Optical Stiffness of an Optically Trapped 4-Cyano-4'-Pentylbiphenyl (5CB) in the form of a Microdroplet in Water

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Abstract

This study aimed to determine the optical stiffness (k_T) of an optical trap system consisting of liquid crystal of 4-Cyano-4'-Pentylbiphenyl (5CB) in the form of a microdroplet in water. The optical stiffness is an essential parameter for calibrating optical trapping for force related measurements and microactuating applications. A 0.5 µL of 5CB was dispersed in 2 mL of deionized water to produce a solution with a 5CB microdroplet. The optical tweezers with a 976 nm laser were used to optically trap a single 5CB microdroplet. It was found that 1.1 µm diameter 5CB microdroplet showed a varied relationship of corner frequency and optical stiffness at increasing laser power density due to weak trapping. However, 2.0 µm diameter 5CB microdroplet showed an increasing relationship of corner frequency and optical stiffness at increasing laser power density in stable trapping conditions. Thus, the diameter of the 5CB microdroplet has a significant effect on stable optical trapping. This study was expected to contribute to the control precision for LC-based sensing and actuating applications.

Keywords: *Optical Trap, Liquid Crystal, 5CB. Microdroplet, Optical Stiffness, Water*

Introduction

Optical trapping is one non-destructive technique to optically manipulate microns and nanoparticles as well as incredibly fragile biological sample [1-3]. An optical trap is established by focusing a strong laser beam on the intended particle using a high numerical objective lens[4, 5]Optical tweezers (OTs) can be used as a probe to study viscoelasticity properties of a single biopolymer, characterize forces of molecular motor and micromolecular interactions in solution[6]. OTs have been used to trap different types of solid particles, such as polystyrene beads[7], gold particles[8], and carbon nanotubes[9]. OTs also successfully trapped a single liquid microdroplet such as air aerosol[10], organic solvent [11] and liquid crystal[12].

Liquid crystal (LC) has been used in many application for actuating [13, 14] and sensing applications[15, 16]. LC is a thermodynamic phase of condensed matter between solid and liquid[17]. LC is a liquid but has internal crystal-liked arrangement consisting of oriented molecules in a specific effective direction. Thermotropic LC in a nematic phase like 4-Cyano-4'Pentylbiphenyl (5CB) can easily form an immiscible microdroplet of various sizes in water[18]. 5CB microdroplet has a spherical shape of bipolar internal configuration because of its hydrophobicity in water[19]. 5CB microdroplet internal configuration is sensitive toward external fields such as electric, magnetic and light [20, 21] This phenomenon occurs due to 5CB molecules tend to be oriented along with the external field directions. The refractive index difference between 5CB microdroplet and water environment made it possible to be trapped using OTs.

Optical trapping of 5CB microdroplets in water has been conducted and reported by many researchers. However, previous research focuses on reporting the visual observation of the trapped 5CB microdroplet but not on empirical quantify of optical stiffness[21, 22]. This study aims to determine the optical stiffness of single optical trapping of an optically 5CB in the form of a microdroplet in water to quantify the strength of the liquid crystal trapped system. Optical stiffness measurement is essential for precise probe control, calibration of OTs and determining of optical forces. Furthermore, this information is helpful in the precision control of LC-based sensors and actuators.

Literature Review

A strong, focused laser beam produces optical tweezers. The laser-focused spot attracts microparticles to be optically trapped in 3-dimensions due to the optical forces[23]. These optical forces are composed of two types of forces: scattering force (F_s) and gradient force (F_g)[2]. F_s pushes particle along the laser beam direction due to the scattering of the incident laser beam. Meanwhile, F_g pulls the particle to the highest intensity gradient of the focused laser beam. The Gaussian laser beam profile has a higher intensity profile at the axis center, thus resulted in a stronger F_g.The stable optical trapping is achieved when the net forces are balanced. Figure 1 illustrates the interaction of F_g and F_s.

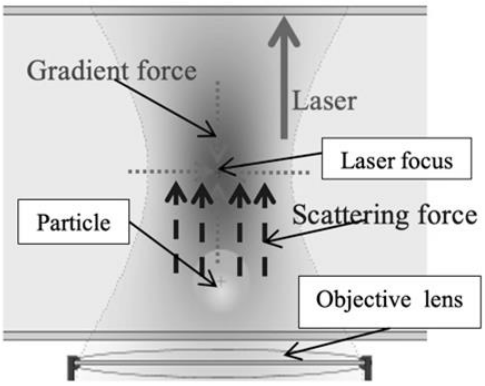


Figure 1. Interaction of gradient (F_g) and scattering force (F_s).

The trapped microparticle in an optical trap behavior can be described as a Hookean spring attached with a mass. F_g and F_s interact to produce restoring force (F_r). The strength of the optical trap is determined by a parameter called optical stiffness (k_T)[24]. Restoring force (F_r), optical stiffness (k_T) and displacement of the trapped particle (x) can be modelled as linear spring by equation (1)[25]:

$$F_r = -k_T x \qquad (1)$$

From the Equation, k_T is proportionate to F_r and x.

The larger value of k_T represents strong particle confinement and vice versa, depending on many factors such as laser power and wavelength, the refractive index of medium and particle, particle type and size[26]. The Power Spectrum Density (PSD) method is used to calibrate the optical stiffness of an optical trap. In this method, other than $k_{T,}$ parameters like corner frequency (f_c) can differentiate the optical trap strength. The relationship of k_T and f_c are related by Equation (2):

$$k_T = 2\pi\gamma_0 f_c \qquad (2)$$

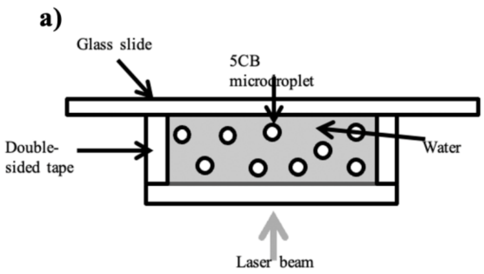
where $\gamma_0 = 6\pi\eta R$, η is the medium viscosity, R is the radius of the trapped particle [27]. Based on Equation (2), f_c is directly proportional to k_T.

Optical trapping of 5CB microdroplets that previous researchers have done focuses on the qualitative observation of trapping behavior. This includes studying suitable laser power for microdroplet trapping, the rotational frequency of microdroplet rotation and the change of microdroplet internal configuration[21]. However, to the best of our knowledge, there is no empirical study investigates the optical stiffness of trapped 5CB microdroplet dependency with the employed laser power density and the diameter of a single trapped LC microdroplet.

Methodology

Preparation of 5CB Microdroplets

In this section, the preparation of a solution containing 5 CB will be described. First, 0.5 µL of liquid 5CB ($C_{18}H_{19}N$, 32850, Aldrich) was mixed with 2 mL of deionized water at room temperature (23 ˚C) in a 2 mL vial to produce a 5CB-contained solution. Next, the mixture was sonicated in an ultrasonic bath (Branson Ultrasonic 2800 bath) for 2 minutes to produce a homogenous solution of 5CB microdroplets. The size of the 5CB microdroplet can be controlled by increasing sonication time. The increasing sonication time reduces the size of the microdroplet formed. Finally, a drop of 2 µL 5CB microdroplet solution was pipetted into a trapping chamber for size-viewing and trapping processes. In this research, the 5CB microdroplet of 1.1 µm ± 0.1 µm and 2.0 µm ± 0.1 µm diameters were selected in this study. Figure 2 shows the schematic diagram and real diagram of the trapping chamber containing 5CB microdroplets.



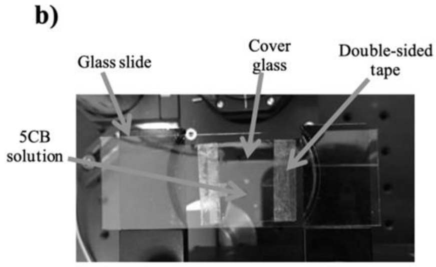
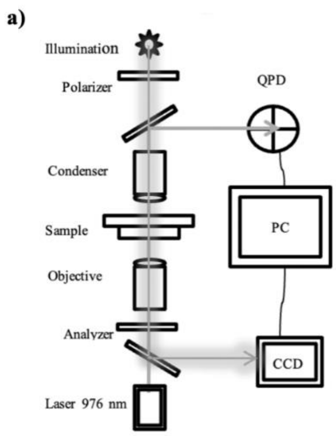


Figure 2. (a) Schematic diagram of trapping chamber containing 5CB microdroplet,(b) Real trapping chamber diagram.

Optical Setup

The optical trapping system was modified from the commercially available module (Thorlabs, OTKB/M). A 976 nm wavelength near-infrared laser beam was used as the primary trapping laser source in this setup. The objective lens (oil-immersion type, 100× magnification, 1.25 NA) focused the sample and trapped the 5CB microdroplet in the sample. The diameter of the laser spot size was 1.1 µm. The optical power density (P) was set to vary from 0.23 MW/cm^2 to 0.58 MW/cm^2. This study chooses only two droplet diameters to compare the strong and weak trapping based on the laser diameter spot size.

The lowest P indicates the minimum power density to start trapping a microdroplet. Condenser lens collected scattered light of trapped 5CB microdroplet. The scattered light was detected by quadrant photo-diode (QPD, PDQ80A). The illumination lamp was used to illuminate the sample and observed using a CCD camera. Analyzer and polarizer were used to identify the internal configuration of the trapped 5CB microdroplet. A custom-made software Optical Tweezers Calculator (OSCal) was used to analyze the scattered light signal to determine f_c and k_T.[27] Figure 3 shows the schematic diagram and real OTs setup.



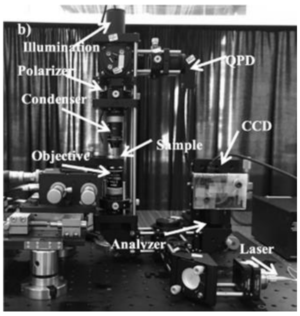


Figure 3. (a) Schematic diagram of OTs setup, (b) Real OTs setup.

Results and Discussion

5CB Microdroplet Trapping and Internal Configuration Observation

The 5CB microdroplet was observed under a CCD camera and cross-polarized view for internal configuration inspection. Based on observation under cross-polarized view, the 5CB microdroplet has a bipolar internal configuration. This internal configuration was expected as no surfactant was being used to prepare a 5CB microdroplet solution. The image of 5CB microdroplet under CCD camera, cross-polarized view and bipolar droplet schematic diagram are shown in Figure 4.

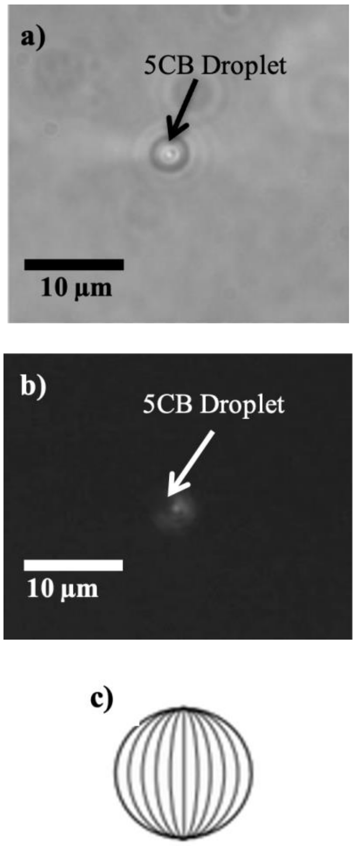
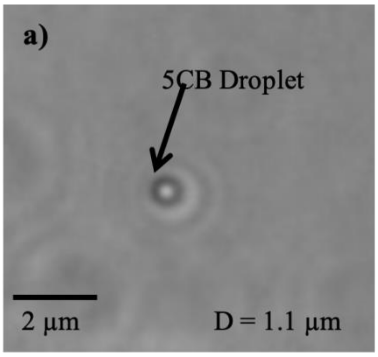


Figure 4. (a) Image of 5CB microdroplet under CCD camera, (b) Image of 5CB microdroplet under cross-polarize view and (c) Schematic diagram of microdroplet bipolar internal configuration.

The trapped 5CB microdroplet of diameter (D) = 1.1 µm ± 0.1 µm and 2.0 µm ± 0.1 µm was shown in Figure 5 (a) and (b).



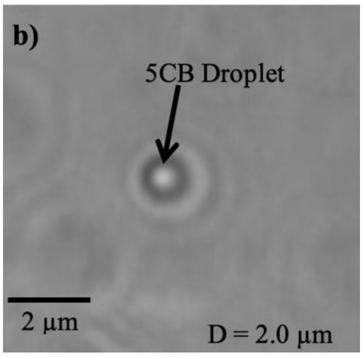


Figure 5. Observation of trapped 5CB microdroplet by a linearly polarized laser beam, (a) *D* = 1.1 µm and (b) *D* = 2.0 µm.

Based on Figure 5, the trapping was possible for both 5CB diameters. The research found that the trapping of the single 5CB microdroplet was stable for D = 2.0 µm but weaker for D = 1.1 µm. However, the trapping of D = 1.1 µm was stable at P = 0.23 MW/cm^2. As the P increase, the trapping fluctuates and is weaker. Meanwhile, for D = 2.0 µm, stable trapping was observed at all P measured.

Corner Frequency (f_c) of Trapped 5CB Microdroplet

The 5CB microdroplet of 1.1 µm ± 0.1 µm and 2.0 µm ± 0.1 µm diameter (D) were optically trapped at P vary from 0.23 MW/cm^2 to 0.58 MW/cm^2. f_c and k_T were analyzed using custom-made software (OSCal). Figure 6 shows a graph of corner frequency (f_c) versus optical power density (P) for 5CB microdroplet D = 1.1 µm and 2.0 µm. f_c is directly proportional to P and inversely proportional to D.

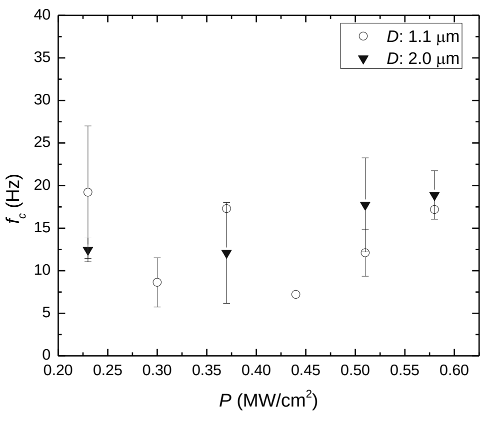


Figure 6. Graph of corner frequency (f_c) versus optical power density (P) for 5CB microdroplet D = 1.1 µm and 2.0 µm.

Based on Figure 6, f_c values were not linear and varied at increasing P for D = 1.1 µm. This fluctuation of f_c is contributed by weak trapping. However, Figure 6 shows f_c values increase at increasing P at D = 2.0 µm due to stable trapping. This trend shows that the size (D) of the 5CB microdroplet affect the stability of the trapping. Figure 6 also highlights that there was no significant difference in D and P on the f_c values. The higher value of f_c indicates the strong optical trap for stable optical trapping. This trend can be seen clearly for D = 2.0 µm.

Optical Stiffness (k_T) of Trapped 5CB Microdroplet

Based on f_c values obtained from Figures 6, k_T values were calculated using custom-made software (OSCal). The dependency of k_T with P is shown in Figure 7.

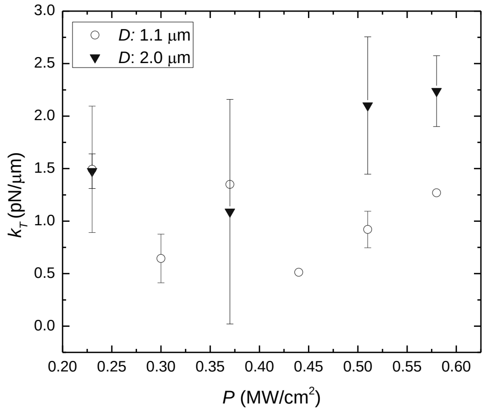


Figure 7. Graph of optical stiffness (k_T) versus optical power density (P) at 5CB microdroplet D = 1.1 µm and 2.0 µm.

Figures 7 shows the graph of optical stiffness (k_T) versus optical power density (P) for 5CB microdroplet D = 1.1 µm and 2.0 µm, respectively. For D = 1.1 µm, the trend of k_T at increasing P was varied. A similar fluctuation trend was observed in Figure 7. For D = 2.0 µm, the increasing trend of k_T increases when at P increases, as shown in Figure 7. There was no significant difference of k_T at lower P. However, at higher P there was a significant difference of k_T. Based on a previous study, k_T is directly proportional to P[28].

Microdroplet size (D) can affect trapping stability. This investigation achieved stable trapping for D = 2.0 µm but weaker for D = 1.1 µm. The stable microdroplet trapping shows an increasing relationship of f_c and k_T at increasing P. However, the weaker trapping shows a varied relationship of f_c and k_T. This research finding proved that the D of microdroplet affect the f_c and k_T. The main reason due to the weaker trapping is the scattering force. It was reported that dominant scattering force affects the trapping of polystyrene bead. Even though the polystyrene bead was not optically trapped in this study, dominant scattering force can affect the trapping of microdroplet. In the case of D = 1.1 ± 0.1 µm 5CB droplet, the laser spot size (d = 1.1 µm) was bigger than the trapped microdroplet diameter. Thus, there is the possibility that the light at the surface of the microdroplet diverges. Less light is refracted into the microdroplet compared to the light scattering at the surface of the microdroplet. This causes the scattering force to be dominant. The dominant scattering force causes trapping to become weaker. For D = 2.0 ± 0.1 μm 5CB microdroplet, the laser spot size (d = 1.1 μm) was smaller than the 5CB microdroplet diameter. Thus, all light is converged at the microdroplet surface, which causes better light refraction inside the microdroplet than the scattering of light at the microdroplet surface. Thus, the scattering force is less dominant and strong trapping occurs.

Conclusion

Based on this research, the optical power density (P) and microdroplet size (D) have provided a significant effect on corner frequency (f_c) and optical stiffness (k_T) trend. The stability of optical trapping depends on the size (D) of the 5CB microdroplet. In stable trapping, as the P increased, an increasing relationship was observed to an increasing of f_c and k_T. In the case of weak trapping, at increasing P, produced varies of f_c and k_T. The dependency of k_T with P and D can be seen clearly if stable trapping is achieved. This increasing trend is essential for precise control of the 5CB microdroplet probe in actuating and sensing applications. In addition, unstable trapping can be avoided by using a microdroplet bigger than laser spot size. However, if the microdroplet is too large, the trapping will become challenging as the microdroplet weight will counter the scattering force of light. In future, we will study the empirical relationship and dependency between D and k_T. This study compared only two sizes of microdroplets. In future work, we would like to extend a broader range of microdroplets size.

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