Optical Feedback Height Control System Using Laser Diode Sensor for Near-Field Data Storage Applications

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Abstract—**We demonstrated a laser diode position sensor for a near-field height control system. The feedback signal of the laser diode sensor that resulted from self-mixing interferometry was characterized and modeled by a simplified method. Due to the fine spatial resolution of the laser sensor, an active height control system with nanoscale position precision was designed and realized under a spinning disk for near-field applications.**

Index Terms—**Data storage, laser sensor, nanoscale active control, self-mixing interferometry.**

I. INTRODUCTION

NEAR-FIELD data storage systems approach the medium with nanometer spacing to break through the diffraction limit that conventional focusing systems have done. Therefore, a precise gap detecting system and a servo control system are of critical importance to make near-field recording feasible. Air gap servo systems employing the dependence of evanescent-wave penetrating efficiency on the gap between the solid immersion lens (SIL) and the disk surface were reported [1]–[5]. However, external optical systems and signal processing systems are necessary for separating air gap signals from the reflected optical power from the SIL. In contrast, laser diode position sensors that employ the dependence of the laser output on the distance between the laser and the target can detect the displacement by monitoring the power modulation of the laser without external optical components [6]–[8]. Therefore, the advantages of compact package and flexibility of integration with other systems make laser diode sensors widely used for displacement, velocity, and acceleration measurement with millimeter-scale precision. However, less attention was paid to apply laser diode sensors in the servo control field, particularly near-field applications. Thus, we demonstrated a height control system for near-field storage applications with nanoscale precision by employing a laser diode position sensor to detect the distance between the sensor and a spinning disk [9], [10]. In this paper, we characterized the signal as a function of the distance between the laser and the target. A simplified method was derived to model the output signals and to compare them with the measured signals. According to the characteristic signal, the configuration and design of a servo control system were presented. The operation of the system under a spinning disk was demonstrated.

II. SIGNAL CHARACTERIZATION

To achieve nanoscale position precision, the feedback signal has to be characterized as a function of the spacing. Many studies presented theoretical models, but most of them emphasized on large spacing detection; therefore, multiple reflection was ignored. However, in near-field storage systems, different assumptions should be considered. The target surface in a storage system is a disk covered by a metal film with high reflectivity. In addition, the spacing between the laser sensor and the target surface is only within several wavelengths. These two conditions implied that multiple reflections should be taken into consideration in the calculation of near-field output modulation. Consequently, we presented a simplified model to characterize the laser sensor signal with a near-field gap.

We considered a laser diode of length L with an external cavity of length d, as shown in Fig. 1(a), where r_1, r_2, and r_3 denote the amplitude reflection coefficients of the laser facets F_1 and F_2 and the external reflector F_3, respectively. If we assume that the reflector is only a few wavelengths away from the laser, i.e., $d \ll L$, the effect of the external-cavity modes due to the presence of the external cavity can be ignored [11]. The coupling condition from the reflected light into the laser cavity alters the effective reflectivity of the laser-emitting facet and then results in the interference with the field inside the cavity. A complex coupling factor, which consists of a phase and an amplitude factor, was employed to describe the coupling condition [12], [13]. The effective reflectivity in terms of reflection coefficients and coupling coefficient

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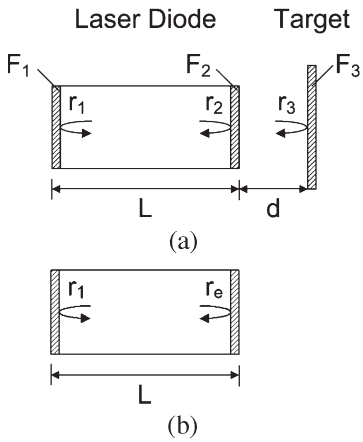


Fig. 1. Configurations of (a) external-cavity laser diode and (b) equivalent laser diode.

was used to present an equivalent laser diode, as shown in Fig. 1(b). Thus

$$r_e = r_2 - \frac{(1-R_2)}{r_2} \sum_{n=1}^{\infty} C_n (-r_2 \cdot r_3 \cdot e^{i\phi})^n \tag{1}$$

where the phase shift Φ resulted from the gap d, i.e.,

$$\phi = \frac{4\pi \cdot d}{\lambda} \tag{2}$$

and the power reflectivity of the laser diode facet R_2, i.e.,

$$R_2 = |r_2|^2. \tag{3}$$

The coupling coefficient C_n represents the ratio of reflected light coupling into the laser diode at the nth reflection. Because the reflectivity coefficient term decreases exponentially and much more rapidly than the coupling coefficient does as the reflection increases, we assume that the reflectivity coefficient term dominates the amplitude and the coupling coefficient is a function of the spacing d and independent of the reflection. Then, we can derive the effective reflectivity as follows:

$$\begin{aligned} r_e &\approx r_2 - \frac{(1-R_2)}{r_2} \cdot C \cdot \sum_{n=1}^{\infty} \left(-r_2 \cdot r_3 \cdot e^{i\phi}\right)^n \\ &= r_2 + \frac{(1-R_2) \cdot C \cdot r_3 \cdot e^{i\phi}}{(1 + r_2 \cdot r_3 \cdot e^{i\phi})}. \end{aligned} \tag{4}$$

The coupling coefficient C is in terms of an amplitude factor and a phase factor. The amplitude factor represents the fraction of reflected light that can couple back to the cavity, and the phase factor is a phase shift at the coupling interface. Therefore, the coupling coefficient can be written as

$$C = A(d) \cdot e^{i\phi_C} = C_c \cdot \left(1 - e^{-2\left(\frac{1}{1+\left(2 \cdot d \cdot \lambda / \left(\pi \cdot \omega_0^2\right)\right)^2}\right)}\right) \cdot e^{i\phi_C} \tag{5}$$

where C_C is a proportional constant.

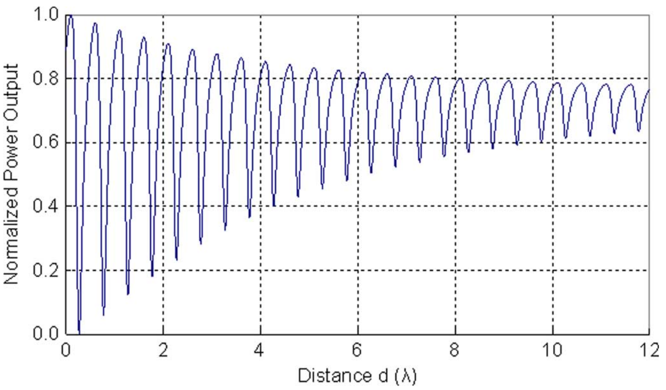


Fig. 2. Simulated self-mixing interferometric fringe.

If we assume a constant drive current applied to the laser diode, the output power can be represented in terms of the applied current I and the threshold current I_{th}, i.e.,

$$P_e \propto (I - I_{\text{th}}) \propto \left[P_C - \ln\left(\frac{1}{\sqrt{R_1 \cdot R_e}}\right)\right] \tag{6}$$

where the power reflectivities R_1 and R_e are given by

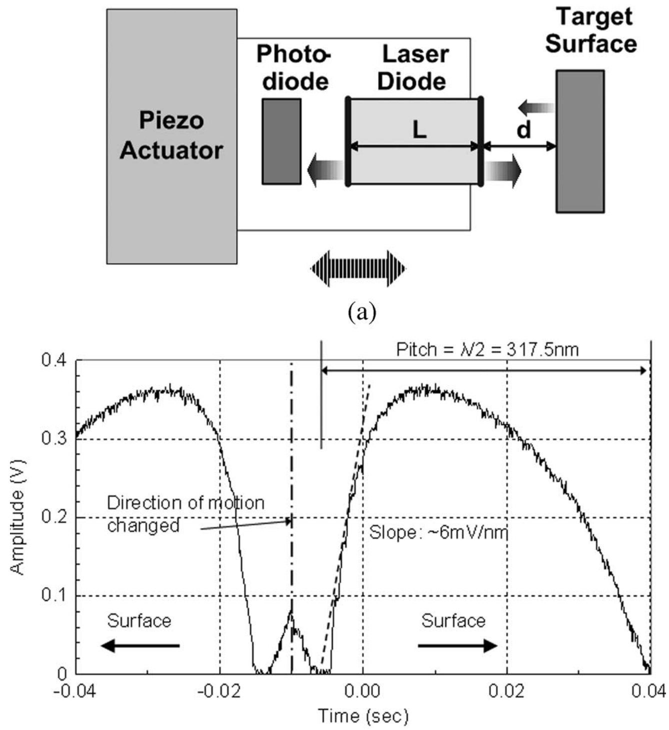
$$R_1 = |r_1|^2 \tag{7}$$

$$R_e = |r_e|^2 \tag{8}$$

and P_C is a constant. In the case of $r_1 = 0.99$, $r_2 = 0.9$, $r_3 = 0.8$, $\lambda = 0.635$ μm, and $w_0 = 1$ μm, we calculated the power output as a function of the spacing between the laser and the target surface according to the previously derived equations, as shown in Fig. 2.

To measure interferometric signals, a silicon wafer coated with an aluminum film was placed in close proximity to the output facet of a laser diode with a wavelength of 635 nm. The laser diode was fixed in a mount attached to a piezoactuator that provided a back-and-forth motion to generate the self-mixing interferometric signal. The experimental setup is shown in Fig. 3(a). Since the optical misalignment caused signal distortion, we kept the angular alignment precision between the two surfaces within 50 μrad.

The monitoring current of the photodiode was converted into a voltage signal, as shown in Fig. 3(b), at a sampling rate of 10 ks/s. The signal is a periodic function of the distance with a maximum amplitude of 0.37 V, and the pitch, which is a complete interferometric fringe, corresponds to a displacement of $\lambda/2$, which is 317.5 nm in this case. Since the absolute value of the measured signals was highly dependent on the gain of the entire system, a comparison of the measured signals and the simulation model was made by normalizing the measured signal to unity and converting it to a function of the relative position in terms of wavelength. Fig. 4 clearly shows that the simplified model agreed well with the measurement. Then, the slope of the signal, the sensitivity of the signal to the position variation, as well as the minimum displacement resolution that the laser sensor can achieve, can be obtained by finding the derivative of the signal function. According to the signal amplitude and the pitch, the slope at the half-maximum



(a)

(b)

Fig. 3. (a) Experimental setup for generating self-mixing inteferometric signals. (b) Measured signal from the photodiode.

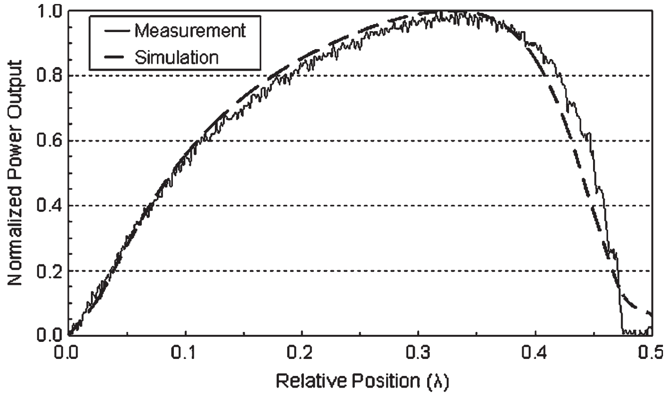


Fig. 4. Comparison of the calculated and measured self-mixing interferometric signals.

level of this laser sensor is 6 mV/nm. Compared with the noise level of this system, an accuracy of less than ±1 nm can be theoretically achieved, which is competitive with other control methods.

III. ACTIVE HEIGHT CONTROL SYSTEM

A. *Configuration of Control System*

The laser-sensing control system for near-field applications consisted of a laser sensor, an actuator, drive circuits, and a controller. The laser sensor was obtained by modifying a commercial laser diode with a wavelength of 635 nm. Because of the compact package, the laser diode sensor was able to be installed on a conventional biaxial pickup actuator. The monitoring output power detected by the photodiode inside the laser diode was converted into a voltage signal and sent to the controller. The proportional–integral (PI) controller generated a drive signal to the pickup driver to actuate the real-time movement of the pickup. To improve phase and gain margins, a lead compensator was integrated into the controller. Some circuits were also designed accordingly to convert signals, drive the actuator, and suppress noise. The configuration of the system is shown in Fig. 5.

B. *Controller Design*

The open-loop frequency response of the actuator consisting of the pickup with the laser sensor and the pickup drive circuit was measured to characterize the dynamic performance of the control plant. As shown in Fig. 6(a), the first resonance frequency is 43 Hz, and the transfer function of the actuator was modeled accordingly. Then, the step response of the pickup was calculated, as shown in Fig. 6(b). The settling time was less than 0.1 s, whereas the overshoot was around 60%.

According to the sensitivity of the feedback signal and the frequency response of the actuator, a PI controller was designed for a spinning disk at a rotation speed of 1200 r/min or greater and with a runout of 20 μm or less. The controller was digitally implemented in a dSPACE system at a sampling rate of 100 kHz. In Fig. 7, the dashed curve shows the designed open-loop dynamic characteristics of the active height controller system. From the calculated data, the bandwidth is 6 kHz, and the phase and gain margins are 52° and -24 dB, respectively. The measured results showed that the controller meets the design requirements and the measured open-loop frequency response agrees well with the design.

IV. EXPERIMENTAL RESULTS

The control system was evaluated by means of an actuated surface test system, as shown in Fig. 8(a). A silicon wafer coated with an aluminum film was attached onto a piezoactuator in proximity to the laser sensor and the two surfaces aligned parallel to each other. The movement of the silicon wafer was synchronized with the vertical movement of a spinning glass disk by converting a real-time displacement signal from an interferometer to a drive signal. The vertical runout at the radial position of 50 mm was 16 μm at a rotation speed of 1500 r/min, whereas the actual displacement of the silicon wafer was 4.8 μm due to the gains of the interferometer and the piezoactuator. The experimental result in Fig. 8(b) showed the capability of the control system using a laser sensor to precisely follow the motion of the silicon wafer and reduce the residual position error to ±3 nm when the laser sensor was in proximity to the target surface within several wavelengths.

We then demonstrated the control system operation under a spinning disk. As shown in Fig. 9(a), the pickup with the laser sensor installed was mounted on a stage that can compensate the angular variation of the disk surface. A 120-mm-diameter glass disk coated with an aluminum film was clamped on an air-bearing spindle. By illuminating an open window at the disk edge, the orientation of the pickup was adjusted until two reflected beams were parallel, ensuring alignment of the laser

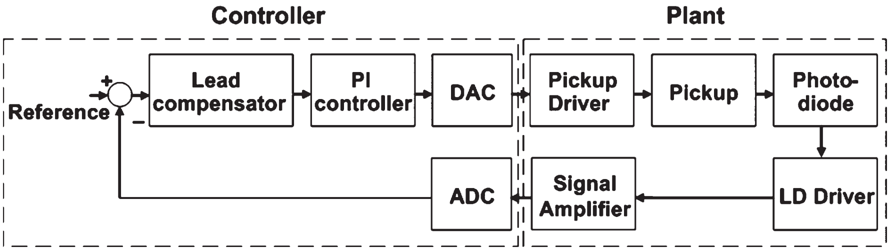
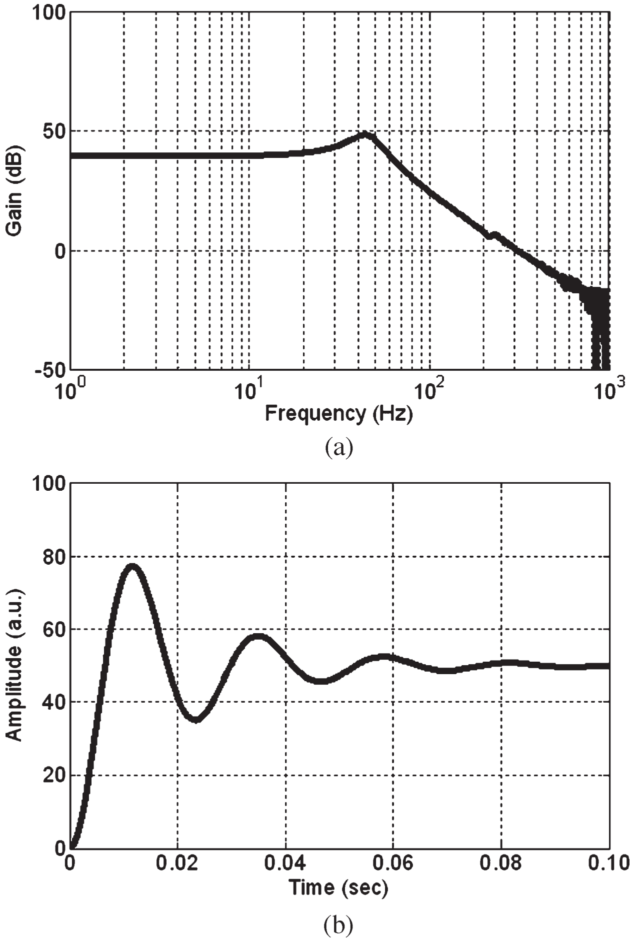


Fig. 5. Block diagram of near-field height control system employing a laser sensor.



(a)

(b)

Fig. 6. (a) Measured open-loop frequency response of the actuator. (b) Calculated step response of the actuator according to the modeling transfer function.

to the disk surface. Fig. 9(b) illustrates the error signal, pickup drive signal, and feedback signal when the servo was in closed-loop operation at rotation speeds up to 1500 r/min, i.e., the linear velocity at the servo radius of about 7.8 m/s and at the vertical runout of 16 μm. In this case, the residual position error was ±9 nm, and the system functioned without a collision between the laser sensor and the disk. However, because of the relatively low amplitude of the original signal and the noise induced by the circuits, the result was inconsistent with the theoretical accuracy of ±1 nm and even higher than that of ±3 to ±5 nm in air gap servo systems. Since the noise frequency was much higher than 100 kHz, the residual error was able to be further reduced to ±4 nm by means of a signal amplifier with a bandwidth of 100 kHz for filtering out noise and increasing the signal-to-noise ratio.

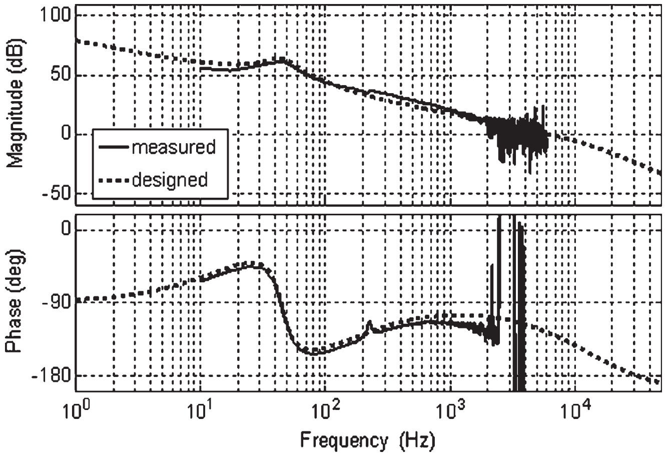
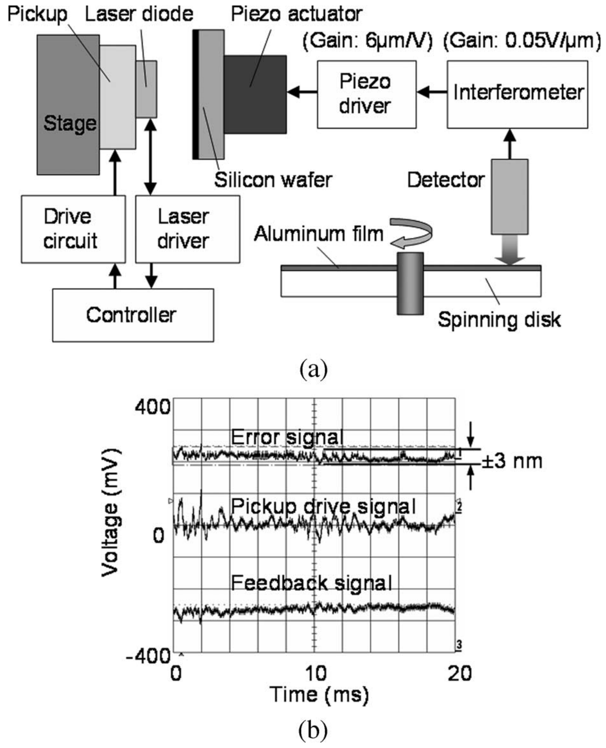


Fig. 7. Open-loop frequency response of the active height control system.



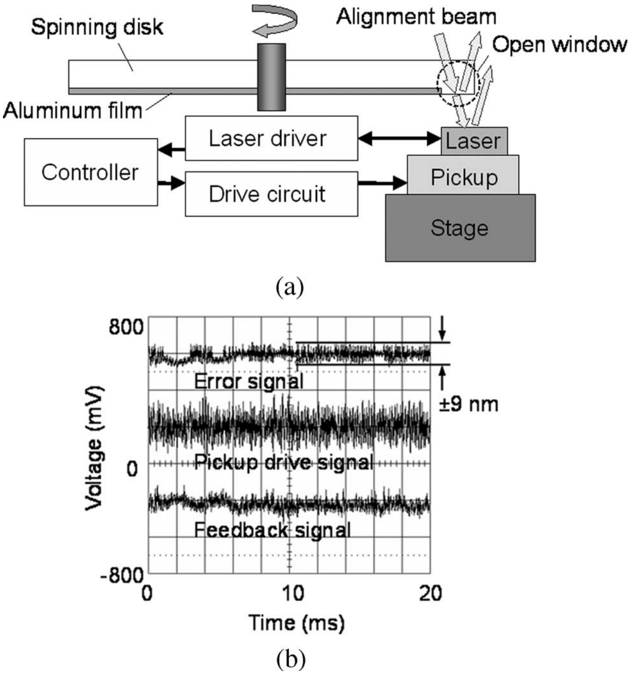
(a)

(b)

Fig. 8. (a) Configuration of an actuated surface test system. (b) Experimental results when the displacement is 4.8 μm at 1500 r/min.

V. CONCLUSION

We demonstrated a laser diode position sensor for a near-field height control system. The system employing the laser sensor can approach the surface of a spinning disk within



(a)

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Fig. 9. (a) Configuration of a spinning disk test system. (b) Experimental results with the runout of 16 μm at 1500 r/min.

a few wavelengths with a position accuracy of ±4 nm. In addition, the dependence of the output power on the near-field distance from the laser sensor was also theoretically and experimentally characterized. A simplified method for near-field self-mixing interferometry was presented to model the signal characteristic in the near-field regime. The system we proposed and realized had advantages of simple configuration and high flexibility of integration with other systems such as subwavelength apertures, very small aperture lasers, and fiber-based light-source module [14]–[18]. Therefore, it opens an alternative approach to achieve high-precision near-field height servo control and can be applied in any fields where nanoscale position precision and gap are required, such as near-field data storage and lithography.

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