Design and simulation of few-cycle optical parametric chirped pulse amplification at mid-IR wavelengths

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Abstract: We present a design for a novel carrier to envelope phase stable optical parametric chirped pulse amplification source in the mid-infrared. We calculate the amplification of a 3.1 μm seed pulse, generated via DFG from a two-colour fibre laser, using a fully three dimensional OPCPA code. We combine this with a ray-tracing code to model pulse compression using a grating compressor and a deformable mirror for programmable phase compensation. The simulation models the complete system based on FROG measurements of the commercially available fibre laser, ensuring the simulation is realistic. The obtained results indicate energetic pulses of 56 fs duration, corresponding to 5.2 cycles, can be produced with calculated pulse energies of up to 9.6 μJ at a central wavelength of 3.3 μm.

OCIS codes: (190.4360) Nonlinear optics, devices; (190.4410) Nonlinear optics, parametric processes; (190.4970) Parametric oscillators and amplifiers; (190.7110) Ultrafast nonlinear optics; (320.5550) Ultrafast optics: Pulses; (320.7080) Ultrafast optics: Ultrafast devices;

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1. Introduction

Ultrashort pulsed light sources in the mid-IR are currently sought for numerous different fields ranging from strong field physics to medical and industrial applications, while the production of intense, few-cycle laser pulses with stable carrier-envelope phase (CEP) has also become a topic of much interest in recent years. Generating such few-cycle, CEP stable pulses in the mid-IR should result in shorter attosecond pulses [1, 2], and allow improved discrimination between tunnelling and multi-photon processes [3]. The broad bandwidths of such pulses are beneficial to spectroscopy since they cover many vibrational transitions in important molecules, and the intrinsic potential CEP stability opens a wide range of applications [4] such as breath monitoring for medical purposes [5]; the identification of bio-marker molecules [6]; monitoring the concentration of green house gases [7] or explosive detection via LIBS [8].

In general, the current generation of energetic few-cycle laser sources is limited to the NIR, normally based on Ti:Sapphire CPA lasers combined with a nonlinear broadening stage and post-compression [9, 10, 11]. These sources are then fitted with feedback systems to ensure CEP stability of the few-cycle pulses, typically giving CEP stable operation for up to a few hours. For some proposed experiments the limitations of such Ti:Sapphire based systems are becoming apparent, as the experimental requirements such as data collection times and long-term stability far exceed the performance of even the best systems. Optical parametric chirped pulse amplification (OPCPA) [12, 13] has been identified as a possible alternative route to few-cycle pulse generation, as it supports extremely high repetition rates, is in principle CEP-preserving, and offers the possibility of direct amplification of few-cycle pulses. Current VIS-NIR OPCPA systems show promising performance as direct alternatives to Ti:Sapphire based lasers, with sub 10 fs durations and mJ level energies [14, 15]. In this paper we investigate the extension of OPCPA to a completely new regime of operation by taking advantage of its inherent wavelength flexibility to design a few-cycle pulse source operating at mid-infrared (mid-IR) wavelengths.

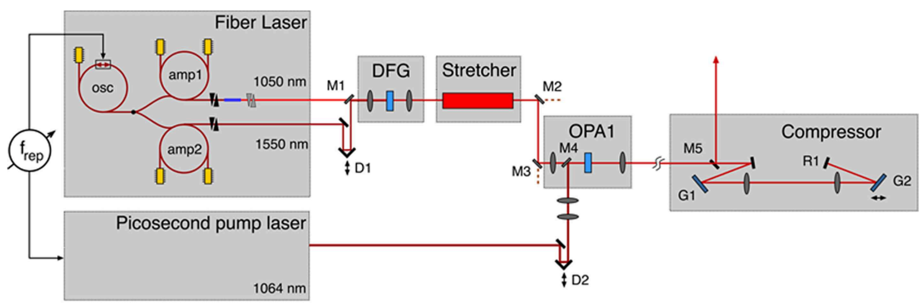

Fig. 1. Mid-IR OPCPA design concept: a commercial fibre laser provides pulses at 1050 and 1550 nm, which are combined through DFG to generate 3.4 μm radiation (HNLF - highly non-linear fibre). The mid-IR DFG output is downchirped in a bulk stretcher and amplified in an OPCPA stage, using a commercial 100 kHz Nd:YVO_4 laser as a pump. Finally, the amplified pulse is compressed by a grating compressor (R1 - retro-reflector).

OPCPA has already been used to produce promising results near 2 μm region [16] and by extending this to the wavelength regime above 3 μm we can begin to access this important wavelength range for spectroscopic applications. In the field of strong field physics, e.g. in high harmonic generation, the ponderomotive energy depends on the square of the wavelength of the driving laser [3, 17], and using the mid-IR we can greatly increase the kinetic energy of the recolliding electron, extending the harmonic cut-off to the keV level [18, 2]. The investigation of strong field physics using NIR drive lasers also unavoidably introduces experimental ambiguities due to a mixture of tunnelling and multiphoton ionisation, which can be avoided by using mid-IR wavelengths, where the lower photon energy ensures we are fully in the regime of tunnelling ionisation.

The generation of low energy radiation in the mid-IR using DFG is an established technique, with the frequency mixing of diode lasers commonly used to create CW beams [19] with close to a mW of power. Using this approach combined with OPA to generate pulses with high energies in the mid-IR requires a complex and costly high energy CPA laser (usually Ti:Sapphire)

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to drive the DFG process, and thus inherits the limited repetition rates and instabilities of such systems. Using a 30 fs Ti:Sapphire CPA system and OPA, pulses of 50 fs duration with 2 μJ energy ($\sim$ 1.5% conversion efficiency) have been produced in the mid-IR [20], but without the CEP stability essential for many applications and with low efficiency. Few-cycle CEP stable pulses have been generated in the 1-2 μm spectral range via CPA driven OPA [21], however this result already required a few-cycle NIR driving laser and cannot reach the mid-IR spectral range above 3 μm. The only few-cycle mid-IR source demonstrated to date is based on four wave mixing in a filament [22], but this is not scalable to high energies, and as is common to all the systems above, it requires a complex Ti:Sapphire CPA system, with the associated limitations of cost, repetition rate and long term stability. All of the Ti:Sapphire based sources mentioned above are limited in repetition rate by thermal deposition, while OPCPA does not involve storage of energy in the amplifying medium, and so is limited in repetition rate only by the available pump laser, with e.g. 100 kHz pumps commercially available. Certain proposed experiments, such as the measurement of double ionisation [23], where the cross section is three orders of magnitude lower than single ionisation, are simply intractable using current few-kHz lasers, making the drive to raise the repetition rate all the more urgent.

2. Concept

When designing the mid-IR OPCPA source shown in Fig.1 we have used parameters of off-the shelf components to ensure the design is relevant. For the seed source we have chosen a single cavity, dual-output fibre laser oscillator (see [24] for details) producing 1 and 1.5μm beams, combined with difference frequency generation (DFG) to shift the wavelength to the mid-IR. The fibre laser oscillator offers a compact and highly stable source with turn-key operation, while the use of DFG between two pulses from a common oscillator cavity ensures the generation of a CEP stable seed pulse for the OPCPA [25]. The use of broadband 1 and 1.55 micron beams from the fibre laser together with the DFG process ensures that we generate both a mid-IR centre wavelength and also a broad bandwidth pulse capable of supporting ultrashort pulse durations.

A simple bulk stretcher is used to chirp the seed pulse, ensuring that beam pointing variations do not impose fluctuations on the CEP stability. The choice of stretcher pulse duration is optimised for overlap with a commercially available 100 kHz repetition rate laser, suitable for use as an OPCPA pump, with a $\sim$10 ps FWHM transform limited pulse duration. The relatively modest stretch factor also eases recompression of the amplified pulse. This is followed by a single

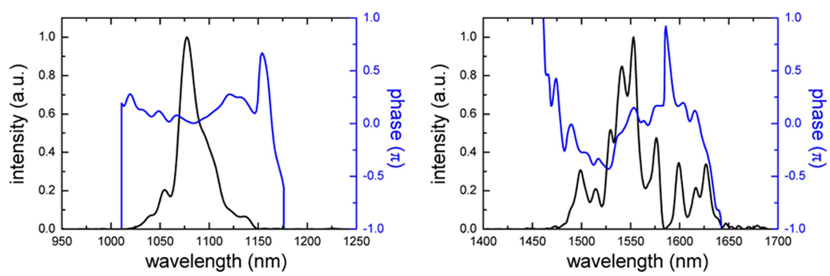

Fig. 2. The retrieved spectral phase and intensity from a FROG measurement of the two arms of a Erbium doped fibre laser. The pulse durations of the 1070 nm arm (left) and 1550 nm arm (right) are 34 and 65 fs respectively. This data is used to create the input pulses for our OPCPA simulation.

OPCPA stage in the current feasibility study, though multiple stages are completely possible. OPCPA can amplify the mid-IR pulse, while also maintaining the broad bandwidth and CEP stability that are crucial advantages for strong field physics. At the same time OPCPA offers the possibility of much increased repetition rates, with a 100 kHz repetition rate envisaged in this design. The parametric amplication simulations are based on a full three-dimensional (3D) model [26] of the coupled wave equations that includes parasitic second harmonic generation (SHG) and takes walk-off and dispersion to all orders into account. The crystal length and poling period are set by choosing a pump intensity close to the damage threshold, then optimising the balance between broadband phasematching and high gain. Though we only model a single OPCPA stage here, the principle of using multiple stages has been successfully demonstrated in many systems [15, 27, 28], implying that our results can easily be scaled to higher energy by the addition of further OPCPA stages. Compression of the pulse requires careful design, as the use of a prism compressor would require a large prism separation to compensate the induced stretch, a major problem in the mid-IR where the detection of beam location is extremely difficult. We have chosen to use a grating compressor, with our configuration corresponding to a simple Martinez-type grating stretcher in a normal, up-chirped CPA system. Even with this simple design, we achieve almost perfect compensation up to the third order of spectral phase, with the residual phase well within the compensation abilities of a simple deformable mirror based programmable phase moduator [29].

3. Mid-IR seed generation

We have previously demonstrated [24] generation of a suitable mid-IR seed pulse via difference frequency generation (DFG) between two arms of an amplified fibre laser oscillator. Using a mode locked Erbium doped fiber oscillator running at 100 MHz two output arms are amplified and compressed to achieve about 4nJ per pulse with a pulse duration of 65 fs full width half maximum (FWHM) and a central wavelength of 1575 nm. One of these arms is then propagated through a highly nonlinear fiber (HNLF) that shifts the wavelength to a central wavelength of 1075 nm with a bandwidth of 150 nm. This pulse is then recompressed to obtain 34 fs with 0.12 nJ per pulse, and DFG between the two arms can then be achieved in an appropriate non-linear crystal. The use of DFG between two pulses from the same oscillator automatically ensures the phase stability of the mid-IR seed [25], and this has been confirmed experimentally [30] to produce CEP stable pulses, with stability maintained over timescales of days [31] . To ensure the modelling corresponds to a physically meaningful result, the phase and amplitude of this fibre source were measured using Frequency resolved optical gating (FROG), and this data, together with the spatial profile, was used as the input for our full 3D simulation code (Fig. 2). The 3D model was applied to the DFG of the mid-IR seed using a 16x19 transverse grid with 256 points in the time domain. It showed that optimum phase matching conditions for DFG (1050-1550$\rightarrow$ 3255 nm) are obtained in collinear geometry using a 2 mm thick periodically poled $LiNbO_3$ (PPLN) crystal with a poling period of 31 μm, assuming a nonlinear coefficient d_{33} of 25.33 pm/V. QPM is handled in the bulk approximation, i.e. the phase mismatch is simply taken to be zero for the specified phase-matched wavelengths. The 1050 and 1550 nm beams were both focussed to 21 μm diameter, giving an intensity of 1 and 18 Gw/cm^2 respectively. Figure 3 shows the spectrum of generated mid-IR pulse, which spans from 2.6 μm to 3.8 μm, corresponding to a transform limited pulse duration of 33.4 fs, or 3.1 cycles of the electric field. The fine details of the generated spectrum are highly sensitive to the input pulse parameters, and further bandwidth optimisation may be possible during an experimental setup. The actual output pulse is down-chirped, and has an energy of 94 pJ.

4. OPCPA and compression

The ouptut of the DFG stage is then numerically propagated through a stretcher in order to match its duration with the that of the chosen pump pulse for the OPCPA. A simple, efficient

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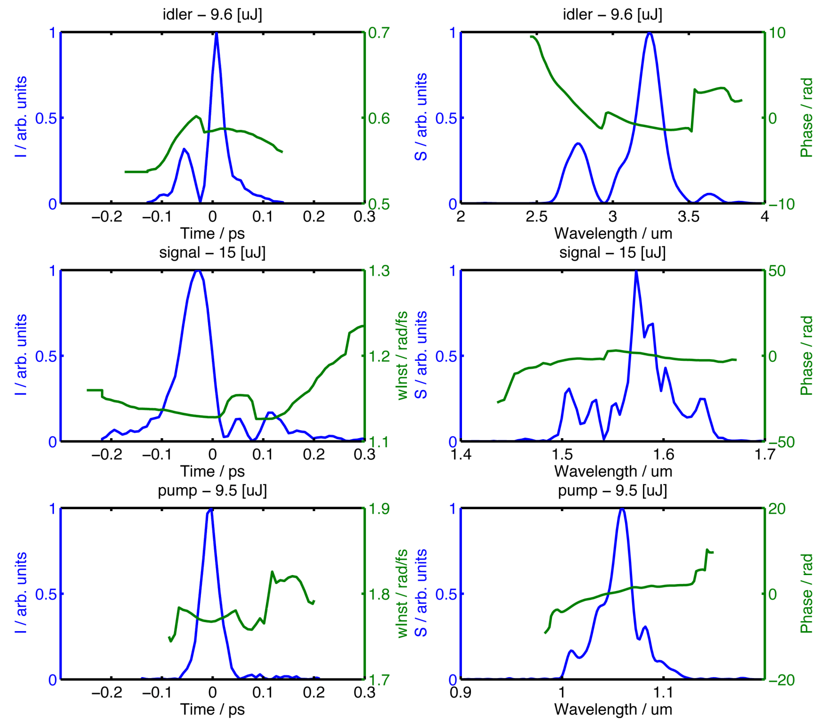

Fig. 3. The calculated output of the DFG stage. The left column shows the temporal intensity (I, blue) and instantaneous frequency (wInst, green) for, from top to bottom, the idler, signal and pump pulses. The right hand column shows the corresponding spectral intensity (S, blue) and phase (green). The generated idler lies in the mid-IR with spectral coverage from 2.8-3.6 μm. The idler intensity is strongly modulated, but as can be seen in Fig 4, this modulation is reduced in the OPCPA process.

and stable option for pulse stretching is to use a 10 cm long bulk Sapphire rod, further increasing the down-chirp to produce a 6.8 ps duration, measured at 30% of the peak intensity to include the low wavelength spectral peak.From commonly available materials which are transparent in the mid-IR, Sapphire presented the best balance between high dispersion in a short length and low absorption. This matches well with the 10 ps pulse duration available from a commercially available, high repetition rate and high energy Nd:YVO_4 pump laser, and ensures that a realistic timing jitter of $\sim$200 fs between pump and seed pulses does not affect the OPCPA process. It is worthwhile to highlight the use of a transform limited pulse from the Nd:YVO_4 pump laser. As has been shown by Schlup et al [32], the energy extraction efficiency in OPCPA using a transform limited pump pulse is higher than from a broadband pump pulse stretched to match the seed pulse. The use of a broadband pump pulse with a precisely tailored chirp rate in theory provides the highest efficiency amplification, but unless the chirp matches exactly the optimum profile, the efficiency will be lower than in the case of using a transform limited pump pulse. We have chosen the latter, "second-best" case as in practice it is the easiest to realise. To amplify the DFG output we use an OPCPA stage consisting of another collinear geometry PPLN crystal, identical to the DFG stage, with a 40 μm seed beam diameter. Here we use a 32x15 point spatial grid and and 2048 points temporally. This gives appropriate phasematching for optical parametric amplification using a 1.064 μm Nd:YVO_4 pump, where the 3.3 μm seed beam is technically the idler wave, and a signal wave is produced at 1.55 μm. Using 35 μJ

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of pump energy over a 40 μm diameter beam, we pump at 70 GW/cm^2, close to the damage threshold for the PPLN, and calculate an OPA gain for single pass amplification of 1.1×10^5. The parasitic second-harmonic generation (SHG), which can reduce the OPCPA efficiency and distort the spectrum is also included in the model. The OPCPA simulation indicates $\sim 10\,\mu$J can be extracted into the 3.3 μm amplified idler. The broad bandwidth spectrum of the DFG seed is mostly maintained, covering 2.8 μm to 3.5 μm, corresponding to an 56 fs transform limited pulse duration, or 5.2 cycles of the electric field at 3.3 μm (Fig. 4). This mid-IR pulse

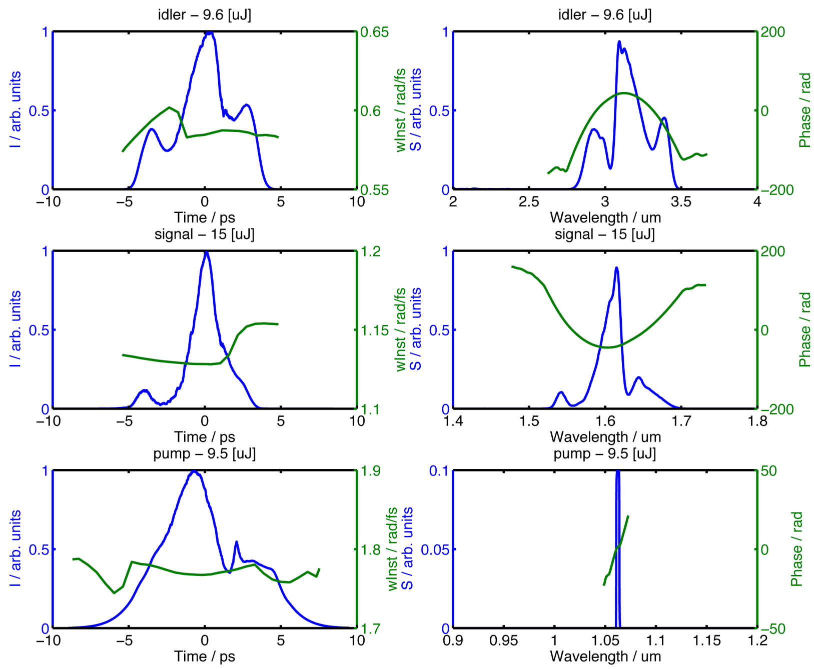

Fig. 4. The calculated output after the OPCPA stage. The left column shows the temporal intensity (I, blue) and instantaneous frequency (wInst, green) for the idler, signal and pump pulses. The right hand column shows the corresponding spectral intensity (S, blue) and phase (green). The amplified mid-IR idler wave now has a smoother spectral profile, with spectral coverage from 2.8-3.5 μm. The spectral phase indicates a strong, mainly second order down-chirp after the stretching process. The broad bandwidth and opposite chirp of the signal wave are as expected from the OPA interaction between a narrowband pump and broadband idler.

is then recompressed using a double-pass grating compressor. The compressor consists of two gold gratings with a blaze angle of 17.5° and a density of 190 lines per mm. The ray tracing code is used to optimise compression by iteratively adjusting the incident angle and the grating separation to precisely compensate the second and third order dispersion. At a tilt of 4.5° from the Littrow angle and a grating separation of 5.9 mm, perfect compensation can be found for the first two orders, while the residual phase has a magnitude of less than 0.1 rad across the full bandwidth. This is within the range of programmable phase compensation using a deformable mirror, and the slope of the residual phase does not exceed the constraints for this type of device. The calculated compressed pulse is shown in Fig. 5, and has a duration of 73 fs when using the compressor only and 56 fs if programmable compensation is used to remove the residual phase. The residual phase is less than 0.06 radian across the entire spectrum and is well within the capabilities of a deformable mirror phase modulator. The shortest pulse duration corresponds

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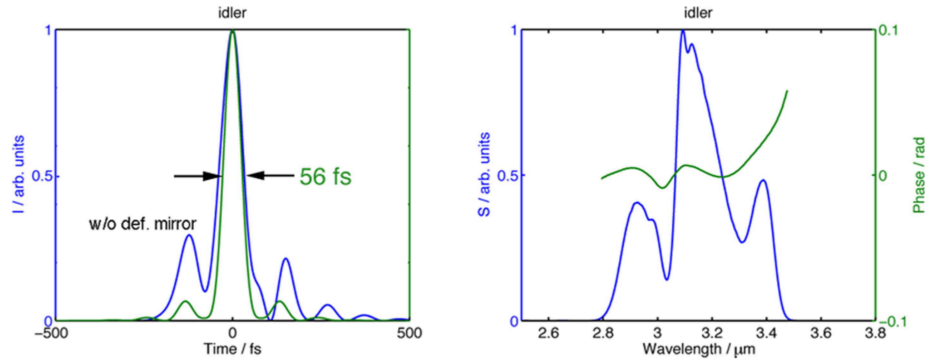

Fig. 5. The left graph shows the pulse in the temporal domain, after compression to 56 fs with (green) the deformable mirror. The blue line shows the 73 fs FWHM compressed pulse without the deformable mirror compensation. The right hand graph shows the spectrum and residual spectral phase that must be corrected by the deformable mirror, which is less than 0.06 radians across the entire spectrum.

only 5.2 cycles of the electric field.

5. Conclusion

We have modeled a completely new mid-IR few cycle CEP stable source based on OPCPA, including the full dispersion and full three dimensional interactions in the OPCPA stages. The simulation confirms the OPCPA can amplify few-cycle bandwidths in the mid-IR, with the simulations predicting energies of 10 μJ per pulse with 35 fs duration after only one stage of amplification. We have based the simulation on parameters of commercially available technology, ensuring that the result is not purely theoretical, but rather that it conforms to a physically realisable system. Furthermore, the selection of a fibre-based laser as a template for the seed pulses ensure that design takes advantage of the inherent stability and turn-key operation available from this technology.

The energy produced from this system is already relevant for spectroscopic applications due to the high repetition rate, but would need to be scaled to higher energies for use in strong field physics. This is possible simply by adding amplifier stages to the above system and increasing the beam size at each new stage to allow higher pump energy while maintaining the same pump intensity. Up to the mJ level, the scalability of such a system is limited only by the availability of an appropriate high energy pump laser, as the components described above (crystals, compressor) are readily available in the aperture sizes needed. Further scaling depends on the identification of suitable large aperture crystals but extremely high energies could be feasible, as demonstrated by the successful use of OPCPA for amplification to multi-Joule levels [27, 28].

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