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A novel concept for increasing the peak sensitivity of 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 LIGO without increasing the light power inside the arm cavities. Numerical simulations show an increased sensitivity between 125 and 400 Hz, with a maximal improvement of about 80% around 225 Hz, while the sensitivity above 400 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. In the near future detuned arm cavities might be a beneficial alternative to RSE, due to the potentially less hardware-intensive implementation of the proposed concept.

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(Some figures in this article are in colour only in the electronic version)

1. Introduction

The first generation of large-scale laser-interferometric gravitational wave detectors [1–4] 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 paper, 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.

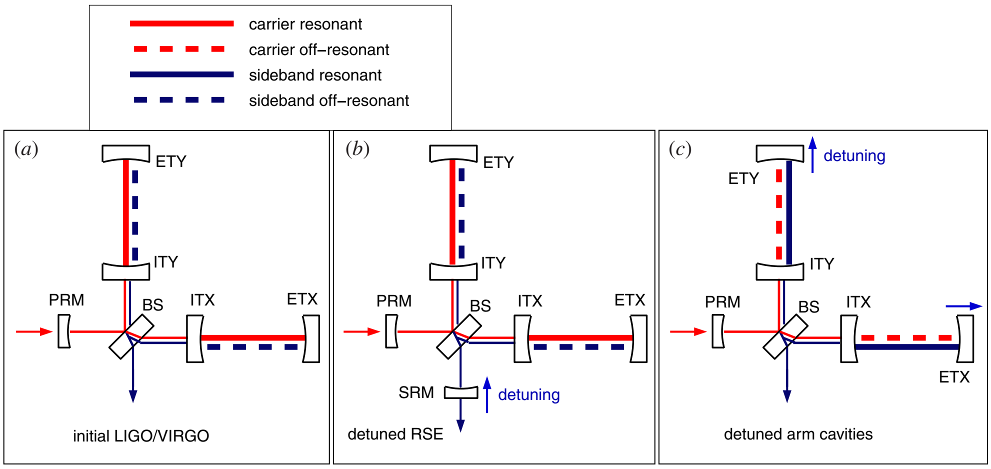

Figure 1. Simplified schematics of the three optical configurations compared in this paper. (*a*) Initial LIGO configuration with arm cavities kept resonant for the carrier light. (*b*) Initial LIGO configuration with additional detuned resonant sideband extraction. (*c*) Initial LIGO configuration with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

In section 2, we give a brief and intuitive description of the principle of an optical configuration employing detuned arm cavities. Using an idealized interferometer 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 with detuned arm cavities to a configuration using, in addition, the advanced technology of resonant sideband extraction (RSE). The potential benefit of using detuned arm cavities for LIGO is evaluated by simulations described in section 5. Finally, we give a summary and an outlook in section 6.

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 arms. 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 toward 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 ($f_{\mathrm{sig}} > 100$ Hz) experience less enhancement than the carrier light.

Table 1. Simulation of an ideal Michelson interferometer with DC-readout.

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°

A new concept that turns this principle around is to use detuned arm cavities[3] as 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 specific single-sided signal sideband frequency, i.e. the cavities are detuned from the carrier frequency. This detuning can easily 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 operating points of the other main mirrors (ITX, ITY and BS) do 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, the achievable circulating power in the current detectors is not limited either by the available laser power or the finesse of the arm cavities. Instead technical problems, like, for example, thermal lensing or parametric instabilities, become limiting factors when the circulating light power is increased [3]. Therefore, we believe it is useful to compare the concept of detuned arm cavities to resonant arm cavities with identical stored optical power.

3. Simulated shot-noise-limited sensitivity for an ideal Michelson interferometer employing power-recycling and 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[4] software [7]. As an example, we have chosen an idealized and simplified Michelson interferometer with the power-recycling employing 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).

By shifting the microscopic position of ETX and ETY we can detune the arm cavities, i.e. shifting their resonance. Here we choose a detuning frequency of 200 Hz corresponding to a detuning of -1°. 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.

[3] Similar concepts were mentioned in [5, 6]; their publications, however, focused on the properties of the opto-mechanical resonance in a detuned arm cavity, while in this paper we investigate the sensitivity enhancement from utilizing the optical resonance.

[4] Our initial simulations did not include either the radiation pressure or optical spring effects. We later confirmed with a separate analysis that these effects play no role for the frequency band and in the configurations analyzed in this paper.

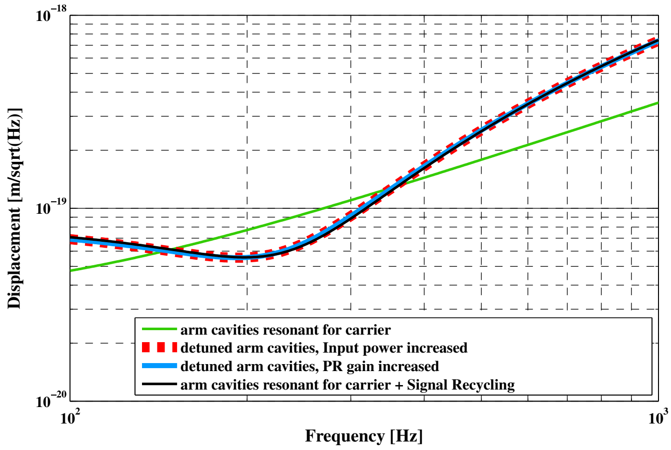

Figure 2. Shot-noise-limited displacement sensitivity of an ideal Michelson interferometer with power-recycling with DC-readout in comparison to two configurations with detuned arms and a configuration using resonant sideband extraction (RSE). Using detuned arm cavities increases the sensitivity in a frequency range from 150 to 350 Hz. Detuned arm cavities give a sensitivity identical to RSE.

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

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

Figure 2 shows the shot-noise-limited displacement sensitivity of the two configurations with detuned arm cavities (red-dashed and blue solid line). In a frequency band between 150 and 350 Hz an increased sensitivity can be achieved. The maximal improvement 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.

4. Comparison of detuned arm cavities and resonant sideband extraction

Resonant sideband extraction (RSE) [10] 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 [9]. Similar to the concept of using detuned arm cavities, RSE allows us 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 the 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°. The finding is that the following two concepts

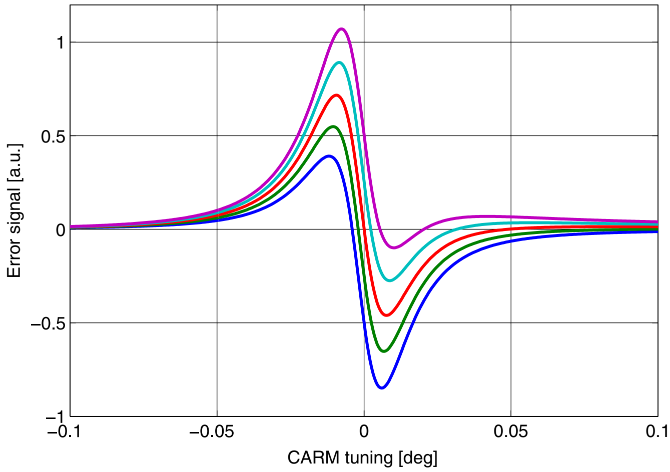

Figure 3. Example error signal for the common mode arm cavity length (CARM) for an interferometer with detuned arm cavities; zero CARM tuning refers to the new detuned operating point. The error signal is obtained by demodulating the light reflected of the back of BS at an additional RF frequency. The plot shows several traces for different demodulation phases (50° to 70°, in 5° increments).

- tuned arm cavities together with RSE and
- detuned arm cavities with the increased power-recycling gain

are in principle 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 the additional degrees of freedom (longitudinal and alignment), detuned arm cavities only require a slightly more complex length sensing and control scheme (see below) and the exchange of PRM by one with 1.7 instead of 10% reflectivity[5]. Furthermore, the Fourier frequency of the peak sensitivity can be adjusted online by tuning the settings of the control system, similarly to an RSE system.

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.

At first glance the length sensing and control for an interferometer with detuned arm cavities looks very similar to the standard LIGO control problem. Effectively, only an offset to the operating point of the common mode arm (CARM) signal has to be introduced. Unfortunately, this offset is much larger than the dynamic range of the original CARM error signal. Hence, in order to obtain a suitable CARM control signal a new RF modulation has to be introduced. Figure 3 shows example error signals for the new CARM operating point derived from the RF modulation at approximately 15 MHz. The demodulation phase in combination with the exact value of the RF frequency determines the operating point of the CARM signal. This poses a new constraint on the quality of the control electronics, which however is a known and understood feature of detuned signal-recycling control systems as

[5] 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.

Table 3. Simulation of initial LIGO with DC-readout. The parameters are taken from [11].

Transmission PRM	2.7%
Transmission ITX/ITY	2.8%
Transmission ETX/ETY	10 ppm
Loss at each coating	90 ppm
Radius of curvature ITX/ITY/PRM	−14.3 km
Radius of curvature ETX/ETY	8.0 km
Input light power at PRM	6 W
Dark-fringe offset at BS for DC-readout	0.3°

well [12]. Preliminary investigations show further that appropriate error signals for all other degrees of freedom can easily be obtained. The detuning of the arm cavities has virtually no effect on the differential mode arm signal and the power-recycling control, but degrades slightly the quality of the small Michelson error signal.

5. Initial LIGO with detuned arm cavities

After we explained the principle operation of the detuned arm cavity concept in the previous section using an ideal Michelson interferometer with power recycling, this section is devoted to simulating the benefit of detuned arm cavities for a real system, i.e. initial LIGO. We used the best estimate for the optical parameter currently available [11]. The values for the most important parameters are given in table 3. The sensitivity achieved with these parameters is shown in figure 4 (green-dashed line). Using resonant arm cavities in the simulation yields an intra cavity power 14.7 kW per arm.

This configuration is in the following compared to one optical scheme employing detuned arm cavities. Since the sensitivity of the initial LIGO detectors is only shot noise limited above 150 Hz [8], we choose here a detuning frequency of 200 Hz corresponding to a detuning of -1°. In order to (at least partly) compensate the decreased power buildup in the arm cavities we use for this simulation a PRM with 1% instead of 2.7% transmission leading to an intra-cavity power of 11 kW. The corresponding shot-noise-limited sensitivity is shown in figure 4 (blue solid line). In a frequency band between 125 and 400 Hz an improvement is achieved. The maximal increase in sensitivity amounts to about 80% around 225 Hz. Above 400 Hz the decrease of the shot-noise-limited sensitivity increases with the frequency. At 1 kHz a sensitivity reduction of 45% is observed.

6. Summary and outlook

We have introduced a new 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 125 and 400 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 implementation of detuned arm cavities might require less new hardware than RSE. This is a considerable advantage; however, further investigations and simulations should be performed to evaluate the performance of the proposed scheme with respect to noise couplings.

We have chosen to validate the concept using the initial LIGO configuration because the real parameters and performance of the running interferometers are well known. Nevertheless,

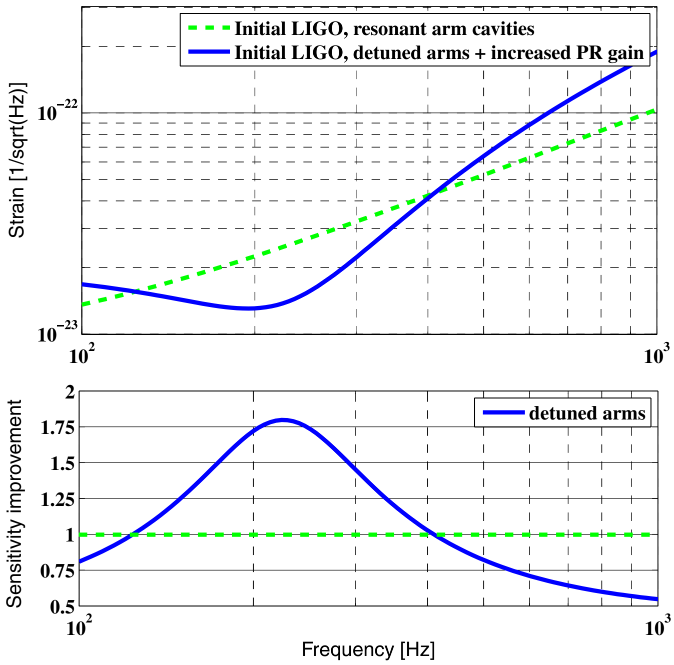

Figure 4. Upper subplot: shot-noise-limited strain sensitivity for initial LIGO using resonant arm cavities (green-dashed trace) and detuned arm cavities (blue solid line). In case of detuned arm cavities the original PRM of 2.7% transmittance was exchanged by on with only 1% transmittance. Still the circulating light power is with 11 kW smaller than for resonant arm cavities (14.7 kW). Using our proposed concepts allows us to increase the sensitivity of initial LIGO in the frequency band between 125 and 400 Hz. Lower subplot: ratio of the achieved strain sensitivities with resonant and detuned arm cavities. A maximal improvement of 80% is achieved around 225 Hz.

the same concept is applicable to these interferometers after the next upgrade: enhanced LIGO. Further investigations are required, however, to understand the technical limits to the circulating power in the arm cavities and the small Michelson in a realistic-enhanced LIGO scenario.

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