A computer-based digital feedback control of frequency drift of multiple lasers

W. Z. Zhao, J. E. Simsarian, L. A. Orozco, and G. D. Sprouse[a)]
Department of Physics and Astronomy, State University of New York, Stony Brook, New York 11794-3800

(Received 12 June 1998; accepted for publication 17 August 1998)

We report a method to monitor and control laser frequencies with an optical cavity and a digital feedback system. A frequency-stabilized He–Ne laser provides the reference that is transferred to several other lasers using a scanning Fabry–Pérot cavity. A personal computer-based multifunction data acquisition system generates the scan wave form, and reads the detector outputs synchronously with the cavity scan. The computer determines the positions of all of the peaks in the scan, and generates output signals to control the laser frequencies. It also provides a visual display of cavity spectra. We have successfully used the setup to achieve a long-term lock of the lasers for magneto-optical trapping of radioactive francium atoms. © *1998 American Institute of Physics.* [S0034-6748(98)03211-0]

I. INTRODUCTION

The long-term (hours to days) stabilization of laser frequencies to a fixed reference is necessary for many applications.[1] While short-term stability (seconds) and linewidth control requires large feedback bandwidth (sometimes into the MHz),[2] long-term stability needs gain at very low frequencies extending to dc.

There are optical and electronic methods to narrow a linewidth that are widely and effectively used, but the implementation of long-term frequency stability is often left to the user by sending analog signals to the frequency control of commercial lasers. A common solution is to use another analog feedback loop to lock the laser either to a sharp atomic or molecular transition,[3,4] or to a cavity fringe of a stabilized Fabry–Pérot interferometer.[5,6]

In this article we present our implementation of long-term stability for multiple lasers. We effectively transfer the long-term stability of a master laser to the others using a Fabry–Pérot resonator, and obtain infinite dc gain in the feedback loop by using digital electronics. A personal computer-based multifunction data acquisition system scans the cavity and synchronously reads the cavity spectra of multiple lasers. By comparing peak positions relative to a stabilized helium–neon laser, the computer generates the error signal and controls the long-term drift of the lasers. Digital control allows a much wider range of correction, and is not subject to the intrinsic drift of analog circuits. These advantages are important for long-term feedback control.

Previously, a scanning Fabry–Pérot interferometer and a stabilized He–Ne laser were used to increase the stability of single-frequency lasers.[7,8] These systems were designed for stabilization of only one laser, and extension to more lasers would require duplication of much of the hardware. Our computer-based system is easily extended to multiple lasers. In addition, the user interface is much like that of an optical spectrum analyzer that allows the operator to monitor the mode structure and stability of the lasers in real time.

II. APPARATUS

Figure 1 shows a schematic diagram of our laser frequency control system. There are four parts: the optical cavity, the stabilized laser system, synchronized scanning of the piezo-electric transducer (PZT) combined with data acquisition, and digital feedback control.

A. The optical cavity

We use a 300 MHz confocal Fabry–Pérot etalon. The mirrors (CVI Laser Corporation) have broadband coatings, with the reflectivity $0.990<R<0.995$ at 632, 718, and 817 nm. A PZT modulates the cavity length. The mirrors are held by a bored INVAR rod, which has a low thermal expansion coefficient. To further stabilize the cavity, we put it inside a copper tube. Two feedback systems[9] control the temperatures of the INVAR and the copper tube independently. An evacuated vacuum system houses the cavity and the copper tube that fit into a 1.5 in. outer diameter (o.d.) stainless steel tube with 2.75 in. commercial copper gasket-sealed antireflection coated view ports on both ends. The resulting thermal drift of the cavity is bounded by 160 MHz in 48 h.

B. Laser system

A stabilized He–Ne laser, Melles Griot (05 STP 901), is the absolute frequency reference. The typical frequency drift is ± 0.8 MHz in 1 h, and ± 1.2 MHz in 8 h. We measured the frequency drift to be ± 1.0 MHz in 1 h by comparing the He–Ne fringes with that of a stabilized laser locked to the Rb D_2 atomic transition (780 nm) using saturation spectroscopy. Two Coherent 899-21 Ti:sapphire ring lasers and an EOSI 2010 diode laser are referenced to the stabilized He–Ne laser. We can externally control their frequencies with dc volt-

[a)]Electronic mail: Gene.Sprouse@sunysb.edu

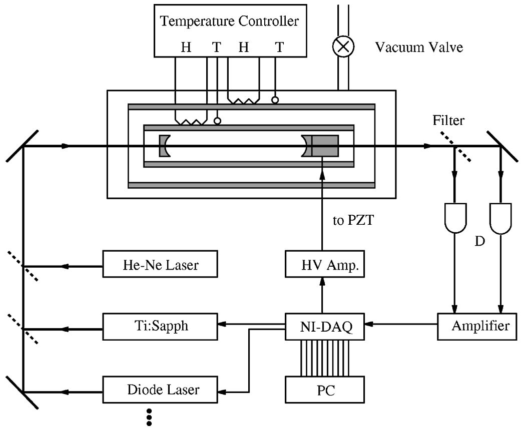

FIG. 1. The schematic diagram of the apparatus.

ages. We send all of the lasers into the cavity simultaneously using beam splitters, and use interference filters to separate the different laser beams at the output of the cavity for detection. In Fig. 1, one of the detectors receives cavity outputs of two lasers.

C. Synchronized PZT scanning and data acquisition

We scan the length of the cavity d with the PZT and obtain the spectra of cavity fringes. The confocal cavity operates in the ''figure eight'' configuration with a free spectral range of $c/4d$ for transmission, where c is the speed of light. Because of the transverse mode degeneracy, mode matching of different wavelengths is possible. Faster collection of the spectral information allows more frequent correction of the laser frequencies with a feedback loop. We used an AT-MIO/AI E series data acquisition board from National Instruments to make the cavity scan and data acquisition as fast as possible. We programmed synchronized wave form generation and data acquisition at a ramping rate of a few hundred Hz with Lab Windows CVI software. A computer monitor continuously displays the spectra. Figure 2 shows cavity fringes of the reference He–Ne and an 817 nm diode laser from two detectors.

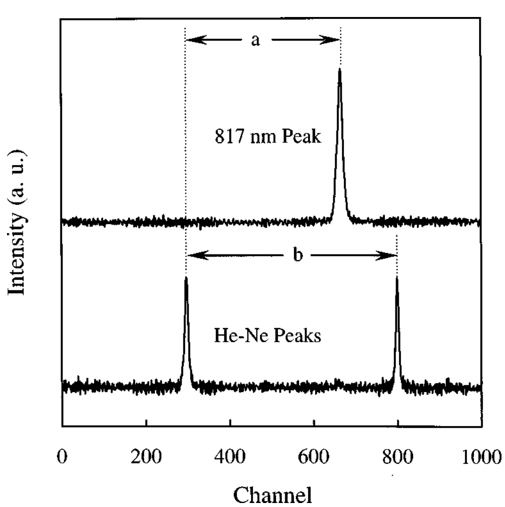

FIG. 2. Typical cavity spectrum obtained for the He–Ne laser and an 817 nm diode laser. The two spectra come from two detectors with the help of an interference filter. The PZT drive voltage is proportional to the channel.

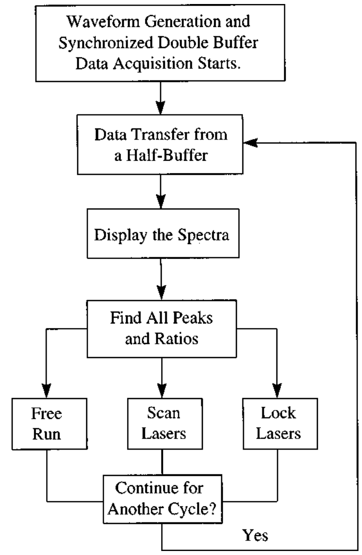

FIG. 3. The block diagram of the program, which controls the cavity scan, data acquisition and lasers.

D. Feedback control

After each scan, the computer calculates the fringe positions of the He–Ne and the other lasers. The program compares them to the He–Ne peak positions. It then corrects the drifts in laser frequency by adjusting the voltages that are sent to the controlled lasers.

Since the cavity always has some small thermal drift, the PZT voltage that produces the same position of the reference laser fringes changes. Also, the voltage interval for one free spectral range will not be constant because of the nonlinearity of the PZT. We found that these variations make it insufficient to use a constant peak separation as a criterion to lock the controlled laser frequencies. We did obtain good performance by maintaining a constant ratio a/b shown in Fig. 2, where a is the distance from a controlled laser peak to a He–Ne peak and b is the distance between two He–Ne peaks. In such a way, we have achieved long-term laser frequency stability.

III. PERFORMANCE

Figure 3 shows a block diagram of the software that controls the cavity, acquires the detector signals, and generates the output voltages for the controlled lasers. The scanning wave form is an increasing and decreasing voltage ramp that is output to the PZT through a scanning interferometer driver (Spectra-Physics model 476). A double buffer (or circulating buffer) data acquisition continuously reads analog-to-digital converters (ADCs) associated with the detector signals synchronized with the scan of the cavity. The wave form generation and data acquisition run in the background, parallel with the other parts of the program for data analysis, spectrum display, and feedback control of the lasers. Our typical sampling rate is 400 000 data points per second. Each ramp cycle consists of equally distributed 2000 data points, corresponding to a ramping rate of 200 Hz. On each cycle, the computer fetches only the cavity spectra associated with the increasing voltage scan from the double buffer. The center of gravity of each spectral peak is calculated. The peak positions fluctuate from scan to scan, even for the stabilized He–Ne laser. We smooth out fluctuations by making a weighted average between the new peak position and the previous one. With a weight of 0.3 to the new position, we can determine the He–Ne reference peak positions to better than 0.5 MHz. Because the spectrum display takes about 50 ms on our PC (Pentium 166 MHz CPU), we only display the spectrum typically every 200 cycles. In our implementation, the feedback control rate is about 110 Hz, due to the time delay on data transfer, data analysis, as well as spectrum display. A faster computer could definitely increase this rate further.

There are three operating modes for every laser being controlled: free running, scanning, and locking. In free run, there is no adjustment of laser frequencies. This mode permits a visual inspection of laser frequencies and modes, while we adjust the laser frequencies manually. In the scanning mode, the computer ramps the laser frequency by increasing or decreasing the digital-to-analog converter (DAC) voltage that controls it. The program controls the speed of the scan. We can monitor the scan from the movement of the cavity fringes, or variation of the ratio a/b as in Fig. 2. This mode can be used to calibrate the laser scanning range. In the locking mode, the computer compares the cavity fringe positions with a set point, and either increases or decreases the DAC associated with the laser according to the error. We optimize the DAC step size for effective locking. While a laser is locked, varying the set point ratio a/b adjusts the laser frequency. We usually scan the laser until a resonance signal appears, then lock the laser, and maximize the signal by changing the set point.

The small thermal drift of the cavity requires adjustment of the PZT drive voltage to have the system referenced to the same He–Ne fringes. The program automatically modifies the voltage ramps to the PZT when the He–Ne peak drifts more than ± 10 channels. This involves stopping the current double buffer data acquisition, loading the new wave form, and restarting the data acquisition. We found by experimentation that it is important to have a continuous wave form scan to the PZT, since the transient effects from stopping and starting the scan distort the spectra and require some time to settle. Whenever a double buffer data acquisition initiates, we delay for 50 ms before fetching new data from the circulating buffer. With our stable optical cavity, the computer only adjusts the wave form every few minutes.

We have successfully locked two Coherent 899-21 Ti:sapphire lasers, and an EOSI 2010 diode laser. The Ti:sapphire laser typically drifts about 50 MHz/h. The EOSI laser has a typical drift of 25 MHz/min and a frequency jitter of about a few MHz in a second. We can lock the frequencies of both lasers relative to the reference laser to within ± 1 MHz with our locking scheme. Our system is not fast enough at present to remove the acoustic noise that is present in the EOSI diode laser. An analog lock to another stable cavity could remove this noise, with the computer controlled feedback system correcting for long-term drifts.

We use the digital optical spectrum analyzer to control the lasers for the trapping and spectroscopy of Fr.[10] A Burleigh wave meter reads all laser frequencies to within ± 0.002 cm^{-1}. The different lasers are adjusted to maximize the trap signal, and then they are locked. We can hold the trap for hours with the above locking scheme. In our experiment, the system controlled and locked three different lasers (an EOSI diode laser at 817 nm, and two Ti:sapphire lasers, one at 817 nm and another at 718 nm) at the same time. It should be possible to control and lock more lasers by separating the cavity output accordingly.

Another feature of the system is that we can keep track of the same He–Ne peak for days by controlling the offset voltage of the PZT. It can allow us to set the laser frequency quickly to where it should be, even after the laser is shut down and back on again. We can re-lock the laser to the resonant frequency with the known ratio of the cavity fringes combined with the wave meter reading.

IV. DISCUSSION

We have developed an optical spectrum analyzer for digital feedback control of laser frequencies. The visual display of the frequency information of many lasers gives the operator excellent monitoring and control of the lasers. We have successfully applied the system to simultaneously lock three lasers to within ± 1.2 MHz for many hours for the laser trapping and spectroscopy of radioactive francium. The maximum rate of error correction in systems with a scanning Fabry–Pérot cavity is limited by the scanning rate of the cavity. In our system, this was about 110 Hz, while in Ref. 7, it was 50 Hz. In Ref. 8, a special driving circuit allowed scanning up to 461 Hz. Our motivation was to provide long-term stability for multiple lasers with a reasonable error correction rate. If faster error correction were required, the data acquisition card could sample two channels at up to 300 Hz scanning rate, but a faster PC would be required to analyze the stream of data and make the corrections.

The system should be useful for applications where it is required to keep laser frequencies close to resonance transitions when frequency references are not available. The system also provides a continuous monitor of the laser performance, such as the frequency stability and the longitudinal mode of the lasers.

ACKNOWLEDGMENTS

The authors would like to thank Yusuf Kinkhabwala for his early involvement in the programming of the data acquisition and analysis. The work is supported by NSF and NIST.

[1] See for example, *Proceedings of 5th Symposium on Frequency Standards and Metrology*, edited by J. C. Bergquist (World Scientific, Singapore, 1996).
[2] See for example, M. Zhu and J. L. Hall, J. Opt. Soc. Am. B **10**, 802 (1993).
[3] J. L. Hall, L. Hollberg, T. Baer, and H. G. Robinson, Appl. Phys. Lett. **39**, 680 (1981).
[4] C. J. Sansonetti, J. Opt. Soc. Am. B **14**, 1913 (1997).
[5] Ch. Salomon, D. Hils, and J. L. Hall, J. Opt. Soc. Am. B **5**, 1576 (1988).
[6] R. W. P. Drever, J. L. Hall, F. V. Kowalski, J. Hough, G. M. Ford, A. J. Munley, and H. Ward, Appl. Phys. B: Photophys. Laser Chem. **31**, 97 (1983).

[7] B. G. Lindsay, K. A. Smith, and F. B. Dunning, Rev. Sci. Instrum. **62**, 1656 (1991).
[8] S. M. Jaffe, M. Rochon, and W. M. Yen, Rev. Sci. Instrum. **64**, 2475 (1993).
[9] The RHM-4000 resistive heater controllers from Wavelength Electronics are used for the temperature stabilization.
[10] J. E. Simsarian, W. Z. Zhao, L. A. Orozco, and G. D. Sprouse, Phys. Rev. A (accepted).