

Simple System for Active Frequency Stabilization of a Diode Laser in an External Cavity

P. A. Borisov¹, P. N. Melentiev², S. N. Rudnev, V. I. Balykin

Institute of Spectroscopy, Russian Academy of Sciences, Troitsk, Moscow oblast, 142190 Russia

e-mail: ¹ elfe@mail15.com, ² melentiev@isan.troitsk.ru

Received March 25, 2005

Abstract—A cheap and easy-to-produce system for the radiation frequency stabilization of a diode laser in an external cavity is developed, realized, and studied. The short-term stability of the laser frequency is 1.5 MHz, whereas the long-term drift is no greater than 1 MHz/h.

INTRODUCTION

Laser systems based on diode lasers are widely used in scientific study and applied problems. The radiation of diode lasers is successfully employed in atomic and molecular spectroscopy, metrology, interferometry, frequency standards, atomic optics, etc. The wide spread of such coherent sources is related to their compactness, low power consumption, and reasonable price. The characteristics of the existing commercial laser systems with an external cavity in Littrow configuration are as follows: laser line width, a few megahertz; continuous tuning range, about 10 GHz; and output power, up to 20 mW. In a few problems, an improvement in the radiation characteristics of commercial laser systems is required. One such characteristic is the long-term stability of the laser frequency. In particular, long-term stability is needed in experiments on atomic optics, where a long-term cyclic interaction of atoms with laser radiation should be realized [1]. The allowed deviation of the radiation frequency over several hours should lie within the natural width of the atomic transition (a few megahertz). Long-term stability of the laser frequency is achieved using various methods of active stabilization [2–7].

A system for the active stabilization of the laser frequency consists of optical and electronic parts. In the optical part, the laser radiation frequency is compared to the reference (predetermined) frequency. The electronic part of the stabilization system generates an error signal that is fed to the laser-frequency control unit. The frequency correction is achieved with a rotation of the diffraction grating in the laser cavity or a variation in the injection current of the laser. If the error signal is compensated for using the diffraction error in the laser cavity, the short-term frequency stability is limited by the cavity response and the presence of its mechanical resonances. Therefore, the laser frequency stability increases when the error signal is also fed to the unit controlling the laser injection current [7].

Two known methods for frequency stabilization employ resonance peak [2–5] and resonance slope [6, 7].

In this work, we develop and study a system for the active frequency stabilization of a laser system with an external cavity in the Littrow configuration [3]. The optical part of the stabilization system is based on the nonlinear absorption resonances in a cell with rubidium vapor obtained by polarization spectroscopy methods. The electronic part stabilizes the slopes of the nonlinear absorption resonances. It is based on simple circuits that can easily be reproduced in laboratories. To compensate for the error signal, we use an intracavity diffraction grating.

The measured short-term stability of the radiation frequency is 1.5 MHz, and the long-term drift is less than 1 MHz/h. These values are better than those of other stabilization systems of this type. The high characteristics of the frequency stability are due to the compactness of the cavity of the laser system [9]. Small sizes make it possible to diminish the frequencies of the mechanical resonances, and a fast response allows the frequency to be controlled using only the diffraction grating.

EXPERIMENTAL SETUP

The active stabilization of the laser frequency employs the slopes of the nonlinear absorption resonances obtained with polarization spectroscopy. The application of these methods enables us to enhance the contrast of the nonlinear absorption resonances with the circular dichroism induced by a strong laser beam [8]. Figure 1 demonstrates the optical part of the system for frequency stabilization. The laser radiation is split into a strong laser beam and a probe laser beam. The strong beam is transmitted by a quarter-wave plate, acquires a circular polarization, and passes through a cell with atomic vapor. The probe beam enters the cell from the opposite side and is spatially matched with the strong beam inside the cell. Then, the probe beam

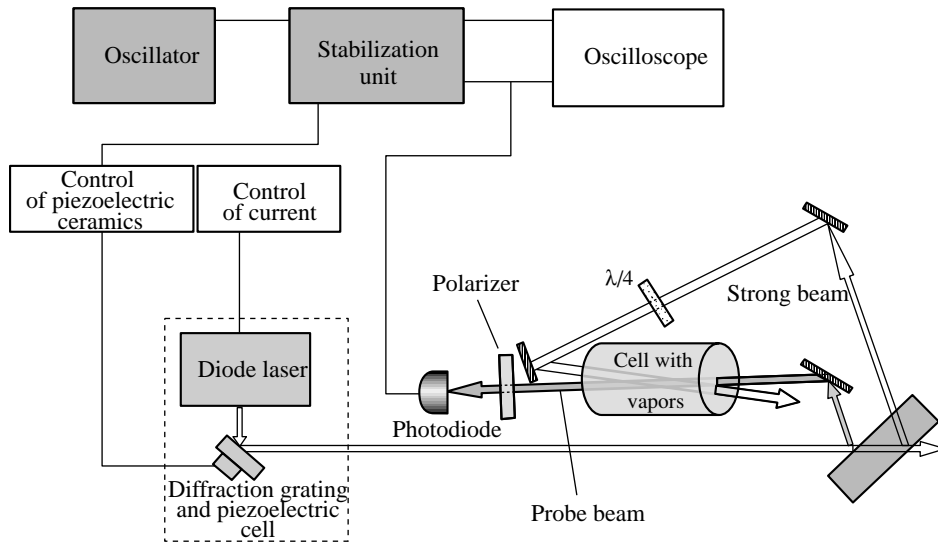


Fig. 1. Optical part of the system for the active frequency stabilization of a diode laser.

passes through the polarizer and strikes the photodiode, whose signal is fed to the electrical part of the system for frequency stabilization.

The power of the strong laser beam should be sufficiently high for the saturation of the absorption at the atomic transition chosen for the stabilization. In the scheme proposed, the power should be less than 0.1 mW. The power of the probe beam should be a few times less than the power of the strong beam.

Figure 2a shows the typical nonlinear absorption resonances for the transition $5S_{1/2}, F = 3 \rightarrow 5P_{3/2}, F'$ of ^{85}Rb atoms. These curves are obtained using the scheme shown in Fig. 1 in the absence of the quarter-wave plate and the polarizer. Figures 2b–2e demonstrate the same nonlinear resonances measured with the above polarization spectroscopy technique (in the presence of the quarter-wave plate and the polarizer). In all of the plots, we clearly see the nonlinear resonance at the frequency of the transition $F = 3 \rightarrow F' = 4$ (PL[3, 4]) of ^{85}Rb atoms and the cross resonances CO[3, 4, 3] and CO[3, 4, 2]. It follows from the comparison of Fig. 2a with Figs. 2b–2e that the polarization spectroscopy makes it possible to substantially increase the contrast of PL[3, 4] resonances.

The system for frequency stabilization is studied in a commercial system based on a diode laser with an external cavity in the Littrow configuration with a radiation wavelength of 780 nm, a power of 10 mW, and a continuous frequency tuning range of 15 GHz [9]. To diminish the effect of external factors on the laser frequency, we place the laser at a thermally stabilized (with an accuracy of 1°C) massive metal platform mounted on an optical plate with a rubber pad. The laser cavity and the metal platform are acoustically and

thermally isolated with a housing made of foam plastic with a thickness of 2 cm.

The optical part of the stabilization system (Fig. 1) consists of a cell containing vapor of a natural mixture of rubidium isotopes, a quarter-wave plate to imbue circular polarization (elliptical polarization with an axial ratio of $I_{\max}/I_{\min} = 1 : 0.85$), a film polarizer with a depolarization ratio of 1%, a photodiode, and aluminum mirrors.

Figure 3 shows the electrical circuit for frequency stabilization. It consists of the power supply (1), preamplifier of the photodiode signal (2), reference-voltage supply (3), proportional-integral amplifier (4), and output amplifier (5) summing the feedback signal and the saw-tooth signal of the modulation unit (oscillator). All amplifiers are implemented on one TL074 microchip (quadruple operational amplifier). To achieve the needed frequency stability, the reference voltage is generated with a source containing a precision temperature-compensated D818 stabiltron. To eliminate the power supply's noise in the microchip of the amplifier, we place it in a metal housing.

EXPERIMENTAL RESULTS

To measure the frequency drift of the stabilized laser with time, we use the PL[3, 4] nonlinear resonance in Rb vapor. The laser frequency is tuned to the center of the slope of the nonlinear resonance. In this case, the variation in the absorption signal in Rb vapor depends linearly on the variation in the laser frequency and indicates a variation in the laser frequency. The method proposed for frequency-stability measurements is convenient for laboratory study, since it does not require additional devices to control the radiation spectrum.

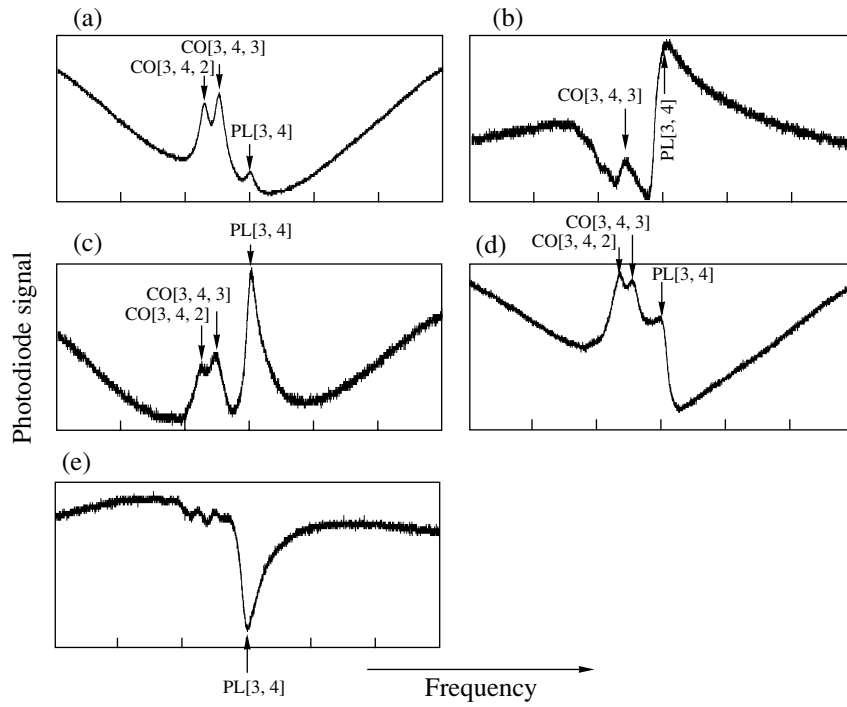


Fig. 2. Nonlinear absorption resonances for $5S_{1/2} \rightarrow 5P_{3/2}$ transitions of ^{85}Rb atoms measured with (a) nonlinear sub-Doppler spectroscopy and (b)–(e) polarization sub-Doppler spectroscopy. Panels (b) and (d) and panels (c) and (e) correspond to different signs of the circular polarization of the strong laser beam.

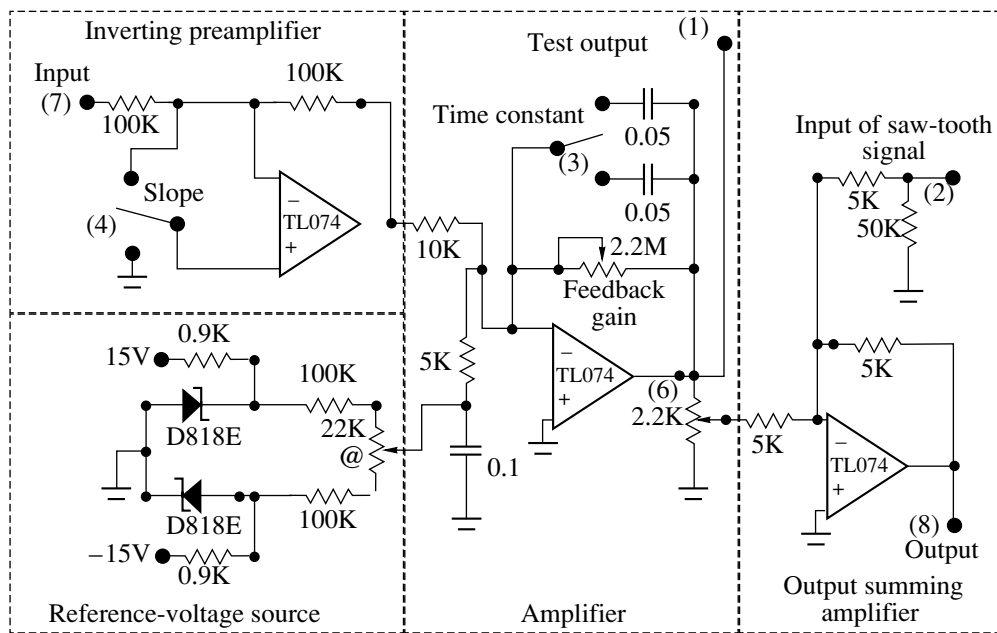


Fig. 3. Electrical part of the system for the active frequency stabilization of a laser: (1) output for monitoring the electrical error signal of the stabilization system, (2) input for the saw-tooth signal of the oscillator that controls the laser-frequency scanning, (3) switch of the time constant of the PI amplifier, (4) switch for choosing the slope of resonance, (5) potentiometer for choosing the frequency-stabilization point on the resonance slope, (6) potentiometer of the feedback level, (7) input for the photodiode signal, and (8) control output of the stabilization system.

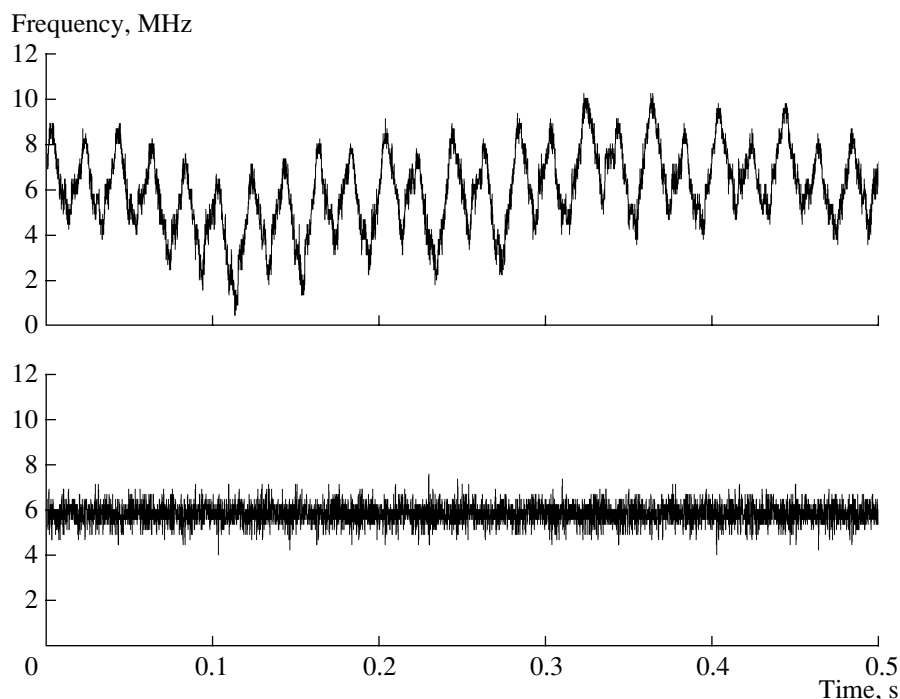


Fig. 4. Plot of the laser frequency vs. time. Illustration of the short-term stability of the laser frequency (upper panel) in the presence and (lower panel) in the absence of the active stabilization of the laser frequency.

The intensity of the strong laser beam affects the width of the nonlinear resonances. An increase in the width of the nonlinear resonances leads to a broadening of the range of the laser-frequency locking but also results in a decrease in the feedback gain. The results of the measurements show that the optimal width of the nonlinear resonances is 20 MHz.

Figure 4 shows the experimental results for the short-term stability of the laser frequency. In the absence of active stabilization (upper panel in Fig. 4), the high-frequency noise in the laser frequency has an amplitude of 10 MHz and exhibits a periodic character with a frequency of 50 Hz. In the presence of the active stabilization (lower panel in Fig. 4), the periodic oscillations of the frequency vanish and the noise amplitude decreases to 1.5 MHz.

The results obtained for various laser systems available in the laboratory show that the noise in the frequency can be decreased to a level lower than 3 MHz provided that a part of the feedback error signal is fed to the laser injection current. We do not employ this approach. Nevertheless, the obtained short-term stability appears two times better. In our opinion, the above characteristics of the frequency stability in the laser system under study result from the smallness of the linear sizes of the cavity. This cavity exhibits faster response than the cavities of the conventional laser systems.

Figure 5 illustrates the measurements of the long-term laser-frequency stability and shows the drift of the

laser frequency with time in the presence and in the absence of the active system for frequency stabilization. It is seen that, in the presence of the system for frequency stabilization, the mean laser frequency varies by 5 MHz during an observation time of 19 h (Fig. 5a). In the absence of active frequency stabilization, the laser frequency drifts away from the contour of the nonlinear resonance in 4 min (Fig. 5b).

The dependence presented in Fig. 5a is measured in the presence of various perturbations acting upon the laser system during measurements. To study the effect of temperature, we blow hot air onto the laser system over a relatively long time interval. Immediately after that, we open up all windows to rapidly decrease the room temperature. In this case, the temperature of objects placed in the vicinity of the laser changes by 10°C. The bends seen on the curve in Fig. 5a correspond to the activation and termination of the external heating of the laser system. It is seen that the laser frequency is virtually insensitive to such perturbations. The final horizontal fragment of the curve in Fig. 5a corresponds to the maximum laser-frequency stability and is measured in the absence of the additional external action upon the laser system. The narrow spikes in Fig. 5a emerge due to acoustic perturbations.

We also studied the laser-frequency stability upon active stabilization in the absence of the thermal stabilization of the platform and in the absence of the protecting housing. In this case, the frequency stability is substantially worsened. Small temperature and external

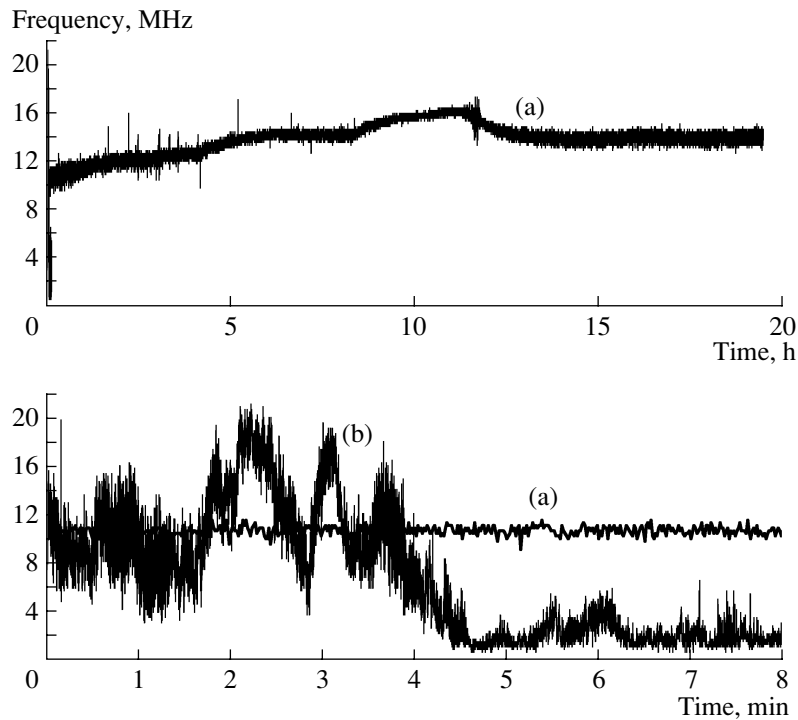


Fig. 5. Long-term stability of the laser frequency (a) in the presence and (b) in the absence of the active stabilization of the laser frequency.

acoustic perturbations lead to jumps in the laser frequency to the neighboring cavity modes.

CONCLUSIONS

A system for the frequency stabilization of a laser system based on a diode laser is proposed and studied. The measured short-term frequency stability is 1.5 MHz, and the long-term drift of the laser frequency is less than 1 MHz/h.

ACKNOWLEDGMENTS

This work was supported in part by the Russian Foundation for Basic Research (grant no. 05-02-16370a), the Ministry of Industry, Science, and Technology of the Russian Federation (grant NSh 1772.2003.2), and the US Civilian Research and Development Foundation (CRDF) (grant RU-P1-2572-TR-04).

REFERENCES

1. V. I. Balykin, V. G. Minogin, and V. S. Letokhov, *Rep. Prog. Phys.* **63**, 1429 (2000).
2. M. Ohtsu and Toshiharu Tako, *Progress in Optics XXV* (Elsevier Science, Amsterdam, 1988).
3. C. Wieman and Holberg, *Rev. Sci. Instrum.* **62**, 1 (1991).
4. T. Kurosu, J. Ishikawa, and N. Ito, *Appl. Phys. B* **63**, 265 (1996).
5. U. Tanaka and T. Yabuzaki, *Jpn. J. Appl. Phys.* **33**, 1614 (1994).
6. V. Yashchuk, D. Budker, and J. R. Davis, *Rev. Sci. Instrum.* **71** (2), 341 (2000).
7. K. Korwin, Zheng-Tian Lu, *et al.*, *Appl. Opt.* **37** (15), 3295 (1998).
8. W. Dembröder, *Laser spectroscopy*, Ed. by F. P. Schafer (Springer Verlag, Berlin, 1982).
9. Laser System, Fiz. Inst. im. P.N. Lebedeva, Akad. Nauk (FIAN), "Avesta-Proekt", vvv@okb.lri.troitsk.ru.

SPELL: OK