Simple and compact 1-Hz laser system via an improved mounting configuration of a reference cavity

Mark Notcutt, Long-Sheng Ma,* Jun Ye, and John L. Hall

JILA, National Institute of Standards and Technology and University of Colorado, Boulder, Colorado 80309-0440

Received January 24, 2005

We report an improved mounting configuration for a passive optical cavity used for laser frequency stabilization. The associated reduction of the vibration sensitivity of the effective cavity length has led to a simple and compact reference cavity system for laser stabilization at the level of 1 Hz linewidth. © 2005 Optical Society of America

OCIS codes: 120.3930, 140.3570.

Narrow linewidth lasers are necessary as local oscillators in optical frequency standards and serve as precision spectroscopic probes and frequency/phase-transfer flywheels.[1–3] A free-running laser is most often servo-locked to the resonance of a Fabry–Perot cavity: the remaining instability of the locked laser is a combination of the instability of the length of the frequency reference itself and the defects of the servo-locking system.[4] Environmental noise sources that modulate the cavity length are mainly of acoustic origin in the range above 50 Hz and seismic origin from 1 to 50 Hz. For Fourier frequencies less than 1 Hz, temperature changes affect the cavity length as well as other dimensions in the experiment that may inadvertently contribute to the instability.

Successful solutions to cavity length changes caused by acoustic and seismic noise have been based on low-pass filtering[1] and active vibration cancellation systems.[2,3] Here we show that designing for low acceleration sensitivity of the cavity length is a great help. For this purpose, shorter cavities are better since the fractional change of the length L is $\mathrm{d}L/L = 0.5\,\rho La/E$, where ρ is the density of the cavity spacer material, E is Young's modulus, and a is the perturbing acceleration. Of course as the cavity length continues to decrease, the free spectral range may become too large to be convenient. Power buildup may also be excessive because one needs to increase the cavity finesse to maintain a reasonable cavity resonance linewidth ($< \sim 25$ kHz). Mechanical thermal noise[5] has become an important consideration in Fabry–Perot cavity design. The contribution from the mirrors, which dominates, scales inversely with cavity length.

In this experiment, we refined an old idea[6] of arranging the cavity support points to be in the symmetry plane between the two mirrors on the cavity ends. For an acceleration along the cavity axis, each half of the cavity is deformed on either side of the central mounting plane. The decrease in length on one side of the mounting is mostly compensated for by an increase in length on the other. Analogous mounting schemes have been used in microwave cavity suspensions.[7] This design for a cavity support system is simple, robust, and offers reduced sensitivity to the cavity's length changes caused by acceleration. The vibration isolation requirements for a stated performance are significantly reduced, and few, if any, disadvantages are introduced.

We mounted the cavity vertically to realize as high a degree of symmetry as possible. In a vertical mounting, the gravity-induced sag of the structure is along the cavity axis, which has the advantage that the cavity spatial mode position does not change on the mirrors' surfaces with acceleration. In addition, support at the geometrical midplane was arranged with a simple, cylindrically symmetric geometry. The choice between a vertical or horizontal mounting of a cavity is complicated when considering the ambient acceleration environment, cross-coupling via Poisson's ratio, and the effects of gravity-induced sag. The configuration used here may not be optimum to minimize the acceleration sensitivity of the frequency reference. However, it did allow the mounting concept to be tested quickly as the symmetry that we exploited was clearly evident.

A low-expansion glass cavity with a spacer length of 50 mm and a diameter of 12.7 mm was mounted as shown in Fig. 1. The linewidth of the cavity resonance at 1064 nm was 65 kHz. A disk of low-expansion glass (52 mm diameter, 10 mm thickness) was prepared with an axial bore of 13.2 mm diameter ($\sim$0.5 mm larger than the cavity spacer diameter), and with three holes drilled (and counterbored) to

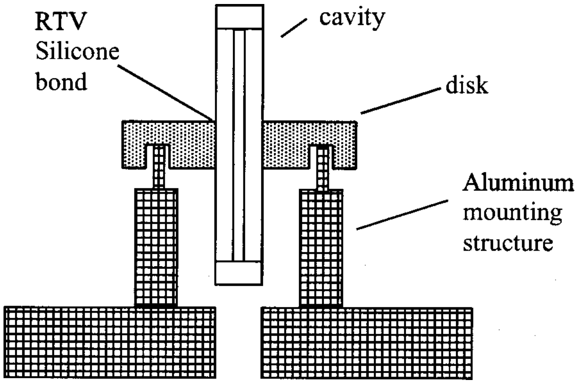

Fig. 1. Schematic of the cavity mounting in side-view cross section.

halfway through the disk thickness at a bolt circle radius of ~20 mm. Using silicone RTV, the disk was bonded to the cavity, so that the midplanes of the cavity and support disk were as closely aligned as possible, within ~0.5 mm. This RTV is not ideal as a vacuum material but has a low Young's modulus so that the cavity was gently supported and the asymmetries of stress in the disk due to the three-point support were reduced in transmission through to the cavity. For the first tests, the vertical cavity and its attached disk were supported from below in the counterbored holes by three posts from the base of the vacuum can housing. A thin layer of indium was added between the support post and the glass disk to deal with any high spots by broadening the contact area.

The cavity mounted in its (evacuated) vacuum can was then tested with acceleration from three piezoelectric actuators, one under each of the can's legs. We measured the acceleration of the assembly with an accelerometer on top of the can. An Nd:YAG laser was servo locked to this cavity[4] using the laser's piezoelectric frequency transducer (unity gain bandwidth 40 kHz), and an optical heterodyne beat signal was generated by comparison with a second laser stabilized to a second, isolated cavity. The actuators under the can's legs were driven with a frequency-swept sine signal, and a transfer function was generated between the signal from the accelerometer placed on the vacuum can and a frequency-to-voltage converted signal derived from the heterodyne beat. Small trial masses were then placed on the end of the cavity spacer to shift the center of mass, and the transfer functions were remeasured. In this way, the coefficient of frequency excursion per unit acceleration was reduced, as shown in Fig. 2. The asymmetry of the drive (cross coupled to tilt) limited useful reductions to about 10 kHz/ms^{-2}, reduced approximately 20-fold from the fully nonsymmetric case of mounting the cavity from one end.

The frequency of the laser stabilized to this cavity was then compared in a beat experiment with that of a second system, with added refinements such as the floating of the optical table on which the experiment was located, temperature control of the vacuum cans (drift < 1 mK/3 h), and Doppler noise cancellation for the fiber[8] that was used to transmit the light from one system to the other. The power incident on the cavity was approximately 150 μW (servo power control did not make a noticeable difference), giving our cavity-based frequency discriminator a shot-noise-limited spectral density of ~300 mHz/$\sqrt{\text{Hz}}$. For the Pound–Drever–Hall lock, phase modulation of the light was in this case applied by driving the piezoelectric frequency transducer on the laser at ~1 MHz.[9] This method may introduce a small amount of AM and synchronous beam steering and hence a locking point offset from the cavity resonance line center; however, the resultant discriminator signal had less 1/*f* noise in the Fourier frequency range below 10 Hz than that obtained from the electro-optic modulators that we tested from time to time.

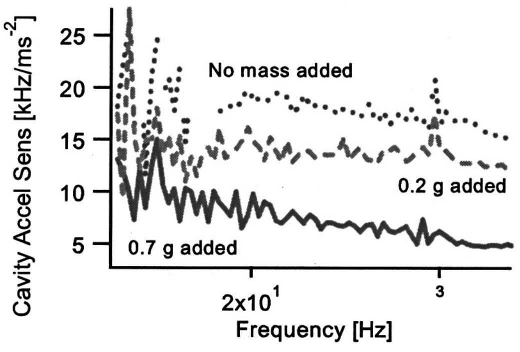

Fig. 2. Vibration transfer function: frequency excursion of the Fabry–Perot (read out with a laser locked to it) per unit acceleration.

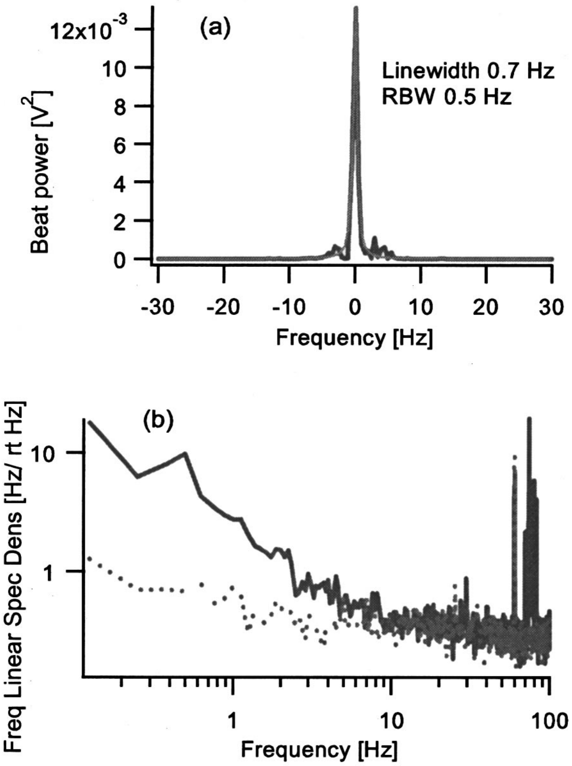

Fig. 3. (a) Heterodyne beat signal when two lasers are independently locked to two vertical cavities, each on a 0.5 Hz vibration isolation stage. 1-Hz linewidth is possible without an elaborate system design around the reference cavity. (b) Frequency noise spectrum (solid curve) of the optical beat derived using a frequency-to-voltage converter, and the noise floor in frequency units (dotted curve) of the poorer of the two systems by measuring the error signal when the laser is not resonant with its cavity.

For laser linewidth measurements, the radio-frequency (RF) beat signal was mixed down to 50 kHz and displayed as volts squared on a fast Fourier transform analyzer (FFT), giving a 3-Hz FWHM beat linewidth. The RF source for the mixing had a linear chirp of on average ~20 Hz/s to compensate for the cavity thermal drifts.

In the next step, two vertical cavities were placed on two separate, commercially available 0.5 Hz isolation platforms. One laser was coupled to its isolation stage through a fiber, while the second laser was located, with the cavity assembly, on the isolated platform. Stability of the error signal was improved with the addition of optical isolation and a detection photodiode of larger area, allowing observation of a steady optical beat of 1 Hz linewidth [see Fig. 3(a)].

Our primary diagnostic of the frequency noise presented in the beat signal is its analysis with a calibrated frequency-to-voltage converter. The average frequency of the beat is represented as a DC voltage (which can drift slowly without being disruptive), and fluctuations are extracted by AC coupling. The voltage signal was analyzed on a FFT giving a single-sided frequency noise spectral density, thus making it possible to examine the contributions to the line shape. The solid curve in Fig. 3(b) is from frequency–voltage data based on the beat of the two lasers and shows the combined noise of the two reference cavities and the two discriminators. The dotted curve is independently derived from the optical discriminator. The dotted curve is independently derived from the optical discriminator signal when the cavity is not locked and off resonance. Due to the low modulation index (~ 0.2), most of the power on the photodiode is due to the reflected optical carrier. With our cavity contrast of $\sim 50\%$, this implies a twofold light level increase (and 3 dB in discriminator noise level increase) compared with the locked case. The noise expected when comparing two similar laser sources is 3 dB above that of a single source, and is thus similar in magnitude to the dotted curve. For Fourier frequencies >30 Hz both spectra are close to shot noise limited. In the off-resonance case (dotted curve) the rise at lower frequencies is due to changes in the level of the unwanted amplitude modulation that accompanies the phase modulation.

The beat data show a limiting $1/f$ noise floor at frequencies less than 8 Hz. Based on the measured acceleration and acceleration sensitivity, this linewidth limit may be associated with remaining spectroscopy problems rather than vibration effects. Optical feedback,[10] a slowly fluctuating locking offset, insufficient low-frequency servo gain, and temperature fluctuations could contribute to this low-frequency noise. Recent studies suggest that thermal noise in the mirrors can also lead to a $1/f$ spectrum, although the predicted magnitudes are much smaller.[5]

In summary, we have dramatically reduced the acceleration sensitivity of the Fabry–Perot cavity to which our laser is locked by using a short cavity with a mounting close to the center of mass. This mounting symmetry gives a common-mode rejection of the elastic deformations of the cavity due to accelerations. With reduced sensitivity, the vibration isolation required to reach 1-Hz level laser linewidths is easily met in a simple and compact system. Future work will attempt to capture also as the long-term stability (30 mHz/s drift) obtained with another JILA system with a two-stage nested thermal shield system.

The authors acknowledge useful interactions with J. C. Bergquist, T. Rosenband, and L. Chen. We thank L. Hollberg for the use of his Minus K stage, T. Brown for the low-noise frequency-to-voltage converter, R. de Salvo for spring designs, and the JILA mechanical workshop. This work was supported by the Office of Naval Research, NASA, the National Science Foundation, and NIST. M. Notcutt's e-mail address is notcutt@jilau1.colorado.edu.

*Permanent address, East China Normal University, Shanghai, China. Present address, Bureau International des Poids et Mesures, Sevres, France.

References

1. B. C. Young, F. C. Cruz, W. M. Itano, and J. C. Bergquist, Phys. Rev. Lett. **82**, 3799 (1999).
2. S. A. Webster, M. Oxborrow, and P. Gill, Opt. Lett. **29**, 1497 (2004).
3. A. Y. Nevsky, M. Eichenseer, J. von Zanthier, and H. Walther, Opt. Commun. **210**, 91 (2002).
4. R. W. P. Drever, J. L. Hall, F. V. Kowalski, J. Hough, G. M. Ford, A. J. Munley, and H. Ward, Appl. Phys. B **31**, 97 (1983).
5. K. Numata, A. Kemery, and J. Camp, Phys. Rev. Lett. **93**, 250602 (2004).
6. M. Notcutt, C. T. Taylor, A. G. Mann, R. Gummer, and D. G. Blair, Cryogenics **36**, 13 (1996).
7. S. Buchman, M. Dong, W. Moeur, S. Wang, J. A. Lipa, and J. P. Turneaure, Adv. Space Res. **25**, 1251 (2000).
8. L.-S. Ma, P. Jungner, J. Ye, and J. L. Hall, Opt. Lett. **19**, 1777 (1994).
9. G. Cantatore, F. Della Valle, E. Milotti, P. Pace, E. Zavattini, E. Polacco, F. Perrone, C. Rizzo, G. Zavattini, and G. Ruoso, Rev. Sci. Instrum. **66**, 2785 (1995).
10. C. Salomon, D. Hils, and J. L. Hall, J. Opt. Soc. Am. B **5**, 1576 (1988).