# The GEO 600 Laser System

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## Abstract

Interferometric gravitational wave detectors require high optical power, single-frequency lasers with very good beam quality and high amplitude and frequency stability as well as high long term reliability as input light source. For GEO 600 a laser system with these properties is realized by stable planar, longitudinally pumped 12 W Nd:YAG rod laser which is injection-locked to a monolithic 800 mW Nd:YAG non-planar ring oscillator. Frequency control signals from the mode cleaners are fed to the actuators of the non-planar ring oscillator which determines the system's frequency stability. The system power stabilization acts on the slave laser pump diodes which have the largest influence on the output power. In order to gain more output power, a combined Nd:YAG-Nd:$YVO_4$ system is scaled to more than 22W.

## Introduction

The sensitivity of interferometric gravitational wave detectors fundamentally depends on the light power circulating in the arms. For the GEO 600 detector about 10 kW of circulating power are needed within in the interferometer arms. Taking into account the finesse of the power recycling cavity and losses in the input optics, an estimated laser output power of 10 W is needed.

In the Fourier frequency band of interferometer sensitivity to gravitational waves, asymmetries and light scattering in the interferometer require a high power and frequency stability at the input light. At the interferometer input in front of the power recycling mirror the most stringent specifications are given in a frequency range between 10 Hz and 100 Hz. In this Fourier band the frequency fluctuations of the input light with respect to the power recycling cavity should not exceed $2x10^{-4}$ $Hz/Hz^{1/2}$ and amplitude fluctuations should stay smaller than $5x10^{-8}$ $Hz^{-1/2}$ [1]. In order to achieve this demanding requirements, a 12 W laser with very good stability was developed and control loops were implemented to fulfill the requirements.

In the following we will give an overview of the injection locked laser system for GEO 600 including the passive stability features, active control actuators and a first power pre-stabilization loop. The frequency stabilization loops are described elsewhere in this volume [2]. An approach to increase laser efficiency and output power is described in the last section.

## Injection Locked Lasers

In order to supply the required input light to the GEO 600 interferometer an injection locked laser system [3] was constructed (fig. 1). The radiation of a stable single frequency laser (master oscillator) is injected to a power oscillator (slave laser). As soon as the resonance of the power oscillator cavity deviates from the master frequency by less than the so-called locking range $\Delta\nu = T_{oc} FSR/(2\pi)\cdot\sqrt{P_{master}/P_{slave}}$, the slave laser emission is synchronized to the master oscillator. If the deviation from exact resonance is kept small compared to the locking range the reduced influence of the slave's eigenfrequency fluctuations $\delta\nu_{slave}$ to the system output frequency can be expressed in terms of their Fourier frequency $f$ $\left|\delta\nu_{system}(f)/\delta\nu_{slave}(f)\right| = 1/\sqrt{1+(\Delta\nu/f)^2}$ [4,5,6,7]. At Fourier frequencies much smaller than the locking range the influence of the slave is strongly suppressed and the system stability is determined by the master laser.

Due to the saturation of the slave laser's gain, the power noise at low Fourier frequencies (the interferometer detection band) is mainly determined by the slave laser's pump source and must hence be controlled at latter or in the high power output beam [ 8,9].

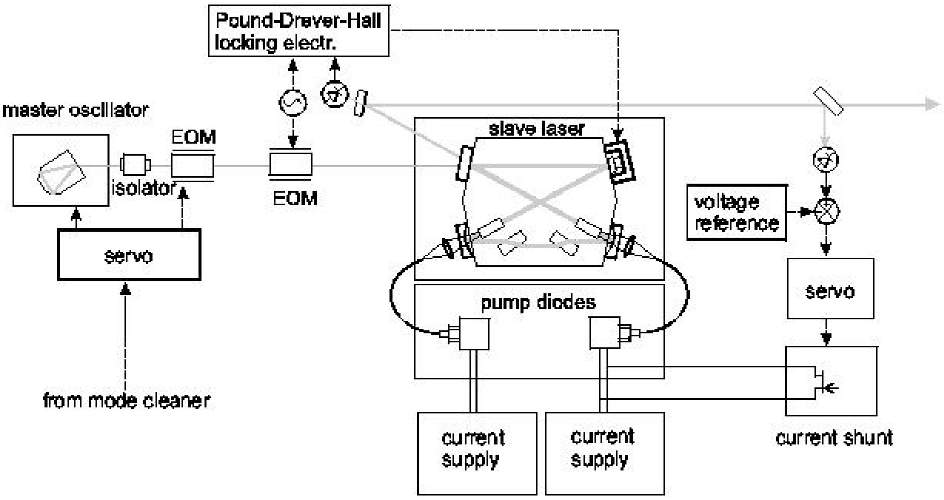

**Figure 1**: Scheme of the GEO 600 injection-locked laser system.

## Master Laser

For GEO 600 a diode pumped monolithic miniature Nd:YAG non-planar ring-laser (NPRO) [10,11,12] (Innolight Mephisto 800 NE) with 800 mW output at 1064 nm wavelength is used as the master oscillator. This type of laser is well known for its high passive stability and good premises for further active stabilization [13,14]. The frequency correction signals from the mode cleaners are fed to a piezo ceramic actuator and a Peltier element, with are attached directly to the NPRO crystal and change the laser frequency by means of stress induction and temperature change. For phase correction with Fourier frequencies above 50 kHz an external electro-optic modulator (EOM) is set in the master output beam. Alternatively stabilization can be achieved by a feedback loop to the pump diode current. A bandwidth of 100 kHz has been achieved so far [15].

## Slave Laser

A planar bow-tie ring-resonator with two end-pumped Nd:YAG rods serves as slave laser for GEO 600 [1,16]. So far two prototypes and five serial versions of the laser with the same optical layout have been assembled and brought to operation. At 2x 17 W pump power from the fiber coupled laser diodes between these laser reach an output power of 12 W to 13.5 W in a $TEM_{00}$ mode. The output beams are typically about 1.1 times diffraction limited and have a degree of polarization of better than 98%.

Apart from a cable feed trough in early copies of the laser the half-monotlithic resonator spacer and the mirrors – of which three are directly glued to the spacer – seal the resonator cavity such that acoustic noise cannot easily disturb the phase of circulating field and air borne pollution of the cavity is reduced. At around 100 Hz to 1000 Hz this quasi-monolithic design [16] reduces the influence of laboratory noise on the laser by two decades as compared to a laser assembled from discrete components (fig.2). A low sensitivity of the slave resonator to temperature changes is achieved by the choice of Invar steel (Ni36Fe64 / 1.3912, $\mathit{alpha}_l$ = 0.8x $10^{-6}$/K) for the resonator block. The overall thermal expansion including the effects of the air at constant pressure in the resonator, the Brewster plates, the piezo and the piezo mount was calculated to be $8.6x10^{-7}$ m/K for the early versions of the laser resonator where the piezo mount was not made from Invar. The expansion for the later full Invar versions is calculated to $2.4x10^{-7}$ m/K. As long as the cavity volume is connected to the environmental air the atmospheric pressure variations change the optical path length in the resonator via the pressure dependent refractive index of air. A literature value for air refractive index yields about 80 MHz/hPa [17], which corresponds for the slave laser cavity to $1.6x10^{-7}$ m/hPa. The piezo actuator of the slave laser has a range of approximately 4 µm (-100V to 500V). This range accomplishes compensation for temperature fluctuations of the cavity of +/- 4.5 K (+/- 16 K) or pressure fluctuations of +/- 25 hPa. A control loop bandwidth of up to 20 kHz can be achieved.

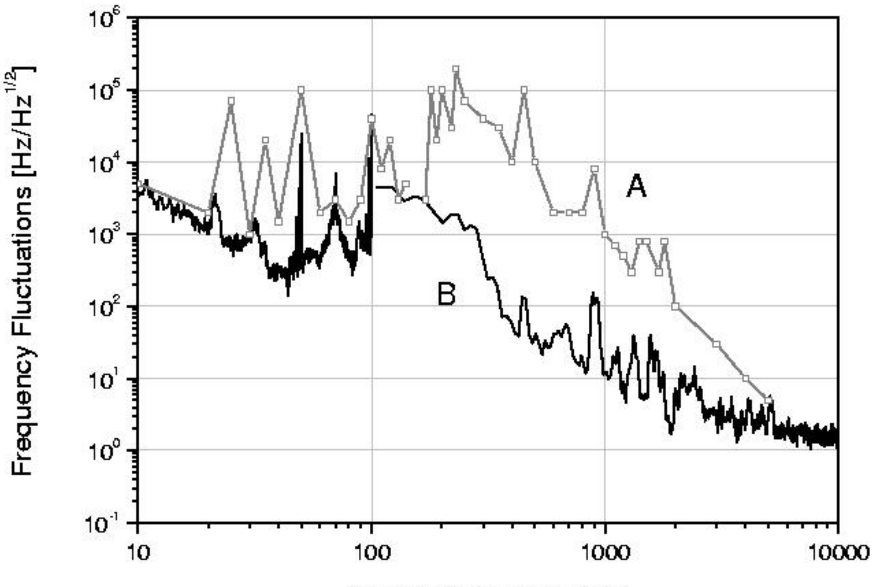

**Figure 2**: Spectral density of the eigenfrequency fluctuations of the slave laser cavity. The data are derived from the piezo length actuator signal that is necessary to keep the slave laser exactly on resonance with a frequency-stabilized master oscillator. A) Conventional laser resonator assembled from multiple discrete components. B) Quasi-monolithic slave laser resonator.

Currently investigations on hermetically air tight resonators are underway. The advantage of an air tight resonator is the independence of atmospheric pressure changes. Alternatively a controlled pressure variation could be used as length actuator. First tests have shown that deliberate slow pressure variations cause at least 3 times less beam jitter than the typical piezo systems, that tilt about 5 to 10 µrad/µm.

## System Performance

The single frequency output power of the injection locked systems is about the sum of the combined master and slave laser powers, i.e. 12.8 W to 14.5 W. With the copy that was implemented at the interferometer site a visibility of 96% has been achieved at the first mode cleaner. This demonstrates a high compatibility of the laser mode with passive stable resonators.

An injection lock servo based on the Pound-Drever-Hall technique with 10 kHz control bandwidth reduces the rms (1 Hz to 100 kHz) deviations of the slave laser cavity from master frequency down to 500 Hz, which is $3\text{x}10^{-4}$ times the locking range of about 1.5 MHz. No detrimental influence of the slave on the system frequency stability has been observed so far.

In order to automatically achieve injection lock an autolock servo was implemented in the laser control system. The autolock detects a loss of lock by a laser output power drop because in this case the slave is not lasing unidirectional anymore but emits a part of the power in either output direction. Lock acquisition can simply be achieved by the application of a voltage ramp to the slave piezo length transducer until a transient lock is found and the servo can be switched back to normal operation. Typically about five seconds are needed to acquire stable injection lock.

After several months of laboratory tests a copy of the laser was brought to the detector site in January 2001. Until September 2001 only a small power drop of 5% was observed. It is likely to be caused by a power drop and a spectral change of the pump laser diodes.

Recently a first electronic intensity noise suppression servo has been implemented. For this purpose about 12 mW of the laser output are coupled from the main beam onto an InGaAs-PIN photoreceiver (fig. 1, right hand side). The output voltage of the receiver is then compared with a stable reference voltage. The resulting error signal is suitably amplified and fed back to a current shunt transistor across one of the slave pump diodes. The servo bandwidth reaches from DC to about 50 kHz. At Fourier frequencies below 2 kHz the residual relative power noise detected in the loop is reduced below $10^{-8}$ / $\text{Hz}^{1/2}$ (fig. 3).

The lowest power noise observed below 50 KHz with an independent photoreceiver outside the control loop is about 2x $10^{-8}$ / $\text{Hz}^{1/2}$. At the current stage of development disturbances at the AC power line frequency and multiples are still observable in the out of loop signal. Further disturbances between 90 Hz and 2 kHz are likely to be introduced by beam jitter on the beam splitter and the photodiodes due to their spatially slightly varying properties. For so far unknown reasons the noise reduction ceases to work below 5 Hz. Further investigation into the latter problem as well as measures against the line noise and beam jitter are currently carried out. All jitter-induced fluctuations in the detected power will be finally removed if the photoreceiver is located after the suspended mode cleaner in vacuum, were the beam jitter is strongly reduced.

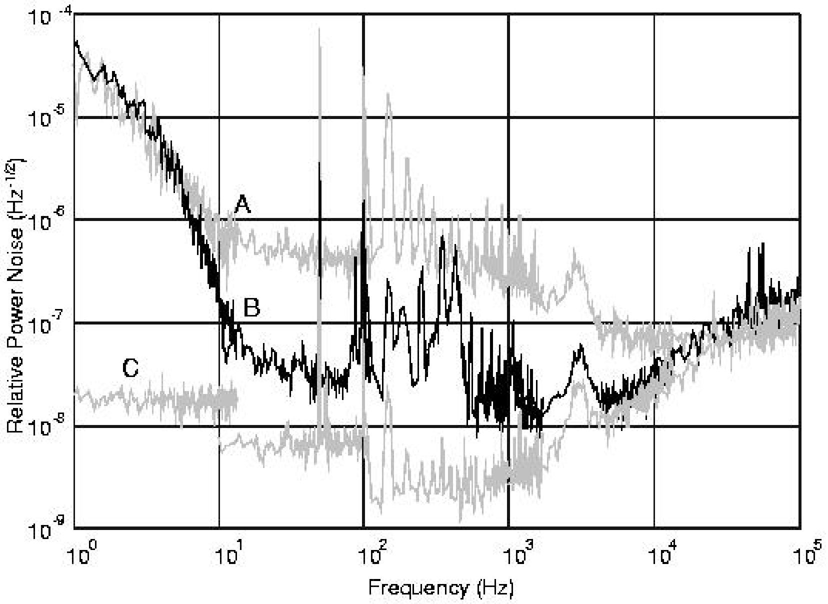

**Figure 3:** Relative Power Noise spectral density of the laser system. A) Without stabilization circuit. B) Out-of-loop signal with independent photoreceiver (not displayed in fig. 1). C) Upper limit of the in-loop signal. Below $10^3$ Hz the true in-loop signal is covered by the spectrum analyzer input noise.

## A Nd:YAG-Nd:$YVO_4$ System

In order to increase the output power of the system without large modifications, an injection locked laser system with a Nd:YAG NPRO as the master laser and a Nd:$YVO_4$ power oscillator as the slave laser has been evaluated.

The advantages of Nd:$YVO_4$ as gain medium as compared to Nd:YAG are its anisotropic emission cross section which furthers polarized laser emission, its birefringence that suppresses depolarization losses, and its lower saturation intensity which affords the application of an output coupler with higher transmission and hence reduces the detrimental effect of other resonator losses. Further more, the pump absorption band of Nd:$YVO_4$ at 809 nm is wider than that of Nd:YAG, which reduces the requirements on the pump diodes. Its general disadvantages are the low thermal conductivity and the brittleness of the material which leads to a low damage threshold with respect to pump power absorption. For end pumped 0.5 % doped rods, damage thresholds of abbout 58 W/mm$^2$ have been reported [18]. This threshold can be increased by 50 % by the application of composite rods with undoped end-caps [19], which reduce the temperature and the thermal stress ad the pumped facet. A problem in combining Nd:$YVO_4$ with Nd:YAG might be its slightly shorter center wavelength of the gain profile at room temperature.

In order to set up an Nd:$YVO_4$ power oscillator, the general layout of the Nd:YAG slave laser has been left unchanged. The Nd:YAG rods were replaced by composite 0.5% doped Nd:$YVO_4$ rods. At the 450 µm radius pump spots a damage threshold of about 55W was calculated. The Brewster plates were removed from the resonator. The mode size in the crystal was increased to 400 µm radius in order to avoid higher mode oscillation. At the same time this increased the efficiency for the fundamental mode. At 2x 22 W pump power 22 W output power in an 1.1 times diffraction limited mode could be extracted through a 16% output coupler.

Despite the slightly shorter center gain wavelength of Nd:$YVO_4$ compared to Nd:YAG at same material temperature, the Nd:$YVO_4$ laser was easily locked to the Nd:YAG NPRO yielding more than 22W single frequency output. This can be explained by a high core temperature of the Nd:$YVO_4$ rod due to the low thermal conductivity of the material and the high thermal load. Comparing the emission of master and stand alone slave individually with respect to their crystal mount temperature[1] we found the same wavelength of 1064.15 nm at 30°C and tuning coefficients of 0.063 nm/K for the Nd:YAG and 0.030 nm/K for the Nd:$YVO_4$.

## Conclusion

The GEO 600 injection-locked laser system approached a reliable performance that moves it from an object of research and laser development to a tool for gravitational wave research. Nevertheless there is an continuous search for further improvements, which will in future be oriented towards the qualification as a front end for a 200 W power stage for future gravitational wave detectors.

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[1] Be aware that due to the different geometry of both crystals and mounts a comparison of crystal temperature is not directly possible from this data.

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