In situ 3-D temperature mapping of high average power cryogenic laser amplifiers

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Abstract: Heat generation is a key obstacle to scaling high energy solid-state lasers to the multi-kilowatt average powers required for several key applications. We demonstrate an accurate, in situ, noninvasive optical technique to that makes three-dimensional (3-D) temperature maps within cryogenic amplifiers operating at high average power. The temperature is determined by analyzing the fluorescence spectra with a neural network function. The accuracy of the technique relies on a calibration that does not depend on simulations. Results are presented for a cryogenic Yb:YAG active mirror laser amplifier operating at different pump conditions. The technique is applicable to other solid-state lasers materials.

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References and links


1. Introduction

Progress in a variety of important laser applications including compact particle accelerators [1], coherent and incoherent sources of ultra-short wavelength radiation [2–5], laser processing of materials [6], extreme ultraviolet lithography [7], and the future prospect of practical inertial confinement fusion power generation [8] generates a demand for lasers with simultaneously high pulse energy and high average power. Despite significant progress in high power pulsed solid-state laser technology [9–14], the development of high energy, multi-kW average power lasers has been elusive. Recently, the first demonstrations of lasers producing > 1 Joule pulses with kilowatt-level average power have been realized by taking advantage of the improved thermal parameters [15,16] and the gain characteristics [17–19] of diode-pumped Yb:YAG at cryogenic temperature. These include the recent demonstration of a chirped pulse amplification (CPA) laser based on cryogenic Yb:YAG active mirror amplifiers that produced 1.5 J stretched pulses at 0.5 kHz repetition rate (0.75 kW average power) which were subsequently compressed to ~5 ps duration [20], and the generation of 100 J pulses at 10 Hz repetition rate with nanosecond pulse duration using cryogenic gas-cooled Yb:YAG amplifiers [21].

Heat generation in these solid-state laser amplifiers is a key obstacle to scaling high-energy solid-state lasers to higher average power. Thermal gradients within the amplifier active material lead to the power-limiting effects of thermal lensing, depolarization, and, ultimately, catastrophic stress fracture of the material. The ability to make spatially resolved measurements of the temperature within the cryogenically cooled gain material is very useful for understanding heat generation and distribution processes, and benchmarking simulations of heat flow to aid in the design of optimized geometries and superior cooling techniques. To our knowledge, no two-dimensional (2-D) or 3-D technique has been developed to measure the temperature of laser materials at cryogenic temperature during operation. A few methods for determining the temperature of solid-state laser materials have been previously demonstrated. Wavefront and depolarization measurements have been made to determine thermal effects present in solid-state lasers [22,23]. However, these methods do not directly measure the temperature and require assumptions to be made about the thermo-optic coefficient and expansion coefficient of the material, as well as being sensitive to a number of parameters. More direct methods to determine the operating temperature of laser gain media have been demonstrated for lasers operating near room temperature, including using the luminescence (fluorescence) of the dopant ion [24–26] and the use of infrared thermal camera to acquire thermal maps [27]. However, thermal cameras cannot be used at cryogenic temperature or through most window materials. The luminescence of transition metals and rare earth elements, including Yb$^{3+}$ [28], has been extensively studied for the development of temperature sensors for a broad range of applications, as discussed in several review papers [29–31]. Most of these studies focused on temperatures near or above room temperature, but some include work on thermographic phosphors in a cryogenic environment. The latter include the use of the luminescence from Mg$_2$FeGeO$_6$:Mn, a laser-induced fluorescence phosphor, for 2-D temperature measurements in the 110-300 K range [32].

A technique to determine the temperature of a cryogenic Yb:YAG laser was reported that uses the intensity ratio of two points in the Yb:YAG fluorescence spectrum [33]. This method was demonstrated in a continuous wave (CW) diode-pumped laser. However, as discussed below, we have observed that this intensity ratio is insufficient to accurately determine the temperature of a pulsed Yb:YAG cryo-cooled amplifier with strong gain where stimulated emission significantly alters the fluorescence spectrum. In this letter, we present a technique...
that overcomes the limitations of this optical technique using the entire information in a selected range of the fluorescence spectrum to accurately measure the temperature of Yb-doped gain media operating at cryogenic temperature. We also show that this technique can be employed to generate 2-D and 3-D maps of the temperature distribution in cryo-cooled laser amplifiers based on spatially resolved measurements of the emission fluorescence. This technique can be implemented in situ, under high power laser operating conditions. We demonstrate the utility of this new technique by recording thermal maps of a cryo-cooled Yb:YAG active mirror amplifier under different pumping intensities and heat removal conditions. While an active mirror Yb:YAG amplifier was used for the measurements presented here, the technique is general and can be used on other cryogenic Yb:YAG oscillator or amplifier geometries and is expected to also be useful on other solid-state laser materials as well.

2. Laser amplifier thermal measurements at cryogenic temperatures

The fluorescence spectrum emitted by Yb:YAG is dependent on temperature. Figure 1 shows emission spectra from a 2 mm thick 3 at. % Yb:YAG crystal at different temperatures between 40 K and 280 K. The temperature was varied with the aid of a closed-cycle He cryorefrigerator. The temperature was determined with a silicon diode attached to the heat spreading plate to which the crystal is soldered. To ensure that this temperature is the same as that of the crystal, individual pump pulses were used to obtain the spectra, eliminating any local heating that could create a temperature difference with respect to the heat sink where the temperature sensor is located. As can be seen from these spectra for the 1015 nm-1029 nm wavelength region, as the temperature of the crystal is increased, the peaks at 1022 nm and 1025 nm decrease in amplitude, broaden, and shift to longer wavelength. In [33], the ratio of the fluorescence intensities at 1022 nm and 1027 nm was used to estimate the local temperature of the active region. However, as can be seen from the normalized spectra in Fig. 1(b) and 1(c), in this high gain medium the spectra are also dependent on the pump power. This is indicates that it is affected by stimulated emission. This is more clearly demonstrated in the plot of Fig. 1(d), which shows this intensity ratio as a function of the crystal temperature for pump pulses of three different energies. These measurements show that the intensity ratio method is influenced by gain effects, leading to discrepancies between the inferred temperature and the measured temperature as large as 20 K in the temperature range from 60 K to 140 K. Therefore, the method previously reported cannot be used to accurately measure temperature profiles in high gain cryogenically cooled amplifiers.

In the following sections, we describe a variation of the fluorescence measurement approach that allows for accurate measurements in the range of temperatures of interest for high power cryo-cooled amplifiers with a resolution of less than 1 K. Instead of using the ratio of the fluorescence intensity at two wavelengths, we make use of the entire fluorescence spectrum in a selected wavelength region as input for a neural network based fitting function [34–36].
3. Temperature mapping technique

The experimental setups used to measure the 2-D and 3-D temperature distribution in a cryogenically-cooled Yb:YAG active mirror amplifier are shown in Figs. 2 and 3, respectively. The active mirror was soldered to a copper heat sink that operates in vacuum cooled by a closed-cycle He cryo-refrigerator. The temperature of the heat sink was monitored by a calibrated Si diode detector. A heater was used to tune the temperature of the gain material for calibration.

3.1 2-D Temperature mapping technique

Figure 2 shows the experimental setup for 2-D temperature mapping. To determine the temperature in the active area (gain region), it is sufficient to collect the fluorescence generated by the 940 nm pump laser. However, since it is also of interest to determine the temperature in the region surrounding the active area where there is no fluorescence, a \( \lambda = 940 \text{ nm} \) fiber coupled laser diode module is used to produce a small diameter “localized pump pulse” that can be displaced to excite the fluorescence at any crystal location of interest. A localized pump pulse duration of 1.5 ms was used to generate fluorescence at a very low repetition rate (single shot) to avoid influencing the thermal profile. These localized pump pulses are delivered through a 600 \( \mu \text{m} \) core diameter fiber which is imaged onto the laser crystal using a single achromatic lens. The magnification of this image system is 5x. The localized pump fiber is mounted in close proximity to a second fiber that collects the fluorescence signal. This 50 \( \mu \text{m} \) core diameter, NA = 0.22 signal fiber delivers the
fluorescence to a 0.66 m focal length Czerny-Turner spectrometer. The end face of the signal fiber is placed at the crystal’s image plane. The tips of both fibers are mounted on an XYZ stage. The depth-of-field of the image system is ~6 mm and the transverse resolution was measured to be better than 0.5 mm. 2-D maps of the temperature in the active mirror Yb:YAG amplifier were obtained by raster scanning the tip of the localized pump and signal fibers through the plane of the fluorescence. A cooled scientific CMOS camera mounted on the spectrometer imaged the fluorescence spectra. The spectral window used for these measurements was 1015 nm-1029 nm with a resolution of about 0.03 nm. Note that this spectral region does not include the dominant emission peak of Yb:YAG at $\lambda = 1030$ nm, but includes the bright emission occurring between 1020 nm and 1029 nm. The exposure time of the camera was selected to be 1 ms, and the acquisition time window was triggered at the beginning of the localized pump pulse. As shown below, this technique allows measurements of the transverse profile of the axial-averaged temperature distribution.

For many cases, this 2-D temperature distribution is sufficient to understand thermal problems and is helpful to design efficient cooling techniques and monitor their performance. To obtain full, 3-D temperature distributions we constructed an alternative system based on the widely used confocal laser scanning microscopy (CLSM) technique [40], described below.

### 3.2 3-D temperature mapping technique

To obtain full, 3-D temperature maps with depth resolution, we constructed the confocal microscope setup shown in Fig. 3. In this setup, Lens 2, the pump fiber and the signal fiber in Fig. 2 are replaced by the confocal setup, which consists of two $f = 30$ mm lenses (L2), a 1000 nm cut-off wavelength long-pass filter, and a long working distance 10x microscope objective. A single mode fiber and a single emitter laser used as the localize pump perform a similar function to the pinhole used in most CLSM. The localized pump is a 50 mW single emitter 940 nm single mode laser diode that is collimated by lens L2. The collimated laser beam is reflected by the dichroic mirror and focused by the 10x objective into the crystal to trigger the fluorescence. The triggered fluorescence is collected by the 10x objective, passes thought the dichroic mirror and finally is focused by the second lens L2 into a 6 $\mu$m core diameter single mode fiber, which delivers it into the spectrometer. The confocal microscope achieves a depth resolution of ~100 $\mu$m defined by the distance over which the intensity of
the fluorescence changes from 10% to 90% when the translation stage is scanned through the front surface of the crystal. The transverse resolution was measured to be better than 0.2 mm. An XYZ stage was employed to move the entire confocal setup to achieve the 3-D temperature measurements. The spectrometer signal was collected by the cooled scientific camera mounted in the image plane of the spectrometer, selecting an exposure time of 0.1 s. In the pumping area, the fluorescence resulting from the pump laser is subtracted so that only the fluorescence from the confocal setup is used in the analysis.

![Conceptual diagram of the experimental setup for 3-D temperature mapping in solid-state laser amplifiers operating at cryogenic temperatures. L1 is an f = 25 mm achromatic lens, L2 is an f = 30 mm achromatic lens. DM is dichroic mirror.](image)

**3.3 Neural network based fitting function**

To achieve accurate local temperature measurements with high resolution over a broad range of pump powers and temperatures the entire fluorescence spectrum from 1015 nm to 1029 nm was used as the input to a neural network based fitting function [34–36]. The neural network used here is a fitting tool of the MATLAB Neural Network Toolbox. This method is widely used in variety of areas including spectroscopy [37–39]. The fitting function is a two-layer feed-forward neural network with sigmoid hidden neurons and linear output neurons. The network can fit arbitrary, multi-dimensional mapping problems well, given consistent data and enough neurons in its hidden layer [34]. To build the fitting algorithm, we recorded fluorescence spectra at known temperatures ranging from 50 K to 140 K with an interval of 5 K. At each temperature, spectra were recorded for 24 different localized pump pulse energies. In both the 2-D and 3-D measurements, the localized pump pulse is limited to very low energy and low average power which does not contribute to any significant heating of the material. The characteristics of the local pump pulses were kept the same during both the training of the neural network and the measurements presented below. These spectra recorded at known temperatures were used to train a 10-hidden-neuron fitting function [39]. The Levenberg-Marquardt backpropagation algorithm [39] was selected to train the network. 70% of the data was chosen randomly to train the network, 15% of the data was used as the validation sample, and the rest of the data was used for testing the performance of the network [34]. The acquisition and fitting of all the calibration spectra can be done in less than one hour. The temperature predicted by the fitting function closely matches the temperature measured by the sensor in the heat spreading plate when negligible power impinged on the crystal. Using a test input of spectra recorded, but not used in the fitting algorithm, we obtained an RMS deviation of 0.24 K from the temperature measured by the temperature sensor. The results of this fitting function are shown in Fig. 4. These measurements, obtained
using a broad spread of pump energies and gain profiles, demonstrate the accuracy of this method for measuring the temperature of the Yb-doped laser media at cryogenic temperatures under varied pumping and energy extraction conditions.

Fig. 4. Results of the calibration of the fitting function with different pump energies from 50 K to 140 K. The horizontal axis is the temperature measured by the semiconductor sensor in the heat sink and the vertical axis shows the temperature deduced by fitting the measured spectra.

4. Results and discussion

Below we discuss the 2-D and 3-D temperature distributions obtained using this technique for different pumping intensities and heat removal conditions. The measurements presented here were made on a cryogenic Yb:YAG active mirror multi-pass amplifier capable of producing 100 mJ-level pulses at 100 Hz repetition rate that is similar to that presented in [41]. The laser amplifier consists of a 2 mm thick, 3 at. % Yb:YAG active mirror pumped with up to 400 W peak power, 1.5 ms duration pump pulses in a 4 mm spot produced by a fiber-coupled laser diode module. Heat removal is accomplished using a closed-cycle He cryo-refrigerator.

4.1. 2-D Temperature maps

Figure 5 shows two different measured temperature maps corresponding to two different pump powers. These temperature maps were acquired by raster scanning the localized pump and the signal fibers over an area of 12 mm x 15 mm on the plane of the Yb:YAG active mirror with a step size 0.5 mm at a rate of ~1 pixel per second. The pulse from the localized pump was delayed with respect to the main pump pulse by 2 ms to avoid a temporal overlap of the fluorescence signals. The peak temperatures measured for the 113 W and 141 W pump power cases are 113 K and 138 K, respectively. The minimum-recorded temperatures outside the pump region are 95 K and 116 K, respectively. It should be noticed that as the fluorescence is collected from the entire thickness of the active mirror, the temperatures correspond to average values along the locally irradiated volume. These values, averaged along the crystal length, are useful for estimating thermal focusing and can be directly compared with simulations. As can be seen from these maps, the temperature profiles are convex and symmetric, as expected for the cooling geometry used in this experiment.
Fig. 5. 2-D Temperature maps measured for different average pump powers. (a) Temperature maps for 113 W and 141 W average pump powers plotted using the same temperature scale; (b) 2-D temperature map for the 113 W pump power case. The temperature color scale ranges from 95 K to 113 K; (c) 2-D temperature map for the 141 W pump power case. The temperature color scale ranges from 116 K to 138 K.

Fig. 6. One-dimensional cuts of the 2-D temperature maps obtained for average pump powers ranging from 56 W to 141 W.

Figure 6 shows one-dimensional cuts of the temperature profiles corresponding to different average pump powers. The pump pulse energy and duration are kept constant, while
the repetition rate was adjusted from 100 Hz to 250 Hz. It can be seen that, as the pump power is increased, the temperature difference between the axial and periphery of the pump spot increases due to a larger radial-cooling component. The increase in the “base” temperature apparent in these plots is mostly due to the increase of the heat sink temperature as the thermal load is increased. While the local heat generation due to the thermal defect of Yb:YAG within the active region is limited to ~15 W, since the stored energy is not extracted by a laser seed, it results a large amount of the spontaneous emission that is absorbed by the heat sink and contributes to the total thermal load.

The temperature is also strongly influenced by the quality of the thermal contact between the Yb:YAG active mirror and the heat sink. Figure 7 shows the results for the same (56 W) pump power for two different solder interface conditions. Figure 7(b) shows the temperature profile obtained with a poor thermal interface. Figure 7(c) shows that obtained with a significantly better thermal interface. The difference is striking, and emphasizes the well-known importance of a good thermal interface in active mirror lasers. These results illustrate the utility of this technique for evaluating the thermal performance of high power cryogenic Yb-doped lasers. For situations where the temperature distribution over the entire amplifier medium volume is required, we have developed the high resolution confocal setup shown in Fig. 3.

![Fig. 7. 2-D temperature mapping comparison of the different heat transfer conditions at same pump condition. (b) Poor heat transfer interface. (c) Good heat transfer interface. Different temperature scales are used for (b) and (c).](image)

4.2. 3-D Temperature mapping

Full 3-D temperature maps were acquired using the confocal microscope setup shown in Fig. 3. The 3-D temperature maps were obtained by scanning the entire confocal setup over the
desired volume with a step size corresponding to 0.36 mm in depth and 0.64 mm transversely. The axial position $Z = 2.0$ mm is defined to coincide with the front surface of the crystal. A volume of $6.4$ mm x $3.2$ mm x $1.8$ mm was scanned. With motorized stages such measurement can be acquired in less than 10 minutes. Figure 8 shows the measured 3-D temperature distribution for two different pump powers. Figure 8(a) and 8(b) show the measured temperature distribution on the crystal surface and the temperature distribution vs. depth from the front surface (AR coated surface) to the back surface (HR coated surface) of the active mirror. At the center of the pump area, the temperature difference between $Z = 0.1$ mm and $Z = 1.9$ mm was measured to be ~6 K for 113 W average pump power and ~3 K for 56 W. Figure 8(c) and 8(d) show the temperature profile vs. depth measured at the center of pump spot, for these pump powers, respectively.

Fig. 8. 3-D Temperature mapping comparison of the different pump powers. $Z = 2.0$ mm corresponds to the front surface of the crystal. (a) 3-D temperature profile of 56 W average pump power. (b) 3-D temperature profile obtained with 113 W average pump power. (c) and (d) Plots of the temperature distributions at the center of pump spots for these two average pump powers. The red dashed lines represent the temperature values from 2-D temperature mapping system, and the blue dashed lines represent the average temperature along $Z$ from the 3-D scan.

The dashed lines in Fig. 8(c) and 8(d) show that the average temperature along $Z$ in the 3-D scans is found to be in good agreement with the corresponding measured temperatures in the 2-D scans of Fig. 5 at the center of the pump spot. Additionally, when the mathematical sum of the spectra corresponding to different known temperatures are input to the fitting function, the temperature that is obtained is the average temperature. This is evidence that the temperature measured in the 2-D scan is an average of the temperature along orthogonal direction, making the 2-D scans useful on their own in many cases.
4.3. Insight from comparison with simulations

In principle, the temperature maps can be obtained from thermal model simulations. However, this is hindered by several unknowns. First, are the crystal thermal properties of Yb:YAG that have not been measured over the entire range of interest. Another uncertainty is created by the role of spontaneous emission and amplified spontaneous emission (ASE) and their absorption, which can alter the pump energy distribution. More importantly, as illustrated in section 4.1 [Fig. 7(a)], is the unknown value of the thermal impedance of the interface between the crystal and the heat sink, which can significantly alter the results. Consequently, the temperature maps cannot be obtained from a simple heat transfer model. This emphasizes the value of being able to directly measure the temperature distribution with a method which does not rely on simulations.

Nevertheless, as illustrated in the example below, comparison of the measured values with thermal model simulations can provide additional information on the gain medium. Figure 9(a) shows a temperature map resulting from a 3-D finite element simulation of the heat distribution for the case in which the temperatures are in the vicinity to 113 K for which the gain medium thermal parameters are available from the literature without the need for extrapolation [conditions corresponding to Fig. 8(b) and 8(d)]. In this model, the only heat source is assumed to be the thermal defect portion of the pump light. Temperature dependent thermal conductivity values were derived from [16]. The results were obtained neglecting the effects of spontaneous emission and ASE, and leaving as adjustable parameter the thermal impedance to heat transfer through the soldered interface between the crystal and the heat sink. Figure 9(b) shows an acceptable agreement between the simulated and measured axial temperature distributions is obtained when the interface thermal conductance is chosen to be 8600 W m\(^{-2}\) K\(^{-1}\). Best fits for other pump powers differ in quality, but all of them require similar values of the interface thermal conductance. This example illustrates the temperature mapping technique can be combined with simulations to obtain information about the gain medium beyond the temperature distribution. In case of a gain medium with better known parameters the measurement technique can serve to validate models.

5. Conclusions

In conclusion, we have developed a new, in situ method to map the 3-D temperature distribution in the gain medium of high average power cryogenic Yb lasers. The usefulness of this technique was demonstrated measuring the temperature distribution in a 100 mJ, 100 Hz Yb:YAG active mirror amplifier under different pump powers and cooling interface.
conditions. 2-D transverse temperature maps are shown to give temperature values that correspond to the average temperature in depth. The technique should also be applicable to other solid-state lasers materials. This technique, combined with thermal modeling, can be expected to aid in the design of high average power solid-state lasers.

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