Ultrahigh long-term dimensional stability of a sapphire cryogenic optical resonator

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Received March 5, 1998

We report on the ultrahigh long-term dimensional stability of a crystalline cryogenic optical resonator (CORE) cooled to liquid-helium temperature. The frequency of a Nd:YAG laser stabilized to a CORE was compared over long times with an independent laser system, a frequency-doubled Nd:YAG laser stabilized to a hyperfine line of molecular iodine at 532 nm. Over a 6-month period the drift was less than 3 kHz. The dimensional stability of the CORE is thus more than 2 orders of magnitude higher than that of the best ultralow-expansion glass ceramic cavities at room temperature.

OCIS codes: 120.0120, 140.0140, 300.0300, 120.3940, 120.4800, 140.4780.

Laser frequency stabilization is central to high-resolution spectroscopy,[1] to the development of optical frequency standards,[2] and for fundamental tests based on clock–clock comparisons, such as tests of special relativity[3,4] and searches for a possible temporal variation of the fundamental constants.[5–7] Glass ceramic reference cavities for laser stabilization have found widespread use. Recently we showed that the use of crystalline cryogenic optical resonators (CORE's) cooled to liquid-helium temperature provides what is now the lowest laser frequency instabilities over short times (minutes). For monolithic diode-pumped Nd:YAG lasers locked to sapphire cavities we have achieved an instability below the 3×10^{-15} level for integration times of the order of minutes,[8] 1 order of magnitude lower than with ultralow expansion (ULE) cavities.[9]

An important issue concerning reference cavities is their long-term drift that is due to stress relaxation. This drift has been extensively studied for glass ceramic cavities.[10,11] Recently Marmet *et al.*[12] used accurate temperature control of an ULE cavity to obtain a linear drift as low as 4.75 kHz/day. It is of interest to compare the performance of ULE and sapphire cryogenic optical resonators with respect to long-term effects. In a comparison between two CORE's we had previously observed that over a period of several days the relative drift was less than 200 Hz. A substantial common mode drift appeared unlikely but could not be completely excluded inasmuch as the two CORE's were fabricated in nominally the same way and at the same time. Here we address the issue of a possible linear drift by comparing a laser stabilized to a CORE with an independent laser frequency stabilized to molecular iodine.[13] We also describe recent improvements and some characteristics of the CORE system.

Our experimental setup (see Fig. 1) consists of three independent systems: two Nd:YAG lasers locked to different CORE's (on a single optical table) and one frequency-doubled Nd:YAG laser locked to a hyperfine transition of molecular iodine at 532 nm. The first two systems, described previously,[8] each contain a diode-pumped monolithic Nd:YAG ring laser (1064 nm), an optical cryostat in which the sapphire CORE is mounted, an active beam-pointing stabilization system, laser-versus-cavity detuning detection by the frequency-modulation technique, and a high-gain servo loop that controls the laser frequency to accurately track the frequency of the CORE. The two similar cryostats are standard liquid-helium systems with superinsulation, liquid-nitrogen jackets, and two liquid-helium pots. Liquid nitrogen is automatically refilled every 2.5 h; liquid helium is manually refilled approximately every 70 h. Each CORE is located in vacuum near the bottom plate of the lower pot and is actively temperature stabilized within 2 mK at 4.3 K. The high-finesse CORE's consist of 3-cm-long cylindrical sapphire spacer tubes (10-mm inner diameter, 26-mm outer diameter, *c* axis parallel to the cylinder and the optical axis). Their end faces are polished flat, and dielectric multilayer-coated sapphire mirrors are optically contacted to them. The cavity linewidths are 36 and 82 kHz (finesse 140,000 and 61,000) and have not degraded over 18 months. The incoupling levels are ~70% and ~30%, respectively.

The Nd:YAG lasers are locked to the TEM_{00} cavity mode by the frequency-modulation technique.[14] One of our two CORE systems has been operated uninterruptedly at liquid-helium temperature for 15 months (starting in February 1997). This continuous operation demonstrates that it is feasible to use CORE's for long-term measurements. During this time it has

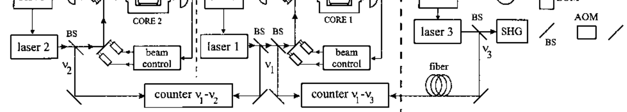

Fig. 1. Setup for measuring the long-term drift of the CORE. The setup for sub-Doppler modulation-transfer spectroscopy of molecular iodine (right) is located in a different laboratory. BS's, beam splitters; LHe, liquid He; SHG, second-harmonic generator; EOM, electro-optic modulator; AOM, acousto-optic modulator.

0146-9592/98/131031-03$15.00/0

not been necessary to pump on the vacuum, as the coolants keep the pressure continuously well below 5×10^{-7} mbars, the value measured in the room-temperature section of the cryostat vacuum.

As a molecular reference we use the a_{10} hyperfine component of the $R(56)32$-0 line of $^{127}I_2$, probed by an externally frequency-doubled monolithic Nd:YAG laser. For stabilization onto the transition we use Doppler-free modulation transfer spectroscopy.[15] The phase modulation sidebands for the pump beam are imparted at 455 kHz by an external electro-optic modulator with a modulation index of 1. The acousto-optic modulator shifts the probe frequency by 80 MHz to avoid interference effects on the detector. The servo system is similar to those of the CORE systems. The 10-cm long iodine cell has Brewster-angle entrance windows and a cold finger. Under operating conditions, the iodine cell's temperature is kept at 0 °C, yielding a linewidth of the hyperfine transition of 1.8 MHz. The temperature of the iodine cell is actively stabilized by use of a two-stage Peltier cooler with an instability of 10 mK over long periods. The 532-nm saturation power is near 6 mW for the pump. Probe power is 680 μW, with 400 μW falling onto the detector.

Beams are split off each laser and overlaid upon two fast photodetectors that generate ac currents at the differences $\nu_1 - \nu_2$ and $\nu_1 - \nu_3$ of two optical frequencies. The beat frequencies are mixed down to ~300 MHz, where the frequency counters have their highest sensitivity, are averaged over 1 s, and are recorded every 1 s by a computer for subsequent statistical analysis.

The instability of the iodine-stabilized laser is roughly constant at a level of 6.5×10^{-13} (root Allan variance) for integration times τ from 1 to 10^4 s, as we deduced from a comparison with a CORE system. The resettability is 150 Hz for the iodine system, which we measured by putting the laser back to lock without changing external parameters such as the temperature of the iodine cell and the gain of the servo system.

Because of evaporation of the coolants the cryostats change their shape slightly, causing the CORE's to move on a time scale of hours, mainly perpendicularly to the laser beams. This movement results in changes in coupling efficiency, in lock errors, and eventually in loss of lock. To reach long locking periods we implement active beam-pointing stabilization systems that keep the laser powers transmitted through the cryogenic cavities constant. For each system the two incoupling mirror mounts are motorized by a total of four dc motors, to have all degrees of freedom needed for best alignment into the cavity. A computerized system monitors the power transmitted through the cryogenic cavities and realigns the mirrors by sending voltage pulses to the dc motors if the intensity has changed by more than 5%. The computer program maximizes the transmitted power by adjusting both incoupling mirrors in the same way in which one would raise a laser mode by hand. The bandwidth of the system is of the order of 0.1 Hz. Figure 2 shows that the variation of the beat frequency between the two CORE-stabilized lasers is significantly reduced. When the beams are locked to the cavities, the incoupling level remains within 3% for several days, whereas without stabilization the incoupling is reduced by 40% after 3 days. This stabilization system allows us to keep our laser systems in lock for an unlimited time, even while we are working on the optical table or refilling the cryostats with liquid helium, and has greatly simplified the long-term comparison with iodine.

Figure 3 shows the beat frequency change between a CORE and the iodine reference over a period of 190 days. Within this period the frequency change has not been more than 14 kHz. The deviations are due mainly to changes in output power of the frequency doubler, affecting the iodine hyperfine transition frequency because of power shifts (approximately 25 kHz/mW). Some excursions that are visible in Fig. 3 occur once the laser is locked to the CORE after a period without light circulating in the cavity. A linear least-squares fit of the data yields a frequency change of 2.7 kHz within 6 months, which sets a limit to a possible drift of the CORE that is 200 times less than for the best ULE cavity. With improvements in the molecular reference, it should be possible to lower this limit further.

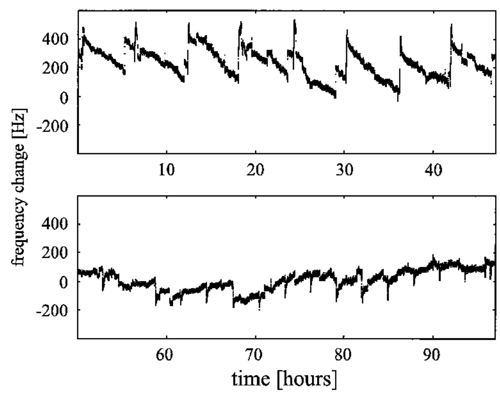

Fig. 2. Long-term traces of the frequency difference of two cryogenic optical resonators at 4.3 K, showing improvement owing to active beam alignment control. Bottom, frequency behavior while the laser beam alignment is on. Top, beam control turned off. The saw-toothed pattern visible in the top plot is due to the periodic depletion of liquid nitrogen. It is strongly suppressed with alignment control. The sharp spikes and fast frequency changes in both plots are due to automatic liquid-nitrogen refill processes, which last a few minutes. Every point corresponds to a 1-s average of the beat frequency.

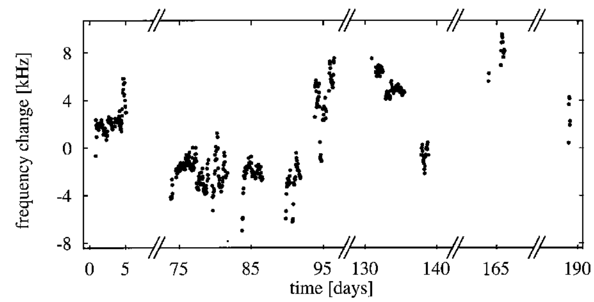

Fig. 3. Long-term trace of the difference frequency between a CORE at 4.3 K and a Nd:YAG laser locked to a hyperfine transition of molecular iodine. Every point corresponds to a 1-h average of the beat frequency.

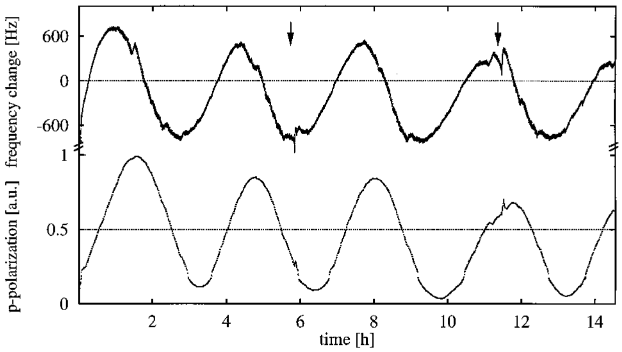

Fig. 4. Resonance frequency behavior of a cryogenic optical resonator at 4.3 K under a continuous polarization change of the incident laser beam. Lower trace, intensity of the *p*-polarization with respect to the optical table. There is no actual phase shift between polarization and frequency. Arrows, automatic liquid-nitrogen refills. Because of the absence of beam stabilization during the measurement the transmitted intensity is decreasing. The frequency trace is partially distorted by the background frequency drift.

There are several environmental changes that affect the frequency stability of the cryogenic resonators: fluctuations of resonator temperature, laser intensity, laser polarization, laser incoupling, and cavity tilt. We have examined the first four. Temperature stability is at the 2-mK level. It is not important at present, as it yields a frequency change of 8 Hz owing to the measured cavity thermal expansion coefficient of 1.5×10^{-11}/K at 4.3 K. The power dependence is weak at the level used (at 10-μW input power, less than 30-Hz change for a 50% power change). We observed a strong dependence of the resonance frequency on the polarization of the incoupled laser light. Figure 4 shows the behavior when the input polarization of the laser of one CORE system is rotated continuously with a motorized half-wave plate. The frequency difference between orthogonal polarizations is 1.2 kHz. It is due not to power modulation or electronic offsets but to birefringence of the mirrors.[16] To avoid the influence of this birefringence it is useful to set the input polarization such that the cavity frequency is an extremum. Finally, the most serious problem at present is the frequency shifts that are due to misalignment of the laser with respect to the cavity as a result of interference effects. This effect is likely to be responsible for the frequency changes that are visible in the lower plot in Fig. 2. For a 3% change in the transmitted power we found a frequency shift of maximum 200 Hz.

In conclusion, we have studied the long-term behavior of the frequency of sapphire cryogenic optical resonators. An active beam alignment control has improved the frequency stability and reliability of the CORE-locked lasers, permitting long-term monitoring of the cavity frequencies. With a hyperfine transition of molecular iodine as a reference, an upper limit for the drift of one cryogenic cavity is 2.7 kHz over 6 months, but the drift is likely to be much less. The high dimensional stability compared with that of glass ceramics is related to the use of a high-quality single-crystal cavity and to the low temperature, which suppresses thermally activated relaxation effects. Finally, the birefringence of a cryogenic cavity was studied.

It is a pleasure to thank J. Mlynek for his constant support. We thank D. Reinelt for his assistance with the cryogenics. S. Schiller thanks J. Ye for helpful discussions. Financial support was provided by the Deutsche Forschungsgemeinschaft and the Optik-Zentrum Konstanz.

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