# Temperature control design of a 30-cm-long high-finesse optical cavity for an enhanced middle- and long-term stability

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***Abstract*—Ultra-stable lasers with high-precision middle- and long-term stability are important in scientific researches. Generally, the middle- and long-term stabilities of ultra-stable laser are mainly determined by temperature control of the optical reference cavity. In this work, we focus on high-precision temperature control for the 30-cm-long high-finesse optical cavity. Overall, a combination of active and passive thermal control methods is applied. Thermoelectric coolers are used to create a temperature-constant housing inside the vacuum chamber, while heating foils are used for precision temperature control inside the thermal shields. Preliminary test shows that the thermoelectric coolers assisted by a water-cooled plate can lower the temperature of the vacuum chamber by 8 degrees Celsius than ambient environment. Theoretically, the calculated time constant of thermal isolation of the home-built 30-cm-long high-finesse optical cavity system is about 11.5 days.**

***Keywords—Ultra-stable laser, Optical reference cavity, Temperature control***

## I. INTRODUCTION

Due to excellent temporal coherence, ultra-stable laser (USL) based on high-finesse Fabry-Pérot cavity made of ultra-low expansion (ULE) meaterials acts as a crucial role in many cutting-edge research fields of optical atomic clock [1], ultra-stable microwave signal generation [2], coherent optical frequency transfer [3], and so on. Although ULE meaterial is adopted in the system, precise temperature control is demanded to keep the high-finesse cavity at zero-expansion temperature. The stability of temperature control is usually on mK level at 1 s. The dominate limitations of the fraction frequency stability of USL beyond 10 s include middle- and long-term (10 s~1000 s) temperature control, residue amplitude modulation of electro-optic modulator [4], optical power fluctuation coupled into cavity [5], and the aging of high-finesse cavity.

Here we focus on the temperature control of our ultra-stable laser assembling a 30-cm long ULE-glass optical reference cavity. Active temperature control is achieved by regulating the thermo-electric cooler (TEC) under the vacuum chamber and heating foil glued on the outer thermal shield, while passive temperature control is by the other two layers of thermal shield. The time constant of the inside ULE-glass optical reference cavity is analyzed approximately 11.5 days.

## II. TEMPERATURE CONTROL DESIGN

Figure 1 shows the schematic of the design of the whole optical reference cavity and its vacuum housing. The system is placed on an active anti-vibration plateform to damp the vibration from the floor. The vacuum chamber made from aluminum alloy is used to provide a high-vacuum environment in order to isolate heat transfer from the external environment. In order to maximize the time constant of thermal isolation, There are three layers of thermal shields are adopted with in the vacuum chamber. The shields are chosen to copper due to its excellent thermal conductivity and low specific heat capacity. In order to reduce the thermal radiation of the shields, the inner and outer surfaces of the thermal shields are polished and plated with gold. To minimize heat transfer from the vacuum chamber to the first thermal shield, glass columns that owns low thermal conductivity are employed and placed in form of three-point mounting that results in self-balancing. Similarly, identical glass columns are used between all the three layers of the thermal shields. Inside the inner thermal shield, we adopt three glass balls to weaken the heat transfer from inner thermal shield to the U-shaped mount made from Zerodur. The 30-cm-long high-finesse optical reference cavity is placed on a U-shaped mount and isolated by four Viton hemispheres to prevent the heat transfer between them.

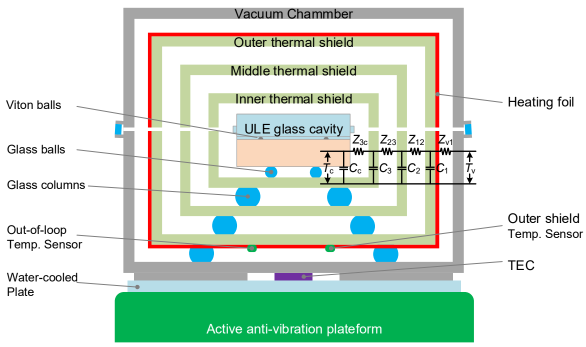


Fig. 1. Simplfied schematic of the optical reference cavity in vacuum.

In order to conduct active temperature control of the vacuum chamber, we glued multiple TECs under the vacuum chamber using thermal conductive silica gel to promote the cooling efficiency. Considering the fact that an optical reference cavity with fused silica mirrors always owns a zero-expansion temperature lower than the ambient environment, we inserted a water-cooled plate between the plateform and vacuum chamber to enhances their heat transfer through the TECs.

In addition, heating foils are glued on the outside surface of the outer thermal shield with thermal-conductive vacuum silicone, as shown in Fig. 2. Distributed on surfaces of the outer thermal shield, five PT-1000 thermistors are arranged for high-precision temperature control. Among them, one

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thermistor is used for active heating control, while the other four are used for out-of-loop monitor.

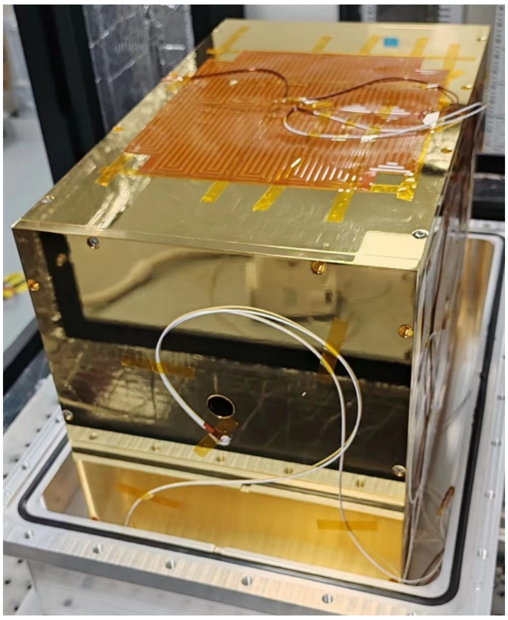

Fig. 2. Inside view of the vacuum chamber. The outer thermal shield are covered by heating foils. PT-1000 thermistors are centered on the surfaces.

## III. NUMERICAL CALCULATION

Theoretically, the temperature variation of each thermal shield with time can be represented by the following differential equations [6,7].

$$\begin{aligned}
\frac{\partial T_{s1}}{\partial t} &= \frac{1}{\tau_{v\text{-}s1}}(T_v - T_{s1}) + \frac{1}{\tau_{s2\text{-}s1}}(T_{s2} - T_{s1}) \\
\frac{\partial T_{s2}}{\partial t} &= \frac{1}{\tau_{s1\text{-}s2}}(T_{s1} - T_{s2}) + \frac{1}{\tau_{s3\text{-}s2}}(T_{s3} - T_{s2}) \\
\frac{\partial T_{s3}}{\partial t} &= \frac{1}{\tau_{s2\text{-}s3}}(T_{s2} - T_{s3}) + \frac{1}{\tau_{c\text{-}s3}}(T_c - T_{s3}) \\
\frac{\partial T_c}{\partial t} &= \frac{1}{\tau_{s3\text{-}c}}(T_{s3} - T_c)
\end{aligned} \quad (1)$$

where $T_v$, $T_{s1}$, $T_{s2}$, $T_{s3}$, and $T_c$ denote the temperature of vacuum chamber, outer thermal shield, middle thermal shield, inner thermal shield, and optical reference cavity, respectively. $\tau_{v\text{-}s1}$ denotes the thermal time constant from vacuum chamber to outer layer of thermal shield, while $\tau_{s2\text{-}s1}$ denotes that from middle layer to outer layer, $\tau_{s1\text{-}s2}$ denotes that from outer layer to middle layer, $\tau_{s3\text{-}s2}$ denotes that from inner layer to middle layer, $\tau_{s2\text{-}s3}$ denotes that from middle layer to inner layer, $\tau_{c\text{-}s3}$ denotes that from optical reference cavity to inner layer, $\tau_{s3\text{-}c}$ denotes that from inner layer to optical reference cavity. According to Eq. (1) and the properties of materials shown in Table 1, the step thermal response is calculated and presented in Fig. 3. The time constant is approximately 11.5 days.

Besides, we experimentally tested that the thermoelectric coolers assisted by a water-cooled plate can lower the temperature of the vacuum chamber by 8 degrees Celsius than ambient environment.

TABLE I. PROPERTIES OF MATERIALS IN THE CALCULATION OF THERMAL TIME CONSTANT

| **Materials** | **Density [kg/m$^3$]** | **Thermal conductivity [W/(m·K)]** | **Specific heat capacity [J/(kg·K)]** | **Radiation coefficient** |
|---|---|---|---|---|
| **ULE** | 2210 | 1.31 | 767 | 0.85 |
| **Aluminium alloy** | 2270 | 210 | 900 | 0.1~0.2 |
| **Gold-plated copper** | 8930 | 398 | 385 | 0.07~0.09 |
| **Silica** | 2200 | 1.38 | 770 | / |

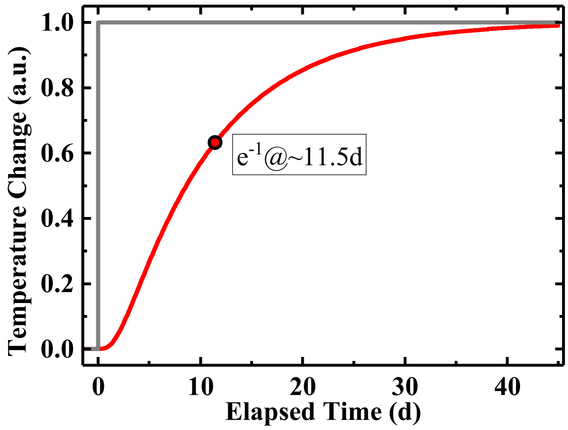


Fig. 3. Temperature step response of the optical reference cavity. The time constant is approximately 11.5 days.

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