Cryogenic optical resonators for laser frequency stabilization

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Abstract

A system for the measurement of frequency stability of high-finesse cryogenic optical cavities has been developed. Two diode-pumped Nd:YAG lasers were locked to two independent cavities (finesse 240 000 and 215 000) operated at 4.2 K with long-term temperature stability at the 2 mK level. The short-term frequency instability of the cryogenic cavities was measured as $\sigma(0.5\,\mathrm{s})$=9.6 Hz, while the long-term instability was limited by an almost linear drift of 33 kHz/h. For the lock instability of Nd:YAG lasers frequency-stabilized to a room-temperature cavity, we have achieved a root Allan variance $\sigma(50\,\mathrm{s})$=120 mHz.

1 Introduction

Ultrastable cavities are required for a number of applications in high-precision experiments. The most prominent ones are linewidth-narrowing and short-term frequency stabilization of lasers for high-resolution spectroscopy [1], and flywheel oscillators in conjunction with molecular, atomic or ionic frequency standards. An important difference between these "microscopic" clocks and cavity-stabilized oscillators is the macroscopic character of the latter's frequency, which depends on the cavity length. This makes them suitable for fundamental tests [2], provided sufficient long-term stability can be achieved. Comparisons of microscopic clocks and macroscopic cavity "clocks" have been employed to test special relativity [3], local position invariance [4], and the variability of the fine structure constant [5].

We are developing a new generation of optical cavities, operated at cryogenic temperature, with expected long-term stability higher than that currently available using room temperature cavities. Future applications include improved versions of the above experiments, as well as novel measurements (see section 3.2).

Cryogenic operation is expected to significantly reduce disturbances of the cavity length of thermal nature. The main advantages are a significantly reduced

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thermal expansion coefficient, higher thermal diffusivity and lower sensitivity to heat dissipation by the electromagnetic field stored in the cavity [6]. Other sources of cavity length instability, such as mechanical deformations induced by seismic noise, support vibrations and tilt, change of local gravitational acceleration, and radiation pressure, will not be reduced. In fact, some of these are likely to be larger in initial experiments, due to mechanical noise generated within the cryostat. A clear proof of the potential of cryogenic cavities was given by Turneaure and Stein using microwave oscillators stabilized to superconducting niobium cavities [5]. A record low instability $\sigma(100\,\mathrm{s})=2 \times 10^{-16}$ was reached, which permitted fundamental tests mentioned above. The subsequent development of sapphire cryogenic cavities [7] led to excellent frequency stability over long integration times as well [8]. Work on applying the concept of cryogenic resonators to the optical frequency domain started some years ago, and a number of different cavities have been built, using spacers made of silicon [9], sapphire [10], and fused silica [11]. In all cases fused silica was used as a mirror substrate material. A cryogenic miniature monolithic quartz resonator has also been demonstrated [11]. We have already reported on the instability of Nd:YAG laser frequency lock to a cryogenic resonator [11] and on cavity thermal expansion measurements [12]. Here we present first measurements on the absolute stability of cryogenic optical cavities. Improvements recently achieved with lock stability are also summarized here [13].

2   Experimental Results

The optical cavities (C1, C2) used in our experiments consist of high-reflectivity concave mirrors optically contacted to fused silica spacers (Herasil 1). The spacer lengths are 3 cm (C1) and 10 cm (C2). The fused silica mirror substrates have 50 cm radii of curvature. The cavities are operated in vacuum at pressures below 10^{-6} mbar. The measured finesses were 240 000 for C1 at liquid Helium temperature and 215 000 for C2 at room temperature, with corresponding linewidths of 25 kHz (C1) and 7 kHz (C2), respectively. The latter value was measured for the TEM_{11} mode, while the TEM_{00} showed a much lower value, probably due to a contamination of the mirror surface. An incoupling of 60% (i.e. 40% reflectivity) at both room and cryogenic temperature was obtained for C1. We used two non-planar ring oscillator Nd:YAG lasers (λ=1064 nm), whose powers were 10 mW (L1) and 50 mW (L2), respectively. The lasers were locked to the cavities using the FM technique. Modulation sidebands were obtained using the mechanical laser tuning elements as phase modulators [14]. Modulation frequencies were 1 030 kHz for L1 and 862.4 kHz for L2. The servos used 4-stage integrators to achieve high gain, and typical unity gain frequencies of 20 kHz.
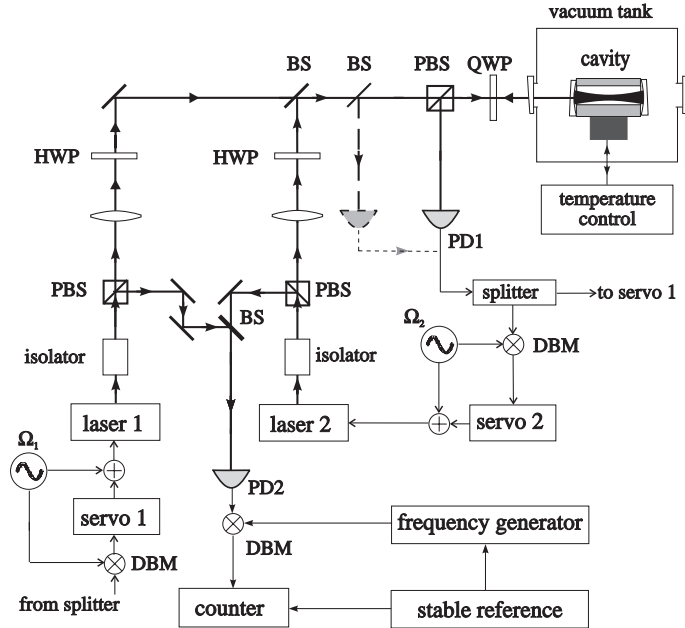
Figure 1: Set-up used for measuring the relative stability of Nd:YAG laser frequency locks.

2.1 Frequency lock of two Nd:YAG lasers to one cavity

We investigated the quality of the locking system by locking L1 and L2 to two different modes of cavity C2, kept at room temperature. Figure 1 shows a schematic of the set-up. The beams of the two lasers, after passing two-stage isolators (81 dB isolation), mode-matching optics and attenuators, are combined using a 50% beam splitter and fed into the cavity. To extract the reflected waves from the reference cavity two schemes were used: the conventional combination of polarizing beam splitter and quarter wave plate or a 50% beam splitter only (shown dashed in the figure). The temperature of the cavity was actively stabilized, while all other optical components were enclosed in a wooden box providing a passive thermal stabilization ($\Delta T < 20$ mK over 10 hours). The laboratory itself was air-conditioned ($\Delta T < 200$ mK over 10 hours). The whole system was mounted on a floating optical table. The lasers were locked to adjacent TEM_{11} modes and the resulting beat frequency of approximately 1.5 GHz was detected by heterodyning a small fraction of the laser waves on a fast photodetector. Temporal variations of the beat frequency were measured using a high-stability frequency counter, after down-conversion to 300 MHz. A 60 h duration lock is shown in figure 2 a, where the gate time for frequency readout was 1 s. An unwanted residual daily modulation is present. The calculated values of the root Allan variance (20 samples) for different integration times are shown in figure 2 b. The values for integration times ≤ 50 s were calculated using a 1-h subset of the data ex-

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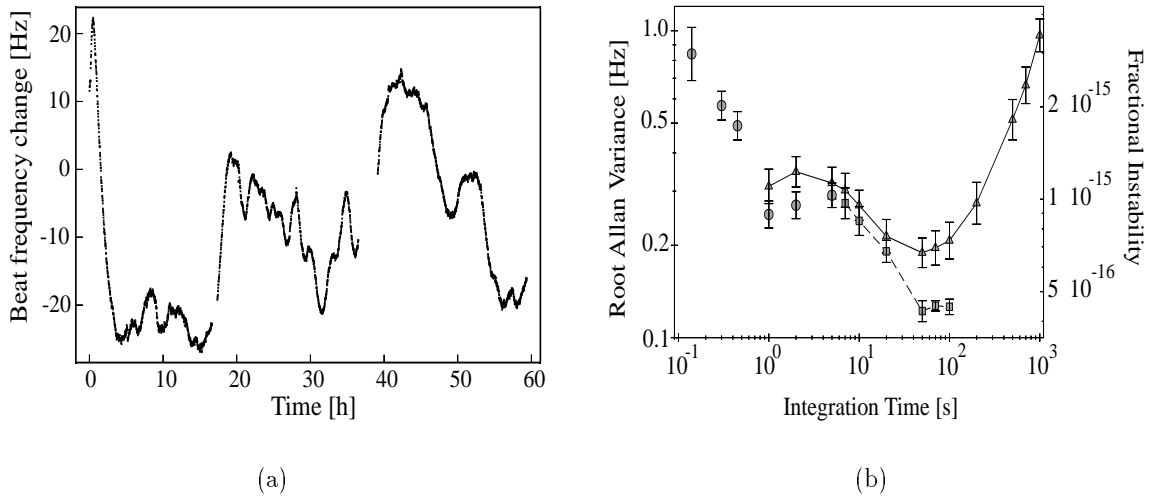<center>(a)</center>

<center>(b)</center>

Figure 2: (a) Beat frequency change of two lasers locked to a single cavity. (b) Root Allan variances calculated from data shown in (a).

hibiting small drift. Values for integration times below 5 s were obtained using the combination of polarizing beam splitter and quarter wave plate in reflection, while the measurements for longer integration times employed the beam splitter. The beat frequency instability exhibits a minimum of 0.12 Hz at 50 s integration time, which represents an eightfold improvement compared to the best literature value for Nd:YAG lasers [15]. This means that we are able to reach a relative lock instability of 5×10^{-16}.

2.2 Stability of cryogenic optical cavities

Figure 3 shows the experimental setup used to characterize the absolute stability of both cryogenically cooled cavities. C1 was mounted inside a liquid Helium glass cryostat while C2 was mounted inside a liquid Helium metal cryostat. With both cryostats a temperature of 4.2 K was reached without pumping on the Helium gas. Each of the cavities was actively temperature-stabilized, using an electrical heater servo whose error signal was provided by an AC resistance bridge thermometer attached to the copper support of the cavity. Independent temperature sensors indicated that the temperature of the cavity support blocks was stable to within 2 mK over one day.

Figure 4a presents a 10 hours measurement (gate time 1 s) of the beat frequency between the two lasers locked to two independent cryogenic cavities. The drift of the beat frequency in this first measurement is larger than an expected change in beat frequency due to temperature instability of the cavities. One pos-
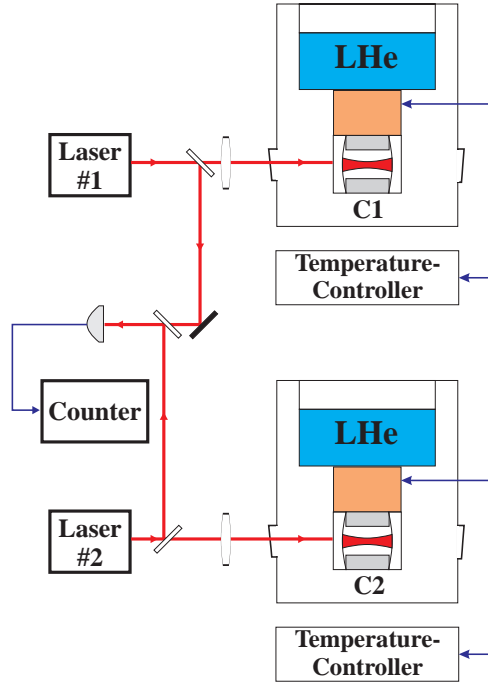
<center>4</center>

Figure 3: Simplified schematic of set-up used for measuring the absolute stability of cryogenic optical resonators C1, C2.

sible explanation is an ageing effect, e.g. in the optical contacts or in the spacers themselves. The root Allan variances are shown in figure 4 b. The minimum value of 9.4 Hz is obtained for an integration time of 0.5 s. For longer times drift is dominant, while for short integration times cavity vibration noise caused by the cryostats dominates.

3 Outlook

3.1 Sapphire cavities

Sapphire, which has already been used for cryogenic microwave cavities, appears as an excellent candidate for cryogenic optical cavities as well. The most straightforward design for an all-sapphire cavity will consist of a sapphire spacer to which mirror substrates of the same material and the same crystal orientation are optically contacted, to avoid differential thermal expansion. At cryogenic temperature (2 - 3 K), the thermal expansion of sapphire is about 10^3 times smaller, its thermal diffusivity about 10^4 times larger, and its sensitivity to heat load about 10^6 times smaller than for fused silica. These properties should considerably enhance the length stability of the cavity, provided a good thermal coupling between the cavity and the cold plate of the cryostat can be achieved. An impor-
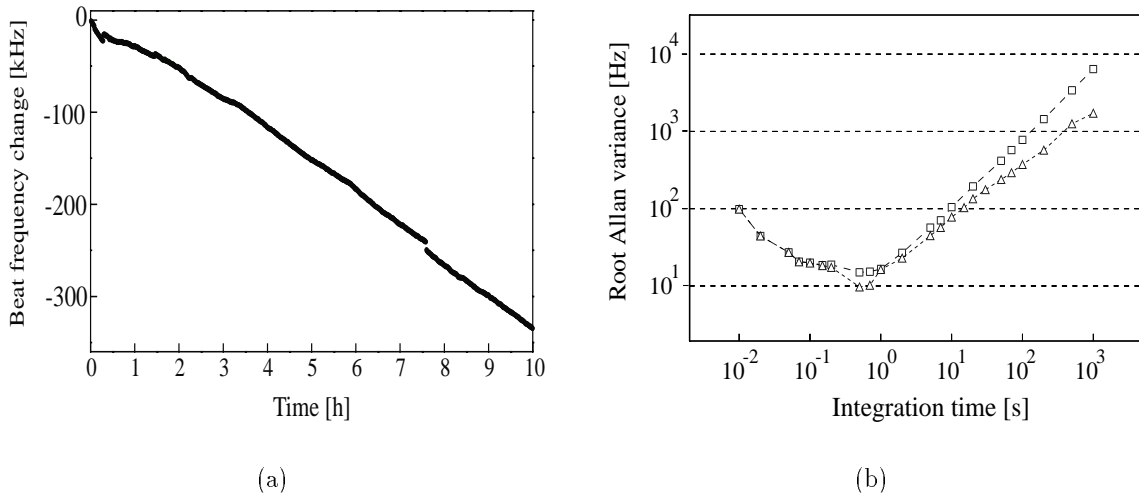
Figure 4: (a) Change in beat frequency of two independent systems.
(b) Root Allan variances of absolute instability of cryogenic cavities.
Boxes indicate the values obtained for the complete set of data,
triangles indicate those obtained after taking out the linear drift.

tant goal in the development of sapphire cavities will be to obtain simultaneously high finesse and high cavity throughput. The technology to achieve sapphire substrate superpolish and low-loss, high-reflectivity multilayer coatings is available. Of major interest will be the study of long-term relaxation effects originating from the bulk and the surface of the spacer material and from the optical contact. These effects are significant in fused silica and glass ceramic cavities [16]. However, they may be significantly reduced for the cryogenically cooled, highly pure single-crystal materials envisioned for the cryogenic optical cavities. In optical cavities of the above standard design, in which the optical wave travels in vacuum, the low dielectric loss of sapphire, essential for microwave cavities, is not made use of. However, as the absorption and scatter losses are small also in the optical domain, a high-finesse monolithic sapphire cavity represents a viable possibility. An all-cryogenic laser plus cavity system has been proposed in [12].

3.2 Force sensors

One interesting use of particular optical cryoresonators is as optomechanical sensors of tiny local forces. These sensors consist of a cavity with one movable mirror. A force that couples to this mirror displaces it and causes a change in mirror separation. This is read out by comparing the cavity resonance frequency with that of a reference oscillator. As the mirror is a mechanical oscillator, it is subject to Brownian noise excitation. The cryogenic environment serves to reduce the spectral density of the noise force by reducing the temperature and increasing

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the mechanical quality factor of the oscillator. Appropriately designed cryoresonators, with a single-crystal silicon or sapphire structure as mirror/mechanical oscillator, should reach very high sensitivity for detection of forces, thanks to the high intrinsic quality factor of these crystals. Silicon mechanical structures can be reliably fabricated using anisotropic etching techniques. Such optomechanical sensors, with optimized mirror mass and mechanical properties, can be employed for a wide range of force measurements. A room-temperature microwave cavity with mirrors attached to pendula has been used for measurements of gravitational force and a determination of the gravitational constant [17]. A prototype cryogenic miniature cavity for the detection of vibrational excitation of one of the mirrors is under development as an optical transducer for multi-mode gravitational bar antennae [18]. Optomechanical sensors have the potential of significantly higher sensitivity than that demonstrated so far and may be applied to other uses as well, such as weighting small masses, gravimetry, detection of electric, magnetic, and Casimir-type forces.

4 Conclusion

We have reported on the status of the development of cryogenic optical resonators for frequency-stabilization of lasers.

We have performed the first measurement of the absolute stability of cryogenic optical cavities by comparing the frequencies of two independent, stable, cryogenic cavities. The initial results are highly encouraging. The origin of cavity drift may be investigated further by using an iodine-stabilized Nd:YAG laser reference. A significant improvement in the locking stability of Nd:YAG lasers has been achieved reaching the 0.1 Hz regime for integration times of 50 s using a room temperature cavity exhibiting a 7 kHz linewidth.

In the near future, the fused silica cavities will be replaced by sapphire ones, which are expected to have significantly better thermal properties. The study of long-term relaxation effects in the sapphire cavities will then become a focus of our work.

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