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Ultra-High Accuracy Measurement of the Coefficient of Thermal Expansion for Ultra-Low Expansion Materials

By Dr. Vivek G. Badami, Dr. Michael Linder

Abstract

Microlithographic systems rely on precision alignment and a high-level of dimensional stability to achieve required performance. In critical applications, immunity to thermally induced dimensional changes is achieved by the use of low coefficient of thermal expansion (CTE) materials such as ULE® in components such as reflective optics and machine structures. ULE® has an expansion coefficient (α) that is typically in the 0 ± 30 ppb K^{-1} range and it may be engineered to achieve a specific value. A high-accuracy determination of the CTE is essential for both process control and for providing an essential input to the design of such systems for error budgeting purposes. Currently, there is a need for CTE determination with an uncertainty $U(\alpha)$<1 ppb K^{-1} (k=2) in the 273-373K (0-100°C) temperature range. This effort is aimed at developing techniques for performing this measurement.

Requirements Definition

S. No.	Parameter	Value
1	Sample materials	• ULE® • Zerodur® • Fused Silica
2	Temperature range for CTE determination	273-373 K (0-100 °C)
3	Sample sizes/envelope	• φ25 × 100 mm cylinder • 25 × 25 × 200 mm block
4	Uncertainty $u(\alpha)$ (k=2)	<1 ppb K^{-1}

Uncertainty Analysis

The mean coefficient of linear thermal expansion α is given by

$$\alpha = \frac{1}{L}\left(\frac{\Delta L}{\Delta T}\right)$$

Standard uncertainty of CTE $u(\alpha)$ based on the above definition given by

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

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

For L = 100 mm, α = 10 ppb K^{-1} and ΔT = 10K the uncertainty contributions from each of the sources of uncertainty is given below

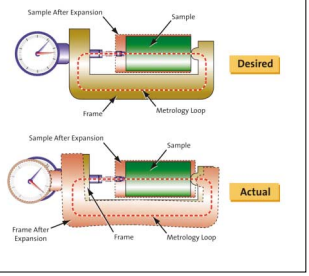
Uncertainty source	Uncertainty value	Contribution (K^{-1})
$u(\Delta L)$	0.5 nm	0.5×10^{-9}
$u(\Delta T)$	0.2 K	0.2×10^{-9}
$u(L)$	10 μm	0.001×10^{-9}
Standard uncertainty in CTE $u(\alpha)$		$\sim 0.53 \times 10^{-9}$

- Dominant uncertainty contributors are uncertainties in ΔL and ΔT
  - Uncertainties in dilatation metrology
    - Primary contributor is uncertainty in sample length change $u(\Delta L)$
    - Uncertainty in length change $u(\Delta L) \leq 0.5$ nm in a sample of length L=100 mm for ΔT=10K
    - ⇒ Dilatation uncertainty $u_{rel}(\Delta L) \leq 5$ parts in 10^9 for ΔT = 10K
    - Uncertainty in sample length $u(L)$ is an insignificant contributor
  - Uncertainties due to temperature metrology
    - Uncertainty in temperature change $u(\Delta T) \leq 0.2$K for ΔT=10K
    - ⇒ Relative temperature uncertainty $u_{rel}(\Delta T) \leq 2$ parts in 10^9
- Above uncertainties constitute top-level uncertainty requirements for the design

Fundamental Issues with Measurement of Dilatation

The fundamental issue with making a dilatation measurement is distinguishing between the dimensional changes of the sample and that of the instrument structure. Dimensional changes of any part of the metrology loop (including the frame or sensors) is indistinguishable from changes of the sample.

The aim of the design is to separate/eliminate or minimize the influence of undetected dimensional changes in the metrology loop not directly attributable to the sample. These undesirable changes may be mechanical, thermal or optical in origin.
The following figures illustrate some current high-accuracy techniques. The metrology loop is identified along with practical realizations of some of these configurations.



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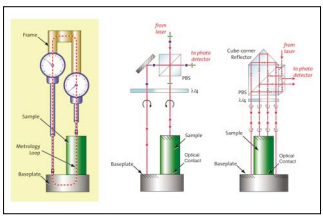
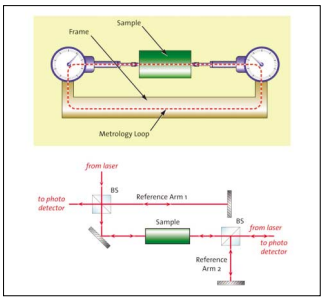
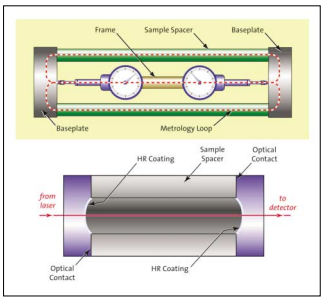
Michelson/Modified Michelson Dilatometer



Double Michelson Dilatometer



Fabry-Perot Dilatometer



Comparison of Current High-Accuracy Methods

Method	Advantages	Disadvantages	Uncertainty estimates
Michelson/ Modified Michelson	▫ Null test can be performed easily ▫ Sample length can be varied ▫ Reduced number of optical contacts relative to Fabry-Perot ▫ Simpler sample preparation relative to Fabry-Perot	▫ Lower sensitivity relative to Fabry-Perot ▫ Some residual uncertainty due to optical contact ▫ Beam interruption cannot be tolerated	5-60 ppb K^{-1}
Double Michelson	▫ No optical contact ▫ Sample length can be varied ▫ Simple sample preparation	▫ Null test cannot be performed easily ▫ Largely non-common path ▫ Lower sensitivity relative to Fabry-Perot	8-40 ppb K^{-1}
Fabry-Perot	▫ High sensitivity ▫ Tight metrology loop ▫ Tolerant to beam interruption ▫ No separate reference arm	▫ Uncertainty due to two optical contacts ▫ Temp. dependent phase change on reflection ▫ Sample length cannot be varied easily ▫ Costly sample preparation	5-10 ppb K^{-1}

Challenges

- Dilatation metrology with uncertainty less than 5 parts in 10^9 for 10K temperature change
  - – Spurious metrology loop displacement
  - – Interferometer nonlinearity
  - – Effects of optical contacts
  - – Temperature dependent changes in phase changes on reflection
  - – Sample alignment stability
  - – CTE variation
  - – Thermal gradients
- Temperature metrology with an uncertainty of 0.2K over 10K step
- Sample heating and cooling
  - – Part time constant
  - – Thermal stability of structure

Timeline

2001	2002				2003	
Q4	Q1	Q2	Q3	Q4	Q1	Q2
Requirements definition/capability survey		Design and build instrument			Debug and test	