Absolute length measurement of Fabry-Perot cavity at 10^{-9} order using frequency modulation technique

Masato Aketagawa[1,#], Hiroshi Iwata[1], Tuan Banh Quoc[1] and Kenji Hirata[1]

1 Department of Mechanical Engineering, Nagaoka University of Technology, Kamitomioka, Nagaoka, Japan 940-2188
Corresponding Author / E-mail: masatoaa@vos.nagaokaut.ac.jp, TEL: +81-258-47-9741, FAX: +81-258-47-9770

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The free spectral range (FSR) of the Fabry-Perot cavity can be determined with the null method using an electric-optical modulator, a frequency modulation and the lock-in detection. From the FSR measurement, an absolute distance between mirrors of the Fabry-Perot cavity can be determined. In this paper, we discuss the reduction of the measurement uncertainty for the FSR. The relative measurement uncertainty ($\Delta FSR/FSR$) of 10^{-8}~10^{-9}order has been achieved.

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1. Introduction

In the near future of semiconductor lithography and ultra precision engineering, the absolute length measurement at a range of 1 m and an uncertainty of nanometer order will be required. Since the free spectral range (FSR) of a Fabry-Perot cavity (FP Cavity) is defined by a half of light velocity in vacuum ($c/2$) divided by product of the geometrical distance between the two mirrors (L) and the refractive index in the FP Cavity (n_c), the FSR measurement is a potential method to measure the absolute length L. We have discussed a method to measure the FSR of a FPC using frequency modulation with one electric optical modulator (EOM) and the null method[1]. A laser beam, modulated by the EOM, to which a sine-wave signal is supplied from a radio frequency (RF) oscillator, is incident on the FP Cavity. The transmitted or reflected light from the FPC is observed and converted to an RF signal by a high-speed photodetector, and the RF signal is synchronously demodulated with a lock-in amplifier by referring to a cosine-wave signal from the oscillator. We have theoretically and experimentally demonstrated that the lock-in amplifier signal for the transmitted or reflected light becomes null with a steep slope when the modulation frequency is equal to the FSR under the condition that the carrier frequency of the laser is slightly detuned from the resonance of the FP Cavity[1]. In this paper, to reduce the uncertainty for the FSR measurement, we discuss a selecting method for laser power, a modulation index and the detuning shift of the carrier frequency, respectively. The uncertainty of FSR measurement is expected to be 10^{-8}~10^{-9}order.

2. Instrumentation and experimental result

Fig. 1 shows the experimental set-up to measure the FSR[1]. In the system, the ECLD (wavelength=780nm, maximum power=20mW, linewidth=300kHz) is used for the light source. The RF oscillator (OSC) feeds the modulation signal to the EOM through the amplifier (Amp) to adjust the modulation index. The oscillator also feeds a reference signal with a suitable amplitude and phase to the lock-in amplifier via an amplifier, an attenuator (Att) and a phase shifter. The phase shift is controlled by adjusting the length of a coaxial cable to set the reference signal to $\cos\omega_m t$. The rubidium frequency standard (RFS) is utilized to stabilize the oscillator and the frequency counter (FC). In the experimental system, the detuning frequency shift (ω_0)[1] is determined from the reflection ratio using a photodetector (PD) and a avalanche photodetector (APD), and locked by the proportional-integral-derivative (PID) controller. In the experiment, the detuning error is approximately ±3% of $\Delta\nu_{FWHM}$ (full-width at half maximum) owing to the set point error for the reflection ratio. The FP-cavity is made using a low-thermal-expansion ceramics and two mirrors. Its FSR and finesse are approximately 750MHz and 300, respectively. To reduce the measurement uncertainty owing to the thermal deformation of the FP-cavity and the fluctuation of the refractive index inside the FP-cavity, the handmade thermal shield box (not shown in Fig. 1)

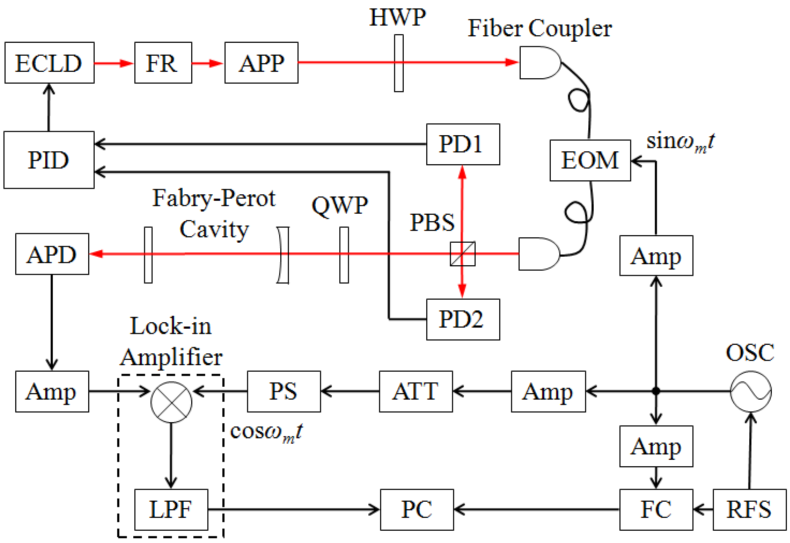

Fig. 1 FSR measurement system. FR: Faraday rotator, APP: Anamorphic prism pair, HWP: Half-wave plate, GTP: Glan-Thomson polarizer, PBS: Polarization beam splitter, QWP: Quarter wave plate, APD: Avalanche photodiode, OSC: oscillator, RFS: Rubidium frequency standard, FC: Frequency counter, Amp: Amplifier, Att: Attenuator, PS: Phase shifter, PID: Proportional-integral-derivative controller, PC: Personal computer.

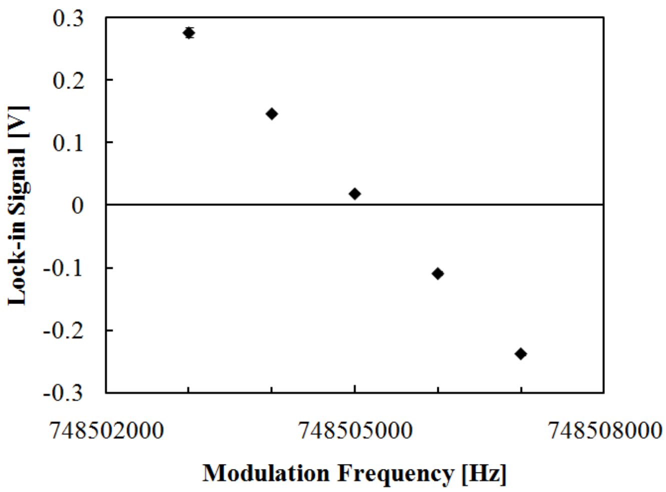

Fig. 2 The relationship between modulation frequency and the lock-in signal. Noise level of the lock-in signal is approximately 3mV.

In order to reduce the amplitude modulation (AM) effect from the EOM, the angle of half wave plate (HWP) in front of the EOM is adjusted in the experiment, and the high quality Glan-Thomson-prism (GTP, extinction ratio~10^{-6}) is used to reduce the AM effect from the EOM[2]. Fig. 2 shows the relationship between the lock-in signal and modulation frequency. In the experiment, the injection power to the FP-cavity, the modulation index, the detuning frequency shift and the frequency scan rate are 4mW, 8rad, +29%*$\Delta\nu_{FWHM}$ and (1kHz/step, 1s/step), respectively. From Fig. 2, the slope around the null cross point is approximately 0.1mV/Hz. On the contrary, the maximum slope is 5mV/Hz in the previous report[1]. Since the noise level of the lock-in amplifier is approximately 3mV, the measurement uncertainty ΔFSR is 3mV/(0.1mV/Hz)=30Hz. Therefore, the relative uncertainty of the FSR measurement equals 30Hz/750MHz~$4*10^{-8}$. The relative uncertainty is improved by double digits from the previous report[1].

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