LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

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Advanced LIGO PSL Front End Amplifiers vs Oscillator

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1. The Advanced LIGO Front End Laser Design

1.1. Overview

The conceptual design for the *Advanced LIGO* Laser is based on an injection-locked high power ring resonator (Slave), which is injection locked to a medium power stage (front end) . (see **Error! Reference source not found.**). For more details on the overall conceptual design see *Advanced LIGO Pre-stabilized Laser Conceptual Design Document* (LIGO-T050035-02-D) In the current baseline of the AdvLIGO PSL an injection-locked 12W oscillator and an NPRO form the front end. Triggered by good initial results and by a request of VIRGO, a Nd:YVO_4 amplifier module was developed by LZH. A NPRO amplified by four such amplifier modules is an attractive alternative for the front-end. The goal of this document is to compare both front end options and to prepare a decision which one to choose.

1.2. The AdvLIGO laser

The heart of the AdvLIGO PSL is formed by a 180W laser system. This laser system can

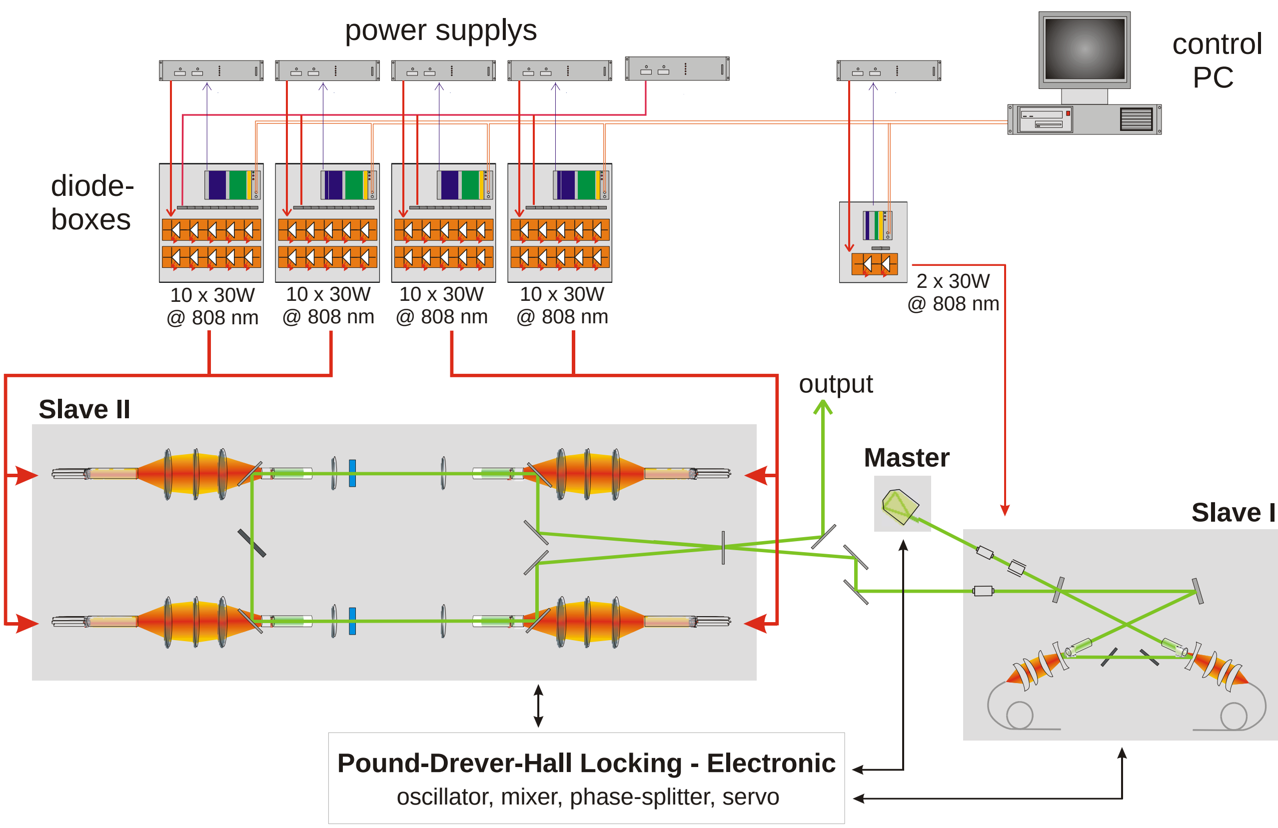

Figure 1-1: Schematic of *Advanced LIGO* laser showing a single-frequency master laser, an intermediate power stage (12W) followed by the high-power stage..

be split into two part: a stable NPRO Master oscillator and several stages to increase the output power with adding as little noise as possible. This is achieved by using the injection locking technique for the high power stage (180W) which transfers the frequency stability of the front end to the high power beam. As the stability range of the injection locking (locking range) depends on the power ratio, a medium power stage is needed between the stable NPRO and the high power slave.

1.2. Target Specifications

Based on the injection locking of the 200W high power ring laser the front end requirements are based on a stable injection locking of this laser. The Figure 1-2 shows the full locking range versus front end output power calculated for the current high power ring resonator design.

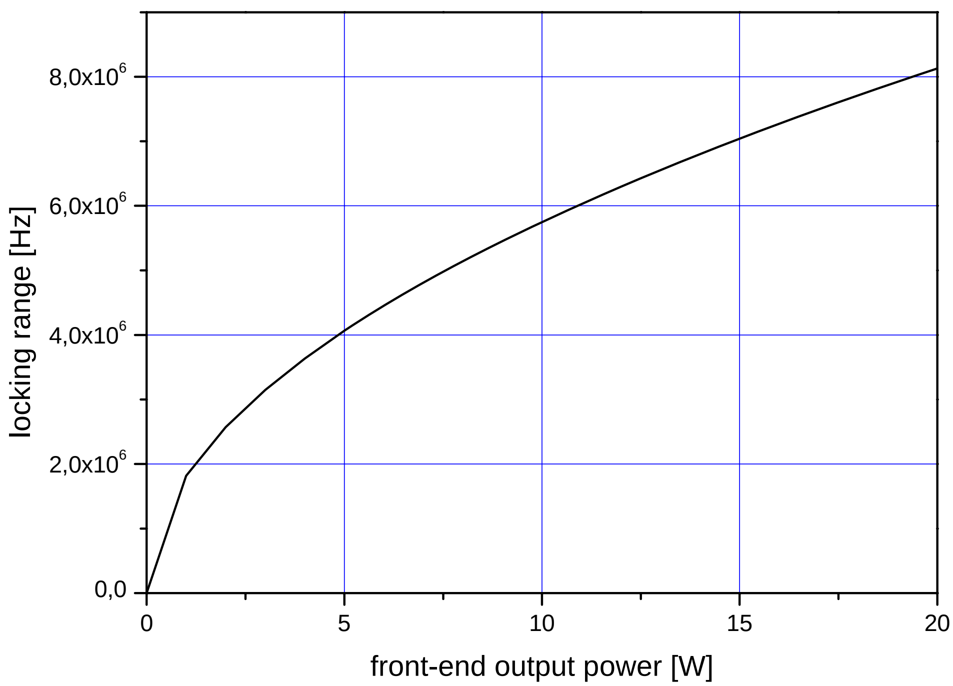

Figure 1-2: Calculated locking range versus front end output power. Calculations based on the current high power ring resonator design.

The specifications on power and frequency fluctuations are based on the target specifications of the advanced LIGO laser (LIGO-T050035-02-D). The front end should meet the following specificatiuons:

Parameter	Specification
1. type of laser	Nd:YAG; Nd:YVO_4
2. wavelength	1064 nm
3. power in a circular TEM_{00} mode	> 95%
5. polarization extinction ratio	500:1 in the vertical plane
6. relative power fluctuations	< 10^{-5} /$Hz^{1/2}$ between 100 Hz and 10 kHz < 10^{-6} /$Hz^{1/2}$ between 100 kHz and 3 MHz < 4 10^{-9} /$Hz^{1/2}$ above 25 MHz (2 times shot noise limit for 100 mA of photodected current
7. frequency fluctuations	< 2 $\times 10^3$ Hz/$Hz^{1/2}$ at 100 Hz < 2×10^2 /$Hz^{1/2}$ at 1 kHz
8. reliability:	
mean time between failure (MTBF)	> 10 000 hours
minimum time between required beam alignment adjustment	> 500 hours

Table 1: Specifications for the front-end laser system.

1.3. Front End Laser Design

For the front end of the Advanced LIGO Laser two potential different laser concepts are available. The first system is a 12 W oscillator based on the proven GEO600 Laser design [ref.1] and the second one is a new developed Nd:YVO_4 amplifier design. Both systems are discussed separately in the next sections.

Nd:YAG Oscillator

The Nd:YAG oscillator design is based on a medium power ring oscillator injection-locked by a monolithic non-planer ring laser (NPRO). The medium power stage consists of a ring resonator in bow-tie configuration and involves two conductively cooled Nd:YAG crystals, each being longitudinally pumped by a fibre coupled laser diode at a derated (< 60 %) output power of about 17 W. Temperature stabilization of the laser crystals and the pump diodes is performed by computer-based PID controllers.

The employment of a low thermal expansion steel for the resonator block in combination with the negation of adjustable resonator components results in a high intrinsic stability and a reduced acoustic sensitivity of the slave oscillator.

The resonator length is controlled by a piezo-electric transducer in combination with a Pound-Drever-Hall stabilization scheme. Figure 1-3 shows the setup of the 12 W oscillator.

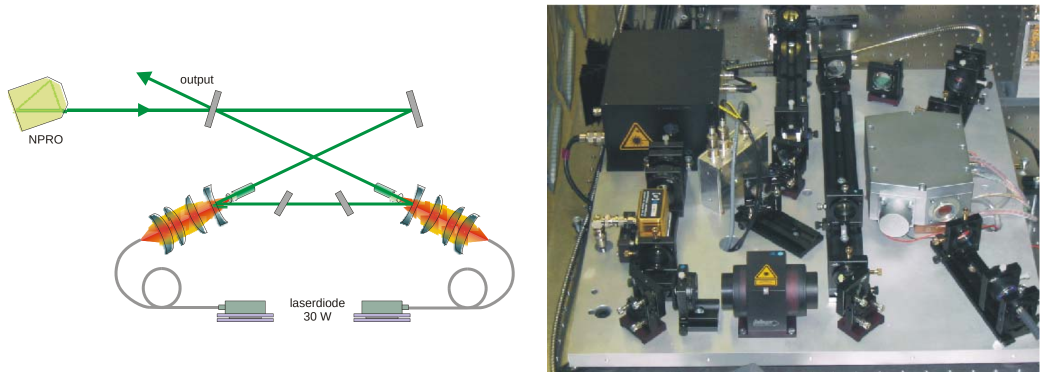

Figure 1-3: 12 W oscillator injection-locked onto a monolithic ring laser.

Figure 1-4 and Figure 1-5 show a pre-mode cleaner scan and a RIN measurement of the 12 W oscillator. The mode content of the oscillator shows that almost 89% of the output power is within the $TEM_{0,0}$ mode. The RIN is in the same range or even under the specifications listed in Table 1.

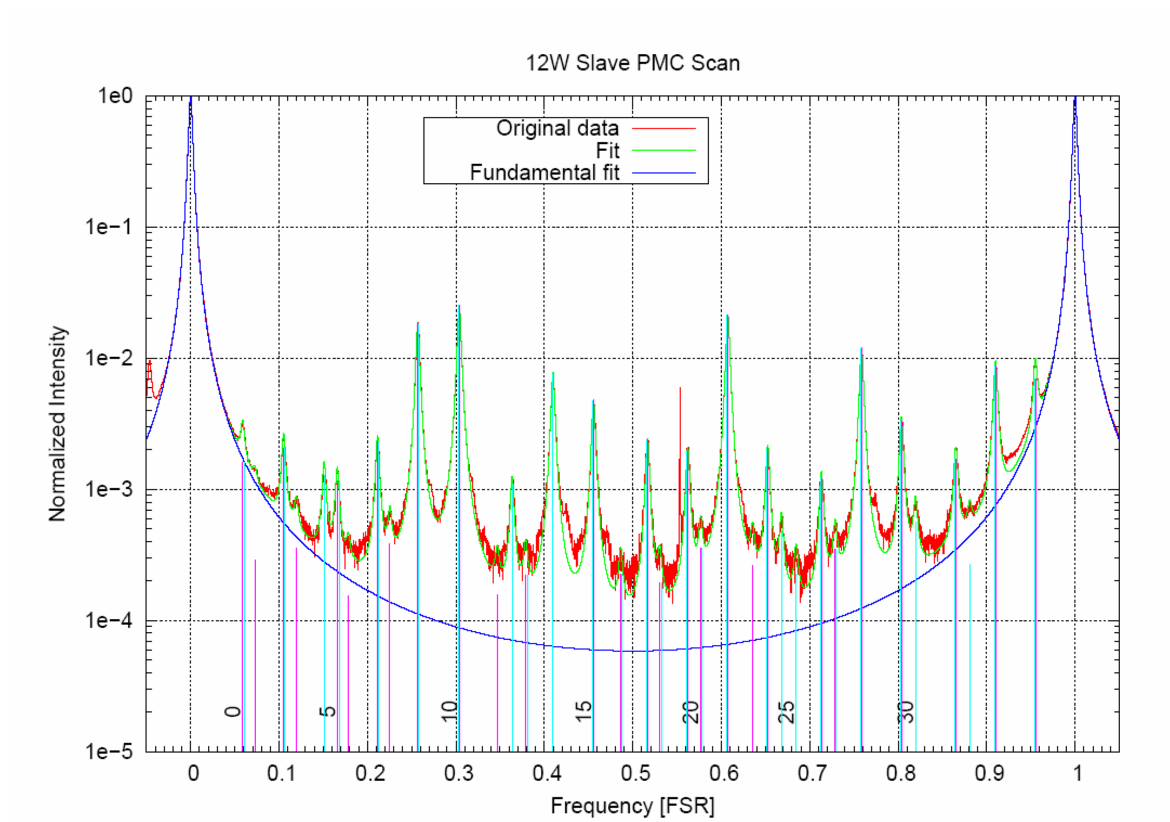

Figure 1-4: Pre-mode cleaner scan of the 12 W oscillator.

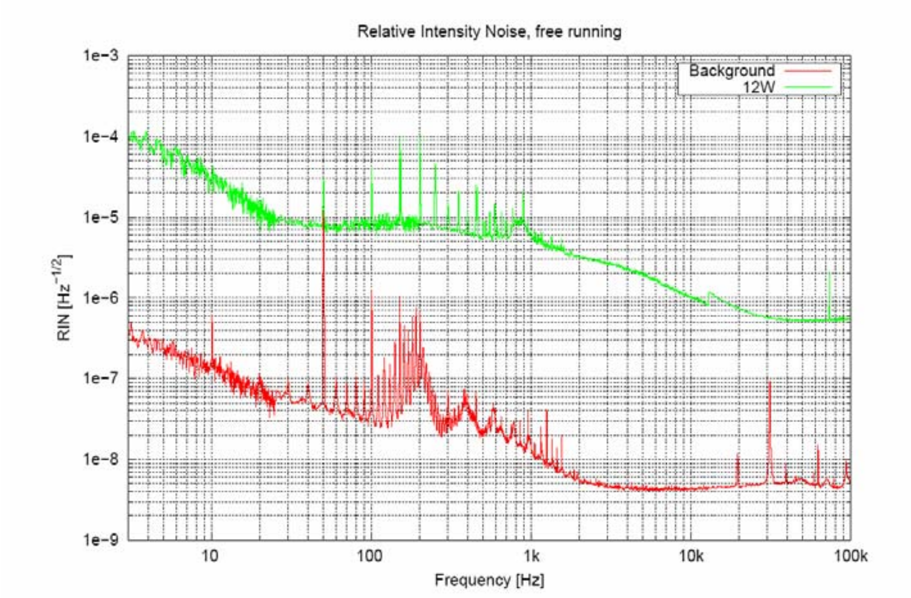

Figure 1-5: Relative intensity noise measurement of the 12 W oscillator.

Nd:YVO_4 Amplifier

The new developed amplifier system is based on a fibre-coupled, end-pumped Nd:YVO_4 amplifier design. The system consists of 4 amplifier stages.

The laser material Nd:YVO_4 is a high gain material which is naturally birefringent in which no depolarisation effects occur. On the other hand the material properties of Nd:YVO_4 like thermal conductivity and mechanical hardness limits the Nd:YVO_4 application to the medium power range. The laser crystals were pumped by fibre coupled laser diodes delivering 45 W of output power. With an appropriate pump spot size, optimized to the seed laser beam efficient amplification was achieved

With a two stage amplifier setup and a pump power of two times 40 W an injected 2 W NPRO can be amplified to 15.5 W. For the four stage design and equal pump and seed powers 35 W output power was achieved. Figure 1-6 shows a sketch of a four stage amplifier design.

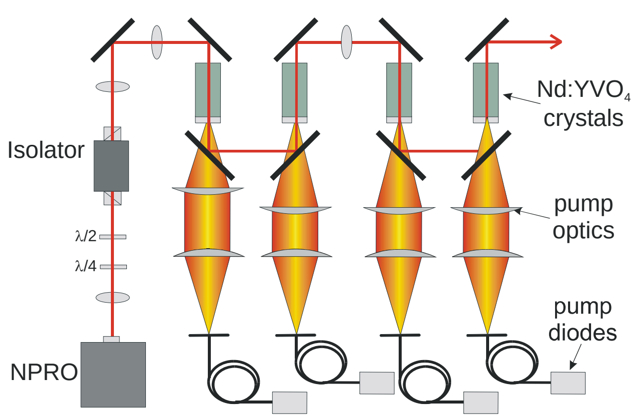

Figure 1-6 Amplifier setup with four amplifier stages

Similar to the 12 W oscillator pre-mode cleaner and RIN measurements were performed to characterize the system. The results of the pre-mode cleaner measurements (Figure 1-7) show that almost 97 % of the power is within the $TEM_{0,0}$ mode for the two stage amplifier and 95 % for the four stage amplifier setup. For comparison, the $TEM_{0,0}$ mode content of the 2 W NPRO is already limited to 97 %. The number of higher order modes is clearly reduced compared to the same measurement of the 12W oscillator. The results show that almost no additional beam distortion was introduced by the amplifiers. The RIN of the amplifier is shown in Figure 1-8 and is equal to the oscillator within the specifications of Table 1.

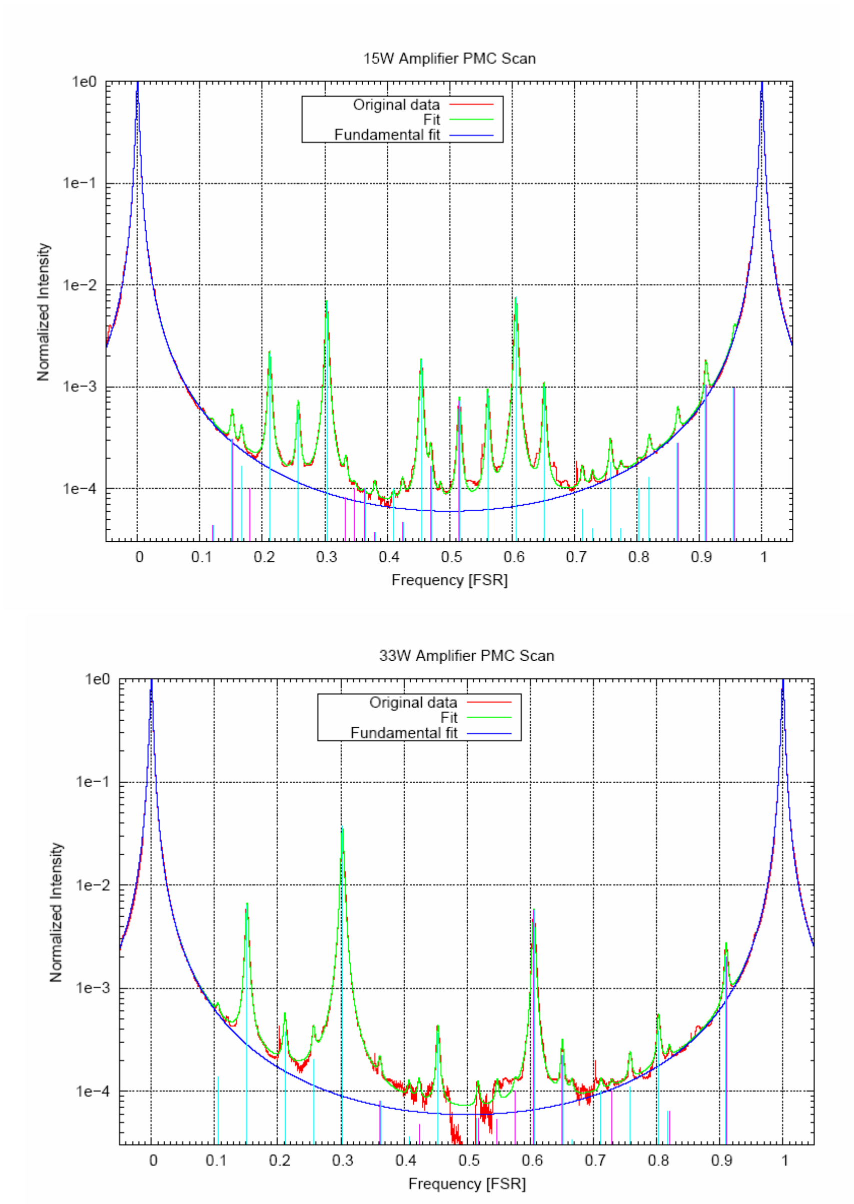

Figure 1-7: Pre-mode cleaner scan of two and four stage amplifier.

The relative intensity noise (RIN) of a NPRO, the laser didoes used to pump the amplifier, a two stage amplifier system and a four stage amplifier was measured. The results are shown in Fig. 1.8.

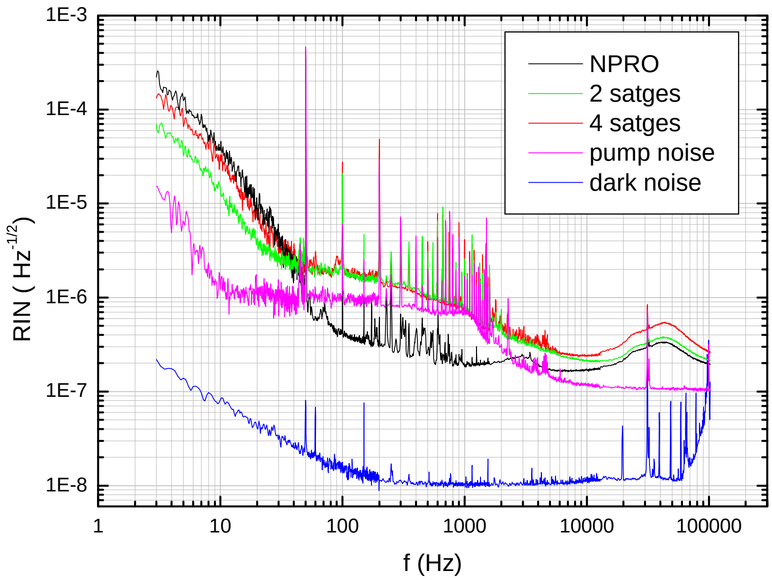

Figure 1-8: Relative intensity noise measurement of the amplifier.

Even though the DC readout scheme was chosen for AdvLIGO some auxiliary signals will be generated by the use of standard rf-heterodyne techniques (Pound-Driver-Hall, differential wavefront sensing). Hence the RIN of the 30W amplifier was measured at rf frequencies (see Fig. 1-9).

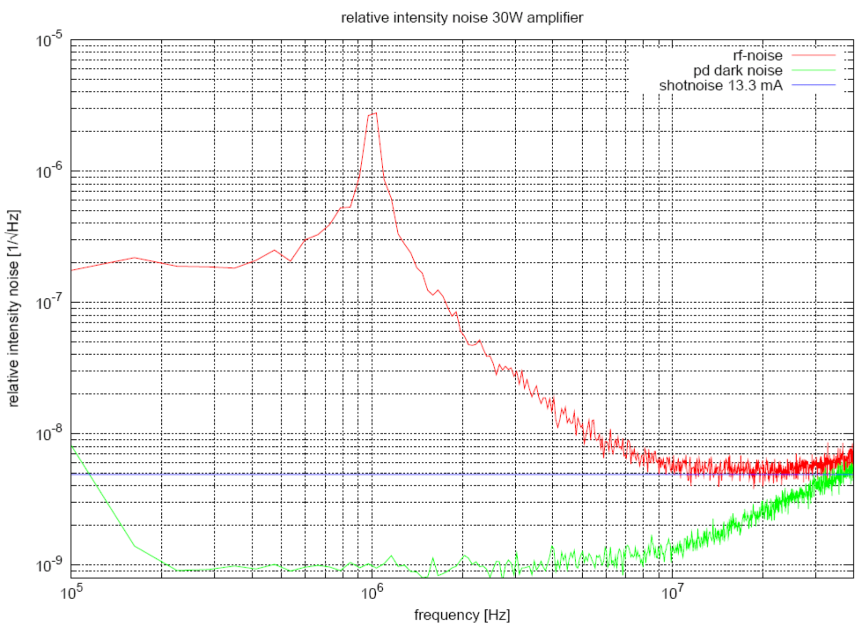

Figure 1-9: Relative intensity noise measurement of the amplifier at rf frequencies

Fig 1-10 shows the RIN of the 200W laser. The blue curve represents the measurement of the 12W front end and the old resonator design (symmetric) and the red curve shows a measurement of the new resonator design for the high power oscillator (asymmetric layout) pumped with the 35W amplifier.

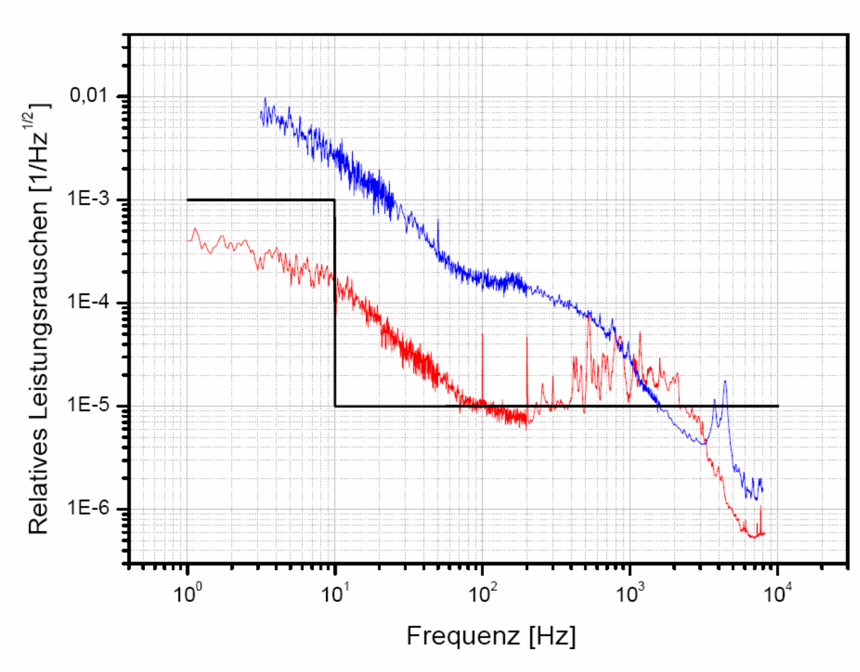

Figure 1-10: Relative intensity noise measurement of the 200W laser with the amplifier as a front end

Design discussion

Comparison of the two laser designs:

Specification	Nd:YAG oscillator	$Nd:YVO_4$ amplifier
Output power	12W	35 W
Mode content	89% in $TEM_{0,0}$	97 % in $TEM_{0,0}$
Polarisation ratio	/ thermal induced birefringence	/ natural birefringence
Optical eff.	35 %	21 %
RIN	$1*10^{-5}$ @ 100Hz	$2*10^{-6}$ @ 100Hz
RIN rf		shot noise limited at 10MHz for 10mA photocurrent
Frequency Noise		
S.F. operation	Pound-Drever hall injection-locking	no active control system
Power adjustment	Via pump current	AOM in seed path
Cooling	Conductively	Conductively

2.1 Discussion

It was clearly demonstrated that a 4-stage $Nd:YVO_4$ amplifier can meet the specification required for the Adv LIGO PSL front-end laser. The amplifier option is a much simpler system. No injection locking (controller, sidebands on the light, photodiodes, oscillator, demodulation electronics) and no demanding modematching is required. The intensity noise of the amplifier is lower above 20Hz and the frequency noise of both designs is determined by the NPRO.

One strong argument in favour or the amplifier option is, that the stand alone 35W front-end could be used in upgrades of Initial LIGO (Enhanced LIGO) and could hence pass extensive testing and long term characterization. Even the frequency noise performance of the Adv LIGO PSL can already be tested to some extend. The frequency noise of the 200W laser will be dominated by the front end and the stabilization scheme of Initial LIGO is very similar to the one of Adv LIGO.

The use in Enhanced LIGO requires an accelerated development and fabrication schedule. This might slow down the preliminary design phase of the AdvLIGO high power stage, will however not delay the delivery schedule of the full PSL.

Furthermore additional costs are involved in the amplifier option which could be covered from the AEI running budget and savings in the LZH program..

The amplifier option requires the use of a 2W NPRO which has not yet proven a reliability as good as the much longer tested 800mW version. The same holds for the amplifiers compared to the 12W oscillator which is in use in the GEO600 detector. Careful testing especially of the long term operation of the amplifier front end would be required if it was chosen as the AdvLIGO PSL baseline.

References:

1. I. Zawischa et al., “The GEO 600 laser system,” Class.Quantum Grav. **19,** 1775-1781 (2002).