Seed laser frequency stabilization for Doppler wind lidar

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We demonstrate a tunable wavelength-locked seed laser source with high-frequency stability to realize the precise measurements of global atmospheric wind field. An Nd:YAG laser at 1 064 nm is used as the master laser (ML). Its frequency is locked to a confocal Fabry-Perot interferometer by using the Pound-Drever-Hall method, which ensures the peak-to-peak value of its frequency drifts less than 180 kHz over 2 h. Another Nd:YAG laser at 1 064 nm, as the slave laser, is offset-locked to the above ML using optical phase locked loop, retaining virtually the same absolute frequency stability as the ML. The tunable ranges of the frequency differences between two lasers are up to 3 GHz, and the tuning step length was an arbitrary integral multiple of 200 kHz. The researched seed laser source is compact and robust, which can well satisfy the requirement of the Doppler wind lidar.

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Wind field, as an important parameter of the atmospheric dynamics and climate variability, can be used to obtain the rule and tendency of atmospheric changes. Doppler wind lidar (DWL) is not only able to obtain the wind field distribution information, but can also measure cloud top height, vertical distribution of cloud, aerosol properties, and changes of the wind field. Currently, DWL is the only tool appropriate for realizing the direct measurements of global three-dimensional (3D) wind profile[1,2]. According to the principle of detection, DWL can be divided into two kinds: coherent DWL, which uses the heterodyne method to detect the aerosol backscatter spectrum, and incoherent DWL, which directly detects both aerosol and molecular backscatter spectra. Very low aerosol concentrations are present in the free troposphere over the mid-oceanic regions and large regions of the southern hemisphere. Consequently, incoherent DWL has incomparable advantages relative to coherent DWL. Meanwhile, the wind profiles over large parts of the tropics, as well as the major oceans, are difficult to measure using ground-based DWL. Therefore, space-borne incoherent DWL is required to measure the whole global wind field. In the system of the space-borne incoherent DWL, the detection unit will falsely treat the frequency jitters of the laser source as the Doppler shifts caused by wind. The speed of spacecraft can also bring the Doppler shifts into the DWL, thereby seriously affecting the measuring accuracy of wind speed[3,4]. As a result, the laser source in space-borne incoherent DWL must have high-frequency stability and large tuning range.

The most common approach for laser stabilization is to use a single laser locked to a stable external reference, and then directly diffracting it with an acousto-optic modulator (AOM) or an electro-optic modulator (EOM). However, this method is not feasible when the tuning range goes up to several gigahertz or higher. In order to solve the above problem, the approach of using two individual lasers to separate the requirements of frequency stability and large tuning range is introduced. The master laser (ML) is locked to a stable reference, and the slave laser (SL) uses optical phase locked loops (OPLL) to synchronize its phase to the ML. The different frequency and highly stable laser can be easily obtained by adjusting the local oscillator[5,6].

In this letter, we demonstrate a compact and robust laser frequency stabilizing system based on Pound-Drever-Hall (PDH)[7−9] method and OPLL. Two Nd:YAG lasers (ML and SL) at 1 064 nm are used. The ML serves as the frequency reference for the SL, which is absolute-locked to a confocal Fabry-Perot interferometer (FPI) using the frequency modulation (FM) technique[10]. The SL is offset-locked to ML by OPLL, retaining virtually the same absolute frequency stability. Based on the above technologies, the frequency of the seed laser source is highly stable and tunable in a wide range. This scheme can also be extended to the area of differential absorption lidar (DIAL) for water-vapor[11], CO_2 concentration[12] sensing, and so on.

Our absolute frequency locking setup for the ML is shown in Fig. 1. The frequency standard is the confocal FPI with finesse of 220 and linewidth of 1.7 MHz sealed in a temperature-controlled box with a temperature stability better than 0.01 K[13]. ML is a commercial 200-mW LD-pumped Nd:YAG continuous-wave (CW) laser (Mephisto OEM) at 1 064 nm with a frequency drift of 45 MHz in 3 h. The ML output is divided into two parts using lens 1. Sixty percent of the light is used to lock this ML, whereas the rest is used to offset lock SL (discussed later). Sixty percent of the laser output is passed through a polarizer, and then phase-modulated by an EOM driven by a 30-MHz sinusoidal voltage. Two sidebands are generated correspondingly. After mode-matching with the TEM00 mode of FPI by lens 2, the modulated laser is reflected from FPI, and then separated from the incident beam with a polarization beam splitter (PBS) and a quarter-wave plate ($\lambda/4$), to be finally received by an InGaAs PIN photodiode (PD) with 300-MHz bandwidth. The output of PD is compared with the local oscillator's signal via a mixer after being processed by the amplifier and bandpass filter. The direct digital synthesizer (DDS) generates a 30-MHz sinusoidal signal used for the laser FM and the error signal demodulation. The phase shifter is used to compensate the unequal delay between these two paths. The low-pass filter isolates the dc part from the output of the mixer, which is an error signal proportional to the laser frequency deviation from the resonant frequency of FPI. The digital servo system based on digital signal processing (DSP) chip samples this error signal, after which the digital proportion-integration-differentiation (PID) control system calculates two feedback signals to stabilize the optical frequency of ML: the temperature feedback with bandwidth of 10 Hz and the piezo transducer (PZT) feedback with bandwidth of 5 kHz.

Figure 2(a) shows the error signals when the ML is scanned by the intracavity PZT actuator. The error signals provide a desired linear region near-zero offset from the resonance with a slope of 0.96 V/MHz. After the ML is locked to the FPI resonance, the relative frequency drifts between them are recorded (Fig. 2(b)). Less than ±20 kHz (with a root mean square (RMS) deviation of 5 kHz) is obtained over 2 h. Because the resonant frequency of FPI fluctuates with the temperature changes, the FPI is sealed in a temperature-controlled box to limit its frequency drifts to approximately 140 kHz[13]. Therefore, the absolute frequency drift of the ML is suppressed to less than 180 kHz over 2 h. To ensure a velocity of wind better than 0.5 m/s, the frequency drifts of seed laser source in DWL should be approximately 1 MHz[14]. The developed absolute frequency locking system well satisfies the requirement of DWL.

In order to retain the frequency stability of the SL corresponding to the ML, the fluctuations of the offset frequency must be suppressed. Usually, OPLL is used to stabilize the relative frequency and phase between two lasers. However, the phase coherent is not necessary in our application. An optical frequency lock loop is sufficient, which drastically alleviates the bandwidth requirement on the control electronics. Figure 3 shows the setup of our offset frequency locking system. Here, 1% of

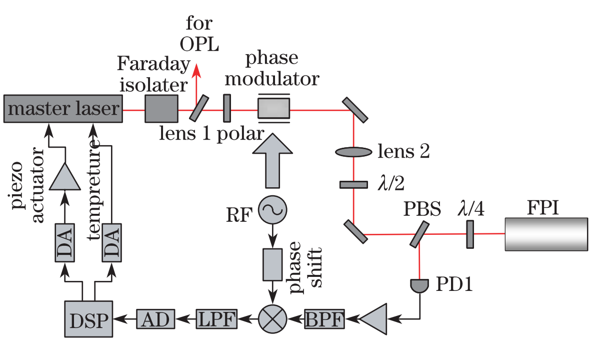

Fig. 1. Absolute frequency locking setup for ML.

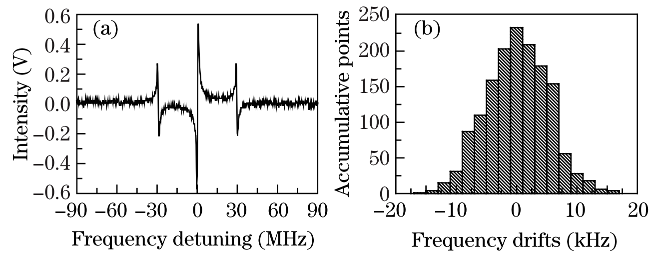

Fig. 2. (a) Error signal measured in the absolute frequency locking setup; (b) statistical graph of the relative frequency drifts between ML and FPI resonance over 2 h.

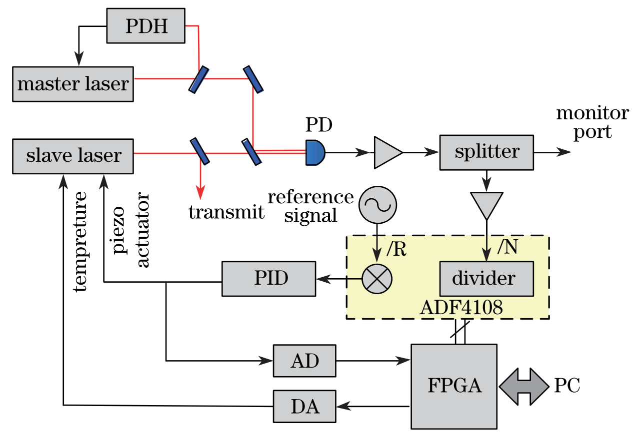

Fig. 3. Setup of the offset frequency locking.

the SL power is taped-off for the offset frequency locking and the remaining 99% is used for injection seeding[15,16]. The beat note is converted into a microwave signal of −5.6 dBm by an ultrafast PIN photodiode. The note is amplified by 9 dB first, then subsequently split by a directional coupler. An approximately −10-dBm signal is used to monitor the frequency fluctuations. The rest of the beat note inputs a digital frequency synthesizer (ADF4108) after again being amplified by 9 dB. This synthesizer consists of two programmable dividers and a low-noise digital phase frequency detector (PFD). The field-programmable gate array (FPGA) programs the divider quotients, R and N. PFD compares the frequency of the reference signal divided by the factor of R and the beat note divided by the factor of N. Finally, an error signal proportional to the frequency difference between the reference signal and beat note is produced. Dual channels tune the frequency of the SL, similarly to that of the ML in the absolute frequency locking system: the fast feedback channel based on PZT and the slow feedback channel based on temperature. The analog PID servo controls the PZT according to the error signal. FPGA monitors the output of PID to avoid the loop losing lock. If the control voltage of the PZT is beyond the given threshold, FPGA will adjust the temperature of the SL to pull it to near zero.

In the offset locking system, the tunable offset frequency between the ML and SL can be realized by adjusting the divider quotient N. Offset frequency is measured with a frequency counter from Agilent (Agilent 53131A) connected to the monitor port. Figure 4(a) shows the frequency stepping performance with fine stepping of 200 kHz, which is only a small portion of the duration of the experiment. Figure 4(b) shows the frequency stepping performance with coarse stepping. The step length can be an arbitrary integral multiple of 200 kHz, and the tunable range can be up to 3 GHz. This tunability of the seed laser source is sufficient to compensate the Doppler shifts caused by the speed of spacecraft in the application of DWL.

To evaluate the stability of the offset frequency locking, the Allan deviation of the beat note fluctuations is measured. Figure 5 shows the Allan deviation of the frequency differences between the offset-locked SL and the ML, which is measured by the Agilent counter when the offset frequency is 2 GHz. The minimum Allan deviation of 2.3×10^{-9} is obtained at 32 s after the loop is locked.

The performance of this offset locking system is mainly affected by the loop bandwidth and the stability of the reference signal. In this system, one tenth of the fine step length is chosen as the loop bandwidth, which is merely 20 kHz. Meanwhile, an ordinary crystal oscillator of 50 MHz is used as the reference signal. If a loop bandwidth higher than 20 kHz is used, as well as an oven-controlled crystal oscillator (OCXO) instead of that ordinary crystal, the stability of the offset frequency will be better, and even the relative phase between the ML and SL can be locked.

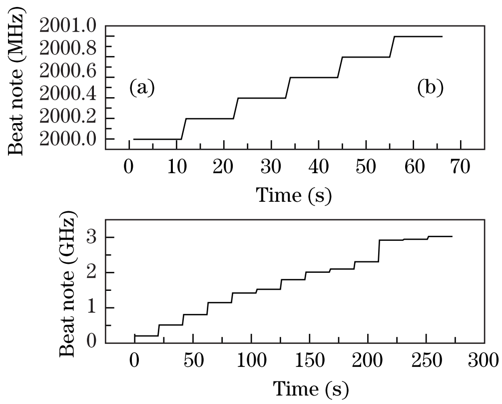

Fig. 4. (a) Frequency stepping performance "fine stepping." Only a small portion of the duration of the experiment is shown; (b) frequency stepping performance "coarse stepping".

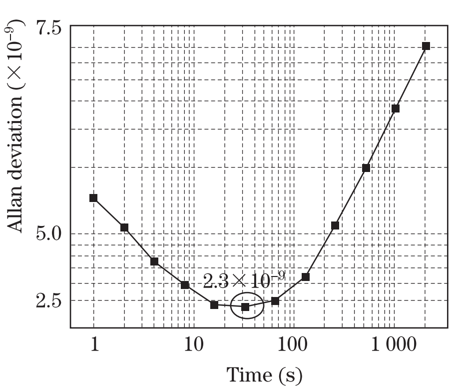

Fig. 5. Allan deviation of the frequency difference between ML and SL. The ML is locked to the resonant frequency of FPI, and the SL is offset-locked 2 GHz away using OPLL.

In conclusion, a compact and robust laser frequency stabilization system with high-frequency stability and large tuning ranges is obtained. The absolute frequency locking system based on PDH and the offset frequency locking system based on OPLL are demonstrated experimentally. Experimental results show that ML suppresses the peak-to-peak value of its frequency drifts to 180 kHz over 2 h. SL offset locks to ML, stabilizing its absolute frequencies to virtually the same submegahertz precision as ML. The offset frequency ranges from DC to 3 GHz, which can be tuned with the step length of arbitrary integral multiple of 200 kHz. This submegahertz frequency precision and gigahertz frequency tuning range well satisfies the DWL requirements.

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