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High Precision Distance Measurement based on External Cavity with Dual Periodic Grating

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A very high-resolution measurement technique is the one based on the resonance phenomenon. In resonance measurements, the cavity length can be estimated using the resonance wavelength and mode number. The optical resonance phenomenon using an external cavity mechanism laser provides high Q-values and is suitable for high-precision distance measurement systems. For measurements using resonance, the advantages are ease of traceability and lack of influence from phase jumping. For dimensional measurement, the longitudinal mode number is also necessary for the cavity length measurement of the external cavity mechanism. We propose a method to accurately number longitudinal modes of external cavity wavelength-scanning diode lasers (ECDLs) for more accurate distance measurement. A method to find the longitudinal mode number of ECDL much accurately, which uses dual periodic gratings is proposed. Dual periodic gratings can resonate in multiple wavelength bands simultaneously. In this paper, a method to increase the longitudinal mode number difference k by using a dual periodic grating instead of a conventional grating so that the resonance occurs in two distant wavelength bands is proposed. The proposed method is validated by experimentally comparing the estimation dispersion of the longitudinal mode number between the single periodic grating and the dual period grating. Experimental verification shows that the dispersion of the longitudinal mode number estimation is decreased by about 150 times. The estimation dispersion of the longitudinal mode number was achieved to 1. (229 words)

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1. Introduction

Ultra-high precision distance measurement using light is mainly based on interference, and time-of-flight method[1-3]. Interferometry is very well developed and can provide high accuracy and long-range measurements[4]. On the other hand, for relatively short distance measurements of several hundred mm or less, higher, and higher resolution is required. A very high-resolution measurement technique is the one based on the resonance phenomenon. In resonance measurements, the cavity length can be estimated using the resonance wavelength and mode number. For measurements using resonance, the advantages are ease of traceability and lack of influence from phase jumping. Resonance is typically applied to light sources such as lasers and sensors. In these applications, it takes advantage of the characteristics of narrow line widths. For dimensional measurement, the longitudinal mode number is also necessary for the cavity length measurement of the external cavity mechanism. It is still a challenge to estimate the longitudinal mode number. For example, the mode number is necessary for the inter-mirror measurement in Fabry-Perot resonance and the sphere diameter measurement in WGM resonance[5,6]. In the resonance phenomenon, it is most important to know the longitudinal mode number to obtain the distance from the wavelength measurement. However, it is generally difficult to know the longitudinal mode number accurately, because of the cavity length is not known. Previously, the mode number was estimated by using two lasers and measuring their frequencies and beat frequencies. The optical resonance phenomenon using an external cavity mechanism laser provides high Q-values and is suitable for high-precision distance measurement systems.

In this paper, Littrow configuration external cavity diode laser (ECDL) was used [7,8]for high precision distance measurement. The light emitted from the laser is collimated by a lens and dispersed by a diffraction grating into different wavelengths. Only the wavelengths that are directly fed back to the laser by the diffraction grating resonate between the laser and the grating. Littrow configuration ECDLs are mainly used as tunable lasers and by rotating the diffraction grating, the resonance can be controlled to occur at various wavelengths. Dispersion of longitudinal mode number estimation is still a problem in the measurement of cavity length by ECDL. A method to find the longitudinal mode number of ECDL much accurately, which uses dual periodic gratings is proposed. This paper aims to experimentally verify the improvement of the accuracy of mode number estimation and resonator length measurement in the proposed method.

2.1 Cavity length measurement principle

Principle of cavity length measurement is described as follows. Cavity length of ECDL, L is determined resonant wavelength λ_m and longitudinal mode number m represented as $2L = m \times \lambda_m$. From this equation, longitudinal mode number estimation can be done by measuring two different optical resonance wavelengths and the difference in their longitudinal mode numbers expressed by following equations

$$m = \frac{k\lambda_{m+k}}{\lambda_m - \lambda_{m+k}} \#(1)$$

Here, m and m+k are the longitudinal mode number, λ_m and λ_{m+k} are the mth and m+kth resonant wavelengths, respectively, and the subscript denotes the longitudinal mode number; L is the resonator length, and k is the difference between the longitudinal mode numbers of the two resonant wavelengths. Difference between longitudinal mode number, k is expressed as following equations

$$k = \frac{\nu_{m+k} - \nu_m}{\Delta\nu} \#(2)$$

where ν_m and ν_{m+k} is the mth and m+kth resonant frequency, respectively and $\Delta\nu$ is the average of the differences between all the neighboring resonance frequencies measured, which is called Free Spectral Range (FSR). The FSR of each resonant wavelength is equal, which is derived by the equation $2L = m \times \lambda_m$. The cavity length L can be obtained by simply measuring multiple resonance wavelengths by substituting Equation (1) and Equation (2) into $2L = m \times \lambda_m$.

2.2 Longitudinal mode number estimation error

However, when there is a wavelength measurement error in the wavelength to be measured, the estimated longitudinal mode number will have some error. The effect of wavelength measurement error on the estimation of the longitudinal mode number is expressed by the coefficient dm/dλ, which can be obtained by differentiating equation (1) by wavelength. The measurement error dλ of the wavelengths of λ_m and λ_{m+k} is assumed to be the same.

$$\frac{dm}{d\lambda} = \frac{k\sqrt{\lambda_m^2 + \lambda_{m+k}^2}}{(\lambda_m - \lambda_{m+k})^2} \#(3)$$

Here, dm denotes the difference in longitudinal mode number dλ denotes the difference in wavelength measurement. Fig 1, in which difference between periods of dual periodic gratings and the difference in longitudinal mode number, k, are set on the horizontal axis and the error in the estimation of longitudinal mode number, dm, is set on the vertical axis, is shown below. The measurement error of the wavelengths is dλ = 10 pm, dλ = 1 pm and dλ = 0.1 pm, respectively and the cavity length is set to 25 mm. Since the vertical axis is logarithmic, it can be confirmed that the difference in longitudinal mode number estimation is greatly reduced by increasing the difference in longitudinal mode number k, which means that the dispersion of longitudinal mode number estimation is considerably improved. Therefore, it is desirable to use two optical wavelengths with as large a wavelength difference as possible, but there is a limit to the wavelength width in ordinary ECDLs. Dual periodic gratings were used to solve this problem. Littrow configuration ECLD with a dual periodic grating is used. The grating in the external cavity is rotated and fixed at the wavelength to be resonated, and then the resonant wavelength is measured. The longitudinal mode number is identified using the two resonance wavelengths of the dual periodic grating. The larger difference between the longitudinal mode numbers of the two resonant wavelengths k is, the better. However, the wavelength width of a typical ECDL is less than 0.1 nm, and the difference between two different longitudinal mode numbers, the longitudinal mode number difference k, can be only a few dozen. Dual periodic gratings are superpositions of two different pitch gratings. Dual periodic gratings can resonate in multiple wavelength bands simultaneously[9-11]. In this paper, a method to increase the longitudinal mode number difference k by using a dual periodic grating instead of a conventional grating so that the resonance occurs in two distant wavelength bands is proposed. The difference between the two pitches of the dual periodic grating determines the distance between the two resonant wavelength bands. The relationship between the grating pitch difference and the longitudinal mode number estimation error dm from equation (3) is shown in Fig 1. The graphs were plotted for uncertainty of 10 pm, 1 pm, and 0.1 pm, respectively. How the dispersion of the longitudinal mode number estimation varies with the cavity length when the same dual periodic grating is used was revealed. Fig. 1 shows how the dispersion of the mode number estimation changes when the cavity length is changed using the same dual periodic grating and two fixed wavelengths. The dispersion of longitudinal mode number estimation increases as the cavity length increases (Fig 1). To maintain the dispersion of longitudinal mode number estimation, it is necessary to use dual periodic grating with significantly different periods as the cavity length increases.

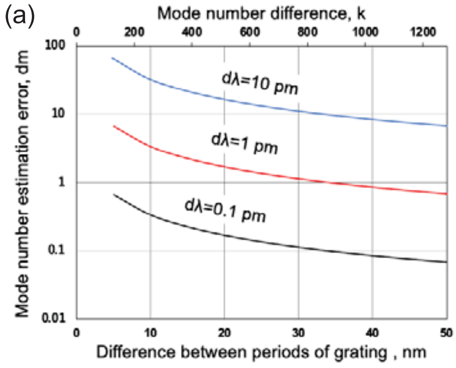

Fig 1 Effect of some factor on mode number estimation error (a) Effect of difference between periods of dual periodic grating and mode number difference on mode number estimation error

3. Experiment

3.1 Experimental Setup

The diffraction grating used was self-made by photolithography

[12,13]. In photolithography, light with a periodic intensity distribution is irradiated onto the photosensitive resin using a rotating Lloyd's mirror optical system. The fabricated grating was measured by atomic force microscopy (AFM) to confirm their shape and pitch (Fig 2). The profile was fast Fourier transformed. The graph shows our dual periodic grating has two pitches which are 0.933 μm^{-1} and 0.954 μm^{-1}.

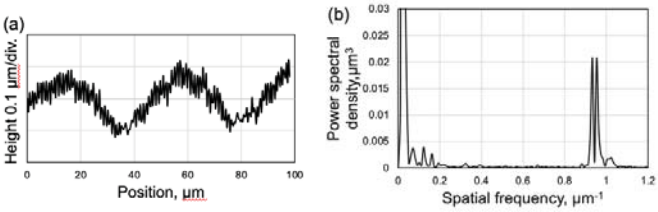

Fig 2 Dual periodic grating profile measured by AFM (a) XZ profile of a dual periodic grating by AFM (b) The XZ profile in (a) with FFT transformation.

The laser cavity with the Littrow configuration is shown in fig3. The length of the extended cavity was approximately 28 mm. The incident angle of the diffraction grating was set to about 47 degrees.

The experimental setup consists of a laser diode, a collimating lens, and a dual periodic grating. A laser diode (Thorlabs SAE1550P2, bandwidth: 1560-1640 nm, AR-coated) and a collimating lens (f = 2.97 mm, NA 0.6) was fixed on the stage. The laser had an oscillation bandwidth of 1600 nm and is equipped with a TEC temperature control mechanism, which maintain a constant temperature of 25 degrees Celsius. The laser had an anti-reflection coating. Lens had an anti-reflection coating. A current of 300mA was applied to the LD. The resonant wavelength was measured from the back face of the LD with a single-mode fiber into an optical spectrum analyzer (Yokogawa AQ6370D, Accuracy: ±10 pm).

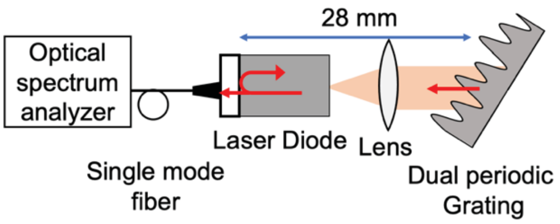

Fig 3 Experimental set up

3.2 Dispersion of longitudinal mode number estimation confirmation experiment

In the experimental apparatus, resonance phenomena in the two wavelength bands were confirmed by the optical spectrum analyzer. The spectral power density at each wavelength is shown on the Fig4. These resonant wavelengths were approximately 1582 nm and 1621 nm. Longitudinal modes were observed when the image was magnified in each resonance wavelength band. About 30 modes were oscillating in each resonance wavelength band. Full width half maximum (FWHM) of each mode was approximately 24 pm. These resonance wavelengths were measured from the top of each mode by quadratic fitting. The resonant wavelength was measured 10 times at intervals of several seconds under the same conditions, and the standard deviation was 0.3~0.4 pm. The longitudinal mode numbers were estimated by measuring the resonant wavelengths, and the dispersion of the longitudinal mode number estimation was compared between single and dual periodic gratings. Specifically, for the single periodic grating, the resonance mode at wavelength of 1621.6986 nm was set as the longitudinal mode number m. The longitudinal mode number was estimated using Equation (1) from all combinations that take the mode number difference 1. This operation was performed for each of the mode number differences 1~30. The variation of the estimated value and average of estimated longitudinal mode number were calculated. For the dual periodic grating, the resonant wavelength of 1621.6986 nm was set as the longitudinal mode number m, and as in the case of the single periodic diffraction grating, from all combinations that take the mode number difference 845~874, the variation of the estimated value and average of estimated longitudinal mode number were calculated. The longitudinal mode number difference k was obtained by calculating the FSR using about 60 resonant wavelengths of multimode oscillation, which were between the wavelength of longitudinal mode number m and m+k and using equation (2). The average FSR, Δν was calculated about 5.46 GHz. From this measured FSR, the longitudinal mode number difference k was calculated from equation (2). The resonant wavelength was measured 10 times at intervals of several seconds under the same conditions, and the standard deviation of resonant frequency was 36.4 MHz. From the error propagation equation (2) with the measured standard deviation of resonant frequency, the maximum dispersion of the longitudinal mode number difference k was estimated to be about 0.24. When estimating the longitudinal mode number, it is important that the longitudinal mode number difference k is accurately determined. From these results, the mode number difference k is obtained accurately to the first place. In the case of the single periodic grating, the variation of the estimated mode number was found to be about 150 when longitudinal mode number k is 30. In the case of the dual periodic grating, the variation of the estimated longitudinal mode number is reduced to about 0.6 (Fig 5). In Fig 5, the error bars show the maximum and minimum values for a given mode number difference. The scale is 500 for the single periodic grating and 5 for the dual periodic grating. Therefore, the proposed method decreases the dispersion of longitudinal mode number estimation by a factor of 150. Substituting the actual measured values into equation (3), the theoretical mode number estimation error becomes about 0.4 which is in close agreement with the experimental values. The cavity length was measured to be 27.46347 mm by these measurements.

From the measurement results, the measurement error of the cavity length due to the mode number estimation error can be expressed as $\Delta L = \Delta m \times \lambda_m / 2$. Here, ΔL is the measurement error of the cavity length, Δm is the longitudinal mode number estimation error. In the case of a single periodic grating, the mode number estimation error is about 150, so the measurement error of the cavity length is about ±64 µm. On the other hand in the case of a dual periodic grating, the mode number estimation error is about 0.6, so the three possible mode numbers is 33871, 33870, and 33869. Then the measurement error of the cavity length is about ±0.81 µm.

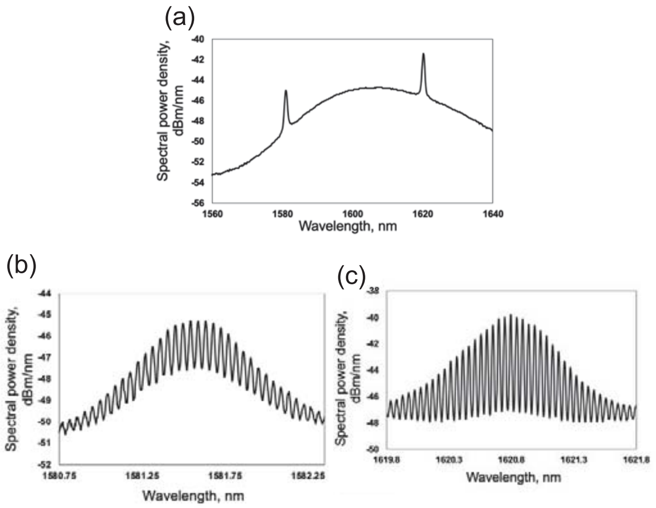

Fig 4 Resonance wavelength spectrum measured by optical spectrum analyzer (a) The entire resonance spectrum, (b) Expanding the resonance spectrum 1582nm band (c) Expanding the resonance spectrum 1621nm band

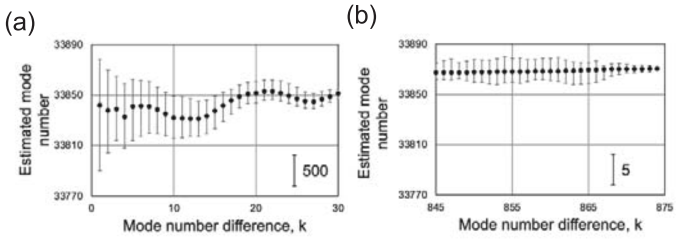

Fig 5 Dispersion of estimated mode number (a) Variation of longitudinal mode number estimation when using a single periodic grating. (b) Variation of longitudinal mode number estimation when using a dual periodic grating.

4. Conclusions

A distance measurement method based on ECDL cavity length measurement are studied in this paper. A method for declining the dispersion of longitudinal mode number estimation using a dual period grating is proposed. The dual periodic grating used was self-made by photolithography. The proposed method is validated by experimentally comparing the estimation dispersion of the longitudinal mode number between the single periodic grating and the dual period grating. Experimental verification shows that the dispersion of the longitudinal mode number estimation is decreased by about 150 times. The estimation dispersion of the longitudinal mode number was achieved to 1. The measurement error of the cavity length was improved from ±64 μm to ±0.81 μm by the proposed method.

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