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A NOVEL DILATOMETER FOR MEASURING COEFFICIENT OF THERMAL EXPANSION OF ULE-MATERIAL USING A FIBER RING LASER

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Abstract: A new type of measuring system for coefficient of linear thermal expansion (CTE) of ULE (Ultra Low Expansion) material by using a fiber ring laser is introduced in this paper. The lasing frequency of the laser is stabilized to one of the transmission peaks of the etalon filter by controlling the resonant frequency of the tunable filter. The spacer of the (Fabry-Perot type) etalon filter is made of ULE material.

We could measure the CTE of ULE by measuring the optical frequency change caused by the temperature change of the etalon spacer. The combined standard uncertainty is estimated as the value of 3.66×10^{-8}.

Keywords: Fabry-Perot etalon, ULE, CTE, fiber ring laser Uncertainty

1. INTRODUCTION

To determine the linear coefficient of thermal expansion (CTE) of solid materials, two physical quantities of displacement and temperature must be measured on a sample that is undergoing a thermal cycle. Three of the main techniques such as dilatometry, interferometry, and thermo-mechanical analysis are usually used for the CTE measurement [1]. The method of measurement for CTE utilizing the dependence of a Fabry-Perot etalon's resonant frequency on mirror separation has been reported [2, R].

The measurement of CTE of ultra low thermal expansion material is not easy to perform with small uncertainty [3].

In this paper, we introduce a new CTE measuring system utilizing a fiber ring laser. To make the single mode laser operation, the Fabry-Perot etalon filter is usually used inside the cavity.

If the temperature of the etalon filter is changed, the optical frequency of the laser will also be changed since the resonant frequency of the filter will be changed due to the thermal expansion of the etalon spacer. The CTE of ULE material can be obtained by measuring the optical frequency changes as a function of the temperature of the spacer of the etalon filter.

Recently, we reported a discretely tunable erbium-doped fiber laser, which operates in single-frequency, and matches to the ITU-T frequency grids of 25 GHz channel spacing [4,5]. We were able to measure the optical frequency as a function of the temperature of the spacer of the etalon filter in the fiber ring laser and then calculated the CTE of the spacer material, ULE.

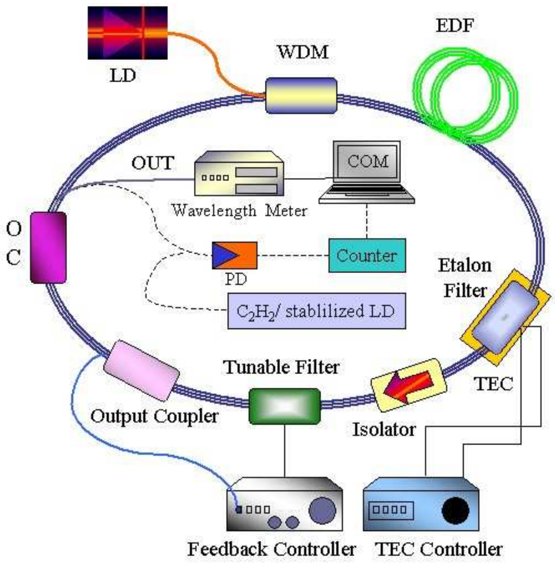

Fig.1. Experimental Setup for CTE measurement
WDM: wavelength-division multiplexer, TEC: thermo-electric cooler, OC : output coupler, PD : photo detector

2. EXPERIMENTAL METHOD

The experimental setup for the CTE measurement of ULE is depicted in figure 1. This configuration is the same as the single mode tunable fiber ring laser. The fiber ring laser consists of several optical components and an erbium-doped fiber (EDF) pumped by a laser diode (LD) of 980 nm wavelength.

The material for CTE measurement is ULE, which is used as the spacer of the air gap etalon filter (AGEF). The length of the spacer is 5.995 94 mm and the finesse of the etalon is 75, so that it has the free spectral range (FSR) of 25 GHz. It provides the optical comb profile with 25 GHz spacing, which matches the ITU-T grid.

A tunable filter with the finesse of 1200 and an FSR of 95 nm is used to reduce the line width of the laser, and to select a specific channel from the optical comb by adjusting the voltage applied to the piezoelectric transducer which is used as the spacer in the tunable filter.

Discrete optical frequency tuning to each channel of the comb is realized through the combined effect of the AGEF and the tunable filter. The fiber laser could be tuning over 75 nm with 25 GHz channel spacing as shown in figure 2 when we have swept the PZT of tunable filter in the ring cavity. The tuning efficiency of the PZT is 3.75 nm/V and the optical spectrum can be discretely selection. To prevent the frequency channel shift (hopping) caused by the temperature change, the lasing single mode laser spectrum was kept locked to one of the transmission peaks of the etalon filter. To obtain the appropriate error signal to control the main cavity length of the fiber ring laser, the cavity of the tunable filter was sinusoidally modulated with a PZT at a frequency of 2 kHz. The first harmonic signal was extracted from the output terminal of the lock-in amplifier and was used as the error signal for the servo loop. The laser frequency was measured by using a precision wavelength meter (Burleigh WA-1500) with high-resolution bandwidth of 10 MHz.

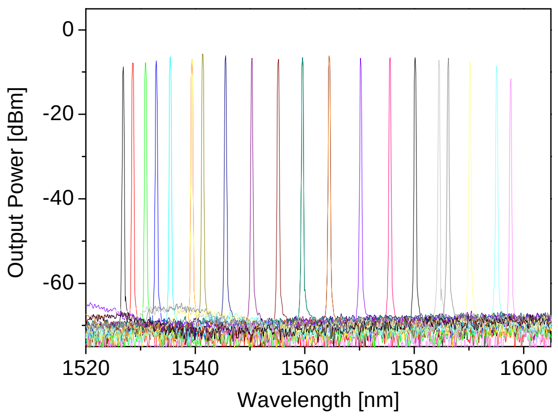

Fig. 2. Optical output spectrum of fiber ring laser

RESULTS

Figure 3 shows the frequency shift caused by temperature change of ULE spacers when the tunable filter was kept locked to the transmission peak of 193.2 THz (1551.72 nm). The average frequency change was measured to be approximately 5.5 MHz/°C in the entire tuning range. The notches appearing in the figure are attributed to the expansion of the length of ULE spacer due to instantaneous temperature change of the thermo-electric cooler (TEC).

Table 1 represents the profiles of frequency offset from the ITU-T grids as the temperature of the AGEF which was increased from 5 ℃ to 60 ℃. These values offer the variation of the frequency shift from the cavity resonance frequency.

Thermal expansion of the optical resonator changes the cavity length. This results in the laser frequency variation along the etalon transmission curve. The shift of the center frequency, $\Delta\nu_0$, due to the change of refractive index of the gas inside of the AGEF, and the thermal expansion of the spacer, can be calculated as follows:

Table 1 Frequency offset from ITU-T grids

Temp-erature [° C]	186.2 THz	188.975 THz	190.9 THz	192 THz	194 THz	196 THz
	Offset frequency from ITU-T Grid Frequency [GHz]					
5	0.24	0.19	0.14	0.09	0.06	-0.01
10	0.29	0.24	0.2	0.14	0.115	0.06
15	0.35	0.29	0.25	0.19	0.165	0.11
25	0.38	0.35	0.29	0.25	0.205	0.17
40	0.38	0.35	0.29	0.25	0.21	0.17
50	0.35	0.34	0.25	0.22	0.15	0.08
60	0.32	0.3	0.2	0.18	0.11	0.01

$$\frac{\Delta\nu_0}{\nu_0} = -\Delta T \cdot \left(\frac{1}{n}\frac{\Delta n}{\Delta T} + \alpha\right) \qquad (1)$$

where, ν_0 denotes the center frequency, $\Delta n / \Delta T$ is the temperature dependence of the refractive index of the gas, and α the CTE of the spacer. Since $\Delta n / \Delta T$ of the AGEF used is only about 10^{-8}, the laser frequency is changed mainly by the temperature change of the spacer of the etalon filter.

Figure 4 shows the calculated CTE (filled circles) and standard uncertainty (error bars) values of the ULE spacer for the temperatures based on Table 1. The error bar represents the combined uncertainty in the center point according to the each temperature variation.

The measurement uncertainty can be estimated with reference paper [3] that the each term is associated with the uncertainty of the measurement of sample length, length change, and temperature change. Then, the combined uncertainty can be determined with the square root of standard deviation including sum of each term. Therefore, the standard uncertainty of CTE u(α) based on the equation (1) definition is given below equation (2)

$$u_c(\alpha) = \sqrt{\left(\frac{1}{L\Delta T}\right)^2 u^2(\Delta L) + \left(\frac{\alpha}{\Delta T}\right)^2 u^2(\Delta T) + \left(\frac{\alpha}{L}\right)^2 u^2(L)} \qquad (2)$$

where $u(\Delta L)$, $u(\Delta T)$ and $u(L)$ are the uncertainties associated with measurement of length change, temperature change and sample length, respectively.

The standard uncertainty value of length change for CTE was evaluated as maximum value of 3.55×10^{-8} at 12.5 ℃.

In order to determine the uncertainty of sample length, the etalon mode equation ($c \cdot q / 2nL$, q: mode number) is used. Then, the standard uncertainty values for sample length measurement was evaluated as maximum value of 8.65×10^{-9} at 12.5℃.

The uncertainty value and contribution from each source are given below table 2.

These measured results matches well with the data of the CTE of ULE provided within uncertainty of measurement [2, 6].

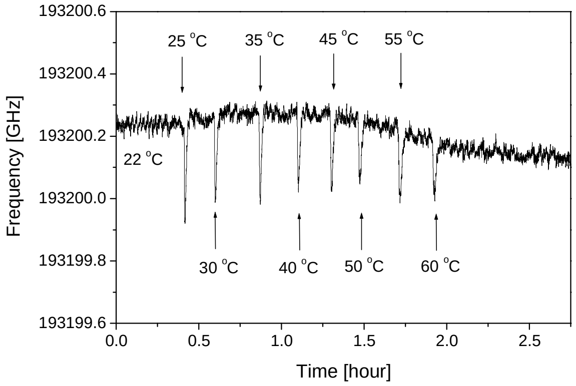

Fig. 3 Frequency shift at one channel due to temperature change

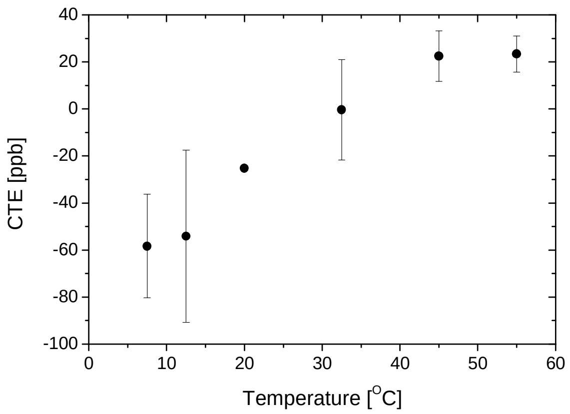

Fig. 4 Measured CTE (filled circles) and combined uncertainty (error bars) of ULE at each temperature.

Table 2 The relative uncertainty for CTE measurement

Uncertainty Source	Uncertainty Value	Maximum Contribution	Type
Length change	1.6 nm	3.55×10^{-8}	A
Temperature change	0.12 ° C	8.65×10^{-9}	B
Sample length	1.4 nm	1.36×10^{-13}	A
Combined uncertainty	3.66×10^{-8}		

4. CONCLUSION

We measured the coefficient of linear thermal expansion (CTE) of ULE material of very small block (6 mm length) using a tunable fiber ring laser. The total uncertainty of the measurement is estimated from measurement of frequency displacement with uncertainty of ± 36 ppb/℃ at maximum point. The measured CTE matches well with the thermal expansion characteristics of ULE reported by Corning. This method can be a good candidate for the CTE measurement of other materials as well.

Now, we are preparing the more precise optical frequency measuring system using the stabilized acetylene laser or optical comb system as the reference frequency sources.

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