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Mid-Infrared Few-Cycle Pulse Generation with a Ho:ZBLAN Fibre Laser

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Abstract: We demonstrate a simple and compact route to few-cycle pulse generation from mid-infrared fibre lasers through nonlinear compression with step-index As_2S_3 fibre and a grating pair, achieving 73 fs pulses (7.6 optical cycles) at 2.86 μm.

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

1. Introduction

The development of few-optical-cycle laser pulse sources is enabling new fields of research such as time-resolved studies of molecular processes on attosecond timescales, in addition to driving new technologies including table-top XUV sources through high-harmonic generation (HHG). After significant progress in the near-infrared region, there is currently strong demand to push the wavelength of few-cycle pulsed lasers to the mid-infrared (mid-IR). In addition to mid-IR wavelengths corresponding to absorption resonances in many important organic materials, enabling investigation and processing of novel molecular matter, the highest energy photon that can be emitted in HHG scales with the driving laser wavelength, suggesting advantages to longer wavelength HHG excitation [1].

Approaches to mid-IR few-cycle pulse generation have thus far principally focussed on parametric wavelength conversion (e.g. optical parametric amplification, OPA) of high-intensity near-IR pump sources, often followed by compression stages to further reduce the pulse duration [1, 2]. Pulse compression setups typically employ a gas-filled capillary / photonic crystal fibre to achieve compression by either spectral broadening (via self phase modulation, SPM) in the gas followed by dispersion compensation [3], or by soliton self-compression through carefully engineering the gas dispersion via pressure tuning [2].

An alternative approach to these complicated and costly parametric conversion schemes is the direct development of ultrafast mid-IR oscillators, for example using rare-earth-doped fluoride fibres to produce much simpler and more compact sources (albeit at lower pulse energies to date). For example, mode-locked holmium- and erbium-ZBLAN mid-IR fibre lasers have been reported with pulse durations as short as 160 fs [4, 5]. Here, we propose and experimentally demonstrate a simple route towards few-cycle pulses from mid-IR fibre lasers using nonlinear compression with highly-nonlinear step-index chalcogenide fibre, producing the shortest pulses from a mid-IR fibre system to date, with 73 fs duration (7.6 optical cycles) at 2.86 μm.

2. Experimental Setup

A mid-IR oscillator is developed using 3 m double-clad holmium-praseodymium-co-doped (3.5 mol% Ho^{3+}, 0.25 mol% Pr^{3+}) ZBLAN fibre (13 μm core diameter, 0.13 NA), pumped by an 1150 nm diode (Fig. 1a). A 43% transmission mirror is used as the output coupler and the addition of a polarisation-dependent isolator with a quarter and half waveplate (QWP & HWP) enables mode-locking by nonlinear polarisation rotation (NPR).

The oscillator output is launched into a 5 μm core, 0.3 NA step-index As_2S_3 fibre after a QWP (to correct for ellipticity in the laser output polarisation) and an isolator (to prevent destabilising back-reflections). As_2S_3 fibre is highly nonlinear and strongly normally dispersive at 2.86 μm; numerical simulations guided the nonlinear compressor design, suggesting that only a short 8 cm length is required to achieve significant spectral broadening through SPM and linearisation of the chirp through dispersion. We note that chalcogenide fibres have previously been considered for pulse compression in the near-IR, although strong two-photon absorption (TPA) proved to be a limiting influence [6]. At lower-photon-energy mid-IR wavelengths, TPA is not a problem, making this approach much more promising. The As_2S_3 fibre output is collimated and the linearly chirped pulses are dispersion compensated using a double pass of a blazed diffraction grating pair, with 70 lines per mm gratings (90% diffraction efficiency per pass). The mirror after the grating pair is slightly angled so the reflected beam is offset from the incoming beam and thus, is picked-off by a D-shaped mirror.

3. Results and Discussion

The Ho:ZBLAN oscillator lases at 2.86 μm and exhibits self-starting mode-locking at $\sim$3 W pump power when the waveplates are adjusted to yield a strong artificial saturable absorption response by NPR. A stable pulse train

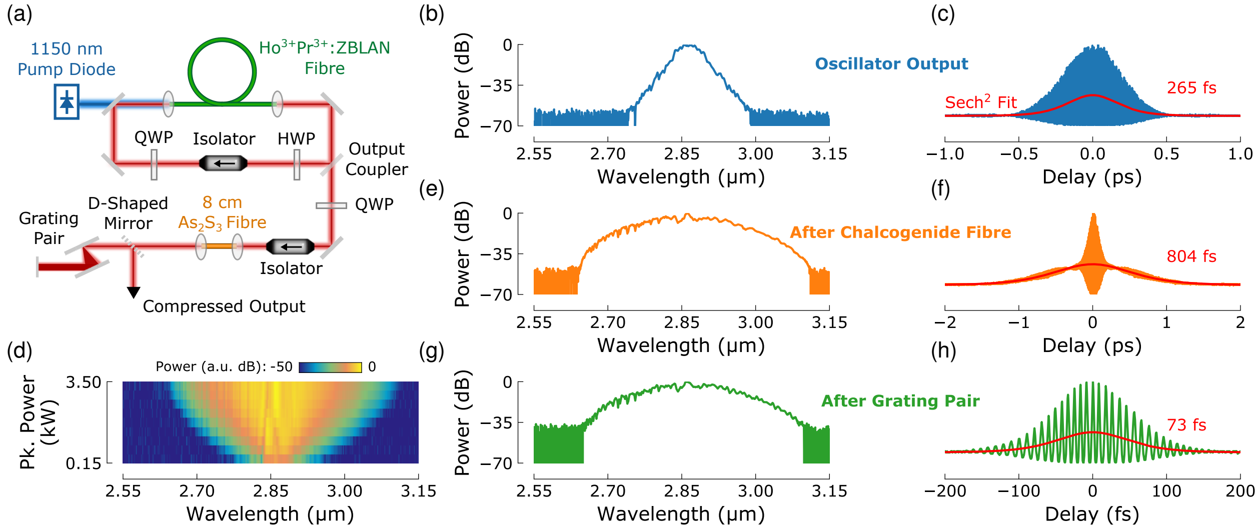

Fig. 1. (a) Experimental setup; (b-c) Ho:ZBLAN oscillator output pulse spectrum and autocorrelation trace; (d) Spectral broadening in As_2S_3 fibre as a function of launched peak power; SPM-broadened (e-f) and compressed (g-h) pulse spectrum and autocorrelation trace.

is produced with 54 MHz repetition rate and up to 200 mW average power. The pulse 3-dB bandwidth is ∼34 nm and the duration is measured to be 265 fs using a custom-built interferometric autocorrelator and assuming a sech^2 profile, indicating the laser produces almost transform-limited pulses with time bandwidth product, TBP= 0.33 (Fig. 1b-c).

The oscillator output is launched into the As_2S_3 fibre with varying power, demonstrating strong spectral broadening as a function of peak power (Fig. 1d). While the oscillator can deliver over 12 kW peak power, the maximum that can be coupled into the As_2S_3 fibre is ∼3.5 kW, due to 40% isolator loss, 20% ZnSe focussing objective loss, 17% Fresnel reflection from the air-As_2S_3 interface and ∼75% coupling efficiency. With ongoing improvements to available mid-IR optical components, the lens and isolator losses could be minimised in future. Despite this low launch efficiency, the high nonlinearity of As_2S_3 enables significant SPM-based broadening up to ∼140 nm bandwidth. At this maximum power, the pulses are also measured to broaden to 804 fs duration during As_2S_3 fibre propagation (Fig. 1e-f) due to dispersion, which linearises the SPM-generated nonlinear chirp and results in a highly chirped pulse with 4.13 TBP.

Finally, to compensate this chirp, we empirically optimise the grating pair separation for maximum compression. With ∼5 cm separation, the pulses are compressed to 73 fs, corresponding to only 7.6 optical cycles where the optical cycle duration at 2.86 μm is 9.5 fs, as shown by the autocorrelation fringe spacing (Fig. 1g-h). The resulting TBP of 0.37 is close to the transform-limited value of 0.315 for sech^2 pulses.

4. Conclusion

We have produced sub-8-cycle pulses from a fibre laser system at 2.86 μm using a mode-locked fibre oscillator and a chalcogenide fibre / diffraction grating pair nonlinear compression stage. The simple and compact setup brings the benefits of fibre laser technology to the few-cycle mid-IR regime, allowing for broader access to ultrashort pulses and permitting new investigations into light-matter interactions in the mid-infrared.

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