Nonlinear Post-Compression of Mid-IR Pulses Using Multi-Pass Cells

Daniel R. Carlson, Drew W. Morrill, Margaret M. Murnane, Henry C. Kapteyn, Michaël Hemmer
Department of Physics, JILA and STROBE NSF Science & Technology Center,
University of Colorado and NIST, Boulder, Colorado 80309, United States
Author e-mail address: michael.hemmer@colorado.edu

Abstract: We report numerical simulations showing self-compression of mid-IR pulses in a multi-pass cell. Balancing of self-phase modulation and material dispersion yields few-cycle pulses for λ_0 = 1.8, 3 and 6 µm wavelengths while mitigating self-focusing.
OCIS codes: (190.5940) Self-action effects; (320.6629) Supercontinuum generation; (320.7110) Ultrafast nonlinear optics.

Nonlinear post compression of optical pulses is a well-established technique to produce pulses with duration in the few-cycle regime. Such compression is typically performed at NIR wavelengths in gas-filled hollow core fibers followed by chirped mirrors [1]. While this method is widespread, it can hardly be scaled beyond a few mJ of energy, typically limited by the energy handling of the waveguide. In the mid-IR spectral range, post-compression has been demonstrated via filamentary propagation in dielectric media [2, 3] and in gas-filled Kagome-type fibers [4]. The method involving propagation in a dielectric medium is scalable to high energy, however it requires striking a fine balance between self-phase modulation (SPM), spectral dispersion, and degree of ionization of the dielectric medium, therefore it offers limited flexibility. In addition, all methods relying on filamentary propagation are intrinsically lossy, typically with a throughput between 50-70%.

Over the past few years a novel approach has been proposed and demonstrated – at NIR wavelength – that relies on the use of multi-pass cells [5]. In this configuration, an optical pulse is passed multiple times through a thin plate of material – or through a gas filled cell. In these setups, the peak power of the oscillating pulses exceeds the critical power for self-focusing (P_{Cr}) and the peak intensity is sufficient to initiate SPM. Simultaneously using a short nonlinear medium and propagating the pulse in a resonating cavity prevents catastrophic self-focusing, maintains an excellent spatial intensity profile, and ensures a homogenous pulse duration across the spatial profile. One of the limitations of this method when operated at NIR wavelength is that it requires the use of chirped mirrors to compensate the spectral phase acquired along with SPM, thereby setting again a limit in energy scaling.

Operating such multi-pass cells at mid-IR wavelengths offers opportunities for energy scaling. Indeed, B-integral scales inversely to the wavelength, P_{Cr} scales quadratically with wavelength, and the normal dispersion contributed by SPM at mid-IR wavelengths is of opposite sign to the typically anomalous dispersion of materials in the NIR. While B-integral and P_{Cr} scaling allow maintaining the spatial profile at high energy during nonlinear propagation, the spectral dispersion balance between SPM and material dispersion alleviates the need for chirped mirrors.

Here, we numerically investigate nonlinear propagation of mid-IR optical pulses typically obtained from mid-IR OPCPAs – with durations in the 5-10 cycle regime – in a multi-pass cell containing a nonlinear medium. We show that pulses in the few-cycle regime can be obtained during such propagation while experiencing no self-focusing. We show that the method scales from wavelengths at 1.8, 3 and 6 µm if parameters are carefully chosen.

1. Mid-IR self-compression in multi-pass cell

We developed a numerical Fourier propagation code that accounts for SPM, self-focusing and linear spectral dispersion in the three spatial dimensions. The code relies on the slowly varying envelope approximation (SVEA) and contains a library of mid-IR materials. We verified the validity of our model by successfully replicating the experimental results reported in [5]. The typical scenario simulated by our code is shown in Fig. 1.

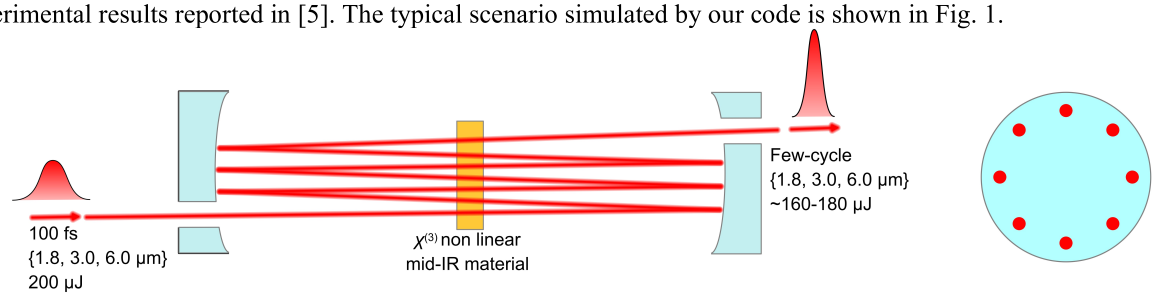

Fig. 1. Layout of the experimental scenario simulated in this study.

We chose to perform simulations of nonlinear self-compression at wavelengths that are commonly used in the high harmonic generation (HHG) community (1.8 μm) or for systems that have been reported and aimed at HHG (3 μm and 6 μm). In order to simplify comparison between the various wavelengths and to illustrate the relative flexibility of the method, we chose to keep the pulse and beam parameters constant for all three wavelengths. We chose a pulse duration of 100 fs, a beam size of 1 mm diameter ($1/e^2$) and an energy of 200 μJ – corresponding to an intensity of 0.5 TW/cm². The free parameters for simulations presented here are the choice of the material, the thickness of the material and the number of passes in the cell. We empirically find that self-compression is achieved when the choice of the material/wavelength pair is such that the material is close to the zero-dispersion, on the anomalous side. For this reason, we chose fused silica, yttrium aluminum garnet (YAG) and zinc selenide (ZnSe) as nonlinear media for 1.8, 3.0- and 6.0-μm simulations respectively. At 1.8 μm wavelength, using a 1 mm thick piece of fused silica, we obtain 9.2 fs FWHM duration pulses after 15 passes in the cell. At 3.0 μm wavelength, using a 1 mm thick piece of YAG, we obtain 33 fs FWHM duration pulses after 10 passes in the cell. Further compression could be achieved at the expense of side pulses similar to those observed for the 1.8 μm case. Finally, at 6.0 μm wavelength, using a 0.2 mm thick piece of ZnSe, we obtain 32 fs duration pulses – albeit with temporal structures highlighting limitations of the SVEA – after 9 passes. For all the simulations we observed no self-focusing during the propagation in the nonlinear medium. The temporal intensity profiles of the seed and compressed pulses are shown in Fig. 2 (bottom) for each wavelength as well as the spectral input and output spectra (Fig.2 – top).

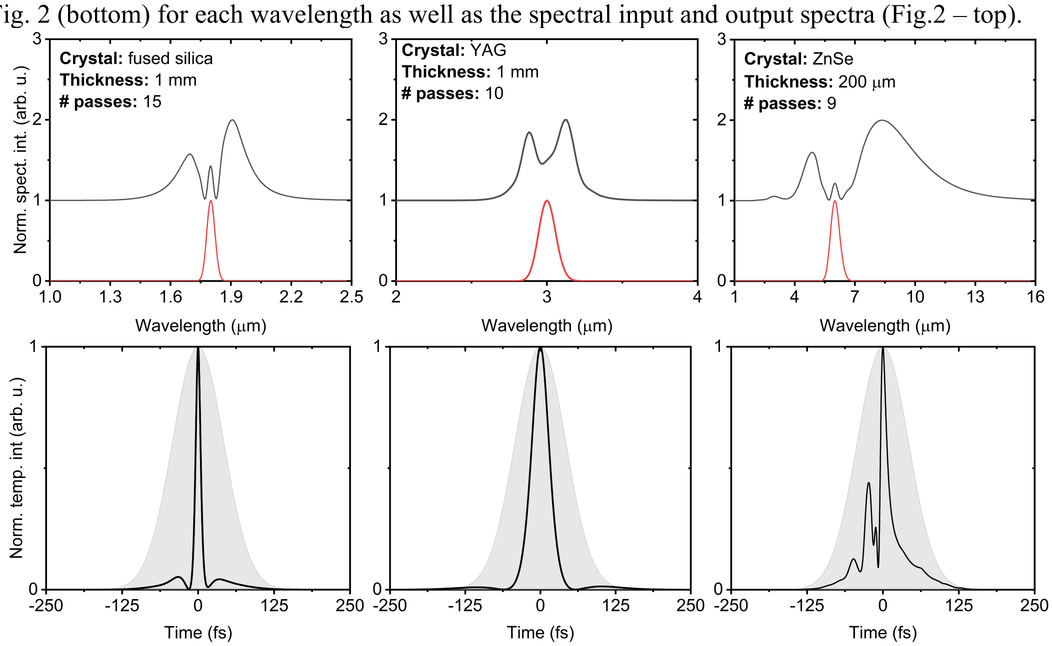

Fig. 2. (Top row) Input of optical pulses injected into the multi-pass cell (red) and spectrum obtained after nonlinear propagation for wavelength of – from left to right – 1.8, 3.0 and 6 μm; (bottom row) temporal intensity profile of optical pulses before (grey shaded region) and after (black line) nonlinear propagation yielding self-compression.

2. Conclusion

We have numerically demonstrated compression of mid-IR pulses without resorting to lossy filamentary propagation and without chirped mirrors. Our method can achieve >90% throughput while allowing the generation of few-cycle pulses in a challenging spectral range. We show that the technique can deliver few-cycle pulses at arbitrary wavelength in the mid-IR. Future work includes simulation of a gas filled multi-pass cell, promising further energy scaling capabilities as compared to the results presented here and to reported results in the NIR.

3. References

[1] M. Nisoli, et *al.*, “Generation of high energy 10 fs pulses by a new pulse compression technique,” *Appl. Phys. Lett.*, vol. 68, no. 20, pp. 2793–2795, 1996.

[2] M. Hemmer, et. *al.*, “Self-compression to sub-3-cycle duration of mid-infrared optical pulses in dielectrics,” *Opt. Express*, vol. 21, no. 23, pp. 28095–28102, 2013.

[3] V. Shumakova *et al.*, “Multi-millijoule few-cycle nid-infrared pulses through nonlinear self-compression in bulk,” *Nat. Commun.*, vol. 7, no. 12877, 2016.

[4] K. Murari *et al.*, “Kagome-fiber-based pulse compression of mid-infrared picosecond pulses from a Ho:YLF amplifier,” *Optica*, vol. 3, no. 8, pp. 816–822, 2016.

[5] J. Schulte, et al., “Nonlinear pulse compression in multi-pass cell,” *Opt. Lett.*, vol. 41, no. 19, pp. 4511–4514, 2016.