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Coherent combining of two femtosecond fiber chirped pulse amplifiers

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Abstract: We demonstrate coherent combining of two fiber chirped pulse amplifiers seeded by a common oscillator. A phase stability of $\lambda/20$ is obtained using a fiber electro-optic phase modulator, and the recombined pulsewidth is 485 fs.

1. Introduction

Ytterbium-doped fiber amplifiers present great advantages in femtosecond regime, including high optical-to-optical efficiency, good thermal handling and high spatial beam quality. However, the tight confinement of the beam inside the fiber and the long interaction length can lead to strong nonlinear effects at high energies. This constitutes a limit to femtosecond fiber chirped-pulse amplifier (CPA) setups.

Different techniques can be used to bypass this drawback and provide higher peak powers. The first one consists in enlarging the mode field area of the fiber amplifier, so that the nonlinear effects can be handled at higher energies. This has been made in the last few years using large mode area fibers [1]. However, the core scaling capability is limited by the transverse multimode character that inevitably appears for large core fibers.

Another way to scale the energy is to use several amplifiers, and to combine them at the output to get the sum of the energies, thereby avoiding detrimental effects at high peak powers in the fiber. This technique is already used in continuous-wave and nanosecond regimes [2], and is scalable in terms of achievable energy. Several combination techniques exist, but only active coherent combining can easily be transposed to the femtosecond regime.

In CW regime, the relative phase between the beams has to be carefully measured and controlled through a feedback loop to be able to coherently add the electric fields. In femtosecond regime, the group delay and the phase have a priori different roles and should be taken independently. In our case, for pulses of duration above 100 fs, we show that a static adjustment of the delay, along with an active correction of the phase, is sufficient to efficiently combine the pulses, because the pulsewidth is long compared to an optical cycle. A major difference for fs regime is also the group velocity dispersion, which has an impact on temporal pulse shapes as opposed to ns regime, and has to be matched in both arms to ensure a good time overlap of the pulses and retrieve the initial duration.

We report on the coherent combining of two standard femtosecond Yb-doped fiber CPA, using active control of the relative phase between the amplifiers. To the best of our knowledge, only one similar experiment has been done independently by another research team and reported very recently, but with another method for the phase control [3]. These combining experiments open a novel way for energy / average power scaling of femtosecond amplifiers.

2. Experimental setup and results

Our experimental setup, depicted in Fig.1, begins with a femtosecond oscillator that delivers 200 fs pulses at 35 MHz repetition rate. It is followed by a stretcher that broadens the pulses to 150 ps. A half wave plate with a polarizing beam splitter allows us to separate the seed into two arms with adjustable power in each. The first one is made of a fiber-coupled LiNbO₃ integrated phase modulator followed by a 2 m Yb-doped double clad LMA fiber amplifier. The second one contains a 2.40 m single-mode fiber that precedes a 1 m Yb-doped double clad LMA fiber amplifier. This discrepancy in amplifier length is only due to the availability of fibers in the lab, and should be corrected in further reports. The aim of the single-mode fiber is to balance the group velocity dispersion of both arms, and it also acts as a coarse delay matching element. Both amplifiers are operated in linear regime. Their respective outputs are collimated and overlap on a 50/50 beam splitter. Provided that the pulses are synchronous and have the same temporal shape, they interfere on the beam splitter and can be recombined coherently.

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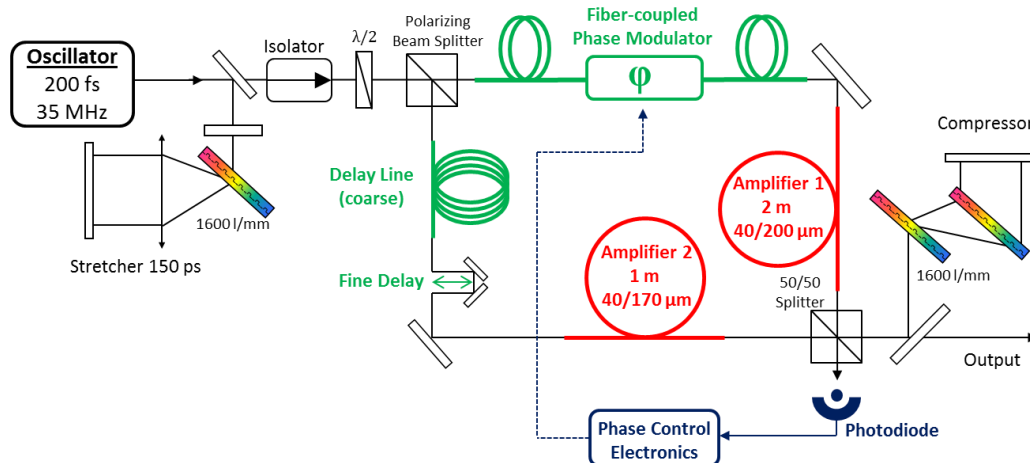


Fig. 1: Experimental setup of femtosecond coherent combining, mixing a CPA architecture with a Mach-Zehnder interferometer.

When the delay between the arms is matched adequately, the overall power is distributed in the two outputs of the recombining 50/50 cube, depending on the relative phase between the two pulses. One of the outputs of the cube goes directly to the compressor, whereas the other one is followed by a photodiode that detects a signal to be minimized. If the delay between the two pulses is not well adjusted, the cube behaves like a simple 50/50 beam splitter for each of them. This setting is tuned by a fine delay on the second arm.

The relative phase between the pulses is controlled using the technique described in reference [5]. A small modulation at 250 kHz is added to the error signal to drive the phase modulator. At the output of the photodiode a lock-in amplifier allows the detection of the small resulting amplitude modulation. This signal is then sent to a digital card that acts as a PID circuit and manages 2π phase jumps to stay in the phase modulator input voltage range. The integration time of the lock-in amplifier is set to 40 μ s, meaning that the maximum phase noise frequency that can be corrected is 12.5 kHz. On Fig. 2 are represented the relative phase between the amplifiers as a function of time and the phase noise spectral density, for free running and phase-locked operation. Most of the phase noise content is below 1 kHz, and our setup is therefore adapted to correct these phase fluctuations. The small phase errors observed around 3s on fig. 2 (left) are due to the electronic circuit that generates a 2π phase jump.

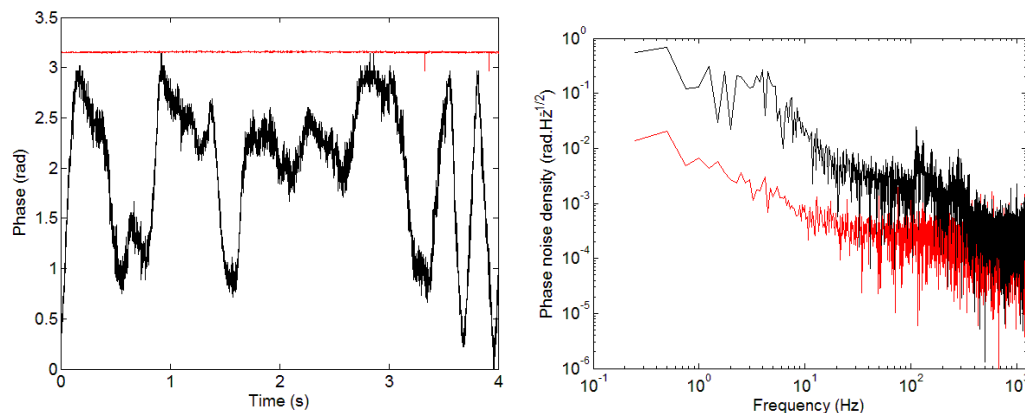


Fig. 2: Retrieved relative phase as a function of time (left) and phase noise spectral density (right), in free running (black) and locked phase regime (red).

We also measured the energy fluctuations at the output of the compressor with a fast photodiode (rise time 1 ns). The temporal traces of the pulses obtained in persistence mode over 10 s are displayed in Fig.3 in both unlocked (left) and locked regime (right). The measured standard deviation of the pulse intensity corresponds to a phase standard deviation of $\lambda/20$. We estimate the contrast between the two outputs to be 70%. This contrast, that determines the combining efficiency, is only limited in our case by a non perfect spatial overlap of the two recombined beam, a well-identified issue that should be solved shortly. The total recombined power at the output of the compressor is 250 mW at 35 MHz repetition rate, limited by the very short length of fiber that is used in first arm for availability reasons.

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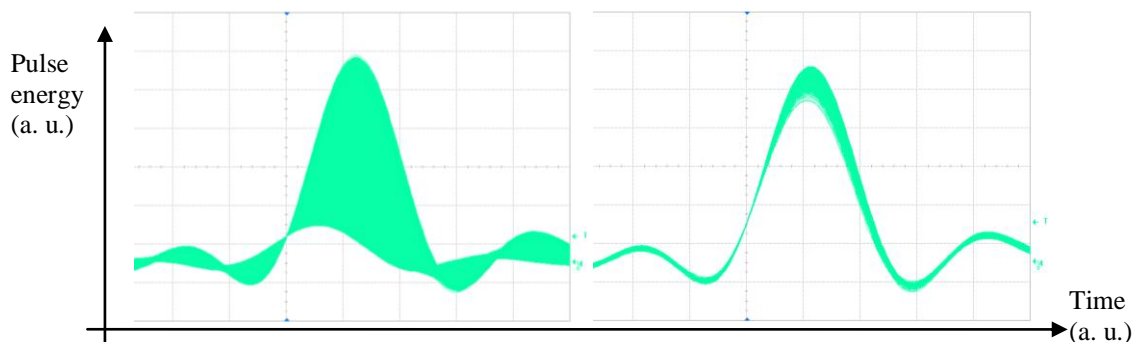


Fig.3: Oscilloscope temporal trace at the output of the compressor for unlocked phase (left) and stabilized phase (right). The persistence time is 10 seconds.

Finally, we focus on the temporal and spectral properties of the pulses for each channel independently, and for the recombined output. The autocorrelations and spectra are plotted in Fig.4. Assuming a Gaussian temporal shape, the pulse duration for isolated arms is 460 fs, while the recombined pulse exhibits 485 fs duration, indicating that the recombination does not affect the pulsewidth significantly. The recombined spectrum is also very similar to isolated ones, and the absence of large modulation shows that the group-velocity delay is adjusted adequately.

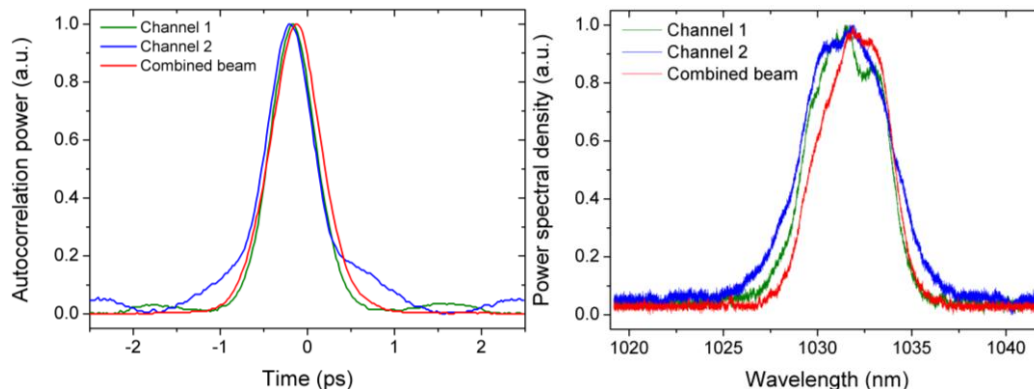


Fig.4: Autocorrelation traces (left) and optical spectra (right) of the output for channels 1 (green) and 2 (blue) independently, and for the recombined beam (red).

3. Conclusion

We demonstrated coherent combining of two fiber chirped pulse amplifiers using a single stretcher and compressor. The RMS residual phase error is $\lambda/20$, and we did not observe any combining-related degradation of the pulse shape or spectrum at this power level. Theoretical and experimental [4] considerations to evaluate the tolerance of the system to residual discrepancies between the arms in terms of phase, group-delay, dispersion, and B-integral indicate that these systems are realistically scalable. This experiment therefore represents a promising result for further investigations in the field of coherent combining of several discrete femtosecond amplifiers. The authors acknowledge the financial support of the RTRA Triangle de la Physique (Femtocombo project).

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