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Post-compression of multi-terawatt long-wave-infrared pulses

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ABSTRACT

We present the development of a robust and efficient post-compressor for long-wave infrared (LWIR) pulses. Based on a systematic characterization of optical materials relevant to the LWIR range, we conceptualized a two-component bulk-material apparatus. Numerical modeling and optimization, validated by two proof-of-principle experiments (low-energy and scaled-up), culminated in an original practical design that is now being deployed to compress a 3 TW, 2 ps, 9.2 µm pulse to 500 fs. Furthermore, the potential for achieving 100 fs (approximately three optical cycles) in a next-generation high-peak-power LWIR laser system is predicted.

Keywords: Post-compression, Long-wave infrared, Ultrashort pulses, High peak power, Infrared materials.

1. HIGH-PEAK-POWER LWIR LASERS

Extending the wavelength range accessible to high-peak-power laser facilities further into the infrared is increasingly demanded within the strong-field research community.[1] Ultrafast LWIR lasers, operating at wavelengths an order of magnitude longer than those of mainstream laser research facilities, are of particular interest and have the potential to become the next frontier in laser physics research and development.

Solid-state systems, which utilize crystalline or glass-like materials as laser active media, overwhelmingly dominate the strong-field physics applications and are typically robust and highly efficient in the near-infrared (NIR, 0.75–1.4 µm) range. Several emerging solid-state lasers operate in the short-wave infrared (SWIR, 1.4–3 µm) and the lower end of the mid-wave infrared (MWIR, 3–8 µm). The accessible wavelength range can be extended via optical parametric amplification (OPA) schemes. However, accessing the high-peak-power long-wave infrared (LWIR, 8–15 µm) regime presents significant challenges due to the large wavelength gap, which results in low efficiency of wavelength conversion, necessitating alternative approaches.

Currently, the only viable method for generating multi-joule ultrashort pulses near 10 µm is the amplification of microjoule seed pulses from OPA-based solid-state systems in high-pressure, mixed-isotope CO_2 laser amplifiers.[1,2] The combination of high pressure and multiple isotopic species of CO_2 suppresses the comb-like rotational-vibrational spectral modulation that would otherwise induce pulse splitting. As a result, a state-of-the-art chirped-pulse amplification (CPA) system at the Accelerator Test Facility of Brookhaven National Laboratory (ATF) can amplify 2-picosecond pulses without significant fragmentation, delivering up to 5 TW peak power at 9.2 µm.

In the mid term, increasing the seed pulse energy to approximately 10 mJ is expected to reduce spectral gain narrowing during amplification, leading to pulse durations around 500 fs. Alternatively, the post-compression scheme described below offers a pathway to similar pulse durations, albeit at the cost of reduced pulse energy. Ultimately, a combination of stronger seed pulses and post-compression is anticipated to enable few-cycle (~100 fs) LWIR pulses with peak powers exceeding several tens of terawatts.

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2. LWIR POST-COMPRESSOR

A post-compressor operates through two key processes: (1) spectral broadening with chirp generation due to self-phase modulation (SPM) in a nonlinear medium and (2) chirp compensation, leading to temporal compression. The latter can be achieved using a dispersive component such as a grating pair or chirped mirror or by exploiting chromatic dispersion in a carefully selected bulk medium. In the LWIR range, the technically simpler bulk-medium approach is feasible since the required negative group-velocity dispersion (GVD) is a common property of transparent materials in this spectral region.

Following a systematic characterization of the nonlinear refraction and absorption properties of IR materials under 2 ps laser pulses at 9.2 µm,[3] we identified KCl and BaF_2 as optimal candidates due to their low linear and nonlinear absorption as well as favorable refractive indices. Notably, KCl exhibits a nonlinear refractive index n_2 approximately twice that of BaF_2, while its GVD is about four times lower.

By placing properly optimized slabs of these materials in sequence—first KCl, then BaF_2—we achieve the following effects: (1) The uncompressed pulse first interacts with the higher n_2 material (KCl), accumulating an optimal SPM-induced chirp, while its GVD effect remains negligible. (2) The second slab (BaF_2), which has a higher GVD, simultaneously introduces additional chirp while compensating for the total chirp from both elements. This partial decoupling of SPM-induced chirping and GVD-based chirp compensation between the two materials enables precise optimization. In the fully optimized configuration, both elements contribute equally to the B-integral, and the second slab fully compensates the accumulated SPM chirp from the combined system. The optimal chirp per element is constrained by the maximum practical nonlinear phase delay (B-integral) of $\sim \pi$, as defined by the onset of microfilamentation.

Reliable post-compression requires precise control of the beam's intensity distribution. While a flat-top profile is typically considered optimal for homogeneous compression, we opted for a near-Gaussian beam to enhance system reliability and improve the efficiency of beam delivery and focusing at the experimental interaction point.

In two proof-of-concept experiments, we first demonstrated the compression of a 2 ps pulse to 480 fs at ∼0.3 J, with values integrated across the entire near-Gaussian beam. In a subsequent scale-up experiment, we improved spatial filtering efficiency, achieving a peak power of 1.6 TW with a 675 fs pulse duration in the central portion of a somewhat reduced-quality beam profile. Both experiments aligned with the numerical simulations performed using our in-house developed computer model.

Building on these results, we conceptualized an original configuration in which two thick lenses, made of KCl and BaF_2, serve both as the bulk-medium components of the post-compressor and as focusing elements in a spatial filter, forming a high-quality near-Gaussian beam (Fig. 1).

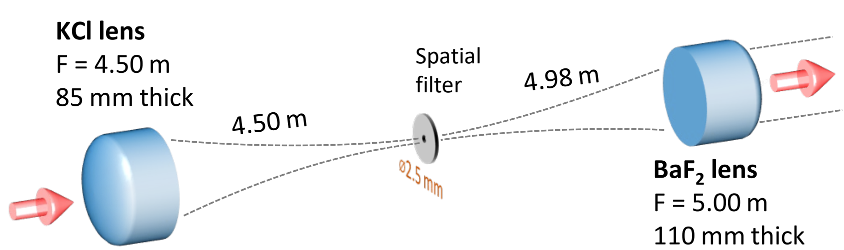

Figure 1. Schematic of an LWIR (9.2 µm) post-compressor, where thick lenses simultaneously function as the active elements of the bulk-material post-compressor and as the focusing elements of the spatial filter.

Numerical modeling results for this system are shown in Fig. 2 and Fig. 3. Simulations were performed for an input beam with a size and intensity variation similar to those typically observed at the output of the ATF laser system. The model assumes cylindrical symmetry of the beam. The input pulse structure corresponds to an experimentally validated output from detailed numerical modeling of ultrashort pulse amplification in a CPA regime in high-pressure, mixed-isotope CO_2 laser amplifiers.

Fig. 2(a) shows the beam profiles at the input of the compressor and immediately after it (right after the BaF_2 lens). To verify the effect of spatial filtering, we modeled the free propagation of the compressed pulse

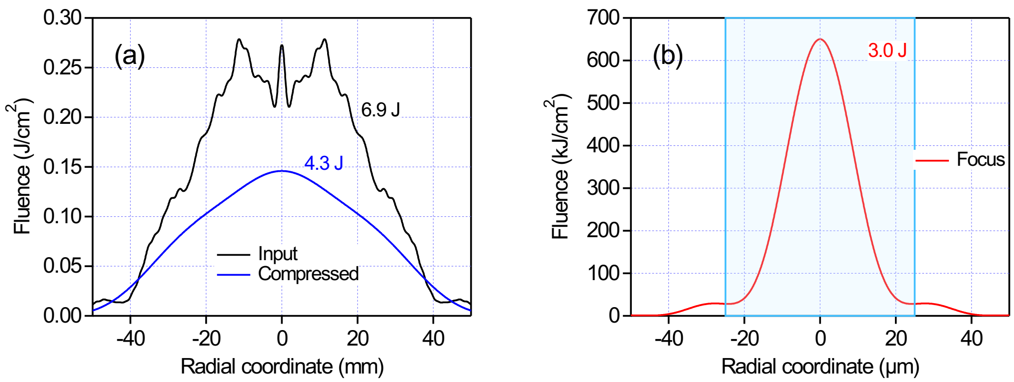

Figure 2. Simulated beam profiles: (a) before (Input) and after (Compressed) the post-compressor and (b) in the focus of an *f/2*, 75 mm diameter optic located 20 m after the BaF_2 lens. Pulse energy is measured within the 50 μm diameter first diffraction maximum, indicated by the shadowed region.

over 20 m and its focusing by a typical *f/2* optic at the interaction point. The beam profile at the focal plane is shown in Fig. 2(b). In calculating the energy at focus, we considered only the portion of the beam within the 50 μm diameter first diffraction maximum, as indicated by the shadowed region.

Fig. 3 shows the temporal pulse structure before and after the post-compressor, as well as at the interaction point. As with the beam profile, only the portion of the beam within the first diffraction maximum was considered in the final focus.

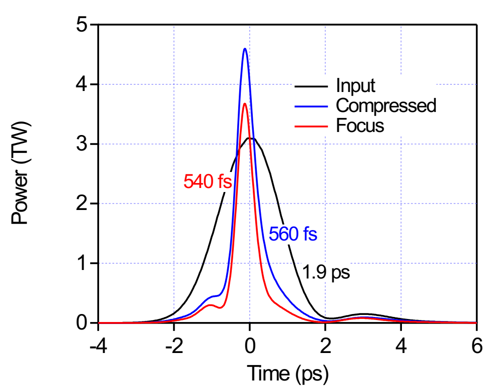

Figure 3. Simulated temporal pulse structure before (Input) and after (Compressed) the post-compressor, as well as in the focus of an *f/2*, 75 mm diameter optic located 20 m after the BaF_2 lens. In the latter case, only the portion of the beam within the 50 μm diameter first diffraction maximum is considered. Pulse durations are defined as full width at half maximum (FWHM).

The thick lenses are currently being procured, and an experimental test of the new configuration is planned in the coming months. Achieving compression results consistent with numerical modeling predictions would represent a major milestone in LWIR laser research and development, immediately enabling several groundbreaking experiments in laser-driven particle acceleration.

3. CONCLUSION

Long-wave infrared lasers can now achieve multi-terawatt peak powers in 2 ps pulses. Ongoing R&D efforts aim to shorten pulse durations and increase peak powers, with the goal of reaching the few-cycle regime at tens of terawatts. The deployment of a first-generation high-energy post-compression scheme will mark a critical step in this direction, opening the path to further advancements.

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