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

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We describe an oblique-incidence optical transmittance technique for determining the pointing stability of a laser. In this technique, we follow the angular drift of 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 2 μradians (1 μradian$=10^{-6}$ radian). To demonstrate this technique, we measured the angular drifts of two commercial intensity-stabilized He–Ne lasers. © *2001 American Institute of Physics.*
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I. INTRODUCTION

The beam pointing stability is one of the important characteristics of a laser. The angular drift of a laser beam 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 DNA molecules). 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.

The pointing stability of a laser system is typically determined from the displacement of the beam position at the focal plane of a suitable lens system.[1–3] The beam displacement (positional stability) is measured with a 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, this technique can detect angular drifts ranging from milliradians (10^{-3} radians) to less than 1 μ radian (10^{-6} radians).[4]

In this article, we describe an alternative method for determine the laser pointing stability. This technique is a variation of optical ellipsometry and is configured such that the sensitivity to the angular drift of a laser beam is maximized.[5–10] It is equally as sensitive as the position sensitive techniques under comparable mechanical environments.

The essence of this alternative technique is that we measure the difference in relative transmittance change between *s* and *p* polarization for a laser beam through a parallel fused silica window at an oblique incidence angle. Such a difference is sensitive to the change in incidence angle and thus can be used to monitor the beam pointing stability. A key advantage of this technique is that it is subject to only the relative intensity noise instead of the absolute intensity noise.[6–10] This enables us to detect the angular drift with a sensitivity of 1.7 μradians.

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II. OBLIQUE-INCIDENCE TRANSMITTANCE DIFFERENCE TECHNIQUE FOR ANGULAR DRIFT MEASUREMENT

In Fig. 1, we show the sketch of the measurement setup for the oblique-incidence transmittance difference technique. 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 $\Omega = 50$ kHz. The polarization modulated beam passes through a parallel fused quartz window at close to the Brewster angle θ_b. The transmitted beam then passes through an analyzing polarizer before it is detected with a photodiode detector. The transmitted laser intensity I_t has terms that vary at various harmonics of the modulation frequency Ω. We measure the magnitude of the second harmonics, $I_t(2\Omega = 100\,\text{kHz})$, with a Stanford Research SR830 digital lock-in amplifier.

Let α be the angle between the *s* polarization and the transmission axis of the analyzing polarizer. It is easily shown that[10]

$$I_t(2\Omega) = (J_2(\pi)/2) I_{\text{inc}} [T_p^2(\theta_{\text{inc}})(\sin\alpha)^2 - T_s^2(\theta_{\text{inc}}) \times (\cos\alpha)^2]. \quad (1)$$

Here, I_{inc} is the intensity of the incidence laser. θ_{inc} is the incidence angle with respect to the fused silica window. $T_s(\theta_{\text{inc}})$ and $T_p(\theta_{\text{inc}})$ are the transmittance through one air-fused silica interface for *s* and *p* polarization, respectively. $J_2(x)$ is the Bessel function of the second kind, and $J_2(\pi) = 0.486$.

The key to this technique is that we initially nullify $I_t(2\Omega)$ by adjusting α such that $T_s^2(\theta_{\text{inc},0})(\cos\alpha)^2 = T_p^2(\theta_{\text{inc},0})(\sin\alpha)^2$. The subsequent change in $I_t(2\Omega)$ is directly proportional to the angular drift $\Delta\theta$ of the laser beam, and the signal is only subject to the relative intensity noise

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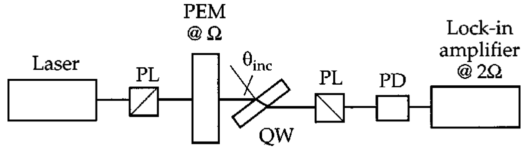

FIG. 1. Optical setup of an oblique-incidence transmittance difference technique for measuring the angular drift of a laser beam is shown. Photoluminescence: Glan–Thompson polarizers; PEM: photoelastic modulator (Hinds Instruments, OR); QW: parallel fused quartz window; and PD: biased silicon photodiode.

instead of the absolute intensity noise.[6–10] The drift in the pointing direction of the laser leads to the same change in incidence angle, $\theta_{\rm inc}=\theta_{\rm inc,0}+\Delta\theta$. This causes the transmittance to change such that

$$T_s(\theta_{\rm inc})=T_s(\theta_{\rm inc,0})+\Delta T_s(\theta_{\rm inc})\equiv T_s(\theta_{\rm inc,0})[1+\Delta_s^{(T)}], \quad (2a)$$

$$T_p(\theta_{\rm inc})=T_p(\theta_{\rm inc,0})+\Delta T_p(\theta_{\rm inc})\equiv T_p(\theta_{\rm inc,0})[1+\Delta_p^{(T)}]. \quad (2b)$$

Here, $\Delta_p^{(T)}\equiv[T_p(\theta_{\rm inc})-T_p(\theta_{\rm inc,0})]/T_p(\theta_{\rm inc,0})$ and $\Delta_s^{(T)}\equiv[T_s(\theta_{\rm inc})-T_s(\theta_{\rm inc,0})]/T_s(\theta_{\rm inc,0})$ are the relative transmittance change in response to the angular drift $\Delta\theta$. As a result, the second harmonics in the transmitted intensity are reduced to

$$I_t(2\Omega)=J_2(\pi)I_{\rm inc}T_p^2(\theta_{\rm inc,0})(\sin\alpha)^2[\Delta_p^{(T)}-\Delta_s^{(T)}]. \quad (3)$$

Let n_g be the refractive index of the fused silica. By choosing the initial incidence angle to be the Brewster angle $\theta_{\rm inc,0}=\theta_b$, $T_p^2(\theta_{\rm inc,0})=T_p^2(\theta_b)=1$, and $T_s^2(\theta_{\rm inc,0})=T_s^2(\theta_b)=4/(1+n_g^2)^2$. And the difference in relative transmittance change between s and p polarization is simplified,

$$\Delta_p^{(T)}-\Delta_s^{(T)}\cong\frac{(n_g^2-1)^2}{n_g^3}\Delta\theta. \quad (4)$$

Experimentally, we can also measure $I_{\rm inc}T_p^2(\theta_{\rm inc,0})(\sin\alpha)^2=I_{\rm inc}(\sin\alpha)^2$ in Eq. (3) *directly* by turning off the photoelastic modulator and mechanically chopping the laser beam. The modulated laser intensity is of square wave form. Under the conditions of $\theta_{\rm inc,0}=\theta_b$ and $T_s^2(\theta_{\rm inc,0})(\cos\alpha)^2=T_p^2(\theta_{\rm inc,0})(\sin\alpha)^2$ or $4/(1+n_g^2)^2(\cos\alpha)^2=(\sin\alpha)^2$, the amplitude of the mechanically modulated laser beam at the first harmonics of the chopping frequency is given by

$$I_t({\rm dc})=\frac{2}{\pi}I_{\rm inc}(\sin\alpha)^2. \quad (5)$$

$I_t({\rm dc})$ and $I_t(2\Omega)$ are detected with the same phase-sensitive detection system. Let $S_t(2\Omega)=\eta I_t(2\Omega)$ and $S_t({\rm dc})=\eta I_t({\rm dc})$ be the output voltages of the phase-sensitive detection stem in response to $I_t(2\Omega)$ and $I_t({\rm dc})$, respectively. We find

$$\Delta_p^{(T)}-\Delta_s^{(T)}=\left[\frac{2}{\pi J_2(\pi)}\right]\frac{I_t(2\Omega)}{I_t({\rm dc})}=\left[\frac{2}{\pi J_2(\pi)}\right]\frac{S_t(2\Omega)}{S_t({\rm dc})}. \quad (6)$$

By combining Eqs. (4) and (6), we find the angular drift $\Delta\theta$ from $S_t(2\Omega)$ and $S_t({\rm dc})$ as

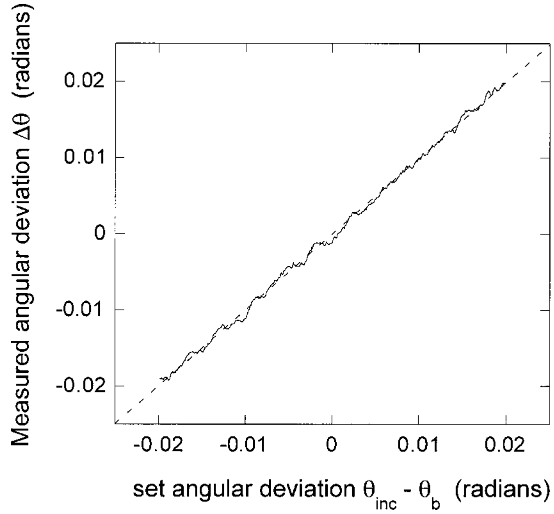

FIG. 2. Measured angular deviation $\Delta\theta$ [computed from Eq. (7)] vs the set incidence angle change $\theta_{\rm inc}-\theta_b$ over a range of 40 milliradians is shown. The dotted line is fit to a linear function with a slope of 0.9968.

$$\Delta\theta\cong\left[\frac{n_g^3}{(n_g^2-1)^2}\right]\left[\frac{2}{\pi J_2(\pi)}\right]\frac{S_t(2\Omega)}{S_t({\rm dc})}. \quad (7)$$

III. EXPERIMENTAL RESULTS

We performed two experiments to demonstrate the oblique-incidence transmittance difference technique. In the first experiment, we verify Eq. (4) through Eq. (7) by measuring $\Delta_p^{(T)}-\Delta_s^{(T)}$ as a function of known incidence angle and comparing the measured $\Delta\theta$ to the known variation of the incidence angle. In the second experiment, we monitor angular drifts of two commercial He–Ne lasers over 24 h using this technique and compare the measurement with available specifications of these two lasers.

A. Calibration of optical transmittance difference versus set change in incidence angle

We use a 1 mW Spectra-Physics 117A He–Ne laser at a wavelength of 632.8 nm. The laser is linearly polarized and can be operated in either intensity stabilization mode or frequency stabilization mode. The parallel fused silica window has a refractive index of $n_g=1.456\,74$ at the He–Ne wavelength. From Eq. (4), we expect

$$\Delta_p^{(T)}-\Delta_s^{(T)}\cong 0.407\Delta\theta. \quad (8)$$

We mount a 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 incidence angle $\theta_{\rm inc}$ in a prescribed fashion. Starting from the Brewster angle θ_b, at each set incidence angle $\theta_{\rm inc}$, we measure $S_t(2\Omega)=\eta I_t(2\Omega)$ and $S_t({\rm dc})=\eta I_t({\rm dc})$ and compute an angular deviation $\Delta\theta$. We then compare the computed $\Delta\theta$ with $\theta_{\rm inc}-\theta_b$. The result is displayed in Fig. 2. 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. In fact by fitting the measured values to a linear function of the set angle (shown in dashed line), we

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obtain a slope of 0.9968. This shows that the oblique-incidence optical transmittance difference technique can indeed be used to determine the laser beam pointing stability.

Subsequently, we measured the beam pointing stability of two low-power commercial He–Ne lasers with this technique. One is a 10 mW LASOS LGK7654-7 He–Ne laser. The other is the 1 mW Spectra-Physics 117A intensity stabilized He–Ne laser. The test laser is mounted on a thick aluminum block that is bolted on a research-grade TMC optical table made by Technical Manufacturing Corp. The latter is not floated during the test. All other optics are mounted on New Focus mirror mounts that are also bolted on the TMC optical table. The temperature near the optical setup is monitored simultaneously with a Type *K* thermocouple. The latter has a reference in liquid nitrogen. The ambient temperature varies in a range of approximately 1 °C.

B. Pointing stability of a 10 mW LASOS LGK7854-7 He–Ne laser

According to the specification, the pointing direction of a LASOS LGK7654-7 He–Ne laser is expected to drift up to 100 μradians during the first 20 min of the warm up. Afterwards, the range of the drift is to be limited to 20 μradians. In Fig. 3(a), we plot the angular drift for a LASOS LGK7654-7 He–Ne laser measured over a 24 h period with the oblique-incidence transmittance difference technique as shown in Fig. 1. The measurement begins immediately after the laser is turned on. The drift during the first 20 min of warm up is shown in an expanded scale in Fig. 3(b). As one can see, during the warm up, the *mean* pointing direction of the laser indeed drifts downward by 50 μradians. In addition, the *instantaneous* pointing direction oscillates about the mean direction. The oscillation initially has a peak-to-peak amplitude of 20 μradians and a period of 20 s. Toward the end of the warm up, the oscillation has a peak-to-peak amplitude of roughly 50 μradians and a period progressively stretched to 100 s. After 1 h of warm up, the mean pointing direction only drifts slowly, by 70 μradians over 24 h. On top of the mean drift, the pointing direction slowly oscillates with a peak-to-peak amplitude of 30 μradians and an averaged period of 3000 s. These results show that other than a long-term drift over a time period of 12 to 24 h, a LASOS LGK7654-7 He–Ne laser has the angular stability fairly close to the specification. It is noteworthy that the pointing direction is not sensitive to the temperature variation over a range of 1 °C.

C. Pointing stability of a 1 mW Spectra-Physics 117A Intensity stabilized He–Ne laser

In comparison, 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 Fig. 4(a), we display the measured change in the pointing direction of the Spectra-Physics 117A laser over 24 h, together with the temperature of the ambient. In Fig. 4(b), we show the drift during the first 500 s. 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 noticeable is that the amplitude and the time period of the oscillation seem to be very sensitive to the temperature drift over just 1 °C. During the first 6 h and the last 6 h of our measurement when the ambient temperature changes by 1 °C, the pointing direction oscillates with a peak-to-peak amplitude of 1.5 milliradians and a time period varying in the range of 1200 to 2400 s. Only during a time interval of 4 h when the temperature is stable within a standard deviation of 0.023 °C, the change in the pointing direction is within a range of ± 0.2 milliradians (i.e., 200 μradians) with a peak-to-peak change of 0.8 milliradians (i.e., 800 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.

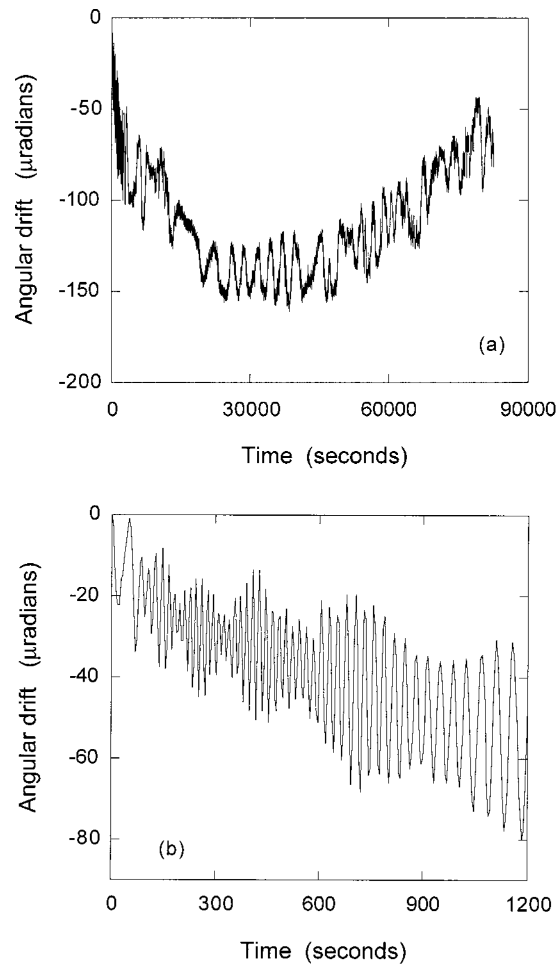

FIG. 3. (a) Measured angular drift of a 10 mW LASOS LGK7854-7 He–Ne laser over 24 h starting immediately when the laser is turned on is shown. The drift angle is determined from Eq. (7). The scale is in μradians. (b) Measured angular drift of the 10 mW LASOS LGK7854-7 He–Ne laser during the first 20 min of warm up is presented.

D. Sensitivity of an oblique-incidence transmittance difference technique to laser beam pointing direction

To determine the sensitivity of our optical transmittance difference technique, we examine the ''quiet'' regions of the

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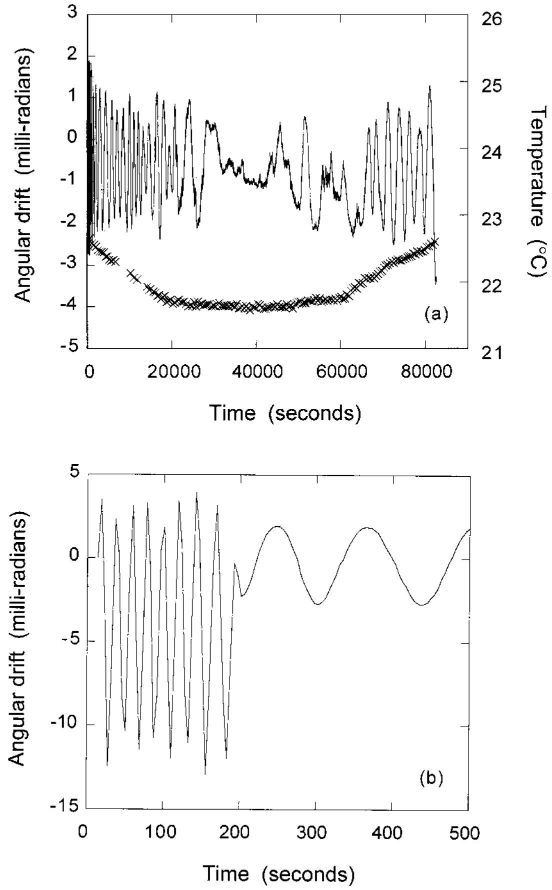

FIG. 4. (a) Measured angular drift (solid line) of a 1 mW Spectra-Physics 117A He–Ne laser in the intensity stabilized mode and the ambient temperature (crosses) over 24 h, starting immediately after the laser is turned on. The scale is in milliradians. (b) Measured angular drift of a 1 mW Spectra-Physics 117A He–Ne laser in the intensity-stabilized mode during the first 500 s is shown. The intensity stabilization takes 200 s to complete.

pointing direction for the LASOS LGK7654-7 He–Ne laser where there are no oscillations. In Fig. 5, we show a measurement of the angular drift of over 6000 s after the laser has been on for 24 h. There are two quiet sections: one from 1000 to 2000 s, and the other from 3800 to 4800 s. The standard deviations in these two regions are 1.7 μradians and 2.0 μradians, respectively. 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 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. Such a high sensitivity is achieved because the angular drift measurement is subject to only the relative noise in the intensity, as is evident from Eq. (3).

IV. DISCUSSION

We have shown here that an oblique-incidence transmittance difference technique is a relatively simple and yet very

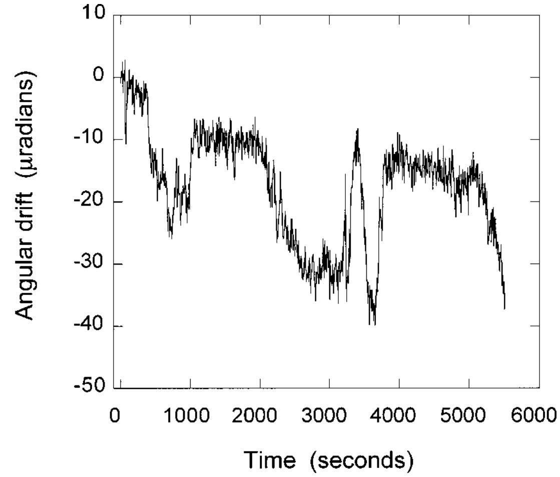

FIG. 5. Measured angular drift of the 10 mW LASOS LGK7854-7 He–Ne laser over a time period of 6000 s, after the laser has been on for 24 h is shown. The data in the quiet regions centered around 1500 s and 4400 s are used to estimate the sensitivity of the oblique-incidence transmittance difference technique for angular drift measurement.

sensitive method for characterization of a laser beam pointing stability. A sensitivity to angular drift of 1.7 μradians is achieved in the present study. The technique is easily extended to measure angular drifts in both the horizontal plane (as we reported here) and in the vertical plane.

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