Absolute frequency measurement of the \(^{40}\text{Ca}^+\) clock transition based on an optical frequency comb

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Abstract. We demonstrate an approach of absolute frequency measurement \(^{40}\text{Ca}^+\) 4S\(^{1/2}\)-3D\(^{5/2}\) clock transition based on an optical frequency comb. Based on this method, the frequency of 729 nm ultra-stable laser is measured by using a self-built 250 MHz Yb-doped fiber optical frequency comb and a beat frequency signal with SNR of about 10 dB has been obtained preliminarily.

1. Introduction

As one of the seven basic physical contents, "time" is used to measure the length and order in which events occur. From the "Gui Meter" more than 3,000 years ago to the "Sundial" of the Sui Dynasty and to the quartz crystal oscillator of the 20th century, the measurement accuracy of time is getting higher and higher. With the rapid development of modern science and technology, especially the emergence of aerospace technology, human beings have put forward higher requirements for the measurement accuracy of time.

Although the research on the atomic frequency standard represented by the caesium Cs atomic clock has made great progress, the atomic frequency standard should be referred to as "atomic microwave frequency standard" in strict sense because of the working carrier of atomic clock is in the range of microwave frequency. Since the emergence of laser, especially femtosecond optical frequency comb, scientific researchers have developed strong interests in the "optical frequency standard" which has a higher frequency stability. At present, the main working ion of single ion optical frequency standard are ytterbium ion \(^{171}\text{Yb}^+\), aluminium ion \(^{27}\text{Al}^+\), indium ion \(^{115}\text{In}^+\), strontium ion \(^{88}\text{Sr}^+\) and calcium ion \(^{40}\text{Ca}^+\) [1-3]. Among them, the highest frequency stability is the \(^{171}\text{Yb}^+\) optical frequency standard whose frequency uncertainty can reach the order of \(10^{-15}\), which is two orders of magnitude higher than the atomic microwave frequency standard [4]. Therefore, the single ion optical frequency standard has become one of the major research directions in the field of metrology.

Since the trapped single ion is in the ultra-high vacuum environment, the collision probability with air is very small, which greatly reduces the collision broadening [5]. The stability of the trapped \(^{40}\text{Ca}^+\) is worse than that of the ultra-stable laser in a short time, but its long term stability is very high, so it can be used as the long-term frequency reference in the optical frequency standard system. By referring the optical frequency comb system to an ultra-stable laser and an ion clock at the same time, the advantages of the ultra-stable laser and the ion clock can be combined to realize a long-time, high-frequency stability optical frequency standard system. In order to realize the optical frequency standard, one of the key steps is to measure the absolute frequency of the clock transition.

2. Measure principle

The absolute frequency measurement principle of \(^{40}\text{Ca}^+\) 4S\(^{1/2}\)-3D\(^{5/2}\) clock transition based on an optical frequency comb OFC is shown in Figure 1. Since the wavelength of the corresponding radiation photon of the \(^{40}\text{Ca}^+\) 4S\(^{1/2}\)-3D\(^{5/2}\) clock transition is 729 nm, we need a 729 nm ultra-stable laser to measure it. The 729 nm ultra-stable laser is divided into two beams by a polarization beam splitter PBS. The reflected beam is guided into an optical frequency comb system for absolute frequency measurement and the transmitted beam passes through an acousto-optic modulator AOM twice before and after the reflection of a 729 nm narrow band high reflection mirror. The frequency-shifted ultra-stable laser are injected into the \(^{40}\text{Ca}^+\) trap system, and by applying different modulation frequencies \(\omega\) to the AOM, the sweep detection can be performed on 10 Zeeman spectral lines corresponding to the \(^{40}\text{Ca}^+\) clock transition.
The absolute frequency measurement process can be divided into three steps. Firstly, the frequency of the 729 nm ultra-stable laser is absolute measured by an OFC. Then, by changing the modulation frequency $\omega$ the 10 Zeeman spectral lines are scanned and detected, and the frequency of the ultra-stable laser is absolute measured at the same time. The final step is to process the measured data. From the above discussion, we can see that the most critical of these three steps is the first step.

The absolute frequency measurement principle of the 729 nm ultra-stable laser can be expressed as the formula 1:

$$f_{729} = nf_{\text{rep}} \pm f_{\text{beat}} \pm f_{\text{ceo}}$$

(1)

Where $f_{729}$ is the frequency of 729 nm ultra-stable ultra-stable laser, $f_{\text{rep}}$ and $f_{\text{ceo}}$ is the repetition rate and the carrier envelope offset frequency of the OFC, respectively, $f_{\text{beat}}$ is the frequency of the beat frequency signal of the ultra-stable laser with the $n$th comb teeth of the OFC. The $n$ is an unknown positive integer before measurement. The $f_{729}$ can be measured roughly by a wavelength meter. The value of $n$ can be calculated by the formula 2.

$$n = f_{729} / f_{\text{rep}}$$

(2)

Then we need judge the relationship between the $f_{729}$ and the frequency of the $n$th comb teeth $f_n$ (equal to judge the arithmetic symbol in front of $f_{\text{beat}}$). When $f_{\text{rep}}$ increases, if $f_{\text{beat}}$ becomes smaller, it means that $f_{729} > f_n$ and the arithmetic symbol in front of $f_{\text{beat}}$ is ""; Otherwise, the arithmetic symbol is "". The last step is judge the arithmetic symbol in front of $f_{\text{ceo}}$. When the $f_{\text{ceo}}$ increases, if $f_{\text{beat}}$ becomes smaller, the arithmetic symbol in front of $f_{\text{ceo}}$ is ""; Otherwise, the arithmetic symbol is "".

![Figure 1](image1.png)

Figure 1. Principle diagram of absolute frequency measurement of $^{40}\text{Ca}^+$ clock transition

3. Experiment setup

The experimental setup is shown in figure 2, consists of a fiber comb, a $^{40}\text{Ca}^+$ trap system, a high power fiber amplifier based on chirped pulse amplification principle CPA, a 729 nm ultra-stable laser, a fiber phase noise compensation system, a beat frequency optical path system and so on.

![Figure 2](image2.png)

Figure 2. Schematic of the experimental setup
The fiber comb was a 250 MHz stable Yb-doped fiber frequency comb with a supercontinuum SC spectrum generated by using a specially designed tapered single-mode fiber, in which an octave-spanning spectrum spanning from 500 nm to 1500 nm had been generated [6]. The carrier-envelope offset CEO signal with high SNR of up to 44 dB and a linewidth of about 110 kHz had been obtained. The repetition rate and CEO signal had been simultaneously phase-locked to a microwave reference frequency. The 729 nm ultra-stable laser was a single frequency Ti: sapphire laser (Coherent, MBR-110) and referred to a Fabry-Perot cavity which made of low expansion material. Because of the fiber comb and the 729 nm ultra-stable laser were not in the same laboratory, it was necessary to use a section of about 50 m polarization-maintaining single-mode fiber to transmit the 729 nm ultra-stable laser to the laboratory where the fiber comb was located. The spectrum broadening of 729 nm ultra-stable laser caused by phase noise introduced by transmission fiber was reduced to 100 mHz after compensation by a fiber phase noise compensation system [7]. The high power fiber amplifier was used to generate a supercontinuum spectrum containing 729 nm components. The beat frequency optical path system was a typical Mach-Zehnder type interferometer and used to detect the fbeat signal.

4. Experiment results
With 21 W of pump power, the output average power of the high power fiber amplifier were 13 W. After being compressed by a pair of transmission gratings, the duration of de-chirped pulses were about 79 fs with an average power of 4.4 W. In order to achieve a SC spectrum containing 729 nm components, the de-chirped pulses were injected into a section of photonic crystal fiber PCF via an aspheric lens with a focal length of 2.97 mm. When the de-chirped pulses exceeding 800 mW (4A) were coupled into the PCF, the resulting supercontinuum spectrum can be covered to 729 nm. With the input power increasing, the range of the supercontinuum extended slowly and simultaneously to the longer and shorter wavelength regions, as depicted in Figure 3.

![Figure 3. The output supercontinuum spectrum of PCF at different pump power](image)

![Figure 4. The spectrum of beat frequency signal](image)
The supercontinuum spectrum and 729 nm ultra-stable laser were injected in the interferometer by a pair of mirrors respectively. By rotating the half wave plates in the two arms separately, a $f_{\text{beat}}$ signal with SNR of 10 dB was obtained, as shown in Fig. 4. However, the SNR of $f_{\text{beat}}$ was relatively low and could not meet the experimental requirements, we will increase the SNR of $f_{\text{beat}}$ to above 30 dB by optimizing optical fiber amplifiers and other means in the next study.

5. Conclusion
In summary, we demonstrate the study of absolute frequency measurement of $^{40}\text{Ca}^+ S_{1/2} - D_{5/2}$ clock transition based on an optical frequency comb. In order to obtain a SC spectrum containing 729 nm components, a set of high power fiber amplifier was constructed. A flat SC spectrum containing 729 nm component is generated by injecting the de-chirped pulses into a section of PCF. Finally, the frequency of 729 nm ultra-stable laser is measured by using the self-built 250 MHz optical fiber comb, and a $f_{\text{beat}}$ signal with SNR of 10 dB is obtained preliminarily.

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