

# Laser development and laser stabilisation for the space-borne gravitational wave detector LISA

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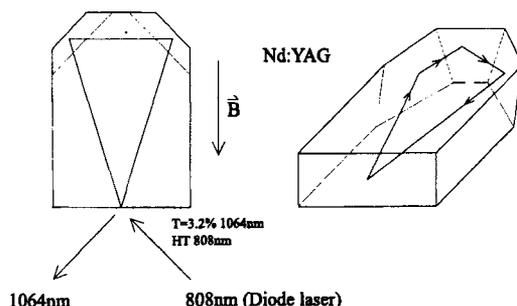
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**Abstract.** For the interferometric readout of the  $10^7$  km optical path length, the LISA mission will rely on a compact, reliable and highly efficient source of stable radiation. The strain sensitivity of the instrument will be limited by photon shot noise in the mHz frequency regime and therefore an output power of at least 1 W is required. The noise added by power and frequency fluctuations of the laser is negligible only for a relative power stability of  $\delta\tilde{P}/P < 2 \times 10^{-4} / \sqrt{\text{Hz}}$  and for a frequency noise spectral density of  $< 30 \text{ Hz}/\sqrt{\text{Hz}}$  within the LISA detection band. The only light source approaching the performance demanded for LISA is a stabilised monolithic diode pumped Nd:YAG ring laser. We report on recent progress in designing and stabilising this laser type for the LISA mission.

## I THE LISA LASER SYSTEM

### A Monolithic miniature Nd:YAG ring laser

The laser system to be used in the LISA mission is a diode laser-pumped monolithic miniature Nd:YAG ring laser (NPRO) which can generate a diffraction limited beam at  $1064 \mu\text{m}$  of up to 1.5 W in the configuration described below. The optical beam path in the NPRO crystal is determined by three internal total reflections and one reflection at the negatively curved front surface [1]. The front surface is dielectrically coated, reflecting about 97 % of the 1064 nm laser radiation and highly transmitting the pump radiation at 808 nm (see Fig. 1).



The high frequency stability required for the LISA mission can only be achieved because of the high intrinsic stability of the NPRO. This stability results from the monolithic and compact design of the resonator and from the outstanding thermal properties of the host material YAG (Yttrium Aluminium Garnet  $\text{Y}_3\text{Al}_5\text{O}_{12}$ ). The low coefficient of thermal expansion ( $7 \times 10^{-6} \text{ K}^{-1}$ ) and the low temperature dependence of the index of refraction ( $9.05 \times 10^{-6} \text{ K}^{-1}$ ) make the laser rather insensitive to temperature fluctuations.

**FIGURE 1.** The beam path in the monolithic, non-planar ring resonator is determined by three total internal reflections and one reflection at the dielectrically coated front surface.

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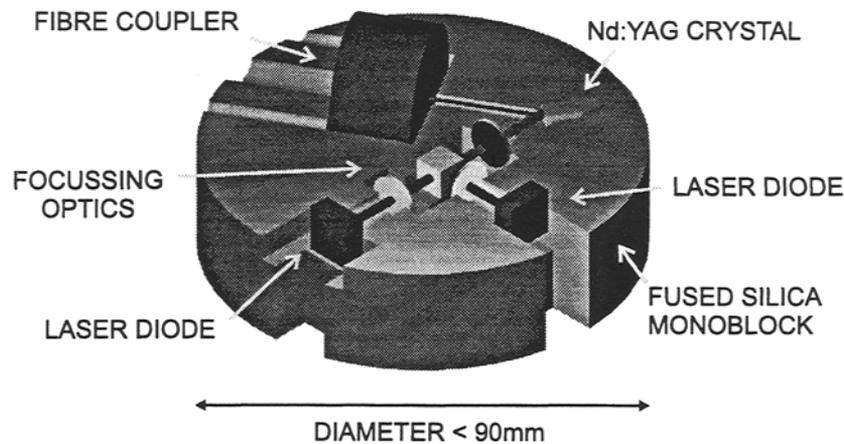
To date there are only few alternatives to Nd:YAG as the active crystal medium. Ytterbium can be used as the active ion, because the efficiency is higher than for  $\text{Nd}^{3+}$  (Neodymium)-ions, but the pump power requirements are also higher because of the extremely high threshold. This results from  $\text{Yb}^{3+}$  being a three level-system rather than the four level  $\text{Nd}^{3+}$ . Yttrium Vanadate ( $\text{YVO}_4$ ) is an alternative candidate for the host material, but its polarisation selectivity interferes with the optical diode required to enforce unidirectional oscillation. Also the thermal properties of  $\text{YVO}_4$  are much worse than those of the YAG. However, the main advantage of Nd:YAG is its availability in radiation hardened quality, which can be used in deep space without significant change of performance.

## B LISA laser system design

The laser system consists of two major components: the laser head and the supply unit. Both the laser head and the supply unit are mounted on a carbon-carbon radiator to radiate away the heat that is due to the consumed electrical power not converted into optical power.

The **laser head** consists of a Nd:YAG NPRO pumped by two long life aluminium-free InGaAsP laser diodes. These single stripe devices have maximum cw output power of 2000 mW. The nominal single-mode, cw output power of the NPRO in this configuration is 1500 mW, but this is downrated for LISA to 1000 mW to improve lifetime and reliability properties. The nominal constant power consumption for the 1000 mW of output power of the complete laser system is approximately 10 W.

The pump light from each laser diode is transferred into the crystal by imaging the diodes' emitting area of  $1 \mu\text{m} \times 200 \mu\text{m}$  at unity magnification onto the entrance surface of the crystal, using two identical lenses with plano-convex surfaces to minimise spherical aberration (best form lens shape). A polarising beamsplitter is inserted between the lenses to combine the pump light from the two diodes, which are orthogonal in polarisation. The optical elements are made of fused silica, which is proven to be resistant to radiation levels as encountered in deep space.



**FIGURE 2.** LISA laser system fused silica monoblock design. The laser head consists of a Nd:YAG NPRO pumped by two laser diodes. The nominal single-mode, cw output power of the NPRO in this configuration is 1500 mW.

All of the above mentioned components are glued to a solid spacer to ensure mechanical stability (cf. figure 2). That spacer is manufactured from a single block of fused silica. Glued to the backs of the diodes and to the bottom of the crystal are three heat sinks (not shown in figure 2), which serve as the mechanical and thermal interface between the laser head and the radiator plate. There is a heater integrated in each heat sink to control the operating temperature of the diodes and the crystal.

The **supply unit** mainly contains two current sources for the laser diodes, three temperature controllers, two for the diodes and one for the crystal, the mixer and feedback servo for the frequency stabilisation and the feedback circuit for power stabilisation. The supply unit power interface to the spacecraft power subsystem will be the only power interface between the laser system and the spacecraft.

## II FREQUENCY STABILISATION FOR LISA

### A Review of requirements

The presence of laser frequency noise can lead to an error in the measurement of each arm length. If the difference in two arm lengths is  $\Delta x$  and the relative frequency stability of the laser is  $\widetilde{\delta f}/f$ , the apparent displacement noise is given by:

$$\widetilde{\delta x} = \Delta x \frac{\widetilde{\delta f}}{f}. \quad (1)$$

For the  $5 \times 10^6$  km arms of LISA, a maximum value of  $\Delta x$  of the order of  $10^5$  km is likely. For a relative arm length measurement of  $2 \times 10^{-12} \text{ m}/\sqrt{\text{Hz}}$ , which is desired to achieve the envisaged overall sensitivity, a laser stability of  $6 \times 10^{-6} \text{ Hz}/\sqrt{\text{Hz}}$  is required.

The current LISA baseline foresees as the primary method of stabilisation to lock the frequency of the laser system onto a resonance of a Fabry-Perot cavity mounted on the optical bench. With the temperature fluctuations inside each craft limited in the region of  $10^{-3} \text{ Hz}$  to approximately  $10^{-6} \text{ K}/\sqrt{\text{Hz}}$  a cavity formed of ULE allows a stability level of approximately  $30 \text{ Hz}/\sqrt{\text{Hz}}$ . This level of laser frequency noise is clearly much worse than the required  $6 \times 10^{-6} \text{ Hz}/\sqrt{\text{Hz}}$  and a further correction scheme is required. Such a correction is provided by comparing the mean phase of the light returning in two adjacent arms with the phase of the transmitted light. The phase difference, measured over the time of flight in the two arms, allows an estimate of laser frequency noise to be made. A detailed analysis can be found in [4].

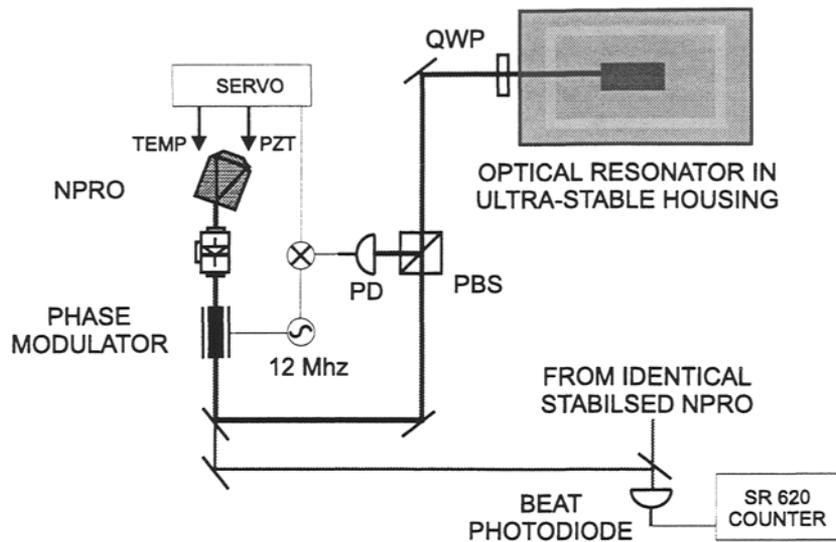
Extensive work has been performed in the field of frequency stabilising non-planar Nd:YAG ring lasers using optical resonators. Unfortunately, most of the work was focussed on the acoustic frequency regime, ranging from a few Hertz to several kilohertz, where the residual frequency fluctuations of the laser have been reduced to  $10^{-2} \text{ Hz}/\sqrt{\text{Hz}}$  [2] [5].

In the frequency regime below 1 Hz the temperature fluctuations of the reference resonator usually set a very stringent limit to the achievable stability. Using an optical resonator at cryogenic temperature is one possibility to overcome this problem and has been successfully applied to reduce the frequency fluctuations below  $1 \text{ Hz}/\sqrt{\text{Hz}}$  at Fourier frequencies down to the millihertz regime [6]. Another approach to reduce the thermal fluctuations of the reference resonator, that has been applied in this work, is to place the resonator inside a very stable thermal shielding and operate it at room temperature.

### B Experimental setup

The basic experimental setup is shown in figure 3. Two laser systems (model *Innolight GmbH Mephisto 800*) are stabilised to two identical reference resonators making use of a rf-reflection locking scheme known as Pound-Drever-Hall scheme: Light from the laser is directed through an electro-optic modulator, which phase modulates the light at 12 MHz or 29 MHz respectively. About 10 mW is split off and mode-matched into the resonator, which consists of two coated ULE substrates that have been optically contacted to a hollow, cylindrical ULE spacer of 210 mm length and a diameter of 80 mm. The substrate coatings both have a transmission of 700 ppm and negligible losses, leading to a finesse of roughly 10,000, which is comparable to what will be chosen for the LISA reference resonator. The light reflected off that cavity is detected on a photodiode and demodulated, producing the bipolar error signal, that is amplified and fed back to the laser frequency actuators. Fast correction signals are sent to a piezo-electric transducer mounted on top of the Nd:YAG crystal and slow signals are fed back to the crystal temperature control.

The most crucial part of the experiment is the ultra-stable housing of the two reference cavities. The purpose of this housing is to simulate the thermal conditions that will be encountered on the LISA optical bench. That means to reduce the thermal fluctuations to a level of  $10^{-6} \text{ K}/\sqrt{\text{Hz}}$  at 1 mHz, which is about the expected temperature stability on the bench, as recent calculations have shown. To reach that goal, the cavity plus shielding is placed inside a cylindrical vacuum chamber of 500 mm diameter and 600 mm length. Inside the



**FIGURE 3.** Scheme of frequency noise reduction setup. Light from the monolithic non-planar Nd:YAG ring laser is phase modulated at 12 MHz by a resonant modulator. About 10 mW are split off and mode-matched into a high finesse ULE optical resonator. The resonator is placed inside a vacuum chamber and 4 layers of cold-coated stainless steel for optimum thermal isolation to outside temperature fluctuations. The light reflected off the cavity is detected on a photodiode and used as a bipolar error signal for the frequency locking of the laser system.

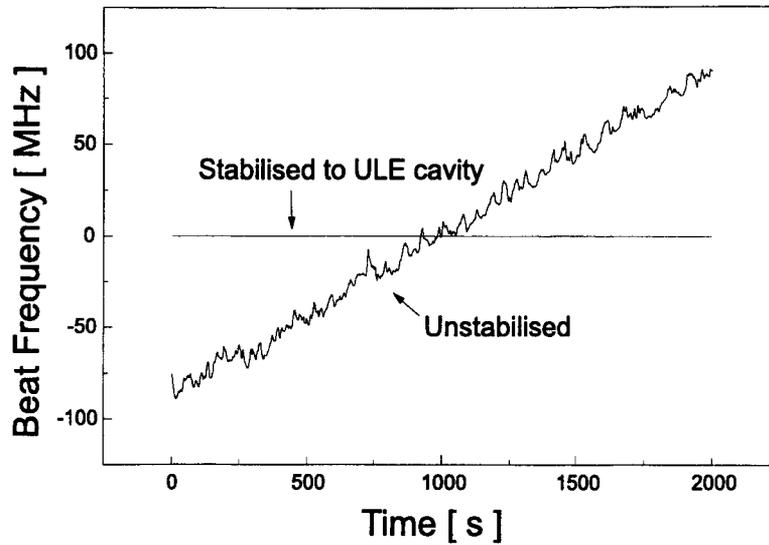
tank the cavity is surrounded by four concentric cylinders of gold-coated stainless steel of very high surface quality that have an excellent reflectivity for thermal radiation at room temperature. The pressure inside the chamber is below  $10^{-6}$  mbar, so the heat transfer by convection is negligible compared to radiation and conduction heat transfer. The contribution of the latter is reduced by mounting the individual steel cylinders on very thin ceramic spacers made of the poor heat conductor Macor.

In summary the three inner cylinders are the equivalent of three thermal low-passes. These consist of the heat capacity of the steel and the heat resistance of the low thermal coupling between the cylinders. Regarding the specific material constants, all three low-passes should have corner frequencies below  $10^{-5}$  Hz and therefore, neglecting any heat leaks, outside temperature fluctuations should be reduced by at least a factor of  $10^{-6}$  at a Fourier frequency of 1 mHz. Assuming an outside temperature stability of  $1 \text{ K}/\sqrt{\text{Hz}}$  at 1 mHz (corresponding approximately to  $1 \text{ K}_{\text{rms}}$  over 1000s) and a thermal expansion coefficient of ULE of  $10^{-8}$ , this experimental setup should allow a reduction of the frequency fluctuations of the NPRO to  $30 \text{ Hz}/\sqrt{\text{Hz}}$  at 1 mHz.

## C Results

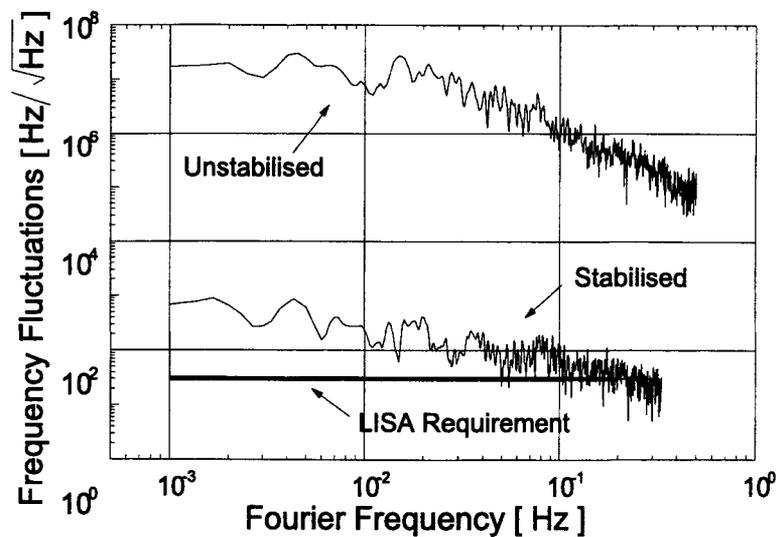
The performance of the stabilisation has been evaluated by measuring the beat frequency of two identical laser systems, each stabilised to its own resonator. The two resonators have been thermally decoupled by placing them in individual vacuum chambers and thermal isolation systems. Figure 4 shows the time series of the beat frequency, that has been measured with the *Stanford Research Systems* frequency counter model *SR620*. Although the mean frequency of the free running system shows a significant drift of yet unclear origin, the frequency has been considerably reduced. Frequency drift and frequency fluctuations of the stabilised system are below 10 kHz maximum deviation from mean.

The requirements on the LISA laser system are defined in the Fourier domain. Therefore the linear spectral density of the frequency fluctuations is of major interest. Figure 5 shows the linear spectral density for the free running and the stabilised laser system. The required maximum level for the frequency noise is shown as well. Although the frequency fluctuations have been significantly reduced, the residual noise still is a factor of 10



**FIGURE 4.** Time series of the beat frequency measured with two identical monolithic Nd:YAG ring lasers. One graph shows the case where both lasers are unstabilised. The other graph shows the case where both lasers are stabilised to individual cavities located in their individual thermal shielding.

above the required noise level. In future steps to improve the experiment we will overcome this problem and reduce the residual noise below the LISA specifications. These steps comprise an enhancement of the feedback gain, as the achieved stability is very close to the gain limit. The next step foresees the implementation of an active temperature control system of the vacuum chambers.



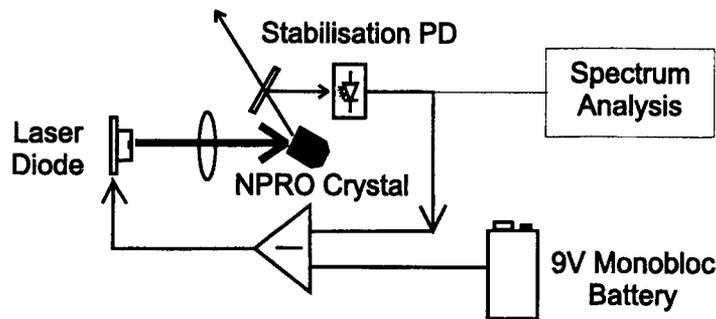
**FIGURE 5.** The graphic shows the linear spectral densities of frequency fluctuations of the free-running and the stabilised monolithic Nd:YAG ring laser. The measurement was done stabilising two lasers to individual cavities and detecting the beat frequency between the lasers. The residual frequency fluctuations of the stabilised system are below the required noise level for Fourier frequencies above 200 mHz.

### III POWER STABILISATION FOR LISA

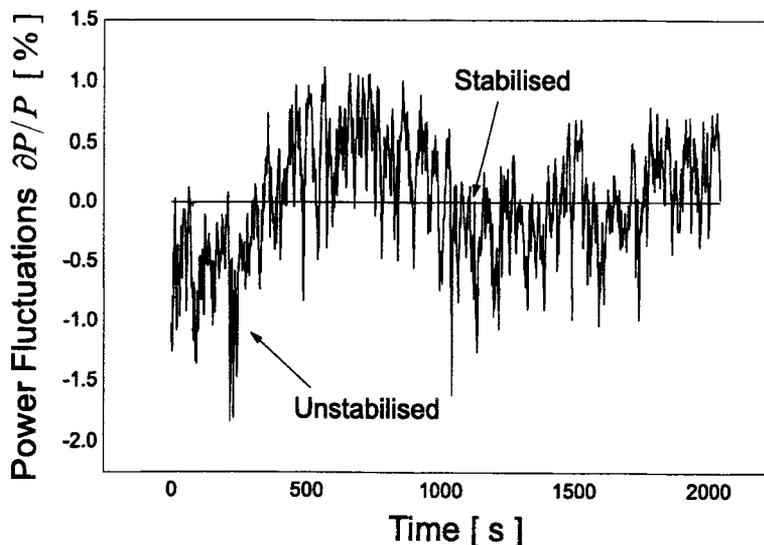
#### A Review of requirements

The tolerable limit to laser power noise is set by the radiation pressure effects of the beam to the proof mass in the inertial sensor. The LISA sensitivity goal requires that spurious accelerations of the proof mass are below a level of  $10^{-16} \text{ m s}^{-2}/\sqrt{\text{Hz}}$ . For a proof mass of 1.3 kg and a reflected light power of  $100 \mu\text{W}$ , the proof mass will undergo a steady acceleration of  $5 \times 10^{-13} \text{ m s}^{-2}$ . To keep the fluctuating acceleration  $< 10^{-16} \text{ m s}^{-2}/\sqrt{\text{Hz}}$  the power stability of the reflected light, and hence of the laser, must be better than  $\delta P/P = 2 \times 10^{-4}/\sqrt{\text{Hz}}$ .

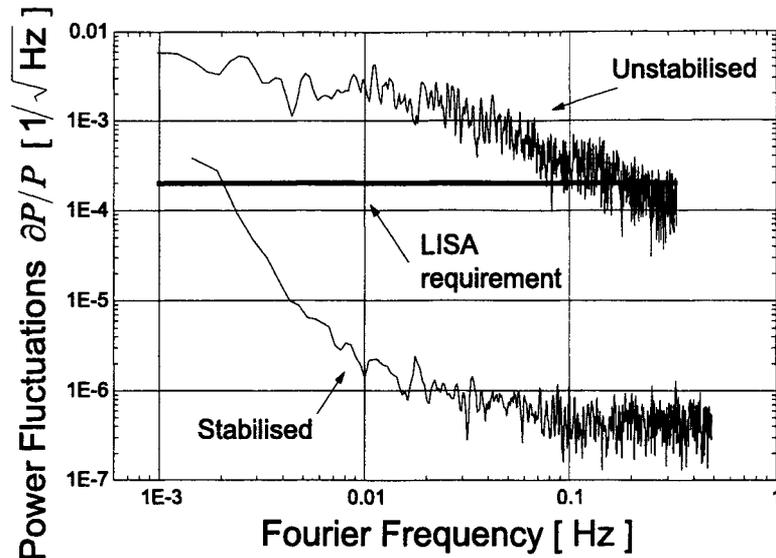
The fundamental limit of the power noise is set by the quantum properties of light. In principle diode-pumped solid-state lasers offer the potential to reach this quantum noise limit (QNL). However, in the LISA frequency band the noise of the free running system is mainly due to noise transfer from pump laser diodes, which is orders of magnitude larger than the QNL.



**FIGURE 6.** Setup of the power stabilisation experiment. A fraction of the laser light (1 mW) is detected with a photodiode. The measured photovoltage across the diode is subtracted from a very stable voltage taken from a monobloc battery. The difference voltage is appropriately amplified and fed back to the pump laser diodes.



**FIGURE 7.** Time series of the power relative fluctuations for the free-running NPRO and for the stabilised system. The typical long term power fluctuations of a few percent have been reduced by three orders of magnitude



**FIGURE 8.** Linear spectral density of power fluctuations for the free-running NPRO and the stabilised system. The power fluctuations have been reduced to below  $10^{-6}/\sqrt{\text{Hz}}$  down to a Fourier frequency of 20 mHz. The steep increase below 20 mHz is due to temperature fluctuations of the voltage reference.

Substantial power noise reduction has been demonstrated for Nd:YAG ring lasers by application of electronic feedback loops [3]. The noise was reduced to less than 10 dB above the quantum noise limit down to a frequency of 10 KHz, corresponding to a relative power noise of less than  $10^{-7}/\sqrt{\text{Hz}}$ . To reach the LISA specifications the existing noise reduction scheme was slightly modified and extended to the low frequency regime.

## B Experimental setup and results

Figure 6 schematically shows the setup of the power stabilisation experiment. A fraction of the laser light (1 mW) is detected with a photodiode. The measured photovoltage across the diode is subtracted from a very stable voltage reference. In this case the reference is a monobloc battery. The difference voltage is appropriately amplified and fed back to the pump laser diodes. The stability is measured as the relative power fluctuations detected with the stabilisation photodiode.

Figure 7 shows the time series of the power relative fluctuations for the free-running NPRO and for the stabilised system. The typical long term power fluctuations of a few percent have been reduced by three orders of magnitude. In the Fourier domain the linear spectral density of power fluctuation have been measured to be  $5 \times 10^{-5}/\sqrt{\text{Hz}}$  at 1 Hz increasing to lower frequencies like  $1/f$  (cf. figure 8). The power fluctuations have been reduced to below  $10^{-6}/\sqrt{\text{Hz}}$  down to a Fourier frequency of 20 mHz. The residual power fluctuations show a steep increase below 20 mHz. The reason for that increase are temperature fluctuations of the voltage reference. The usage of a temperature stabilised reference in the future should reduce the residual low frequency noise well below the envisaged LISA noise level.

## IV CONCLUSIONS

Starting with the well known design of the non-planar Nd:YAG ring-laser, we have developed a compact monobloc laser head design. This design seems well suited for an application as the laser system of the space-borne gravitational wave detector LISA in terms of laser output power, mechanical stability and radiation resistance.

A laboratory prototype of the LISA laser system has been stabilised in frequency and power. The frequency fluctuations have been reduced below the required noise level of  $30 \text{ Hz}/\sqrt{\text{Hz}}$  at Fourier frequencies above 200 mHz and are about a factor of 10 above the requirement a 1 mHz. A variety of possible improvements make it likely that the noise will be significantly reduced below the requirements in the near future.

The power fluctuations of the stabilised system have been reduced more than two orders of magnitude below the LISA requirements above Fourier frequencies of 20 mHz. Below that, the achieved stability is yet limited by temperature fluctuations of the voltage reference.

## V ACKNOWLEDGEMENTS

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