Frequency stabilization of pulsed CO_2 laser using setup-time method

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A new method for laser-frequency stabilization by controlling the pulse setup time is presented. The frequency-stabilization system monitors the pulse setup time continuously, and controls it by adjusting the cavity length. Laser frequency is stabilized to the center of the gain curve when the setup time is the shortest. The system is used to stabilize a radio-frequency-excited waveguide CO_2 laser tuned by grating, and the shift of laser frequency is estimated to be less than ±25 MHz for an extended period. The system has the advantages of compact structure, small volume, and low cost. It can be applied for frequency stabilization of other kinds of pulsed lasers with adjustable cavity.

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In recent decades, there has been an increased use of lasers, such as laser radar, laser communication, and laser spectroscopy. However, laser frequency fluctuations often reduce the necessary standards for these applications, and the shift of laser frequency can degrade the sensitivity of many high-resolution optical metrology systems. Lasers with high-stability frequency standard have become very promising optical sources in many application fields[1−10].

At present, frequency can be stabilized by passive or active means. Laser frequency is susceptible to thermal expansion of the cavity and the refractive index of the working medium. It can be changed with circumstance pressure and temperature fluctuations. Passively frequency-stabilizing methods involve controlling the environmental conditions or choosing low-expansion materials to render the cavity insensitive to external effects. Lasers using passive frequency stabilization can obtain high short-term frequency stability; however their long-term frequency stability is low. This method requires complex experimental equipment and special materials of high cost and in large volume. In the active methods, frequency fluctuations generate signals and physical phenomenon. These signals, called feedback signals, can be sampled. According to the feedback signals, the length of the optical cavity is adjusted automatically to make the correction to the laser frequency. Active frequency stabilization methods are widely used because they can provide long-term frequency stability. However, most active frequency-stabilization methods, such as the optogalvanic Lamb-dip method, the saturated absorption method, the Stark effect method, and the photocurrent of molecular device method, require expensive absorption cells or detectors to detect the feedback signals. In 1996, Talvitie *et al*. constructed a laser system operating at 780 nm using low-expansion materials, which can compensate for the external effects. By placing the laser system in a pressure-proof and temperature-controlled housing, the short-term frequency stability was better than 10^{-10}[11]. In 1995, Tochitsky *et al*. stabilized the frequency of the sequence-band CO_2 laser using 4.3-μm fluorescence[12]. A two-channel heterodyne system was used in this experiments, and long-term stability and reproducibility were achieved at approximately 10 kHz. In 2005, the frequency and power of radio frequency (RF)-excited CO_2 laser were stabilized using photoacoustic effect generated from the laser itself by Choi[13]. The relative stability of the optical frequency was 5.57×10^{-8}. In 2010, a digital laser-locking scheme was implemented and characterized based on Pound-Drever-Hall locking method. A measurement of the relative frequency noise between two lasers locked to the same cavity was taken, giving an upper bound on the noise performance of the digital system[14].

Many methods have been developed to stabilize the frequency of continuous wave (CW) laser; however, few methods have been reported for the pulsed laser. In this letter, a new method for laser-frequency stabilization by controlling the pulse setup time is presented. In this system, a high-speed counter is used to record the setup time, and a controlling circuit is designed to analyze and calculate the time period. The laser frequency is then stabilized by adjusting the cavity length in order to select the shortest setup time. Meanwhile, the highest power can be obtained according to the laser theory. This system stabilizes the laser frequency by detecting the output of pulsed laser without any frequency discriminator; thus, it has the advantages of compactness, small size, and lower cost.

According to the laser theory and our experimental study of the RF-excited waveguide CO_2 laser[15−21], the pulse setup time varies with output power. The relationships of the laser intensity and laser setup time versus cavity length are shown in Fig. 1. Tian *et al*. analyzed the relationship between the pulse intensity and the transmittivity of output mirror[22]. The laser intensity in the cavity is increased, and the pulse setup time is reduced with the decrease of transmittivity of the output mirror. In fact, the decrease of transmittivity of the output mirror is equivalent to the increase of the laser

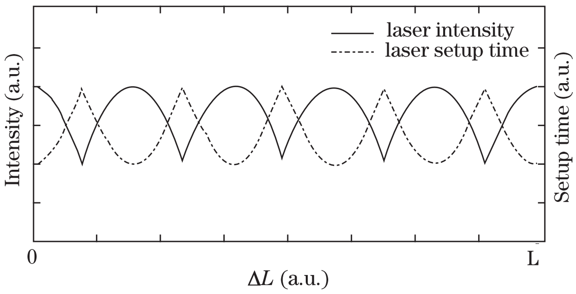

Fig. 1. Laser intensity and laser setup time versus cavity length relations.

gain in the cavity. Therefore, we can conclude that the laser pulse setup time varies with the gain in the cavity. According to the laser theory, there exists a gain peak on the laser gain curve. The laser pulse setup time is the shortest at the highest gain. The laser frequency can be stabilized if the laser is locked at the center of the gain curve. In other words, the laser frequency can be stabilized if the laser is locked at the point of the shortest pulse setup time.

On the basis of the above theory, we constructed a system to stabilize the frequency of the RF-excited waveguide CO_2 laser. The process of frequency stabilization of the pulse laser is shown in Fig. 2. The laser begins to output pulses at a certain time delay after being triggered by RF signals. After being split by a beamsplitter, the optical signals are changed into electric pulses by the detector and become amplified. A high-speed counter is adopted to count the clock signals, beginning with the RF signal and ending with an electric pulse changed into a square wave by the shaping circuit. A microprocessor is then used to read the data from the counter, as well as to analyze and calculate the time period. The time values are compared with one another to select the shortest time period. The corresponding voltage is then amplified and fed back to the piezoelectric transition (PZT) to adjust the cavity length of the pulse laser. The frequency is thus stabilized to the center of the gain curve.

The frequency-stabilization system consists of four parts: waveform-conversion circuit, high-speed counter, central controlling circuit, and digital-to-analog (D/A) converter. Because the analog signal obtained from the detector cannot be incepted by the digital counter, a waveform-conversion circuit is designed using a high-speed voltage comparator. The laser pulse is changed into a transistor–transistor signal and is input into the counter. The high-speed counter, composed of complex programmable logic device (CPLD), records the period time by counting the clock signal of the CPLD (frequency is 40 MHz) from laser trigger to laser output, and saves the data into a latch. Then, a microprocessor, as the central controller, is used to read the data from the latch, as well as to analyze and calculate the time period. The values of the times are compared with one another to select the shortest time period. Finally, the digital voltage is converted into analog voltage by the D/A converter. The analog voltage is amplified and fed back into the PZT, adjusting the cavity length of the pulse laser to control the laser frequency. Accordingly, the laser frequency is stabilized to the center of the gain curve. Using the software, a digital filter is designed, which has highly improved the accuracy previously prevented by noise and error from the system and other apparatuses. These four parts comprise a high-speed closed-loop control system. The time recording precision is 25 ns. In addition, a circuit is designed to display the setup-time value. The display cycle is 200 ms. Consequently, the variance of the setup time can be recorded and observed periodically.

The configuration of the pulse RF-excited waveguide CO_2 laser tuned by grating used for frequency stabilization is shown in Fig. 3. The waveguide channel with a cross-section of 2.25 × 2.25 (mm) is a sandwich structure made of metal and ceramics. The length of the laser cavity is 750 mm. A grating is placed on one side of the laser cavity. A plane output mirror is mounted on the other side of the cavity. The plane diffraction grating is used as wavelength selector. A PZT is attached to the rear of the diffraction grating. The laser frequency can be tuned by changing the voltage on the PZT. The frequency of the RF source is 80 MHz. The laser can be run in pulse or CW mode.

According to the setup-time method, the laser needs to work in the pulse mode. At a pulse repetition rate of 10 kHz, P(20) 10.6-μm laser output could be obtained. This is detected by a high-speed photovoltaic HgCdTe detector. The laser pulse shape is shown in Fig. 4. The square wave at the top of the figure is a trigger signal, and a laser waveform is at the bottom. The tailing phenomenon is obvious; the pulse width is 700 ns, and the tailing continues for dozens of microseconds. The setup time is the period from the beginning of the trigger signal to the laser pulse. Figure 4(a) shows the pulse laser waveform when the laser is in the open-loop condition, and the setup time is approximately 12 μs. It shows that the value of the setup time fluctuates greatly from the oscilloscope. Figure 4(b) shows the output waveform when the laser is in the closed-loop condition. At this time, the setup time is approximately 4 μs, and the drift of the setup time is shorter.

The experimental results are illustrated in Fig. 5. The setup time has been recorded under and out of the control of the frequency-stabilization system. The dotted line represents the variance of the setup time when the

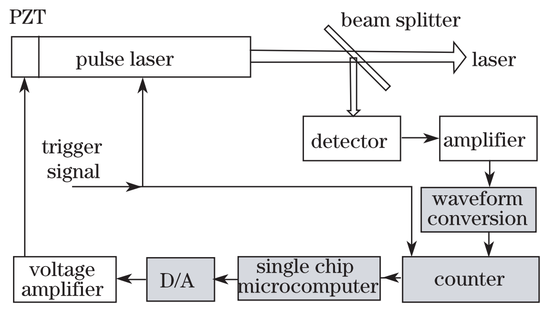

Fig. 2. Process of the frequency stabilization.

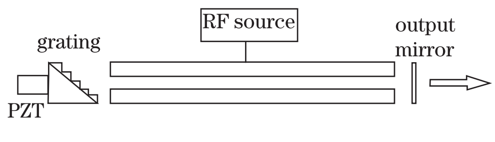

Fig. 3. Structure of RF-excited waveguide CO_2 laser.

laser is in open-loop condition. Within 30 min, the setup time changes constantly, and the variance is approximately 16 μs. The solid line represents the variance of the setup time while the frequency-stabilization system is in closed-loop condition. Although the setup time still changes, the variance of the setup time is reduced to 4 μs.

The gas mixture in the laser is CO_2, N_2, and He, with a total pressure 40 torr. The gain curve for the laser medium is shown in Fig. 6. According to the gas laser theory, the line width is approximately 200 MHz ($\approx$5 MHz/torr for CO_2 laser). From Fig. 5, when the frequency-stabilization system is in closed loop, the variance of the setup time is reduced to one-fourth of that in the open-loop condition. Correspondingly, as shown in Fig. 6, the frequency drift is estimated to be less than $\pm$25 MHz; thus, the frequency of the pulsed laser is stabilized.

In conclusion, the setup-time method for frequency stabilization is presented. The frequency of the pulsed laser is stabilized by integrated circuit without any complicated frequency discriminator. Therefore, the frequency-stabilization system has the advantages of simplicity, small volume, low cost, and high stability. It can be applied in the frequency stabilization for other types of pulsed laser. In our experiment, the frequency-shift value of the pulse RF-excited laser is less than $\pm$25 MHz; thus, this method is proven to be feasible. However, compared with other frequency-stabilization methods, the frequency fluctuation in our experiment is slightly larger. Further experiments are being conducted to achieve higher frequency stability.

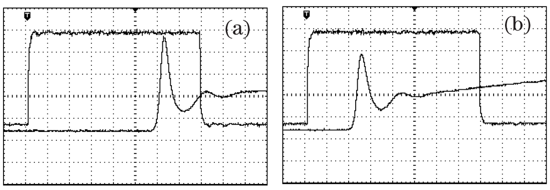

Fig. 4. (a) Trigger signal and laser waveform in the condition of open loop; (b) trigger signal and laser waveform in the condition of closed loop.

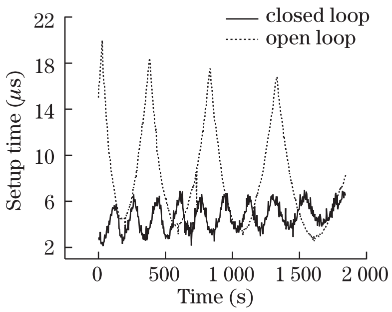

Fig. 5. Variances of the setup time in open- and closed-loop conditions.

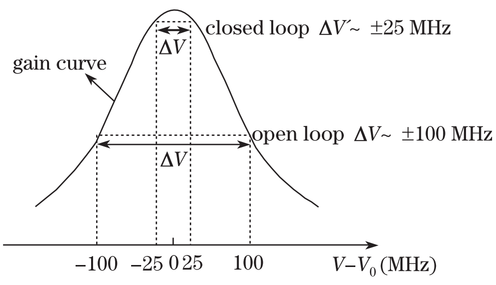

Fig. 6. Variances of the frequency under open- and closed-loop conditions.

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