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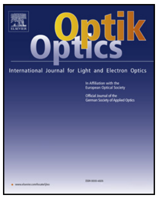

Original research article

Experimental study of variable thermal lens in a two-stage chirped-pulse high-power Ti:sapphire amplifier at 1kHz

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ABSTRACT

In general, misalignment, surface quality of optical components, thermal and nonlinear properties, doping level and inhomogeneity in the gain material can induce unexpected pulse propagation effects on intnese femtosecond laser pulses. Among them, the thermal lens in a thermally loaded material is more serious since it limits power scaling and degrades maximum achievable intensity at the focus by introducing distortion into the wavefront. Thereby, an understanding of thermally distortion wavefront is of great importance for optimum design of high power laser amplifiers and efficient serving femtosecond lasers in various specific applications. In this paper, we experimentally studied beam quality and wavefront distortion in a longitudinally pumped two-stage chirped pulse high power Ti:sapphire amplifier laser at 1 kHz operation in terms of pump power. The amplifier crystals are cooled thermoelectrically to below −10 °C. A simple formula for coupling the thermal lens in a two-stage amplifier consists of a regenerative amplifier followed by a single-pass amplifier pumped equally by the Nd:YLF laser at 527 nm with maximum average output power of 44 W and 130 ns pulse duration at 1 kHz is presented. The wavefront curvature of the compressed laser pulses with ~40 fs pulse duration and center wavelength of 800 nm is evaluated directly by Shack-Hartmann Wavefront Sensor (SHWS) with help of the Zernike polynomials. While the beam radius and spatial beam quality M^2 factor are estimated by knife-edge testing. Also, the optical wavefront distortion caused by an iris inserted into the beam path of a high power laser for quick spot size adjustment has been presented. When diameter of the iris is about 75% of the laser beam size (corresponding to 67% fraction transmission), laser beam distortion associated with the iris is negligible.

1. Introduction

The titanium sapphire crystal has the broadest tuning range (660–1180 nm), high thermal conductivity $k_c = 0.33$ W/(cm K) and high emission cross section (2.8×10^{-19} cm^2 @790 nm) compared with other common tunable solid-state laser materials. These unique properties make it suitable for ultrafast high power chirped pulse amplifier (CPA) laser systems as well as broadband tunable single or dual-wavelength CW or pulsed lasers [1]. Ti:sapphire laser with potential of flexible wavelength and diverse pulse generation has been widely used in many applications such as frequency comb generation, pump-probe time-resolved spectroscopy, metrology, precision spectroscopy, imaging, material processing, medicine, micro surgery, nonlinear optics, holography, micromachining, remote sensing and lidar [2–7]. Advances in generation few-cycle high power femtosecond lasers have opened a new door

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for generation secondary sources in extreme UV (EUV) and soft x-ray region via high harmonic generation technique from solids (SHHG) or gases (GHHG) by focusing the intense laser pulses onto a solid-target, or into an atomic gas, respectively, or via coherent harmonic generation (CHG) by interaction femtosecond pulses with relativistic electrons in a periodic magnetic field (called modulator) followed by chicane and radiator (see, i.e [8–18]. and references therein). In most of these applications, it is essential to have a laser beam with stable pointing and good focusability. For example, high-intensity laser pulses on the order or above of 10^{14} W/cm^2 are used for HHG and the cutoff photon energy for a given atomic state depends on the peak intensity of the driving laser. In ultrafast imaging, the resolution of the system can be limited either by thermal aberration or by fluctuation of the focus position. In pump-probe time-resolved experiments the beam pointing stability and focus spot size can greatly improve the signal to nose ratio (SNR) and spatial resolution. In precise micro-machining, the depth and width of the cut can be affected by fluctuation of either focus spot position (laterally or longitudinally) or focus spot size of the laser beam. In general, the focusability of laser beam limits by aberrations depending on quality of wavefront of the laser beam. In other words, wavefront aberration adversely impacts the performance of imaging systems in terms of resolution, in laser communications in terms of bit error rates, and in high energy physics in terms of ultimate on-target intensity.

The application of CPA to ultrafast amplifiers originated with the work of Mourou and his co-workers [19,20]. This is a scheme to amplify picosecond or femtosecond laser pulses. In solid state lasers [21–25] as well as fiber lasers and optical parametric chirped pulse amplification (OPCPA) technique [26–29] the CPA technique has made possible the generation of energetic few optical cycle pulses and therefore achieving high peak power pulses. Nowadays, nearly all ultrafast, high power lasers that use CPA technique are equipped with single- or multi-stage amplifier including regenerative amplifier, multipass amplifier, or singlepass amplifier.

On the other hand, the development of high-throughput Ti:sapphire laser plays a major role in advanced manufacturing and industrial applications. However, the maximum achievable energy from an amplifier limits by thermal lensing, gain saturation, amplified spontaneous emission (ASE), repetition rate, damage threshold of the gain medium and optical components. The gain increases by improving brightness of the pump source [30], however, with the expense of increasing radial temperature gradient within the gain medium and thus introducing wavefront degradation. In addition, pump induced thermal lens in end-pumped lasers alter the stability and mode-matching efficiency of the laser [31]. The thermal effects limit the performance of high-power and high-energy CPA lasers and an exact knowledge of the thermal effects such as thermal lens, thermally induced birefringence, and spherical aberration in the gain material is therefore important for optimum design of high power laser amplifiers and efficient serving femtosecond lasers in various specific applications.

The thermal distribution in single-pass amplifiers may be evaluated numerically [32–34] and analytically [35–42], however, they are limited to certain boundaries conditions and also do not give any information about the degradation of the beam quality. Therefore, due to the complex mechanisms of thermal effects in laser materials which can magnifies by gain properties, non-symmetrical pump distribution, and complexity of the system, experimental study is often the only accurate method for characterization of thermally induced beam quality distortion in the real situation. One simple way to characterize the thermal lens is using a probe beam propagating through the laser rod and subsequently measures the axial shift of the focal point [43–45]. The disadvantages of this method are low accuracy especially when thermal lens is not strong and complexity of the setup which needs more optics and optical sources. This method can be improved for quantitatively real-time measuring thermal lens by monitoring the laser output directly without any probe beam [46,47]. However, the above mentioned methods are not able to determine the aberrations which can be addressed by using Shack–Hartmann Wavefront Sensor (SHWS) with more accuracy and more sensitivity in real-time [48]. This technique has another advantage that can be used for measuring wavefront of the broadband sources with ultrafast pulses which cannot normally be tested with interference based methods. The SHWS can also provide information on the optical system performance, including peak-to-valley (PV) wavefront deviation, RMS wavefront error, modulation transfer function (MTF), and point spread function (PSF). The alignment errors and surface quality of the optical components in a complex optical system can also be analyzed by SHWS with observing wavefront tilt.

For more practical experiments where a high pulse repetition rate with high peak power is needed, thermal lens becomes more important. Cryogenically cooled Ti:sapphire amplifier at temperatures below 130 K can be used for managing thermal lens by increase in the thermal conductivity and decrease in dn/dT at low temperatures [49–51]. However, use of these systems has been relatively limited, despite most of the commercially available Ti:sapphire amplifiers with moderate power are thermoelectrically cooled (TE) to below −10 °C.

In some experiments such as generation isolated attosecond pulses where phase stability of the driving pulse train is crucial, a hybrid of SHWS and a deformable mirror or an adaptive optics are proposed for correction the shape of the wavefront [52]. If the shape of the aberrated wavefront is known, a deformable mirror can reshape it into an ideal plane wave [48,52]. However, the adaptive optics or deformable mirrors are not yet widely adopted in the life sciences community. Wavefront sensors are inherently complex instruments and this is greatly magnified when it is mixed with a complex deformable mirror or an adaptive optics. The control of such multi-parameter system is very complex. The themporal frequency response must be faster than the coherence time, however, the response time limits the resolution with limiting the number of channels.

Nevertheless, thermal effects in multi-stage ultrafast laser amplifiers at high repetition-rates of 1 kHz and pulse energies of ~10 mJ with strong gain narrowing near gain saturation has rarely been investigated. When the pump laser is focused onto a Ti:sapphire crystal, nonunifirm heat distribution causes a thermal lens which gets worse at higher repetition rates as the heat load per unit area increases. In this work, the thermal lens in a longitudinally pumped two-stage high power Ti:sapphire chirped pulse amplifier laser at 1 kHz operation with strong gain narrowing around gain saturation versus pump power has been experimentally studied. The amplifier crystals are cooled by a thermoelectric cooler to below −10 °C. A simple formula for coupling the thermal lens in a two-stage amplifier consists of a regenerative amplifier followed by a singlepass amplifier pumped equally by the Nd:YLF laser at