TWO-DIMENSIONAL DISPLACEMENT MEASUREMENT USING WAVELENGTH-MODULATION HETERODYNE GRATING INTERFEROMETRY

Hung-Lin HSIEH[1], Wei-Cheng WANG[1], Yu-Cheng WANG[1] and Ju-Yi LEE[2]

1 Department of Mechanical Engineering, National Taiwan University of Science and Technology, No.43, Sec. 4, Keelung Rd., Da'an Dist., Taipei 106, Taiwan, hlhsieh@mail.ntust.edu.tw
2 Department of Mechanical Engineering, National Central University

Abstract:

A wavelength-modulation heterodyne grating interferometry for two-dimensional displacement measurement is proposed. This technique has the advantages of heterodyne interferometry, grating-based interferometry, and Michelson interferometry. A heterodyne light beam is obtained from a tunable diode laser using the triangular wave modulating method. While the heterodyne light beam is normally incident into a transmission type grating, two detection parts for in-plane (IP) and out-of-plane (OP) displacement measurements will be obtained. The optical phase variations resulted from the moving grating in OP direction and IP direction are carried on the heterodyne interference signals. By means of measuring the phase variations of the interference signals from the moving grating, the grating movement in two dimensions can be acquired simultaneously without changing the optical configuration. The experimental results show that our proposed wavelength-modulation heterodyne grating interferometry is capable of sensing two-dimensional displacement with high measurement resolution. The measurement range and resolution can achieve millimeter and nanometer levels.

Keywords: wavelength-modulation, grating, heterodyne, two-dimensional

1. INTRODUCTION

Displacement measurement with nanometric resolution has become an important issue in the academic and industrial fields. Especially, in nano-lithography, MENS manufacturing techniques, nano-sensing techniques and semiconductor industry, the displacement measurement shows its unique importance. Many displacement measurement techniques have been proposed in the past few years [1-4]. Among them, optical interferometry has been greatly employed in scientific investigation or industrial application due to it can offer the advantages of wide measuring range and high metric resolution simultaneously [4-5]. If high frequency noises are considered, the measurement resolution of heterodyne interferometer can achieve sub-nanometer level. There are several electrical-type modulation techniques to generate a heterodyne light source such as acousto-optic modulator (AOM), electro-optic modulator (EOM), and Zeeman laser. We have successfully proposed a heterodyne interferometry using EOM for long displacement measurement with high measurement resolution [5-7]. However, the modulation techniques mentioned above are very expensive, even if those techniques have been proven to be very useful ways to measure the displacement.

Laser diode (LD) is gaining as an important light source in recent years. The luminous power and wavelength of the LD can be modulated by controlling the injection current. This feature has been used instead of the heterodyne frequency shift architecture [8-10]. Various ways using LD for displacement measurement have been proposed. However, most of the interferometers are designed for one-dimensional IP or OP displacement measurement. In general, a pair of interferometers which are perpendicular to each other can be used to measure two-dimensional displacement. However, the orthogonality of the two interferometers is essential to provide measurement accuracy. The additional expense of another interferometer is also a disadvantage.

In this paper, a heterodyne interferometer using LD light source is designed to measure IP and OP displacements simutanoursly. The IP displacement information is obtained by grating interferometry configuration and determined by the relation of the grating pitch and optical phase variation. Moreover, the OP displacement is aquired by the Michelson interferomtry configuration which is determined by the relation of the wavelength of the light source and optical path difference. Benefiting from the proposed heterodyne interferometric phase measurement and the optical configuration, this method has advantages of high measurement resolution, relatively straightforward operation, and high system stability.

2. MEASUREMENT METHOD

In this study, three techniques have been used for wavelength modulation, in-plane measurement, and out-of-plan measurement, respective. The principles of the three techniques are explained in detail as follows

The scheme of our proposed wavelength-modulation heterodyne light source is shown in Fig. 1. .A light beam with a central wavelength of λc is emitted from the LD. The LD is driven by a triangular wave with period T. the driving current is used to modulate the wavelength of the LD and can be expressed as follows:

$$\lambda(t)=\begin{cases}\lambda_0+\Delta\lambda\cdot t, & 0<t<T/2\\ \lambda_0-\Delta\lambda\cdot t, & T<t<T\end{cases} \qquad (1)$$
$$\lambda(t+T)=\lambda(t)$$

where λ_0 stands for the central wavelength, $\Delta\lambda$ means the modulation depth of the wavelength, t and T are the time and modulation period, and $\Delta\lambda$ is far less than λ_c.
As the two beams interfere, the intensity signal obtained from the photodiode can be written as

$$I(t)\propto I_0\left[1+\cos\left(\frac{4\pi\cdot\Delta l}{\lambda_0}-\frac{4\pi\cdot\Delta\lambda\cdot\Delta l}{\lambda_0^2}\cdot t\right)\right] \qquad (2)$$

where Δl means path-difference between beam l_1 and l_2, $4\pi\Delta l/\lambda_0$ means the phase difference resulting from the optical-path-difference between the two beams, $4\pi\Delta\lambda\Delta l/\lambda_0^2$ stands for the beat frequency resulting from the driving signal. Therefore, the heterodyne light source can be obtained.

Furthermore, a schematic diagram of the proposed wavelength-modulated heterodyne grating shearing interferometry is shown in Fig. 2. The displacement measurement is classified as either IP or OP detection. These two detection methods are based on utilization of grating-based interferometry and Michelson interfeoremtry, respectively. As the wavelength-modulation heterodyne light beam enters a polarizer with 45˚ polarization status and falls incident into the grating, part of the light beam will be reflected while the other part will pass through. The reflected detection part is used for OP displacement measurement. According to our previous study [7], the interference signal obtained by photo-detector (PD_1) can be written as

$$I_1\propto AC\cos\left[\frac{4\pi}{\lambda_0}\Delta l_{OP}-\frac{4\pi\cdot\Delta\lambda\cdot\Delta l_{OP}}{\lambda_0^2}\cdot t+\Delta\phi\right] \qquad (3)$$

where $\Delta\phi$ represent the initial phase difference between the two beams, Δl_{OP} indicates the variation of OP displacement. The value of $\Delta\phi$ is a constant, therefore, this value can be ignore in OP detection configuration. The relationship between the phase difference and OP displacement (Δl_{OP}) is formulated as

$$\Delta l_{OP}=\Delta\Phi\lambda_0/4\pi \qquad (4)$$

By means of Eq. (4), the OP displacement can be calculated from the measurement of the phase difference variation and the wavelength of the light source.

Moreover, the IP displacement can be obtained by using the grating-based detection configuration. In this detection configuration, the interference signals measured by photo-detector (PD_2) can be written as follows [7]:

$$I_2\propto AC\cos\left[\frac{4\pi}{\lambda_0}\Delta l_{IP}-\frac{4\pi\cdot\Delta\lambda\cdot\Delta l_{IP}}{\lambda_0^2}\cdot t+2\phi_g\right] \qquad (5)$$

where Δl_{IP} stands for the path-difference between the +1st order and -1st order diffracted beams, ϕ_g represents the phase difference induced from the moving grating in IP direction. The value of Δl_{IP} is a constant, therefore, this value can be ignore in IP detection configuration. As a result, the IP displacement (Δd_{IP}) can be shown by

$$\Delta d_{IP}=\Delta\phi_g\, p/4\pi \qquad (6)$$

where p means the period of the grating. By means of Eq. (6), the IP displacement (Δd_{IP}) can be calculated from the measurement of the phase difference variation ($\Delta\phi_g$) and the grating period (p).

3. EXPERIMENTAL RESULTS

The experimental configuration is depicted in Fig. 3. A diode laser (Model: 710, Newport) with center wavelength 658nm was used as a light source. A function generator (Model: AFG 3022B, Tektronix) was used to generate a 70 mV triangular wavefront for wavelength modulation. The wavelength variation is set to be 0.03nm. A semi-transmission grating with 1.667 μm pitch was mounted on the commercial piezo-stage (Model: P-562.6CD, Physik Instrumente). The stage was operated in a close-loop configuration for comparing the experimental results obtained by our proposed method and the internal capacitance sensor. A software lock-in amplifier was used to calculate the phase difference between the corresponding directions.

In order to demonstrate that our proposed method is capable of measuring two-dimensional displacement without changing the optical configuration, the experiments of the IP and OP displacement measurement have been performed. The piezo-stage was asked to move with 3.5 μm continuous amplitude along the IP direction by sending a sinusoidal wavefroms from the function generator. Figure 3 shows the experimental results obtained by our method and the capacitive sensor. Experimental curves have been plotted with 5 second-delay to conveniently distinguish the measurement results. As shown in Fig. 4, the curves are similar with a peak to peak amplitude of 3.501 μm and 3.503 μm, respectively.

Furthermore, the piezo-stage was asked to perform with 3.5 μm continuous amplitude along the OP direction. The experimental results are shown in Fig. 5. The same applies to Fig. 5 which have a peak to peak amplitude of 3.502 μm and 3.504 μm, respectively. Clearly, the two methods give almost the same measurement results. Also, it is worth noting that the measurement curves obtained using our method in the OP and the IP directions are as linear as those obtained using the capacitive sensor. This demonstrates that the proposed interferometry has ability and potential to measure IP and OP displacements as a commercial instrument.

4. CONCLUSIONS

A wavelength-modulation heterodyne grating interferometry is proposed for two-dimensional displacement measurement. The proposed interferometry is designed by combining the advantages of wavelength-modulation, grating, and Michelson interferometries. The experimental results demonstrate our proposed interferometry is capable of sensing in-plane and out-of-plane displacement simultaneously. The measurement resolution can achieve to 2 nm for milli-metric measurement range.

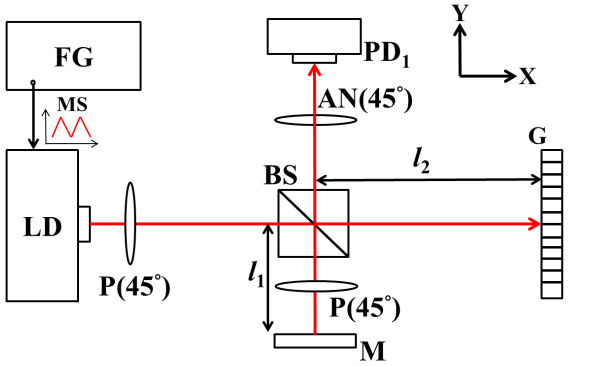

Fig. 1: Scheme of the wavelength-modulation heterodyne light source

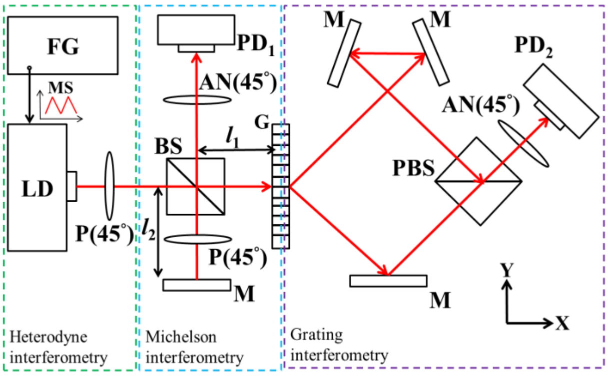

Fig. 2: Optical configuration of the wavelength-modulation heterodyne grating interferometry

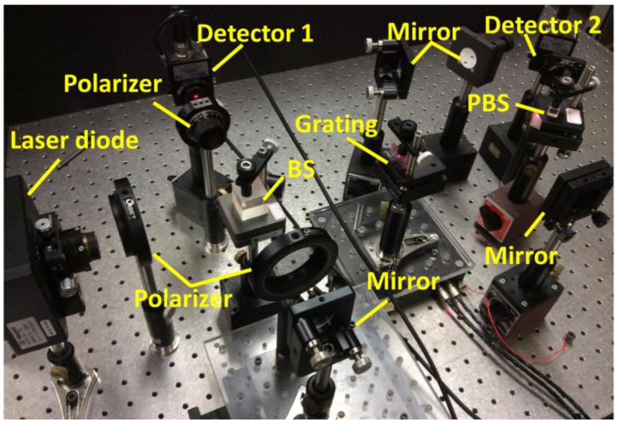

Fig. 3: Experimental configuration for IP and OP measurement.

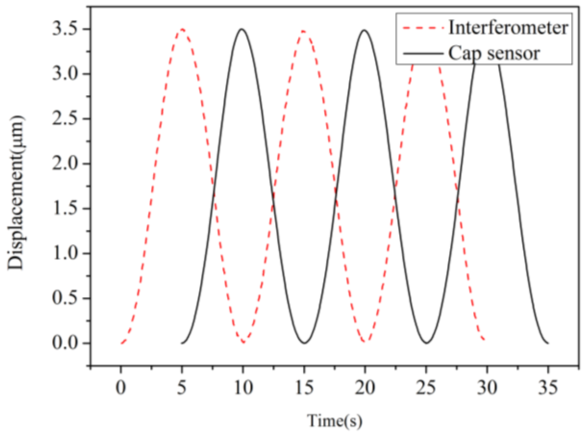

Fig. 4: Experimental result of IP displacement measurement.

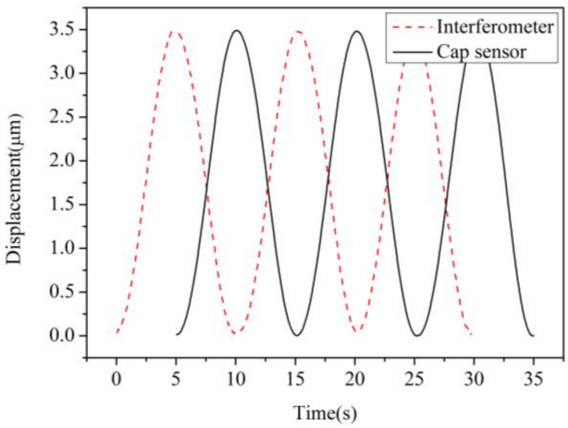

Fig. 5: Experimental result of OP displacement measurement.

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