# The GEO 600 Stabilized Laser System and the Current-Lock Technique

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**Abstract.**

This talk will give an overview over the GEO 600 laser-diode pumped Nd:YAG laser system. After an introduction which defines the requirements, we describe the laser design and the laser frequency stabilization scheme.

Due to its low power noise in the radio frequency region and due to its good spatial beam quality, an injection-locked master-slave design is used for the GEO 600 laser. This laser system has an output power of 12 W and a good spatial profile ($M^2 \leq 1.05$).

A monolithic non-planar ring-oscillator (NPRO) with an optical power of 0.8 Watt is used as the master laser. By stabilizing the NPRO to a reference cavity we achieve an frequency noise spectral density of less than $1 \mathrm{mHz}/\sqrt{\mathrm{Hz}}$ for fourier frequencies between 10 Hz and 1 kHz at the feed-back loop error point.

Finally we present a new scheme to stabilize the frequency of a NPRO by feeding back to the power of its laser-diode pump-source. First experiments with this so-called current-lock technique led to a robust lock and simultaneously to a reduction in power-noise of the NPRO without an additional power stabilization control system.

## INTRODUCTION

All gravitational wave detectors currently under construction will use laser diode pumped Nd:YAG laser systems as their light source. The reasons for the selection of Nd:YAG systems are their high efficiency and the availability of a very stable master-oscillator, the so-called NPRO (Non-Planar Ring-Oscillator). Especially the low free-running frequency-noise of the NPRO makes it possible to reach the demanding frequency stability requirements of gravitational wave detectors. Although the GEO 600 detector use a dual-recycled interferometer with a folded optical path in the interferometer arms, the stability requirements for the laser

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system are very similar to the needs of the LIGO [2], VIRGO [7], and TAMA [10] detectors, which use different optical layouts.

To reach shot noise limited performance of the GEO 600 detector for fourier frequencies above 200 Hz a light power of 5 W needs to be injected into the power recycling cavity. Due to losses in the optical chain before the power recycling mirror an output power of the pre-stabilized laser system of more than 10W is anticipated. The power-stability requirement on the GEO 600 laser is set by analyzing two different paths on which power noise can couple into the interferometer output: a) Deviations from the dark fringe locking point of the interferometers will transfer low frequency power noise of the laser into an artificial gravitational wave signal. The power stability requirements in the low fourier frequency region are plotted in Figure1. b) In the radio-frequency region amplitude modulation of the laser light will change the amplitude of the modulation sidebands and therefore couple directly into the heterodyne readout of the interferometer. As in the GEO 600 detector the light passes sequentially two suspended modecleaners we decided to phase modulate the laser beam with the heterodyne rf-frequencies $\omega_{\rm rf}$ behind the first modecleaner. This allows the first modecleaner to act as a passive power noise filter at $\omega_{\rm rf}$ and relaxes the power noise requirements of the pre-stabilized laser system in the rf-region.

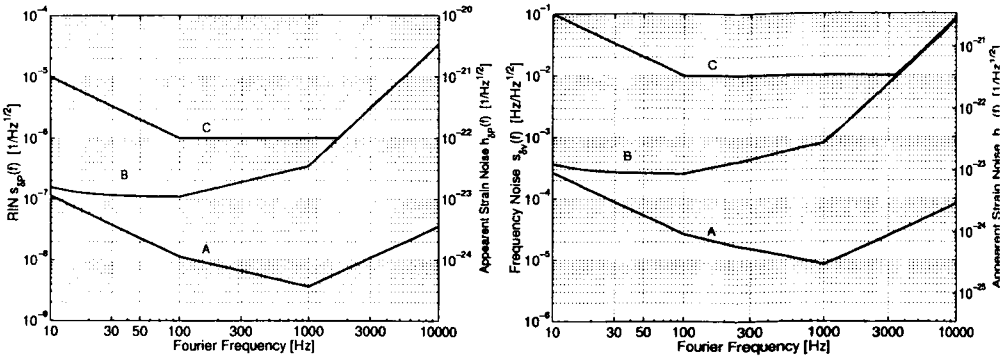

**FIGURE 1.** Requirements for the power-stability (left) and frequency-stability (right) of the GEO 600 laser system. The upper curves labeled with C are the demanded requirements for the pre-stabilized laser, the curves labeled with B reflect a limit for the fluctuations allowed for light entering the power recycling cavity and the lower curves show the stability requirements at the beam splitter.

The frequency stability requirements for the pre-stabilized laser system are also plotted in Figure1. GEO 600 will use a method based on the Schnupp locking-scheme to control the interferometer longitudinal degree of freedom. As this method requires a small difference in the interferometer armlength, $\Delta L \leq 10$cm, frequency noise of the laser system will be transfered into a signal at the gravitational wave output port of the detector.

Both graphs in Figure1 show three different curves: the upper curves labeled with C are the demanded requirements for the pre-stabilized laser, the curves labeled with B reflect a limit for the fluctuations allowed for the light entering the power recycling cavity and the lower curves show the stability requirements at the beam splitter. The difference between the curves B and C defines the noise reduction that needs to be achieved by the so called second-loop control systems which measure the fluctuations of the light before the power recycling cavity and feed back to the laser system to reduce these fluctuations. Therefore the pre-stabilized laser system has to provide low-noise actuators for these feed-back control systems.

In this contribution we introduce the layout and performance of the GEO 600 high-power laser-system and the frequency stabilization scheme employed. The free-running noise spectral density as well as the achieved noise reduction will be presented and the source of the remaining fluctuations will be discussed. Finally we present a new scheme to stabilize the frequency of a NPRO by feeding back to the current of its laser-diode pump-source and the advantages of this scheme will be discussed.

## THE INJECTION-LOCKED LASER-SYSTEM

The GEO 600 high-power Nd:YAG laser system uses the injection-locking method [9] to transfer the high frequency stability of a low-power master laser to a high-power oscillator, called the slave laser. A schematic drawing of the GEO 600 laser is shown in Figure 2. The master laser used in the GEO 600 laser system is a laser-diode pumped monolithic Nd:YAG ring-laser (NPRO) with an output power of 0.8 W (Innolight, Modell Mephisto 800). The advantage of the monolithic design invented by Kane and Byer [6] is the high intrinsic frequency and power stability which is orders of magnitude better than the free-running stability of $Ar^+$ lasers. After passing an optical diode to isolate the NPRO against light coming from the high-power slave and an electro-optical phase modulator used in the injection-locking control scheme, the light of the NPRO is injected into the slave cavity. Two Nd:YAG rods each of which is end pumped by a fiber-coupled laser-diode-module with 17 W optical power are used as the gain elements in a four mirror slave-oscillator ring-cavity. One of the mirrors is mounted on a piezo-electric transducer (PZT) to control the length of the cavity in order to keep the difference between the frequency of the slave laser and the NPRO frequency well within the injection locking range of 1.6 MHz. The control loop bandwidth of approximately 10 kHz was limited by mechanical resonances in the PZT. To increase the mechanical stability of the slave laser cavity the mirrors and the PZT were mounted on a rigid copper spacer. This reduced the vibrations of the slave cavity in the acoustic frequency region by an order of magnitude.

Two brewster plates in the slave laser cavity compensate for the astigmatism introduced by the non-normal reflection of the curved mirrors, reduce the depolar-

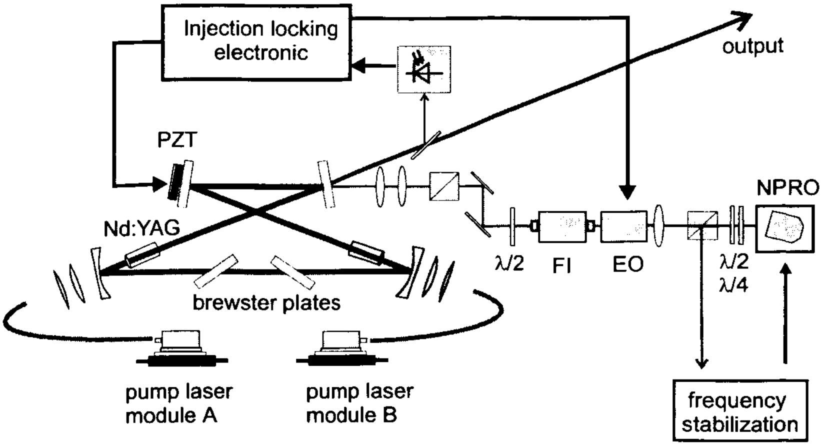

**FIGURE 2.** Setup of the GEO 600 high power laser system. A frequency-stabilized NPRO with 0.8 W output power is used as a master laser. The injection-locked slave laser with 12 W output power and a $M^2 \leq 1.05$ is pumped by two fiber-coupled diode-laser-modules each with 17 W optical power.

ization losses and define the polarization of the 12 W output beam. The spatial profile of the high-power laser beam was measured to have a $M^2$ value of less than 1.05 which agrees well with the maximum light power of 95 that could be coupled into the $TEM_{00}$ mode of a cavity.

## FREQUENCY STABILIZATION

With a robust and high-bandwidth injection-locking control loop in place, the frequency-stability of an injection-locked laser system is determined by the stability of its master laser [1], [4]. Therefore a frequency stabilization of the NPRO to the resonance frequency of a high-finesse ring-cavity could be used to reduce the frequency fluctuations of the high-power system. The ring-cavity used for GEO 600 is formed by three mirrors which are optically contacted to a rigid spacer made from ultra-low expansion material (ULE). To avoid contaminations and length fluctuations of the cavity introduced by acoustics the reference cavity was placed inside a high-vacuum-system ($p \leq 1 * 10^{-8}$ mbar). We used the Pound-Drever-Hall method to get an error-signal for the frequency stabilization loop. By feeding back to the PZT frequency actuator of the NPRO the laser was first locked with a low bandwidth loop to the cavity to perform a measurement of the free-running frequency noise of the NPRO (see Figure 3, upper curve). According to the work of Day et al. [3] this free-running frequency noise is mainly due to fluctuations of the index of refraction in the NPRO crystal caused by fluctuations of the pump-diode power.

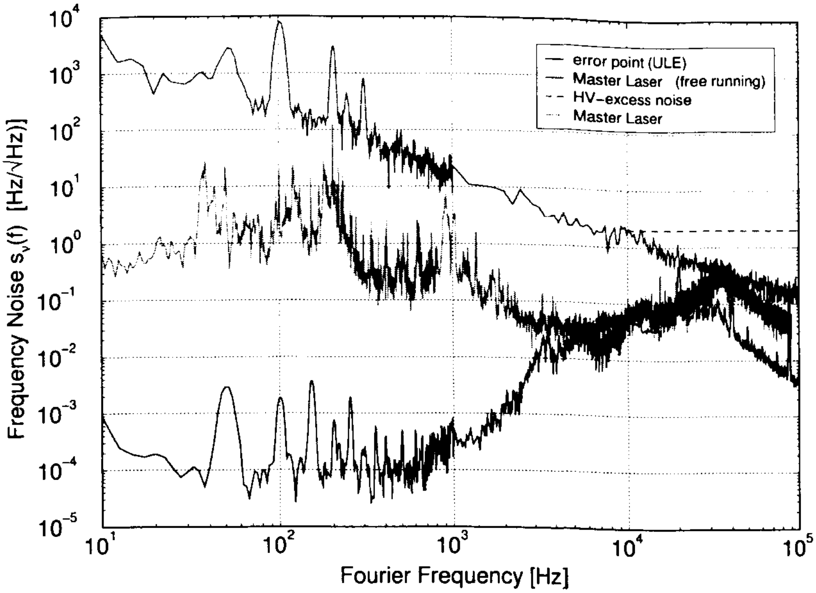

**FIGURE 3.** Frequency noise of the free-running NPRO (upper curve), of the stabilized NPRO at the error point of the stabilization loop (lower curve) and of the stabilized NPRO with respect to an analyzer cavity (middle curve).

By adding a fast electro-optical phase shifter to the control system we increased the bandwidth to 1 MHz and achieved high low-frequency gain. The lower curve of Figure3 shows the spectral density of the error point noise of this feed-back loop. The high noise reduction at low fourier frequencies reflects the high gain of the control system in this frequency region.

By splitting the NPRO beam and shifting the frequency of one part of it with an acousto-optical modulator (AOM) we were able to lock the NPRO to the reference cavity and simultaneously couple a fraction of the light into an analyzer cavity. A second Pound-Drever-Hall scheme was used to measure the frequency fluctuations of the frequency-shifted NPRO beam with respect to the analyzer cavity. The middle curve in Figure 3 shows the measured noise spectral density which is significantly higher than the error-point noise (lower curve.) This additional noise is probably due to mechanical resonances of the optical table as well as vibrations coupled into the reference and analyzer cavity. We expect, that a pendulum suspension of the cavities will reduce the out-of-loop noise significantly as it was demonstrated by Nakagawa et al. [8].

By feeding back to the AOM we were able to lock the frequency-shifted NPRO to the analyzer cavity. The measured drift between the reference and the analyzer cavities was 300 Hz/s.

To assure that the frequency noise of the injection-locked system is dominated by the noise of its master laser we used the analyzer cavity to measure the frequency fluctuations of the complete injection locked system. No difference to the noise of the master laser could be found.

## THE CURRENT LOCK TECHNIQUE

As already stated above, the free-running frequency noise of a NPRO laser is dominated by the fluctuations of the index of refraction in the Nd:YAG crystal which are caused by power-fluctuations of the diode-laser pumping the NPRO [3]. To get a quantitative understanding of the cross-coupling between pump-power fluctuations and the NPRO frequency we measured the transfer function between fluctuations of the current through the pump-laser-diodes and NPRO frequency (see Figure4).

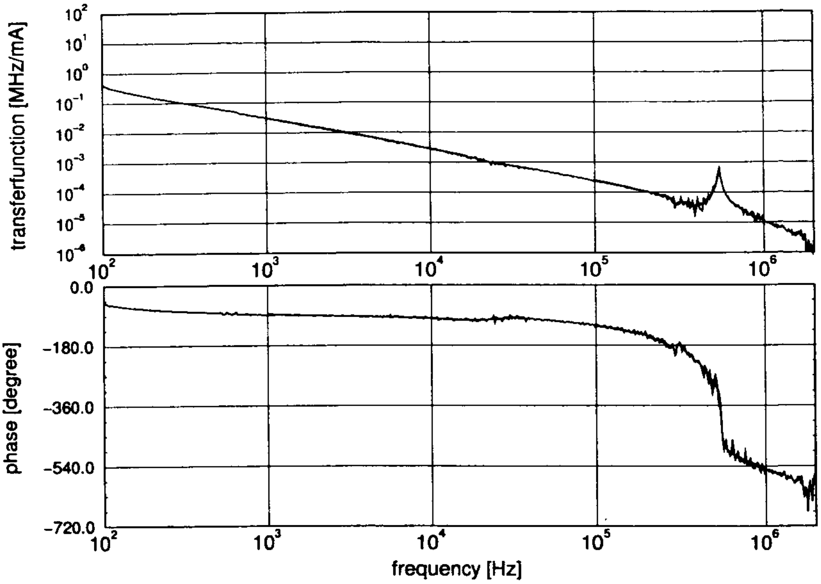

**FIGURE 4.** Transferfunction between fluctuations of the current through the pump-laser-diodes and NPRO frequency. The structure around 500 kHz corresponds to the relaxation oscillation of the used NPRO.

Based on this transfer function we designed a controller to lock the laser frequency to a reference cavity by feeding back to the current of the NPRO pump laser-diodes. This so-called current-lock [11] has several advantages:

-To design a high-bandwidth frequency-stabilization control system only one actuator is required (instead of the PZT and the phase-correcting pockels-cell needed

in the conventional scheme).

-The pump-diode-current actuator needs only a low voltage signal (compared to the PZT and the pockels cell which both need high voltage amplifiers).

-No beam-pointing is introduced by changing the pump-diode-current (instead of the pointing introduced by the PZT actuator).

-No PZT frequency-actuator is needed on the NPRO which makes the fabrication easier and allows a better thermal engineering and a different design of the magnetic-field that is needed to assure single direction operation of the NPRO.

In addition to the demonstration of a stable lock one very interesting result was obtained: Instead of increasing the NPRO-power-fluctuations by feeding a signal to the pump-diode-current, the NPRO power fluctuations were reduced by about 6dB. The reason is, that the current lock decreases the pump-diode-power fluctuations which are also driving the power fluctuations of the NPRO. Earlier experiments [5] to reduce the NPRO intensity noise were limited by the spatial variation of the pump-laser-fluctuations and the lack of information on which spatial part of the pump beam is sensed by the NPRO. The NPRO frequency deviations used as an error signal in the current-lock technique, however are only sensitive to pump-diode-fluctuations in the active path of the NPRO crystal.

Further current-lock experiments are planned to show how much NPRO power-noise-reduction is achievable and if the current lock technique can be employed in the stabilization scheme of the GEO 600 laser.

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