Long-term frequency stabilization of a continuous-wave tunable laser with the help of a precision wavelengthmeter

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For the first time to our knowledge we experimentally demonstrate an efficient method for the reduction of long-term radiation line drift in single-frequency cw Ti:sapphire and dye lasers that relies on a fast and precise wavelengthmeter together with a digital–analog feedback system. Generation line drift of lasers is reduced approximately by an order of magnitude down to 40 MHz/h, which corresponds to the residual drift in readings of the wavelengthmeter itself. The implemented automatic frequency control system allows us to lock the laser generation frequency to a specified absolute value. This approach may be used in single-frequency lasers of different types (solid-state, fiber, diode, dye lasers, etc.) and allows reduction by an order of magnitude or more of the long-term generation line drift in lasers that are not equipped with other systems for long-term stabilization of output radiation frequency.   © 2007 Optical Society of America

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1. Introduction

Many applications of tunable cw lasers in addition to a narrow laser output line also require low spectral drift of the radiation line over a long period of time. For instance, in many problems of atom cooling and trapping, as well as in those of isotopically selective photoionization and others, the admissible laser radiation line drift may be less than ~100 MHz over several hours.

Values of long-term radiation line drift exhibited by passively stabilized tunable single-frequency cw lasers under typical laboratory conditions are as high as several hundred megahertz to several gigahertz per hour (see, for example, [1–4]). Reduction of long-term drift in the laser radiation line is usually achieved by stabilization of the laser's output frequency with the use of an external thermostabilized interferometer or an atomic or molecular absorption line. The advantage of frequency stabilization with the use of a thermostabilized reference interferome-

ter is that such stabilization may be achieved at any given wavelength within the working spectral range of the laser. However, the residual long-term drift of the generation frequency with this method may amount to 10–100 MHz/h [5–8]. Stabilization of the laser's output frequency to an atomic or molecular absorption line eliminates drift down to 1 MHz/h and less [9–11], although this method is limited in the choice of available wavelengths.

It is necessary to note that in many cases frequency stabilization of laser radiation is only used for reduction in the long-term spectral drift of the laser line. The reduction in the short-term linewidth of the laser radiation associated with this is not always necessary. For many applications, a radiation line with the short-term width on the level of several megahertz (which is typical of passively stabilized cw solid-state, dye, and other tunable lasers) is more than adequate.

Apart from analog feedback systems used for reduction of long-term drift of the laser radiation line, there are also digital (computer-controlled) systems [8,9].

In [8], for the correction of slow frequency drift in the output of a Ti:sapphire and a diode laser the

authors used a scanning Fabry–Perot interferometer, a frequency-stabilized He–Ne laser, and a computer-controlled feedback system. The spectral positions of the interferometer transmission peaks for the He–Ne radiation were compared with the positions of the transmission peaks for the output of the Ti:sapphire or the diode laser, and, as the latter peaks shifted around, an error correction signal was supplied to piezoelectric transducer (PZT) elements on which the cavity mirrors of these lasers were mounted. Reported in [8], an analog–digital feedback system demonstrated a reduction of the long-term wavelength drift of both the Ti:sapphire and diode lasers down to $\sim$2.5 MHz over several hours. A similar computer-controlled system was used in [12].

Frequency stabilization by a high-precision radiation wavelengthmeter presents another possibility in this field. Owing to the recent progress in the development of radiation wavelengthmeters, their absolute measurement precision has reached levels of 4×10^{-8} [13], 2×10^{-8} [14], and even 2×10^{-9} [15], whereas the measurement time may be as low as 10 ms and less [14]. Such devices perform digital processing of data collected from a single scanning Michelson interferometer [13] or from a number of static Fizeau [14] or Fabry–Perot [15] interferometers, and the result, the radiation wavelength, is available for use in other concurrently running software applications in real time. The wavelength radiation of a test laser in such lambdameters is calculated with the help of the recorded interference fringe pattern from a laser with known wavelength (He–Ne, Nd:YAG, or other laser).

In [16], an automatic digital control system based on a high-precision lambdameter was for the first time experimentally implemented for long-term frequency stabilization of a pulsed single-frequency dye laser that had inherent drift of the controlled parameter within $\sim$30 MHz over 10 h. This system achieved reduction in the long-term drift of the output radiation line of this pulsed single-frequency dye laser down to 60 MHz; however, [16] does not specify over which period of time.

In this paper, we present possibilities to reduce the long-term drift in the output lines of frequency-unstabilized cw single-frequency lasers (Ti:sapphire and dye) with the help of a computer-controlled feedback system based on a fast high-precision radiation wavelengthmeter.

2. Experiment

In the experiments we used Ti:sapphire and dye cw passively stabilized single-frequency ring-cavity lasers by Tekhnoscan Co. (Novosibirsk, Russia) [17], as well as radiation wavelengthmeter (RWM) WS/8 manufactured by Ångström Co. (Novosibirsk, Russia). Laser radiation was guided into wavelengthmeter WS/8 through a single-mode fiber. The absolute precision of this RWM amounts to 3×10^{-8}, which corresponds to $\sim$15 MHz within the dye laser output range (570–620 nm) and to $\sim$10 MHz within

the wavelength range of the employed Ti:sapphire laser (850–900 nm). The relative precision of this RWM is by an order of magnitude higher and amounts to 1–2 MHz within the working range of the radiation wavelengths. Wavelengthmeter WS/8 has four Fizeau interferometers, the internal volume of the longest (highest resolving power) interferometer is kept in vacuum, and its temperature is monitored by a sensor. The measured wavelength values are corrected with the temperature sensor readings taken into account, that is, unlike the wavelengthmeter used in [16], which provides for thermostabilization of Fizeau interferometers, RWM WS/8 uses temperature correction of the measured wavelength values. RWM WS/8 operates in combination with a PC through a USB interface. Values of measured wavelengths are displayed on the computer screen and can also be accessed through a software dynamic-link library module provided in the standard software package of this wavelengthmeter.

For long-term stabilization of the laser generation frequency with wavelengthmeter WS/8 a computer application was developed that emulates an analog system of the laser output frequency stabilization. The application is based on Lab Windows 8 and has all the necessary control and adjustment functions inherent in an analog system: adjustment of the error signal gain, error signal phase switch, adjustment of the feedback ring response time, and monitoring of the error signal and the laser output wavelength. In the application program it is necessary to set the reference radiation wavelength (otherwise it is set to the laser output wavelength at the moment of system activation) and then the program generates an error signal as the current output wavelength walks off the reference value. The error signal is supplied to a digital-to-analog converter (USB3000) and then to the input of the electronic control unit of the laser. The maximum feedback ring speed is limited by the wavelength readout time, which in the case of WS/8 was $\sim$50 ms.

The Ti:sapphire and dye cw lasers have identical systems of continuous generation frequency detuning: This detuning is performed by three PZT elements that control the positions of three cavity mirrors. The width of the continuous detuning range provided by these three PZT elements is approximately 6 GHz for the dye laser and 5 GHz for the Ti:sapphire laser. The error signal from the output of the digital-to-analog converter is fed to a high-voltage amplifier that controls the PZTs. The layout of the experimental setup is shown in Fig. 1. In the course of the initial experiments we also used an I_2 vapor cell for concurrent control of the changes in the laser radiation wavelength and for estimation of the residual self-drift of the RWM readings. To do this, we used two photodetectors, one of which registered fluorescence intensity as the laser output line was tuned onto the slope of the I_2 absorption line, and the second monitored the intensity of the laser output radiation. The signal from the first photodetector was normalized to the output of the second one and allowed to
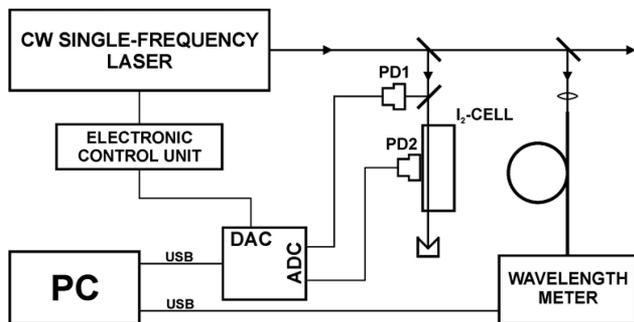
Fig. 1. Experimental layout: PD1, PD2, photodetectors; DAC, digital-to-analog converter; ADC, analog-to-digital converter; PC, computer; USB, USB interface connexion.

Fig. 3. Temporal dependence of the output frequency of a cw single-frequency ring dye laser in the frequency stabilization mode registered with an I_2 absorption line.

measure the change in the output radiation frequency of the laser.

Presented in Fig. 2 is the dependence of the generation frequency of an R6G dye laser on time in the mode of stabilization by the wavelengthmeter (the generation frequency reading was taken from the wavelengthmeter). The laser output frequency was in this case locked to the value of 511.59620 THz. Registered frequency excursion around the set value is within ±10 MHz over more than 1 h, the linewidth of the laser radiation output being ~10 MHz.

It should be pointed out that the time dependence of the laser generation frequency given in Fig. 2 was recorded with the help of the same wavelengthmeter as was used to stabilize the laser output frequency. In case the wavelengthmeter has its own long-term readout drift, such a graph of the output laser frequency versus time will also include this drift. In Fig. 3 we demonstrate the dependence of the laser output frequency on time in the stabilized mode, which was recorded from the I_2 absorption line as outlined before. This dependence has a certain slope that reveals a residual long-term drift in the wavelengthmeter readings amounting to ~20 MHz over 30 min or 40 MHz/h. This parameter may be reduced several

times down to the <10 MHz/h level if continuous calibration of the wavelengthmeter is used.

Similar experiments were conducted on the stabilization of the output radiation frequency of a cw single-frequency ring Ti:sapphire laser. During these experiments not only the long-term drift of the output radiation frequency was studied (which is approximately the same as that for the dye laser) but also the possibility to adjust the set frequency value in certain limits without deactivation of the stabilization system. This possibility was experimentally proven within the range of continuous detuning of the laser output frequency. Figure 4 illustrates controlled adjustment of the generation frequency of the Ti:sapphire laser: The initial slanted curve (3.5 min) corresponds to the drift of the laser output frequency in unstabilized mode at the rate of ~430 MHz/h. After that, the frequency stabilization system is engaged and at various intervals the set frequency value is changed, the stabilization system adjusting the laser output frequency to coincide with the new value. The figure demonstrates that the laser output frequency can be automatically set to different specified values to a precision of several megahertz. As a matter of fact, a tunable laser with a long-term frequency stabiliza-
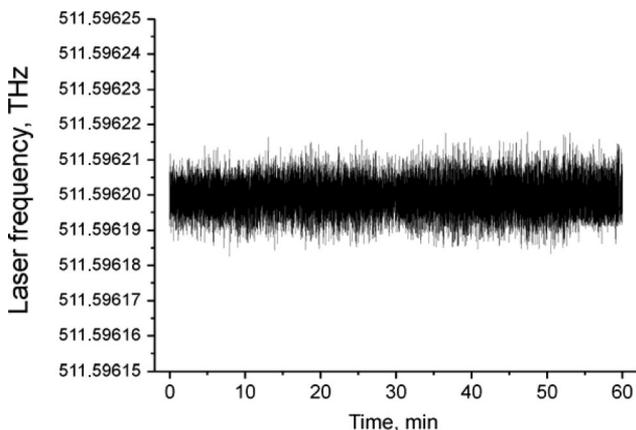

Fig. 2. Plot of the generation frequency of a cw single-frequency ring dye laser versus time with the frequency automatically stabilized to the absolute value of 511.59620 THz.
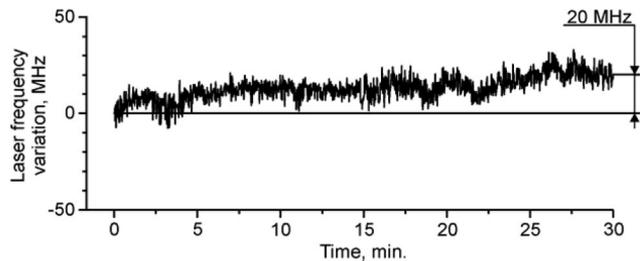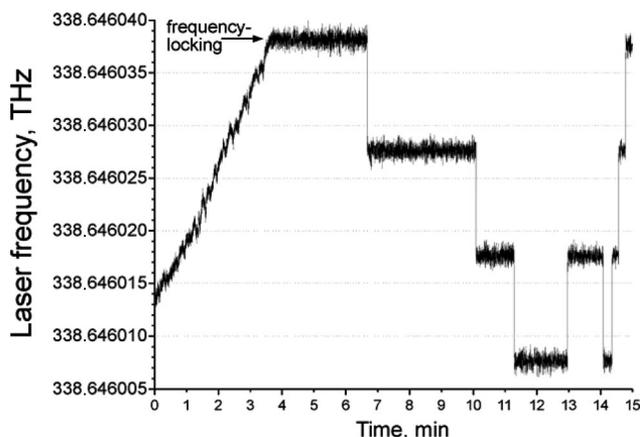

Fig. 4. Dependence of the output frequency of a cw single-frequency ring Ti:sapphire laser on time in the frequency stabilization mode and with changing the set frequency values. Initial slope on the plot (0–3.5 min) corresponds to the generation frequency drift of the laser with the stabilization system disengaged. Further on, the laser output frequency is set to different values through the controlling software.

tion system based on a high-precision radiation wave-lengthmeter presents new broad possibilities for computerized real-time control of the laser radiation frequency within the laser's continuous frequency-detuning range.

One of the interesting questions raised in the course of the present work was whether it is possible to narrow the laser generation line by using this type of frequency stabilization system. The answer to this question is no because such a system is not fast enough. A relatively long period of wavelength read-out only permits us to remove the slow drift of the laser output frequency and does not affect the fast frequency jitter with typical magnitudes of 10 MHz for dye lasers and 2–3 MHz for Ti:sapphire lasers.

Theoretically, the laser output frequency may be corrected through a RWM in two different ways: continuously (or quasi-continuously, taking into account the finite speed of the RWM) and discretely at intervals whose length may be controlled. The results reported in this work have been obtained using the first of the methods; however, we also tested the second option, which gives similar results with greater variations of the laser output frequency around the specified value.

3. Conclusion

In the present study for the first time to our knowledge an efficient method has been experimentally demonstrated for the reduction of the long-term radiation line drift of single-frequency cw Ti:sapphire and dye lasers that is based on a high-precision fast radiation wavelengthmeter and a combined digital–analog feedback system. Such a system may be used in single-frequency lasers of different types (solid-state, fiber, semiconductor, dye jet, etc.) and leads to more than an order of magnitude reduction of the long-term drift of laser radiation lines. In our experiments with single-frequency cw Ti:sapphire and dye lasers, long-term generation line drift was reduced to $\sim$40 MHz/h, which corresponds to the residual self-drift in the wavelengthmeter readings. When continuous wavelengthmeter calibration is used, this drift can be further reduced to a few megahertz per hour.

Application of the high-precision radiation wave-lengthmeters as spectral references opens a new approach to long-term stabilization of the radiation frequency of single-frequency lasers. The best modern radiation wavelengthmeters feature high measurement precision (down to 10^{-9}) and speed, which make it possible to use such wavelengthmeters in automatic real-time radiation wavelength control systems for lasers. One of the very obvious advanced features of this approach is the possibility to lock the laser output frequency to a given absolute value, which can be subsequently adjusted.

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