Progress on a Compact Ultra-stable Laser System for Photonic Microwave Generation

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Summary-The technique for low noise photonic microwave generation [1-5] based on ultra-stable cavity [6-8] and optical frequency comb is being used in a growing number of fields. The optical frequency generated from stable laser locked to high-finesse cavities can be converted into microwave signal with high fidelity. In addition to continuously pushing the relative frequency stability of the ultra-stable laser system used in laboratory to new limit, various field operation scenarios need the cavity-stabilized laser to be compact and portable. In particular, the focus of our lab is that this ultra-stable microwave conversion scheme can serve as local oscillators of the fountain clocks to improve stability and compactness. In this paper, we present the experimental characterization of a compact ultra-stable laser system for photonic microwave generation and efforts to improve its robustness. As the core component, a commercial ULE cavity with length of 25 mm and truncated cubic geometry, which is rigidly fixed to provide effective isolation from vibration disturbances. The thermal noise limit stability of the cavity is predicted at 5E-15. ***Keywords—ultra-stable laser; photonic microwave generation; compact prototype***

I. INTRODUCTION

Nowadays, the fountain clocks certainly keep important roles in many time-keeping applications, and efforts on improving the performance of the fountain clocks are still of great significance. Therefore, the realization of extremely low noise microwave local oscillators is of great importance for fountain clocks reaching high stability. Through the optical-to-microwave down-conversion scheme, the frequency stability of the ultra-stable laser can be perfectly transferred to the microwave domain, and a microwave signal with the stability of the order of 1E-15@1s can be obtained. Using this ultra-stable photonic microwave source as a local oscillator, a fountain clock can reach its ultimate quantum-projection noise limitation [2]. Practical applications of these systems as reference oscillators, such as high accuracy Radar systems, deep space navigation, and synchronization, are limited by their dimensions. Although the optical fiber comb can be very compact, the reference FP cavity is always bulky and immobile. To meet transportation, requirements, the cavity should be rigidly held while still immune to vibrations.

Ultra-stable lasers[5][2][5] are the most important part of the photonic microwave generation system. To obtain an ultra-stable laser, its frequency is typically locked to a vibration isolated, high-finesse FP cavity with the Pound-Drever-Hall (PDH) technique. Therefore, the stability of the reference cavity itself is mainly influenced by environmental disturbance. We will introduce the design and construction of an ultra-stable laser system locked to a vibration-isolated high-precision cavity. Formerly with the assistant of the femtosecond frequency comb, the table-top ultra-stable microwave generation system has achieved a stability of 1E-15, and the stability of the NIM6 fountain clock with the ultra-stable microwave as local oscillator archived below 5E-14$\tau^{-1/2}$[3]. Through the compact design this article introduced, we hope can obtain portable microwave generation of the same order of magnitude.

II. METHODS & RESULTS

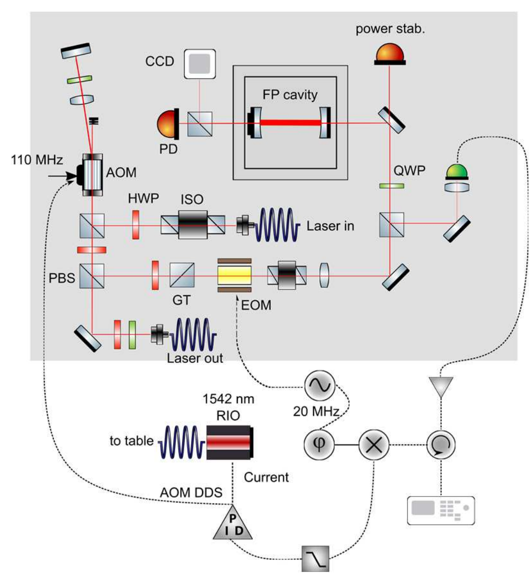

Fig 1. Schematic of the laser stabilized on the FP cavity. Red lines indicate optical signals, black lines denote the propagation of the electronic signal. A 1.5 μm RIO laser is stabilized to a commercial ULE cubic cavity by the PDH technique. All the components are height fixed at 27 mm to reduce vibration sensitivity. The EOM creates the sidebands used by the PDH frequency stabilization. Slow stabilization is applied to the current of the RIO laser diode, and fast stabilization is applied to the AOM. The gray block represents the optical breadboard placed on an active vibration isolation platform.

As shown in Fig 1, a low RIO laser output is coupled to an ultrastable cavity that set on an optical bread bord platform with a dimension of 40 cm *50 cm. The laser passes a 60 dB optical isolator to block the reflection back into the laser source. A double-pass scheme is used to stabilize the laser power and to shift the frequency by controlling the AOM driving RF. The intensity of the light incident in the cavity is also stabilized to minimize the thermal fluctuations of the cavity length due to the heating of the mirrors. The following polarizing beam splitter and half waveplate allow fine-tuning of the optical power. After passing through a Grant-Taylor polarizer, the beam is phase modulated at 20 MHz using an Electro-Optical Modulator (EOM).

We use two lenses to realize the mode-matching before injecting the beam into the cavity. The reflected signal beam is picked off with an optical isolator combined by a polarizing beam splitter and a quarter waveplate by a fast photodetector, whose output is compared with the local oscillator's signal via a mixer. The detected signal is amplified, filtered, and then mixed with a local oscillator to produce the error signal. The PDH stabilization is accomplished via feedback to the laser diode current and the laser cavity piezoelectric transducer (PZT).

The commercial cavity (Stable Laser Systems) has a cubical geometry of length 2.5 cm. The AR coating of the mirrors allows operation at 1.542 μm, in the telecom wavelength region. So, the free spectral range is 6 GHz. The spacer is made of Ultra-Low Expansion (ULE) material, with Fused Silica (FS) mirrors substrates to reduce the thermal noise floor. The FS mirror design has a drawback that the Coefficient of Thermal Expansion (CTE) increases to 64 ℃, due to the mismatch between the FS substrate and that of the ULE.

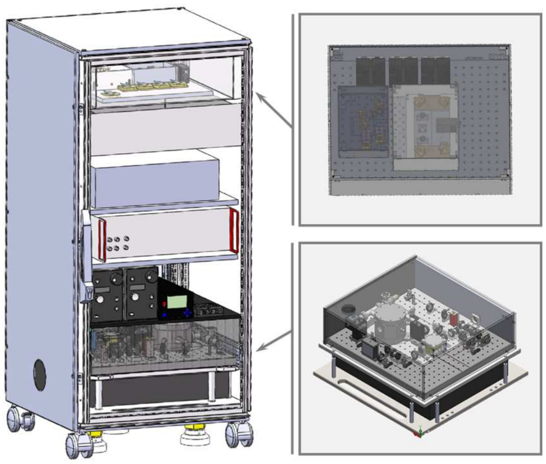

Fig 2. Left: the whole package of the photonic microwave generation system, in a 19-inch cabinet with a height of 1.2 m. **Right top:** the highly compact fiber frequency comb system. **Right bottom:** a compact optical device layout for coupling the laser beam to the cavity and distinguishing error signals. The optical table installed cavity is a 40 cm × 50 cm breadboard. The FP cavity is enclosed in a vacuum chamber sinking in the center. To balance the load, several excavations were carried out under the bank of the breadboard.

The cavity mirrors have a diameter of 1.27 cm, and the configuration is plano-concave with a radius of curvature of 500 mm. The designed finesse of the mirror is larger than 350 000. The Four-point tetrahedral mounting of truncated cube F-P Cavity is installed in a Vacuum chamber. The stainless-steel vacuum enclosure is approximately a cylinder with a radius of 75 mm and a height of 100 mm. A 2 L/s ion pump ensures a vacuum level at 10^{-5} Pa. Two interior stages of temperature control with thermoelectric coolers are used for sub mK level temperature maintenance. For the present cavity, it is roughly estimated to have a noise floor of 7E−15.

This setup is protected from environmental perturbations by being mounted on a commercial active vibration isolation unit. And the platform unit is set within an enclosure made of Polycarbonate plastic and lined with acoustic insulation foam. The useful output of the laser system is delivered from a fiber port located. The cavity is placed in a vacuum chamber with the pressure held at ~ 1E-5 Pa. To maintain the temperature of the cavity stable and uniform, the temperature of the vacuum chamber is held at the zero-crossing temperature of the cavity spacer around 64 ℃.

The integrated fiber frequency comb is located at the top of the cabinet, while the ultra-stable laser system is located at the bottom for a better stability. In addition, the entire system consists of several electrical components for power supply and servo control.

III. Conclusions

The integration and reliability enhancement of cubic cavity-based ultra-stable laser systems are of significance for practical applications of ultra-stable microwave generation. In the next step, we will finish the locking procedure. Then we plan to carry out transporting tests for the whole package and verify the stability advantages of the low height (fixed at 27 mm) optical components. These efforts will also benefit the development of portable optical clocks.

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