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A novel concept for increasing the peak sensitivity of initial LIGO by detuning the arm cavities

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Abstract. We introduce a concept that uses detuned arm cavities to increase the shot noise limited sensitivity of initial LIGO without increasing the light power inside the arm cavities. Numerical simulations show an increased sensitivity between 150 and 350 Hz, with a maximal improvement of about 45 % around 230 Hz, while the sensitivity above 350 Hz is decreased. Furthermore our concept is found to give a sensitivity similar to that of a conventional RSE configuration with a Signal-Recycling mirror of moderate reflectivity. However, due to the easier implementation of detuned arm cavities compared to RSE, our concept might be a beneficial alternative to increase LIGO's black hole binary horizon in the near term future.

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1. Introduction

The first generation of large-scale laser-interferometric gravitational wave detectors [1, 2, 3, 4] is now in operation and collects data of impressive sensitivity and bandwidth. The optical configurations of these kilometer long gravitational wave observatories are based on a Michelson interferometer. Moreover, the standard configuration, implemented in the three LIGO interferometers as well as in Virgo and TAMA300, employs cavities in the arms of the interferometer and Power-Recycling to increase the storage time of the light inside the interferometer. In order to get an optimal power increase inside the arm cavities, these are kept to be resonant for the carrier light. However, as we show in this article, detuning these arm cavities by a few hundred Hz has the advantage of a larger signal gain in a certain frequency band and might therefore be favorable.

In section 2 we give a brief and intuitive description of the principle of an optical configuration employing detuned arm cavities. Using initial LIGO as an example we show in section 3 that with detuned arm cavities the shot noise limited sensitivity can, in a certain frequency range, be increased using the same optical power circulating in the arm cavities as in the case of tuned arm cavities. In section 4 we compare the interferometer response of initial LIGO with detuned arm cavities to a configuration also based on initial LIGO but using in addition the advanced technology of resonant sideband extraction (RSE). Finally we give a summary and an outlook in section 5.

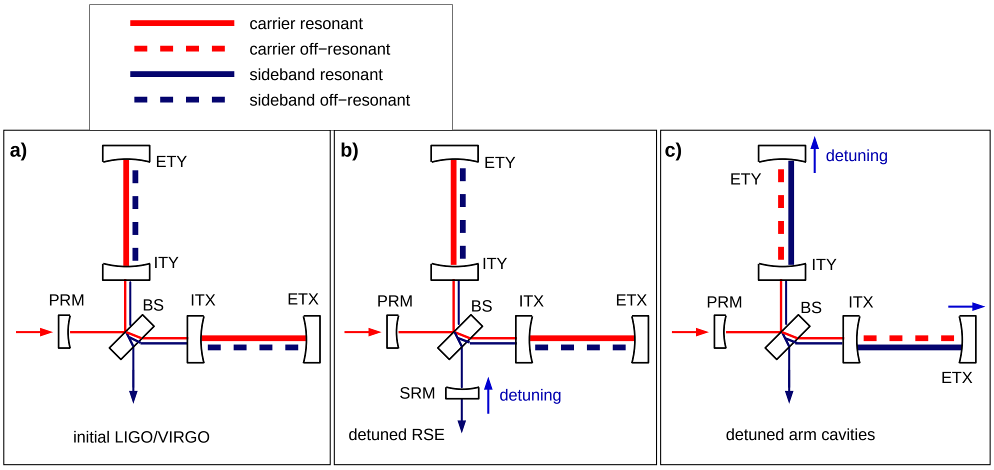

Figure 1. Simplified schematics of the three optical configurations compared in this article. a) Initial LIGO configuration with arm cavities kept resonant for the carrier light. b) Initial LIGO configuration with additional detuned resonant sideband extraction. c) Initial LIGO configuration with arm cavities detuned to be resonant for the gravitational wave signal sidebands (abbreviations are explained in the text.)

2. The principle of detuned arm cavities

Figure 1 a) shows a simplified schematic of the initial LIGO optical layout. The red and the dark blue lines indicate in which part of the interferometer carrier light (red) and gravitational wave signal sidebands (dark blue) are present. The carrier light enters the interferometer through the Power Recycling mirror (PRM) and is split by the beam splitter (BS) in equal shares into the X and Y arm. The arms consist of an arm cavity each, formed by two mirrors separated by 4 km (ITX and ETX, ITY and ETY). These arm cavities are chosen to be resonant for the carrier light resulting in a larger power enhancement inside. The small Michelson interferometer formed by BS, ITY and ITX is kept on a dark fringe, thus no carrier light is leaving the interferometer towards the output port, but all light is going back to the input port so that it becomes further resonantly enhanced by PRM. The presence of a gravitational wave produces phase modulation sidebands around the carrier light. Because the signal sidebands in the two perpendicular arms have opposite phase they can interfere constructively at the BS to leave the interferometer at the output port. With the arm cavities being set on resonance for the carrier light, the signal sidebands of interest ($f_{sig} > 100\,\mathrm{Hz}$) experience less enhancement than the carrier light.

A new concept that turns this principle around is shown in Figure 1 c). In contrast to the conventional initial LIGO scheme the length of the arm cavities was chosen to be resonant for a certain single-sided signal sideband frequency, i.e. the cavities are detuned from the carrier by the detuning frequency, f_{detune}. This detuning can easiest be realized by shifting ETY and ETX in common mode either to shorten or to lengthen the arm cavities, corresponding to making them resonant for the upper and the lower signal sideband, respectively. The microscopic position of all other mirrors (ITX, ITY, BS and MPR) does not need to be changed. The obvious drawback of this scheme, in the following referred to as *detuned arm cavities*, is the lower optical power inside the arms, compared to arm cavities resonant for the carrier light. However, since several serious technical problems of the current gravitational wave detectors are proportional to the circulating light power, the concept of detuned arm cavities might be beneficial, compared to resonant arm cavities with identical stored optical power.

3. Simulated shot noise limited sensitivity of initial LIGO with detuned arm cavities

In order to evaluate the benefit from detuning the arm cavities and resonantly enhancing the gravitational wave signal sideband we performed numerical simulations of the shot noise limited sensitivity using the FINESSE software [5] (The simulation does not include radiation pressure nor optical spring effects, because these effects play no major role in the configurations analyzed in this paper.). As an example we have chosen an idealized and simplified initial LIGO interferometer with tuned and detuned arm cavities of 4 km length. To simplify the simulation of shot noise, a DC-readout scheme was used. Table 1 gives a summary of the simulation: With an input power of 4 W a circulating light power of 10 kW is achieved in each arm cavity. The corresponding shot noise limited displacement sensitivity of such a configuration with arm cavities resonant for the carrier light is shown in Figure 2 (green solid trace)‡.

Transmission PRM	10 %
Transmission ITX/ITY	3 %
Transmission ETX/ETY	0 %
Input light power at PRM	4 W
Light power in each arm	10 kW
Dark fringe offset at BS for DC-readout	0.3 deg

Table 1. Simulation of a simplified initial LIGO configuration with DC-readout.

By shifting the microscopic position of ETX and ETY we can detune the arm cavities, i.e. shifting their resonance. Since the sensitivity of the initial LIGO detectors is only shot noise limited above 150 Hz [6], we choose here a detuning frequency of 200 Hz corresponding to a detuning of -1 deg. This results in a reduction of the power buildup in the arm cavities by a factor of 6.25 which can be compensated by increasing either the input power from 4 to 25 W or the Power-Recycling gain (reducing the transmission of PRM from 10 to 1.7 %) in order to restore the nominal 10 kW intra-cavity power. Table 2 shows the parameters used for the simulation of tuned and detuned arm cavity configurations.

Figure 2 shows the shot noise limited sensitivity of the two configurations with detuned arm cavities (red dashed and blue solid line). In a frequency band of approximately 200 Hz width, between 150 to 350 Hz, an increased sensitivity can be achieved. A maximal improvement of approximately 45 % is obtained around 230 Hz. Below 150 Hz and above 350 Hz the sensitivity of the configurations with detuned arm cavities is worse than for tuned arm cavities.

‡ Our simulation gives a sensitivity slightly better than the design sensitivity of initial LIGO. This originates from the fact that the shot noise is lower in the DC-readout configuration.

Scheme	Tuning ETX/ETY [deg]	Input power [W]	Transmission PRM [%]
arm cavities resonant for carrier	90/0	4.0	10.0
detuned arm cavities, input power increased	89/-1	25.1	10.0
detuned arm cavities, PR gain increased	89/-1	4.0	1.7

Table 2. Parameters used for the simulation of tuned and detuned arm cavity configurations. All scenarios lead to an intra-cavity power of 10 kW.

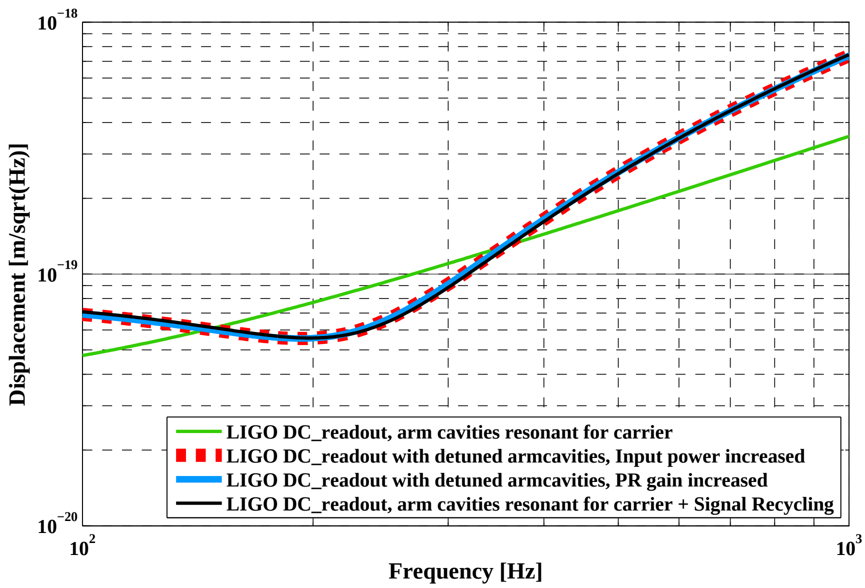

Figure 2. Shot noise limited displacement sensitivity of initial LIGO with DC-readout in comparison to two configurations with detuned arms and a configuration using resonant sideband extraction (RSE). Using detuned arm cavities increases the sensitivity in a frequency range from 150 to 350 Hz. Around 230 Hz a maximum sensitivity gain of approximately 45 % is obtained. Detuned arm cavities give a sensitivity identical to RSE.

4. Comparison of detuned arm cavities and resonant sideband extraction

Resonant sideband extraction (RSE) [8] is a well known concept for increasing the sensitivity of gravitational wave detectors by placing an additional mirror in the output port of the instrument (see Figure 1 b). This concept is foreseen to be implemented in the second generation instruments such as Advanced LIGO [7]. Similar to the concept of using detuned arm cavities, RSE allows to increase the sensitivity of the interferometer in a certain frequency band by sacrificing the sensitivity outside this band.

Our simulations show that the sensitivity of a detector using detuned arm cavities can exactly be reproduced by using tuned arm cavities and RSE (see black solid line in Figure 2). For the simulation of RSE we used a Signal-Recycling mirror (SRM) with a reflectivity of 58 % and a tuning phase of 70 deg. The finding is that the following two concepts

- Tuned arm cavities together with RSE
- Detuned arm cavities with increased Power-Recycling gain

are in principal equivalent.

Interestingly, the implementation of the second concept is significantly easier. While RSE requires the installation of an additional suspended mirror and a completely new control scheme for additional degrees of freedom (longitudinal and alignment), detuned arm cavities only require the insertion of an electrical offset into the arm length servos and the exchange of PRM by one with 1.7 instead of 10 % reflectivity§. The Fourier frequency of the peak sensitivity can be adjusted by changing the electrical offset. When implementing detuned arm cavities into a currently running detector the bandwidth of the signal enhancement (corresponding to the reflectivity of the SRM in RSE) is linked to the Finesse of the arm cavities. A potential disadvantage of detuned arm cavities might be the slightly higher light power inside the small Michelson interferometer originating from the increased Power-Recycling gain.

5. Summary and outlook

We introduced a concept that uses detuned arm cavities combined with a moderately increased Power-Recycling gain to increase the shot noise limited sensitivity of initial LIGO for frequencies between 150 and 350 Hz, without increasing the light power inside the arm cavities. This concept is found to give a sensitivity similar to that of a conventional RSE configuration with a SRM of moderate reflectivity. The easier implementation of detuned arm cavities compared to RSE seems to be a considerable advantage. Additional investigations and simulations are required to evaluate the performance of the proposed concept especially with respect to noise couplings.

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§ Both, Virgo and GEO 600, already replaced their PRM by one of higher reflectivity during recent commissioning periods. Thereby no significant problems had been encountered.

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