Diagonalizing sensing matrix of RSE interferometer

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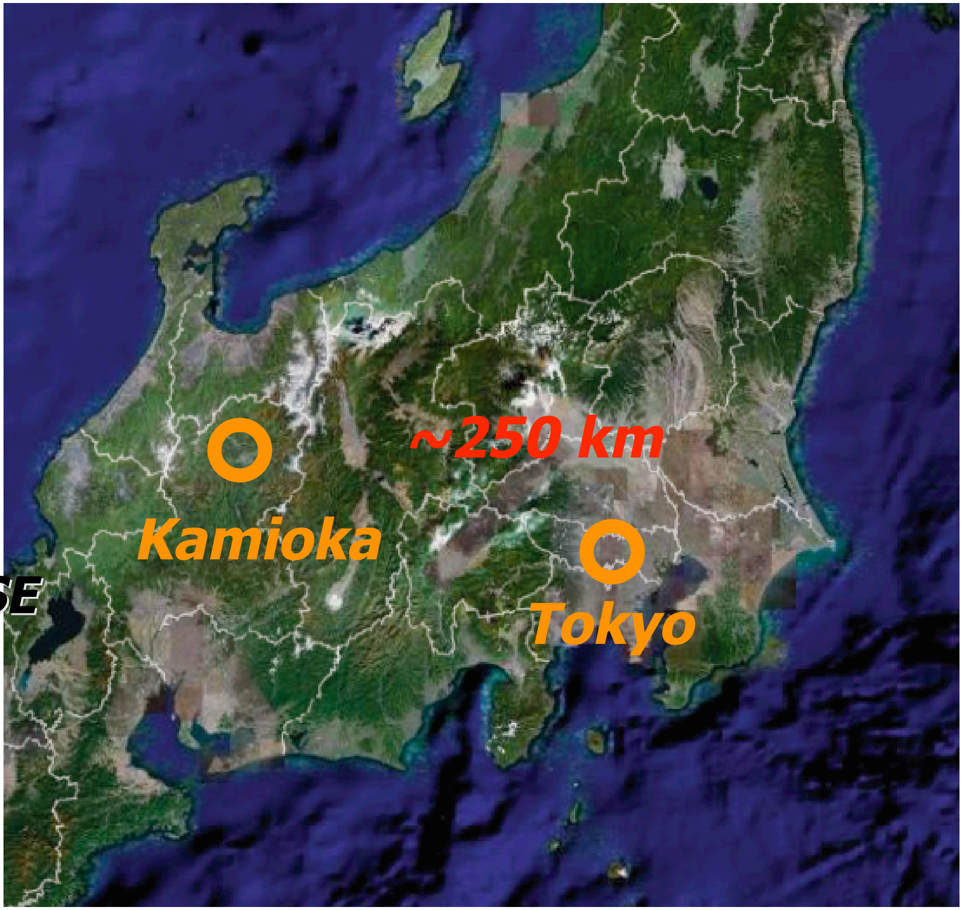
Introduction

- **Background**
  - ***LCGT : (exact) broadband RSE***
    - *3km long*
    - *Underground*
    - *Cryogenic*
  - ***No specific R&D for broadband RSE***



- **Goal**
  - ***Develop length sensing scheme***

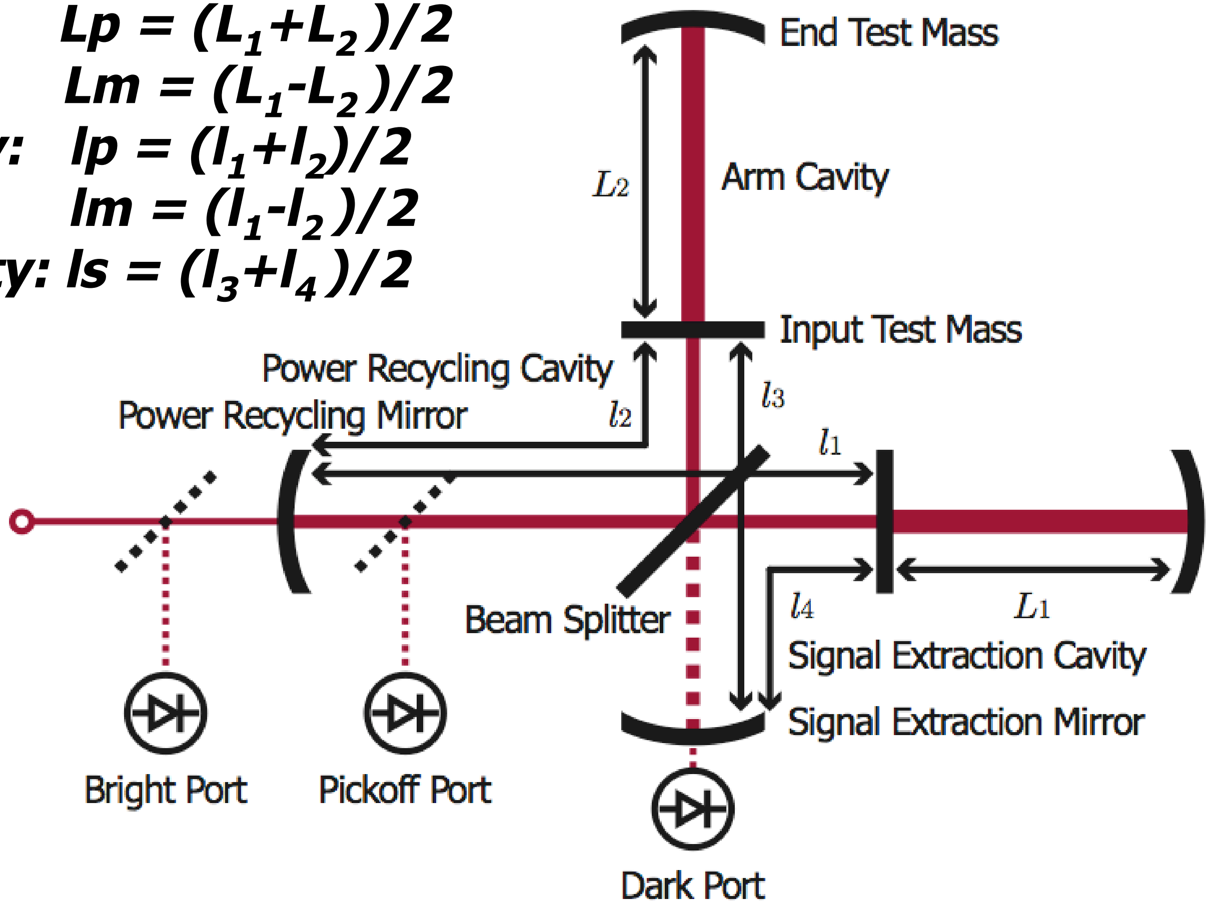
- **Points**
  - ***(Sufficiently) Diagonal sensing matrix***
  - ***Robust sensing scheme***
  - ***Scheme less sensitive to various noises***
  - ***Easy to acquire lock***

RSE interferometer

- **Additional mirror (SEM) at dark port**
  - ***LCGT: (exact) broadband RSE***

- **Length degrees of freedom**
  - ***Common-arm:*** $Lp = (L_1+L_2)/2$
  - ***Differential-arm:*** $Lm = (L_1-L_2)/2$
  - ***Power-recycling cavity:*** $lp = (l_1+l_2)/2$
  - ***Michelson :*** $lm = (l_1-l_2)/2$
  - ***Signal-extraction cavity:*** $ls = (l_3+l_4)/2$

- **Signal ports**
  - ***Bright (reflection)***
  - ***Pickoff***
  - ***Dark (GW-readout)***



Historical review

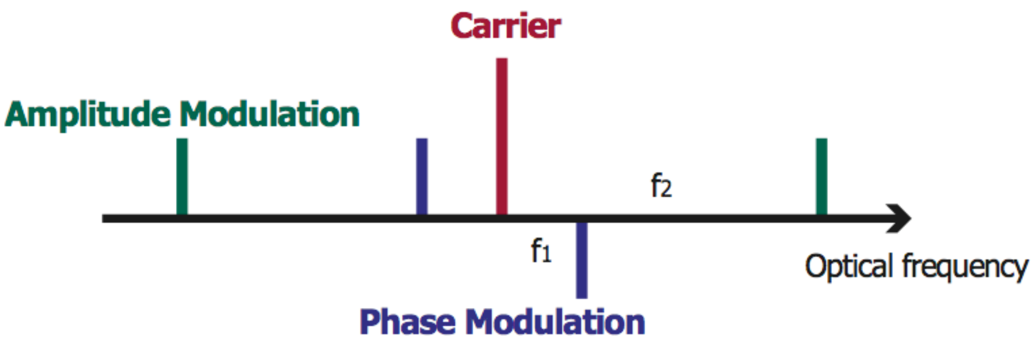
- **Idea of RSE**
  - ***MPQ***
    - *Jun Mizuno*
- **Several schemes and experiments (past)**
  - ***MPQ***
    - *Gerhard Heinzel et al.*
  - ***Caltech***
    - *James Mason et al.*
  - ***Australian National University***
    - *Daniel Shaddock et al.*
  - ***University of Florida***
    - *Guido Müller et al.*
  - ***NAOJ (Suspended w/o PRM as a part of full-RSE)***
    - *Osamu Miyakawa, Kentaro Somiya*
- **Several schemes and experiments (on-going)**
  - ***40m@Caltech : Suspended, detuned (broadband)***
    - *LIGO 40m team*
  - ***4m@NAOJ (full-RSE this time!) : Suspended, Broadband***
    - *Fumiko Kawazoe, Volker Leonhardt et al.*
  - ***Tabletop@ANU : Fixed, detuned***
    - *David Rabeling et al.*

Base line

- **Readout scheme**
  - ***RF readout***
  - ***DC readout is still under consideration***

- **Modulation scheme**
  - ***Double modulation (producing balanced sidebands)***
  - ***Double demodulation***
  - ***Parallel EOM modulation (to avoid sub-sidebands)***

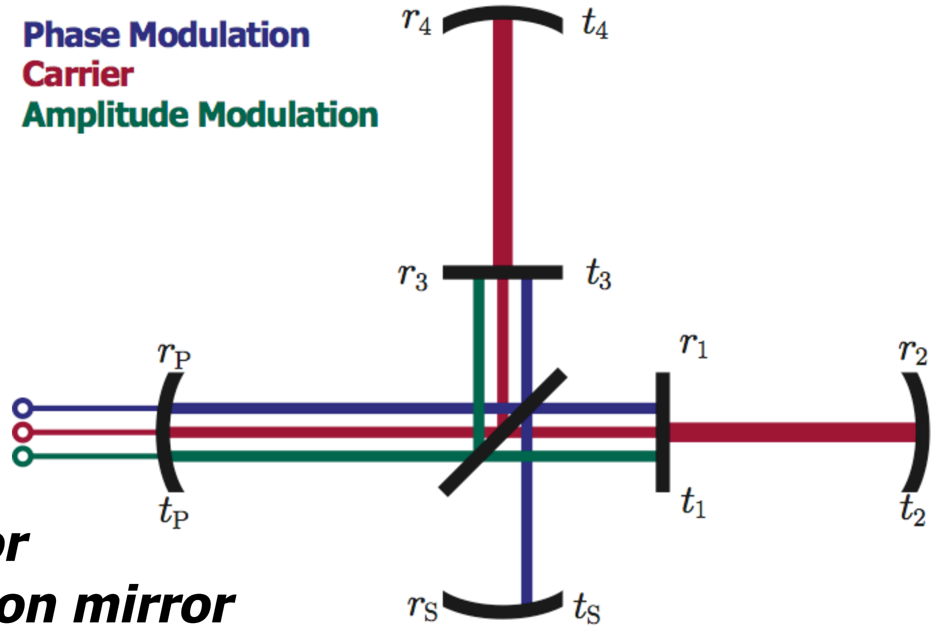
- **Modulation arrangement**
  - ***Carrier***
  - ***Phase modulation***
  - ***Amplitude modulation***

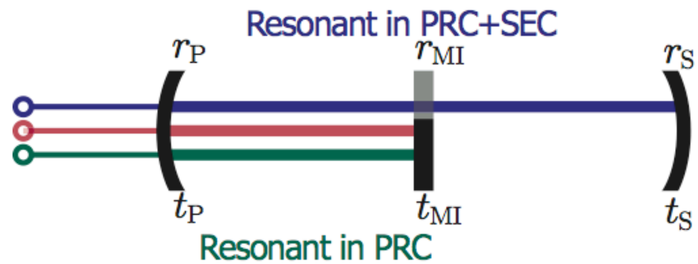


- **Signal extraction**
  - ***Arm control signals from CR x PM***
  - ***Signals for central part of RSE from PM x AM***

Modulation design (1)

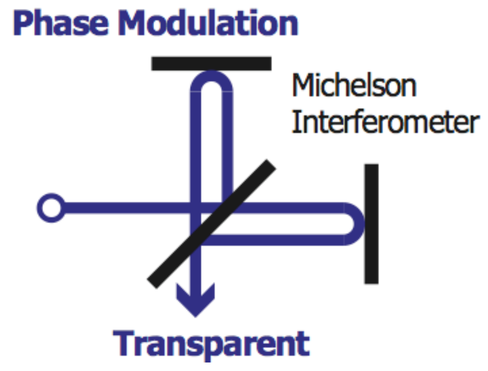
- **Carrier**
  - ***Circulates inside arms and PRC***
- **Phase modulation (f_1)**
  - ***circulates inside PRC+SEC***
- **Amplitude modulation (f_2)**
  - ***circulates inside PRC***
- **No longer coupled cavity**
  - ***For both modulation side bands***
  - ***PM: Michelson as a steering mirror***
  - ***AM: Michelson as an ideal reflection mirror***



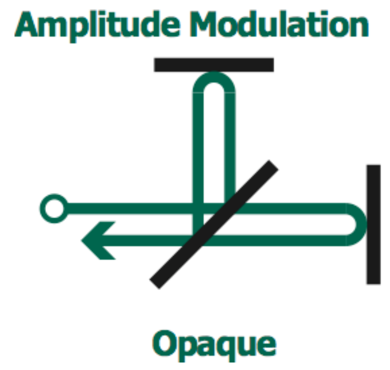


Modulation design (2)

- **Michelson interferometer (MI) is a kind of "mirror"**
  - **r_{MI}, t_{MI} are functions of l_{sch} and Ω_m**
    - $r_{MI} = \cos(l_{sch}\,\Omega_m/c)$
    - $t_{MI} = i\,\sin(l_{sch}\,\Omega_m/c)$



- **Point 1**
  - **MI is transparent to PM**
    - $r_{MIPM} = \cos(l_{sch}\,\Omega_{PM}/c) = 0,\ \ l_{sch}\,\Omega_{PM}/c = 0+n\pi$



- **Point 2**
  - **MI is opaque to AM**
    - $r_{MIAM} = \cos(l_{sch}\,\Omega_{AM}/c) = 1,\ \ l_{sch}\,\Omega_{AM}/c = \pi/2+m\pi$

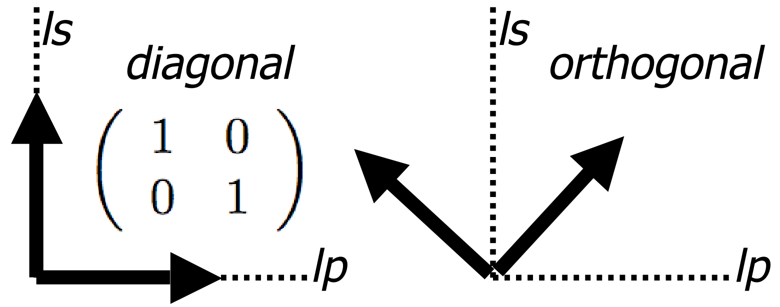
- **Example:**
  - $l_{sch} = 7.5\ m$
  - $\Omega_{PM} = 10\ MHz$
  - $\Omega_{AM} = 60\ MHz$ ($2\Omega_{PM} = 20MHz$, $4\Omega_{PM} = 40MHz$ does not work)

Signal extraction matrix

- **L-signals**
  - ***From CR x PM***
  - ***Almost diagonal due to carrier enhancement in arms***

$$\begin{pmatrix} 1 & 1 \\ -1 & 1 \end{pmatrix}$$

- **I-signals (central part of RSE)**
  - ***From PM x AM***
  - ***Orthogonal (instead of diagonal)***



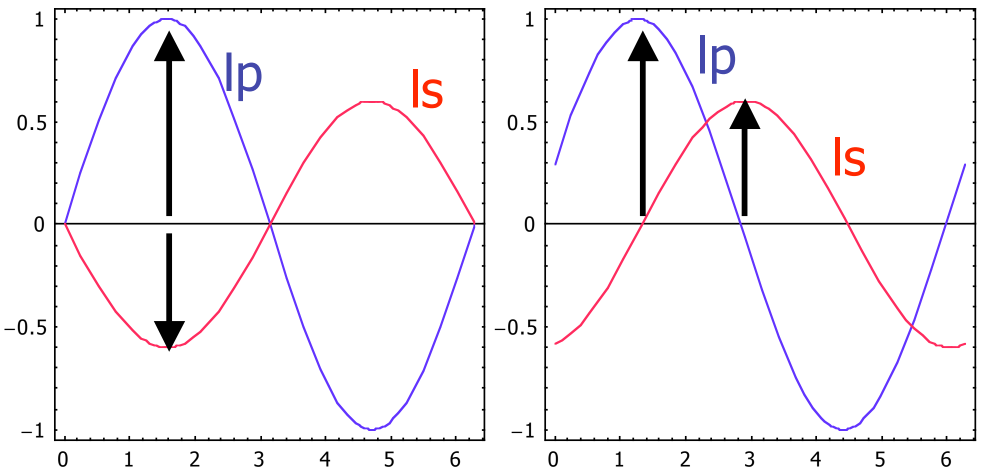
- **LCGT base line**

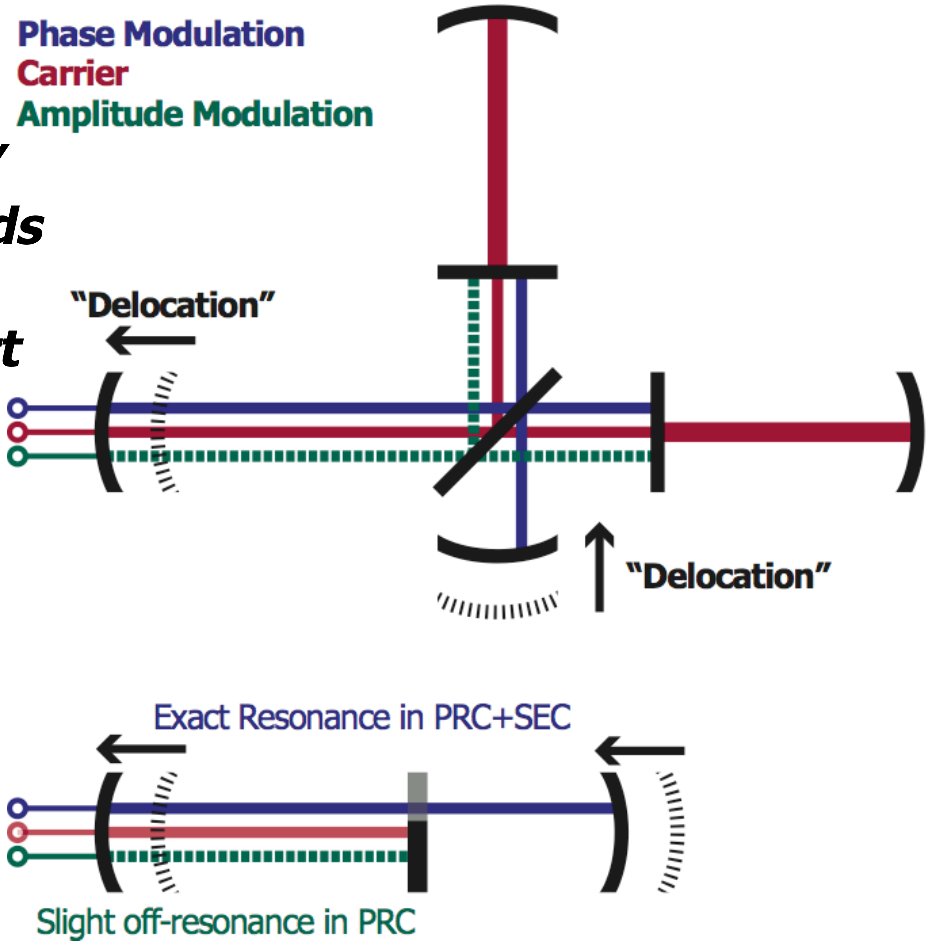
Black: Analytic results
Red: Numerical simulation using "FINESSE"

	DM	Phase		Degrees of freedom				
Port		*RF1*	*RF2*	*Lp*	*Lm*	*lp*	*lm*	*ls*
Bright	CRPM	0	-	**1** *1*	0 *0*	0.0036 *0.0026*	0 *0*	0.0026 *0.0013*
Dark	CRPM	90	-	0 *0*	**1** *1*	0 *0*	0.001 *0.00125*	0 *0*
Bright	AMPM	0	0	0.0017 *0.0021*	0 *0*	**1** *1*	0 *0.0006*	0.73 *0.51*
Dark	AMPM	90	0	0 *0*	0.001 *0.00238*	0 *0*	**1** *1*	0 *0*
Pickoff	AMPM	0	0	-0.00032 *-0.0019*	0 *0*	-1.3 *-1.65*	0 *-0.0012*	**1** *1*

“Delocation”

- **Same modulation arrangements**
  - **PM:** ***circulates inside PRC+SEC***
  - **AM:** ***circulates inside PRC***
- **The idea**
  - ***Make use of slight “off-resonance”***
    → Causes rotation of sideband fields
  - ***Different demodulation phases***
  - ***Two diagonal signals from one port***





Sensing matrix

- **Almost diagonal!**
  - **Perfect separation for Ip and Is (in principle)**

- **Some effect on**
  - **Signal strength**
  - **Off-diagonals**

Black: Analytic results
Red: Numerical simulation using "FINESSE"

	DM	Phase		Degrees of freedom				
Port		*RF1*	*RF2*	*Lp*	*Lm*	*lp*	*lm*	*ls*
Bright	CRPM	-1.3	-	**1** / *1*	0 / *0*	0.00356 / *-0.0026*	0 / *-0.000062*	0.00256 / *-0.0013*
Dark	CRPM	90	-	0 / *0*	**1** / *1*	0 / *0*	0.001 / *0.0013*	0 / *0*
Bright	AMPM	-1.3	14.4	0.001 / *-0.0017*	0 / *0*	**1** / *1*	0 / *0*	0 / *0*
Dark	AMPM	90	-14.4	0 / *0*	0.001 / *-0.0017*	0 / *0*	**1** / *1*	0 / *0*
Pickoff	AMPM	-1.3	42.4	0.001 / *0.00088*	-0.001 / *0*	0 / *0*	0 / *0*	**1** / *1*

Summary

- Base line signal sensing scheme for LCGT
- Simple arrangement of modulations
  - PM: inside PRC+SEC
  - AM: inside PRC
- Delocation enables diagonal signal sensing
- Still need to verify
  - Lock acquisition
  - Noise issue
  - Robustness