LIGO-G 930046-00-M

Robbie,
this is the final
draft of my
transparencies.
David has
approved it.

- Martin 930603

INTERFEROMETER TOPOLOGY AND CONTROL SYSTEMS

CANDIDATE LIGO INTERFEROMETER OPTICAL AND SERVO TOPOLOGY: ASYMMETRY MODULATION

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June 8, 1993

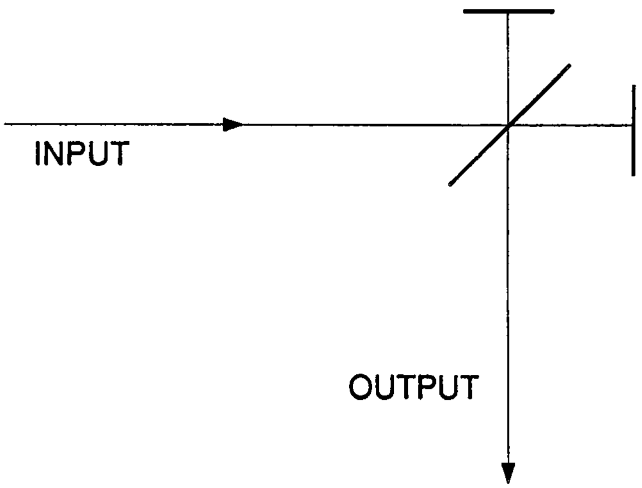
"Asymmetry" Scheme for Gravitational Wave Signal Extraction and Auxiliary Sensing

- Method of extracting gravitational wave signal and auxiliary signals for control of mirror positions
- Status; Work remaining to qualify scheme for LIGO
- Caltech tabletop prototype

“Asymmetry” Scheme for Gravitational Wave Signal Extraction

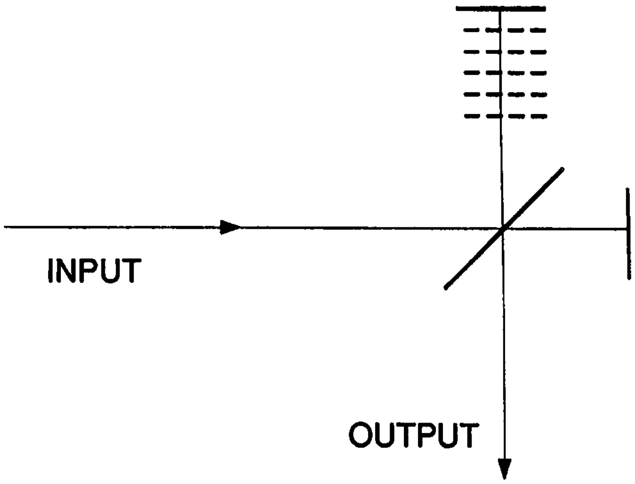
(Schnupp, ’86 or ’87)

Symmetric Michelson interferometer:



- Output dark for all wavelengths if dark for any.

Introduce asymmetry by shifting one mirror away from beamsplitter by a (large) integral number of half-wavelengths of green light:



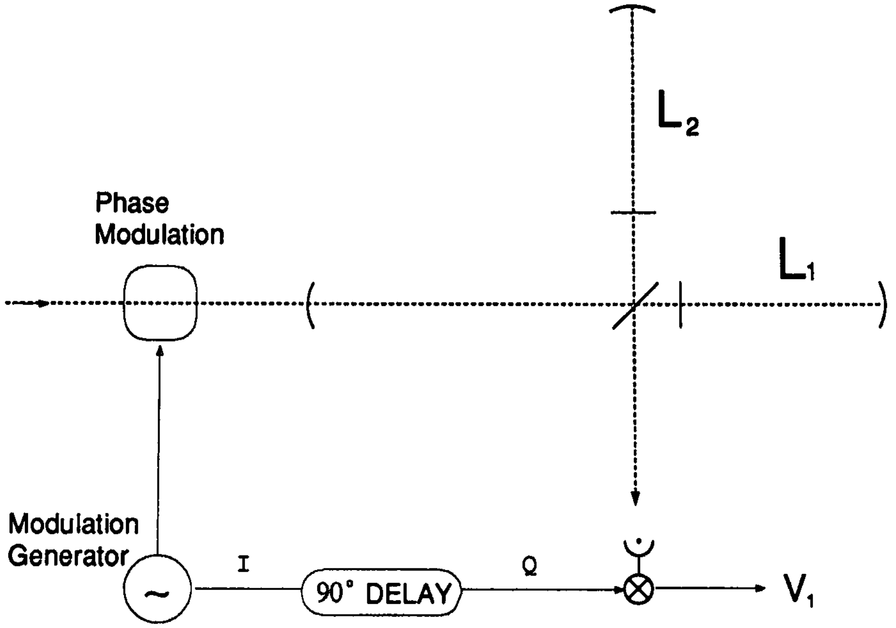
Now output is dark for green, not dark for other wavelengths.

In particular: Modulate phase of input light at radio frequency

- Modulation imposes sidebands on incident light.
- Effect of gravitational wave is slow motion of mirrors. Carrier ("green") light at output beats against sidebands, producing amplitude modulation.
- Gravitational wave is detected by demodulation.

Full interferometer exactly analogous.

- **High sideband transmission (from laser to output) possible because sidebands made to resonate in recycling cavity.**



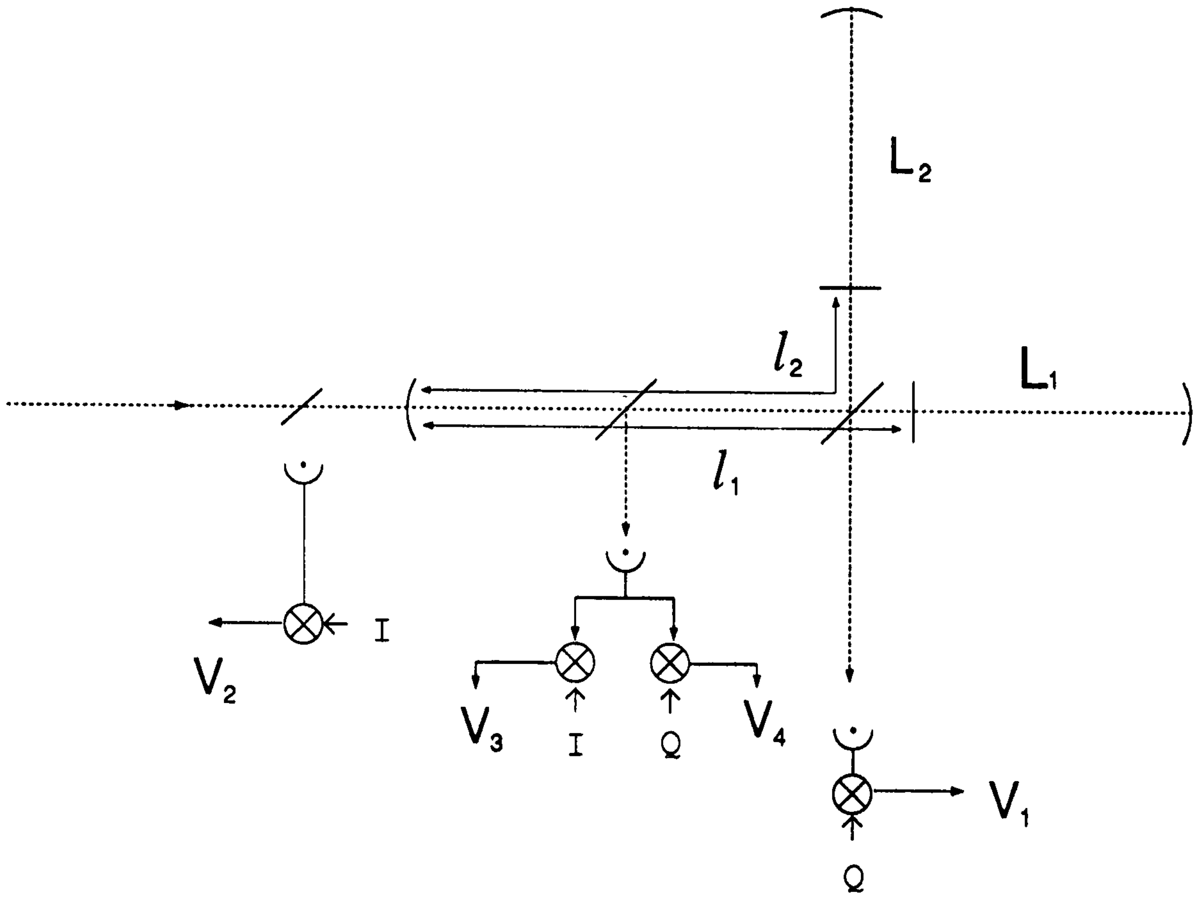
Signal at output:

$$\begin{aligned} V_1 &\propto L_1 - L_2 \\ &\propto \text{Gravitational Wave Signal} \end{aligned}$$

- **Planned asymmetry: 60 cm**
- **Shot noise level insensitive to details of modulation scheme**
- **No known mechanisms by which asymmetry would degrade noise performance measurably**

"Asymmetry" Scheme for Auxiliary Sensing

Signals corresponding to remaining three degrees of freedom needing to be controlled also available:



$$V_2 \propto \delta L_1 + \delta L_2 + \varepsilon_2(\delta l_1 + \delta l_2) \qquad \varepsilon_2 \simeq 0.006$$
$$V_3 \propto \delta L_1 + \delta L_2 + \varepsilon_3(\delta l_1 + \delta l_2) \qquad \varepsilon_3 \simeq 0.002$$
$$V_4 \propto \varepsilon_4(\delta l_1 - \delta l_2) \qquad \varepsilon_4 \simeq 0.002$$

Challenges:

- "Ill conditioned" system: V_2,V_3 (and, if demodulator phase not quite right, V_4) all more sensitive to $L_1 + L_2$ than to other two degrees of freedom.

  Solution: separate signals by taking linear combinations, or use high gain in one loop

- When not near resonant state, gain in each loop depends on other degrees of freedom: difficult to understand acquisition (and to diagnose problems if not working)

  May require use of alternate auxiliary sensing scheme for lock acquisition

Benefits:

- Extreme optical simplicity

Progress:

- Low frequency analysis and numerical model completed
- Frequency response analysis nearly complete; Numerical model being debugged
- Prototype assembled and functioning

The Table-Top Prototype

Differences from LIGO:

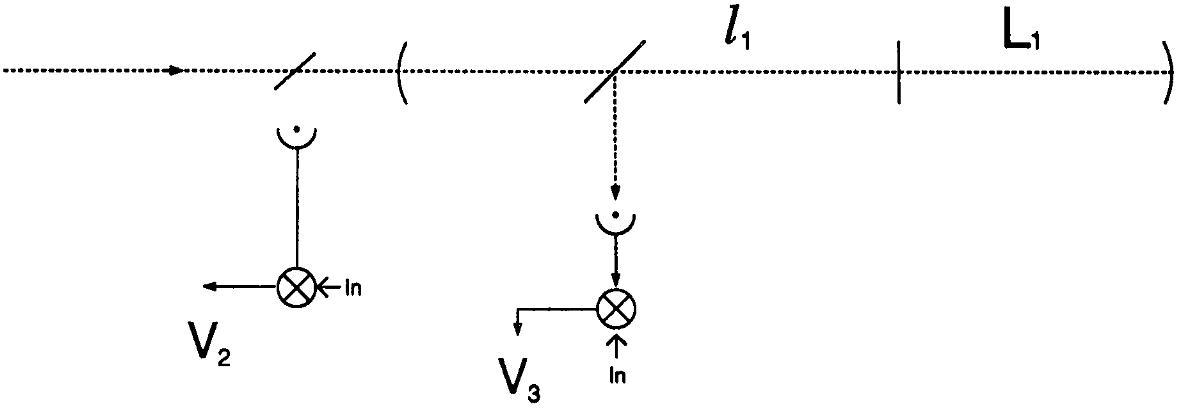
- Lengths: arm cavities 6 m instead of 4000 m
- Characteristic frequencies 20 kHz, 200 kHz instead of 5 Hz, 90 Hz
- Spectra of disturbances ~500 Hz (acoustic) instead of ~5 Hz (seismic/stack)

Similarities:

- Mirror transmissions: 20% recycling mirror, 10% cavity input mirrors (3%, 3% respectively in LIGO)
- Modulation frequency: 12 MHz

Results

- Model verification for the 'coupled cavity' subsystem



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- Lock acquisition for full interferometer
- Low frequency model verification in progress

Work remaining:

- Complete experimental verification of low frequency model
- Verify frequency response analysis and numerical model against each other, and possibly against prototype
- Design a controller for LIGO and verify performance by modelling

OUTLINE FOR PRESENTATION ("10.15 1) Schnupp (mr, 25)") MR, 930527

[0?] Introduction: statement (in about two sentences) summarizing what is about to be presented

- method of extracting gravitational wave signal and auxiliary signals

- work done; work remaining to qualify scheme for ligo

- Caltech tabletop prototype

Gravitational Wave Signal Extraction

[2] mechanism - one transparency (2?); use sideband (preferred) or common mode/differential phase modulation explanation
- mention fact that sidebands resonate in recycling cavity (hard to explain in common mode/differential phase modulation framework)

[1]- size of asymmetry planned - shot noise identical to within a few percent for all modulation techniques considered - no known mechanisms by which asymmetry could degrade noise performance measurably - advantage: extreme optical simplicity

Auxiliary Signal Extraction

[1] - schematic showing where light extracted and demodulated - statement of dependence of signals on lengths in interferometer

[1]- challenges:
- "ill conditioned' system: V2,V3 (and, if demod phase not quite right, V4) all more sensitive to L1+L2 than to other two degrees of freedom.

  Solve by decoding or high gain in one loop

- when not near resonant state, gain in each loop depends on other degrees of freedom: difficult to understand acquisition (and to diagnose problems if not working)

  May require use of alternate auxiliary sensing scheme for lock acquisition

[1] Strategy of verifying adequacy for ligo

- low frequency analysis and numerical model

- frequency response analyzed; numerical model being debugged

- prototype

[1] The Experiment

- differences from ligo

  lengths, characteristic frequencies

  spectra of disturbances, bandwidth limitations in actuators

- similarities:

mirror reflectivities (list values)

modulation frequency

[1] - results:

model verification (including servo model and proposed method of dealing with ill conditioning) for coupled cavity experiment (show diagram)

[1] lock acquisition for full interferometer (show photograph)

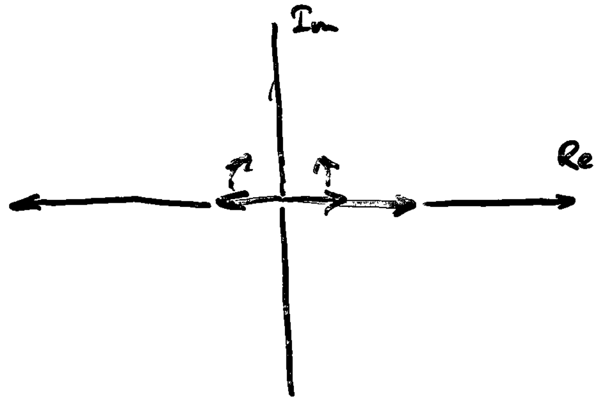
low frequency model verification in progress; would like to test frequency response as well

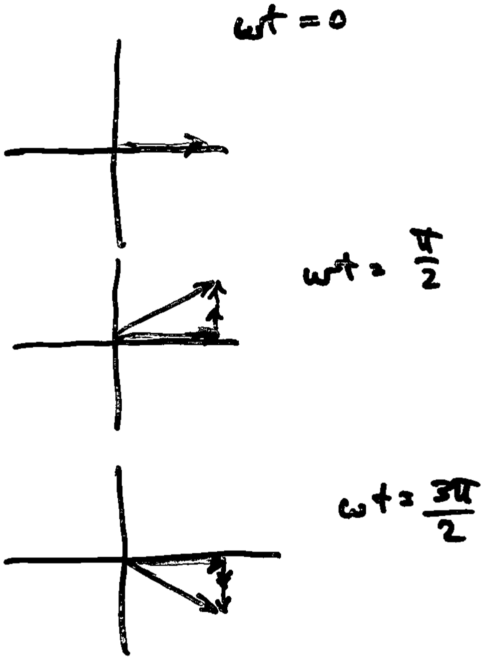
[1]Work Remaining

verify frequency response analysis and computer model against each other

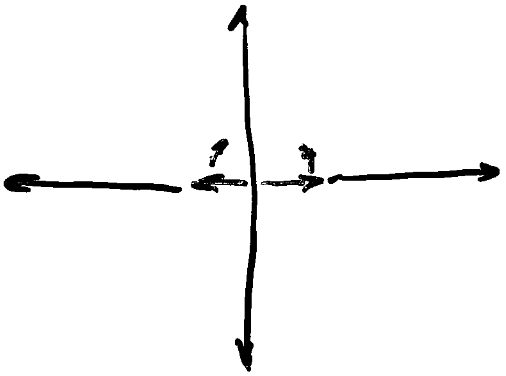
design a controller for ligo and verify performance by modelling

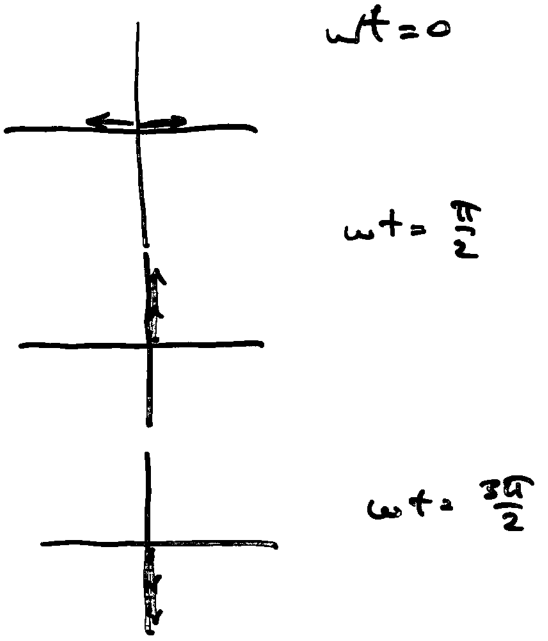
Represent with a phasor diagram in which carrier is stationary and sidebands rotate:





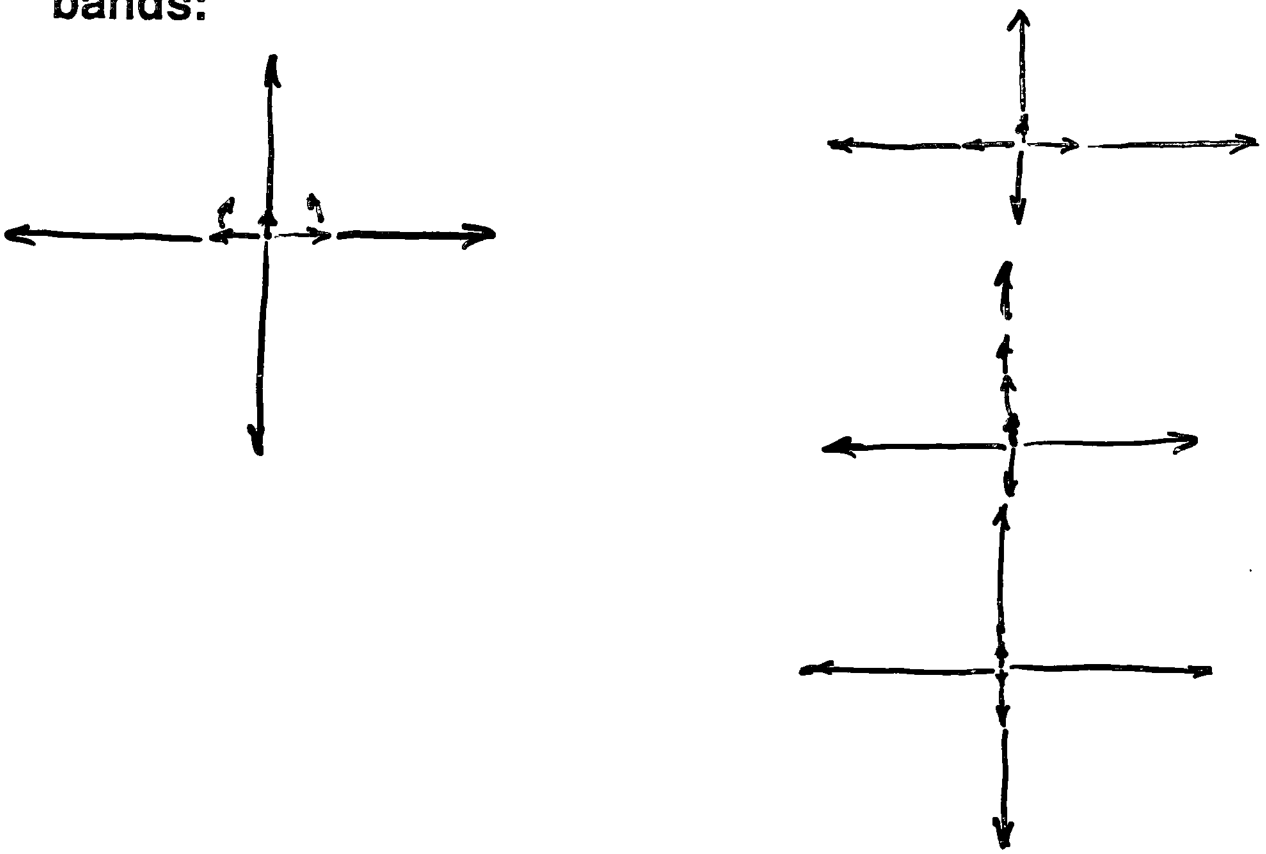
In absence of gravitational wave, only sidebands at ouput (sideband transmission maximum for quite large $(\lambda_m/4)$ asymmetry):





- Intensity of output light has only DC and 2ω frequency components.

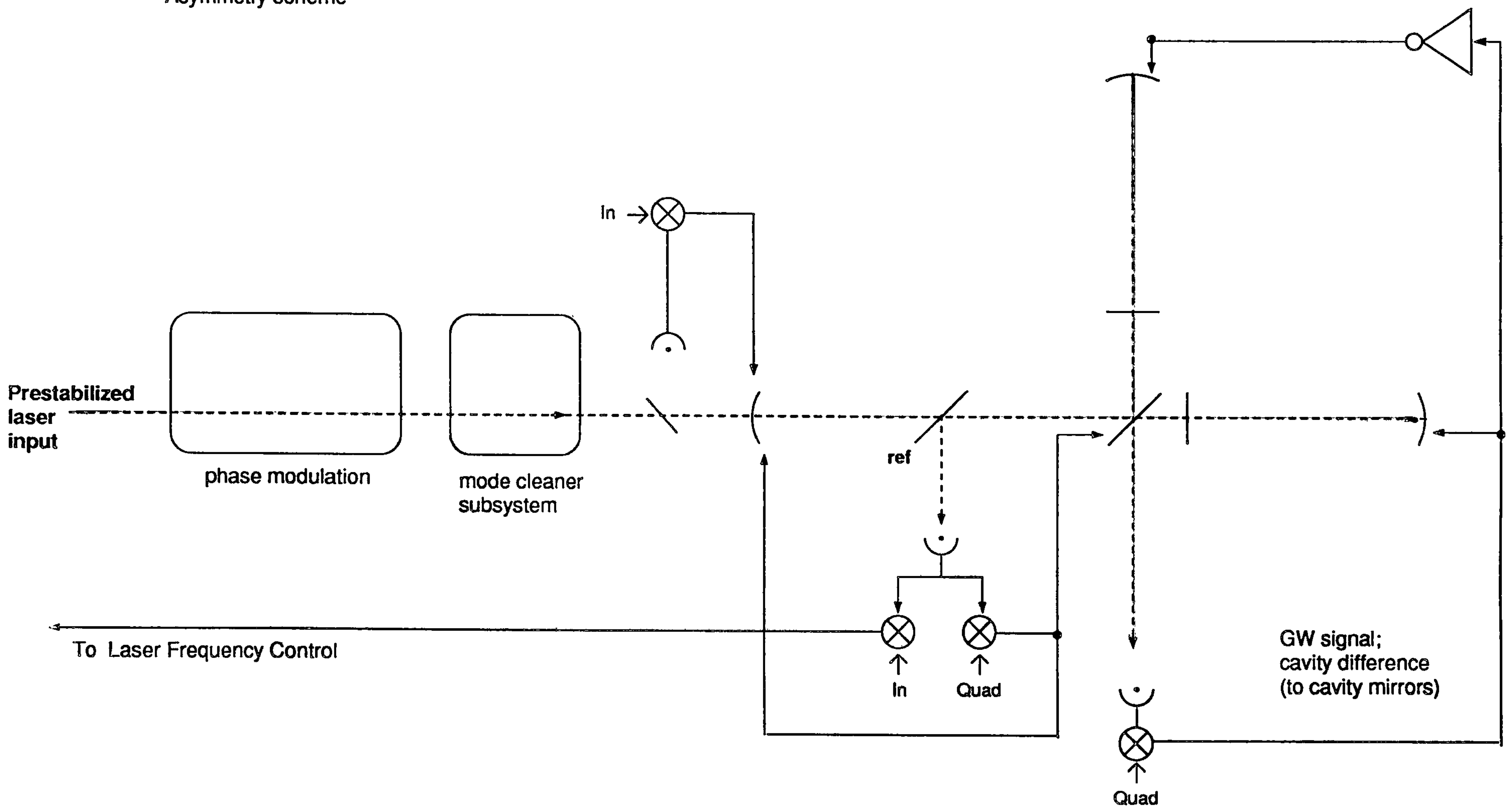
In presence of gravitational wave, carrier plus sidebands:



Output intensity contains component at frequency ω, proportional to gravitational wave amplitude.

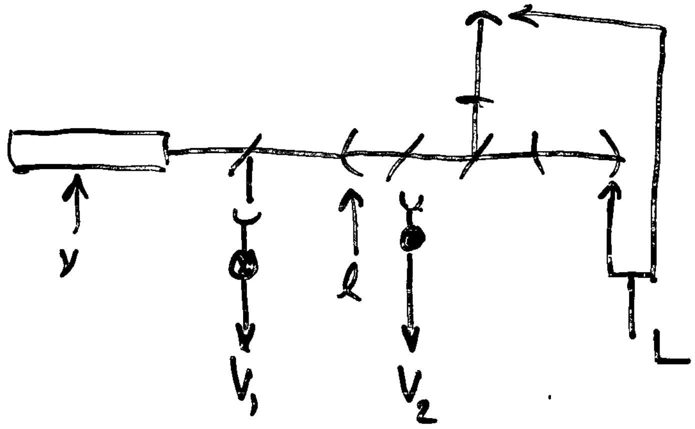
Detectable by demodulating at frequency ω.

Asymmetry scheme



Numerical Example

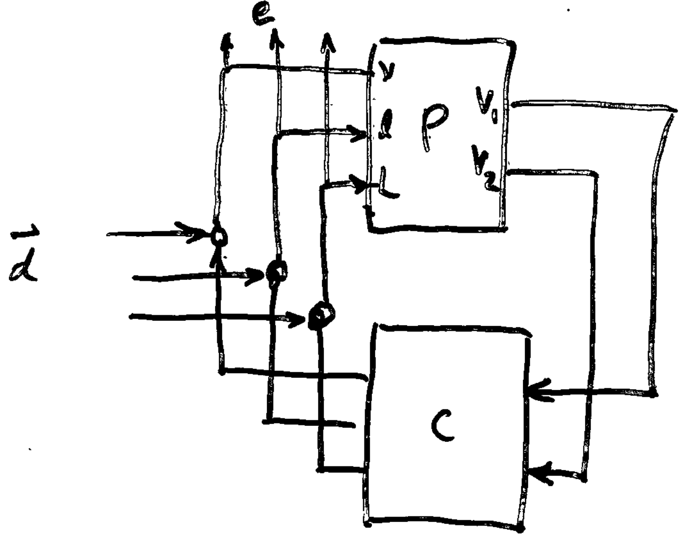
Inter ferometer



"Plant" P

$$P \begin{bmatrix} y \\ l \\ L \end{bmatrix} = \begin{bmatrix} V_1 \\ V_2 \end{bmatrix}$$

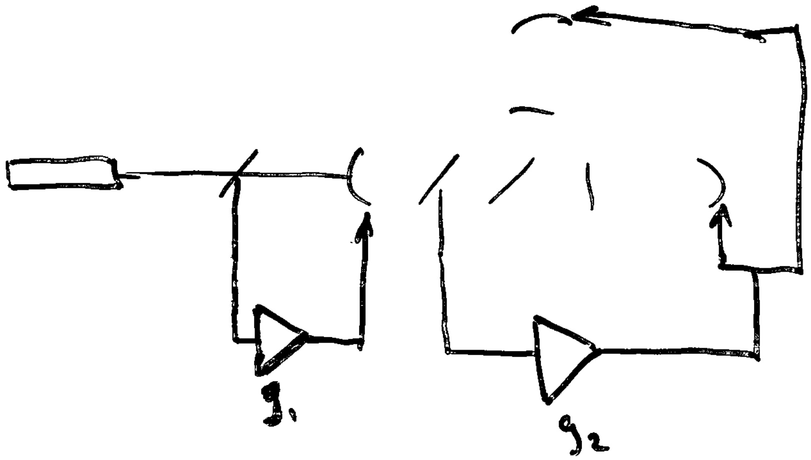
Feed back with controller C $\quad C \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} y \\ l \\ L \end{bmatrix}$



$$\vec{e} = \left[1 + CP\right]^{-1} \vec{d}$$

$$P = \begin{bmatrix} -72 + \frac{1}{400} & 1 & -72 \\ -589 + \frac{1}{400} & 1 & -589 \end{bmatrix}$$

Case 1: Feedback to masses without "inversion"



$$C = \begin{bmatrix} 0 & 0 \\ g_1 & 0 \\ 0 & g_2 \end{bmatrix}$$

Set g_1, g_2 s.t. gain through driven masses $\simeq 100$ (ie. $[1+CP]^{-1}_{22} = [1+CP]^{-1}_{33} = \frac{1}{101}$)

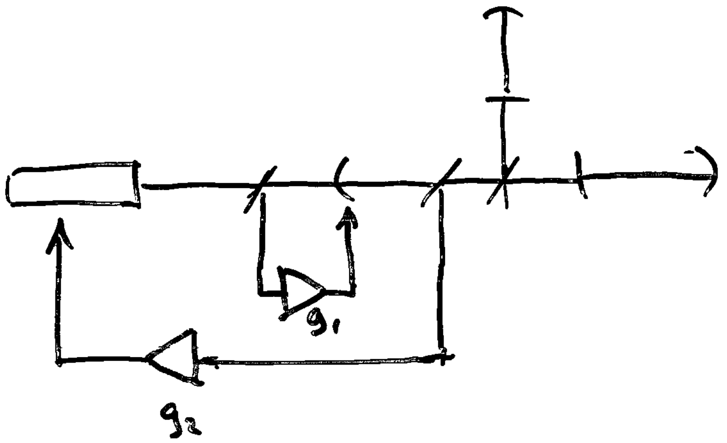
measure of performance: weighted disturbance suppression

$$W[1+CP]^{-1}$$

take $W = \begin{bmatrix} -\frac{1}{400} & 1 & 0 \\ -150 & 0 & 150 \end{bmatrix}$

in this case, max element of $W[1+CP]^{-1}$ is 1.4

Case 2: High gain feedback to laser:



Same constraint on gain through driven mass, but allow high gain in feedback to laser

$$[1+CP]^{-1}_{11} \simeq \frac{1}{16000}$$

Now max element of $W[1+CP]^{-1}$ is 0.01.