Synthesis Chains Based on Ultra-Stable Cryogenic Sapphire Oscillator at NICT

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***Abstract*—A synthesis chain based on a cryogenic sapphire oscillator (CSO) has been developed at NICT. The 11.2005GHz output of the CSO is down-converted to 1-GHz for laboratory distribution. The short-term frequency stability of the down-converter itself is better than 1×10^{-15} at an averaging time of 1 second. The long-term drift of the CSO is suppressed by referencing it to a hydrogen maser linked to Japan Standard Time. For microwave interrogation to the cesium atom, a 9.192-GHz up-converter was developed.**

I. INTRODUCTION

Stable reference sources such as hydrogen masers and voltage-controlled crystal oscillators are used as local oscillators (LO) for atomic frequency standards. The performance of the standard is often limited by its LO's short-term frequency stability. In fact, the frequency stability of the NICT (National Institute of Information and Communications Technology) cesium atomic fountain NICT-CsF1 is limited by that of our hydrogen maser [1]. And, also the measurement performance of the NICT optical frequency comb with its repetition rate locked to the hydrogen maser is limited by the hydrogen maser [2]. To overcome these limitations, NICT have introduced a cryogenic sapphire oscillator (CSO), developed in University of Western Australia (UWA) [3, 4]. The CSO has a short-term frequency stability of about 100 times better than that of the hydrogen maser. By using this ultra-stable source as a flywheel, it is expected to improve the performance of the frequency standards developed in NICT.

The NICT CSO oscillates at 11.2005GHz, with a short-term stability better than 2×10^{-15} at an averaging time of 1 second. In order to make the most of this highly stable signal for several experiments in several locations it is necessary to develop synthesis chains to change the oscillation frequency of the CSO to the appropriate frequency without any drastic degradation of the frequency stability of the synthesized signal [5, 6]. At first, for the purpose of laboratory distribution, we developed a synthesis chain to down-convert from 11.2005GHz to 1GHz. This 1GHz signal is distributed to other experimental rooms via coaxial cable. For dissemination of the 1GHz signal to distant sites, an optical fiber link is used [7, 8]. Additionally, a 9.192GHz synthesizer is required for microwave interrogation to the Cs atoms. We assembled a synthesis chain to up-convert the distributed 1GHz signal to 9.192GHz.

In this paper we describe the scheme and the characteristics of the 1GHz down-converter and the 9.192 GHz up-converter. As an application that makes use of this ultra-stable reference, we show the frequency stability measurement of a 729nm ultra-narrow linewidth clock laser, developed for our calcium ion frequency standard, using an optical frequency comb, in which the repetition rate is locked to the 1GHz signal from the synthesis chain based on the CSO.

II. CYOGENIC SAPPHIRE OSCILLATOR AT NICT

The cryogenic sapphire oscillator is based on a high quality HEMEX single-crystal sapphire. It is a cylindrically-shaped resonator, in which the resonance modes of the electromagnetic field within are located along the inside circumference of the sapphire in a so-called Whispering Gallery formation. The sapphire cylinder is enclosed in a silver-plated copper cavity, which has a small heater to control the temperature of the sapphire. This copper cavity is mounted in a vacuum can for isolation from environmental perturbations, which is then immerged in a liquid helium bath. The sapphire crystal, kept slightly above liquid helium temperature, has a high unloaded quality factor of about 10^9, it works as an ultra narrow band-pass filter. For microwave oscillation, the CSO employs a loop configuration, where a low noise RF amplifier provides sufficient gain. The oscillation frequency is servo-controlled by a Pound frequency

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stabilization scheme. The circulating power is also controlled to improve the long-term stability. Details are described in ref [3, 4].

The NICT CSO was developed at UWA then air-transported to Japan, where it is now maintained in a temperature-controlled room (+/- 0.2 deg C). In NICT, the sapphire crystal inside the vacuum can is maintained in a 250 liter liquid-helium dewar. The boil off rate of the liquid helium is about 8 liters per day and it is necessary to refill the liquid helium every three weeks for continuous operation. The NICT CSO oscillates in a $WGH_{16,0,0}$ mode at 11.2005GHz, which has a temperature turning point at 7.3K. Fig. 1 shows the frequency stability of the CSO. From the stability of the beat note between two nominally identical CSOs, the fractional frequency stability of the CSO itself is estimated as better than 2×10^{-15} for an averaging time of 1 second, reaching a minimum about 5×10^{-16} at 30 to 60 seconds. It is about two-orders of magnitude better than that of the hydrogen maser.

By comparison with a hydrogen maser, we have confirmed that the NICT CSO has a fractional frequency drift rate of about 10^{-14} /day, thought to be chiefly attributable to ambient room temperature fluctuations. Although the long-term stability is still worse than the hydrogen maser, this drift is much smaller than the results of the previously developed CSOs [9] as the frequency and power control servos are improved, and the environment at NICT is carefully controlled.

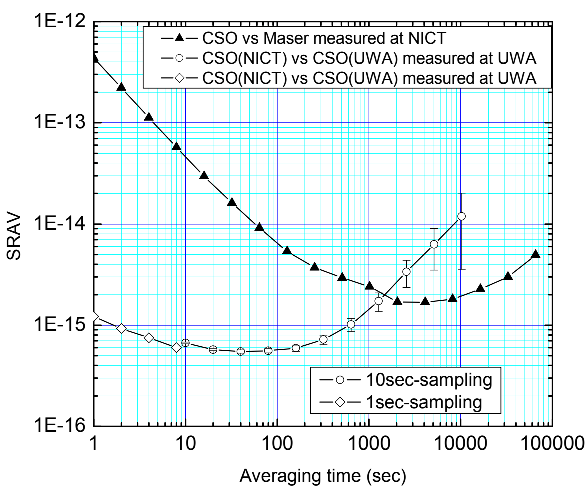

Fig.1 Frequency stability of NICT cryogenic sapphire oscillator. SRAV: square root of Allan variance.

III. 1GHz Down-converter

In order to use the CSO signal for several experiments developed in other rooms, we have developed a synthesis chain to down-convert from 11.2005GHz to 1GHz. Fig.2 shows the block diagram of the 1GHz down-converter. The output signal of a 1GHz low-noise surface acoustic wave (SAW) oscillator is amplified and injected into a nonlinear transmission line. The nonlinear transmission line is used for frequency multiplication as a frequency comb generator. The 11th harmonic (11GHz) is band-pass filtered and mixed with the 11.2005GHz output from the CSO to generate a

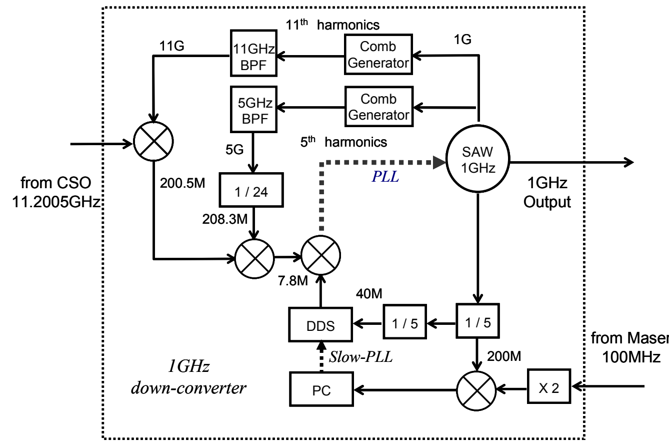

Fig.2 Block diagram of 1GHz down-converter

200.5MHz signal. The 5th harmonic (5GHz) from another nonlinear transmission line is divided to 208.3MHz by divide-by-eight and divide-by-three pre-scalars. The 208.3MHz signal is mixed with the 200.5MHz to generate 7.8MHz. Fine tuning of the down-converter is achieved by controlling a commercial direct digital synthesizer (DDS) in the chain. To avoid stability degradation due to the DDS it has modified to take its external reference from a 40MHz signal generated from the 1GHz signal of the SAW oscillator through two divide-by-five stages. The zero beat between the two 7.8MHz signals at the last mixer is used to phase-lock the 1GHz SAW oscillator to the CSO. The relation between the output frequencies of the CSO, the DDS and the SAW is given by,

$$CSO - \left(11 + \frac{5}{24}\right) \cdot SAW = DDS\,.$$

Consequently, the 1GHz signal is controllable with a resolution of about 0.1μHz maintaining the stability of the CSO.

The intermediate signal (200MHz) in the down-converter is mixed with a doubled 100MHz signal from the hydrogen maser in order to compensate the long-term frequency drift dependence of the CSO. The output voltage from the mixer is monitored via an analog to digital converter and the frequency of the DDS is steered to make the output voltage constant over the long-term. By this slow stabilization, the frequency difference between the output signal from the down-converter and the hydrogen maser becomes zero, making it traceable to Japan Standard Time (JST) [10] and International Atomic Time (TAI).

A. Performance check in the Short-term

We assembled two nominally identical 1GHz down-converters to evaluate the performance of the down-converter itself. The 11.2005GHz signal from the CSO is divided into two signals which are used for phase-locking two 1GHz down-converters. By varying the frequency of each down-converter's DDS the 1GHz output signals are independently tunable. Figure 3 shows the residual phase noise spectral density of the down-converter measured with an Agilent E5500 phase noise measurement system, where the 1GHz signal from one down-converter is used as a signal and the other as a reference. The resultant residual phase noise was measured to be -118 rad^2/Hz at 1Hz from the carrier and below -140 rad^2/Hz for Fourier frequency beyond 100Hz. A peak at around 100kHz from the carrier is due to the 1GHz SAW oscillator itself, which is unavoidable.

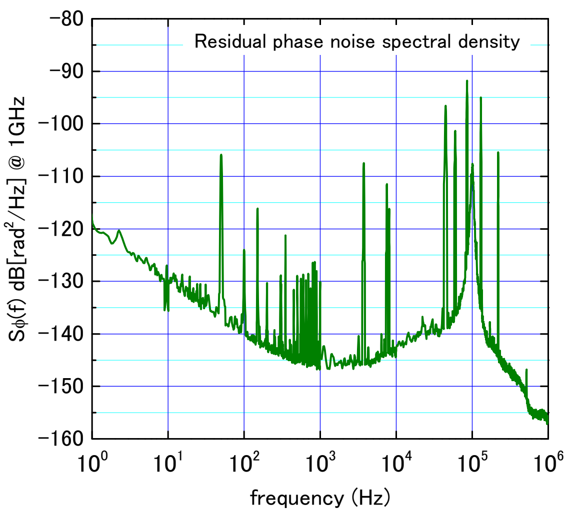

Fig. 3 Residual phase noise density of two identical down-converters at 1GHz

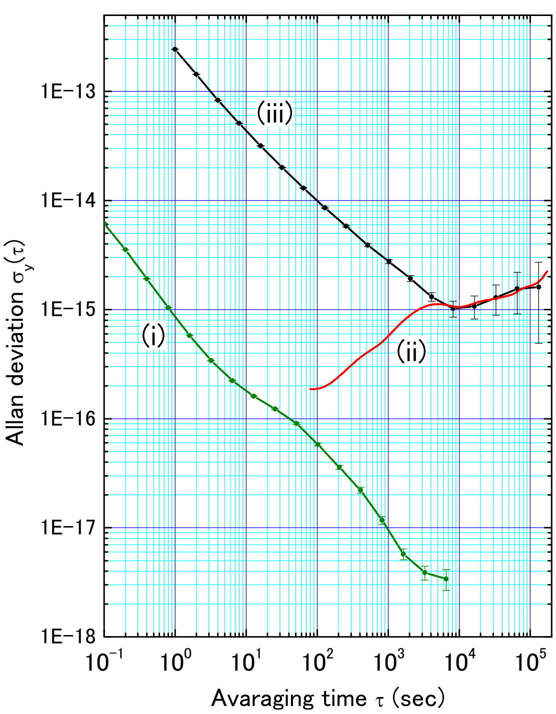

Fig. 4 Fractional frequency stabilities (i) of two 1GHz down-converters without steering to the hydrogen maser, (ii) of two 1GHz down-converters which are loosely locked to two masers independently and (iii) of two hydrogen masers.

To measure the residual frequency stability of the down-converter, we used an Anritsu Corporation frequency stability measurement system. Both 1GHz signals are down-converted to 10.1MHz by mixing with a common reference (989.9MHz) and the phase difference between two 10.1MHz signals is measured with high-speed analog to digital converter with a low-pass filter [11]. By this dual-mixing time difference (DMTD) method, we can obtain more reliable results than deducing the stability from the output voltage of a mixer. Figure 4 shows the residual frequency stability of the 1GHz down-converters, which is better than 1×10^{-15} at an averaging time of 1second with a measurement bandwidth of 5Hz. It can be seen that the down-converters do not degrade the short-term stability of the CSO.

B. Long-term stabilization to the hydrogen maser

The NICT CSO has a long-term frequency drift of about 1×10^{-14} per day. The frequency drift of the CSO is compensated by mixing with the output of the hydrogen maser and steering the output frequency of the DDS in the down-converter. The steering is adjusted to null the output voltage of the mixer after averaging over 1000 seconds. By this digital steering, the 1GHz output is loosely locked to the hydrogen maser, which is linked to Japan Standard Time. Fig. 4 shows the residual frequency stability between two down-converters, which are loosely locked to two independent hydrogen masers. It can be seen that the synthesized signal's long-term stability corresponds to that of two hydrogen masers. This indicates that both 1GHz signals are independently well-stabilized to the hydrogen masers.

IV. 9.192GHz UP-CONVERTER

A 9.192GHz microwave souse is generated from the transmitted 1GHz signal (from 11.2005GHz via 1GHz to 9.192GHz). The simplified diagram of the 9.192GHz up-converter is shown in Fig.5. In the first stage, the distributed 1GHz is phase-locked to a 1GHz SAW oscillator. This tracking filter provides a stable amplitude source for the synthesis chain. The 1GHz output signal from the SAW oscillator is amplified and injected into a comb generator. The 9th harmonic (9GHz) of the comb is band-pass filtered and mixed with the 8.992GHz output from a dielectric resonant oscillator (DRO) to generate 8MHz. The fine tuning of the up-converter is achieved by controlling a DDS in the chain. This DDS also is modified to take its reference from the 40MHz reference as described above. The zero beat between the down-converted 8MHz and 8MHz output from the DDS is used to digitally phase-lock it to the 8.992GHz DRO. A portion of 8.992GHz output is mixed with 200MHz to generate a 9.192GHz signal by means of band pass filter. The 9.192GHz output power is adjustable by varying the 200MHz signal level via a variable attenuator.

To evaluate the performance of the 9.192GHz up-converter itself, we assembled two nominally identical up-converters, which were locked to one common 1GHz reference. Figure 6 shows a residual phase noise spectral density and a residual frequency stability of the 9.192GHz up-converters including the 1GHz tracking filter. The phase noise was measured directly by the Agilent E5500 and the fractional frequency stability was measured by a beat measurement with a 5Hz low pass filter.

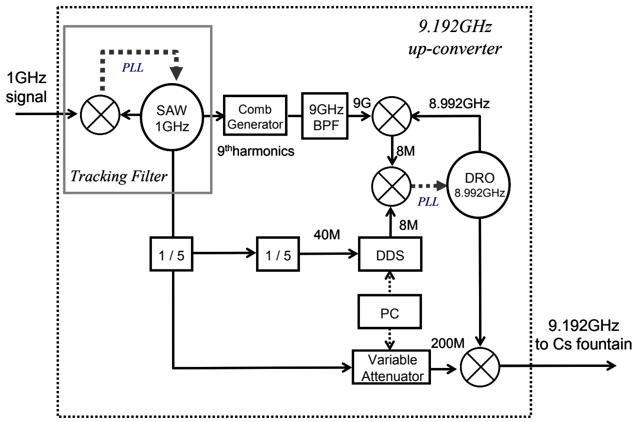

Fig.5 Block diagram of 9.192GHz up-converter

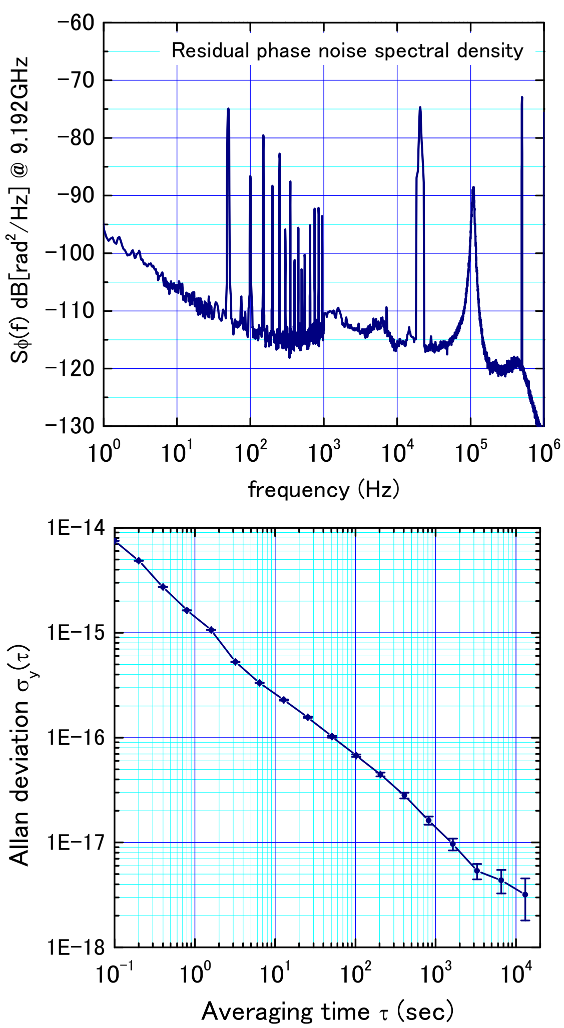

Fig.6 Residual phase noise spectral density (Upper) and residual frequency stability (Lower) of 9.192GHz up-converters

A phase noise of -97 rad^2/Hz at 1Hz from the carrier and a short-term frequency stability of 1×10^{-15} at an averaging time of 1 second were measured.

V. Application To Measurement of Ultra-narrow Linewidth Clock Laser for Optical Standard

At NICT, two optical frequency combs based on femtosecond-pulse mode-locked Ti:sapphire lasers have been developed. These lasers have a relatively broadband spectrum, which permit the determination of the carrier envelope offset frequency without extra broadening by the photonic crystal fiber. In addition, a 729nm ultra-narrow linewidth laser has been developed as a clock laser for a single Ca^+ ion clock. Details about the broadband optical frequency combs and the clock laser are described in [2, 12]. As an application of this highly stable reference, we performed frequency stability measurements of the 729nm clock laser using the optical frequency comb. The repetition rate of the optical comb was phase-locked to the 1GHz signal derived from either the CSO or the hydrogen maser. Fig.7 shows the results of frequency stability measurements. When the ultra-stable CSO reference was used, a fractional frequency stability of 10^{-15} at 1 second was observed. Details will be described elsewhere.

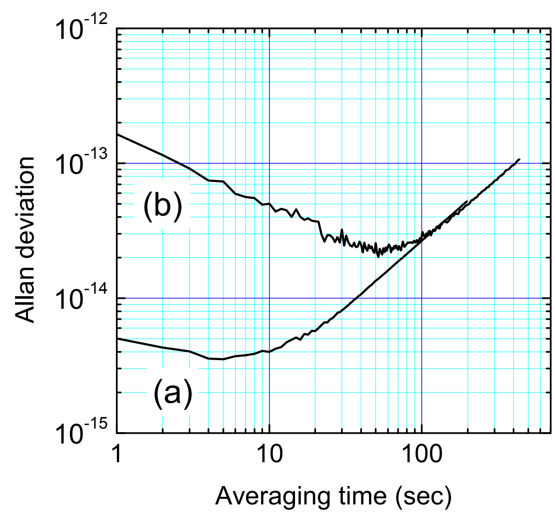

Fig. 7 A fractional frequency stability of 729nm clock laser by the optical frequency comb based on (a) the CSO and (b) the hydrogen maser.

VI. Summary

NICT has introduced a UWA built cryogenic sapphire oscillator with a short-term frequency stability better than 2×10^{-15} at 1 second. We have developed synthesis chains to down-convert the 11.2005GHz output frequency of the CSO to 1GHz signal and to up-convert the resulting 1GHz signal to 9.192GHz. These frequency converters make it possible to tune the microwave frequency without degradation of the short-term stability of the CSO. The 1GHz down-converters are loosely locked to the hydrogen masers, which are traceable to Japan Standard Time. As an application, we performed the frequency stability measurements of the clock laser using the optical comb referencing to the synthesized signal derived from the CSO. We achieved a much better result than that when limited by the maser. We will use this highly stable signal as a reference of our atomic fountain NICT-CsF1 soon.

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