Experimental investigation of a control scheme for a tuned resonant sideband extraction interferometer for next-generation gravitational-wave detectors

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Abstract. LCGT plans to use a tuned RSE interferometer as its optical configuration. A tuned RSE interferometer has five degrees of freedom that need to be controlled in order to operate it as a gravitational-detector, although it is expected to be very challenging because of the complexity of its optical configuration. A new control scheme for a tuned RSE interferometer has been developed and tested with a prototype interferometer to demonstrate the lock of the tuned RSE interferometer. The whole RSE interferometer was successfully locked with the control scheme. Here the control scheme and the current status of the experiment are presented.

1. Introduction

Presently several lazer interferometer gravitational-wave detectors, such as LIGO[1], GEO600[2], VIRGO[3], and TAMA300[4], are in operation around the world. In addition to the present detectors, there are plans to upgrade them to next-generation interferometers. Amongst them there are Advanced LIGO[5] and LCGT[6], which plan to use the RSE technique to enhance their detector sensitivities. The LCGT plans to use a tuned RSE configuration while the Advanced LIGO plans to use a detuned RSE configuration. Despite the great advantage of better sensitivity, the RSE configuration poses a more difficult challenge in controlling the interferometer in order to use it as a gravitational-wave detector due to the increased number of degrees of freedom (DOF) that need to be controlled. Therefore, designing a control scheme as simple as possible, and demonstrating it are vital before the technique is adapted in large-scale interferometers such as LCGT. In section 2, the control scheme is described and in section 3, the current status of the experiment is presented.

2. Control of the RSE interferometer

2.1. *Degrees of freedom in the RSE interferometer*

The RSE has five DOFs to be controlled as shown in Fig.1. They are the average length and the differential length of the two Fabry-Perot (FP) cavities, $L+$, and $L-$, respectively, as indicated by red arrows, the average length and the differential length of the power recycling cavity(PRC), $l+$, and $l-$, respectively, as indicated by green arrows, and the average length of the signal extraction cavity(SEC), ls, as indicated by blue arrows.

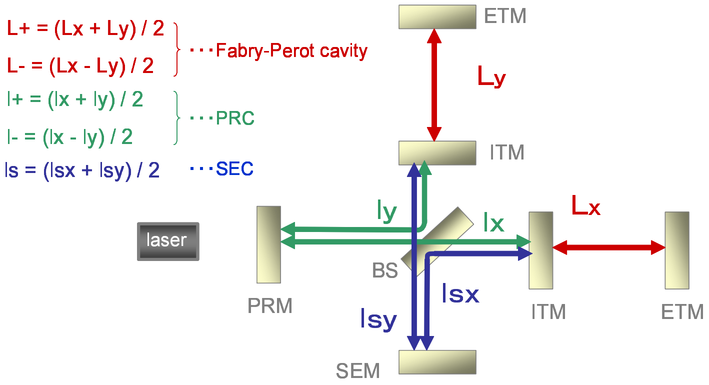

Figure 1. Degrees of freedom in the RSE interferometer.

It is known from experience with present detectors that use the Pound-Drever-Hall (PDH) method that the FP cavities are relatively easy to control with clear control signals as the cavities have high finesse. On the other hand, it is expected to be quite challenging to obtain clear control signals of the central part of the RSE, because the resonant conditions of the light fields inside the central part will be strongly affected by both the PRC, and the SEC. Thus the control scheme has to be designed in such a way that it maneuvers the resonant conditions of the light inside.

2.2. *The control scheme*

The outline of the control scheme is as follows. It is based on the PDH method. The FP cavity lengths are controlled with a single modulation-demodulation technique and the central part of the RSE is controlled with a double modulation-demodulation technique with amplitude modulation (AM) sidebands and phase modulation (PM) sidebands. By using the double modulation-demodulation technique, the control signals for the central part will be affected very little by the carrier resonance conditions which contain mainly the control signals for the FP cavities, thus it decouples the FP cavities and the central part.

2.3. *The central part*

The central part is designed so that the AM and the PM sidebands behave in the following way. The lengths of two paths that compose the Mihelson interferometer have a macroscopic asymmetry such that when the carrier interferes destructively at the dark port (DP), the AM sidebands interfere constructively at the bright port (BP) and destructively at the DP, while the PM sidebands interferes destructively at the BP and constructively at the DP. Thus the AM sidebands “reflect completely” from the Michelson part while the PM sidebands “transmit completely” through the Michelson part. This condition is met when the round trip Michelson asymmetry length is designed to be equal to $(2m+1)/2$ ($m = 0, 1, 2, \ldots$) times the wavelength for the AM sidebands and integer multiple of the wavelength for the PM sidebands. In our design it is 3λ for the AM sidebands and $\frac{1}{2}\lambda$ for the PM sidebands, as shown in Fig.2. Two

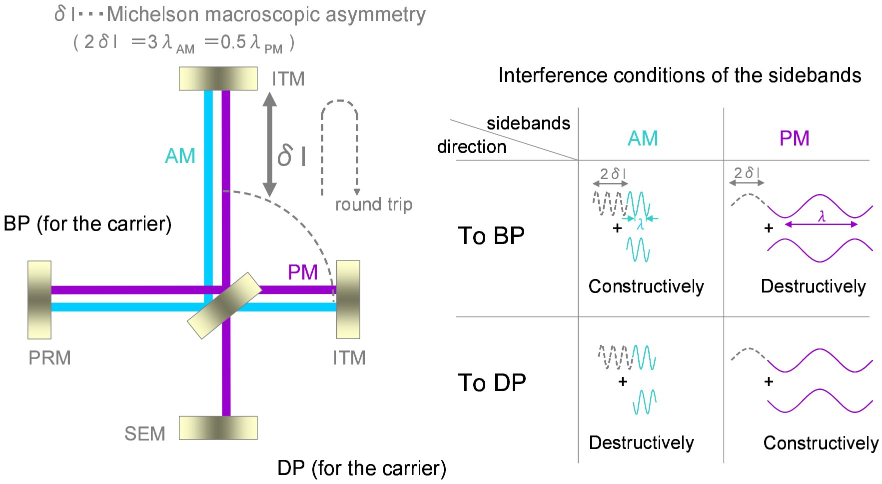

Figure 2. Interference conditions of the two sets of sidebands in the central part of the RSE interferometer.

cavities' macroscopic lengths are designed so that the AM sidebands resonate inside the PRC and the PM sidebands resonate inside the compound cavity made of the PRC and the SEC[7]. This enables the PM sidebands to be sensitive to the length of the SEC while the AM sidebands is not affected by the SEC length, thus ensuring independent control signals for $l+$ and ls.

2.4. Delocation scheme

In addition we have designed an additional scheme to optically diagonalize the control signal matrix[8]. It could provide possible advantages such as a better signal to noise ratio, a simpler lock acquisition process, and a more robust control of the interferometer. The scheme is applied as shown in Fig.3. The physical position of the power recycling mirror (PRM) and the signal extraction mirror (SEM) is shifted in the same direction by the same amount, as indicated by red arrows in the figure. After the technique is applied, the AM sidebands are off resonant inside the PRC while the PM sidebands stay resonant inside the compound cavity. Due to

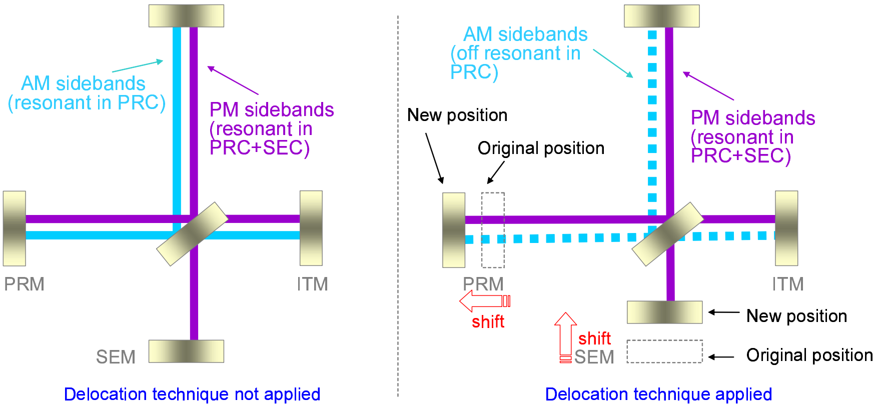

Figure 3. Central part with and without the delocation technique.

the change in the resonance condition of the AM sidebands, there are changes in the proper demodulation phases, and when the delocation scheme is applied properly each demodulation phase for the three control signals is orthogonal to each other at the pick-off port (PO). Thus the signal matrix can be optically diagonalized as shown in Table.2. For comparison, the normalized matrix without the delocation technique is listed on Table1. Although the three signals can be diagnolized at the PO, in reality l_- should be detected at the DP where the shot noise is smallest.

Table 1. Normalized control signal matrix

	$L+$	$L-$	$l+$	$l-$	ls
BP(SD)	1	8.0×10^{-6}	-2.6×10^{-2}	6.2×10^{-4}	1.3×10^{-2}
DP(SD)	-2.2×10^{-8}	1	1.4×10^{-8}	1.3×10^{-2}	2.0×10^{-8}
BP(DD)	-4.9×10^{-2}	-1.1×10^{-4}	1	-8.6×10^{-3}	-5.3×10^{-1}
DP(DD)	-1.0×10^{-4}	7.6×10^{-2}	1.4×10^{-3}	1	1.1×10^{-5}
PO(DD)	-1.5×10^{-1}	-1.2×10^{-2}	1.1	-2.2×10^{-2}	1

Table 2. Normalized diagonalized control signal matrix

	$l+$	$l-$	ls
PO(DD)	1	-4.2×10^{-3}	5.5×10^{-4}
DP(DD)	2.2×10^{-3}	1	-5.6×10^{-5}
PO(DD)	5.0×10^{-4}	-1.1×10^{-7}	1

3. Experimental status

In 2006 we designed and built a prototype tuned RSE interferometer inside the campus of National Astronomical Observatory of Japan(NAOJ). Figure 4 shows the optical layout of the prototype interferometer. The test masses are suspended as a double pendulum to suppress the mirror motion at frequencies above the resonant frequency. The test mass motion around its resonant frequency is damped by the Eddy current damping system.

The lock of the central part of the RSE has been successfully demonstrated. As of July 2007, the two Fabry-Perot cavities are individually locked instead of controlling the $L+$ and the $L-$ DOFs which is a designed configuration. The lock is demonstrated without the delocation scheme at present. Figure 5 shows the lock states. Each state indicates as follows.

- State 1 : Michelson is locked to dark fringe at the DP.
- State 2 : Power-recycled Michelson is locked.
- State 3 : Central part is locked.
- State 4 : Tuned RSE is locked

In state 3, the carrier is not yet resonant inside the PRC because it is not resonant inside the FP cavities, thus there is no phase flip due to the carrier resonance. Figure 6 shows the DC power detected at various ports, (i.e. DP, BP, PO, transmitted port for the inline FP cavity and

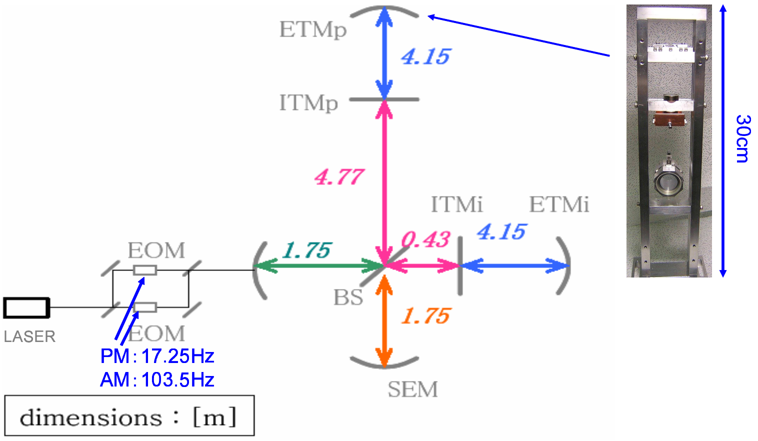

Figure 4. Optical layout or the prototype interferometer.

for the perpendicular FP cavity.) Each lock state is separated with boxes with colors specified in Fig.5. In order to verify the locking status, resonant conditions for the two sets of sidebands are monitored with optical spectrum analyzer placed at the DP and the PO. Figure 7 shows the output of the optical spectrum analyzers. The red curves are the output power at the PO and the blue curves are output power at the DP. Colored boxes indicate the lock state, as specified in Fig.5. In state 1, neitherf the AM nor the PM sidebands are resonant. In state2, the AM sidebands are resonant inside the PRC, thus there are resonant peaks of the AM sidebands detected at the PO. The PM sidebands are not yet resonant. In state3, the PM sidebands are resonant inside the compound cavity made of the PRC and the SEC thus there are resonant peaks of the PM sidebands detected at the DP.

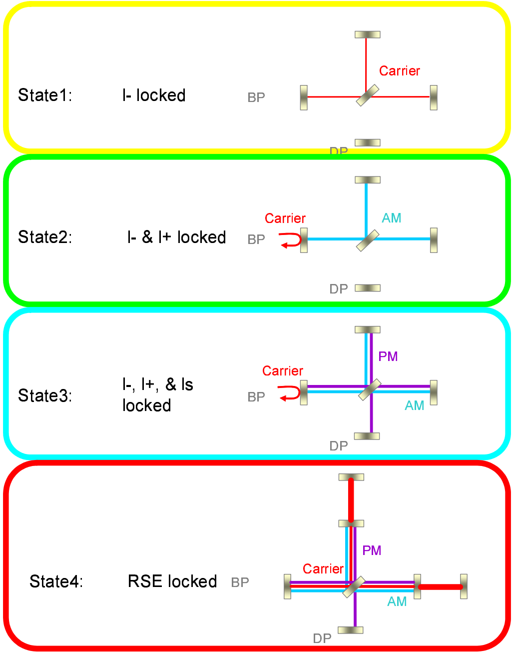

Figure 5. Lock states of the interferometer.

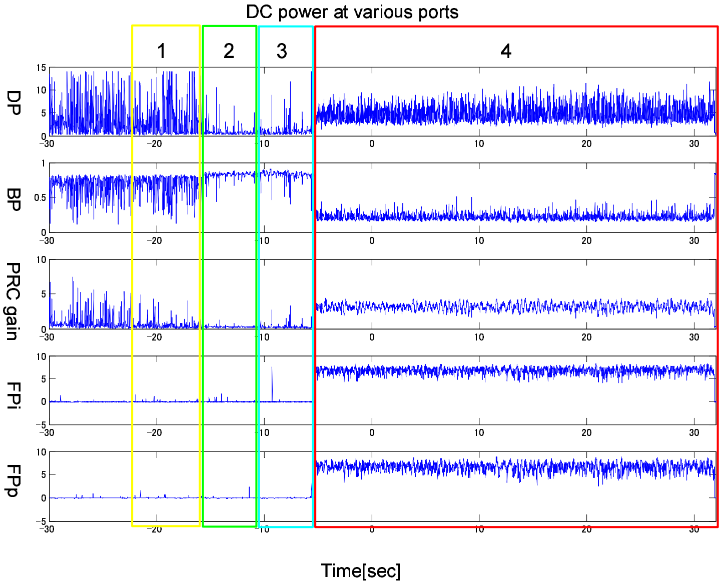

Figure 6. DC power at various ports.

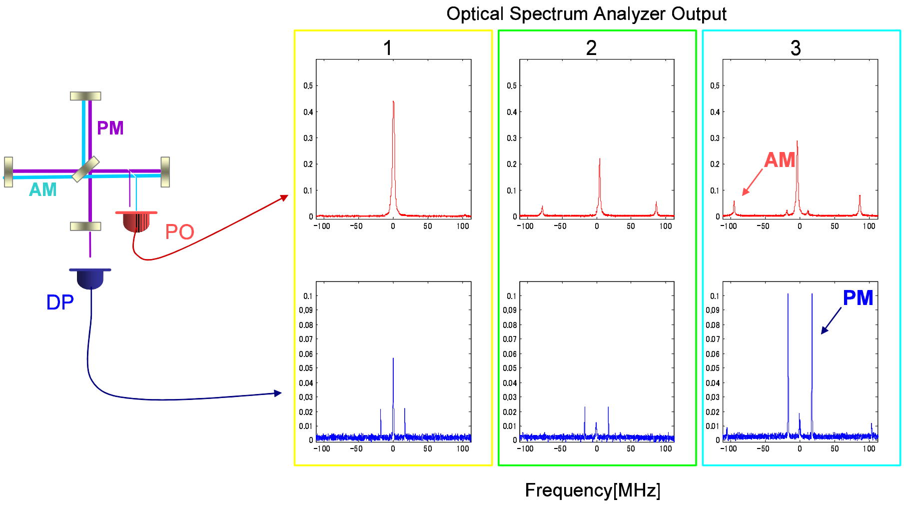

Figure 7. Sideband resonant peaks inside the PRC and the SEC.

4. Summary and future work

The new control scheme of a tuned RSE for next-generation gravitational-wave detectors was developed and has been tested with a prototype RSE interferometer. The lock of the tuned RSE interferometer has been successfully demonstrated. As of July 2007, the FP cavities are individually controlled, which differs from the final control design which controls the common and the differential signals of the cavities. Towards the lock of the tuned RSE interferometer with the final design, the common and the differential control will be tested. The delocation scheme can be tested after the full lock is successfully demonstrated.

4.1. Acknowledgments

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