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A simple, low cost and robust method for measurement of the zero-crossing temperature of an ultralow expansion cavity

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Abstract
We present a simple, low cost and robust method to measure zero-crossing temperature (ZCT) of an ultralow expansion (ULE) cavity. Low cost fiber electro-optic modulator (EOM) and free space EOM as a frequency bridge and a frequency ruler respectively are used to precisely measure the frequency of cavity mode relative to atom transition which acts as an absolute reference frequency. Neither an expensive optical frequency comb and *another* ULE cavity-based stabilized laser for reference frequency, nor Pound–Drever–Hall locking system for coupling laser is required, but still allows easily using data acquisition card to record abundant data of cavity mode frequency in short term. Using our presented method, the ZCT fitting error can reach 0.01 °C and the total uncertainty can reach 0.22 °C, meaning that our presented method is accuracy and reliable.

Keywords: zero-crossing temperature, ULE cavity, dual frequency modulation

(Some figures may appear in colour only in the online journal)

1. Introduction

Ultralow expansion (ULE) cavity is a Fabry–Pérot optical interferometer, which is made of ULE material with zero-crossing temperature (ZCT) [1] and coated optical mirrors with high reflectivity. It can provide a stable frequency reference to achieve a narrow laser linewidth [2–5], and thus becomes a key instrument in many applications, such as optical clock [6–9], characteristic measurement of light and particle [10, 11], gravitational wave detection [12] and frequency criterion [13, 14].

The length of ULE cavity, which determines the frequency of locked coupling laser, is easily influenced by many environmental factors, including mechanical vibration, temperature variety and air flow. In order to reduce these influences, the cavity is usually installed on an isolated plate, equipped with a temperature controller and housed in vacuum chamber. To further weaken external influences and keep stability for long term, the temperature of ULE cavity needs to be set at ZCT where the cavity length and its deviation both have minimum values. The ZCT range is usually designed to room temperature for convenient control. However, under current fabrication technology the control accuracy of ZCT is usually several degrees because it is easily influenced by many parameters, including proportions of the material components, cavity geometry, and even small changes in the manufacturing environments [15–20]. Therefore, measuring the ZCT of ULE cavity is the first step before using it.

The currently existed methods to measure ZCT need recording the beat note between a locked coupling laser and another external stabilized laser source. The coupling laser is usually locked to one cavity mode of the cavity by Pound–Drever–Hall (PDH) technique [21]. The external laser source acts as reference frequency and usually be provided by one

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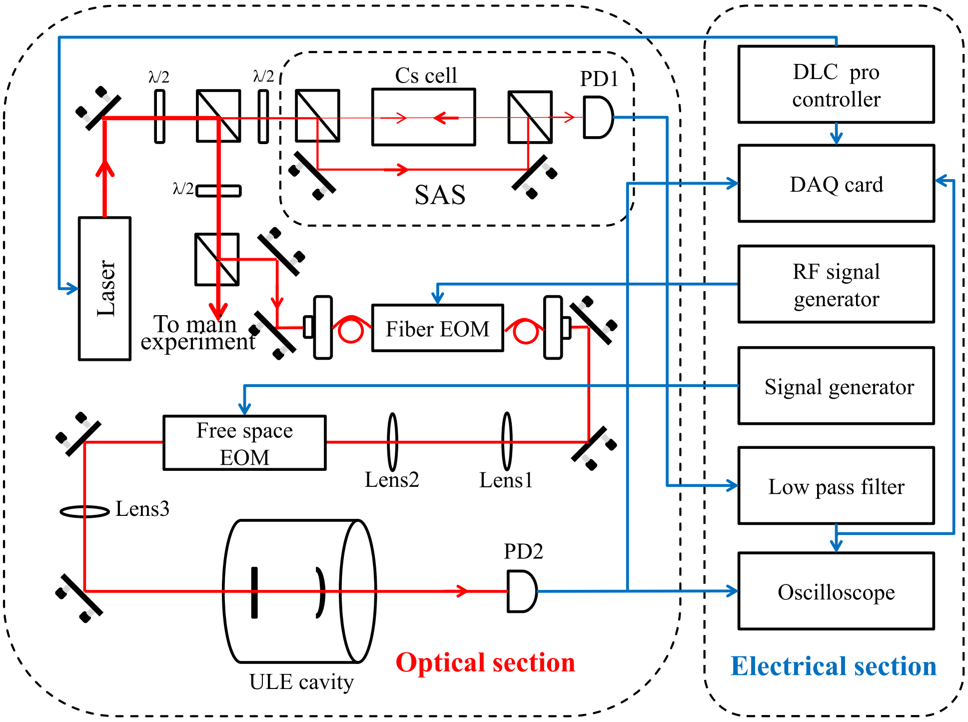

Figure 1. Schematic diagram of the experimental setup. The red lines with arrows represent optical propagations and blue lines represent electrical transfers. ULE: ultralow expansion; PD: photodetector; SAS: saturated absorption spectroscopy; EOM: electro-optic modulation; RF: ratio frequency; DAQ: data acquisition.

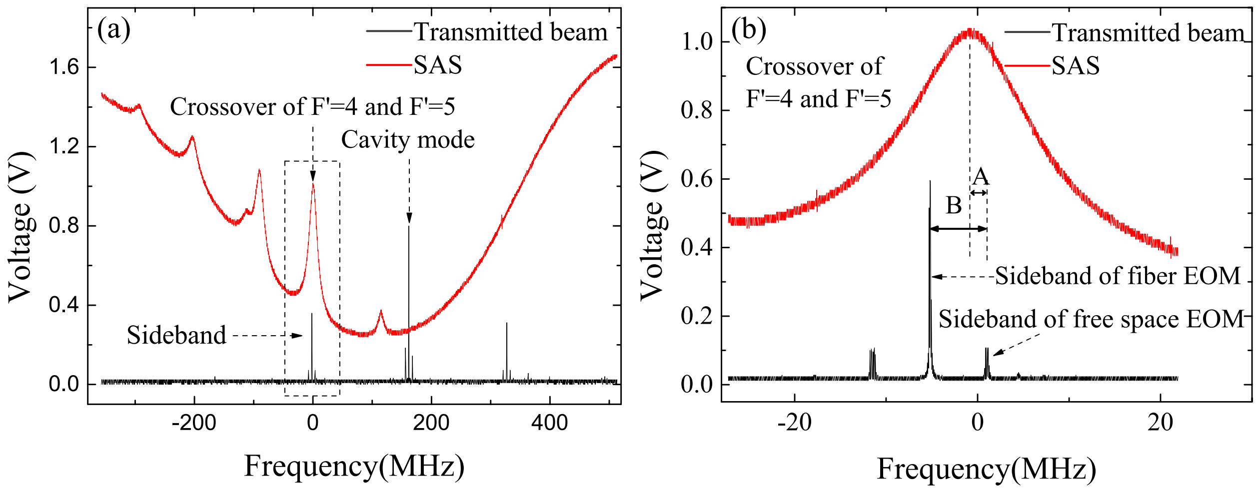

Figure 2. Saturated absorption spectrum (red line) and transmitted spectrum of coupling laser (black line) (a) and the spectra near crossover of $6P_{3/2}$, $F' = 4$ and $F' = 5$ from $6S_{1/2}$, $F = 4$ (b), which is chosen to be reference frequency and also the zero point of horizontal axial. A is the interval of reference frequency and sideband of free space EOM. B represents the modulation frequency of free space EOM, which is a frequency ruler.

mode of an optical frequency comb [22–24] or a laser which is locked to *another* ULE cavity with better (or at least the same) quality [18, 25]. However, many groups are not equipped with expensive frequency comb (more than 200 000 dollars) or two ULE cavities (50 000 dollars for each). Also, if our goal is only to measure ZCT there is no need to equip such expensive instruments. To reduce the cost of these reference equipments, some researchers use atom or molecule transitions as reference frequency [26]. [26] has simplified the ZCT measurement setup by using a narrow clock transition. However, the authors have to use manual work to record the transition spectrum because that a data record program can not be available. If abundant data can be recorded in short term, the accuracy will improve largely. In addition, the coupling laser still needs to be locked to a cavity mode.

Here, we present a simple, low cost and robust method to measure the ZCT of an ULE cavity, in which neither expensive optical frequency comb and *another* ULE cavity-based stabilized laser for reference frequency, nor PDH locking system for coupling laser is required. Our presented method

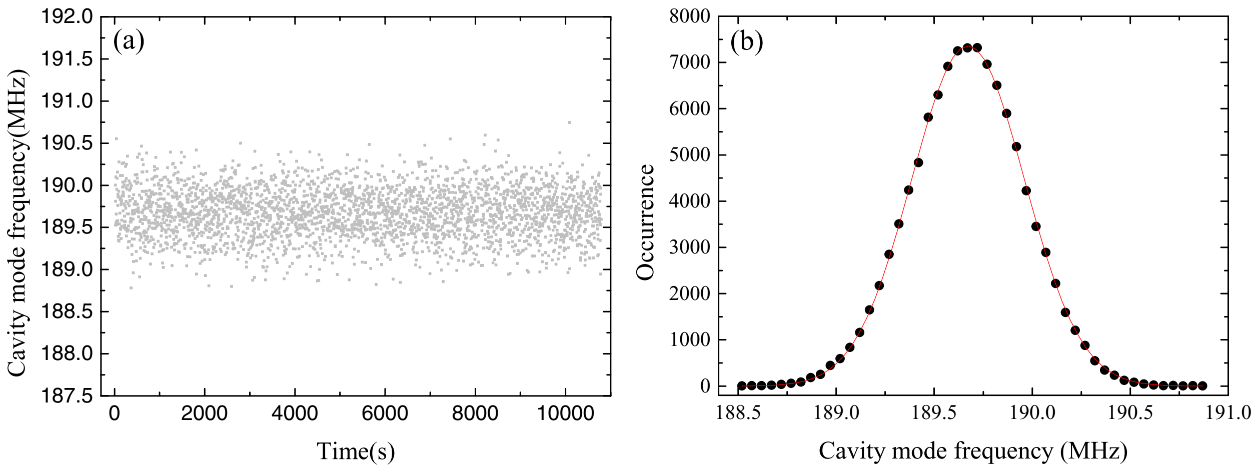

Figure 3. The measured frequency of cavity mode relative to reference frequency (a) and their statistical occurrence (b). The solid line is Gaussian fitting result.

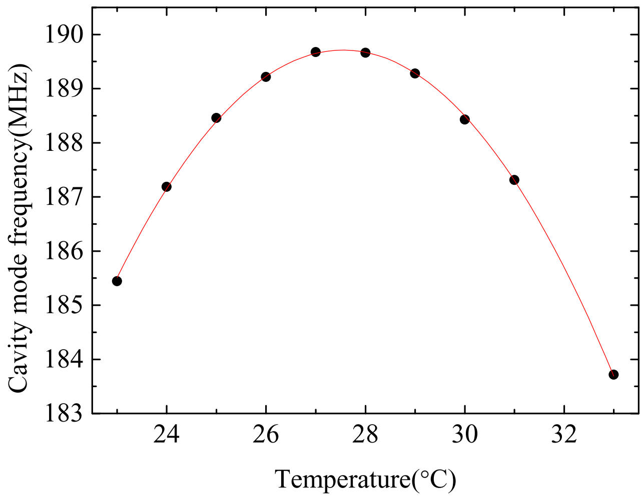

Figure 4. The fitted frequency of cavity mode relative to reference frequency as a function of temperature. The solid line is quadratic fitting result based on equation (2).

also allows easily using data acquisition card to record abundant data of cavity mode frequency in short term. The performance of our method will be compared with other three methods.

2. Experimental setup

The experimental setup is schematically shown in figure 1. It consists of optical and electrical sections. In the optical section, a diode laser (Toptica, DLC pro, 852 nm) is divided into two beams. One beam goes into an standard saturated absorption spectroscopy (SAS) setup for producing reference frequency. To avoid the influence from environment, the Cs cell is surrounded by permalloy magnetic shielding (magnetic field is less than 1 mG and the corresponding Zeeman shift is less than 1 kHz) and the whole optical setup is enclosed in a box. The other beam is coupled into a commercial ULE cavity (Stable Laser System, VH-6010), hold in a vacuum of

Table 1. Error list.

ZCT fitting	Cavity mode fitting	Ref. freq.	Thermal resistor accuracy
0.01 °C	0.20 °C	0.10 °C	0.01 °C

5.4×10^{-6} Pa. In our experiment, the mirror is coated with large wavelength range (600–1000 nm) and has a medium level of finesse (10 000) with aim to lock several lasers to the kHz order. Even fused silica (FS) has lower thermal noise limit than ULE [17, 27], there is no necessary for our requirement. We use ULE material instead of FS to make mirror substrate to avoid large differences of the coefficients of thermal expansion (CTE) with ULE spacer [28], that may induce ZCT below the room temperature and introduce extra problems for FS, like water condensation on cavity housing [16].

This coupling laser is modulated by a fiber electro-optic modulator (EOM) (Photline, NIR-MPX800-LN-10) and a free space EOM in order. The modulation powers of fiber and free space EOMs are 30 mW and 50 mW, respectively to have moderate amplitudes for sidebands produced by them. In the electrical section, the DLC pro controller is used to scan laser frequency and provide trigger signal to the data acquisition (DAQ) card (PCI-6014). The signals of SAS and transmitted beam, detected by the photodetectors 1 and 2 (Thorlabs, PDA36A-EC), respectively, are monitored by an oscilloscope. To reduce the electrical noise, a low-noise preamplifier (Stanford Research Systems, SR560) is used to increase signal-to-noise of SAS signal. Finally, we use a LabVIEW programme to deal with the data of SAS and transmitted signals based on DAQ card. All of these equipments above are easily available for typical optical laboratories and can be used for other purposes after measurements.

3. Operations and results

The basic principle of ZCT measurement is the same as before, that is when temperature stays at ZCT the cavity length has

Table 2. Comparison with other methods.

Methods	Ref. freq.	Laser locked?	Cost	β_{eff} (ppb K^{-2})	T_0 (°C)	Error (°C)
Reference [24]	frequency comb	yes	high	9.2	1.49	0.1[a]
Reference [25]	ULE cavity	yes	high	1.54	12.5	0.1[b]
Reference [26]	atom transition	yes	low	1.3	31.71	0.36[b]
This work	atom transition	no	low	1.16	27.55	0.22

[a] Reproduced by experimental data, including fitting error of ZCT 0.02 °C and fitting error of cavity mode frequency 0.1 °C.
[b] Only contains fitting error of ZCT as other errors are unknown.

the minimum value, inducing that the frequency of each cavity mode reaches its maximum value. The differences between our methods and other existed methods contain two sides. One side is where the absolute reference frequency comes from and the other side is how to calculate the frequency of cavity mode relative to reference frequency. We use a simple and low cost SAS, instead of expensive frequency comb and another ULE cavity-based stabilized laser, to obtain absolute reference frequency. The SAS of cesium atom D2 line from $6S_{1/2}$, $F = 4$ and transmitted spectrum of coupling laser are shown in figure 2. The crossover of $6P_{3/2}$, $F' = 4$ and $F' = 5$ is chosen to be the absolute reference frequency for that it has the largest peak.

When the coupling laser frequency is scanned, a cavity mode near our chosen reference frequency is shown with in figure 2(a) (the strongest peak). Usually there may be large interval between the reference frequency and the cavity mode frequency, like the case shown in figure 2(a), inducing the inconvenience of comparing relative frequency between them. To precisely measure this cavity mode frequency relative to reference frequency, a fiber EOM as a frequency bridge and a free space EOM as a frequency ruler will be used, that are explained in detail below. We firstly add certain radio frequency on a fiber EOM to form a sideband near the reference frequency. Then we turn on the radio frequency of a free space EOM to form new sidebands. Its modulation frequency is fixed at 6.22 MHz where the modulation efficiency is maximum. Thus the modulation frequency of free space EOM, shown by ‘B’ in figure 2(b), can act as a frequency ruler to measure the frequency of sideband formed by fiber EOM relative to reference frequency. Finally, taking the driven frequency of fiber EOM as a frequency bridge, we can derive the cavity mode frequency relative to reference frequency.

To measure their relative frequency more precisely, we reduce the scanning amplitude of coupling laser and choose a suitable modulation frequency of fiber EOM to make the reference frequency in the middle of sideband produced by fiber EOM and sideband produced by free space EOM, shown in figure 2(b) where a modulation frequency of 181.4 MHz is used. To quickly record enough data of the relative frequency in short term, we use a LabVIEW programme based on DAQ card to acquire these spectra, followed by judging the optimal maximum values, recording the corresponding horizontal values and deriving the ratio of A to B. The meanings of A and B are shown in figure 2(b). Based on this ratio, the cavity mode frequency relative to reference frequency can be derived. Figure 3(a) shows such a record at a temperature of 27.00 °C. The total number of recorded data is 1.1×10^5 with an acquired speed of 10 per second. These data are counted statistically in figure 3(b) with a statistical interval of 0.05 MHz. By using a standard Gauss function, the central frequency is fitted to be 189.673(5) MHz. The width is fitted to be 0.575(2) MHz and the noise mainly arise from noise of SAS, distortion of linear response of laser piezo and electric noise from DAQ card.

We then repeat the procedures above at different temperatures. It is noticed that we may need to change the modulation frequency of the fiber EOM to make reference frequency satisfy the condition in figure 2(b) for precise measurement when temperature changes. Finally we plot the relationship between the fitted cavity mode frequency and temperature, shown in figure 4. The error of each dot is on the order of kilohertz, thus it is unseen in the graph. It is expected to find that there is a maximum value and the frequency variation near the maximum frequency is smaller than far away.

In the following we analyze the relationship between cavity mode frequency and temperature. Even the mirror substrate of our cavity is also made of ULE material, their batch are different, inducing the CTE for the ULE mirror and ULE spacer a little different [16]. In [16], the authors have analyzed in detail the thermal distortion of ULE cavity with components of FS mirror and ULE spacer. Those conclusions and formulas are also applicable for our cavity.

According to [16], under the first order approximation the effective CTE of ULE cavity α_{eff} can be written as:

$$\alpha_{eff}(T) = \beta_{eff}(T - T_{0\_eff}), \tag{1}$$

where T is temperature and T_{0_eff} is the effective ZCT of whole cavity, β_{eff} is effective linear temperature coefficient of CTE and has the order of ppb K^{-2}. Considering the length deviation $\Delta l = \frac{1}{2} l_0 \beta_{eff}(T - T_{0\_eff})^2$ [29], the relationship between the frequency deviation of cavity mode $\Delta\nu$ and temperature can be written as:

$$\Delta\nu = \nu - \nu_0 = -\frac{1}{2}\beta_{eff}\nu_0(T - T_{0\_eff})^2, \tag{2}$$

where ν_0 and l_0 are the resonance frequency of cavity mode and cavity length at the ZCT, respectively.

We fit the data in figure 4 with the equation above. The maximum value of cavity mode frequency is fitted to be 189.71(2) MHz. Considering the frequency of cross-over of $6P_{3/2}$, $F' = 4$ and $F' = 5$ from $6S_{1/2}$, $F = 4$ is 351 721 828.67(1) MHz [30], the absolute frequency of our chosen cavity mode ν_0 is obtained to be 351 722 018.38(2) MHz. As the value of $a\nu_0$ is fitted to be 0.203(1) MHz K^{-2}, the value of a is obtained to be 0.58(1) ppb K^{-2}. The ZCT is fitted to be 27.55 °C with a fitting error of 0.01 °C. Except for this fitting error, there are also other errors (or uncertainties) which can affect the final accuracy of measure ZCT, shown in table 1. They mainly include fitting error of maximum value of cavity mode frequency (0.02 MHz) in figure 4 and error of reference frequency (0.01 MHz) [30]. Considering the variety between temperature and cavity mode frequency near ZCT shown in figure 4, these two items correspond temperature uncertainties of about 0.20 °C and 0.10 °C respectively. In addition, the detected uncertainty of thermal resistor is 0.01 °C. Thus the total uncertainty of measured ZCT is estimated to be 0.22 °C. As the main errors come from the ones from cavity mode fitting and reference frequency, it is expected to improve the measurement accuracy of ZCT by using the narrow atom or ion clock transition. For our coated mirror, it cover many species transitions, including Ca^+, Sr, Yb, Sr^+, Yb^+ *et al* [31–36]. By using these narrow transitions, it may be accurate enough to measure the long term drift at certain temperature.

To judge the performance of our method, we compare the performance of our method with other three kinds of typical methods in table 2. Among these methods, the reference frequency covers frequency comb [24], ULE cavity [25], and atom transition [26] respectively. We need to notice that in [25, 26] the uncertainty only contains the fitting error of ZCT. The influences of other errors are small for [25], but large for [26]. Combing all errors in our measurements, the uncertainty of our method can reach 0.22 °C. Thus the accuracy and reliability can be improved with our presented method when using atom or molecule transition as reference frequency.

4. Conclusion

In our presented dual frequency modulation method to measure the ZCT of ULE cavity, a fiber EOM as frequency bridge and a free space EOM as frequency ruler are used to precisely measure the frequency of cavity mode relative to atom transition which acts as a absolute reference frequency. Neither expensive optical frequency comb and *another* ULE cavity-based stabilized laser system for absolute reference frequency, nor PDH locking system for coupling laser is required, but still allows easily recording abundant experimental data in short term based on DAQ card. The measured uncertainty of ZCT shows that our presented method is still accuracy and reliable enough when assembling all the advantages of existed three methods.

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