The Experimental plan of the 4m Resonant Sideband Extraction Prototype for The LCGT

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Abstract. The 4m Resonant Sideband Extraction (RSE) interferometer is a planned prototype of the LCGT interferometer. The aim of the experiment is to operate a power-recycled Broadband RSE interferometer with suspended optics and to achieve diagonalization of length signals of the central part of the interferometer directly through the optical setup. Details of the 4m RSE interferometer control method as well as the design of the experimental setup will be presented.
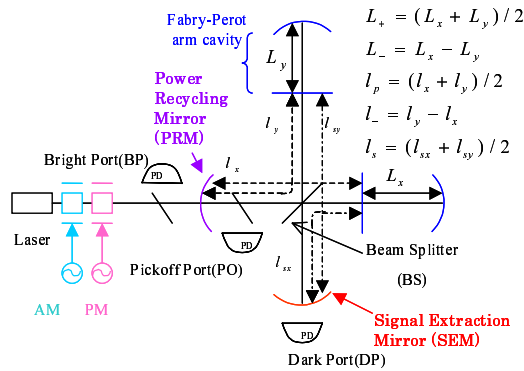
1. Introduction: The Next Generation Interferometer

Currently several interferometers are being operated or are about to be operated throughout the world. To achieve better sensitivity to the gravitational strain, next-generation interferometers will be built in the United Stetes and in Japan. The LCGT interferometer[1], planned to be built in Japan, will use a Resonant Sideband Extraction (RSE) technique[2] to improve the detector sensitivity and to increase the chance of detecting gravitational wave signals.

In order for the interferometer to operate properly all length degrees of freedom must be sensed and controlled. There are five degrees of freedom in the RSE interferometer which must be controlled as seen in Fig. 1. They are common and differential lengths of Fabry-Perot arms (L_+, and L_-), common and differential lengths of a Power Recycling Cavity (l_+, and l_-), and a common length of a Signal Extraction Cavity (l_s). There are three ports for detecting the lengths, Dark Port (DP), Bright Port (BP), and Pickoff Port (PO).

The control scheme of the RSE interferometer has been developed and the 4m prototype experiment will demonstrate the control scheme before it will be adopted by the LCGT interferometer. The 4m interferometer will have the same optical settings as the LCGT interferometer, Power-recycled Broadband RSE interferometer, except for the cavity lengths. The 4m interferometer will also test a scheme to diagonalize length signals of the central part of the interferometer directly through the optical settings.

The control scheme will be introduced in Section 2, the experimental design will be presented in Section 3, the schedule of the experiment will be shown in Section 4, and the conclusion will be presented in Section 5.
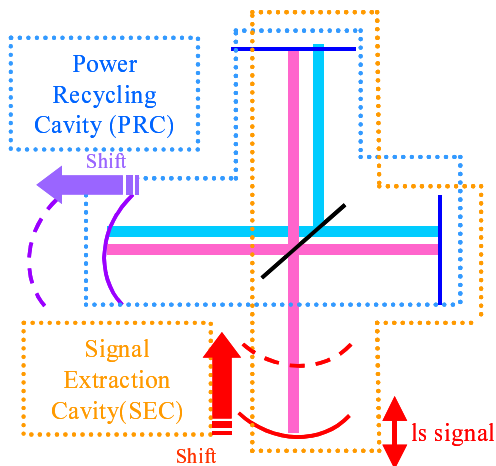
Figure 1. Degrees of freedom in the RSE interferometer.

2. Control Scheme

2.1. Signal extraction.

All degrees of freedom will be controlled by a frontal modulation. In order to extract the information of the length degrees of freedom in the central part of the RSE interferometer (the l_+, l_-, and l_s signals), a double demodulation technique will be used. There will be a set of amplitude modulated (AM) sidebands and a set of phase modulated (PM) sidebands at each modulation frequency in addition to the carrier which has the frequency of the laser. The Fabry-Perot cavity length signals are obtained by beating the carrier with one of the two sidebands. The length signals of the central part are obtained by beating between the two sidebands.

2.1.1. Behavior of the two sidebands in the Michelson interferometer.

In order to extract the length control signals of the central part of the interferometer efficiently, the AM sideband is designed to resonate inside the Power Recycling Cavity (PRC) and the PM sideband is designed to resonate inside the the compound cavity made by the PRC and the Signal Extraction Cavity (SEC). The Michelson asymmetry factor α determines how the two sidebands behave in the Michelson interferometer. It is expressed as $\alpha = \Delta l \omega_m / c$, where the ω_m are the modulation frequencies, c is the speed of light, Δl is the Michelson asymmetry, introduced to completely reflect the AM sideband while transmitting the PM sideband, as shown in Fig. 2. For the AM sideband $\cos(\alpha_{AM}) = \pm 1$, while for the PM sideband it is $\sin(\alpha_{PM}) = \pm 1$. In this way, the PM sideband is sensitive to the l_s signal and the AM sideband is not. Thus, beating between the two enables one to extract the l_s signal most efficiently.

Figure 2. Behavior of the two sidebands in the central part of the interferometer and the delocation scheme.

2.1.2. **Delocation scheme.** In order to control the interferometer properly, all the length control signals need to be extracted clearly. The scheme being used in current interferometers is already capable of extracting clear L_+ and L_- length signals. The l_+, l_s, and l_- also need to be extracted clearly. Diagonalizing these three signals at the PO enables one to do it. The way to diagonalize the three signals (delocation technique) has been developed[3] and it will be tested with the 4 meter test interferometer.

Figure 2 shows how the delocation technique will be operated. By shifting the position of the Power Recycling Mirror (PRM) and the Signal Extraction Mirror (SEM) by the same magnitude and direction, the resonating condition of the AM sideband will be disturbed while that of the PM sideband will be kept. When choosing the demodulation phases to extract the l_+, l_s, and l_- signals at their maximum values, one can choose three sets of demodulation phase that are about 90 degrees rotated with respect to each other, thus making it possible to extract clear diagonalized signals with very little signal mixing. One can also extract perfectly separated signals by choosing the demodulation phases that makes undesirable signals to be 0 at the cost of a decrease in the magnitude of the desired signal, which turns out to be negligible.

2.1.3. **Signal extraction matrix.** Figure 3 shows the default signal extraction matrix of the central part of the LCGT interferometer, calculated by using the parameter designed for the 4m interferometer. The l_+ signal and the l_s signal mix at the PO, which can be separated by adding and subtracting signals from the BP and the PO. On the other hand, when the delocation technique is adopted, the l_+, l_s, and the l_- signal at the PO will be diagonalized and each of them can be extracted clearly without any additions or subtractions. Thus the delocation scheme provides simpler way for extracting clear signals. At the same time, it is confirmed by simulations that the clear l_- signal can be extracted from the DP.

	port	Demodulation	Dem. Phase (PM, AM)	l+	l-	ls
l+	BP	$f_{PM} \cdot f_{AM}$	(0,0)	1	-0.005	-0.504
l-	DP	$f_{PM} \cdot f_{AM}$	(90,0)	-0.000	1	-0.000
ls	PO	$f_{PM} \cdot f_{AM}$	(0,0)	1.657	0.001	1

Figure 3. Signal extraction matrix without the delocation scheme.

	port	Demodulation	Dem. Phase (PM, AM)	l+	l-	ls
l+	PO	$f_{PM} \cdot f_{AM}$	(173,46)	1	-0.000	0.000
l-	PO	$f_{PM} \cdot f_{AM}$	(90.23158)	0.000	1	-0.000
ls	PO	$f_{PM} \cdot f_{AM}$	(172.6,138.7)	0.000	-0.000	1

Figure 4. Signal extraction matrix with the delocation scheme.

3. Experimental Design
3.1. **Control parameter.**
Table 1 shows the designed control parameter.

- Frequency of the PM sideband
  We choose the frequency of the PM sideband to be 17.25 MHz because of the practical reason.

- Michelson asymmetry factor
  The asymmetry factor for the PM sideband is expressed as $\omega_{PM}\Delta l/c = \pi(2m + 1)/2$ $(m = 0, 1, 2, ...)$. To make the asymmetry length practical for the length of the existing vacuum chambers, we chose $m = 0$, thus $\omega_{PM}\Delta l/c = \pi/2$.
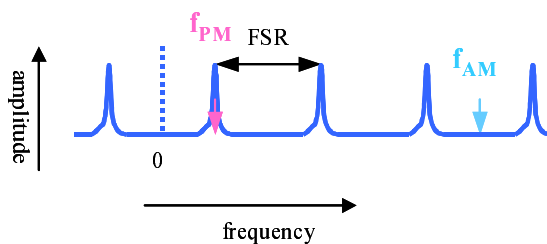
Table 1. Control parameter.

Parameter	values
Frequency of the PM sideband	17.25 MHz
Frequency of the AM sideband	103.5 MHz
Free Spectral Range of the PRC	34.5 MHz
Free Spectral Range of the SEC	34.5 MHz
Arm cavity finesse	2000
Michelson length asymmetry	4.35 m

- Frequency of the two sidebands
  The asymmetry factor for the AM sideband is expressed as $\omega_{AM}\Delta l/c = n\pi$ $(n = 1, 2, 3, ...)$. From this and $\omega_{PM}\Delta l/c = \pi/2$, the ratio of the frequency of the AM sideband to that of the PM sideband is determined to be $f_{PM} : f_{AM} = 1 : 2n$. If the ratio 1:2 is used, beating between the two sidebands would produce the same frequency component as beating one of the sidebands with the carrier, resulting in the problem of the L and l signals mixing. The ratio 1:4 can not be used, firstly because in this case the reflectivity of the Michelson for the AM sideband is 1, making it impossible for the PM to be either resonant or anti-resonant inside the PRC.[1] Secondly, there will not be enough separation between the frequency of the PM sideband so that the beat component between the third harmonics of the PM sideband and the carrier may not be negligible compared to the beat between the PM and the AM sidebands. Available photodetectors restrict us to choose f_{AM} to be much higher than 100 MHz, thus choosing $n < 4$ is required. Thus we chose $n = 3$ and $f_{PM} : f_{AM} = 1 : 6$

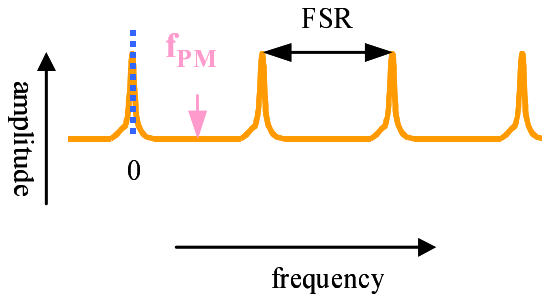- Free Spectral Range (FSR) of the PRC
  Figure 5 shows the amplitude of the light inside the PRC as a function of the frequency of the light. When the light is resonant inside the cavity its amplitude is at maximum and when it is anti-resonant the amplitude is minimum. The distance in frequency between resonance peaks is called Free Spectral Range (FSR) and it is expressed as $c/2L_{PRC}$ where L_{PRC} is the length of the PRC. Note that the carrier is anti-resonant without the presence of the Fabry-Perot arms which will introduce a phase flip when present. The length of the PRC is set to be anti-resonant for the AM sideband so that with a phase flip due to the reflection from the Michelson part it becomes resonant inside the cavity. The PM sideband can be either resonant or anti-resonant inside the cavity. Designing the PM sideband to be resonant in the cavity will let us choose the shortest cavity length as shown in Fig. 5 and when this is the case $c/2L_{PRC} = 2f_{PM} = 34.5$MHz thus $L_{PRC} = c/4f_{PM} = 4.34$m.

Figure 5. Resonance curve of the AM sideband and the PM sideband in the PRC.

[1] When the PM sideband is neither resonant nor anti-resonant in the PRC, there will be a phase shift in a demodulation phase for l_- signal. It will disturb the l_+ and l_s signals at the PO.
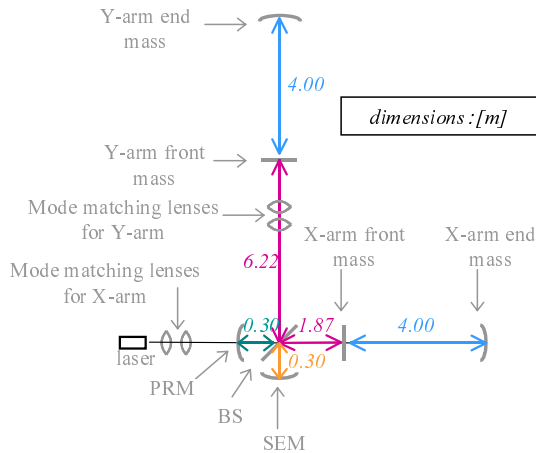
- FSR of the SEC

  The SEC is designed to be anti-resonant for the PM sideband so that the sideband will be resonant in the compound cavity formed by the PRC and SEC. Choosing the FSR of the SEC to be $c/2L_{SEC} = 2f_{PM}$ let us choose the shortest length of the SEC, as shown in Fig. 6. Note that the carrier is resonant in the SEC. $L_{SEC} = c/4f_{PM} = 4.34$.

Figure 6. Resonance curve of the PM sideband in the PRC.

3.2. **Layout of the interferometer.**

Figure 7 shows the designed layout of the entire interferometer. This design is without the delocation scheme. When the delocation scheme is operated the length of the PRC and the SEC will be 3.5 cm longer/shorter than this design. The signal extraction matrix of the entire interferometer with this design is calculated and shown in Fig. 8.

Figure 7. Designed layout of the test interferometer.

	port	Demodulation	Dem.phase (MHz)	L+	L-	l+	l-	ls
L+	BP	f_{PM}	0	1	-0.000	-0.002	-0.000	0.001
L-	DP	f_{PM}	90	0.000	1	-0.000	0.001	-0.000
l+	PO	$f_{PM}*f_{AM}$	PM,AM (0,0)	-0.003	-0.000	1	-0.005	-0.504
l-	DP	$f_{PM}*f_{AM}$	(90,0)	-0.000	0.003	-0.000	1	-0.000
ls	PO	$f_{PM}*f_{AM}$	(0,0)	-0.047	0.000	1.657	0.001	1

Figure 8. Signal extraction matrix of the entire interferometer.

4. Schedule Of The Experiment

The schedule of the experiment is shown in Table 2.

Table 2. chedule of the Experiment.

Year	Plan
1st	Lock the Fabry-Perot Michelson interferometer with a single demodulation technique. Prepare for a double demodulation technique by making electronic circuits.
2nd	Lock the full RSE with the double demodulation technique.
3rd	Test the delocation scheme.

5. Conclusion

The 4m Resonant Sideband Extraction (RSE) interferometer experiment is about to be commenced as the prototype of the LCGT. It will first demonstrate the control scheme developed for the LCGT, and then test the delocation scheme to diagonalize the length sensing signals of the cental part of the RSE interferometer.

6. Acknowledgments

References

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