An Integrated Pulsed Optically Pumped Rb Clock

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Abstract Rb atomic clock refers to the microwave transition of ^{87}Rb atoms, generally considered as a low-cost and low-performance atomic frequency standard. The maturity of semiconductor laser offers us a new opportunity to improve the Rb atomic clock. However, there are also many challenges in terms of electronic system and optical bench. Despite the performance superiority of the pulsed optically pumped (POP) Rb atomic clock has been demonstrated in the laboratory, there still no integrated prototype emerges to date. Here, we report the design and characteristics of an integrated POP Rb atomic clock. The primary test shows short-term stability of $3.2\times10^{-13}\tau^{-1/2}$ (1-1000s) and 4000s frequency stability of 8.5×10^{-15} in air. The size and power consumption are 23 L and 45 W, respectively.

Keywords—Pulsed optically-pumped; atomic clock; integrated prototype.

I. INTRODUCTION

The lamp-pumped Rb atomic clock (generally called Rb atomic clock) has been used in wireless communication, satellite navigation, etc. Due to the complex spectrum of the lamp, the isotopic filtering technique is required in the Rb atomic clock [1,2]. Moreover, the lamp spectral profile has a bandwidth of about 1GHz [3]. Those deficiencies of the lamp have a strong impact on the signal-to-noise ratio. Semiconductor laser not only has a linewidth of MHz level, but also has controllable intensity and frequency (using AOM), which enables significant improvements in the signal-to-noise ratio and long-term stability.

It is well known that the narrower laser linewidth yields a larger light shift, one of the main limits for the long-term stability. The time-domain Ramsey oscillation technique is proposed to overcome this issue, which is named the pulsed optically pumped (POP) Rb atomic clock [4]. Although the POP Rb clock inherits some characteristics of Rb atomic clock, there are many differences between them. Firstly, in a lamp-pumped Rb clock, temperature variation of the filter cell affects the profile and amplitude of the pumping light, so the inverse temperature point is a combination of the filter cell and absorption cell [5], which leads to the mixture ratio of buffer gases is different from that of the POP Rb clock. Secondly, Ramsey oscillation technique requires digital circuits, while the lamp-pumped Rb clock could be realized with a simpler analog circuit [6]. Last but not least, the laser system requires frequency stabilization, beam expansion and the optical switch, leading to a larger size compared with the lamp [7]. Despite many technical challenges, POP Rb atomic clock is still considered a promising competitor for the next-generation space-borne clock [8,9]. Recently, the POP Rb clock has attracted much attention around the world [10-14]. The performance potential of such kind of atomic clock has been demonstrated in laboratory. Unfortunately, there still no integrated prototype emerges. After several years of effort, we have integrated the optical module, physical module and electronic module, finally realized a POP Rb atomic clock prototype of 23 L volume. Here, we introduce the characteristics and performance of the atomic clock.

II. METHODS/RESULTS

The physics package is based on a magnetron microwave cavity, whose volume is only 32 mL. ^{87}Rb atoms with a mixture of buffer gases of Ar and N_2 are filled in a glass cell. The vapor cell is placed into three layers of magnetic shields, to avoid the effects of geomagnetic fluctuation. The whole physics package is sealed with atmospheric pressure to keep the air pressure stable. Benefitting from the small cavity, sealed chamber and precise temperature control [15], the vapor cell exhibits 0.5 mK temperature fluctuation in air within one day. The laser system used a distributed feedback (DFB) diode emitting at 780.24 nm. The laser frequency is stabilized to the saturated-absorption spectroscopy CO2-23. We also develop an integrated frequency synthesizer with a 100MHz local oscillator. A customed direct digital synthesizer (DDS) is responsible for frequency scanning and frequency hopping. We have realized an integrated POP Rb clock based on the above-mentioned modules. Fig.1 shows the photograph of the prototype. The size and power consumption are 23 L and 45W, respectively.

The clock operation consists of three phases: quantum state preparation, Ramsey interrogation and signal detection. The total cycle period is 4.7 ms, the optical pumping duration is 0.4ms, the two separated microwave pulses are both 0.4 ms, the Ramsey time is 3.3 ms, which is set close to coherent relaxation time and the probe pulse is 0.2 ms. We have the central Ramsey fringe contrast larger than 50 %, presenting a linewidth of ~150 Hz.

The clock places on a homemade cooling baseplate for heat dissipation. 100 MHz signal from the clock is measured referring to a hydrogen maser, which shows short-term stability of 1×10^{-13}/s and long-term stability better than 1×10^{-15} . Fig. 2 shows Allan deviation plot of the fractional frequency. When the averaging time is 1-1000 s, the frequency stability averages down by $3.2\times10^{-13}\tau^{-1/2}$, typical white frequency noise behavior, which is limited by the frequency and amplitude noise of the laser. It shows a 4000 s stability of 8.5×10^{-15}. It should be noted that our result gets in a typical laboratory environment, which is different from previous works under vacuum [10, 12].

Fig.1 Photograph of the POP Rb atomic clock prototype

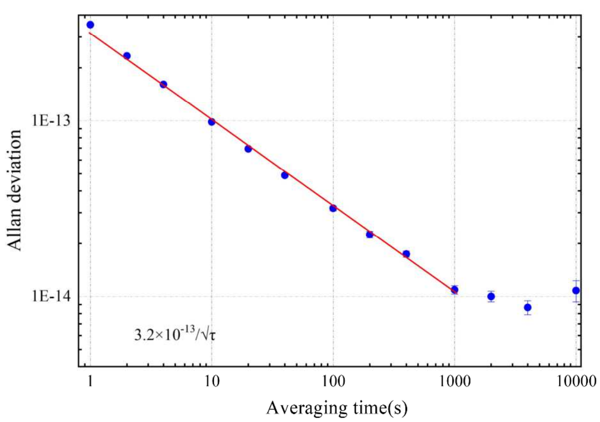

Fig.2 Fractional frequency stability (1.7×10^{-13}/day linear drift removed), the red line shows the square-root dependence.

III. DISCUSSION AND CONCLUSIONS

In conclusion, a POP Rb atomic clock phototype is successfully completed, which shows a primary short-term stability of $3.2\times10^{-13}\tau^{-1/2}$ (1-1000s) and 4000s stability of 8.5×10^{-15} in air. At present，the system has not yet been optimized for long-term stability. We will analyze and optimize contributions of the physics effects, and the ultimate goal is to reach 5×10^{-15} precision with the proposed POP Rb atomic clock.

It should be noted that, although we have completed the prototype of POP Rb atomic clock, there are still many technical challenges for the commercial prototype. For example, we should address the continuous operation issue, which requires the laser frequency in lock for years. Additionally, the system is sensitive to vibrations, especially the optical system, high optical integration should be considered.

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