Stroboscopic step height measurement with two-wavelength interferometer using single diode laser source

Xuefeng Zhao*, Takamasa Suzuki and Osami Sasaki
Faculty of Engineering, Niigata University
8050 Ikarashi 2, Niigata, 950-2181, Japan

ABSTRACT

We propose a two-wavelength interferometer that is used to a stroboscopic step height measurement. Different from most two-wavelength interferometers, in present experiment, two slightly different wavelengths are simultaneously oscillated by currently and thermally controlling a laser diode to work at mode hop region. By use of this two-wavelength laser source, a Twyman-Green interferometer, whose reference arm and object arm have known step height r and unknown step height h, respectively, is constructed. Three independent interference patterns corresponding to different OPDs are formed and they can be simultaneously taken by a CCD camera. Furthermore, tilting the reference, spatial frequencies are introduced into the interference patterns. Taking the Fourier transform of these patterns, three fringe amplitudes are obtained and their expressions can be solved for the unknown step height. As we can capture clear image of the interference patterns in a very short time by use of the high speed shutter function of the CCD camera, the error induced by the external disturbance is farthest reduced.

Keywords: interferometry; optical metrology; laser diode; height measurement

1. INTRODUCTION

Theoretically, the one-wavelength interferometers measure the phase difference within a range of one wavelength. To measure a step shape whose height is larger than a half of wavelength, the 2π-ambiguity problem must be solved. A two-wavelength interferometer (TWI)[1-11] is an easy way to expand the measurement range without the 2π-ambiguity problem, because a long synthetic wavelength, which is generated by two short and visible wavelengths, is available. There are several methods to construct a TWI. The most useful construction is to use two independent laser sources whose laser beams are mixed by a beam splitter[3-8]. But the interferometer becomes complicated and precise alignment is required. Other methods to get two-wavelength light source include: to place a narrowband interference filter in front of the white light source[9]; to extract two from multi-wavelengths of an argon ion laser[2]; to use a tunable two-wavelength laser diode array[10]; and to extract from the same superluminescent emission by a couple of the interference filters[11]. The complexity and the high cost are demerits of them.

We have recently presented a new version of the two-wavelength laser source[12]. When a single commercial laser diode (LD) is modulated by the injection current, and it is simultaneously controlled by the temperature controller, the mode hopping occurs in the laser and two wavelengths can be generated at the same time. These two wavelengths have slight difference, so as to result long synthetic wavelength. It is valuable for the long measurement range, compact, in-process, and low cost measurement system. In our paper, we present a stroboscopic step-height measurement system using this two-wavelength laser source. Since the interferograms, which are used to calculate the unknown step-height, can be simultaneously and instantaneously measured, an in-process measurement can be realized.

In the next section we will introduce the two-wavelength laser source, describe the theory of the stroboscopic step-height measurement system, and analyze some error sources.

* zhaoxf@teoptlab.eng.niigata-u.ac.jp; phone and fax: +81-25-262-7215

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2. THEORY

2.1 Two-wavelength single diode laser source

One of the properties of the LD is the phenomenon of mode hopping. The reason is that, under certain injection current and junction temperature, the center frequency of the LD hops over discrete wavelength bands and does not show continuous tuning over a broad range.

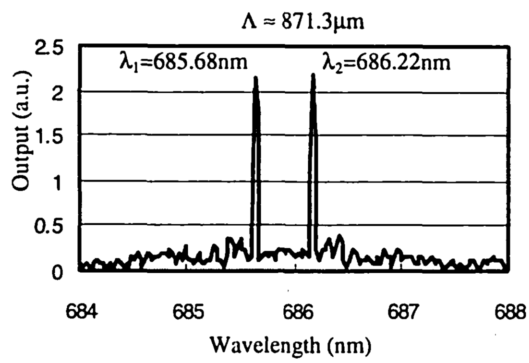


Figure 1. Emission spectrum of the two-wavelength single diode laser source.

In most LD interferometer, the mode hop makes the measurement impossible and it should be prevented. This disadvantage, however, may enable us to possess a compact and easy operational two-wavelength laser source. Because if we adjust current and temperature precisely, two wavelengths, as shown in Fig.1, can be simultaneously generated when mode hopping occurs. The spectra and the output powers of these two wavelengths are different with the different LDs. In our case, wavelengths are λ_1=685.68nm and λ_2=686.22nm. The synthetic wavelength, which is defined as

$$\Lambda=\frac{\lambda_1\lambda_2}{|\lambda_1-\lambda_2|}, \tag{1}$$

reaches to about 871.3μm, and the measurement range can be expanded greatly.

2.2 Stroboscopic step-height measurement system

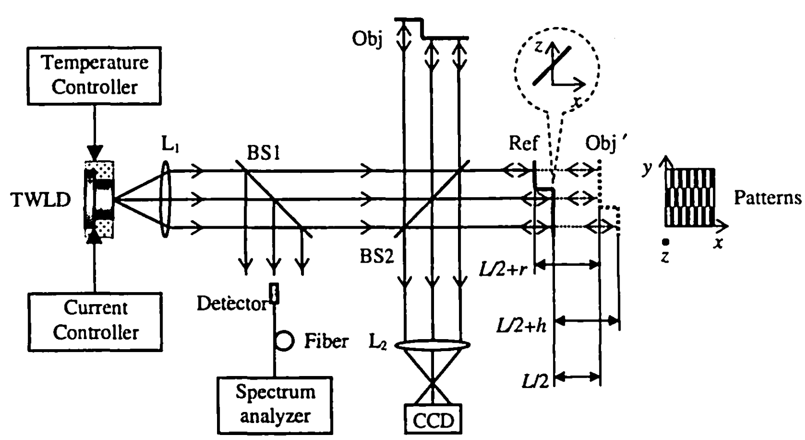


Figure 2. Experiment setup: TWLD, two-wavelength laser diode; L1, L2, lenses; BS1, BS2, beam splitters; Ref, reference step-height; Obj, Obj', object step-height and its image.

Figure 2 shows the experiment setup of our present stroboscopic step-height measurement system that uses the two wavelength single diode laser source. The temperature of the LD is kept constant with the automatic temperature controller that uses the Peltier element. By changing the laser's injection current, the mode hopping occurs and two wavelengths are simultaneously generated. Collimated by an objective, the two-wavelength laser beam passes through BS1 and illuminates a Twyman-Green interferometer with an optical path difference L. Portion of the laser beam is reflected by BS1 and laser's spectrum is watched by an optical spectrum analyzer. In the interferometer, two gauge blocks are used as an object with unknown step height h and another two are tilted as a reference with known step height r. Thus three interference patterns, in which the spatial frequencies are introduced, can be formed according to different OPDs L, L+2r and L+2h. They are simultaneously detected by a CCD camera. Taking the Fourier transform of these patterns, the unknown step-height h can be extracted. Moreover, since the CCD camera is equipped with high speed shutter function, the clear interferograms are captured in a very short time, the error induced by the external disturbance is farthest reduced. Consequently, an in-process measurement can be realized.

Next we discuss how to obtain the unknown step-height from three interferograms mentioned above. The intensity distributions of the interference pattern corresponding to wavelengths λ_1 and λ_2, in which the spatial frequencies are introduced in x-direction, can be given by

$$g_i(x) = a + b\cos(2\pi f_i x + \phi_i) \quad (i = 1,2)\,, \tag{2}$$

where a, b, f_i and ϕ_i are dc component, ac component, the spatial-carrier frequencies introduced by the tilted reference, and the phases, respectively. Because the output powers of two wavelengths can be precisely adjusted to be almost same by changing the LD's injection current, we consider the dc and ac components corresponding to λ_1 and λ_2 are approximately equal. The resulting fringe pattern is given by

$$\begin{aligned} g(x) &= g_1(x) + g_2(x) \\ &= 2a + 2b\cos\left[\pi(f_1 - f_2)x + \frac{\phi_1 - \phi_2}{2}\right]\cos\left[\pi(f_1 + f_2)x + \frac{\phi_1 + \phi_2}{2}\right]. \end{aligned} \tag{3}$$

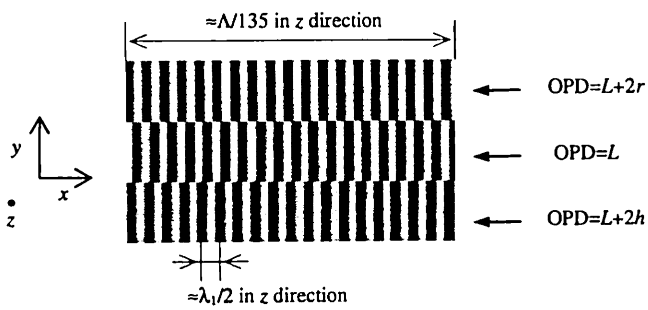


Figure 3. Simulated interference patterns.

Figure 3 shows the simulated interferogram with the image size of 320 pixels in x-direction. Because synthetic wavelength is much larger than both λ_1 and λ_2, the spatial period corresponding to Λ is also very wide. It is impossible to record both high and low frequency patterns in one image. The image shown in Fig. 3 only records 1/70 of the synthetic period. Furthermore, the difference of λ_1 and λ_2 is very small, so that f_1 and f_2 can be considered to be approximately equal in such a small range. That is, only one spatial-carrier frequency

$$f_0 = \frac{f_1 + f_2}{2} \tag{4}$$

exists in $g(x)$ and the term

$$\pi(f_1 - f_2)x = 0\,. \tag{5}$$

Then Eq. (3) can be rewritten as

$$g(x) = 2a + 2b\cos\frac{\phi_1 - \phi_2}{2}\cos\left(2\pi f_0 x + \frac{\phi_1 + \phi_2}{2}\right). \tag{6}$$

Taking the Fourier transform of above equation, the amplitude of the carrier frequency is found as

$$\begin{aligned} B &= 2b\cos\frac{\phi_1 - \phi_2}{2} \\ &= 2b\cos\frac{\pi OPD}{\Lambda} \end{aligned}. \tag{7}$$

The same process is applied to the interference patterns three times. The amplitudes of the carrier frequency corresponding to OPDs L, $L+2r$ and $L+2h$ are obtained as

$$B_L = 2b\cos\frac{\pi L}{\Lambda}, \tag{8}$$

$$B_r = 2b\cos\frac{\pi(L+2r)}{\Lambda}, \tag{9}$$

and

$$B_h = 2b\cos\frac{\pi(L+2h)}{\Lambda}. \tag{10}$$

We use above equations solve for the unknown step-height h. It is given by

$$h = \frac{\Lambda}{\pi}\cos^{-1}\frac{\frac{B_h}{B_L}}{\sqrt{\left[\left(\cos\frac{2\pi d}{\Lambda} - \frac{B_r}{B_L}\right)/\sin\frac{2\pi d}{\Lambda}\right]^2 + 1}} - \frac{\Lambda}{\pi}\tan^{-1}\left[\left(\cos\frac{2\pi d}{\Lambda} - \frac{B_r}{B_L}\right)/\sin\frac{2\pi d}{\Lambda}\right] \tag{11}$$

The measurement range is from 0 to $\Lambda/4$.

2.3 Error sources

There are a number of sources of error that must be considered in the system. The algorism, the reference step height error and the tilt error between two surfaces of the reference step-height can all affect the system performance. To evaluate their effectiveness, computer simulations were carried out.

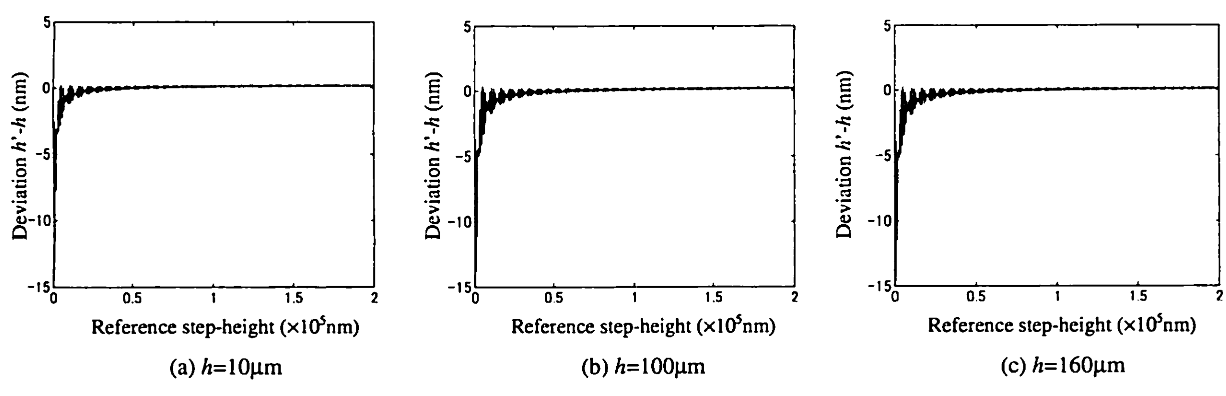


Figure 4. Deviation versus reference step-height for different object step-heights.

First of all, the reference step-height r must be determined. We gave three different object step-heights of h=10μm, h=100μm, and h=160μm, simulated the interferograms, and calculated measurement step-height h'. In Fig. 4 the deviations $h'-h$ are plotted as a function of the reference step-height, which changes from 0 to 200μm. The deviation appears periodically and its amplitude attenuates with the reference step-height increase. After r reaches to 100μm, the deviation changes are not obvious. So we select 100μm as the reference step-height.

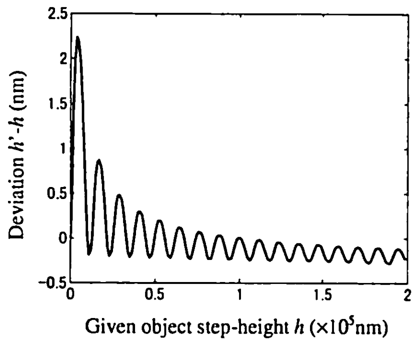


Figure 5. Deviation versus given object step-height.

The measurement error due to the algorism was evaluated under the ideal condition. The simulation process is similar to above. We first give an object step-height h; then simulate the interferograms; finally calculate the unknown measurement step-height h' by using the given reference step-height r. In this case, r is 100μm. Figure 5 displays the deviation $h'-h$ versus the given object step-height h. The maximum deviation is less than 2.5nm.

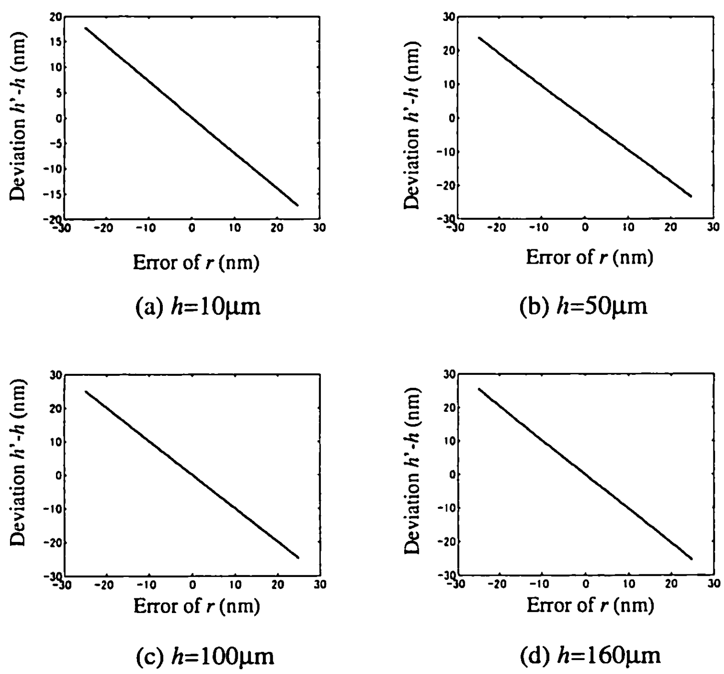
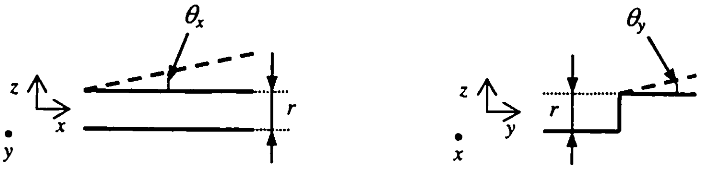


Figure 6. Deviations due to the reference step-height error for different object step-heights.

Figure 6 gives the deviation $h'-h$ versus reference step-height error, which varies within the range of -25nm to +25nm. The object step-heights are assumed to be 10μm, 50μm, 100μm, and 160μm, respectively. Inspection of these graphs shows that the measurement error is proportional to the reference step-height error.



(a) In x-direction (b) In y-direction

Figure 7. Tilt errors between two surfaces of the reference step-height.

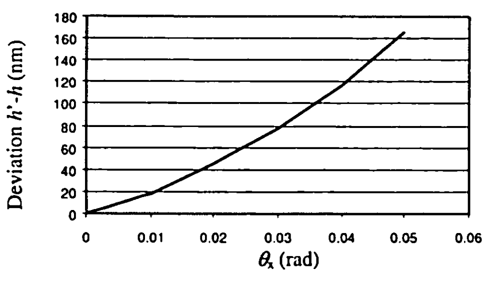


Figure 8. Tilt error in x-direction induces large measurement error.

As shown in Fig. 7, there are two kind of tilt error between two surfaces of the reference step-height. The tilt error in y-direction is equivalent to the step-height error as described above. It can be reduced by processing the patterns located near the boundary between two interferograms. The tilt error in x-direction leads to the spatial frequency increase. Assume that the tilt angle θ_x in Fig. 7(a) varies within 0.05rad, we calculated the deviation h'-h and plot it in Fig. 8. It shows that the main error in present measurement system comes from the x-direction tilt error between two surfaces of the reference step-height. The measurement error that occurs at the tilt angle 0.05rad is 165nm. It is less than Λ/5000.

3. CONCLUSION

A stroboscopic step height measurement has been proposed. Several techniques enable it to have such advanced features as wide measurement range, in sensitive to the external disturbance, easy to construct, and low cost, etc. The measurement range is from 0 to Λ/4. It is valuable for an in-process measurement.

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