Laser pointing stability measured by an oblique-incidence optical transmittance difference technique

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ABSTRACT

We describe an oblique incidence optical transmittance difference technique for determining the pointing stability of a laser. In this technique, we follow the angular drift a monochromatic laser beam by measuring the relative changes in transmittance through a parallel fused quartz window for s- and p- polarized components of the beam in response to the drift. This method is shown in the present experiment to have the sensitivity to detect angular changes in the range of 1.7 μradians. To demonstrate the technique we measured the angular drifts of two commercially available lasers.

INTRODUCTION

Beam pointing stability is one of the most important characteristics of a laser. The angular drift of a laser is of particular concern in applications such as laser-based metrology (from long-distance guiding systems to short-distance scanning microscopes), and laser-based material processing (from optical lithography, laser machining, to optical manipulation of atoms). The beam pointing stability of a laser system and how it is actively compensated for in a given application is often the main factor that limits the achievable precision of the application.

Laser beam pointing stability is typically determined by measuring the displacement of the beam position in the focal plane of a suitable lens system [1-3]. The beam displacement (positional stability) is measured with a four-quadrant position sensitive detector. The angular drift is obtained by dividing the appropriate focal length from the displacement. Depending upon how such a measurement is implemented, particularly the mechanical stability of the measurement system, the technique can detect angular drifts ranging from several milliradians to 1 μradian [4].

For this study, we present an alternative method for determining laser beam pointing stability: oblique-incidence transmittance difference (OI-TD). OI-TD is a modified form of optical ellipsometry that is configured so that the sensitivity to the angular drift is maximized [5-10].

EXPERIMENTAL DETAILS

The optical setup for the OI-TD technique may be found elsewhere. We alternate the polarization of a test laser beam from originally s-polarization (transverse electric) to p-polarization (transverse magnetic) with a photoelastic modulator at a frequency of Ω = 50 kHz. The polarization-modulated beam passes through a parallel fused quartz window at close to Brewster angle, θ_b. The transmitted beam then passes through an analyzer before being detected with a photodiode. The detected laser intensity has terms that vary with time at various harmonics of the modulation frequency Ω. We measure the second harmonic, I(2Ω = 100kHz), with a lock-in amplifier.

Let $T_p(\theta_{inc})$ and $T_s(\theta_{inc})$ be the transmittance as a function of incidence angle, θ_{inc}, for p- and s-polarization components of laser light through the fused quartz window. Let $T_p(\theta_{inc,0})$ and $T_s(\theta_{inc,0})$ be the corresponding transmittance before angular drift. Since, the drift in the pointing direction of the laser leads to the same change in the quartz window incidence angle, $\theta_{inc} = \theta_{inc,0} + \Delta\theta$, the transmittance changes due to angular drift such that we can define $\Delta_p^{(T)} = [T_p(\theta_{inc}) - T_p(\theta_{inc,0})]/T_p(\theta_{inc,0})$ and $\Delta_s^{(T)} = [T_s(\theta_{inc}) - T_s(\theta_{inc,0})]/T_s(\theta_{inc,0})$ and we measure $\Delta_p^{(t)} - \Delta_s^{(t)}$ as follows. Prior to measuring the angular drift, we adjust the transmission axis of the analyzer so that I(2Ω) is proportional to $\Delta_p^{(t)} - \Delta_s^{(t)}$ directly. It can be shown that if $\theta_{inc,0} = \theta_b$, the difference in relative transmittance between s- and p-polarized light is related to the angular drift in the following way [11]:

$$\Delta_p^{(t)} - \Delta_s^{(t)} \approx \frac{(n_g^2 - 1)^2}{n_g^3}\Delta\theta . \qquad (1)$$

Where n_g is the index of refraction of the fused quartz window.

RESULTS AND DISCUSSION

We performed two experiments to demonstrate the OI-TD technique. In the first experiment, we verify equation 1 by measuring $\Delta_p^{(T)} - \Delta_s^{(T)}$ as a function of known incidence angle. In the second experiment, we monitor the angular drifts of two commercial He-Ne lasers over 24 hours to compare the measurement obtained using the OI-TD technique with available specifications of the two lasers.

To determine the accuracy of the OI-TD technique, we use a 1 mW Spectra-Physics 117A He-Ne laser at a wavelength of 632.8nm. The laser light is linearly polarized and is operated in the intensity stabilized mode. The parallel fused quartz window has a refractive index of $n_g = 1.457$ at the He-Ne wavelength. From equation 1, we expect

$$\Delta_p^{(T)} - \Delta_s^{(T)} \approx 0.407\Delta\theta . \qquad (2)$$

We mount the parallel fused quartz window on a rotation stage so that the window can be rotated about the vertical axis. In this way, we can change the angle of incidence, θ_{inc}, in a prescribed fashion, where at each set incident angle we measure $\Delta_p^{(T)} - \Delta_s^{(T)}$ and compute the angular deviation, Δθ. We then compare the computed Δθ with $\theta_{inc} - \theta_b$. The result is displayed in figure 1. The incidence angle is varied from $\theta_b - 0.02$ radians to $\theta_b + 0.02$ radians with a step size of 8.5 μradians. Over a range of 40 milliradians, the measured angular deviation follows the set change in incidence angle extremely closely. This shows that the OI-TD technique can indeed be used to determine laser beam

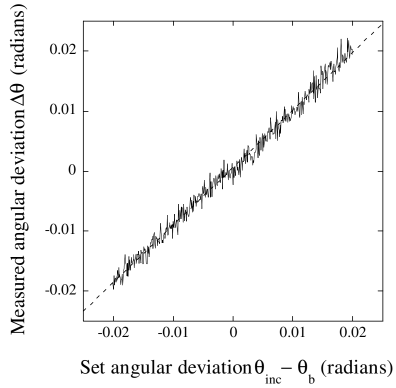

Figure 1. Measured angular deviation $\Delta\theta$ [computed from equation 2] vs. the set incidence angle change, $\theta_{inc} - \theta_b$, over a range of 40 milliradians. The dashed line is a fit to a linear function with a slope of 0.963.

pointing stability. Subsequently, we measured the beam pointing stability of two low-power commercial He-Ne lasers using the OI-TD technique. One is a 10mW LASOS LGK-7654-7 He-Ne laser. The other is a 1mW Spectra-Physics 117A intensity stabilized laser. According to its specifications, the pointing direction of a LASOS LGK-7654-7 He-Ne laser is expected to drift up to 100 μradians during the first 20 min of warm up time. Afterwards, the range of the drift is limited to 20 μradians. In figure 2, we plot the angular drift for a LASOS LGK7654-7 He-Ne laser measured over a 24-hour period using the OI-TD technique. The measurement begins immediately after the laser has been turned on. The drift during the first 20 min of warm up shows that the mean pointing direction of the laser indeed drifts downward by 50 μradians. Toward the end of the warm up, the oscillation has a peak-to-peak amplitude of 50 μradians and a period progressively stretched to 100s. After 1 hour of warm up, the mean pointing direction only drifts slowly by 70 μradians over 24 hours. On top of the mean drift, the pointing direction slowly oscillates with a peak-to-peak amplitude of 30 μradians and an average period of 3000s. These results show that, other than a long-term drift over a period of 12 to 24 hours, the LASOS LGK7854-7 He-Ne laser has the angular stability fairly close to the specifications. It is noteworthy that the direction is not sensitive to temperature variation over a range of 1°C.

In comparison to the LASOS laser, the beam pointing stability of the Spectra-Physics 117A He-Ne laser in the intensity-stabilized mode is very poor, and has a large temperature dependence. In figure 3, we display the measured change in the pointing direction of the Spectra-Physics 117A laser over 24 hours, together with the temperature of the ambient. In the first 200 s, the SP117A laser is in the process of establishing the intensity stabilization, the pointing direction is oscillatory with a peak-to-peak amplitude of 15 milliradians and a time period of 20 s. Once the intensity stabilization is established, the change in the pointing direction slows down and yet remains oscillatory. Most noticeably, the amplitude and the time period of oscillation seem to be very

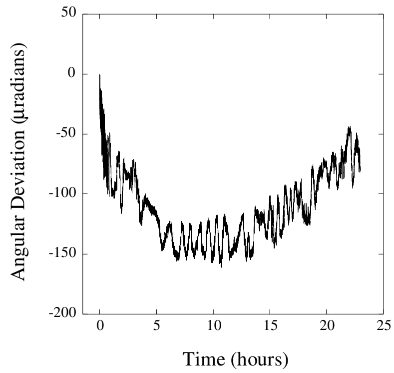

Figure 2. Measured angular drift of a 10 mW LASOS LGK7854-7 He-Ne laser over 24 hours starting immediately when the laser is turned on.

sensitive to the temperature drift over just 1^{o}C. During the first and last 6 hours of our measurement, when the ambient temperature changes by 1^{o}C, the pointing direction oscillates with a peak-to-peak amplitude of 1.5 milliradians and a time period veryhing in the range 1200 to 2400s. Only during the time interval of 4 hours, when the temperature is stable within a standard deviation of 0.023 ^{o}C, the change in the pointing direction is within a range of ±0.2 milliradians (i.e., 200 μradians). Roughly speaking, the beam pointing stability of a Spectra-Physics 117A He-Ne laser is worse by a factor of 100 than that of a LASOS LGK7854-7 He-Ne laser. To determine the sensitivity of our optical transmittance difference technique, we examine "quiet" regions of the pointing direction for the LASOS LGK7854-7 He-Ne laser, where there are no oscillations. The standard deviations in this region is 1.7 μradians. If we use the standard deviation of the data in these quiet regions as a measure of the sensitivity of our technique, we can conclude that

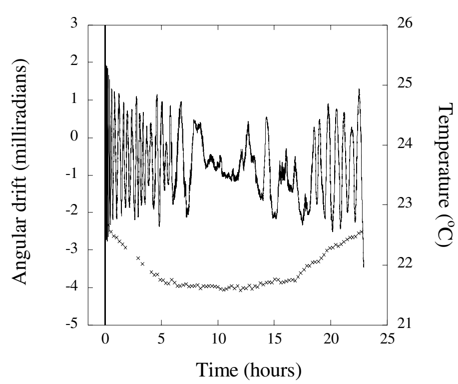

Figure 3. Measured angular drift (solid line) of a 1mW Spectra-Physics 117A He-Ne laser in intensity stabilized mode and the ambient temperature (x) over a 24 hour period, starting immediately after the laser is turned on.

our current transmittance difference measurement setup can detect angular drifts as small as 1.7 μradians with a signal to noise ratio of 1-to-1.

CONCLUSION

We have shown that an oblique incidence transmittance difference technique is a relatively simple yet very sensitive method for characterization of a laser beams pointing stability. We demonstrate that a sensitivity to an angular drift of 1.7μ radians is achieved in the present study. Finally, it is noteworthy, that this technique is easily extended to measure angular drifts in both the horizontal (reported here) and vertical planes.

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