PRAMANA
— journal of
physics

Vol. 65, No. 4
October 2005
pp. 699–705

Construction of an optical tweezer for nanometer scale rheology

A RAGHU and SHARATH ANANTHAMURTHY
Department of Physics, Bangalore University, Bangalore 560 056, India
E-mail: sharath_ananthamurthy@hotmail.com

Abstract. The optical tweezer is a versatile set-up that can be employed in a wide variety of studies investigating the microscopic properties of materials. In particular, this set-up has in recent times been gainfully employed in probing rheological properties of materials that exhibit viscoelasticity. These measurements can provide data at the micro and nanometer scales, not normally accessible by rheometers that are used for measurements on bulk samples. In this work we describe a single laser beam optical tweezer set-up, which is built around an inverted open microscope. The trapped polystyrene particle bead's deviation from the trap potential minimum is monitored by laser back-scattering technique and the bead position measured by a quadrant photodiode detector. Additionally, a provision is made for video microscopic studies on dispersed beads using a CCD camera. A single particle microrheological experiment that can be performed using the set-up is described with relevant calculations.

Keywords. Micro and nanorheology; viscoelastic materials; soft matter; optical tweezer.

PACS Nos 83.85.Ei; 47.80.+v; 83.60.Bc; 83.60.Df

1. Introduction

Rheological measurements on soft condensed matter systems at micro or nanoscopic scales often reveal properties of the material that are markedly different from the measurements at a larger length scale, which are more indicative of the bulk properties. Such measurements are especially significant when one is attempting to probe mechanisms that are normally operational at these scales, as in biological cells or the inter-particle forces in colloids [1–3]. A large variety of experimental techniques exist to carry out these investigations. These are, dynamic light scattering (DLS), diffusing wave spectroscopy (DWS), atomic force microscopy (AFM), video microscopy, laser deflection particle tracking (LDPT), surface force apparatus (SFA) and optical tweezers, to name a few. While optical DLS and DWS are powerful techniques, they often yield quantities that are averaged over a large number of particles within the neighborhood of the region under consideration. Thus the mean squared displacement of a single particle which serves to probe the local homogeneities of a material, cannot be directly measured [4,5]. Atomic force microscopes enable local probing of small volume samples but are expensive. Optical

tweezers have seen many improvements over the years and are simple to build [6–12]. They are used for measuring the motion of an isolated particle in soft matter and from this, a study of the rheology at micro and nanoscales is made possible. Additionally, they enable precise measurements of very small forces that come into play as a result of the elastic properties of materials. Moreover, they offer the possibilities of interesting science with a relatively low-cost set-up at the university level.

Within the purview of optical tweezer based studies there exist various techniques to study microrheology. They are: (a) tracking the diffusion of tracer particles [1,4], (b) measurement of correlations in the Brownian motion of two optically trapped probe particles, also called two-point microrheology [13–15], (c) measurement of viscous drag acting on an optically trapped probe particle in linear motion [16], (d) tracking the rotational diffusion of disk-shaped particles [17] and (e) optical microrheology using rotating trapped particles [18].

In this work, we outline an optical tweezer-based experimental set-up that we are building. Currently configured as a single beam tweezer, this makes it possible for us to carry out passive as well as active rheological measurements on viscous and viscoelastic materials (as in technique (a) above). We describe the measurements that can be carried out and indicate the possible studies on a nanoscale with our set-up.

2. The set-up

2.1 *The apparatus*

Figure 1 is a schematic view of the set-up. The tweezer is built from a single beam diode laser (830 nm, 100 mW, Thorlabs, USA) used to achieve three-dimensional confinement of a latex bead, immersed in a viscous fluid. A second diode laser (635 nm, 5 mW, Thorlabs, USA) serves to track the position of the bead in the xy plane through back-scattering.

An aspheric lens (AS) and anamorphic prism pair (APP) collimates and circularizes the initially diverging 830 nm laser beam. A dichroic mirror (DM_1, max. refractive at 635 nm, max. reflective at 830 nm) combines the two laser beams that pass through lenses L_1 and L_2 of equal focal lengths (f), for beam steering. The second dichroic mirror (DM_2) reflects the laser beam towards a high numerical aperture oil-immersion microscope objective lens (1.25 NA, EA 100× long barrel, semi plan, Olympus, Japan). The objective strongly focuses the laser to a diffraction-limited spot at the trap center. The microscope objective is placed at a distance from a second lens (L_2), to achieve slight overfilling of the laser beam at the entrance aperture of the objective. This maximizes the trap stiffness [6,8,12]. The test sample is placed in a well constructed by a rubber 'o' ring on a clean cover-slip. This cover-slip is mounted on a high precision (subnanometer) XY-piezoelectric transducer stage (PZT, PXY 200 SG, PiezoSystem, Jena GmbH, Germany). The position readout of the stage displacement is facilitated by a card (EDA 3, PiezoSystem Jena), interfaced to a computer through a shielded BNC connector board (model BNC-2110; National Instruments, USA). Data acquisition is through a 16-bit DAC (PCI-6036E, National Instruments). The PZT stage is

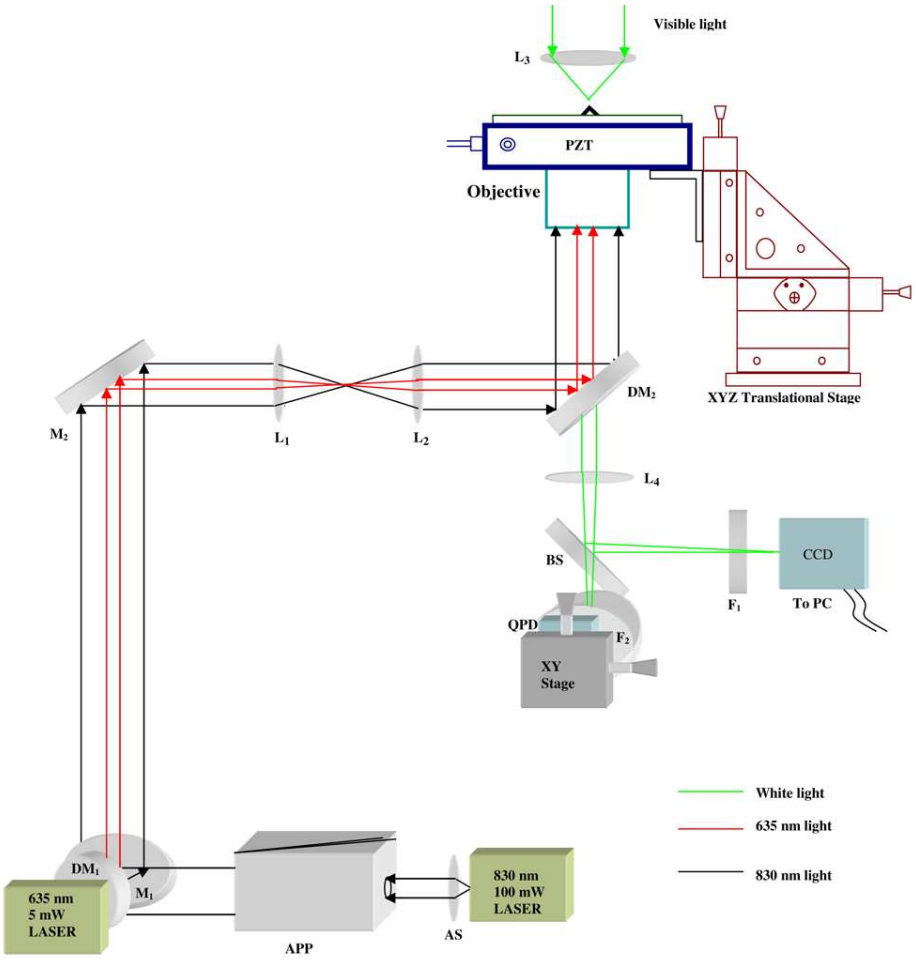

Figure 1. Front view of tweezer set-up.

mounted on a crossed roller bearing XYZ-translation stage (model 9066M-XYZ-R, New Focus, USA) that serves in coarse movement of the sample. Crossed roller bearing stages offer the advantage of a higher degree of linear motion than conventional stages. The back-scattered light from the tracking laser is focused onto a position-sensitive quadrant cell photo-receiver (2901-M, QCP, New Focus, USA), after passing through a line filter (F_2, centered at 635 nm). Visible light from a 75 W lamp sent through the front of the objective illuminates the sample. The same microscope objective also serves in imaging the trapped bead. Visualization of the trapped bead is achieved through a CCD CMOS camera (EDC-3000, Electrim Corporation, USA). An edge filter (F_1, 550 nm cut-off) prevents damage to the camera by IR radiation. To achieve stable and minimal vibration environment, the entire set-up is built on a vibration isolation (Holmarc, India) system. All optics are from Thorlabs, USA and opto-mechanical devices are from Holmarc, India.

2.2 *Calibration and estimates*

Following refs [10,11] we estimate the typical optical trap force F on the polystyrene bead ($n_2 \approx 1.58$, 3 μm size) suspended in water ($n_1 \approx 1.33$) to be

$$F = Q(n_1 P/C_0), \tag{1}$$

where Q the scaling constant is ≈0.25 for our system, P is the power of the laser at the trap and C_0 is the velocity of light in vacuum. Though the initial power of the laser is 100 mW, attenuation after passing through all the optical components, reduces this power to 60 mW at the back focal plane of the objective. We have measured a transmission of about 33% through the microscope objective, using a power meter. However, this direct measurement underestimates transmission through the objective, because of specular reflection losses from the surface of the probe of the power meter placed at the specimen plane [12]. From [12], wherein transmission is measured by other means (which employs two identical objectives), this is reported to be 60% on an average. Taking this into account, along with power loss through other optics the power P at the specimen plane reduces to 36 mW and by eq. (1), we estimate a force of ≈40 pN. However, this theoretical estimate is much greater than measured values and therefore it is imperative that the trapping force actually be measured so as to calibrate our set-up. This work is in progress. Several methods are described in [8,12,19] to calibrate the trapping force. Here, we choose to employ the more sensitive power spectrum method to calibrate the trap. We provide a brief detail of the method.

The QCP is first calibrated by fixing a bead to a cover slip and measuring the translation of the bead when the piezostage is moved. This method is described in detail elsewhere [8,19]. Position fluctuations of the trapped bead are then measured accurately by the calibrated detector. The trap stiffness k_{trap} is obtained from the plot of power spectral density (PSD) calculated from the position fluctuations of the trapped bead, using one of the several available algorithms. The PSD is given by

$$\langle r(\omega)^2 \rangle = \frac{k_{\text{B}}T}{2\gamma\,\pi^2[f^2 + f_{\text{c}}^2]}. \tag{2}$$

Here $\gamma = 6\pi\eta\,a$ is the Stokes coefficient and η is the viscosity of the medium in which the bead of radius a is immersed. The power spectrum is approximately constant at low frequencies and the slope of the spectrum changes significantly when corner frequency f_{c} is reached. The corner frequency value is used to estimate trap stiffness, by the relation: $k_{\text{trap}} = f_{\text{c}}(12\pi^2\eta\,a)$. Figure 2 shows an ideal plot of the power spectrum. Soni *et al* [8] have measured corner frequencies for different powers of 1064 nm laser and record for 50 mW power, a value of $f_{\text{c}} = 2.35$ Hz. This corresponds to a trap stiffness of 0.4×10^{-6} N/m, in their case. Scaling this to take into account the medium we use (ethylene glycol), we expect our trap stiffness to have a value around 3×10^{-6} N/m.

3. Proposed measurements

With our set-up, both active (optical tweezer) and passive (video microscopy) rheological measurements are possible. Initially, investigations will be carried out on

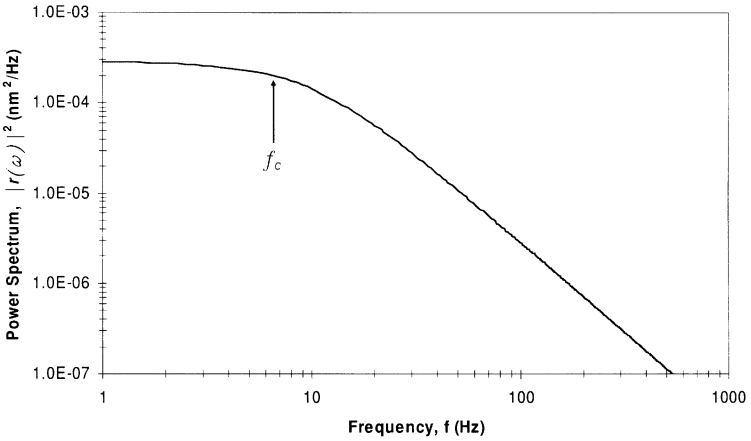

Figure 2. Ideal power spectrum of a bead in an optical trap.

polymer solutions such as polyethylene oxide in water or suspension of silica particles in ethylene glycol [2]. In passive measurements we intend to study the Brownian (thermal) fluctuations of a polystyrene bead of known size. We release the trapped bead by blocking the trapping laser and monitor its movement by capturing images using a CCD camera at a fast frame rate of 60 frames/s. This results in a resolution in spatial displacement of 1.6 μm/frame. In our set-up we use a 75 W lamp which should ensure adequate illumination at a fast frame rate. Use of a 5X eyepiece at the camera results in a magnification of about 10 nm/pixel. Since the diffusion is typically smaller than the bead diameter in a 1/60 s CCD field interval, particle misidentification should not be an issue [20]. From these images the mean square displacement (MSD=$\langle\Delta\vec{r}^2(\tau)\rangle$) of the bead can be obtained. The MSD can be related to the frequency-dependent shear modulus $\vec{G}_1(s)$ by the generalized Stokes–Einstein relation [1,2]. In Laplace transformed form this is

$$\langle\Delta\vec{r}^2(s)\rangle = \frac{k_{\mathrm{B}}T}{\pi as\vec{G}_1(s)}, \tag{3}$$

where $\langle\Delta\vec{r}^2(s)\rangle$ is the Laplace transform of $\langle\Delta\vec{r}^2(\tau)\rangle$, as a function of Laplace frequency s, τ is the lag time, a is the radius of the bead and $\vec{G}(s)$ is the shear modulus of the medium. This method is valid, provided, the medium is homogenous on a length scale of the particle radius. The MSD of the particle provides a measure of the frequency-dependent complex shear modulus $\vec{G}^*(\omega)$ of the medium in which the particle is embedded.

Active rheological measurements using optical tweezer are accomplished by subjecting the medium surrounding the trapped particle to a local stress with a corresponding optical force of few pN. The PZT stage when translated by small amounts results in an applied strain to the surrounding material. This results in particle displacement from the trap center, and the particle experiences an attractive force due to trap given by [10]

$$F = k_{\mathrm{trap}} r \mathrm{e}^{-r^2/R^2}\hat{r}. \tag{4}$$

The force is approximated by Hooke's law with an effective trap stiffness, k_{trap}, r is the radial distance from the trap center and R is $1/e$ times the width of the Gaussian laser profile at the trap.

Our PZT stage has a resonant frequency of 350 Hz. Using a 5 Hz signal from the function generator and choosing suitable voltage range to obtain 100 nm displacement amplitude of the stage, we can achieve a speed of fluid flow of about 3.14 μm /s. This corresponds to a viscous drag force of 1.42 pN on a 3 μm polystyrene bead in ethylene glycol. By measuring the oscillating bead position using the QCP we can probe the local rheological response.

4. Conclusion and future directions

In passive studies on simple fluids the MSD scales linearly with the lag time τ, and helps us in understanding the linear viscoelastic properties of the medium. However, this scaling is found to be different in complex fluids [5,21]. We are interested in exploring these issues in future studies. In active microrheological studies, subjecting the medium to nonlinear stresses can result in new and interesting responses of the medium and throw light on the nonlinear properties of the medium. Additionally, dynamical stressing of the material can be carried out by periodic modulation of the laser intensity. It will be interesting to study the nature of the MSD of tracers in such situations.

In conclusion, we have presented here a brief outline of a single beam optical trap design and described the proposed calibration method. This trap based on an inverted open microscope set-up can be employed in a versatile manner for micro and nanorheological studies on viscoelastic materials.

Acknowledgement

One of the authors SA acknowledges a research grant under the 'Nano Science and Technology Initiative' (Phase II) of the Department of Science and Technology, Government of India. The authors wish to thank the anonymous referee for pertinent remarks and useful suggestions, which helped in revising this paper.

References

[1] D T Chen, E R Weeks, J C Crocker, M F Islam, R Verma, J Gruber, A J Levine, T C Lubensky and A G Yodh, *Phys. Rev. Lett.* **90**, 108301-1 (2003)
[2] T G Mason and D A Weitz, *Phys. Rev. Lett.* **74**, 1250 (1995)
[3] A Ashkin, *Proc. Natl. Acad. Sci.* **94**, 4853 (1997)
[4] T G Mason, K Ganesan, J H van Zanten, D Wirtz and S C Kuo, *Phys. Rev. Lett.* **79**, 3282 (1997)
[5] Ashis Mukhopadhyay and Steve Granick, *Curr. Opin. Colloid Interface. Sci.* **6**, 423 (2001)
[6] Stephen P Smith, Sameer R Bhalotra, Anne L Brody, Benjamin L Brown, Edward K Boyda and Mara Prentiss, *Am. J. Phys.* **67**, 26 (1999)

[7] John Bechhoefer and Scott Wilson, *Am. J. Phys.* **70**, 393 (2002)
[8] G V Soni, Feroz Meeran Hameed, T Roopa and G V Shivashankar, *Curr. Sci.* **83**, 1464 (2002)
[9] Koen Visscher, Steven P Gross and Steven M Block, *IEEE J. Sel. Top. in Quantum Elect.* **2**, 1066 (1996)
[10] L A Hough and H D Ou-Yang, *J. Nanoparticle Res.* **1**, 495 (1999)
[11] A Ashkin, *Biophys. J.* **61**, 569 (1992)
[12] Keir C Neuman and Steven M Block, *Rev. Sci. Instrum.* **75**, 2787 (2004)
[13] John C Crocker, M T Valentine, Eric R Weeks, T Gisler, P D Kaplan, A G Yodh and D A Weitz, *Phys. Rev. Lett.* **85**, 888 (2000)
[14] A J Levine and T C Lubensky, *Phys. Rev.* **E65**, 011501 (2001)
[15] L Starrs and P Bartlett, *Faraday Discuss.* **123**, 323 (2003)
[16] B K Rafal Lugowski and Y Kawata, *Opt. Commun.* **202**, 1 (2002)
[17] Z Cheng and T G Mason, *Phys. Rev. Lett.* **90**, 018304 (2003)
[18] Alexis I Bishop, Timo A Nieminen, Norman R Heckenberg and H Rubinsztein-Dunlop, *Phys. Rev. Lett.* **92**, 198104 (2004)
[19] Frederick, Gittes and Christoph H Schmidt, in *Methods in Cell Biology* edited by Michael P Sheetz (Academic Press, California, USA) vol. 55, p. 138
[20] John C Crocker and David G Grier, *J. Colloid. Inter. Sci.* **179**, 298 (1996)
[21] T Gisler and D A Weitz, *Phys. Rev. Lett.* **82**, 1606 (1999)