Frequency stabilization of a monolithic Nd:YAG ring laser by controlling the power of the laser-diode pump source

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Abstract

The frequency of a 700 mW monolithic non-planar Nd:YAG ring laser (NPRO) depends with a large coupling coefficient (some MHz/mW) on the power of its laser-diode pump source. Using this effect we demonstrate the frequency stabilization of an NPRO to a frequency reference by feeding back to the current of its pump diodes.

We achieved an error point frequency noise smaller than $1\,\mathrm{mHz}/\sqrt{\mathrm{Hz}}$, and simultaneously a reduction of the power noise of the NPRO by 10 dB without an additional power stabilization feed-back system.

Due to the demanding requirements of recent experiments in quantum optics, laser spectroscopy and laser metrology there has been much interest in laser stabilization over the last years. Although very good stability was achieved with Ar^+ lasers[1], diode-laser pumped solid-state lasers were chosen for almost all modern high-precision experiments. The reason for this choice is that the free-running frequency noise of these lasers is 2 to 3 orders of magnitude smaller than for Ar^+ lasers, and the intensity noise of solid-states-laser is also much lower. Furthermore, solid-state lasers have a very high electrical-to-optical efficiency, which is important especially in space applications like inter-satellite communication or high power applications as laser interferometric gravitational wave detectors.

Many of these experiments rely on the high intrinsic stability of Nd:YAG non-planar ring oscillators (NPRO)[2], the output of which is used in the experiment directly or is amplified either by injection locking[3–5] or in a configuration with master oscillator and power amplifier[6]. The free-running frequency noise spectral density of NPROs is of the order of $1\ \mathrm{kHz}/\sqrt{\mathrm{Hz}}$ at 10 Hz and falls like $1/f$ at higher frequencies. The unstabilized power noise of such lasers has a level of $10^{-7}/\sqrt{\mathrm{Hz}}$. Although this intrinsic stability is quite high, experiments like gravitational wave detectors require a frequency stability in the $\mathrm{mHz}/\sqrt{\mathrm{Hz}}$ range, and simultaneously the power noise needs to be reduced by at least an order of magnitude.

The commonly used schemes to reduce the frequency noise of NPROs rely on stabilizing the laser frequency to a fixed-spacer reference cavity or an atomic resonance by feeding back to two different actuators: the temperature of the Nd:YAG crystal in the low Fourier frequency range below 1 Hz, and for higher frequencies to a piezo-electrical transducer (PZT) mounted on top of the crystal that changes the laser frequency due to stress-induced birefringence. The resonances of the PZT above 100 kHz limit the useful bandwidth of the latter actuator. Good results were achieved especially by using an additional external phase shifter (Pockels cell) as a fast actuator to increase the unity gain frequency of the feed-back control loop up to 1 MHz. For example Bondu et al.[7] report a frequency noise spectral density below $10^{-4}\,\mathrm{Hz}/\sqrt{\mathrm{Hz}}$ with respect to the reference cavity (in-loop) and in the order of $10^{-2}\,\mathrm{Hz}/\sqrt{\mathrm{Hz}}$ with respect to an independent cavity (out-of-loop).

Although these results already meet the demanding requirements of first generation gravitational wave detectors, no attention was paid to the power noise and spatial beam fluctuations. Currently performed cross coupling measurements[8] predict a non-negligible pointing and also power noise introduced by feeding a signal to the NPRO's PZT. Furthermore, care has to be taken that residual amplitude modulation of the phase-correcting Pockels cell does not compromize the shot noise limited performance of the NPRO in the frequency range above 5 MHz, which is essential for the heterodyne detection scheme used in many experiments. On the other hand the power stabilization scheme normally employed adds a signal to the current of the pump source of the NPRO, which has the undesired effect of changing the NPRO frequency. These problems together with the understanding of the fact that the free-running frequency noise of the NPRO is mainly due to power fluctuations of the laser-diode pump source[9] led us towards the new stabilization scheme. (A related scheme with a separate heating laser was used by Heilmann et al.[10] to stabilize a twisted-mode-cavity laser.)

Figure 1 shows a sketch of the experimental setup. A 700 mW NPRO built by Laser Zentrum Hannover was mode-matched to a high-finesse fixed-spacer ring cavity made from ultra-low-expansion material (ULE). This resonator has a finesse of 58 000 and is put in a vacuum tank to avoid contamination and acoustic disturbances.

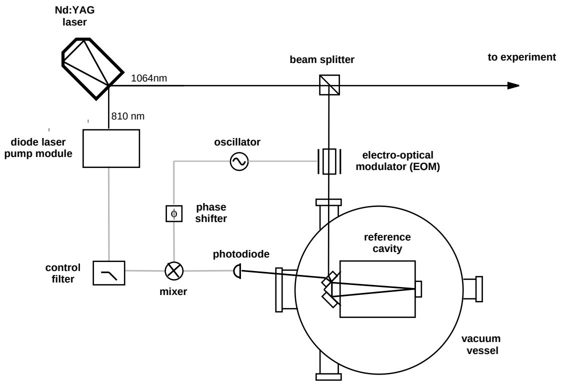

Fig. 1. Schematic of the experimental setup. An NPRO is stabilized to a rigid-spacer reference cavity by using the Pound-Drever-Hall scheme to achieve an error signal for the control loop feeding back to the current of the NPRO's pump diode.

Before entering the cavity the light passes through a Faraday isolator to avoid back-reflections of the light into the laser and is transmitted through an electro-optical modulator (EOM). The EOM was driven by an rf-oscillator at $\omega_{\mathrm{mod}} = 29\,\mathrm{MHz}$ to produce phase modulation sidebands on the light. Once the laser frequency ω_{L} is near a resonance ω_{C} of the cavity, an asymmetry between these sidebands and the reflected carrier produces an amplitude modulation of the light at ω_{mod} which then, detected by an InGaAs photodiode and demodulated at ω_{mod}, gives an error signal for the frequency stabilization servo system. A phase shifter between the rf-oscillator and mixer is used in this well established Pound-Drever-Hall locking scheme[11] to optimize the slope of the frequency error signal.

To measure the transfer function $T_{\mathrm{cur}\to\omega}$ between a signal added to the current of the pump diodes and the frequency of the NPRO we first locked the laser to the reference cavity using the conventional method of feeding the filtered error signal back to the PZT frequency actuator of the NPRO. The gain of this feed-back loop was reduced to give a unity gain frequency of only 100 Hz. This servo was necessary to keep the laser frequency within the central part of the cavity linewidth, as only under this condition the Pound-Drever-Hall error signal is proportional to the difference frequency $\delta\omega = \omega_{\mathrm{L}} - \omega_{\mathrm{C}}$ between laser and cavity resonance. To measure $T_{\mathrm{cur}\to\omega}$, which is shown in Figure 2, we summed the source signal of a network analyzer with Fourier frequency above the unity gain frequency of the servo to the laser-diode pump-current and measured the change of the laser frequency at the error point of the Pound-Drever-Hall circuit.

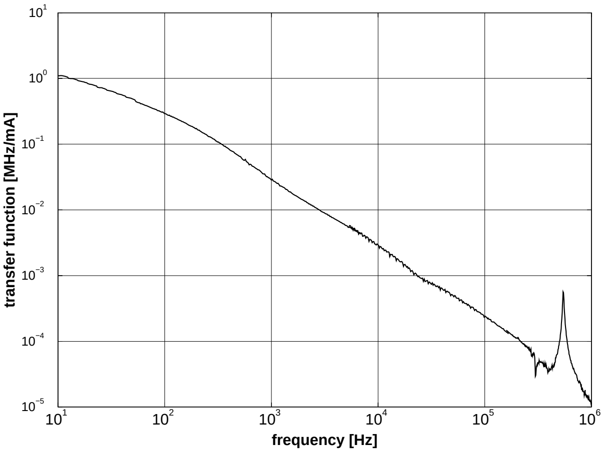

Fig. 2. Transfer function $T_{\mathrm{cur}\to\omega}$ of a signal summed to the current of the NPRO's pump diode and the NPRO frequency. Power fluctuations of the pump diodes together with this strong coupling are responsible for the free-running laser frequency noise and allows the frequency stabilization of an NPRO by changing the power of its pump source.

According to a model by Day et al.[9] this coupling is due to thermally induced changes of the optical path length in the laser crystal. By calculating the optical path length change of a typical NPRO crystal due to sinusoidal power fluctuations of its pump diode, Day et al. were able to model the transfer function $T_{\mathrm{cur}\to\omega}$ with good agreement to the experimental result between 100 Hz and 100 kHz. Furthermore by assuming a flat spectral density of the power fluctuations of the pump LDs their model was able to predict the free-running frequency fluctuations of the NPRO. Our measurements in Figure 2 shows $T_{\mathrm{cur}\to\omega}$ to Fourier frequencies up to 1 MHz, and particularly in the frequency range of the NPRO's relaxation oscillation frequency. It is worth mentioning that the power fluctuations of the pump LD which drive the relaxation oscillations cause a resonant response not only in the NPRO power but also in its frequency. This is clearly not a thermal effect but probably due to changes in the index of refraction caused by oscillations in the atomic polarization of the active laser medium.

Based on this transfer function we designed a control system to lock the laser frequency ω_{L} to the cavity resonance ω_{C} by feeding back to the pump LD current. Figure 3 shows the spectral density of frequency fluctuations $\delta\omega = \omega_{\mathrm{L}} - \omega_{\mathrm{C}}$.

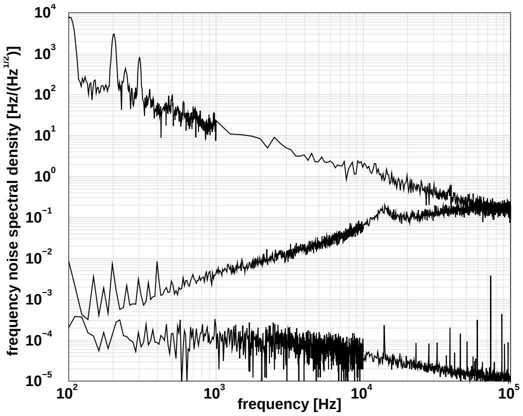

Fig. 3. Frequency noise spectral density of the monolithic Nd:YAG laser relative to a rigid-spacer reference cavity. The upper curve shows the free running noise and the middle curve is a measurement taken at the error point of a feedback loop that stabilizes the laser frequency by feeding back to the current driving its laser-diode pump source. The lower curve represents the electronic noise of the measurements.

The upper curve shows the free-running frequency noise of the NPRO and the lower curve was measured at the error point of the closed frequency stabilization loop. The bandwidth of this control system was 80 kHz and the frequency fluctuations could be reduced to below $10\,\mathrm{mHz}/\sqrt{\mathrm{Hz}}$ for Fourier frequencies below 2 kHz, which is comparable to the noise reduction we could achieve with a conventional split control loop feeding back to the laser PZT and also a phase correcting Pockels cell behind the laser.

Due to the coupling between the laser frequency and the power of the LD pump source, the frequency measurement simultaneously measures the power fluctuations of the pump LD integrated over the spatial profile of the laser gain. Therefore this frequency servo simultaneously reduces the power noise of the NPRO. Figure 4 shows the power noise with and without frequency servo closed. Although the noise is reduced significantly, there is less noise reduction than the servo-system gain would suggest. This is probably due to the fact that the spatial overlap between the laser volume and the pump volume is not perfect. This means that a fraction of the absorbed pump-light can deposit heat in the Nd:YAG crystal but does not change the gain in the laser volume. Hence fluctuations of this pump light may cause frequency fluctuations by changing the index of refraction of the crystal but do not change the laser power. As the spatial distribution of the power fluctuations is not constant over the beam profile of the laser-diode bar, the correlation between the power and frequency fluctuations of the NPRO caused by pump-power fluctuations is not perfect.

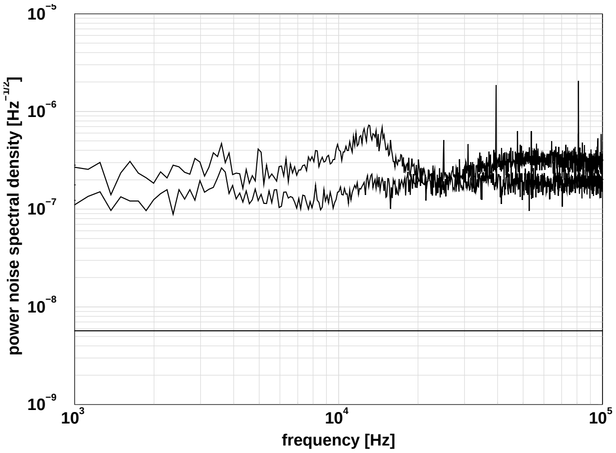

Fig. 4. Spectral density of the power fluctuations of a monolithic Nd:YAG laser. The upper curve (at low Fourier frequencies) shows the noise of the unstabilized laser and the middle curve was measured while the laser frequency was stabilized using the current lock. Both measurements were taken without any dedicated active intensity stabilization. The lower straight line corresponds to the shot noise limit of this measurement.

To summarize: we have introduced a new scheme to stabilize the frequency of an NPRO laser which only uses the built-in laser-diode current actuator. One advantage of this method in comparison with the conventional scheme is the much simpler controller needed. Only low voltage feed-back electronics is used and no cross-over has to be designed between the PZT and an external Pockels cell actuator, both of which need notoriously noisy high-voltage amplifiers. Furthermore, beam pointing and power fluctuations which are introduced by the PZT could be avoided.

The detection of the frequency noise is a non-demolition measurement of the NPRO power fluctuations and should in principle avoid the 3 dB penalty that is the minimum to be paid in conventional power stabilization servos[12]. However, more investigations are needed to clarify why the power noise reduction in our experiment was smaller than expected.

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