Rubidium-beam microwave clock pumped by distributed feedback diode lasers*

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A rubidium-beam microwave clock, optically pumped by a distributed feedback diode laser, is experimentally investigated. The clock is composed of a physical package, optical systems, and electric servo loops. The physical package realizes the microwave interrogation of a rubidium-atomic beam. The optical systems, equipped with two 780-nm distributed feedback laser diodes, yield light for pumping and detecting. The servo loops control the frequency of a local oscillator with respect to the microwave spectrum. With the experimental systems, the microwave spectrum, which has an amplitude of 4 nA and a line width of 700 Hz, is obtained. Preliminary tests show that the clock short-term frequency stability is 7×10^{-11} at 1 s, and 3×10^{-12} at 1000 s. These experimental results demonstrate the feasibility of the scheme for a manufactured clock.

Keywords: quantum frequency standard, atomic clock, atomic beam, distributed feedback

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1. Introduction

Compact manufactured thermal-atomic-beam clocks are playing central roles in time-keeping, navigation and telecommunication. Caesium-beam clocks based on magnetic-state selection are widely applied due to their remarkable long-term frequency stability and high accuracy.[1] However, their short-term stability is limited by the low state-selection efficiency. With the development of suitable light sources such as lamps and lasers, optical methods adopted in compact caesium clocks have greatly improved the short-term stabilities and other performances.[2–4] However, the manufactured optically pumped caesium clocks with high performances are not commercially available yet.

Likewise, ^{87}Rb, as another alkali atom, is also suitable for the atomic reference in quantum frequency standards, especially in cold-atom frequency standards such as fountains[5] and space cold atomic clock,[6] because of the small collision frequency shift of ^{87}Rb. As for the thermal ^{87}Rb-beam clock, although the central frequency of clock decreases from 9.2 GHz of ^{133}Cs to 6.8 GHz of ^{87}Rb and the microwave line width broadens due to larger velocity, the high efficiency of optical pumping can compensate for the loss in short-term frequency stability. Before suitable diode lasers for ^{87}Rb are available, a lamp-pumped rubidium-beam experiment was carried out to measure the hyperfine separation of ^{87}Rb,[7] and clock based on the same method was also proposed.[8] A rubidium beam clock pumped by an external cavity diode laser (ECDL) reached a short-term stability of $1.4 \times 10^{-12}\tau^{-1/2}$,[9] demonstrating the potentially high performance of compact rubidium-beam clock. However, the relatively low reliability of external-cavity laser restricts the long-term operation of this type of clock.

Distributed feedback (DFB) diode lasers show advantages in long-term operation because of their large mode-hopping free ranges. Although DFB laser diode usually has a broader spectral line width than ECDL, which may lead to additional noise in detection, manufactured clock with a DFB laser can have small size and weight, meanwhile exhibiting better reliability. As far as we know, no experimental research on DFB-pumped thermal-rubidium-beam clocks has been reported. In order to evaluate the properties of the rubidium-beam clock pumped and detected by DFB lasers, we build an experimental system and investigate the microwave spectra of ^{87}Rb and the short-term frequency stability of the clock.

The rest of this paper is structured as follows. In Section 2, the principle of the experiment is introduced. In Section 3, the experimental set-up is described in detail. In Section 4, the microwave spectrum and the frequency stability of the clock are demonstrated. Finally, it is conducted and some conclusions are drawn from the present studies in Sections 5 and 6, respectively.

2. Principle

The energy levels of ^{87}Rb including the ground state and the first two excited states are shown in Fig. 1. The transition between the $m_F = 0$ sublevels of the two hyperfine lev-

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els of the ground state, i.e. transition between $5^2S_{1/2}$, $F = 2$, $m_F = 0$, and $5^2S_{1/2}$, $F = 1$, $m_F = 0$ sublevels, is chosen as the clock transition (0–0 transition), because its frequency varies least with external magnetic field, in the frequencies for all the hyperfine transitions. The transition frequency is 6.835 GHz.

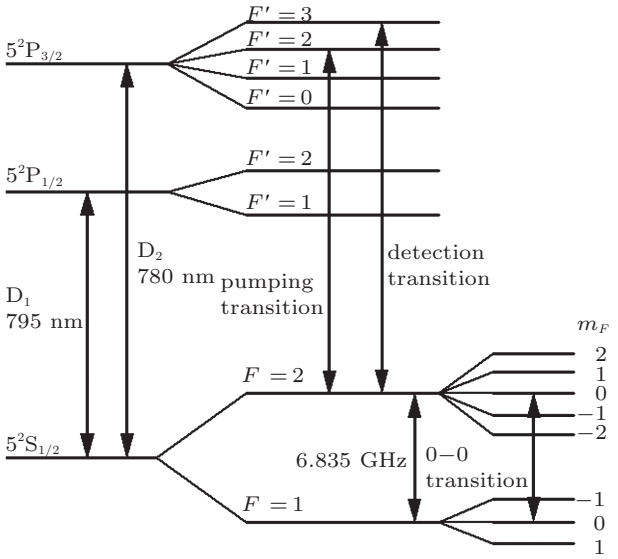


Fig. 1. Energy levels of ^{87}Rb, where the clock transition (0–0 transition), the pumping transition and the detection transition adopted in the experiment are marked.

In order to observe the microwave spectrum of the clock transition, one must prepare the initial states of the atoms so that a population difference exists between the $m_F = 0$ sublevels of the ground state before microwave interrogation. Traditionally, this is realized by magnetic state selection, leading to a loss in the atomic beam intensity due to the velocity-dependent feature of the method. Besides, the large magnetic field has several subtle effects on clock performance, such as Majorana transition,[10] inhomogeneity of the static magnetic field, and asymmetry populations between different Zeeman sublevels.[11] Optical pumping largely enhances the beam intensity meanwhile avoiding the drawbacks mentioned. Moreover, instead of deflecting the unwanted atoms, the optical pumping method pumps atoms from the unwanted levels to the target level. The pumping efficiency, which is characterized by the fractional population difference between the clock sublevels, can be calculated from the rate equation. For ^{87}Rb, the difference can reach 41% in a single laser configuration when the excitation scheme is 2-2'(D_2), referring to the transition between $5^2S_{1/2}$, $F = 2$ and $5^2P_{3/2}$, $F' = 2$ levels, and σ-polarized.[12,13] The advantage in optical-pumping efficiency, compared with that of ^{133}Cs ($\sim$16%),[14] mainly stems from fewer Zeeman sublevels of ^{87}Rb.

After the optical pumping, microwave interrogation is accomplished in a separated-oscillating-field configuration proposed by Ramsey,[15] where the atomic beam passes through two short interaction regions and a long microwave-free distance between them. Near the central frequency of the microwave spectrum, Ramsey fringes emerge with narrowed line widths. Moreover, the Ramsey method lowers the requirement for magnetic field inhomogeneity along the beam trajectory in the microwave cavity. Near the central frequency, the transition probability for atoms with uniform velocity is theoretically $P = [1 + \cos(2\pi\Delta\nu T)]\sin^2(2bt)/2$ where $\Delta\nu$ is the frequency difference between the input microwave and the atomic transition, b is half of the Rabi frequency, T and t are respectively the microwave-free time and the interaction time. The line width is $1/2T$ for uniform velocity, and $0.48\alpha/L$ when the velocity distribution of atoms in the beam is taken into account,[16] where α is the most probable velocity and L is the microwave-free length.

Finally, optical detection detects the number of atoms that have undergone the microwave transition. Instead of absorption, fluorescence detection is usually used because it significantly reduces the microwave-free background when the atomic beam is optically thin, which is usually the case. Either a pumping transition or a cyclic transition can be used. The former simplifies the clock construction because part of the pumping light can be split for detection without needing an acousto-optic modulator (AOM) or another laser diode. On the other hand, the cyclic transition scheme can enhance the number of photons that an atom emits during the detection, hence increasing the signal-to-noise ratio (SNR).

3. Experimental set-up

The clock is composed of a physical package, optical systems and electric servo loops as shown in Fig. 2.

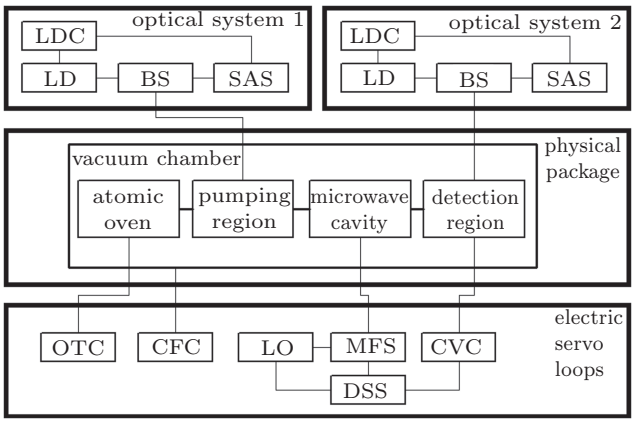


Fig. 2. Block diagram of the clock. LD: laser diode; LDC: laser diode controller; BS: beam splitter; SAS: saturated absorption spectrum; OTC: oven temperature controller; CFC: C-field controller; LO: local oscillator; MFS: microwave frequency synthesizer; CVC: current-voltage converter; DSS: digital servo system. Note that C-field coils and magnetic shield are not shown explicitly in the diagram.

An oven containing one gram of naturally occurring rubidium, of which the atomic percent abundance of ^{87}Rb is 27.8%, generates the atomic beam via a collimator which is

composed of about 240 tubes each with 1 mm in diameter and 6 mm in length. The distance between the collimator output port and the detection region is 0.4 m, and the restricted aperture of the detection region is 3×7 mm^2. The detailed design of the Ramsey-type microwave cavity can be found in Ref. [17]. Its resonant frequency is 6.835 GHz, which is tunable in a range of 100 MHz. The measured loaded quality factor is 800, which is relatively low in order to suppress the cavity pulling effect. The interaction length and the microwave-free length are 15.8 mm and 199.8 mm, respectively. Based on the previous equations, the theoretical line width in our experiment is 6.9×10^2 Hz at an oven temperature of 160 °C. The microwave cavity is surrounded by coils that generate a static magnetic field (C-field) used for the separation of the clock transition from those magnetic-field sensitive ones. The typical operating value of the C-field is 4.4×10^{-6} T, leading to a separation of 62 kHz according to the Breit–Rabi formula.[16] The microwave cavity and the C-field coils are shielded by a three-layer magnetic shield. Two light collectors are mounted on both sides of the cavity, in order to collect the fluorescence during pumping and detecting. Each collector is composed of concave mirror pairs and a photodiode (Hamamatsu S5107). The fluorescence signal can be used simultaneously for stabilizing the microwave frequency and laser frequency. The physical package is installed inside a cylindrical vacuum chamber with Φ 0.2 m×0.6 m in size, where the vacuum is maintained by an ion pump. The pressure is 2×10^{-7} Pa at room temperature and 5×10^{-6} Pa when the oven is heated to 160 °C.

We use two DFB lasers for pumping and detecting separately in order to realize the cyclic transition detection scheme. The lasers are commercial products with a spectral line width of less than 2 MHz and an output power over 60 mW. The two optical systems are essentially identical, except the frequencies of the lasers. The two lasers are frequency-locked with separated saturated absorption spectra. The pumping laser is 2-2'(D_2), to achieve a maximal pumping efficiency as previously mentioned. The detection laser is 2-3'(D_2). The output light intensity of each system into the physical package is 25 mW/cm^2, and the laser beam size is 1 cm^2.

The electric control loops are composed of a local-oscillator, a microwave frequency synthesizer, a digital servo system, and circuits for controlling the oven temperature and C-field. The local oscillator is a 10-MHz oven-controlled crystal oscillator that has a free running frequency stability of 2×10^{-12} at 1 s. The 6.8-GHz microwave is synthesized from the oscillator output by a commercial synthesizer. The microwave power is tuned to maximize the amplitude of the Ramsey fringe. The microwave frequency is square-wave modulated to generate an error signal for feedback control of the local oscillator. The phase noise of output microwave at 156 Hz, twice the typical modulation frequency in our experiment, is −96 dBc/Hz, which exerts a theoretical limit to the frequency stability of $2.5 \times 10^{-13}\tau^{-1/2}$ due to the intermodulation effect.[18] The digital servo loop is based on a personal computer plug-In module (National Instruments PCI-4461).

4. Results and discussion

The microwave spectrum is scanned near the central frequency of the clock transition, with the oven temperature regulated at 160 °C and the microwave power optimized for the maximization of the Ramsey fringe. In a broad scan, the three Rabi pedestals are shown in Fig. 3, with a separation of about 60 kHz. Due to the fast scan speed, the Ramsey fringe is not clearly recorded in the broad scan. In a narrow scan, the central part of the Ramsey fringe is shown in Fig. 4. The Ramsey fringe is superimposed on a large background caused by scattered light. The time-varying background causes the distortion of the recorded line. The Ramsey fringe has a line width of 7×10^2 Hz, close to the theoretical expectation.

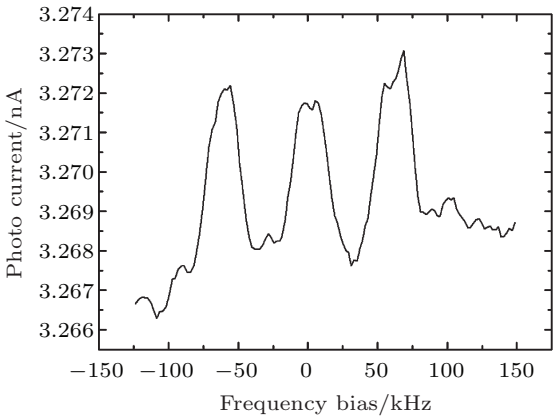


Fig. 3. Detected photo current with respect to the frequency bias from central frequency (in the broad scan case).

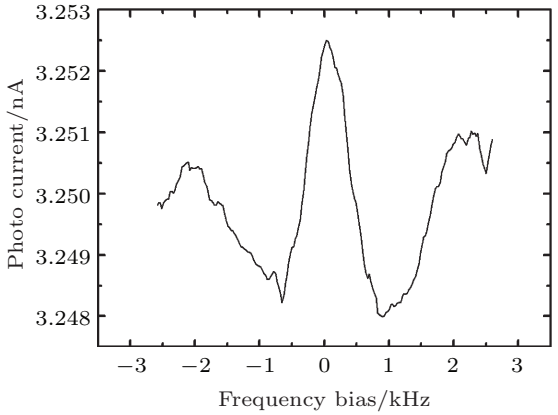


Fig. 4. Detected photo current with respect to the frequency bias from central frequency (in the narrow scan case).

In order to investigate the short-term stability, during a continuous operation for three hours, the fractional frequency difference is measured against a free-running high-stable oven-controlled crystal oscillator (OCXO) to have an Allan deviation below 5×10^{-13} from 1 s to 30 s, and below

2×10^{-11} for a one-day operation. The measured Allan deviation is plotted in Fig. 5, where the clock short-term frequency stability is fitted to $7 \times 10^{-11}\tau^{-1/2}$. This result is a demonstration of the clock frequency stability because the line variation is almost inversely proportional to the square root of integration time, indicating that the instability of the OCXO has not appeared in this measurement.

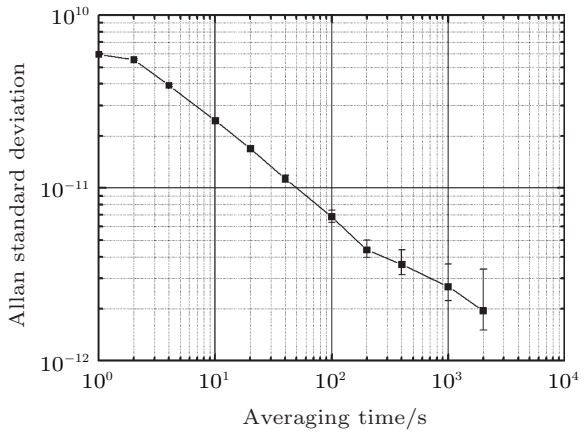


Fig. 5. Allan standard deviation during a 3-hour measurement.

5. Discussion

The short-term stability is not so good as expected due to the relatively low SNR in the present experiment. First, the measured signal amplitude is smaller than expected. A continuous operation for several days with an oven temperature above 160 °C results in the degrading of the microwave spectrum amplitude and broadening of the laser spectrum of the atomic beam, indicating that ^{87}Rb atoms which are not in the atomic beam begin to accumulate in the chamber. The large atomic velocity distribution along the light path broadens the laser spectrum due to Doppler effect, and collisions between the atoms weaken the atomic beam intensity. Adding efficient rubidium getters and adopting ^{87}Rb isotope will ameliorate this consequence. Second, the large background due to scattered light greatly contributes to the noise. Diminishing the detection light intensity and optimizing the light path are helpful. To further increase the SNR, a static magnetic field can be applied to the pumping and detecting regions, avoiding Hanle effect that would reduce the pumping efficiency due to coherence between Zeeman sublevels.[19]

Other improvements can make the clock more compact and robust. The optical system can be simplified by adopting one-laser-frequency scheme, where the pumping light also serves as the detection light, eliminating the need for two laser diodes. Moreover, the laser frequency can be stabilized based on fluorescence from the pumping region. Finally, placing the physical package into a sealed tube with a small pump will greatly reduce the total size and weight of the clock.

6. Conclusions

A thermal rubidium-beam microwave clock, which is optically pumped and detected by two DFB lasers, is constructed and tested at Peking University, China. The microwave spectrum of the transition between ^{87}Rb hyperfine levels of the ground state is obtained. The short-term frequency stability is $7 \times 10^{-11}\tau^{-1/2}$ from 1 s to 10^3 s. This preliminary result demonstrates the feasibility of our scheme. With further improvement in the physical package and the optical systems, the short-term frequency stability has a potential surpassing those of traditional caesium clocks.

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