Intense, wideband optical waveform generation by self-balanced amplification of fiber electro-optical sideband modulation

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We demonstrate a simple method to obtain accurate optical waveforms with a gigahertz-level programmable modulation bandwidth and a watt-level output power for wideband optical control of free atoms and molecules. Arbitrary amplitude and phase modulations are transferred from microwave to light with a low-power fiber electro-optical modulator. The sub-milliwatt optical sideband is co-amplified with the optical carrier in a power-balanced fashion through a tapered semiconductor amplifier (TSA). By automatically keeping TSA near saturation in a quasi-continuous manner, typical noise channels associated with pulsed high-gain amplifications are efficiently suppressed. As an example application, we demonstrate interleaved cooling and trapping of two rubidium isotopes with coherent nanosecond pulses.

Keywords: pulse shaping; laser cooling and trapping; high gain optical pulse amplification; self-phase modulation; amplified spontaneous emission; sideband modulation.

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I. Introduction

Optical control of atomic motion is traditionally accomplished by weakly dressing atoms in their ground-state manifolds, such as laser cooling, atom interferometry, and ion-based quantum information processing [1-7]. The long coherence time associated with the weakly dressed ground states makes it possible to precisely control the dynamics using modulated CW lasers, typically through acousto-optical modulation (AOM) with a megahertz (MHz)-level bandwidth [8]. On the other hand, full control of the strong-transition dynamics between ground and excited states becomes an emergent scenario, with many applications in atomic and quantum optics, such as for ultrafast optical acceleration of spinor matterwave [9-13], precise control of light-assisted interactions [14,15], and to access subradiant physics [16-18]. Since strong transitions have coherence time radiatively limited to tens of nanoseconds, their full and coherent control requires optical waveforms with modulation bandwidth at the gigahertz (GHz) level beyond standard CW modulation technology. Although ultrafast pulses can have bandwidth beyond terahertz (THz), the pulse spectral brightness is usually too weak to efficiently drive the narrow transitions [19-21].

Efforts have been made to generate intense, coherent optical waveforms with GHz modulation bandwidth for atomic physics applications [22]. For example, coherent pulse trains with short inter-pulse delays are generated in the time domain to excite atoms efficiently [11,21]. Fiber electro-optical modulators (fEOMs) with ~10 GHz bandwidths are exploited to transfer modulation from microwaves to light [18,22-26]. Compared with shaping ultrafast pulses, modulation of CW lasers is more convenient for achieving long coherence time for, e.g., complex optical control with composite pulses [13,18,27]. However, the integrated lithium-niobate-based fEOM suffers from severe photo-refractive damage at short wavelengths, limiting the throughput to a few tens of milliwatts or less in atomic physics applications [18,22-25]. The weak signal could be amplified into a watt-level output using tapered semiconductor amplifiers (TSAs) under a double-pass configuration [22,28,29]. However, unlike continuous seeding [25,28], when the seeding waveform...
is modulated in amplitude, the amplified spontaneous emission (ASE) can be severe. The ASE problem is partially addressed in Ref. [22] by carefully managing the optical gain in both the time and frequency domains, although the remaining ASE that shares the time-frequency window with the amplitude-modulated waveform output can still be detrimental. In Refs. [18,24], ASE is reduced by amplifying a CW laser first and then pulsing the high-power output into the EOM with a low enough duty cycle for wideband modulation without damaging the EOM. Although pulsed waveforms with hundreds of milliwatts of power can be achieved this way, the procedure precludes the possibility of generating continuous waveforms with high average power. Apart from the ASE problem, it is known that when amplifying amplitude-modulated light, the transient change of the gain saturation level in TSA associated with the electron-hole density leads to self-phase modulation (SPM) [30-35] and distortion of individual output waveforms.

In this work, we introduce a simple method to achieve intense, wideband programmable optical waveforms with substantially suppressed noise associated with ASE and SPM effects. The method starts with phase-modulating a CW laser with EOM at a microwave carrier frequency \( f_c \). Complex waveforms are transferred from the microwave to the optical sidebands of the EOM output, which is then filtered and amplified with TSA. To suppress the SPM waveform distortion and ASE noise, we use the optical filter to balance the power between the desired sideband (when the EOM microwave modulation is on) and the optical carrier (when the modulation is off) so as to maintain a nearly constant seeding power and a consistent level of TSA saturation. The optical carrier off-resonant to the atomic transition can be subsequently filtered away. We demonstrate the method with a wideband optical waveform generation system with \( \sim 1 \) W output power and \( \omega_M \sim 2 \pi \times 4 \) GHz programmable waveform modulation bandwidth for fast cooling and control of rubidium (Rb) isotopes. As to be clarified shortly, the modulation bandwidth is limited by the carrier frequency \( f_c \) in the sideband modulation scheme. By increasing the microwave carrier frequency, waveform modulation bandwidth beyond 10 GHz can be achieved [18].

In the following, we first outline the operation principle of the amplified optical waveform generation system. We then detail the performance of our Rb laser system and present an example application of the system for cooling and trapping with interleaved nanosecond pulses.

### 2. Methods

#### 2.1. Sideband modulation

The setup of our laser system is schematically illustrated in Fig. 1. A frequency-stabilized CW laser (an external-cavity diode laser, ECDL) is phase-modulated through EOM by an amplitude and phase-modulated microwave signal \( V(t) = V_0 A(t) \cos(\omega_c t + \varphi(t)) \). Here, \( \omega_c = 2 \pi f_c \), at the 10 GHz level is the microwave carrier frequency. \( A(t) \in [0,1] \) and phase \( \varphi(t) \in [0,2\pi] \) are the amplitude and phase modulation functions to be transferred to light, respectively. We use complex \( E_{in} \) to represent the optical field. The output from EOM can be expressed as

\[
E_{out}(t) = e^{i\theta_{0} A(t)} e^{i\rho(t)} E_{in}(t) = \sum_n f_n^{2} e^{i\theta_n (A(t))} e^{i\rho_n (A(t))} E_{in}(t). \tag{1}
\]

As described by the second line of Eq. (1), the phase-modulated output can be decomposed into an array of optical sidebands, with the \( n \)-th-order \( E_{out}(t) \) subjected to complex modulation function \( C_n(t) = f_n^{2} e^{i\theta_n (A(t))} e^{i\rho_n (A(t))} \). Here, \( f_n \) is the \( n \)-th-order Bessel function. The maximum electro-optical phase shift \( \theta_0 = \beta V_0 \) is determined by the peak microwave voltage \( V_0 \) and the EOM phase response coefficient \( \beta \). By adjusting \( V_0 \) to let \( \theta_0 = \theta_n \sim n_0 + 1 \), the magnitude of \( \mid f_n^{2} e^{i\theta_n (A(t))} \mid^2 \) can be maximized to the \( (n_0) \)-th-order maximum as \( f_{n_0,\text{max}} ^2 \) for efficient generation of an \( (n_0) \)-th-order sideband. To transfer a specific complex modulation to the \( (n_0) \)-th-order sideband, i.e., for \( C_n(t) = a(t) e^{i\varphi(t)} \), one simply programs the rf waveform as

\[
A(t) = f_{n_0,\text{max}}^{-1} (a(t) / \theta_{n_0}) / \theta_{n_0}, \quad \varphi(t) = \phi(t) / \theta_{n_0}. \tag{2}
\]
The desired $n_0$ sideband is optimally selected and amplified as the output, as to be discussed in the following. The frequency span of the $C_{n_0}$ signal [Eq. (2)] $\omega_m$ is limited by the requirement that the single sideband has to be isolated during the output, leading to the $f_n$-limited modulation bandwidth in the sideband modulation scheme [36].

2.2. The first optical filter

We send the fEOM output $E_{\text{fEOM, out}}$ through an optical filter (Filter 1 in Fig. 1) to select the desired $(n_0)$th-order sideband and to attenuate the optical carrier ($n = 0$) to a suitable level. Here, we consider the simplest example of optical filtering by grating diffraction. A grating constant $d < 2\lambda$ is preferred to achieve good diffraction efficiency near the Littrow angle $\alpha \approx \arcsin(\lambda/2d)$ [37]. With the filter input expanded into a Gaussian beam profile with Gaussian waist $w$ and the diffraction order mode-matched by the single-mode fiber, the fiber output power is approximately filtered in frequency by

$$H(\omega) = \eta e^{-(\omega - \omega_A)^2/\Delta\omega_1^2},$$

Here, $\eta$ is the maximum filter efficiency. The central frequency $\omega_A = \omega_0 + n_0\omega_c$ resonant to an atomic transition frequency is achieved by offset-locking the ECDL frequency $\omega_0$ and tuning the grating angle $\alpha$ to maximize $H(\omega_A)$. By adjusting the laser beam polarization, an $\approx70\%$ grating diffraction efficiency can be achieved in the near-infrared region, leading to a typical $\Delta\approx 40\%$ overall efficiency after fiber-coupling losses. The filter bandwidth $\Delta\omega_1 = \frac{2\pi}{w \tan \alpha} = \frac{2\pi}{w} \sqrt{4d^2/\lambda^2} - 1$ can be adjusted with $w$ to match

$$H(\omega_A)/H(\omega_A) \approx f_0^2\text{, max}.$$  

As such, the resulting output $E_{1,\text{out}}$ is quasi-continuous during the full-contrast $A(t)$ modulation with approximately constant average power.

2.3. Self-balanced amplification

At near-infrared wavelengths, to avoid photo-refractive damage, the fEOM throughput is limited to less than ten milliwatts. With a sideband modulation efficiency limited to $f_{\text{max}}^2$ [Eq. (1)] and after the Filter 1 loss $\eta$ [Fig. 1(a), Eq. (3)], the filtered $E_{1,\text{out}}$ is typically less than 1 mW. The weak signal can be amplified into a watt-level output using TSAs under a double-pass configuration [22,28,29]. The ASE associated with the high gain can be efficiently suppressed by saturating the TSA gain with a strong enough constant seeding [28]. Here, for the amplification of seeding $E_{1,\text{out}}$ with a time-dependent amplitude, the optical gain $g(t)$ and the effective index $n(t)$ of TSA are expected to display time-dependent dynamics associated with semiconductor carrier density [30–35], leading to time-dependent ASE and SPM to severely degrade the quality to the amplified $E_{1,\text{out}}$.

In this work, we realize that for a high enough microwave modulation carrier frequency $\omega_c \gg 1/\tau_c$, where $\tau_c$ is the effective relaxation time of carrier density [30–35], the TSA carrier density can hardly follow the microwave modulation, but stays at a saturation level determined by the average seeding power. Therefore, when the quasi-continuous seeding maintains a nearly constant average power during the full $A(t)$ modulation in a self-balanced fashion, ASE can be suppressed in a way similar to the case of CW seeding [28], while SPM can be suppressed in a way similar to those achieved in multi-sideband seeding with large enough frequency intervals [34,35].

2.4. The second optical filter

With the microwave carrier frequency $\omega_c$ at the 10 GHz level or higher [18], the amplified quasi-continuous $E_{\text{out}}$ from TSAs can already be directly applied to resonantly drive atomic systems with their $(n_0)$th-order sideband. However, the off-resonant optical carrier and additional sidebands could be detrimental to certain applications, such as for resonant imaging applications. To further select the $(n_0)$th-order sideband from the quasi-continuous output, an optional Filter 2 with bandwidth $\Delta\omega_2 \ll \omega_c$ can be constructed with a grating filter [Fig. 1(b)] [18,37] or with other types of narrow-line filters [38].

3. The Rubidium Laser System

So far, we have outlined the general operation principle and key elements of the amplified laser system. In the following, we provide additional details of the laser system designed for cooling and coherent manipulation of $^{87}$Rb, $^{85}$Rb isotopes. Here, to cover the needed frequency range spanned by the $^{87}$Rb ground-state hyperfine splitting, $f_{\text{hyg}} = 6.83$ GHz, we lock the ECDL to the $F = 1 - F = 0, 1$ cross-over peak of the saturation spectroscopy. Part of the output can be shifted directly with AOM to address the $F = 1 - F = 2$ repumping transition. The majority of the ECDL output is then modulated by fEOM with a carrier frequency of $\omega_c = 2\pi \times (f_{\text{hyg}} + \Delta f) = 2\pi \times 6.36$ GHz, with the $n_0 = -1$ sideband to resonantly address the $F = 2 - F = 3$ transition of $^{85}$Rb. The $\Delta f = -0.47$ GHz is determined by the ECDL locking point as well as additional AOMs for the cooling laser control. We correspondingly set Filter 2, with a bandwidth $\Delta\omega_2 \approx 6$ GHz. The filter function $H(\omega)$ is estimated by measuring the $n_0 = -1$ ($-1$-order) output with a Fabry–Perot (F-P) spectrometer (Supplementary Material).

We heat the fEOM (EOSpace, Model PM-055-20-PFA-PFA-780-UL) to ~90°C to increase the photo-refractive damage threshold [18], with which we find that the optical throughput can be kept at a 5 mW level over a long time. With 30 mW output from the ECDL and after the insertion and fiber-coupling losses, we obtain $P_{\text{f}} = 0.6$ mW of the filtered output $E_{1,\text{out}}$ to seed TSA 1. The highly efficient EOM allows us to reach $\theta_{\text{g}} = 1.8$ [Eq. (1)] to optimize the $-1$st order with less than 100 mW of microwave power. To fully utilize the $E_{1,\text{out}}$ for the double-pass seeding without optical damage, we limit the TSA 1 driving current to $I_1 = 1.0$ A to obtain $P_1 = 140$ mW. The output is divided by a beamsplitter (BS in Fig. 1).
30 mW output is fiber-coupled to seed TSA$_2$, while the rest is sent for other applications. To allow the TSA$_2$ output to repump the $^{87}$Rb $F = 1$ atoms, an AOM controlled $\sim 0.5$ mW of ECDL output is also combined to seed TSA$_2$. By operating TSA$_2$ at $I_2 = 1.7$ A, a $P_2 \approx 720$ mW output is obtained, which is directly applied to the laser cooling and coherent control experiment without being filtered by optional Filter$_2$.

As detailed in the Supplementary Material, the spectrum density of the coherent TSA$_1$ output is $\sim 75$ dB above the ASE background at the seeding frequency, which comprises $\xi_1 = 90\%$ of the total output power $P_1$. Compared with free-running, the $E_{\text{f1,out}}$ seeding leads to $\sim 10$ dB suppression of ASE background, similar to Ref. [28]. Similarly, ASE suppression is also obtained for TSA$_2$, with the coherent output comprising $\xi_2 = 84\%$ of $P_2$ and is $\sim 70$ dB beyond the ASE background in spectral density. As discussed in Sec. 2.2, with Filter$_1$ bandwidth $\Delta \omega_1 \approx \omega_\alpha$, the $E_{\text{f1,out}}$ seeding maintains the average seeding power $P_{\text{f1}}$ during modulation of EOM, leading to a nearly identical level of ASE suppression regardless of the $E_{\text{f1,out}}$ modulation strength. In addition, for the quasi-continuous seeding by $E_{\text{f1,out}}$, the 6.4 GHz frequency separation is large enough that SPM is largely suppressed too, as being characterized by merely $2\% - 4\%$ of optical power redistributed into additional sidebands during the optical amplification.

3.1. Accurate waveform generation

The microwave amplitudes $A(t)$ and $\varphi(t)$ are programmed according to Eq. (2) to transfer specific waveforms to light. We then perform beat note measurements to characterize the output waveforms from TSA$_{1,2}$. In particular, we mix $E_{\text{out}}$ with a strong local field $E_r$ through a BS to measure the interference $s = \text{Re}(E_r^*E_{\text{out}}e^{-i\varphi(t)})$, where $\omega_\alpha = 2\pi \times 1.2$ GHz is the relative frequency shift between the local field and the unmodulated ECDL output. All measurements are performed with a fast photodetector (Thorlabs PDA8GS) with a 9.5 GHz detection bandwidth.

Typical beat note measurements for the TSA$_2$ output are given in Fig. 2 with the waveforms programmed as chirp pulse modulation according to Eq. (2) with $C_{\text{rf}}(t) = \sin(\pi t / \tau) e^{i\phi_0}$, $\sin(\pi t / \tau)$ during $0 < t < \tau$. Here, $\tau = 10$ ns pulses are chirped with $\phi_0 = 10 \degree$, 40 rad in Figs. 2(a-i) and 2(b-i), respectively. The corresponding range of frequency sweep, $\Delta f = \phi_0 / \tau$, is 1 GHz and 4 GHz, respectively. By performing Fourier transform of the beat note data within a shifting Blackman window with a $T_w = 3$ ns width, the beat notes are demodulated into the $f - t$ spectrographs in Figs. 2(a-ii) and 2(b-ii) in log scale. We further plot the target $\phi(t) - t$ curves in red lines onto the spectrographs to demonstrate the accuracy of the frequency-phase control. It is important to note that $E_{\text{out}}$ has an approximate constant total power, as in Figs. 2(a-iii) and 2(b-iii), during the full amplitude and phase modulation. The self-balanced output power is a result of balanced $E_{\text{f1,out}}$ by Filter$_1$ to seed TSA$_{1,2}$.

To further confirm the accuracy of the modulated sideband, we use the known target waveform phase $\phi(t)$ to demodulate $E_{\text{f1,out}}(t)$ from Figs. 2(a-i) and 2(b-i) data with a 250 MHz bandwidth. The real parts of $E_{\text{f1,out}}(t)$ are plotted in Figs. 2(a-iv) and 2(b-iv) to compare with the target waveforms. Here, we see small deviations of waveform amplitudes from their target values. The deviation is primarily due to the nonlinearity of rf and optical amplification, which can, in principle, be compensated for by correcting the Eq. (2) model. On the other hand, the optical

![Fig. 2. Characterization of chirped pulses from TSA$_2$ output without Filter$_2$. The frequency sweep range $\Delta f$ is 1 GHz and 4 GHz for data in (a) and (b), respectively. The heterodyning beat notes are given in (i), from which we derive the (ii) spectrogram and (iv) in-phase quadrature Re$[E_{\text{out}}]$. As in (iii), due to the self-balanced amplification, the total output power stays approximately unchanged, with a fractional deviation <15% during the full-pulse modulation.](image-url)

![Fig. 3. Accurate phase modulation of TSA$_2$ output. The heterodyning beat notes in (a) are digitally demodulated as described in the text to obtain the time-dependent phase $\phi(t)$ in (b). The complex data is presented in (c) the phasor diagram.](image-url)
frequency and phase are programmed with remarkable accuracy. The accurate phase programmability is further demonstrated in Fig. 3, where \( \tau = 20 \) ns pulses are programmed with interleaved phases \( \{ \phi_m = 2m \pi, \phi_{m+1} = (m+1) \pi / 6 \} \) for integer \( m \) with a constant amplitude.

### 3.2. Interleaved cooling and trapping with (in)coherent nanosecond pulses

Beyond \(^{87}\text{Rb}\) cooling, the high-power optical waveform generation system is equipped in our lab more generally for cooling, trapping, coherent control, and laser spectroscopy of \( \text{Rb} \) isotopes (Fig. 4)\(^{27,39} \). To address a specific atomic hyperfine transition, we set the microwave modulation frequency \( \omega_m \) to the corresponding value and program the slowly varying amplitude and phase of optical pulses according to Eq. (2). All D2 transitions of both \( \text{Rb} \) isotopes, as shown in Fig. 4(a), are able to be generated by the waveform modulation, except for the repumping transition of \(^{87}\text{Rb}\), which is provided by the unmodulated sideband as mentioned before. To simultaneously address multiple transitions, we simply program each component independently according to Eq. (2). The final voltage signal \( V(t) \) to drive the \( \text{fEOM} \) sums over all the components weighted by the required amplitude ratio, followed by proper normalization to ensure the maximum voltage still optimally drives the \(-1\)st sideband in this work.

Here, we demonstrate the wideband performance of the system by magneto-optical trapping (MOT) with interleaved nanosecond pulses. In particular, microwave pulses with duration \( \tau \), carrier frequency \( \omega_\text{c} \), amplitude \( A_j \), and phase \( \phi_j \) are applied with a full duty cycle to \( \text{fEOM} \) in an interleaved fashion to alternatively address \(^{85}\text{Rb}\) and \(^{87}\text{Rb}\). To address \(^{87}\text{Rb}\), the carrier frequency \( \omega_{j,c} = 2\pi \times 6.36 \) GHz is chosen as before at even pulse number \( j = 2n \). To address \(^{85}\text{Rb}\), \( \omega_{j,c} = 2\pi \times \{2.32, 5.23\} \) GHz are chosen at odd pulse number \( j = 2n + 1 \) with two sidebands, with \( A_j = \{1, 5\} \) for repumping and cooling, respectively. A common “MOT detuning” from the cooling sidebands to the hyperfine transitions is set as \( \Delta_c = -2\pi \times 11 \) MHz for both isotopes. The microwave signal \( V(t) \) to drive the \( \text{fEOM} \) is then synthesized as described above. As such, both isotopes are subject to a repetitive train of square pulses with a 50% duty cycle at a repetition rate of \( f_\text{rep} = 1/2\tau \). Importantly, for \( \Gamma_c < 1 \), the coherent dynamics should be driven by the pulse train. Here, the lifetime \( \tau_c = 1/\Gamma_c \approx 26 \) ns sets the “coherent memory time” for the pulse-to-pulse excitation. To demonstrate the associated dynamics, we sample the pulse duration \( \tau \) from 0.15 ns up to 1 \( \mu \)s and program the interleaved pulses in a “coherent mode” with constant \( \phi_j \). For comparison, \( \phi_j \) is randomized in a “random mode” to suppress the inter-pulse-driven coherent dynamics.

The amplified TSA2 output waveforms are analyzed with the heterodyning method described in Fig. 2. Examples for \( \tau = 5 \) ns and \( \tau = 50 \) ns are given in Fig. 4(b). The heterodyne beat notes that are not shown are recorded in the “coherent mode,” although the phase coherence does not appear in the time-resolved spectrum. The gain saturation by TSAs has not been compensated for during waveform programming. SPM suppression is not perfect either. The nonlinearity during the TSA optical amplification leads to weak but visible additional sidebands on the log scale, particularly for the \( j = 2n + 1 \) pulses when two seeding sidebands are injected to the TSAs. These additional sidebands hardly impact the operation of the mixed MOT.

The amplified nanosecond pulses with a total power of 700 mW are sent to a double-MOT system, where a 2D-pulse source MOT feeds a second MOT in the standard 3D configuration. After loading the second MOT for 1 s, we successively take two fluorescence images for \(^{85}\text{Rb}\) and \(^{87}\text{Rb}\), each with 5 ns exposure time with a CCD camera, by setting the MOT beams resonant to the respective cooling transitions. Typical fluorescence counts are plotted in Figs. 4(c) and 4(d) as a function of pulse duration \( \tau \) for both isotopes. Beyond \( \tau = 50 \) ns, the MOT driven by interleaved pulses behaves similarly in the “coherent” and “random” modes in terms of atom number, as suggested by fluorescence imaging. The critical role of phase coherence emerges for \( \tau < 20 \) ns, where cooling and trapping occur only for coherent pulses. Here, for the MOT operation, the laser excitations are weak enough in the linear regime,
and the atomic dynamics is largely decided by the spectrum of the pulses, which forms a frequency comb with $f_{\text{rep}}$ periodicity. In particular, as in Fig. 4(c), the locations of fluorescence dips for both isotopes coincide mostly with the spectral analysis, which predicts efficient excitation of “open” and “depumping” transitions by the frequency combs in both isotopes. Without further exploring the cooling scheme in this work, we note that cooling and trapping by the nanosecond coherent pulse train can be an interesting topic for future broadband cooling and trapping.

4. Summary and Outlook

Novel research scenarios in atomic physics and quantum optics\cite{9,12,14,16,24} require generation of powerful, arbitrarily shapable optical waveforms with GHz-level modulation bandwidth. A useful strategy has been to optically amplify weak signals from high-speed integrated modulators\cite{22,23,25}. However, a common problem in this approach is associated with amplification noise and signal distortions, particularly if the signal level is not a constant, so the level of the amplifier’s gain saturation is modulated in time\cite{30–35}.

In this work, we have explored a self-balancing technique in amplifying sideband modulation to suppress signals. Sub-milliwatt signals from an fEOM are amplified into watt-level output. The ASE noises are suppressed to a level similar to those achieved in constant seeding\cite{28}, and a 1%-nonlinear SPM sideband suppression is achieved for reducing the signal distortion in an output-power-independent manner\cite{39}. The technique exploits relatively slow carrier-relaxation dynamics in TSAs, as has been observed previously\cite{34}. We note a similar strategy is followed in Refs.\cite{11,25} in a pre-designed manner instead of being automatic. For the laser system demonstrated in this work, we remark that the amplification of self-balanced seeding drifts on a time scale of hours to slightly affect the repeatability of the waveforms. The discrepancies are about a fraction of the distortion observed in Fig. 2. The drifts are likely due to the change of optical alignments and the TSA chip working condition. Improved output waveform stability may be achievable in future work by combining inline optical monitoring with active waveform corrections.

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