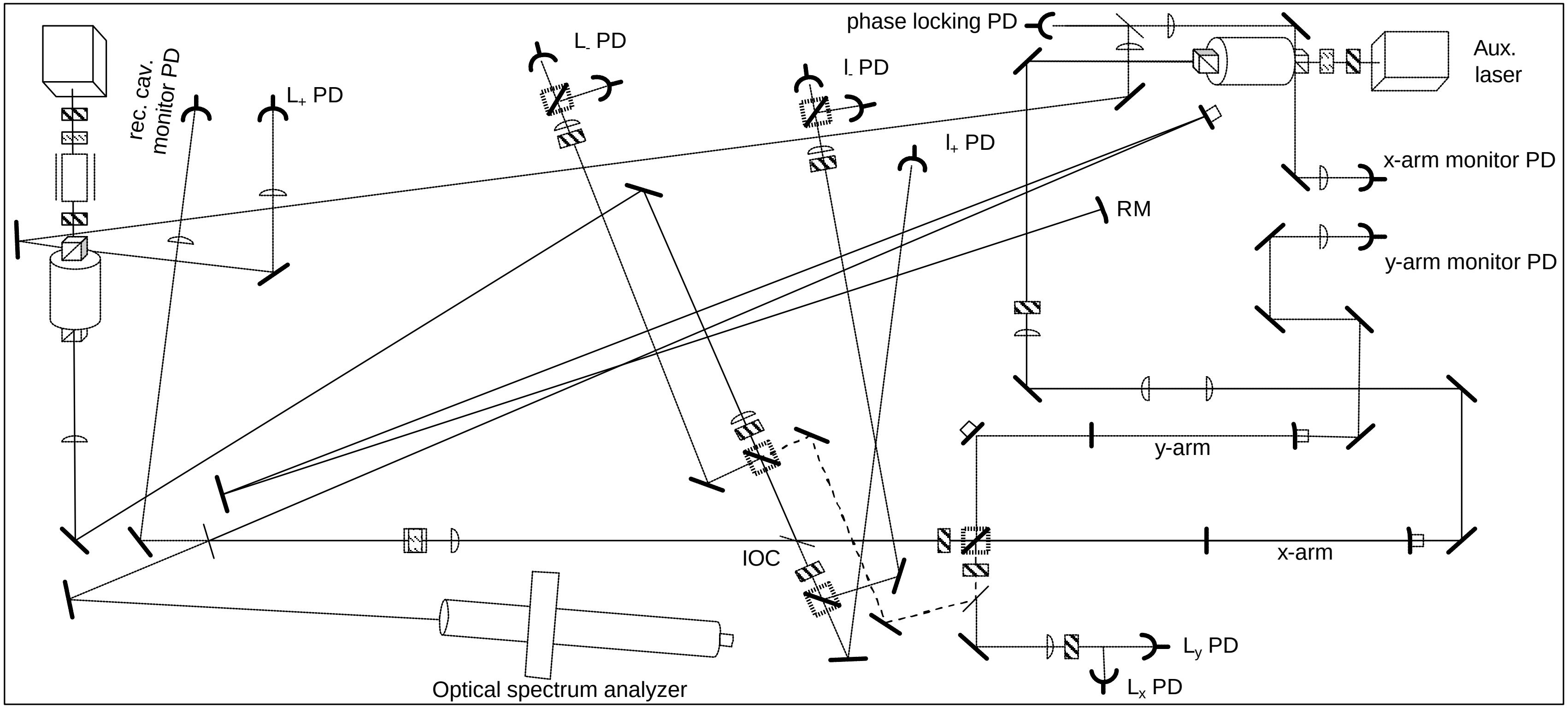


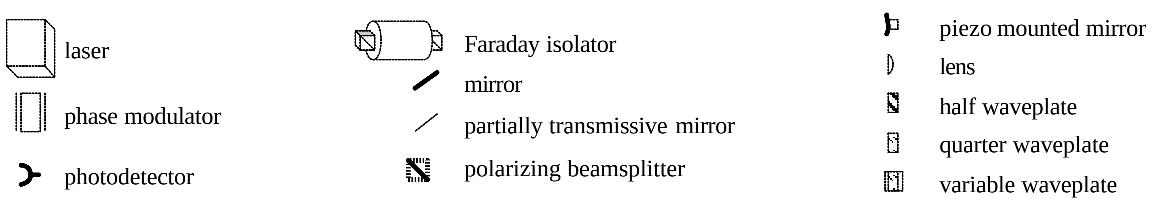
transmission line resonance



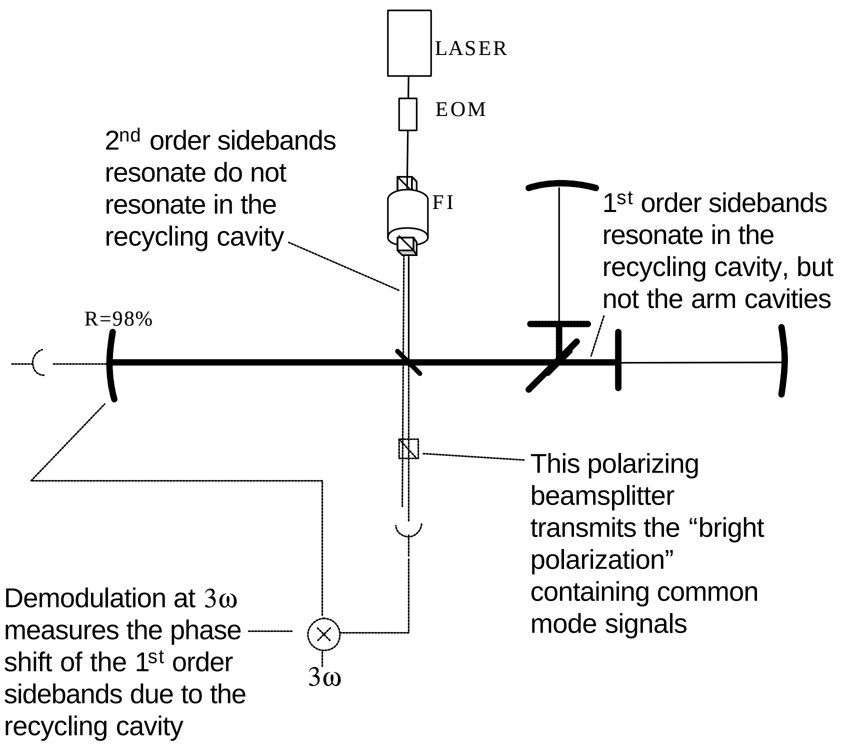


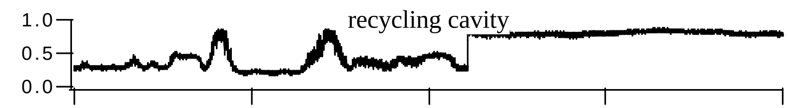
Putting it all together – the PRSE experiment



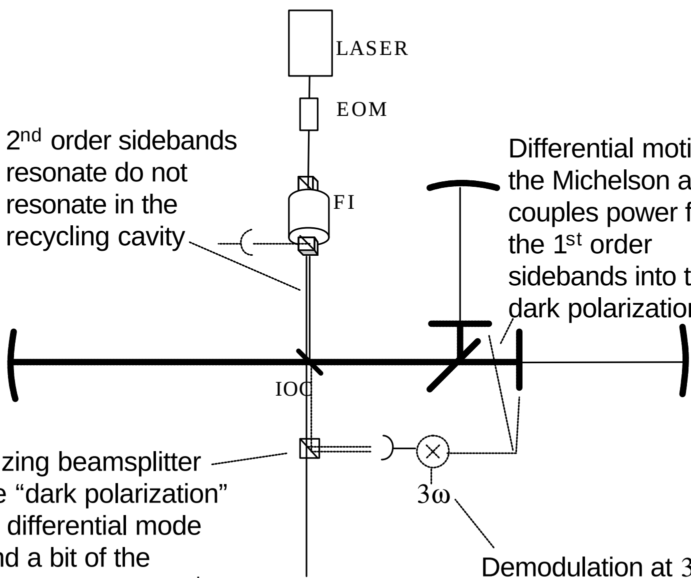


Lock acquisition – dl_+





Lock acquisition – dl_-

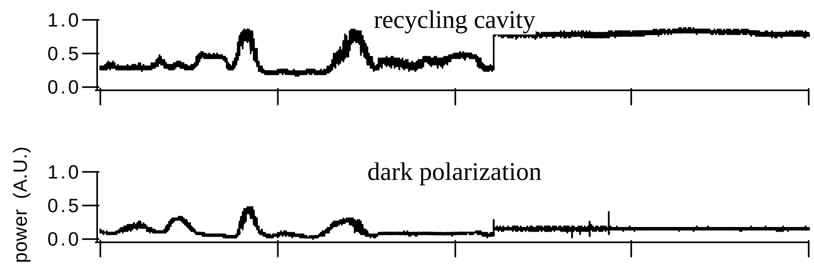


2nd order sidebands resonate do not resonate in the recycling cavity

Differential motion of the Michelson arms couples power from the 1st order sidebands into the dark polarization

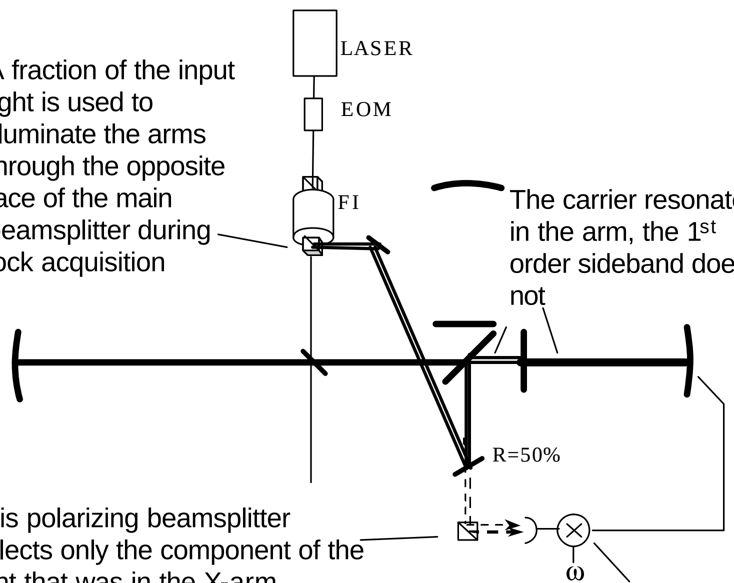
This polarizing beamsplitter reflects the “dark polarization” containing differential mode signals, and a bit of the (orthogonally polarized) 2nd order sidebands for use as a local oscillator

Demodulation at 3ω measures the presence of the 1st order sidebands due to the Michelson



Lock acquisition - dl_x

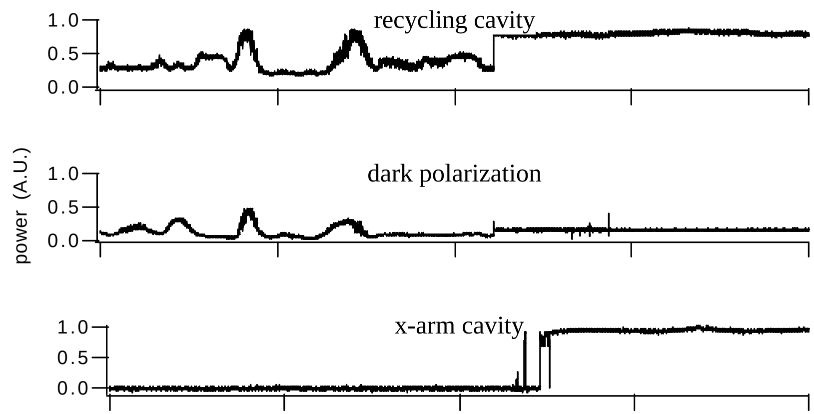
A fraction of the input light is used to illuminate the arms through the opposite face of the main beamsplitter during lock acquisition



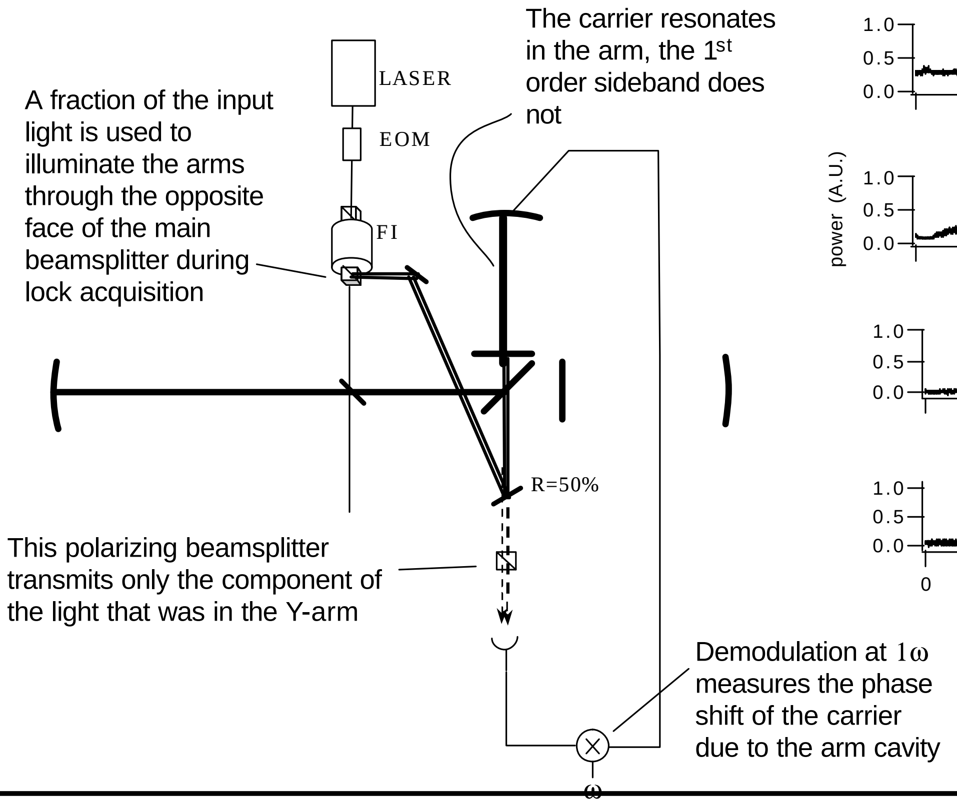
The carrier resonates in the arm, the 1[st] order sideband does not

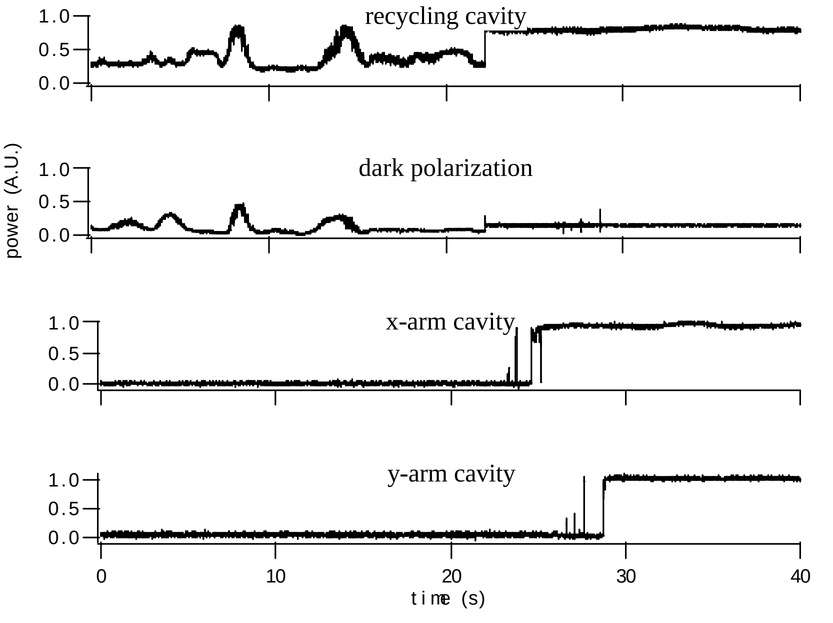
This polarizing beamsplitter reflects only the component of the light that was in the X-arm

Demodulation at 1ω measures the phase shift of the carrier due to the arm cavity



Lock acquisition - dl_y

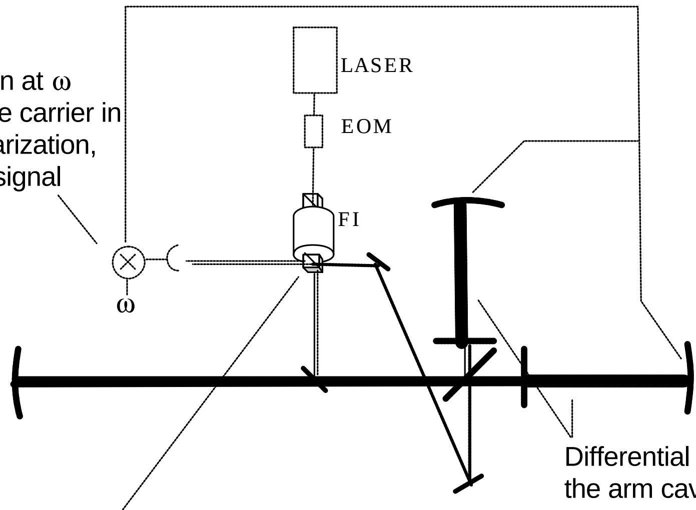




Control Signals – dL_-

- Once lock is acquired the control of the cavities is switched to the dL_- and dL_+ signals

Demodulation at ω measures the carrier in the dark polarization, i.e. the GW signal

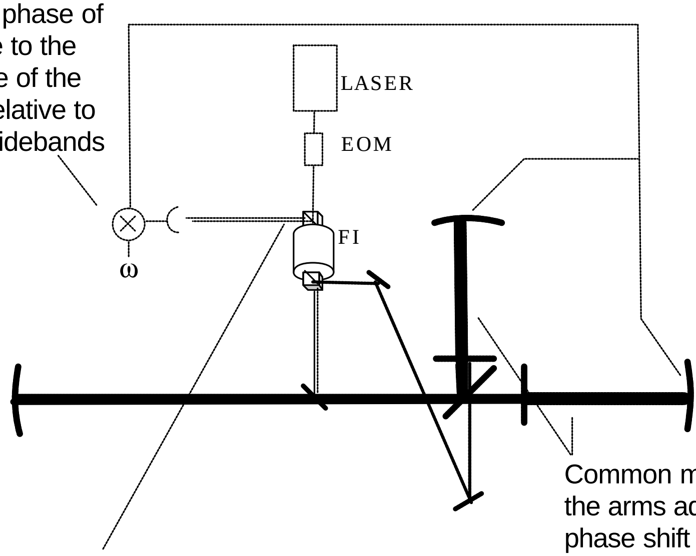


A polarizing beamsplitter reflects the differential mode signals in the dark polarization and a bit of the bright polarization for use as a local oscillator

Differential motion of the arm cavities couples power from the carrier into the dark polarization

Control Signals – dL_+

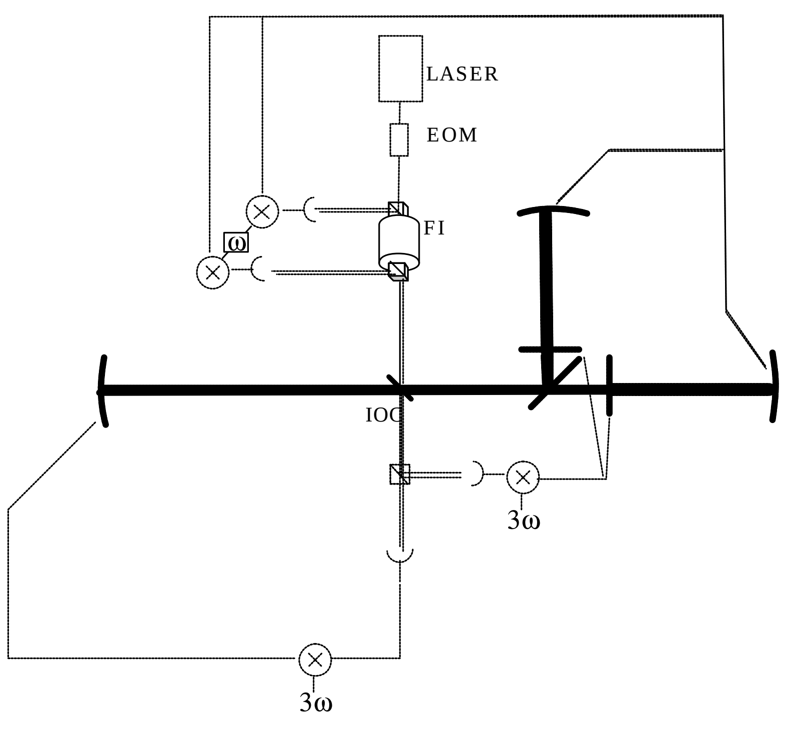
Demodulation at ω measures the phase of the carrier due to the common mode of the arm cavities relative to the 1st order sidebands



The light returning to the laser is the bright polarization and contains the common mode signal of the arm cavities.

Common motion of the arms adds a phase shift to the carrier in the bright polarization

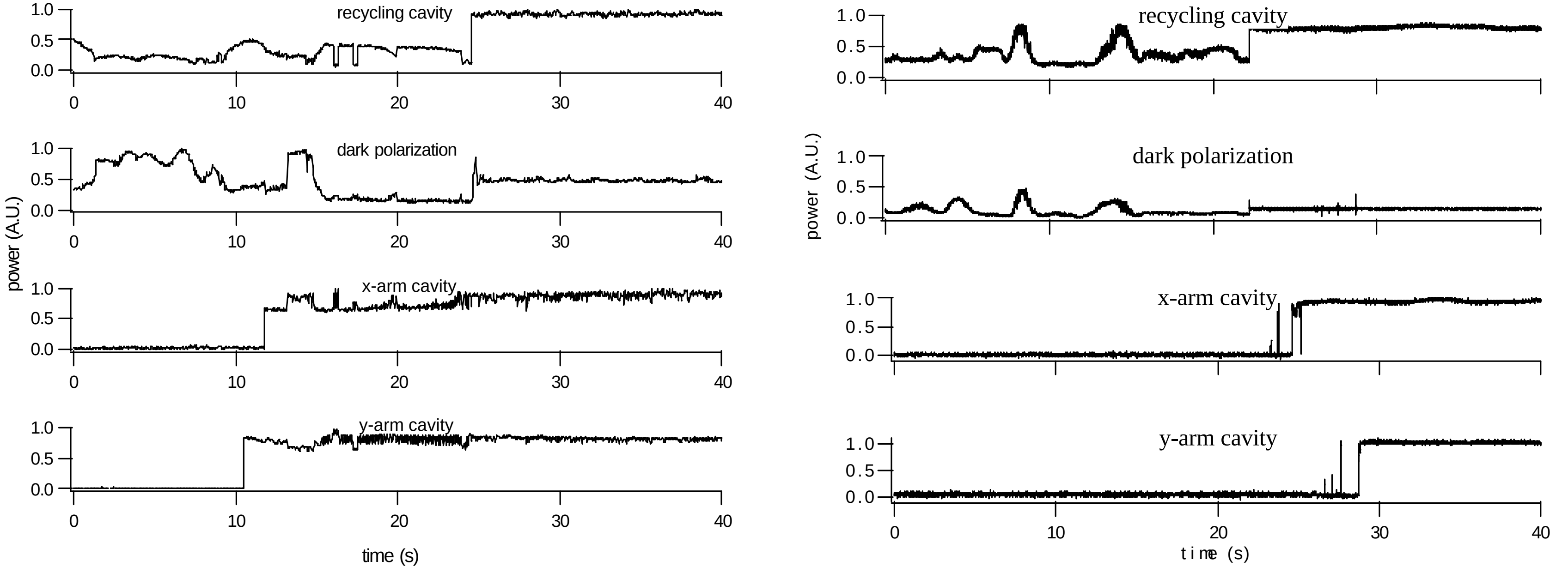
Control Signals



- The control scheme is basically that of TAMA300
- The Michelson interferometer does not need asymmetry
  - Leaky polarizing beamsplitters couple sidebands to the dark polarization detectors for use as a local oscillator

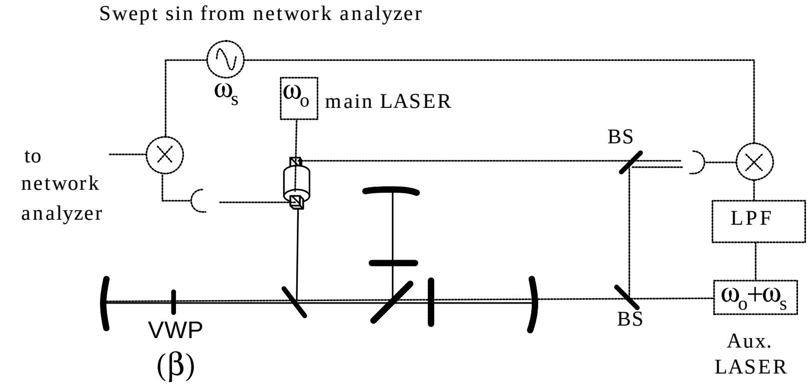
Lock acquisition order independence

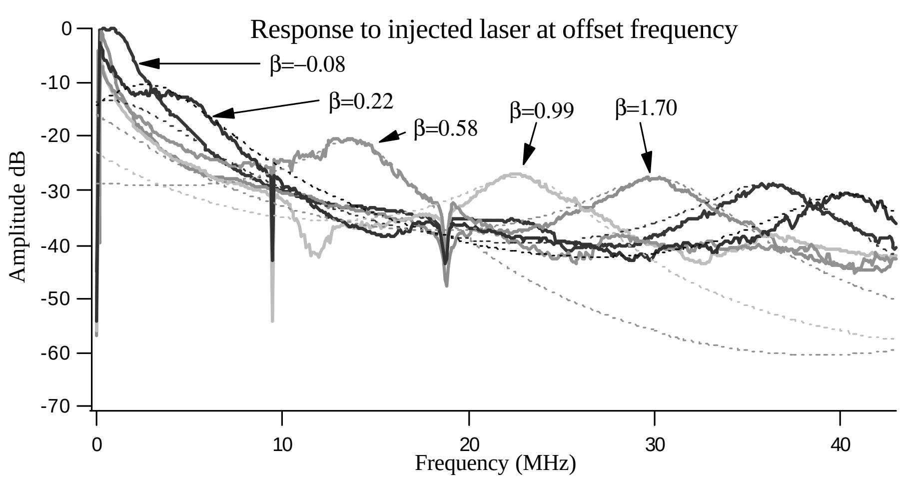
- One strength of the polarization RSE configuration is the clean separation of the control signals. That is evident by the fact that the arm cavities can be locked before or after the recycling cavity



RSE transfer functions

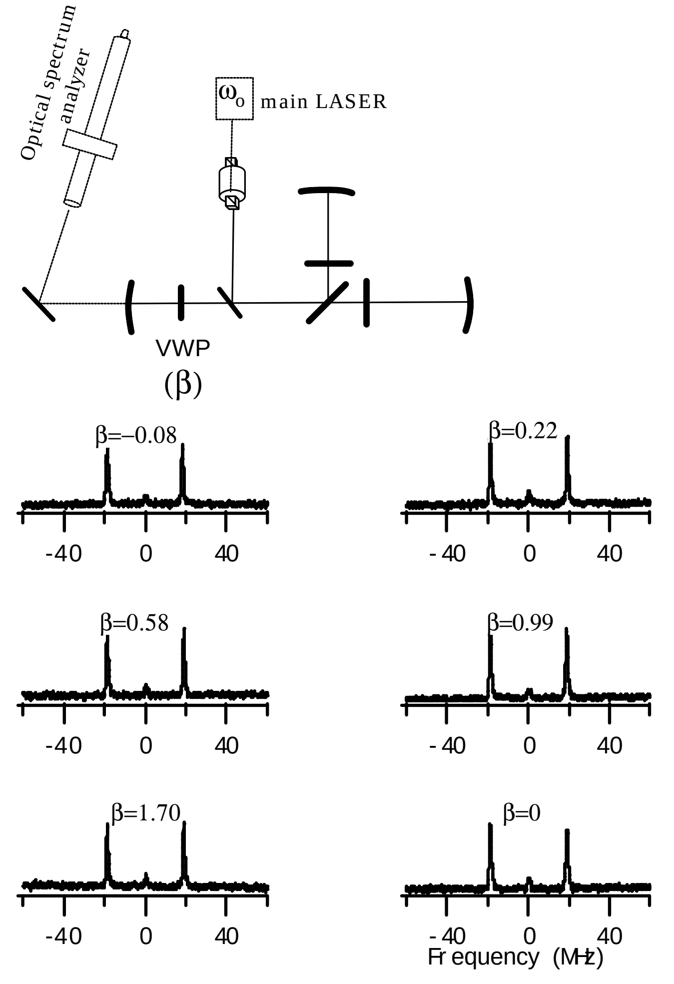
- Auxiliary laser was offset frequency locked and injected into one arm cavity to simulate GW sidebands
- The frequency response of the interferometer was mapped out for various detunings
- The detuning was changed without disturbing lock





Balance of RF sidebands

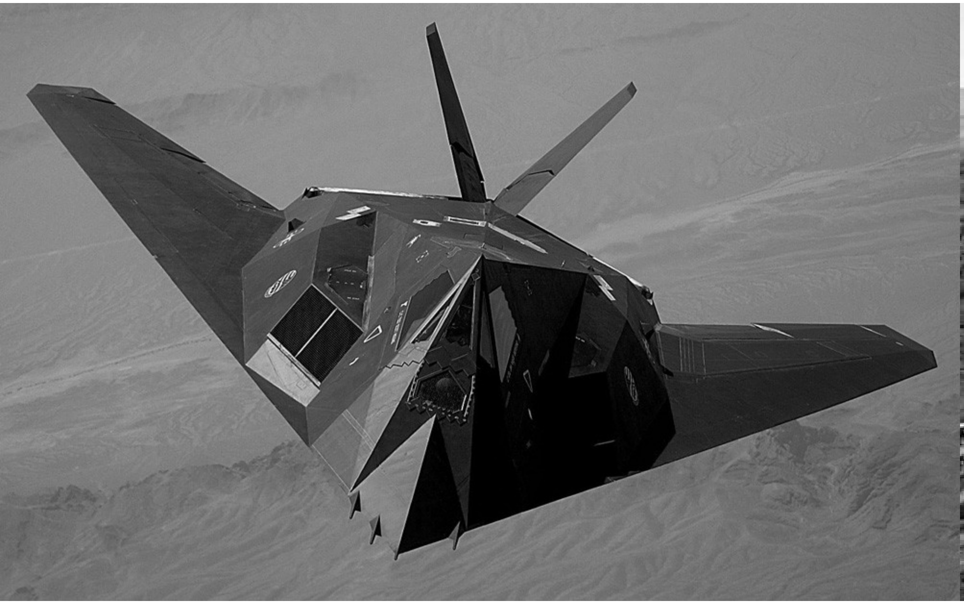
- Balanced RF sidebands are necessary for low-noise RF readout of the gravitational wave signal
- Detuning produces an imbalance in the *signal* sidebands in the dark polarization
- *RF* sidebands are unaffected by detuning
  - used for signal readout (in the bright polarization) are balanced regardless of the detuning
  - Demodulation phase does not need to be reoptimized after changing the detuning



Discussion

- The polarization RSE configuration offers many advantages over other RSE configurations
  - Simple, familiar control scheme
  - RF readout without excess noise
  - Can operate without Shnupp asymmetry, reducing noise and control loop couplings
  - Variable bandwidth and continuously tunable peak frequency without breaking lock
- The cost of these advantages is the use of polarizing optics
  - Tolerances need to be set for several parameters that can couple noise to the output
  - High quality polarizing optics need to be developed and characterized
  - Computer models for interferometer analysis need to be modified to be able to represent this configuration

Q: What do these things have in common?



A: Their designs have been constrained by the capabilities of the computer models available for their analysis

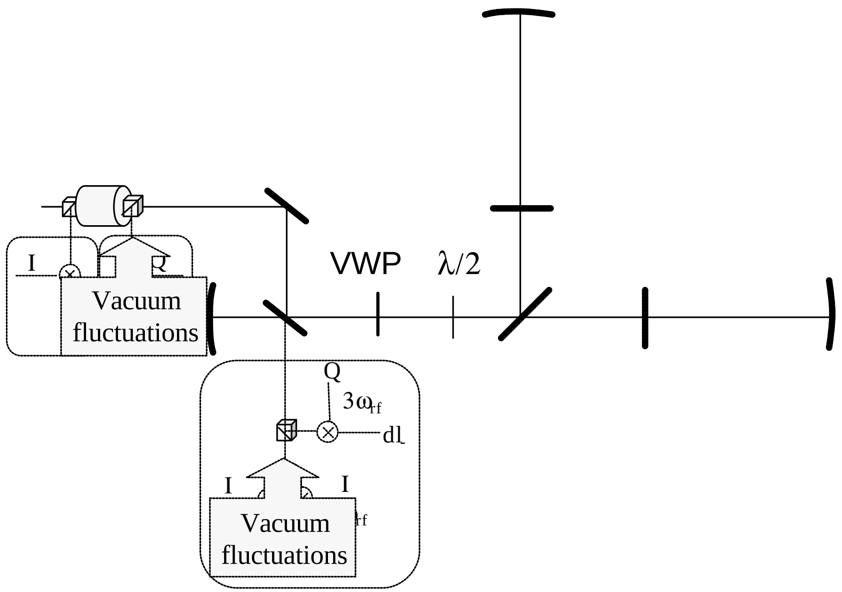
- Most of our computer models of interferometers (e2e, finesse) can not yet handle polarization well, so they cannot model polarization RSE

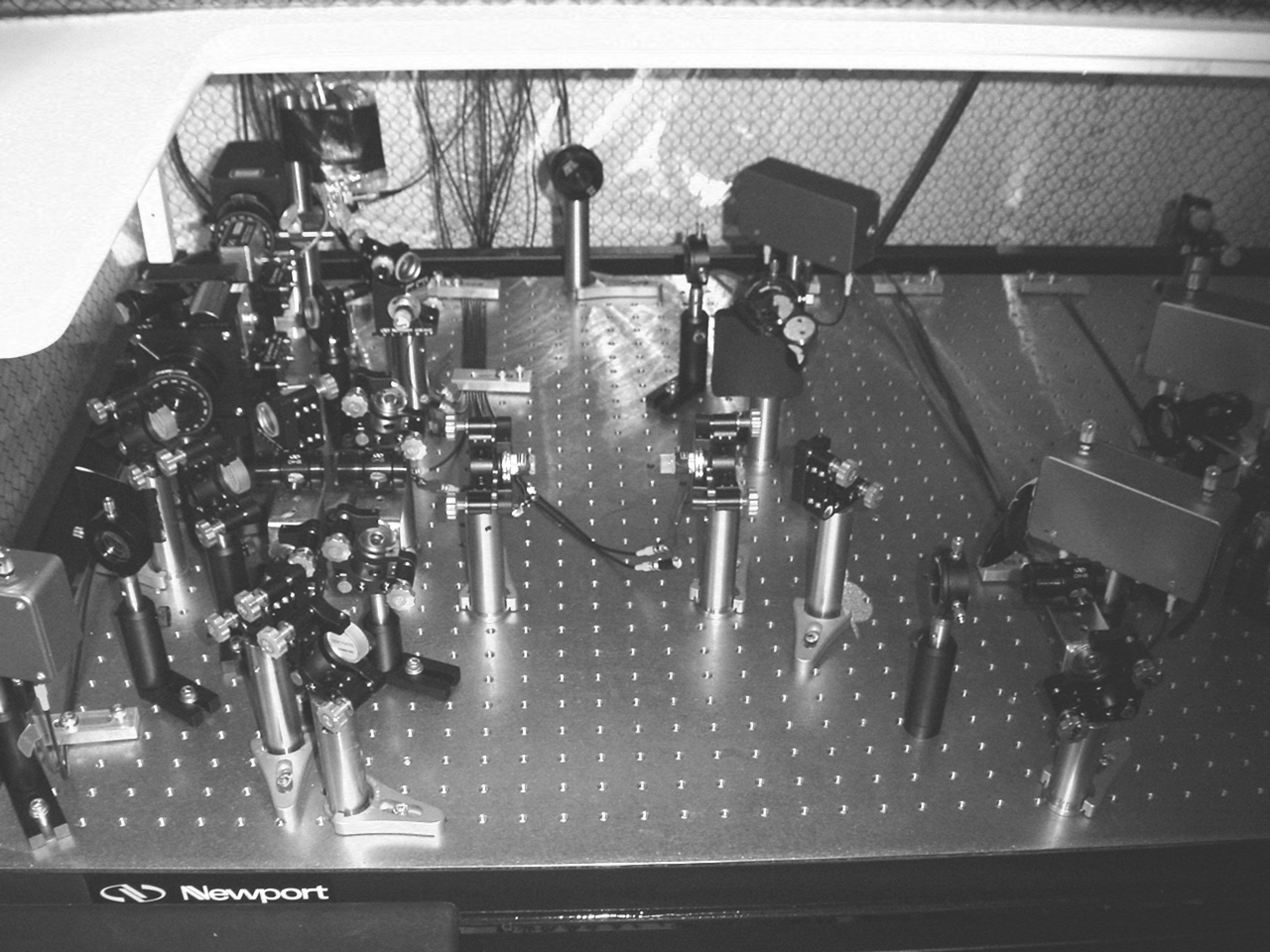
Summary

- A TAMA300-like control scheme was used to control a polarization RSE interferometer
- The frequency response is continuously adjustable
- Lock acquisition and control were robust and unaffected by the frequency tuning
- RF readout can be implemented without introducing excess noise
- Implementation will require extensive use of polarizing optics, which haven’t been used in a gravitational wave detector before

Quantum noise in polarization RSE

- Vacuum fluctuations that enter through the L- detection ports produce quantum noise
- Optical spring effect is polarization RSE

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