An Acetylene Optical Clock with Maser-like Performance Assembled from Commercially Available Products

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Summary: Vescent and the Danish National Metrology Institute (DFM) have demonstrated hydrogen-maser-like performance of an acetylene optical clock assembled by simple integration of the two companies' commercial-off-the-shelf (COTS) products. A 100 MHz clock output with frequency instability of $2.6\times10^{-13}/\sqrt{\tau}$ and a long-term instability reaching 8×10^{-15} around τ = 2,000 s was demonstrated by combining Vescent's FFC-100 frequency comb with the DFM Stabiλaser 1542$^{\varepsilon}$ optical frequency reference.

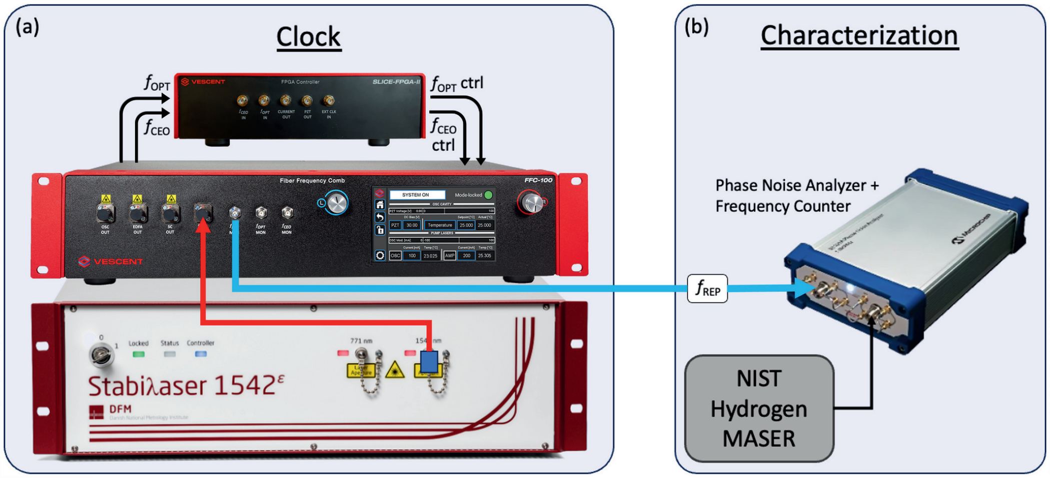

Figure 1. (a) Commercial components required for the acetylene optical clock demonstration. Shown are the DFM Stabiλaser 1542$^{\varepsilon}$ acetylene optical frequency reference (bottom) whose optical output is connected to the Vescent FFC-100 fiber frequency comb (middle) for optical heterodyne detection. RF beat notes are then sent to the Vescent SLICE-FPGA-II digital feedback controller (top) where control signals are generated and sent back to the FFC-100 to stabilize the repetition rate. (b) Characterization setup to measure the acetylene clock against a NIST active hydrogen maser.

<u>Introduction:</u> Advanced clocks capable of exhibiting sub-picosecond timing instabilities are becoming necessary for advancements in critical application spaces such as resilient positioning, navigation, and timing (PNT), distributed radar networks, very-long-baseline interferometry (VLBI), and in distributed database networking and time protocols. State-of-the-art optical clocks meet the stringent timing stability requirements of these applications but are currently constrained to laboratory environments due to the low technology readiness level (TRL) of many, if not all, of their necessary subsystems. These critical subsystems include optical frequency combs (OFC's), narrow-linewidth lasers, low-noise control electronics, and atomic/molecular physics packages. Recent developments at both Vescent and DFM have led to the release of COTS products that can be easily combined to make a high-performance optical molecular clock that rivals the performance of state-of-the art masers [1] but with *drastically* reduced size and environmental susceptibility, comparable to cesium beam tube clocks (*e.g.*, Microchip 5071A).

Setup and Results: The setup used by Vescent for this demonstration is shown in Figure 1. Note that this setup takes <30 minutes of assembly and warm-up time to achieve the optical clock performance described below. The systems are placed on a desk and plugged directly into wall power without any need for environmental isolation. The full optical clock includes: (1) the DFM Stabiλaser 1542 optical frequency reference (OFR) and (2) the Vescent FFC-100 OFC and SLICE-FPGA-II digitål feedback controller.

(1) The DFM Stabiλaser is based on frequency-stabilizing a narrow linewidth laser to an overtone transition in acetylene near 1542 nm using frequency modulation (FM) saturated absorption spectroscopy. The DFM Stabiλaser outputs >10 mW of the frequency-stabilized light in a PM1550 fiber. The laser, spectroscopy cell, modulators, and control electronics are all contained in a 3U rackmount chassis with a volume of approximately 30 L. The integrated linewidth of the 1542 nm output is measured to be <600 Hz using the $1/\pi$ rad^2 method [2].

(2) The Vescent FFC-100 OFC is based on robust telecom fiber technology and enclosed in a 10 L, 2U rackmount chassis. The fully phase-stabilized comb performs at a fractional frequency instability level of $<5\times10^{-17}/\tau^{3/2}$ (modified Allan deviation, in-loop), which indicates the amount of instability the comb would contribute to any optical clock measurement. Vescent's OFC's have been designed and tested to operate reliably over large temperature ranges and have been proven to maintain continuous operation over several months (thus far limited by user-initiated interventions to disable the measurement).

Briefly, the 1542 nm optical output from DFM's Stabiλaser is connected to the FFC-100 front panel and a heterodyne beatnote (f_{opt}) between the stabilized 1542 nm optical frequency (f_{1542}) and the nth optical mode of the OFC (f_n) is generated internal to the FFC-100:

$$(1) \quad f_{opt} = | f_n - f_{1542}|$$

All the optical and electrical signal conditioning to produce a high signal-to-noise f_{opt} beatnote signal is contained inside the FFC-100. The resulting f_{opt} signal is output from an SMA port on the front panel and connected to the SLICE-FPGA-II. The SLICE-FPGA-II performs a digital proportional-integral-derivative (PID) lock of the f_{opt} beatnote to an internal RF oscillator with the control signal connected to the "PZT MOD" input (a high-speed actuator controlling the comb's repetition rate) on the FFC-100 back panel. In this configuration, the nominal 100 MHz repetition rate (f_{rep}) of the mode-locked laser at the heart of the FFC-100 is fully defined by the following equation:

$$(2) \quad f_{rep} = \frac{f_{1542} \pm f_{opt} \pm f_{CEO}}{n}$$

where f_{CEO} is the carrier-envelope offset frequency defined by the evolution in the pulse-to-pulse change of the carrier-envelope phase of the mode-locked laser. The f_{CEO} signal is generated and appropriately conditioned automatically inside the FFC-100 and the f_{CEO} output is connected to the SLICE-FPGA-II. A second PID loop performed by the SLICE-FPGA-II locks the f_{CEO} frequency to an internal RF oscillator with the control signal connected to the "Current MOD" input on the FFC-100 back panel. With f_{1542}, f_{opt}, and f_{CEO} all stabilized, the 100 MHz f_{rep} output from the frequency comb is now fully stabilized and has a frequency instability of:

$$(3) \quad \partial f_{rep} = \frac{(|\partial f_{1542}|^2 \pm |\partial f_{opt}|^2 \pm |\partial f_{CEO}|^2)^{1/2}}{n}$$

Equation (3) illustrates the power of optical frequency division provided by the comb, wherein the absolute instability on each of the three frequencies on the right side of the equation are divided by n where $n \approx 1.94\text{x}10^6$. Since f_{1542} is an optical frequency of ~194 THz while f_{opt} and f_{CEO} are much lower RF frequencies of <50 MHz, the noise on the repetition rate is dominated by ∂f_{1542} such that $\partial f_{rep} \approx \partial f_{1542}/n$. Therefore, the stability of the 100 MHz f_{rep} output from the FFC-100 mimics the pristine stability of the acetylene optical reference and faithfully transfers it down to the RF domain where the clock signal can be integrated directly into existing timing infrastructure. To demonstrate this, the 100 MHz clock output from the acetylene clock is measured against an active hydrogen maser at the National Institute of Standards and Technology (NIST) in Boulder using a Microchip 53100A phase noise analyzer and frequency counter (*Note: Per NIST policy, NIST does not endorse this measurement, nor does it declare this hardware "fit for purpose"*).

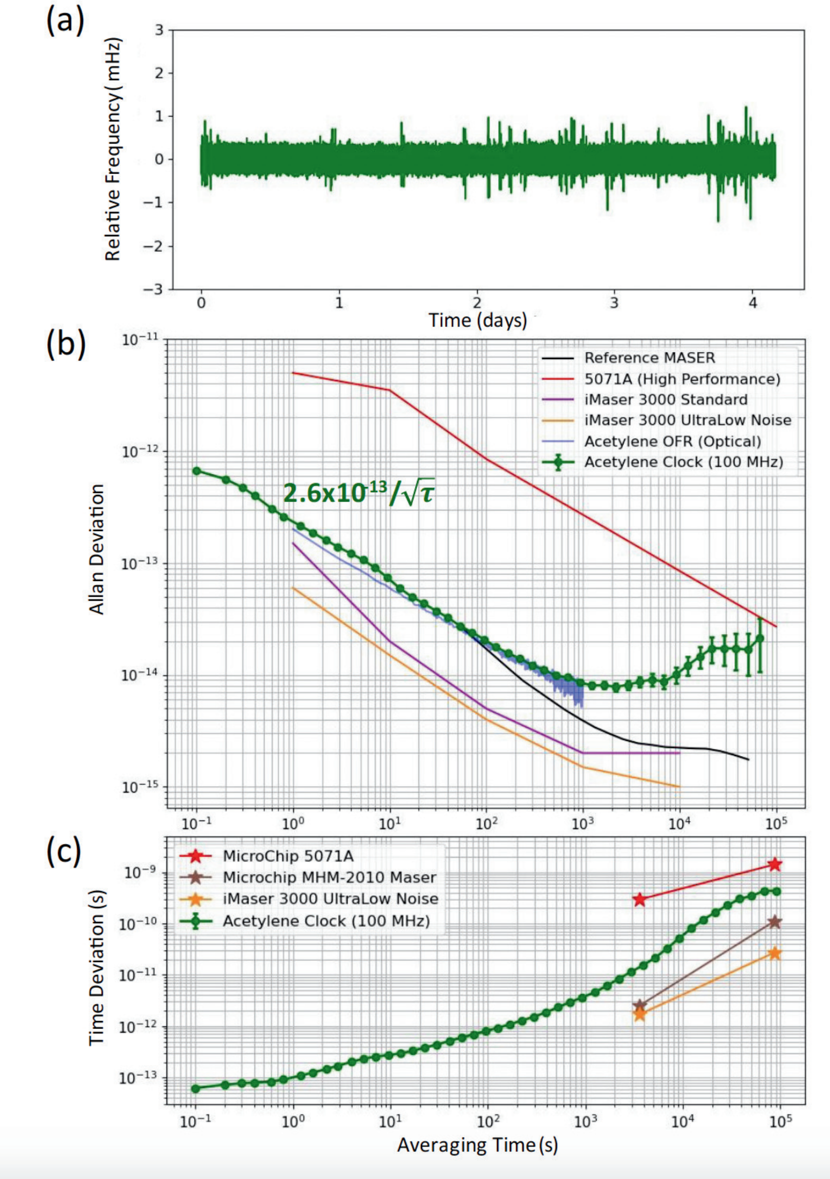

Figure 2. (a) Frequency counter data showing the acetylene clock output frequency subtracted from the mean 100 MHz frequency as a function of time. The frequency counter is clocked by a NIST active hydrogen maser. (b) The fractional frequency instability (Allan deviation) extracted from the frequency counter data shown in (a) is plotted in green as a function of averaging time. The black line is the measured frequency instability of the reference NIST maser extracted from a separate measurement against another NIST maser. The blue line is the optical 1542 nm instability of the Stabiλaser used here, extracted from a separate three-corner hat measurement performed by DFM against two other Stabiλaser units. The red line is the specification of the Microchip 5071A (high-performance model) Cs beam tube clock. The magenta line is the frequency instability specification of the T4 Science iMaser 3000 (standard model). The yellow line is the specification of the ultralow-noise model of the T4 Science iMaser 3000. (c) The time deviation of the acetylene clock extracted from the frequency counter data shown in (a) is plotted in green. The time deviation specification at 1 hour and 1 day for three comparable state-of-the-art commercial clocks are shown as red, brown, and orange stars

The frequency counter data relative to the mean 100 MHz frequency is plotted in Figure 2a. In Figure 2b, the fractional frequency instability (Allan deviation) of the 100 MHz acetylene clock output measured against the NIST maser is shown to be $2.6x10^{-13}/\sqrt{\tau}$ with a long-term instability reaching $8x10^{-15}$ around τ = 2,000 s. Also shown in Figure 2b is the RF frequency instability of the NIST maser used to measure the acetylene clock, the optical frequency instability of the DFM Stabiλaser extracted by DFM in a three-corner hat measurement against two other Stabiλaser units, and the frequency instabilities of state-of-the-art commercial clocks available on the market, including a high-performance cesium beam tube clock (Microchip 5071A) and T4 Sciences iMaser 3000 in both the standard and ultralow-noise models. In Figure 2c, the time deviation of the acetylene clock extracted from the frequency data shown in Figure 2a is plotted in green. The time deviation of the acetylene clock at 1 hour and 1 day of averaging time is 10 ps and 450 ps, respectively. We compare this performance to the time deviation specifications of three state-of-the-art commercial clocks [3], including the Microchip 5071A Cs beam-tube clock (293 ps at 1 hour), the Microchip MHM-2010 maser (2.5 ps at 1 hour), and the ultralow-noise model of the T4 Sciences iMaser 3000 (1.7 ps at 1 hour).

The acetylene clock presented here, composed of all COTS components, has a short-to-mid-term instability rivaling that of a commercial maser but with *drastically* lower environmental sensitivity and size compared to a maser. Compared to the Microchip 5071A high-performance cesium beam tube clock, the acetylene clock presented here has 20-50x better instability out to averaging times of ~2,000 s and is similar in size and environmental sensitivity.

Conclusion: By connecting COTS subsystems available from Vescent (FFC-100 + SLICE-FPGA-II) and DFM (Stabiλaser 1542^{ε}), we have demonstrated an acetylene optical clock with maser-like performance after <30 minutes of setup time (including unboxing and warm-up). The two subsystems were unboxed and placed on a desk to operate without any need for environmental isolation. Both rackmount subsystems are currently available for sale through Vescent.

References:
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