Optical-feedback Semiconductor Laser Michelson Interferometer

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ABSTRACT

An optical-feedback semiconductor laser Michelson interferometer (OSMI) is presented for measuring microscopic linear displacements without ambiguity in the direction of motion. The two waves from the interferometer arms, one from the reference mirror and the other from the reflecting moving target, are fed back to the lasing medium ($\lambda = 830$ nm), causing variations in the laser output power. We model the OSMI into an equivalent Fabry-Perot resonator and derive the dependence of output power on path difference between the two interferometer arms. Numerical and experimental results obtain output power that varies periodically (period $= \lambda/2$) with path difference. The output power variation exhibits an asymmetric behavior with the direction of motion, which is utilized to measure the amplitude of vibration of (1) a piezoelectric transducer (PZT) and (2) an audio speaker with directional discrimination.

INTRODUCTION

Industrial applications of displacement measurements require both accuracy and directional discrimination capability which are essential particularly in the motion control of mechanical components along different axes. For versatility, it is also desired that displacement sensors be compact, sturdy, and economical to operate.

Feedback phenomenon in semiconductor laser (SL) diodes has been applied in designs of several displacement-measuring instruments that satisfy the above requirements. These instruments employ self-mixing interference in the SL light source to carry out small displacement and low-amplitude vibration measurements with high resolution (Donati et al., 1995; Gouaux et al., 1998; Donati et al., 1996; Gharbi et al., 1997; Chebbour et al., 1994).

In this paper, we demonstrate a new optical-feedback detection scheme for microscopic displacement measurements that uses an 830-nm SL in a Michelson architecture. The instrument which we refer to as the optical-feedback semiconductor laser Michelson interferometer (OSMI) measures displacement of the reflecting target without ambiguity in motion direction. Magnitude and direction of sample displacement are obtained from the periodic and asymmetric variation of the SL output power that results from the change in the path difference between the reference mirror and the reflecting sample. The OSMI has a resolution =415 nm; dynamic range $\approx 10^{-3}$ m (SL coherence length). A theoretical model (Zhang et al., 1996) is developed to calculate the dependence of SL output power on path difference of the two interferometer arms. Finally, the OSMI performance is evaluated by measuring the vibrational amplitude of voltage-driven piezoelectric transducer (PZT) and audio speaker.

METHODOLOGY

In the experiments (Fig. 1), a Fabry-Perot type SHARP LTO15MFO V-channel substrate double-

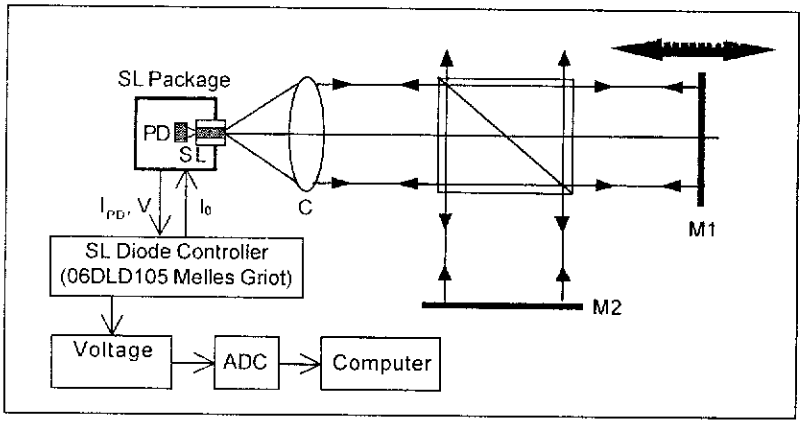

Fig. 1. Experimental setup. The moving M_1 in the OSMI is mounted on two kinds of test targets (M_2 is stationary): (1) PZT-driven stage and (2) audio speaker diaphragm. Each target provides displacement to mirror M_1 along the optical axis of the SL and the objective lens C. A precision diode controller provides injection current I_0 to SL and monitors I_{PD} and V.

heterostructure SL (λ = 830 nm) was used as a light source. The commercial SL package also contains a built-in photodiode (PD) for monitoring the output power at the SL rear facet. The SL is operated by a precision laser controller (Melles Griot Laser Diode Controller 06 DLD 105) that is equipped with a built-in temperature controller that maintains the SL ambient temperature at T=25^{0}C. The output of the SL front facet is collimated by an infinity-corrected microscope objective lens C (Natchet: numerical aperture NA = 0.35, 20X) and split into two beams by a 50/50 (transmission/reflection ratio) beam splitter BS. The individual beams are reflected back to the laser medium by plane mirrors M_1 and M_2. Variations in the OF strength are obtained by varying the position of M_1 relative to M_2 which is held stationary. The M_1 was mounted on two kinds of vibrating test targets: (1) piezoelectric transducer-driven (Thorlabs: peak-to-peak driving voltage range $0 \leq V_d \leq 10$ volts, dynamic range $\approx$ 15 μm), and (2) audio speaker. The two voltage-driven test targets are provided with periodic signals by a function generator (SRS Model DS345) with variable control in amplitude and frequency. The variation in the SL output power that is caused by the change in path difference (or change in L_1 since L_2 is fixed) is observed by measuring the voltage (proportional to SL power) of the built-in PD. A voltage amplifier was employed to improve the dynamic range of the PD signal. The amplified voltage is sent to an 8-bit analog-to-digital converter and then data is processed and stored in a computer.

RESULTS AND DISCUSSION

Figs. 2a and 2b present time-plots for the motion of the PZT with a triangular and sinusoidal voltage driving signal, respectively. Similarly, Figs. 2c and 2d are plots for the case of the voltage-driven audio speaker. All driving signals were set to a frequency of 1.0 Hz. For each plot, the top-most trace represents the driving voltage signal, the lowest trace denotes the variation in the SL output power, and the middle trace represents the derivative of SL output power. Note that the SL output power variation is not only periodic but asymmetric (ramp-like) in form to provide directional discrimination. The interval between spikes of the middle trace (which is equal to the resolution of the proposed instrument) corresponds to a $\lambda/2$ (= 0.415 μm) displacement. The middle trace easily allows fringe (spike) counting to determine the amplitude of vibration of the moving target and it also discriminates the target's direction of motion (upward spikes correspond to direction approaching the SL; downward spikes away from the SL). Counting the number of spikes that occur within a continuous set (of upward or downward spikes), we find that the amplitudes of vibration for the PZT (V_d = 4.0 V p-p) and for the speaker (V_d = 2.0 V p-p) are 5.395 μm and 9.96 μm, respectively.

For the case where the driving signal is triangular, the spikes are equally spaced in time. On the other hand, for the sinusoidal signal, the interval between adjacent spikes is closest with each other at t values corresponding to the inflection points of the driving signal where the magnitude of the slope (or speed) is maximum, and becomes wider at points approaching the extrema of the driving signal. It is evident from the plots in Fig 2 that the OSMI could not only measure amplitude and direction of the displacement, but also allows the observation of the decrease and increase of target speed (i.e., acceleration). Several measurements of vibration amplitude of the two test targets were taken at different driving voltage V_d values (1.0 – 10.0 V) with signal frequency of 1.0 Hz. A linear dependence

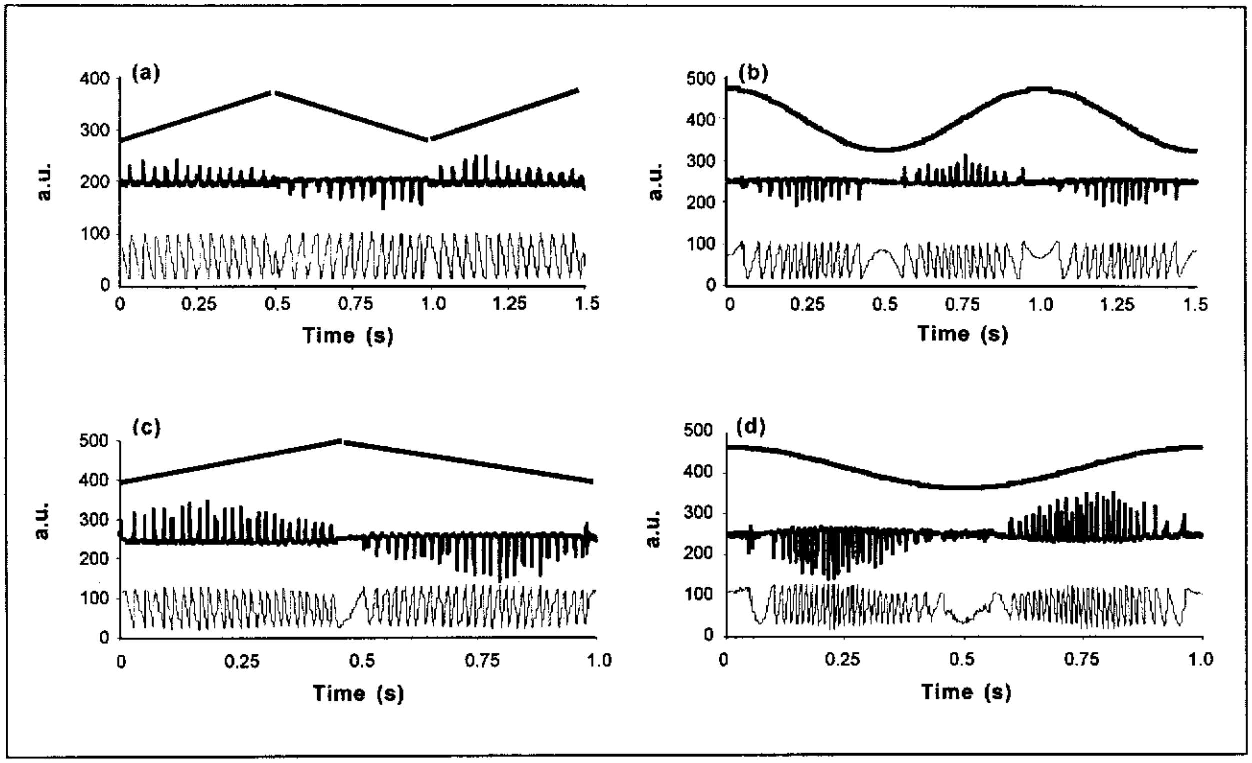

Fig. 2. SL output power variation and its derivative with 1.0 Hz driving signal for the two test targets. Plots (a) and (b) are for the PZT sample with 4.0 V (p-p) triangular and sinusoidal driving signals, respectively. Plots (c) and (d) are for the audio speaker with 2.0 V (p-p) triangular and sinusoidal signals, respectively.

(within the considered range) between the vibration amplitude and V_d was obtained for the two test targets as shown in Fig. 3. Note, for the case of the PZT, that a driving voltage of V_d = 10.0 V resulted in a vibration amplitude of about 15 mm which is the device's maximum extension as specified by the manufacturer.

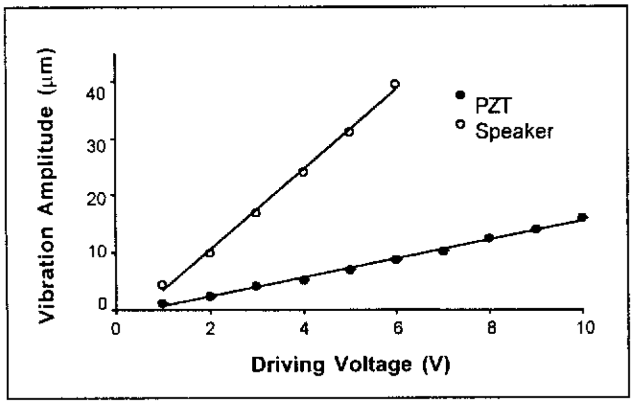

Fig. 3. Amplitudes of vibration of the two test targets vs. driving voltage V_d. Points were obtained by counting the spikes of the differentiated power variation where the interval between adjacent spikes is equal to $\lambda/2$. The uncertainty in the measured amplitude is $\pm \lambda / 4 \approx \pm 0.2075$ μm.

CONCLUSION

The output power of an 830 nm semiconductor laser subject to optical feedback from a Michelson interferometer (i.e., with two external cavities) was found to vary periodically with the motion of one mirror when the other is stationary. The SL power variation was shown to be symmetric or asymmetric in form depending on the lengths of the two external cavities. We have proposed an instrument (OSMI) that measures microscopic displacements and has the capability to discriminate motion direction based on the asymmetric and periodic power variation of the SL. The proposed instrument, with a $\lambda/2$ - resolution (0.415 μm), is able to measure the vibrations of a PZT actuator and an audio speaker driven by 1.0 Hz triangular and sinusoidal signals with peak-to-peak voltage ranging from 1.0 V to 10.0 V.

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