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Demonstration and comparison of tuned and detuned signal recycling in a large-scale gravitational wave detector

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Abstract
The British/German gravitational wave detector GEO 600 located near Hannover in Germany is the first large-scale gravitational-wave detector using the advanced technique of signal recycling. Currently the instrument operates in detuned signal recycling mode. Several problems arise due to the fact that the signal recycling cavity changes amplitude and phase of all light fields (carrier and sidebands) present at the dark-port. In addition, in the case of detuned signal recycling this leads to unbalanced sideband fields at the detector output. The large amplitude modulation caused by this asymmetry does not carry any gravitational wave information, but might be the cause of saturation and nonlinearities on the main photodiode. We developed and demonstrated a new control method to realize tuned signal recycling operation in a large-scale gravitational wave detector. A detailed comparison of tuned and detuned signal recycling operation is given. The response function of the system (optical gain) was measured and compared, as was the size of amplitude modulation on the main photodiode. Some important noise couplings were measured and partly found to be strongly reduced in the case of tuned signal recycling operation.

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

1. Introduction

Placing a mirror (MSR in figure 2) in the dark port of an interferometric gravitational wave detector can significantly increase its sensitivity in a certain frequency band [1]. Furthermore, this technique known as signal recycling (SR) allows a frequency-dependent shaping of the detector response. The bandwidth of the signal recycling resonance is determined by the reflectivity of the signal recycling mirror. A high reflectivity gives a large increase in the response function in a narrow band (narrow-band operation), while a moderate reflectivity yields a medium improvement of the response function over a broader frequency range (broadband operation). The frequency of maximum response, also called tuning frequency, is determined by the length of the signal recycling cavity and can be chosen by the microscopic position of the signal recycling mirror. In this paper we will refer to *tuned* signal recycling as the case when one of the resonances of the signal recycling cavity is centred at the frequency of the carrier, in contrast to *detuned* signal recycling where the signal recycling resonance is shifted to a frequency different from the carrier. The difference between the frequency of the signal recycling resonance and the carrier frequency is referred to as the detuning frequency.

Until recently, the GEO 600 detector has been operated with detuned signal recycling in order to shift the peak sensitivity to frequencies between 350 and 1000 Hz [2]. This was done to optimize the science contribution of the GEO 600 detector to the LSC (LIGO Scientific Collaboration) detector network. However, the use of detuned signal recycling brings some disadvantages. In contrast to a Michelson interferometer having only power recycling, the signal recycling cavity changes amplitude and phase of any light component present at the dark port, for instance the gravitational wave signal or radio frequency (RF) sidebands used for detector control.

Figure 1 gives a qualitative overview of the light fields in the signal recycling cavity for tuned and detuned operation. In the tuned case, the differential arm length information can be derived completely from demodulation of the photo current detected at the dark port in the in-phase quadrature (in the following referred to as P quadrature). In the detuned signal recycling case this information is in a frequency-dependent way spread over both quadratures, P and Q (out-of-phase quadrature) and both have to be analysed to obtain the best signal-to-shotnoise ratio. A detailed description of this effect and its consequences for the calibration of the instrument can be found in [3, 4].

The asymmetry of the RF control sidebands at the dark port causes a strong amplitude modulation of the light on the main photo detector at precisely the modulation frequency. This amplitude modulation is many orders of magnitude larger than that caused by potential gravitational wave signals and can lead to saturation in the main photodetector [5][3].

It was also observed in the detuned case that various noise sources, for instance oscillator phase noise and laser intensity noise, couple to the gravitational wave channel in a more complex way than one would expect from simple models. A suspected cause for this is the imbalances of the sidebands at the dark port.

The facts given above made it highly desirable for us to directly compare tuned and detuned signal recycling operation in GEO 600. In section 2, we describe the GEO control scheme implemented for detuned signal recycling, while in section 3 we introduce a new technique, allowing the operation of tuned signal recycling. In sections 4–6, important aspects of tuned and detuned signal recycling (510 Hz) are compared: section 4 shows measurements of the optical gain, in section 5 a comparison of the size of the amplitude modulation at the main photodiode is given, and finally in section 6 we show exemplary measurements of some noise coupling transfer functions to the gravitational wave channel.

[3] At the LIGO detectors an additional feedback loop (called *I-servo*) is used which reduces the part of the RF signal that is not suppressed by the interferometer control loop. This is done by adding an appropriate RF-signal, essentially a sine wave at the modulation frequency, with correct amplitude and phase, directly to the PD-resonant circuit, thereby cancelling the RF-signal (at this frequency) in one quadrature [6].

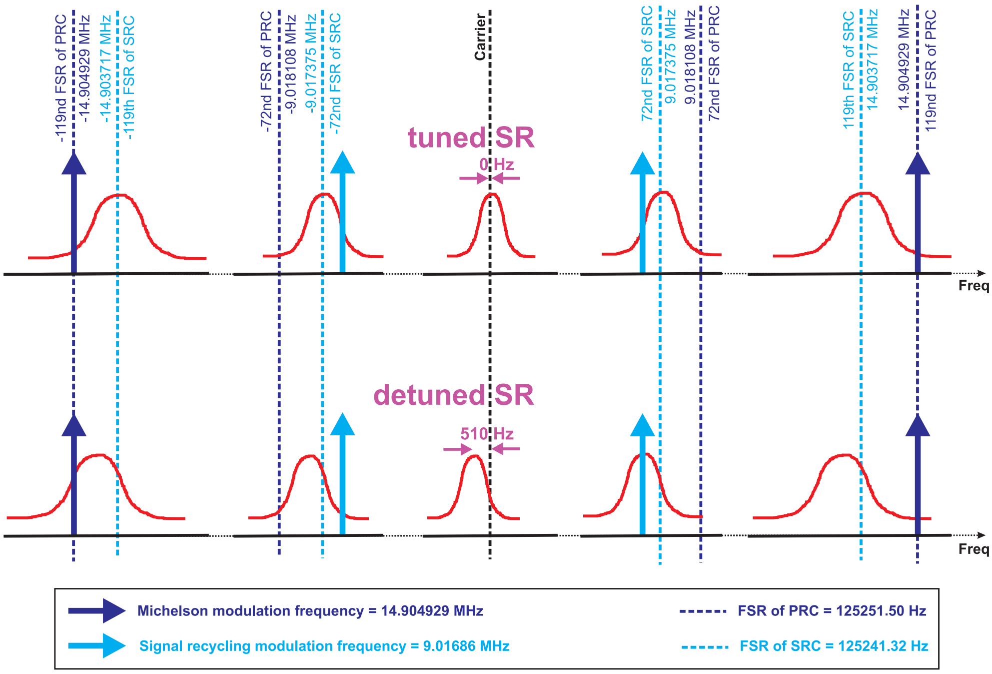

Figure 1. Overview of the resonance conditions for carrier (black dashed line), Michelson control sidebands (dark blue arrows) and signal recycling control sidebands (light blue arrows) inside the signal recycling cavity for tuned and detuned (510 Hz) signal recycling in the upper and lower subplot, respectively. The comb of equidistant resonances of the signal recycling cavity (SRC) is indicated by the red Airy peaks. Due to the Schnupp asymmetry the shape of the resonance gets wider for frequencies far off the carrier. The gravitational wave signal is located around the carrier. The frequency of the Michelson modulation was chosen to be resonant in the 119th free spectral range (FSR) of the power recycling cavity (PRC). In detuned signal recycling the two Michelson sidebands see different resonance conditions inside the SRC: the lower one is nearly resonant, while the upper one is nearly off resonance. When going from detuned to tuned signal recycling using the method described in this paper the frequency of all sidebands will stay the same, but the comb of signal recycling resonances (red curves) is shifted by 510 Hz towards higher frequencies. In the tuned case the sidebands used for Michelson control are balanced as well as those used for signal recycling control.

2. Control scheme for signal recycling in GEO 600

The signal used to control the microscopic position of the signal recycling mirror (MSR) is derived from a radio frequency modulation/demodulation technique. Figure 2 shows a simplified diagram of the control of two degrees of freedom, the Michelson differential arm length and the length of the signal recycling cavity in blue and green respectively. Two sets of phase modulation sidebands are created in front of the power recycling mirror (MPR in figure 2). Due to Schnupp modulation, a fraction of these sidebands leaves the interferometer at the dark port [7]. The error signal for controlling the differential arm length of the Michelson interferometer is derived from the photodiode PDO placed at the dark port of the interferometer. For the sensing of the signal recycling loop a pick-off beam from one of the interferometer arms is used (PDBSs: sensing the beam from the beam splitter AR coated side).

For various reasons (described in detail in [8]) it was so far not possible to realize lock acquisition for the tuned configuration of GEO 600. Therefore a procedure was developed to

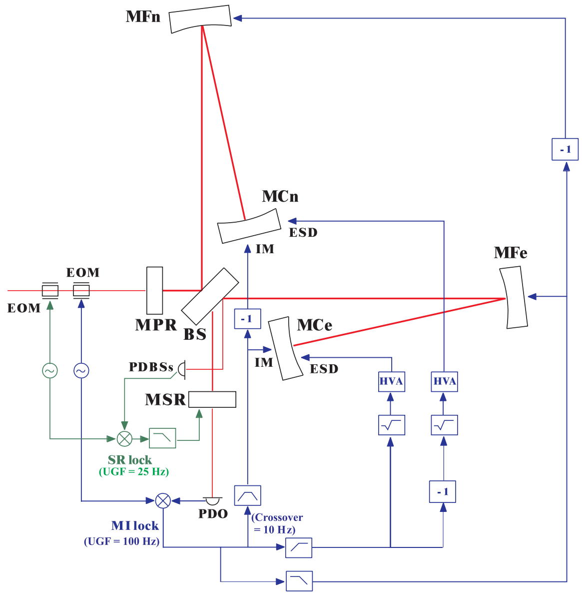

Figure 2. Simplified control scheme for two longitudinal degrees of freedom of GEO 600. Shown are the Michelson differential loop and the signal recycling loop in blue and green, respectively. The control signals used for lock acquisition are not shown in the diagram.

acquire lock at a high detuning (a few kHz) and then gradually tune the signal recycling cavity to lower frequencies. This so-called tuning is done by changing the radio frequency of the Schnupp modulation and other relevant parameters [9].

Figure 3 shows the error signal of the signal recycling loop for different modulation frequencies versus the position of the signal recycling mirror. These simulations were done using the FINESSE software [10]. In the case of detuned signal recycling, the error signal structure shows three zero crossings. The two outer ones are referred to as the lower and upper sidebands corresponding to a negative or positive detuning, while the zero crossing in the centre corresponds to the tuned case. So far the zero crossing corresponding to the upper sideband was chosen to be the nominal operating point. If the modulation frequency is increased, the zero crossings from the lower and upper signal recycling sideband are shifted towards the zero crossing corresponding to tuned signal recycling, i.e. the whole error signal structure gets squeezed, but keeps its shape. As the signal recycling mirror is locked to the upper sideband crossing zero, the position of the mirror is shifted corresponding to the change of the modulation frequency of the SR control sideband. This tuning technique works for tunings as low as about 300 Hz.

As indicated in the second subplot of figure 3, for tunings below 300 Hz the error signal structure is not only squeezed, but also changes its shape significantly. The error signals of the upper and lower sideband become asymmetric around their zero crossings. For the extreme condition of a modulation frequency corresponding to the tuned case the zero crossings of the sidebands vanish completely. For frequencies corresponding to tunings between 300 and 0 Hz and the presence of electronic or seismic noise, the error signals cannot be used for a stable control of the signal recycling mirror. Their close-to-linear range is too small to hold the mirror in a defined position, given that the control bandwidth of the signal recycling loop

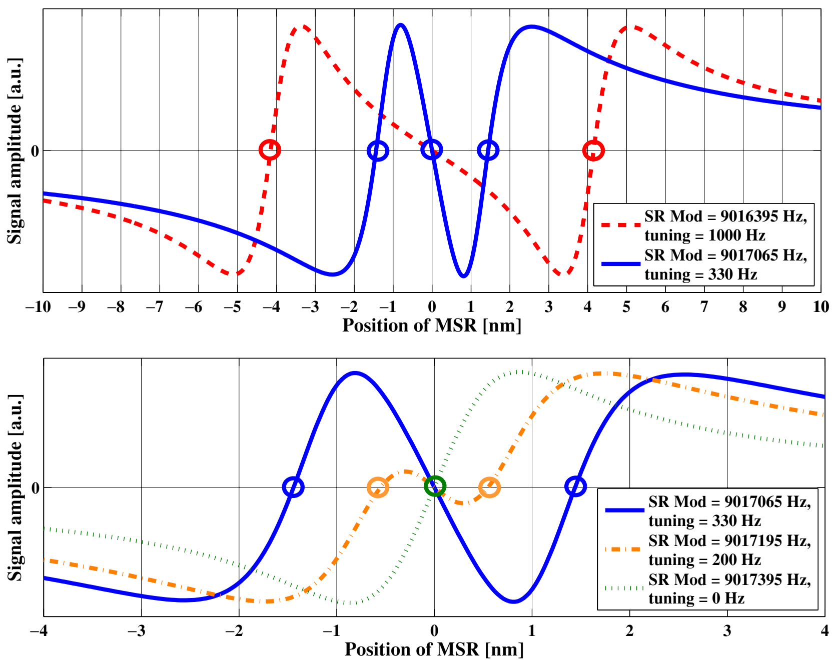

Figure 3. Signal recycling error signals derived from an RF modulation demodulation technique versus microscopic position of the signal recycling. The error point is plotted for various modulation frequencies corresponding to detunings of the signal recycling cavity between 1000 Hz and 0 Hz. By increasing the modulation frequency the structure gets more and more squeezed.

is only about 25 Hz. Therefore reaching the tuned case in small steps seems not a promising technique here.

3. A new method for locking tuned signal recycling

One possible way to reach the tuned case is to start from the lowest stable tuning, then make the microscopic position of the signal recycling mirror 'jump' over the region where the control signals are not valid, and 'catch' it again at the tuned state, where reasonable control signals can be derived. This can be done without changing the signal recycling modulation frequency by jumping from the zero crossing corresponding to the upper sideband to the zero crossing corresponding to the tuned case.

We realized this jumping by pushing the signal recycling mirror in the direction corresponding to a smaller detuning frequency and stopping it near the zero crossing of the tuned case. In order not to disturb the other control loops, for example the loop controlling the differential arm length of the Michelson interferometer, the signal recycling mirror has to be pushed over the region of non-valid error signals quickly.

In detail the procedure works as follows: we start from a modulation frequency corresponding to a tuning of about 350 Hz where the signal recycling mirror is locked at the position corresponding to the zero crossing of the error signal around the upper sideband. Then we switch off the signal recycling control loop to be able to push the signal recycling mirror away from its operating point. At the same time we push the signal recycling mirror

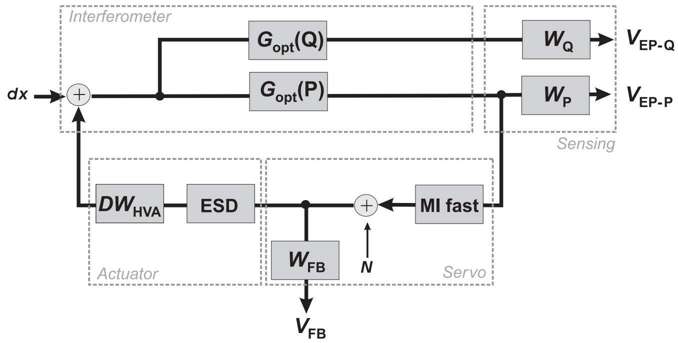

Figure 4. A simplified diagram of the loop controlling the differential arm length of the Michelson. The diagram contains only components important for calibration and measuring the optical gains G_{opt} from the two orthogonal signal quadratures P and Q. Abbreviations used: MI fast: electronics of the servo, W_{FB}: whitening filter of feedback signal, ESD: high voltage amplifier (HVA) and ESD (electros static drive), DW_{HVA}: HVA dewhitening filter, W_P: whitening filter for P signal, W_Q: whitening filter for Q signal, N: noise injected, dx: mirror displacement, V: voltage.

as hard as the coil-magnet actuators allow. After 4 ms of pushing, the mirror has covered half the distance between the zero crossing of the upper sideband and that from tuned case which is in this case a distance of 0.7 nm. Then the sign of the force applied to mirror is inverted to decelerate the mirror in 4 ms from maximum speed to a velocity near zero when the mirror finally reaches the tuned position. After these 8 ms the signal recycling feedback loop is closed again, but with opposite polarity, to account for the different sign of the slope around the zero crossing of tuned signal recycling[4]. The short duration of the described procedure fulfils the time requirement, and other loops are not disturbed.

Finally, a few control parameters need to be adjusted to account for the different operating point of the signal recycling loop. The gain of the signal recycling loop needs to be adjusted for the different slope of the error signal. Furthermore in the case of tuned signal recycling the pole of the signal recycling cavity for carrier light is shifted towards lower frequencies, thus all signals generated from the dark port need to be adapted. This is done by switching an additional differentiator into the loop controlling the Michelson differential arm length and adjusting gains for Michelson longitudinal and alignment control systems.

Using this technique it was also possible to jump twice the distance (about 3 nm) with the signal recycling mirror, and thereby go from the zero crossing of the upper sideband to that of the lower sideband.

4. Measurements of optical gain and sensitivity

The response function of the Michelson differential error signal to differential arm length fluctuations, the so-called optical gain G_{opt}(P), is frequency dependent in the case of detuned signal recycling. The signal is also inherently spread between the two orthogonally demodulated signal quadratures, P and Q.

Figure 4 shows a simplified diagram of the loop controlling the differential arm length of the Michelson. The optical gain of the P quadrature can be described by the following

[4] Another possibility would be to change the modulation frequency while the mirror is being pushed, and then to keep the sign of the control loop.

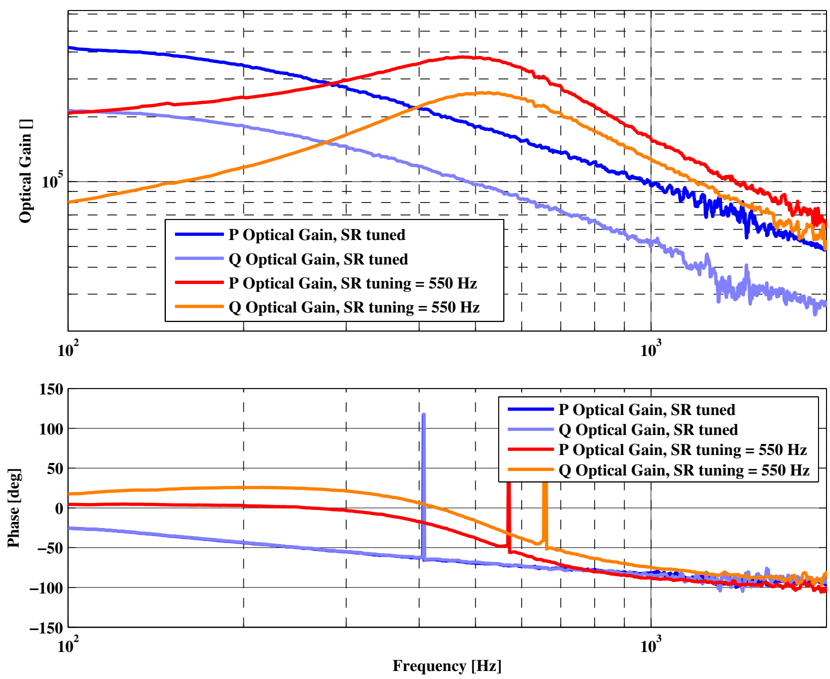

Figure 5. Measurement of the optical gains for tuned and detuned signal recycling for the two orthogonal quadratures P and Q. For the tuned case the demodulation phase was not optimized. Therefore the differential armlength signal is still clearly present in the optical gain of the Q-signal.

expression

$$G_{\mathrm{opt}}(\mathrm{P}) = \frac{V_{\text{EP-P}} \cdot DW_{\mathrm{P}}}{V_{\mathrm{FB}} \cdot DW_{\mathrm{FB}}} \cdot \frac{1}{A_{\mathrm{ESD}}} \cdot \frac{1}{DW_{\mathrm{HVA}}} \tag{1}$$

where $V_{\text{EP-P}}$ is the error signal from the P quadrature recorded in the data acquisition system (DAQS) and V_{FB} is the record of the feedback. A_{ESD} and DW_{HVA} represent the responses of the actuators, DW_{FB} is the response of the feedback whitening filter and DW_{P} is the inverse of the P error signal whitening filter. For the measurement of the optical gains, noise was injected in order to dominate the feedback signal and the P signal.

Figure 5 shows measurements of the optical gains for detuned and tuned signal recycling for the two quadratures. In the detuned case the optical gain shows a maximum at the frequency of the signal recycling detuning. The width of the maximum is given by the bandwidth of the signal recycling cavity, which is about 700 Hz for the currently installed signal recycling mirror with a transmission of about 2%. In the tuned case the maximum of the optical gain is centred around 0 Hz and the bandwidth of the response function is decreased to 350 Hz. (Below 100 Hz the intermediate mass split path of the Michelson longitudinal servo starts to influence the measurement of the optical gain.)

By going to tuned signal recycling no improvement in sensitivity was observed. As shot noise contributes to the noise level of GEO 600 for frequencies above 1 kHz, the sensitivity got worse in that frequency range when going to tuned signal recycling. At low frequencies we observed no increase in sensitivity because in that frequency range the shot noise is masked by the noise contribution of several technical noise sources.

5. Reduction of the RF amplitude modulation

In detuned signal recycling the RF sidebands from the Schnupp modulation which originally represented a pure phase modulation get partly converted to amplitude modulation inside the signal recycling cavity. The light hitting the main photo diode shows strong amplitude modulation at the frequency of the Michelson control sidebands which are in the case of GEO 600 at a frequency of about 15 MHz.

Some of our observations indicated that the strong amplitude modulation (in detuned SR) together with a high averaged photo current might cause saturation effects and nonlinearities in the photodiode. A detailed description of these problems can be found in [5]. However, it is important to mention that most of the spurious effects depend on the size of the RF amplitude modulation. Therefore it would be desirable to reduce the size of the amplitude modulation.

In the case of tuned signal recycling we have been able to reduce the rms of the signal in the Q quadrature, which is a good measure of the size of the amplitude modulation, by a factor of 12 compared to detuned operation.

6. Comparison of noise transfer functions for tuned and detuned signal recycling

Measurements of the transfer functions from various technical noise sources to the error signal of the differential arm length servo (and hence the gravitational wave channel) during detuned operation indicate complex couplings [11]. Many of the measured transfer functions contain resonance and notch structures that could not be explained even by a complex frequency domain model of the interferometer [12].

Asymmetry of the radio frequency sidebands in the detuned case was suspected to be the origin for some complexity of the observed in the noise couplings. To investigate this we performed measurements for four important technical noise sources for tuned and detuned signal recycling in order to check whether the couplings get simpler and perhaps less significant for tuned signal recycling.

- *Oscillator phase noise (OPN)*: the two sets of upper plots in figure 6 show the measurements of the coupling from oscillator phase noise (of the modulation used for creating control signals for the differential arm length of the Michelson interferometer and the local oscillator signal) to differential arm length. In the P quadrature the coupling in the tuned case is dramatically reduced over a wide frequency range by about two orders of magnitude. This can be explained by the reduction of the rms of the signal in the Q quadrature; see section 5. The coupling of OPN to the Q quadrature is for a frequency below 500 Hz significantly decreased by up to a factor of 100 at 100 Hz. A detailed description of potential coupling mechanisms can be found in [11].
- *Oscillator amplitude noise (OAN)*: the two sets of lower plots in figure 6 show the measurements of the coupling from oscillator amplitude noise (of the modulation used for creating control signals for the differential arm length of the Michelson interferometer) to differential arm length. The amplitude noise in the EOM path is eventually imparted on the carrier and control sidebands and couples to the detector output via asymmetries in the interferometer, as explained in [12]. Again the coupling into both quadratures is strongly suppressed in tuned signal recycling due to more balanced sideband conditions at the dark-port.
- *Laser power noise (LPN)*: the two sets of upper plots in figure 7 show the measurements of the coupling from laser power noise to differential arm length. The coupling to both quadratures is decreased on average by about a factor of 5 to 10 over the frequencies

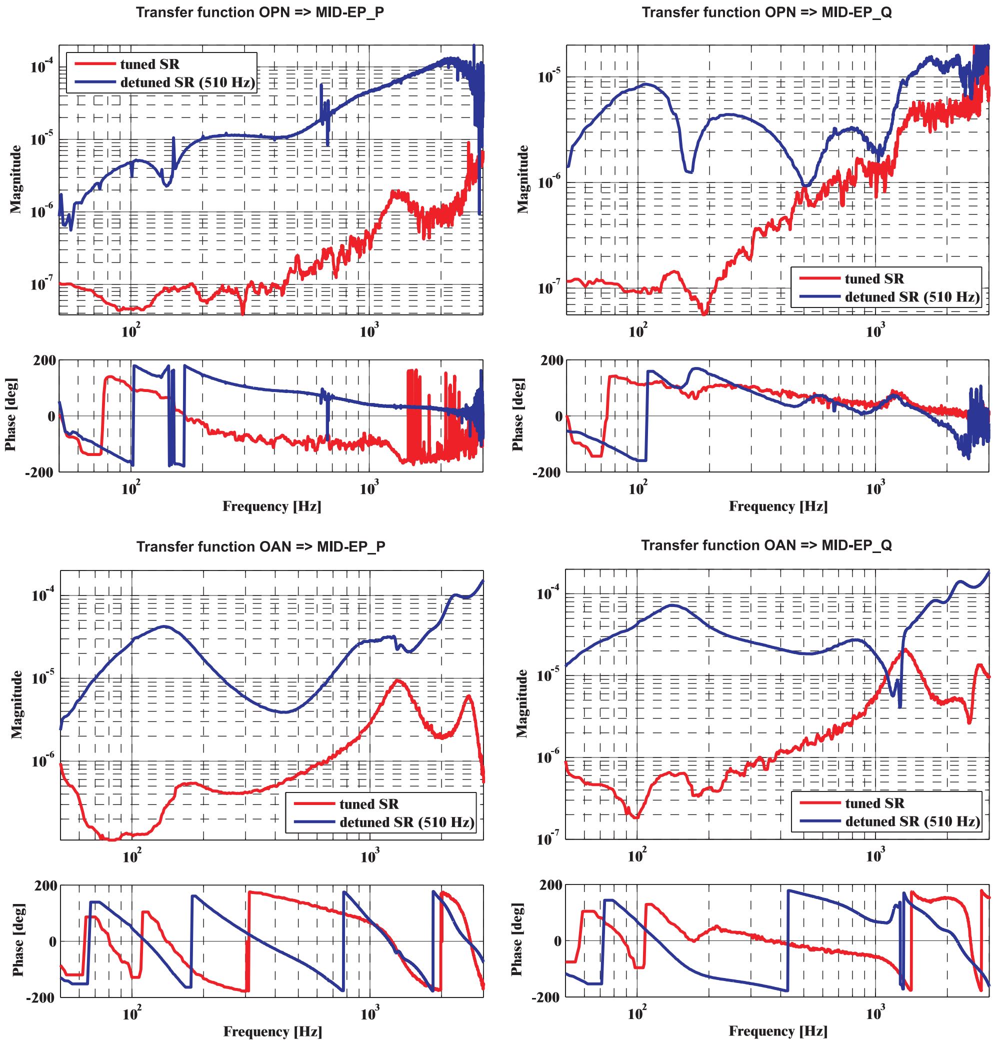

Figure 6. Measurements of the transfer functions from oscillator phase noise (OPN) and oscillator amplitude noise (OAN) to the error signal of the differential arm length servo. The red trace represents tuned signal recycling, while blue indicates a detuning of 510 Hz. The magnitudes of transfer functions are normalized by magnitudes of the optical gains from figure 5.

of interested. In addition at least in the P quadrature the structure of the coupling got slightly simpler. The strongly pronounced notch structure around 1.5 kHz vanishes for tuned signal recycling.

- *Laser frequency noise*: the two sets of lower plots in figure 7 show the measurements of the coupling from laser frequency noise to differential arm length. At low frequencies we observed a moderate reduction of the coupling in the tuned case, while for higher frequencies the coupling is significantly increased. On the other hand the very distinct notch structures between 1 and 2 kHz seem to vanish completely.

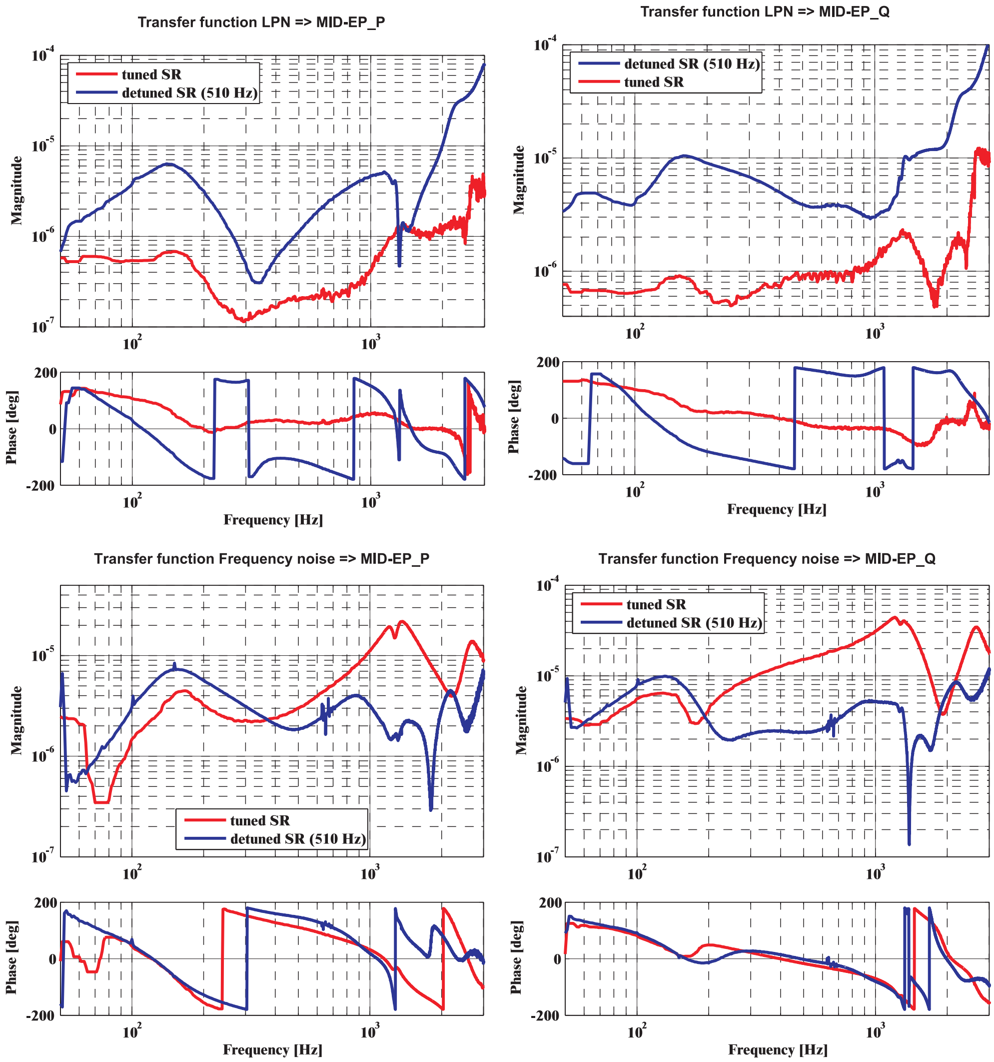

Figure 7. Measurements of the transfer functions from laser frequency noise and laser power noise to the error signal of the differential arm length servo. The red trace represents tuned signal recycling, while blue indicates a detuning of 510 Hz. The magnitudes of transfer functions are normalized by magnitudes of the optical gains from figure 5.

7. Summary

We developed and demonstrated a new technique for rapidly changing the signal recycled GEO 600 gravitational wave detector from the detuned to the tuned operating state. With this method, the signal recycling mirror is shifted accurately between two positions within milliseconds. This allowed for jumping with the signal recycling mirror from a position corresponding to a positive detuning of 510 Hz to a position corresponding to the tuned case and also from a positive detuning of 510 Hz to the corresponding negative detuning of −510 Hz. The method is generally applicable and only limited by the strength of the actuators used for longitudinal control of the signal recycling mirror.

A comparison of tuned and detuned (510 Hz) signal recycling was given. The measurements of the optical gain for the tuned case show that the maximum in the signal response is shifted to the lower end of the detection band. In the tuned case the rms of the signal in the Q quadrature, which is a measure of the amplitude modulation, is reduced by a factor of 12. The measurement of various noise couplings to the gravitational wave channels were performed for tuned and detuned signal recycling. The transfer functions are shown to be significantly different. For most of the noise sources (except laser frequency noise) we found the magnitude of couplings being dramatically decreased in tuned signal recycling. Furthermore in the tuned case the complexity of transfer functions seems to be, at least for some couplings, slightly reduced. These findings support the decisions to operate the LCGT detector with tuned signal recycling [13], and advanced LIGO in detuned signal recycling, but with a homodyne readout [14].

In the future we will try to improve the simulations of the noise couplings in order to reproduce the measured results. A deeper understanding of the complex noise couplings, originating from imbalanced sidebands, is not only important for commissioning of the current interferometers, but also essential for the design of next generation gravitational wave detectors.

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