Coherent combining of broadband pulses after free space optical parametric amplification

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Abstract: In this study, we present the proof of concept of the polarization-based filled-aperture coherent combination of two distinct broadband sub-20fs transform limited pulse duration optical parametric chirped pulse amplification systems in free-space. An average combination efficiency of 90% is demonstrated.

1. Introduction

Coherent beam combining (CBC) is a very promising technology for peak and average power scaling. To this day only a few experimental efforts exist where the aim was to combine broadband sub-50 fs transform-limited duration (TLD) high energy (≈ mJ level) wave-packets [1–3]. The aforementioned type of research is focused exclusively on tiled-aperture CBC in the far-field, which can offer record breaking peak powers and intensities at the cost of enormous focusing optics, relatively poor beam quality and practically immovable experimental area. Nevertheless, whenever the budget for large aperture optics is a more concerning issue than the laser induced damage threshold of the compressor or the optics after the combination, one should always consider the filled-aperture case. This way one can achieve advantageous beam shape, use standard optics and in general exploit the combination result as a standard laser light source i.e. for near-field applications. Therefore, in this work, we present the first step to fulfill our main goal of coherently combining two independent and different co-seeded optical parametric chirped pulse amplification (OPCPA) systems in free space by exploiting the filled-aperture method. For a proof of principle the pulse energy was heavily attenuated and, subsequently, the beams were spatially filtered. Under these conditions we have managed to show the capability of the state of the art technology to combine sub-20 fs TLD chirped pulses and stabilize the final output to the intrinsic normalized shot-to-shot energy standard deviation of incoherently combined channels.

2. Experiments and Main Results

The principle scheme of the experiment can be seen in Fig. 1a. For our purposes we used the frontend of the “L1-Allegra” [4] and the auxiliary output for femtosecond precision synchronization (“F-Sync”) [5]. These systems were co-seeded by the Ti:Sapphire oscillator and later combined at PBS1. The pulses were stretched to about 1 ps. We used Hänsch - Couillaud polarization detection scheme ($\lambda/4$ + PBS4) [6], which generated the piezo actuator driving analog error signal for phase stabilization. Beam profiler and spectrometer were utilized for temporal and spatial alignment. Light port and dark port photodiodes were used for efficiency measurements, which was defined as:

$$[\text{Efficiency}] = E_\text{L}/(E_\text{L} + E_\text{D}), \tag{1}$$

where E_L – energy measured by the light port photodiode and E_D– energy measured by the dark port one. With this set-up we have tested the long term shot-to-shot stability of the combined output and the whole CBC efficiency, which are presented in Fig. 1.b,c. Here we can see that on average, a 91.5% efficiency was measured, which was stabilized for about 30 min despite the combined 22m optical path in the system. After that we ran out of the PID controller range, meaning that this problem could be avoided by utilizing a slow drift compensation. From the beam shapes, spectral forms, spectral phase difference, and the imperfections of the polarizer, we have calculated that the spatial and temporal field properties limited the CBC efficiency to 96.8 %. Experimentally, we were only a few percent off from this theoretical limit, which could be caused by non-optimal working energy range of the dark photodiode. We have found that for our different OPCPA systems combination the spectral phase matching was of high importance. This was achieved by measuring the spectral phase difference via the Fourier transform method [7] for spectral interference fringe analysis and correcting the error with separate acousto-optic programmable dispersive filters (Dazzler, Fastlite). Without the aforementioned correction the efficiency was limited to about 80%.

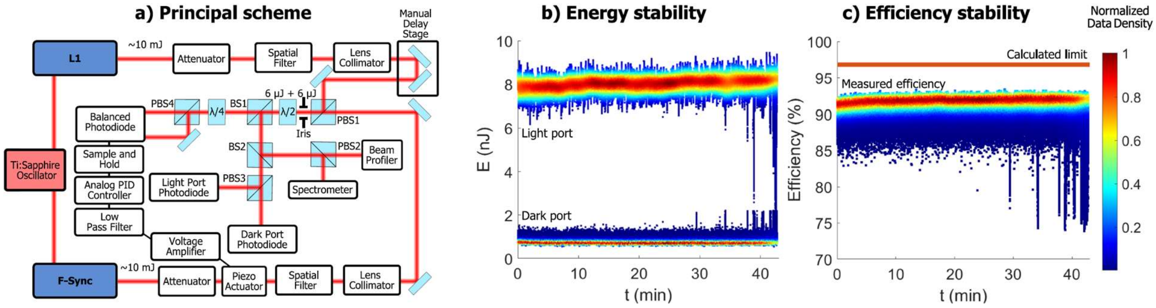

Fig. 1. a) - Principle layout of the coherent combination scheme. PBS - polarizing beam splitter, BS - beam splitter, $\lambda/4$ - quarter wave plate and $\lambda/2$ – half wave plate. b,c) – Long term shot-to-shot stability measurement.

The normalized short term standard deviation of the stabilized light port output was 4.5%. The same stability was observed for incoherently combined beams, suggesting, that here we were limited by the intrinsic noise of both channels. On the other hand, coherent combination without any feedback increases the standard deviation by at least 10 times. The TLD of the combined pulse was measured to be 17 fs. We claim that the combined pulse must be compressible, since F-Sync dispersion was matched to L1 and L1 was compressed to 15 fs pulse duration.

3. Conclusion

In this work, we have demonstrated the high efficiency coherent combining of broadband chirped pulses, amplified in separate and different OPCPA systems. Prior to the combination, the beams were attenuated and spatially filtered. The linearly polarized part of the output was stabilized to the intrinsic noise of the incoherently combined output, even though each of the separate channels propagates ≈ 22 m before the combination. The spectral phase matching was found to be an important factor when dealing with different systems. Therefore, two acousto-optic programmable dispersive filters were highly important to ensure the higher combination efficiency. The transform limited pulse duration of the achieved combined spectrum is 17 fs. To our knowledge, this is the spectrally broadest output provided by the filled-aperture coherent combination. We envision that this approach could be utilized for practical high energy broadband table-top systems with moderate size optics, that are operating below the damage threshold of the common compressor.

4. References

[1] S. Bagayev, V. Trunov, E. Pestryakov, S. Frolov, V. Leshchenko, A. Kokh, and V. Vasiliev "Super-intense femtosecond multichannel laser system with coherent beam combining," Laser Phys. **24**, 074016 (2014).

[2] V. Leshchenko, V. Vasiliev, N. Kvashnin, and E. Pestryakov, "Coherent combining of relativistic-intensity femtosecond laser pulses," Appl. Phys. B **118**, 511–516 (2015).

[3] C. Peng, X. Li, X. Liang, and R. Li, "Four-beam tiled-aperture coherent beam combining of high-power femtosecond laser with two compressors," IEEE Photonics J. **14**, 1–4 (2021).

[4] P. Bakule, R. Antipenkov, J. Novák, F. Batysta, R. Boge, J. T. Green, Z. Hubka, M. Greco, L. Indra, A. Špaček, J. A. Naylon, V. Šobr, B. Tykalewicz, T. Mazanec, P. Strkula, and B. Rus, "Readiness of L1 allegra laser system for user operation at eli beamlines," in High Intensity Lasers and High Field Phenomena, (Optica Publishing Group, 2020), pp. HF1B–7.

[5] E. C. Erdman, J. Novák, R. Antipenkov, B. Tykalewicz, P. Mazrek, M. Horáček, J. A. Naylon, P. Bakule, and B. Rus, "Femtosecond synchronization of OPCPA based F − SYNC and L1 − Allegra lasers," in High-power, High-energy Lasers and Ultrafast Optical Technologies, vol. 12577 (SPIE, 2023), pp. 10–12.

[6] T. Hansch and B. Couillaud, "Laser frequency stabilization by polarization spectroscopy of a reflecting reference cavity," Opt. Commun. **35**, 441–444 (1980).

[7] M. Takeda, H. Ina, and S. Kobayashi, "Fourier-transform method of fringe-pattern analysis for computer-based topography and interferometry," JOSA A **72**, 156–160 (1982).