# High-speed sinusoidal phase modulating laser diode interferometer with a feedback control to eliminate external disturbance

Takamasa Suzuki*, Toshiyuki Maki, and Osami Sasaki
Niigata University, Faculty of Engineering

## ABSTRACT

A surface profiler incorporating a feedback controller that eliminates external disturbances is proposed and demonstrated. Its overall performance is dependent upon the frequency response of the feedback loop. The frequency of modulating signal strongly influences response of the feedback controller. When using an integrating-bucket method, however, the CCD camera must be operated at the NTSC-approved modulating frequency. Our technique uses electronic-shutter equipped CCD camera. The shutter function enables us to apply high-speed sinusoidal phase modulation to the conventional integrating-bucket method under the NTSC standards.

**Keywords:** interferometer, bucket method, laser diode, sinusoidal phase modulation, electronic shutter

## 1. INTRODUCTION

As with any technology, each successive generation of interferometer reveals the shortcomings of its predecessor. Earlier models, which were highly vulnerable to external disturbances that could, and often did deteriorate measurement accuracy, have been replaced by feedback-type laser diode (LD) interferometers. They can also measure vibration[1, 2] by detecting minute changes in the interference signal itself, when a photodiode (PD) is used as a photodetector. Temporal signals detected by the PD are easily processed. When the LD is not being actively modulated, the interference signal itself can be used as a feedback signal. If the LD is modulated with a continuous signal, however, the feedback signal is extracted by using a modulating signal. In this case, the frequency response of the feedback system will depend on the modulating frequency used. Not surprisingly, as modulating-signal frequency rises, the quality of the feedback system used to eliminate mechanical disturbances does so, as well. This disturbance-elimination technique was used in phase-shifting interferometers (PSIs)[3,4]. Surface-profiles were measured, not on sophisticated optical benches, but rather, on a simple wooden table in these PSIs. Since their interference signals are modulated by step-type signals, static fringe pattern itself detected by spatial filtering detectors can be easily used as a feedback signal. The PSI, however, requires four fringe images having a phase-shift of $(\pi/2)i$ (i=0, 1, 2, 3). It is not so easy to apply a shift of $\pi/2$ precisely at the phase of interference images.

On the other hand, another technique, so called integrating-bucket method[5] is convenient when a CCD camera is used to capture images. The phase is detected using the four images obtained in a given modulating period. Parameter-adjustments are easier when using this method, than when the PSI is employed. The parameters in this instance are initial phase of the modulating current, and modulation depth that depends on the amplitude of the modulating current[6]. Modulating frequency is restricted by NTSC standards, when using a general-purpose CCD camera. In such instances, the frequency response of the feedback signal extracted from the interference signal is poor[7]. Therefore, equipping the bucket-type interferometer with an adequate feedback control proved to be extremely difficult.

The CCD camera-based technique we propose here uses an electronic shutter that enables us to control the charge-storage period, which, in turn permits the frequency of the modulating signal to be greatly increased.

## 2. PRINCIPLE

### 2.1 Optical setup

The setup is shown in Fig. 1. the beam radiated from the LD is collimated by lens L1, and fed into a Twyman-Green interferometer. The interference fringe is then divided by beam splitter BS2. One of these fringes is acquired with a CCD camera as a spatial-temporal signal S(t, x, y) and processed by computer. The other temporal signal S(t), which is detected by a PD is processed by feedback-signal generator (FBSG) to produce the signal required for disturbance elimination.

* Correspondence: E-mail: takamasa@eng.niigata-u.ac.jp; phone/FAX: +81-25-262-7215

The complex video signal output based on the NTSC standards is fed into the modulating-signal generator (MSG). This modulating signal $I_m(t)$ and feedback signal F(t) are injected into the LD through the laser diode modulator LM. When we use sinusoidal signal

$$I_m(t) = m\cos(\omega_c t + \theta) \quad (1)$$

as the modulating signal, the interference signal is then given by

$$S(t, x, y) = a + b\cos[z\cos(\omega_c t + \theta) + \alpha(x, y)], \quad (2)$$

where

$$z = 2\pi m\beta L_0 / \lambda_0^2 \quad (3)$$

and

$$\alpha(x, y) = 4\pi L(x, y) / \lambda_0 \quad (4)$$

represent modulation depth, and phase distribution on the test-surface, respectively. z is determined by amplitude m, modulation efficiency β, and optical pass difference $L_0$. The L(x, y) represents the profile of the object.

### 2.2 Bucket method

Schematic of the bucket method is shown in Fig. 2. Images detected by CCD camera are given by the temporally integrated values of the incident interference signal. We can detect four images

$$p_i(x, y) = \int_{(T/4)(i-1)}^{(T/4)i} S(t, x, y)dt \quad (i=1\sim4), \quad (5)$$

when the charge-storage period T is set to a quarter period of the modulating signal. Phase α(x, y) is then given by

$$\alpha(x, y) = \frac{p_1 + p_2 - p_3 - p_4}{p_1 - p_2 + p_3 - p_4}, \quad (6)$$

under the conditions z=2.45 rad and θ=56°. The problem with this method is that the modulating frequency is restricted to a frame-rate of 1/30 sec.

### 2.3 Modification of the bucket method

Figure 3 illustrates the method used to increase modulation frequency under NTSC standards. One quarter-period of a

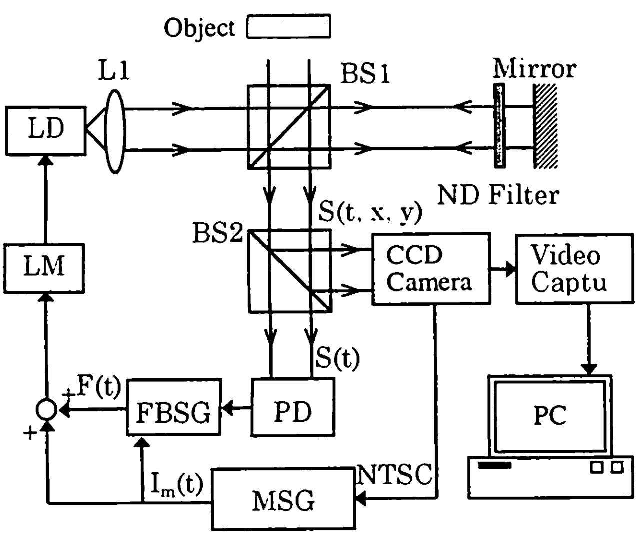


**Fig. 1** Setup of high-speed sinusoidal phase modulating laser diode interferometer

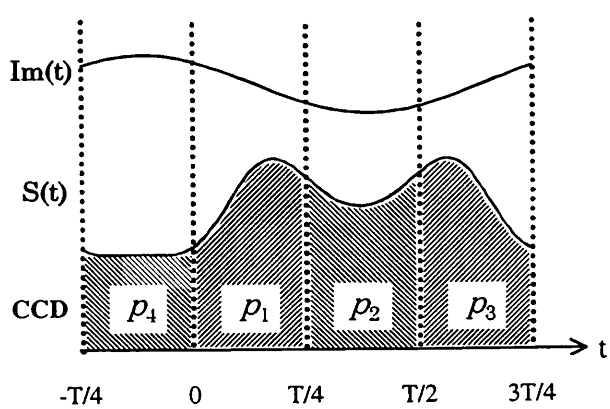


**Fig. 2** Integrating bucket method

conventional modulating signal (Fig. 3 (a)) is equal to a frame rate of 1/30 sec. In other words, the frequency of the modulating signal becomes 7.5 Hz, under NTSC standards. The technique under discussion (Fig. 3 (b)) uses the shutter function of the CCD camera. The integrated signal is cleared once at the rising edge of the shutter pulse, after which a newly integrated signal is readout at the rising edge of the CCD readout pulse. In this case, the quarter period of the modulating signal ($T_{m2}$), or storage time, is equal to the shutter-speed ($T_s$), and represented by

$$T_{m2}/4 = T_s \,. \qquad (7)$$

It indicates the need for a modulating signal whose frequency ($f_{m0}$) is $1/(4T_s)$ Hz. In the bucket method, however, the phase of the modulating signal has to be shifted by $\pi/2$ in every integration as shown in Fig. 2. This condition is expressed as

$$T_f = \left(n \pm \frac{1}{4}\right) T_{m2} \,, \qquad (8)$$

where n is an integer. Equations (7) and (8) provide relation

$$n = \mathrm{round}\left[\frac{1}{4}\left(\frac{T_f}{T_s} \mp 1\right)\right], \qquad (9)$$

where round[ ] rounds off the argument. From Eqs. (7), (8), and (9), the actual modulating frequency $f_{m2}$ ($=1/T_{m2}$) is given by

$$f_{m2} = \frac{1}{4T_f}\left\{4 \cdot \mathrm{round}\left[\frac{1}{4}\left(\frac{T_f}{T_s} \mp 1\right)\right] \pm 1\right\}. \qquad (10)$$

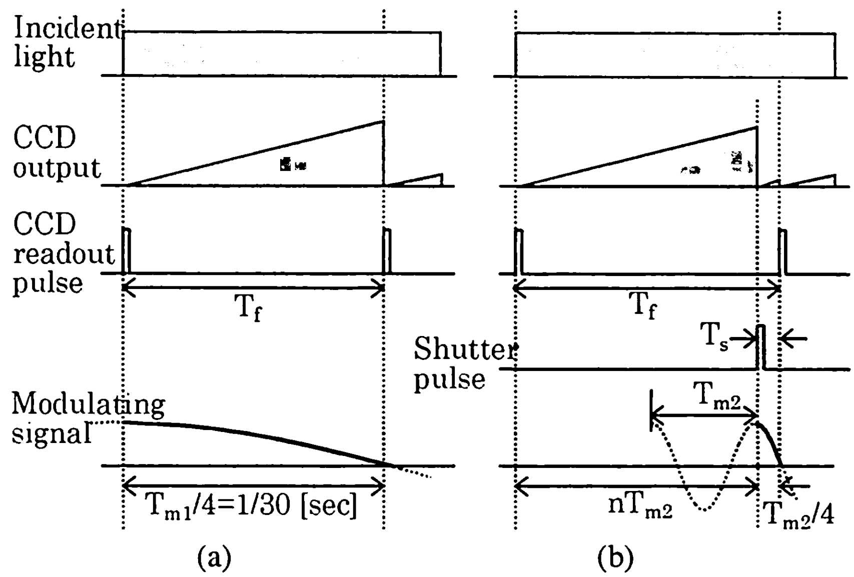


**Fig. 3** Schematic of (a) conventional modulating signal and (b) high-speed modulating signal.

## 3. EXPERIMENT

In the setup shown in Fig. 1, the wavelength of the LD was 685 nm. The size and number of pixels in the CCD image-sensor were 6.35 μm × 7.40 μm and 768(H) × 494(V), respectively. After selecting shutter-speed to be 1/10000 sec, we confirmed its acquisition by observing the shutter-pulse, which was determined to be 92 μs. This figure provided the

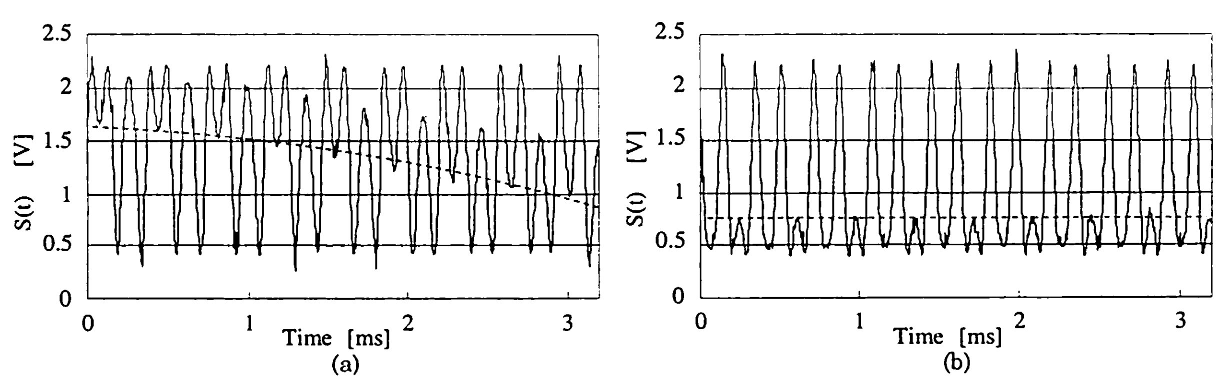


**Fig. 4** Interference signals observed by the photodiode (a) without feedback control and (b) with feedback control.

required modulating frequency ($f_{m0}$) of 2717.4 Hz. The modulation frequency $f_{m2}$ is calculated as per Eq. (10). They were 2707.5 Hz for n=90 and 2722.5 Hz for n=91, respectively. The frequency of the particular modulating signal we used was 2722.5Hz, because it was in rough agreement with to $f_{m0}$. We calculated the difference between those phases detected by modulating signal $f_{m0}$ and $f_{m2}$, respectively. The phase difference was $1.57\times10^{-4}$ rad. This corresponds to a distance of $1.71\times10^{-4}$ nm. This error is small enough to be used in performing surface profiles.

In the MSG, the field signal is separated from the CCD camera's complex video signal. The modulating signal is mixed with the feedback signal F(t) and fed to the LD.

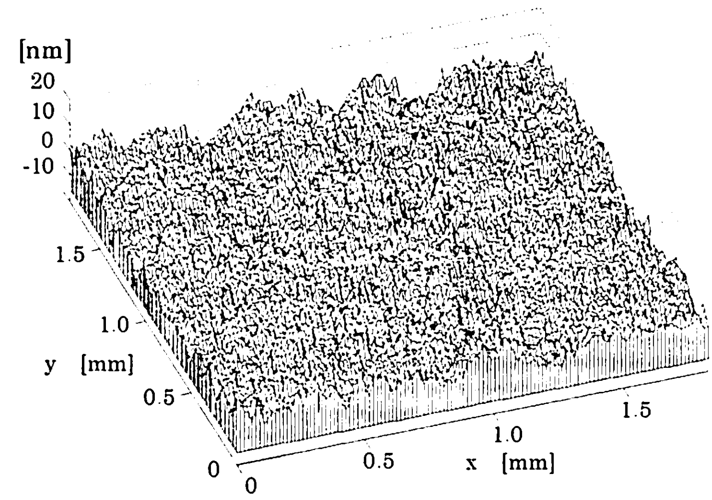


**Fig. 5** Surface profile of the plane mirror measured by the proposed system.

We measured interference, as well as the surface-profile of a plane mirror. These measurements were not implemented using any dedicated optical benches, but simply fixed to a horizontal surface, which in this case, was a steel desk. Interference signals detected with the PD are shown in Fig. 4. Dashed lines indicate the phase variations. When the feedback control was turned off, undesirable phase-changes induced by external disturbances were superimposed upon S(t) as shown in Fig. 4(a). Such phase-changes were completely eliminated in S(t), when observed during feedback control as shown in Fig. 4 (b).

Finally, surface profile measurement was demonstrated with the feedback control. Figure 5 provides the result. The roughness of the mirror was determined to be $\lambda/40$ for the peak-to-valley. Using our system, measurement repeatability is estimated to be $\lambda/120$ rms, through several measurements.

## 5. CONCLUSIONS

We have proposed a feedback-based integrating-bucket method that eliminates external disturbances. The shutter function of the CCD camera enables us to apply high-speed sinusoidal phase modulation, which results in excellent feedback-control, to the conventional integrating-bucket method. Measurement results obtained on an ordinary horizontal surface indicate that external disturbance is eliminated, while at the same time, surface-profile measurement is accurately performed.

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