Combined laser heating and tandem acousto-optical filter for two-dimensional temperature distribution on the surface of the heated microobject

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Abstract. Recently it has been shown that it is possible to measure the two-dimensional distribution of the surface temperature of microscopic specimens. The main component of the system is a tandem imaging acousto-optical tunable filter synchronized with a video camera. In this report, we demonstrate that combining the laser heating system with a tandem imaging acousto-optical tunable filter allows measurement of the temperature distribution under laser heating of the platinum plates as well as a visualization of the infrared laser beam, that is widely used for laser heating in diamond anvil cells.

1. Introduction

The laser-heating (LH) in a diamond-anvil cell (DAC) is the only experimental tool able to create extreme static pressures ($P > 100$ GPa) and temperatures ($T > 3000$ K) and is widely used in high-pressure research on materials science and geophysics [1]. A conventional LH system consists of one or two diode pumped fiber lasers with an adjustable total power up to 200 W at 1064 nm wavelength. Recently the two-dimensional (2-D) distribution of the surface temperature of a tungsten filament heated by a constant current from a stabilized current source was measured using a tandem acousto-optical tunable filter (TAOTF) [2]. A set of spectroscopic images (up to a few hundreds) is taken by the TAOTF imaging system in order to fit the measured spectral curves in each pixel to the Planck radiation function and determine the temperature of the sample using the gray body approximation. It is experimentally shown that this technique provides aberration-free spectral imaging suitable for precise multispectral imaging radiometry. In this paper, we demonstrate that combining the LH system with TAOTF allows measurement...
of the temperature distribution under laser heating of a platinum plate. The heating of plates requires knowledge of the precise focus position of the ir laser beam because it is easy to melt the material down and make a hole in the plate. We also provide a method to visualize the ir laser beam, invisible to the human eye, that is widely used for LH in DAC. This will allow us to apply numerical method describing the heat propagation in a media for the determination of the thermal parameters of solids and liquids under high pressure and temperature (HPHT). Visualization of the ir laser beam found to be extremely helpful for aligning invisible ir laser.

2. Method
A multi-functional in-situ measurement system under high pressure equipped with a TAOTF, and LH system in DAC was developed at Scientific and Technological Center of Unique Instrumentation of Russian Academy of Sciences. The system consists of four components (figure 1):

(i) fiber laser, which is designed to allow precise control of the total power in the range from 2 to 100 W by changing the diode current;
(ii) TAOTF imaging spectrometer for measuring the temperature distribution;
(iii) diffraction spectrometer for measuring the spectrum of the ruby for pressure measurement;
(iv) optical system to focus laser beams on the sample and image it.

The system is unique and allows making measurements of following parameters and signals:

(i) temperature distribution in a DAC under HPHT conditions using Planck’s law;
(ii) pressure in a DAC using a Raman signal;
(iii) Raman scattering of specimens under high pressure and small flat specimens removed from the DAC after HPHT treatment.

The method of the temperature distribution measurements on the heated surface is well-known [3,4]. Temperature in a DAC can be determined from the radiation emitted by a material using Planck’s blackbody equation (for details see [5, 6]):

\[ I(\lambda, T) = \frac{\varepsilon c_1}{\lambda^5 \left[ \exp \left( \frac{c_2}{\lambda T} \right) - 1 \right] }, \]

where \( I(\lambda, T) \) is the spectral intensity, \( \varepsilon \) is the sample emissivity, \( \lambda \) is wavelength, \( T \) is the temperature, and \( c_1 \) and \( c_2 \) are physical constants \( (c_1 = 2\pi c^2, c_2 = h c / k_B) \), c is the speed of light, \( h \) is the Planck constant, \( k_B \) is the Boltzmann constant). When \( \lambda T < c_2 \), the temperature of the sample surface can also be calculated using Wien’s approximation to Planck’s law:

\[ I(\lambda, T) = \frac{\varepsilon c_1}{\lambda^5} \exp \left( -\frac{c_2}{\lambda T} \right). \]

Defining a normalized intensity, \( J = \ln \left( \frac{I(\lambda, T) \lambda^5 / c_1}{\lambda^5} \right) \), Wien’s second law can be expressed as a linear equation in \( T \):

\[ J = \ln \varepsilon - c_2 / (\lambda T). \]

The use of the Wien approximation for temperature measurements introduces negligible error for \( T < 4000 \) K, and simplifies data processing [7, 8]. Description of the procedure of the linear least squares fitting and the form of set of equations to determine coefficients of the Wien equation (3), \( \ln \varepsilon \) and \( c_2 / T \), can be found elsewhere [9]. The standard deviation of the temperature obtained the linear least squares fitting do exceed 60 K.

Measurements of the temperature distribution of a tungsten filament heated by a constant current with TAOTF can be found elsewhere [2]. Briefly, 2-D temperature measurement is based on the use of TAOTF synchronized with a digital video camera. A single acousto-optical
tunable filter (AOTF) is a solid state spectral band-pass filter that works on the principle of acousto-optic anisotropic diffraction in a birefringent crystal [10]. Single AOTF as well as other spectral elements have already been in use for one-point temperature measurements [11]. Strong chromatic drift and spatial aberrations of the spectroscopic image in a conventional AOTF based imaging system can reach several percent of the field of view. This makes it difficult to obtain accurate spectral measurements using AOTF images. To overcome this problem, TAOTF is used for temperature distribution measurements. As shown in [12], increased spectral contrast the TAOTF system combines reliable spectral imaging with several important features: absence of image distortions and chromatic drift. The measured intensity in each pixel \((x, y)\) of the TAOTF spectroscopic image is proportional to the intensity of light irradiated by the corresponding element of the specimen surface at a given \(\lambda\).

The TAOTF was designed and assembled as a separate PC-controlled spectral imaging device. Its main parameters are as follows: tuning range 650–1100 nm; spectral resolution \(\delta(\lambda) = 2\) nm (at \(\lambda = 633\) nm); spatial resolution \(600 \times 500\) resolved elements; field of view \(3^\circ \times 3^\circ\); entrance pupil diameter 8 mm; and residual spatial distortion less than 0.1. Tuning time is about 20 \(\mu\)s. Therefore, the registration time is determined mainly by the exposure time of C1 camera sensor.

A tungsten ribbon filament lamp is used as a known source of spectral radiance \(I(\lambda)_{\text{standard}}\). Calibration is based on a blackbody calibration standard operating at a temperature of 1700 K. The lamp is placed at the position normally occupied by the sample so that the spectral intensity \(I(\lambda)_{\text{optics}}\) of the lamp is acquired through the optical pathways. To determine the spectral radiance of the heated specimen, \(I(\lambda)_{\text{corrected}}\), the following equation is used:

\[
I(\lambda)_{\text{corrected}} = \frac{I(\lambda)_{\text{measured}}I(\lambda)_{\text{standard}}}{I(\lambda)_{\text{optic}}},
\]

where \(I(\lambda)_{\text{measured}}\) is the spectral intensity of the specimen in a DAC during laser heating. The beam of the heating laser is focused on the sample by a long working distance OB1.

An experimental LH-TAOTF setup operating in the reflection configuration is shown in figure 1. The sample stage can move in the \(x\), \(y\), and \(z\) direction using computer-controlled motorized actuators (Standa 8MVT40-13). We choose the direction of the \(z\)-axis as the one parallel to the ir laser beam. The specimen is secured to the stage by a GSEG+CARS (GeoSoilEnviroCars, University of Chicago) designed DAC holder. Calibration of the movement of the focal spot from the ir laser was done using the optical system.

The design of the LH system is similar to that described in [8]. The main difference is that in our configuration the LH is applied to one side of the specimen (plate, DAC). The technical design of the fiber laser allows precise control of the total power (range from 2 to 100 W) by changing the diode current.

3. Results
Measurements of the temperature distribution of the laser-heated surface of a free plate are very sensitive to the focal plane position of the laser beam. As the 1064 nm laser beam is invisible, it is difficult to find the focal plane of the laser beam after the objective OB1.

In this report, we propose a technique of aligning ir laser by using the TAOTF. We found that TAOTF allows us to visualize a beam of the ir laser on the C1 camera and to find the position of the focal plane of the ir laser. To perform this task, the TAOTF filter is tuned to a wavelength 1038 nm, which is close to the 1064 nm laser line. Figure 2 shows the intensity of the laser beam distribution in the focal plane of the LH-TAOTF system measured when an aluminum plate was illuminated by ir laser. The calibration of the field of view was done using a glass plate with 50 \(\mu\)m square grating (figure 3).

To minimize the contribution of the black body radiation for a heated body we used a 1064 nm (98%) mirror for visualization intensity distribution of the ir laser beam in a focal area. Figure 4 shows the intensity of the laser beam distribution in the focal plane of the LH-TAOTF system.
Figure 1. The sketch of the LH-TAOTF system. The radiation emitted from the sample is directed through two optical paths: mirrors M1, M2, M3, and M4 to align the ir laser, and measure the temperature on the front side of the sample; and mirrors M5, M6, M7, M8, and M9 to align 532 nm laser and to measure the ruby fluorescence for pressure measurement in a DAC. A double-sided high magnification imaging system is based on two long working distance infinity corrected objectives OB1 (10x, M, Plan Apo, L, NA = 0.28, f = 20 mm, infinity corrected objective Mitutoyo, USA) and OB2 (50x, Plan Apo, ULWD, NA = 0.42, WD = 22.5 mm, infinity corrected objective, Edmund Optics, USA). Each of the imaging systems consists of: camera, C1 (Allied Vision Mako G-030B) this camera runs 300 frames per second, resolution 644(H) × 484(V) pixels, and C2 (ImagingSource DFK 22AUC03); notch filter NFT, to cut off light from the 532 nm from the camera detectors; long focal distance or lenses L1 (f = 500 mm), L2 (f = 300 mm) to focus thermal radiation on the camera detectors; and beam splitters BS1 and BS2 used to direct light from the two bulbs towards the objectives OB1 and OB2, respectively. The lens L3 (f = 60 mm) is used to focus light on the pinhole of the spectrometer (M266, Solar Laser Systems). A dichroic mirror D (1064 nm) separates the laser beams and visible radiation coming from the sample for spectroscopic temperature measurements and sample imaging [8]. A π-shaper is located between mirrors M3 and D and designed to allow precise control of the LH spot shape (e.g., gauss, flat-top, donut [8]) and size (from 8 to 100 µm [8]).
Figure 2. Image of the 1064 nm laser beam using TAOFT was tuned to 1038 nm with the laser focused on an aluminum plate. The power of the laser beam was 5 W.

Figure 3. Image of the glass plate with 50 µm square grating. The TAOTF was tuned to 632 nm.

cannot be achieved by standard methods. The proposed method of visualization of the ir laser beam allows focusing of the invisible ir lasers and can be used to precisely align the laser beam in a DAC to achieve high efficiency of the LH. Our measurement shows that the diameter of the laser spot at focus was around 9 µm and the depth of focus was around 80 µm.

Aligning and focusing of the ir laser beam make it easy to measure temperature distribution. The temperature distribution on the platinum plate heated by a high power laser is shown in figure 6. The number of the TAOTF images spectroscopic images \( I(x, y, \lambda_N) \) was \( N = 75 \). These were obtained with a OB1 microobjective, exposure time 83 µs, constant spectral step 2 nm from...
Figure 4. Intensity of 1064 nm laser beam distribution measured using TAOFT at 1038 nm. The power of the laser beam was 5 W.

Figure 5. Lateral scans of 1064 nm laser beam using TAOTF at 1038 nm taken at different $z$ positions. Position $z = 0$ corresponds focusing of the laser on the surface of a specimen. Laser was focused on the 1064 nm mirror. The laser power was 5 W.

610 to 760 nm, and derived from the Planck’s law temperature distribution. The registration time of 75 images was 6.2 ms. The thermogram (figure 6) and temperature profiles (figure 7) show that temperature distribution over the filament surface is significantly non-uniform.
Figure 6. 2-D temperature distribution $T(x, y)$: $x - y$ scan. The laser power was 5 W.

Figure 7. 2-D temperature distribution $T(x, y)$: $z - x$ scan. The laser power was 5 W.

The minimal temperature shown in figure 7 is around 1750 K. To measure temperature distribution below 1750 K longer exposure time is required. Unfortunately higher exposition time leads to a saturation of the signal in the area of high temperature ($> 2000$ K). We see several solutions to overcome this problem. One of such solutions is to use a camera with higher dynamic range.

4. Conclusion
In this report, we demonstrate that combining the LH system with TAOTF allows us to measure the temperature distribution under LH of the platinum plate as well as to visualize of the invisible ir (1064 nm) laser beam, which is used for LH in the DAC. The temperature distribution $T(x, y)$ was determined by fitting the actual signal to Planck’s equation at each point of the specimen.
surface. In this study, we assume the variation of the specimen emissivity to be small over the spectral tuning range and measured temperature range.

Acknowledgments
This work was supported by program of the Presidium of the Russian Academy of Sciences (No. I.11P “The physics of high energy density matter at high pressures”) and grant from the National Science Foundation (No. EAR-1215796).

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