Coherent Amplification network (CAN) : taking high energy physics and space physics to a new level

Friday, 16 October 2015 14:20 (20 minutes)

1 - Introduction and context

For the last decade, ytterbium-doped fiber amplifiers have been demonstrating their strong potential to amplify ultrashort pulses at high average powers, close to the kilowatt level [2]. Indeed, the low quantum defect of the ytterbium ion and the high surface-to-volume ratio of the fiber geometry provide a very good thermal handling, allowing the amplification of pulse trains up to several tens of MHz. In addition, the fiber technology presents numerous practical advantages such as compactness, robustness and ease-of-use, which bring strong benefits to most of the laser sys- tems requiring high average powers. However, the counterpart related to the fiber geometry is the tight confinement of the laser beam inside the fiber core over long interaction lengths. This leads to strong accumulations of nonlinear effects, especially Self-Phase Modulation (SPM) encountered in the femtosecond regime, which distort the output pulse temporal profile and limit the maximum peak power achievable.

Large Mode Area (LMA) fibers, exhibiting Mode Field Diameters (MFD) ranging
typically from ~ 30 μm (bendable) to ~ 80 μm (rod-type), allow to reach higher
energies while preserving the temporal pulse quality. Along with Chirped-Pulse Amplification (CPA), energies up to the mJ and peak powers beyond the GW levels have been demonstrated from a single fiber amplifier [3]. However, scaling the core size in LMA fibers inevitably leads to multimode operation that affects the spatial profile of the beam. Moreover, even in a quasi-single-mode operation, the generation of high average powers in very large mode area fibers as rod-type fibers leads to modal in- stabilities, evolving in a manner quite difficult to predict.

During the last few years, novel fiber amplification architectures involving Coherent Beam Combining (CBC) have demonstrated new records in terms of pulse energy and peak power. Although CBC presents a high potential to scale the energy of femtosecond fiber systems, historical Ti:Sa systems are still the only ones that can provide very high peak powers and short pulse durations. However, the performances of a larger scale CBC system involving femtosecond fiber amplifiers could theoretically compete with these systems, provid- ing in addition multi-kHz repetition rates and much higher wall plug efficiencies. These last features could allow femtosecond sources to address new applications, mostly in the high intensity regime as particle beam acceleration, XUV photolithography, nuclear waste transmutation, or space debris removal [4].
To reach the high peak/average powers and efficiency requirements for these applications, the CBC of thou- sands of fiber amplifiers was envisaged [5]. Active phase locking, which is compatible with a large number of fibers, involves phase detection, calculation of the correction and compensation of the phase of each am- plifier [6]. To explore the coherent combining of thousands of fiber amplifiers, a massively scalable phase measurement technique must be developed.

In this context, the Ecole Polytechnique and Thales now collaborate through the XCAN project in order to explore, demonstrate and improve the efficiency and reliability of femtosecond laser systems based on the CBC of a scalable number of fiber amplifiers.

2 - The XCAN design

The principle of CBC is to divide a single source into several independent channels, each with a dedicated fiber amplifier. The outputs of the N amplified channels are coherently combined in free space into one single beam, which carries N times the power of a single fiber. Therefore, coherent fiber beam combining architecture is a parallel amplification architecture.

In the femtosecond regime, the Coherent Amplification Network (CAN) laser is inserted inside a CPA ar- chitecture. After a master oscillator, the femtosecond pulse is chirped to decrease the peak power before amplification. The power of the chirped pulse is then divided into N fibers. Each fiber is amplified. In the so-called tiled aperture configuration, the outputs of the N fibers are arranged in an array and collimated in the near field of the laser output. The N beamlets then interfere constructively in the far field, and give a bright central lobe, when all the beams are in phase. The output beam then propagate in free space, is compressed and recombined whereas a small fraction of the total field is sampled and redirected to a phase-matching feed- back loop. The XCAN architecture is made of 61 channels, allowing an hexagonal arrangement of the beams that provides higher combination efficiency compared to a classical square layout.

Due to phase noise perturbations induced by fiber amplifiers, the phase of each fiber needs to be precisely controlled. Phase fluctuations caused by intrinsic perturbations of the fiber amplifiers and environment changes such as temperature or pressure have a bandwidth in the range of the 100 Hz [6]. Moreover, in the case of femtosecond, the difference of length between all the fibers has to be corrected so that all the pulses arrive at the same time. Controlling both the phase and the delay of the pulses is then compulsory for this CAN architecture [7]. An interferometric technique, based on the analysis of an interference pattern of the output beams recorded on a camera, performs a collective phase measurement of the beams from a single image.

This method is a promising candidate towards very large channel counts applications, and the largest reported number of combined fiber amplifiers uses this technique [8]. Moreover, this phase control architecture is highly scalable and could combined thousands of fibers with conventional hardware at bandwidth compatible with fiber amplifiers noise [9]. However, previous experiments were realized in continuous regime. In the XCAN project, this interferometric technique will be adapted to femtosecond regime integrating pulse synchronization measurement and control. The performances expected are set to 10 mJ pulses of 350 fs duration at 50 kHz repetition rate, whose realization is to be expected in the next three years.

The system will be all-fibered from the oscillator to the final combination step, which is necessarily performed in free space. The use of a tiled-aperture combination geometry sets some practical constraints in order to avoid any congestion along the combined beam propagation path. In particular, forward pumping of the power amplifiers is preferred at first, and the use of bendable LMA fibers of moderate MFD allows to lighten the congestion constraints at the fiber entrances. These two arguments tends to lower the output energy available from a single channel for a given nonlinearity level. Once the XCAN architecture will be demonstrated, efforts will be made on investigating backward-pumped rod-type fibers in such a geometry to scale further the CBC potential. Moreover, parallel studies on beam shaping will be followed in order to optimize the pupil filling and increase the achievable maximum combination efficiency.

References

1. G.A. Mourou, D. Hulin and A. Galvanauskas, ¡◦ The road to High Peak Power and High Average Power Laser: Coherent Amplification Network (CAN), AIP Conference Proceedings, Third International Conference on Superstrong Fields in Plasmas, 827, Dimitri Batani and Maurizio Lontano, 152 (2006)

2. T. Eidam, S. Hanf, E. Seise, T.V. Andersen, T. Gabler, Opt. Lett. 35, 94 (2010)

3. F. Ro¨ser, T. Eidam, J. Rothhardt, O. Schmidt, D.N. Schimpf, J. Limpert, A. Tu¨nnermann, Opt. Lett. 32, 3495 (2007)

4. C. Jauregui, J. Limpert, A. Tu¨nnermann, Nature Photonics 7, 861 (2013)

5. G. Mourou, B. Brocklesby, T. Tajima, J. Limpert, Nature Photonics 7, 258 (2013)

6. T.Y. Fan, IEEE J. Sel. Top. Quantum Electron. 11, 567 (2005)

7. L. Daniault, M. Hanna, L. Lombard, Y. Zaouter, E. Mottay, D. Goular, P. Bourdon, F. Druon, P. Georges, Opt. Lett. 36, 621 (2011)

8. J. Bourderionnet, C. Bellanger, J. Primot, A. Brignon, Opt. Express 19, 17053 (2011)

9. M. Antier, J. Bourderionnet, C. Larat, E. Lallier, J. primot, A. Brignon, IEEE J. 20, 5 (2014)

Summary

The XCAN collaboration program between the Ecole Polytechnique and Thales aims at developing a laser system based on the coherent combination of several tens of laser beams produced through a network of amplifying optical fibers [1]. As a first step, this project aspires to demon- strate the scalability of a combining architecture in the femtosecond regime providing high peak power with high repetition rate and high efficiency. The initial system will include 61 individual phased beams aimed to provide 10 mJ, 350 fs pulses at 50 kHz.

Primary author: Dr DANIAULT, Louis (Ecole Polytechnique)

Co-authors: Dr BRIGNON, Arnaud (Thales Research & Technology); Dr LARAT, Christian (Thales Research & Technology); Mr SIMON-BOISSON, Christophe (Thales Optronique SA); Dr LALLIER, Eric (Thales Research & Technology); Dr MOUROU, Gérard (Ecole Polytechnique); Dr CHANTELOUP, Jean-Christophe (CNRS); Mr LE DORTZ, Jérémy (Thales Research & Technology); Dr BOURDERIONNET, Jérôme (Thales Research & Technology); Dr ANTIER-MURGEY, Marie (Thales Optronique SA); Mr DU JEU, Rémi (Thales Optronique SA); Ms BELLANGER, Séverine (Ecole Polytechnnique)

Presenter: Dr DANIAULT, Louis (Ecole Polytechnique)

Session Classification: Frontiers in laser technology

Track Classification: Presentations