A simple technique for accurate characterization of thermal lens in solid state lasers

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ABSTRACT

Thermal lensing in diode pumped solid state lasers can seriously affect laser performance and cause beam distortions resulting in degradation of beam quality. Estimating thermal lens is important in designing stable laser cavities with minimum laser mode size fluctuations and high output power. The common techniques used to estimate the thermal lens under lasing condition deploy a probe beam or a wave front sensor. Both these techniques need precise alignment and the laser beam quality factor has to be measured separately for thermal lens calculations. It is well-known that beam quality varies considerably at different pump intensities. We demonstrate a simple technique based on ABCD law for Gaussian beams that is capable of estimating the thermal lens accurately by taking into account the fluctuation of beam quality factor at various pump intensities. The technique is experimentally tested using a diode-pumped Yb:KYW laser at different pump intensities.

1. INTRODUCTION

High power diode-pumped solid state lasers (DPSSL) are a rapidly growing technology that is attractive for various applications in scientific and industrial fields. DPSS lasers are highly efficient, reliable and durable with superior beam quality when compared to flash-lamp pumped lasers. However, power scaling of diode pumped solid state lasers is one of the main issues in designing lasers. End-pumping with high power laser diodes creates thermal problems which in turn limits the power scaling. Thermal lensing affects the performance and stability of the resonator, and it should be well understood and studied before designing of a high power laser. The chosen thermal lensing measurement technique should be suitable for end-pumped geometries such that characterization could be done accurately under lasing action.

In various works, thermal lensing and thermal beam distortions have been measured experimentally by different techniques such as interferometric techniques, wavefront sensing, using a probe beam, or studying cavity stability regions. In the first three methods a second laser is used either as a probe beam or a reference beam. In the wavefront sensing method a sensor is used to measure the wavefront of a reference beam to find the phase distortions due to thermal effects and the focal length of the thermal lens. A second laser adds to the complexity of the measurement system in these methods.

ABCD matrix analysis of a laser output beam can also be used to measure thermal lensing[1],[2]. By calculating the beam radius at the output coupler with added lens element (thermal lensing can be modeled as a thin lens inside the crystal) and comparing the calculated value to the experimentally measured output beam radius, the focal length of the induced thermal lens can be estimated. ABCD matrix analysis can also be applied under nonlasing condition where a probe beam is passed through a pumped laser crystal. By measuring the dimension of the probe beam as it propagates and comparing

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the measured values to the calculated ABCD matrix analysis, the thermal lens can be estimated. It should be noted that the laser beam quality factor M^2 should be taken into account because it greatly affects beam propagation. Unfortunately, to simplify the issue it is quite common to assume a perfect Gaussian beam quality for this kind of measurements. On the other hand, separate measurements of the laser beam quality factor can solve the problem only partially because of the added inherent uncertainty between the two different sets of experiments, i.e. one for the output beam width and the other for the beam quality. To complicate the matter it is also well-known that beam quality varies considerably at different pump intensities.

In this paper, a simple modified technique based on ABCD matrix analysis is presented which allows determination of the thermal lensing effect directly from one measurement of the laser beam width and without the need of a second laser or a reference beam. This technique combines the laser beam quality measurement and thermal lens analysis into a single experiment thus eliminating uncertainties coming from the two separate measurements (i.e. from beam width and beam quality) and from the fluctuation of the beam quality factor at various pump intensities. Initially, the beam quality factor of the output beam is measured. This measurement also gives the beam waist of the focused laser beam. Taking these data into account and modeling thermal lens as a thin lens inside the crystal, the ABCD matrix analysis is used to calculate the beam propagation inside the laser cavity as well as its propagation through the beam quality measurement setup. By comparing the calculated value of the beam waist of the focused laser beam to the experimentally measured one, the focal length of the induced thermal lens can be estimated. In this method the beam quality factor, M^2, is directly deduced from the beam radius measurements while measuring the beam waist of the focused laser beam which improves the simplicity and accuracy of the proposed method.

2. METHODOLOGY

Thermal lens depends directly on the absorbed pump power, and affects the beam quality depending on its strength. The M^2 is a measure of the beam quality of a laser beam and is affected by thermal lensing; therefore, it has to be measured for the different values of laser output power.

In order to measure the M^2 factor a lens is usually placed at a fixed distance from the output coupler, and the spot sizes of the focused beam are measured at different distances from the lens as shown in figure 1. The M^2 factor and the beam waist, $\omega_\circ$, of the laser beam can then be determined by fitting the measured spot sizes to the Gaussian beam propagation equation given by

$$\omega(z) = \omega_0 \left[1 + \left(\frac{M^2 \lambda_0 z}{n \pi \omega_0^2} \right)^2 \right]^{1/2} \quad , \tag{1}$$

where $\lambda_\circ$ is the wavelength of the light and z is the position along the propagation direction of the beam. The thermal lens can be modeled as a thin lens inside the crystal with different focal lengths for different laser output powers. A laser cavity with a variable lens can be simulated using the ABCD matrix roundtrip model to find the focal length at which the beam waist from the model matches the beam waist obtained from the experimental measurement. It is important to note that the M^2 factor used in the ABCD modeling must have the same value that was measured experimentally at each output power level. In this way the simulated laser cavity will be analogous to the experimental laser cavity, and the thermal lensing effect can be studied very accurately.

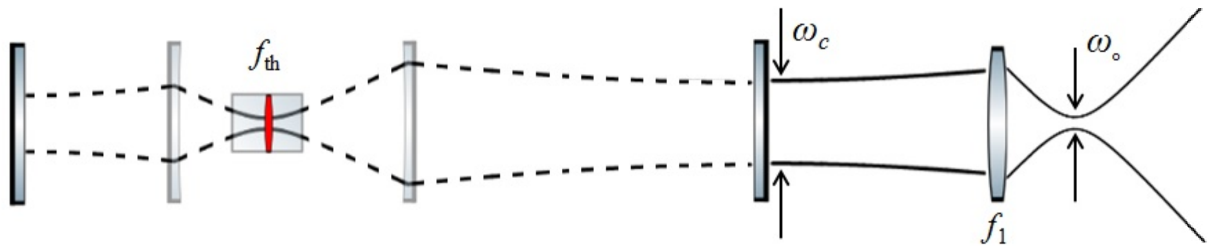

Figure 1. Beam propagation inside the cavity (dashed line) containing the thermal lens f_{th} and the output beam (solid line). The beam waist at output coupler is ω_c and the beam waist of the focused laser beam is $\omega_\circ$ with the lens f_1 placed outside the cavity.

Other methods that have employed ABCD matrix analysis, measure thermal lens focal length by measuring spot sizes of the laser beam at different distances from the output coupler without the use of the focusing lens element [1],[2]. This requires additional set of measurements for obtaining beam quality factor at each power level; quite often, beam quality measurement is either disregarded or the beam quality factor is assumed to be $M^2 = 1$. Knowing beam quality at each power level is essential factor in ABCD matrix analysis method, and ignoring it can result in considerable error. In our proposed method the thermal lens is determined directly from beam quality measurement at each power level in just one step.

3. EXPERIMENTAL SETUP

The schematic diagram of experimental setup of a diode pumped continuous wave laser is presented in figure 2. The output from the fiber-coupled laser diode was first collimated with a f = 30 mm collimator lens and, subsequently, focused onto the laser crystal by a f = 100 mm focusing lens through a dichroic mirror M_1. The resonator consisted of an HR (highly reflecting) flat mirror M_3 and spherical mirrors M_2 (radius r = 500 mm) and M_3 (radius r = 750 mm). The transmittance of the output coupler (OC) at the laser wavelength was T = 8%. The output beam was focused by a lens with f = 150 mm and the beam radii were measured for several points along the propagation direction using the beam profiler. The beam radii at each position were measured ten times and averaged to reduce the measurement errors.

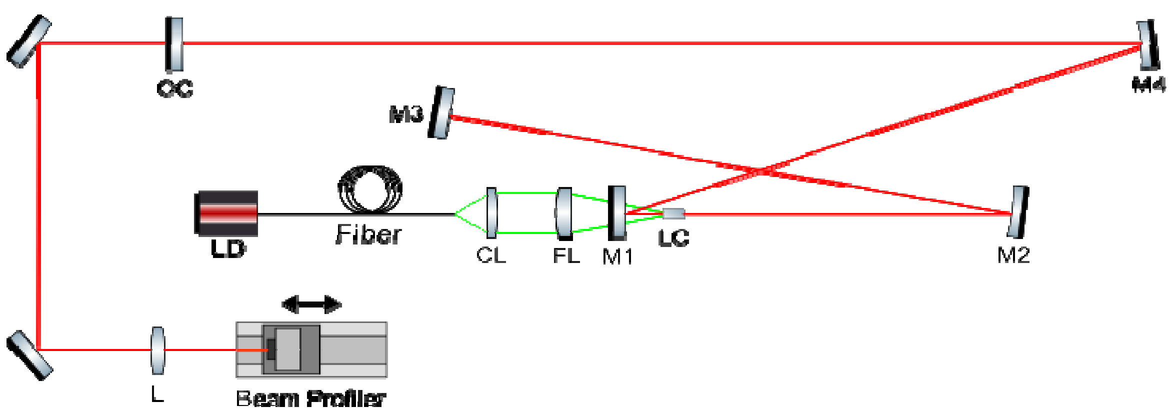

Figure 2. Experimental setup of the thermal lensing measurement system

A 2 mm long (N_g-cut) 5 at. % Yb^{+3}-doped KYW crystal was used as the active medium. According to simulations, the cavity beam waist radius inside the crystal was about 175 µm. The 1:3.3 imaging system used focused the pump beam to a spot size of about 180 µm, which is very close to the cavity mode. Indium foil was used to wrap the laser crystal to improve the thermal conduction between the laser crystal and the aluminum heat sink. The top and the bottom surfaces of the crystal were connected to the heat sink and cooled by running water at 16 ˚C at a flow rate of 0.7 liters/minute. The optical surfaces of the crystal were antireflection coated for both the pump (λ = 975-985 nm) and output (λ = 1010-1070 nm) wavelengths. A calibrated power meter was used to monitor the average output power.

4. RESULTS AND DISCUSSION

Incident pump power applied was limited to 20 W to avoid any damage to the crystal. With an 8% output coupler, a threshold of 7.5 W and a slope efficiency of 56% were measured with respect to the absorbed pump power. With respect to the incident pump power, the laser threshold was at 12.9 W with slope efficiency of 51% as shown in figure 3. Absorption in the crystal under nonlasing condition is about 61% for incident pump power of 13.9 W and corresponding output power of 0.5 W. The absorption in the crystal increases to 70% with incident pump power of 19.8 W. The maximum continuous wave output power reached was 3.5 W at the fundamental TEM_{00} mode.

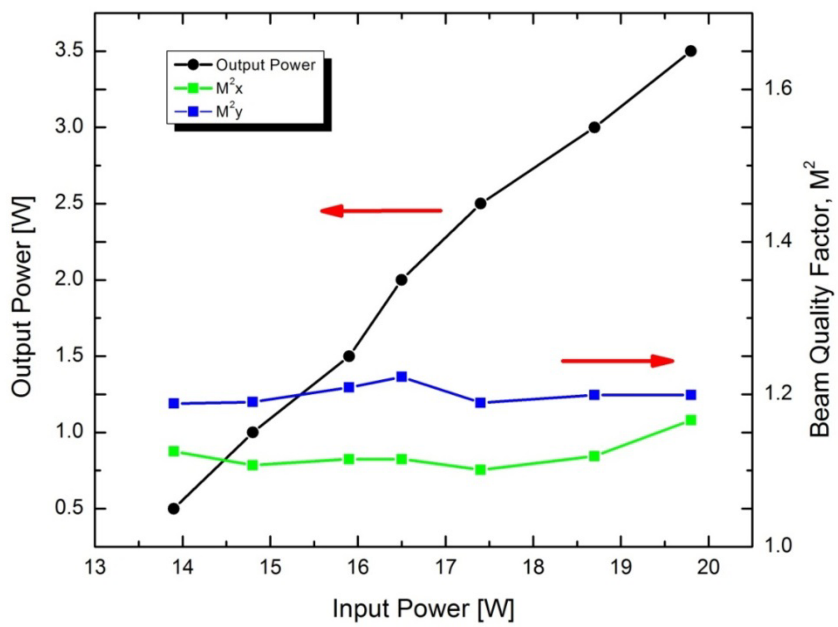

Figure 3. Measured output power and M^2 values for horizontal and vertical directions.

The beam quality of a laser was first measured for different output powers. The beam was focused by a lens with f = 150 mm and the beam radii were measured for several points along the propagation direction using the beam profiler. The beam radii at each position was measured ten times and averaged to reduce the measurement errors. The beam waist $\omega_{\circ}$ and the beam quality factor M^2 were found by fitting equation (1) to the measured data. As an example, the data and fitting curves for output powers of 1 W and 3 W are shown in figure 4. The M_x^2 represents beam quality in horizontal plane and the M_y^2 represents the beam quality in vertical plane. The output power with respect to the incident pump power, along with corresponding M^2 values are shown in figure 3. Near diffraction limited beam quality (M^2<1.2) was obtained throughout the experiment.

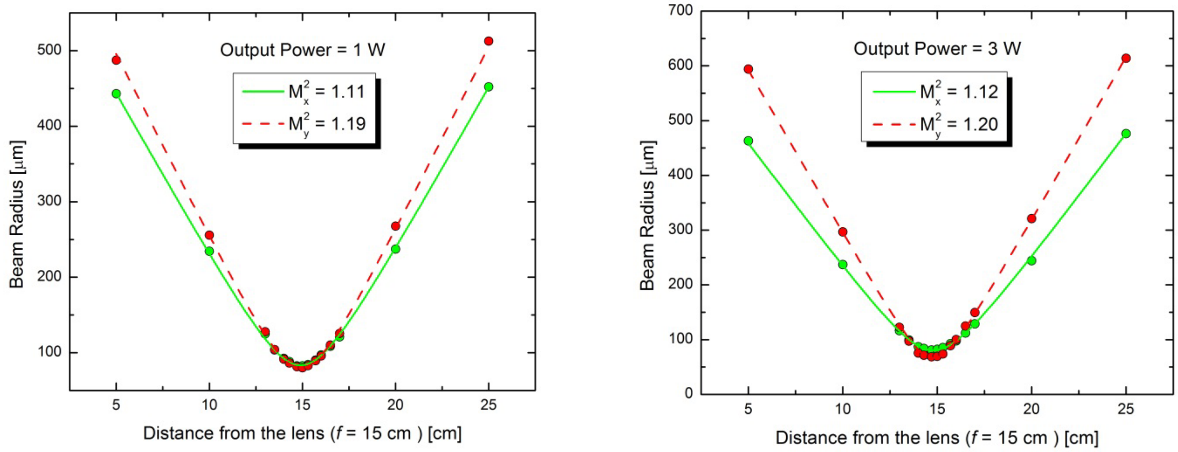

Figure 4. Laser output beam quality M^2 at 1 W and 3 W output power.

Variation of focusing power of the thermally induced lens was estimated by using the ABCD matrix analysis (with the help of LASCAD software package) and is shown in figure 5. It can be seen that the thermal lens is much stronger in the N_p direction compared to the N_m direction. This can be explained by cooling geometry, lower thermal conductivity and higher thermo-optic coefficient dn/dT of the Yb:KYW in the N_p direction.

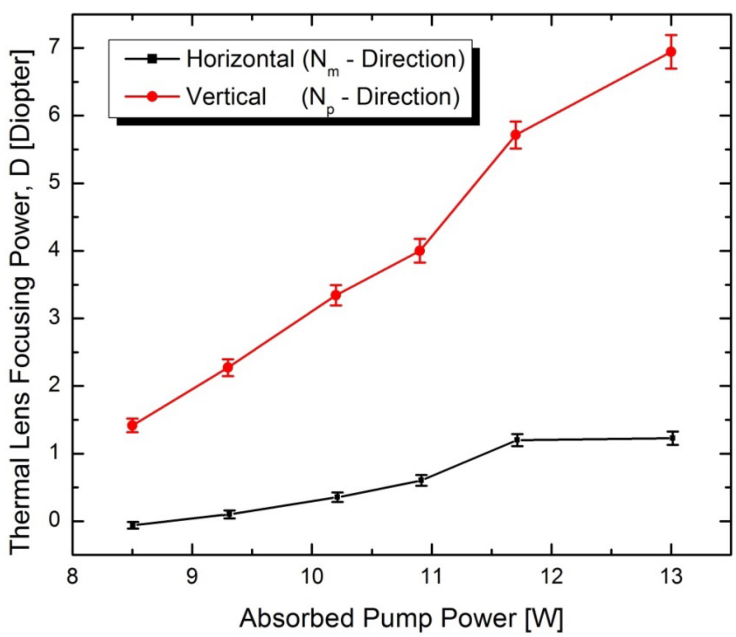

Figure 5. Thermal lens focusing power for vertical and horizontal directions.

In order to demonstrate of importance of beam quality measurement on the result of thermal lensing calculation, we also performed the ABCD matrix analysis with the assumed perfect beam quality ($M^2 = 1$). Figure 6 shows the results of the thermal lensing measurement for both cases.

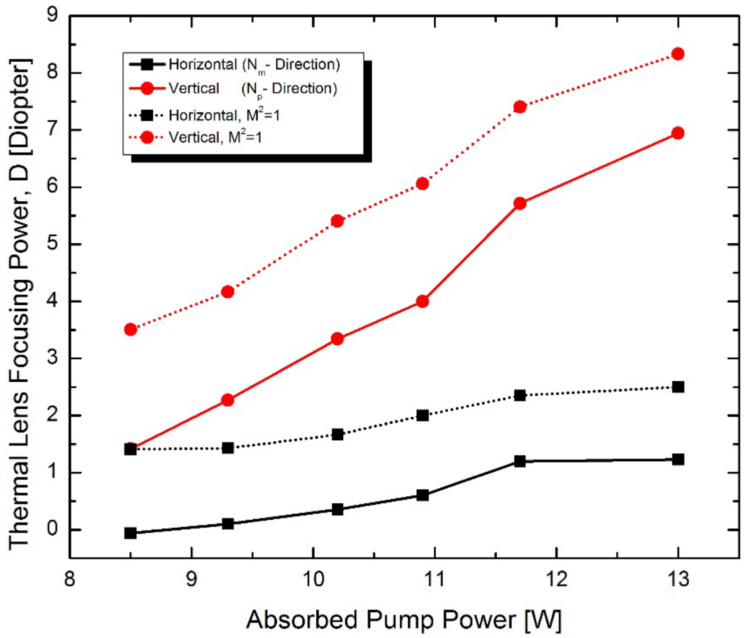

Figure 6. Thermal lensing focusing power for the actual (solid lines) and perfect (dashed lines) output beams.

As it can be seen form figure 6, assuming the perfect beam quality can result in big error in thermal lensing calculation and should be avoided. The error can be as big as 1.5 D in our calculated thermal lensing results. It should be noted that in our experiment the beam quality was below 1.2 for all power levels. Having a larger beam quality factor can result in even bigger error.

In order to compare our proposed method to a standard [1],[2] method based and ABCD matrix analysis we also measured the output beam characteristics with respect to the distance from the output coupler at each power level. We then used the output beam profile to fit the data to the Gaussian propagation equation and find the beam width at the output coupler. By having the beam width at the output coupler and the output beam profile we can back propagate the beam to find the thermal lens. The process of fitting in this method is problematic since the beam waist at the output coupler cannot be measured directly due to the mechanical constraints and should be estimated from the fitting procedure. However in our proposed method, the beam waist of the focused laser beam can be measured accurately which contributes to the accuracy of our method. In addition in our proposed method the measurements can be performed around the beam waist in both directions along the propagation axis. While in the standard method the beam profile is measured only after the output coupler, i.e. the measurement can be performed only in the propagation direction of the beam. The extra sampling points around the beam waist will result in better fitting accuracy and more accurate thermal lensing measurements. In addition in conventional method where both the beam quality factor and the output beam profile is measured at each power level, any time delay between these two sets of measurements can result in error due to laser output beam variation with time. However in out technique, the measurement is done in one step. An example of fitting procedure in the proposed method and the conventional method is shown in figure 7.

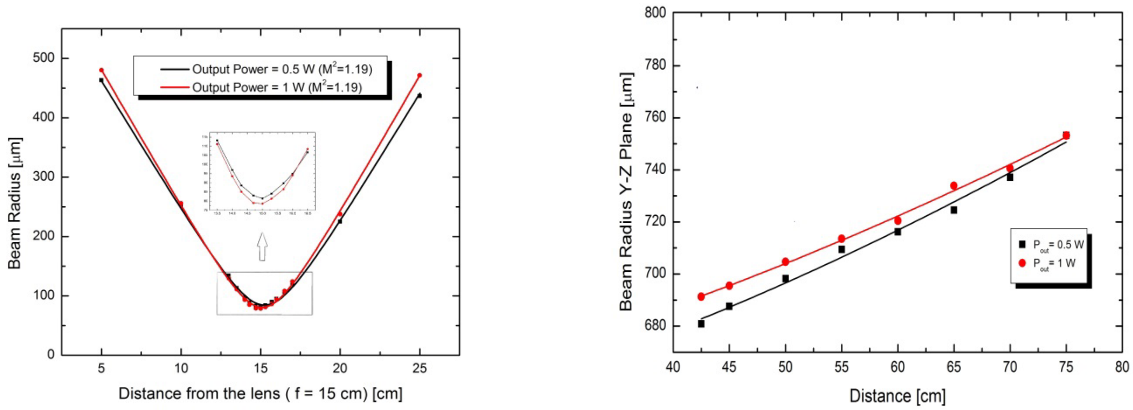

Figure 7. Comparison of fitting procedure in (a) proposed method and (b) conventional method

It should be noted that, in the conventional method in addition to the beam profile measurement after the output coupler, the beam quality should also be measured at each power level using the setup similar to the one shown in figure 2 which adds to the complexity of the system and uncertainty between the beam quality and beam waist measurements at the corresponding output power level.

5. CONCLUSIONS

In this paper an experimental method is proposed to measure the thermal lensing effect. The proposed method is based on the ABCD matrix analysis with reduced complexity and increased accuracy. It was shown that in our proposed method, the thermal lensing effect can be measured and calculated directly from the beam quality factor measurement at each power level. Results of the experiments were used to verify the simplicity and accuracy of our proposed method in comparison with standard technique used in the literature.

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REFERENCES

[1] Loiko, P. A., Yumashev, K. Y., Kuleshov, N. V., Savitski, V. G., Calvez, S., Burns, D. and Pavlyuk, A. A., "Thermal lens study in diode pumped Ng- and Np-cut Nd:KGd(WO_4)$_2$ laser crystals," Optics Express 17(26), 23536-23543, (2009).

[2] Hoos, F., Li, S., Meyrath, T. p., Braun, B. and Giessen, H., "Thermal lensing in an end-pumped Yb:KGW slab laser with high powersingle emitter diodes," Optics Express 16(9), 6041-6049 (2008).