Improvement of intermodal frequency stability of two-mode HeNe laser

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Abstract. A method of improving intermodal frequency stability of two-mode helium-neon laser has been developed. The approach is based on using in the stabilization circuit a signal processor for real-time analysis of data from an LF amplitude and an HF frequency detector. We propose to use the signal from the LF detector in the initial phase of the stabilization process and the signal from the HF detector afterwards. Experiments proved that with the suggested design it is possible to obtain frequency stability of the intermodal frequency better than 100 Hz or 2*10⁻¹⁰ for 1000s averaging. In the paper we also show the influence the intermodal frequency stability on the absolute stability of the laser frequency.

1. Introduction

Despite constant advances in semiconductor, fiber and solid state laser technologies, the gaseous helium-neon lasers are still the preferable choice in the industrial metrology. Currently the majority of commercially available high precision measurement systems are based on laser sources of this kind. Their narrow line width, excellent beam quality, good natural frequency and amplitude stability and relatively low cost make them perfect in all demanding metrology applications. Main applications of HeNe laser like shift or vibration measurements require good stability of the absolute frequency [1-8]. In other applications like optical vortices or Fizeau interferometers either amplitude or combined amplitude/frequency stability is required [9-11]. There have been reported He-Ne lasers with stabilized intermodal beat frequency [12-13] for use for example in laser distance meters [14]. The stability of the intermodal beat frequency was reported worse than 5 kHz. In [15] we presented the laser with intermodal frequency stability better than 2kHz. In this paper we show a method of construction of the two-mode He-Ne laser with the intermodal beat frequency stability value better than 100 Hz. Using light sources with such high modulation frequency stability allow omitting the influence of the source on the overall measurement accuracy when using such lasers as the source in a precision laser range finders.

2. Stabilization of the two-mode HeNe laser

The stability of a resonant cavity is determined by the change in its optical length. This change is due essentially to three causes:

1) thermal drift,
2) elastic vibrations of the structure,
3) fluctuations in the refractive index of the medium.

The cavity resonance frequency (for TEM₀₀ modes) is given by

\[ \nu_c = \frac{c}{2nL} \]  

where \( c \) is the speed of light, \( n \) is the refractive index along \( L \), \( q \) is the number of half wavelengths in \( L \) and \( L \) is the distance between the resonator mirrors.

For the internal mirror laser the largest influence on the overall frequency stability of the laser has the thermal drift of the resonator. Far less important, but not negligible, is the influence of the other two
effects. In [5] we showed the comparison of the influence of those factors on the frequency stability of two-mode HeNe laser.

Figure 1. Block diagram of a two-mode HeNe laser stabilized with the modes’ balance method

In the case of the most commonly used 1mW tubes, the usual method of obtaining the laser stability is keeping the balance between the power of two output modes of the laser [5, 7] – figure 1. In this method the modes intensity ratio is taken as the error signal for the stabilization loop. The desired situation (with error signal equal to zero) is when mode intensities become equal.

3. Experimental setup

Figure 2. Schematic diagram of the experimental setup. DSP, digital signal processor; NPBS, non-polarizing beam splitter. For clarity electronic blocks interfacing DSP with the optoelectronic elements of the laser tube are omitted.

A schematic diagram of the experimental setup is shown in the figure 2. The operation of the internal-mirror 1mW He-Ne laser (Lasos model LGR3655S) was controlled by a Digital Signal Processor DSP. Around the tube a thin thermal heater was wrapped. The parasite beam of the tube was used for the mode-intensity stabilization of the laser [15].

A part of the main output beam, split by the Non Polarizing Beam Splitter NPBS was directed to the High-Frequency Detector. The Detector HF was used for measuring the intermodal frequency of the
laser, while the Detector LF was used for monitoring the modes’ intensity. Information from both detectors were gathered and analyzed by the DSP. Depending on the measured values the power of the thermal heater was altered.

During the laser warmup there was observed the fluctuation of the intermodal frequency resulting from intra-cavity phase anisotropies [16] and from frequency pulling effect [17,18]. Discontinuities occurred during single mode operation regime of the laser. For the stabilization either the mode spacing with higher or with lower frequency was to be chosen. The choice had no influence on the following analysis. The only necessary requirement was that the laser had smooth mode change (i.e. no so called “mode flip”).

![Intermodal frequency change of the laser during heating up of the laser. The frequency measured in points A to F is decreasing.](image)

**Figure 3.** Intermodal frequency change of the laser during heating up of the laser. The frequency measured in points A to F is decreasing.

The idea of further improvement of intermodal beat frequency stability of the laser was to measure directly the beat frequency of the laser and to compare it to the predefined reference frequency. The comparison result was to be treated as the error signal and was, in the feedback loop, to be used for altering the temperature of the laser resonator.

As it was shown in [18] the intermodal beat frequency value declines with the resonator temperature (Fig. 3). Therefore the laser had to be locked first using standard mode balance method and only after the laser became stable the signal from the HF detector could have been used. The control loop of the laser was driven by the difference between the current value of the intermodal frequency and the value set as the reference.

![The functional diagram of the circuitry used for beat frequency measurement](image)

**Figure 4.** The functional diagram of the circuitry used for beat frequency measurement
In the figure 4 there is shown the functional diagram of the circuitry used for beat frequency measurement. In order to achieve higher accuracy and better measurement resolution the signal detected in the Detector HF was downconverted in the Mixer with the LO signal generated in the digital PLL. The output frequency of the DPLL was controlled by the DSP processor through a simple Serial Peripheral Interface SPI. Because of the high frequency of the detected signal and the required measurement precision special precautions were made to deliver to the mixing circuit high quality, low jitter clock from the PLL circuitry.

4. Measurements results of laser stability

![Diagram of measurement setup](image)

**Figure 5.** Measurement setup for estimation of SSFLC laser beam frequency stability and intermodal beat frequency stability. NPBS – Nonpolarizing Beam Splitter, P – Polarizer, D1, D2 – Detectors

The laser stability measurements were conducted in the circuit shown in the Figure 5. Simultaneous measurement of the intermodal and the absolute frequency of the laser were performed. The intermodal frequency was read from the detector D1 and the absolute frequency of the vertically polarized mode from the detector D2. The detectors were integrated with counters (Lasertex, model AVM-02) clocked from the same clock source as the DSP processor - the SSFLC stabilized laser and the D1 detector were clocked from the same 10 MHz clock. With this configuration of the clock path the stability of the clock source is irrelevant.
The frequency stability of the experimental laser is shown in the Figure 6 and as the Allan Variance plot in the Figure 7. The measurements were conducted for 48 hours (in the Figure 6 only first 10000s are shown). The intermodal frequency was very stable with small exception of the 0.2-2 seconds averaging range. The small “hump” in the variance plot at these averaging times was caused by either small backreflections within the testing circuit or imperfections of the laser loop control.
Registering signals from both photodetectors we compared the stability of the intermodal and absolute frequency. In the Figure 8 there is shown Allan Variance plot of the absolute frequency of the laser stabilized with “classic” and with the intermodal method. As it can be seen, the stabilization on constant value of the intermodal frequency causes worse stability of the absolute frequency. This behavior was expected as it was described in [18-20].

![Allan Variance plot](image)

**Figure 8.** Allan Variance plot of the absolute frequency of the laser stabilized with signal from LF detector (solid line) and with the signal from HF detector (dashed line).

5. Conclusions

In the paper we reported a new method of intermodal frequency stabilization in two-mode HeNe lasers. The method allows obtaining excellent stability of the mode beat frequency. Laser constructed according to the proposed method can be used in the applications like laser rangefinder, where the precision of the light source is important. Required for the proposed laser, the high-frequency electronics is currently cheap and easily obtainable. The method is not optimal if the absolute frequency stability is important.

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