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Final report on pulse synthesis and comparative analysis of the methods studied

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Deliverable Nature	
R = Report, P = Prototype, D = Demonstrator, O = Other	R
Dissemination Level	
PU = Public PP = Restricted to other programme participants (incl. the Commission Services) RE = Restricted to a group specified by the consortium (incl. the Commission Services) CO = Confidential, only for members of the consortium (incl. the Commission Services)	PP

A. Abstract / Executive Summary

We report on the work performed towards the study of laser pulse- and beam-shaping mechanisms and ultrashort pulse measurements, relevant for the generation of ultrahigh temporal contrast. This document describes the achievements in the following activities:

- Development of an ultrabroadband optical parametric chirped pulse amplification (OPCPA) laser system;
- Development of ultrashort pulse measurement devices
- Evaluation of pulse / beam shaping mechanisms for enhanced interaction

B. Deliverable Report

1 Introduction

Over the past years the technique of optical parametric chirped pulse amplification (OPCPA) has established itself as a leading concept for generating ultrabroadband, ultrashort laser pulse at high repetition rates. On the other hand, the compactness and efficiency of ytterbium-doped, diode-pumped lasers makes this technology very attractive for pumping optical parametric amplifiers. Current developments in ultrafast OPCPA have successfully led to the generation of phase-controlled, few-cycle, high-energy pulses at high repetition rate, making this technology the most promising concept for future ultrafast laser sources.

Over the past years we have been developing a diode-pumped laser program, with the objectives of improving the experimental capability of our facility. This was mainly motivated by the need to increase the shot repetition rate at the 100 mJ level to 10 Hz. In parallel we have carried out an OPCPA program based on ultrabroadband, noncollinear amplification in the nonlinear crystal yttrium calcium oxyborate (YCOB), with the objective of providing mJ-level, sub-20 fs pulses for experiments. These goals of expanding our laser capability have recently acquired additional priority given the selection of our facility for the National Roadmap of Strategic Scientific Infrastructures (2015-2020)

One of the major challenges to the generation of ultrahigh intensity pulses lies in increasing the contrast (signal to noise ratio), that is, minimizing the pulse pedestal due to amplified spontaneous emission and spurious pulses around the main pulse. On the other hand, the development of suitable diagnostics for measuring pulse contrasts that can reach 10^{12} is also a technological challenge.

One of the techniques for improving the contrast may lie on the generation of specially shaped pulses, either for pumping OPCPA or for direct interaction with the target. Pulse shaping can take place over several degrees of freedom, e.g. temporal shape, spatial shape, frequency, chirp, wavefront, and polarization. Different techniques can be used depending on pulse parameters such as its duration, energy or wavelength region, with the ultimate goal being to improve the performance over what is obtained with regular Gaussian-shaped TEM pulses.

2 Objectives

The goal is to study and test methods and technologies for temporal and spatial pulse shaping, in pulse durations from tens of fs to tens of ps. This will be applied to the particular cases of (i) broadband OPCPA pulses and (ii) high energy pulses for efficient SHG and OPCPA pumping.

To achieve this we have been working on the development and commissioning of a noncollinear, ultrabroadband OPCPA system. It is pumped by ytterbium-based diode-pumped amplifiers, capable of high repetition rate operation and therefore enabling high peak and average powers.

In order to characterize the performance of this system we have developed two new pulse measurement diagnostics: an optical parametric amplifier correlator (OPAC) and a compact single-shot autocorrelator for operation at 800-1000 nm.

Finally, we have centred our research in pulse shaping in the generation and characterization of pulses exhibiting orbital angular momentum, a topic which is currently the subject of great interest from both laser developers and users.

3 Work performed / results / description

The main achievements over the reporting period are described below.

a) Development of an ultrabroadband optical parametric chirped pulse amplification (OPCPA) laser system

This work consists of three main blocks:

- Two stage, diode-pumped, Yb-based CPA pump laser at 515 nm;
- White-light continuum generation stage for the signal;
- Noncollinear OPCPA based on YCOB in the range 800-1000 nm.

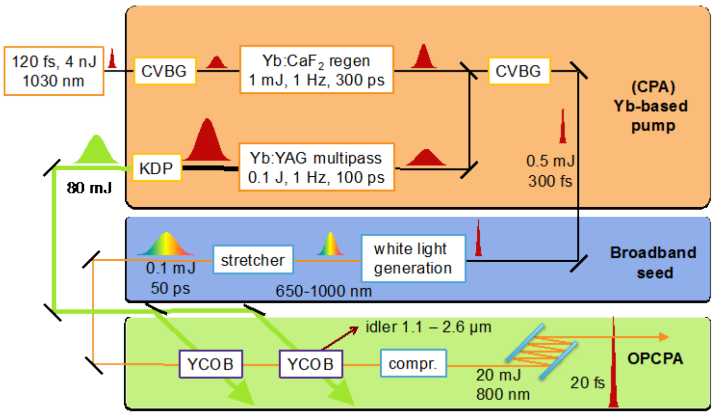

Fig. 1 – Setup of ultrabroadband OPCPA system based on YCOB.

Fig. 1 shows a schematic of the overall system. We have installed a 100 mJ, 1 Hz, diode-pumped, hybrid picosecond laser amplifier for OPCPA pumping, consisting of a 3 mJ, 10 Hz, $Yb:CaF_2$ regenerative amplifier and 100 mJ, 1 Hz, eight passes Yb:YAG amplifier at 1032 nm. Currently the multipass amplifier is being upgraded to perform at 10 Hz with enhanced energy.

The amplification chain follows the chirped pulse amplification (CPA) arrangement, seeded by a commercial mode-locked Ti:sapphire oscillator delivering 4 nJ, 150 fs, 76 MHz pulses at 1030 nm. A 35.2 mm long, 5 × 8 mm^2 aperture chirped volume Bragg grating (CVBG) in double pass configuration is used as stretcher/compressor. In the present configuration, pulses from the oscillator are stretched to ~330 ps. An auxiliary compact (19 cm long) and low dispersion (600 grooves/mm) Treacy compressor was added before the $Yb:CaF_2$ amplifier in order to pre-compensate the intra-cavity material dispersion, ensuring the overall temporal reciprocity between pulse stretching and compression.

The regenerative amplifier consists in a 1.35 m linear cavity, where a 3at% Yb-doped CaF_2 crystal, placed at the cavity waist, is pumped by a 75 W fibre-coupled diode laser (Amtron GmBH) at 940 nm in a double-pass configuration. This pre-amplifier delivers 3 mJ pulses with good energy stability (RMS <1.8%) at a repetition rate of 10 Hz and at a central wavelength of 1035 nm. The output pulses are then divided at an 80:20 beam splitter. The most energetic fraction is sent to the CVBG for compression. This process has an efficiency of ~50 %, resulting in <400 fs, ~1.2 mJ pulses. These pulse are then focused on a sapphire crystal, generating a white light continuum with an energy of the order of the µJ, which seeds the OPCPA.

The remaining fraction (~0.6 mJ) after the beam splitter seeds the multipass amplifier, reaching 110 mJ after eight passes through a 3at% Yb-doped YAG crystal pumped by a 4 kW diode laser stack at 940 nm. This amplifier operates at 1 Hz, with pulse stability similar to that of the regenerative amplifier. The output pulse spectrum redshifts to 1032 nm and narrows down to 3 nm FWHM, corresponding at final output (chirped) pulse length of ~150 ps. They are then sent to a 15 mm length DKDP crystal cut for type I SHG, generating green pulses at 516 nm with ~30 % efficiency conversion, and used to pump the OPCPA.

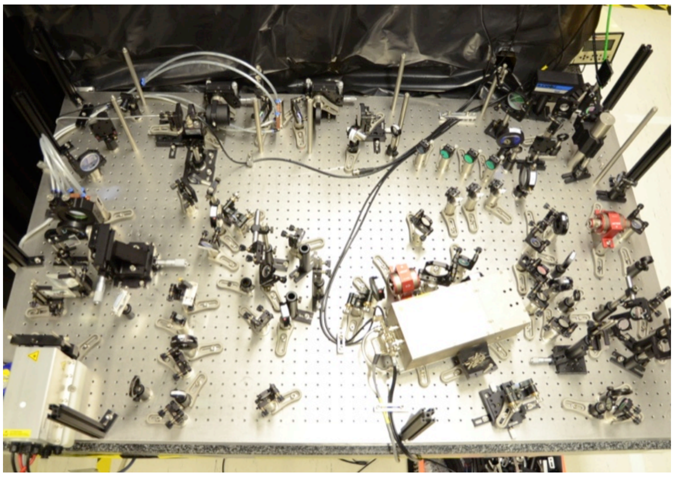

Fig. 2 – Diode-pumped hybrid Yb:CaF_2/Yb:YAG amplification laser chain.

Concerning the noncollinear OPCPA system, the main focus of this period was the numerical and experimental study of YCOB as a nonlinear media and the development of the two-stage setup based on this crystal, its characterization and optimization. We have also tested and characterized the performance and spectral transmission of the stretching and compression stages, consisting respectively of a 10 cm long SF11 block (stretcher), and a transmission grating + SF11 prism pair (compressor).

Following our simulations (H. Pires *et al.* J. Opt. Soc. Am. 2014) the YCOB crystals are cut at specific phase matching angles to maximize nonlinear efficiency. We started by performing single stage amplification (i.e. one single YCOB crystal), and by adjusting the phase-matching angle we were able to enhance amplification over a given bandwidth of the WLC. The maximum amplified bandwidth (FWHM) occurred for spectra centred in the wavelength region 850-900 nm, corresponding to a noncollinear angle of ~3.8°.

Temporal resynchronization of the outgoing signal and pump pulses was performed into a second YCOB crystal and a double stage was put into place, to further amplify the laser pulses. However, because of damage to the optics it was not possible to operate the double-stage setup at full power yet. Nevertheless, the second stage was optimized in terms of the amplification bandwidth (Fig. 3), extending 215 nm, from 825 to 1040 nm. The compression of such a broad spectrum to its Fourier transform limited duration would potentially allow the generation of high energy, sub-10 fs pulses, even shorter than the 20 fs goal. A future goal is also to make use of the idler pulse as a source of mid infrared (1.1 to 2.6 µm, up to the limit of the transparency range of YCOB) coherent pulses.

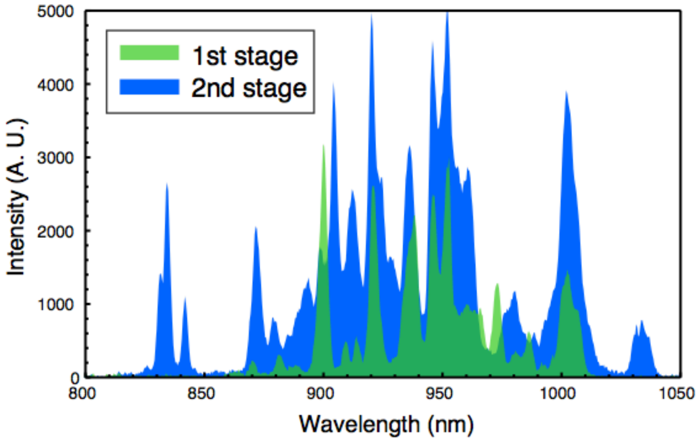

Fig. 3 – Gain bandwidth for the output spectra after the first optical parametric amplifier stage (green) and after the second amplifier (blue).

<u>b) Development of ultrashort pulse measurement devices</u>

During the course of this project several important changes took place at our facility. One of them was the adoption of the Yb-based diode pumped laser to become our main user-oriented system. This led to a number of adaptations in the existing stretcher, compressor and pulse diagnostics in order to accommodate the change in the central wavelength from 1053 nm to 1030 nm.

Two new pulse measurements diagnostics were developed for this purpose: an optical parametric amplification correlator (OPAC) and a compact, ultrashort-capability, single-shot autocorrelator, both at 1030 nm. The OPAC is based on the design of Divall & Ross (Opt. Lett. 29, 2273, 2005) and is illustrated in Fig. 4.

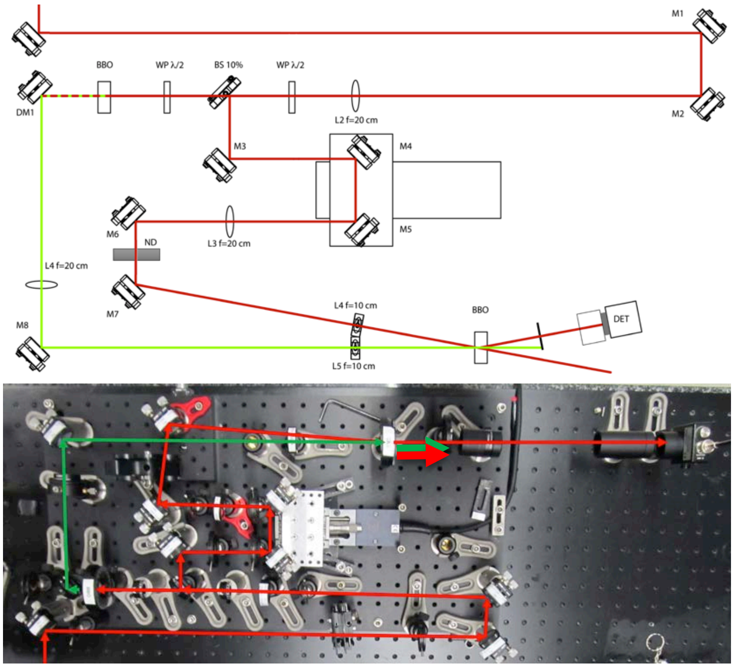

Fig. 4 – Setup of optical parametric amplification autocorrelator: schematic (above) and view from top (below).

The OPAC is capable is performing measurements over a window of 100 ps and is fully computer-controlled in a dedicated LabView environment. The operating principle consists in frequency doubling a fraction of the pulse to be characterized, and the two pulses are then mixed in an OPA configuration in a nonlinear crystal. The 1030 nm idler resulting from the interaction is then detected by a photomultiplier, providing a measurement of the correlation. This means that when the pump and signal pulse are not overlapped there is virtually no signal (apart from parametric fluorescence or scattering from the crystal surfaces) enabling high contrast measurements, which is a significant advantage of this device. The sensitivity may be controlled by adjusting a set of calibrated neutral density filters in the path of the signal beam and the photomultiplier gain.

The measurement step and the number of measurements at each position can also be controlled by the user. Fig. 5 shows a snapshot of a measurement evidencing a pre-pulse at 25 ps . A future upgrade of the device will include the capability of automatically switching the ND filter when the detected signal is out of the current measurement range.

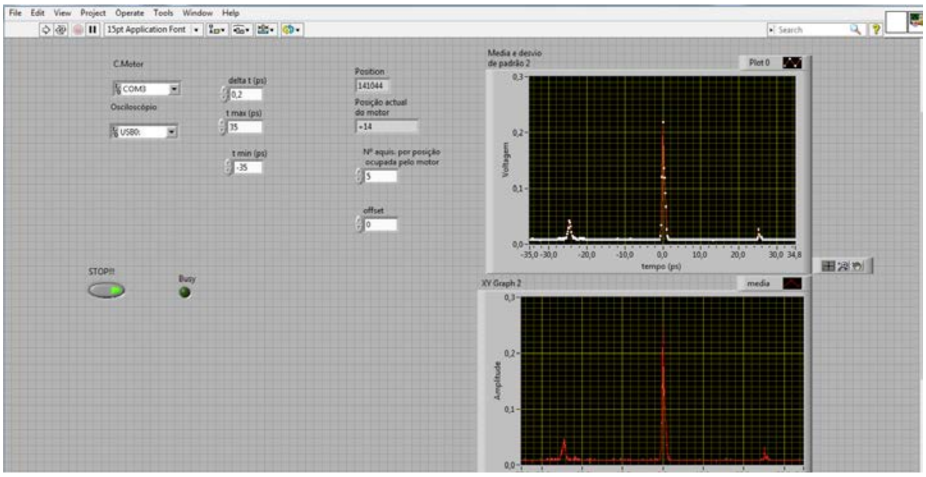

Fig. 5 – Snapshot of the OPAC measurement console.

c) Evaluation of pulse / beam shaping mechanisms for enhanced interaction

During the course of this work we have evaluated the achievements and the performance of different pulse shaping techniques, from the perspective of laser development but also from the laser user. This work was done in collaboration with the theory and numerical simulation team of our institution at IST, who have also been analysing the effect of using shaped laser beams, e.g. the use of pulses with orbital angular momentum (OAM) to drive spiral plasma wavefronts.

Laser pulses with OAM exhibit spiralling wave vectors and a spiralling phase. As a result, the optical isosurfaces with identical electric or magnetic field amplitudes spiral along the laser. In addition, its intensity profile is doughnut-shaped. The potential of these shaped pulse to explore relativistic laser plasma interactions has just started to be unraveled in the field of plasma-based acceleration. [J. Vieira, J.T. Mendonça, Nonlinear laser driven donut wakefields for positron and electron acceleration, Phys. Rev. Lett. 112 (2014), 215001; J.T. Mendonça, J. Vieira, Donut wakefields generated by intense laser pulses with orbital angular momentum, Phys. Plasmas 21 (2014), 033107]

A major challenge, however, is the production of ultra-intense OAM lasers. We have started exploring new paths to produce intense OAM lasers for laser-plasma interactions. From a simulation point of view, using very large scale, massivelly parallel ab-initio simulations and theory, we demonstrated that stimulated Raman backscattering processes could generate and amplify OAM lasers towards the Petawatt horizon in plasmas [J. Vieira, subm. to Nat. Photon. 2015]. These results can be transported to other amplifying medium because plasma non-linear optical properties can also be found in other non-optical materials.

On a parallel development, in a work done in collaboration with the Institute for Telecommunications at IST we have evaluated the use of laser light exhibiting OAM for encoding optical information. An experimental setup for modulation and demodulation of free space OAM-carrying beams was conceived based on twisted nematic (TN) spatial light modulator (SLM) technology. Fig. 6 shows the setup, consisting of a HeNe laser, a CCD wavefront sensor (Phasics SID4) and two TN-SLMs (Cambridge Correlators SDE1024). The beam wavefront was modulated by creating a computer-generated hologram on the first SLM. Then the modulated beam is propagated in air for a short distance, after which it is demodulated in a second TN-SLM where a symmetrical hologram is generated.

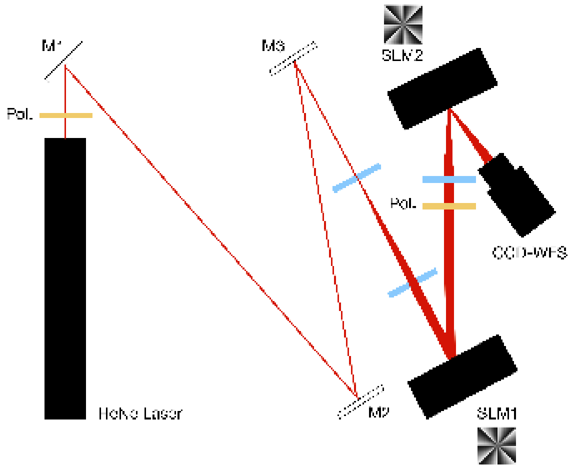

Fig. 6 – Setup for modulating and demodulating an OAM-carrying beam.

Fig. 7 shows an example for beam modulation, in this case for a wavefront exhibiting eightfold symmetry. The intensity clearly shows the expected amplitude-phase coupling effects for TN technology where the intensity follows the phase profile: the obtained intensity profile is annular but the ring consists of separate peaks instead of a smooth continuous shape. We have identified the cause for this to be the SLM technology, and other groups have obtained improved results by using parallel aligned nematic (PAN) liquid crystal SLMs. In our case, the results could be improved by using slightly elliptically polarized light.

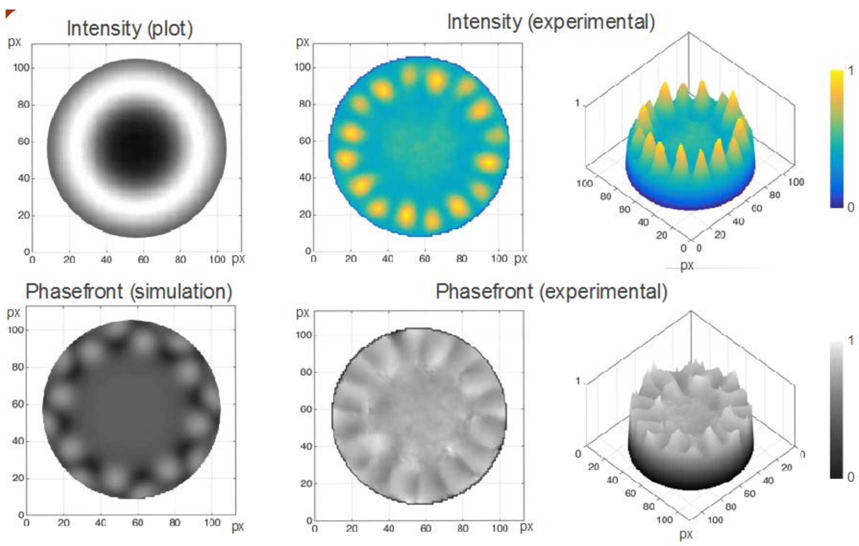

Fig. 7 - Normalized intensity and phase profiles for an OAM-carrying beam with eightfold symmetry.

Fig. 8 shows the results for beam demodulation. A complementary spiral phase computer-generated hologram is loaded into the second SLM. The results for the phase clearly show the removal of the previous modulation. As for the intensity, partial compensation of the doughnut-light shape is obtained, but again due to the SLM technology used a residual modulation remains.

This work has allowed us to identify the main limitations and most important parameters in using this technology, and constitutes an essential stepping-stone towards applying it successfully for the modulation of broadband, short pulses.

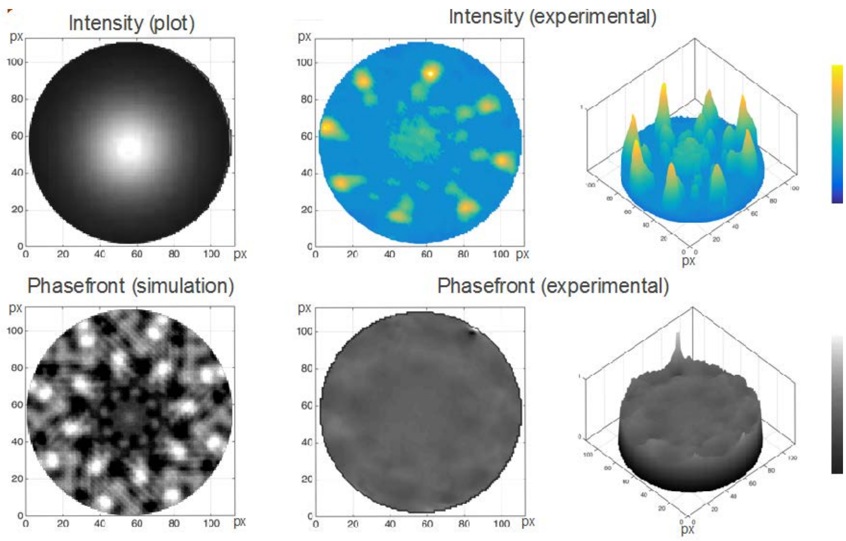

Fig. 8 - Normalized intensity and phase profiles for an eigthfold OAM demodulated beam.

4 Conclusions

A diode-pumped laser, consisting of a 100 mJ, 1 Hz, Yb:CaF_2 / Yb:YAG amplifier at 1032 nm was successfully developed. Frequency-doubling was achieved, and the pulses are currently being used to pump a two-stage YCOB-based optical parametric chirped pulse amplifier. The first experimental OPCPA tests have shown a performance compatible with that predicted by numerical simulations. The amplifier spectrum allows the potential generation of pulses well within the target parameters of the system.

We have developed two pulse measurement diagnostics suitable for characterizing the pump and the output of the OPCPA system: an OPAC, for both pulse duration and contrast measurements, and a broadband single-shot autocorrelator, currently under characterization.

Finally, we have focused on the properties and the generation of laser pulses exhibiting orbital angular momentum, both at the level of numerical simulations and experiments. We have installed a setup for testing the encoding of optical information through OAM in a laser beam and successfully performed modulation and demodulation.

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Invited talks

G. Figueira, to be presented at the 2nd International Symposium on High Power Laser Science and Engineering, Suzhou, March 2016

G. Figueira, “Extended performance of the L2I high intensity laser facility”, *ICO-23 – 23rd Congress of the International Commission for Optics*, Santiago de Compostela (Aug. 2014).

G. Figueira, “Generation of ultrabroadband energetic laser pulses by noncollinear optical parametric chirped pulse amplification”, *RIAO/OPTILAS 2013 – VIII Iberoamerican Conference in Optics*, Porto (Jul. 2013).

Regular talks

C. P. João, H. Pires, and G. Figueira, “Development of compact 100 mJ-level diode-pumped Yb:CaF_2/Yb:YAG laser amplification chain for pumping broad- band optical parametric amplifier”, *ICO-23 – 23rd Congress of the International Commission for Optics*, Santiago de Compostela (Aug. 2014).

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