Investigating the laser sources used in displacement measurements

M. A. Amer and H. Hussein

Division of Length and Precision Engineering, National Institute of Standards, Tersa St., El-Haram, P.O.Box: 136 Giza, Egypt.

Abstract:

In order to set up a displacement measuring interferometer with high accuracy, the properties of the laser source (either Zeeman-stabilized He-Ne or acousto-optic frequency-split laser) used should be investigated. The warm-up time behaviour, the laser frequency stability, the temperature dependence of the laser frequency and its reproducibility are evaluated. Also, the laser wavelength was accurately determined by measuring the beat frequency between the laser under test and the Iodine-stabilized He-Ne laser. An Allan deviation of 6.89 X 10^{-11} $\tau^{-1/2}$ for averaging time of 3 seconds was found.

Key Words:

Heterodyne Interferometry, Displacement Measuring Interferometers, Frequency stability.

Introduction:

With the wide spread of laser applications in scientific research, industry, medicine, communication, it may be interesting to consider a laser field that has been active since the beginning of the laser era. This research area is concerned with precision measurements made with the use of highly stabilized lasers. One of the most important applications at NIS is the use of displacement measuring interferometers. In all cases, studying the characteristics of the laser source used is the aim of the present work, since the accuracy of the measurements depends on the frequency stability and the splitting frequency of the laser sources used. However in such applications, stability alone is not enough, it is also necessary that the wavelength of the oscillation be accurately reproducible and known in terms of the wavelength primary standard (He-Ne laser stabilized to the hyperfine components of R(127) transitions of I_2^{127}).

Applications of displacement measuring interferometers:

A Displacement Measuring Interferometer (DMI) measures linear and angular displacements with very high accuracy and precision. DMIs are used in a variety of applications which can be broken into two broad categories:

i. High-resolution real-time position control systems, such as those used in semiconductor lithography, e-beam and laser reticle writers, CD measurement tools, process equipment, and memory repair tools [1].

ii. Characterization of high resolution, high frequency mechanical motions such as piezo transducers, linear and rotary scale calibration, AFM stage calibration, and calibration of Coordinate-Measuring Machines (CMMs) [2].

Laser theory of operation:

For a DMI system to operate in optical heterodyne mode, the beam from the laser head must have two components that are orthogonally polarized and differ in frequency by a fixed amount. The frequencies must be known and need to remain stable over the lifetime of the laser. Two different methods of generating the frequency split are used in industry; Zeeman technology and an acousto-optic method. The theory of operation of the laser under test in this study is based on the acousto-optic method which uses a frequency shifter, such as a Bragg cell [3], to produce the frequency difference. This technique yields a frequency split that is much greater than that of the Zeeman technique (20 MHz). The split also remains constant because the Bragg cell is driven by a stable quartz oscillator. The main aim of this work is to verify the stability of both the splitting frequency and the laser's frequency.

Experimental setup:

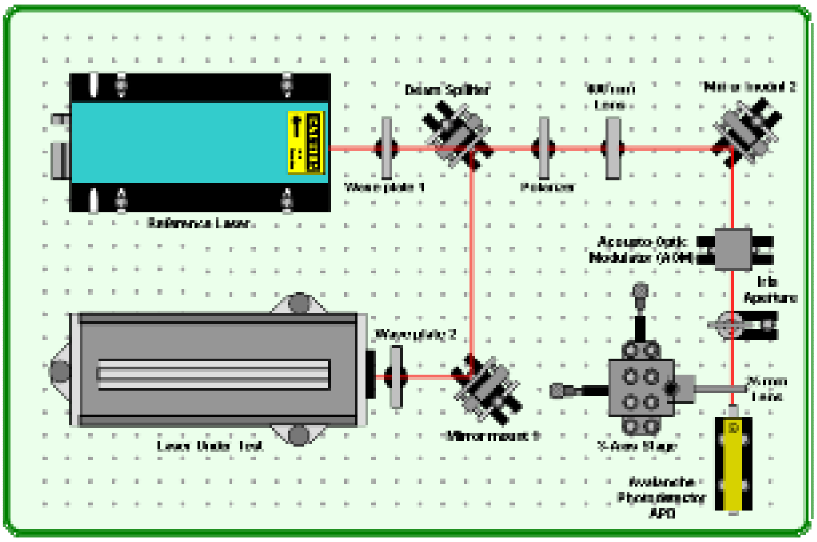

Figure 1: The heterodyne interferometry system optical setup.

The optical setup (see Figure 1) is designed to compare the primary optical frequency standard – a He-Ne Iodine-Stabilized laser (reference laser) with the laser under test. A fast silicon avalanche photodetector is used to detect the heterodyne signal resulting from mixing both of the output beams of the reference laser and the laser under test. The overlapping and combining of the output beams are accomplished with high-reflectance mirror #1 and a beam splitter. The combined beams are focused onto the photodetector with a 25 mm focal-length mounted on a 3-axis stage. An acousto-optic modulator (AOM) is used for optical isolation. Alignment and focusing of the laser beams into the AOM are achieved with a 400 mm lens and mirror #2, and an adjustable iris aperture selects the desired Bragg order from the AOM output. A $\lambda/4$

waveplate is used in waveplate #2 position in order to select which of the two laser modes will pass through the linear polarizer and heterodyne with the reference laser.

Experimental work and results:

Since the displacement measurements depend to a certain extent on the frequency stability of the laser source and on the splitting frequency as well, it is essential for the frequency of a DMI laser to be highly stable. If the laser frequency drifts, the unequal path length of the interferometer changes its length and the system detects a false impression of what it believes to be a motion of the target. In the following series of experiments, we attempted to: evaluate the degree of frequency stability of the laser source with time (warm-up behaviour), investigate the change of operating temperature on the laser frequency, study the reproducibility of the laser wavelength at the same operating conditions from time to time, and monitor the variation of the splitting frequency with time.

1. Determination of the warm-up time

From OFF position, the laser under test was switched on and the heterodyne signal was monitored for 10 minutes to show the short-term warm-up behaviour and to determine the time required to lock its modes in position. This time was shown in Figure 2 to be 470 seconds (nearly 8 minutes). Afterwards, measurements were continued for one more hour and the standard deviations of the frequency measurements were calculated every five minutes during this hour to give us an idea about the minimum time required before the laser reaches its optimum frequency stability when one can use it in displacement measurements without doubting the results. As shown in Figure 3, the standard deviation values start to decrease gradually as time goes on, and after 3 segments of measurements (15 minutes) these values reach a comparatively steady value fluctuating between 237 – 588 KHz. From these available data one can confirm that the laser can be used safely in displacement measurements after nearly 25 minutes of its operation.

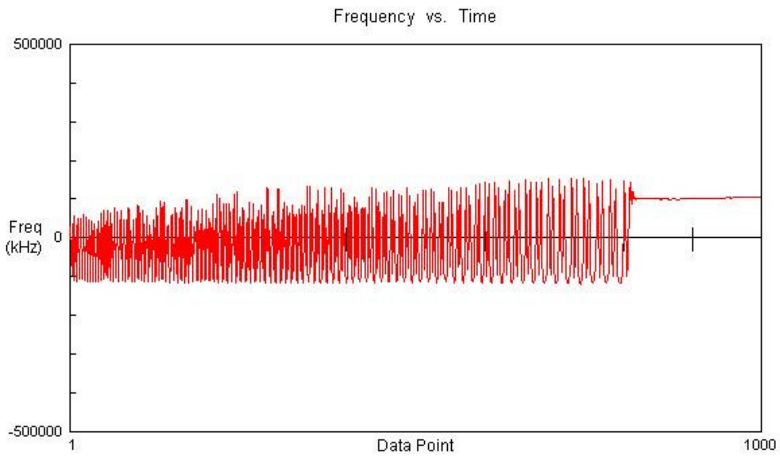

Figure 2: The short-term warm-up behaviour of the laser under test.

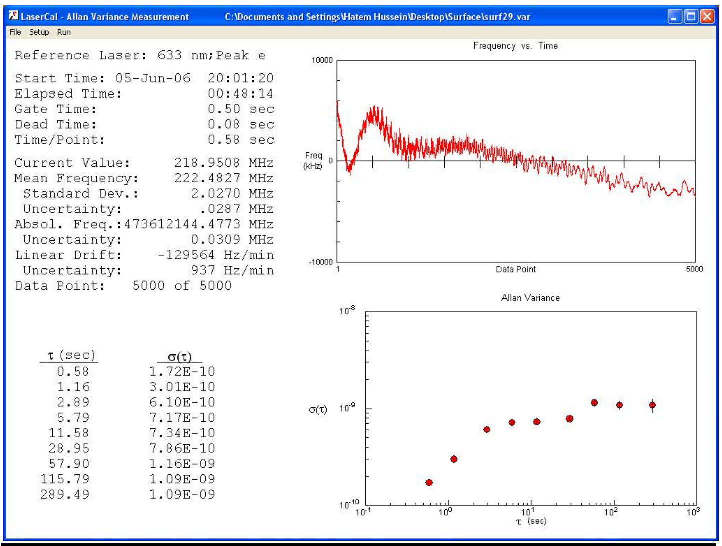

Figure 3: The long-term warm-up behaviour of the laser under test.

2. Studying the laser stability

The root Allan variance [4,5] is a convenient measure of the stability of the laser frequency in the time domain. It simply calculates the differences between the frequency values of the reference laser and the one under test averaged over successive time intervals of duration τ. In order to implement that target, only one of the laser modes was selected by a $\lambda/4$ waveplate of Figure 1 and as shown on the RF spectrum analyzer in Figure 4 to heterodyne with the reference laser. The frequency stability, in terms of Allan deviation, was calculated to be $6.89 \times 10^{-11}\ \tau^{-1/2}$ for averaging time of 3 seconds and with a stability floor of $5.03 \times 10^{-10}\ \tau^{-1/2}$ for 58-s integration time.

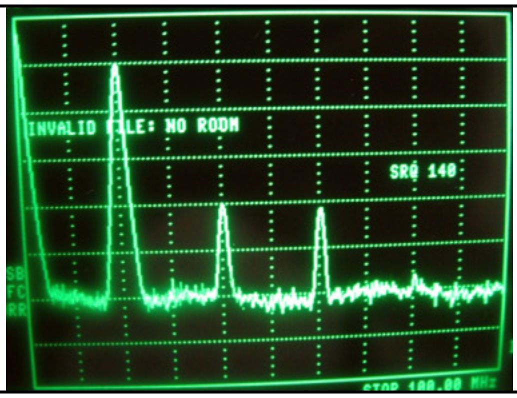

Fig. 4.a. From left to right: The heterodyne signal between the two Zeeman modes, the heterodyne signal between each mode and the primary standard laser.

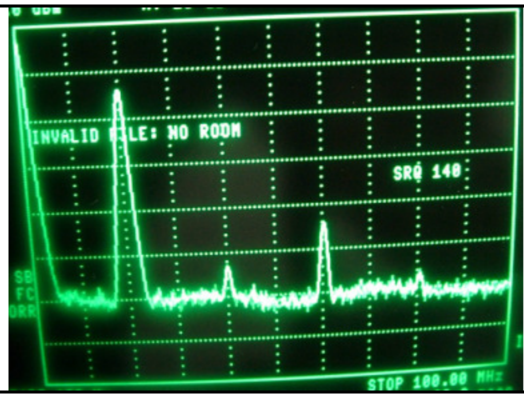

Fig. 4.b. One of the modes is nearly masked by the ¼ wave-plate.

3. <u>Environmental working conditions effect on the laser frequency</u>

Environmental errors are the largest contributor to most DMI systems. Controlling or monitoring the environment or minimizing the measurement time will reduce environmentally induced errors. DMIs working environment varies from a temperature controlled laboratory to an optical testing workshop or even to a production line in a factory. Therefore, studying the change of the laser frequency as a function of temperature was of great importance to the users of these equipment. In this respect, the laboratory temperature was kept constant at 17 ˚C for a period of two hours to allow the laser to be thermally stabilised before recording the laser frequency. This experiment was repeated several times in the temperature range (17-25 ˚C) in order to determine the coefficient of the change of the laser frequency with temperature. From the results and the graph depicted in Figure 5, this coefficient was calculated to be -1.12 MHz/˚C. Obviously, the primary reason for this drift in frequency is the change of the laser tube length due to temperature fluctuations.

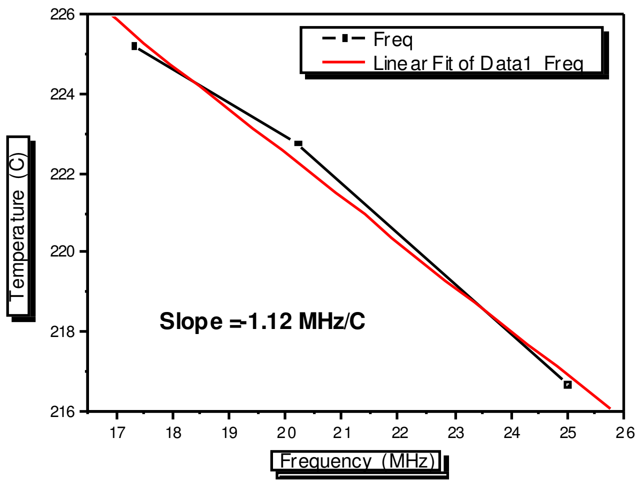

Figure 5: Variation of the laser frequency with laboratory temperature.

4. <u>Reproducibility of the laser frequency</u>

Among this series of evaluation experiments, the reproducibility of the laser frequency was checked. To achieve this goal, the laser frequency was repeatedly measured at the same laboratory environmental conditions (at a temperature of 20 ˚C) during a period of three days in order to assess the degree of repeatability of the frequency on a day-to-day basis. It was found that the laser frequency values oscillate around ±2.5 MHz from the last measured value. It is also noted that this result has no effect on the competence of the displacement interferometer measuring system.

5. Monitoring the change of the splitting frequency with time

The last and most affecting parameter in displacement measurements is the degree of invariability of the laser splitting frequency. In order to assess to what extent this splitting frequency is fixed in value, the reference laser in Figure 1 was switched OFF, the laser under test was switched ON from OFF situation to monitor the warm-up frequency change of the modes spacing, and the $\lambda/4$ waveplate was removed from its mount in waveplate #2 position to allow the two laser modes to heterodyne together. The results of the measurements presented in Figure 6 show an extremely solid value of the splitting frequency of 20 MHz with frequency stability, in terms of Allan deviation, of $1.33 \times 10^{-15}\ \tau^{-1/2}$ for averaging time of 3 seconds and with a stability floor of $1.48 \times 10^{-14}\ \tau^{-1/2}$ for 58-s integration time. This result is not surprising since the splitting technique depends on a very stable quartz oscillator.

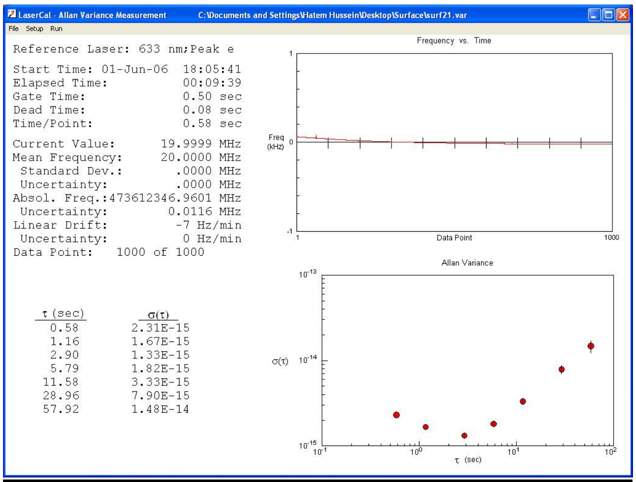

Figure 6: Determination of the splitting frequency stability with time.

Conclusion:

Zeeman-stabilized and acousto-optic frequency-split lasers have been used successively in displacement measuring interferometers and the fundamental purpose of this work was the establishment of confidence in measurements made by such lasers in our laboratories. In this work, the warm-up time behaviour, frequency stability, environmental working conditions effect on the frequency stability and the degree of invariability of the laser frequency splitting were measured and optimized.

The absolute frequency stability for such laser was investigated using standard heterodyne interferometry technique and Allan deviation statistics which was found to be $6.89 \times 10^{-11}\ \tau^{-1/2}$ for averaging time of 3 seconds. The carried out research showed that this laser possess stability and reproducibility quite enough for such measurements.

References:

1. F. Demarest, "High-resolution, high-speed, low data age uncertainty, heterodyne displacement measuring interferometer electronics", Meas. *Sci. Tech.* 4 (1998)1024-1030.
2. N. Bobroff, "Recent advances in displacement measuring interferometry", *Meas. Sci. Tech.* 4(9), pp. 907-926 (1993).
3. G. E. Sommagren, "Apparatus to transform a single frequency, linearly polarized laser beam into a beam with two, orthogonally polarized frequencies", USA Patent 4684828, (1987).
4. D. W. Allan, "Time and Frequency (Time-Domain) Characterization, Estimation, and Prediction of Precision Clocks and Oscillators" *Characterization of Clocks and Oscillators*, Washington D.C.: U.S. Government Printing Office, (1990).
5. D. B. Sullivan, D.W. Allan, D.A. Howe, and F.L. Walls, *Characterization of Clocks and Oscillators*, NIST Tech Note 1337, (1990).