Optics Communications 355 (2015) 230–238

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Handling beam propagation in air for nearly 10-fs laser damage experiments

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ARTICLE INFO

Article history:
Received 27 April 2015
Received in revised form
9 June 2015
Accepted 19 June 2015
Available online 6 July 2015

Keywords:
Laser damage
Ultrashort pulse
Kerr effect
Air ionization

ABSTRACT

We present the design and operation in air of a laser test-bench able to measure the laser-induced damage threshold of optical materials and components with ultrashort pulses down to nearly 10 fs pulse duration. Working in air environment brings the advantage of convenience and rapid diagnostics, provided that the laser beam is properly handled. As a preliminary step, a careful analysis of the spatial, spectral and temporal properties of the ultrashort laser beam is performed to characterize its propagation till the focal plane where the target is located. The results allow us to determine an upper limit of the incident energy below which the beam propagation is not affected by nonlinear effects, like Kerr effect or air ionization, which could skew the determination of laser-induced damage threshold. Finally, we demonstrate the capability of the laser test-bench by measuring the damage threshold of fused silica irradiated by single ultrashort pulses of nearly 10 fs pulse duration.

1. Introduction

Laser sources of pulse duration of few optical cycles ($\sim$10 fs) are today routinely operated permitting to explore with unprecedented time resolution the basic atomic events of energy exchange in matter with fascinating developments in attoscience, material science, ultrafast chemistry and biology [1–4]. With the continuous increase of peak and average powers delivered by the laser sources, ultrafast processing and micromachining of materials are also emerging markets [5]. Indeed, due to their ease to trig nonlinear absorption in any kind of materials, ultrafast lasers can deposit their energy in a small volume and induce changes with a minimum number of incident photons. As a result, they have the capability to machine matter with high resolution, much below the diffraction limit, and with enhanced control, resulting in calibrated outcomes and minimal collateral effects and affected zone [6–10]. However, the use of ultrafast lasers of pulse duration of few optical cycles is still scarce due to their difficulty of manipulation and transport, especially in air where several physical phenomena may take place at relatively low intensity. Indeed, if we assume the interaction of a 10 fs laser pulse of 10 μJ energy at the surface of a dielectrics, one should expect a laser-induced threshold for ablation in the range of 1 J/cm² [11,12]). However, it corresponds to an incident beam power close to the critical power in air ($\sim$10 GW [13,14]) and an intensity in the Rayleigh range close to air ionization and intensity clamping ($\sim 5\times10^{13}$–10^{14} W/cm² for pulse range of 100 fs duration [15–19]). In those conditions, maintaining the optical properties of the incident laser beam till the sample located in the focal plane of a focusing element may be highly questionable. Precise diagnostics of the beam propagation and of the interaction outcomes thus appear as a prerequisite for any envisioned industrial implementation of micromachining applications based on the use of laser pulses of duration of few optical cycles.

Laser developments are also boosted by the on-going quest to ultrahigh intensity science, with huge efforts for scaling up the laser energy and scaling down the pulse duration and size of the focused beam. The perspective is here to open a route to explore the physics in the ultra-relativistic regime with expected breakthroughs in numerous topics of high field and ultrafast science from nuclear physics and engineering to medicine or astrophysics [20]. In that context, a critical issue for safe development and operation of emerging laser infrastructures of Petawatt class, combining hundreds of J and sub-15 femtosecond pulses [21], must address the problem of damage of the optical materials and components ensuring the transport and delivery of the ultrahigh

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http://dx.doi.org/10.1016/j.optcom.2015.06.049
0030-4018/

intensity beam to the target. Such damage evaluation shall be ideally conducted in vacuum to provide the exact conditions of operation for the optical components and materials under test. Laser-induced damage threshold (LIDT) is expected to vary depending on the ambiance (air/vacuum) that may affect the energy exchange between the surrounding gas and the surface of the material. For instance, considering metals, smaller ablation thresholds have been measured in air compared to vacuum [22]. Nevertheless, performing damage tests in air will provide LIDT data from which one can define important fluence parameters for safe and reliable operation of optical components and laser systems. Such quantitative evaluation of performance of optics is of high interest for laser manufacturers and optics suppliers, since it enables rapid feedback and comparative assessments for optimization of optical components.

The purpose of this work is twofold. After the detailed description of the laser damage test-bench (Section 2), we firstly address the difficulties implied by the use and the manipulation of ultrashort laser pulses down to nearly 10 fs pulse duration in the regimes of damage and ablation of optical materials (Section 3). In particular, we determine the exact laser conditions in which the threshold of modification of matter is then evaluated. Secondly, to demonstrate the capabilities of the test-bench, we show the reliable measurement of the laser-induced damage threshold (LIDT) of a given material (fused silica) extensively used in optics and photonics (Section 4).

2. Experimental arrangement of the damage and ablation test-bench

The damage and ablation test-bench uses the ASUR laser infrastructure (**A**pplications des **S**ources **U**ltra-**R**apides) of LP3 laboratory [23]. The ASUR platform is a multiline femtosecond laser source based on Ti:Sapphire and Chirped Pulse Amplification technology (Amplitude Technologies, France).

The general schematic of the test-bench is shown in Fig. 1. The beam line ASUR 5 a (1 mJ, 25 fs, 100 Hz, linear polarization) is directed by a concave mirror of 5 m radius of curvature (ROC) into a 3 m long vacuum chamber sealed by two fused silica Brewster windows. In the focal plane, the beam is filtered by a conical pinhole yielding a cleaned Gaussian pump beam suitable for cross-polarized wave (XPW) generation [24]. XPW technique consists of a degenerate four-wave mixing process performed in an asymetric χ(3) tensor host material leading to the generation of a new pulse with a polarization orthogonal to the pump pulse. The two outcomes of XPW technique is the enhancement of the temporal contrast of the generated pulse as well as its spectral broadening favorable to further pulse shortening [24,25]. In our setup, XPW conversion takes place in two successive BaF_2 crystals ([011] crystallographic orientation) separated of 10 cm and also set in the vacuum chamber. The distance between the pinhole and the first crystal is approximately 10 cm. These two distances have been optimized to get a good XPW efficiency and robustness of the performances. We obtained a XPW conversion efficiency of ~10% with the delivery of a XPW signal up to 80 μJ before recompression (with ~2.5% rms shot to shot energy fluctuations). The pump signal is suppressed by polarization filtering through four successive Brewster polarizers. The XPW signal is further collimated using a concave mirror (ROC = 5 m), which position is carefully adjusted by means of a wavefront sensor (Sid-4, Phasics). After collimation, the beam diameter is approximately 3 mm. The XPW signal is finally recompressed by a set of chirped mirrors CM and a pair of wedges L_p.

The pulse duration is controlled with a second-order autocorrelator (Femtometer, Femtolasers Gmbh) located approximately 20 cm after

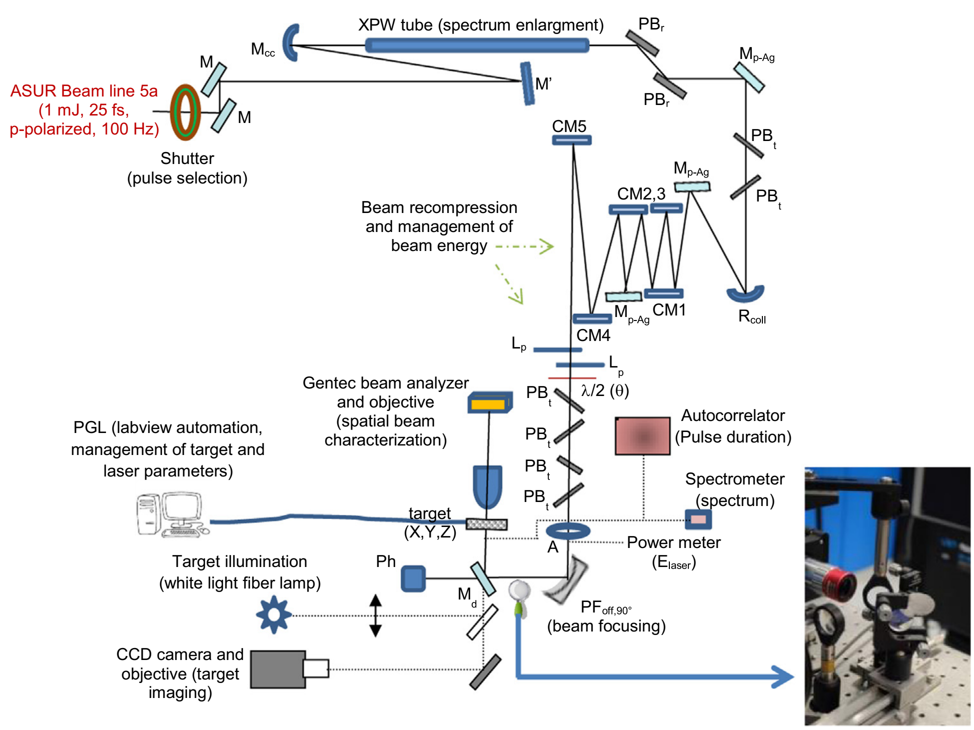

Fig. 1. Scheme of laser damage and ablation test-bench and diagnostics. M: R_{max}@800 nm, 45° incidence. M′: R_{max}@800 nm, 0° incidence. M_{cc}: concave mirror with 5 m radius of curvature. XPW tube: vacuum tube with a spatial filter and two cascaded BaF_2 crystals for bandwidth enlargement through XPW 3rd order nonlinear effect. $M_{p\text{-}Ag}$: low dispersion Ag metallic mirror. R_{coll}: collimation concave mirror (ROC = 5 m). $PB_{r,t}$: Brewster polarizer (resp. in reflection and transmission) for XPW cleaning (pump filtering) and beam attenuation. CM1-5: chirped mirrors for pulse temporal recompression. L_p: thin prismatic wedge with translation for fine tuning of the spectral phase. $\lambda/2$ (θ): motorized half-wave plate. (A) iris diaphragm. $PF_{off,90°}$: off-axis (90°) focusing parabola. M_d: large bandwidth R_{max} mirror, 45° incidence. Ph: photodiode for control of incident energy on target. PGL: Labview software for management of the target (translation) and laser irradiation conditions (energy, number of shots). To the right, the inset shows a photograph of the arrangement of the focusing zone.