Visible Lasers with Subhertz Linewidths

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We report a visible laser with a subhertz linewidth for use in precision spectroscopy and as a local oscillator for an optical frequency standard. The laser derives its stability from a well-isolated, high-finesse, Fabry-Pérot cavity. For a 563 nm laser beam locked to our stable cavity, we measure a linewidth of 0.6 Hz for averaging times up to 32 s. The fractional frequency instability for the light locked to the cavity is typically 3×10^{-16} at 1 s. Both the linewidth and fractional frequency instability are approximately an order of magnitude less than previously published results for stabilized lasers. [S0031-9007(99)09100-0]

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Stable and spectrally narrow lasers are important for optical frequency standards and also for measurements of fundamental constants, high-resolution spectroscopy, and fundamental tests of physics [1,2]. It has already been demonstrated that the frequencies of several types of lasers can be locked to resonances of Fabry-Pérot cavities with precisions better than 0.1 Hz [3]. What remained to be demonstrated, however, was that the resonance frequency of a reference cavity could have a stability better than 1 Hz. Previously, the narrowest reported visible-laser linewidth was 10 Hz for a 1 s averaging time [4]. Here we report a linewidth of 0.6 Hz for averaging times up to 32 s. Previous results from our group (21 Hz linewidth for 70 s averaging times [5]) were limited by cavity length changes caused by vibrational noise. The improvement reported here derives from modifications that include cavities with more stable material properties and better isolation of the cavities from mechanical vibrations.

The central component of our stabilized laser is a high-finesse ($\mathcal{F} > 150\,000$) Fabry-Pérot cavity [5]. We use a dye laser at 563 nm as the optical source that is locked to this reference cavity. Rather than locking the laser directly to the high-finesse cavity, we first prestabilize it to a cavity with a finesse of $\approx$800 using a Pound-Drever-Hall frequency modulation (FM) lock [6]. An intracavity electro-optic modulator (EOM) in the dye laser provides high-frequency correction of laser frequency noise. A piezoelectric transducer (PZT) behind one of the dye-laser cavity mirrors eliminates long-term frequency drifts between the dye laser and the low-finesse cavity. A loop bandwidth of $\approx$2 MHz in this prestabilization stage narrows the dye-laser short-term ($\tau < 1$ s) linewidth to $\approx$1 kHz.

An optical fiber delivers light from the dye-laser table to a vibrationally isolated table that supports the high-finesse cavity. An acousto-optic modulator (AOM) mounted on the isolated table shifts the frequency of the incoming light to match a cavity resonance. Again, we implement the lock using the Pound-Drever-Hall technique. The feedback loop performs corrections at frequencies as high as $\approx$90 kHz by varying the AOM drive frequency and at low frequencies by adjusting a PZT on the prestabilization cavity.

The high-finesse cavity must have intrinsically low sensitivity to temperature variations and must be well protected from environmental perturbations. The spacer between the cavity mirrors is composed of a low-thermal-expansion material. While we have used both Zerodur and ULE spacers [7,8], the data reported here were collected using ULE spacers. Our spacer is cylindrical with a 15 cm outer diameter and a 24 cm length. The spacer is tapered at both ends to provide greater stiffness than that of a cylinder with the same length and mass. A 1 cm diameter core is drilled through the center of the cylinder. A second core is drilled from the side of the cylinder into the center to allow evacuation of the intracavity region. The cavity mirrors are made with ULE substrates and are optically contacted onto the ends of the spacer.

The cavity is supported inside an evacuated chamber by an aluminum v-block. Four cylindrical pieces of Viton embedded in the v-block serve as the contact points with the cavity. The Viton contacts help to provide high-frequency vibration isolation, damping for mechanical motion, and thermal isolation for the cavity (the thermal time constant between the cavity and the vacuum chamber is $\approx$14 h). Evacuating the chamber reduces shifts of the cavity resonance caused by index-of-refraction changes in the intracavity volume and thermally insulates the cavity from the environment. The temperature of the vacuum chamber is held at $\approx$30 °C, which is near the temperature at which the coefficient of thermal expansion for the cavity spacer is zero. The residual temperature fluctuations of the vacuum chamber are $\approx$10 mK.

We protect the cavity from vibrational noise by mounting the vacuum chamber on a passively isolated optical table. The table is suspended by vertical strands of surgical tubing stretched to $\approx$3 m. The fundamental stretch mode and the pendulum mode of the suspension both have frequencies of $\approx$0.3 Hz. This suspension system reduces the amplitude of the transmitted vibrational noise at frequencies greater than 3 Hz by more than a factor of 50. In many systems the cavity is isolated by using a pendulum suspension inside the vacuum chamber, but our table suspension is sufficiently good so that we can semirigidly mount the cavity inside the vacuum chamber. Dashpots filled with grease at each corner of the table provide viscous damping (damping time constant $\approx$1 s). Proximity detectors at three corners of the table serve as sensors for stabilizing the table position relative to the floor. A servo system drives heaters surrounding the surgical tubing so as to stabilize the table position with a time constant of $\approx$100 s. To prevent the coupling of acoustic noise into the cavity, we enclose the optical table in a wooden box lined internally with lead foam [9].

The intracavity light heats the mirror coatings, thereby shifting the cavity resonance by $\approx$1 Hz/μW. We minimize this shift by coupling only 100 μW to 200 μW of 563 nm light into the cavity and controlling the circulating optical power by monitoring the light transmitted through the cavity. Active control of the rf power driving the AOM (also used for frequency control) stabilizes the output power from the cavity to $\approx$0.1%.

To characterize the cavity's stability, we constructed a second cavity and vibrationally isolated table similar to that described above. The dye-laser output is split into two parts, each of which couples through an optical fiber onto one of the reference cavity tables. Since the prestabilized dye-laser light has a linewidth of $\approx$1 kHz and the rf lock to the reference cavity has a loop bandwidth of $\approx$50 kHz, very little correlation exists between the frequency fluctuations in the two beams at frequencies $\lesssim$10 kHz, which contribute dominantly to the linewidth. Consequently, it is appropriate to consider beams locked to the two cavities as independent sources when measuring noise at frequencies $\lesssim$10 kHz.

We expect negligible correlation between environmental perturbations of the two reference cavities. The masses of the two vibrationally isolated tables differ by a factor of 4, and the spring supports for one table are attached to the ceiling, while the spring supports for the other table are supported by posts resting on the laboratory floor. These differences cause the coupling of mechanical vibrations to differ for the two tables. Additionally, the separate vacuum chambers, temperature control systems, and acoustic-isolation boxes provide further decoupling between the two cavities. The largest common-mode variations probably arise from long-term drifts of the room temperature. Temperature-induced effects should occur dominantly at very low frequencies, so they should not degrade the short- and medium-term stabilities observed here. (Long-term drifts will be removed when the laser is locked to an atomic reference.)

Part of the beam locked to one of the cavities is split off and travels from one isolated platform to the other. There, it is heterodyned with part of the beam that is stabilized to the second cavity, providing a measure of the relative frequency deviations between the two optical beams. The beams locked to the two cavities differ in frequency by $\approx$400 MHz. Mixing the beat note with a precision rf source translates the beat-note frequency lower to facilitate high-resolution analysis. A fairly uniform drift of the beat-note frequency ($\lesssim$2 Hz/s), which may be caused by a slow temperature drift of one of the cavities, is removed by mixing the beat note against an rf source with a matching linear frequency chirp.

Residual relative motion between the two isolated optical tables makes Doppler-shift contributions to the beat-note frequency width. We measure these contributions using an auxiliary beam sent between the tables [5]. On one of the tables, a beam is split into two parts—one of which is given a precise frequency offset for use as a frequency reference. The second beam travels from one table to the other along a path very near ($\approx$1 cm) the beam path used for the intercavity beat note and then retroreflects back to the initial table. The heterodyne beat note between the auxiliary beam and the reference beam contains frequency fluctuations from relative table motion twice as large as the corresponding fluctuations on the intercavity beat signal. We digitally divide the frequency of this Doppler-shift beat signal by a factor of 2. The resulting signal can then be mixed with the intercavity beat signal to remove contributions to the noise from the relative table motion. Typically, relative table motion is not the dominant source of frequency noise, so we often omit this correction. A similar Doppler-cancellation technique will be critical for avoiding linewidth degradation while transporting light from the vibrationally isolated table to an atomic reference [5,10].

We have analyzed the beat signal between the beams locked to the two cavities using both frequency-domain and time-domain techniques. We use a fast Fourier transform (FFT) spectrum analyzer to measure the spectrum of the beat note, as shown in Fig. 1. The width of the spectrum at its half-power point is 0.9 Hz. Correcting for the 0.477 Hz resolution bandwidth of the spectrum analyzer, we infer that at least one of the beams has a frequency width less than 0.6 Hz at 563 nm for averaging times up to 32 s. This fractional linewidth of 1×10^{-15} is more than an order of magnitude smaller than previously published results.

An additional measurement in the frequency domain involves using a spectrum analyzer as a frequency discriminator [11]. The resolution bandwidth of the spectrum analyzer is set wide enough to include all noise frequencies of interest. The frequency span is zeroed, and the center frequency is set at the -3 dB point of the beat note. This arrangement converts frequency noise of the beat note into amplitude noise on the intermediate frequency output from the spectrum analyzer, which is then analyzed on an FFT spectrum analyzer. This technique directly reveals the noise power spectral density. Hence, it was a particularly useful diagnostic in the early stages of the work as we searched for the dominant contributions to the laser linewidth. Conversion of the noise power spectral density to a laser linewidth gives a result consistent with the more direct linewidth measurement.

For time-domain measurements, we mix the beat signal down to dc and record the phase evolution using a computer-based data acquisition system. Figure 2(a) shows a typical time record. The extreme values of the mixer output correspond to phase differences between the two beams of $\Delta\phi = 0$ rad and π rad. Typically, $\Delta\phi$ varies less than π rad for times on the order of 1 s, consistent with our subhertz linewidth measurement. Unfortunately, the relative phase differs sufficiently from the in-quadrature condition ($\Delta\phi = \pi/2$ rad) so that the conversion from beat-signal amplitude to $\Delta\phi$ is nonlinear and indeterminate at the extrema. We can, however, frequency divide the beat note by a factor of 20 and measure similar time records of $\Delta\phi/20$ [see Fig. 2(b)]. In this case, the in-quadrature condition is maintained for time durations long enough to facilitate easy determination of the phase noise for averaging times less than a few seconds. For time intervals ≥ 0.5 s, we perform time-domain measurements using an automated dual-mixer time-difference measurement system [12]. The fractional frequency instabilities, or Allan deviations $\sigma_y(\tau)$, determined using these two measurement techniques are plotted in Fig. 3, alongside the reported Allan deviations for a number of other stable laser systems. For the 30 ms to several second time scale relevant for our proposed optical standard [5], the Allan deviation of our laser is approximately an order of magnitude less than that of the other stable lasers.

We have made preliminary investigations of the sensitivity of the laser-beam frequencies to various environmental perturbations of the reference cavity or laser locking system. For example, we have examined the tilt and acceleration sensitivity of the cavities by using solenoids to apply sinusoidal driving forces to the vibrationally isolated optical tables. Tilting a cavity modifies the optical resonance frequencies because of distortions of the cavity caused by the redistribution or reorientation of the support forces. Accelerations modify the resonance frequencies because the support forces change to balance inertial forces, again distorting the cavity. For fixed drive amplitude, inertial forces vary with the square of the drive frequency. Cavity distortions due to accelerations dominate in our system at drive frequencies $\gtrsim 0.1$ Hz.

Driving one of the tables at a low frequency of 0.01 Hz tests predominantly the tilt sensitivity of the cavity resonance. For table tilts as large as 20 μrad, frequency shifts are less than 2 Hz. Consequently, driving the table with similar amplitude at a higher frequency of 1 Hz mainly probes the acceleration sensitivity of the cavity systems. At higher motional frequencies, we observe considerable broadening of the beat-note frequency width. Much of this broadening is caused by Doppler shifts from the component of the table motion along the direction of the beam traveling between the two tables. Generally, applying the Doppler-shift correction described earlier reduces the beat-note width by a factor of 5 to 10. Assuming the residual broadening is caused by inertial forces on the cavities gives an acceleration sensitivity of ≈ 100 kHz/(m/s^2). Theoretical estimates of the sensitivity of our cavity to accelerations suggest that the dominant shifts should be caused by vertical accelerations, which is consistent with

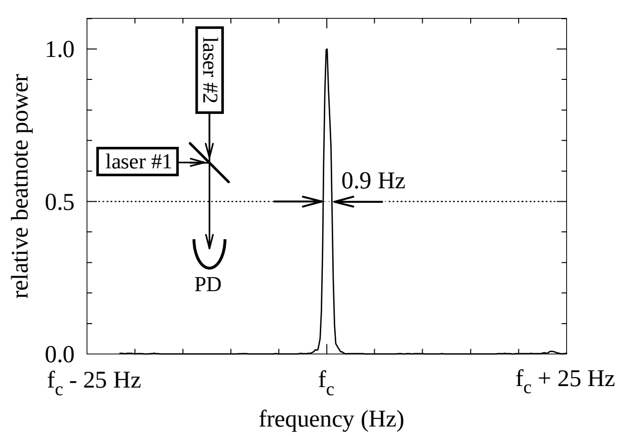

FIG. 1. Power spectrum of the beat note between two laser beams stabilized to two independent cavities. The averaging time is 32 s. The resolution bandwidth of the spectrum analyzer is 0.447 Hz. A nearly uniform relative cavity drift of 2.4 Hz/s is suppressed by mixing the beat note with a swept synthesizer. (PD) photodiode.

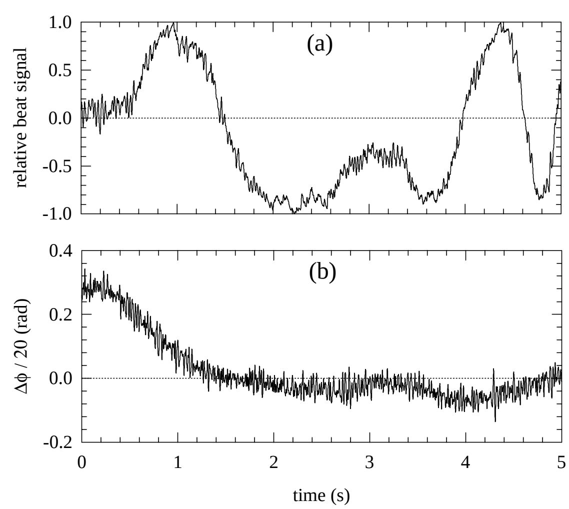

FIG. 2. Two time records of the beat signal between two stable 563 nm laser beams. The waveform sampling rate is 2 kHz. (a) The extrema of the mixer output of ± 1 correspond to relative phases $\Delta\phi = 0$ rad and π rad. For clarity, an 8 Hz, first-order, low-pass filter on the mixer output suppresses some high-frequency noise components. (b) Frequency division of the beat signal by 20 facilitates conversion from the mixer output amplitude to a phase for sample periods of many seconds, and allows calculation of the Allan deviation between 2 ms and 2 s. The signal bandwidth exceeds 50 kHz.

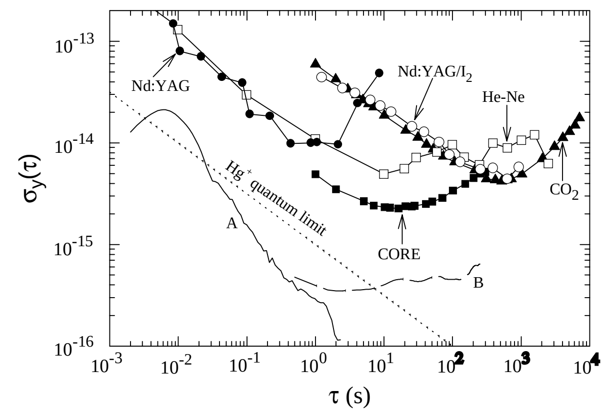

FIG. 3. Allan deviation curves for stabilized lasers. We calculate $\sigma_y(\tau)$ for one of our sources from an analog-to-digital sample of the beat signal (curve *A*) and using a dual-mixer measurement system (curve *B*). The dotted line shows the quantum noise limit for a Hg^+ optical frequency standard with one ion and a 30 ms Ramsey interrogation time [13]. Results for other stabilized lasers: (Nd:YAG) Nd:YAG lasers locked to Fabry-Pérot cavities [14]; (Nd:YAG/I_2) iodine-stabilized Nd:YAG lasers [15]; (He-Ne) methane-stabilized He-Ne lasers [16]; (CO_2) CO_2 lasers locked to OsO_4 [17] (see comparable results in Ref. [18]); (CORE) Nd:YAG lasers locked to cryogenic resonator oscillators [19].

our observations for various motional modes of the tables. The estimated sizes of the shifts agree within an order of magnitude with the experimental results.

Our laser is suitable for precision spectroscopy and for optical frequency standards. It has a linewidth of less than 0.6 Hz at 563 nm for averaging times up to 32 s. Future efforts will involve more detailed study of the sensitivity of the laser frequency to environmental perturbations such as temperature, acoustic noise, optical-power fluctuations, and laser-beam misalignment. The frequency instability of our laser is still approximately an order of magnitude higher than the linewidth limit set by the lock to the Fabry-Pérot cavity. Consequently, further improvement may be achieved. Although the results presented here are sufficiently good for the Hg^+ optical standard that we are assembling [5], lasers with lower linewidths could be beneficial for other standards based on longer-lifetime metastable states in atoms or ions. One possible route to more reliable laser operation is the development of an all-solid-state replacement for the dye laser [20]. Finally, we are assembling a cryogenic Hg^+ ion trap [21] for our proposed optical frequency standard. This system, coupled with a frequency chain to microwave frequencies, may eventually provide a time standard with an accuracy near 10^{-18}.

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