Experimental study of thermal lensing of Nd:YAG laser

HU Shao-yun*, ZHONG Ming, ZUO Yan, and FAN Hong-ying
Southwest Institute of Technical Physics, Chengdu 610041, China

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A wavefront method of measuring the thermal lensing of solid-state lasers is proposed. This method is easy to implement and has a high spatial resolution for diagnosing thermal lensing. By this method, the thermal lensing of Nd:YAG laser is studied in detail. And this work provides a means for studying the thermal effects of laser medium and many instructional parameters for optimizing the design of the laser cavity.

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Beam focusing and higher-order wavefront distortion due to heat dissipation in a laser gain medium are important considerations in the design of solid-state lasers because wavefront distortion can profoundly influence the performance of a given laser design. Although the effects of heat dissipation in laser materials can be calculated for a particular geometry with appropriate boundary conditions, the material inhomogeneity as well as the nonuniform optical pumping are difficult to be evaluated by numerical modeling alone. Therefore, an accurate characterization of thermal lensing for each rod of laser material installed in a particular laser cavity can be achieved only by careful measurement of the transmitted wavefront.

When a beam of light acting as a probe is transmitted through a heated laser rod, the thermal lensing can be measured with an interferometer or with a wavefront sensor such as the Shack-Hartmann wavefront sensor. For measurements of the thermal lensing, where many waves of curvature may be imposed on the probe beam, wavefront sensors offer a practical easy-to-use alternation to interferometers.

Wavefront sensors are insensitive to vibration and able to measure larger wavefront distortion. They can make differential measurements that yield only thermal lensing information and ignore aberrations in both optical elements used to implement the measurement and the cold laser rod itself. Wavefront sensors operate on the principle that light travels in a straight line. If we adopt a definition for the wavefront as the surface normal to the direction of propagation of light, then wavefront sensors actually measure the slope of this surface. When the wavefront is reconstructed from the measured slope data, a lot of information on focusing and high-order optical aberrations can be obtained by using expansion of Zernike polynomials. This information can be used to optimize the cavity designs by abnegating the laser rods or cavity optics that do not meet the specifications, and selecting appropriate materials or optics according to the requirements.

The heat dissipation in a laser medium will produce changes in the refractive index and the shape of the laser rod as well as the birefringence phenomenon at the same. These factors constitute the so-called thermal lensing, that is

$$f_{\mathrm{th}}^{-1} = f_{\mathrm{tho}}^{-1} + f_{\mathrm{end}}^{-1} + f_{\mathrm{bi}}^{-1} \tag{1}$$

where f_{th} is the thermally induced focal length. f_{tho} is the thermally induced focal length due to the change of refractive index only, f_{end} is the focal length caused by the end face effect of the rod only, and f_{bi} due to the birefringence phenomenon. Also the three factors boil down to the optical path difference (OPD) of the probe beam when transmitting through the thermal medium. The OPD at an arbitrary radius r from the axial center of the rod is given by

$$OPD(r) = \frac{\mathrm{d}n}{\mathrm{d}T}\int_0^L (T(r,z) - T_c)\mathrm{d}z + \sum_{i,j=1}^{3} \frac{\partial n}{\partial \varepsilon_{i,j}} \langle \varepsilon_{i,j}(r) + (n_0 - 1)\varepsilon_z(r)\rangle = \langle \frac{\mathrm{d}n}{\mathrm{d}T}[T(r) - T_c] + (n_0 - 1)\varepsilon_z(r) + \sum_{i,j=1}^{3} \frac{\partial n}{\partial \varepsilon_{i,j}} \varepsilon_{i,j}(r)\rangle \tag{2}$$

where L is the length of laser gain medium, $T(r)$ is temperature distribution at an arbitrary radius r from the axial center of the rod, n_0 is the refractive index of medium, $\varepsilon_z(r)$ is the change of axial length, and $\varepsilon_{i,j}(r)$ is the thermally induced tensor. From equation (2) we can see that the right side includes three factors that cause the thermal lensing in the laser gain medium, i. e. the first term is of the thermal dissipation, the second term represents the end face effect of rod, and the third is due to the thermally induced birefringence. Assuming that the thermal lens in laser medium is an ideal thin lens, the relation between phase difference $\Delta\Phi_f$ and thermal focal length f_{th} is given by

* E-mail: kloudey@sina.com

$$\Delta\Phi_f = \frac{kr^2}{2f_{th}} \tag{3}$$

where r is the radius of laser rod and $\Delta\Phi_f$ is given by

$$\Delta\Phi_f = k \cdot \Delta OPD \tag{4}$$

where $\Delta OPD = OPD(r) - OPD(0)$; $OPD(r)$ is the OPD at r from the axial and OPD(0) is the OPD on the rod axial. Inserting (4) into (3), we obtain

$$f_{th} = \frac{r^2}{2\Delta OPD} \tag{5}$$

From equation (5) we can see that, for a particular laser, we can obtain its thermal focal length f_{th} after acquire ΔOPD. And in order to measure the ΔOPD, we can use Shack-Hartmann wavefront sensor, which can display peak-valley value, root mean square value and other relative optical parameters at the same time.

Now we will experimentally study Thermal Lensing.

When measuring the thermally induced distortions, the choice of the probe beam is of particular importance. We should choose the probe wavelength to be very close to the laser wavelength, in order to ensure that the measured OPD is as close as possible to the real OPD. Grossard used a probe beam at 1 079 nm when measuring the thermal lensing at 1 064 nm[1]. However, due to the practical impossibility to manufacture dichroic mirrors that are highly reflective and highly transparent for such close wavelengths. Instead one can also set the probe wavelength in the red region of the spectrum, where the sensitivity of the CCD matrix of the Shack-Hartmann sensor is higher. Meanwhile, the probe beam must have weak temporal coherence and relatively high degree of spatial coherence because the Shack-Hartmann sensors are sensitive to coherent crosstalk.

In a typical optical system for measuring thermal lensing in laser rod, the crystal end face and the Shack-Hartamnn microlens array have to be conjugated, so that the magnification can be a constant no matter whatever the phase profile is in the object plane. We consider the two-lens optical system as is represented in Fig. 1. The paraxial transfer matrix from the crystal end face to the microlens array is

$$T = \begin{bmatrix}1 & d_2\\0 & 1\end{bmatrix}\begin{bmatrix}1 & 0\\-1/f_2 & 1\end{bmatrix}\begin{bmatrix}1 & d_{int}\\0 & 1\end{bmatrix}\begin{bmatrix}1 & 0\\-1/f_1 & 1\end{bmatrix}\begin{bmatrix}1 & d_1\\0 & 1\end{bmatrix} = \begin{bmatrix}-\frac{f_2}{f_1} & 0\\ -\frac{1}{f_1}-\frac{1}{f_2}+\frac{d_{int}}{f_1 f_2} & -\frac{f_1}{f_2}\end{bmatrix} \tag{6}$$

If the imaging system is adjusted so that $d_{int} = f_1 + f_2$, the transfer matrix will simply be equal to the well-known matrix of an afocal telescope. And the wavefront at the exit aperture of the rod will be imaged onto the sensor free from diffraction effects due to propagation.

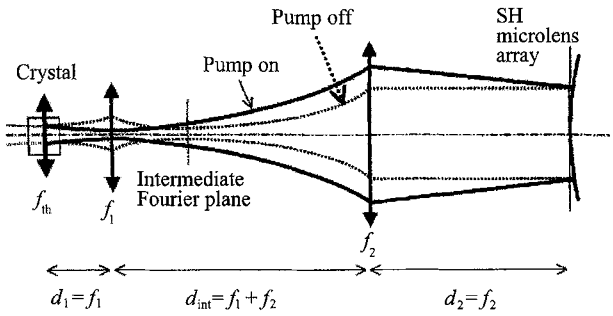


Fig. 1 Afocal imaging system used to image the end face of the crystal onto the SH microlens array

This two-lens afocal system is particularly convenient because the entrance and exit pupils are conjugates, and it has a constant magnification for finite conjugate imagery. This permits to select an image size that fits within the aperture of the sensor but does not depend on the location of the object. In the example system of Fig. 1, the object plane coincides with the end of the laser rod and the image plane coincides with the microlens array. The object plane and image plane are located conveniently at distances d_1 and d_2 from lenses L1 and L2 respectively.

The complete experimental setup is shown in Fig. 2. The crystal is positioned at the waist of the probe beam, whose diameter is adjusted to be equal to the cavity fundamental mode diameter. The pump source in the experiment is a Nd:YAG crystal, its maximal output energy is about 200 mJ. The probe source was a fiber-coupled LD with about 100 microwatts output power. The wavefront imaging system described above consisted of two lenses with focal length of 60 mm and 600 mm respectively, so that the magnification $G=10$. An uncoated glass plate is inserted into the pump beam path in order to reflect a fraction of the probe beam. An interference filter at 670nm is added in front of the Shack-Hartmann microlens array to avoid any parasitic photons at pump or laser wavelengths. The Shack-Hartmann sensor is a HASO series wavefront sensor, which consists of 32 × 32 square microlenses.

The first step in the measurement process, once the optical setup is completed, is to record a reference wavefront. For thermal lensing measurements, the appropriate reference is recorded with the laser rod in a place at room temperature. After the reference is recorded, the wavefront measurements are carried out for varying the levels of pump power, and the results are analyzed.

Fig. 3 shows the wavefront measured with the Nd:YAG crystal. From Fig. 3 we can see that focus appears to be the largest among all the wavefront deviations and after focus removed the RMS spatial deviation on residual wavefront is only about 0. 01 μm. Fig. 4 shows the measured histograms, including third-order spherical aberration, focus and astigmatism. In this figure, Ast. 0° represents 0° astigmatism coefficient, Ast. 45° represents 45° astigmatism coefficient and 3rd order Sph. Ab. represents 3rd order Spherical aberration coefficient. The seventh bar in the histogram indicates the RMS deviation which gives an estimation of the magnitude of the total aberrations. According to these measurement results, the thermal effects can be compensated easily by adjusting the cavity[2]. Fig. 5 shows the beam spots (measured by Spiricon LBA-400 beam profile analyzer) before and after adjusting the laser cavity according to the wavefront measurement results. From the two figures we can see the beam quality of the latter is improved.

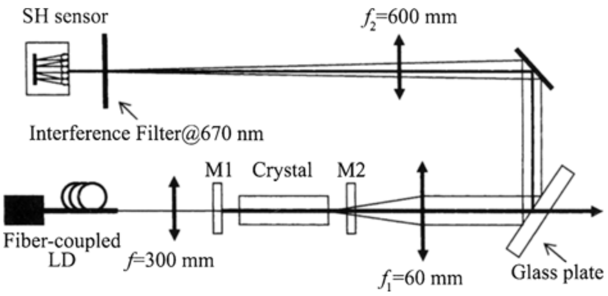
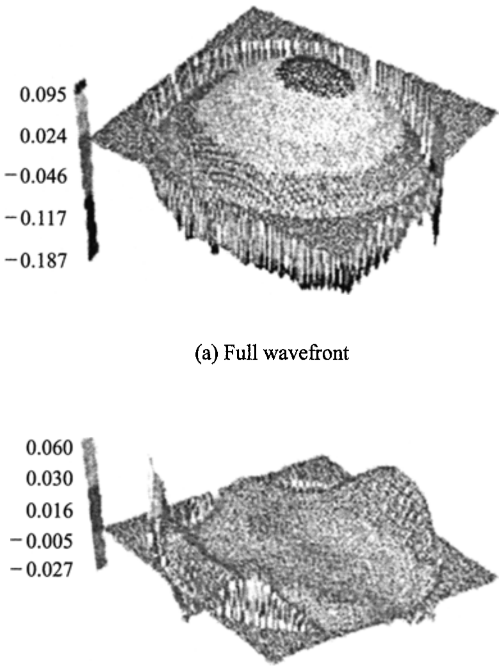


Fig. 2 Experimental setup for measuring the thermal lensing of a Nd:YAG laser



(a) Full wavefront

(b) Focus removed

Fig. 3 Wavefront obtained experimentally with Nd:YAG

Wavefront distortion due to thermal lensing is the key factor that affects the output properties of solid-state lasers. We use the Shack-Hartmann wavefront sensor for the first time to measure and analyze the thermal lensing of Nd:YAG crystal in an experiment successfully. The Shack-Hartmann sensor offers a practical and easy-to-use alternation to the other wavefront analyzers and can

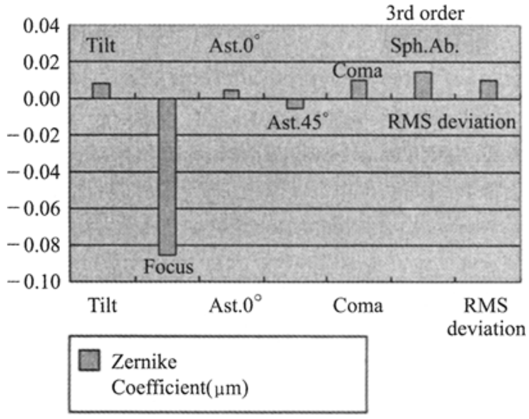
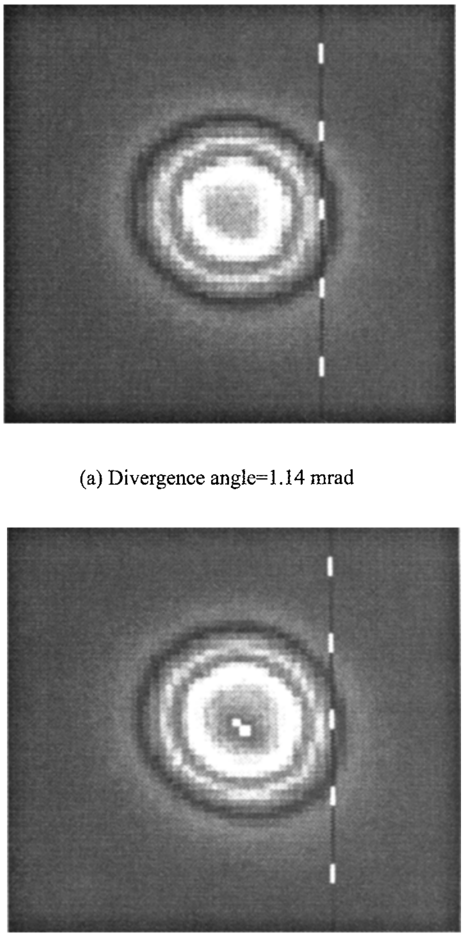


Fig. 4 Zernike coefficients histogram



(a) Divergence angle=1.14 mrad

(b) Divergence angle=1.08 mrad

Fig. 5 Beam spots before and after adjusting cavity

operate under both lasing and nonlasing conditions. The output information can be used to optimize the cavity designs by abnegating the laser rods or cavity optics that do not meet the specifications, and selecting appropriate materials or optics according to the requirements.

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