QUANTITATIVE OPTICAL MANIPULATION OF A SINGLE 4-CYANO-4'-PENTYLBIPHENYL MICRODROPLET IN WATER FOR ACTUATING AND SENSING APPLICATIONS

MUHAMAD SAFUAN BIN MAT YENG @ MAT ZIN

SULTAN IDRIS EDUCATION UNIVERSITY

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ABSTRACT

The study aims to formulate the production of 4-cyano-4'-pentylbiphenyl **(**5CB) microdroplets within a suitable range to be optically trapped, to optically trap a single 5CB microdroplet in water within a suitable size range, to optically micro-control the microdroplet using a circularly polarized laser, and to quantitatively determine factors affecting the optical manipulation of the microdroplet. 0.5 µL 5CB was mixed with the deionized water and sonicated to produce bipolar and radial 5CB microdroplet suspensions. The 5CB microdroplet was observed under optical microscopy and its size distribution was measured using ImageJ, while its stability was measured using UV-Vis spectroscopy. A linearly polarized laser beam of 976 nm wavelength was used to optically trap a single 5CB microdroplet in water at a specific laser power density. A circularly polarized laser beam was used to optically trap a single 5CB microdroplet to study its orientation control, rotatability control, and simultaneous translation micro-control. A single 5CB microdroplet was trapped and introduced to the cetyltrimethylammonium bromide (CTAB) solution to study its visual internal configuration change and optical signal. The finding shows that the size distribution of 5CB microdroplet suspension decreased with time. However, it was stable and sustained in 1-hour monitoring. The 5CB microdroplet could be linearly translated and rotated, enabling the simultaneous translation-micro-control. The corner frequency (f_c) and angular speed (ω) showed an increasing trend with optical power density (P) increment. Exposing CTAB solution to the trapped 5CB microdroplet changed its internal configuration from bipolar to radial, optical signal and displacement variance (σ^2). In conclusion, the trapped 5CB microdroplet could be micro-controlled as a microactuator while f_c, ω, and σ^2 measurements were characteristics of microdroplet-based sensors. This study implies that the optical trapping of a single 5CB microdroplet in water has potential for prospective actuating and sensing applications.

PEMANIPULASIAN OPTIK KUANTITATIF BAGI SATU MIKROTITISAN 4-SAIANO-4'-PENTILBIFENIL TUNGGAL DALAM AIR UNTUK APLIKASI PENGGERAKAN DAN PENDERIAAN

ABSTRAK

Kajian ini bertujuan untuk merumuskan penghasilan mikrotitisan 4-saiano-4'-pentilbifenil (5CB) dalam julat yang sesuai untuk diperangkap secara optik, untuk memerangkap secara optik satu mikrotitisan 5CB tunggal di dalam air dalam julat saiz yang sesuai, untuk memikrokawal mikrotitisan tersebut menggunakan alur laser berkutub bulat, dan untuk menentukan secara kuantitatif faktor-faktor yang mempengaruhi pemanipulasian optik mikrotitisan tersebut. 0.5 µL 5CB telah dicampur dengan air ternyahion dan disonikasi dalam tempoh masa yang khusus untuk menghasilkan ampaian mikrotitisan 5CB dwikutub dan jejarian di dalam air. Mikrotitisan 5CB telah diperhatikan melalui mikroskopi optik dan taburan saiznya diukur menggunakan ImageJ manakala kestabilannya diukur menggunakan spektroskopi UV-Vis. Satu alur laser berkutub linear yang mempunyai panjang gelombang 976 nm digunakan untuk merangkap secara optik satu mikrotitisan 5CB tunggal pada ketumpatan kuasa laser tertentu. Alur laser berkutub bulat pula telah digunakan untuk merangkap secara optik satu mikrotitisan 5CB tunggal bagi mengkaji kawalan orientasi, kawalan kebolehputaran, dan translasi mikrokawalan serentak mikrotitisan tersebut. Satu mikrotitisan 5CB tunggal juga diperangkap dan didedahkan kepada larutan setiltrimetilammonium bromida (CTAB) untuk mengkaji perubahan konfigurasi dalaman secara visual dan signal optik mikrotitisan tersebut. Dapatan menunjukkan bahawa taburan saiz ampaian mikrotitisan 5CB berkurang dengan masa. Akan tetapi, mikrotitisan tersebut stabil dan kekal dalam pemantauan selama 1 jam. Mikrotitisan 5CB tersebut juga boleh diperangkap secara linear dan diputar, membolehkan translasi-mikrokawalan serentak. Frekuensi penjuru (f_c) dan kelajuan sudut (ω) menunjukkan trend yang meningkat dengan peningkatan ketumpatan kuasa laser P. Pendedahan larutan CTAB terhadap mikrotitisan 5CB yang diperangkap telah menukarkan konfigurasi dalaman daripada dwikutub kepada jejarian, isyarat optik dan sesaran varians (σ^2) mikrotitisan tersebut. Kesimpulannya, mikrotitisan 5CB tunggal yang diperangkap boleh dimikrokawal sebagai mikropenggerak manakal pengukuran f_c, ω, dan σ^2 pula merupakan ciri-ciri penderia berasaskan mikrotitisan. Kajian ini menunjukkan bahawa perangkap optik satu mikrotitisan 5CB tunggal dalam air berpotensi untuk prospektif aplikasi penggerakan dan penderiaan.

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LIST OF SYMBOLS

SYMBOLS	MEANING	UNITS
r	Radius	m
k_B	Boltzmann constant	J/K
T	Temperature	K
F_g	Gradient force	N
F_s	Scattering force	N
D	Diameter	m
λ	Wavelength	nm
n	Refractive index	---
F_r	Restoring force	N
σ^2	Displacement variance	V^2
k	Optical stiffness	pN/μm
f_c	Corner frequency	Hz
ω	Angular speed	Hz
Γ	Optical torque	Nm
P	Optical power density	MW/cm^2

LIST OF CONSTANT

SYMBOLS	MEANING	UNITS
π	Pi constant	
k_B	Boltzmann constant	J/K

LIST OF ABBREVIATIONS

ASCII	American Standard Code for Information Interchange
CCD	Charged Couple Device
NA	Numerical Aperture
PSD	Power Spectrum Density
QPD	Quadrant-Photodiode
WD	Working distance
ET	Equipartition Theorem
BS	Boltzmann Statistics
NLCM	Nematic Liquid Crystal Microdroplet
PDMS	Polydimethylsiloxane
LC	Liquid Crystal
SDS	Sodium Dodecyl Sulfate
CTAB	Centrimonium Bromide

APPENDIX LIST

CHAPTER 1

INTRODUCTION

1.1 Research Background

The light radiation pressure exerts a force when it comes into contacts with a particle. The force that arises from the light radiation pressure is called optical force. The optical force was applied in an instrument called optical tweezers. Arthur Ashkin, the pioneer of optical trapping, was awarded the 2018 Nobel Prize in Physics for his invention of optical tweezers for biological applications (Goswami, 2018). Optical tweezers use a strong, focused laser beam to confine the particle by benefiting optical force. Optical

forces mainly contributed to the pulling gradient force and pushing scattering force in optical trapping.

It is possible to manipulate small objects in the range of micrometers or smaller using light by optical tweezers (Malmqvist & Hertz, 1992; Pai, Zandrini, Mart, & Bragheri, 2018). The intense focus laser beam creates an optical trap where it provides non-contact micro-manipulation of a non-destructive technique of the trap particle. Subsequently, optical trapping provides minimization of the sample flaw, especially when handling soft and fragile particles like biological material. Optical trapping not only provides manipulation of the trap particle but also provides several applications. In the context of optical trapping applications, it is possible to conduct physical measurements such as viscosity, stiffness, and elasticity for example, DNA, with the help of polystyrene or silica probing (Buosciolo et al., 2004; Müllenbroich et al., 2013). The study of the microparticle trajectory by the optical trapping is useful for microrheological measurement (Aziz et al., 2015). These are the several applications performed by the optical trapping.

Optical trapping is also used in the chemistry field. This process is called laser trapping. Laser trapping application involves the system domain from quantum-scale atom trapping to the micro-scale system (David et al., 2013; Neves et al., 2015). Laser trapping shows a novel potential for light-matter interaction in molecular systems by triggering nucleation-induced crystallization growth and supramolecular assemblies (Sugiyama et al., 2012; Supian et al., 2010). Figure 1.1 (left) illustrates the laser trapping principle, while Figure 1.1 (right) illustrates the trapping assembly of

nanoparticles, polymers, and molecular clusters. The red parabolic line represents the optical potential energy in the sample.

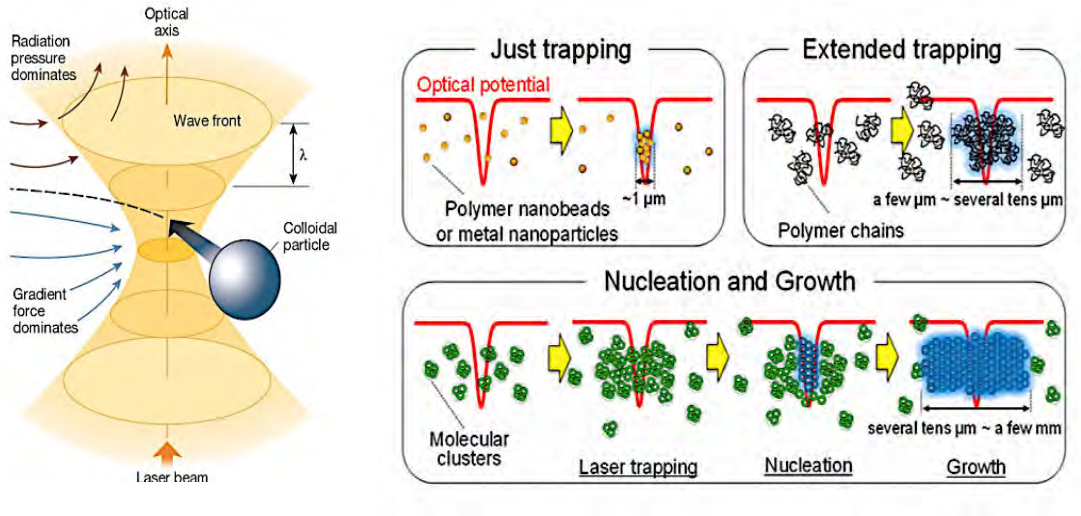

Figure 1.1. (Left) Laser trapping principle. (Right) Schematic representations for the trapping and assembly of nanoparticles, polymers, and molecular clusters. [Adapted from (Sugiyama et al., 2012).

The application of laser trapping can be classified into Just trapping, Extended trapping, and Nucleation and Growth. The "Just trapping" refers to the laser trapping of polymers that occurs within the laser spot size in the range of ~ 1 μm. The "Extended trapping" of polymer chains can occur within a few to several tens microns beyond laser spot size due to the nature of the polymer, for example, due to intermolecular interactions. Lastly, in the context of nucleation and growth, nucleation is induced, resulting in a large crystal scale from several ten microns to a few millimeters. The extension of optical trapping beyond just trapping capability has opened a new direction in molecular control using light.

Recently, the optical trapping has shifted from trapping solid matter to soft matter, such as liquid crystals. Liquid crystal has unique properties where it co-exists in between solid and liquid states, anisotropic, birefringent, and sensitive to electric and magnetic fields (Brasselet & Juodkazis, 2009; Phanphak et al., 2014). Optical trapping of the liquid crystal can be performed in the form of a liquid film or a microdroplet (Brasselet, 2008; Brasselet et al., 2003). Interestingly, liquid crystal obtains multiple domain configurations, such as nematic, smectic, and cholesteric, which are sensitive to the light polarization state (Brasselet & Juodkazis, 2009). 4'-Pentyl-4-cyanobiphenyl (5CB) is one of the most attractive nematic liquid crystals (NLC) as it exhibits liquid crystal properties of nematic phase domain at room temperature (18–35 °C) (Hanemann et al., 1995). Therefore, 5CB is a suitable model compound to study the physical behavior of simple nematics. Figure 1.2 shows the chemical structure of 5CB.

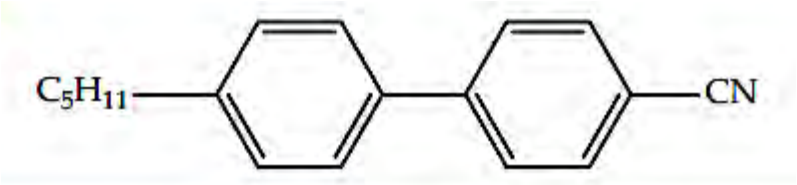

Figure 1.2. 5CB chemical structure. Adapted from (Yeng, Ayop, & Sasaki, 2022).

The dispersion of liquid crystals with an immiscible solvent such as water creates liquid crystal droplets. For example, 5CB produces a nematic liquid crystal droplet in water. In droplet form, the nematic liquid crystal has a unique internal configuration. Internal configuration refers to the domain alignment within the nematic liquid crystal droplet. The internal configuration can be controlled by surface modification with a surfactant. Tailored polarization of light can manipulate a single

nematic liquid crystal microdroplet (Usman et al., 2011). Figure 1.3 shows an example of the internal configuration of a nematic liquid crystal microdroplet.

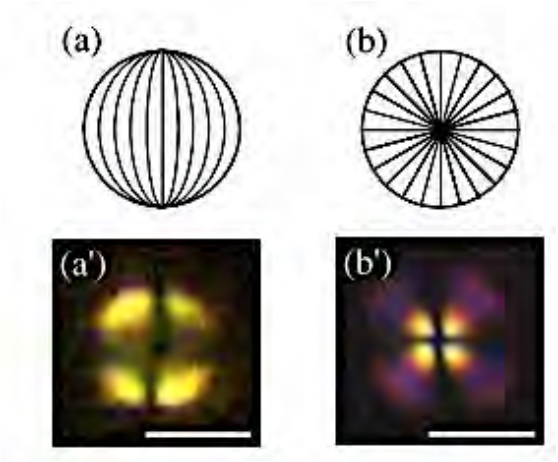

Figure 1.3. Liquid crystal internal configuration in a nematic liquid crystal microdroplet (a) bipolar and (b) radial. Observation under cross-polarization view [Adapted from ((Brasselet & Juodkazis, 2009)].

Optical trapping of nematic liquid crystal microdroplets is possible when the refractive index of the droplet is larger than the surrounding refractive index. Instead of using solid silica and polymer particles, an optically engineered liquid crystal microdroplet is flexibly shaped, allowing rotational control when exposed to the light polarization during optical trapping (Pai et al., 2018). This proposed study will help to design microfluidic devices that integrate liquid crystals as optically controlled microactuators in water filtration devices, lab-on-chips, liquid crystal-based sensors, or new technologies.

As sensitive sensors, liquid crystal droplets are indispensable in environmental and biomedical science (Niu et al., 2016). This is because liquid crystal droplets are a potential optical, biological sensor due to high birefringence and high sensitivity of

liquid alignment of liquid crystal molecules to minute variation on the surface. Molecular events occurring at an interface between liquid crystal and water can be amplified and converted into electrical signals by the change in orientation of liquid crystal molecules, which are visible to the naked eye under a polarizing microscope (Niu et al., 2016). The liquid crystal-based sensor can detect proteins, nucleic acids, acetylcholine, glucose, enzymes, cholic acid, antibodies, and other molecules during sensing application.

1.2 Problem Statement

Optical tweezers are commonly used to trap and manipulate particles in a liquid. For example, most microscopic biological particles must be trapped within the liquid. Recent studies showed that microparticles in liquids can form two-dimensional structures by laser guidance (Kudo et al., 2016; Shih et al., 2021; Wu et al., 2018). However, it was experimentally successful with gold nanoparticles and polystyrene beads, even if the theoretical explanation of the observed phenomena is not yet mature. One hypothesis states that the lattice-like arrangement is due to light propagation through the dielectric properties of the trapped particles. Liquid crystals can have both solid-like and liquid-like properties. The magnetic, electrical, and optical methods can control the internal configuration inside the liquid crystal droplet. The physical properties of liquid crystals depend highly on the alignment of liquid crystal molecules in a closed cell. The study of optical trapping utilizing light propagation catalyzes new pathways in the assembly, manipulation, and crystallization

of microparticles, nanoparticles, supramolecules, and soft matter, as anticipated in this study.

The previous researcher reports that the general formulation of nematic liquid crystal microdroplet production thus leads to a reproducibility problem (Choi et al., 2015; Juodkazis et al., 1999; Lee et al., 2015; Murazawa, S. Juodkazis, 2005; Suga et al., 2018; Z. Wang et al., 2020). There are no specific formulations, recipes, or technical reports to prepare nematic liquid crystal microdroplets. The reported nematic liquid crystal microdroplet was relatively large (>10 μm) (Duan et al., 2019; Kiang-Ia et al., 2021; Shechter et al., 2020). The nematic liquid crystal microdroplet must be a small, miniaturized version of the liquid crystal-based probe. The bigger liquid crystal microdroplet is inert with a small optical force in optical trapping application. The smaller probe can increase surface volume sensitivity for sensing applications.

Furthermore, although previous researchers reported optical trapping of a single nematic liquid crystal microdroplet, they only reported qualitative observation of nematic liquid crystal microdroplet trapping by studying the behavior of the trapped liquid crystal microdroplet under light polarization (Phanphak et al., 2014; Shechter et al., 2020; Usman et al., 2013). No study quantifies the change in the internal configuration of the nematic liquid crystal microdroplets in terms of optical signal but instead just observing the changes visually (Murazawa, Juodkazis, Matsuo, et al., 2005; Shechter et al., 2020). The study of the optical stiffness of nematic liquid crystal microdroplets based on the optical which is relevant for evaluating the strength of the optical trap, is also not reported. Hence, there is a lack of information on the trend of

optical stiffness with exposure to different optical power densities and microdroplet sizes for soft matter optical trapping.

In addition, the optical manipulation of the liquid crystal microdroplet has been reported on the dynamic behavior when the laser polarization state used is varied (Saito & Kimura, 2022). However, there is no combination of simultaneous translational and polarization control of liquid crystal microdroplet has been reported. This combination is expected to enrich liquid crystal microdroplets for actuating application. In the context of rotational study, the laser power used is larger, and the size of the microdroplet is bigger, as reported by previous researchers. This becomes an issue when the use of strong laser power tends to destroy the liquid crystal nematic phase, and bigger microdroplets are challenging to actuate in tiny areas of actuation. Hence, there is a requirement to reduce laser power and microdroplet size for actuating application using liquid crystal microdroplet trapping.

The conventional liquid crystal-based sensor observes the transition liquid crystal configuration without converting the changes into a quantitative signal, possibly causing the false judgment when the liquid crystal microdroplet is smaller (Lee et al., 2015; Niu et al., 2016). The existing liquid crystal-based sensor requires many large liquid crystal droplet sizes for detection because the detection is based on the internal configurational change of bigger microdroplets (Lee et al., 2015; Niu et al., 2016). The current liquid crystal-based sensor applied a lasing technique to increase the detection sensitivity by using only a single microdroplet. However, the microdroplet used for detection is stuck on the glass slide or hung at the end of the micro syringe which causes deformation in shape because of poor control, immobilize and bigger droplet size,

leading to a reduction in sensitivity (Duan et al., 2019; Duan, Hao, et al., 2020; Duan, Li, et al., 2020). Determining the properties of liquid crystal-based probes is essential for future use in microactuators and microsensors in liquids.

This study uses a nematic liquid crystal microdroplet solution. The challenge of this study is to produce a nematic solution with a homogeneous size with a specific internal configuration in the 5CB microdroplet and quantifying the optical manipulation of 5CB microdroplet due to the nature of soft matter. The molecular alignment that determines the internal configuration is possible by inducing surface modification of the microdroplets. Furthermore, this study develops the optical manipulation of a single microdroplet for a liquid-crystal-based actuator and a liquid-crystal-based sensor involving optical signal transition in a liquid-crystal configuration with a quadrant photodiode (QPD).

1.3 Research Objective

This study aims to optically trap and manipulate 4-Cyano-4'-pentylbiphenyl (5CB) microdroplets in water. The objectives of the study are:

1. To formulate the production of 5CB microdroplets within a suitable range to be optically trapped.
2. To optically trap a single 5CB microdroplet in water within a suitable size range using 976 nm laser.
3. To optically micro-control a single 5CB microdroplet in water using a circularly polarized laser.

4. To quantitatively determine factors that affect the optical manipulation of the 5CB microdroplet for actuating and sensing applications.

1.4 Significance of Research

This research examines the optical trapping array of nematic liquid crystal microdroplets. This research studies and observes the interaction of light with 5CB microdroplets. It explains the physical interaction between 5CB micro-droplets for non-contact micro-actuators in liquid crystal-based sensor applications.

In addition, the importance of this research lies in the polarization control of light using 5CB microdroplets. This study hypothesizes that light polarization affects the capture of 5CB microdroplets as they are prone to a light polarization state. Varying the laser polarization state used leads directly to a change in the intrinsic configuration of the 5CB microdroplet. The cross-polarization view and electrical signal from QPD observe and detect intrinsic configurational changes within the 5CB microdroplet.

Because liquid crystal is inherently birefringent, this study assumes that the optical strength of 5CB microdroplet capture varies with the polarization state of the capture laser at the same optical density. In addition, due to internal light loss and light loss at the interface, it is expected that the optical strength is not constant for all 5CB microdroplet sizes in the tuned range.

The optical signal change of the internal configuration of the 5CB microdroplet is characterized in the context of corner frequency and optical stiffness measurements. This finding is crucial for application in microactuators and sensor applications. Determining optical stiffness is useful for precisely controlling liquid crystal-based probe applications because optical stiffness shows the trend of the optical trapping with respect to varied parameters such as laser power and microdroplet size. Hence, the researcher can predict the suitable laser power and probe size for prospective application. In addition, optical stiffness measurement results are expected to vary for the internal configuration of bipolar and radial 5CB microdroplets. This finding helps to precisely characterize the transient change of liquid crystal-based sensors especially during the transitional change from bipolar to the radial internal configuration of liquid crystal microdroplets, to determine the significant difference to be applied for quantitative sensing mechanism, instead of observing them visually, in the microsensor application.

1.5 Limitation of Research

This study focuses on 5CB microdroplet trapping. The phase selected for trapping is nematic. The single droplet in the nematic phase is optically captured. 5CB is used as the primary liquid crystal to produce a 5CB microdroplet. As already mentioned, 5CB exists as a liquid crystal at room temperature; Thus, it instantly creates 5CB micro-droplets in the water. Deionized water is chosen as the primary liquid for optical capture. Other liquid crystals could exist as a pure solids or liquids at room

temperature, which is unsuitable for producing microdroplets. Therefore, the 5CB is dispersed and homogenized in deionized water at room temperature.

The laser tweezers optically trap a single 5CB microdroplet in water with a radius of 0.6 µm to 3.7 µm. The 5CB micro-droplet radius of less than 0.5 µm is challenging to see clearly under the CCD camera due to the resolution limitation of the optical tweezers. In addition, capturing more than one droplet at a time can be problematic as it disrupts the 5CB optical signal. Subsequently, the internal configuration of the 5CB microdroplets is focused on the bipolar and radial configurations.

The optical trapping process of this experiment depends on the optical tweezers OTKB(/M). Furthermore, the setup of the optical trap of this experiment depends on the oil immersion objective lens (NA 1.25, 100×) and the optical resolution ≈ of 500 nm. Optical resolution is the limitation of the instrument used to perform optical capture. The laser power ranges from 0.2 MW/cm^2 to 7.3 MW/cm^2. The lower laser power is essential for capturing 5CB microdroplets sensitive to temperature changes. Too much laser power severely destroys the nematic phase of the 5CB microdroplet.

1.6 Thesis Outline

This thesis essentially consists of 5 chapters. Chapter 1 provides the background to the study and the direction and goal of the research. The central part of this chapter is the problem and the research goal.

Chapter 2 deals with the principle of optical trapping. The theory for calibrating the optical stiffness of the optical tweezers is presented. The previous reports on the optical trapping of solid particles and liquid microdroplets are presented. The introduction of liquid crystals, and the optical capture of liquid crystals are also discussed. In addition, the use of liquid crystal microdroplets in actuator and sensor applications is also described.

Chapter 3 describes the methodology of the research. The first part of the methodology is the setup and alignment of optical tweezers. The second part involves the preparation of the 5CB microdroplet suspensions in water. The fourth part is the optical trapping of the 5CB microdroplet in water using a linearly and circularly polarized laser beam. The methodology's last part analyzes the distribution size and stability of the 5CB microdroplet suspension, the simultaneous translation and micro control, the corner frequency, the angular velocity, and the displacement variance of the captured single 5CB microdroplet.

In Chapter 4, the results of the conducted experiment are discussed. The 5CB treatment generates the ultrasonic microdroplet and is observed under the optical microscope. The distribution size and the stability of the 5CB microdroplet are

presented. In addition, the effect of the linearly and circularly polarized laser beam on the trapped 5CB microdroplet is observed. The corner frequency and angular velocity of the trapped 5CB microdroplet are discussed. In addition, the transitional change in the internal configuration of 5CB is quantitatively calculated and presented.

Chapter 5 discusses the conclusion of the research findings on the research findings. Finally, recommendations are given to improve and expand the research for further studies.

1.7 Summary

This chapter presents the background of the study, the problem, the research goals, the importance of the research, and its limitations.