Frequency stabilization of diode laser to 1.637 μm based on the methane absorption line

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The frequency of an external-cavity diode laser has been stabilized to 1.637 μm by using the reference of absorption lines of methane. The method can be applied to wavelength division multiplexed optical communication, fiber-optic sensing systems, as well as the high-sensitivity detection of methane. The derivative-like error signal yielded by frequency modulation and phase sensitivity detection technology is inputted into the PI feedback loop circuit in order to stabilize the frequency to the line center. After stabilization, the frequency fluctuation of diode laser is held within 5.6 MHz, and the root of Allan variance of error signal reaches a minimum of 1.66×10^{-10} for an average time of 10 s.

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Diode lasers have several favorable characteristics for actual applications such as single-frequency, wide tunability, narrow line width, moderate power, and convenient operation. Therefore frequency stabilization of such a device deserves an outstanding interest in view of a variety of applied fields, for example optical communication, high-resolution molecular and atomic spectroscopy, and lots of experiments in gas remote sensing detection.

The core of laser frequency stabilization is the generation of error signal passing through zero at the lock frequency. Many traditional methods for stabilization utilize feedback to minimize laser frequency offset from an absolute frequency reference such as transmitted signal of Fabry-Perot (F-P) resonator, absorption lines of molecule and atom, and so on. Though the laser can be stabilized to arbitrary wavelength by use of the F-P resonator[1], the cavity-transmitted signal is perturbed by thermal, mechanical variations or other reasons. Therefore it needs strict conditions and better servo lock circuit. The disadvantages can be eliminated by applying the absorbance of molecule and atom because of its steady absorption signal. The stabilization of required wavelength can also be realized by use of abundance absorption lines of different molecular species. In recent years the researchers have developed many different frequency standards. Nakagawa *et al.*[2] stabilized the laser frequency to the absorption lines of acetylene at 1.5 μm for optical communication, Koch *et al.*[3] stabilized the diode laser to absorption lines of water vapor in the 944-nm wavelength region for lidar remote sensing of water. However the line widths of molecular absorption lines are so wide that the frequency stability becomes rather poor. The sub-Doppler absorption lines including atomic saturation absorption spectroscopy[4], molecular cavity saturation absorption[5], selective reflection spectroscopy[6], and other methods such as atomic modulation transfer spectroscopy[7] and Zeeman shift[8] have been applied to obtain the better stability. For the wavelength standard of near 1.6 μm, these methods are not fit for the application because they are either complex or not able to output the corresponding wavelength.

In this paper, the frequency stabilization scheme is based on frequency modulation and phase sensitivity detection techniques. The third derivative was adopted as the error signal. Meanwhile the frequency stabilization of 1.637 μm was realized by employing the absorption lines of $2\nu_3$ band R(9) manifold of methane.

Figure 1 shows the schematic diagram of the apparatus used for stabilizing a diode laser to a molecular absorption line. An external-cavity diode laser (ECDL) (Sacher TEC500), with an emission wavelength of near 1.637 μm and a power of about 1 mW, was used for the spectroscopic investigation. The output from the laser is separated to two beams by beam splitter after passing through an isolator. The diode is placed within an external cavity based on the Littman configuration. The cavity is composed of the rear reflective facet of diode, a grating, and a separately adjustable end mirror. By changing the voltage of piezoelectric transducer (PZT) actuator on the tuning mirror, the laser can be continuously scanned over most of its gain profile, while maintaining a line width below 2 MHz with single mode operation.

Frequency modulation and phase sensitivity detection required that a sinusoidal modulation of 4 kHz be imposed on the laser frequency for modulation spectroscopy.

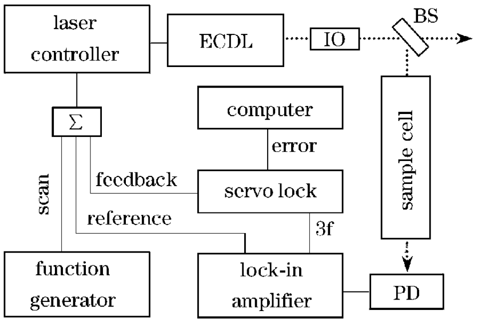

Fig. 1. The experimental setup to stabilize the ECDL. IO: optical isolator; BS: beam splitter; PD: photoelectrical detector; $\sum$: adder.

The modulation signal was from the internal oscillator sine wave in a digital lock-in amplifier (Stanford Research Systems Model SR830). A function generator (Aglent 33120) gave a 218-mV rms (root mean square) ramp at 7 Hz. Both the small sine voltage and the ramp voltage were inputted to the dc bias voltage (~34 V) on the PZT through the fine frequency external input of the laser controller.

The sample cell, a 30-cm long copper tube with a diameter of 30 mm, was pumped out to 10^{-4} Pa by molecular pump (Alcatel ATP 80/100) and filled with pure methane (99.99%). The gas pressure was detected by pressure sensor (Motorola MPX100). The absorption signal was detected by an InGaAs PD (Hamamatsu G8605-23 NEP=10^{-14} W/Hz$^{1/2}$) with thermoelectrical cooling. The time constant was 300 μs. The lock-in amplifier demodulated the detected signal and outputted the odd harmonic to input into the PI feedback loop circuit (PIFLC).

The voltage-tuning rate of PZT is an important parameter for determining the frequency stabilization range, which is different for different modulation frequency. From the theory of harmonic detection, the amplitude of the second harmonic (2f) signal is the function of the modulation amplitude, and at the maximum of amplitude the modulation amplitude is 2.1 times of the absorption line width at a given modulation frequency. Now the modulation voltage added to PZT can modulate the frequency corresponding to 2.1 times of the absorption line-width. The line width can be measured by F-P cavity. Figure 2 represents the amplitude of 2f signal as the function of modulation voltage with about 800 MHz of absorption line width. The voltage-tuning rate is 9.13 GHz/V.

The absorption lines of $2\nu_3$ band R(9) manifold of methane have been selected as a frequency reference at 1.637 μm. Figure 3 shows the absorption spectrum of this band at 15-Torr pressure. This absorption profile is composed of eight absorption lines and five lines can be distinguished. In the experiment the absorption profile near 1637.834 nm is selected to stabilize the ECDL to the resonance. The absorption line width is about 800 MHz and the laser power for stabilization is 100 μW.

After the frequency-modulated laser passed through the sample cell, the detected transmitted signal was demodulated by lock-in amplifier so as to obtain the harmonic signal. The odd harmonic is a derivative-like signal and the zero crossing occurs at line center so that it can be alternated as error signal. When the order of harmonic is increased, the derivative signal at the zero crossing is steeper and the discriminating power is stronger. Figure 4 represents the comparisons of first- (1f) and third-order harmonic (3f) signals of the absorption line. The zero crossings of the two harmonic signals are corresponding to the absorption line center. Obviously, the error signal of 3f has the steeper slope than that of 1f. So it has a stronger discriminating power. As a result, 3f was chosen as the error signal in the experiment. In order to obtain an optimum discriminating power for the 3f signal, the relation between the modulation voltage and the slope of zero crossing of 3f signal was analyzed. In Fig. 5, the slope at the modulation voltage of 140 mV has a maximum value. For a wider absorption line, a steeper error curve

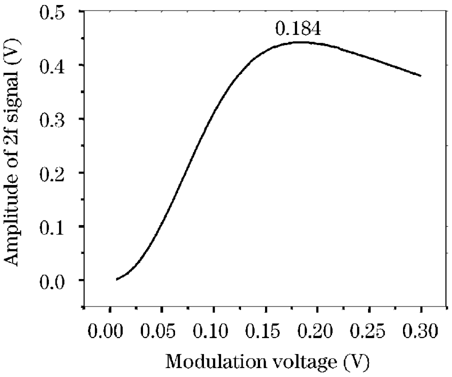

Fig. 2. The amplitude of 2f signal versus modulation voltage.

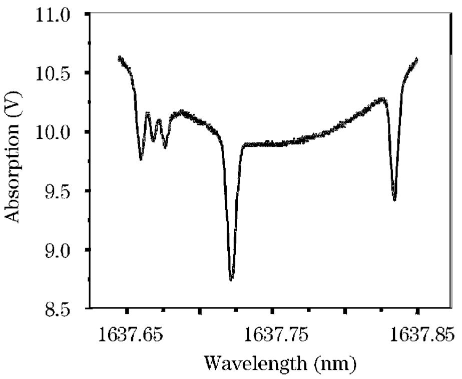

Fig. 3. Absorption spectrum of the $2\nu_3$ band R(9) manifold of methane near 1.637 μm.

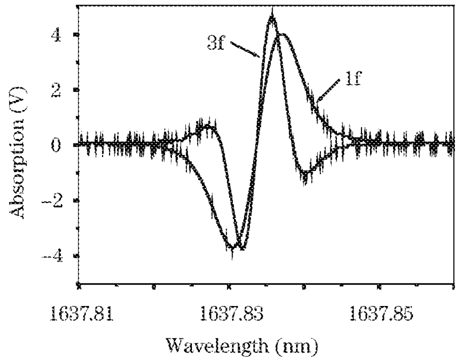

Fig. 4. The comparison between first- and third-order harmonics.

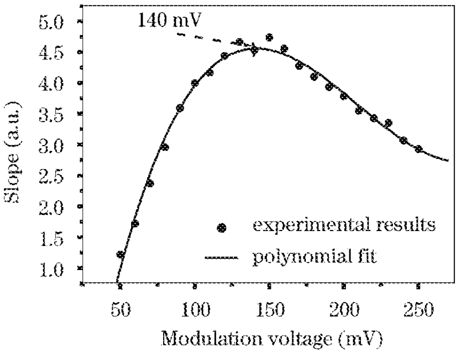

Fig. 5. The relation between modulation voltage and the slope of zero crossing of 3f signal.

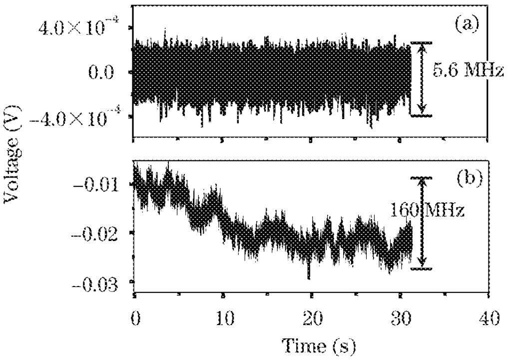

Fig. 6. The error signals with (a) and without the PIFLC (b).

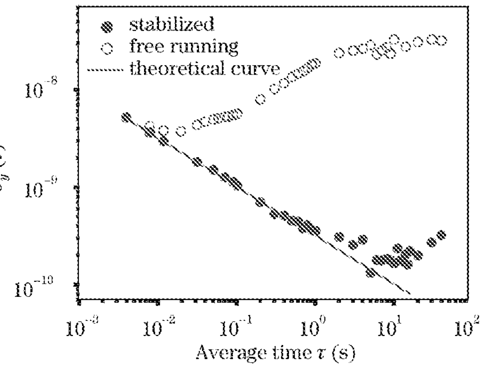

Fig. 7. Square root of the Allan variance values ($\sigma_y(\tau)$), calculated from the error signal with and without lock.

can yield a good frequency stabilization result. So such a modulation voltage was chosen to obtain the error signal.

The error signal was inputted into the PIFLC and the output signal of the circuit fed back to the laser controller to control the voltage of PZT so as to offset the drift of frequency. The frequency excursions of applying the PIFLC to the laser and not applying are shown in Figs. 6(a) and (b) with 2-ms integrating time per measurement point. When the control loop was activated, the error signal shows that the laser was held within 5.6 MHz of line center for 31.25 s. However the frequency dither was 160 MHz for the free running laser. For such a wide frequency fluctuation of stabilized laser, we can reduce it by narrowing the absorption line width.

The Allan variance $\sigma_y^2(\tau)$[9] was used to evaluate the accuracy and fluctuation of the diode laser frequency. It was measured as a function of the averaging time τ by a computer counter. For a free-running diode laser, the error signal fed back to the laser controller is proportional to the fluctuation of the laser frequency. For a stabilized diode laser, the Allan variance value $\sigma_y(\tau)$ is proportional to $\tau^{-1/2}$ for $\tau < 1$ s and therefore the frequency fluctuation is almost attributable to the white noise and flicker phase-noise in this range which come from the detector noise, the modulation noise, and other electronic noise. Under the influence of these noises, $\sigma_y(\tau)$ is determined by

$$\sigma_y(\tau) \approx \frac{1}{Q \cdot \mathrm{SNR}} \tau^{-1/2}, \qquad (1)$$

where Q and SNR denote the quality factor and the signal-to-noise ratio of the molecular spectrum used for the frequency discrimination, respectively. In Fig. 4, SNR is estimated to be 30. From the theoretical simulation shown in Fig. 7, Q is estimated to be 10^8. For longer integration time τ, a frequency flicker noise dominates and degrades the long-term frequency stability, which comes from the frequency dithering of the laser because of the room-temperature drift, incident current jitter, the shake of experimental flat, and also the gentle error signal. The minimum $\sigma_y(\tau)$ for stabilized diode laser is 1.66×10^{-10} at 10 s. However the minimum $\sigma_y(\tau)$ for free-running diode laser is 3.74×10^{-9} at 0.02 s. Comparing the two results, it can be seen that long-term frequency stability is improved considerably, which demonstrates the effectiveness of this simple method of stabilization. In order to obtain a better result, the low noise detection instruments and a better PIFLC with a proper time constant were required to enhance the short-term stability. Meanwhile for improving the long-term stability, a group of highly precise temperature controller and constant current source are required for the laser, a stable environment is also necessary.

In conclusion we have realized to stabilize the frequency of a diode laser to 1.637 μm using the absorption lines of methane. The error signal is originated from the 3f signal of absorption line. By measuring the relation between the slope of the error signal and the modulation voltage, an optimum modulation voltage of 140 mV was adopted to stabilize the laser. However the frequency fluctuation is up to 5.6 MHz, which can be reduced by narrowing the absorption line width. By means of the measure of Allan variance of error signal, the minimum $\sigma_y(\tau)$ is 1.66×10^{-10} at 10 s for stabilized laser and such a method can yield a relative frequency stability of the order 10^{-9}–10^{-10}. This method is shown to be simple and stable.

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