The GEO 600 laser source: a 12 W frequency-stabilised injection-locked Nd:YAG laser system

Oliver Sascha Brozek, Kasem Mossavi, Karsten Danzmann
Max-Planck-Institut für Quantenoptik, Callinstrasse 38,
D-30167 Hannover, Germany, osb@mpq.mpg.de
Ivo Zawischa, Michael Peterseim, Carsten Fallnich, Herbert Welling
Laser Zentrum Hannover e. V., Hollerithallee 8,
D-30149 Hannover, Germany
Volker Quetschke, Harald Lück, Benno Willke
Institut für Atom- und Molekülphysik, Universität Hannover,
Callinstrasse 38, D-30167 Hannover, Germany

Abstract

GEO 600 [9] is a dual-recycled laser interferometer gravitational wave detector built as a German-British joint project. The detector site is located south of Hannover in Germany. To achieve the target strain sensitivity of $10^{-22}/\sqrt{\mathrm{Hz}}$ a highly stabilised laser system with an output power in the order of 10 W is necessary. We have set up an injection-locked, frequency stabilised laser system, consisting of a monolithic Nd:YAG ring laser and a high power slave laser. Descriptions of the requirements, the design of the stabilised laser system and the noise performances are given in this contribution.

1. Introduction

The detection of gravitational waves with Michelson-type laser interferometers sets very high demands on the light source, e.g., output power, power and frequency noise, transversal mode purity. All presently constructed interferometric gravitational wave detectors are using laser-diode pumped Nd:YAG laser systems consisting of monolithic Nd:YAG ring lasers (NPRO) [5,6] with amplification stages involving a MOPA [8] (LIGO) or an injection-locked high power slave laser [1,10] (GEO 600, VIRGO, TAMA, ACIGA). The use of an amplifier stage simplifies the design of the system, however higher pump power and more effort on improving the transversal beam quality are necessary. Furthermore the intensity noise of the laser is increased at RF-frequencies above shot noise due to the amplification process. Whereas injection-locking requires active stabilisation

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of the slave laser length but does not produce excess intensity noise [1,4,7]. The slave laser resonator improves the spatial beam quality of the laser system.

2. Requirements for the GEO 600 Laser System

The GEO 600 gravitational wave detector uses a dual recycling scheme [9] with a high power recycling factor of about 2000. To achieve a strain sensitivity which is limited by the thermal noise of the mirror test masses - depending on the signal recycling factor and its center frequency - the interferometer has to be illuminated by 5 W of laser light. Taking transmission losses of the input optics and the two GEO 600 mode cleaners into account the output power of the laser system must be in the order of 10 W. Laser intensity noise produces an apparent strain noise due to a non perfect fringe locking of the Michelson interferometer caused by finite servo gain. For GEO 600 the excepted maximum fringe offset is in the order of $10^{-6}\,\lambda$. The Schnupp modulation scheme which is used for deriving the error signals for the interferometer control loops requires an arm length asymmetry for the Michelson interferometer. This results in coupling of frequency noise to strain noise. The frequency noise requirements are derived for a maximum asymmetry of 0.1%. The laser noise specifications result from a maximum noise contribution of 1/15th compared with the thermal noise level, which is the fundamentally limiting noise source for the detector. The intensity and frequency noise requirements are shown in fig. 1. The power recycling cavity will have a finesse of 6000. As a result of this high finesse both power and frequency noise are filtered for Fourier frequencies above the cavity pole of 10 Hz. This passive filtering relaxes the noise specification of the prestabilisation (C) and for the laser light entering the power recycling cavity (B).

3. The Laser System

The GEO 600 laser system is made up off three main parts, the master laser, the slave laser and a high finesse reference cavity (fig. 2.). The master laser is a commercial monolithic Nd:YAG laser-diode pumped nonplanar ring oscillator (Mephisto 800, Innolight GmbH) with an output power of 800 mW. Using the Pound-Drever-Hall locking scheme [1,3] the master laser is frequency stabilised with a servo bandwidth of around 1 MHz to a high finesse ULE ring cavity. The finesse of the cavity was determined to be 58 000 by measuring the amplitude transfer function and independently by measuring the cavity decay time.

The slave laser is a Nd:YAG ring laser with two laser crystals each longitudinally pumped by 808 nm fiber coupled laser-diodes. These laser-diodes are operated at an output power of 17 W each, down rated from their maximum

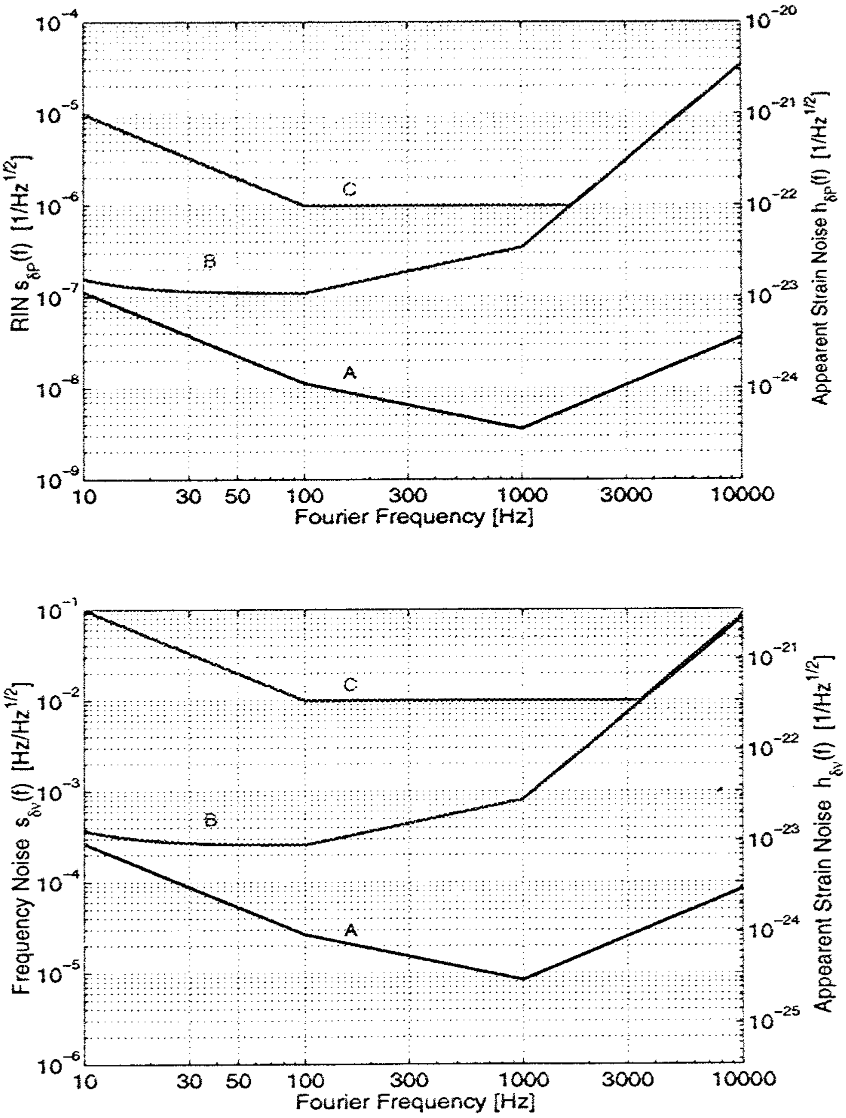

Fig. 1. Specification for the laser relative power noise and laser frequency noise. A: at the main interferometer, B: for light entering the power recycling cavity, C: prestabilised laser system.

power of 30 W to increase the life time. The slave laser resonator is optimized for this pump power and the resulting thermal lenses in the Nd:YAG crystals. Two fused silica substrates are placed at the Brewster angle in the resonator to enforce linear polarization and to reduce the astigmatism of the resonator. The output power is 12 W with more than 99% in linear polarization. The transversal mode structure was checked by measuring the transmission of the attenuated slave laser output power through a Fabry-Perot ring resonator [8]. Around 95% could be coupled into the cavity, which is in good agreement with the measured

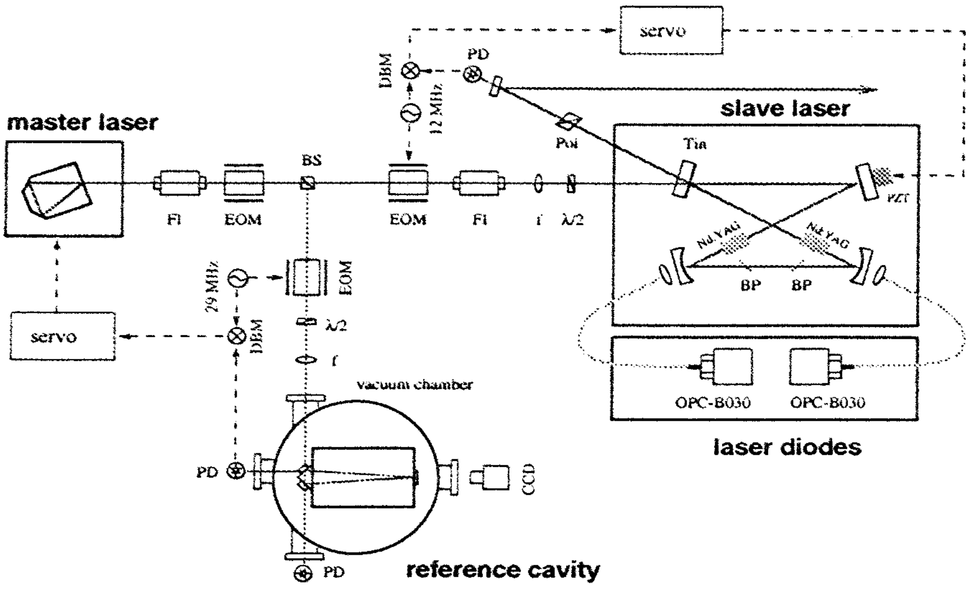

Fig. 2. Setup of the GEO 600 laser system.

M^2-factor of 1.05. The length of the slave laser resonator is locked to the master laser using the Pound-Drever-Hall stabilisation scheme. The servo bandwidth of the injection-locking servo is 10 kHz, limited by the mechanical resonances of the piezo-electric transducer that is used as the feedback element.

4. Noise Measurements

The power fluctuations of the free running and the injection-locked slave laser were measured with a high bandwidth InGaAs photo detector using 12 mA of photocurrent (fig. 3.). The power noise below 10 kHz is dominated by the current noise of the laser-diodes pumping the slave laser. The free running slave laser shows a relaxation oscillation peak at 280 kHz, which vanishes if the laser is injection-locked. In that case the power noise of the master laser is dominating for frequencies above 100 kHz. The power noise reaches the shot noise level of the 12 mA at 3 MHz. The peak at 12 MHz results from the phase modulation used for the locking of the slave laser. The frequency noise of the free running and the stabilised master laser is shown in fig. 4. The servo gain around 1 kHz is approximately +100 dB. An independent frequency noise measurement using a second cavity showed that the out-off-loop frequency noise is much higher than the error point noise. This is due to acoustic and seismic excitation of the cavities which were not suspended. The frequency noise of the injection-locked laser system was measured in the same way. No difference between the frequency noise of the master laser and the injection-locked laser system was observed.

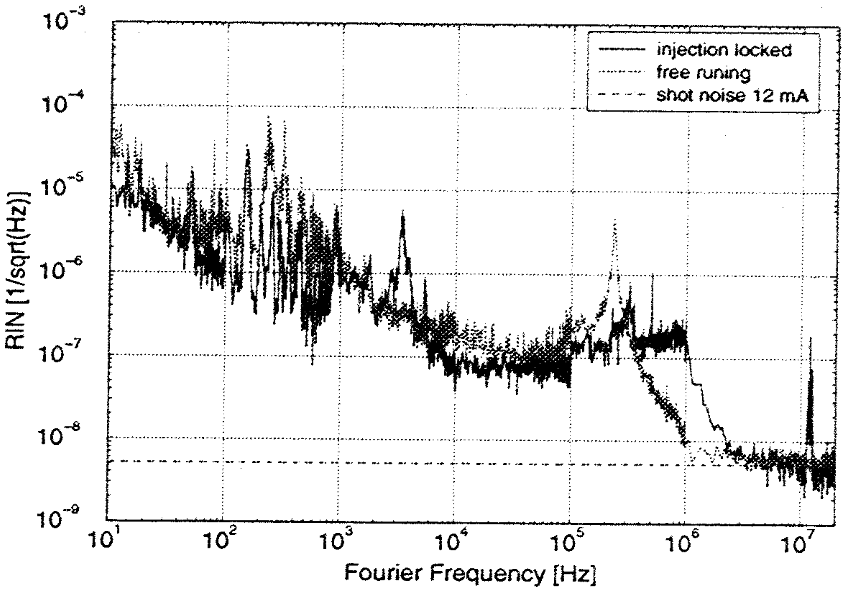

Fig. 3. Intensity noise of the free running and the injection locked slave laser.

5. Summary

An injection-locked laser system for the gravitational wave detector GEO 600 with an output power of 12 W has been developed. The master laser was frequency stabilised to a high finesse ring cavity and the frequency noise measured

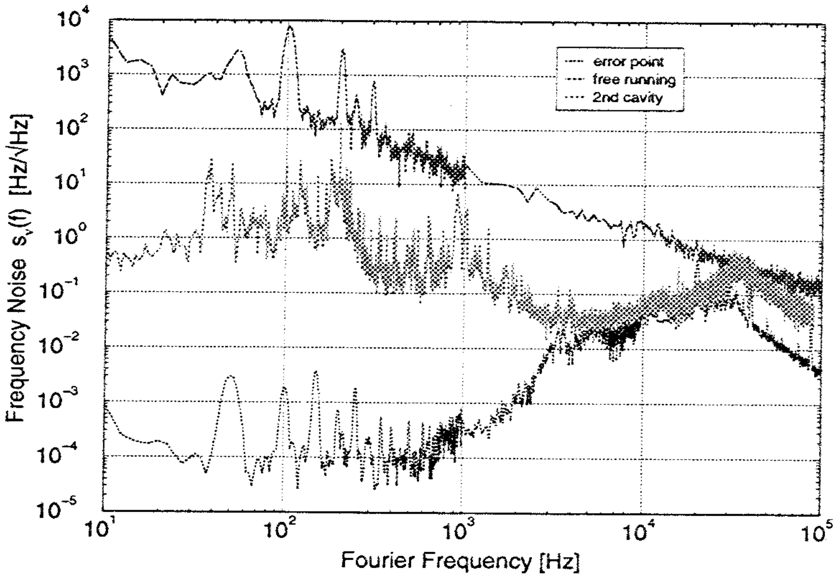

Fig. 4. Frequency noise of the free running NPRO (top curve), the error point frequency noise (bottom curve) and the frequency noise measured with a second cavity (middle curve).

at the error point is less than 1 mHz/$\sqrt{\text{Hz}}$ for Fourier frequencies below 1 kHz. The injection-locked laser system showed the same frequency noise as the master laser. Further investigations will involve the active power stabilisation of the laser system and an increased servo gain of the frequency stabilisation for Fourier frequencies between 1 kHz and 100 kHz. A pendulum suspension for reference cavity similar to the GEO 600 mode cleaner suspension to decouple seismic and acoustic excitation of the reference cavity will be implemented.

Acknowledgments

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6. References

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