# Long-term frequency stabilisation of a CW single-frequency laser using a high-precision wavelength meter

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## ABSTRACT

In the present paper it has been demonstrated that the suggested and for the first time experimentally tested method for considerable reduction in long-term radiation frequency drift of CW single-frequency Ti:Sapphire and dye lasers based on a fast high-precision radiation wavelength meter and a digital-analogue feed-back system can present an efficient alternative to conventional methods for long-term frequency stabilisation. Long-term frequency drift of the lasers was improved from ~450 MHz/h in free-running regime to less than 40 MHz/h in the regime of frequency stabilisation. Application of a wavelength meter as a spectral reference allows reduction in the long-term frequency drift down to the level of residual drift inherent in the wavelength meter. An interesting prospective feature of the suggested method is the possibility to use a wavelength meter for periodical operative wavelength correction of more than one laser, which can also be performed remotely when a laser and the wavelength meter are connected with a long optical waveguide and the wavelength value is transmitted though the Internet. The proposed method of stabilisation can be used for single-frequency lasers of any type (solid-state, diode, fibre, dye lasers, etc.), in which continuous controlled radiation frequency detuning is possible.

**Keywords:** single-frequency laser, wavelength meter, long-term frequency stabilisation.

## 1. INTRODUCTION

Continuous-wave single-frequency lasers without frequency stabilisation typically exhibit output line width by several orders of magnitude narrower than the amount of long-term drift of the output wavelength. Long-term spectral drift of the generation line in such lasers arises from a multitude of external influences including changes in ambient temperature, air currents, mechanical drift of optical elements, etc. Values of long-term radiation line drift exhibited by passively stabilised tuneable single-frequency CW laser under typical laboratory conditions are as high as several hundreds of MHz to several GHz per hour (see, for example, [1–4]). Reduction of long-term drift in the laser radiation line is usually achieved by stabilisation of the laser's output frequency with the use of an external thermo-stabilised interferometer or atomic/molecular absorption line. The advantage of frequency stabilisation with the use of thermo-stabilised reference interferometer is that such stabilisation 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/hour [5–8]. Stabilisation of the laser's output frequency to an atomic or molecular absorption line eliminates drift down to 1 MHz/hour 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 stabilisation of laser radiation is only used for reduction in the long-term spectral drift of the laser line. The reduction in the short-term line width of the laser radiation associated to this is not always necessary. For many applications, a radiation line with the short-term width on the level of several MHz (which is typical of passively stabilised CW solid-state, dye, and other tuneable lasers) is more than adequate.

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In order to reduce this long-term radiation line drift, various methods for frequency stabilisation are employed that rely on the use of thermo-stabilised reference interferometer, atomic or molecular absorption line, another highly stable laser, etc. Apart from analogue feed-back systems used for reduction of long-term drift of the laser radiation line there are also digital (computer controlled) systems [8, 9].

In Ref. [8], for correction of slow frequency drift in the output of a Ti:Sapphire and a diode laser authors used a scanning Fabry-Perot interferometer, frequency-stabilised He-Ne laser and a computer controlled feed-back system. Spectral positions of interferometer transmission peaks for the He-Ne radiation were compared to positions of 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 PZT elements on which cavity mirrors of these lasers were mounted. Reported in Ref. [8] analogue-digital feed-back system demonstrated a reduction of the long-term wavelength drift of both Ti:Sapphire and diode lasers down to ~2.5 MHz over several hours. A similar computer controlled system was used in Ref. [12].

Frequency stabilisation by a high-precision radiation wavelength meter presents another possibility in this field. Owing to the recent progress in development of radiation wavelength meters, their absolute measurement precision reached levels of $4\times10^{-8}$ [13], $2\times10^{-8}$ [14], and even $2\times10^{-9}$ [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. Wavelength radiation of a test laser in such lambdameteres is calculated with help of recorded interference fringe pattern from a laser with known wavelength (He-Ne, Nd:YAG or other laser).

Stabilisation of laser generation frequency by a wavelength meter is, in some aspects, similar to stabilisation of laser generation frequency with a reference interferometer because analogous interferometers may be used in wavelength meters. However, a stabilisation system with the use of a wavelength meter has a number of specific features:
1. This system must have a digital (or computer-based) part because the laser radiation wavelength is obtained as from digital processing of data on relative position of interference fringes produced by the stabilised laser and those produced by a reference source, which may be built into the meter or a separate unit (in the latter case the data on interference fringe position for the reference laser are stored in memory and then repeatedly used);
2. Because of the digital part this system is slower in comparison with analogue ones;
3. In this system it is possible to lock the laser radiation frequency to a specified absolute value in contrast with a system that locks the laser output frequency onto a transmission peak (or peak slope) of the reference interferometer where frequency referencing is relative.

Since the speed of this stabilisation system is limited by computer calculation of the laser radiation wavelength, this system can be used for relatively slow correction of the laser output wavelength, *i.e.* for reduction of long-term drift of the generation frequency.

In Ref. [16], an automatic digital control system based on a high-precision lambdameter was for the first time experimentally implemented for long-term frequency stabilisation of a pulsed single-frequency dye laser that had inherent drift of the controlled parameter within ~ 30 MHz over 10 hours. 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 Ref. [16] does not specify over which period of time.

In the present paper, possibilities to reduce the long-term drift in the output lines of frequency-unstabilised CW single-frequency lasers (Ti:Sapphire and dye) with the help of computer-controlled feed-back system based on a fast high-precision radiation wavelength meter.

## 2. EXPERIMENT

In experiments we used Ti:Sapphire and dye CW passively stabilised single-frequency ring-cavity lasers by Tekhnoscan Co. [17] as well as radiation wavelength meter (RWM) WS/8 manufactured by Ångström Co. Laser radiation was guided into the wavelength meter WS/8 through a single-mode fibre. Absolute precision of this RWM amounts to $3\times10^{-8}$, which corresponds to approximately ~15 MHz within the dye laser output range (570–620 nm) and to ~ 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 radiation wavelengths. Wavelength meter WS/8 has 4 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 wavelength meter used in Ref. [16], which provides for thermo-stabilisation 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 also can be accessed through a software DLL module provided in the standard software package of this wavelength meter.

For long-term stabilisation of the laser generation frequency with wavelength meter WS/8 a computer application was developed that emulates an analogue system of laser output frequency stabilisation. The application is based on Lab Windows 8 and has all necessary control and adjustment functions inherent in an analogue system: adjustment of the error signal gain, error signal phase switch, adjustment of the feed-back ring response time, 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. Maximum feed-back ring speed was limited by the wavelength read-out time, which in the case of WS/8 was around 50 ms.

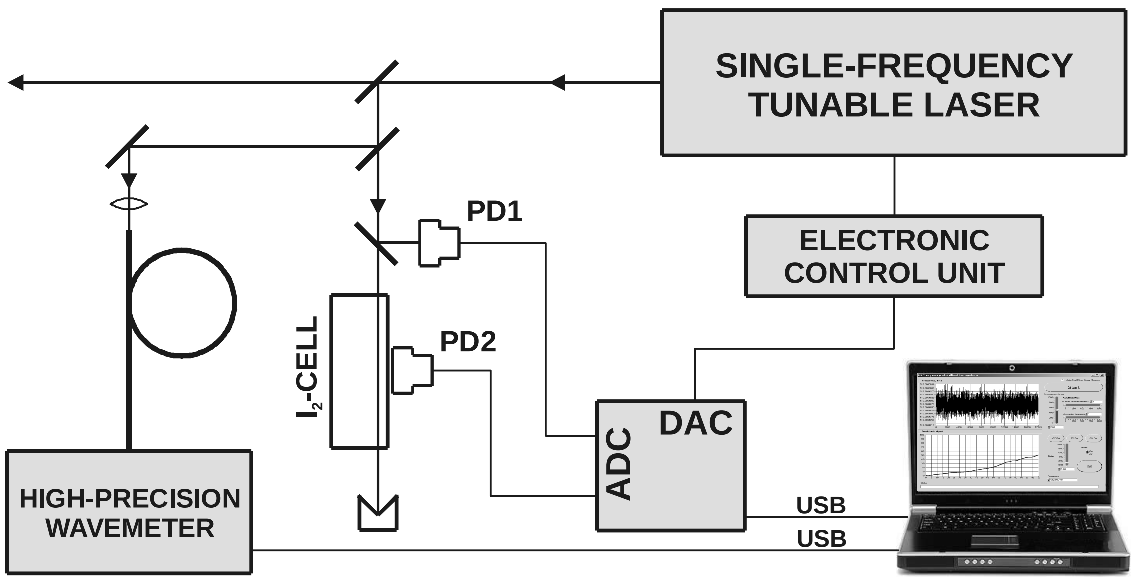


Fig. 1. Experimental layout: PD1, PD2 - photo-detectors; DAC - digital-to-analogue converter, ADC - analog-to-digital converter; USB - USB interface connexion.

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 positions of three cavity mirrors. The width of 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-analogue converter is fed to a high-voltage amplifier that controls PZT's. The layout of the experimental set-up is shown in Fig. 1. In the course of initial experiments we also used an $I_2$ vapour cell for concurrent control of the changes in the laser radiation wavelength and for estimation of the self residual drift of the RWM readings. To do this we used two photo-detectors, one of which registered fluorescence intensity as the laser output line was tuned onto the slope of $I_2$ absorption line, and the second monitored the intensity of the laser output radiation. Signal from the first photo-detector was normalised to the output of the second one and allowed to measure the change in the output radiation frequency of the laser.

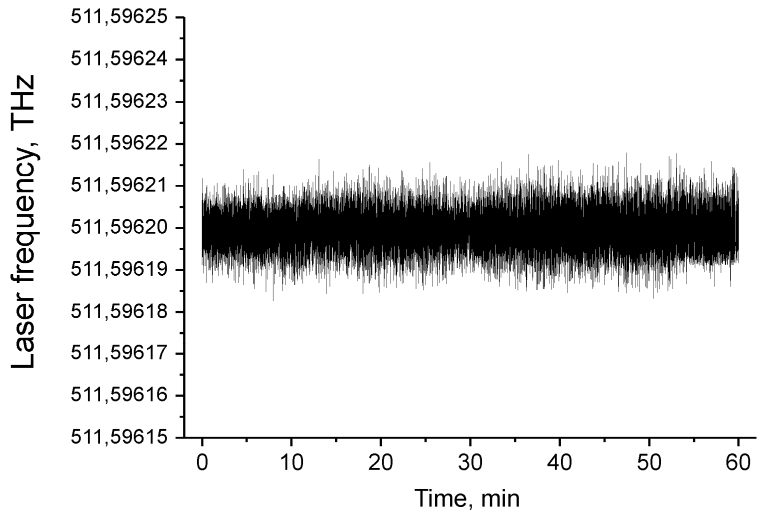


Fig. 2. Plot of generation frequency of CW single-frequency ring dye laser *versus* time with the frequency automatically stabilised to the absolute value of 511.59620 THz.

Presented in Fig. 2 is dependence of the generation frequency of R6G dye laser upon time in the mode of stabilisation by the wavelength meter (generation frequency reading was taken from the wavelength meter). The laser output frequency was in this case locked to the value 511.59620 THz. Registered frequency excursion around the set value are within ± 10 MHz over more than 1 hour, the line width of the laser radiation output being ~10 MHz.

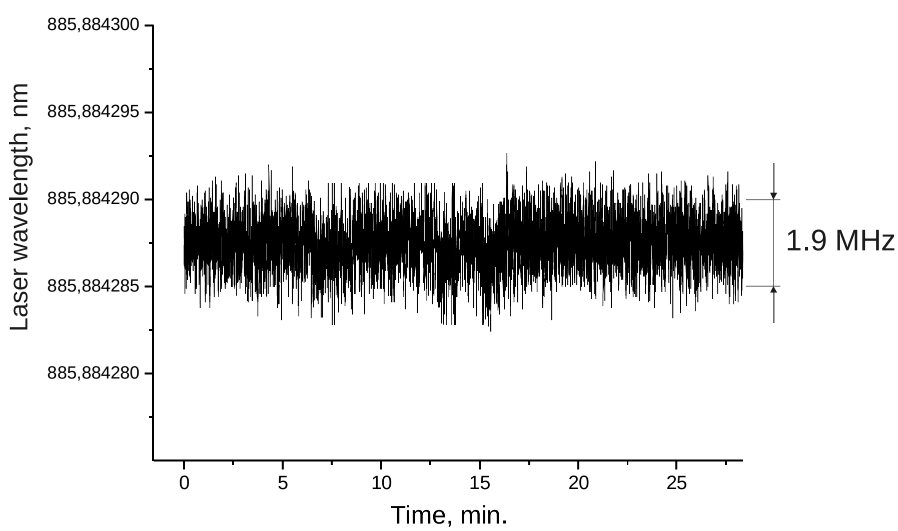


Fig. 3. Plot of wavelength radiation of CW single-frequency Ti:Sapphire laser *versus* time with the wavelength automatically stabilised to the absolute value of 885,884287 nm.

Presented in Fig. 3 is dependence of the wavelength radiation of Ti:Sapphire laser upon time in the mode of stabilisation by the wavelength meter. The laser output wavelength was in this case locked to the value 885,884287 nm. Registered frequency excursion around the set value are within ± 1.4 MHz over more than 25 min., the line width of the laser radiation output being ~2 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 wavelength meter as was used to stabilise the laser output frequency. In case the wavelength meter has its own long-term read-out drift, such graph of the output laser frequency *versus* time will also include this drift. In Fig. 4 we demonstrate the dependence of the laser output frequency upon time in the stabilised mode, which was recorded from the $I_2$ absorption line as outlined before. This dependence has a certain slope which reveals a residual long-term drift in the wavelength meter readings amounting to approximately 20 MHz over 30 minutes or 40 MHz/hour. This parameter may be reduced several times down to < 10 MHz/hour level if continuous calibration of the wavelength meter is used.

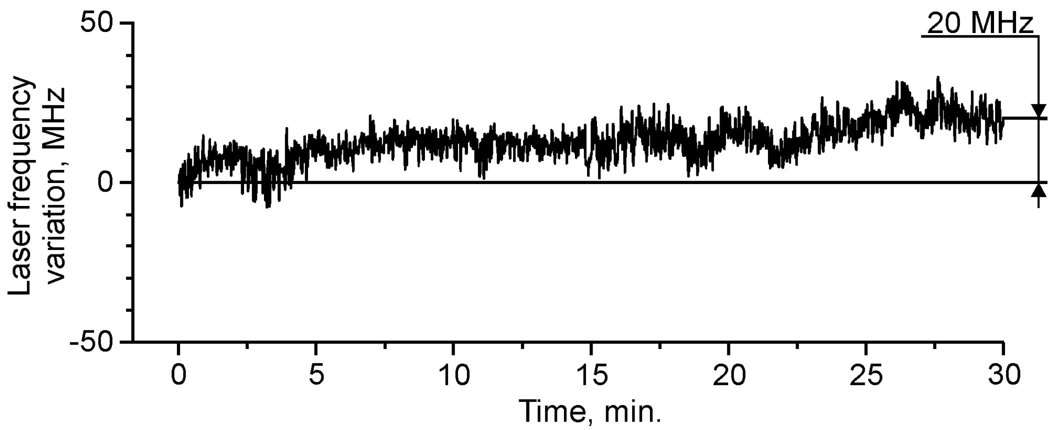


Fig. 4. Temporal dependence of the output frequency of CW single-frequency ring Dye laser in the frequency stabilisation mode registered with an $I_2$ absorption line.

Similar experiments were conducted on stabilisation 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 stabilisation system. This possibility was experimentally proven within the range of continuous detuning of the laser output frequency. Fig. 5 illustrates controlled adjustment of the generation frequency of the Ti:Sapphire laser: the frequency stabilisation system is engaged and at various intervals the set frequency value is changed, the stabilisation 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 MHz. As a matter of fact, a tuneable laser with a long-term frequency stabilisation system based on a high-precision radiation wavelength meter presents new broad possibilities for computerised real-time control of laser radiation frequency within the laser's continuous frequency detuning range.

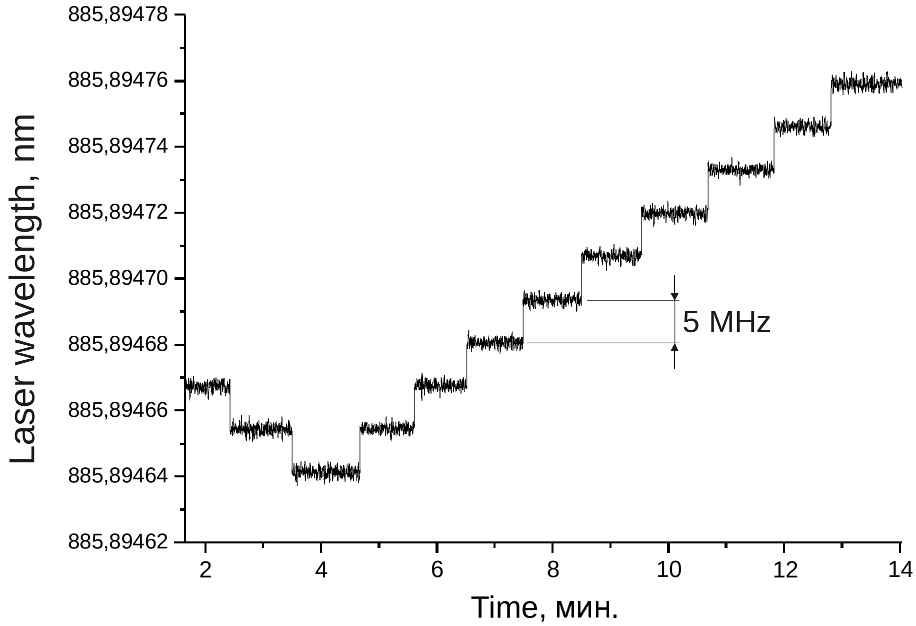


Fig. 5. Dependence of output frequency of a CW single-frequency ring Ti:Sapphire laser upon time in the frequency stabilisation mode and with changing set frequency values. The laser output frequency is set to different values through the controlling software.

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

## 3. DISCUSSION

Theoretically, the laser output frequency may be corrected through a RWM in two different ways: continuously (or quasi-continuously, taking into account 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.

It is pertinent to note that periodical correction of laser radiation wavelength by a wavelength meter can be simultaneously carried out for several lasers. The radiation wavelength meter we used in our experiments has an accessory opto-mechanical switching device with 8 input fibres. This switcher can be controlled through a USB port and provides guiding of radiation from different lasers into the single radiation wavelength meter. With the response time of wavelength meter on the order of 50–80 ms, it can correct radiation frequencies of more than 10 lasers in 1 second. Thus, one high-precision radiation wavelength meter can control frequencies of many single-frequency tuneable lasers in real time. When it is necessary to reduce long-term frequency drift of output from many lasers, using a wavelength meter may be the best way in spite of relatively high cost of high-precision radiation wavelength meters. Additionally, for laboratories already possessing this type of radiation wavelength meters will find the possibility to stabilise laser output an unexpected and welcome bonus.

The residual drift of laser generation frequency in our experiments amounted to approximately 40 MHz/hour in the stabilisation mode based on the wavelength meter. This drift was due to the residual self drift of the radiation wavelength meter induced by small fluctuations of the ambient temperature. This residual drift can be further reduced when continuous (or quasi-continuous) calibration of wavelength meter readings is used. In order to do this one of the inputs of the opto-mechanical switching device with multi-fiber input can be used, through which the radiation of the reference laser is supplied. Continuous (or quasi-continuous) calibration of the wavelength meter readings, their residual drift may be reduced down to several MHz/hour.

For slow correction of the output frequency of lasers both “fast” wavelength meters based on fixed interferometers and “slow” meters based on scanning Michelson interferometers can be used. The most important requirement for all these wavelength meters is extremely low residual drift of readings.

## 4. SUMMARY

Digital systems for correction of long-term drift in laser radiation frequency that utilise high-precision radiation wavelength meters with optical fibre input open new opportunities for controlling laser spectral parameters. These systems feature the possibility to correct the laser radiation wavelength from time to time, for instance, once every few seconds or minutes. Such periodic correction allows the system to control several lasers, radiation from which can be sequentially guided into the wavelength meter through an optical multiplexer. Moreover, the distance between the control system and the operated laser may be quite long (hundreds of metres and more) since the radiation is guided to the wavelength meter through an optical fibre and the correction signal can be transmitted to the laser, for example, over the local network or Internet. When periodically corrected for spectral position of radiation line of a single-frequency laser, such system can be efficiently operated remotely. For instance, one high-precision wavelength meter may be used for simultaneous correction of long-term drift of radiation lines from multiple lasers installed in different labs within one building. This kind of opportunities are available for the first time when using the proposed method of output wavelength stabilisation in single-frequency lasers with the help of digital system based on a high-precision wavelength meter.

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