Generation of a ruler marked out every a wavelength by a sinusoidal wavelength-scanning interferometer with double feedback control

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ABSTRACT

Phase modulation amplitude Z_b caused by a sinusoidal wavelength-scanning and conventional phase α of an interference signal are kept at π and $3\pi/2$, respectively, with feedback control systems for a displacement of an object larger than a half-wavelength. A voltage applied to a device that provides the wavelength-scanning becomes a ruler marked out every a wavelength. Real-time distance measurement is carried out with this interferometer.

1. INTRODUCTION

Since many applications for distance metrology require absolute distance measurements in real-time, two-wavelength interferometers equipped with a function of real-time measurement were developed. Recently wavelength-scanning interferometers with a wide scanning width of about 10 nm are applied to absolute distance measurement[1,2]. In this paper we employ a sinusoidal wavelength-scanning interferometer using a superluminescent diode[2], and propose an interference signal processing with feedback controls. In addition to a conventional phase α an interference signal of the sinusoidal wavelength-scanning interferometer has phase-modulation amplitude Z_b that is proportional to an optical path difference (OPD) L and the wavelength-scanning amplitude b. L and b are controlled with a double feedback system so that the phase α and the amplitude Z_b are kept at $3\pi/2$ and π, respectively. Voltage applied to a device which gives a displacement to a reference mirror to change the OPD becomes a ruler with scales smaller than a wavelength. Voltage applied to a device which determines the amplitude of the wavelength-scanning becomes a ruler marked out every a wavelength. These two rulers enable us to measure an absolute distance longer than a wavelength in real-time.

2. PRINCIPLE

2.1 Interference signal

Figure 1 shows a setup of the interferometer. A continuous spectrum of the SLD appears on the focal plane of lens L2 and L3. Slit SL transmits a portion of the spectrum. The first-order reflection from the grating G2 produces a collimated beam whose propagating direction is constant for all of wavelengths contained in the spectrum of the SLD. The slit is connected with a magnetic coil of a speaker and vibrated sinusoidally with an angular frequency of ω_b. The central wavelength of the light passing through the slit is sinusoidally scanned and it is expressed by $\lambda(t) = \lambda_0 + b\cos(\omega_b t)$. Intensity $I_M(t)$ of the beam is detected with photodiode PD2. Interference signal $S_D(t)$ detected with photodiode PD1 is divided by the intensity $I_M(t)$ to obtain an interference signal as follows:

$$\begin{aligned} S(t) &= S_D(t)/I_M(t) = A + B\cos(Z_b\cos\omega_b t + \alpha) \\ &= A + B\cos\alpha\,[J_0(Z) - 2J_2(Z)\cos(2\omega_b t) + \ldots \\ &\quad - B\sin\alpha\,[2J_1(Z)\cos(\omega_b t) - 2J_3(Z)\cos(3\omega_b t) + \ldots], \qquad (1) \end{aligned}$$

where $Z=(2\pi b/\lambda_0^2)L$, $\alpha=-(2\pi/\lambda_0)L$. L is an optcal path difference (OPD), and J_n is the nth order Bessel function.

2.2 Measurement by double feedback control

First, we explain how to measure a fractional value of OPD L with a feedback control. Feedback signal generator FSG1 produces a feedback signal $A_1=BJ_2(Z_b)\cos\alpha=g\cos\alpha$. Feedback controller FC1 produces voltage V_α applied to the PZT. The feedback system controls the position of reference mirror M2 or OPD so that the feedback signal A_1 becomes zero. Change of the OPD caused by this feedback control is illustrated in Fig.2. At first the OPD is L and the position of signal A_1 is point Q. The position of signal A_1 moves to stable point P by the feedback control. Then phase α becomes $3\pi/2+2m\pi$, where m is an integer. The OPD at the stable point of the feedback control is given by

$$L_z=L-L_\alpha=3\lambda_0/4+m\lambda_0\,. \qquad (2)$$

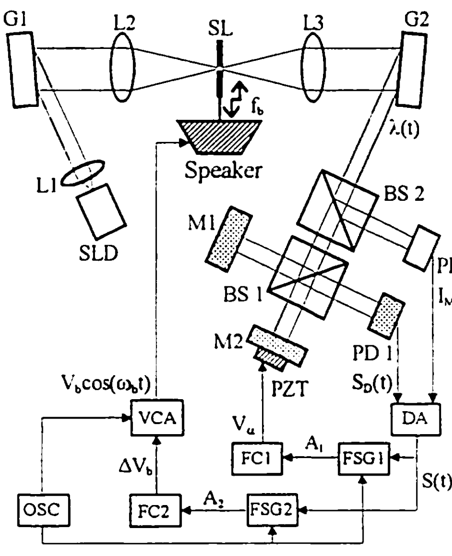

Fig. 1. Interferometer for real-time distance measurement.

L_α is a fractional value of OPD L to be measured. L_α can be obtained by measuring the applied voltage V_α and using the relation of $L_\alpha=\beta V_\alpha$. Its

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measurement accuracy is the order of nanometers.

Next, we explain how to measure an integer multiple of the wavelength in the OPD L. A feedback signal of A_2= $=2B\sin Z_b$ is generated in feedback signal generator FSG2. Feedback controller FC2 produces voltage ΔV_b which is fed to voltage control amplifier VCA and decides the amplitude V_b of the voltage applied to the speaker. The feedback system controls the amplitude V_b or the amplitude b of the wavelength scanning so that the signal A_2 becomes zero. This makes modulation amplitude $Z_b=(2\pi b/\lambda_0^2)L_z$ equal to π. Then the following equation holds:

$$b=\lambda_0^2/2L_z=2\lambda_0/(4m+3)\,. \qquad (3)$$

Values of b are discrete corresponding to values of m. Since the amplitude b is proportional to the amplitude V_b, values of V_b are also discrete. These discrete values of the amplitude V_b at which Z_b is equal to π are refereed to as stable points of V_b.

A value of b is obtained from the measured value of V_b, and a measured value of L_Z is calculated by the relation of $L_Z=\lambda_0^2/2b$. Since L_Z is given by Eq.(2), the following value is calculated using the measured value of L_Z:

$$m_c = (L_z - 3\lambda_0/4)/\lambda_0\,. \qquad (4)$$

Integer m can be decided by rounding off the value of m_c to an integer if measurement error of L_z is smaller than $\lambda_0/2$. Finally the OPD is calculated with a formula

$$L= 3\lambda_0/4+m\lambda_0+L_\alpha\,. \qquad (5)$$

It is noted that once the relation between the integer values of m and the stable points of V_b is given, the OPD can be obtained directly from Eq.(5) without calculation of m_c. This means that the stable points of V_b is regarded as a ruler marked out every a wavelength and the voltage V_α is regarded as a ruler with scales smaller than a wavelength. The calibration of the ruler produced by the voltage V_b can be made automatically with the double feedback control by changing the OPD at intervals of about a wavelength.

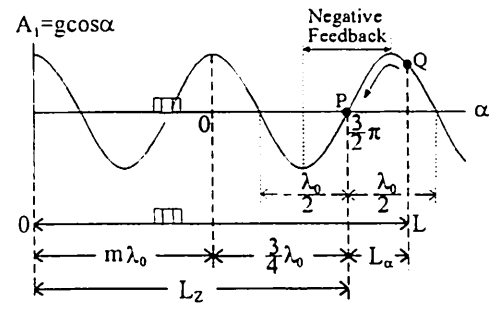

Fig.2. Relations between L, L_α, and L_z.

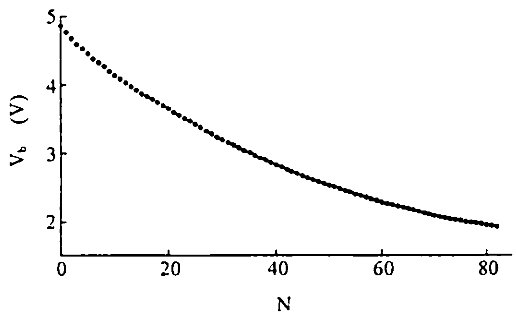

Fig.3. Stable points of V_b.

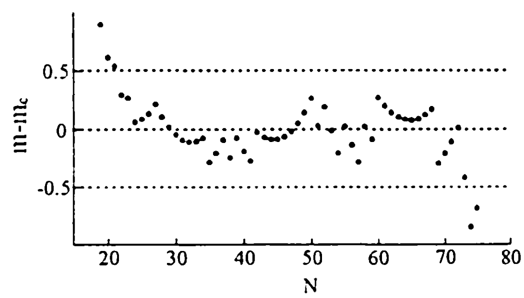

Fig.4. Values of m-m_c at stable points of V_b.

3. RESULTS

Central wavelength λ_0 and spectral bandwidth of the SLD were 788.7 nm and 20 nm, respectively, in the interferometer shown in Fig.1. The frequency $f_b=\omega_b/2\pi$ was 400 Hz. Mirror M1 fixed on a stage was used as an object. By giving a displacement to the object and increasing the OPD at intervals of about one wavelength, we could move a stable point of V_b to the next point sequentially. We obtained 83 stable points of V_b, as shown in Fig.3 whose horizontal axis is number of the stable points. We tried to decide integer m. We converted the stable points of V_b shown in Fig.3 into values of b with the relation of $b=1.59V_b+0.059$, and obtained measured values of L_Z. Values of m_c were calculated from the measured values of L_Z with Eq.(4). Figure 4 shows differences between the value of m_c and an integer of its round number. Since the absolute value of the difference was less than 0.5 in the region of N=20-70, we could determine values of integer m. From this result, the relation of m=46+N was obtained.

4. CONCLUSIOS

The sinusoidal wavelength-scanning interferometer with the double feedback control system produced a ruler with scales smaller than a wavelength and a ruler marked out every a wavelength. These two rulers enabled us to measure an absolute distance longer than a wavelength in real-time. The measurement range of OPD was from 37 μm to 102 μm where value of b changed from 8.3 nm to 3.1 nm, and the measurement error is less than 8 nm.

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