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A method of step height measurement within the unambiguous range of two laser wavelengths interferometer

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ABSTRACT

When two laser beams of different wavelength are simultaneously applied to a Michelson interferometer, a moiré of parallel patterns appears due to the difference in optical path length between the reference beam and the measuring beam. The pattern appears with a wavelength of $\lambda_a\lambda_b/|\lambda_a-\lambda_b|$, and the distance between the zeroes of the envelope is also $\lambda_a\lambda_b/|\lambda_a-\lambda_b|$. Using the moiré of parallel patterns, unambiguous range of step height is half of $\lambda_a\lambda_b/|\lambda_a-\lambda_b|$. However, intensity varies with an average wavelength of $\lambda_a\lambda_b/(\lambda_a+\lambda_b)$, and intensity variation differs between the zeroes of each envelope. The unambiguous range is several times wider than $\lambda_a\lambda_b/|\lambda_a-\lambda_b|$. Intensity variation over the unambiguous range is measured, and coincides with calculated intensity variation, step height can be measured.

1. Introduction

When a single laser beam is applied to a Michelson interferometer, the intensity of interference varies periodically with step height change. The period is $\lambda/2$, where λ is the wavelength of the laser beam. Discontinuous changes of step height within half the wavelength can be uniquely determined. Higher step heights cannot be uniquely determined, however, because the interference intensifies periodically. There is an uncertainty of $(\lambda/2)c$ with a measured step height, where c is an integer. Because light wavelengths are short, uniquely determinable step heights are also short. Homodyne interferometers are useful for a wide range of position determinations [1], but step height measurements are limited to within $\lambda/2$.

When two laser beams of different wavelength are applied to a Michelson interferometer, a moiré of parallel patterns appears [2,3]. Although intensity varies with an average wavelength of $\lambda_a\lambda_b/(\lambda_a+\lambda_b)$, the pattern appears with a wavelength of $\lambda_a\lambda_b/|\lambda_a-\lambda_b|$. The distance between the zeros of the envelope is also $\lambda_a\lambda_b/|\lambda_a-\lambda_b|$. The formula $\lambda_a\lambda_b/|\lambda_a-\lambda_b|$ is called the equivalent wavelength. Using equivalent wavelengths instead of a single wavelength of light widens the measurable step height. Unambiguous range of step height is half of $\lambda_a\lambda_b/|\lambda_a-\lambda_b|$.

It has been shown by de Groot [4] that the unambiguous range of two laser wavelengths interferometer is several times wider than $\lambda_a\lambda_b/|\lambda_a-\lambda_b|$, because intensity variation differs between the zeroes of each envelope within the unambiguous range. In the method of de Groot, phases of the two lasers at a point are measured separately, and the point within the unambiguous range is determined by calculation.

The proposed analysis uses two lasers simultaneously. It also uses intensity variation over several zeroes of the envelopes, because intensity variation differs between the zeroes of each envelope. This paper will describe how, when two laser beams are applied to a Michelson interferometer, by using the proposed analysis, an integer j times wider than $\lambda_a\lambda_b/|\lambda_a-\lambda_b|$ is uniquely determinable while retaining nanometer order measuring errors. In industrial use, a preliminary step height measurement with a wider measuring error than in previous methods allows precise measuring of a wide range of step heights.

2. Theory

Fig. 1 shows the setup of two lasers applied to a Michelson interferometer. The two lasers have different wavelengths. The mirror is perpendicular to the reference beam, and moves back and forth so that the optical path length of the reference beam varies. Fig. 2 shows four laser beams entering the detector. These four beams are expressed as in [5], namely:

$$E_a = a_1 \exp((i)(2\pi\nu_a t - k_a L)) \tag{1}$$

$$E'_a = a_2 \exp((i)(2\pi\nu_a t - k_a(L+X))) \tag{2}$$

$$E_b = b_1 \exp((i)(2\pi\nu_b t - k_b L)) \tag{3}$$

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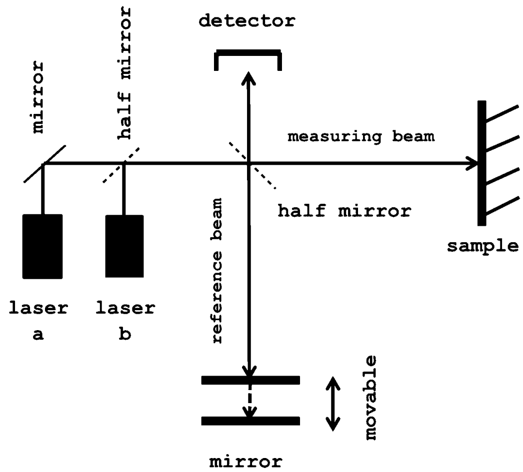

Fig. 1. Setup of two lasers applied to Michelson interferometer.

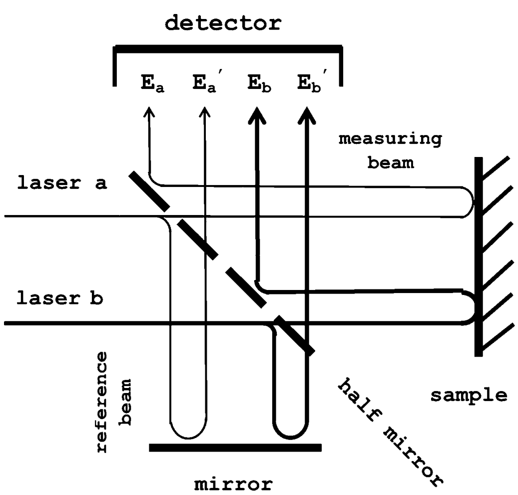

Fig. 2. Four laser beams entering the detector.

$$E_b' = b_2 \exp((i)(2\pi \nu_b t - k_b(L + X))) \tag{4}$$

where X is the optical path length difference between the reference and measuring beams. Intensity of interference at the detector is expressed as

$$I = |E_a + E_a' + E_b + E_b'|^2 \tag{5}$$

The result of Eq. (5) is expressed as [6]

$$I = 2a_1 a_2 \cos(k_a X) + 2b_1 b_2 \cos(k_b X) + a_1^2 + a_2^2 + b_1^2 + b_2^2 \tag{6}$$

Because the frequency of light is high, other terms of Eq. (6) average out to zero. To simplify Eq. (6), let $a_1 = a_2 = b_1 = b_2 = 1/2$, then

$$I = \left(\frac{1}{2}\right) \cos(k_a X) + \left(\frac{1}{2}\right) \cos(k_b X) + 1 \tag{7}$$

Eq. (7) can be rewritten as

$$I = \cos\left((k_a - k_b)\frac{X}{2}\right) \cos\left((k_a + k_b)\frac{X}{2}\right) + 1 \tag{8}$$

Using Eq. (7), Fig. 3(a and b) shows the calculated intensity variation of interference with the optical path length difference between the reference and measuring beam, setting $\lambda_a = 635$ nm and $\lambda_b = 785$ nm. Because ν_a and ν_b are irrational numbers, not integers, in the strict sense the same intensity variation of interference does not reappear. In a practical sense, however, the ratio ν_a:ν_b can reduce to a simple ratio of whole numbers m:n, and intensity variation from optical path length difference occurs periodically.

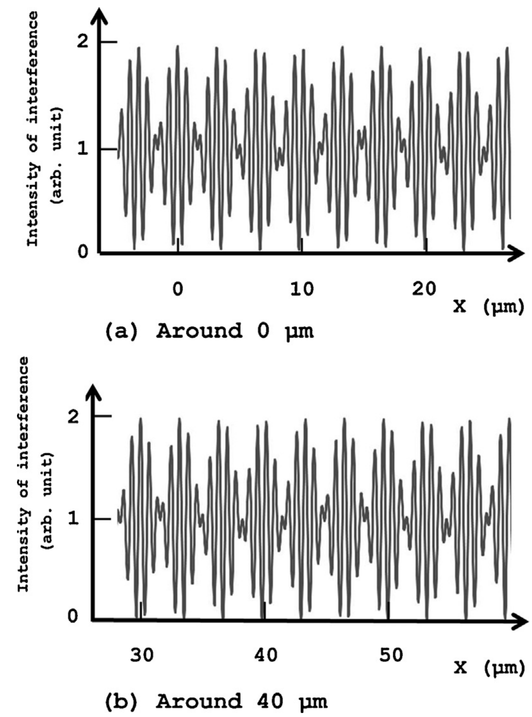

Fig. 3. Calculated intensity variation of interference with optical path length difference between reference beam and measuring beam X. (a) X is around 0 μm. (b) X is around 40 μm. Setting $\lambda_a = 635$ nm and $\lambda_b = 785$ nm, and all laser beams coming into the detector are of equal amplitude.

As shown in Fig. 3(a), intensity variation between zeros of the envelope is different from that of the next zeros of the envelope. Intensity variation around 0 μm in Fig. 3(a) reverses around 23 μm, and reappears around 46 μm in Fig. 3(b). To be exact, the optical path length difference of zero corresponds to $m\lambda_a(=n\lambda_b)$, and the period of optical path length difference is $m\lambda_a(=n\lambda_b)$.

We can derive the equivalent wavelength of $\lambda_a\lambda_b/|\lambda_a - \lambda_b|$ from the $\cos((k_a - k_b)X/2)$ term in Eq. (8). Comparing the range of $m\lambda_a(=n\lambda_b)$ to $\lambda_a\lambda_b/|\lambda_a - \lambda_b|$, when $m - n = j\,(m > n)$, then $m\lambda_a(=n\lambda_b)$ is j times wider than $\lambda_a\lambda_b/|\lambda_a - \lambda_b|$. Eq. (7) shows that intensity is maximized and symmetrical when $X = 0$. This phenomenon also appears at $m\lambda_a(=n\lambda_b)$, and appears periodically at $gm\lambda_a(=gn\lambda_b)$, where g is integer.

3. Instruments

Fig. 4 shows an instrument for measuring step height. No part of the instrument is mechanically movable, making possible precise measurements free of backlash. The reflection mirror for the reference beam is slightly inclined so that the optical path length difference ranges over the period. CCD or CMOS detectors must be used to simultaneously measure intensity variation over the period.

Intensity variation over the period is preliminarily measured or calculated, but intensity variation need not be measured over the period. Intensity variation of the latter coincides with the former, so step height can be measured, and laser beam diameters can be reduced.

The CMOS sensor receives two intensity variations from two step surfaces. Fig. 5(a) shows intensity variation of the upper step surface. In an area of the CMOS sensor that receives the upper step surface, every row of CMOS pixels receives the same intensity variation as in Fig. 5(a). Every pixel of column s receives maximum intensity and corresponds to an optical path length difference of zero. Fig. 5(b) is obtained from the lower step surface. In this case, column number r corresponds to optical path length difference of