Fast frequency stabilization of a cw dye laser

R. L. Barger and J. B. West

Time and Frequency Division, National Bureau of Standards, Boulder, Colorado 80302

T. C. English

Department of Physics and Astrophysics, University of Colorado, Boulder, Colorado 80302
and
National Bureau of Standards, Boulder, Colorado 80302

(Received 18 March 19 5)

A system is described ior stabilizing a cw dye laser frequency to a high-finesse optical cavity. The length of this optical cavity is locked to a CH_4-stabilized He-Ne laser with a tunable frequency-offset technique. A very fast servo system (using an intracavity KD*P crystal), a long dye laser cavity, and the stabilized optical cavity result in an absolute frequency stability of 1 kHz for an integration time of 10^{-4} sec and 300 Hz for 300 sec. Intensity is stabilized to one part in 10^4.

PACS numbers: 42.60.E

Tunable cw dye lasers have previously been stabilized by locking the laser frequency to a transmission fringe of a high-finesse optical cavity, [1] resulting in short-term frequency fluctuations of about 50 kHz and a drift of about 1½ MHz/min. Locking the frequency to a suitable molecular transition[2] removes this drift but restricts the frequency tuning capabilities. The technique which we report here gives a greatly improved short-term stability, essentially eliminates long-term drift, and retains the full tuning flexibility of the laser.

The laser frequency is locked to a high-finesse optical cavity in a way similar to that described in Ref. 1. Short-term improvement is obtained through use of a very fast servo control system having unity gain at 0.3 μsec. Very little noise is generated by the long-cavity dye laser in times shorter than this. Long-term drift is reduced by locking the length of the optical cavity used for dye laser servo control to the simultaneously transmitted fringe of a 3.39-μm He-Ne local oscillator.[3] The frequency of this local oscillator is made stable and tunable by frequency offset locking it from a methane-stabilized He-Ne laser. This long-term stabilization technique is extremely versatile in that the dye laser can be tuned to any frequency desired and then stabilized with a stability approaching that of the methane-stabilized laser. With this method, the dye laser short-term stability (up to 10^{-1} sec) is improved to 1 kHz, the medium-term (~1 sec) to ~3 kHz, and the long term (300 sec) to 300 Hz. This level of stability makes the dye laser suitable for spectroscopic studies with resolution greater than 10^{11}.

The laser is constructed using components common to many contemporary dye lasers: a good optical-quality ribbon dye jet with off-axis Ar^+ laser pumping, three-mirror (5 cm R, 10-cm R, flat output) astigmatically compensated cavity, quartz birefringent wavelength selector, and two piezoelectrically tuned air-spaced etalons of 1.5- and 15-mm lengths and 30% reflectivity coatings. The cavity is constructed of 2-m-long Invar rods to which all components are rigidly mounted. The output mirror, mounted on a large extension (12 μm/1000 V) piezoelectric (PZT) crystal assembly, is used for the slow servo control of the cavity length (below 1 kHz). Fast control (above 1 kHz) is accomplished with an intracavity deuterated DKP (KD*P) crystal with faces polished at Brewster angle. This crystal produces a phase correction of about 1 rad for an applied voltage of 1000 V. The piezoresonances of the crystal are damped to negligible magnitude by acoustic matching to NaCl crystals which are covered with a silicone rubber compound.

Running multimode with Rhodamine 6G dye and a 6% transmitting output mirror, the laser spectral width is about 0.1 Å and the efficiency is about 25% (2-W output for 8-W all-line power from the Ar^+ pump laser). With insertion of the two etalons, as much as 200 mW of single-mode output power is obtained, and insertion of the KD*P crystal causes a loss in single-mode power of less than 5%. By electrically ganging the PZT crystals of the output mirror and the etalons, continuous single-mode tuning is possible over a range of about 3 GHz, this range being limited by the finite extension of the output mirror PZT. The free-running stability of the laser is approximately 2 MHz.

The high-finesse optical cavity used as a frequency discriminator is constructed from a solid rod of quartz of 7.5-cm diameter and 18-cm length with a small bore for the light path. The cavity is optically isolated from the laser with a $\frac{1}{4}\lambda$ plate and linear polarizer. Cavity length control is obtained with a PZT stack on one end. The mirrors (31.7 cm R, flat) and PZT stack are mounted with epoxy to give an air-tight cavity. The cavity has a measured finesse of about 950 (with an efficiency of 30%) in the visible and 30 at 3.39 μm, giving fringe widths of about 0.8 and 30 MHz, respectively.

The error signal for servo control is the difference between the photodiode signals of the transmission fringe and a reference beam which bypasses the cavity. The zero for the error signal is located about halfway up the side of the fringe. This fast differencing technique together with the intensity stability achieved results in negligible conversion of intensity noise to frequency noise.

The servo electronics have a unity gain point at 500 kHz with a 9 dB/octave roll-off from dc to 50 kHz and 6 dB/octave from 50 to 500 kHz. The error signal is processed by a fast amplifier[4] which splits the signal into low-, intermediate-, and high-frequency components with crossovers at 1 and 150 kHz. The low component is amplified and applied to the PZT stack on the laser's output mirror. The intermediate component is amplified with a ±150 V op amp, and the high component with a high-speed ±15 V op amp. The faster components are applied to opposite electrodes of the KD*P crystal.

The laser intensity is stabilized using an amplifier similar to the fast one described above together with an ADP modulator having a half-wave voltage of about 250 V, which is placed at the exit of the dye laser. This intensity servo technique is similar to a slower one described elsewhere.[5] The intensity stability, analyzed with a separate diode and linear amplifier, has an Allan variance[6] σ equal to about 1×10^{-4} and is nearly constant for integration times τ between 10^{-4} and 10 sec.

To analyze the frequency stability an analyzing cavity was used which was nearly identical to the servo cavity. The difference between its fringe and reference signals was amplified with gain flat to 5 MHz. The amplified signal was fed to a voltage-to-frequency converter whose output went to a computing counter which computed σ.

The over-all wide-band frequency stability is indicated in Fig. 1. The upper trace is the fringe transmitted

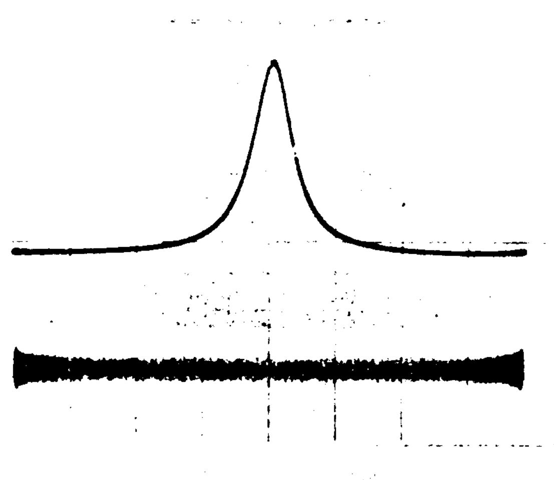

FIG. 1. Wide-band frequency stability bandwidth = 5 MHz, sweep time = 20 msec. Upper trace, transmission fringe of analyzing cavity, full width half-maximum = 0.8 MHz. Lower trace, servo loop error signal, vertical scale of equivalent frequency is 15 kHz per box.

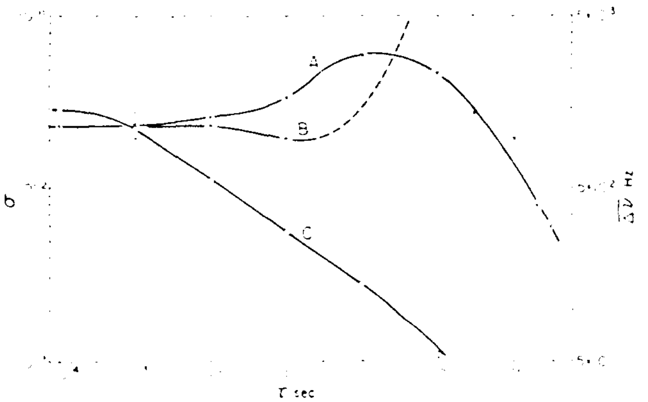

FIG. 2. Allan variance σ for stabilized dye laser. τ is the integration time. Curve A: both servo and analyzing cavities stabilized to CH_4-stabilized laser through a 3.39-μm local oscillator. Curve B: both cavities free running, dashed portion is estimated σ for $\tau > 10^{-1}$ sec. Curve C: servo loop error signal.

by the scanning analyzing cavity with the laser frequency stabilized to the servo cavity. The fringe width is 0.8 MHz and the sweep time is 20 msec. It is evident that with this resolution the frequency noise, which would appear only on the side of the fringe, is indistinguishable from the high-frequency amplifier noise. The lower trace is the servo loop error signal, discussed below, with a vertical frequency fluctuation scale of 15 kHz per large division.

Detailed frequency stability results are shown in the Allan variance plot of Fig. 2 for integration times of 10^{-4}–300 sec. The σ of all three curves at $\tau = 10^{-4}$ sec is approximately equal to the σ_{eq} corresponding to amplifier input noise, which decreases with increasing τ with a slope of $-\frac{1}{2}$ and flickers out at $\tau = 10^{-1}$ sec with $\sigma_{eq} = 7 \times 10^{-14}$. This equivalent frequency noise has not been subtracted from the frequency stabilities shown in Fig. 2. Data shown in curve A were taken with both the servo and analyzing cavities stabilized to the frequency-offset-locked 3.39-μm local oscillator. Curve B shows corresponding data taken for $\tau < 0.1$ sec without this cavity stabilization. The dashed portion of this curve for $\tau > 0.1$ sec shows the estimated deterioration of stability due to cavity temperature drifts and strain instabilities in the cavity PZT crystals, which can easily give a frequency drift of 100 kHz in 10 sec. This long-term drift has been the main disadvantage of the technique of frequency stabilization to an optical cavity, but it is essentially eliminated by stabilizing the cavity to the CH_4-stabilized laser. This is demonstrated by the long-term portion of curve A where the stability is 300 Hz ($\sigma = 6 \times 10^{-13}$) for $\tau = 300$ sec.

For longer times, the stability should continue to improve until that of the methane-stabilized laser, about 1×10^{-13}, is reached. The hump in curve A, with a maximum $\sigma = 3$ kHz at $\tau = 1$ sec, is caused by noise of the 3.39-μm fringe amplifiers being mapped into cavity instability, and hence into dye laser frequency instability. Better 3.39-μm frequency discrimination would remove this hump and result in better stability for $\tau > 10^{-2}$ sec.

Curve C shows the equivalent frequency noise of the servo loop error signal, i.e., the amplified wide-band servo signal before the 9 dB/octave filtering. This curve represents the best stability which could be achieved with this servo system; the divergence of curves A and B from this is brought about by conversion into frequency noise of optical system and cavity vibrations, optical feedback, and the finite gain of the 3.39-μm cavity servo system in the region of 10^{-3}–10 sec.

With the dye laser stabilized, the frequency can be scanned over a range of about 2.5 GHz by using the $\pm$ 220 MHz tuning capabilities of the 3.39-μm frequency offset lock. A system is now being constructed to allow simultaneous pressure tuning of the dye laser and servo cavities; this should allow scanning of the stabilized frequency over a range of about 2 Å.

The authors are pleased to acknowledge the expert advice of Dr. J.L. Hall on design of electronics, and that of Dr. D.A. Jennings on dye lasers.

[1]R.L. Barger, M.S. Sorem, and J.L. Hall, Appl. Phys. Lett. 22, 573 (1973).
[2]F.Y. Wu, R.E. Grove, and S. Ezekiel, Appl. Phys. Lett. 25, 73 (1974).
[3]This technique of cavity length control is described in R.L. Barger and J.L. Hall, Appl. Phys. Lett. 22, 196 (1973).
[4]This amplifier is similar to one designed by J.L. Hall for use in an intensity servo system; we understand that a publication on this subject is being prepared.
[5]W. Hartig and H. Walther, Appl. Phys. 1, 171 (1973).
[6]Analysis of frequency stability in terms of the Allan variance is described in D.W. Allan, Proc. IEEE 54, 221 (1966).