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Frequency stabilized HeNe gas laser with 3.5 mW from a single mode

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ABSTRACT

This paper describes an optical frequency stabilization technique using a three-mode Helium Neon laser at 632.8 nm. Using this configuration, a maximum frequency stability relative to an iodine stabilized laser of 6×10^{-12} (71 s integration time) was achieved. Two long term measurements of 62 h and 40 h showed fractional frequency fluctuations of 6.2×10^{-10} (2σ) and 1.6×10^{-10} (2σ) when correcting for known frequency fluctuations outside the controller bandwidth, respectively. This stabilization scheme maximizes the available optical power (1.7 mW in this instance) because the output mode is in the center of the HeNe gain curve. This stabilization technique was also verified for a larger HeNe laser with a lower free spectral range. While not optimized for this configuration and laser, we demonstrated fractional frequency fluctuations below 1×10^{-8} with 3.5 mW of usable output power. This is useful for multi-axis systems or systems employing fiber coupling. In this paper, the overall system is described and data containing the frequency locking signal sensitivity, profile during laser warm up, sensitivity to environmental fluctuations, and optical power of the locking signal is shown.

1. Introduction

Helium Neon (HeNe) gas lasers are widely used in research and industrial applications because they are directly traceable to the meter [1,2], have a narrow linewidth [3], have high coherence, and can be frequency stabilized via relatively simple techniques [4–7]. Stabilized HeNe lasers are frequently employed as the source for displacement interferometry applications, most requiring low optical power (around 1 mW). However, as the optical system complexity increases and more fiber-based, remote delivery systems are developed, fiber insertion losses can significantly reduce the total available power to the system. Instead, diode lasers or solid state lasers are used which have significantly higher output power but either suffer from a high capital cost for the laser or have insufficient linewidth, coherence, or frequency stability for the intended application. Conversely, HeNe lasers only need a higher output power out of a single mode to further their practicality in future optical systems. The output power of stabilized HeNe lasers has largely been limited because the frequency stabilization techniques require lasers with at most two modes present.

The two most common HeNe laser frequency stabilization techniques are based on Zeeman stabilization [6,8] and intensity balancing [4,9]. Zeeman stabilization is typically employed using a single mode laser, limiting the overall optical power available to less than a milliWatt. The axial magnetic field in a Zeeman laser splits the level scheme of the gain medium into two different indices creating two coaxial output beams with slightly different frequencies. The frequency difference is dependent on the magnetic field strength and has a minimum when absolute frequency is in the center of the gain curve [6]. Typically, the two output beams have a frequency difference between 1 MHz and 4 MHz for commercial systems. The output beams are orthogonally polarized and both are circularly polarized. This laser stabilization technique has been widely used in displacement interferometry specifically for its two frequency, orthogonal output. However, the two orthogonal polarization states are not perfect due to manufacturing tolerances and optical mixing, which leads to nonlinearity in the measured phase [10]. Also, the split frequency can be limited which can be a problem for high speed measurements, particularly when the target shows a high negative Doppler shift.

Frequency stabilization via intensity balancing is typically achieved with a longer laser tube, allowing for two simultaneous modes within the HeNe gain curve, spaced several hundred MegaHertz apart. Consecutive modes in a laser without Brewster windows have alternating orthogonal polarization states. When both modes are nearly symmetric with the center of the gain curve,

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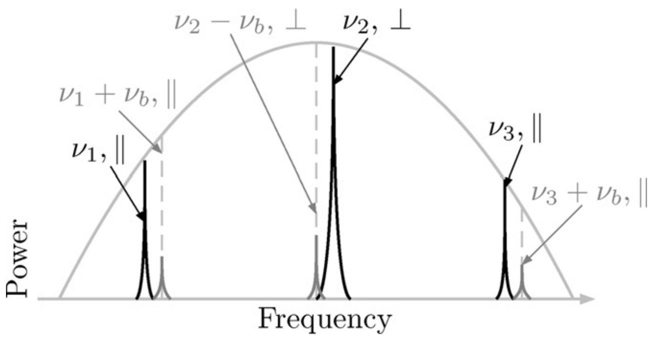

Fig. 1. Schematic of the three main modes and three mixed modes when nominally symmetric within the HeNe gain profile. Consecutive laser modes are orthogonally polarized and the smaller modes have the same polarization state as their nearest main mode. Because of this, ν_2 and $(\nu_2 - \nu_b)$ can be isolated with a polarizer or optical isolator.

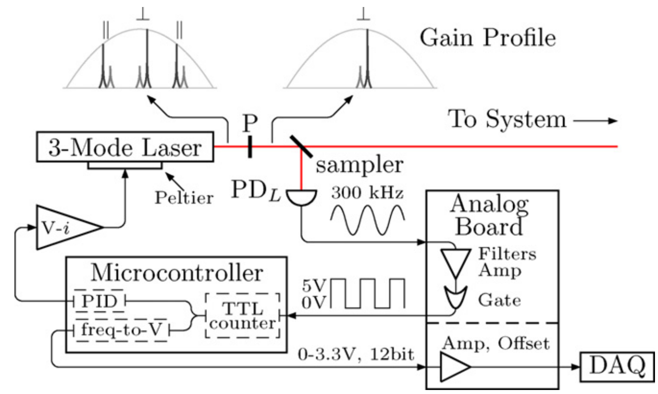

Fig. 2. Combined optical and electrical schematic for stabilizing the three-mode laser. The central modes are isolated with a polarizer (P). A part of the beam is sampled and detected using a photodiode (PD$_L$). The nominally 300 kHz locking signal is filtered, amplified, and gated into a 5 V TTL and sent to a microcontroller. A microcontroller measures the frequency and generated a PID signal relative to a set point. The controller signal is then converter to a current, driving a peltier which changes the laser cavity by thermal expansion.

a part of the output beam is split by polarization. The optical power of both polarization states is detected, compared, and the difference is used for feedback. Since both modes are balanced relative to the center of the HeNe gain curve, the total potential power is not optimal because the center of the HeNe gain curve is not used, limiting the power of a single mode to approximately 1.3 mW [11].

In previous research, we demonstrated a frequency stabilization technique which used a HeNe laser with three modes nominally symmetric within the gain profile [12]. The three-mode HeNe laser has three main modes along with three additional mixed modes, each with a low power and adjacent to a main laser mode [13–15]. A schematic of this is shown in Fig. 1. In this technique, a mixed mode within the optical cavity is used to stabilize the absolute laser frequency. As the laser modes slew due to laser cavity expansion, the relative location of the mixed modes to their adjacent main modes changes as a function of absolute frequency. The central mode, which has the highest optical power of the three, can be isolated due to its orthogonal polarization state and used for practical applications[1]. The slight frequency difference (below 1 MHz) between the main central mode and the smaller central mode can be detected and used for feedback stabilization.

Like the Zeeman and intensity balanced lasers, the feedback stabilization method is fairly simple: detect a signal representative of an absolute frequency shift and change the cavity appropriately to stabilize that signal. However, no external magnetic field is necessary and the central part of the HeNe gain profile is used, which means a higher output is available for the desired application.

In this paper we discuss the basics of the three-mode laser operation and theory. Frequency stability results relative to an iodine stabilized laser for two controllers are shown and discussed. In the preliminary configuration, the absolute fractional frequency stability was better than 5 parts in 10^{10}. After improving the controller, this was reduced to 2.5 parts in 10^{10} with 2 mW available for use. Additionally, we demonstrated this stabilization technique on a second laser with a free spectral range (FSR) much smaller than the first laser. The smaller FSR and longer optical cavity allows for a higher output power. Once stabilized with the outer modes blocked, this longer laser had an output power greater than 3.5 mW.

2. Three-mode stabilization

Lamb [13] first described the model of the three-mode laser where, when nearly symmetric in the HeNe gain profile, the three-mode laser contains three additional low power modes. The three additional smaller modes arise from third-order nonlinear harmonics and their exact frequency difference with respect to their nearest adjacent mode depends on cavity tuning and the excitation state of the active medium. In this work, the frequency difference between a smaller mode and its main mode, ν_b, ranged between 200 kHz and 550 kHz. As shown in Fig. 1, the three main modes from lowest frequency to highest are ν_1, ν_2, and ν_3 and the three smaller mode frequencies are $(2\nu_2 - \nu_3)$, $(\nu_1 + \nu_3 - \nu_2)$, and $(2\nu_2 - \nu_1)$. Alternative expressions for the three smaller modes are $(\nu_1 + \nu_b)$, $(\nu_2 - \nu_b)$, and $(\nu_3 + \nu_b)$, respectively.

The locking signal is obtained by isolating ν_2 and $(\nu_2 - \nu_b)$ using a polarizer or optical isolator because successive modes of a laser without Brewster windows have orthogonal polarization states. In this particular system, we used a 30 dB optical isolator to block the orthogonal outer modes and prevent optical feedback in the cavity. An optical spectrum analyzer was used to verify no outer modes were present. The output beam was sampled and ν_b was detected with a low speed photodiode (<600 kHz) and used for feedback stabilization. As the laser frequency changes due to thermal fluctuations in the cavity, the frequency of ν_b changes because the locations of the three modes (and subsequent mixed modes) change. The laser frequency was stabilized by detecting the frequency changes of ν_b relative to a microcontroller clock and stabilizing those changes by thermal actuation, chosen here for practical reasons with the given HeNe laser. The feedback system consisted of a custom analog interface board, a microcontroller prototyping board employing a PID controller, and a custom current amplifier driving a peltier device which changes the laser cavity length by heating or cooling the laser tube. A schematic of the system is shown in Fig. 2. Fig. 3 shows a schematic of the setup for comparing the three-mode stabilized laser with an iodine stabilized laser.

The locking signal amplitude is small compared to the DC signal level. The custom analog interface board contains a high pass filter (10 Hz) and a two stage amplifier to ensure sufficient signal amplitude to trigger the 5 V TTL gate. The 300 kHz, 5 V TTL signal is counted by the microcontroller over a 20 ms interval to obtain ideally 6000 counts. Using this method, the controller frequency resolution is 50 Hz. The deviation from 6000 counts is then sent to a PID controller with anti wind-up. The number of counts is also used for a generic frequency to voltage converter to measure the frequency reading in the microcontroller. Both the PID controller and frequency to voltage signals are converted to 12 bit analog signals 0–3.3 V. They are then sent to the analog board where they

[1] Smaller modes have the same polarization as their closest main mode.