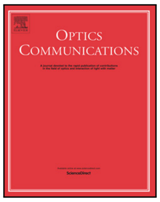
Optics Communications 423 (2018) 134–139

Contents lists available at ScienceDirect

Optics Communications

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



Laser thermal distortion all-time metrology system for solid-state laser based on phase measuring deflectometry

Meng Yan, Lei Huang [*], Licheng Sun, Junbiao Fan

Center for Photonics and Electronics, Department of Precision Instruments, Tsinghua University, Beijing 100084, China

ARTICLE INFO

Keywords:
Laser
Solid-state
Thermal effects
Wave-front sensing

ABSTRACT

We report a low-cost laser thermal distortion all-time metrology system (LATAMS) to overcome the intrinsic limitations of conventional approaches. The LATAMS is especially useful for the thermal distortion measurement of the laser crystal in solid-state lasers, compared with other approaches. A LATAMS setup is constructed and embedded into an existing solid-state laser, consisting of displaying the fringe patterns and recording the changes processes. The LATAMS could provide high-precision real-time thermal distortion measurement throughout the whole process of the solid-state laser. The experimental results successfully demonstrated its capability in measuring the wavefront distortion of laser crystal.

1. Introduction

Solid-state lasers are widely developed and applied in many applications due to its advantages of good beam quality, high pumping efficiency and compact structure. During the working process of solid-state lasers, in order to depress unwanted waste heat [1], caused by the quantum-defect and nonradiative relaxation of particles, various cooling structures are introduced to the gain medium. As the unwanted waste heat could only be transmitted through the boundary of gain medium, inhomogeneous temperature distribution will essentially emerge [2], which will result in the thermal distortion (including the refractive index gradient and the crystal deformation), typically performed as a defocus contribution to the wavefront of the laser beam [3,4]. The thermal distortion in the laser gain medium has become one of the most serious problems in the solid-state laser, as it critically affects the conversion efficiency and the laser beam quality, especially in the high power laser. Obviously, the accurate acquisition of the thermal distortion, especially under operating condition, is greatly important to the design and control of high power and high beam quality solid-state laser.

Although two conventional approaches, the interferometry and the Shack–Hartmann sensing, have been suggested to obtain the thermal distortion [5]. However, these methods have intrinsic limitations. Due to a delicate calibration process for the configuration, the interferometry method has practical challenges. The coherent optical detection of the interferometer is very sensitive to the vibration and the temperature of the environment [6]. Practically, it is quite hard to get stable and distinct fringe patterns under the condition that the gain medium heat sink has water flow. Lateral shearing interferometer with high sensitivity is a choice to achieve the detection of thermal distortions. But it costs high and the calculation algorithm is complex [7,8]. Moreover, the instantaneity is hard to achieve for the lateral shearing interferometers using the multi-images acquisition method [9]. For the single-image acquisition lateral shearing interferometer (e.g. PHASICS SID4 four-wave lateral shearing interferometry), the wavefront instantaneity could be achieved. But it is not easy to establish a similar measurement system in a solid-state laser [10]. Although widely used in the field of wavefront measurement [11], the Shack–Hartmann sensor (SHS) is not recommended to accurately acquire the thermal distortion of the gain medium. The air turbulence in the optical path and the ambient vibration could have apparent influences on the accurate acquisition of the position of the centroid for each sub-aperture beam when measuring the thermal distortion using the SHS. Based on this point, generally, the measurement result of the SHS consist not only the pure thermal distortions of the laser rod, but also the distortion induced by the air turbulence and ambient vibration [12]. Furthermore, due to the limitation of the lenslet array number (e.g. maximal 100 × 100 lenslet array in a 10 mm × 10 mm aperture) and the aperture (e.g. 100 μm × 100 μm each single aperture in a 100 × 100 lenslet array) of micro-lens array, it is very difficult for this approach to achieve high-precision and large dynamic range (i.e. acquiring large wavefront distortion) [13]. Additionally, an auxiliary beam expansion or shrink system is always needed to match the detection beam size to aperture of the SHS.

The theoretical thermal simulation model [14,15], not practical measurement data, is always used as an important approach to give

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[*] Corresponding author.
E-mail address: hl@mail.tsinghua.edu.cn (L. Huang).

https://doi.org/10.1016/j.optcom.2018.04.001
Received 8 January 2018; Received in revised form 7 March 2018; Accepted 2 April 2018

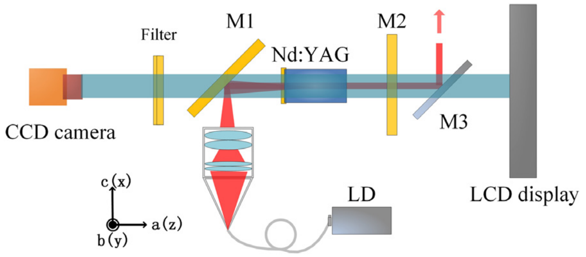

Fig. 1. The schematic diagram of the LATAMS, including a CCD camera, a LCD display and an Nd:YAG laser. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the reference data of thermal distortion, which will result in certain inaccuracy and unreliability for the design and optimization of the solid-state lasers.

We report a low-cost laser thermal distortion all-time metrology system (LATAMS) that overcomes the intrinsic limitations of conventional approaches. In the presented thermal distortion metrology, a detection configuration is primarily composed of a liquid crystal display (LCD) and a charge-coupled device (CCD) camera. While the solid-state laser operating, the modulated fringe pattern from the LCD is distorted when passing through the thermal distorted gain medium. The distorted fringe pattern carrying the distortion information is captured by the CCD camera. A phase-shift algorithm is used to achieve the wavefront slope from the detected phase distributions, and a reconstruction algorithm is used to reconstruct the wavefront from the extracted wavefront slope. In the LATAMS, the compact structure ensures the flexibility of the system adjustment, while the incoherent detection light beam ensures the adaptability to the environment disturbance. The LATAMS could provide high-precision real-time thermal distortion measurement throughout the whole process of the solid-state laser, from the startup to the shutdown.

2. Configuration and principle

A schematic diagram of the LATAMS configuration (an Nd:YAG laser as the example) is depicted in Fig. 1. The red area indicates the laser beam path (1064 nm), while the blue area indicates the incoherent detection light beam path. The modulated fringe pattern from LCD will be distorted by the working Nd:YAG crystal and then directly enter into the CCD camera, before which a low pass filter is used to filter the pumping 808 nm and 1064 nm to avoid the cross-talking problem in the image capture. Note that the detection light beam will not be affected by the laser beam when passing through the Nd:YAG crystal, while only the distortion of the gain medium could make it distorted for its incoherence.

The wavefront distortion could be obtained based on the phase deflectometry [16]. Before the laser operating, the sinusoidal fringe pattern (Fig. 2(a)) passing through the Nd:YAG crystal enters into the image plane of the CCD camera. The initial irradiance distribution $I_0(x,y)$ (i.e. no pumping, no distortion) of the sinusoidal fringe pattern in the vertical direction on the CCD camera could be expressed in Eq. (1).

$$I_0(x,y) = A(x,y) + B(x,y)cos(2\pi x/g + \phi_0(x,y)). \tag{1}$$

Here, $A(x,y)$ is the background irradiance distribution and $B(x,y)$ is the amplitude modulation. ϕ_0 is the initial phase of the LATAMS system. g is the period of the sinusoidal fringe pattern. When the laser is operating, the heated Nd:YAG crystal will distort the sinusoidal fringe pattern (Fig. 2(b)) and additional phase will emerge [17]. Therefore, the irradiance distribution $I(x,y)$ of the deformed sinusoidal fringe pattern could be expressed in Eq. (2).

$$I(x,y) = A(x,y) + B(x,y)cos(2\pi x/g + \phi(x,y) + \phi_0(x,y)). \tag{2}$$

Here, $\phi(x,y)$ is the additional phase caused by the thermal distortion of the Nd:YAG crystal [18].

In the LATAMS, two techniques, including the eight-image acquisition technique based on the four-step phase-shift method and the one-image acquisition technique based on the Fourier transform method, are proposed to acquire the additional phase.

In the eight-image acquisition technique, the measured irradiance distribution I_n after the Nth phase-shift can be rewritten as Eq. (3), assuming $\varphi_0(x,y) = 2\pi x/g + \phi_0(x,y)$ and $\varphi(x,y) = 2\pi x/g + \phi(x,y) + \phi_0(x,y)$.

$$I_n(x,y) = A(x,y) + B(x,y)cos(\varphi(x,y) + \delta_n) \tag{3}$$

where $n = 0,1,2,3$. N is the total number of the phase shifts ($N = 4$ in the eight-image acquisition technique). δ_n is the shifting phase for each phase shift ($\delta_n = 2\pi n/N$). Based on Eqs. (2) and (3), $\varphi(\mathrm{x,y})$ could be expressed in Eq. (4).

$$\varphi(x,y) = -arctan\left[\frac{\sum_{n=0}^{N-1} I_n \sin(2\pi n/N)}{\sum_{n=0}^{N-1} I_n \cos(2\pi n/N)}\right]. \tag{4}$$

$\varphi(\mathrm{x,y})$ is the wrapped phase limited in $[-\pi,\ \pi]$, which could be unwrapped as the continuous phase [19,20]. Then the additional phase $\phi(x,y)$caused by the thermal effect can be expressed in Eq. (5).

$$\phi(x,y) = \varphi(x,y) - \varphi_0(x,y). \tag{5}$$

In the eight-image acquisition technique, the additional phase $\phi_x(x,y)$ in the X direction (i.e. the horizontal direction) could be calculated by four vertical sinusoidal fringe patterns. And the additional phase $\phi_y(x,y)$ in the Y direction (i.e. the vertical direction) could be calculated by four horizontal sinusoidal fringe patterns.

The one-image acquisition technique based on the Fourier transform method is used to detect and calculate the additional phase $\phi(x,y)$ when the thermal distortion changes rapidly. In order to measure the changes of the phase in the X and Y directions by one image, we use the orthogonal fringe pattern, which is different from the fringe pattern in eight-image acquisition technique. The irradiance distribution $I(x,y)$ of the orthogonal fringe patterns on the CCD camera could be expressed in Eq. (6).

$$\begin{aligned} I(x,y) = {} & A(x,y) + B(x,y)\cos(2\pi x/g + \phi_x(x,y)) \\ & + B(x,y)cos(2\pi y/g + \phi_y(x,y)). \end{aligned} \tag{6}$$

Here, $A(x,y)$ is the background irradiance distribution and $B(x,y)$ is the amplitude modulation. g is the period of the orthogonal fringe pattern. $\phi_x(x,y)$ and $\phi_y(x,y)$ are the additional phase in the X and Y directions caused by thermal distortion respectively. A Fourier transform method introduced by Takeda et al. [21] could be used to calculate the additional phase.

Based on the obtained additional phase, i.e. $\phi_x(x,y)$ and $\phi_y(x,y)$, the distribution of the wavefront slope in the X and the Y directions (Fig. 2(c)) could be written in Eqs. (7) and (8) [22]. Finally, by applying the numerical integration, the wavefront distortion could be reconstructed according to Eq. (9) [16].

$$P_x(x,y) \cong \frac{g}{2\pi d}\phi_x(x,y) \tag{7}$$

$$P_y(x,y) \cong \frac{g}{2\pi d}\phi_y(x,y) \tag{8}$$

$$\partial D_x(x,y) = P_x(x,y)\partial x \tag{9}$$

$$\partial D_y(x,y) = P_y(x,y)\partial y. \tag{10}$$

Here, $P_x(x,y)$ and $P_y(x,y)$ are the distribution of the wavefront slope in the X and Y directions respectively. d is the distance between the LCD sinusoidal fringe plane and the left surface of the Nd:YAG crystal. For the convenience of the wavefront distortion calculation, the left surface of the Nd:YAG crystal is set as the object plane of the CCD camera. The 8 mm camera lens and small aperture make the imaging system achieve