

Angle measurement by injection detection in a laser diode

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Abstract. We propose a new technique to measure the angle of a remote flat surface with respect to the propagation direction of a laser beam, based on injection detection in a laser diode. The surface under test acts as the remote mirror of an external cavity laser, and causes the laser diode to operate in the coherent collapse regime. The power emitted by the laser depends on the alignment of the remote surface, and an ac technique enables us to measure angle with a sensitivity of 0.1 arcsec (i.e., 5×10^{-7} rad). The attained performances are comparable to those of existing autocollimators, with the advantage of simplicity and compactness that makes the new technique interesting for the development of a measuring instrument. © 2001 Society of Photo-Optical Instrumentation Engineers. [DOI: 10.1117/1.1332276]

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1 Introduction

Several sensing schemes based on laser diodes (LDs) have been proposed for different application fields (i.e., laboratories, industries, medicine, civil engineering). Advantages of these sensors generally are compactness, accuracy, low cost and low invasiveness.

A very simple and interesting approach for interferometric measurements is based on the so-called self-mixing or feedback configuration, in which a fraction of the light emitted by an LD is reflected back by a remote target and allowed to reenter the laser cavity.¹⁻³ A mixing between the lasing and the reflected field is generated so that the emitted power is modulated by an interferometric signal, from which the displacement, vibration, distance or velocity of the remote target can be measured.¹⁻⁶

This paper is based on a modification of the basic self-mixing configuration, namely, an experimental configuration in which a large optical feedback level is produced by the remote reflector, as opposed to the small or moderate feedback of the well-known interferometric scheme.¹ In presence of strong feedback, the LD operates in the so-called coherence-collapse regime,⁷⁻¹⁰ i.e., we have a sort of external cavity laser (ECL) in which the remote reflector acts as the external mirror. Interestingly in this regime, when the remote reflector is caused to vibrate by a loudspeaker, the power emitted by the LD is amplitude modulated by a signal that exactly resembles the driving waveform. Our investigations show that this effect, far from being an interferometric one, is a kind of a LD-based injection-detection scheme,¹¹ sensitive to the total effective attenuation in the external cavity round trip. As a consequence, the angle of the remote surface can also be measured by this technique.

We demonstrate that the new injection detection scheme is capable of measuring the angle of the remote surface with a high sensitivity (0.1 arcsec, corresponding to 5

$\times 10^{-7}$ rad), comparable to that attained by commercial autocollimators.¹² Only the LD, a simple collimating lens, an attenuator and a small mirror mounted on a vibrating piezoelectric transducer (PZT) that generates angle dithering are required for the complete setup. The proposed technique has several advantages, such as compactness, accuracy and low cost, and it is thus attractive for the development of a measuring instrument.

The paper is organized as follows. In Sec. 2, experiments on the strong-feedback regime in a LD are described; in Sec. 3, the principle of angle measurement by the new technique is illustrated; and in Section 4, experimental results on angle measurement are reported and the performance attained by the proposed technique are summarized.

2 LDs in the Strong-Feedback Regime

The conventional experimental setup for self-mixing interferometry and for investigations of angle measurement is shown in Fig. 1. A lens collimates the light from a 800 nm single-mode Fabry-Pérot LD from Hitachi onto a properly aligned remote mirror. The mirror is mounted on a loudspeaker so as to vary its distance from the LD by a small amount. The variable attenuator is used to set the desired level of optical feedback. Power emitted by the rear facet of the LD is collected by the monitor photodiode included into the LD package, and the photocurrent is amplified using a transimpedance configuration. The goal of the experiment is to analyze the behavior of the LD when the feedback level is increased.

In Fig. 2, the signal waveforms measured at the output of the transimpedance amplifier for different levels of the optical feedback are shown. The loudspeaker is driven by a sine wave. Figure 2(b) represents the case of small optical feedback (i.e., less than 10^{-7} round-trip power attenuation in the external cavity). The measured signal is a conventional interferometric one, represented by the expression

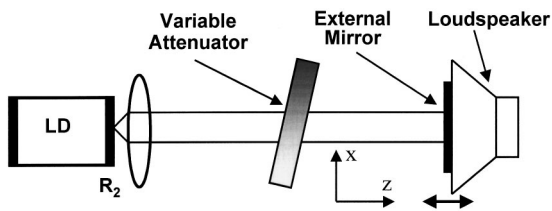


Fig. 1 Basic experimental setup with LD, collimating lens, variable attenuator and remote reflector mounted on a loudspeaker.

$\cos[2ks(t)\phi_0] = \cos[2 \cdot 2\pi/\lambda \cdot s(t) + \phi_0]$, where λ is the LD emission wavelength and $s(t) = \sin(2\pi f_s t)$ is the target displacement. The interferometric signal is a periodic function of the target displacement, and the period is $\lambda/2$. When the feedback is increased to a moderate level (i.e., around 10^{-5} in power), the signal amplitude increases, and the signal waveform becomes distorted up to a point where it becomes sawtooth-like and exhibits hysteresis.^{1,13} This situation, shown in Fig. 2(c), is typical of the self-mixing interferometric configuration, and has widely been demonstrated as capable of measuring the target displacement with $\lambda/2$ resolution without sign ambiguity, using a single interferometric channel.¹ As the feedback level is increased above 10^{-4} in relative power, the interferometric signal shows frequent discontinuities and eventually disap-

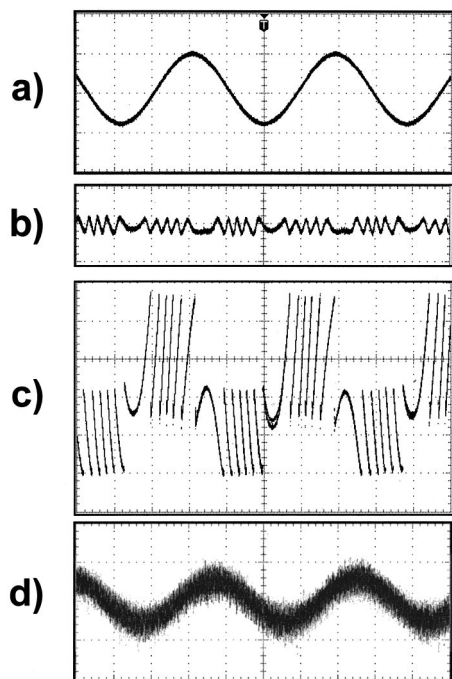


Fig. 2 Signal waveforms measured from monitor photodiode for different optical feedback levels: (a) sine waveform driving the loudspeaker, the vertical scale is 50 mV/div corresponding to $1.3 \mu\text{m}/\text{div}$ displacement in the z -direction and the horizontal scale is 1 ms/div; (b) signal for small optical feedback, the vertical scale is 500 mV/div (the conventional interferometric waveform is observed); (c) signal for moderate optical feedback, the vertical scale is 500 mV/div (the interferometric waveform is sawtooth-like and exhibits hysteresis); and (d) signal for strong optical feedback, the vertical scale is 500 mV/div (the noise level is increased and a sine wave is observed instead of the interferometric one).

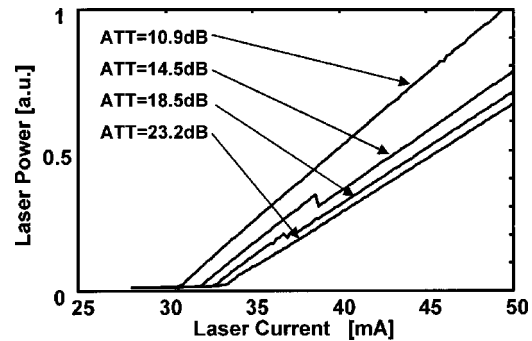


Fig. 3 Experimental P - I curves measured from monitor photodiode for the LD in the strong optical feedback regime using the set-up of Fig. 1 for different values of total round-trip attenuation in the external cavity (values are reported on the graph). Variations in the threshold and slope efficiency of the LD can be observed.

pears, because the LD exhibits mode jumps and no longer operates on a single longitudinal mode. When the feedback level is in the range 10^{-1} to 10^{-3} , the LD enters the so-called coherent-collapse regime and the relative intensity noise (RIN) abruptly increases⁷⁻¹⁰ by 20 dB. Interferometric signals are no longer observed because the LD linewidth is enormously increased and its coherence length is reduced. Interestingly, as shown in Fig. 2(d), in this regime a signal is still present, having the same waveform shape that drives the loudspeaker and a proportional amplitude. At first glance, the signal of Fig. 2(d) seems to be a replica of the target displacement in the z direction, thus suggesting that a noninterferometric measurement of the axial displacement could be performed. Actually, further investigations show that this is not the case. Rather, the observed effect is a combination of the nonideality of the target movement and of the sensitivity of the LD to variations in the total external cavity attenuation.

Theoretical and experimental analyses carried out in this work demonstrate that the LD in the coherence-collapse regime performs a sort of injection-detection scheme, which is sensitive to variations in the total attenuation of the external cavity round-trip. In fact, in this regime the remote reflector acts as the external mirror of an external cavity laser (ECL), which is conceptually equivalent to a LD with an increased output facet reflectivity R'_2 . It turns out that both laser threshold and slope efficiency depend on R'_2 , that is, on the total round-trip attenuation in the external cavity. This is confirmed by the results shown in Fig. 3, that reports several power-current (P - I) curves measured for different total attenuation in the external cavity, obtained by adjusting the variable attenuator. It is thus clear that, for a given injection current, a small variation in the total external cavity attenuation produces a small variation in the power emitted by the LD. How this is related to the signal reported in Fig. 2(d) can be explained by referring to Fig. 4(a), where it is schematically shown that a slight tilt of the remote mirror is equivalent to an increase of the round-trip attenuation. In fact, the reflected light is slightly offset with respect to the LD emission spot, and a smaller fraction of the reflected light effectively couples to the LD cavity mode. This is equivalent to an increase of the round-trip attenuation. The signal of Fig. 2(d) is caused by the

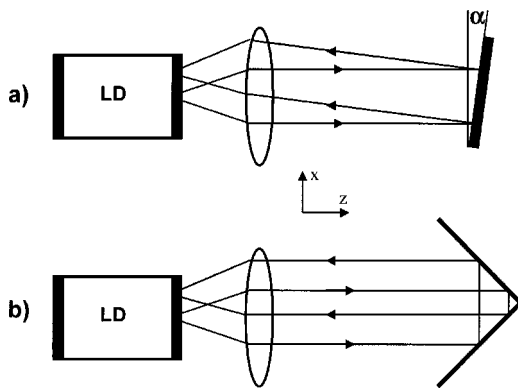


Fig. 4 Nonideal remote reflector alignment causes an increase of the round-trip attenuation in the external cavity, because the reflected light is offset with respect to the emitter laser spot: (a) effect of tilt angle α for a mirror and (b) effect of transversal displacement for a corner-cube.

very small (and unavoidable) sinusoidal tilt that the vibrating loudspeaker impose to the target stuck onto it. Figure 4(b) shows that a variation in the external cavity attenuation can also be caused by a small lateral offset imposed to a corner-cube used as a target instead of the mirror. When the corner-cube is stuck onto the loudspeaker, a signal similar to that of Fig. 2(d) is again observed, because of the small transversal component (in the x direction) of the target displacement.

3 Angle Measurement—Principle

In the previous section it was shown that the novel injection detection scheme working in the coherence-collapse regime is also sensitive to the angle of the remote surface respect to wavevector of the laser beam. This is confirmed by the result of Fig. 5, which shows the experimental plot of the dc power emitted by the LD (measured by the monitor photodiode) for a fixed LD current as a function of the tilt angle α of the remote mirror. The emitted power has a parabolic dependence on the tilt angle. The plot of Fig. 5 refers to the angle lying in the x - z plane, while the angle in the perpendicular plane y - z was set to zero (i.e., optimal

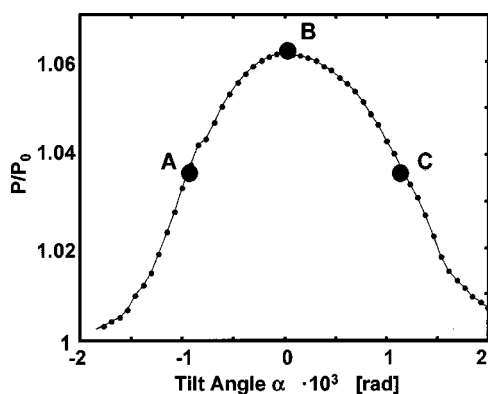


Fig. 5 Experimental measurement of P/P_0 as a function of remote mirror tilt angle α : P , power emitted in the coherence-collapse regime with remote reflector; P_0 , power emitted by unperturbed LD; LD current, 60 mA; and total round-trip attenuation in the external cavity, 14 dB.

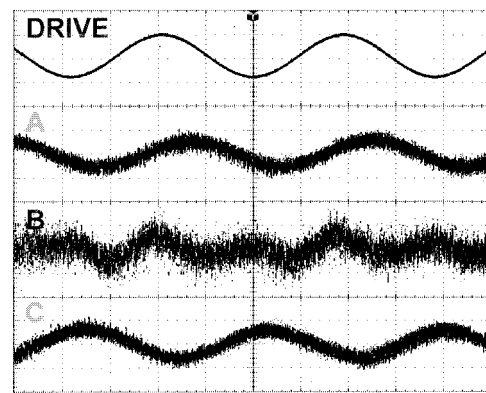


Fig. 6 Scope traces of signal waveforms detected by monitor photodiode when the mirror is stuck onto a vibrating loudspeaker, generating also a sine tilt. Upper trace: loudspeaker drive waveform. Traces A, B, and C refer to dc tilt points shown in Fig. 5 with corresponding label. Signal A is in-phase with drive waveform, signal B is out-of-phase, signal C exhibits only the second harmonic. Vertical scale is 500 mV/div (A and C) and 200 mV/div (B), horizontal scale is 1 ms/div, and total round-trip attenuation in the external cavity is 14 dB.

alignment in the y - z plane, corresponding to maximizing the emitted power). Actually, the power emitted by the LD is a 3-D paraboloid, since it has a parabolic dependence on both the x - z and y - z plane angles.

When the external reflector is actuated by the loudspeaker, a signal similar to that of Fig. 2(d) is again observed, because of the resulting sinusoidal tilt imposed to the mirror. Interestingly, the signal is in-phase or out-of-phase with respect to the waveform that drives the loudspeaker, depending on the dc offset tilt angle of the mirror. This is clearly shown in Fig. 6, which displays the different ac signals obtained for dc angles corresponding to points A, B, and C of Fig. 5. It is also noted that when the dc offset tilt angle is zero (i.e., optimal external mirror alignment, point B) the power modulation has only the second harmonic component.

A measurement of the angle of the remote surface can be performed by measuring the dc power emitted by the LD (see Fig. 5). However, the accuracy is negatively affected by common-mode disturbances, such as temperature-induced LD threshold change or variations in the round-trip loss of the external cavity. By this dc-type method, an accuracy of 10 arcsec (i.e., 5×10^{-5} rad) is attainable for a target distance of 0.8 m, when the LD temperature is stabilized within 0.1°C by a Peltier cell.

A much better accuracy is attained by performing an ac-type measurement, by introducing a small dither $\Delta\theta$ in the remote surface angle α by means of a small mirror mounted onto a PZT actuator vibrating in flexure mode at a frequency f_d . The ac measurement also enables us to eliminate the temperature control because it is intrinsically independent of common mode disturbances. The first harmonic sinusoidal component of the output signal at f_d is proportional to the first derivative of the parabolic curve of Fig. 5, and hence it is proportional to the angle α to be measured, except for large angles where the derivative saturates. The sign of the angle can be easily recovered by

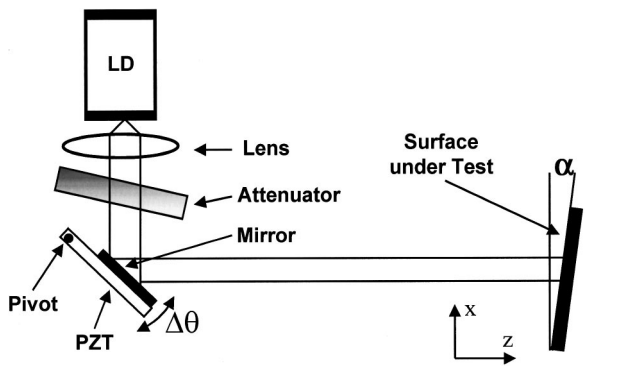


Fig. 7 Experimental setup for accurate angle measurement by the ac technique. A sine dither at frequency f_d is applied to the PZT, which is vibrating in flexure mode.

comparing the output signal phase with that of the sinusoidal dither drive at f_d .

4 Angle Measurement—Experiment

The experimental setup for accurate angle measurement is shown in Fig. 7. A small mirror is mounted on the bending PZT operating in flexure mode, driven by a sine wave at frequency $f_d = 180$ Hz. It generates a small dither $\Delta\theta(t) = \theta_0 \sin(2\pi f_d t)$ in the x - z plane, with an amplitude θ_0 of the order of 5×10^{-6} rad. The distance of the remote surface from the LD is 0.7 m, and the laser is operated at 70 mA injected current with no temperature control. The output signal is fed to a fast Fourier transform (FFT) spectrum analyzer to detect the amplitude of the first harmonic component. The remote mirror is coarsely tilted and aligned by precision screws, while the fine angle variation is achieved by another bending PZT driven by a variable dc voltage, onto which the target mirror is stuck. The amplitude of the signal first harmonic is plotted in Fig. 8 as a function of the tilt angle α . A good linearity is obtained between -5×10^{-4} and $+5 \times 10^{-4}$ rad. The sensitivity (i.e., the smallest measurable angle) is reported to be 5×10^{-7} rad (i.e., 0.1 arcsec) for a 1 Hz noise bandwidth. The measured sensitivity value is actually limited by $1/f$ mechanical and vibration noise of the laboratory environment. The theoretically attainable electronic-noise limited sensitivity is 5×10^{-8} rad for a 1 Hz noise bandwidth (i.e., one order

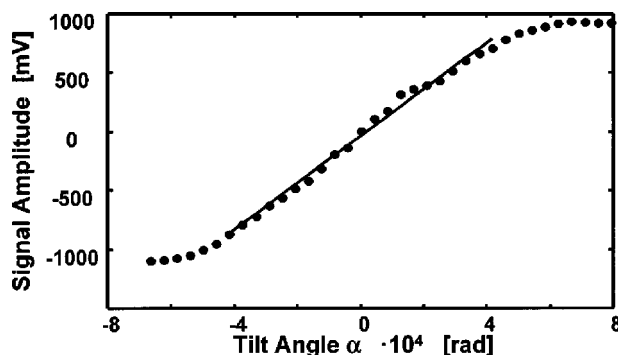


Fig. 8 Amplitude of the first harmonic of detected signal at frequency f_d as a function of the tilt angle α of the surface under test.

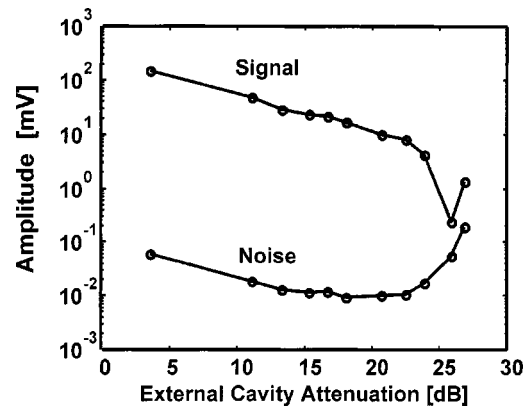


Fig. 9 Plot of the amplitude of the detected signal at frequency $f_d = 180$ Hz and of the noise as a function of the total round-trip optical attenuation in the external cavity. Noise is measured at 1 kHz to eliminate $1/f$ ambient mechanical fluctuations and to show the effective SNR attainable by the LD in the coherence-collapse regime. Noise bandwidth is 1 Hz.

magnitude smaller). The latter value takes into account the fact that the RIN of the LD operating in the coherence-collapse regime is 20 dB larger than that of the unperturbed laser.

Obviously, the measurement channel can be duplicated to measure also the angle in the y - z plane. This can be easily done by adding another dither $\Delta\varphi$ in the y - z plane at a different frequency.

Common-mode LD output power variations are cancelled out by dividing the ac sinusoidal signal by the dc power term exceeding the unperturbed value P_0 . This procedure also makes the measurement independent from the total round-trip attenuation in the external cavity, provided the LD still operates in the coherent-collapse regime. The influence of the optical attenuation in the external cavity is shown in Fig. 9, where both the amplitude of the dithering signal at frequency f_d and the noise are reported. Interestingly, the SNR remains constant up to attenuations as large as 20 dB. For larger attenuations the LD exits the coherence-collapse regime and enters the mode-hopping regime, so the signal amplitude decreases and the noise increases. When the remote surface is a mirror, total optical power attenuation as large as 22 dB is tolerated in the external cavity. For a glass surface, the maximum allowed extra attenuation is 9 dB. The measurement is effective on remote surfaces with diameter as small as 2 to 3 mm, and the maximum allowed distance of the surface is 3.5 m. Since the information on the angle is contained in the power emitted by the LD as a modulation term, this information could be retrieved at any point along the beam propagation path (i.e., even at the remote surface site) by spilling some power by means of a beamsplitter.

A comparison with the performance attained by commercial autocollimators is worthwhile. Autocollimators are based on a light source whose image is collimated by a telescope onto the surface under test.¹² In visual autocollimators, the reflected spot is imaged onto a graduated screen or eyepiece that enables the user to directly check for the alignment of the surface with an accuracy ranging from 1 arcsec to several tens of arcseconds. Electronic autocollimators make use of an automatic scheme for the detection

of the reflected spot position, e.g., based on a four-quadrant photodiode. The accuracy then attains 0.005 to 0.1 arcsec typically, and the dynamic range can be 5 decades. A relevant part of cost of these instruments is presented by the precision collimating optics that determine the instrument performance, which is limited by diffraction.¹² A large diameter and a long focal length of the output lens both help in improving the sensitivity, but the overall length of the more accurate instruments can be several tens of centimeters.

The newly proposed measuring scheme based on injection-detection in a LD is very compact, because all the required components (i.e., LD, low-cost collimating lens, attenuator, bending PZT and electronic circuits) can fit into a few centimeters size box. Since injection-detection of the reflected light takes place within the LD, the angle sensitivity of the scheme does not critically depend on the diameter of the collimating lens. This also helps in reducing the minimum allowed diameter of the surface under test, that for some existing autocollimators should be larger than few tens of millimeters, especially for the case of 4% reflectivity glass surfaces.

5 Conclusions

We demonstrated a new method for the measurement of the angle of a remote flat surface based on injection-detection in a LD in the strong-feedback regime. This scheme demonstrates that a LD can be used for sensing purposes even in the so-called coherence-collapse regime. The method is easy to implement and has a sensitivity of 0.1 arcsec (i.e., 5×10^{-7} rad), which is comparable to that of commercial electronic autocollimators.

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