Optical frequency stabilization of a compact heterodyne source for an industrial distance measuring interferometer system

Leslie L. Deck and Michael L. Holmes

Zygo Corporation, Laurel Brook Road, Middlefield, CT. 06455-0448

Introduction

Many optical metrology applications such as heterodyne interferometry and high resolution spectroscopy require a spectrally stable source. Despite advances in solid state laser technology, He-Ne lasers are still often chosen for these applications due to their spectral purity. Heterodyne interferometry applications are particularly aided by this and the relatively simple method of producing two orthogonal, frequency separated components via the Zeeman effect.

The ideal Zeeman He-Ne laser produces a beam consisting of two orthogonal, frequency shifted, circularly polarized beams. A traditional frequency stabilization technique for these lasers involves adjusting the laser cavity length in a feedback loop with the control signal derived from the intensity difference between these two beams.[1] A stabilization system based on this principle typically consists of a birefringent element to convert the polarization to linear and a polarization beam-splitter to separate and direct the two linear polarizations onto two detectors, which are differenced to create the control signal. From the standpoint of providing a stable source for heterodyne interferometry, this traditional approach is often adequate. However as laser production costs drop, the stabilization system becomes an increasingly large fraction of the total system cost. Furthermore, additional optical and electronic components are needed to establish the heterodyne reference, further increasing system cost and complexity.

We describe a simpler stabilization scheme that can be implemented when the two orthogonal frequency components possess elliptical rather than circular polarization.[2] Invariably, small stresses in the end mirrors of non-Brewster windowed HeNe lasers, due either to mounting or coating stresses, cause enough birefringence to produce an elliptical output beam. Indeed, careful control of the mirror mounting process during laser manufacture can repeatedly produce a particular beam ellipticity. Given elliptically polarized lasers with a particular ellipticity, the stabilization scheme described requires no optical components at all, just two detectors to measure the relative intensity of the two beams. The scheme further provides a variety of ways for producing the heterodyne reference signal required for heterodyne interferometry applications.

Method description

Consider a single mode HeNe laser whose beam is elliptically polarized with constant ellipticity e defined by $e = |E_{\min}| / |E_{\text{maj}}|$, where E_{maj} and $E_{\min}$ are the complex electric field amplitudes of the major and minor axes of the polarization ellipse. This beam is incident onto a pair of detectors situated as shown in Figure 1. Detectors #1 and #2 are oriented at an angle of incidence θ_i to the incident beam with the detector planes parallel to each other. The detectors are standard silicon detectors without an anti-reflection coating. Under these circumstances, the bare silicon surface quickly grows a thin oxide layer 5 to 10nm deep. This SiO_2 layer provides good protection against water and other airborne contaminants but is thin enough to ignore when modeling the optical properties of the detector. Another nice bonus with this configuration is that optical feedback into the laser from scatter off of surfaces is virtually eliminated.

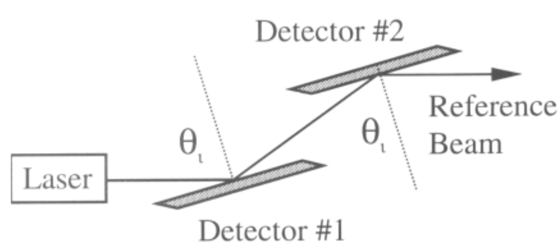

Figure 1: Detector geometry

The detector assembly is axially rotated so the S and P polarization states defined by the detector orientation relative to the beam are aligned with the major and minor axes of the polarization ellipse, so that the complex electric field components E_S and E_P satisfy $E_S = E_{\mathrm{maj}}$ and $E_P = E_{\min}$. If the laser is now Zeeman split, the light exiting the laser is composed of two orthogonal, elliptically polarized beams at two slightly different optical frequencies determined by the Zeeman effect. Each beam has two complex electric field amplitudes E_S and E_P, which for beam #1 (with optical frequency ω_1) can be written as;

$$E_{1,S} = |E_{1,S}|\exp(i\omega_1 t), \quad E_{1,P} = e|E_{1,S}|\exp(i\omega_1 t + \varphi) \tag{1a}$$

while for beam #2 they are

$$E_{2,S} = e|E_{2,P}|\exp(i\omega_2 t - \varphi), \quad E_{2,P} = |E_{2,P}|\exp(i\omega_2 t) \tag{1b}$$

where we have used the definition for e and invoked orthogonality ($E_{1,S}E_{2,S}{}^* + E_{1,P}E_{2,P}{}^* = 0$). When the laser is stable, the two beams will have equal intensity so $|E_{1,S}| = |E_{2,P}|$ and $|E_{1,P}| = |E_{2,S}|$.

The instantaneous intensity seen by the first detector I_{D1} is given by the transmittance of the P and S polarization states of both beams,

$$I_{D1} = \left\{ \left| t_S(\theta_i,\theta_r)(E_{1,S} + E_{2,S}) \right|^2 + \left| t_P(\theta_i,\theta_r)(E_{1,P} + E_{2,P}) \right|^2 \right\}\eta \tag{2}$$

where $t_{P(S)}(\theta_i,\theta_r)$ and $r_{P(S)}(\theta_i,\theta_r)$ are the transmission and reflection amplitudes for the P(S) polarization states obtained from the Fresnel formula for a single boundary[3], θ_i and θ_r are the angles of incidence and refraction respectively at a detector boundary, $\eta = \dfrac{n_{Si}\cos(\theta_r)}{n_{air}\cos(\theta_i)}$ is required for energy conservation for the transmitted beam in the detector material and $n_{Si(air)}$ is the index of refraction for silicon(air). For clarity, we will omit the explicit dependence of the amplitudes on the angle of incidence and refraction in what follows.

The intensity seen by detector #1 modulates at the heterodyne beat frequency $\Omega = \omega_2 - \omega_1$ as can be confirmed by substitution of the complex field components Eq. 1. One obtains after some arithmetic;

$$I_{D1} = \eta E_1^2\left(|t_S|^2 + e^2|t_P|^2\right) + \eta E_2^2\left(e^2|t_S|^2 + |t_P|^2\right) + 2eE_1E_2\eta\left(|t_S|^2 + |t_P|^2\right)\cos(\Omega t - \varphi). \tag{3}$$

The 2nd detector observes the transmitted portion of the ray reflected from detector #1 and also modulates at the heterodyne frequency;

$$I_{D2} = \eta E_1^2\left(|t_S|^2|r_S|^2 + e^2|t_P|^2|r_P|^2\right) + \eta E_2^2\left(e^2|t_S|^2|r_S|^2 + |t_P|^2|r_P|^2\right) + \\ + 2eE_1E_2\eta\left(|t_S|^2|r_S|^2 + |t_P|^2|r_P|^2\right)\cos(\Omega t - \varphi). \tag{4}$$

The ideal control signal is $\mathrm{K}_{\mathrm{ideal}} = \langle I_1\rangle - \langle I_2\rangle$, where $\langle I_{1,2}\rangle$ represents the time averaged intensity signal from the two orthogonal frequency shifted beams. As these individual beam intensities are not available, the following control signal is used,

$$\mathrm{K} = G\left(\langle I_{D1}\rangle - R\langle I_{D2}\rangle\right). \tag{5}$$

Where G is the electrical (trans-impedance) gain of detector #1 and R is the ratio of the gains of detector #2 to detector #1. For good closed loop performance, the average must be taken over a time interval short compared to the cavity length variations, but long compared to the heterodyne frequency. Using the time averaged portion of Eqs. 3 and 4, and the requirement that $\mathrm{K} = 0$ when the two beams have equal intensity, determines the necessary gain ratio R;

$$R = \frac{|t_S|^2 + |t_P|^2}{|t_S|^2|r_S|^2 + |t_P|^2|r_P|^2} \quad \textbf{(6)}$$

This gain ratio is dependent on the detector geometry and material, but independent of ellipticity. With this value for R, the control signal K measures the deviation of the two beams from equal intensity.

Control signal sensitivity

The sensitivity of the control signal to small changes of intensity in the neighborhood of the stability point can be easily obtained through differentiation in the linear approximation. We assume that for small changes ε in intensity, the two beams satisfy: $I_1(\varepsilon) = I - \varepsilon$ and $I_2(\varepsilon) = I + \varepsilon$. The sensitivity is then found to be

$$\frac{\partial \mathrm{K}}{\partial \varepsilon} = G\left(1-e^2\right)\eta\left[\left(|t_P|^2 - |t_S|^2\right) - R\left(|t_P|^2|r_P|^2 - |t_S|^2|r_S|^2\right)\right]. \quad \textbf{(7)}$$

As expected, the sensitivity vanishes for circular polarization $(e=1)$ and is maximized for linear polarization. Figure 2 shows the sensitivity, normalized by $G\left(1-e^2\right)\eta$, as a function of the angle of incidence. The sensitivity peaks at a value of 2 which also corresponds to the peak sensitivity expected from the ideal control signal, but this only occurs at an angle of incidence equal to Brewsters angle for silicon;

$$\theta_B = \tan^{-1}\left(n_{Si}/n_{air}\right) \cong 74.5°.$$

This makes intuitive sense, in that at Brewsters angle, the p-polarization reflection amplitude is zero, thereby maximizing the effective separation of the s and p polarization components, which by design coincide with the principle axes of the polarization ellipse.

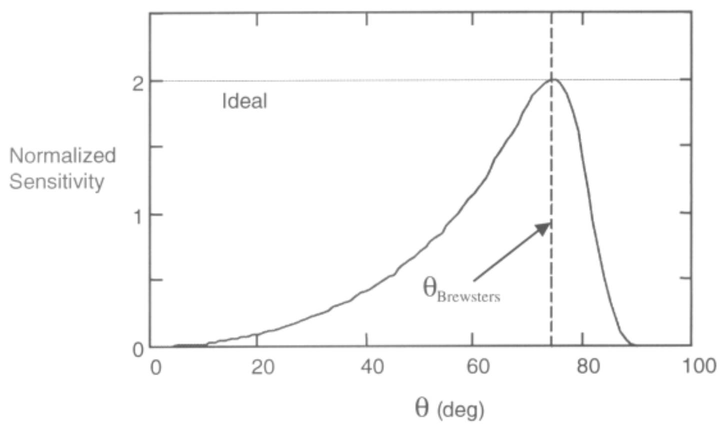

Figure 2: Control signal sensitivity as a function of detector angle.

Heterodyne Reference

Heterodyne interferometry applications require a reference signal at the base heterodyne frequency to extract the Doppler shift from the test signal. Since both detectors see the heterodyne frequency, either one can be instrumented to receive this signal. From the formulas for the time dependent detector signals, Eqs. 3 and 4, the heterodyne signal contrast when the laser is stable with the two beams at equal intensity I works out to be $2e/\left(1+e^2\right)$ for both detectors. This ellipticity dependence is opposite to that found in the control signal sensitivity, Eq. 7, which underscores a basic tradeoff in the stabilization system when used for heterodyne interferometry, one can improve stabilization only at the cost of reducing the heterodyne reference signal contrast.

For extremely high heterodyne frequencies, or in an electrically noisy environment, especially if the phase sensitive detection system is remote, it is difficult to transmit an electrical reference signal undistorted. Under these conditions an optical reference signal is preferred, which is available in the beam reflected from detector 2. The intensity of this beam is given by;

$$I_{\mathrm{REF}} = \left| r_S r_S \left(E_{1,S} + E_{2,S} \right) \right|^2 + \left| r_P r_P \left(E_{1,P} + E_{2,P} \right) \right|^2, \qquad \textbf{(8)}$$

and has a heterodyne contrast identical to that seen by the detectors.

Experimental Verification

A small (~80mm cavity) single mode Zeeman split laser tube manufactured at our Zygo Laser Division facility (Longmont, CA) was stabilized using our method. Laser light emerged from both ends of the tube and the stabilization control assembly was located to intercept the 30μwatts leaking out the rear cavity mirror. The two frequency components were orthogonally elliptically polarized with an ellipticity $e = 0.54$. Four cylindrical permanent magnets surrounding the tube produced a split frequency of 3.6MHz. The two stabilization detectors were OSD100-0-COW large area uncoated silicon diodes from Centro Vision Inc. (Newbury Park, CA) and were both arranged at Brewsters angle and separately amplified before differenced to create the control signal. For this detector geometry and using a refractive index of 3.6-0.02i for silicon, the optimal gain ratio R is;

$$R = \frac{\left|t_S\right|^2 + \left|t_P\right|^2}{\left|t_S\right|^2 \left|r_S\right|^2} = 6.5. \qquad \textbf{(9)}$$

The control signal was sent to a simple PI temperature controller, which controlled the current to a Minco (Minn. MN.) thin-film heating element attached to one end of the laser tube. When powered up, current to the heating element was set to maximum until the tube reached a predefined setpoint temperature, whereupon the feedback controller was engaged. The reference beam exiting the second detector was coupled into a 250μm core multimode fiber.

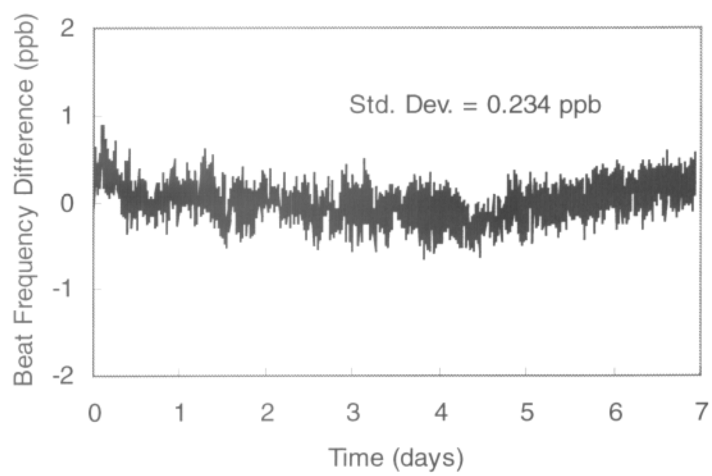

Figure 3: Laser frequency stability over 7 days.

The 350μwatts emanating from the front was used to monitor the laser stability by interfering it against a frequency standard and continuously monitoring the beat frequency. Figure 3 shows the beat frequency between the laser and the standard for 1 week starting from controller lock. The frequency stability measured 0.234 ppb (111 KHz) rms over the 7 day period.

Summary

We have shown that given a single mode, Zeeman split, elliptically polarized laser, only two detectors are required to generate an efficient frequency stabilization control signal. When coupled with a simple PI controller and a thermal transducer we have achieved optical frequency stabilization to better than 1 part per billion over 7 days. The detector geometry is compact, robust and inexpensive, and provides a number of convenient ways of generating a heterodyne reference signal, making the method useful for distance measuring interferometry applications.

References

[1] I. Tobias, M.L. Skolnick, R.A. Wallace, T.G. Polanyi, "Derivation of a frequency-sensitive signal from a gas laser in an axial magnetic field," Appl. Phys. Lett., **6**, 198-200 (1965)

[2] U.S. Patent pending.

[3] M. Born and E. Wolf, "Principles of Optics", 6th Ed., Pergamon Press (1989), Chap. 1.6.4