Few-Cycle Pulse Generation from a 3 \( \mu \)m Fiber Laser


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Abstract: We demonstrate the generation of 70-fs pulses (\( \sim 7 \) 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. © 2018 The Author(s)

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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 non-linearly 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 \( \mu \)m 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 (\( \sim 7 \) 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 \( \mu \)m 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 \( \mu \)m core, 0.3 NA step-index As\(_2\)S\(_3\) fiber after a quarter waveplate that corrects the ellipticity in the laser output polarization and an isolator to prevent destabilising back-reflections. As\(_2\)S\(_3\) fiber is highly normally dispersive and nonlinear at 3 \( \mu \)m. 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\(_2\)S\(_3\) 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 \( \mu \)m and achieves self-starting mode-locking with \( \sim 3 \) W pump power, producing a periodic pulse train with 54 MHz repetition rate and up to 200 mW average power. The pulse bandwidth
(full width at half maximum) is \( \sim 34 \text{ nm} \) 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, \( \text{TBP} = 0.33 \) (Fig. 1b).

The pulse bandwidth after the As\(_2\)S\(_3\) fiber is found to increase quasi-linearly as a function of launched peak power, due to intensity-dependent SPM (Fig. 1c), in strong agreement with numerical simulations (Fig. 1f). After optical component losses (and 17% Fresnel reflection from the air-As\(_2\)S\(_3\) interface), the maximum launched peak power into the As\(_2\)S\(_3\) 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\(_2\)S\(_3\) 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 \( \sim 5 \text{ cm} \) separation, we obtain compressed pulses with 70 fs duration, corresponding to only \( \sim 7 \) optical cycles where the optical cycle duration at 2.86 \( \mu \text{m} \) 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 \( \mu \text{m} \) using a mode-locked fluoride fiber oscillator and an As\(_2\)S\(_3\) 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