50-fs pulse bursts via gain-managed nonlinear amplification

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Abstract. We report the first gain-managed nonlinear amplifier operating in burst mode, delivering 50-fs, 600-nJ pulses. Due to a complex interplay between nonlinearity and gain, the amplification is influenced non-trivially and collectively by all the pulses within a burst.

The demonstration of the ablation-cooled regime of highly efficient material removal [1], where subsequent ultrafast pulses arrive to ablate the material quickly enough that the majority of the delivered energy departs from the focal spot via the hot material ejected during ablation rather than thermal diffusion to the surrounding regions [2], has triggered a surge of interest in the so-called burst-mode operation of ultrafast lasers. In burst mode, the laser produces groups (bursts) of pulses with very small temporal spacing measured, ideally, in picoseconds, followed by a temporal gap before the next burst is produced. However, despite the much greater importance of pulse shortness compared to single-pulse ablation due to the use of far lower pulse energies, the overwhelming majority of burst-mode amplifiers produce pulses of several 100 fs in duration, beginning with the first burst-mode fiber laser [3]. While isolated remarkable results have been claimed [4], albeit by assuming a Lorentzian deconvolution factor and electronic generation of short pulses stands out as the most attractive path to truly robust systems [5], there is further need for the generation of sub-100 fs pulses from simple and power-scalable setups.

The demonstration of gain-managed nonlinear amplification (GMNA) by Frank Wise and co-workers [6] is arguably the most creative advance in ultrashort pulse amplification since self-similar amplification due to its technical simplicity and elegant interplay of nonlinear pulse broadening and spectral shifting of the gain spectrum, allows the reliable and repeatable generation of sub-50 fs pulses from a fiber amplifier. It is only natural to explore burst-mode amplification in the GMNA regime. However, as we show in this contribution, this combination is not straightforward due to how the evolution of each pulse in the GMNA regime affects the gain dynamics, thereby their amplification in a complex and collective manner.

Here, by focusing on a simplified model of this collective interaction and aided by numerical simulations, the counter-intuitive scaling of the GMNA process through the addition of multiple pulses, a burst can constructed while each pulse remains within the attraction basin of GMNA. As a proof-of-concept, we report the generation of 50-fs pulses with 600 nJ per pulse. This result is obtained at low intra-burst repetition rates limited by pump power, but a clear path to scaling to GHz repetition rates is identified.

To better understand how different burst parameters affect pulse performance, we analyzed the temporal and spatial changes in population inversion across the fiber in burst-mode amplifiers. This modeling helped us identify the cyclic steady-state gain for various burst configurations, enabling the optimization of burst parameters to achieve bursts with uniform pulses while reducing the amplification of spontaneous emission. The inclusion of gain-managed nonlinearity introduces a significant factor; in this regime, the strong signal absorption towards the end of the fiber makes it essential to consider the impact of signal-induced gain replenishment carefully. This insight into the gain dynamics of burst-mode, gain-managed nonlinearity systems is critical for developing high-performance laser amplifiers capable of producing sub-50 fs pulses.

We identify the required pulse energy, which depends on several key factors: average signal power, pulse repetition rate, burst repetition rate, and burst on-time. By keeping the pulse repetition rate constant, we focus on adjusting the average power and the burst parameters. We then select a suitable nonlinear amplification regime and determine the fiber and seed characteristics. This approach enables us to generate flat-top bursts with short pulses and circumvent the demanding hundreds, or even kW, average powers. The laser system built for this purpose uses a harmonically mode-locked nonlinear polarization evolution oscillator centered at 1030 nm with Yb-doped gain fiber. A linear preamplifier stage increases the pulse energy without degrading the pulse parameters. With the help of a grating compressor and a hard-cut filter, we control the chirp and the spectral content of the seed pulses before the main amplification stage. The final and main amplifier uses large-mode area gain fiber with a 25-µm core diameter to amplify the signal. A commercial mode-field adapter is integrated to ensure the beam's seamless transition and spatial coherence between the single-mode and large-mode-area fibers. Apart from a discrete free-space component dedicated to spectral filtering and chirp management for the seed pulses leading into the main amplifier, the entirety of the laser system is configured in an all-fiber architecture.

The sketch of the amplifier and the experimental results are depicted in Figure 1. The input burst has characteristics of a 1-MHz burst repetition rate, a 233-ns burst duration, and a 60-MHz intra-burst pulse frequency, as shown in Figure 1 (a), which enters the amplifier to achieve high pulse energies. We start with a narrow-band seed centered around 1035 nm and, through the gain-managed nonlinearity regime, roughly 10-fold broaden the spectrum. The optical spectra for the seed and the amplified pulses are shown in Figure 1 (b). We use standard intensity and interferometric autocorrelation methods to understand the pulse width and quality. The intensity autocorrelation averaged across multiple bursts is plotted, indicating a full width at half maximum of 70 fs, shown in Figure 1 (c). The pulse width corresponds to 50 fs for Gaussian pulses. The inset in this panel is the corresponding interferometric and its low-pass filtered traces. To confirm the uniformity of the pulses in the bursts, we use a high-bandwidth photodetector operating in the linear regime to correctly capture the differences in pulse intensities. Figure 1 (d) demonstrates the comparison between input (i) and amplified (ii) pulse and burst trains. The red dashed lines highlight the intensity level around the peak of the pulses, which emphasizes the absence of undesirable gain saturation effects. By integrating burst-mode gain-managed nonlinearity, this research sets a new standard for optimizing pulse energy and burst parameters, improving the precision of burst-mode fiber lasers in producing high-energy ultrafast pulses.

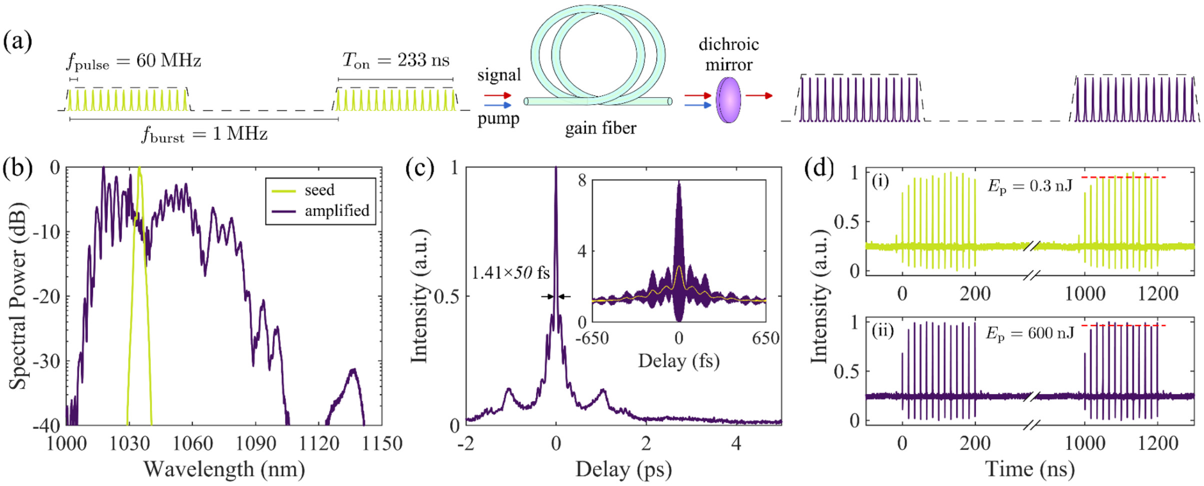

Figure 1: Burst-mode fiber laser amplification and pulse characterization. (a) Illustration of the burst configuration pre- and post-amplification, highlighting the amplification process. (b) Normalized optical power spectra of seed and amplified gain-managed nonlinearity pulses. (c) Intensity autocorrelation trace; the inset presents the corresponding interferometric autocorrelation. (d) Temporal profiles of pulse trains: (i) seed pulse train and (ii) amplified pulse train. The dashed red line highlights the uniformity of the bursts.

References

[1] C. Kerse, *et al.*, “Ablation-cooled material removal with ultrafast bursts of pulses,” *Nature* 537, 84 (2016).
[2] M. Park, *et al.*, “Mechanisms of ultrafast GHz burst fs laser ablation,” *Sci. Adv.* 9, eadf6397 (2023).
[3] H. Kalaycioglu, K. Eken, and F. Ö. Ilday, “Fiber amplification of pulse bursts up to 20 µJ pulse energy at 1 kHz repetition rate,” *Opt. Lett.* 36, 3383 (2011).
[4] J. Ma, H. Liu, Y. Chen, N. Zhang, and P. P. Shum, “Generation of 35 fs, 20 µJ, GHz pulse burst by hybrid fiber amplification technique,” *Opt. Express* 31, 34224 (2023).
[5] H. Ye, L. Pontagnier, E. Cormier, and G. Santarelli, “Multi-gigahertz femtosecond pulses from linear and nonlinear propagation of a phase-modulated laser,” *Opt. Lett.* 47, 5405 (2022).
[6] P. Sidorenko, W. Fu, and F. Wise, “Nonlinear ultrafast fiber amplifiers beyond the gain-narrowing limit,” *Optica* 6, 1328 (2019).