A Field-deployable Optical Clockwork Capable of Supporting Instabilities Below 1×10^{-17}

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Abstract: A field-deployable optical clockwork with in-loop instabilities below 1×10^{-17} is presented. Individual optical subsystem performance is analyzed, and the potential for integration into next-generation quantum sensors is discussed. © 2021 Vescent Photonics

1. Optical Clockwork Overview

1.1. Motivation

Next-generation quantum sensors are currently being investigated in laboratories for a variety of applications. One application area that can greatly benefit from increased precision in sensors is positioning, navigation, and timing (PNT). However, the present technology does not meet the low size, weight, and power (SWaP) and ruggedization requirements for deployed applications, preventing these experiments from leaving the laboratory.

In this effort, we focus on an optical clockwork that will aid both civilian and military applications including improved GPS instabilities and navigation in GPS-denied environments. Vescent Photonics has been developing ruggedized optical subsystems for a variety of field-deployed applications including optical frequency combs (OFCs) and optical frequency references (OFRs). The in-loop performance of the clockwork is discussed below, as well as limitations of the OFR used to make an optical clock.

1.2. Optical Frequency Comb

The OFC presented in this work is similar to systems previously developed at NIST [1], but with improved noise performance and ruggedization (the 10 L, 40 W rack-mount unit is shown in Figure 1a, but comb modules are also under development that fit inside of a 1 L volume and consume less than 15 W of wall-plug power). The current performance of Vescent's commercial OFC has f_{CEO} linewidths < 100 kHz (Figure 1b) and can be stabilized to under 1 rad of integrated phase noise (500 Hz – 5 MHz). Optical locks between the comb and OFRs typically show integrated phase noise below 0.3 rad over the same integration range. In-loop characterization of these stabilized parameters show that the OFC can support optical clocks with instabilities below 1×10^{-17} (the Allan Deviation traces show in Figure 1c are very near the counter limits). The performance level of Vescent's frequency comb can support most next generation optical clocks.

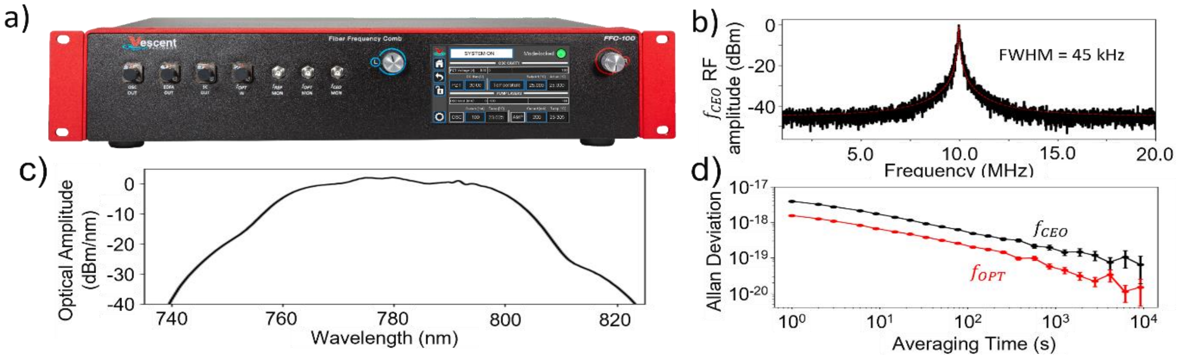

Figure 1a) Vescent's commercial frequency comb product (FFC-100). b) The RF spectrum of the FFC-100's f_{CEO} parameter with a FWHM fit of 45 kHz. c) Optical spectrum of frequency-doubled comb light. d) In-loop Allan Deviation versus averaging time for the two comb parameters (f_{CEO} and f_{OPT} or the heterodyne between the comb and an optical reference laser). These indicate the noise floor achievable of the repetition rate of the laser (f_{REP}) which is also the clock readout.

1.3. Heterodyne Agile Laser System

The OFR presented in this work is based on a two-laser micro-optic design that also contains a spectroscopy cell for laser stabilization. One laser is stabilized to a D2 hyperfine transition (780 nm) of a Rb spectroscopy cell via FM spectroscopy at the kilohertz level while a secondary laser is offset phase-locked to the first laser. This allows the secondary laser to have the precision and accuracy of the first laser while at the same time being tunable. The tunability of the laser output was not utilized for this clock setup but is actively being implemented in cold-atom clocks where time-multiplexed, frequency-agile tuning schemes are often necessary. The total system is shown in Figure 2a, requires less than 20 W of electrical power, and has a 0.5 L volume. Prior investigations have shown that the optical stability has a dependency on room temperature on the order of 1×10^{-10}/°C, and improvements to the thermal design are being considered to reduce long-term frequency instabilities.

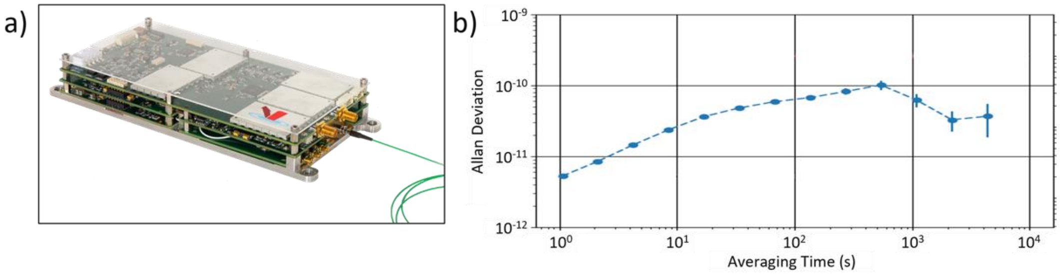

Figure 2a) Picture of the OFR (called the heterodyne agile laser (HAL) system) based on stabilization to the Rb D2 line. b) Allan deviation of the heterodyne beat between two HAL systems (results have been divided by √2 to indicate the performance of a single laser system).

2. Demonstration of a Deployable Optical Clock

A ruggedized optical clock was demonstrated based on an OFR and OFC developed at Vescent Photonics and the schematic is shown in Figure 3a. The most basic implementation of an optical clock is to stabilize an optical tooth of an OFC to an OFR via offset phase locking, and then to detect and stabilize the comb's f_{CEO} parameter to an RF oscillator. The optical technique presented here has been modified in the following ways: 1) an optical tooth of the OFC is stabilized to a narrow linewidth laser to improve the short term performance of the comb; 2) the OFC is frequency-doubled and heterodyned with an OFR based on D2 hyperfine spectroscopy; and 3) long term correction signals are generated from the OFC and OFR heterodyne and are used to correct the optical frequency of the narrow linewidth laser.

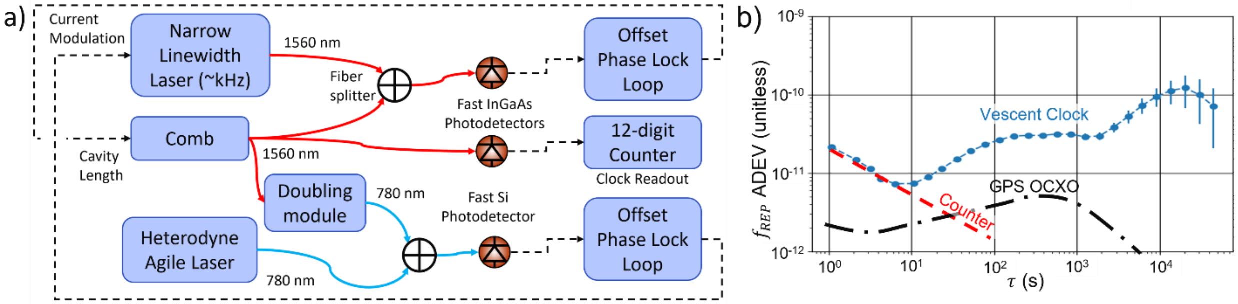

Figure 3a) Optical clockwork schematic based on a Vescent OFC and OFR. In this implementation, the optical frequency comb is heterodyned with a narrow-linewidth laser (RIO Planex) for good short term instability performance. A portion of the comb optical output is also frequency-doubled and heterodyned with an OFR based on Rb D2 hyperfine spectroscopy (~6 MHz natural linewidth). The measured frequency drift of the optical comb against the Rb OFR is then used as a long-term correction signal for the narrow linewidth laser. The comb module utilizes the f-2f self-referencing technique to detect f_{CEO}, which is stabilized via an offset phase lock loop. b) Allan Deviation of the repetition rate as compared to a GPS-referenced crystalline oscillator (SRS 740 with OCXO option). Instability data below 10 s averaging times are currently counter-limited, and alternate measurement techniques are being investigated to measure the performance at these timescales.

The clock readout of the system is the OFC's repetition rate, and Allan Deviation characterization of this signal are included in Figure 3b. Instabilities are dominated by the OFR (however, below 10 s averaging times the measurement is limited by the HP53132A counter). Alternate measurement techniques, such as down-mixing the repetition rate to < 1 MHz and utilizing a zero-dead time counter, are being investigated to fully characterize this clock at short time scales. The OFC and OFR have a total volume of 1.5 L and require only 35 W of total electrical power for operation; further reductions in volume and power consumption are still possible and are being considered.

[1] L. Sinclair, I. Coddington, W. Swann, G. Rieker, A. Hati, K. Iwakuni and N. Newbury, "Operation of an optically coherent frequency comb outside the metrology lab," Optics Express, Vol. 22, pp. 6996-7006 (2014).