Frequency Comb Development at the NRC

Claude Marceau, Scott Beattie, Marina Gertsvolf
National Research Council Canada
Ottawa, Canada
claude.marceau@nrc-cnrc.gc.ca

***Summary*— We describe the portable fiber combs that were recently set up at the NRC. We also describe two of their intended applications: the frequency measurement of a strontium-88 ion clock against the primary standard NRC-FCs2 and ultra-stable radio frequency synthesis.**

Keywords*— *frequency combs; atomic clocks; ultra-stable RF.;

I. Introduction

Since the first demonstration of a fully controlled optical frequency comb (OFC) in 1999 [1], OFCs have revolutionized frequency metrology by coherently bridging the gap between microwave and optical frequencies [2]. They are nowadays used in a large range of applications including astronomy, spectroscopy, attosecond science and atomic clock comparison [2]. Optical atomic clocks with systematic fractional frequency uncertainty reaching two orders of magnitude lower than the best Caesium fountain clocks [3] now represent several potential candidates for the future redefinition of the SI second, which is likely to occur in the next 5-10 years [4,5]. The accurate knowledge of the absolute frequencies of these optical atomic clocks is among the requirements set by CCTF [5] on the roadmap to a redefinition. This measurement can only be obtained by direct comparison with a primary standard operating at microwave frequencies, and, consequently, require OFCs.

In this work, we describe the portable fiber OFCs that were recently implemented at the NRC and two of their intended applications. First, they will be used to perform precision frequency measurements of a $^{88}Sr^{+}$ ion clock at 674 nm [6,7] against the NRC-FCs2 primary frequency standard [8]. Second, they will generate ultra-stable radio frequencies (RF) to serve as a local oscillator for FCs2. This has the potential to improve by a factor of three the short-term stability of FCs2, and thus reduce averaging time by a factor of nine, dramatically reducing the time required for a reevaluation of the systematic uncertainties of FCs2.

II. Er fiber combs

NRC erbium fiber combs were built in a collaboration between NIST and NRC. One comb and its pump lasers are shown in Fig. 1. An earlier generation of the combs was described in [9]. Briefly, each comb starts with an oscillator pumped at 1480 nm by a diode laser. Mode-locking is made “turn-key” by a saturable absorbing mirror at one end of the cavity. An erbium doped fiber amplifier after the oscillator isolator is pumped in both forward and backward directions by 980 nm diodes. A highly nonlinear fiber is then used to widen the spectrum to over an octave. Frequency doubling of light at 1960 nm is achieved by a periodically poled KTP waveguide. The carrier envelope offset beat signal, f_0, is isolated by a filter or a grating around 980 nm and it is digitally phase-locked by applying feedback to the oscillator pump laser current.

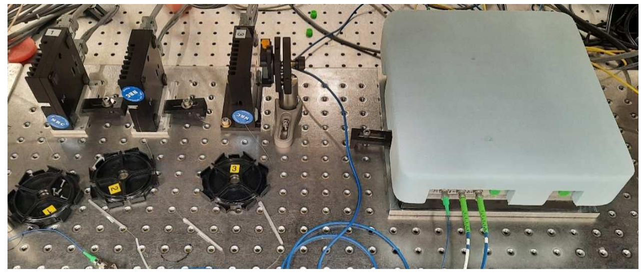
Fig. 1 – One erbium fiber comb (right) and its three pump lasers.

The repetition rate, f_r, varies with temperature at a rate of -10 ppm/°C [9]. The total length of the spliced fibers in the oscillator was precision cut to obtain 1560 nm pulses at a repetition rate of 160 MHz within a few degrees Celsius tuning from room temperature. The full dynamic range of the piezoelectric transducers (PZTs) glued to the oscillator fiber yields approximately 800 Hz of tuning range for the repetition rate. The two PZTs are used to lock one mode of the OFC to an ultra-stable external laser reference. Temperature control with four Peltier elements under the comb aluminum enclosure was implemented to increase the repetition rate tuning range and ensure that the PZTs remain near the middle of their range.

III. Towards Strontium-88 ion clock frequency measurement against NRC-FCs2

The single ion clock probing the 0.4 Hz natural width electric quadrupole transition 5s $^2S_{1/2}$ – 4d $^2D_{5/2}$ in $^{88}Sr^{+}$ was described in [10]. Previous frequency measurements [6,7] have compared the single ion clock at 445 THz (674 nm) to a hydrogen-maser that serves as our local realization of Coordinated Universal Time (UTC-NRC). The ion clock last reported a 3×10^{-15} fractional uncertainty at one second [7]. Recently, our primary frequency standard, NRC-FCs2 caesium fountain clock was commissioned and began reporting to BIPM [8]. The next measurement campaign of the $^{88}Sr^{+}$ ion clock will be against NRC-FCs2. This will eliminate the GPS link uncertainties from the error budget.

A simplified schematic of the setup is shown at Fig. 2. The 674 nm ion clock laser is locked through the Pound-Drever-Hall technique to a ULE cavity maintained in ultrahigh vacuum at its zero thermal expansion temperature [10]. The erbium comb

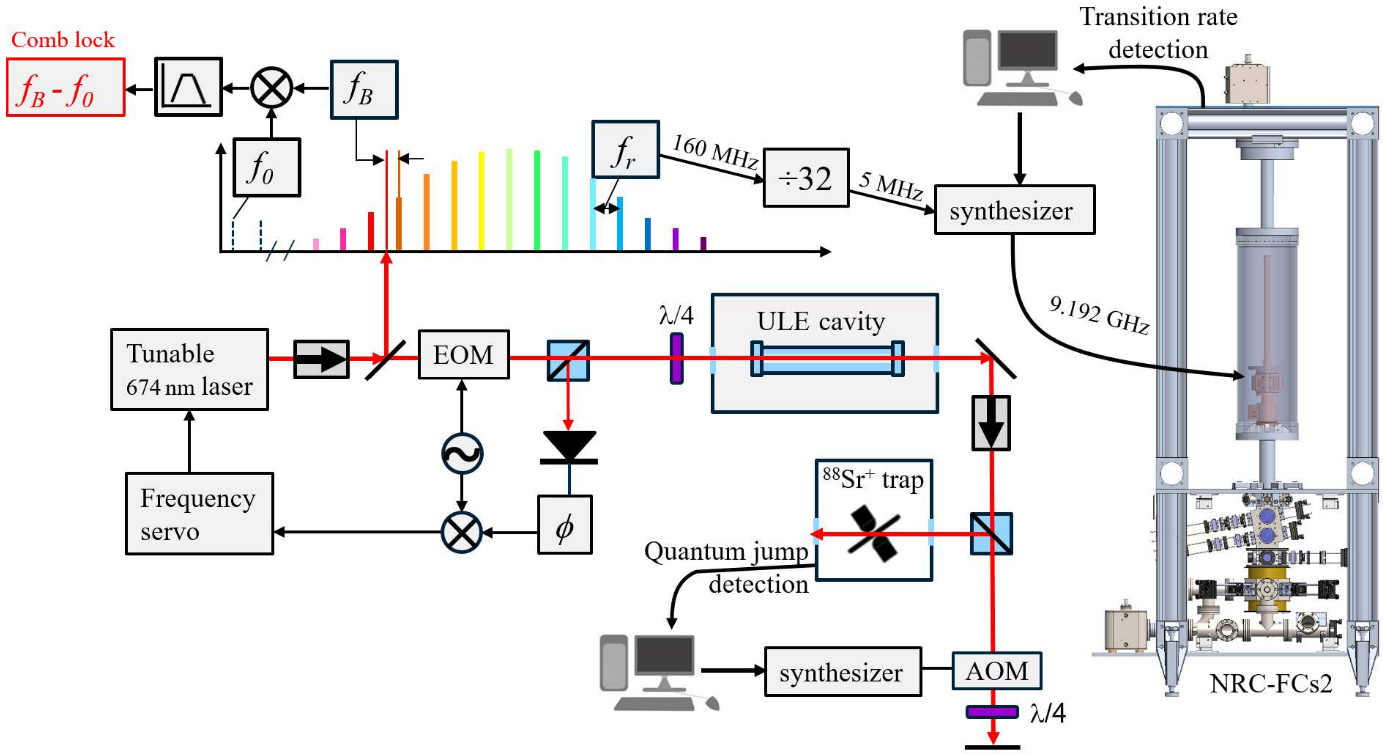

Fig. 2 – Schematic of the experiment setup. See text for details.

centered at 1560 nm is broadened through supercontinuum generation to reach the 674 nm spectral range. A heterodyne beat, f_B, of the closest comb tooth with the clock laser is measured by a photodiode. The carrier-envelope offset frequency f_0 is locked. In order to minimize f_0 noise coupling to the repetition rate, the difference between f_B and f_0 is locked using the two PZTs glued to the comb oscillator fiber [9]. The lock point f_B-f_0 is adjusted so that f_r equals 160 MHz to better than 1 part in 10^{10}. This ultra-stable RF signal is then divided by 32 and fed to the microwave synthesizer. On the ion clock end, the clock laser is shifted by an acousto-optic modulator (AOM) in a double pass geometry. Three pairs of Zeeman levels are probed subsequently and detection is done by the electron shelving method [6,7]. Feedback is applied to the AOM by a synthesizer. Both NRC-FCs2 and the ^{88}Sr$^+$ clock are referenced to the same local oscillator, the ULE cavity, and can be compared directly. This setup will allow the most precise measurement of the ^{88}Sr$^+$ clock frequency.

IV. Ultra-stable RF generation

One current limitation of FCs2 is the stability of the local oscillator (1×10^{-13} at one second), a hydrogen maser, used to synthesize the 9.192 GHz microwave clock radiation [8]. It was reported that a cryogenic silicon cavity in the near infrared had a fractional uncertainty as low as 4×10^{-17} at one second integration time [11]. Frequency division by OFCs is then possible to generate ultra-stable RF with comparable levels of stability. While achieving such low RF noise level is possible but challenging, other factors, internal to FCs2, would limit its stability to around 3×10^{-14} at one second. Ultra-stable RF achieving about 1×10^{-14} fractional uncertainty at one second would be sufficient to improve FCs2 stability by a factor of three and thus reduce averaging time by a factor of nine. This could expedite a reevaluation of the systematic uncertainties of FCs2. Several options to improve the local oscillator stability of FCs2 are being considered such as building a dedicated new ultra-stable cavity or using the existing cavity at 674 nm as in Fig. 2.

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