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Precise calibration of zero-crossing temperature and drift of an ultralow expansion cavity with a clock transition spectrum*

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We report a clock transition spectrum approach, which is used to calibrate the zero-crossing temperature and frequency drift of an ultralow expansion (ULE) cavity with a Hertz level resolution. With this approach, the linear and nonlinear drifts of the ULE cavity along a variety of controlled temperatures are clearly presented. When the controlled temperature of ULE cavity is tuned away from the zero-crossing temperature of the ULE cavity, the cavity shows larger and larger nonlinear drift. According to our theoretical analysis and experimental results, we investigate more details of the drift property of the ULE cavity around the zero-crossing temperature, which has seldom been explored before. We can definitely conclude that the zero-crossing temperature of our ULE cavity used in an ytterbium (Yb) lattice clock is around 31.7 °C.

Keywords: clock transition spectra, ULE cavity, frequency drift, zero-crossing temperature

PACS: 32.70.Jz, 37.10.Jk, 42.62.Fi **DOI:** 10.1088/1674-1056/27/5/053201

1. Introduction

The second is currently defined by the transition between the two hyperfine levels of the ground state of cesium 133 atom at the General Conference of Weights and Measures in 1967 and its accuracy has reached 1.1×10^{-16} by a cesium fountain atomic clock (NIST-F2) recently.[1] Due to its longer measuring time, it is hard to reach a higher accuracy. In recent years, due to its unprecedented stability and accuracy, optical clocks based on a single ion in radio-frequency trap and cold neutral atoms in an optical lattice have surpassed the cesium atomic fountain clock, which is used as the primary standard of time and frequency.[2–5] So, the redefinition of the second is proposed. The optical clock shows great potential applications in secondary representation of second definition, geodesy, gravitational redshift, fundamental physics constants, and the search for dark matter.[6–8] The core elements of the optical lattice clock are a cold atom system and a narrow linewidth clock laser. For the narrow linewidth laser system, the most important part is the ultralow expansion (ULE) high finesse optical cavity. Recently, researchers at the Physikalisch-Technische Bundesanstalt (PTB) and the Joint Institute for Laboratory (JILA) have cooperated to obtain a laser linewidth of about 10 mHz with a cavity mirror substrate, mirror coatings, and a cavity spacer based on a single crystal silicon material at 1540 nm at a zero-crossing temperature around 124 K.[9] However, currently, the narrow linewidth clock laser is realized by stabilizing the clock laser to the TiO_2–SiO_2 based ULE cavity to obtain a Hz or sub-Hz level narrow resonance.[10] For this kind of ULE cavity, it is composed of a titania-doped glass spacer such as Corning glass and two highly reflective fused silica mirrors. The ULE cavity exhibits excellent short-term stability for laser linewidth narrowing, and long-term stability compared with the traditional Fabry–Pérot cavity. However, the long-term drift of the ULE cavity will ascribe to aging and the presence of slow temperature fluctuations. Typically, resonant frequency drift rates range from mHz up to Hz per second. Also, there is a zero-crossing temperature for the working temperature point of the ULE cavity, which shows the least linear frequency drift per day. Depending on the homogeneous grade of the spacer material and the doping fabrication procedure, the zero-crossing temperature ranges from 5 °C to 35 °C. Generally speaking, once the concentration and fabrication process are fixed, the zero-crossing temperature of the ULE cavity is fixed too. It was also reported that the zero-crossing temperature of the ULE cavity can be tuned by applying fused silica mirrors and ULE rings.[11] Nonetheless, the exact value of the zero-crossing temperature of the ULE cavity has to be accurately measured, so that the clock laser can show better stability and less drift. So how to determine and control the temperature so that the ULE cavity can work at the zero-crossing temperature is a crucial matter.

Usually one uses an optical frequency comb phase-locked

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to the reference frequency for the zero-crossing temperature measurement. The optical frequency comb links the microwave and the optical frequency domain. It is a powerful tool with which the inter-comparison of various clocks of different atomic species is very straightforward. But we know that a frequency reference with higher stability is also required when measuring the clock transition frequency with the optical frequency comb. Normally its center frequency and repetition frequency are both locked to the H-maser as a reference. When the clock transition frequency to be measured is beating with the frequency component of the optical frequency comb, we can obtain

$$f = f_0 + N f_{\rm rep} + f_{\rm b}, \tag{1}$$

where f_0 is the comb-offset frequency, $f_{\rm rep}$ is the comb-repetition frequency in microwave domain, and $f_{\rm b}$ is the measured beat frequency between the laser frequency and the Nth comb tooth. The absolute frequency and the drift of frequency can both be obtained. Then the zero-crossing temperature of the ULE cavity is effectively estimated. But the measurement system is a little complicated because it strongly depends on a very stable frequency comb and an effective frequency comb component output. The frequency comb just acts as a bridge between the ULE cavity resonant frequency and the reference source.

Another method is to use a similar ULE cavity with lower thermal noise instability as a reference. The change in the resonant frequency of the test cavity mode is measured by observing the driving frequency change of an additional acousto-optic modulator (AOM) for the reference ULE cavity while the test cavity temperature is ramped.[10] Without a systematic study of the reference cavity, one cannot give the long-term drift of the reference cavity or thermal calibrations. This method can be utilized to roughly estimate the zero-crossing temperature of the test cavity where the limitation arises from the long-term instability of the reference cavity and the variability of room temperature.

In this paper, we will demonstrate a much easier and more sensitive method to determine the zero-crossing temperature of the ULE cavity. Here the ultra-narrow clock transition spectra are used as a much better reference. With the help of the narrow clock transition spectrum, we can easily discern the frequency drifts around the zero crossing temperature of the ULE cavity.

2. Experiment

In our experiment, ultra-cold atoms were confined in an optical lattice created by a retro-reflected high power 759 nm laser beam. Our clock laser (578 nm) was aligned along the direction of tight lattice confinement to stimulate the ultra-narrow clock transition of ytterbium (Yb) 171 fermion isotopes. The details of our setup are described elsewhere.[12] We have obtained the Hertz-level clock spectrum already. The clock laser is locked to the clock transition frequency by applying a correction frequency to the relevant AOM as shown in Fig. 1.

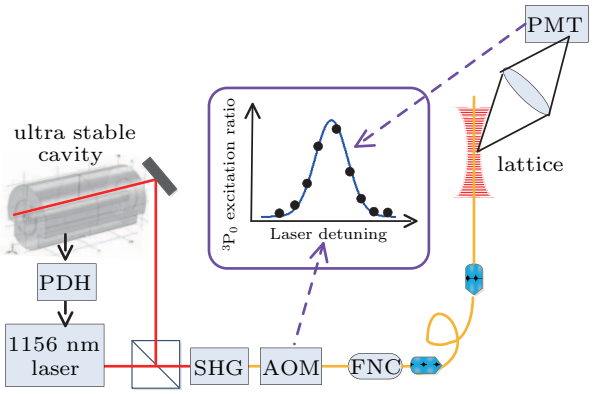


Fig. 1. (color online) Schematic setup for zero-crossing temperature measurement. Normalized clock transition spectrum of $^1S_0 \rightarrow {}^3P$ clock transition (Lorentz fitting of the black dots) is derived according to fluorescence signal collected by the photo-multiplier (PMT) while sweeping continuously AOM driving frequency.

The controlled temperature and its fluctuation will change the length of the ULE cavity, and the relative change of the length of the ULE $\Delta l/l$ is equal to $\Delta\nu/\nu$. Usually it is an easy way to measure the change of the resonant frequency instead of that of the length of ULE cavity. There is a zero-crossing temperature at which the ULE cavity has the minimum cavity length expansion, that is, the clock laser locked to the ULE cavity has the least frequency drift. It can be described by the formula[13] $\Delta\nu/\nu = \Delta l/l \sim 10^{-9}(T - T_0)^2$, where T_0 is the zero-crossing temperature and T is the actual controlled temperature. It seems that the resonant frequency shows approximately quadratic dependence on temperature. To obtain the zero-crossing temperature, we have to record the resonant frequency with different controlled temperatures of the ULE cavity. Our clock laser (Toptica) is realized by a second harmonic generation system. A laser diode at 1156 nm is amplified by a tapered semiconductor amplifier to give an output power around 500 mW, and the fundamental laser is frequency-doubled by a ring cavity to generate the clock laser at 578 nm. The narrow linewidth of the clock laser is realized by locking the 1156 nm laser to a ULE cavity (Atfilms). The Pound–Drever–Hall (PDH) technique is adopted to stabilize the clock laser frequency to the resonance of the ULE cavity. So in order to keep the clock laser with best long-term stability, it is necessary to measure the exact zero-crossing temperature and degrade the temperature fluctuations. The uncertainty of the zero-crossing temperature depends mostly on the uncertainty of the resonant frequency. A stable reference plays an essential role in the frequency measurement. The more stable the reference is, the more accurate the measurement will be.

3. Experiment results

In the experiment, we set the controlled temperatures of the ULE cavity to be at several points along 30–35 °C. For each point, the ULE cavity stays in thermal equilibrium for more than five days. We measure the zero-crossing temperature of the ULE cavity with the help of an optical frequency comb as shown in Fig. 2(a). We also measure the zero-crossing temperature of the ULE cavity with a clock transition spectrum as shown in Fig. 2(b). The measurement processes with the frequency comb and the clock transition spectrum are almost the same. We use the optical frequency comb to measure the resonant frequency to determine the zero-crossing temperature. The method with which we use for the clock transition spectra is to record the frequency of the clock transition by matching the radio frequency of the AOM with the resonant frequency of the ULE cavity. Obviously, we can see that the results obtained from the two methods are different.

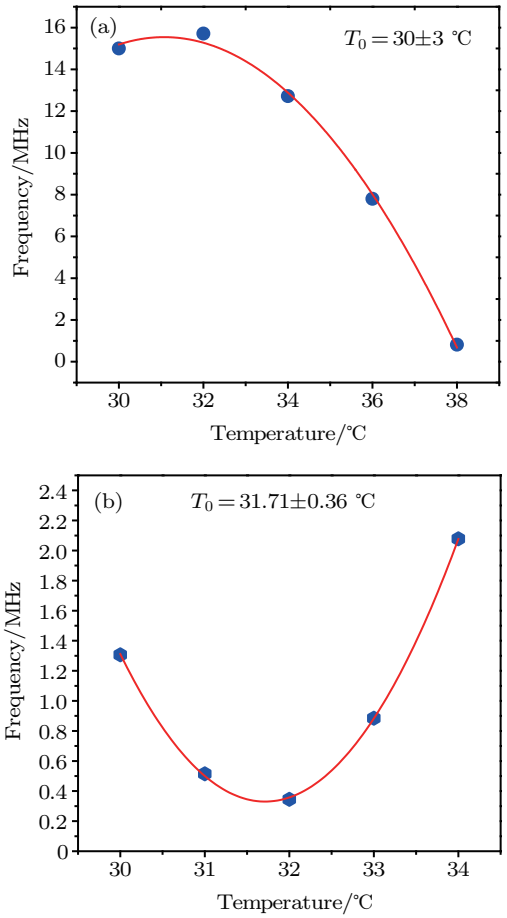


Fig. 2. (color online) Measurements at different controlled temperatures along 30–35 °C in the cases with (a) an optical frequency comb and (b) clock transition spectra. The red line is quadratic fitting of the experimental data, from which the zero-crossing temperature is derived.

From the fitting of the frequency drifts of the ULE cavity at different temperatures, we can obtain the zero-crossing temperature of our ULE cavity to be around 31.7±0.36 °C. In order to judge which method is more precise, now we record the clock transition spectra along every temperature point, respectively. We adopt the Rabi excitation, and the clock duration time is 50 ms, with a Fourier-limited linewidth of about 17.8 Hz. We scan the AOM driving frequency in steps of 2 Hz and the normalized excitation ratio of the clock transition is monitored. So, the long-term drift of resonant frequency can also be determined by continuous measurement over several days, and the results are shown in Fig. 3.

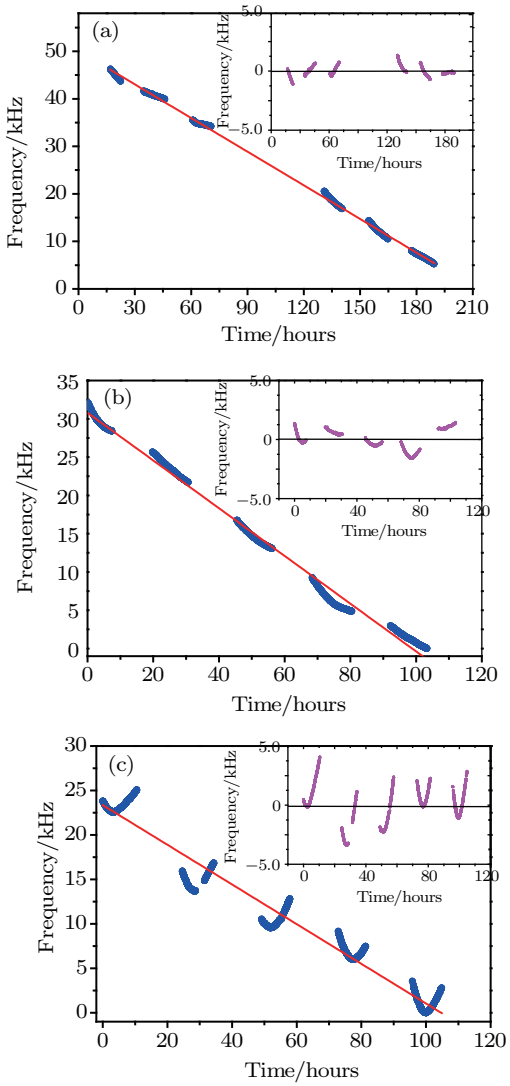


Fig. 3. (color online) Frequency variations with time of the ULE cavity at controlled temperatures of (a) 32 °C, (b) 33 °C, and (c) 34 °C, respectively. The insets show frequency drifts with the linear drifts removed.

In Fig. 3, it seems that when the controlled temperature is away from the zero-crossing temperature, the linear drift rates of the ULE cavity almost stay the same except in (b), which maybe comes from the measuring time not being long enough. But compared with the nonlinear drift, the linear drift is small. The nonlinear drift in the inset is obtained by subtracting the linear drift (red curve) from the total frequency drift (blue curve). But the nonlinear drifts grow stronger during the different periods of the day. The further away from the zero-crossing temperature the controlled temperature is,

the more obvious nonlinearity the clock transition spectrum shows. For comparison, we show the frequency drifts for three different temperature points. The applied driving frequency of the AOM matched to the clock transition frequency is plotted with blue line over several days. The clock transition spectra are recorded about ten hours every day.

In order to consider the influence of the nonlinear frequency drift on the linewidth of the clock transition spectrum, we choose the condition that the ULE cavity is controlled at 34 °C, at which the ULE cavity has the maximum nonlinear drift. Moreover, we record the linewidths of the different times during one day as shown in Fig. 4.

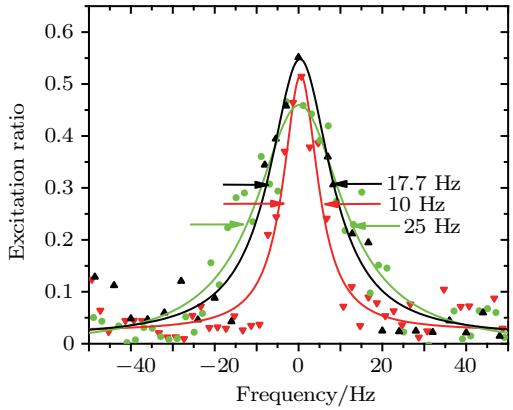


Fig. 4. (color online) Normalized excitation spectra of clock transition. Differences in linewidth is corresponding to different drift rates of ULE cavity.

Over 24 hours, spectral linewidths according to the different drift rates are recorded. We can obtain a Fourier-limited linewidth of 17.8 Hz with the proper choice of the clock laser intensity when ignoring the drift of the cavity. However, considering the contribution of cavity drift, we can record different linewidths. Figure 4 shows several typical linewidth values, with the ULE cavity controlled at 34 °C. The red line reflects that the resonant frequency of ULE cavity is decreasing, while the green one indicates that the resonant frequency is increasing. The linewidth of the transition spectrum is obtained by Lorentz fitting the curve of transition possibility versus AOM driving frequency.

We change the controlled temperature to the zero-crossing temperature, 31.7 °C. We can see that only linear drifts exist there over the entire time. The linewidth of the clock transition is 17 Hz under the same Rabi excitation condition as shown in Fig. 5(a).

As to the frequency drift, it seems that the method with the optical frequency comb is much noisier than that with clock transition spectra (see Figs. 5(b) and Fig.5(c)). We cannot see the nonlinear frequency drift with the ULE cavity controlled at the zero-crossing temperature with the clock transition spectrum method in Fig.5(c). However, based on the results in Fig.3, when the controlled temperature is away from the zero-crossing temperature, the nonlinear drift appears. It means that the method with the clock transition spectra is very sensitive to the nonlinear drift of the ULE cavity due to the variation of the controlled temperature, which is impossible to reveal by using the optical frequency comb method.

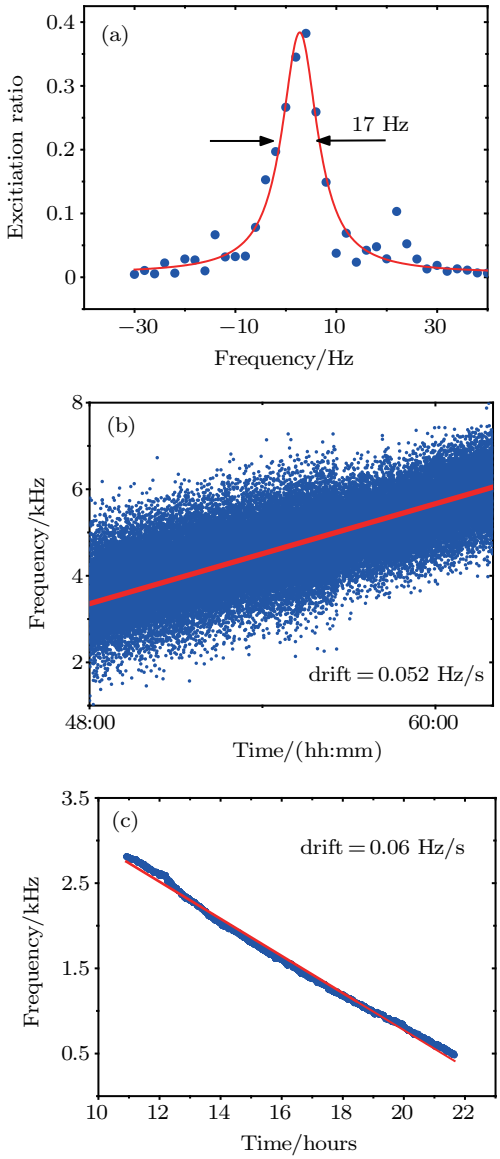


Fig. 5. (color online) (a) Normalized excitation spectra of clock transition at 31.7 °C. (b) Frequency drift rate versus time of ULE cavity in 24 hours, measured with the optical frequency comb. (c) Frequency drift rate measured with clock transition spectra.

4. Conclusion

In this work, we have described a method to precisely measure the zero-crossing temperature of the ULE cavity with the help of narrow Yb clock transition spectra. Compared with the traditional optical frequency comb method, the clock transition spectra method has higher resolution to reveal more details about the spectral linewidth and nonlinear frequency drift of the ULE cavity to precisely determine the zero-crossing temperature.

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