Time Programmable Frequency Comb

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Abstract: We demonstrate a programmable optical frequency comb that emits coherent pulses with user-specified time and phase at sub-10 attosecond accuracy while maintaining the underlying referenced stability characteristic of combs.

The optical frequency comb is the preeminent tool for optical metrology due to its precise, rigid, and referenced optical output that acts as a frequency-time ruler. In contrast to this established use as a fixed ruler, we combine a self-referenced, optically stabilized comb with a digital system for phase tracking and control to use the comb as a precisely timed, coherent pulse synthesizer. This time programmable frequency comb emits pulses at specific but variable times with sub-10 attosecond accuracy while maintaining its >100THz coherence bandwidth. Here, we discuss the basic operation and performance of the time programmable comb as well as applications in overcoming typical challenges in comb-based sensing. Fields including spectroscopy, compressive sensing, time transfer, and precision ranging could all benefit from coherent control of comb pulse timing.

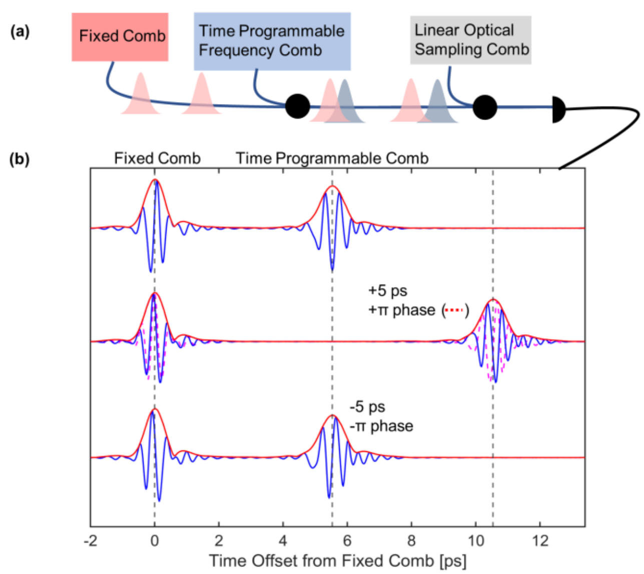

Fig. 1. Demonstration of the time programmable frequency comb. **(a)** Setup to measure the movement of the time programmable comb using a comb fixed in time as the zero-point and a third comb as the sampling comb. The fixed and time programmable comb run at the same repetition rate while the sampling comb is offset by 2 Hz. **(b)** The measured output of (a) showing pulse envelope (red) and downmixed carrier phase (blue). The time programmable comb was commanded to move +5ps, add +π in phase (red dashed), then move -5ps with -π phase.

As applications of frequency combs have expanded, they are now commonly used as more than optical rulers [1]. For active sensing, many experiments make use of two or more frequency combs with mismatched repetition frequencies [2]. When using fixed frequency combs in these experiments, the basic "ruler" spacing set by the comb repetition rate, f_{rep}, may not be well matched with the application, leading to a degradation in measurement speed, sensitivity or resolution depending on the tradeoff chosen [3,4]. Additionally, the frequency comb output, by its nature, is held fixed and cannot be adjusted in real time based on the sensing results.

Here, we move beyond these challenges by demonstrating a time programmable frequency comb (TPFC) with an agile pulsed output that can be shifted in time and phase in a coherent and trackable way as shown in Fig. 1. The TPFC is fundamentally composed of an optically self-referenced frequency comb with its two degrees of freedom locked, here a 200-MHz repetition frequency Er:fiber laser with 1f-2f f_0 detection [5], and precise phase control. We use digital electronics due to the dynamic range available for tracking, namely we need to track >100 trillion optical cycles with sub-cycle precision. To implement the commanded pulse time or phase changes, the digital electronics adjust the offsets of the frequency comb's two phaselocks. The speed of the commanded change is limited by the physical actuators, namely a rate of 40 ns/s for the pump current and cavity PZTs in our laser. In addition to sending the command, the digital electronics track the real-time comb pulse timing and phase, making both available to the larger measurement application. Fig. 2 demonstrates movement of the TPFC over the full 5 ns non-ambiguity range with no bias for the commanded step size and 6.0 attosecond accuracy.

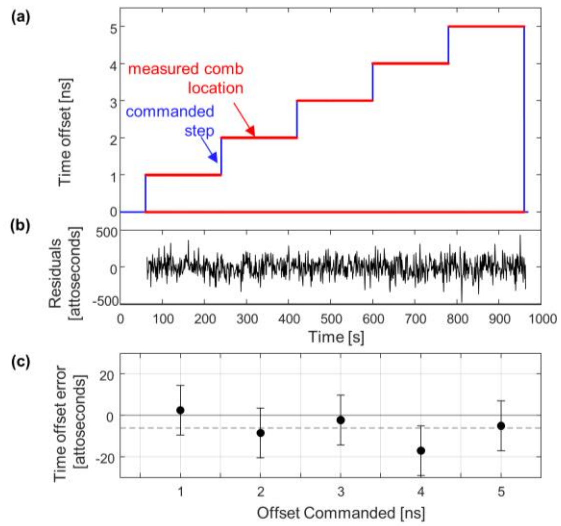

Fig. 2 Measurements showing the accuracy of the time steps taken at a 6 kHz sampling rate. **(a)** The time programmable comb was commanded to move in a square-wave fashion (to cancel slow fiber noise) with the amplitude increasing by 1 ns every 120 seconds. The red dots show the measured top and bottom locations of the comb's square wave while the blue line shows the command amplitude. **(b)** Residuals between commanded and measured comb pulse locations. **(c)** The average residual for each commanded location with a mean offset (dashed line) of -6.0 attoseconds.

A number of existing applications will benefit from the ability to control the time and phase of the output pulses from the comb source. In dual-comb applications, the relative temporal spacing between two frequency combs could be scanned coherently over a specified limited range rather than the full inverse repetition rate, effectively mimicking a higher repetition rate. This scanning has been implemented incoherently in spectroscopy and dual-comb ranging but using the TPFC one could do so coherently while simultaneously tracking the exact location of the comb pulses [6,7]. By incorporating the TPFC within a larger phase-locked loop, a system could track a weak incoming frequency comb signal in both time and phase, akin to the use of tracking oscillators in rf superheterodyne receivers with similar impact on SNR.

In conclusion, we developed a new optical tool, the time programmable frequency comb, that combines the rigid frequency-domain characteristics of a self-referenced comb locked to a reference oscillator with a newfound agility in time and phase. In principle, any self-referenced comb with phase-tracking control electronics could be converted into a TPFC, broadening the impact of this work to any field where frequency combs are used, and precise time control could enable new experimental work.

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