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Measuring grating period of dual-periodic grating with dual-wavelength external cavity diode laser

Shuzo MASUI[1], Shuhei GODA[2], Shotaro KADOYA[1], Masaki MICHIHATA[2], and Satoru TAKAHASHI[1]

[1]*Research Center for Advanced Science and Technology, The University of Tokyo*
[2]*Department of Precision Engineering, The University of Tokyo*

masui.s@nanolab.t.u-tokyo.ac.jp

Abstract

In recent years, there has been a growing interest in periodic structures with multiple periodicities, such as metasurfaces and subwavelength structures. Therefore, a need to develop a high-precision measurement method for grating structures with multiple structural frequencies. Although conventional grating period measurement techniques such as CD-AFM and diffractometry are already well studied for single-period gratings, few studies have applied these techniques for multi-pitched gratings. This paper proposes a grating period measurement technique for multi-period gratings using a Littrow configuration external cavity diode laser (ECDL). We demonstrated the proposed measurement method of dual-period gratings fabricated by interference lithography. As a result, we succeeded in measuring the grating period within 1% error with only 180 seconds rotation of the grating. In the future, more accurate measurement is expected by precisely measuring the resonance wavelength and investigating the effect of the grating orientation error.

Keywords: Diffraction grating, External cavity diode laser, Interference lithography

1. Introduction

Nano- and micro-order periodic structures play an essential role in science and industry along with the progress of microfabrication technologies. In particular, single-period lattice structures, such as diffraction gratings, have become a fundamental technology for spectrographs, linear encoders, etc. Moreover, they are also indispensable for micro measurement technology as calibration samples for length measuring SEM (CD-SEM) and atomic force microscopy (AFM)[1,2]. For this reason, precise measurement methods for single-period lattice structures have been actively reported[3].

However, in recent years, diffraction devices with multiple spatial frequencies, such as metasurfaces and multi-period diffraction devices, have been actively studied[4]. In the case of multi-period structures, it is difficult to measure the grating period using the conventional grating measurement method assuming a single periodicity.

In this study, we propose a new method for measuring the grating period of multi-periodic structures using an external cavity laser diode(ECLD). Since the grating periods can be measured with a slight angular rotation, the measurement device can be downsized compared with the conventional X-ray diffraction or AFM measurement.

2. Measurement principle

In this study, we adopted the Littrow configuration of an ECLD, as shown in the measurement system in Figure 1. In the Littrow configuration, the laser diode (LD) emitted light incidents to the diffraction grating. The first-order diffracted light returns in the same direction as the incident light, resulting in resonance. In this study, we assume an *n*-fold periodic grating to be incorporated into the external resonator. In this case, the resonant wavelength λ_n that appears according to each grating period is expressed by the following equation using the incident angle (Littrow angle) ϑ_L and the n_{th} period Λ_n,

$$\lambda_n = 2\Lambda_n \sin\theta_L\,. \tag{1}$$

Furthermore, in the proposed method, the grating period can be measured by precisely measured resonance wavelengths and their shift when a slight angle of ~200″ rotates the grating. Therefore, the wavelength shift of the n_{th} resonant wavelength $d\lambda_n$, when a slight angle $d\vartheta$ rotates the multi-period grating, can be approximated as follows

$$\begin{aligned}\lambda_n &= 2\Lambda_n[\sin(\theta_L + d\theta) - \sin\theta_L] \\ &\approx 2\Lambda_n \cos\theta_L\, d\theta.\end{aligned} \tag{2}$$

Then, using Eqs. (1) and (2), the n_{th} lattice period Λ_n and the Littrow angle ϑ_L can be expressed from the rotational angle $d\vartheta$, resonant wavelength λ_n and shift amount $d\lambda_n$ as follows

$$\Lambda_n = 1/2\sqrt{\lambda_n^2 + (d\lambda_n/d\theta)^2}\,. \tag{3}$$

$$\theta_L = \arctan(\lambda_n\, d\theta/d\lambda_n)\,, \tag{4}$$

From the above results, we can expect to measure the grating period of the multi-period grating at once by measuring both the slight rotation angle and the resonant wavelength.

3. Experimental method

The experimental setup is shown in Figure 1. First, an anti-reflection coated LD (Wavelength: 1520-1565 nm) was collimated by a collimator to a beam diameter of ~1 mm and incident on the diffraction grating. Next, the grating was placed on a rotating stage and measured with an autocollimator (measurement range: 200″, resolution: 0.05″). Finally, the resonant beam was obtained as the zeroth-order light, and the resonant wavelength was measured with an optical spectrum analyzer (OSA, 20 pm resolution).

Next, we used a double-periodic grating to demonstrate the measurement principle of multi-periodic gratings as a measurement target. Figure 2 shows a double-periodic grating fabricated by multiple-exposure interference lithography using a rotational Lloyd's mirror setup [5]. The reflectance at near-infrared wavelengths was improved by coating the surface of the lattice with 100 nm of Au. The details of the fabrication process are omitted in this paper.

Due to the undulation of the interference fringes, the lattice period of the two overlapping fringes is several hundred micrometers, making it difficult to measure the grating period using AFM. Therefore, the two superposed periods Λ_1 and Λ_2 were estimated from the average lattice period Λ_{ave} and the undulation period Λ_{beat} observed by the microscope using the following equations.

$$\Lambda_{1,2} = (\Lambda_{\text{ave}}^{-1} \mp \Lambda_{\text{beat}}^{-1})^{-1}. \quad (5)$$

As a result, two lattice periods were computed, as shown in Table 1.

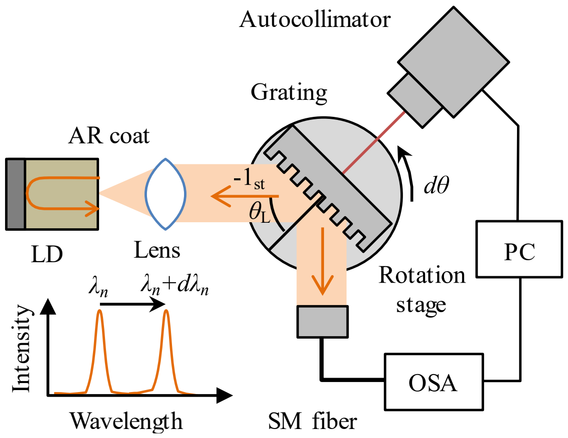

Figure 1 Measurement setups for multi-period grating.

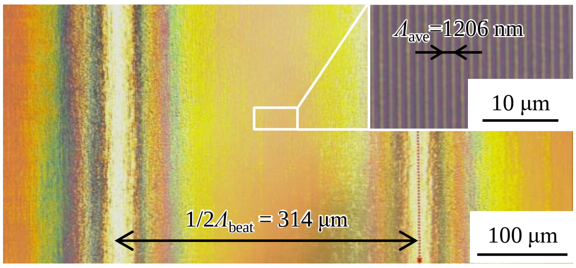

Figure 2 Microscopic image of the fabricated dual-period grating.

Table 1 Calculated grating periods.

Measurement result		Calculated result	
Λ_{beat} [μm]	Λ_{ave} [nm]	Λ_1 [nm]	Λ_2 [nm]
628	1206	1208	1204

4. Experimental results

As a measurement procedure, the double-periodic grating was first aligned to resonate at an appropriate Littrow angle ϑ_L. Then, the two resonance wavelengths and the grating angle were measured by every ~10″ rotation.

Figure 3 shows the variation of the two resonance wavelengths together with the first-order functions fitted by the least-squares method. The resonant wavelength at a whole rotation angle of ~180″ was shifted by ~2 nm, enough to be measured with an optical spectrum analyzer. Furthermore, the grating period $\Lambda_{1,2}$ and the Littrow angle ϑ_L calculated from the slope of the linear plot in Fig. 3 and Eqs. (3) and (4) are shown in Table 2. As a result, we succeeded in measuring the two grating periods $\Lambda_{1,2}$ and the Littrow angle ϑ_L within a measurement error of 2-3 nm and ~0.1°, respectively. The measurement error may be caused by the misalignment of the grating, LD, and autocollimator. The angular measurement resolution of the autocollimator is 0.05″, and the wavelength measurement resolution of the optical spectrum analyzer is 20 pm. Therefore, it is expected that the measurement accuracy can be improved by the precise alignment of the experimental apparatus. These results demonstrate the grating period measurement method proposed in this study for multi-period gratings.

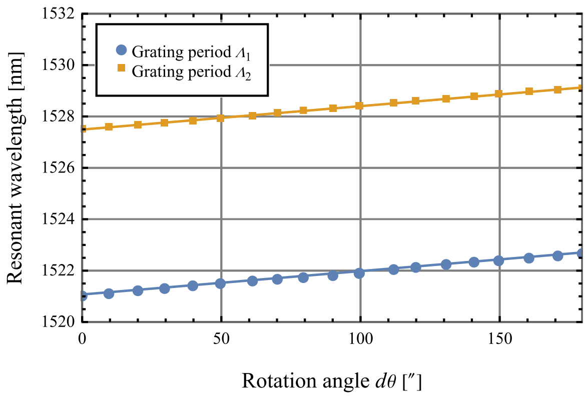

Figure 3 Measured wavelength shift of dual-period grating.

Table 2 Measured two grating periods.

Grating period	Resonant wavelength $\lambda_{1,2}$ [nm]	Calculated period [nm]	Measurement result [nm]	Measurement error [%]
Λ_1	1527	1208	1210	0.12
Λ_2	1521	1204	1207	0.31

Table 3 Measured Littorow angle.

Grating Period	Littrow angle [deg.]	Measurement Result [deg.]	Measurement error [%]
Λ_1	39.2	39.1	−0.28
Λ_2	39.2	39.0	−0.40

5. Conclusions

In this study, we proposed and demonstrated measurement of the grating period of a multi-period grating using a Littrow configuration ECLD. By simultaneously measuring the rotation angle, the resonance wavelength, multiple grating periods, and Littrow angles can be measured simultaneously. In the experimental demonstration of the measurement principle, we succeeded in measuring the lattice period with a measurement error of ~0.3% for a double-period diffraction grating fabricated by interference lithography. Accurate measurement of grating periods of the dual-periodic grating can be expected to contribute to new optical measurements, such as the development of multi-scale encoders.

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