# Atomic Clocks, Gravimeters and Interferometer Research at KRISS

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## ABSTRACT

The Center for Time and Frequency at the Korea Research Institute of Standards and Science (KRISS) is responsible for the maintenance, improvement, and dissemination of time and frequency standards in Korea. In this paper, we will introduce current research activities regarding the development of precision atomic clocks, atomic gravimeters, miniature atomic clocks, and Bloch oscillation interferometers.

## INTRODUCTION

The development of a cesium fountain clock (realizing the current definition of the SI "second") and an Ytterbium optical lattice clock (for the future re-definition of the "second") are primary areas of research for time and frequency standards. The uncertainty of a state-of-art Cs fountain clock is as low as $10^{-16}$ and optical clocks have already surpassed the most accurate Cs fountain clock. The science and technology used for the development of Cs fountain clocks has been applied to build atomic gravimeters because Ramsey-type interrogation using two hyperfine states is a common scheme for both areas of research. High precision atomic clock technology combined with MEMS (microelectromechanical systems) technology has resulted in chip-scale, miniature atomic clocks, which have had wide applications in the modern world. The development of atomic interferometers based on the Bloch oscillation of ultra-cold atoms is another effort to realize ultimate precision in "force" related measurements.

## ATOMIC FOUNTAIN PRIMARY FREQUENCY STANDARD, KRISS-F1

The cesium atomic fountain primary frequency standard (PFS) is a means that realizes the definition of the SI second and contributes to TAI (International Atomic Time). These days, type-B uncertainty of state-of-art Cs fountain PFS approaches $10^{-16}$ by reducing two leading uncertainties, which are collisional frequency shift and distributed cavity phase shift [1-4]. We are developing a fountain primary frequency standard in order to contribute to TAI. The frequency of a Yb optical lattice clock developing at KRISS will be precisely measured by comparing the frequency of the fountain PFS for the future redefinition of the SI second.

Atomic fountain PFS, KRISS-F1 is a Rb/Cs double fountain [5]. We can trap two species at the same time with cooling laser beams, forming (111)-geometry. Since a laser system for cesium had been constructed at present, we have been experimenting with a Cs fountain. The physics package of KRISS-F1 consists of a trap chamber followed by an optical pumping section, state selection cavities, and a detection section. Most of the vacuum components are made of nonmagnetic metals like titanium, copper, and aluminum in order to reduce distortion of the magnetic field. We developed a novel fluorescent collection system that enables us to measure fluorescent signals from both atoms simultaneously. As atomic sources, we used an alkali atom evaporator which can be controlled by the heating current, instead of a pure alkali metal. We have developed microwave cavities with low DCP (distributed cavity phase shift) error based on Ref [6], in collaboration with the Pennsylvania State University [7].

The stable, long-term operation of fountain clocks, without the need for intervention, is preferred. With the goals of continuous operation of KRISS-F1 and minimal outages for maintenance, we have given special attention to the design of the physics package and the laser system. Features include precisely pre-aligned six fiber collimators that are directly attached to the surfaces of trap chamber ports to minimize changes in beam alignments. Small photodiodes in each fiber collimator monitor the trapping laser power. Two CCD cameras are installed on the trap chamber to monitor the cloud size and initial position during the operation of the frequency standard. We monitor the temperature of the physics package with sixteen calibrated PT-100 temperature sensors that are distributed over the physics package for an automatic calibration of the frequency shift due to blackbody radiation. A computer controlled two-axis high-resolution tilting system of the entire physics package has been developed for an evaluation DCP error. One of the key issues regarding stable fountain clock operation is the robustness of the laser system. Therefore, we have developed a stable laser system based on a DBR (distributed Bragg reflector) diode laser, which is more immune to acoustic and vibrational shocks than an ECDL (extended-cavity diode laser). We used a DBR diode laser with a maximum output power of 180 mW as a master laser that is amplified with a semiconductor tapered amplifier for laser cooling with maximum output power of 2 W. The master DBR laser is frequency stabilized to a Cs D2 transition line (F=4 to F′=5) with modulation transfer spectroscopy (MTS) [8]. A DBR diode laser is also used as a repuming laser. The output beam of the tapered amplifier is divided into two for upward and downward cooling beams followed by AOMs (acousto-optic modulators), then coupled into PM fibers going to the physics package. Even though DBR lasers are used in the operation of KRISS-F1, the short-term stability of KRISS-F1 due to the laser noise is measured to be $1.8\times10^{-14}$ at 1 s averaging time [9].

Previously the short-term stability of KRISS-F1 was $1.5\times10^{-13}/\tau^{-1/2}$ with a H-maser as a local oscillator (LO), which is limited by the phase noise of the LO. An ultra-low-phase-noise microwave source enables quantum-projection-noise (QPN) limited performance of an atomic fountain clock [10]. Therefore we, in collaboration with the University of Adelaide under an ARC (Australian Research Council) Linkage project, have introduced a liquid helium cryocooled sapphire oscillator (CSO) to generate an ultra-stable X-band signal [11]. The best short-term stability of KRISS-F1 for the highest detected atom number is $3.5\times10^{-14}/\tau^{-1/2}$ with the CSO as a LO which is limited by the QPN [12].

We are currently evaluating the cold collision and DCP shifts for an accuracy evaluation. Other frequency shifts are evaluated to be less than $10^{-16}$ or low $10^{-16}$. We aim for a total uncertainty of KRISS-F1 at the low $10^{-16}$ level.

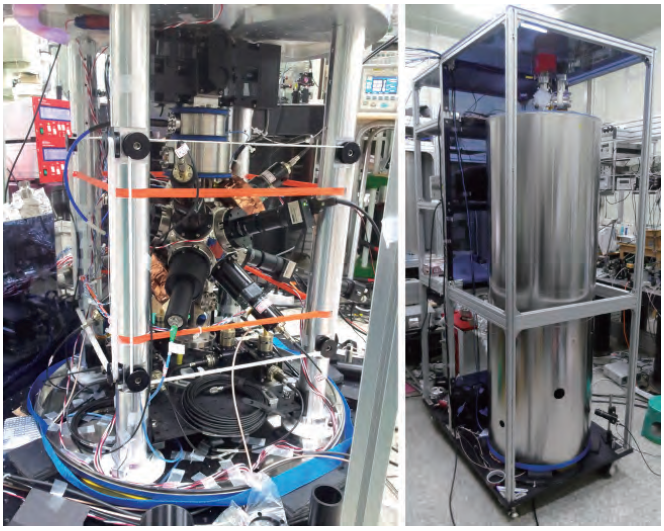

**Fig. 1:** Pictures of the lower part of the fountain clock¥ without magnetic shields (a) and the entire physics package with magnetic shields (b).

## OPTICAL LATTICE CLOCK

Cs fountain clocks with an uncertainty level at the low $10^{-16}$ level satisfies almost all of the requirements for the current public and the industrial sector; however, scientific research (e.g., fundamental physics, astronomy, and geophysics) still requires better clock performance, for which very narrow optical transitions of the single ion in Paul trap or neutral atoms in optical lattice have been studied. Several optical clocks in the world already have demonstrated $10^{-18}$ level of systematic uncertainty and stability [13, 14], hence the re-definition of the "second" using optical clocks is being discussed in the Consultative Committee for Time and Frequency (CCTF) [15].

At KRISS, $^{171}$Yb optical lattice clocks have been studied [16-18]. $^1S_0$-$^3P_0$ (518 THz) transition of the $^{171}$Yb atom with about 10 mHz linewidth is adequate for clock transition. Yb atoms are trapped in an optical lattice using a 759 nm laser light that gives the same potential depth (ac Stark shift) for the excited and ground states of the transition (magic wavelength) [19]. The optical lattice clock using many atoms has an advantage in the lower quantum projection noise compared to single ion clock. Also in the optical lattice clock where atoms are confined in a spatially localized area, Doppler-free spectroscopy is possible and environmental conditions such as magnetic/electric field and temperature are easily controlled. However, the light-induced shift originating from an oscillating electric field of lattice lasers and the collisional shift coming from collisions between atoms tightly localized in a site of lattice are disadvantages.

To evaluate the shifts, special efforts were needed. The optical lattice of our system was built with a cavity with finesse of 150, by which the lattice-induced shift could be studied over a wide range of trap depth, and the polarization of the lattice was purified well by using a polarizer installed inside the cavity. In addition, the collisional shift of atoms in the lattice was studied in [18]. The study was focused on finding the spectroscopy condition where the collisional shift is cancelled. Another study of interest is the precise determination of the shift of atoms by environmental blackbody radiation [19, 20], where the atoms in the lattice should be enclosed in a good thermal conducting chamber.

A clock laser with an ultra-narrow linewidth used in Rabi or Ramsey spectroscopy of cold atoms trapped in an optical lattice is an important part of clockworks. The success of the research is critically depending on the stability and linewidth of the laser. Clock lasers at 578 nm whose frequency were stabilized to a 10-cm long supercavity were developed and the stabilities are at the level of $2 \times 10^{-15}/\tau^{1/2}$ at 1-s average time. With this clock laser, the accuracy evaluation of optical clocks is possible down to $2 \times 10^{-17}$ level in 100 s average time, however it takes 40,000 s of it for $1 \times 10^{-18}$ level. To reduce the time for the evaluation, a clock laser with a stability lower than $1 \times 10^{-16}/\tau^{1/2}$ is under development.

The oscillation of an electro-magnetic field of a clock laser can be counted by the optical comb, i.e. the optical comb roles as a frequency converter between the frequency range of radio and optical frequencies [21], thereby the optical clock can serve as a practical clock. We have an erbium doped fiber comb system with an electro optical modulator (EOM) inside a cavity. EOMs control the repetition frequency of the optical comb, by which one of the optical components of the comb is phase-locked the clock laser; thus, the repetition frequency of the optical comb has the same stability as the clock laser. The stability of the repetition frequency of the optical comb was compared to the synthesized RF frequency from a cryogenic sapphire oscillator (CSO) used as a local oscillator of Cs fountain clock, and a stability of $5 \times 10^{-15}/\tau^{1/2}$ at 1-s average time was obtained [12]. The stability would be better if two clock laser systems and optical combs are used.

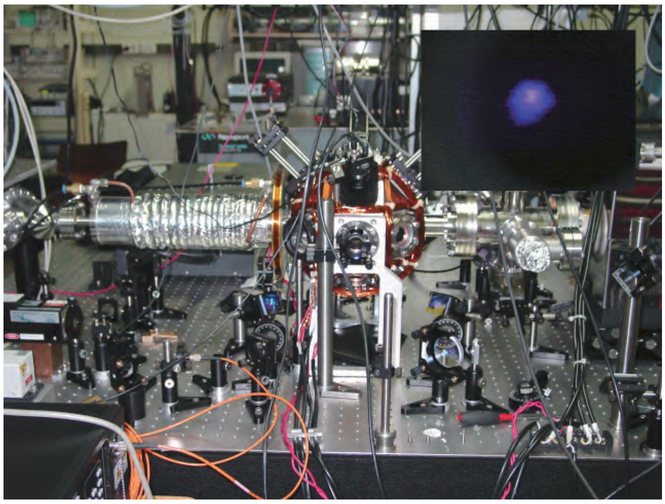

**Fig. 2:** Experimental setup for $^{171}$Yb atoms optical lattice clock.

The gravity by the Earth produces a time dilation of $10^{-18}$ for 1-cm height difference on its surface, which is a big obstacle in research of optical clocks because the geoid of the Earth is not yet defined with great accuracy. Thus the aim of uncertainty we are trying to reach with the optical lattice clock in KRISS is at the $10^{-18}$ level, at the present stage.

## ATOMIC GRAVIMETER

An atomic gravimeter has been attracting much attention as a promising technology for multidisciplinary applications and for high precision measurements in fundamental physics [22-26]. The atomic gravimeter has surpassed the sensitivity of its classical counter part FG5 but is still not the case in terms of absolute values. One of our goals is to develop a gravimeter with an uncertainty of better than $\Delta g/g=10^{-9}$ beyond that of FG5. An acceleration measurement is based on the difference of the phases accumulated along two paths of partial wave packets while being split and recombined by sequences of light pulses.

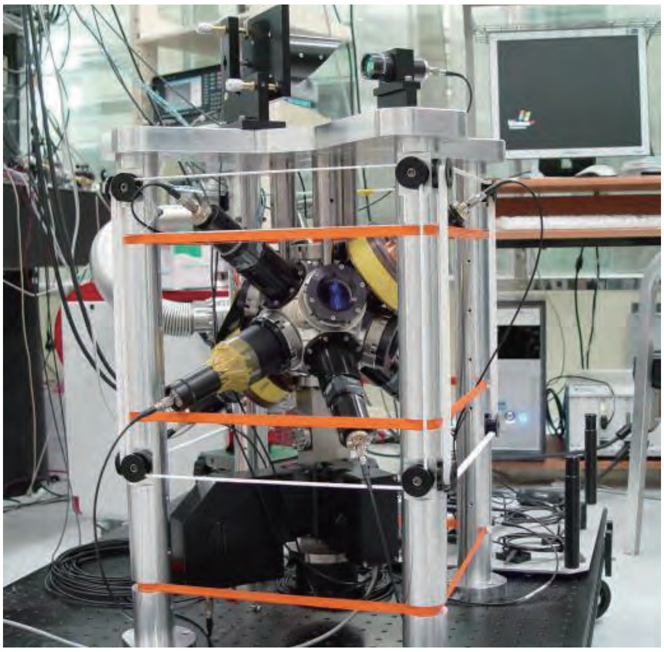

**Fig. 3:** A physical package of an atomic gravimeter.

A few $10^8$ $Rb^{87}$ atoms are captured in a magneto-optical trap as shown Fig. 3 and are cooled down to temperatures of a few μK. After free falling, they are manipulated by two counter propagating Raman pulses.

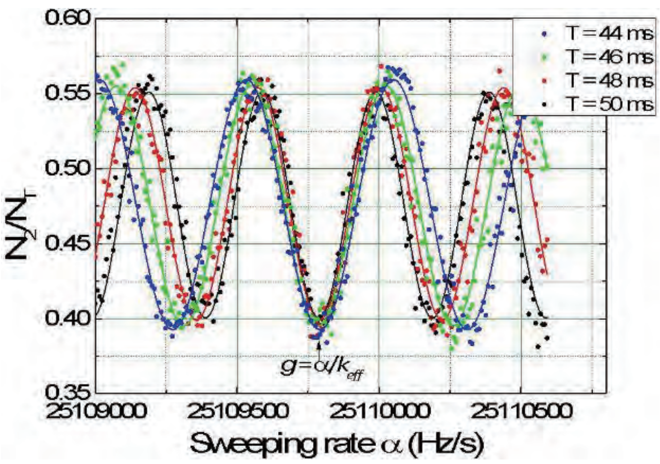


**Fig. 4:** Interference signals generated by two counter-propagating Raman lasers with pulses sequences of $\pi/2$-$\pi$ -$\pi/2$.

By compensating g (gravitation acceleration)-induced Doppler shift by scanning of frequency sweeping rate α, we can find the minimum fringe of excitation probability $N_2/N_T$ ($N_2$ is atom number of excited state, $N_T$ is the total atom number), which is independent of time interval T between pulses as shown Fig. 4. Gravitation acceleration g can be induced from a minimum positon α by the equation of $g = \alpha / k_{eff}$, where $k_{eff} = k_1 + k_2$ ($k_1$ and $k_2$ are wave numbers for two counter-propagating beams).

The sensitivity of our gravimeter is limited by parasitic vibrations. Now we are improving the sensitivity by using a technique of vibration rejection, based on active feedback or post-correction by the residual ground vibration noise measured with a low noise seismometer.

## MINIATURE ATOMIC CLOCK

Miniature (or chip-scale) atomic clocks have potential applications in a variety of industries, including military use, because of its small volume and low power consumption. For this reason, a substantial amount of research on miniature atomic clocks has been carried out in research institutes, universities, and industries [27-31].

KRISS is developing a miniature atomic clock for civil and military uses. Fig. 5 shows the physical package with 1 $cm^3$ of volume with integrated components. The physical package consists of a VCSEL, an optical neutral density filter, a quarter wave plate, a Cs vapor cell with Ne buffer gas, and a photodiode. Each component is mounted on an organic substrate. The substrates of the component are vertically stacked and electrically interconnected. Two sets of a micro-heater and a resistance temperature detector (RTD) are installed for temperature control of the VCSEL and the Cs vapor cell. For generating a constant magnetic field, a Helmholtz coil and a mu-metal shield are integrated.

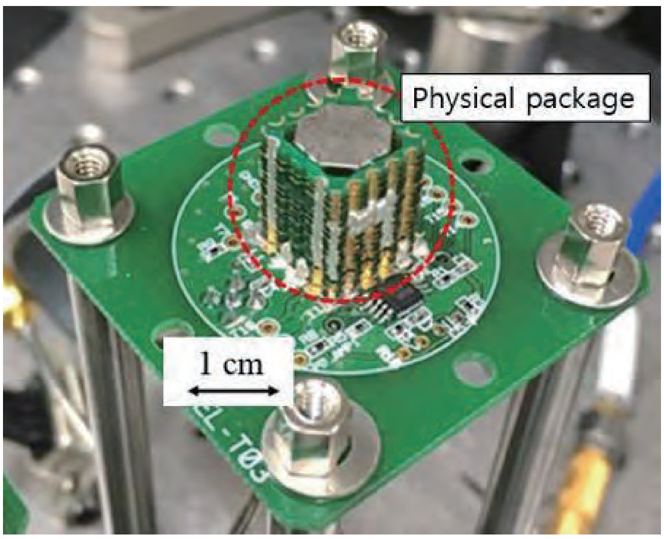


**Fig. 5:** Physical package of a miniature atomic clock.

Fig. 6 shows the coherent population trapping (CPT) resonance curves measured by a lock-in detection from the fabricated physical packages in Fig. 5. For a CPT resonance in cesium, the current of the VCSEL is modulated at the frequency of around 4.6 GHz so that the frequency difference between the -1st and +1st sidebands of the VCSEL output is near 9.2 GHz, which corresponds to the resonant frequency between the two ground states of cesium. The 4.6 GHz microwave for the VCSEL current modulation is again modulated at the frequency of 1 kHz for a lock-in detection. The resonance curves measured at the cell temperature of 80 ˚C and 85 ˚C, respectively, have linewidths of ~ 8 kHz.

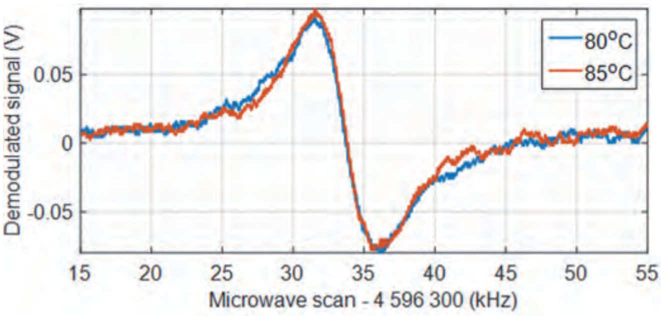


**Fig. 6:** CPT resonance curves obtained from the physical package.

## BLOCH OSCILLATION INTERFEROMETER

Ultracold atomic systems have played pivotal roles in high-precision measurements such as atomic fountain clocks, optical clocks, and fine constant measurements. Since the realization of Bose-Einstein Condensates (BEC), many experimental attempts have been made to utilize the BEC for higher precision interferometry with the expectation that the high phase density of BEC would increase the precision [32]. However, the high interaction energy between the atoms in BEC, due to its high density, turned out to be the main drawback leading to frequency shifts in spectroscopies, and fast decoherences in interferometries.

However, Fermi degenerate gas, which is sufficiently highly dense compared to the conventional cold atomic system, is interaction-free due to the Pauli principle, and could be employed for high precision interferometry to overcome the interaction-induced decoherence problem of BEC interferometry [33].

We employ Fermi degenerate gas for the Bloch oscillation interferometry [34] to measure the acceleration. Under the influence of a constant external force F, atoms loaded in an optical lattice performs oscillatory behavior in the quasi-momentum space with the Bloch oscillation period $T_B = h/Fd$ (h: Planck constant, d: lattice constant). Compared to the conventional free fall interferometry, the advantage of the Bloch oscillation interferometry is that it requires a very short free fall distance (a few micrometers) to measure the gravitational force since the atoms repeat the oscillation within a finite range of optical lattice sites.

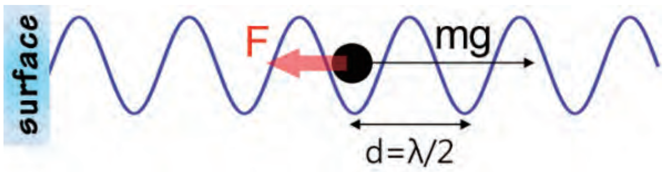


**Fig. 7:** Surface force measurement using Bloch oscillations.

The surface force such as Casimir type force could be measured by preparing the Bloch oscillation interferometer close to the surface of the sample substrate as described in the Fig. 7. The surface force F leads to the shift ΔT in the Bloch oscillation period. The measurement of Bloch oscillation period determines the surface force $F = mg\Delta T / T_0$, where $T_0 = h/mgd$ is the Bloch oscillation period without the effect of the surface.

Currently, we are at the stage of building the experimental apparatus. Fermionic $^{40}K$ atoms are employed for the Bloch oscillation interferometry, and $^{87}Rb$ atoms for sympathetic cooling coolant for $^{40}K$ atoms. Our system consists of a two-dimensional magneto-optical trap (MOT), and three-dimensional MOT (Fig. 8). As an atomic beam source for loading the three-dimensional MOT, we use a unique two-dimensional MOT system using frequency modulated MOT laser. After the three-dimensional MOT loading process, the atoms are loaded into a quadrupole-Ioffe-configuration trap. The RF-induced evaporative cooling is performed in the magnetic trap for the realization of $^{87}Rb$ BEC, and $^{40}K$ fermi degenerate gas. We have realized $^{87}Rb$ BEC with over $2 \times 10^7$ atoms. The laser cooling and sympathetic cooling of $^{40}K$ is currently being investigated.

The µm-range surface force measurement has been elusive since the conventional cantilever type method fails to work over this range. Bloch oscillation interferometry with ultra-cold atoms performs mainly on the µm-range. We expect that Bloch oscillation interferometry would

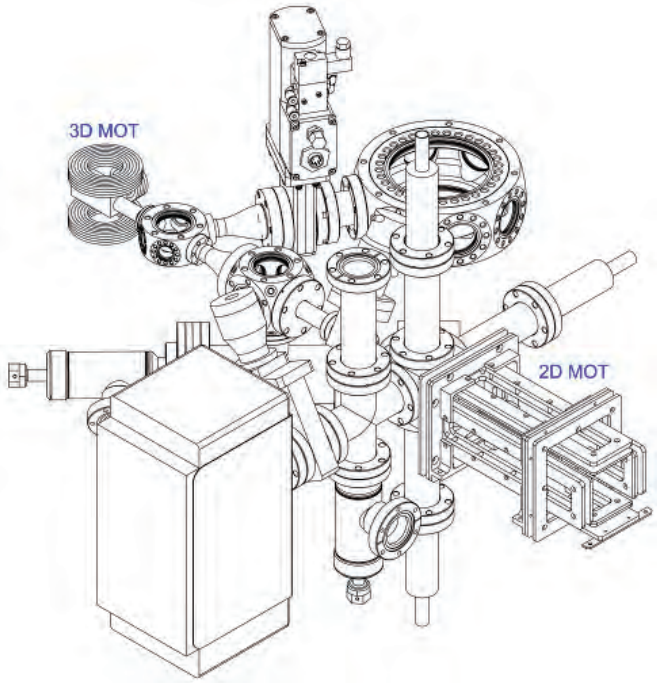


**Fig. 8:** Schematic of our experimental apparatus.

provide unique experimental platforms to extend the surface force measurement range above μm-range leading to the further study of various types of the μm-range forces such as Casimir-Lifshitz force.

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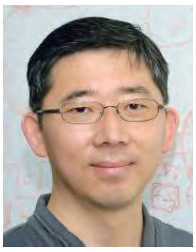

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