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Hybrid spatiotemporal coherent pulse addition of a picosecond flashlamp-pumped Nd:YAG laser

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Abstract: We demonstrate active and passive coherent pulse addition in a flashlamp-pumped Nd:YAG amplifier chain for pumping OPCPA systems. The amplification of 200 ps pulses to 216 mJ is achieved with a 79% combination efficiency.

OCIS codes: (140.3280) Laser amplifiers; (140.3298) Laser beam combining; (140.3530) Lasers, neodymium.

1. Introduction

Optical parametric chirped pulse amplification (OPCPA) is an effective method for generating few-cycle pulses with terawatt to petawatt peak powers [1]. While such laser pulses are needed for fundamental studies of relativistic phenomena such as high-order harmonic generation and particle acceleration, energy scaling of OPCPA sources is limited by the requirement of joule-class picosecond pump lasers. Nonlinear phenomena such as self-focusing or accumulation of B-integral fundamentally limit the direct amplification of picosecond pulses. Chirped pulse amplification (CPA) was developed to circumvent these effects for femtosecond pulses by significantly reducing pulse intensities by temporal stretching through dispersive optical elements. Although CPA is a widely used and mature technology, it is highly impractical, if not impossible, to implement for picosecond pulses with bandwidths less than a few nanometers.

In recent studies, the application of coherent beam combining (CBC) [2] and divided-pulse amplification (DPA) [3] to short pulses has led to unprecedented laser performance. In pulsed CBC, a seed from a master oscillator is spatially separated into multiple amplifier channels and subsequently recombined back into a single pulse. The temporal analog, DPA, involves multiplexing a pulse in time through the use of birefringent crystals or interferometric delay lines thus providing an alternative to CPA for limited bandwidth pulses. Collectively known as coherent pulse addition, these two techniques can be demonstrated simultaneously allowing for the scaling of both peak and average powers while remaining below optical damage and nonlinear thresholds [4]. Pulse multiplexing/demultiplexing stages comprising of a separate splitter and combiner require active phase stabilization while stages which share the same optical elements for splitting and recombination are passively phased due to intra-cavity activity. In temporal combination, the onset of gain saturation, and consequently the accumulation of differing nonlinear phase, limits the performance of passive coherent pulse addition. Active temporal splitters have been able to compensate for some gain saturation effects which degrade the combination efficiency, however temporal pulse train shaping in DPA is reasonably limited to only four pulse replicas [5].

A majority of demonstrations of all forms of coherent pulse addition have used fiber laser technology due to their excellent beam quality and ability to produce high average power outputs in a single pass. However, in order to reach joule-class laser pulses from this technology a large number of fiber lasers must be coherently combined. An alternative approach is through the use of flashlamp-pumped solid-state amplifiers which are widely available and produce high energy outputs. In this contribution we investigate both active and passive coherent pulse addition using both DPA and CBC in a flashlamp-pumped Nd:YAG amplifier chain. In a proof-of-principle experiment, both active and passive coherent combining methods were implemented simultaneously for the first time, allowing the amplification and subsequent recombination of four pulse replicas.

2. Experimental setup

A schematic of the experimental setup is shown in Fig. 1. Since the end goal of this system is to pump a high energy few-cycle OPCPA system, a portion of the energy from an octave-spanning Ti:Sapphire oscillator is first used to seed a Nd:YAG regenerative amplifier. A volume Bragg grating (VBG) integrated in the amplifier narrows the spectral bandwidth to produce 200 ps transform-limited pulses at 1064 nm. The regenerative amplifier is operated at 2.5 Hz with an output energy of ~0.3 mJ and is followed by a double-pass pre-amplifier which increases the pulse energy to 5 mJ.

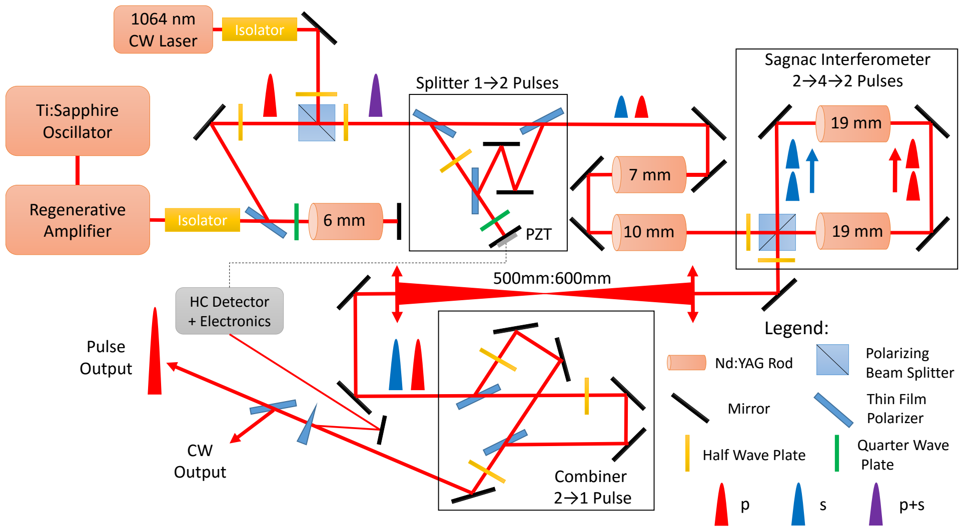

Fig. 1. Schematic of the laser system.

Before the DPA stage, we inject a 1064 nm CW pilot laser which co-propagates with the pulses through the subsequent amplifiers, allowing active stabilization of the optical path lengths using a Hänsch-Couillaud detector and a piezoelectric stage [6]. Measurements of the interferometric stability of the DPA system resulted in RMS phase errors of 85 and 57 mrad for the pulsed and CW beams, respectively. To implement DPA, a Mach-Zehnder-type splitter was used to temporally separate both the pulsed and CW beams into p- and s-polarized replicas with a delay equal to the optical path length difference between the two arms (790 ps). The two-pulse replicas are amplified to a total energy of 50 mJ through a 7 and 10 mm diameter amplifier chain.

Next the pulses are amplified inside of a Sagnac interferometer (SI) with two 19 mm amplifiers. The SI serves both as a pulse splitter and combiner in passive combination, since the counter-propagating pulses share the same optical path. The p- and s-polarized pulses before the SI are rotated by a half-wave plate to form four pulse replicas, where the two replicas with p-polarization are counter-propagating to the two s-polarized replicas. These four pulses recombine back into two at the polarizer after one round trip in the SI and exit together. Finally, the remaining two pulses are recombined to a single pulse using a Mach-Zehnder interferometer that is matched to the splitter optical path difference. The aperture of the polarizers in the final combiner currently limits the output energy to 216 mJ; however with larger-aperture polarizers we anticipate that the energy can be scaled further.

3. Experimental results

To characterize the potential for simultaneously applying actively phased temporal and spatial coherent pulse addition the SI was replaced with a Michelson interferometer where each arm is an amplifier channel. The two temporally-divided cross-polarized pulses were spatially separated into two paths of equal lengths using a polarizing beam splitter (PBS), where each pulse travel their respective arm, become amplified and return to the output port of the PBS, retaining almost their same temporal separation. Fig. 2(a) compares the results from the single channel to the two channel case. It can be seen that for the two channel case, the combination efficiency converges to the theoretical bottom limit thus proving impractical. Several reasons warrant the inefficient coherent combination including the beam pointing instability due to the large thermal effect of the flashlamps, the large amount of phase and amplitude noise introduced by the firing of the flashlamps, or the effectiveness of our phase stabilization system. These theories have yet to be verified and are a subject of future research.

The combination efficiency of the SI was tested and is plotted in Fig. 2(b). A single pulse is used to seed the SI with equal splitting between both propagating directions. Using 10 ns and 200 ps pulses pre-amplified from the 7 and 10 mm rods, the combining efficiency of the SI was tested at various energy levels to observe the B-integral effects while having the 19 mm amplifiers within the SI unpumped. Then one, two and four 19 mm amplifiers within the SI were pumped. It can be seen that having only two amplifiers pumped allows for the optimum combining efficiency. In the final case, both the DPA and SI stages were tested together resulting in up to four pulse replicas separated in both time and space. The combination efficiency for the hybrid demonstration is shown in Fig. 2(c). All the amplifiers were operated under the saturation fluence, therefore a 50:50 division was made in the splitter.

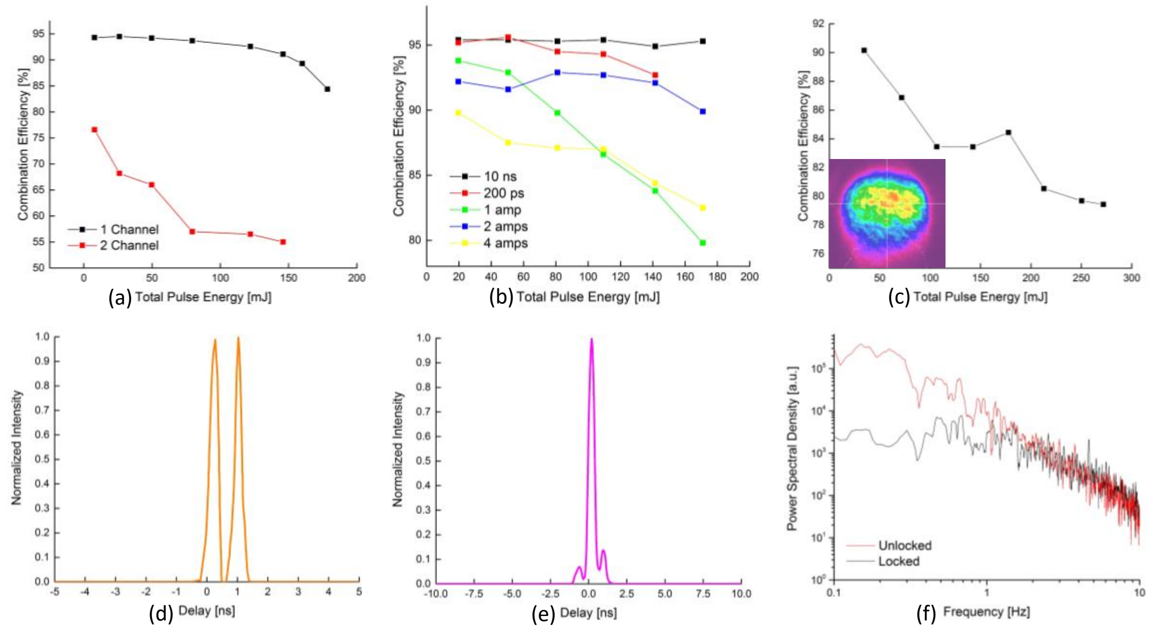

Fig. 2. (a) Combination efficiency plot of temporally divided pulses for one and two amplifier channels. (b) Combination efficiency plot of spatially divided pulses in the SI for multiple configurations. (c) Combination efficiency plot of the four pulse hybrid combination. Inset shows a beam profile of the pulse output at maximum energy. (d) Temporally divided pulses of equal amplitude before the temporal combiner. (e) Coherently combined output pulse. (f) Comparison of the noise power spectral density in the laser system unlocked and phase-locked.

Fig. 2(d) shows a trace of the two temporally divided pulses after exiting the SI and before entering the combiner. It can be seen that the two pulses retained almost exactly the same amplitude after both temporal and spatial amplification. In the final combined output pulse shown in Fig. 2(e), a pre- and post-pulse appear next to the main pulse due to the imperfect nature of the TFPs. One advantage of the hybrid design is that any depolarization of the pulses during amplification is back-reflected from the PBS in the SI and ejected into a beam dump, thus eliminated from appearing as a satellite pulse. The intensity contrast for the pre-pulse is 93:1 while the post-pulse contrast is 86:1. Lastly, Fig. 2(f) shows the suppression of noise of the phase-locking system. It can be seen that only frequencies below ~2.5 Hz were suppressed by the feedback system, where higher frequencies were passively stabilized through control of the laboratory environment.

4. Conclusion and outlook

In conclusion, we demonstrate the application of hybrid coherent pulse addition in a flashlamp-pumped Nd:YAG amplifier chain producing 200 ps, 216 mJ, 1.08 GW pulses. Fundamentally limited by the damage threshold of the optics, this system could potentially produce picosecond pulses in excess of 5 J by scaling to larger aperture combiners. This proof-of-principle experiment is a precursor to a new state-of-the-art multidimensional amplifier system that is under construction for coherently combining multijoule picosecond pulses. These pulses could potentially pump petawatt-level OPCPA systems for a number of interesting applications in relativistic physics.

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