Modeling the beam profile of an infrared laser to create optical tweezers in high pressure cells

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Abstract. In this paper, a modeling of a laser optical system for heating samples in a high-pressure cell was performed, in which the laser heating system and the optical system for measuring the temperature distribution are separated. It is shown that a setup with separate heating and temperature measurement systems allows one to: (i) adjust the optical temperature measurement system regardless of the alignment of the IR laser; (ii) obtain the optimal spot of the IR laser beam and control the beam in the future using a movable lens and an acousto-optical deflector.

1. Introduction
Laser heating in a high-pressure cell is a unique method that allows one to study the behavior of a substance under extreme conditions, high static pressures, and temperatures [1]. Recently it was shown that the method of laser heating of matter in high pressure cells can be combined with laser tweezers [2,3]. It has been shown that digital holographic microscopy can be used for accurate 3D tracking and calibration of a colloidal probe trapped in a diamond anvil cell (DAC). Polystyrene beads were optically trapped in water at high pressures. A simulation of the scattering of laser radiation from a ball showed a 10% decrease in the radius of the ball due to the high applied pressure. Thus, it has been demonstrated that the use of laser tweezers is a convenient optical tool for determining the bulk modulus of the probe material.

The development of acousto-optical research methods has led to the creation of a fast laser beam control system in optical tweezers [4,5]. To apply this method, a high-pressure cell requires the creation of a layout in which the laser system for heating the samples and the optical system for measuring the temperature distribution are separated.

The purpose of this study is to develop and model a new laser optical system for heating samples in a high-pressure cell, in which the laser heating system and the optical temperature distribution measuring system are separated.

In this paper, it will be shown that a setup with separate heating and temperature measurement systems allows you to: (i) adjust the optical temperature measurement system regardless of the alignment of the IR laser; (ii) obtain the optimal spot of the IR laser beam and control the beam in the future using a movable lens and an acousto-optical deflector.
2. Description of the optical setup
An integral part of high-temperature heating systems (K) at high pressures are: (1) a powerful laser (figure 1); (2) a diamond anvil (figure 2). A description of the high-pressure cell with diamond anvils can be found in [6, 7].

In the Scientific and Technological Center for Unique Instrumentation of the Russian Academy of Sciences, a unique setup for laser heating in high-pressure cells has been developed and created, which allows measuring the temperature distribution and emissivity at high pressures and temperatures [6–8]. This setting (figure 1) consists of two modules: a laser heating system and an imaging optical system.

In our setup, sample heating is carried out by focused radiation of an IPG LK-200-OM-V CW fiber laser with the following characteristics: emission wavelength $\lambda = 1.07 \ \mu m$, maximum power 200 W, beam quality factor $M^2 = 1.06$, beam waist at intensity level $1/e^2$ $w = 29.64 \ \mu m$, beam divergence at intensity level $1/e^2$ $\theta = 24.31 \ \text{mrad}$, Rayleigh range $z_c = 2.44 \ \text{mm}$. For the spatial parameters of the laser Gaussian beam, the invariant is performed [9-11]: $h_\theta = h_w^2 / z_c = M^2 \lambda / \pi = 0.36 \ \text{mm} \cdot \text{mrad}$.

![Figure 1](image)

**Figure 1.** The setup scheme of laser heating in a high-pressure cell using an acousto-optical filter.

A cell with a diamond anvil (figure 2) is mounted on a three-coordinate motorized table with micrometric screws. The motorized table allows the maximum movement of the sample 100 $\mu m$ in increments of 1.25 $\mu m$, which is sufficient to focus the radiation of a 200 W laser on the sample. In our experiments, the thickness of the diamond in the anvil is 2.5 mm. To effectively heat a sample in a high-pressure cell, diamond is separated by a layer of thermal insulator, for example, a salt layer with a thickness of 20 $\mu m$. 
Figure 2. Diamond anvil alignment setup and laser beam caustic in a diamond anvil: a) focusing on the surface of a diamond, b) focusing on the sample; $W$ is the waist of the focused Gaussian beam, $F'$ is the rear focal point of the lens $L_3$, $f'$ is the rear focal length of the lens, $H, H'$ are the front and rear principal points of the lens, $2h_h$ is the diameter of a quasi-parallel Gaussian beam, $D_o$ is the diameter of the laser beam on the sample, $D_d$ is the diameter of a laser beam on a diamond surface in a diamond anvil, $z$ is the magnitude of the displacement of the lens $L_3$ to focus the Gaussian beam on the sample, $\Delta z$ is the lens $L_3$ shift from $z$ position.

Laser radiation hits two alignment mirrors $M1$ and $M2$ with high radiation resistance (Figure 1). The laser beam intensity at the output of the collimator has a Gaussian distribution and spontaneous polarization. After the collimator, an $L_3$ lens is installed, which can be moved along the optical axis. The purpose of the $L_3$ lens is to focus the laser radiation on the sample. Moving the $L_3$ lens allows one to change the size of the laser beam on the sample. After the lens, the laser beam passes through the PBS1 polarization beamsplitter (Figure 1). The vertical polarization of the laser radiation enters the sample and heats it up, and the horizontal-polarized laser beam is scattered on the heat shield $LB1$. The test sample is located in cells with diamond anvils. The output of the imaging optical system is a hyperspectral image of the thermal radiation from the sample. The thermal radiation of spontaneous polarization from the sample transmitted through the polarization beamsplitter PBS1 is divided into two polarizations: horizontal, which is not used, and vertical. Radiation of a heated sample with vertical polarization is collected by a 20x microscope lens with a large working distance of 20 mm (OBJ x20 M Plan Apo L, NA = 0.28) and enters the acousto-optic monochromator (TAOTF). Due to the fact that the TAOTF is a polarizing device with linear vertical polarization, the use of a polarizing beamsplitter does not introduce losses. The radiation transmitted through the monochromator (TAOTF) is focused by the $L_1$ lens (AC254-400-B Thorlabs, $f' = 400$ mm) onto the matrix of a monochrome video camera (Allied Vision Mako G-030B) connected to a computer. To implement the
positioning of the sample, its backlight is used with white light. The optical illumination branch includes a 100 W halogen lamp, the radiation of which is transmitted to a beamsplitter BS1 (Thorlabs BS016) using a L2 lens with a focal length $f' = 30$ mm and an adjustment mirror M3 and is focused on the sample using an OBJ ×20 lens. During the experiment, the beamsplitter BS1 is removed from the setup. This allows one to increase the intensity of the signal of thermal radiation and to eliminate spurious illumination.

After installing the high-pressure cell in the setup, it is necessary to perform its positioning. To do this, the backlight (halogen lamp, figure 1) is turned on through a BS1 beamsplitter. Then the TAOTF is set to the wavelength with maximum optical transmittance and by moving the cell using the microscrews of the movable table, a clear image of the sample is found on the video camera.

The next step is the positioning of laser radiation on the sample. For this, it is necessary to mount the L3 lens with a microscrew so that the sample is in its back focal plane. The power of the fiber laser is set to a minimum level. The TAOTF filter wavelength is chosen equal to 1040 nm. The procedure considered above makes it possible to obtain an image of an IR laser on a sample; it was described in [8].

3. Modeling a focusing optical system

The advantage of the laser system under consideration is that it provides the possibility of separate focusing of laser radiation. This allows one to change the temperature gradient on the sample while maintaining its clear image. The longitudinal movement of the L3 lens allows you to control the size of the beam on the sample and on the surface of the diamond.

During the simulation in Zemax the focusing of a Gaussian laser beam LK-200-OM-V was examined with the abovementioned radiation parameters using the L3 lens (figure 1) with the following focal lengths: 30, 40, 50, 100 and 150 mm.

![Graph](image)

**Figure 3.** The distribution profile of the relative intensity $I(r)$ of the laser beam:
(a) at the output of the LK-200-OM-V laser, (b) on the focusing lens L3.

Figure 3a shows cross sections of the field intensity distributions at the laser output. To ensure the required laser beam size in the diamond anvil, the beam was expanded using a collimator. As a result, a quasi-parallel Gaussian laser beam was formed with a waist radius at intensity level $1/e^2$ $h_w = 2.5$ mm (figure 3b) and divergence $\theta = 0.58$ mrad. Further, this beam is focused by the lens L3. The size of the beam on the sample in the diamond anvil is determined by the focal length of the focusing lens L3 and the position of the lens relative to the surface of the diamond. The actual position of the waist of the focused beam is shifted due to the Gaussian beam passing through the diamond-
sample medium. The diameter of the waist of the focused beam is the same both in air and in the medium and is [10]:

\[ 2h' = \frac{4M^2\lambda}{2h} = 1.27 \frac{M^2\lambda}{2h} \]

In our optical system \( 2h = 5 \text{ mm} \).

Let the lens L3 focus the beam on the surface of the diamond. To focus the IR laser on a sample in a diamond anvil, it is necessary to move the lens L3. The magnitude of the movement of the lens is determined by the formula [12]:

\[ z = -\left( \frac{d_1}{N_1} + \frac{d_2}{2N_1N_2} \right) \]

where \( d_1 \) is the diamond thickness (in our setup \( d_1 = 2.5 \text{ mm} \)), \( d_2 \) is the thermal insulation layer thickness (in our setup \( d_2 = 20 \text{ μm} \), and the layer is made of NaCl), \( N_1 = n_2/n_1 \) and \( N_2 = n_1/n_2 \) are the relative refractive indices of the media, \( n_1 \) is the refractive index of air, \( n_2 \) is the refractive index of diamond (\( n_2 = 2.4 \)), \( n_3 \) is the refractive index of salt (\( n_3 = 2 \)).

Substituting the parameters of the diamond anvil in (2), one obtains \( z = -1.05 \text{ mm} \). At a focal length of the focusing lens of 40 mm, the diameter of the Gaussian beam at the \( 1/e^2 \) level on the diamond surface is 132 μm, and on the sample 12 μm.

After that, the focusing lens L3 is shifted by \( \Delta z \). If \( \Delta z < 0 \), then the focusing lens shifts to the diamond anvils, and for \( \Delta z > 0 \), from it. The shift of the focusing lens L3 from the found position by \( \Delta z \) leads to an increase in the diameter of the Gaussian beam on the surface of the diamond and on the sample. Figure 4 shows the dependences of the beam diameter on the sample and on the diamond surface with a lens shift of L3 in the range \(-2 \ldots 0.5 \text{ mm} \). For a special case of the displacement of the L3 lens by \( \Delta z = -0.5 \text{ mm} \) and the focal length of the lens L3 \( f' = 40 \text{ mm} \), the cross sections of the transverse distributions of the field intensity on the diamond surface and on the sample are shown in Figure 5.

![Figure 4](image-url)

**Figure 4.** Dependences of the beam diameter on the diamond surface \( D_{d} \) (a) and on the sample \( D_{s} \) (b) on the displacement by \( \Delta z \) of the lens L3.

From the dependencies in figure 4(b) it can be seen that a lens with a focal length of 150 mm creates the largest heating spot at the focus (~44 μm). Unfortunately, approximately a spot with the same diameter (~50 μm) is created on the surface of the diamond. Diamonds used in anvils are generally transparent to IR radiation. However, the ingress of powerful laser radiation on dust particles on the
A diamond can lead to damage. Therefore, it seems important to make an IR laser spot on the diamond surface of the largest possible diameter. Analysis of the results presented in figure 4 shows that the optimal solution is to use a lens with a focal length of 40 mm. Experience has shown that using lenses with a shorter focal length \( f' < 30 \) mm is not possible due to the geometry of such lenses. For a lens with a focal length of 40 mm with intermediate defocusing \( \Delta z = -0.7 \) mm, the diameter of the IR laser on the diamond surface is 217 μm (figure 4a), while the beam diameter on the sample is 85 μm (figure 4b). Note that the problem of radiation resistance is also characteristic of the optical elements of laser technological heads forming the radiation of high-power fiber lasers [13].

![Figure 5. Cross sections of the transverse distribution of the field intensity on the diamond surface (a) and on the sample (b) at the focal length of the lens L3 \( f' = 40 \) mm and \( \Delta z = -0.5 \) mm.](image)

Thus, (i) the separation of the heating system and the temperature measurement system, (ii) the use of focusing lenses with a focal length of 40 mm and (iii) the possibility of its longitudinal movement (defocusing) make it possible to obtain an optimally large spot of an IR laser on a sample (≈85 μm) and significantly reduce the intensity of the laser radiation flux on the diamond surface.

4. Conclusion

In this work, a setup of a laser optical system for heating samples in a high-pressure cell is proposed in which the laser heating system and the optical system for measuring the temperature distribution are separated. For the proposed optical system, the focusing of an IR laser beam in a high-pressure cell was simulated using lenses with a focal length of 30…150 mm.

The simulation results in Zemax optical systems CAD allow us to draw the following conclusions:

1. The proposed setup allows (i) creating laser tweezers in a high-pressure cell and simultaneously (ii) measuring the particle temperature and (iii) observing the motion of particles in a high-pressure cell using an optical system.

2. The formation of a waist on the sample is optimal when using a lens with a small focal length to focus the IR laser. In this case, the ratio of the area of the spot on the surface of the diamond and on the sample is maximum, which results in weak heating of the diamond and strong heating of the sample. To reduce the power density on the surface of the diamond, it is acceptable to select or shift the focusing lens so that the constriction is behind the sample.

3. To focus the beam on the sample and not a high radiation load on the diamond surface, it is acceptable to use a lens with a focal length of 40 mm and a distance of \( \Delta z = -0.5 \) mm. In this case, a beam is formed with a diameter of 200 μm on the diamond and 65 μm on the sample.
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