

METROLOGY

Coherent optical clock down-conversion for microwave frequencies with 10^{-18} instability

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Optical atomic clocks are poised to redefine the *Système International* (SI) second, thanks to stability and accuracy more than 100 times better than the current microwave atomic clock standard. However, the best optical clocks have not seen their performance transferred to the electronic domain, where radar, navigation, communications, and fundamental research rely on less stable microwave sources. By comparing two independent optical-to-electronic signal generators, we demonstrate a 10-gigahertz microwave signal with phase that exactly tracks that of the optical clock phase from which it is derived, yielding an absolute fractional frequency instability of 1×10^{-18} in the electronic domain. Such faithful reproduction of the optical clock phase expands the opportunities for optical clocks both technologically and scientifically for time dissemination, navigation, and long-baseline interferometric imaging.

Motivated by placing tighter constraints on physical constants and their possible variations (1, 2), precise measurements of gravitational potential (3), and gravitational wave detection (4), the accuracy and stability of optical clocks have continued to improve, such that they now outperform their microwave counterparts by orders of magnitude. These clocks—based on optical transitions in atoms and ions such as ytterbium, strontium, and aluminum (5, 6)—take advantage of an operating frequency that can exceed 1000 THz. This corresponds to subdividing a second into mere femtoseconds, allowing for an extremely precise measurement of time. The frequency stability of an optical clock, best described as the fraction of the clock's frequency fluctuations relative to its nominal operating frequency, can now reach below 10^{-18} (3). Perhaps more importantly, optical clocks can reach 10^{-16} performance in a matter of seconds, rather than the month-long averaging required of a microwave Cs fountain clock, which currently defines the *Système International* (SI) second, to reach this level (7). With such extraordinary performance, in conjunction with optical clocks meeting other benchmarks laid out by the International Committee for Weights and Measures (CIPM) (8), a redefinition of the SI second appears inevitable.

The range of applications enjoyed by optical clocks can be further extended by transferring

their stability to the electronic domain. Doppler radar sensitivity, particularly for slow-moving objects, is strongly determined by the frequency noise of the transmitted microwaves and could see a large sensitivity enhancement by using optically derived electrical signals (9–11). Astronomical imaging and precise geodesy with very-long-baseline interferometry (VLBI) also rely on highly frequency-stable electronic sources (12). In ground-based VLBI, microwave and millimeter wave signals are detected at receivers spread across the globe and are coherently combined to form exceptionally high-resolution images of cosmic objects. Moving to a space-based VLBI network greatly increases the resolution (13) and avoids atmospheric distortions that limit the observation time. In spaced-based VLBI, maintaining phase coherence with electronic local oscillators that have optical clock-level stability could increase the observation time from seconds to hours, with a commensurate increase in the number of objects that can be imaged with high fidelity.

With the use of fiber-based optical frequency combs (OFCs) and state-of-the-art photodetectors, we have generated and evaluated microwave signals that preserve the phase of the optical clocks from which they are derived with subfemtosecond precision. The resulting frequency stability on a 10-GHz carrier is better than any other microwave source and represents a 100-fold stability improvement over the best Cs fountain clocks. Moreover, the inaccuracy of the optical-to-microwave frequency conversion was measured to be less than 1×10^{-19} . Preservation of the optical clock phase opens up the possibility of distant optical clock synchronization with microwave carriers for applications in navigation and fundamental physics. Lastly, coherently linking an optical atomic frequency standard to the electronic domain allows for future calibration of electronic clocks, an important consid-

eration for the redefinition of the SI second based on an optical atomic transition.

Generating an electronic signal linked to an optical clock is the physical implementation of dividing the optical clock frequency by a large integer (10). The concept is shown in Fig. 1. The first element in this division process is the OFC—a laser source consisting of an array of discrete, evenly spaced frequency tones that span hundreds of THz (14, 15). When an OFC is locked to a clock, each individual tone of the comb carries the same frequency stability as that of the master clock. [Transferring the clock stability to each line is nearly perfect; added instabilities are only at the 10^{-20} level or below (16–18).] The broad spectrum of the comb gives rise to a train of optical pulses with subpicosecond duration. The repetition rate of these pulses, typically in the range of tens of MHz to a few GHz, is coherently linked to the optical clock frequency but is divided down to a much lower microwave frequency. Importantly, the clock frequency fluctuations also divide, such that the fractional frequency stability is maintained. Thus, locking an OFC to an optical clock operating at 259 THz and fractional frequency instability of 10^{-16} can produce a 100-MHz pulse train whose repetition fractional frequency instability is also 10^{-16} .

The repetition rate of an OFC is accessible with electronics, such that illuminating a high-speed photodiode with a locked OFC can, in principle, create a train of electrical pulses with optical clock stability. Optical-to-electrical conversion that preserves optical clock-level stability is not straightforward, however, for this process must contend with the photodiode's nonlinear response engendered by the high peak intensities of ultrashort pulses, the quantum limits of light detection, and the vagaries of electron transport dynamics (19–21). Considerable effort has been devoted to understand and overcome the limitations of photodiodes for optical-to-electrical conversion of ultra-stable optical pulse trains, leading to new detector designs (22) and techniques to lower the impact of quantum noise in the phase stability of the optically derived electronic signal (23). This progress has set the stage for the demonstration of electrical signal generation that faithfully reproduces the frequency and phase of a state-of-the-art optical clock.

With frequency stability better than any other microwave source, measurements required constructing two systems and comparing them against one another (24). A simplified schematic diagram of the microwave generation and measurement is shown in Fig. 1B. Ten-GHz microwaves were derived from two independent Yb optical lattice clocks, each of which demonstrate state-of-the-art stability (3), and absolute frequency verified against the SI second (25). The OFCs were based on two home-built erbium fiber mode-locked lasers with

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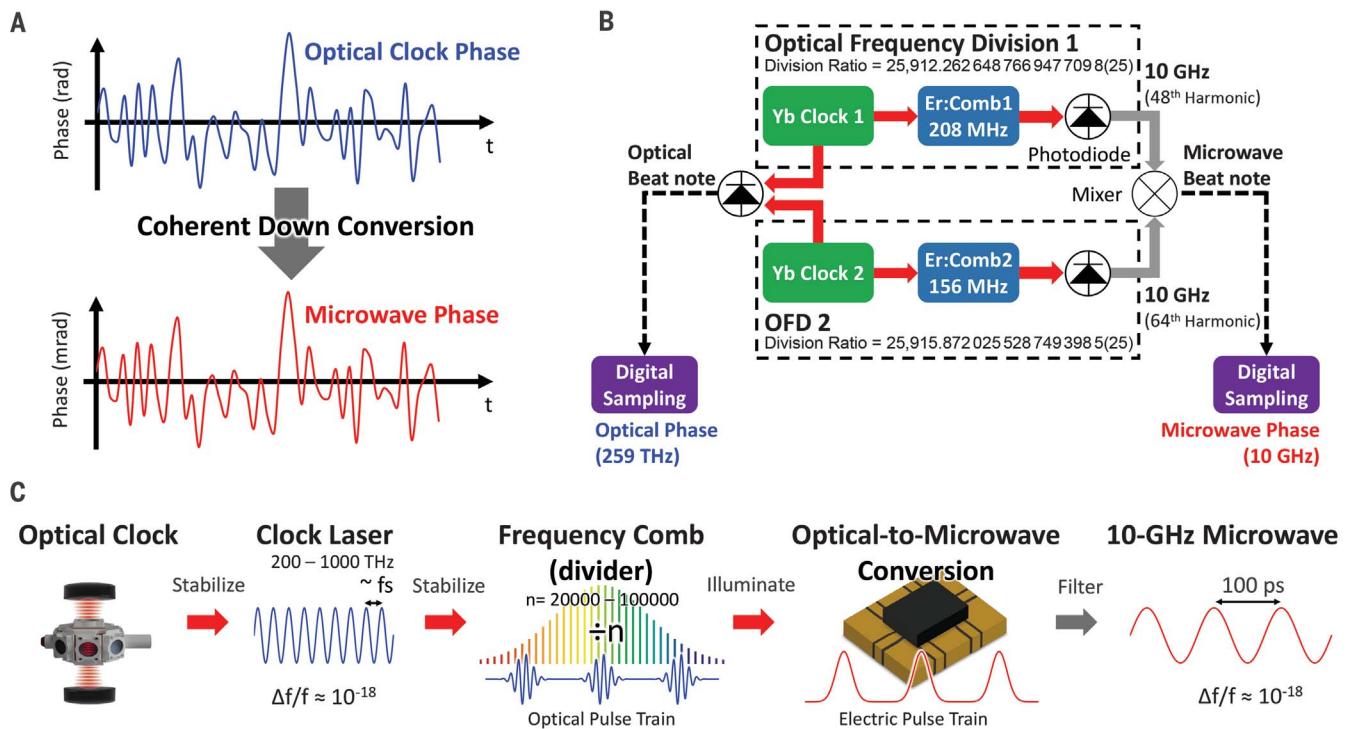


Fig. 1. Coherent optical clock down-conversion. (A) The optical clock phase is transferred to the microwave domain with fluctuations scaled by the optical-to-microwave frequency ratio. (B) Simplified setup of phase and frequency stability measurements. The output of two independent Yb optical atomic clocks generate microwave signals at 10 GHz, where the ratio of the optical to microwave frequencies is determined to 19 digits of precision. By frequency-mixing the 10-GHz outputs, the relative phase fluctuations are

recorded. A direct optical beat note reporting the relative optical phase of the Yb clocks is also recorded. Er, erbium; OFD, optical frequency division. (C) Schematic of microwave generation from an optical atomic clock. An OFC is stabilized to the optical clock laser. Optical-to-microwave conversion through high-speed photodetection generates a train of electrical pulses. Selectively filtering the electrical signal results in a microwave tone that is phase-coherent with the optical clock. $\Delta f/f$, fractional frequency instability.

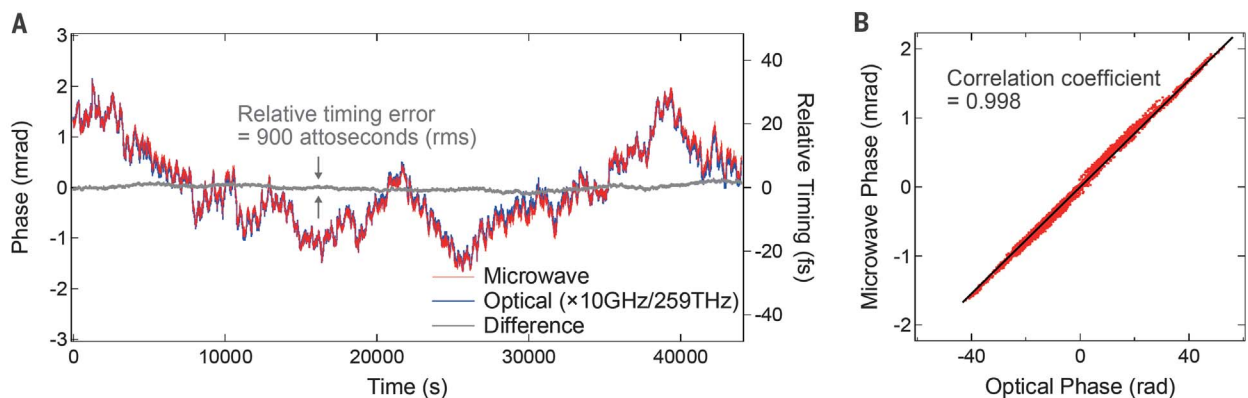


Fig. 2. Optical and microwave phase, timing, and relative coherence. (A) Phase and corresponding timing fluctuations in optical and microwave domains. The point-by-point difference in the (scaled) optical and microwave phase records is shown in gray. (B) Phase correlation plot demonstrating a correlation coefficient of 0.998. The black line is the expected slope given by the optical-to-microwave frequency ratio.

respective repetition rates of 208 and 156 MHz. These OFCs were engineered for long-term, phase-slip-free operation and contribute negligible excess noise. The optical pulse trains from the OFCs were detected with photodiodes designed for high speed and high linearity (22), from which electrical pulse trains were generated. The frequency spectrum of these electri-

cal pulses is an array of tones at the harmonics of the pulse repetition rate. Electrical band-pass filters (100-MHz bandwidth) selected a single frequency near 10 GHz from each system for evaluation. Because the repetition rates of the two lasers are not the same, the nominal 10-GHz outputs represented the 48th and 64th harmonic of the respective systems.

These 10-GHz outputs were combined in a microwave frequency mixer, producing a difference frequency near 1.5 MHz that was digitally sampled and analyzed with software-defined radio (26), from which the microwave phase was extracted. From the phase, frequency stability and accuracy were determined. In addition to the comparisons of the microwave

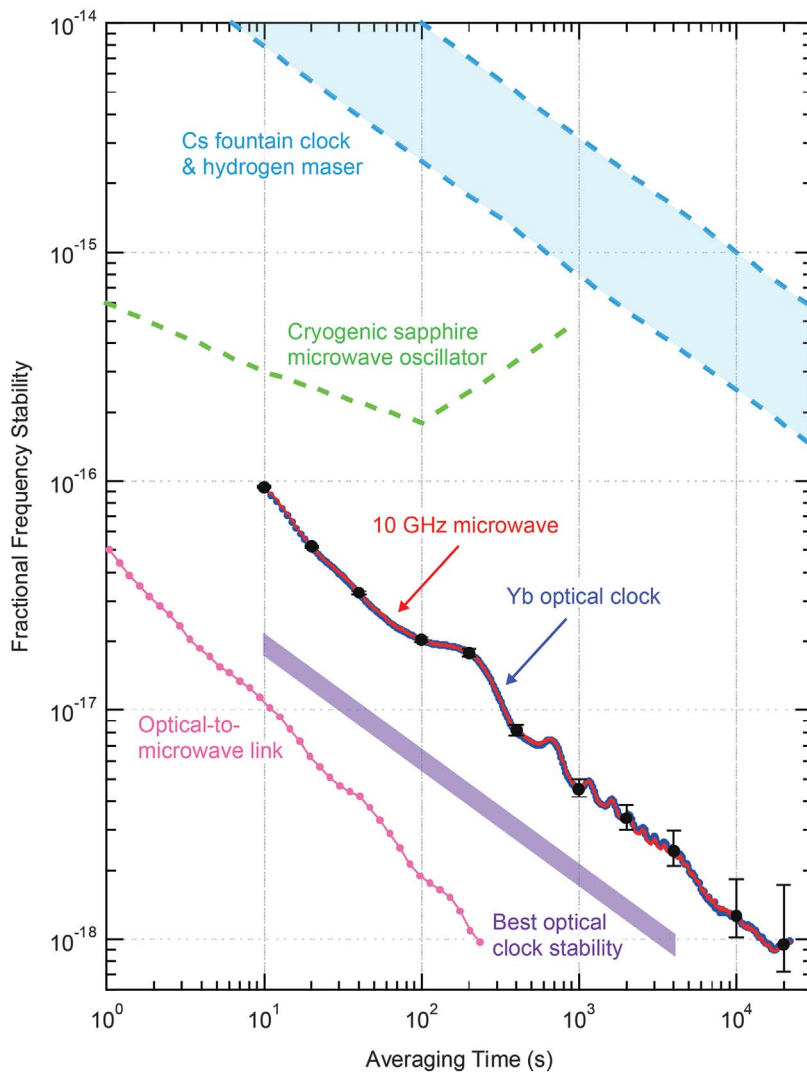


Fig. 3. Fractional frequency stability comparison of state-of-the-art sources. The microwave and optical signals locked to the Yb clocks are reported in terms of the total Allan deviation, with error bars representing 1σ confidence intervals. The white frequency noise asymptote is $1.6 \times 10^{-16} / \sqrt{\tau}$. Additionally, the residual instability of the optical-to-microwave link is well below state-of-the-art optical clocks (7, 29–31). For all plots, the frequency stability is given by the Allan deviation.

outputs, a direct optical comparison of the clocks was made. This was performed by combining the optical clock signals onto a single photodetector, directly generating an electrical signal at an intentionally offset beat frequency between the clocks. This beat frequency was also digitally sampled and recorded. Comparing the phase of the difference frequency of the microwave outputs to that of the optical beat frequency allowed for confirmation of high-fidelity phase and frequency transfer to the electronic domain.

It is interesting to note the level of resolution required to measure a fractional frequency instability of 10^{-16} at 1 s on a 10-GHz signal. This implies tracking phase changes corresponding to only one-millionth of a cycle. As such, standard frequency counting techniques,

although adequate to measure beat frequencies between state-of-the-art optical clocks, cannot yield the required precision for our microwaves. Achieving this level of phase resolution, and maintaining it over several hours, was accomplished in the following ways. First, we utilized microwave amplifiers with low flicker noise, and we routed signals with temperature-insensitive cabling. This gave us an output with ample power (~ 10 mW) without sacrificing stability. Second, by frequency-mixing the 10-GHz outputs, we shifted the measurement to a 1.5-MHz carrier. This reduced the requirements on the fractional stability that we had to measure by ~ 7000 (10 GHz/1.5 MHz). By digitally sampling the 1.5-MHz carrier, the phase difference between the 10-GHz outputs could be tracked with high resolution. Another ad-

vantage of this measurement scheme is that the high phase resolution is achievable without requiring the two sources to oscillate at exactly the same frequency. This gives our measurement system some dexterity in comparing high stability signals from independent sources.

Optical and microwave phase fluctuations, continuously recorded over 44,000 s, are shown in Fig. 2. In Fig. 2A, the phase fluctuations of the optical clock have been scaled by a factor equal to the optical-to-microwave frequency ratio (nearly 26,000) to illustrate the extremely high fidelity in the optical-to-microwave transfer. The relative phase can also be expressed as a timing fluctuation and is bounded by ± 30 fs for both optical and microwave signals. Also shown in Fig. 2A is the point-by-point difference between optical and microwave measurements, limited to root mean square (RMS) fluctuations of 60 mrad, corresponding to a RMS relative timing fluctuation of only 900 as. This implies that optical clocks with even higher stability can be converted to microwave signals without loss of fidelity. The strong correlation between the optical and microwave phases is shown in Fig. 2B. The degree of correlation is quantified by the correlation coefficient, ranging from zero for completely uncorrelated phases to a maximum value of 1 for complete linear correlation between optical and microwave phase (27). The calculated correlation coefficient for the data in Fig. 2 is 0.998. Such femtosecond-level, high coherence optical-to-microwave conversion opens up the possibility of connecting distant optical clocks with a microwave link. Currently, these clocks can be linked optically through fiber or over free space (28), enabling state-of-the-art clock comparisons and synchronization. Free-space optical links are particularly useful for the many situations where a dedicated fiber link is not available but can become ineffective because of poor weather or dusty conditions. The lower loss of microwave transmission could prove advantageous under such conditions by providing a link that would be impossible to maintain optically.

Whereas fluctuations in the phase provide all the frequency and timing stability information of an oscillator, the fractional frequency instability is the more typical performance benchmark. Figure 3 displays the fractional frequency instabilities derived from the same 44,000-s duration phase measurements shown in Fig. 2A. The frequency stability of the derived microwaves followed that of the optical clocks precisely, ultimately yielding an absolute fractional frequency instability of 1×10^{-18} . This is 100 times more stable than the Cs fountain clocks that currently serve as the best realization of the SI second. The short-term stability also exceeds that of other microwave sources, the best of which are microwave oscillators based on whispering gallery mode resonances in cryogenically cooled sapphire (29). There

Table 1. Frequency accuracy evaluation of the optical-to-microwave link. The optical clock frequency offsets were measured both optically and on the derived 10-GHz microwaves, then compared. The difference in the two measurements is consistent with zero at the 10^{-19} level. Yb1, Yb clock 1; Yb2, Yb clock 2.

Measurement	Frequency offset (Yb1 – Yb2) at 259 THz (Hz)	Fractional frequency offset
Optical	–0.0152862	$(-5.8986 \pm 0.095) \times 10^{-17}$
Microwave	–0.0152926	$(-5.9011 \pm 0.096) \times 10^{-17}$
Difference	0.0000064	$(2.5 \pm 9.6) \times 10^{-20}$

are several known techniques for improving optical clock performance beyond that which is demonstrated here—such as real-time blackbody-shift corrections (3), zero dead-time operation (30), and high-performance laser local oscillators (31)—that have led to lower instabilities as indicated in the purple line of Fig. 3. Separate measurements of the added instability due to noise in our optical-to-microwave transfer, shown in pink in Fig. 3, reach 5×10^{-17} at 1 s and 1×10^{-18} at 200 s (24). This indicates that our optical-to-microwave down-conversion can support the highest stability optical clocks yet demonstrated without degradation.

In addition to stability, we examined possible frequency offsets in the optical-to-electrical transfer that would degrade the accuracy of the resulting microwave signal (24). This is best analyzed by comparing the separation in the Yb clock frequencies as determined by the microwave measurement and as determined by the direct optical beat. Table 1 shows the results of our accuracy analysis and includes directly measured frequency differences without accounting for known systematic shift mechanisms in the clock systems (such as blackbody radiation-induced shifts). Both optical and microwave measurements yielded a fractional frequency offset near 5.9×10^{-17} , consistent with the known offset between the Yb clocks used in our experiments. More importantly, the difference in the offset from microwave and optical measurements, again represented as

a fractional offset, was only 2.5×10^{-20} . This is smaller than the statistical uncertainty of 9.6×10^{-20} of the point-by-point difference shown above in Fig. 2. Thus, any unintentional offsets resulting from the frequency transfer from the optical to the microwave domain are well below the $\sim 10^{-18}$ accuracy level of a state-of-the-art optical clock (3, 32).

Transferring the phase, the frequency stability, and the accuracy of optical clocks to the electronic domain has resulted in 100-fold improvement over the best microwave sources. With microwave signals having optical clock stability, one can envision a robust, phase-coherent system of ultrastable electronic signals capable of supporting future radar, communications, navigation, and basic science. Moreover, with residual instability of the optical-to-microwave link below that of the best optical clock demonstrations to date, further improvements to the absolute stability of microwaves can be expected.

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SUPPLEMENTARY MATERIALS

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Supplementary Text
Figs. S1 to S8
Table S1
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Good timing for microwave technology

Timing standards around the world define the second using atomic clocks, specifically the microwave frequencies emitted from trapped atoms. Optical clocks, which are based on optical transitions of atoms, operate at much higher frequency and have been shown to exhibit better stability. Nakamura *et al.* demonstrate a framework that carries the improved stability of the optical domain over to microwaves (see the Perspective by Curtis). In addition to contributing to the eventual redefinition of the second based on optical clocks, this work will also lead to improvements in microwave-based technologies such as astronomical imaging and geodesy through very long baseline interferometry, radar, communications, and navigation systems.

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