

Optical two-tone time transfer

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Subpicosecond time synchronization can enable future optical timekeeping networks [F. Riehle, *Nat. Photonics* 11 (1), 25 (2017)], including coherent phased array radar imaging at gigahertz levels [Collaboration, Event Horizon Telescope, *Astrophys. J. Lett.* 875 (2019)], intercontinental clock comparisons for the redefinition of the second [Dimarcq *et al.*, *Metrologia* 61 (1), 012001 (2024)], chronometric leveling [Takamoto *et al.*, *Nat. Photonics* 14 (7), 411 (2020)], and synchronization of remote assets, including future satellite-based optical time standards. With optical clocks now operating on mobile platforms [Roslund *et al.*, *Nature* 628 (8009), 736 (2024)], free-space synchronization networks with compatible performance and the ability to operate under platform motion are essential to expand the reach of precision timing. Recently, femtosecond-level optical time-transfer techniques have been developed that can operate over hundreds of kilometers despite atmospheric turbulence, signal fade, and dropouts [Giorgetta *et al.*, *Nat. Photonics* 7, 434 (2013); Caldwell *et al.*, *Nature* 618 (7966), 721 (2023); Shen *et al.*, *Nature* 610 (7933), 661 (2022)]. However, practical challenges remain for these pulsed techniques on moving platforms, including dispersion management for variable link lengths and Doppler-induced pulse ambiguities. Continuous-wave techniques overcome these limitations but are prone to femtosecond-level cycle slips during signal fades and dropouts [Gozzard *et al.*, *Phys. Rev. Lett.* 128, 020801 (2022)]. Here we report an optical time-transfer scheme with femtosecond-level performance that overcomes the practical limitations of dispersion and dropout-induced cycle slips and can also support moving platforms. Importantly, the setup reduces hardware requirements by employing an integrated photonics transceiver and telecom-band lasers that are compatible with full photonic integration. Using this scheme, subfemtosecond synchronization was demonstrated over a free-space link of about 100 m for several hours. Similar performance was demonstrated over a 1-km fiber non-polarization-maintaining link without dispersion compensation. Finally, the link was used to syntonize two iodine optical clocks and then compare them over 4 days. Importantly, the system maintains femtosecond-level performance for received optical power as low as 1 picowatt, compatible with ground-to-satellite link-loss budgets.

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I. INTRODUCTION

With the development of optical atomic clocks, advances in timing precision have greatly outpaced global-scale synchronization capabilities. Laboratory optical clocks now achieve subfemtosecond timing jitters at 1 s and fractional frequency uncertainties at 10^{-18} levels [1]. Recently developed mobile optical atomic clocks achieve 10 fs timing jitter at 1 s and fractional frequency instabilities at 10^{-15} levels after 1000 s [2]. Current free-space

microwave timing links [3–7], on the other hand, are limited to instabilities of 10–100 ps; optical laser ranging (i.e., time transfer by laser link [8]) realizes similar performance.

Optical time-transfer techniques have been developed to address this performance gap. In one approach, stable trains of ultrashort optical pulses are exchanged over a free-space link to provide femtosecond-level synchronization [9–11] at distances over 300 km with only picowatts of received power [12]. Along with the primary frequency comb, which is a fundamental component of the optical reference, this method employs a second frequency comb at each network node, adding complexity, power consumption, and expense to the optical transceiver. In addition, the transceiver requires careful dispersion management for the transmission of ultrashort pulses. An alternative approach uses a continuous-wave (CW) laser to transfer timing information between remote sites, analogous

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to a technique originally developed for canceling Doppler shifts in fiber links [13,14]. This scheme shifts system complexity from the laser system to the optical terminal, since adaptive optics are necessary to track the optical carrier phase without cycle slips over turbulence [15].

In this work, we report the development of an optical time-transfer scheme that maintains subfemtosecond synchronization at 1 s and a frequency precision below 10^{-17} . The technique replaces the second local-oscillator frequency comb in Ref. [9] with two telecom distributed-feedback (DFB) lasers, which are transmitted across the link. The differential optical phase between them determines the optical group delay associated with the link. This two-tone approach measures the same information encoded in the temporal pulse but does so with a frequency-domain projective technique. Related approaches have been employed for precision ranging and frequency transfer measurements across free-space optical links [16–19]. Our technique goes beyond synthetic wavelength-based laser ranging in two important ways. First, this two-way method purposefully removes the range term from the comparison data. Second, all lasers are phase-referenced to an atomic clock so that they are explicit carriers of timing information. Importantly, this technique does not require dispersion compensation, maintaining performance even in the presence of large and dynamically changing dispersion characteristic of a moving platform.

The two DFB lasers provide operational simplicity and reduce the size, weight, and power for the optical transceivers. Additionally, the use of CW telecom lasers designed to operate on the fixed International Telecommunication Union (ITU) grid allows for an optical transceiver that is directly compatible with existing coherent optical terminals (e.g., [20]). As discussed below, key performance metrics, such as resolution and dynamic range, are easily adjusted to optimize system performance for specific applications. Finally, removing the requirement to track timescale variations at optical carrier levels eliminates the need for adaptive optics at the terminals. The technical simplicity and reduced footprint of the optical and electronic hardware are amenable to multinode optical timing networks, a key requirement in the redefinition of the SI second and an optical-clock-derived GNSS/GPS constellation.

The timing information necessary for synchronization is derived from an optical transceiver contained within a simplified, purpose-designed photonic integrated circuit (PIC), which minimizes out-of-loop paths between the timescale reference and measurement planes. The result is subfemtosecond temporal synchronization for time periods exceeding 10^4 s, equivalent to a frequency resolution of less than 10^{-19} . This performance is sufficient to synchronize state-of-the-art optical clocks for extended durations with reasonable system complexity and size. Finally, we

present a practical demonstration of the technique that continuously compares two iodine optical clocks [2] over a free-space link for 4 days.

II. DESCRIPTION OF THE TECHNIQUE

The two-tone technique is based on the principle that any variation in the envelope arrival time for a pulse train is equivalently captured in the frequency domain where the comb spectrum exhibits a linear spectral phase with a slope given by the arrival time (Fig. 1) [21]. The linear component of this spectral phase and thus any deviation of the underlying timescale can be reconstructed by sampling the spectral phase at only two frequencies.

Consider a timing network with two sites, A and B, that have a free-space or fiber optic link between them (Fig. 2). At site A, two CW lasers with frequencies $f_A^{(1),(2)}$ and frequency spacing $\Delta f = f_A^{(1)} - f_A^{(2)}$ are each phase-locked to the frequency comb of an optical reference. The self-referenced frequency comb colocated with the optical reference operates as a transfer oscillator, imprinting the comb spectral phase at the two CW laser frequencies onto their respective carrier phases. Frequency instability of the clock becomes a variation of the envelope arrival time for each comb pulse with respect to a local reference plane. This arrival time variation is then manifest as a differential optical phase between the two CW lasers. The frequency reference at site B contains its own frequency comb and two CW lasers $f_B^{(1),(2)}$ with the same frequency spacing $\Delta f = f_B^{(1)} - f_B^{(2)}$. These two lasers are similarly phase-locked to the site B comb.

Both pairs of CW lasers are then exchanged across the optical link. An optical transceiver at each site separates the two incoming CW lasers and optically interferes them with the local copies. A heterodyne beat for each CW pair is detected at the difference of the site A and B offset

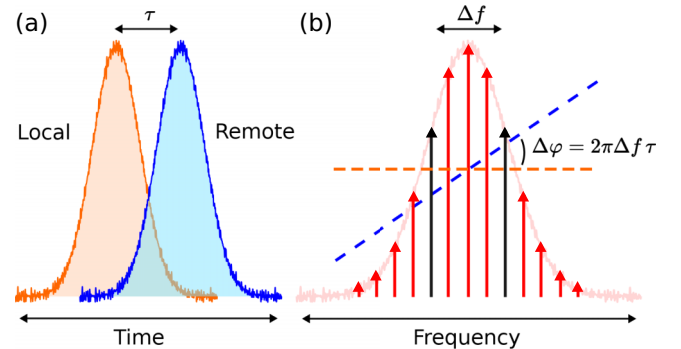


FIG. 1. Two-tone time-transfer concept. (a) Optical pulse delay between local (orange) and remote (blue) pulses. The difference in their respective timebases is τ . (b) Frequency-domain representation wherein the delay τ creates a linear spectral phase $\Delta\phi = 2\pi\Delta f\tau$ with respect to the reference pulse. The delay τ is extracted by sampling this phase at two points separated by Δf .

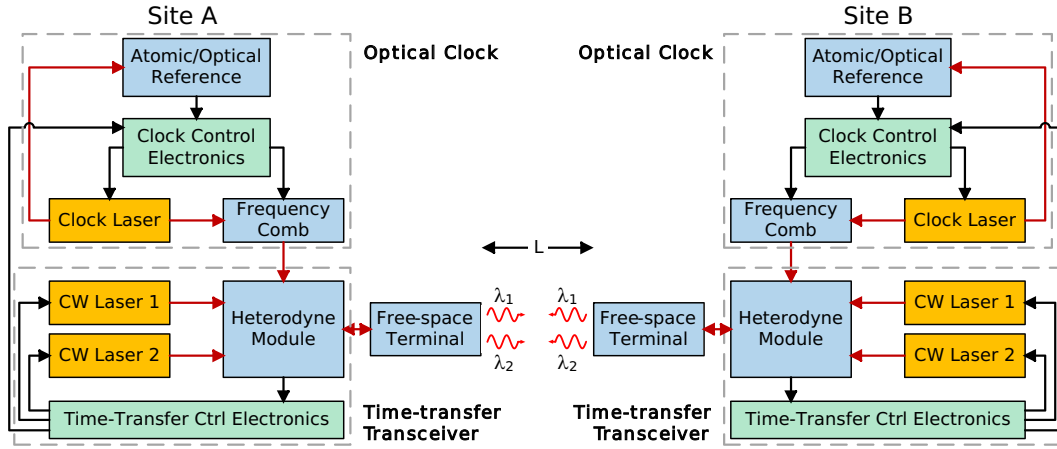


FIG. 2. Optical two-tone time-transfer scheme. Each site contains an optical reference to which a frequency comb is stabilized. Light from the frequency comb is introduced onto a heterodyne transceiver along with two CW lasers. These CW lasers are phase-stabilized to the comb, which maps the temporal jitter of the comb pulses onto their differential optical phase. The CW lasers are exchanged between the two sites, and heterodyne beats between the local and remotely received lasers reveal the one-way group delay, which includes the link time-of-flight (TOF) as well as timing error between the two reference oscillators. One CW laser at each site is utilized for classical communication (not presently demonstrated) to exchange its one-way timing information, which allows deducing the two-way relative timebase error between the sites.

lock frequencies, and demodulation of this beat reveals the optical phase accumulated between the two sites, $\varphi_{A \rightarrow B}^{(k)} = 2\pi f^{(k)} \tau_{A \rightarrow B}^p$, where $k = 1$ or 2 and $\tau_{A \rightarrow B}^p$ is the phase delay across the link. The one-way group delay across the link $\tau_{A \rightarrow B}^g$ is then recovered from the difference in the optical phases accumulated by the two lasers, $\delta\varphi_{A \rightarrow B} = \varphi_{A \rightarrow B}^{(1)} - \varphi_{A \rightarrow B}^{(2)} = 2\pi \Delta f \tau_{A \rightarrow B}^g$. The group delay $\tau_{A \rightarrow B}^g = T_{A \rightarrow B} + \Delta t_{A,B}$ contains both the transit time $T_{A \rightarrow B}$ between the two separated temporal reference planes and the relative timescale difference $\Delta t_{A,B}$. The same processing scheme occurs at the second site to recover $\tau_{B \rightarrow A}^g = T_{B \rightarrow A} - \Delta t_{A,B}$, and the individual group delays measured at each site are combined to separate relative clock drift from transit time variations. Assuming a reciprocal optical link ($T_{A \rightarrow B} = T_{B \rightarrow A}$), the relative difference in the timescales at site A and B is $\Delta t_{A,B} = (\delta\varphi_{A \rightarrow B} - \delta\varphi_{B \rightarrow A})/4\pi \Delta f$. Thus, the two-tone detection scheme is equivalent to directly measuring a temporal envelope shift for pulses of bandwidth Δf . The tradeoff between sensitivity and dynamic range is determined by the spacing Δf between the two CW lasers, which is adjustable depending upon the application. The minimum timing deviation measurable with the two-tone technique is

$$\Delta t_{A,B,\min} = \frac{T}{2\pi} \times \sqrt{\frac{2}{N} + \kappa \times \Delta_{\text{rms}}^2}$$

where $T = 1/\Delta f$ is the period of the synthetic fringe, Δ_{rms} is the root-mean-square phase noise for one of the CW optical phase-locks to the comb, N is the total number of signal photons detected for both sites per acquisition

period, and $4 \leq \kappa \leq 8$ is a numerical constant that depends upon the link length [22].

The local synthetic fringe can be temporally aligned with its own local frequency comb for absolute time synchronization. The optical signal consisting of the interference between the local frequency comb and both of the phase-locked CW lasers provides a measure of the temporal cross-correlation between the comb envelope and the synthetic fringe. By digitally adjusting the phase of one of the CW laser offset locks, the temporal delay between the comb and synthetic fringe can be adjusted to maximize the cross-correlation [22], aligning the local timebase and two-tone measurement with femtosecond accuracy (see Appendix, Fig. 11).

Using two CW lasers for generating the continuous synthetic fringe signal makes efficient use of all detected photons over the link. In addition, since the typical synthetic fringe period is about $1000 \times$ larger than the individual optical cycles of each CW laser (5-fs period at 1550 nm), the technique is tolerant of signal dropouts from turbulence or weather [23]. Signal dropouts do not affect the timescale continuity if the two clocks do not drift away from each other by more than the period of one synthetic fringe during the dropout. For a CW laser separation of 100 GHz, corresponding to a single ITU grid channel spacing, the synthetic fringe has a period of 10 ps. State-of-the-art optical clocks maintain picosecond-level holdover for many days [24] and portable optical clocks maintain it for several hours [2]. Thus, cycle slips in the observed timescales would not occur even for extended dropouts [e.g., low earth orbital periods of approximately 1.5 h].

The dynamic range beyond one synthetic fringe is readily extended using a variety of techniques. For the comb-based time-transfer technique, a separate CW laser with an electro-optic phase modulator (EOM) at each site was used to establish a coarse time-transfer system [10], which can be easily incorporated into the two-tone technique. An alternative approach utilizes a phase modulator to create a static sideband. The frequency spacing between the carrier and the sideband defines a second synthetic wavelength. The modulation frequency is chosen to resolve the picosecond (millimeter) range ambiguity of the CW laser synthetic wavelength [25,26]. For example, 100 MHz phase modulation creates a synthetic wave with period 5 ns, sufficient to resolve the uncertainty of GPS synchronization. Finally, the sideband frequency for coarse timing is tunable in real time and can be adapted to optimize the system for different applications.

III. DEMONSTRATION

Our initial demonstration uses two 1550-nm DFB lasers separated by two dense wavelength division multiplexing (DWDM) channels on the ITU grid ($\Delta f = 200$ GHz), providing a synthetic fringe period of 5 ps. All optical multiplexing/demultiplexing is done with discrete telecom components (DWDM filters) at the input and output of the PIC, which combine or separate the light in the two ITU channels. The PIC [Fig. 3(a)] consists of a six-port device fabricated on a 10 mm $\times$ 20 mm glass substrate that uses an ion exchange process to define the waveguides directly on glass. V-grooves are attached to the substrate ends for fiber-coupling the inputs and outputs; excess loss at the PIC fiber interfaces is less than 0.5 dB per facet. The PIC design [Fig. 3(b)] includes a 50-50 coupler that

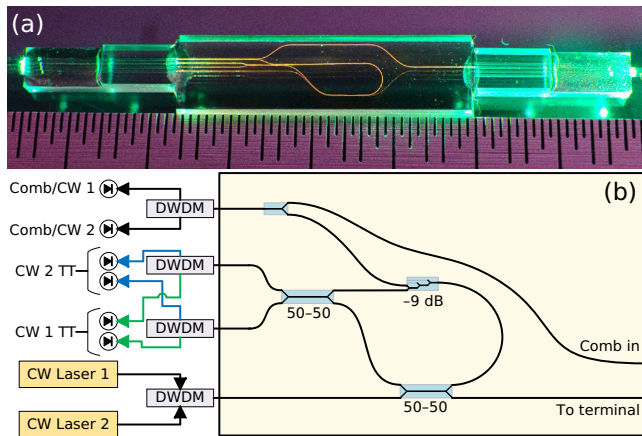


FIG. 3. PIC transceiver for two-tone time transfer. (a) Photograph of the fiberized transceiver. Green light is coupled onto the PIC to illuminate the waveguides. For scale, the finest gradation on the adjacent ruler is 0.5 mm. (b) Schematic of the PIC transceiver. Overlap of all relevant fields occurs on-chip, which minimizes out-of-loop pathways to the millimeter scale.

sends half the power for each local laser to the free-space terminal port. The other half is attenuated by 10 dB and interfered with the optical signals received from the remote site (over the same terminal port) using a second coupler. A portion of the light dumped at the attenuator is combined with the comb light to generate the beatnotes necessary to phase-stabilize the CW lasers to the frequency comb. This topology eliminates any differential path length between the two local CW lasers and minimizes out-of-loop pathways between the comb stabilization reference plane and that for the interference with remote light.

Each site uses a custom electronic circuit for balanced photodetection and signal conditioning, which delivers amplified signals to a field programmable gate array (FPGA). The FPGA phase-stabilizes the two CW lasers to a 200-MHz fiber frequency comb and analyzes the beatnotes between local and remote CW lasers to retrieve the one-way group delay.

IV. COMMON CLOCK DEMONSTRATION

The sensitivity limit for the two-tone technique was assessed by colocating both sites and stabilizing all four CW lasers to the same frequency comb. This was accomplished by dividing the common frequency comb between the two PICs with a telecom 50-50 splitter, which minimizes relative clock drift between the sites. Any remaining clock noise is attributed to either differential path lengths between the comb split and the two PICs or the technique itself. Following phase-stabilization of the two CW lasers on the PIC, the output from each PIC was transferred to a breadboard free-space link with a 5-meter optical fiber and exited through an optical collimator. The two collimators were separated by about 1 m, with one collimator mounted on a translation stage to precisely adjust the link distance. One-way group delays were acquired at each site while adjusting the translation stage. The sum and difference of the one-way delays yield the link time-of-flight (TOF) and the residual timing difference between the two sites, respectively [Fig. 4(a)]. The TOF signal closely mirrors the individual one-way group delays measured at each site, and a translation of about 33 ps, corresponding to around 6500 optical fringes, is tracked without any wraps. The timing signal, however, maintains femtosecond instability (subfringe) throughout the translation due to the reciprocal link. The data processing algorithm to track one-way group delays larger than the ambiguity range of the system is discussed in Sec. VIII.

The timing deviation noise floor measured as a function of received power is shown in Fig. 4(b). Above 100 pW, the signal-to-noise ratio is power-independent and limited by residual technical phase noise on the four CW laser offset locks, which provides a timing sensitivity of about 400 attoseconds with 1 s averaging. Conversely, below 100 pW the deviation scales as $1/\sqrt{N}$. The measured

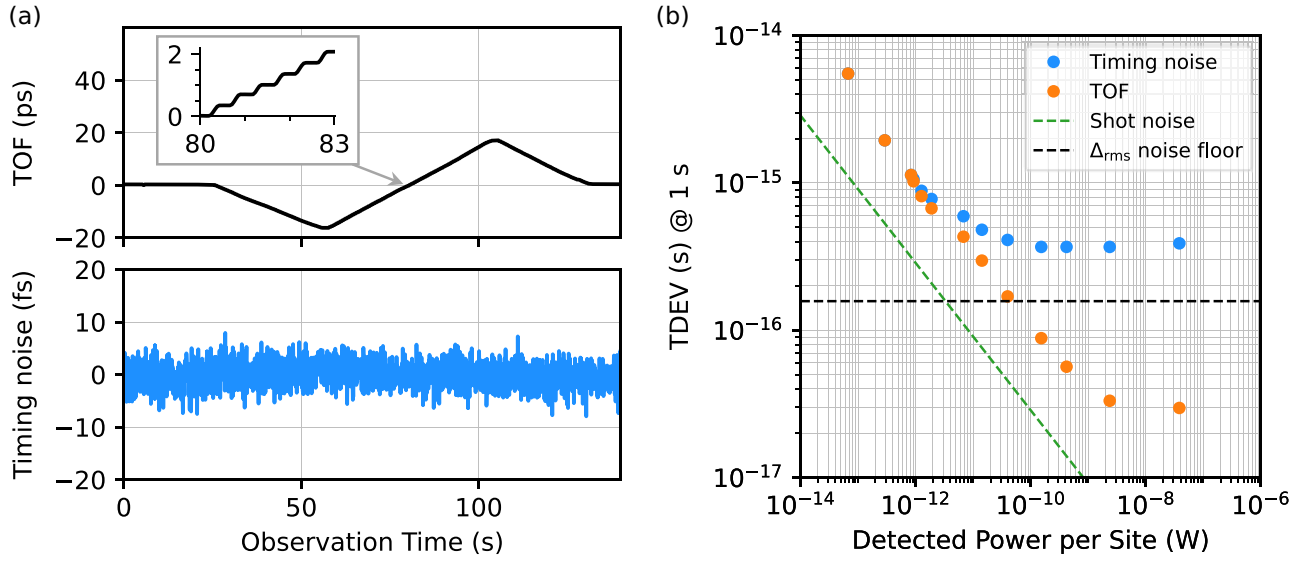


FIG. 4. Demonstration of the two-tone concept and detection sensitivity. (a) The distance between two sites is varied in a controlled manner to provide a temporal displacement of 33 ps (equivalent to about 6500 optical fringes). The TOF signal (top panel) shows the expected temporal profile, including individual steps of the translation stage (inset). The two-way timing noise signal (bottom panel) exhibits temporal precision at the femtosecond level (5-ms sample interval) throughout the induced translation. (b) The time deviation (TDEV) sensitivity at an averaging interval of 1 s is shown as a function of the total received power at each site. For received powers exceeding 100 pW, the timing sensitivity is limited by the residual noise of the offset locks to ~ 400 as. Below 100 pW, the timing sensitivity scales as $1/\sqrt{N}$, but still is capable of synchronization to 1 fs with 1 pW of received power. For short links where $\kappa = 8$, this datum is within about double of the prediction for $\Delta t_{A,B,\text{min}}$.

deviation is roughly twice larger than the theoretical prediction over the entire power range (see Sec. VIII). Nevertheless, 1 fs timing sensitivity is observed for only 1 pW of received power. A straightforward approach to lower the technical noise floor is to use narrow linewidth CW lasers in place of the DFBs. Such lasers would likely decrease the offset lock residual phase noise by a factor of 10 and lead to a corresponding increase in the timing resolution. To further extend link distances, $100 \times$ amplification of the launched beams is readily achievable with commercial 1 W optical amplifiers.

The two-way TOF ranging precision is not limited by the same technical noise and exhibits $1/\sqrt{N}$ scaling for received powers up to about 10 nW. This is due to the correlation of the offset lock noise between the sites, which is removed by subtracting the two one-way group delays measured at each site. However, this classical correlation disappears for long links, and the detection limits for both the timing and TOF modes converge to a value $\sqrt{2}$ smaller than the residual noise limit arising from the phase-locks seen in Fig. 4(b) [22].

To extend the free-space link, we constructed two collocated free-space optical terminals in our facility. Each terminal included 1550 nm telescope optics that expanded the beams to 7 mm. Light was launched free-space to a retroreflector approximately 45 meters away and returned to the adjacent terminal for a folded path length of about 90 meters. Fifty meters of optical fiber delivered the light

from each PIC to the terminals, for a total link length of 200 meters (fiber and free-space combined). Two-way timing errors were measured with 100 pW of received power across the 90-meter free-space link. Despite several picoseconds of fluctuation between the two terminals and the thermal sensitivity of the 110-m delivery fiber, the technique achieves 500-as temporal resolution with 1 s of averaging and maintains subfemtosecond timing deviation between the two sites over several hours [Fig. 5(a)]. The corresponding fractional frequency fluctuation [Fig. 5(b)] is 10^{-15} after 1 s and below 10^{-18} at 1000 s, compatible with state-of-the-art laboratory optical clocks [1,24].

Dispersion compensation was not necessary for the 110-m PM-1550 fiber delivering light to the optical terminals (dispersion equivalent to 315 km of atmosphere at sea level). The two-tone approach has inherent immunity to dispersion, by operating in the frequency domain and the direct projection of the linear component from the entire relative spectral phase. This allows synchronization to be maintained for dynamically changing optical path lengths (e.g., satellite tracking through the atmosphere, synchronization with mobile planes or ships). A nonreciprocal timing error $\Delta t_{\text{error}} \sim 10^{-19}$ s/km of air propagation arises due to the different offset frequencies at each site [22].

The ability to operate in highly dispersive environments was further demonstrated by linking the two sites with 1 km of SMF28 optical fiber. For this length of fiber, the equivalent dispersive distance in air is given as

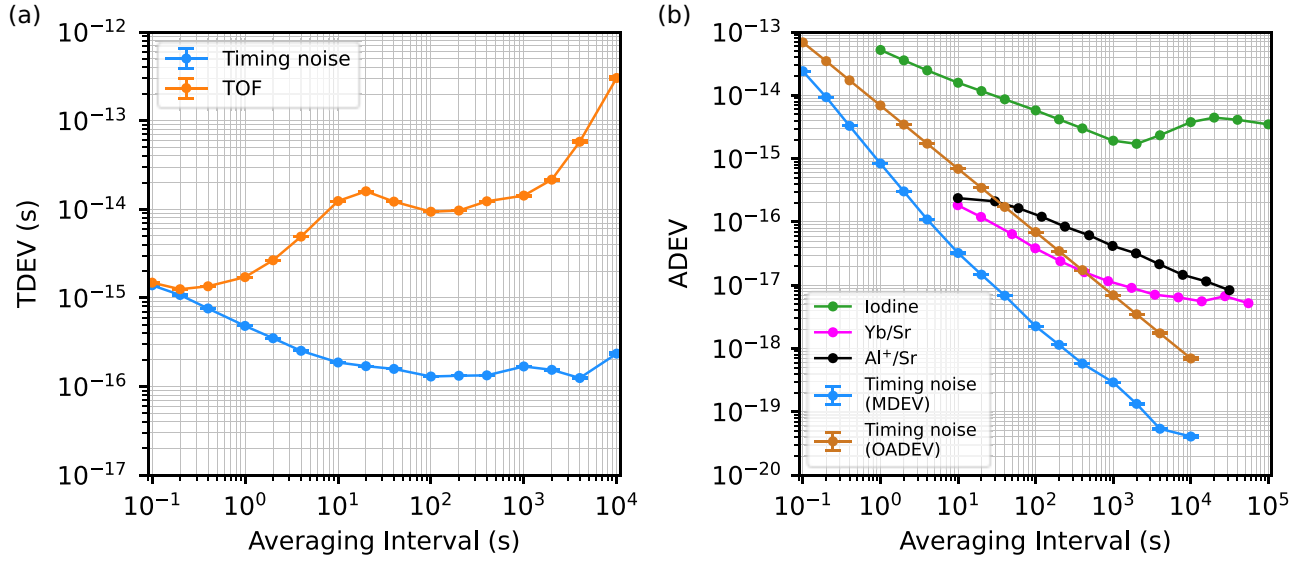


FIG. 5. Common clock two-tone performance measured over 90 m free-space link with 100 pW of received power. (a) The TDEV for the measured timing noise between the two sites is 500 as at 1 s of averaging and maintains less than 1 fs of deviation for time periods up to 10^4 s. Notably, the excess ~ 100 m of fiber for delivery to the optical terminals does not degrade the instability. (b) The technique provides a fractional frequency instability of less than 10^{-18} at 1000 s [modified Allan deviation (MDEV)]. The Allan deviation (ADEV) for several state-of-the-art optical clocks [1] as well as a mobile iodine optical clock [2] are shown for comparison. OADEV, overlapping Allan deviation.

$L_{\text{air}} = (GVD_{\text{fiber}}/GVD_{\text{air}}) \times L_{\text{fiber}} = 2715 \times L_{\text{fiber}}$, where GVD is the group velocity dispersion for the medium; in terms of dispersion, 1 km of SMF28 is equivalent to propagation through 2715 km of air. The two-way timing jitter power spectral densities for both the SMF28 and 90-m free-space links are shown in Fig. 6, displaying

nearly equivalent white phase noise floors of $0.7 \text{ fs}/\sqrt{\text{Hz}}$. Importantly, no modifications were made to the optical transceivers between the two experiments, demonstrating the ability to operate in environments where the link distances are dynamically changing. Furthermore, the link used unpolarized fiber, illustrating the ability to synchronize assets with femtosecond precision over legacy non-polarization-maintaining fiber links.

V. CLOCK COMPARISON

Following the measurements characterizing the performance of the technique using a single frequency comb common to both sites, the timing deviation between two independent iodine atomic clocks was measured over the original short, 1-m free-space link. The iodine clocks exhibit short-term instabilities of about $5 \times 10^{-14}/\sqrt{\tau}$ and $2 \times 10^{-14}/\sqrt{\tau}$, respectively. A portion of each clock's 200-MHz frequency comb was delivered via a 10-m optical fiber to its corresponding transceiver PIC to stabilize the local CW lasers. The laser pairs were exchanged over the free-space link, and the resultant beatnotes were processed by the FPGA to extract the timing deviation between the clocks. A 1064-nm optical beatnote between the iodine clocks was also monitored with a conventional frequency counter for cross-validation.

Initially, the two clocks were deliberately frequency offset from one another by known values to verify the calibration of the two-tone technique. The observed timing deviation accumulates error linearly in time with the

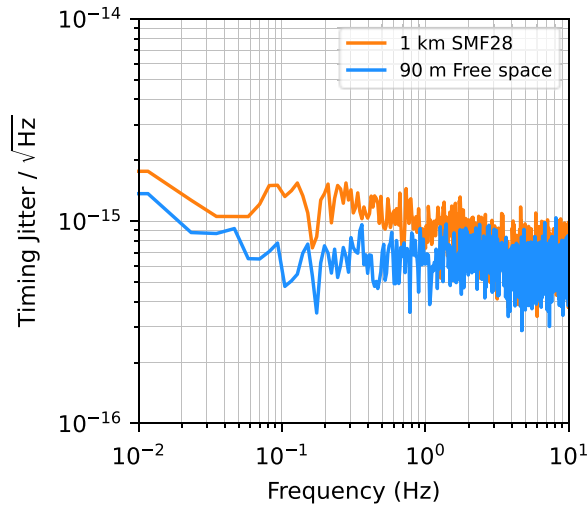


FIG. 6. Power spectral densities of the measured timing noise for the 90-m free-space and 1-km SMF28 fiber links using identical optical transceivers for the measurements. Despite the significant difference in dispersion between the links, the white phase noise floor is nearly identical at $<1 \text{ fs}/\sqrt{\text{Hz}}$.

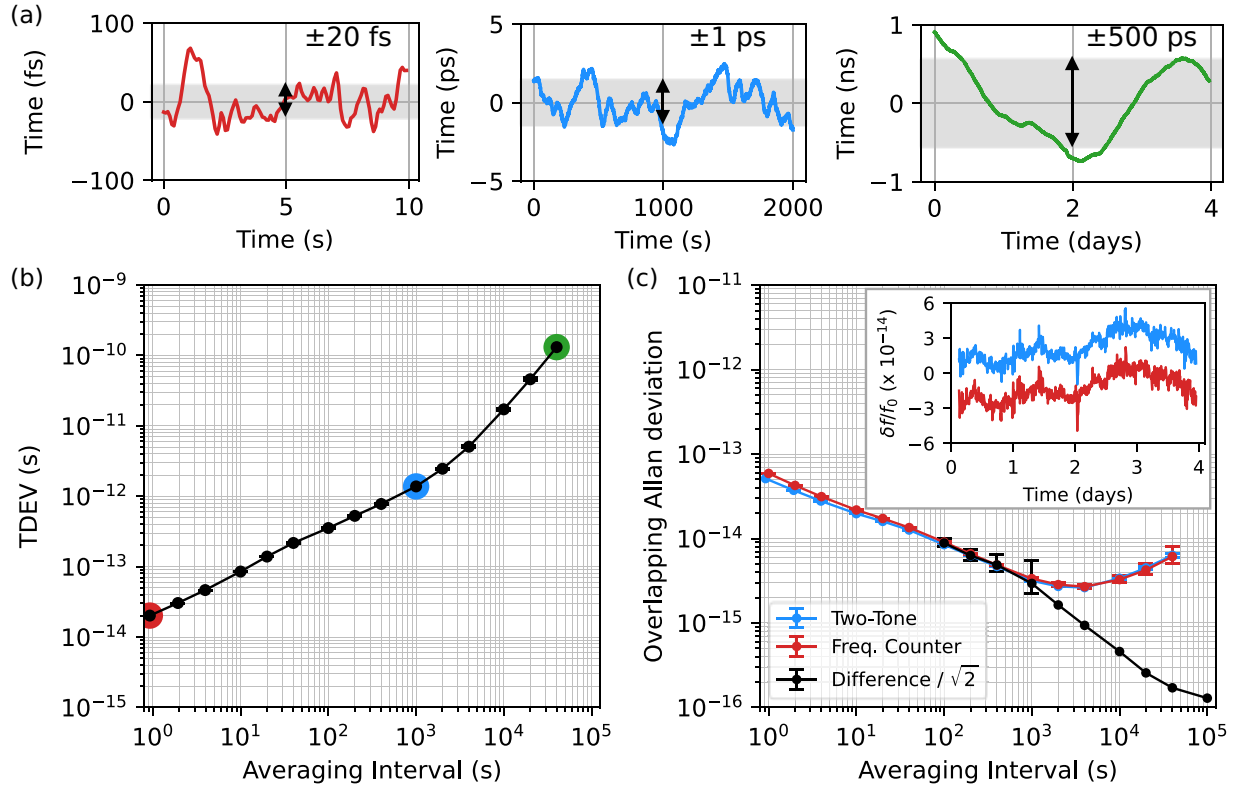


FIG. 7. Comparison between two iodine optical clocks with the two-tone technique. (a) Time traces highlighting the temporal instability recorded between the two clocks for several observation periods. The two-tone measurement operated continuously for a period of 4 days. (b) Timing deviation measured over a 4-day period. The shared instability between the two clocks is 20 fs at 1 s of averaging and 600 ps after one day. The colored dots correspond to the observation periods displayed in panel A. (c) Overlapping Allan deviation for the fractional frequency fluctuations measured by both the two-tone technique and a frequency counter. The inset shows the raw frequency record for the two techniques over the entire 4-day period.

expected slopes (see Appendix, Fig. 10). Once the calibration was verified, one of the clock comb offset lock frequencies was updated to reduce the frequency offset to about 10^{-15} .

After initial syntonization, timing fluctuations between the two clocks were measured over 4 days (Fig. 7). A relative wander between the two timescales of ± 500 ps was observed over this period, and the corresponding timing deviation is displayed in Fig. 7(b). The relative timing instability between the two clocks is 20 fs at 1 s of averaging [Fig. 7(a)], approximately $40\times$ larger than the two-tone noise floor. Moreover, these two systems maintain synchronization below 10 ps for nearly 2 h [Fig. 7(b)]. The timing fluctuations in Fig. 7(a) are converted to frequency variations in Fig. 7(c); the simultaneous frequency counter measurement is inset. The congruence between the frequency traces and Allan deviations illustrates the fidelity of the two-tone approach for comparison of optical timescales. The discrepancy between the two Allan deviations at short times is attributed to comparing results from a Λ -frequency counter (Keysight 53230A [27]) to the two-tone method that conducts Π -averaging [28,29].

VI. DISCUSSION

For the data presented above, the individual one-way TOF information was extracted in real time using the data-processing algorithm presented in Sec. VIII, and the two-way timing signal was computed in postprocessing. Implementation of an optical communications channel to extract the two-way timing signal in real time as well as signal processing algorithms for real-time syntonization and synchronization of the clocks is currently under development.

The two-tone approach offers several unique advantages for operation under motion. The technique does not possess an intrinsic optical Nyquist limit, and the maximum Doppler shift resolvable is determined by the bandwidth of the photoreceiver and digital processing unit. Detection of Doppler shifts arising from terminal motion with relative speeds of 1 km/s is enabled with 10-GHz photoreceivers. Digitization and processing approaching these rates are possible with modern, commercially available FPGAs [30], and the required digital signal processing has already been developed for radar, coherent optical communications, and radio astronomy [31–34]. Notably, the

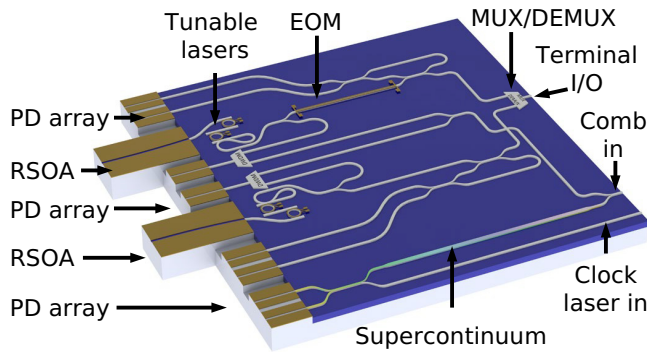


FIG. 8. Photonic integrated transceiver concept. Hybrid or heterogeneous integration of active and passive photonic platforms allows for integrating the entire optical transceiver, including the two CW lasers and wavelength (de)multiplexers, onto a single PIC. An on-chip EOM in one (or both) arms can be used for coarse time transfer and conventional optical communications. If the passive platform is sufficiently nonlinear, dispersion engineering allows for on-chip supercontinuum generation from the frequency comb, which in turn allows for frequency comb self- and optical- referencing on the same PIC to define a single timing plane for the entire clock/time-transfer system. RSOA, reflective semiconductor amplifier; PD, photodetector; EOM, electro-optical modulator; MUX/DEMUX, wavelength multiplexer/demultiplexer.

bandwidth needed to follow gigahertz Doppler shifts is incumbent upon the digital processor and not any optical actuators [35–38].

Compatibility with fiber delivery also allows the integration of the two-tone scheme into fiber-optic networks for time and frequency dissemination. The technique is wavelength agnostic and can be employed with any pair of wavelength division multiplexing channels in the telecommunication grid, including the O, C, and L bands. This provides an opportunity to utilize existing bidirectional, long-haul fiber-optic infrastructure for time transfer with femtosecond precision. Such functionality can enable applications including intracontinental clock comparisons [39] as well as synchronization in a large scientific facility [40]. The technique is also compatible with the 1064-nm region under consideration for future space-based optical communication links [41,42]. Depending on the optical reference (e.g., iodine), one of the time-transfer lasers can also serve as the optical clock CW laser, reducing the laser count for the transfer link to one.

The present implementation motivates integration of additional functionality onto the transceiver PIC. Several hybrid integration strategies are commercially available to directly interface multiple DFBs with silicon (Si) or silicon nitride (SiN) platforms, including butt-coupling or flip-chip bonding of the laser to the PIC. Furthermore, narrow-linewidth CW lasers on platforms such as Si or SiN [43–47] are under development and may support the

future integration of lower-intrinsic-linewidth lasers with the rest of the transceiver. Similarly, advances in nonlinear nanophotonics allow for supercontinuum generation and electro-optic modulation on platforms such as thin-film lithium niobate [48–51], or hybrid wafer level integration of SiN with lithium niobate [46]. These could enable combining frequency comb referencing with the time-transfer system to define a single temporal reference plane for the system. A concept model for an integrated optical transceiver is shown in Fig. 8. On-chip lasers and DWDM filters can be used to multiplex and demultiplex the two wavelengths on chip. An on-chip EOM in one or both arms can be used for coarse time transfer and conventional optical communication [10,25]. A small portion of the incoming comb light is interfered with each laser to provide the beatnote signals necessary for stabilizing the lasers to the frequency comb. The remaining comb light is used to drive octave-spanning supercontinuum generation for self-referencing. A portion of the supercontinuum is overlapped with the clock CW laser to fully stabilize the frequency comb to the optical reference.

VII. CONCLUSION

Here we introduced a practical, two-way CW time-transfer scheme compatible with optical atomic clocks and references. The technique leverages the stability and benefits of frequency combs already built into the local optical clocks, while avoiding the technical challenges associated with exchanging ultrashort pulses over the link. This projective technique retains the benefits of comb or single laser transfer while reducing the system size, weight, power, and cost and providing new opportunities to address platform motion and operate across hybrid fiber and free-space links.

Two-tone time transfer provides synchronization below 1 fs with picowatts of received power, compatible with 100-km+ terrestrial links or ground-to-satellite links. The technique is readily extendable to multiple nodes with appropriately chosen CW laser offset frequencies. Combined with portable optical clocks, it offers a promising path to global synchronization at picosecond levels.

VIII. METHODS

A. Optical architecture

A block diagram of the optical architecture at each site is shown in Figs. 2 and 3(b). DFB lasers centered at 1536.6 nm (ITU Channel 51) and 1535.0 nm (ITU Channel 53) are used at each site. These lasers have approximately 200 kHz linewidths; the 200-GHz spacing between them creates a synthetic fringe with a 5-ps period. The two lasers are multiplexed together with a telecom component and coupled into the PIC. The combined CW light is split with a 50-50 coupler, and one output is directed

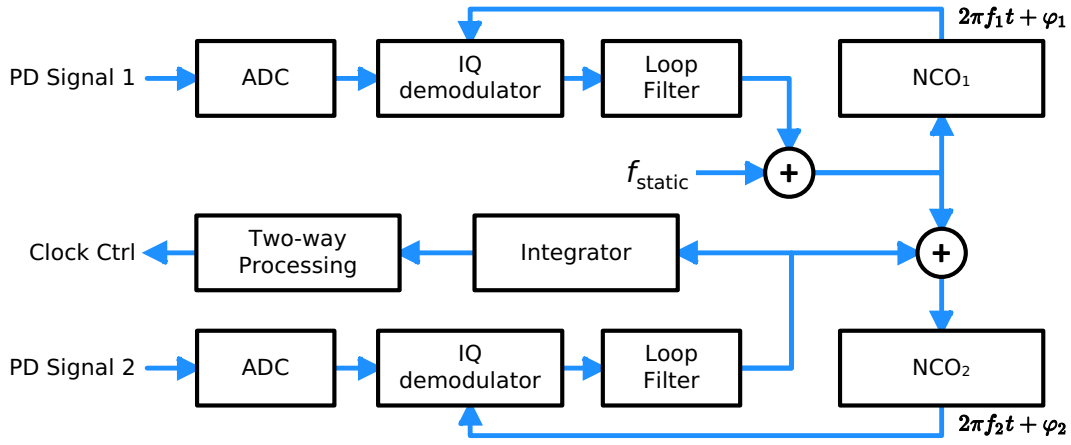


FIG. 9. Signal processing block diagram for the two-tone technique. The heterodyne beatnote between the local and remote light is digitized for each of the two wavelengths. A numerical tracking oscillator (NCO) is phase-locked to the first heterodyne beat, and the resultant phase of this tracking oscillator mirrors the optical phase variations φ_1 . A second tracking oscillator, consisting of the sum between the first tracking oscillator and a correction signal, is then phase-locked to the second heterodyne beat, which likewise reproduces the optical phase variations φ_2 . The correction signal is integrated to yield the phase difference between the two beatnotes $\varphi_2 - \varphi_1$, which is proportional to the one-way group delay. ADC, analog-to-digital converter.

to the free-space terminal. The other output is attenuated and split again. A portion of this output is combined with light from a 200 MHz frequency comb, exits the chip, is demultiplexed with another telecom component, and the two CW laser-comb beatnotes are detected. The other portion is combined with half of the received light on a 50-50 coupler, after which it is demultiplexed off-chip, and each wavelength is separately detected with a balanced detector.

For this scheme, there are two noncommon optical paths for which differential fluctuations manifest as noise or drift in the detected timescale. First, there is differential path between the local and received light in the heterodyne interferometer. Second, there is differential path between the local light that is phase-locked to the comb and that which optically interferes with the received light. Importantly, both differential pathways are on the PIC, which allow them to be millimeter size rather than tens of centimeters as with a fiber-based transceiver. All the fiber pathways and telecom components off-chip are common mode and do not affect the performance of the two-tone technique. Moreover, the compact size of the transceiver (5 mm $\times$ 20 mm) allows for uniform temperature control of the device. The PIC was copackaged with a thermistor and a thermoelectric cooler for temperature control to minimize the temperature coefficient of the transceiver, though temperature stabilization was not implemented to obtain the present results. One drawback of performing the optical interference entirely on chip is the 3-dB loss incurred by the 50-50 coupler that separates the local and received light.

The insertion loss from the terminal to the photodetector is measured to be 6 dB. This includes 3 dB from the use of a 50-50 coupler to separate the local and received

light, 1 dB from the two chip-to-fiber interfaces, 0.5 dB for propagation and additional PIC splitter losses, and 1.5 dB from the telecom components used to wavelength-separate the light.

The CW lasers at each site are phase-stabilized to the frequency comb with a digital phase-locked loop filter and current modulation. Both CW lasers at a given site are phase-locked to their nearest comb tooth with the same offset frequency. The difference in offset frequencies between the two sites determines the demodulation frequency in the digital signal processing and is chosen to be 10 MHz. Typical integrated residual phase noise for the two phase-locks is 0.75 rad in a 5 MHz bandwidth.

B. Digital signal processing

Extracting the one-way group delays is accomplished with digital signal processing on an FPGA at each site. The basic algorithm used to process the two beatnotes is depicted in Fig. 9. The FPGA implements a numerically controlled oscillator (NCO) that is used to in-phase/quadrature-demodulate the optical beatnote between the local and remotely received lasers at the first optical frequency. The frequency of NCO₁ is constantly adjusted from the initial setpoint f_{static} with a servo to keep it in quadrature with the incoming signal. By adjusting the frequency rather than the phase of NCO₁, there is no need to process phase wraps and the algorithm is effectively granted infinite phase range. This is demonstrated in Fig. 4(a), where the system is tracking ± 20 ps deviations in the TOF despite a 5-ps ambiguity range. After suitable adjustment of the phase-locked loop parameters, the phase fluctuations of NCO₁ are the inverse of the relative phase

fluctuations between the local and remote CW laser at the first optical frequency. Currently, the typical bandwidth for this servo is about 10 kHz due to decimation of the input signal and subsequent low pass filtering. We suspect that the limited servo gain creates a multiplicative error in the tracked phase. An improved servo scheme with larger bandwidth and gain is currently under development and has already demonstrated roughly a halving of the timing deviation (200 as at 1 s at high received powers).

A frequency correction is added to NCO₁ to create NCO₂, which is then used to demodulate the optical beatnote between the local and remotely received lasers at the second optical frequency. The correction frequency is also constantly adjusted by a servo to null the phase fluctuations between NCO₂ and the second optical beatnote. The phase of NCO₂ then corresponds to the phase difference of the two remote CW lasers accumulated over the link, which is directly proportional to the one-way group delay. The integral of the correction frequency corresponds to the phase difference of the two remote CW lasers accumulated over the link. The FPGA runs at a clock rate of 200 MHz, and the one-way group delay is processed at a rate of 200 Hz.

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DATA AVAILABILITY

The data that support the findings of this paper are not publicly available because they contain commercially sensitive information. The data are available from the authors upon reasonable request.

APPENDIX

Demonstration of syntonization between two iodine clocks

The comb repetition rates for two iodine clocks in the comparison measurement were initially syntonized by performing a microwave phase comparison (using a Microchip 53100A) and then appropriately adjusting the comb offset frequencies to null any linear phase accumulated. The optical comb tooth number (i.e., the comb tooth number that is phase-locked to the optically stabilized laser) is determined by both systems, which relates the change in the comb offset lock frequencies necessary to induce a target offset in the repetition rates. Initially, these offset frequencies were adjusted to induce a coarse frequency offset of 5×10^{-11} between the two systems. The time offset between the two systems was measured across the free-space test link with the two-tone technique, and the observed phase accumulation is shown in Fig. 10(a). The phase accumulates linearly in time with a slope 50 ps/s, which corresponds to the expected offset of 5×10^{-11} . A fine frequency offset of 7×10^{-15} was then implemented, and the timing signal observed over the link is seen in Fig. 10(b). Here, temporal fluctuations between the clocks are similar in magnitude to the linear phase

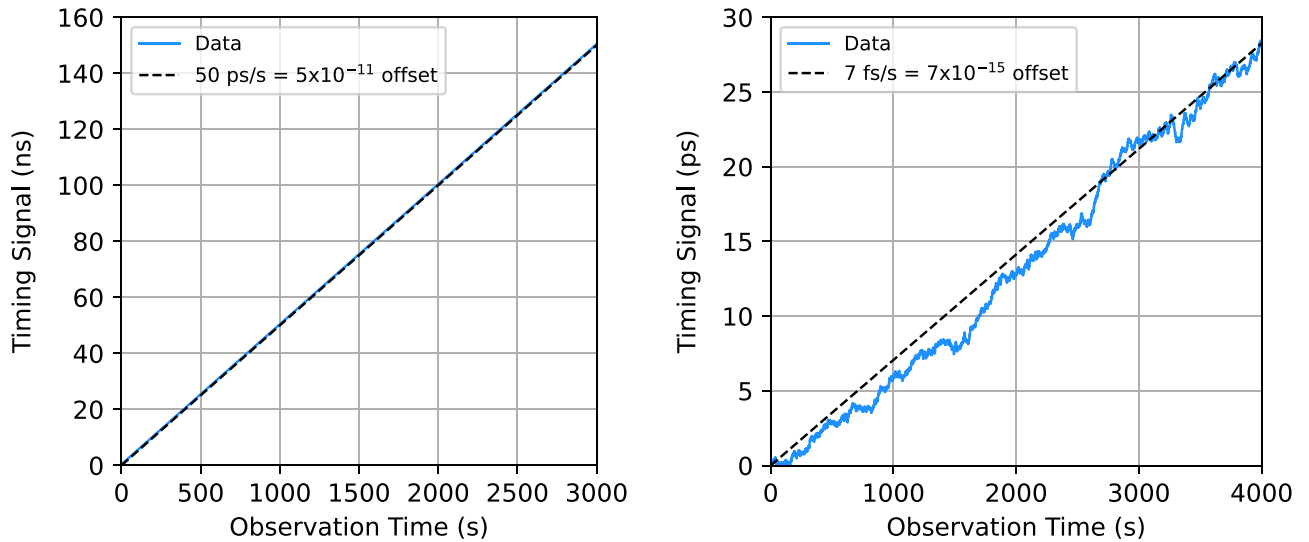


FIG. 10. Syntonization of iodine clocks using the two-tone method. The frequency comb offset lock frequencies are purposefully changed with knowledge of the comb tooth number to induce a desired frequency offset between the two clocks. (a) The frequency offset is altered to create a 5×10^{-11} offset between the two systems. A linear phase accumulation of 50 ps/s is measured between the two systems with the two-tone technique. (b) The frequency offset is altered to create a 7×10^{-15} offset between the two systems, and a corresponding linear phase of slope 7 fs/s is measured.

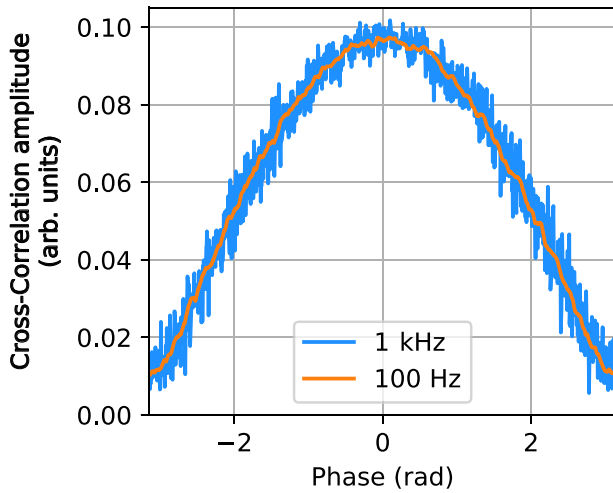


FIG. 11. Cross-correlation between the frequency comb temporal envelope and the two-tone synthetic tone. The phase set-points are adjusted for the phase-locked loops stabilizing the two CW lasers to the frequency comb. The experimentally measured cross-correlation is shown for two values of a digital low-pass filter: 1 kHz and 100 Hz.

accumulation from the intentional frequency offset. However, a linear fit yields a slope of 7 fs/s, which agrees with the expected offset. Thus, the two-tone technique provides a straightforward mechanism to syntonize multiple optical references.

Temporal alignment of synthetic fringe to frequency comb envelope

For absolute timing, information necessary to temporally align the synthetic tone with the comb envelope is contained in the beatnote of the comb and both CW lasers exiting the PIC [22]. This beatnote is measured prior to separating the comb-CW laser light into the two ITU channels. Figure 11 shows an example of temporal alignment for the experimental parameters described in this work. We note that the cross-correlation fringe displayed in Fig. 11 exhibits a 5-ps width corresponding to the CW laser frequency spacing of 200 GHz. Thus, a signal-to-noise ratio of about 1000 is required to split this fringe to the level required for femtosecond-level absolute synchronization. As this is an entirely local measurement (i.e., neither signal is transmitted over the link), it is straightforward to obtain a signal with a high signal-to-noise ratio, and femtosecond-level alignment is readily achievable (e.g., see Fig. 4(b) of the main text).

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