A Compact Optically Pumped Cesium Beam Clock with a Differential Detection Scheme

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***Abstract*—Compact optically pumped cesium beam clocks have become a focus in cesium clock research due to their high atomic utilization and excellent short-term frequency stability. However, stray light noise, one of the main noise sources, limits the stability improvement. In this paper, we present a compact optically pumped cesium clock that uses differential detection to reduce the impact of stray light on clock performance. It incorporates an additional fluorescence collector to capture stray light during detection and subtract it from the clock transition signal, effectively reducing stray light level. Consequently, this scheme significantly enhances the signal-to-noise ratio, improving the short-term frequency stability of the compact optically pumped cesium clock.**

Keywords—cesium beam clock; differential detection; stray light noise; signal-to-noise ratio

I. INTRODUCTION

Among the various atomic clocks used for timekeeping, compact cesium beam clocks play a critical role in fields such as satellite navigation, communication, and time synchronization systems due to their portability and excellent frequency stability [1], [2]. According to different atomic state preparation methods, compact cesium clocks mainly include two types: magnetic state selection clocks and optically pumped clocks [3], [4]. Although magnetic cesium clocks have been widely used in many fields, the low atomic utilization rate limits the increase in signal-to-noise ratio (SNR) of the clock signal. In contrast, optical cesium clocks have a higher atomic utilization rate and therefore are expected to provide better stability performance.

Although compact optically pumped cesium clocks have a theoretical advantage in frequency stability, their current performance falls short of expectation. Therefore, it is crucial to identify and reduce the level of noise. In optically pumped cesium clocks, atomic state preparation and clock transition detection are completed by lasers, so stray optical noise is inevitably introduced into the clock signal. This noise arises from laser beams that do not interact with the atoms and are incident on the photodetector as stray light, decreasing the SNR. It introduces a significant DC voltage offset and degrades the quality of the clock transition signal due to laser noise. Although subsequent circuits could eliminate the offset signal, they fail to fundamentally reduce the negative impact of stray light noise and instead increase the circuit design complexity. Additionally, the electrical method cannot mitigate laser noise, which limits the improvement of the SNR. In contrast, differential detection schemes in gas cells are used to eliminate laser noise and improve the SNR of the clock signal, demonstrating significant effectiveness [5], [6]. However, there are few reports on differential detection schemes in atomic beam systems.

In this paper we introduce a compact optically pumped cesium clock based on differential detection. This clock incorporates an additional fluorescence collector, identical to the one collecting the clock signal, to capture stray light. The captured noise signal is then subtracted from the clock signal, resulting in a pure clock signal. This scheme eliminates the background caused by stray light and reduces laser noise, thereby improving the SNR and enhancing the short-term stability of the compact optically pumped cesium clocks.

II. METHODS

The fundamental principles of a differential detection-based optically pumped cesium clock are similar to those of a conventional one [7, 8]. Figure 1 illustrates the transition line selection for the pumping laser and detecting laser in our clock. Both the pumping and detecting lasers originate from the same laser source. An acousto-optic modulator shifts the frequency of the detecting laser by 251 MHz to obtain the pumping laser.

In the vacuum, the atomic beam interacts with a frequency-locked pumping laser corresponding to the cesium atomic energy level transition line F = 4↔F = 4' to generate the imbalance population in the ground state levels. These atoms are then excited by a 9.192631770 GHz microwave magnetic field within a Ramsey cavity surrounded by a homogeneous static magnetic field, resulting in clock transitions. A detecting laser, frequency-locked to the cycling transition line F = 4↔F = 5', passes through an window into the fluorescence collector and induces the cesium atoms to emit photons. The fluorescence collector collects these photons and directs them to the photodetector, obtaining the clock transition signal. This signal stabilizes the oscillator frequency at the clock transition

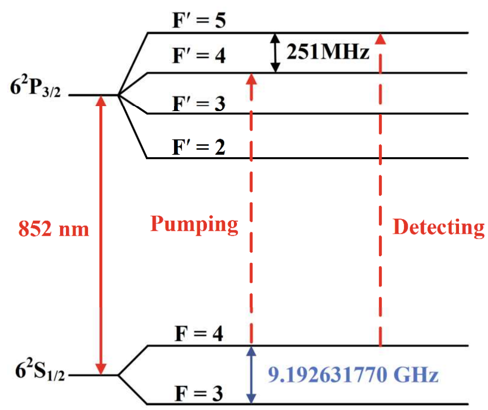

Fig. 1. The selection of the transition lines for the pumping and decting laser in our atomic clock

frequency. Consequently, the quality of the clock signal directly impacts the overall performance of the clock.

Stray light noise often occurs during the detection process due to imperfect transmission through the window or improper collimation of the detecting laser. Therefore, an additional fluorescence collector is introduced to eliminate the stray light. This paper describes two differential detection configurations for the optically pumped cesium beam clocks, as illustrated in Fig. 2(a) and 2(b). The main difference is whether the stray light collector is in a vacuum environment. Furthermore, in order to ensure consistency, the structural dimensions and physical parameters of the stray light collector must match those of the fluorescence collector, and the power of the two incident beams must be equal.

Fig. 2(a) shows the first differential configuration, with the stray light collector placed in the vacuum. In this structure, the atomic beam also intersects with the laser. To avoid unnecessary resonance between this laser and the cesium atoms, an additional acoustic-optic modulator frequency-shifts the detecting laser, ensuring it only collects the stray light. Additionally, the two laser beams incident on the fluorescence collector and the stray light collector pass through the same window. It implies that any variations in laser power caused by the tilt and coating parameters of the windows could be neglected.

Fig. 2(b) shows another differential configuration, where the stray light collector sits outside the cesium beam tube. Since the cesium atomic beam does not pass through the stray light collector in this configuration, the laser frequency could be identical to the frequency of the detecting laser. In addtion, the stray light collector features rotatable windows at both ends. Adjusting the angle of these windows allows for better matching of the stray light caused by the tilt of the windows on the cesium beam tube during clock signal detection, ensuring experimental consistency. The physical parameters of this window match those welded to the cesium beam tube.

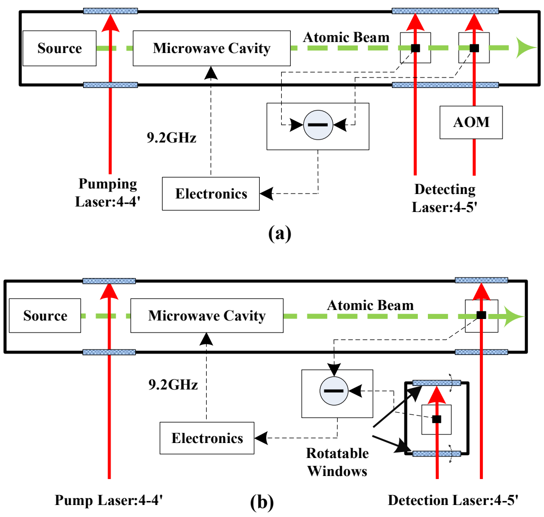

Fig. 2. Schematic diagram of two differential detection configurations for the optically pumped cesium clock: (a) stray light collector in the vacuum, and (b) stray light collector in an atmospheric environment.

III. Discussion

The differential detection scheme offers significant advantages over the single detection scheme used in compact optically pumped cesium beam clocks by addressing stray light noise at its source. It simplifies subsequent circuits and inherently produces a pure clock transition signal.

To implement this scheme, we explore two configurations. When the stray light and the fluorescence collectors are in the same vacuum, the two laser beams pass through the same window. This setup could be insensitive to external environments. However, an extra acousto-optic modulator in this configuration increases the system's complexity. Alternatively, the second configuration allows the two lasers to use the same frequency, eliminating the need for additional optical devices. However, it is more susceptible to external environmental influences, particularly ambient light, which is considered for its impact on the system in practice.

IV. Conclusions

In this proceeding, we have presented a compact optically pumped cesium beam clock based on a differential detection scheme. This differential scheme could remove background signals caused by stray light through optical means and reduce laser noise. As a result, it improves the SNR of the clock signal and enhances the short-term frequency stability of the optically pumped cesium clock.

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