Development of Fully Self-Controllable High-Finesse Optical Reference Cavities

Dongdong Jiao[1,3], Mengfan Wu[1,3], Jing Gao[1,3], Han Zhang[2,4], Junlong Liu[2,4], Guanjun Xu[1,3*], Qi Zang[1,3], Jie Cui[5], Ruifang Dong[1,3,6,7*], Tao Liu[1,3,6,7*], Bo Qu[5], and Shougang Zhang[1,3,6,7]

[1]*National Time Service Center, Chinese Academy of Sciences, Xi'an 710600, China*
[2]*Hubei Feilihua Quartz Glass Co., Ltd., Jingzhou 434000, China*
[3]*Key Laboratory of Time Reference and Application, Chinese Academy of Sciences, Xi'an 710600, China*
[4]*Innovation Center for Special Optical Glass Materials Technology, Jingzhou 434000, China*
[5]*Xi'an SNP Precision Optics Co., Ltd., Xi'an 710100, China*
[6]*School of Astronomy and Space Science, University of Chinese Academy of Sciences, Beijing 100049, China*
[7]*Hefei National Laboratory, Hefei 230088, China*

(Received 21 October 2024; accepted manuscript online 11 December 2024)

High-finesse optical reference cavities are essential tools for fundamental research. In response to China's historical reliance on importing high-finesse optical reference cavities, we successfully developed a cavity using ultralow expansion glass (ULE) materials and processed it entirely in China. Using the method of measuring the cavity linewidth, a finesse of approximately 480000 was obtained in our experiments. We adopted a relatively simple and effective approach to test the optical reference cavity, which involved measuring the resonant points using an ultrastable laser. Remarkably, an expansion coefficient of the Chinese ULE optical reference cavity reached up to the order of 10^{-9}/K within the temperature range of 27 ℃ to 40 ℃, with the zero expansion point occurring at approximately 34 ℃. These findings demonstrate China's independent capability to develop high-finesse optical reference cavities, which is a significant advancement in precision optics.

DOI: 10.1088/0256-307X/42/1/013701 CSTR: 32039.14.0256-307X.42.1.013701

1. Introduction. A high-finesse optical reference cavity is an indispensable scientific instrument in fundamental research areas[1–6] such as ultrastable lasers, gravitational wave detections, gravitational redshift measurements, relativistic tests, and high-precision spectral analyses. Moreover, it is crucial in industrial fields[7–10] like navigation, laser gyroscopes, and laser ranging. In these applications, the finesse and linear expansion coefficients of the optical reference cavity are pivotal performance metrics that are intricately linked to the materials used to fabricate these cavities. The choice of materials directly influences the precision and stability of the cavity, making it a critical factor in the development of high-performance optical reference cavities.

An optical reference cavity comprising a spacer and two mirrors with high reflectivity is typically fabricated from ultralow expansion glass (ULE). ULE is a silicon dioxide (SiO_2) glass material enhanced with titanium dioxide and is known for its exceptional stability. The length stability of the ULE optical reference cavity is crucial for its core performance in applications such as ultrastable lasers, gravitational wave detection, and high-precision measurements. However, the cavity length is susceptible to environmental influences such as temperature fluctuations, mechanical vibrations, and air currents.[11] Notably, at a specific temperature near room temperature, the ULE material exhibits a unique property in which its thermal expansion coefficient approaches zero. This temperature is referred to as the zero-temperature drift point.[12] At this point, the length of the ULE optical reference cavity is remarkably stable against temperature changes and the cavity length reaches its minimum.[13] Therefore, to minimize the temperature sensitivity of the ULE optical reference cavity length, it is important to advance the development of ULE materials and accurately measure the zero-temperature drift point of the ULE optical reference cavity. This precision is essential to enhance the performance and reliability of optical reference cavities in various scientific and industrial applications.

Considering the intricacies and challenges involved in the production of ULE materials, the majority of ULE materials are currently manufactured by Corning, Inc., USA. These materials boast a thermal expansion coefficient within an impressive range of 0 ± 30 ppb/K from 5 ℃ to 35 ℃.[14] Moreover, within a broader temperature range of 0 ℃ to 40 ℃, the zero-temperature drift point of the ULE material of Corning is adjustable.

There are typically three approaches to determining the zero-temperature drift point of a ULE optical reference cavity.[11–13,15] The first approach involves the use of an optical frequency comb locked to a high-precision reference frequency. The zero-temperature drift point can be determined by measuring the absolute frequency of the laser locked to the ULE optical reference cavity at var-

*Corresponding author. Email: xuguanjun@ntsc.ac.cn; dongruifang@ntsc.ac.cn; taoliu@ntsc.ac.cn
© 2025 Chinese Physical Society and IOP Publishing Ltd. All rights, including for text and data mining, AI training, and similar technologies, are reserved.

ious temperatures. The second method employs a more stable ULE optical reference cavity as a benchmark. The zero-temperature drift point is derived by monitoring the resonance frequency variations of the ULE optical reference cavity with respect to the temperature changes. The third technique relies on the atomic clock transition spectrum or saturated absorption spectrum as a reference. The zero-temperature drift point is identified by measuring the resonance frequency of the ULE optical reference cavity across a range of temperatures.

In this study, the development of a high-finesse optical reference cavity using materials and processes executed entirely by Chinese enterprises is presented. Using the cavity linewidth measurement method, our experiments demonstrated a finesse of approximately 480000 for the optical reference cavity. A straightforward approach for testing the cavity was adopted, which involved measuring its resonant points using an ultrastable laser. The thermal expansion coefficient of the Chinese ULE optical reference cavity was in the order of 10^{-9}/K within a temperature range of 27 ℃ to 40 ℃, with the zero expansion point occurring at approximately 34 ℃. These findings indicate that China can develop high-finesse optical reference cavities independently.

2. Fundamental Theory. An optical reference cavity is pivotal for precise physical measurements. It serves as a frequency reference source for ultrastable lasers, which significantly influences their performance. To ensure that ultrastable lasers deliver optimal results, the quality of the optical reference cavity is typically assessed using parameters such as the finesse and linear expansion coefficient.

2.1. Finesse. In spectroscopy, the finesse, F, is a key metric used to assess the spectral resolution of an optical reference cavity. A higher finesse indicates a superior capacity for resolving spectral lines and suggests lower optical losses within the cavity. The finesse F is defined as the ratio of the free spectral region to the linewidth of the optical reference cavity.[16]

$$F = \frac{FSR}{\Delta v_{\mathrm{C}}} = \frac{\pi\sqrt{R}}{1-R}, \tag{1}$$

where FSR is the free spectral range of the optical reference cavity, Δv_{C} is the linewidth of the optical reference cavity, and R is the reflectivity of the two mirrors.

The finesse of an optical reference cavity encompasses many significant characteristics that reflect its optical performance in terms of loss and mirror reflectivity. A higher finesse value indicates several beneficial qualities such as reduced optical losses within the cavity, enhanced reflectivity of the cavity mirrors, narrower linewidths of the resonance peaks of the cavity, and an extended photon lifetime within the cavity. For an optical reference cavity with a finesse of 190000, the reflectivity of the cavity mirror was calculated to be approximately 0.9999907 using the aforementioned formula. When the finesse was increased to 200000, the mirror reflectivity increased to approximately 0.9999911.

2.2. Linear Expansion Coefficient. At the zero-temperature drift point, the rate of the length change of the ULE optical reference cavity in response to temperature variations was at its minimum. This implies that the cavity length is least sensitive to temperature fluctuations at this specific temperature. The relationship between the length of the ULE optical reference cavity and temperature is given by,[14]

$$\Delta L/L = \alpha(T)(T - T_0), \tag{2}$$

where ΔL is the length variation of the optical reference cavity, L is the length of the ULE optical reference cavity, T is the actual temperature, and T_0 is the effective zero-temperature drift point. $\alpha(T)$ is the instantaneous thermal expansion coefficient of the ULE at the temperature T, and its unit is ppb/K.

The quadratic relationship of the instantaneous thermal expansion coefficient of the ULE material with temperature T near the zeroexpansion temperature point T_0 can be expressed as follows:[14]

$$\alpha(T) = a(T - T_0) + b(T - T_0)^2, \tag{3}$$

where the typical value of the linear temperature coefficient a is approximately $1.8 \times 10^{-9}/\mathrm{K}^2$, and the quadratic coefficient b is approximately $-10 \times 10^{-12}/\mathrm{K}^3$.[14] If the zeroexpansion temperature $T_0 = 25$℃ for the ULE material, then the thermal expansion coefficient of the optical reference cavity material is approximately 9×10^{-9}/K when the optical reference cavity temperature T is 30°.

3. Design of an Optical Reference Cavity. As depicted in Fig. 1, the optical reference cavity consists of a spacer and two mirrors with high reflectivity.[17] The cavity was equipped with two vent holes and a light hole, all positioned perpendicular to each other. The spacer and mirrors are securely bonded using an optical contact. The surfaces of the mirrors and spacer that come in contact with the optical contact are machined to an exquisite finish with a roughness of less than 5 Å (RMS), ensuring a smooth and stable bond.

The ULE used for the fabrication of the optical reference cavity was sourced from Hubei Feilihua Quartz Glass Company, China. The ULE manufacturing method used in this study is described as follows:[18,19] Chemical vapor deposition was employed using silicon tetrachloride and titanium tetrachloride as sources of silicon and titanium, respectively. Following evaporation and gasification in an evaporator, hydrolysis occurs under high-temperature conditions of a hydrogen-oxygen flame, which results in the deposition of SiO_2-TiO_2 particles onto the target material. These particles were subsequently melted into a glassy state to produce quartz glass doped with titanium dioxide. This production process mitigates fluctuations in the distribution of titanium within the quartz glass ingot, which can arise from the varying reaction rates of the raw materials during hydrolysis in the hydrogen-oxygen flame. These variations result in different particle nucleation and growth rates. Consequently, this method addresses the relatively poor consistency in the performance of the thermal expansion coefficient across different regions of the ultralow expansion coefficient quartz glass ingots.

The mirrors had a thickness of 25.4 mm and a diameter of 6.3 mm, whereas both the vent hole and light hole measured 12 mm in diameter. The cavity was cubic with a side length of 50 mm. To minimize the sensitivity of the cavity to vibrations, the corners of the cubic optical cavity were precisely cut. The optimal cutting depth, derived from extensive finite element simulation calculations, ensures that the cavity maintains low vibration sensitivity, which contributes to its overall stability and performance.

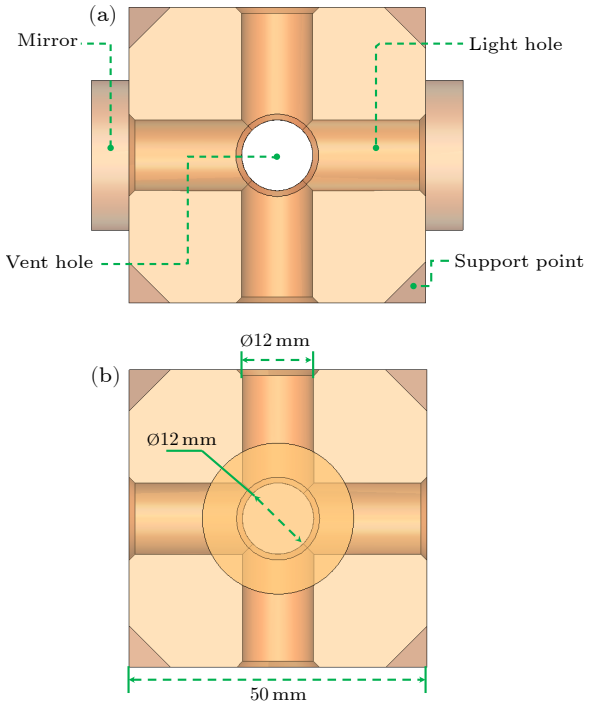

Fig. 1. Sketch of the cubic optical reference cavity. (a) Side view. (b) Front view.

The mirrors were crafted using a ULE substrate and coated with high-quality dielectric coatings composed of SiO_2 and Ta_2O_5. In this study, ion beam sputtering was used to fabricate ultra-lowloss coatings with extremely high precision.[20] A periodic multilayer dielectric highly reflective film was designed, and the optimal coating parameters were calculated and experimentally obtained. The loss obtained by the loss measuring instrument was less than 5 ppm, which includes losses such as absorption and scattering and does not include the transmission loss. Based on the analysis of the theory of periodic multilayer dielectric high reflection films, materials with good uniformity, low stress, small absorption, strong adhesion, and good temperature stability were selected, and the optical and mechanical properties of the materials were studied, focusing on solving the problem of ultra-low loss. Using an ultra-high purity water cleaning production line and detection equipment, the reflectivity was guaranteed to reach 99.9995%.

Before applying the coating, the substrate surface was meticulously polished to achieve a roughness of less than 1 Å (RMS), thereby ensuring a flawless foundation for the reflective layer. Careful attention to the surface finish of the substrate is crucial for optimizing the reflectivity of the mirror and the overall performance within the optical reference cavity. By refining the use of auxiliary materials and purification techniques, along with fine-tuning the processing parameters, we achieved an exceptional surface roughness of less than 1 Å. Concurrently, attaining nanometer-level control over the contamination particles of the lens surface is vital for enhancing the lens quality. Considering that conventional cleaning methods do not satisfy these stringent requirements, a novel cleaning technology tailored for ULE was developed by exploring the intrinsic properties of ULE materials. This innovation emphasizes the optimization of chemical cleaning agents and the refinement of process parameters to ensure the effective removal of nanoparticles from ultra-smooth optical surfaces. Following the cleaning process, the components were rigorously inspected under a 500x dark field microscope to confirm the absence of any contaminating particles.

4. Experimental Scheme Design. A schematic of the finesse measurement is shown in Fig. 2. The photoelectric detectors and optical switches may introduce measurement errors. Therefore, to mitigate these effects, an ultrastable laser in the laboratory served as the light source for measuring the finesse of the optical reference cavity. The laser was directed into the cavity under investigation. To achieve resonance between the laser frequency and optical cavity, the laser frequency must be tuned to match the resonance frequency of the cavity. This tuning was facilitated by a signal source that emitted an SMB100 signal and an electro-optic modulator. The modulator frequency was swept using a triangular wave from the signal source. A PD was used to collect the transmitted signal from the optical reference cavity during testing. The cavity linewidth can be determined by analyzing the transmitted signal. For a known linewidth, the finesse of the optical reference cavity can be calculated using Eq. (1), which provides a precise measure of the spectral resolution and optical performance of the cavity.

The experimental scheme for measuring the linear expansion coefficient of the optical reference cavity is illustrated in Fig. 2. First, an ultrastable laser was introduced into the optical reference cavity for measurement. The frequency of the laser is changed by the frequency shifter to resonate with the measured optical reference cavity; the signal source frequency of the frequency shifter was f_{T1}, and the temperature of the PT1000 thermistor placed on the optical reference cavity was recorded as T_1; the optical reference cavity was then heated to T_2, and the frequency of the signal source was f_{T2}; the linear expansion coefficient of the optical reference cavity is obtained as,

$$\alpha = \frac{|f_{T2} - f_{T1}|}{v_0(T_2 - T_1)}, \tag{4}$$

where v_0 is the laser frequency.

Compared with the beat frequency comparison method, this approach is considerably more straightforward. This facilitates the direct determination of the linear expansion coefficient of the optical reference cavity by simply monitoring the shift in its resonant frequency. This

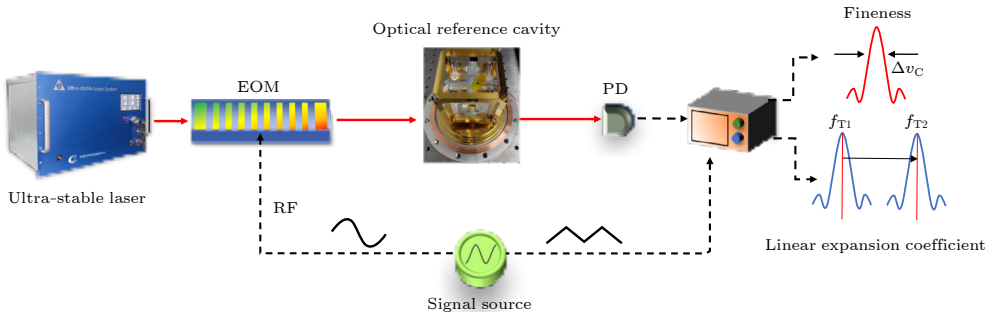

Fig. 2. Experimental scheme of the finesse and the linear expansion coefficient of Chinese ULE-made optical reference cavity.The ultrastable laser denotes a 1550 nm transportable ultrastable laser with sub-Hz linewidth; EOM represents an electro-optic modulator; PD is a photodetector; OSC denotes an oscilloscope; and RF represents a radio-frequency signal.

direct measurement method eliminates the need for complex frequency comparisons, streamlines the process, and provides a more efficient means of assessing the thermal properties of a cavity.

5. Results and Discussion. The experimental results of the finesse measurements for the Chinese ULE-fabricated optical reference cavity are shown in Fig. 3. By applying a Lorentzian fit to the transmission peak signal of the cavity, the cavity linewidth was determined to be approximately 6.25 kHz. Using Eq. (2), the finesse of the optical reference cavity was calculated to be approximately 480000. This level of finesse is comparable to that of the optical reference cavities developed by leading countries in Europe and America, thereby indicating that the Chinese ULE-made cavity can provide extremely high spectral resolution. Such high-resolution cavities are invaluable assets in many fields that require precision measurements and scientific research. For instance, a cavity with this level of finesse can offer a very narrow laser linewidth, which is essential for applications requiring ultrastable lasers.

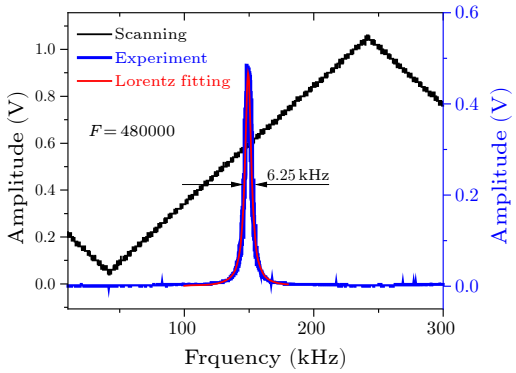

Fig. 3. Experimental measurement results of the finesse of Chinese ULE-made optical reference cavity. The black solid line denotes the triangular wave signal used to drive the EOM. The blue solid line represents the transmission peak signal of the Chinese ULE-made optical reference cavity, which is collected through the oscilloscope. The red solid line is the Lorentz fitting of the transmission peak signal of the Chinese ULE-made optical reference cavity.

The experimental data for the linear expansion coefficient of the Chinese ULE-made optical reference cavity are shown in Fig. 4. Within the temperature range of 26 ℃ to 40 ℃, a quadratic relationship was observed between the variation in laser frequency Δv and temperature T. For instance, at 27 ℃, the laser frequency variation was approximately 50.5 MHz; at 34 ℃, it was approximately 43.6 MHz; and at 39 ℃, the variation was approximately 51 MHz. Over the same temperature interval, the instantaneous thermal expansion coefficient of the Chinese ULE-made optical reference cavity exhibited a linear relationship with temperature T. The coefficient was measured to be in the order of 10^{-9}/K, which is within the range of 27 ℃ to 40 ℃. The linear temperature coefficient α for the Chinese ULE-made optical reference cavity was determined to be approximately $1.42 \times 10^{-9}/\mathrm{K}^2$, which is marginally lower than the standard value for the linear temperature coefficient of Corning ULE optical reference cavities.

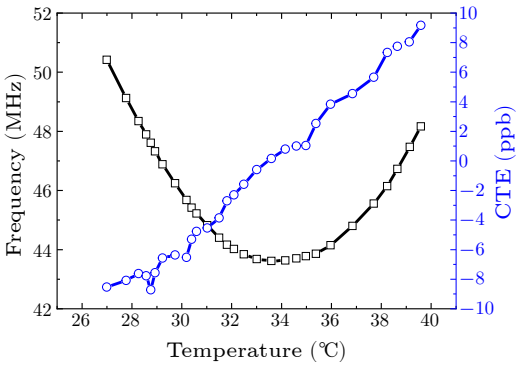

Fig. 4. Experimental results of the linear expansion coefficient of Chinese ULE-made optical reference cavity.

6. Conclusions. A high-finesse optical reference cavity was successfully developed with all the materials sourced from, and processes performed by Chinese companies. Using a method that measures the cavity linewidth, the finesse of our optical reference cavity was determined to be approximately 480000. Our testing approach is relatively straightforward and relies on the measurement of resonant points within the optical reference cavity using an ultrastable laser. The thermal expansion coefficient of our Chinese ULE-made optical reference cavity was measured to be within the order of 10^{-9}/K across the temperature range of 27 ℃ to 40 ℃, aligning with the typical values observed for the linear expansion coefficient of Corning ULE

optical reference cavities. Moreover, the zero-expansion point was identified at approximately 34 ℃. These results demonstrate that China possesses the comprehensive capability to independently develop high-finesse optical reference cavities.

Acknowledgements. This project was supported by the National Natural Science Foundation of China (Grant Nos. 12103059 and 12033007), the National Major Science and Technology Infrastructure Project of China (Grant No. 2017-000052-73-01-002401), Xi'an Science and Technology Bureau (Grant No. E019XK1S04), Sanqin Talents' Special Support Program (Grant No. 09R0557A00), the Youth Innovation Promotion Association of the Chinese Academy of Science (Grant No. 1188000XGJ), and the Innovation Program for Quantum Science and Technology (Grant No. 2021ZD0300900).

References

[1] Campbell G K, Boyd M M, Thomsen J W, Martin M J, Blatt S, Swallows M D, Nicholson T L, Fortier T, Oates C W, Diddams S A, Lemke N D, Naidon P, Julienne P, Ye J, and Ludlow A D 2009 *Science* **324** 360

[2] Müller H, Peters A, and Chu S 2010 *Nature* **463** 926

[3] Müller H, Stanwix P L, Tobar M E, Ivanov E, Wolf P, Herrmann S, Senger A, Kovalchuk E, and Peters A 2007 *Phys. Rev. Lett.* **99** 050401

[4] Xie X P, Bouchand R, Nicolodi D, Giunta M, Hänsel W, Lezius M, Joshi A, Datta S, Alexandre C, Lours M, Tremblin P A, Santarelli G, Holzwarth R, and Coq Y L 2017 *Nat. Photon.* **11** 44

[5] Katori H 2011 *Nat. Photon.* **5** 203

[6] Swallows M D, Bishof M, Lin Y, Blatt S, Martin M J, Rey A M, and Ye J 2011 *Science* **331** 1043

[7] Huntemann N, Okhapkin M, Lipphardt B, Weyers S, Tamm C, and Peik E 2012 *Phys. Rev. Lett.* **108** 090801

[8] Sherman J A, Lemke N D, Hinkley N, Pizzocaro M, Fox R W, Ludlow A D, and Oates C W 2012 *Phys. Rev. Lett.* **108** 153002

[9] Kennedy C J, Oelker E, Robinson J M, Bothwell T, Kedar D, Milner W R, Marti G E, Derevianko A, and Ye J 2020 *Phys. Rev. Lett.* **125** 201302

[10] Chou C W, Hume D B, Rosenband T, and Wineland D J 2010 *Science* **329** 1630

[11] Jiang Y Y, Ludlow A D, Lemke N D, Fox R W, Sherman J A, Ma L S, and Oates C W 2011 *Nat. Photon.* **5** 158

[12] Liu H, Jiang K L, Wang J Q, Xiong Z X, He L X, and Lü B L 2018 *Chin. Phys. B* **27** 053201

[13] Li T, Lu X T, Zhou C H, Yin M J, Wang Y B, and Chang H 2021 *Acta Phys. Sin.* **70** 073701 (in Chinese)

[14] Legero T, Kessler T, and Sterr U 2010 *J. Opt. Soc. Am. B* **27** 914

[15] Wang C H, Ji Z H, Gong T, Su D Q, Zhao Y T, Xiao L T, and Jia S T 2019 *J. Phys. D: Appl. Phys.* **52** 455104

[16] Black E D 2001 *Am. J. Phys.* **69** 79

[17] Webster S and Gill P 2011 *Opt. Lett.* **36** 3572

[18] Moore T, Brady B, and Martin L R 2006 *Combustion and Flame* **146** 407

[19] Zhang H, Liu J L, Geng A X, Zhou Y, Zhu M Y, and Liu Z L 2024 *Glass* **8** 7

[20] Liu J, Chen B X, Xu G J, Cui X X, Bai B, Zhang L B, Chen L, Jiao D D, Wang T, Liu T, Dong R F, and Zhang S G 2017 *Acta Phys. Sin.* **66** 080601 (in Chinese)