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Stabilized High Power Laser for Advanced Gravitational Wave Detectors

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Abstract. Second generation gravitational wave detectors require high power lasers with several 100 W of output power and with very low temporal and spatial fluctuations. In this paper we discuss possible setups to achieve high laser power and describe a 200 W prestabilized laser system (PSL). The PSL noise requirements for advanced gravitational wave detectors will be discussed in general and the stabilization scheme proposed for the Advanced LIGO PSL will be described. Special emphasis will be given to the most demanding power stabilization requiremets and new results (RIN $\leq 4\times10^{-9}/\sqrt{\mathrm{Hz}}$) will be presented.

1. Introduction

Several laser interferometric gravitational wave detectors worldwide are approaching their design sensitivities and will soon start long data-taking runs [1][2][3][4]. Upgrades to the long-baseline detectors are planned to improve their sensitivities and scientific reach for astrophysical sources. For example the Advanced LIGO Project (AdvLIGO) [5] has recently been approved by the National Science Board in the USA. A program called AdvVIRGO [6] is in the definition phase with the goal to improve the sensitivity of the VIRGO detector. Both projects expect sensitivity improvements of approximately a factor of ten. The limiting noise source of these detectors in the high Fourier frequency region is the shot noise in the photodetection process at the interferometer output port. As this noise scales with the square-root of the light power in the interferometer and the gravitational wave signal scales proportional to the power, an increase in circulating power in the interferometer would improve the signal to noise ratio. Hence all advanced gravitational wave detectors call for higher laser power to be injected into the interferometers. Limits to the circulating power are set by the thermal handling capability of the interferometer and by the radiation pressure noise imposed on the suspended mirrors, especially at low frequencies. A power level close to 200 W is anticipated for the Advanced LIGO detector. In addition to the high output power the frequency, power and pointing stability of the laser system is important for the success of advanced gravitational wave detectors. To achieve the required stability levels the fluctuations of the unstabilized system (free-running) have to be reduced by feedback control systems or passive filtering.

This paper will describe a 200 W high power laser system designed for use in advanced gravitational wave detectors. A stabilization scheme designed for the Advanced LIGO detector will be discussed and used as an example to illuminate some of the challenges of a pre-stabilized laser system for advanced gravitational wave detectors.

2. High Power Generation

First generation gravitational wave detectors use laser-diode pumped solid-state lasers with an output power between 10 W and 20 W. To increase the circulating power in the interferometer to a level close to one MW either the Finesse of the relevant cavities or the injected laser power has to be increased. Different concepts are proposed in the literature to achieve power levels of 100 W and above. A common feature of these concepts is that they use a stable low power master laser with low frequency fluctuations. The proposed master-oscillator power-amplifier (MOPA) systems as well as injection locked high power stages inherit the frequency stability of the master laser. The compensation of thermally induced birefringence and thermal lenses is one of the main design issues in the high power stage. Zig-zag paths of the optical axis relative to the thermal gradient are used in side-pumped or end-pumped slab amplifier configurations [7] [8] to reduce thermo-optical effects. In fiber amplifiers [9][10] the absorption length of the pump light is increased to reduce thermal loading. And disc lasers or active mirror lasers [11] reduce thermal effects by designing the optical axis to be parallel with the direction of the thermal gradient. The laser system that was chosen for the Advanced LIGO PSL is based on an injection-locked oscillator concept [12] that relies on a birefringence compensation scheme. In order to achieve an output power of nearly 200W in a diffraction-limited beam a ring laser with four identical end-pumped laser heads was developed. The laser heads are grouped in pairs and combined with a quartz rotator and two lenses to form a birefringence compensated unit [13]. To achieve stable single-frequency operation a two stage Pound-Drever-Hall injection locking technique was applied to transfer the frequency stability of a master laser first to an intermediate 12 W ring oscillator and then to the high power slave laser. The 12 W intermediate power stage is similar to the laser used in the GEO 600 detector [14].

Figure 1 shows the optical layout of the 200W laser system. A bundle of 10 fiber-coupled laser-diodes (maximum power 30 W each, core diameter 600μm, NA 0.22, wavelength 808 nm) are used to end-pump four Nd:YAG rods. Each rod has a diameter of 3 mm and its doped region is 40 mm long. They have 7 mm long undoped end caps to reduce thermal loading of the entrance surface. In order to achieve a uniform pumplight distribution and to avoid a transfer of the image of the fiber bundle onto the gain profile a fused silica rod is used as a pump light homogenizer. A side benefit is that a diode failure can be compensated by increasing the power of the remaining 9 diodes without changing the pump profile and the gain distribution. The injection-locking is reliable and stable with re-locking times of the full system of less than 1 s. After lock acquisition the power increases from 175 W to 195 W within the first 10 min and does not vary more that 5% for an 8 hour long continuous single-frequency operation.

3. Laser Stabilization

Frequency, power and spatial fluctuations of the input light couple into the gravitational wave channel. The relevant transfer functions depend strongly on the interferometer layout and on the filtering function of the optical cavities used. Even though no general requirements on the laser stability can be set, it is clear that the laser fluctuations in advanced gravitational wave detectors have to be reduced by many orders of magnitude to achieve the design sensitivity. In this section we will describe a stabilization scheme for the Advanced LIGO PSL. Even though it has features specific for Advanced LIGO it can serve as an example for describing the general stabilization concepts. The Advanced LIGO PSL has to provide 165 W of power at the interface to the suspended modecleaner with a higher order mode content of less than 5%. Figure 2

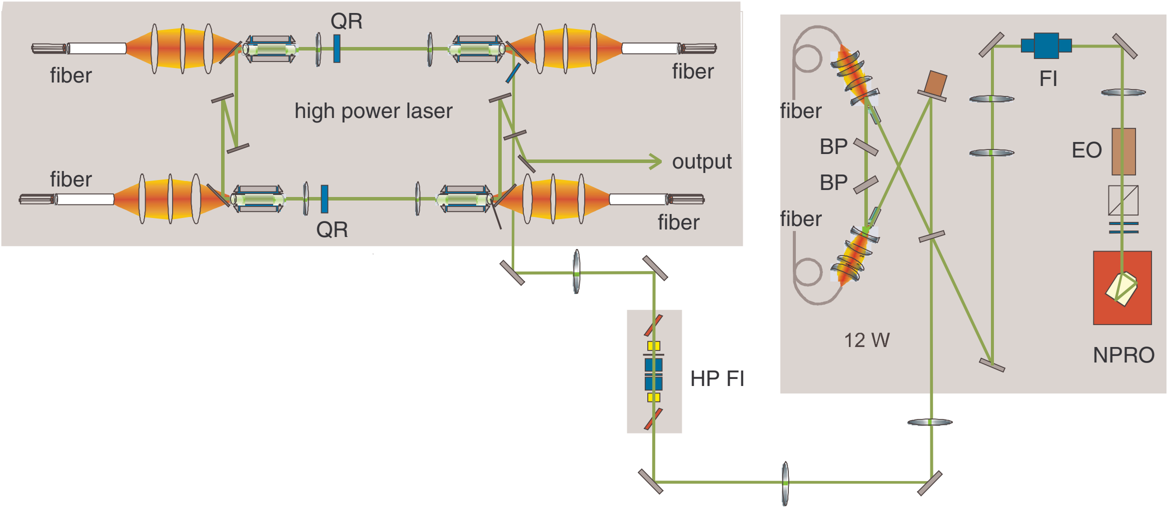

Figure 1. Optical layout of the 200 W laser: The beam from a 12 W injection-locked laser system is injected into the high-power slave-cavity which uses two pairs of birefringence compensated end-pumped Nd:YAG rods. The 12 W stage is injection locked to an 800 mW NPRO that provides a high frequency stability that is inherited by both injection locking stages. FI: Faraday Isolator, EO: electro-optical modulator, HPFI: high power Faraday Isolator, BP: Brewster plate, QR: quartz rotator

shows the anticipated stabilization scheme. The light of the NPRO is phase modulated by an electro-optical modulator and then amplified by the 12 W and the high power stage. The two injection-locking control loops are represented by the arrows marked with the letter a. A rigid-spacer ring-cavity called a pre-modecleaner (PMC) is used to spatially filter the laser beam. A length control loop keeps the PMC resonant with the laser field (arrow d). The PMC will be housed in a vacuum enclosure to avoid acoustic coupling to either the beam geometry or the frequency of the transmitted beam. A beam is split off after the PMC for frequency stabilization purposes. This beam double passes an acousto-optical modulator which is used in the first diffraction order as a frequency shifter and the light is then modematched into a reference cavity. A control loop stabilizes the laser frequency to this cavity by feeding back to the frequency actuators of the NPRO. The suspended modecleaner of Advanced LIGO will be a much quieter reference and the AOM frequency shifter can be used as an actuator to stabilize the laser to the modecleaner. Finally a so called tidal actuator which changes the temperature of the reference cavity will be used as an actuator to stabilize the laser to the slow drift of the arm cavities caused by the earth tides. The frequency control is very similar to the one used for the initial LIGO detector [15] which has already demonstrated that the stability level necessary for Advanced LIGO can be reached.

The power control (see arrows c) is split into three sections: The first loop stabilizes the power noise of the NPRO and mainly reduces the fluctuations at the relaxation-oscillation frequency of the master laser. The second loop senses the noise of the high power laser and feeds back to the current of the high power pump diodes. The error signal for the third loop will be generated by sensing the power fluctuations downstream of the suspended modecleaner. The control signal of that loop will be added into the error point of the second loop. The demanding power stability requirements and what has been achieved are subject of the next section.

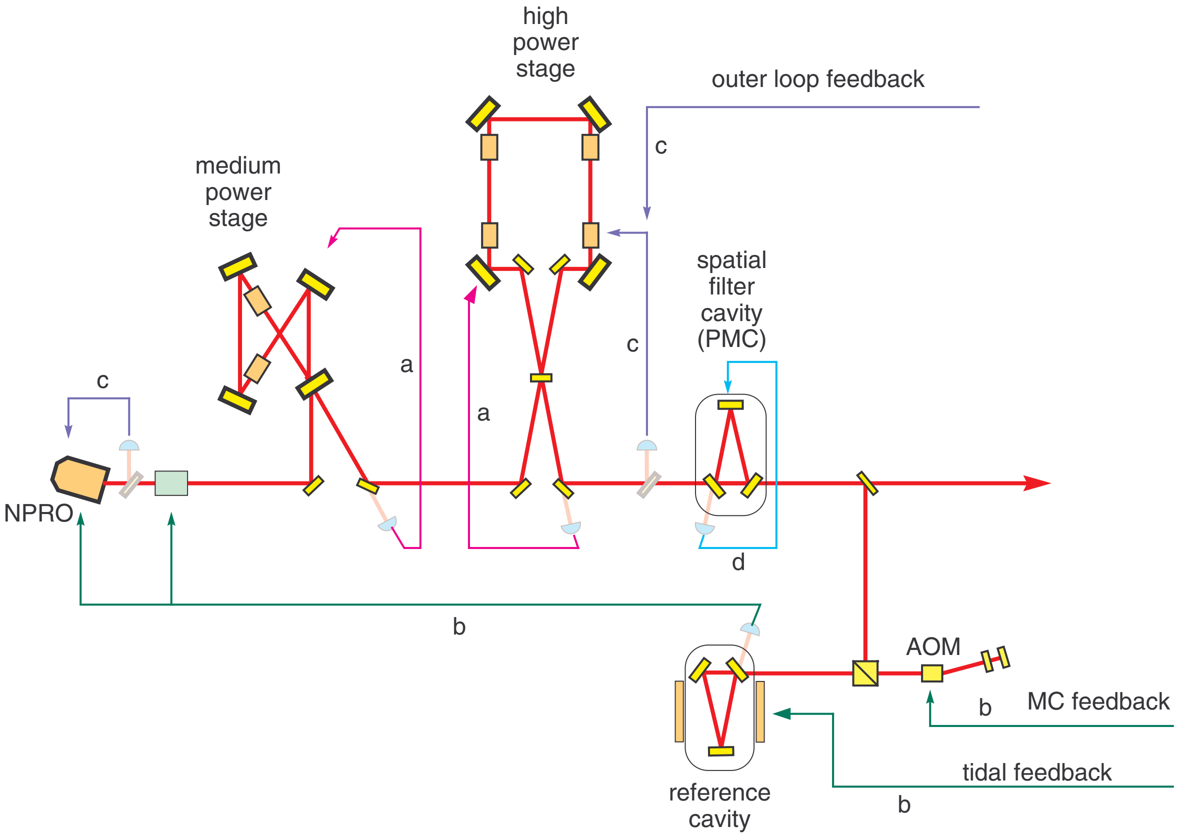

Figure 2. Stabilization scheme of the Advanced LIGO PSL . The different control loops are ordered by function. a: injection locking, b: frequency stabilization, c: power stabilization, d: length control of the filter cavity

4. Power stabilization

Various coupling mechanisms of laser power fluctuations into the gravitational wave channels exist in advanced gravitational wave detectors . These coupling mechanisms depend strongly on the interferometer design and can be divided into two classes. The first class couples directly via fluctuations in the light power detected on a photodiode, for example due to an intentional or accidental deviation from the dark-fringe operation point. The second class couples via radiation pressure fluctuations into the position of either the interferometer or modecleaner mirrors. Even though the beamsplitter ideally causes the technical power fluctuations injected into the two interferometer arms to be equal, an asymmetry in the interferometer arms can cause a differential arm length change to be produced by laser power fluctuations. In case of the Advanced LIGO detector the power stabilization requirement is set by the radiation pressure effects in the interferometer arms which are expected to show an asymmetry of 1% . The most stringent requirement for the relative intensity noise is RIN $\leq 2\times10^{-9}/\sqrt{\mathrm{Hz}}$ at 10 Hz Fourier frequency. Starting from a free running RIN of approximately $10^{-5}/\sqrt{\mathrm{Hz}}$ a control loop with more than 80 dB loop gain has to be designed. As described above the purpose of the first power stabilization loop is to stabilize the master laser in particular at its relaxation oscillation frequency. If not stabilized, the up to 40 dB high relaxation oscillation peak at frequencies around 500 kHz could cause problems in the control loops of the interferometer. As the free running noise of the 200 W laser at lower frequencies is dominated by the high power stage, a

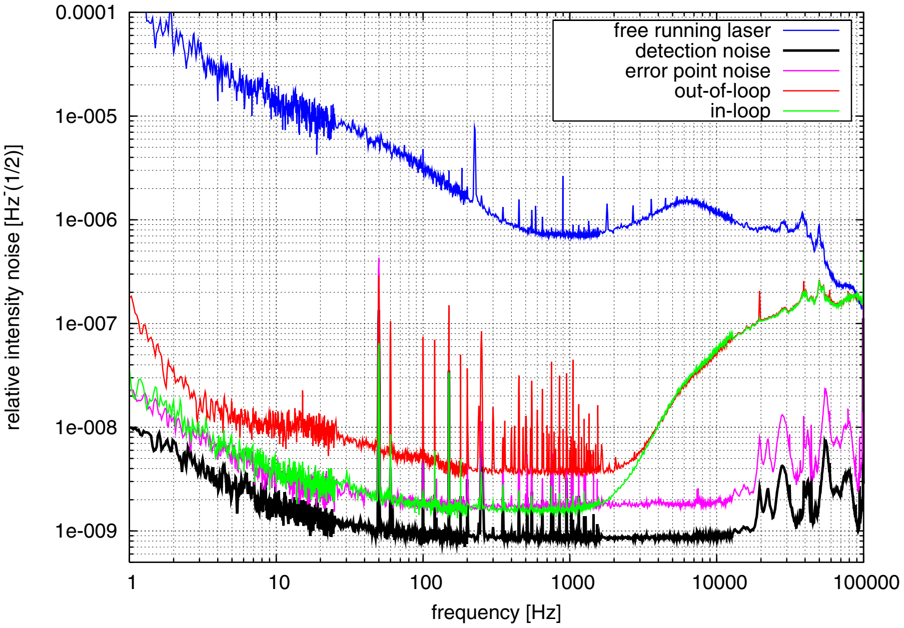

Figure 3. Relative power noise of a free-running and stabilized 12 W laser system. The gain in the control loop is sufficient to bring the in-loop result close to the AdvLIGO requirements. The discrepancy between the in-loop and the out-of-loop result is not understood and subject of ongoing investigations.

second loop is required which senses the power fluctuations downstream of the PMC and feeds back to the pump diodes of the high power stage. It has been shown by several groups [16][17], that the detection of power fluctuations at the RIN $\leq 2\times10^{-9}/\sqrt{\mathrm{Hz}}$ level is problematic. As the 200 W laser was not available and the main challenge lies in the noise sensing and not in the control loop design, we set up a power stabilization experiment with a 12 W GEO 600 type laser which shows a similar free running noise level as the 200 W laser. The results are shown in Figure 3. The lowest curve shows the dark noise and the curve above represents mainly the noise of the voltage reference used to subtract the large DC signal produced by the detected 75 mA of photocurrent. A measurement of the noise spectrum on the in-loop photodiode $\mathrm{P_{IL}}$ shows, that the loop gain was sufficient to reduce the laser power fluctuations to at least the level given by the noise of the voltage reference. A measurement utilizing an independent photodiode not included in the control loop path $\mathrm{P_{OUT}}$ shows, however, that the achieved noise level especially at low frequencies is worst than the in-loop measurement would suggest. We investigated a number of effects that could produce the additional noise in the light sensing, for example pointing of the beam on the photodiode in combination with photodiode non-uniformities, polarization fluctuations in combination with a polarization dependent splitting ratio between $\mathrm{P_{IL}}$ and $\mathrm{P_{OUT}}$ and electronic noise in the control loop. (A detailed discussion of these investigations will be given elsewhere [18].) Even though the results shown in Figure 3 represent, to the best of our knowledge, the lowest demonstrated RIN levels worldwide, more investigations are needed to find the excess noise in the RIN sensing and to demonstrate the stability required for the Advanced LIGO PSL.

5. Summary

We described a 200 W prestabilized laser system that is under development for use in advanced gravitational wave detectors. An injection-locked end-pumped rod oscillator with birefringence compensation was chosen for the high power stage. We used the stabilization scheme of the Advanced LIGO PSL as an example to describe possible stabilization techniques. The power noise reduction was identified as the most challenging stabilization task in the PSL. New results with RIN $\leq 4 \times 10^{-9}/\sqrt{\mathrm{Hz}}$ were presented and possible limitations in the sensing of power fluctuations were discussed.

References

[1] Lueck H 2005 *J. Phys. Conf. Ser.* this issue
[2] Sigg D 2005 *J. Phys. Conf. Ser.* this issue
[3] Braccini S 2005 *J. Phys. Conf. Ser.* this issue
[4] Arai K 2005 *J. Phys. Conf. Ser.* this issue
[5] Giaime J 2005 *J. Phys. Conf. Ser.* this issue
[6] Punturo M 2005 *J. Phys. Conf. Ser.* this issue
[7] Saraf S *et al* 2005 *Opt. Lett.* **30** 1195
[8] Munch J 2005 Presentation at March meeting of the LIGO scientific collaboration http://www.ligo.caltech.edu/docs/G/G050207-00.pdf
[9] Liem A 2003 *et al Opt Lett* **28** 1537
[10] Limpert J 2003 *et al Opt. Express* **11** 818
[11] Karszewski M 1998 *et al OSA Tops, ASSP 19* 296
[12] Frede M 2005 *et al Opt. Express* **13** 7516
[13] Frede M 2004 *et al Opt. Express* **12** 3581
[14] Zawischa I *et al* 2003 *Class. Quantum Grav.* **19** 1775
[15] Savage R *et al* 1998 *Laser Physics* **8** 679
[16] Rollins J *et al* 2004 *Opt. Lett.* **29** 1876
[17] Barr B *et al* 2005 *Class. Quantum Grav.* **22** 4279
[18] Seifert F *et al* , in preparation