Compact Optical Frequency Standard with MEMS Vapor Cells

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***Abstract*—This work introduces an innovative optical frequency standard that leverages MEMS vapor cells to achieve exceptional stability. To attain these objectives, we have integrated the modulation transfer spectroscopy (MTS) technique, which not only ensures high stability but also contributes to minimal power consumption in a compact form factor. Employing MTS with a high signal-to-noise ratio and utilizing a full bandwidth, high-speed servo feedback, we have successfully stabilized the laser frequency at the hyperfine transitions of rubidium atomic lines within the MEMS vapor cell. Furthermore, after the laser is locked, there is a significant narrowing effect on the laser linewidth. The current specifications of our compact optical frequency standard include a frequency Allan deviation of 4.8E-13@1s and the laser linewidth of only 18 kHz.**

Keywords—optical frequency standard, chip-scale optical clock, optical clock, modulation transfer spectroscopy.

I. INTRODUCTION

Over the past decade, there has been significant advancement in the field of optical clock technology. Optical clocks based on lattice-trapped atoms and single-ion systems have achieved unprecedented precision levels below 10E-18. However, the state-of-the-art optical clocks are typically restricted to laboratory settings due to their size and complexity. With the development of MEMS (Micro Electro Mechanical Systems) processing technology, many efforts have been made towards the miniaturization of vapor cell in optical clocks, which can reduce the power consumption and the cost of the clock's physics package. In this study, we present a novel optical frequency standard that capitalizes on MEMS vapor cells to attain remarkable stability. By harnessing modulation transfer spectroscopy[1-2] (MTS) with an elevated signal-to-noise ratio, coupled with the implementation of a full bandwidth and a high-speed servo feedback system[3-6], we have efficaciously locked the laser frequency to the hyperfine transitions within rubidium atomic lines encapsulated by the MEMS vapor cell. The compact optical frequency standard we have developed has achieved a frequency Allan deviation of 4.8E-13@1s, and exhibits a laser linewidth of 18 kHz.

Our advancements, which have harnessed MEMS vapor cells, have laid crucial groundwork for the future realization of chip-scale optical frequency standards. Concurrently, this approach has provided a novel avenue for the development of narrow-linewidth lasers, offering a promising direction for the enhancement of laser technology in a variety of applications. In addition to being used as a portable optical frequency standard, this compact, narrow-linewidth, high-stability laser can have various other applications, such as laser interferometry, laser cooling, geodesy, and so on.

II. EXPERIMENT

A. MEMS Vapor Cells

Most MEMS vapor cells adopt the three-layer structure of Glass-Si-Glass, their thickness is generally limited within 2 mm restricted by DRIE (deep reactive ion etching) of silicon, which is difficult to provide sufficient thickness. Here we present a new three-layer structure of Si-Glass-Si, which has a horizontal optical path. Figure 1(a) shows the vapor cell, which has a global dimension of 14 × 14 × 4.3 mm and an inner optical chamber dimension of 10 × 6 × 4 mm, its optical path length can reach up to 10 mm. Figure 1(b) shows the BF33 borosilicate glass used, it has two chambers burnished in side, which connected with a micro-channel, Rb dispenser is activated to release rubidium atom vapor in the small chamber, atom vapor can diffuse into the large chamber through the micro-channel and the residuals of activated dispenser are left in the small chamber, which avoids interfering interaction between light and Rb atom in the large chamber. Figure 1(c) shows a photo of the MEMS vapor cell. The preparation method of the MEMS vapor cell is as follows: At first, anodic bonding is performed with the BF33 borosilicate glass and a 150-µm-thick silicon slice which are ultrasonic cleaned. Second, fill the Rb dispenser (SAES Getters RB/AMAX/PILL/1-0.6) into the small chamber. Third, the second anodic bonding is performed with the two-layer structure and another silicon slice. Finally, a 980 nm laser beam with 15 W is focused on the surface of the Rb dispenser for 20 seconds to activate the Rb dispenser.

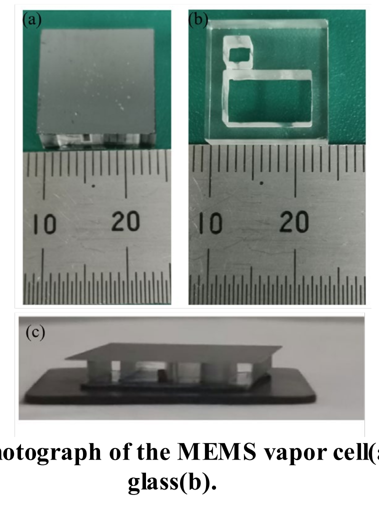

Fig. 1. Photograph of the MEMS vapor cell(a) and glass(b).

B. MTS System

A compact optical frequency standard based on the modulated transfer spectroscopy principle was constructed using the homemade MEMS vapor cell, as depicted in Figure 2. The laser, after traversing an isolator, is bifurcated into two beams by a polarizing beam splitter, with one beam dedicated to internal system locking and the other for external monitoring purposes; a subsequent polarizing beam splitter further divides the laser into two distinct beams, one serving as the pump beam and the other as the probe beam. The pump beam undergoes phase modulation via an electro-optic modulator and is directed into the MEMS vapor cell following two reflections; the probe beam enters the MEMS vapor cell and counteraligns with the pump beam in an opposing trajectory; the probe beam is then focused onto a photodetector through a lens. Ultimately, a mixer is employed to modulate and demodulate the signal detected by the photodetector, yielding the modulated transfer spectroscopy signal. The signal captured by the photodetector corresponds to the saturated absorption spectroscopy signal (SAS), while the demodulated signal by the mixer is identified as the modulated transfer spectroscopy signal (MTS). Leveraging the high signal-to-noise ratio of the modulated transfer spectroscopy signal, the laser frequency can be precisely locked onto the atomic transition line.

Currently, in compact optical frequency standards, the electro-optic modulator employed is the commercially available Qubig-PM7-NIR_4, and the photodetector is the commercially available Thorlabs-PDA8A. The laser source is a self-constructed 780 nm IF-ECDL. The quantum reference is the ^{87}Rb within the self-constructed MEMS vapor cell.

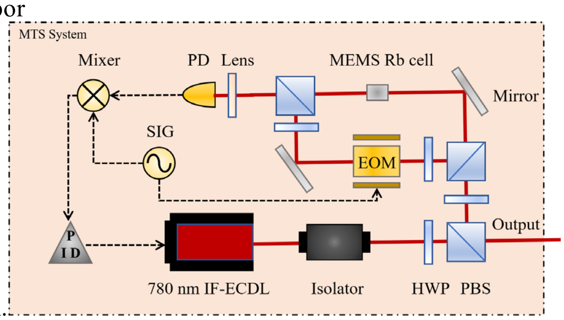

Fig.2 Schematic diagram of experimental set-up, the compact optical frequency standard with MEMS vapor cells.

III. RESULTS

Based on the compact optical frequency standard depicted in Figure 2, a quantum reference spectrum was obtained as shown in Figure 3. The red curve represents the Saturated Absorption Spectroscopy (SAS) signal detected by the photodetector, while the black curve represents the Modulated Transfer Spectroscopy (MTS) signal demodulated by the mixer. The MTS signal is a frequency discrimination signal, with the laser being locked at the zero crossing of the MTS signal. The slope at the center of the frequency discrimination signal often reflects the frequency discrimination sensitivity of the spectral line, hence the steeper the slope of the spectral line, the better.

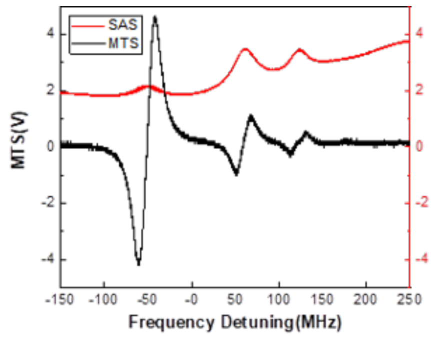

Fig. 3.The quantum reference spectrum :Saturation absorption spectroscopy (red-solid line) and modulation transfer spectroscopy (black-solid line) of the compact optical optical frequency standard D2 line.

The shape of the spectral line varies with different vapor cell temperatures. By optimizing the cell temperature, the maximum slope of the spectral line can be found. At a cell temperature of 80°C, the slope of the MTS corresponding to the 87Rb atom transition from $5S_{1/2}$ F=2 to $5P_{3/2}$ F'=3 is maximized. Utilizing the frequency discrimination signal obtained from the Modulated Transfer Spectroscopy technique, the laser frequency is locked onto the transition from F=2 to F'=3 through a servo loop, and the stability of the locked laser frequency is measured.

In this paper, the frequency stability is measured by two methods: beating frequency measurement and self-estimaed frequency measurement. Two identical systems were constructed and then frequency-shifted by 110 MHz using an Acousto-Optic Modulator (AOM) for beat frequency testing. The results of the beat frequency test are depicted by the black line in Figure 4. The compact optical frequency Standard with MEMS Vapor Cells' beat frequency stability is 4.8E-13@1 s.

By translating the voltage fluctuations of the error signal into frequency fluctuations, the self-estimaed stability of the system is represented by the red line in Figure 4, with the stability of 1.3E-14.

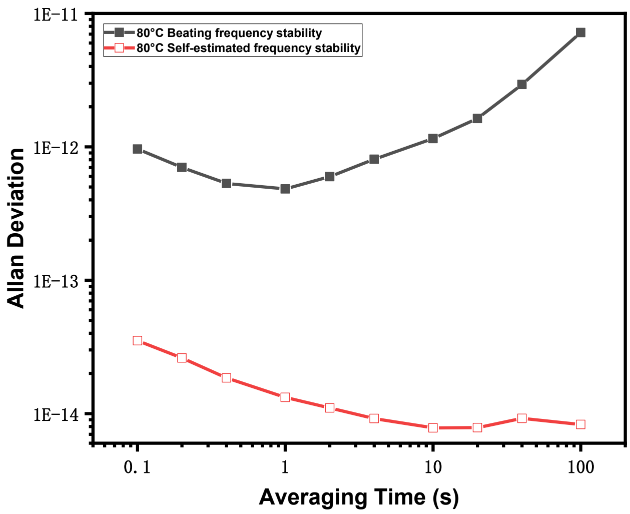

Fig.4 Frequency stability the of the compact optical frequency standards.

Frthermore, beat frequency testing has shown that the laser linewidth, which was in the tens of kHz before locking, has been significantly narrowed to 18 kHz through high-speed servo feedback locking.

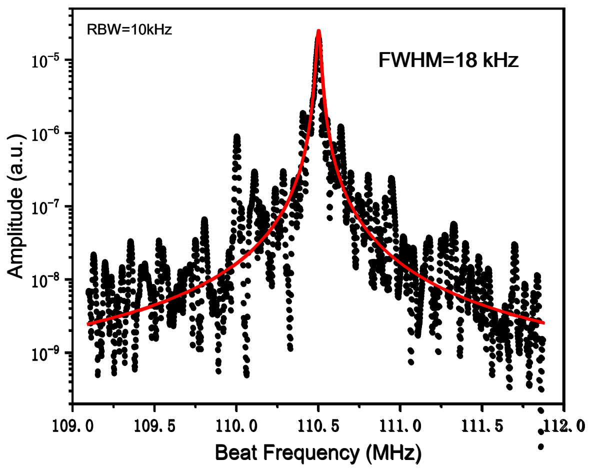

Fig.6 Typical beating data of two compact optical frequency standards.

IV. CONCLUSION

This paper introduces a new optical frequency standard that leverages MEMS vapor cells to achieve exceptional stability and a narrow linewidth, which using the modulation transfer spectrum technique with no Doppler background, high signal-to-noise ratio, and high sensitivity to lock the clock laser frequency to the atomic hyperfine energy level. The current specifications of our compact optical frequency standard include a frequency Allan deviation of 4.8E-13@1s and the laser linewidth of only 18 kHz. Employing a MEMS vapor cell in an optical frequency standard allows for a substantial reduction in system volume, preparing the groundwork for future miniaturization and chip-based integration.

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