Photon Efficient Optical Time Transfer

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***Summary*— We present a novel frequency comb-based system for optical two-way time-frequency transfer to support very long distance free-space links between clocks. Our Photon Efficient Agile Comb Optical Clock Synchronization (PEACOCS) system supports sub-femtosecond oscillator synchronization with up to -90 dB of link loss equating to few picowatt levels of received power. Such low power operation is a promising step towards terrestrial links in the hundreds of kilometers as well as ground-to-satellite links.**

Keywords—optical time-frequency transfer, optical free-space links

I. Introduction

Optical atomic clock networks between space and ground promise an exciting new frontier for experimental physics including gravitational wave detection [1], tests of General Relativity [2], and searches for dark matter [3]. To enable such networks, optical two-way time and frequency transfer (O-TWTFT) has demonstrated uncertainties below the current state-of-the-art optical clocks [4,5,6], including operation to moving platforms [7]. Furthermore, recent work has explored ways to reduce the required received optical powers without hardware modifications to conventional O-TWTFT systems [8]. While [8] showed promising results for low-power, long distance operation, the slow update rates required to achieve these results preclude the use of such a setup for time transfer to moving platforms. Here we present a system that further improves the photon efficiency of O-TWTFT while maintaining sufficiently high update rates for future operation to platforms in motion.

II. System Description

Previous O-TWTFT systems use a single frequency comb at each site locked to an optical atomic clock or reference oscillator. The combs at the two sites are run at different repetition rates, $f_{r,1}$ and $f_{r,2}$, to generate interferograms every $1/\Delta f_r = 1/(f_{r,1} - f_{r,2})$ via linear optical sampling when mixed. The envelope timing or carrier phase of these interferograms maps to the corresponding property of the received pulses, and two-way combining of the timing information at each site generates clock offset information that can be used to syntonize or synchronize the system.

In [8] we reduced Δf_r to increase the number of photons that contributed to each interferogram. In the system presented in this work, we push Δf_r to zero, that is run the combs at each site at the same repetition rate. The optical heterodyne needed to detect the timing signals in the rf domain is created by phase locking the pulses from the two sites temporally such that the two pulses continue to overlap on the detector despite pathlength changes due to fiber and atmospheric noise. A schematic of this system is shown in Figure 1(a).

Each site has a Clock Comb that is locked to the reference oscillator and sent over the free-space link to the other site. The second comb at each site, the Tracking Comb, is used as a local oscillator for the incoming Clock Comb. The phase of the Tracking Comb is adjusted to keep every pulse of the Tracking Comb overlapped in time with the Clock Comb pulses. The error signal for this tracking lock is generated by a fiber-based timing discriminator.

The timing discriminator differentiates between the timing signals we are interested in and turbulence-induced fluctuations in the signal amplitudes. Using variations in the group velocity between the fast and slow axis of PM fiber, we generate two heterodyne signals: one with the tracking pulse delayed relative to the clock pulse and one where the tracking pulse leads the clock pulse. When the phase of the clock pulse moves due to changes in the phase of the clock comb or time-of-flight variations the heterodyne voltage signals from one channel's detector, V_1, will increase and the other, V_2, will decrease as the peak of Clock Comb pulse moves closer and further away from the peak of the Tracking Comb pulse, respectively. By calculating an error signal according to $E = (V_1-V_2) / (V_1+V_2)$ we can use V_1 and V_2 to detect changes in timing independent of signal-fades which cause both V_1 and V_2 to decrease. Other variants of this timing discriminator are also possible.

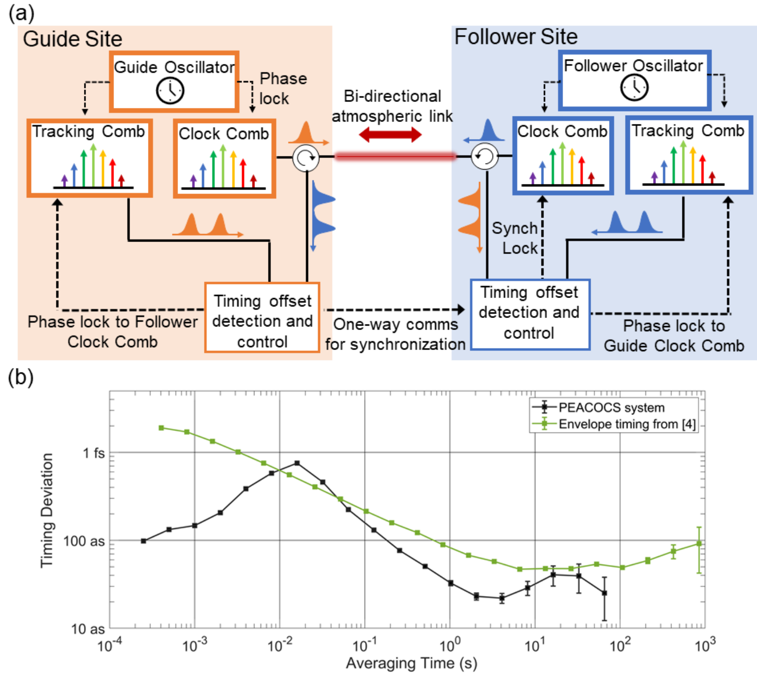

Fig. 1. (a) Schematic of PEACOCS system with a Clock Comb and Tracking Comb at each site. The Clock Combs are sent over the bi-directional free-space link through the atmosphere. The timing information in the Clock Comb pulses is measured through heterodyne detection with the Tracking Comb at each site. To ensure sufficient heterodyne signal, the phase of the Tracking Comb "tracks" the phase of the other site's Clock Comb and this signal in turn gives the timing information used to determine the offset between the clocks at each site. (b) Timing deviation for time transfer with the PEACOCS system over 2 kilometer link with -65 dB of link loss (black squares) compared to envelope timing for a path with similar integrated turbulence but only -55 dB of link loss from [4] (green squares).

III. Initial Results

We have performed preliminary testing of this system over several testbeds in our laboratory. The transmitted Clock Comb powers are about 2.5 milliwatts for these tests. Using fiber to connect the two sites we have measured the noise characteristics of the system as we increase the attenuation between the sites. We have demonstrated operation down to 1 picowatt of received power, which equates to much less than 1 received photon per pulse. At these powers and over a shorted link, we can transfer time with sub-femtosecond precision from 1 millisecond to 10 seconds of averaging and can transfer frequency at 2.5×10^{-16} instability with 1 second averaging.

To test the system over the atmosphere we have set up an outdoor, free-space link covering 2 kilometers. Figure 1b shows some initial results from these 2 kilometer tests that indicate the system can still provide high performance in the presence of air turbulence. Further testing is underway to explore the behavior of the system at stronger turbulence levels.

IV. Conclusions

In this paper we have presented PEACOCS, a new system for low-power O-TWTFT that also holds promise for future work to moving platforms. The initial results from this system show sub-femtosecond time transfer is possible at received powers of only picowatts, a factor of 1000x reduction in received power compared to previous comb-based O-TWTFT systems.

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