Frequency Stabilization via the Mixed Mode in Three Mode HeNe Lasers

J.D. Ellis[1], K. Joo[1], E.S.Buice[1,2], J.W. Spronck[1], R.H. Munnig Schmidt[1]
[1]*Mechatronic System Design, Delft University of Technology, The Netherlands*
[2]*As of 19-01-10 at Lawrence Livermore National Laboratory, U S A*

j.d.ellis@tudelft.nl

Abstract

This paper describes a three mode HeNe laser frequency stabilization technique using the mixed mode frequency to obtain a fractional frequency stability of $2\text{x}10^{-11}$. The mixed mode frequency occurs due to optical nonlinear interactions with the adjacent modes at each of the three modes [1].

1 Introduction

In precision displacement interferometry systems, the laser source frequency must be stabilized to provide an accurate conversion ratio between phase change and displacement. In systems, such as lithography applications, which require high speed, high accuracy and low data age uncertainty, it is also desirable to avoid periodic nonlinearities, which reduces computation time and errors. One method to reduce periodic nonlinearity is to spatially separate the measurement and reference beams to prevent optical mixing, which has been shown for several systems (e.g. [2-4]). Using spatially separated beams and the proper optical configuration, the interferometer can be fiber fed, which can increase the interferometer's stability by reducing the number of beam steering optical elements. Additionally, as the number of measurement axes increases, a higher optical power from the laser source is necessary.

2 Laser Stabilization

The three mode laser has six different frequencies present within the gain curve, three main modes and three mixed modes, as shown in Figure 1A. By using a laser without Brewster windows, the main three modes alternate polarization state. Additionally, each mixed mode has been shown to have the same polarization state as its nearest main mode [1]. After isolating the central and central-mixed modes, at absolute frequencies (ν_2- ν_b) and (ν_2), the resulting interference signal with a frequency of ν_b can be measured (~100s kHz). This signal can then be stabilized relative to a crystal oscillator to stabilize the absolute laser frequency. Figure 1B shows a schematic for stabilization and heterodyne frequency generation. The central modes are isolated using an optical isolator and a portion of the main beam is split off and detected.

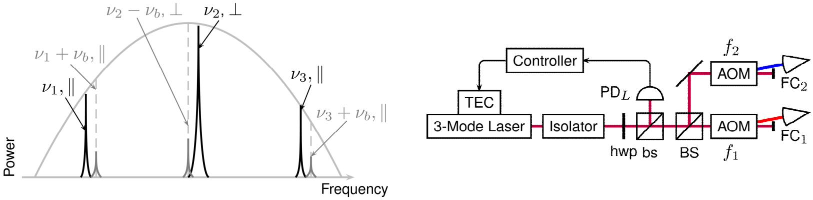

Figure 1: Left: Schematic of the main modes and mixed modes present in the three mode HeNe laser. Right: Schematic of the mixed mode isolation, stabilization feedback system, and optical heterodyne generation.

The controller consists of a pulse counter with 50 Hz resolution, a PID control section, and a digital to analog converter which sends the control signal to a thermo-electric cooler (TEC). Depending on the measured mixed mode frequency deviation, the TEC changes the laser tube temperature, causing an expansion or contraction of the cavity length which stabilizes the measured mixed mode signal. Using this control signal, the frequency stability of the central mode can be determined compared to the locking signal. This is shown in Figure 2A, where a portion of the absolute signal relative to an iodine laser and the mixed mode signal (after applying a linear scaling factor) is shown. In addition to the PID signal, the controller also outputs a separate DC signal based on the original frequency to voltage conversion, which has a resolution of ~10 Hz and is shown in Figure 2B. The mixed mode voltage conversion signal is slightly nonlinear as expected from previous research.

Figure 2C shows the frequency difference between the absolute frequency stability and mixed mode frequency after removing a linear trend, which is the conversion factor from mixed mode to absolute frequency stability. The sensitivity, for this particular laser, from absolute frequency stability to mixed mode frequency is -0.5936 MHz/kHz. When this laser was originally compared against the iodine reference laser, the controller was not tightly tuned because it is easier to determine a correlation coefficient between the absolute and mixed mode frequency fluctuations. After tuning the controller and shielding the laser, the mixed mode frequency fluctuations were limited to ~50 Hz, which is the resolution of the controller, which is shown in Figure 2D.

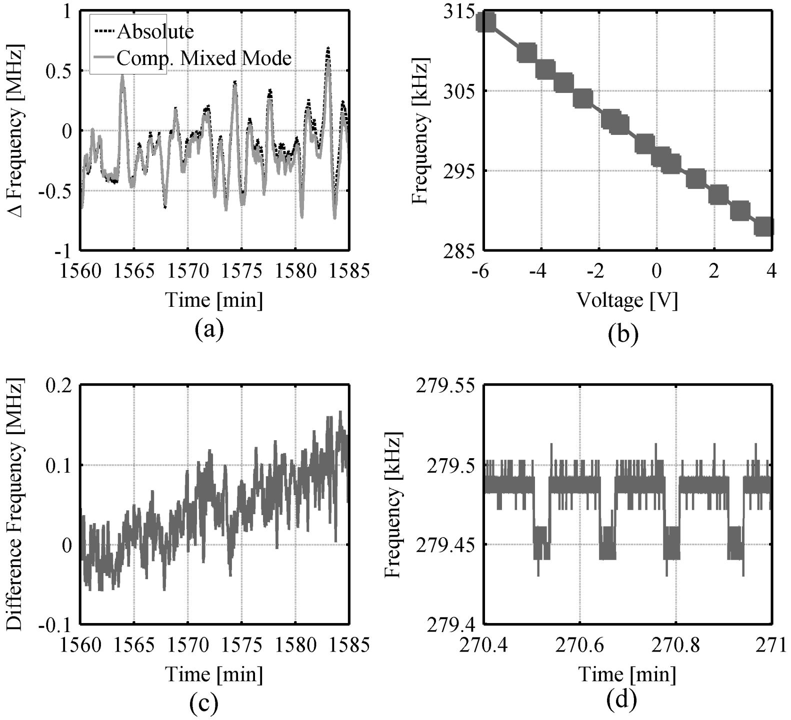

Figure 2: A) Measured frequency change relative to the absolute reference and the mixed mode signal (after correction). B) Slightly non-linear mixed mode signal frequency to voltage conversion. C) Difference between the absolute frequency fluctuations and the corrected mixed mode signal. D) Tight tuning of the mixed mode signal after determining correlation coefficients.

Using this method, we demonstrated an absolute frequency stability of 1 part in 10^{10} compared to an iodine stabilized laser over a 24 hour period, with a peak to peak value better than 1 part in 10^{9}. This was measured prior to tuning the controller for the tightest locking signal. After tuning the controller and shielding the laser, the estimated fractional frequency stability is better than 2 parts in 10^{11} over 1 second and 2 parts in 10^{12} over 24 hours, as shown in Figure 3A. During this measurement period, the peak to peak fractional stability (noise density) was better than 2 parts in 10^{11}, as shown in Figure 3B. It should be noted, this assumes constant sensitivity coefficients between the frequency to voltage converter and absolute frequency stability to mixed mode frequency. An additional benefit of using a three mode laser is that the central mode has a power greater than 2 mW, which is suitable for multi-

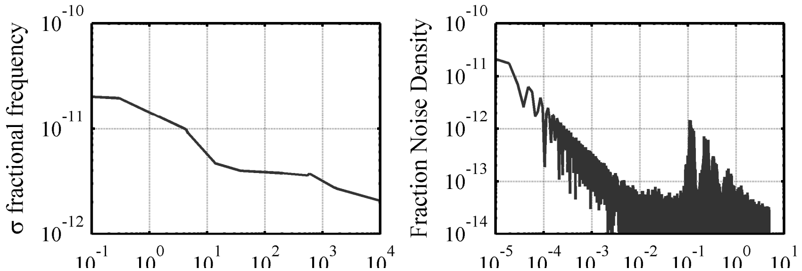

Figure 3: A) Allan variance after tuning the PID controller and shielding the laser, including conversion to fractional stability. B) Noise density of the locking signal after converting to fractional frequency fluctuations.

axis interferometry applications provided the heterodyne frequency is sufficiently far away to prevent frequency mixing. This system employs two acousto-optic frequency shifters, driven at a chosen split frequency to produce a fiber-coupled source with no source mixing. This can then be split using fiber-optic splitters for multiple measurement axes.

3 Conclusions and Future Research

Based on this research, non-spectroscopic based laser systems are nearing the stabilization level of the iodine stabilized reference laser. We currently demonstrate an order of magnitude less stability than an iodine laser, however, the absolute frequency value is unknown. Future research efforts should focus on determining a link between absolute frequency and the mixed mode signal, as well as tighter locking and increasing the power output.

This work was supported by the Dutch IOP (projects IPT06104 and IPT04001). The authors would like to thank TNO Science & Industry and the NMi van Swinden Laboratorium BV in the Netherlands in their partnership for this project.

Lawrence Livermore National Laboratory is operated by Lawrence Livermore National Security LLC, for the U.S. Department of Energy, National Nuclear Security Administration under Contract DE-AC52-07NA27344. LLNL-PROC-423493.

References:

[1] Ellis, J., *et. al.* Opt. Express **18**; 1373-1379 (2010)
[2] Lawall, J. and Kessler, E., Rev. Sci. Instrum. **71**; 2669-2676 (2000)
[3] Wu, C., *et. al.* App. Opt. **38**; 4089-4094 (1999)
[4] Joo, K., *et. al.* Opt. Lett. **34**; 386-388 (2009)