Downsampling of optical frequency combs for carrier-envelope offset frequency detection

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We explore downsampling of optical frequency combs by way of pulse gating for efficient spectral broadening and f-2f interferometry. We downsample a 250 MHz repetition-rate comb to 25 MHz, thereby enabling detection of the comb's carrier-envelope offset frequency. Pulse gating can both increase timing jitter of the comb's pulse train and induce spurious frequency offsets of the comb's spectrum. To investigate these effects, we characterize the phase-noise spectrum of the downsampled comb, determine the effects of timing jitter deliberately imposed on the pulse gate, and demonstrate the null frequency shift of the comb's optical spectrum to the level of several microhertz.

Optical frequency combs are a critical tool in the measurement of optical frequencies, and they enable applications including optical clocks, optical waveform generation, precision spectroscopy, and low-noise frequency synthesis [1, 2]. Traditional ultrafast laser technology yields frequency combs with repetition rates typically between 100 MHz and 1000 MHz, but many applications would benefit from repetition rates of tens to hundreds of gigahertz. Such applications include frequency comb spectroscopy [3], astronomical spectrograph calibration [4, 5], and advanced optical and microwave signal processing [6, 7], where high repetition rates provide higher power per mode and enable line-by-line addressing of individual comb teeth.

Stabilization of the comb's carrier-envelope offset frequency (f_0) is key for these applications. However, such frequency control is challenging for gigahertz repetition-rate combs due to low peak power, which inhibits the spectral broadening needed for $f-2f$ nonlinear interferometry [8]. Systems affected by this challenge include gigahertz-rate laser [9] and electro-optic [10] combs, as well as a new class of frequency combs based on parametric oscillation in high-Q microresonators [11, 12].

In this Letter, we discuss repetition-rate downsampling by way of optical pulse gating. This technique provides a solution for spectral broadening and f_0 detection of high-repetition-rate optical pulse trains. Downsampling, pulse gating, or "pulse picking" is a well-established technique [13, 14], and has been critical to the generation of energetic, offset-stabilized ultrashort pulses at kilohertz repetition rates [15]. In previous experiments f_0 was stabilized before downsampling [16, 17]. Here we measure the carrier-envelope offset frequency of a downsampled comb and investigate whether f_0 is preserved in the downsampling process.

In our experiments, we downsample a 250 MHz input comb to 25 MHz and measure its offset frequency after amplification and spectral broadening (Fig 1). Anticipating future experiments at repetition rates >10

GHz, we characterize the effects of electronic pulse-gate noise on the downsampled optical pulse train. Expanding on a previous study [18], we show that only phase noise that exceeds a threshold value affects the downsampled pulse train. Improper temporal alignment of the optical pulse train and the gating signal modulates the amplitude of the downsampled optical pulse train. Importantly, we demonstrate that pulse gating preserves the offset frequency of the downsampled comb to the level of several microhertz.

We begin our investigation of the pulse gating technique by downsampling a 250 MHz Er:fiber comb by a factor of ten to facilitate detection of its carrier-envelope offset beat. Our pulse gating scheme (Fig. 1a) employs a Mach-Zehnder electro-optic modulator (EOM) driven by 25 MHz rectangular electronic gating pulses with 80 ps rise time and 3.5 ns duration. The electronic pulse generator and the repetition rate of the 250 MHz comb are both referenced to a hydrogen maser. The bias of the EOM is set for maximum extinction outside the gate, which has an amplitude equivalent to V_π of the EOM [13]. A stable 25 MHz optical pulse train with high contrast results from this downsampling scheme (Fig. 1b). The average power of this pulse train is reduced from 30 mW to 400 μW by the pulse gating process and the insertion loss of the EOM. We amplify the pulse train to an average power of 35 mW by use of a normal-dispersion erbium-doped fiber amplifier, which provides some spectral broadening and pulse compression [19]. Further spectral broadening is obtained by launching the amplified, <100 fs, 1.4 nJ pulses into 20 cm of highly nonlinear fiber (HNLF) [20]; the resulting supercontinuum spectrum is shown in Fig. 1c. For comparison, we also present the supercontinuum generated by the 250 MHz comb with the EOM set for constant maximum transmission. In this case the average power of the amplified 250 MHz comb when it enters the HNLF is 85 mW, corresponding to 340 pJ per pulse.

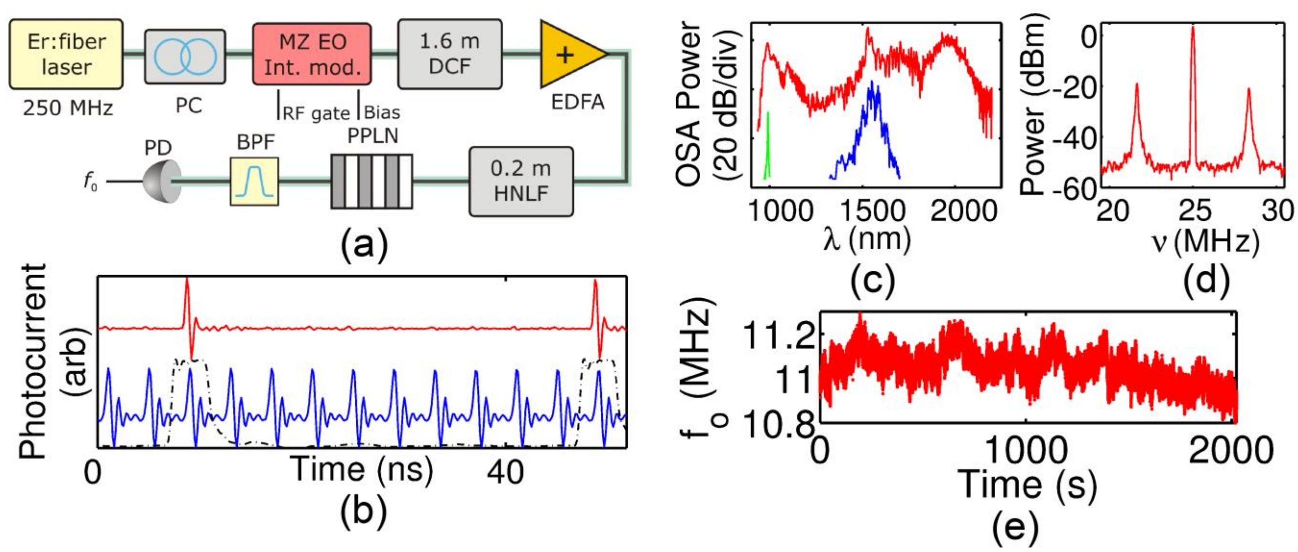

Figure 1. a) Schematic for detection of the offset beat of a 250 MHz Er:fiber comb. b) Input and downsampled pulse trains from a 1 GHz photodetector. c) Octave-spanning supercontinuum generated by downsampling (red), second harmonic generated for f_0 detection (green), and for comparison the supercontinuum generated by the same apparatus without downsampling (blue). d) Detected f_0 beat at 100 kHz RBW; signal-to-noise ratio is 30 dB. e) Counted frequency of the detected free-running offset beat. Data is taken for more than 2000 s at 10 ms gate time.

To detect f_0, the octave-spanning supercontinuum shown in Fig. 1c is sent into a free-space $f-2f$ interferometer consisting of a half-wave plate and a periodically poled lithium niobate (PPLN) crystal quasi-phase-matched for second-harmonic generation at 1980 nm. The generated 990 nm light is shown in Fig 1c. A 10 nm band-pass filter at 990 nm selects this second harmonic and the colinear supercontinuum at 990 nm, which are then photodetected to observe f_0 with 30 dB signal-to-noise ratio; see Fig. 1d. Figure 1e shows a 2000 s record of f_0 for our downsampled comb.

While Fig. 1 presents an absolute frequency measurement of f_0 enabled by our downsampling technique, it does not demonstrate the deterministic connection between the input and downsampled comb spectra that is essential for applications. To understand their relationship, we present a simple model of downsampling and experimental tests of its conclusions.

We model the gated pulse train's electric field as the product of the incoming comb's field and a time-varying amplitude modulation. For an incoming optical frequency comb with repetition rate f_r, complex single-pulse field $A(t)$, and pulse-to-pulse carrier-envelope phase shift ϕ, pulse gating by a train of rectangular pulses of length t_g and repetition rate f_g yields a downsampled comb with field

$$a(t) = \left[\Sigma_n A(t - n/f_r)e^{in\phi}\right]\left[\Sigma_m \mathrm{Rect}\left(\frac{t-m/f_g}{t_g}\right)\right] \quad (1)$$

where Rect is the rectangle function and n and m count the pulse number of the incoming pulse train and the electronic gate. Regardless of the gate frequency, the temporal separation of pulses in the downsampled optical pulse train is restricted to integer multiples of the incoming comb's repetition period [18]. The frequency content of the downsampled pulse train $a(t)$ can be calculated via the convolution theorem:

$$\mathcal{F}\{a\}(f) \sim 4\pi f_r \sum\nolimits_{nm} \frac{1}{m} \mathcal{F}\{A\}\,(f_o + nf_r) \times$$
$$\sin\left(\pi m t_g f_g\right)\delta\left(f - f_o - nf_r - mf_g\right), \quad (2)$$

where f_o is the carrier-envelope offset frequency of the incoming comb, $f_o = f_r \cdot \phi/2\pi$. The downsampled pulse train has frequency content at optical modes $f_o + nf_r$, as well as at intensity modulation sidebands whose frequency offsets mf_g are harmonics of the gating frequency. To avoid the generation of spurious modulations, pulse gating at an integer sub-harmonic of the incoming repetition rate, $f_g = f_r/N$, is essential. In this case overlap of the intensity modulation components created by pulse gating results in a downsampled frequency comb with a single mode spacing. Moreover, the downsampled comb has the same offset frequency as the incoming comb.

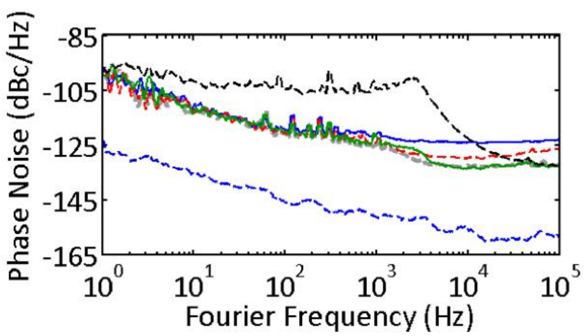

Figure 2. Measured phase noise of spectral components of the supercontinuum, selected by a 1650 nm long pass filter (dashed red) and a 990±5 nm band pass filter (solid blue), the entire downsampled 25 MHz frequency comb measured immediately before the EDFA (green), the 250 MHz comb (dashed gray, shifted by $20\log(1/10) =$ -20 dB), and the gate generator (dashed black). We also display the measurement noise floor (dashed blue).

Notably, for sub-harmonic gating, jitter of the electronic gate less than its duration does not contribute to noise on the downsampled comb. We model jitter as gate-to-gate arrival-time delays Δt_m. The downsampled comb's amplitude $a(t)$ does not deviate from that of Eqn. (1) provided that the jitter is a sufficiently small $|\Delta t_m| < t_g/2$, i.e., that the optical and gating pulses are always substantially overlapped. Thus, we expect that the carrier-envelope offset frequency of the incoming comb is preserved by downsampling even with jitter on the gate signal.

To test the impact on the downsampled optical waveform of electronic jitter, we compare the phase-noise spectrum of the comb's repetition rate at different points in our apparatus (Fig. 2). Relative to the phase noise of the 250 MHz comb, which has been shifted by -20 dB to facilitate comparison, the downsampled frequency comb's phase-noise spectrum exhibits only a small increase at ~3 kHz, likely corresponding to the corner in the gate generator's phase noise at the same frequency. The phase noise of the far ends of the supercontinuum similarly matches the 250 MHz comb below 1 kHz. The higher phase noise in the supercontinuum beyond 1 kHz is likely due in part to four-wave mixing between ASE and the comb light that occurs in the HNLF.

The timing jitter of our gating pulse train is between 5 ps (obtained by integrating the phase noise plotted in Fig. 2 to 100 kHz) and 10 ps (extrapolating constant phase noise to the 12.5 MHz Nyquist frequency and integrating). These jitter values are small relative to the 4 ns period of the incoming optical pulse train. As the repetition rate of the incoming optical pulse train increases to >10 GHz, the gate duration must correspondingly decrease for single-pulse gating, and timing jitter on the gate may become a significant fraction of the gate duration. To explore the effects of timing jitter larger than our pulse generator's inherent 5 to 10 ps, we impose excess jitter on the gating signal. The relative timing between the gating signal and the incoming optical pulse train is modulated at 5 MHz with an amplitude of 250 ps. The effect of this jitter is manifest in the microwave power of the gated comb as 5 MHz intensity-modulation sidebands and depends on the optical pulse alignment within the gate; see Fig. 3a. Pulses with a mean position within 250 ps of the gate edge are substantially modulated by the 5 MHz gate-delay signal. This agrees with the prediction of a sharp threshold on the acceptable level of timing jitter on the gate.

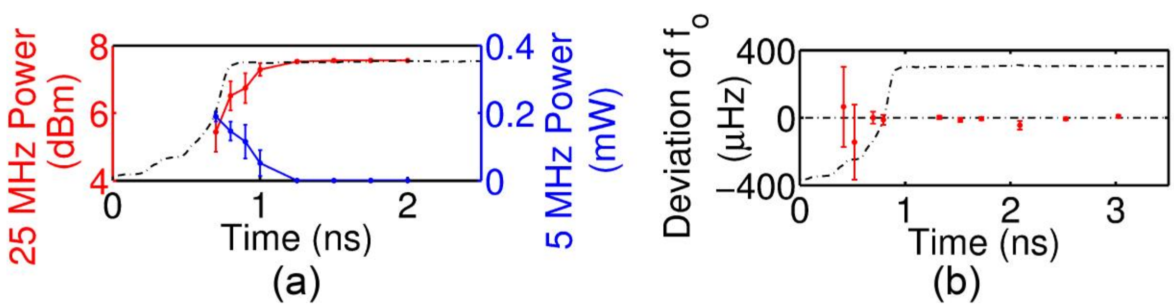

Figure 3. a) Amplitude of the downsampled pulse-train modulation due to 250 ps jitter at 5 MHz rate. The position of a data point on the x-axis indicates its mean position within the gate, shown in dashed black. Measurement uncertainties arise due to a latency between the optical trigger and the start of the electronic gating signal which varies on the order of 50 ps. b) Deviation of the carrier-envelope offset frequency of the downsampled comb relative to the 250 MHz comb's offset as a function of the alignment of optical pulses within the gate.

To establish that the comb's carrier-envelope offset frequency is preserved in the downsampling process, we perform a frequency comparison of the 25 MHz downsampled comb and a separate output of the 250 MHz comb. This 250 MHz output is intensity modulated so that a measurement of the nonzero optical heterodyne beat frequency between an intensity modulation sideband and a pulse-gating sideband of the downsampled comb reveals the relative frequency offset of the two combs. Figure 3b shows the null frequency shift between the 25 MHz and 250 MHz combs, which we have characterized for different alignments of the optical pulse within the gate. At the level of several microhertz, better than 10^{-18} relative to the 200 THz optical carrier frequency, we observe no frequency shift between the 250 MHz comb and the downsampled 25 MHz comb. One factor that may contribute to the greater measurement uncertainties in the data points taken on the leading edge of the gate is the change in the carrier-envelope phase due to distortion of the optical intensity envelope by the rising edge of the gate.

Downsampling via pulse gating offers a promising route to offset frequency stabilization of high-repetition-rate combs. In our experiments downsampling facilitated detection of f_0 at a signal-to-noise ratio sufficient for measurement and stabilization, which would otherwise have required significantly higher average power. The effects of timing jitter on the gating signal are negligible so long as the incoming optical pulse train does not interact with the edge of the gate, but when it does, timing jitter induces amplitude noise on the transmitted pulses due to the effective time-varying transmission of the EOM. Our experiments demonstrated that downsampling preserves f_0, as required for application of the technique.

To employ downsampling as demonstrated here with repetition rates >10 GHz will require electronic gates with duration <100 ps. Technology to downsample with gates as short as 20 ps is commercially available, while 100 Gb/s integrated circuits and 25 GHz demultiplexing have been demonstrated [21, 22]. Barring the use of such state-of-the-art electronics, pulse gates of duration longer than the incoming optical pulse train's repetition period can be employed. This will be technically easier to achieve, but determining the effect of transmitting several pulses per gate on the downsampled comb will require further investigation.

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