

High-energy Fiber-delivered Ultrashort Pulses on Demand

Michael Wahl,^{1,*} Yuanchi Qing,¹ Myles Silfies,¹ and Thomas Allison¹

¹ Department of Physics and Astronomy, Stony Brook University, Stony Brook, New York 11794-3800, USA

*michael.j.wahl@stonybrook.edu

Abstract: We describe a nonlinear Er:doped fiber amplification scheme for producing fiber-delivered, 44 fs pulses with 100 kW peak power at arbitrary (0-60 MHz) repetition rate. Subsequent spectral broadening produces 80 THz of bandwidth. © 2025 The Author(s)

Er:fiber lasers provide a robust, compact, and inexpensive platform for many fields of the optical sciences. In particular, modelocked Er:fiber oscillators can form the backbone for pump-probe spectroscopy [1], metrology, and nonlinear optics. An initial limitation of Er:fiber lasers was their limited wavelength tunability, though many solutions now exist to broaden and shift the narrow bandwidth, including nanowaveguides [2], small core fibers [3,4], and bulk crystals.

The nonlinear interactions required to generate broad bandwidths generally require amplification and temporal/spatial compression prior to frequency conversion. It is possible to achieve these prerequisites in an all-fiber platform with nonlinear Er:doped fiber amplifiers (EDFAs), which generate a broadened spectrum via self-phase modulation in the fiber [5]. An ensuing length of single mode, anomalous dispersion fiber compensates for the normal dispersion of the Erbium gain fiber and recompresses the pulse [6]. Ultimately, nonlinear EDFAs can generate bandwidths of up to ~ 100 nm, and can directly deliver sub-50 fs, 100 kW peak power pulses. One can further broaden the bandwidth by launching these compressed, high-energy pulses into small core, highly nonlinear fibers (HNLFs) [3]. This all-fiber scheme has the added benefits of long-term stability and alignment insensitivity.

These EDFA/HNLF schemes use a finely tuned combination of self-phase modulation and dispersion to achieve ultrashort, high-energy pulses. This delicate balance is usually optimized only in a narrow range of EDFA pump power, seed power/chirp, and fiber lengths. Many applications desire high-energy pulses at a variable repetition rate or average power, but changing the duty cycle would nominally upset this delicate balance, e.g., by changing the per-pulse EDFA gain [7].

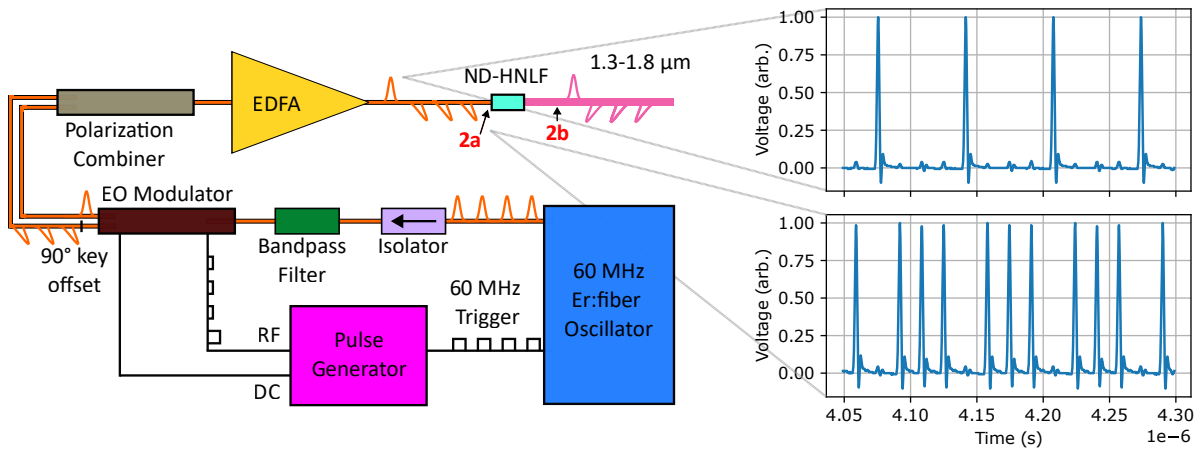


Fig. 1. Experimental setup depicting a 25% duty cycle. The internal memory of the pulse generator can be programmed to output an arbitrary RF pulse pattern, which is reflected in the polarization axis of each corresponding optical pulse.

Here we present a novel EDFA/HNLF scheme designed to produce consistent, ultrashort pulses at arbitrary repetition rate. Our implementation of tunable repetition rate aims to maintain the same per-pulse EDFA gain using the polarization modulation scheme illustrated in Figure 1. Pulses from an Er:fiber oscillator are programmably routed to two parallel arms using an electro-optic Mach-Zehnder interferometer. The two outputs are then combined in a polarization beam combiner, with one arm having a 90° twist which switches the linear polarization of

undesired pulses from the slow axis to the fast axis. The pulse contrast between the fast and slow axes after the polarization combiner is 17 dB. Additionally, the two arms are of slightly different lengths to provide further contrast via a timing offset. The combination of delay and polarization offset allows for downstream pulse picking with timing and/or polarization-sensitive nonlinearities (e.g. sum-frequency generation), or even a simple polarizer.

The polarization-modulated pulse train is amplified in the nonlinear EDFA, and then passes through 85 cm of passive polarization-maintaining fiber (PM-1550) for compression. After the EDFA, a pulse to pulse contrast of 15 dB is maintained, as exhibited in the traces on the right of Figure 1. Figure 2a below shows the results of recompression on selected pulses at different modulation duty cycles. The duration of the main pulse is 44 fs, independent of the duty cycle, even at repetition rates as low as $f_{rep}/10000 = 6$ kHz.

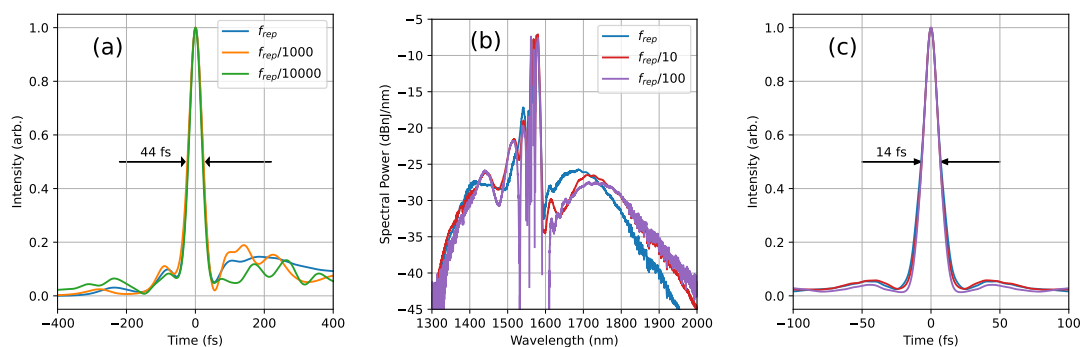


Fig. 2. (a) Second harmonic frequency resolved optical gating (SHG-FROG) reconstructions of selected pulses at the beginning of the HNLF (location 2a in Fig. 1). (b) Spectra of selected pulses coming out of the HNLF (location 2b in Fig. 1). (c) Transform limit of the HNLF spectra.

The compressed pulses are sent into a polarization-maintaining, normal dispersion HNLF (ND-HNLF) spliced to the end of the compression fiber. Figure 2b highlights that the pulse-picked ND-HNLF spectra are largely independent of repetition rate as well. If an application desires the shortest possible pulse, recompression can yield transform limited pulses of 14 fs duration (Fig. 2c).

Alternatively, the broad spectrum can seed an optical-parametric amplifier (OPA) for generating higher energy on-demand pulses with tunable wavelength. For example, using the HNLF output to seed the OPA described by Catanese et al. [8], one can produce >200 nJ pulses tunable in the near-IR with arbitrary repetition rate. In this scheme, the timing offset introduced by our Mach-Zehnder/polarization combiner scheme helps provide further contrast in the amplified pulse train, since only pulses with the correct timing collide with synchronized pump pulses in the OPA.

This work was supported by the U.S. Air Force Office of Scientific Research under award number AFOSR FA9550-20-1-0259, and the National Science Foundation under award number 2216021.

References

1. M. C. Silfies, G. Kowzan, N. Lewis, and T. K. Allison, “Broadband cavity-enhanced ultrafast spectroscopy,” *Phys. Chem. Chem. Phys.* **23**, 9743–9752 (2021).
2. M. A. Foster, A. C. Turner, M. Lipson, and A. L. Gaeta, “Nonlinear optics in photonic nanowires,” *Opt. Express* **16**, 1300 (2008).
3. F. Tauser, F. Adler, and A. Leitenstorfer, “Widely tunable sub-30-fs pulses from a compact erbium-doped fiber source,” *Opt. Lett.* **29**, 516 (2004).
4. A. Sell, G. Krauss, R. Scheu, R. Huber, and A. Leitenstorfer, “8-fs pulses from a compact Er: fiber system: quantitative modeling and experimental implementation,” *Opt. Express* **17**, 1070 (2009).
5. F. Tauser, A. Leitenstorfer, and W. Zinth, “Amplified femtosecond pulses from an Er: fiber system: Nonlinear pulse shortening and selfreferencing detection of the carrier-envelope phase evolution,” *Opt. Express* **11**, 594 (2003).
6. H. Timmers, A. Kowligy, A. Lind, F. C. Cruz, N. Nader, M. Silfies, G. Ycas, T. K. Allison, P. G. Schunemann, S. B. Papp, and S. A. Diddams, “Molecular fingerprinting with bright, broadband infrared frequency combs,” *Optica* **5**, 727 (2018).
7. D. Brida, G. Krauss, A. Sell, and A. Leitenstorfer, “Ultrabroadband Er: fiber lasers,” *Laser Photonics Rev.* **8**, 409–428 (2014).
8. A. Catanese, J. Rutledge, M. C. Silfies, X. Li, H. Timmers, A. S. Kowligy, A. Lind, S. A. Diddams, and T. K. Allison, “Mid-infrared frequency comb with 6.7 W average power based on difference frequency generation,” *Opt. Lett.* **45**, 1248 (2020).