Heat Flow Analysis of Micro-objects Using Optical Tweezers

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In the Heat Asymptotics Research Project, transient heat flow dynamics are examined in real systems and compared to theoretical results. To implement these studies for microscopic objects, an optical tweezers system is built, aligned, and characterized by two methods. A suitable colored glass material for object fabrication is purchased and found to heat up appreciably when exposed to the heating laser at high power. However, the heating laser was not transmitted efficiently through the existing objective lens and its beam path diverged from the path of the trapping laser in the system. Future groups working on this project will need to address these problems before heat flow experiments can be conducted.

OCIS codes:

1. INTRODUCTION

Starting as early as the late 1960's soon after the development of the laser, Arthur Ashkin, while working at Bell Labs, first observed acceleration and trapping of micron-sized particles using a focused laser beam [1]. The single-beam gradient force optical trap, later known as "optical tweezers", was later developed by Ashkin and his colleagues in the late 1980's [2]. They were able to trap a large range of particle sizes reliably in three dimensions by focusing a laser beam to a very small spot size using a large numerical aperture microscope objective. Since then, optical tweezers have been used in a wide range of biophysics applications to trap and measure the force response of single molecules [3] and cells [4]. The field of optical tweezers has expanded greatly in the intervening decades. While more advanced systems can now make use of spatial light modulators to finely tune the shape of the trap or higher-order laser modes to produce torque on the trapped particle and precisely control its spatial orientation [5], relatively inexpensive and simple systems can now be used in many labs for a variety of experiments.

An optical trap essentially acts as a spring that obeys Hooke's law. If a trapped object moves slightly out of the center of the trap, the trap exerts a restoring force on the object that is directed toward the center of the trap. This restoring force could result from two different sources depending on the difference in size between the trapped object and the wavelength of the laser used to trap it. If the wavelength of the trapping laser is much smaller than the size of the object, the change in momentum of photons refracted through the object contribute to a corresponding change in momentum of the object that always centers the object in the trap. If the wavelength is much larger than the size of the object, the electric field of the laser can be thought to polarize the object into a small electric dipole. This dipole then feels an attractive force toward the local region of highest electric field intensity, which in this case is the center of the trap. [6]

The goal of this project is to use a simple optical tweezers system to investigate heat flow in micron-scale objects over very short timescales. In the University of Oregon department of mathematics, Peter Gilkey has contributed several papers [7] [8] [9] and a book [10] to the study of heat asymptotics, which refers to transient heat flow dynamics in objects. For well over a century scientists have been familiar with the steady-state heat dynamics of a bulk object gradually coming to the same temperature as the surrounding medium. However, Gilkey's work indicates that in the asymptotic limit immediately after an object is immersed in a medium of a different temperature, the heat flow dynamics become more complicated. For macroscopic objects, heat flow dynamics can differ greatly depending on whether an edge, corner, or face of the object is studied. For microscopic objects, the shape of the object strongly affects the short-term heat flow dynamics.

The purpose of the Heat Asymptotics Research Project is to examine real systems to confirm the theorized heat flow dynamics for both size regimes. To study macroscopic objects, an aluminum object such as a cube, torus, or sphere will be heated and quickly immersed in a water bath. Thermocouples attached to various surfaces and edges of the objects will record transient temperature data with a very high time resolution. To study microscopic objects, the objects of different shapes will be fabricated on the scale of a micron. These objects will then be placed in a flow cell, trapped using optical tweezers, and heated up with another laser. This will increase the kinetic energy of the object and cause it to vibrate. When the laser is shut off and the object begins to cool we can measure its vibration over short timescales and easily convert the vibrational data into an effective temperature as a function of time.

2. METHODS AND MEASUREMENTS

The first task of this group was to reconstruct the optical tweezers system used by previous groups (see Figures 1,2). A fiber coupled laser diode sent 637 nm light through a beam expander where it was then directed up into a 100x microscope objective lens by a dichroic mirror and three aluminum coated mirrors. The objective lens focused the light onto a flow cell (microscope slide containing a solution of water and silica microspheres). The slide was mounted on a piezo controlled translation stage array which allowed for precise movement of the sample in three dimensions. A halogen light illuminated the sample from above and sent blue light back through the objective lens where it was transmitted through the dichroic mirror and focused onto a CCD to image the contents of the microscope slide.

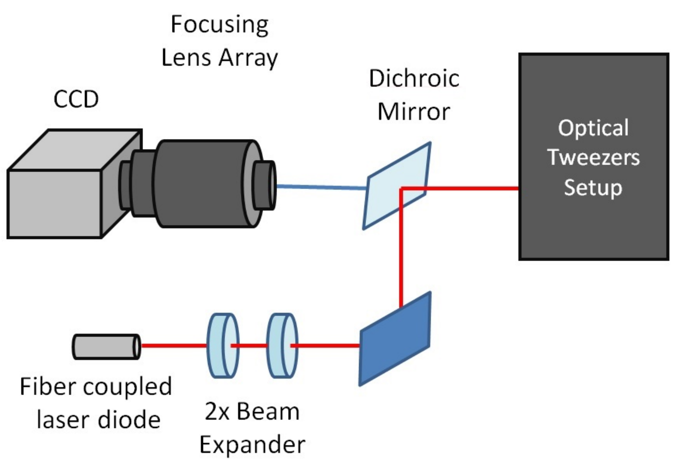

Fig. 1. Model of the overall optical tweezers system. A fiber coupled laser diode sent collimated laser light into a beam expander where it was directed into the optical tweezers setup by two mirrors. The optical tweezers had a halogen lamp which sent white light through the dichroic mirror where it was focused on the CCD to produce images of trapped objects.

An issue previous groups experienced with creating flow cells was maintaining longterm viability. Beads would commonly get stuck to the glass slide after a few hours, which would not be ideal in future stages of the project when each flow cell would contain ∼5-10 beads fabricated in CAMCOR at the rate of 1 bead per hour. This group experimented with adding supplements such as bovine serum albumen (BSA) and polyethylene glycol to the bead solution based on other optical tweezers articles, but both substances provided little to no use in extending the lifetime of a flow cell. Altering the entire procedure for creating flow cells (as detailed on the Wiki page) showed the best results with some flow cells lasting as long as 4 days. Furthermore, samples could be placed in a sonicator for 3 minutes, which dislodged beads stuck to the microscope slide, and have trappable beads

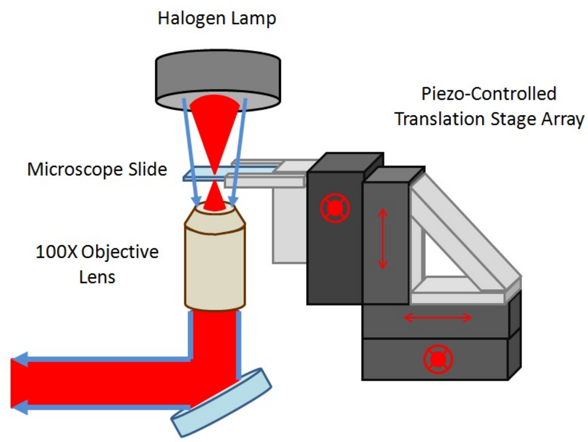

Fig. 2. Model of the optical tweezers system. A 100x microscope objective lens tightly focused the laser light to a very small part of a microscope slide containing a microsphere solution. The slide was mounted to a three-dimensional translation stage with a fourth piezo driven stage added for increased precision. A halogen lamp sent light back through the system to illuminate the sample on a CCD.

for ~ 1 hour. Lastly, this group found that the ideal bead solution dilutions for each wavelength of the trapping laser were a 1:1000 ratio for visible light and 1:2000 for NIR and IR light.

This group took Brownian motion measurements for both 637 nm and 980 nm trapping lasers (see Figures 3 and 4). (For exact instructions on taking Brownian motion measurements, see the Wiki page.) It was found that for both lasers, the trapping strength in the x and y direction were nearly the same when the laser power was below 30 mW. Above those powers, the beads were so strongly trapped, the beads did not move enough for the tracking software to accurately measure their position. Previous groups found that the trap strength in the y direction was an order of magnitude smaller than the x direction, but this group aligned the objective lens using a level to ensure the trapping laser was not entering the back of the lens at an angle which would create an asymmetric trap.

To further characterize the trap strength of the 980 nm laser, a Stoke's drag force measurement was taken (see Wiki page for further details). Because the trap strengths for the x and y direction were in close agreement, the Stoke's drag force measurement was only performed in the x direction, but the results showed a linear upward trend, on par with measurements taken by previous groups (see Figure 5) .

The eventual goal of this research project was to couple a 1550 nm laser and 980 nm laser into the same fiber using a wavelength division multiplex (WDM) so they would be focused to the same spot in a flow cell. The 980 nm laser would trap micro-objects, and the 1550 nm laser would heat up the objects. Theses wavelengths are convenient because WDM's for these wavelengths are readily available; however, this group encountered a problem with the objective lens. The objective lens does not transmit 1550 nm light efficiently. According to manufacturers, at best, the objective lens will transmit 28 % of the light entering it. When this group performed our own measurements, we found that only $0.5\% - 2\%$ made it through the immersion oil and objective lens (see Figure 6).

Lastly, this group found a colored glass bandpass filter (Thor-

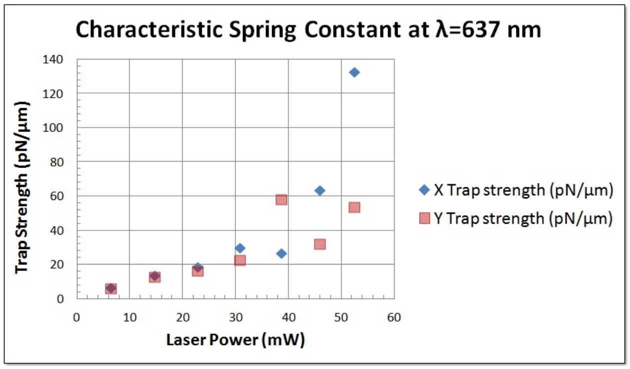

Fig. 3. Brownian motion measurement of the trap strength for $\lambda = 637$ nm. The trap strength in the x and y direction is the same below 30 mW, which is an improvement to data from previous groups which showed the trap strength in the y direction as being an order of magnitude lower than in the x direction. Above 30 mW, the trap strengths vary, but this is due to the tracking software being unable to differentiate minute position changes of the microsphere at higher trap strengths.

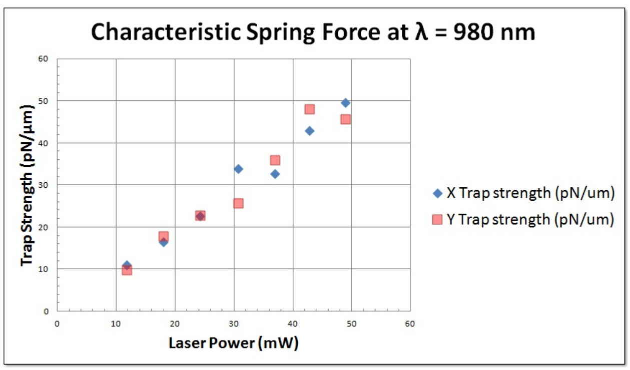

Fig. 4. Brownian motion measurement of the trap strength for $\lambda = 980$ nm. Consistent with data from the Brownian motion data taken for the 637 nm trap, the trap strengths in the x and y directions were the same below 30 mW. The variance between the x and y directions above 30 mW was decreased due to refinement in batch processing.

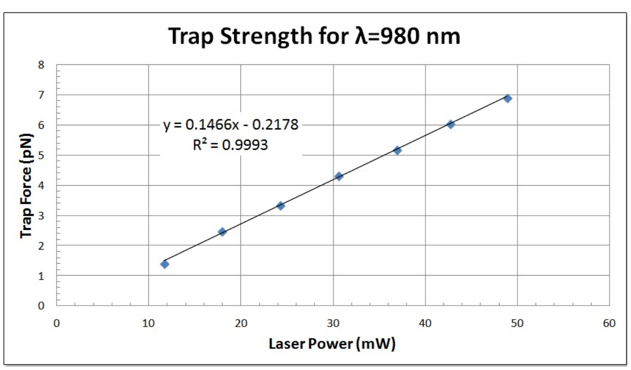

Fig. 5. Stoke's drag force measurement of the trap strength for $\lambda = 980$ nm. The trap strength increased linearly as the laser power was increased, and the trap force values were nearly identical to values measured by previous groups.

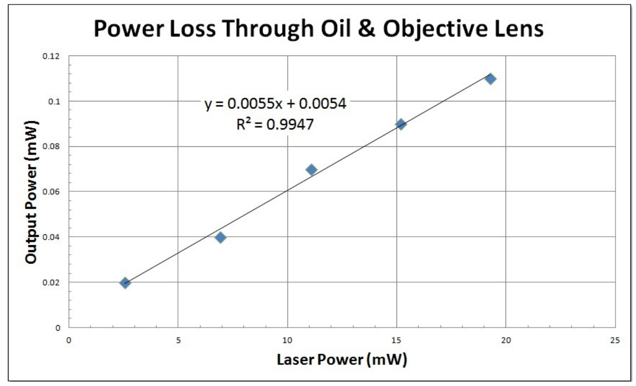

Fig. 6. Loss of optical power due to the objective lens for $\lambda = 1550$ nm. The output power was reduced by two orders of magnitude. Overall, the objective lens only transmitted 0.5% of the input power.

labs FGB67) that transmitted 980 nm light and absorbed 1550 nm light, meaning it could be trapped by the NIR light and heated with the IR light. To ensure the material could be heated with a 1550 nm light, this group exposed the material to ∼30 mW of collimated 1550 nm light for 5 seconds; however; no permanent change to the material was observed. The material was then exposed to ∼ 850 mW of unfocused 1550 nm light for 10 seconds, which produced a visible burn mark (see Figure 7). It can be inferred that a focused beam of 1550 nm light will be capable of heating micro-objects in future experiments.

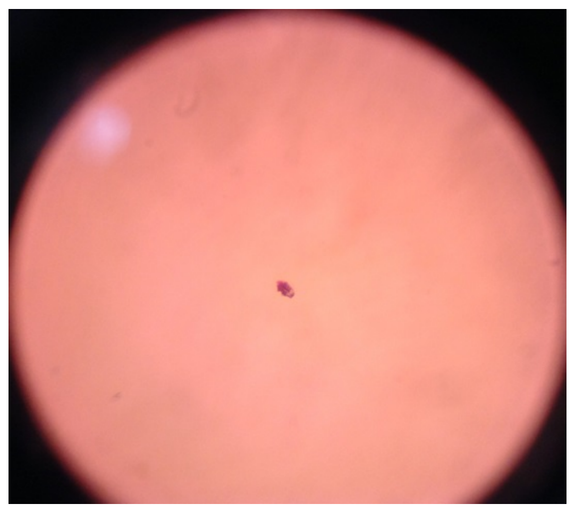

Fig. 7. Damage to FGB67 colored glass from exposure to ∼ 850 mW of unfocused 1550 nm light. Thus, the material will be feasible for future micro-object heat asymptotics research since it transmits 980 nm light and absorbs 1550 nm light.

3. CONCLUSION

This group located a colored glass that could be used to fabricate micro-objects which could be trapped by a 980 nm laser and heated by a 1550 nm laser in order to study transient heat flow in those objects. The trapping strength of the 980 nm laser was characterized by Brownian motion and Stokes' drag measurements. However, the 1550 nm laser does not propagate through the system or existing objective lens efficiently. Therefore future groups working to advance this project must first acquire a microscope objective and output collimator that can efficiently transmit both 980 nm and 1550 nm light. The fiber outputs of both lasers will need to be connectorized and attached to an appropriate WDM so that both wavelengths can be output along the same optical path in the system. After the system is precisely aligned for these wavelengths, a quadrant photodiode should be integrated into the system to accurately track object positions with a high time resolution. The micro-objects will be fabricated using the focused ion beam instrument in CAMCOR. If these objects can be consistently located within the sample flow cells, their transient heat flow dynamics can then be studied.

4. REFERENCES

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