Step-height measurement with a two-wavelength laser diode interferometer using time-sharing sinusoidal phase modulation.

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ABSTRACT

The system we propose uses two separate wavelengths to measure step-height. Two laser diodes alternately modulated with a sinusoidal signal separate a like number of overlapping interference images detected by CCD camera, the phase map being obtained by a modulated LD. In this instance, the 1 μm step-height was accurately detected.

Keywords: interferometer, two-wavelength method, step-height measurement, laser diode, sinusoidal modulation

1. INTRODUCTION

While it is difficult for ordinary interferometers to measure step-shapes whose height is greater than a half of one wavelength, two-wavelength interferometers (TWIs) can do the job effortlessly. Multiple laser diode (LD) setups, which previously attracted some attention, shared one notable problem; how best to separate interference signals generated by two independent LDs. While one interference signal can be detected by shutting off the bias current of the second LD, the latter device is inevitably damaged by the sudden change. Moreover, while such interference signal can be detected and separated by polarization[1], interference filters[2], or the heterodyne technique[3], multiple photodiodes (PDs) are required. At present, we can use only one PD, when processing transient interference, because individual signals are separated according to the frequency[4] or the initial phase[5] of the modulating signal, in which case, real-time signal processing can be implemented. The PD or object, however, must be scanned mechanically with regard to surface-profile measurement. It is a time-consuming process.

In this paper, we propose a TWI that uses the integrating-bucket method, in conjunction with our new modulating technique. CCD image sensor is ideal for gauging 2-dimentional surface-profiles because no mechanical scan is required and it can be easily linked with a computer. We use a function of charge-integration in the CCD image sensor and time-shared sinusoidal phase-modulation to separate the interference fringes. As of this writing, a step-height of 1 μm has been measured by our system with an accuracy of 5 nm rms.

2. PRINCIPLE

2.1 Optical setup

The setup is shown in Fig. 1. Laser beams radiated from LD1 and LD2 fuse within beam splitter BS1. From there, they are fed into a Twyman-Green interferometer. Bias- and modulating-currents for the LD are mixed by the laser diode modulator (LM), and injected into each LD. I_1 and I_2 represent dc bias currents employed. When sinusoidal modulating currents

$$Im_i(t) = m_i \cos(\omega_c t + \theta) \qquad (i=1, 2) \qquad (1)$$

are used, the interference signals generated by the beams emanating from LD1 and LD2 are given by

$$S_i(t, x, y) = a_i(x, y) + b_i(x, y)\cos[z_i \cos(\omega_c t + \theta) + \alpha_i(x, y)], \qquad (i=1, 2) \qquad (2)$$

where

$$z_i = 2\pi m_i \beta_i L_0 / \lambda_i^2 \qquad (i=1, 2) \qquad (3)$$

represents modulation depths, as determined by the optical pass difference L_0, and

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$$\alpha_i(x,y) = 4\pi L(x,y)/\lambda_i \quad (i=1,2) \tag{4}$$

are phase distributions related to the surface profile of L(x, y), respectively. β_i represents the modulation efficiency of the LD.

2.2 Bucket method

Schematic explanation of the bucket method is shown in Fig. 2. In order to explain, as simply as possible, attention should focus on a single interference signal as shown in Fig. 2 (a). Images detected by CCD image sensor are given as temporally integrated values of the incident interference signal. When the charge-storage period is set to one quarter of a modulating period, we are able to detect four separate images

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

during modulation. Then, by simply calculating the intensity of these images, we arrive at quadratic signals

$$p_1 + p_2 - p_3 - p_4 = A_s \sin\alpha(x,y), \tag{6}$$

and

$$p_1 - p_2 + p_3 - p_4 = A_c \cos\alpha(x,y). \tag{7}$$

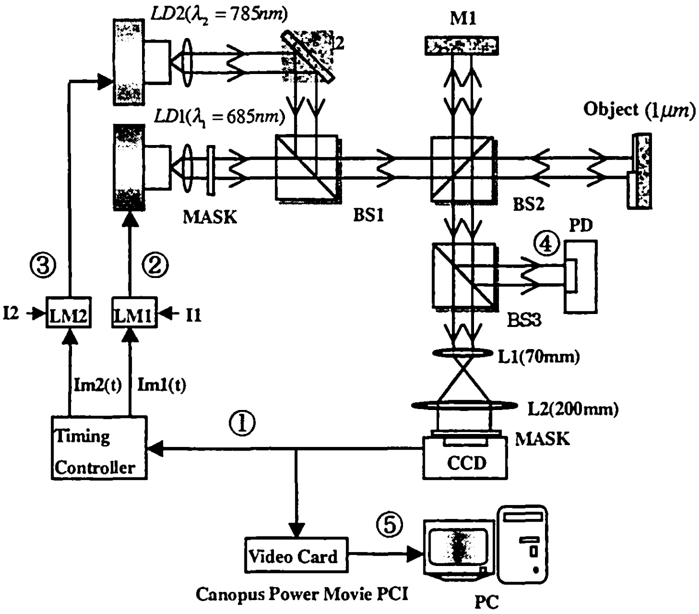

Fig. 1 Experimental setup of two-wavelength laser diode interferometer using time-sharing sinusoidal phase modulation.

Amplitudes A_s and A_c possess equal value, under the conditions z=2.45 rad and θ=56°. Phase α(x, y) is given by

$$\alpha(x,y) = \frac{p_1 + p_2 - p_3 - p_4}{p_1 - p_2 + p_3 - p_4}. \tag{8}$$

In a variation of the above-outlined technique, sinusoidal modulating current is alternately injected into the LD as shown in Fig. 2 (b). During the period T1, current-flow is channeled to LD1. When viewed by CCD camera, interference fringes $S_1(t)$ and $S_2(t)$ can be seen overlapping one another, because bias currents are injected into both LDs. All images p_{2k} (k=1~4) detected with respect to LD2, however, are the same. At this point, we can detect $\sin\alpha_1(x, y)$ and $\cos\alpha_1(x, y)$, using Eqs. (6) and (7). In contrast, during the period T2, images p_{1k} (k=5~8) undergo no change, due to the absence of any modulating signal, where LD1 is concerned. This allows us to obtain quadratic signals $\sin\alpha_2(x, y)$ and $\cos\alpha_2(x, y)$, That is, the quadratic signals are obtained for a sinusoidal phase-modulated LD.

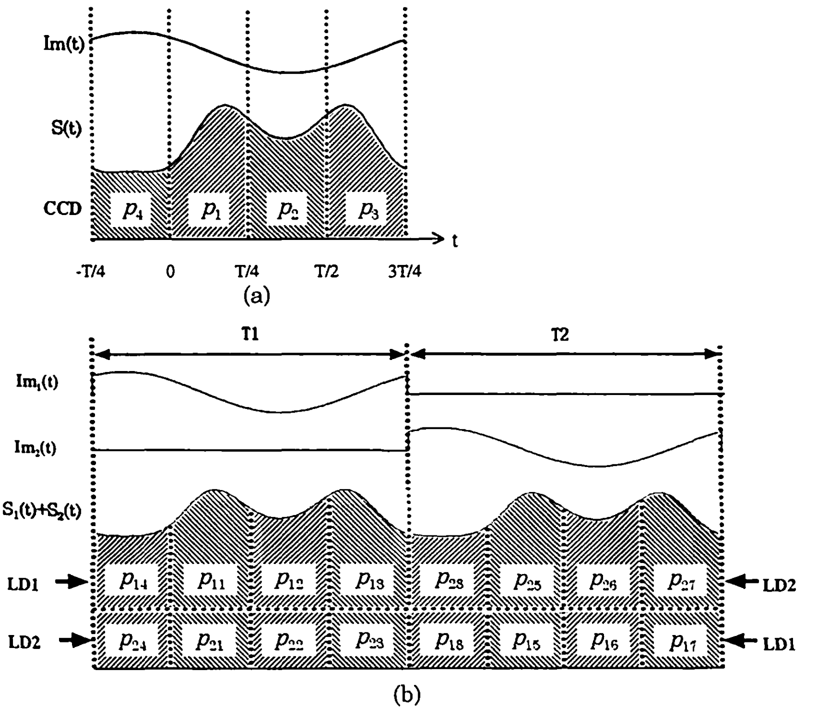

Fig. 2 Integrating-bucket method with (a) the ordinary modulating technique and (b) the time-shared sinusoidal phase modulation.

2.3 Step-height measurement

The difference between $\alpha_1(x, y)$ and $\alpha_2(x, y)$ is given by

$$\Delta\alpha(x,y) = \alpha_1(x,y) - \alpha_2(x,y) = 4\pi L(x,y)/\Lambda, \qquad (9)$$

where

$$\Lambda = \lambda_1\lambda_2 / |\lambda_1 - \lambda_2| \qquad (10)$$

is a synthetic wavelength.

When L(x, y) is larger than half of one wavelength, exact phase $\hat{\alpha}(x,y)$ is expressed by

$$\hat{\alpha}_1 = \alpha_1(x,y) + 2n\pi, \qquad (11)$$

where n is an integer. From Eqs. (4), (9), and (11), L(x, y) is calculated as

$$L(x,y) = \frac{\lambda_1\{\alpha_1(x,y) + 2\pi\cdot \mathrm{INT}[R\cdot\Delta\alpha(x,y) - \alpha_1(x,y)]/2\pi\}}{4\pi}, \qquad (12)$$

wherein $R=\Lambda/\lambda_1$ represents the ratio of the synthetic wavelength to that of the LD, and INT[ ] gives the integer of the argument.

3. EXPERIMENT

The experimental setup is shown in Fig. 1. The wavelengths of LD1 and LD2 were 685 nm and 785 nm, respectively. Synthetic wavelength Λ became 5.38 μm. The test surfaces shown in Fig. 1. consist of gauge blocks whose thickness differs 1μm. The combined interference fringe is magnified, using lenses L1 and L2, and the image is captured by a CCD camera whose pixel size and count are 6.35μm × 7.40μm and 768(H)× 494(V), respectively. The video signal from this device is fed to the video-capture board, allowing phase distribution to be calculated, using Eq. (12). The precise timing of the modulating process is shown in Fig. 3. Circled numbers in Fig. 3 correspond directly to those in Fig. 1. Since images corresponding to even or odd fields are detected by turns, in general-purpose CCD cameras, it requires the use of a special modulating signal to detect the four images desired in Eq. (8). The ODD/EVEN filed signal is separated from the video signal, and then fed into the timing device. Modulating signals $Im_1(t)$ and $Im_2(t)$, which remain synchronous with the field

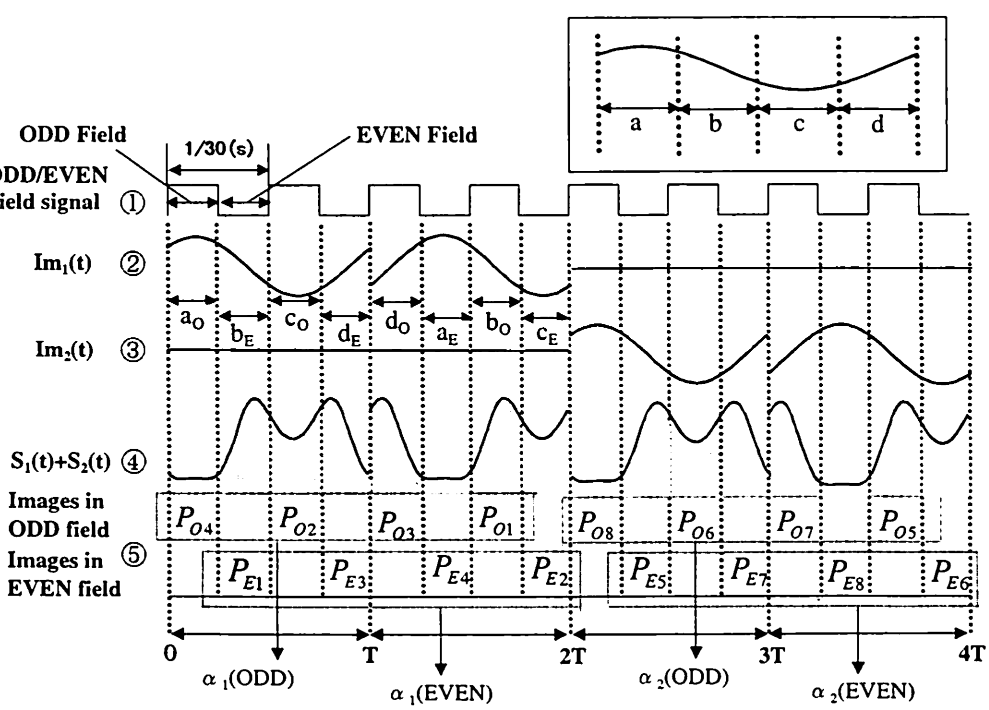

Fig. 3

Timing chart of the modulating process.

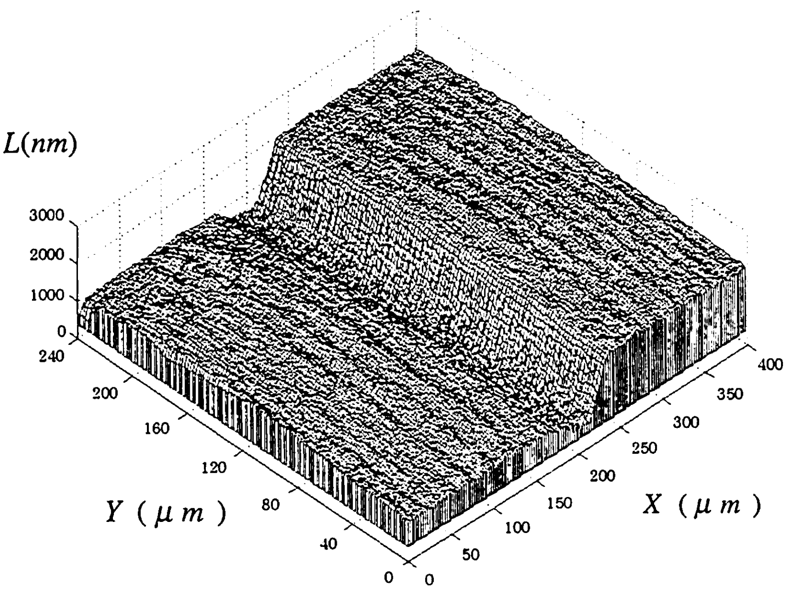

Fig. 4 Measurement result of the step-height of 1μm.

signal are generated by a oscillator which has an input terminal for an external sync signal. As the even/odd cycle continues, two periods of sinusoidal modulating signals are injected into one LD. The phases of the modulating signals $Im_1(t)$ and $Im_2(t)$ are changed by $\pi/2$ at T and 3T, respectively. Four images must be detected at the four sections shown in the inset of Fig. 3. These sections correspond to a_O~d_O and a_E~d_E, respectively. Subscripts O and E represent odd and even fields, respectively. Four images P_{Ok} (k=1~4) corresponding to the odd field are obtained in the periods a_O, b_O, c_O, and d_O. Phase α_1(ODD) in the odd field is calculated using these four images. In the period from 2T through 4T, phase α_2(ODD) is derived from P_{Ok} (k=5~8). Therefore, step-height is obtained, using Eq. (12). In the same manner, phases α_1(EVEN) and α_2(EVEN) are derived from P_{Ek} (k=1~4) and P_{Ek} (k=5~8), respectively.

Figure 4 gives the result of step-height measurement. A step-height of 1μm is detected. Measurement accuracy was estimated to be within 5 nm rms, as measured by a flat mirror. The figure applies only to the odd field, in this instance because the rate of image-transfer from the video capture board to the computer was insufficient to transfer images in the even field.

4. CONCLUSIONS

A TWI that uses the integrating-bucket method, in conjunction with a new modulating technique was proposed. Time-shared sinusoidal phase modulation enables us to obtain the integrated interference fringes required for phase calculation. Quadratic signals can be clearly separated, step-height of 1μm was measured accurately within 5 nm rms.

We have described here a practical method of simultaneously measuring step-height in two fields. It is dependent, however, on as-yet-unattained improvements in the rate of image-transfer. Once this has been accomplished, it should lead to improvements in the spatial resolution of the measurement.

REFERENCES

1. A. J. den Boef, "Two-wavelength scanning spot interferometer using single-frequency diode lasers," Appl. Opt. 27, 306-311 (1988).
2. Y. Ishii and R. Onodera, "Two-wavelength laser-diode interferometry that uses phase-shifting technique," Opt. Lett. 16, 1523-1525 (1991).
3. Z. Sodnik, E. Fischer, T. Ittner, and H. J. Tiziani, "Two-wavelength double heterodyne interferometetry using a matched grating technique," Appl. Opt. 30, 3139-3144 (1991).
4. O. Sasaki, H. Sasazaki, and T. Suzuki, "Two-wavelength sinusoidal phase / modulating laser-diode interferometer insensitive to external disturbances," Appl. Opt. 30, 4040-4045 (1991).
5. T. Suzuki, K. Kobayashi, and O. Sasaki, "Real-time displacement measurement with a two-wavelength sinusoidal phase-modulating laser diode interferometer," Appl. Opt. 39, 2646-2652 (2000).