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Robust and Efficient Temporal Pulse Combining Enabling Practical Coherent Pulse Stacking Amplification Systems

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Practical use of laser plasma accelerators will require drivers with high peak power and high repetition rate. Spatially and temporally coherently combined fiber laser arrays offer one of the most promising pathways to such drivers. Temporal combining of ~100 stretched pulses, implemented as a coherent pulse stacking amplification (CPSA) technique [1], enables near-complete extraction of stored energy in each fiber channel with low nonlinear phase per pulse, and reduces fiber-array size approximately by 100-fold as necessary for making this approach practical. However, stacking a large number of pulses robustly and efficiently is a challenging technical problem.
We report achieving high robustness and efficiency when stacking 81 pulses with multiplexed Gires-Tournois Interferometer (GTI) cavities. This performance was achieved by carrying-out theoretical analysis for finding the required degree of system stability and GTI-cavity alignment accuracy, implementing advanced hardware and fast algorithms for multi-dimensional robust control of this complex system, and developing methods and automated techniques for high accuracy optical alignment of GTI stackers. For large beams in a stacker supporting high energy and power the two critical alignment dimensions are far-field angular, and piston-error alignments of each individual GTI cavity. Far-field angular alignment accuracy depends on the beam size, and for ~6mm diameter beam supporting ~1J stacked pulses it requires better than +-5 μrad precision. Piston errors not exceeding ~1μm (i.e. one optical wavelength) are universally required. We determined metrics for quantitatively tracking the GTI cavity alignment errors, and developed automated alignment hardware and algorithms for achieving and maintaining this required high-degree of alignment precision in real time, which is also crucial for running such coherently combined system in practice. To ensure high degree of stacking stability, we actively locked the "master" 1GHz repetition-rate mode-locked oscillator by referencing it to a rubidium frequency standard whose long-term stability is <1ppb.
Utilizing these techniques we demonstrated highly repeatable day-to-day operation of 81-pulse burst stacking (compatible with ~10mJ per channel) from 85μm core fiber amplifiers, with stacking efficiencies >83% and stacked-pulse peak power stability of <1%. This demonstrates the practicality of the CPSA technique as the key enabler of high energy and power LPA drivers.

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