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# Nd:YAG laser frequency stabilization to a supercavity at the 0.1 Hz level

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**Abstract**

We present a study of frequency locking two diode-pumped Nd:YAG non-planar ring oscillator lasers to a Fabry-Perot cavity with 215 000 finesse. Measurements of the beat frequency between the two lasers, locked to adjacent $TEM_{11}$ modes, show a root Allan variance of 0.25 Hz for 1 s integration time and a minimum of 0.12 Hz for 50 s integration time.

The diode pumped monolithic Non-Planar Ring Oscillator (NPRO) Nd:YAG laser [1] has recently emerged as a source particularly suited for metrological applications, since it exhibits excellent free running frequency stability [2], low amplitude noise [3], compact size and long lifetime. Application examples include gravitational wave interferometers [4], QED tests [5], displacement [6] and acceleration sensors [7], and experiments in quantum optics [8]. The Nd:YAG NPRO is also the source for a potential new frequency standard in the optical domain, through frequency stabilization of its harmonic to hyperfine transitions of molecular iodine [9].

In view of these uses, frequency stabilization of monolithic Nd:YAG lasers has been extensively studied. Stabilization to high-finesse cavities has yielded low laser frequency noise at kHz noise frequencies [10]. On time scales between 0.1 and 1 s, frequency stability at the 1 Hz level relative to the cavity frequency has been reached [11,12].

Significant further inprovements in lock stability are highly desirable, especially for longer integration times. The development of cryogenic optical cavities with the potential of high dimensional stability [13] will require relative stability at the sub-Hz level for integration times of the order of hours. Force sensors employing pendular cavities [14], passive resonant gyroscopes, Doppler sensors, satellite-based optical cavities [15] are future areas of applications. From the technical point of view, it is important to seek to extend the excellent lock stability demonstrated for the He-Ne lasers (root Allan variance (100 s) < 50 mHz) [16] to a different laser system.

In this Letter, we report the first results on the long term (> 5 s) frequency stability of two NPROs locked to different transverse modes of a room temperature high finesse cavity. The system employed is similar to previous ones, but particular emphasis has been put on improving those parameters necessary to achieve good long term lock stability.

Fig. 1 shows a schematic of the apparatus used for the measurements. Two lasers, L1 with 50 mW and L2 with 10 mW output power, were locked to a cavity

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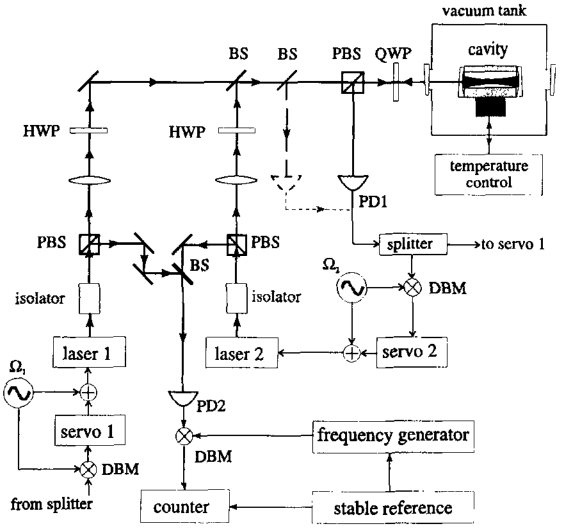


Fig. 1. Set-up for lock stability characterization. PD photodiode, PBS polarizing beam splitter, BS 50% beam splitter, DBM double balanced mixer, QWP quarter wave plate, HWP half wave plate.

using the FM technique [17]. The modulation sidebands were obtained by mechanical modulation of the laser cavities via piezoelectric actuators [18]. Sideband frequencies were $\Omega_1$ = 820 kHz for L1 and $\Omega_2$ = 1.034 MHz for L2; the indices of modulation were 0.4 and 0.3, respectively. The modulation exhibits a temporally stable residual AM at a level of $10^{-4}$.

The beams of the two lasers, after passing two-stage Faraday isolators (85 dB isolation) and mode matching optics, are combined using a 50% beam splitter and fed into the supercavity, which consists of two high-reflectivity concave mirrors optically contacted to a 10 cm long fused silica spacer (Herasil 1). The fused silica mirror substrates have a 50 cm radius of curvature and were coated by Research Electro-Optics. The cavity is kept in a vacuum tank at pressures below $10^{-3}$ mbar. Optical access to the tank is through a glass window. A cavity finesse of 215 000 was measured for the $TEM_{11}$ mode; the $TEM_{00}$ mode exhibited a lower value of 70 000, probably due to a contamination of the mirror surface. The lasers were therefore locked to two $TEM_{11}$ modes spaced one free spectral range apart. 20% of the laser power was coupled into the cavity, i.e. a cavity reflectivity of 80% was obtained. The FSR of the cavity was measured to be 1 504.76 MHz, corresponding to a length of 9.96 cm.

To extract the reflected waves from the reference cavity two variations were used: the conventional combination of polarizing beam splitter (PBS) and quarter wave plate (QWP) or a 50% beam splitter only. The reflected light of both lasers is detected by a single rf photodetector, the photocurrent is split and mixed with two local oscillators to generate two error signals. The servo amplifiers consist of four integrators plus lead-lag compensators. The gain is approximately 200 dB at 0.1 Hz and unity at 20 kHz. To measure the frequency of the beat, small fractions of the two laser waves, obtained from the ordinary beams of two polarizers, were heterodyned on a fast detector. Temporal variations of the beat frequency were measured, after down-conversion to around 300 MHz, using a high-stability frequency counter SR620 with a rated stability of $2 \times 10^{-11}$ for an integration time of 50 s.

The light powers incident onto the cavity, adjustable by means of half-wave plates, proved to be critical parameters. A high power level yields a better signal to noise ratio in the detection of the signal reflected from the reference cavity, but it can degrade the stability of the mode frequency of the resonator, resulting in a worse short term behaviour of the beat frequency. This has been reported earlier [12,19] and may originate from heat dissipation on the reflecting coating of the high finesse mirrors. In our case the degradation of the beat frequency due to thermal effects was rather constant even over one day. Actual cavity input powers used were 4 mW from L1 and 2 mW from L2.

Particular effort was put into reducing temperature variations in the system. The cavity was actively temperature stabilized using an electrical heater servo-controlled by an AC resistance bridge thermometer. The error signal of the temperature control servo showed variations smaller than 0.2 mK for periods up to 10 h. The optical window through which the laser light entered the vacuum tank was independently actively temperature stabilized. A passive temperature stabilization was realized for the rest of the optics by enclosing it in a foam-lined wooden box. With the laboratory air-conditioned with 0.25 K stability, the stability inside the box reached 50 mK over a 10 h period.

The main result is displayed in Fig. 2, which shows the beat frequency over a period of 60 h. Gate time while taking data was 1 s, while in the figure a point corresponds to a 60 s interval. The discontinuities in the data resulted from transferring the data files for

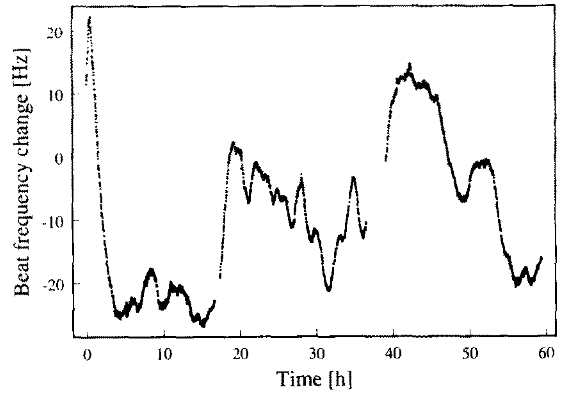


Fig. 2. Change in the beat frequency. Reference value is 1 504 759 143.86 Hz.

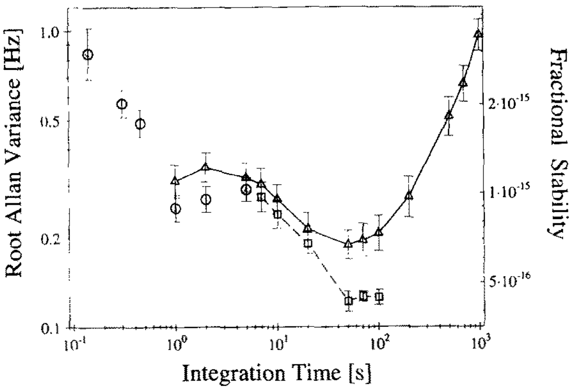


Fig. 3. Root Allan variance values. Triangles, values calculated over the 60 h data file; squares, values from a 4900 s subset; circles, values from a different set-up (see text).

off-line analysis. The large drift at the beginning is due to the thermalization of the optical components; the causes of the sudden drifts occurring around 18 and 39 h are unknown. The calculated values of the root Allan variance (20 samples) for different integration times are shown in Fig. 3 (solid line). Data of Fig. 2 was taken using the 50% beam splitter technique. With the combination of PBS and QWP it was possible to obtain a better short term stability (circles in Fig. 3), while the long term stability was worse (not shown in Fig. 3). We believe this is due to the fact that in the latter case circularly polarized light was used. Birefringence in the substrates may split the mode frequency degeneracy of the two linear polarizations. Since the lock error signal contains contributions of both polarizations a change of input polarization due to birefringence of external optical elements, for example of the vacuum tank entrance window, may cause a change of the lock point.

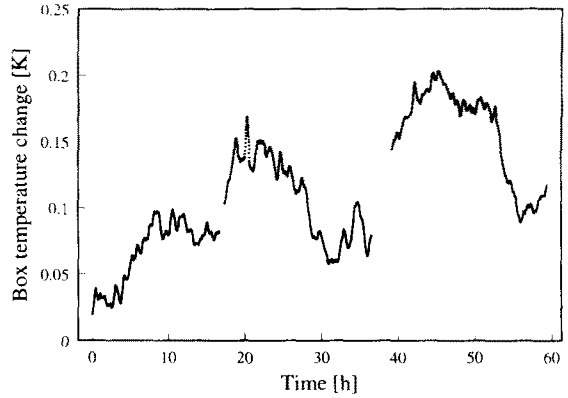


Fig. 4. Temperature evolution inside the box containing the optics.

Considering a 4900 s subset of the data around 26 h exhibiting the least drift, lower instability values are obtained on a longer time scale (squares in Fig. 3). We find a minimum 0.12 Hz beat frequency root Allan variance for 50 s integration time, which represents an eight-fold improvement compared to the best literature value for Nd:YAG lasers [12]. Analysing the 50 s integration time root Allan variance values over the full 60 h, no single value above 0.25 Hz was found. Note that the instability of the frequency counter system contributes 30 mHz to the 50 s values.

We think that the variations in the beat frequency occurring over time scales of a day are still due to temperature changes in the optics. Evidence is provided by the record of the temperature inside the box enclosing the optics, see Fig. 4. In addition to the polarization state changes described above, temperature also affects the behaviour of optical components such as beam splitters, with the result of changing e.g. the coupling between the lasers and the cavity and a consequent change in the length of the resonator due to a different thermal load. Finally, thermal expansion of the cavity also contributes to a certain extent to change the beat frequency.

As a general check of our experiment a system consisting of two lasers locked to two cavities was also realized, which permits to measure the absolute stability of the laser frequencies. The second cavity had the same type of mirrors as the first one but a 3 cm long spacer. It showed a finesse of 275 000, the highest value reported so far, to our knowledge, for the Nd:YAG wavelength. A minimum root Allan variance of 35 Hz for 100 ms integration time for the beat frequency between the two independently stabilized systems was obtained. Root Allan variances for longer integration times were dominated by individual cavity drifts, whose relative extent was around half a MHz over time scales of one day. Due to the use of fused silica as a cavity material rather than ultra-low expansion glass ceramic (ULE), whose thermal expansion coefficient is about 10 times smaller, our instability was about 10 times larger than in the work of Sampas et al. [20].

The observation of various effects degrading the lock stability suggests that room for further improvement exists. A reduction in the susceptibility to laboratory temperature fluctuations may be obtained by placing as many optical elements in the vacuum region as possible. A servo control of the power transmitted through the cavity can compensate for beam pointing instability and improve the stability of the thermal load on the cavity mirrors. At the present instability level no influence of residual amplitude modulation (RAM) was seen; if this becomes relevant in the quest for enhanced locking stability, active control of RAM can be implemented [21].

With the single FM detector schemes described, cross talk of the locking systems may occur. Therefore an alternate set-up was tested, in which each laser was coupled to the reference cavity through one of the two end mirrors, respectively. Two completely separated locking systems, with respective FM detectors, were used. The latter are not affected by the waves transmitted through the resonator since its narrow linewidth suppresses their phase modulation. Root Allan variances about 30% lower than the previous ones were obtained for integration times between 2 and 10 s.

In conclusion, we have demonstrated that Nd:YAG NPROs can be reliably frequency locked with less than 0.15 Hz average individual instability relative to cavity frequencies of high finesse resonators. The lowest individual instability achieved was 0.10 Hz during a 1 h run. This level of average individual instability is seven times lower than the previously reported values, and is achieved for times two orders of magnitude longer (50 s). Thus, NPROs are promising sources for experiments that require long-term lock-stability.

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