Few-Cycle Pulse Generation from a 3 μm Fiber Laser

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Abstract: We demonstrate the generation of 70-fs pulses (∼7 optical-cycles) from a mid-infrared mode-locked Ho:ZBLAN fiber laser using nonlinear compression with step-index chalcogenide fiber. Experiments are supported by numerical modelling, confirming the scalability of this approach.

OCIS codes: 320.7090 Ultrafast lasers; 320.5520 Pulse compression; 190.4370 Nonlinear optics fibers

1. Introduction

Few-optical-cycle pulse sources are an enabling technology for a growing number of important applications, including time-resolved studies of ultrafast molecular processes and the development of table-top XUV sources through high-harmonic generation (HHG). Following significant achievements in the near-IR, there is presently strong demand to push the operating wavelength of few-cycle pulsed lasers into the mid-IR: a spectral region containing absorption resonances of many important organic molecules and technical materials, in addition to favouring HHG processes since the underlying ponderomotive force scales with driving laser wavelength [1]. To date, the most widely explored approach to develop mid-IR few-cycle sources has utilised parametric wavelength conversion (e.g. optical parametric amplification, OPA) of high-power near-IR sources [1, 2]. Despite impressive performance, such devices are bulky and costly, driving significant research into alternative approaches.

Fluoride fiber lasers are emerging as promising mid-IR sources: recent results have demonstrated output powers exceeding 30 W, femtosecond mode-locking with durations as short as 180 fs, and the development of complementary fluoride fiber components to enable all-fiber devices [3–6]. The limited gain bandwidth of rare-earth-doped fluoride fibers, however, prohibits few-cycle pulse generation direct from fiber oscillators. A solution is to exploit nonlinear compression: a widely used technique to nonlinearly broaden (e.g. through self-phase modulation, SPM) the pulse bandwidth, enabling subsequent compression by chirp compensation. To date, this approach has been applied to OPA sources in the mid-IR using gas-filled capillaries for spectral broadening, although a simpler and more compact approach is required if this technique is to be applied to fiber systems while maintaining the compact-form-factor advantage [7]. Here, we propose and experimentally demonstrate a simple approach to few-cycle pulse generation from 3 μm fiber lasers by exploiting nonlinear compression in highly-nonlinear step-index chalcogenide fiber, producing the shortest pulses from a mid-IR fiber system to date, with 70 fs duration (∼7 optical cycles), and further validating the technique's scalability using simulations.

2. Experimental Setup

A nonlinear polarization evolution (NPE)-based mode-locked laser is developed using 3 m double-clad holmium-praseodymium-co-doped (3.5 mol% Ho^{3+}, 0.25 mol% Pr^{3+}) ZBLAN fiber (13 μm core diameter, 0.13 NA), pumped by an 1150 nm diode and with 43% output coupler (Fig. 1a). The oscillator output is launched into a 5 μm core, 0.3 NA step-index As_2S_3 fiber after a quarter waveplate that corrects the ellipticity in the laser output polarization and an isolator to prevent destabilising back-reflections. As_2S_3 fiber is highly normally dispersive and nonlinear at 3 μm. Numerical simulations (using a generalized nonlinear Schrödinger equation) guided the compressor design, showing that only a short 8 cm length is required for significant SPM-based spectral broadening (and linearisation of the chirp through dispersion). The As_2S_3 fiber output is collimated and the linear chirp of the pulses is dispersion compensated using a double-pass blazed diffraction grating pair, with 70 lines per mm gratings (90% diffraction efficiency per pass).

3. Results and Discussion

The Ho:ZBLAN oscillator emits at 2.86 μm and achieves self-starting mode-locking with ∼3 W pump power, producing a periodic pulse train with 54 MHz repetition rate and up to 200 mW average power. The pulse bandwidth

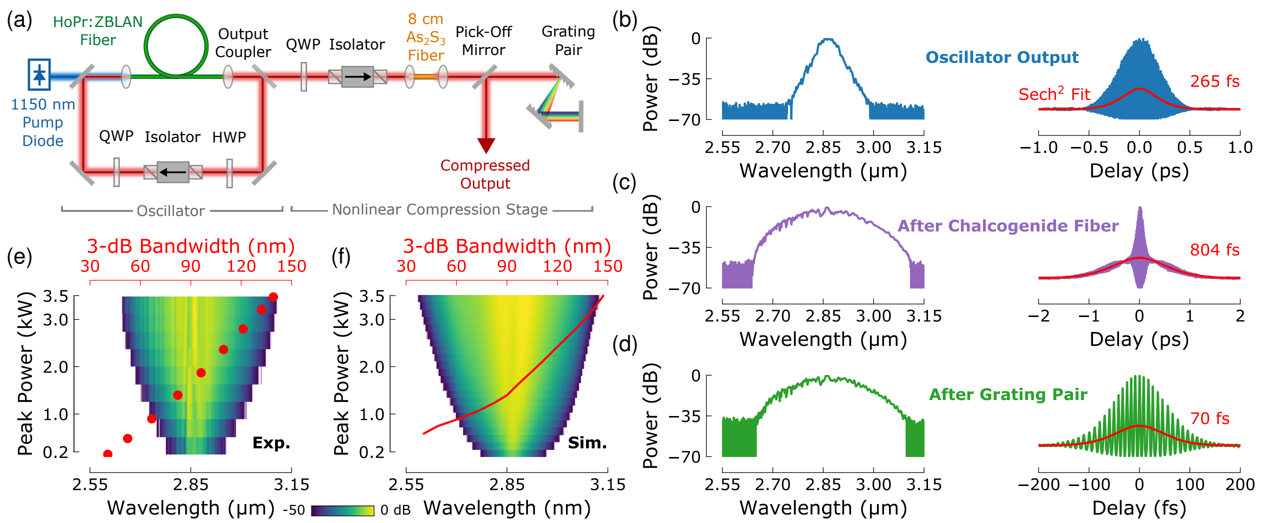

Fig. 1. (a) Experimental setup; (b) Ho:ZBLAN oscillator output pulse spectrum and autocorrelation trace; SPM-broadened (c) and compressed (d) pulse spectrum and autocorrelation trace; spectral broadening in As_2S_3 fiber as a function of launched peak power, (e) experimental and (f) numerical.

(full width at half maximum) is $\sim$34 nm and the duration is measured to be 265 fs using a custom-built interferometric autocorrelator and assuming a sech^2 profile, highlighting that the laser produces almost transform-limited pulses with time bandwidth product, TBP$=0.33$ (Fig. 1b).

The pulse bandwidth after the As_2S_3 fiber is found to increase quasi-linearly as a function of launched peak power, due to intensity-dependent SPM (Fig. 1e), in strong agreement with numerical simulations (Fig. 1f). After optical component losses (and 17% Fresnel reflection from the air-As_2S_3 interface), the maximum launched peak power into the As_2S_3 fiber is 3.5 kW, resulting in spectral broadening to 141 nm (Fig. 1c). The pulses are also measured to broaden to 804 fs duration during As_2S_3 fiber propagation due to dispersion, which linearises the SPM-generated nonlinear chirp and results in a highly chirped pulse with 4.13 TBP. Finally, the grating pair separation is experimentally optimised: at $\sim$5 cm separation, we obtain compressed pulses with 70 fs duration, corresponding to only $\sim$7 optical cycles where the optical cycle duration at 2.86 μm is 9.5 fs, as shown by the autocorrelation fringe spacing (Fig. 1d). The resulting TBP of 0.37 is close to the transform-limited value of 0.315 for sech^2 pulses.

To explore the scalability of this technique, we simulate the spectral broadening with further increasing input power, observing continuation of the quasi-linear dependence on power (Fig. 1f). For example, with 7 kW launched power, a 195 nm spectral width is predicted, enabling compression to sub-5-cycle durations using this technique. Experiments are underway to verify this by amplifying the pulses prior to nonlinear compression.

4. Conclusion

Seven-cycle pulses have been generated from a fiber laser system at 2.86 μm using a mode-locked fluoride fiber oscillator and an As_2S_3 fiber / diffraction grating pair nonlinear compression stage. The simple and compact design brings the benefits of fiber laser technology to the few-cycle mid-IR region, paving the way to new investigations and applications of light-matter interactions in the mid-infrared.

References

1. I. Pupeza, D. Sánchez, J. Zhang, N. Lilienfein, M. Seidel, N. Karpowicz, V. Pervak, E. Fill, O. Pronin, Z. Wei, F. Krausz, A. Apolonski, and J. Biegert, Nature Photon. **9**, 721 (2015).
2. U. Elu, M. Baudisch, H. Pires, F. Tani, M. H. Frosz, F. Kottig, A. Ermolov, P. S. J. Russell, and J. Biegert, Optica **4** (2017).
3. V. Fortin, M. Bernier, S. T. Bah, and R. Vallee, Opt. Lett. **40**, 2882 (2015).
4. S. Antipov, D. D. Hudson, A. Fuerbach, and S. D. Jackson, Optica **3**, 1373 (2016).
5. S. Duval, M. Bernier, V. Fortin, J. Genest, M. Piché, and R. Vallée, Optica **2**, 623 (2015).
6. G. Bharathan, R. I. Woodward, M. Ams, D. D. Hudson, S. D. Jackson, and A. Fuerbach, Opt. Express **25**, 30013 (2017).
7. R. I. Woodward, D. D. Hudson, A. Fuerbach, and S. D. Jackson, Opt. Lett. **42**, 4893 (2017).