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Stabilization of Laser Frequency Based on the Combination of Frequency Locking and Power Balance Methods

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Abstract: In this study, a new laser frequency stabilizer based on the combination of power balance and frequency locking methods is presented. These methods have been widely used in the two-mode laser frequency stabilizers. But in this study, we design and simulate an optical setup and thermal cavity controller to improve the frequency stability of three-mode He-Ne laser. Stabilization of the secondary beat frequency (frequency locking) and amplitudes of three modes (power balance) cause standing position of them to be fixed in the gain profile. The results of simulations by SIMULINK indicate that thermal coefficient of the laser cavity and frequency stability are equal to 1.2 Hz/nm and 3 parts in 10^{10}, respectively.

Key words: Frequency locking, frequency stabilization, He-Ne laser, power balance

INTRODUCTION

This study presents a new three-mode He-Ne laser frequency stabilizer. A precision stabilized laser is necessary in many optical instruments, e.g., nano-metrology systems (Yokoyama *et al.*, 2005; Olyaee and Mohammad Nejad, 2007a). The accuracy of nano-metrology measurements is essentially depended on the frequency stability of the laser cavity. The stabilized multimode lasers as reference sources are widely used in various applications such as laser interferometers.

Many efforts are still being developed for two-mode laser frequency stabilization systems. First, Balhorn *et al.* (1972) presented two-mode He-Ne laser stabilizer. The stability was increased by utilizing the improved circuits and cavity length controllers (Eom *et al.*, 2002; Kim and Kim, 2002; Huang *et al.*, 2000). But, three-mode He-Ne lasers should be stabilized by more complex instruments. Stabilization of the frequency and power of three-mode He-Ne laser was first introduced by Suh *et al.* (1993). Also in development of two-mode He-Ne laser frequency stabilization, a three-mode oscillation in the gain curve was observed (Yokoyama *et al.*, 1994). This stabilization was based on the frequency pulling effect. And finally an effective method with high frequency stability was reported by Yeom and Yoon (2005). The square-root Allan variance between their stabilized laser and iodine stabilized He-Ne laser and the frequency fluctuation were reported as 5×10^{-11} at average time of 1sec (short time) and ±1 MHz, respectively.

In the present study, we design a laser frequency stabilization system for three-mode He-Ne lasers. The designed stabilizer is based on the combination of frequency locking and power balance methods. We improve the frequency stability of three-mode laser software based by combination of two mentioned methods. The simulation results indicate that the laser frequency fluctuation reaches about 148 kHz.

MATERIALS AND METHODS

The free spectral range or mode spacing in the laser cavities is determined by:

$$\mathrm{FSR} = \frac{c}{2nL} \tag{1}$$

Where:
L = The cavity length
n = The refractive index of medium
c = The velocity of light in free space

Therefore, by increasing the cavity length of a laser, such as a He-Ne laser, the mode spacing decreases. According to the dimension and structure of the cavity, the frequency difference range is 3 MHz to 1 GHz in

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Corresponding Author: Saeed Olyaee, Department of Electrical Engineering, Shahid Rajaee Teacher Training University (SRTTU), Lavizan, 16788, Tehran, Iran Tel/Fax: +982122970006 commercial Zeeman He-Ne lasers, He-Ne lasers with an Acousto-Optical-Modulator (AOM) and stabilized two-longitudinal-mode laser cavities (Yan *et al.*, 2003). Inhomogeneous line broadening or Doppler broadening of the laser is described as:

$$g(\nu)=\left(\frac{4\ln 2}{\pi}\right)^{1/2}\frac{1}{\Delta\nu_D}\exp\left[-4\ln 2\left(\frac{\nu-\nu_0}{\Delta\nu_D}\right)^2\right] \tag{2}$$

Where:

$\Delta\nu_D$ = The Doppler line width

ν_0 = The central optical frequency

The curve for the neon in a He-Ne laser will have a half-width in the order of 1.5 GHz at 633 nm wavelength. As a result, the number of modes in the gain curve can be determined by the cavity length. Considering the 35 cm cavity length, the gain profile of the laser source can contain three longitudinal modes. The polarization of the side modes (λ_2 and λ_3) is orthogonal to the polarization of the central mode (λ_2) due to the polarization anisotropy of the laser mirrors (Yeom and Yoon, 2005). Assuming the linearly polarized modes, the side modes can be separated from central mode by a polarizing beam splitter. The electrical fields of three modes are obtained as:

$$\begin{aligned}\vec{E}_1 &= E_{01}\cos(2\pi\nu_1 t+\varphi_{01})\vec{a}_1\\ \vec{E}_2 &= E_{02}\cos(2\pi\nu_2 t+\varphi_{02})\vec{a}_2\\ \vec{E}_3 &= E_{03}\cos(2\pi\nu_3 t+\varphi_{03})\vec{a}_3\end{aligned} \tag{3}$$

Where:

E_{0j} (j = 1, 2, 3) = The electrical fields amplitudes

$\vec{a}_j$ = The unit vectors

φ_{0j} = The initial phases

The intermode beat frequency decreased resulting from the cavity thermal expansion. By differentiation of Eq. 1, it can be given by:

$$d\nu_b=-\frac{c}{2L^2}dL \tag{4}$$

Where:

$d\nu_b$ = The drift of intermode beat frequency

dL = The cavity length thermal expansion

Interference of the reference and measurement beams produces three intermode angular beat frequencies, $\Omega_H = 2\pi(\nu_3-\nu_2)$, $\Omega_L = 2\pi(\nu_2-\nu_1)$ and $\Omega_H+\Omega_L = 2\pi(\nu_3-\nu_1)$. By using a proper signal conditioner, as shown in Fig. 1, the secondary angular beat frequency, $\Omega_S = |\Omega_H-\Omega_L|$, is extracted (Olyaee and Mohammad Nejad, 2007b). The photocurrent is converted to voltage signal and after amplification, $\Omega_H+\Omega_L$ is eliminated by the Band Pass Filter (BPF.1). Then by using a Double-Balanced Mixer (DBM) and another Band Pass Filter (BPF. 2), the secondary beat frequency is extracted.

If the intermode beat frequencies are kept constant, the standing position of modes can be fixed in the gain curve (Yokoyama *et al.*, 1994). Therefore, cavity length and standing position of modes are fixed by measuring the secondary beat frequency and feedback to the heater (Fig. 2).

Owing to the square-law behavior of the photo-detector, the photocurrent is calculated as:

$$I_{APD} \propto |E_1+E_2+E_3|^2 \tag{5}$$

Substitution of Eq. 3 into 5 and elimination of dc and high order frequency components because of using a

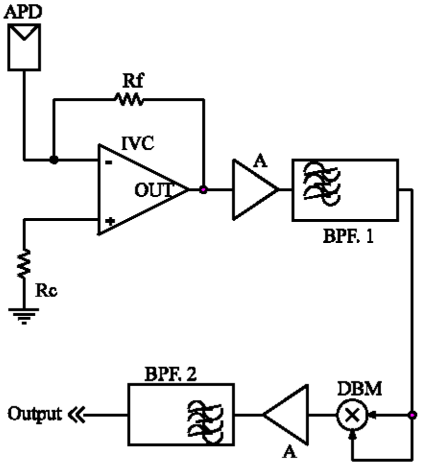

Fig. 1: Extracting the secondary beat frequency by signal conditioner circuit

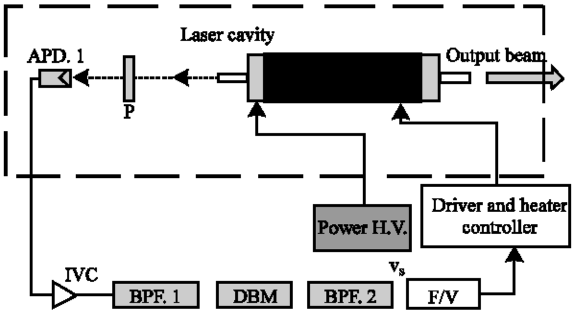

Fig. 2: The schematic diagram of the designed frequency stabilization system based on the frequency locking method

band pass filter, as shown in Fig. 2, the output signal of the BPF. 1 can be written as:

$$V_{BPF.1} \propto E_{o1}E_{o2}\cos\left(2\pi\nu_L + \varphi_{o2} - \varphi_{o1}\right) + E_{o2}E_{o3}\cos\left(2\pi\nu_H + \varphi_{o3} - \varphi_{o2}\right) \quad (6)$$

Where, $\nu_H = \nu_3 - \nu_2$ and $\nu_L = \nu_2 - \nu_1$ are the higher and lower intermode beat frequencies, respectively. This signal is self-multiplied by a double-balanced mixer and then BPF. 2 eliminates dc and high frequency components. Therefore:

$$V_{BPF.2} = k_1 E_{o1} E_{o2}^2 E_{o3} \times \cos\left(2\pi\nu_S + \left(\varphi_{o3} - 2\varphi_{o2} + \varphi_{o1}\right)\right) \quad (7)$$

Where:
k_1 = The transfer gain

As shown in Fig. 2, the output signal of the frequency to voltage converter (F/V) is sent to driver and heater controller stage to adjust the laser cavity length.

In addition, if amplitudes of modes are kept constant, as a result, the laser frequency can be stabilized (Eom *et al.*, 2002). Figure 3 represents the designed power balance stabilization system for three-mode He-Ne laser. Two beams are separated by a polarizing beam splitter in accordance with polarization properties of them and are incident on the avalanche photodiodes. Photocurrents of APD.2 and APD.3 are converted to voltage. Because there are high order frequency components in the output of the current-to-voltage converter (IVC.1), a low pass filter is used. Therefore, the output signals of two paths are given, respectively by:

$$V_1 = k_2 \frac{E_{o2}^2}{2} \quad (8a)$$

$$V_2 = k_3 \left(\frac{E_{o1}^2 + E_{o3}^2}{2} \right) \quad (8b)$$

Where:
k_2 and k_3 = The transfer gains of two paths

The differential value can be applied as an error signal to heater controller of the laser cavity. The cavity length is adjusted by controlling the current of thin-film heater.

Figure 4 shows the optical head of a new scheme of laser frequency stabilizer by combination of designed frequency locking and power balance stabilization systems. The back beam of three-mode laser is separated by a non-polarizing Beam Splitter (BS). After passing the reflected beam through 45° linear polarizer, it is focused on a high-speed low-noise SLIK avalanche photodiode (APD.1). A signal having primary beat frequencies is produced by avalanche photodiode resulting from interference of the electrical fields of three modes after passing through the linear polarizer. The passed beam of non-polarizing beam splitter is directed towards the polarizing beam splitter and two photo-currents in accordance with amplitude of the electrical fields are produced.

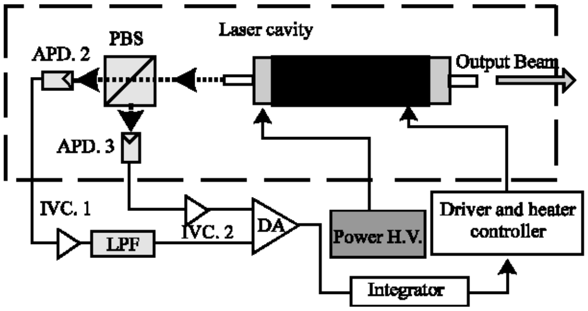

Fig. 3: The schematic diagram of the designed frequency stabilization system based on the power balance method

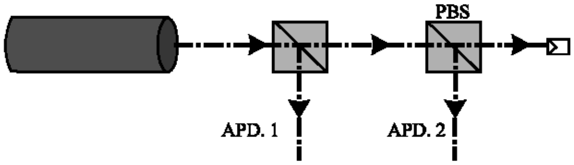

Fig. 4: The optical head of laser frequency stabilizer

The output signal of APD.1 through the current to voltage converter is sent to the band pass filter (Fig. 5). Earlier, interference of modes produces intermode beat frequencies and dc components. Therefore, it is needed to extract the secondary beat frequency by double-balanced mixer and another band pass filter. Then, the signal is sent to a frequency to voltage converter (F/V). The output signal of F/V can be used as a part of error signal. On the other hand, in parallel path, a differential amplifier produces another part of the error signal.

According to Fig. 4, the central mode and side modes are incident on the APD.2 and APD.3, respectively. Therefore, a low pass filter is needed at the end of IVC.1. Two error signals are added by a dc level to produce control signal.

If the standing position of modes is not changed, the control signal will be constant. Changing in the cavity length causes the error signal to be produced. The control signal is sent to a Voltage Control Oscillator (VCO) and through a phase/frequency detector and loop filter is sent to a Pulse-Width Modulation (PWM) controller.

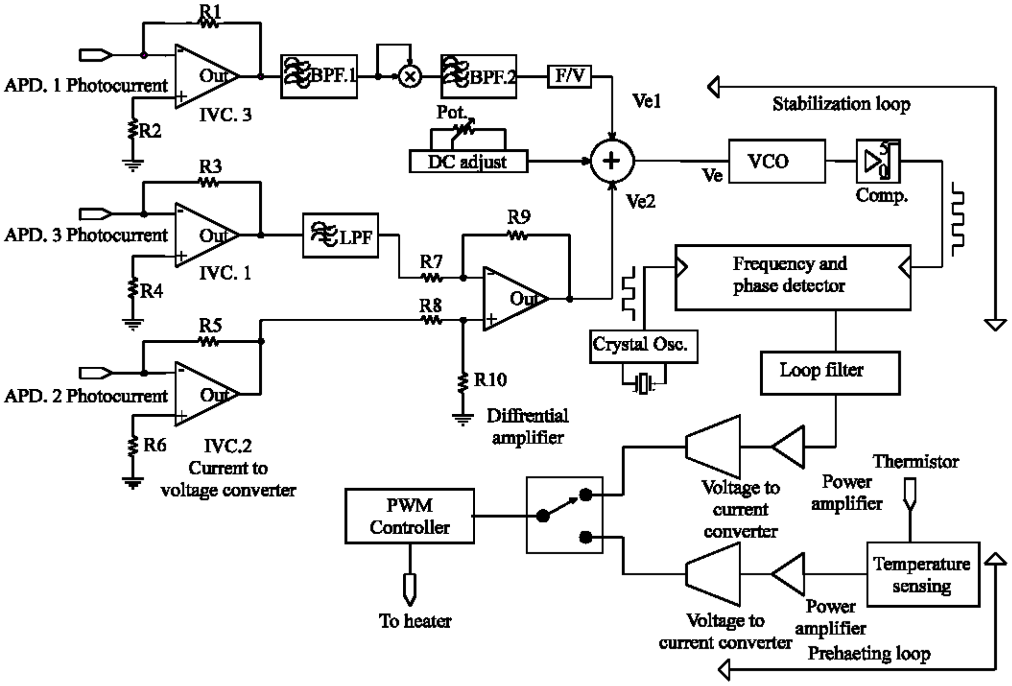

Fig. 5: The laser frequency stabilization system based on the combination of frequency locking and power balance methods

When laser turn on, as shown in Fig. 5, a pre-heating cycle is activated. Therefore, the temperature of laser cavity reaches suitable value. The cavity temperature can be measured by a thermistor. Then, stabilization loop is closed and cavity length is controlled. The loop filter is chosen as a PID controller in which can be adjusted the transient time and steady-state response.

This study that is a joint study between the Optoelectronic and Laser Laboratory of Iran University of Science and Technology (IUST) and Shahid Rajaee Teacher Training University (SRTTU), is based on the theoretical materials which all results are obtained from software simulations.

RESULTS AND DISCUSSION

To have a three-mode laser, the free spectral range and secondary beat frequency are considered as 435 MHz and 300 kHz, respectively, at 633 nm wavelength (Yokoyama *et al.*, 2005).

From Eq. 4, the intermode beat frequency is decreased by 387.4 Hz resulting from one period change ($\lambda/2$). Consequently thermal coefficient is given about 1.2 kHz μm^{-1}.

The stabilization of three-longitudinal-mode He-Ne laser based on the thermal phase locking of the secondary beat frequency was reported by Yeom and Yoon (2005). They improved the short-term frequency stability to 5×10^{-11}. But we suggest a power balance stabilizer in parallel to the phase locking of the secondary beat frequency to achieve higher stability.

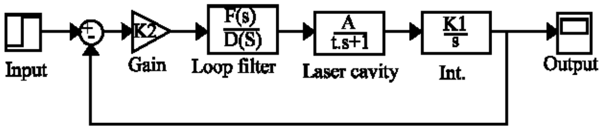

Fig. 6: The block diagram of the laser cavity and its stabilizer

Thermal transfer function of the laser cavity and its enclosure is complex, but its Laplace (S) transfer function can be modeled in the SIMULINK as (Chien and Pan, 1991):

$$G(S) = \frac{A}{1+\tau S} \tag{9}$$

Where:

A = The transfer gain of power driver

τ = The time constant of laser cavity

The loop filter is defined as a Laplace transfer function, F(S)/G(S), which is designed for PID controller (Fig. 6).

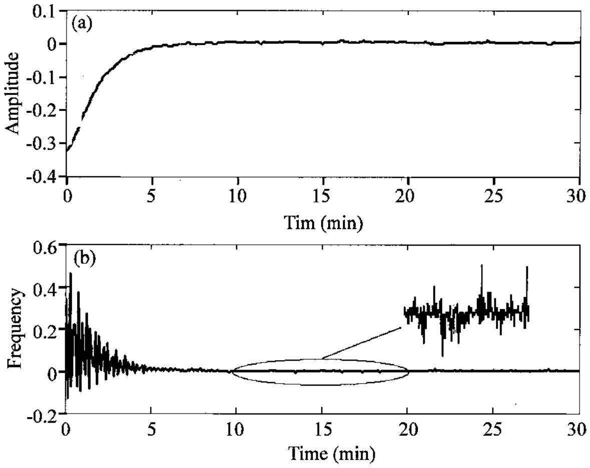

Fig. 7: The result of stabilization, (a) response to the step and (b) laser frequency fluctuations

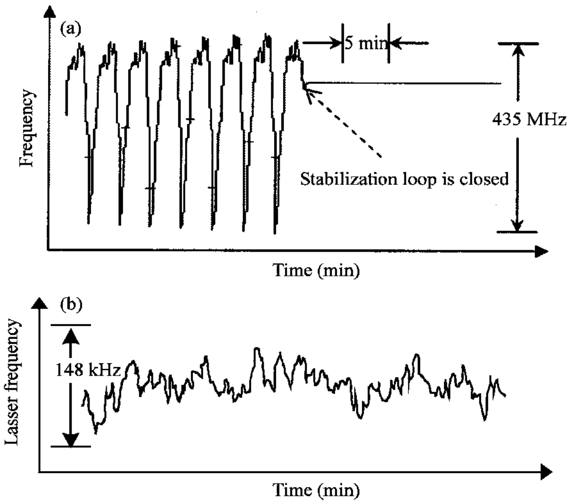

Fig. 8: (a) Simulation result of the beat frequency fluctuations and (b) estimated fluctuations of the laser frequency in the steady state regime

The simulation results for laser behavior are also shown in Fig. 7. First, preheating cycle is activated to reach suitable temperature. Then stabilization loop is closed. According to Fig. 5, in stabilization loop, two error signals (Ve_1 and Ve_2) are added to a dc level (V_{dc}).

In the experimental setups, the stability is commonly measured by Allan variance between the stabilized laser and iodine stabilized He-Ne laser and here we assumed ideal laser for comparing (Fig. 8). As shown in Fig. 8a, the peak-to-peak range of error signal corresponded to the beat frequency. When stabilization loop is closed, this range considerably decreases. The frequency instability can be estimated from the error signal fluctuations which it is theoretically confined to about 148 kHz, as shown in Fig. 8b. This value corresponds to stability of 3 parts in 10^{10} or 3×10^{-11} which is better than other stabilizers.

CONCLUSIONS

A new system of frequency stabilization based on the frequency locking and power balance methods has been presented. The stabilization system was designed for three-mode He-Ne laser with 435 MHz free spectral range and 300 kHz secondary beat frequency. The simulation results indicated that frequency fluctuations was successfully reached about 148 kHz or frequency stability of 3×10^{-11}.

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