Length Sensing and Noise Issues for a LIGO II RSE Interferometer

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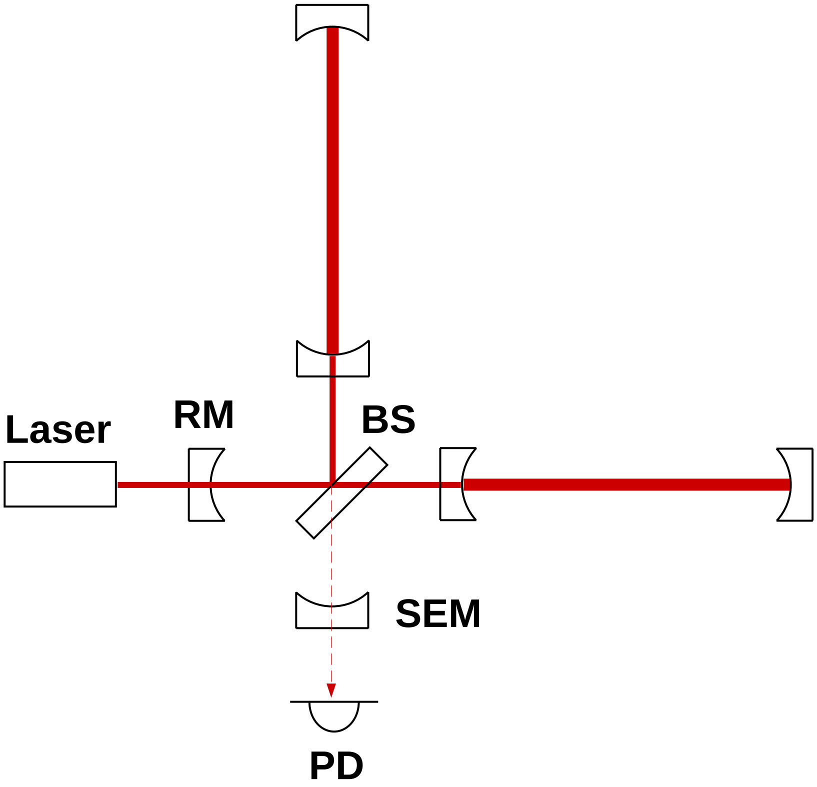
Cast

- Caltech
    - James Mason
    - Phil Willems
- Visitors
    - Seiji Kawamura (TAMA)
    - Osamu Miyakawa (TAMA)
    - Gerhard Heinzel (TAMA)
- Actively involved with LSC AIC working group

Resonant Sideband Extraction

- Add a mirror at the anti-symmetric port



- This mirror creates a coupled cavity system

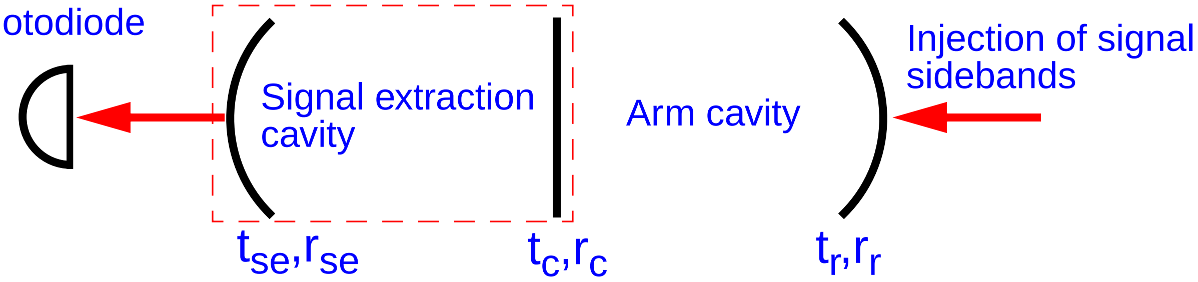
›› RSE uses this coupled cavity to increase the bandwidth over that of the simple arm cavities (signal cavity resonant - “broadband”)

›› Potential sensitivity improvement due to favorable redistribution of losses, hence higher amount of stored light energy

›› Transfer function can be tuned to have high sensitivity at a particular frequency (signal cavity off resonant - “detuned”)

Three Mirror Coupled Cavity

- Idealize the signal half of the interferometer as a 3 mirror coupled cavity



Photodiode

Signal extraction cavity

Arm cavity

Injection of signal sidebands

t_{se}, r_{se}

t_c, r_c

t_r, r_r

- Signal extraction cavity as a “compound mirror”

$$r_{cm}(\phi) = r_c - \frac{T_c r_{se} e^{-i\phi}}{1 - r_c r_{se} e^{-i\phi}}$$

›› Assume short signal cavity, so that the relevant time is the arm cavity round trip time

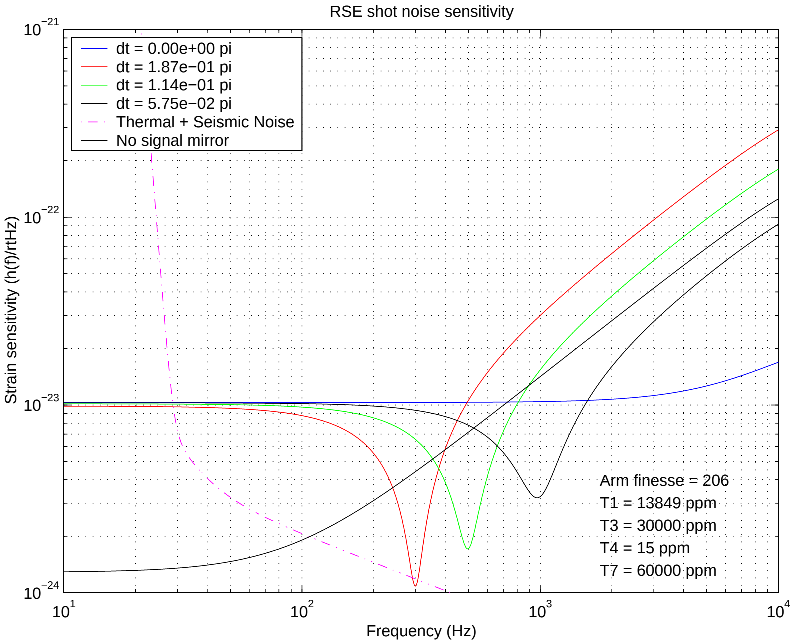
›› If signal cavity is anti-resonant, the effective finesse of the arm cavity increases, and the bandwidth decreases (Signal recycling)

›› If signal cavity is resonant, the effective finesse of the arm cavity decreases, and the bandwidth increases (RSE)

›› If the signal cavity is somewhere in between, the phase shift upon reflection makes the coupled cavity resonant at a frequency other than that of the carrier (+ bandwidth effects...)

RSE Shot Noise Sensitivity

- Some frequency responses



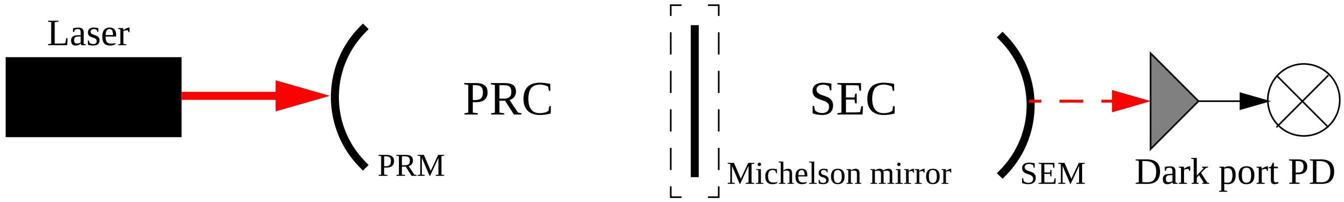
- Features

  ›› Can reach the thermal noise floor at any frequency through appropriate choice of signal mirror transmissivity

  ›› Optimization of response for broadband signals almost always is a detuned configuration (not-so-narrow-band)

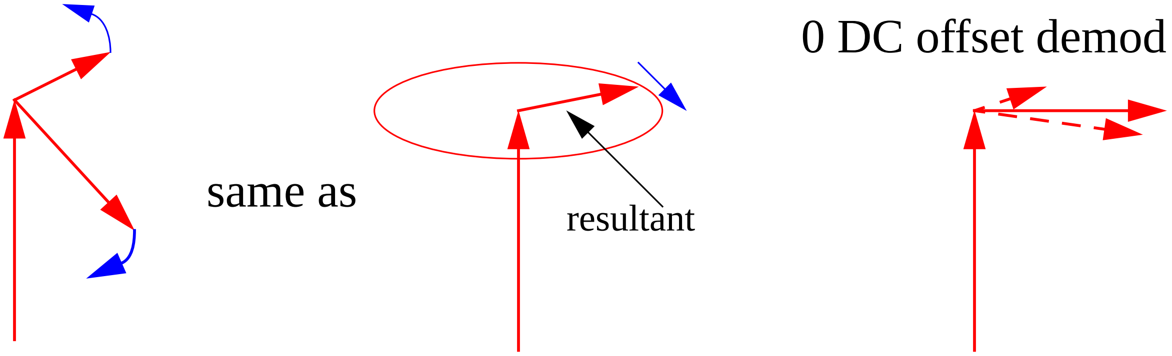
Interferometer Length Control

- RSE - 5 degrees of freedom
  - 4 cavities (2 arms, power and signal cavities)
  - Michelson condition (dark fringe for carrier)
- Optical heterodyne signal extraction
  - Frontal modulation
  - Add’l demodulation frequency required
    - **Add a modulation to input spectrum, AM, PM or SSB**
- GW signal readout
  - Requires strong RF sideband field at the dark port
  - RF transmission approximated by 3 mirror cavity
    - **Asymmetry is the tunable parameter**



Interferometer Length Control, Part 2

- SEC phase is not fixed
  - ›› Detuning is important for detector optimization
- Sideband transmission to dark port affected
  - ›› In general, only one SB can transmit with high efficiency
  - ›› Requires either change in length of SEC, or change in frequency of modulation to achieve high transmission
- Sidebands are unequal in magnitude and phase inside the detuned interferometer
  - ›› There exists only one demodulation phase which has no offset, per photodiode, per demodulation frequency



  - ›› Have to be a little more careful how we choose our signals for control

Length Sensing Proposal

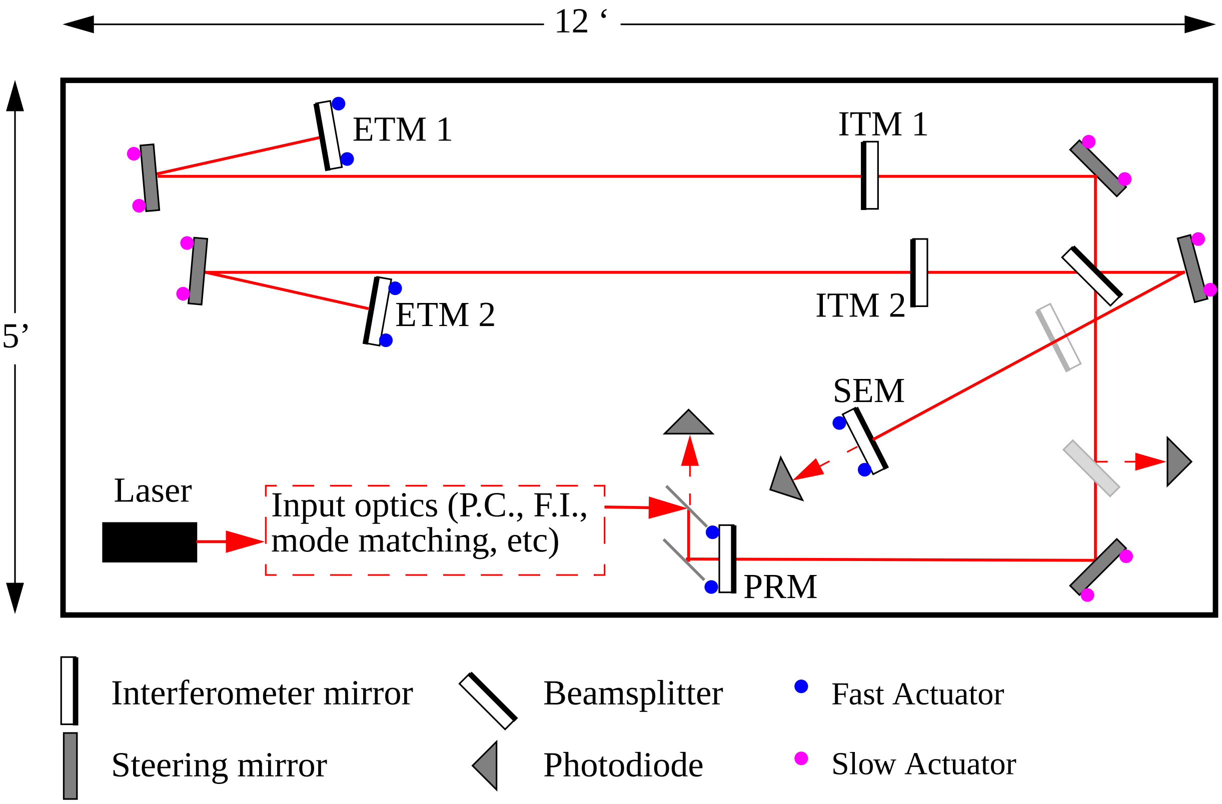
- PM sidebands + SSB
  - ›› Fixed, integer multiple frequencies (f and 3f)
    - – **Allows use of single (short) mode cleaner to filter light before entering interferometer**
    - – **Requires length adjustment of SEC to detune (few centimeters)***
- DC plant example, detuned interferometer
  - ■ **DOF 1 = Φ+, DOF 2 = Φ−,DOF 3 = ϕ+, DOF 4 = ϕ−,DOF 5 = ϕs**

```
In[9]:= dof = {{m4, 1, m6, 1}, {m4, 1, m6, -1}, {m1, 1}, {m3, 1, m5, -1, m4, 1, m6, -1}, {m7, 1}};
        outindex = {index[m1, 1, 2], index[m1, 2, 1], index[bb1, 1, 1]};
        DCMatrix[dof, outindex, 0.14, 3 mfreq, .1]
        DCMatrix[dof, outindex, -0.01, 2 mfreq, .1]
        DCMatrix[dof, outindex, 1.002, mfreq, .1]

        0.219911 demodulation at 81. MHz

              DOF 1     DOF 2    DOF 3    DOF 4     DOF 5
        PD 1  -871.789  0        36.1086  -0.81204  0.712219
        PD 2  -657354.  1.85623  -3840.6  243.758   -213.794
        PD 3  0         61.8037  0        0.470631  0

        -0.015708 demodulation at 54. MHz

              DOF 1     DOF 2  DOF 3     DOF 4     DOF 5
        PD 1  0         0      -11.8966  0.106232  -0.510697
        PD 2  -9.33543  0      1104.65   1.53611   -121.269
        PD 3  0         0      0         0.263903  0
```

- ›› Nearly diagonal
  - – **Only one signal, l_s, is not the dominant signal in its port**
- ›› By using a SSB as 2nd frequency, the (3f - f) signals remain largely unaffected by detuning

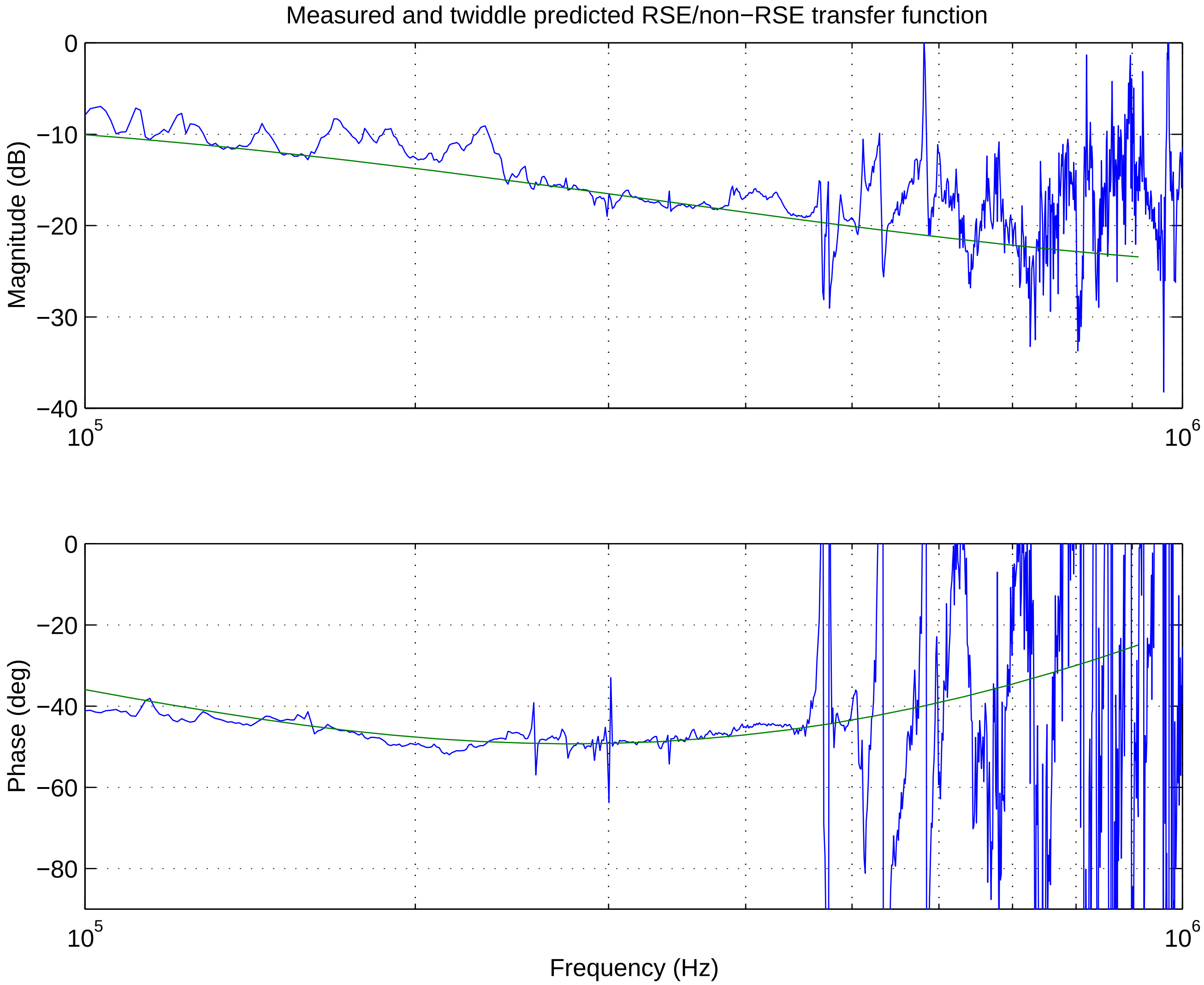
Experimental Work

- Prototype RSE on an optical table
  - Fixed mass interferometer
  - Use a signal extraction scheme which would be proposed for LIGO II
  - Lock in both broadband and detuned operation
    - **Make relevant transfer function measurements to verify understanding of control scheme**



Current Results

- Locked full RSE, broadband



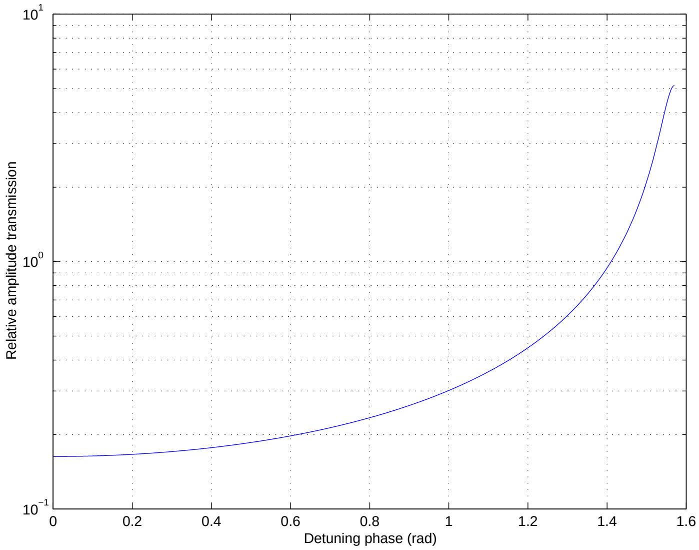
- Current work directed at locking in detuned configuration

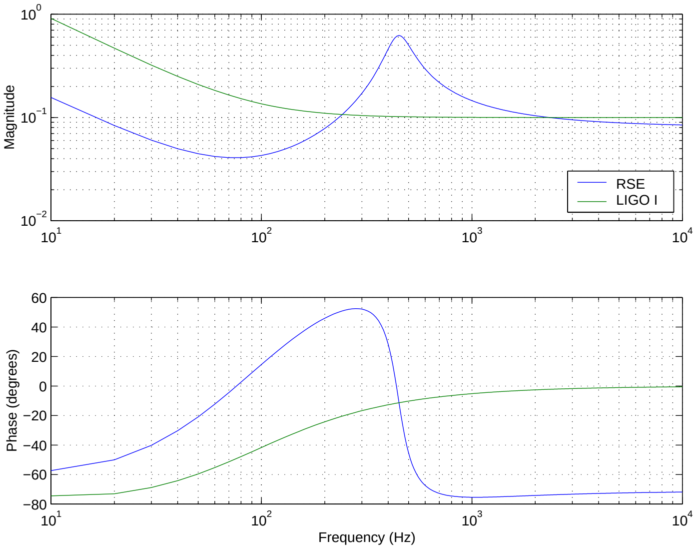
Laser Noise Coupling

- Amplitude and frequency noise on input light generates signal at GW output
  - Mostly couples through interferometer imperfections, e.g. deviations from resonance and arm cavity mismatches
- Noise signals arise from beat between:
  - Carrier defect (DC) and noise on RF sidebands
  - RF sidebands (DC) and noise on carrier
- Differences with LIGO I
  - Higher power
    - **Noise terms scale with amplitude**
  - Output (signal) cavity
  - Imbalanced sidebands at dark port
  - Demodulation phase varies with detuning

Work in Progress

- Deriving analytical calculation of noise at output
- Writing Matlab code to generate noise predictions
- Intermediate results
  - Carrier terms
    - **DC defect - better than LIGO I**
    - **Noise terms - worse than LIGO I**





  - RF sideband terms - about the same as LIGO I
- To do
  - Gain confidence in code and calculations
  - Understand demod. phase and imbalanced sideband effects