Long-term wavelength drift compensation of tunable pulsed dye laser for sodium detection lidar

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\textbf{A B S T R A C T}

Wavelength stabilization for a pulsed laser presents more challenges than that of continuous wave laser. We have developed a simple and efficient long-term wavelength drifting compensation technique for tunable pulsed dye lasers (PDL) applied in sodium detection lidar system. Wavelength calibration and locking are implemented by using optogalvanic (OG) spectroscopy in a Na hollow cathode lamp (HCL) in conjunction with a digital control software. Optimization of OG signals for better laser wavelength discrimination and feedback control is performed. Test results indicate that locking the multimode broadband PDL to the Na atomic transition corresponding to 589.158 nm is well achieved although the temperature in the laboratory is unstable. Through active compensation, the maximum wavelength drift is reduced from over 5 pm to 0.42 pm in 10 h and the maximum wavelength drift rate of the PDL is improved from 3.3 pm/h to 0.3 pm/h. It has been used to efficient sodium resonance fluorescence lidar detection. This technique is economical and easy to implement, and it provides flexible wavelength control and allows generalization for some other applications which require the wavelength of tunable pulsed lasers to be fixed at an atomic resonance transition references.

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1. Introduction

With large output energies and high resolution capability, pulsed lasers possess extensive applications in the fields such as atmospheric remote sensing, laser guide stars, laser isotope separation and some other laser spectroscopy studies. For the broadband sodium lidar applications, pulsed dye laser (PDL) plays an important role in studies of the complex mechanisms near the mesopause region of the atmosphere (~80–105 km). High spatial and temporal resolution data are provided to indicate the seasonal and diurnal variations of sodium layers, which will furthermore drive on the study of dynamical processes in the atmosphere like gravity and tidal waves [1,2]. These lidars requires wavelength stabilization of laser source to an absolute wavelength reference corresponding to the sodium D\textsubscript{2} resonant transition in a long time. However, the PDL have poor long-term wavelength stability, which significantly affect the lidar echo signal. Instability of the laser cavity will give rise to a considerable wavelength drifts if no measures are adopted. What is more, the dye cell used in the PDL is more susceptible to temperature fluctuations and mechanical vibrations in experiment environment than other types of lasers.

To implement laser wavelength stabilization, a spectral line of an atomic or molecular transition, or a cavity fringe of a stabilized Fabry–Perot interferometer is used as the wavelength standard [3,4]. Various techniques for stabilizing a continuous-wave (CW) laser wavelength have been well developed and used in vary fields [5–10]. Nevertheless fewer methods have been proposed for a pulsed-output laser directly. The pulsed laser system contains more laser-intensity fluctuations and potential noise in mechanical adjustment, and the short pulse signals make the wavelength discrimination more difficult than that of CW laser [11,12]. Therefore the direct wavelength control and stabilization for a pulsed laser presents more challenges.

Stricklin et al. [13] demonstrated a design for reducing long-term wavelength drifts of a commercial PDL, in which interferograms generated by a Fabry–Perot etalon were measured and a liner CCD array was used along with an analog device. Bian et al. [14] presented a more simple method to stabilize a multimode PDL by searching the maximum slope of the transmission curve of an external cavity Fabry–Perot interferometer. These methods make
use of purely optical reference for laser wavelength stabilization, which is useful when atomic resonance line references are not easily accessible. However, they may be more sensitive to drifts of temperature, pressure and aging of the apparatus than the schemes based on atomic and molecular spectroscopy. Gong et al. [15] reported a novel method for the wavelength stabilization of a pulsed difference frequency laser, which were successfully used in CO$_2$ differential absorption lidar.

The pulsed laser optogalvanic (OG) effect has been studied extensively and turned out to be useful for laser wavelength calibration or locking to a characteristic transition [16–19]. Atomic vapor cells which are usually required to be stabilized at high temperature are not needed. Using a commercial hollow cathode lamps (HCL), which is easier to operate and has a durable rated lifetime of more than 5000 mAh, an electrical signal for wavelength discriminating can conveniently be obtained. With the discharge plasma of HCL acting as a sensitive non-optical detector, the detection apparatus is greatly simplified. Besides, no background filtering is needed as the OG signal is insensitive to the background light. Another outstanding feature of OG spectroscopy technique lies in its many reference lines in the near-infrared regions [20].

In this paper, we present a simple and effective implementation of long-term wavelength stabilization of a PDL based on OG spectroscopy and digital control. To improve the signal-to-noise ratio (SNR) as well as provide better laser wavelength discriminating and tuning sensitivity, the normalization of the pulsed OG signals and the optimization of HCL operating parameters, mainly including the incident laser beam energy and the operating current, are discussed. Digital control based on virtual instrument software is designed to achieve convenient operation of laser wavelength scan/calibration and correction, flexible adjustment of feedback parameters, and visual monitoring of the laser performance. Experiments results indicate that for a multimode tunable PDL, the wavelength drifts encountered when the laser works in free-running mode are compensated successfully. The technique can suffice the application requirement for our sodium resonant fluorescence lidar and can also be generalized to locking pulsed lasers to some other characterized atomic transitions.

2. System description

The experimental set-up for wavelength control and locking is shown in Fig. 1. Pumped by a pulsed Nd:YAG laser, which yields a frequency-doubled light of 532 nm wavelength, the multimode tunable PDL (Sirah, CSTR-D-24), with double grating resonator, 2400 grooves/mm, and a spectral line width of 0.0012 nm, deliver a pulse at a repetition rate of 30 Hz. The grating used for wavelength tuning mounted in the laser cavity is connected to a stepper motor. One step of the motor move can result in a wavelength change of 0.2 pm.

In our experimental setup, the main laser beam is sent vertically up into air for upper atmospheric detection, while only a small fraction is split off for laser locking. A speed photodetector is used to monitor the laser intensity. A continuously variable ND filter is used to adjust the energy of the laser beam coupled into a fiber. The laser beam from the fiber illuminates the plasma through the window on top of a sodium HCL which has an absorbed wavelength at 589.158 nm. As the key component of this control system, the HCL is used to generate OG signal and acts as the wavelength discriminator. A RC circuit is used to read the discharge voltage. The voltage across the HCL vary with the laser wavelength. When the laser beam is resonantly absorbed in the plasma, the voltage reach a peak. If there is a wavelength deviation away from the right atomic transition central wavelength, the amplitude of the OG signal would decrease.

Generally a dedicated boxcar averager is used for measuring pulsed signals [19]. It is very helpful for static gate work, however it may be time inefficient if used for waveform recovery. High-speed digital oscilloscopes offer superior performance in waveform recovery applications. In our system, a digital oscilloscope (DPO 2014, Tektronix), which is available in many labs and can obtain more detail, is used to capture the whole pulsed waveform (rather than a simple voltage value) for more accurate detection of the OG signal intensity. The time-resolved OG signals recorded with oscilloscope are shown in Fig. 2. Due to the inevitable noise from shot-to-shot fluctuations of the pulsed laser, the signal is averaged result of multiple pulse, which would improve the signal-to-noise ratio (SNR). The number of averaged samples on the oscilloscope can be choose by the integer power of 2, and its maximum is 512. Determination of averaging samples should be according to the condition of system noise as well as the response speed of wavelength correction. In our experiment, OG signals are averaged over 128 samples, which can obtain high enough SNR. Larger averaging samples can suppress the laser and electronic noise or other interference better, however, longer acquisition time will be needed, and as a result the response speed will slow down. The blue curve with plus signs corresponds to the situation when the laser wavelength is not resonant to the desired electronic transition. The red curve with triangular signs corresponds to...
to the situation when the wavelength of laser is tuned to the transition line at 589.158 nm which is the working wavelength of sodium lidar. In this case, a significant peak of the OG signals appeared. The green curve in the figure is the trigger signal from the laser system.

By rotating the grating in the laser cavity, a wavelength scanning can be done, and a profile of OG voltage signal versus laser wavelength can be obtained. By setting proper initial grating position and looking for the resonance peak in the scanned OG spectrum, the laser can be tuned to the desired wavelength corresponding to the D2 transition line of the sodium atom. By obtaining the OG signal in real time, a proper digital feedback to the laser cavity generates, and the stepper motor will then be commanded to move to follow the peak of the OG signal. Thus the drifts in laser wavelength can be compensated. All data are collected and processed by a computer.

3. Optimization of the OG signal

3.1. Normalization of the time-resolved OG signals

Based on the time-resolved OG signal waveform information, the discharge intensity of HCL can be described by the maximum value or the integral average value over a fixed time window. As shown in Fig. 2, the OG signal data during the period from 10 μs to 20 μs is the signal of interest, hence the 10 μs wide signal is extracted. As the sampling rate of the oscilloscope is 1 GS/s, the extracted signal data contains sampling points of 10 K. These signal points are integrated and their mean is calculated. The discharge intensity of HCL normalized using integral average algorithm for each wavelength is given by

$$S = \frac{1}{n} \sum_{i=1}^{n} S_i$$  (1)

where $n$ is the number of sampling points of the extracted signal, which is 10 K in this experiment, and $S_i (i=1,2,\ldots,n)$ is the value of a single sample point, $S$ is the integral averaged value of sample $S_i$. The measured OG effect scan profiles of sodium–neon HCL around the sodium resonance wavelength of 589.158 nm are shown in Fig. 3(a) and (b) (blue dots), which represent the OG signals for all wavelengths normalized by their own maximum values and integral average values with a time window, respectively. The solid red curves show the fitted spectrum. The results indicate that the OG spectrum curve obtained by integral average normalization in Fig. 3(a) is smoother than maximum normalization in Fig. 3(b). The former restrains the noise efficiently, and more distinct OG effect features can be obtained, which will be greatly beneficial to laser wavelength discriminating [21]. Considering these, in the following experiments the integral average algorithm is applied to obtain highly accurate OG signal intensity.

3.2. Considerations of the operating parameters on HCL

As the HCL is used as an OG signal inducer, the observed OG signals are strongly dependent on the initial plasma conditions of the HCL, such as current, incident laser energy, irradiating region, etc. [17,18]. We scanned the laser wavelength around the sodium resonant transition wavelength at 589.158 nm. The amplitude, half-width and slope near the peak of OG profile with various laser energies (Fig. 4) and HCL operating currents (Fig. 5) are investigated. The amplitude is normalized to the ratio of the peak intensity to the background baseline offset value of the OG scan profile. The spectrum data between peak and 2 pm on the left side of the peak normalized using integral average algorithm is linear fitted (shown with a green dotted line in Fig. 3(a)). The slope of the OG spectrum used in this experiment is given by the slope of this fitting line.

Fig. 4 illustrates the variations of the amplitude, half-width and slope of the OG spectrum as the laser energy increases. As can be seen from the curves, both the amplitude and the half-width are rapidly increased with the augment of laser energies in the low energy region. Then with the continuous increasing of energy, the amplitude begins to flatten and the half-width continues to grow slowly. For the slope of the OG effect profiles, it does not vary linearly with the applied laser energy. Increasing the laser beam energy increases the slope in the low energy region, and a maximum slope can be observed around 80 μJ.
Fig. 5 shows dependences of the amplitude, half-width and slope in OG spectrum on the operating current of the HCL. It can be seen that as increasing of the operating current of the HCL, the amplitude and slope of the OG spectrum are increased in the low current region, and a maximum slope is obtained at operating current of 9 mA. In the high current region, with the increasing operating current, the slope decreased and the amplitude becomes weakly dependent on the current. For the half-width, it is decreased slowly and finally flat out as the increasing of operating current.

Based on the analysis above, an operating current of 9 mA applied on HCL is taken as the optimum value and the optimum energy of laser beam impinging on the cathode material in HCL is set to 80 µJ where the OG spectrum experiences relatively large amplitude and slope. As a result more distinct OG signal features can be obtained, providing a better sensitivity for laser wavelength discriminating and drift correction. Higher energy or larger discharge current does not help to improve the amplitude significantly, instead, laser wavelength discriminating sensitivity is decreased as a consequence of saturation broadening and collision broadening.

4. Wavelength calibration and lock

To obtain the desired working wavelength of the broadband sodium lidar, the exact position of the OG resonant peak should be determined. A virtual instrument program based on LabVIEW is designed to achieve adjusting and stabilizing wavelength of PDL. It can allow users modify control parameters conveniently and provide a visually monitoring of laser control information. There are two operating modes for laser wavelength control, the “Manual control” mode and the “Auto-Lock” mode. In the “Manual control” mode, users can freely adjust the position of the tuning grating in a variable interval back and forth so the laser wavelength is tuned flexibly. This mode can be used to calibrate and set the laser wavelength quickly. In the “Auto-Lock” mode, automatic locking the PDL wavelength to the sodium transition line can be accomplished. The procedure is illustrated in Fig. 6 via a block diagram, which mainly includes laser and oscilloscope initialization, wavelength scanning, OG signal sampling, signal normalization, wavelength correction, etc. These main modules are connected programatically based on data flow.

Wavelength scanning is to achieve searching of laser wavelength corresponding to the OG peak. When there are significant changes in the laser system, such as transport of the laser or re-installation of the system, a large deviation in wavelength may be resulted. In this situation a relatively large scanning range of wavelength should be done to make sure that the desired peak position can be included. The initial wavelength can be accomplished with the help of a wavemeter to determine the approximate output laser wavelength. The scanning range and step size can be set and modified conveniently by the graphical user interface (GUI) of virtual instrument software. A small step-size can implement finer wavelength tuning and provide clearer resolution of OG signals. In this experiment, we choose 40 pm as our initial wavelength scan range.

The OG signal corresponding to each wavelength value is recorded by the digital oscilloscope with the help of signal sampling procedure module. After wavelength scanning finished, normalized OG signal profiles can be attained and displayed. In general, Fig. 4. The variations of amplitude, half-width and slope of the OG spectrum with different energy of laser beam irradiating the HCL. The operating current of the HCL is fixed at 9 mA.

Fig. 5. The variations of amplitude, half-width and slope of the OG effect profile in the sodium HCL with various operating current applied to the HCL. The energy of the laser beam injected into the HCL is about 80 µJ.

Fig. 6. The block diagram of the control program, which realizing the oscilloscope and laser initialization, wavelength scanning, data acquisition, laser wavelength monitoring and compensating.
the OG peak can be obtained by finding the maximum OG signal. However, noise is inevitable in the pulsed laser system. In this experiment, the line shape of the whole OG spectrum is not be concerned, instead, the position of the OG resonant peak is more crucial point. Thus, a curve fitting (see Fig. 3(a) in Section 3) is performed to find the exact position of the OG peak. It is worth noting that the backlash of the stepper motor would appear in the process of wavelength scanning. Thus, we adopt a method that combines coarse scanning, fine scanning and reiterating scanning to make the backlash offset each other [15], and then the desired wavelength of the pulsed dye laser can be determined.

After locating the desired wavelength, the wavelength automatic correction module executes. In this process, the OG signals are monitored continuously and a proper feedback control signal will be generated to adjust the stepper motor’s position to keep track of the laser wavelength. Wavelength-modulation and phase-sensitive-detection techniques in conjunction with a proportional-integral-derivative (PID) feedback servo loop that are usually applied in wavelength stabilization of CW laser are difficult for this pulsed dye laser. Thus, a digital control method based on software is utilized. Fig. 7 illustrates the subprogram flow chart of the basic principle for pulsed laser wavelength correction employed in LabVIEW program. The direction and step size for dragging the laser are decided by the difference of the normalized OG signal \( V_1 \) and the previous value \( V_{i-1} \), which is stored by using a shifting register in the program. The first correction direction is arbitrary. The normalized OG signal \( V_i \) is monitored and compared with \( V_{i-1} \) continuously. If \( V_{i} \) is larger than \( V_{i-1} \), the program perceives that the previous correcting direction is wrong and the laser wavelength is deviating from the resonant transition further. Then reverse the moving direction (\(-n\)), otherwise remain it unchanged (\(+n\)). The motor step size is optimized for effective compensation. If the difference between \( V_{i} \) and \( V_{i-1} \) exceeds the preset threshold value \( d_0 \), the step motor moves double the distance for more effective compensation (\(-2n\)). Thus by making the resonator stepper motor move either forward or backward, the wavelength drift can be compensated.

5. Results and discussion

This wavelength stabilization technology has been developed and tested on a multimode tunable nanosecond PDL for a sodium resonance fluorescence atmospheric lidar application. To evaluate the performance of the stabilization system, the OG signals from the sodium HCL are monitored for 10 h. For comparison, variations of the OG signals generating from the free-running mode laser are also recorded. Fig. 8 presents the test result without and with engaging the wavelength compensation. The laser initial wavelength is tuned close to the sodium transition line at 589.158 nm. When the PDL has no absolute wavelength reference, the observed drift in the normalized OG signal is evident as shown in Fig. 8(a), and there is a maximum reduction of more than 0.55 units (arbitrary unit) from the peak in the recording time of 10 h. During the test, the maximum drift rate of OG signal is 0.36 units/h shown with a black fitting curve. According to the OG response curves in Fig. 3(a), the wavelength discrimination can be approximated as a linear function near peak with a slope of 0.108 units/pm, thus the maximum drifts in central wavelength of the PDL during the test are calculated to be over 5 pm and the maximum drift rate of laser wavelength is approximately 3.3 pm/h. Fig. 8(c) shows the simultaneously recorded lab temperature. By contrast, with the wavelength compensation system engaged, the normalized OG signal variation remains within 0.045 units from the apex over 10 h recording time shown in Fig. 8(b), corresponding to a wavelength stability of better than 0.42 pm. During this period the maximum drift rate of the OG signal is reduced to be 0.034 units/h, shown with a black fitting curve in Fig. 8(b). Thus the maximum wavelength drift rate of the pulsed dye laser is estimated to be 0.3 pm/h. The simultaneously recorded lab temperature is shown in Fig. 8(d). The experiments results show that the laser wavelength instability in free-running mode have been reduced to a large extent with compensation. This laser wavelength control system could satisfy the application of efficient sodium resonance fluorescence lidar detection.

It should be noted that our method is designed mainly for achieving better long-term wavelength stability within an allowable error limit. It is difficult to greatly reduce the short-term (in seconds) wavelength variations, such as jitter associated with the dye cell in dye lasers, which are more crucial for a single mode laser. In our implementation, the scanning speed of the laser wavelength and the correction rate for wavelength deviation are mainly limited by the average sampling on oscilloscope and the time delay for data transferring to computer. The long-term stability of the laser cavity is mostly disturbed by some slow processes, such as the ambient temperature and pressure fluctuations. Therefore the wavelength drift can be well compensated using this feedback control. This technique has been successfully applied to our Na lidar system. Reducing pulse laser noise disturbance can decrease the average sampling time, thus feedback correction rate can be increased. This will definitely improve the wavelength stability significantly. A higher-performance digital oscilloscope or using a high-speed data acquisition system may also improve the control performance further.

6. Conclusions

In this paper, a simple and effective method for long-term wavelength drift compensation of pulsed lasers for sodium lidar application has been presented. By utilizing a digital wavelength calibration and lock based on the virtual instrument control program and OG spectroscopy, the maximum wavelength drifts of the multimode broadband PDL is reduced from over 5 pm to 0.42 pm in a recording time of 10 h when the temperature in the laboratory is unstable. During the test, the maximum wavelength drift rate is improved from 3.3 pm/h to 0.3 pm/h.

Compared with other complicated laser wavelength stabilization scheme, the method herein involves less optical and electronic
components. With the advantages of simple implementation, flexible operation and effectiveness, this approach can be easily developed to be applied to lock some other pulsed lasers wavelength to characteristic transition of different atomic species (e.g., K, Cs). The digital control algorithm can also be adjusted flexibly via software according to different control expectation. In addition to the atmospheric lidar system, this method is also useful in other spectroscopic experiments involving the use of a tunable pulsed laser, such as the selective excitation and multi-step excitation experiments, which also require a particular wavelength remained for long periods.

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