Chip-scale Optical Clock Based on Modulation Transfer Spectroscopy

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***Summary*— We propose a scheme for realizing a chip-scale optical clock based on modulation transfer spectroscopy. By using on-chip laser, lithium niobate thin film waveguides and MEMS cells, the laser frequency can be stabilized at the hyperfine transition of rubidium atomic line. In this way, the volume and power consumption of the optical clock can be greatly reduced while the performance is guaranteed.**

Keywords—chip-scale optical clock; modulation transfer spectroscopy; lithium niobate modulators; compact optical frequency standard; frequency stability.

I. INTRODUCTION

Atomic clocks are the most accurate time and frequency standards available [1-2]. At present, the best atomic clock is the optical clock, whose frequency instability and accuracy have reached the level of 10^{-18} [3]. Optical clocks are used in advanced technology fields such as positioning, navigation, reconnaissance and communication, which plays a vital role in both basic research and practical application.

However, optical clocks always have huge volume, complex system and high cost, which greatly limit their application scenarios. Therefore, it is particularly important to prepare chip-scale optical clock. Two basic problems must be solved in the development of chip-scale optical clock: reducing the volume and power consumption of optical clock system; obtaining narrow linewidth spectral lines of thermal atoms. Some researchers use two-photon transition scheme [4-6], which can obtain a compact, low-power optical clock. But in this scheme, the fluorescence collection system is more challenging for the whole chip integration.

This paper proposes an experimental scheme for realizing a chip-scale optical clock based on modulation transfer spectroscopy [7-10] that can stabilize the laser frequency to the hyperfine transition of rubidium atoms line. In this work, it is intended to choose rubidium as the quantum reference, with ^{7}Rb D_2 line $5S^{1/2}$ F=2→$5P^{3/2}$ F'=3 as the clock transition. By choosing 780nm on-chip laser with narrow linewidth laser as the clock lase, and directly stabilizing the laser frequency to the rubidium atomic hyperfine transition line with the method of high signal-to-noise-ratio modulation transfer spectroscopy and fast feedback mechanism, we propose an experimental scheme for realizing a chip-scale optical clock system.

II. METHODS

The experimental setup is shown in Figure 1. The whole system will be built on silicon substrate, which can adopt waveguide transmission. We plan to use the home-made lithium niobate film waveguides as electro-optic modulator, and the small rubidium cell prepared by MEMS. In our experimental scheme, the 780nm narrow linewidth laser is divided into two beams. One beam is pumping laser, which through the lithium niobate film, and the other beam is the detection laser. The system intends to use radio frequency to modulate the laser field, optical coherence detection and sensitivity demodulation, which transfer of modulated signal from pump beam to unmodulated detection laser by four-wave mixing. The modulation transfer spectroscopy with high sensitivity, high resolution and no Doppler background are obtained, which can be used to stabilize the laser frequency. At last, the spectrum will be able to be modulated and demodulated by the feedback control circuit, and the frequency synthesis circuit is controlled by the feedback servo circuit， which provides the frequency standard of the rubidium atomic clock.

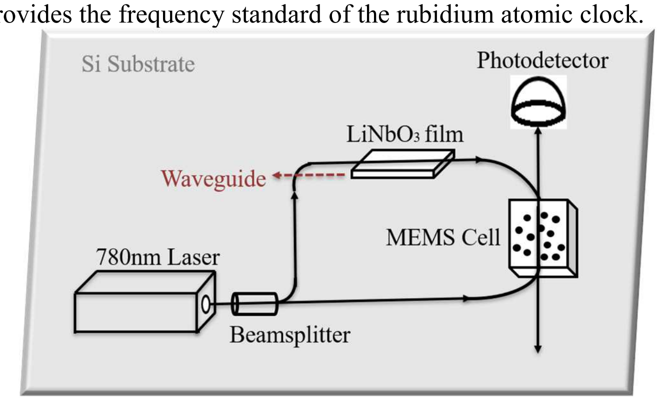

Fig. 1. Experimental setup of the chip-scale optical clock based on modulation transfer spectroscopy.

We have built a set of principle of a compact MTS optical clock as shown in Figure 2, the size of which is 25cm*25cm*15cm, in order to achieve the final chip-scale optical clock. At present, the compact optical clock uses an external cavity semiconductor laser, a commercial EOM and an ordinary Rb cell.

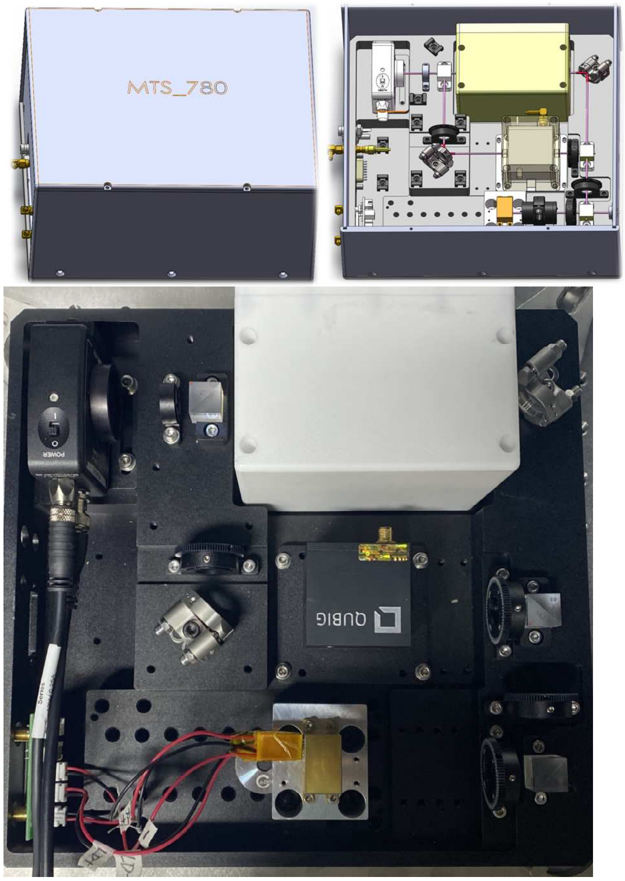

Fig. 2. The compact MTS optical clock is used for proof of principle, whose size is 25cm*25cm*15cm.

The optical clock based on modulation transfer spectroscopy uses the ^{87}Rb D_2 transfer line $5S_{1/2}$ F=2→$5P_{3/2}$ F'=3, as shown in Figure 3. The natural linewidth of ^{87}Rb D_2 transfer line is 6 MHz, so the modulation frequency will have to be 7-10 MHz taking into account all kinds of broadening. The modulation depth will have to be deeper than 1rad, which is feasible with modulation transfer spectroscopy.

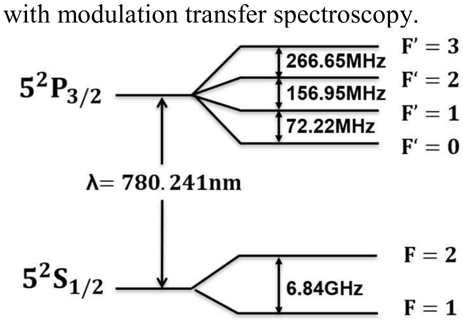

Figure 3. Relevant ^{87}Rb energy levels.

When a modulated light and an unmodulated light interact with atoms, the unmodulated light will also appear sideband due to the four-wave mixing effect, which is modulation transfer spectroscopy. The saturation absorption spectroscopy (SAS) and corresponding modulation transfer spectroscopy (MTS) of the ^{87}Rb D_2 transfer line $5S_{1/2}$ F=2→$5P_{3/2}$ F'=3 are shown in Figure 4.

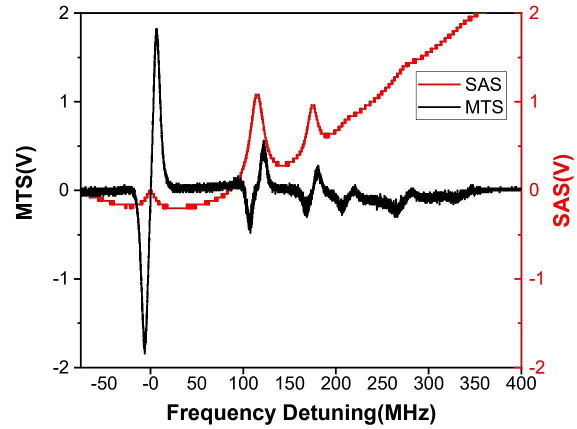

Figure 4. Saturation absorption spectroscopy (red-solid line) and corresponding modulation transfer spectroscopy (black-solid line) of the ^{87}Rb D_2 transfer line $5S_{1/2}$ F=2→$5P_{3/2}$ F'=3.

III. Discussion

For laser frequency stabilization, people are most interested in the slope of the center point of the spectral line, and the magnitude of the slope often reflects the frequency discrimination sensitivity of the spectral line. That is to say, the higher the slope, the better. In this work, the MTS signal slope of the compact optical clock is 200 mV/MHz . The best Allan deviation is expected to be on the level of 10^{-14} .

This compact MTS optical clock verifies the principle of frequency stabilization of modulation transfer spectroscopy and prepares for the chip-scale optical clock. In the future, we will gradually chip the core components in the optical clock. The chip-scale optical clock intends to use modulation transfer spectroscopy technology with high signal-to-noise ratio and full bandwidth high speed servo feedback mechanism. By using 780nm on-chip laser with narrow linewidth laser as the clock laser, and directly stabilizing the laser frequency to the atomic hyperfine transition ^{87}Rb D_2 line, the optical clock achieves a stable standard frequency. And we intend to use home-made lithium niobate film waveguides as electro-optic modulator and MEMS cells in order to achieve on-chip integration.

IV. Conclusions

We propose a scheme for a chip-scale optical clock based on the modulation transfer spectroscopy, which using on-chip laser, the lithium niobate film waveguides and MEMS cells. It can simultaneously pursue the high frequency instability and compactness, extending the application range of the chip-scale optical clock.

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