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OPTICAL TRAPPING OF A SINGLE CHLOROFORM MICRODROPLET IN WATER

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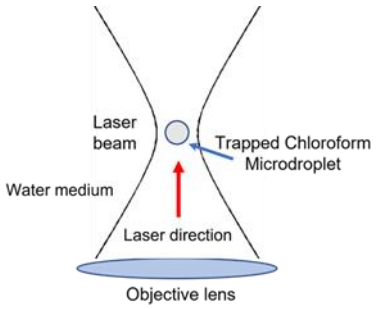
Graphical abstract



Abstract

The study aims to optically trap a single chloroform ($CHCl_3$) microdroplet in water using optical tweezers. The study also investigates the effect of the preparation procedure by sonication on the chloroform microdroplet size and its stability in water. This microdroplet can potentially act as a carrier containing active molecules and for sensor applications in a fluid. The chloroform is sonicated in deionized water to produce a chloroform microdroplet solution. The size of the resultant microdroplets is observed under the optical microscope. The stability of the chloroform microdroplets in water was studied by monitoring the absorption spectra within a specified duration of time for 1 hour. A single chloroform microdroplet in the water is trapped using a 976 nm continuous laser beam with optical tweezers. The finding shows that the average size of the produced chloroform microdroplets does not vary significantly when the sonication time is less than 10 minutes. Furthermore, Chloroform microdroplets in water were stable within an hour of monitoring time. This study confirmed that a single chloroform microdroplet could be stably trapped using optical tweezers. It implies that the chloroform can form stable microdroplets in water and can be optically trapped under a focused laser.

Keywords: Chloroform, microdroplet, optical tweezers

Abstrak

Kajian ini bertujuan untuk memerangkap mikrotitisan kloroform ($CHCl_3$) tunggal secara optik di dalam air menggunakan penyepit optik. Kajian ini juga menyelidik kesan prosedur penyediaan dengan sonikasi terhadap saiz mikrotitisan kloroform dan kestabilannya di dalam air. Mikrotitisan tersebut berpotensi sebagai pembawa yang mengandungi molekul aktif dan boleh dikawal dengan bebas menggunakan penyepit optik untuk aplikasi penderia di dalam bendalir. Kloroform disonikkan dalam air ternyahion untuk menghasilkan larutan mikrotitisan kloroform. Saiz mikrodroplet terhasil dicerap dengan mikroskop optik. Kestabilan mikrotitisan klorofom di dalam air dikaji dengan pemantauan spektrum penyerapan dalam sela masa yang ditetapkan selama satu jam. Satu mikrotitisan kloroform di dalam air diperangkap dengan penyepit optik menggunakan alur laser selanjar berpanjang gelombang 976 nm. Dapatan menunjukkan saiz purata mikrotitisan kloroform tidak berubah dengan signifikan terhadap masa sonifikasi kurang 10 minit. Mikrotitisan kloroform di dalam air adalah stabil dalam tempoh pemantauan satu jam. Kajian ini mengesahkan bahawa satu mikrotitisan kloroform tunggal boleh diperangkap dengan stabil menggunakan penyepit optik. Ini menunjukkan bahawa kloroform boleh membentuk mikrotitisan stabil di dalam air dan dapat diperangkap secara optik dengan laser terfokus.

Kata kunci: Kloroform, mikrotitisan, penyepit optic

1.0 INTRODUCTION

Chloroform ($CHCl_3$) is an organic compound used as an organic solvent. Functional molecular sensors and actuators such as calixarene uniformly dissolve in the chloroform [1], [2]. Therefore, the chloroform in the form of a microdroplet can act as a carrier or probe to contain these molecular sensors or as a microreactor [3]. The chloroform can form into microdroplets in water because its solubility in water is 8.09 g/L.

To control a single microdroplet, optical tweezers offer opportunities for 3-dimensional non-contact manipulation [4]–[6]. Figure 1 illustrates the trapped chloroform microdroplet with optical tweezers. The objective lens of high numerical aperture creates an intensely focused laser to cause the microdroplet to be attracted. The trapping is due to the optical tweezers' gradient and scattering forces with the trapped object.

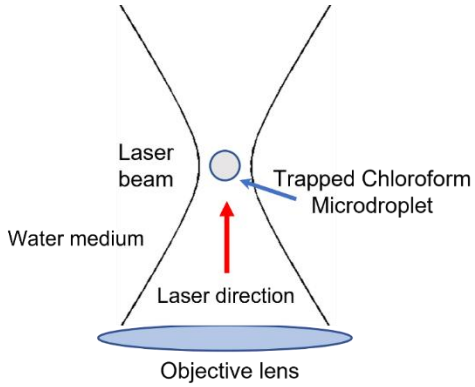


Figure 1 Trapped Chloroform Microdroplet by Optical Tweezers

Half of the 2018 Nobel Prize in Physics went to work by Arthur Ashkin on applications of optical tweezers in biological systems [7], [8]. The discovery enables the precise control and manipulation of microparticle objects, such as natural cells and colloids, using a focused laser without mechanical contact [9]–[11]. An intense, focused laser can induce the crystallization and self-organization of a molecular system [12], [13]. Optical manipulation with optical tweezers is possible if the trapped particle is optically denser than its surroundings. Therefore, it is possible to trap a liquid microdroplet using optical tweezers [14]–[18]. This effect allows the possible non-contact manipulation of the molecular sensor or microvial in the form of a microdroplet.

Recent studies report the optical trapping of organic solvents in the microdroplet [19], [20]. The results underscore that optical trapping of organic solvents in the form of microdroplets in water is possible by considering solvent solubility, density, and refractive index. This microdroplet can potentially act as a carrier to contain active molecule and can be freely controlled using optical tweezers for sensor applications in a fluid. In this study, we report on chloroform microdroplet production and its stability in water. Subsequently, a single chloroform microdroplet's stability within optical trapping is presented. Chloroform microdroplet production is essential in determining the correct distribution size of microdroplets for optical trapping applications. Too small microdroplets are invisible due to the limited resolution of an optical microscope, while too large microdroplets are inert to optical forces exerted by optical tweezers. In addition, the stability of the chloroform microdroplet solution is critical to ensure that the microdroplet is well dispersed, stable and will not either burst or sink into the selected medium within the monitoring time. This research is expected to provide a deeper understanding and fundamental knowledge of how a solvent can be made into microdroplets. Among future application of the optically controlled chloroform, micro-droplet are as a drug delivery carrier in a microfluidic channel lab- on-chip and ideal reaction micro-vessel for single-molecule studies.

2.0 METHODOLOGY

In this study, the preparation of chloroform microdroplets solution required 10 µL and 20 µL of chloroform liquid into separate 2 mL vials, each containing 1 mL of deionized water. The mixture was sonicated for 0.5 minutes in an ultrasonic bath (GT Sonic, VGT-1620QTD) to obtain chloroform microdroplet solutions. The sonication time for each sample was varied to 0.5, 1, 4, and 10 minutes to observe the effect of sonication time on the size of the produced microdroplets. Next, 5 µL of the chloroform-microdroplet solution was pipetted into a sample chamber and viewed under an optical microscope (Olympus GX-51). A CCD camera (Moticam 3) recorded the image of the chloroform microdroplet. The average distribution size of chloroform microdroplets produced was analyzed using ImageJ software from the image at a focal plane.

The microdroplet stability investigation and optical trapping experiment of the chloroform microdroplets were performed separately. Microdroplets suspension was monitored in elapsing time to investigate the stability of microdroplets solution in a vial. 1.8 mL chloroform microdroplet solution was transferred into a quartz cuvette for UV-Vis spectroscopic analysis (Agilent 8453). Figure 2 illustrates the light passing through the chloroform microdroplet solution. Figure 3 shows the absorption spectrum of a chloroform microdroplet solution. The stability of the solution was justified by monitoring the spectrum peak (λ = 198 nm) for an hour. The change in peak absorption indicates the change in microdroplets distribution along the path of the light transmission in the cuvette.

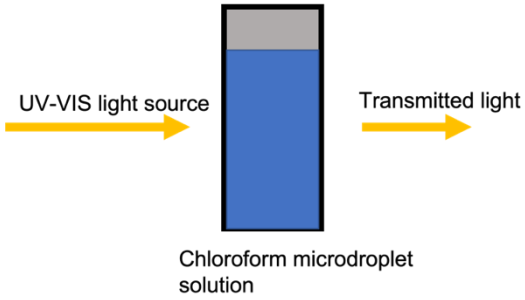


Figure 2 The stability monitoring of a chloroform microdroplet solution

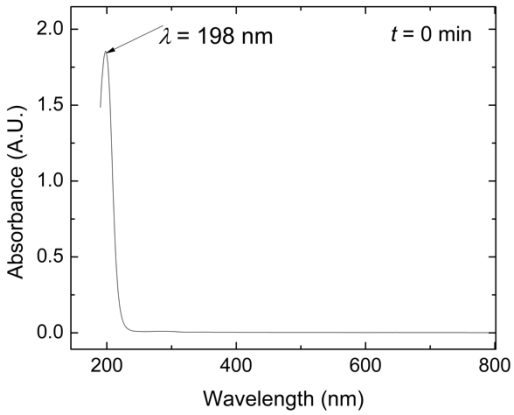


Figure 3 The absorption spectrum of a chloroform microdroplet solution.

To optically trap a chloroform microdroplet, a 5 µL chloroform microdroplet solution was pipetted into a dedicated cell chamber. Optical tweezers (OTKB/M Thorlabs) with a continuous 976 nm laser beam of 1.1 µm spot size were used to establish an optical trap in the sample chamber. The schematic diagram of the used optical tweezers is shown in Figure 4. The illumination lamp was directed to the sample chamber via a condenser lens. The illumination light passed the sample, collected by the objective lens, and directed to the CCD camera for visual observation. At the same time, the laser beam was focused inside the sample chamber by the objective and formed a trap spot. The laser power density varied from 1.1, 2.3, 3.6, 4.8, 6.1, and 7.3 MW/cm² to investigate the effect of increasing laser power on the trapped single chloroform microdroplet. The trapping stability of the microdroplet was monitored within a specified duration.

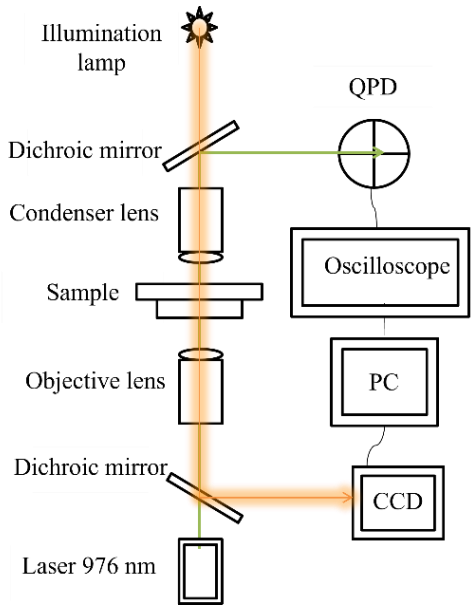


Figure 4 The schematic diagram of the optical tweezers.

3.0 RESULTS AND DISCUSSION

3.1 Effect of Sonication Time on the size of Chloroform Microdroplet

The effect of sonication time on the size of produced microdroplets was examined by putting the sample under optical microscopy observation. Figure 5 shows one of the observation images obtained under the optical microscope. One can immediately see microdroplets of various sizes. The size distribution was analyzed to get the average size for a sample after a predetermined sonication time.

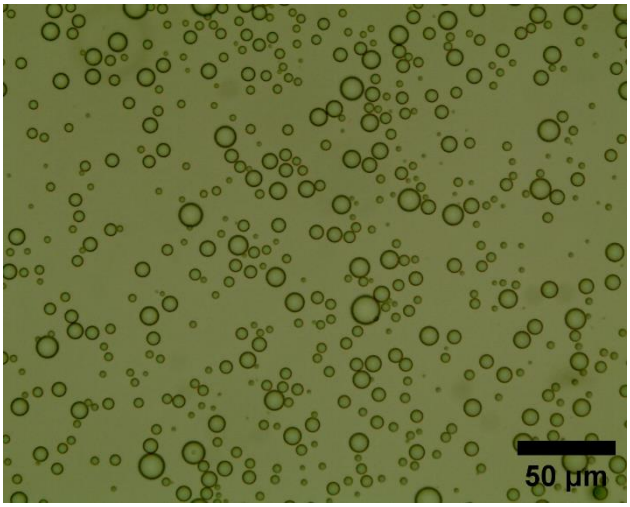


Figure 5 An image of chloroform microdroplet suspended in the water of 1-minute sonication

The effect of sonication time during solution preparation on the size of microdroplets in water was examined. Figure 6 shows the average radius of chloroform microdroplets, r, measured after being sonicated for a predetermined duration of time.

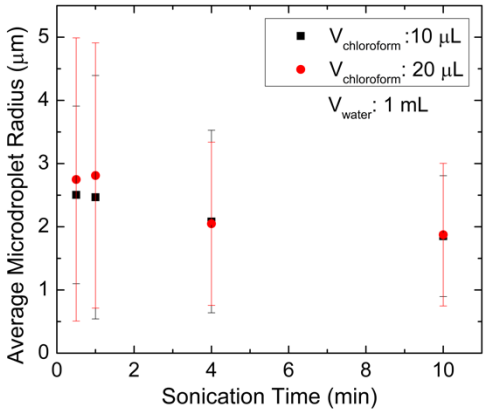


Figure 6 The average radius, r, of chloroform microdroplets versus sonication time for a mix of 10 µL and 20 µL chloroform in 1 mL water

Figure 6 shows no apparent change of r from the 0.5 to 4.0 minutes of sonication time with a broad range of sizes. However, as the sonication time increased to 10 minutes, r significantly decreased. The variation in r distribution also narrowed as the sonication time increased. The result offers guidance in producing a microdroplet of desired sizes. In this study, a 0.5-minute sonication time was sufficient to generate a wide variation in microdroplet size. Therefore, the microdroplet size can be chosen for a specific purpose.

Table 1 Selected material solubility in water and relative refractive index of the solvent to water

Material	Solubility in water* (g/L)	The relative refractive index of the material-to-water*
Ethanol	1000.00	1.011
Chloroform	8.70	1.086
Polystyrene bead	0	1.195

*data from https://pubchem.ncbi.nlm.nih.gov/

Chloroform can form microdroplets due to its low water solubility. Table 1 tabulates selected material solubility in water and the relative refractive index of the material to water for comparison. Polystyrene bead is the common solid substrate in optical trapping applications [21]. Meanwhile, optical trapping of ethanol microdroplet is impossible because ethanol completely solutes in water and cannot form a microdroplet solution as it has higher solubility. In this study, the sonication was used to produce chloroform microdroplets. The sonication process disperses chloroform liquid in water. The dispersed chloroform coalesces to form microdroplets. The microdroplets can break off and form smaller microdroplets. Longer sonication time may lead to smaller microdroplets, as shown in Figure 6.

3.2 Microdroplet Stability in Water

Figure 7 shows the absorption spectrum of a chloroform microdroplet solution. The arrow indicates the absorption peak of interest to monitor chloroform microdroplets concentration along the cuvette's light propagation (refer to Figure 2). The inset shows the zoomed graph at a 198 nm wavelength peak.

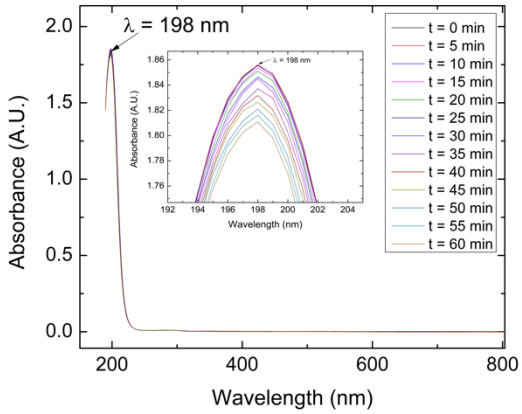


Figure 7 Absorption spectrum of chloroform for 1 hour monitoring period

The absorbance peak of chloroform microdroplets in the microdroplet solution at 198 nm wavelength was observed for 1 hour to determine its stability. Figure 8(a) shows the absorbance of chloroform versus time. During the 1-hour monitoring, there was 2% reduction in chloroform microdroplets in 1 hour. The decrease could be due to the sinking or evaporation of the chloroform microdroplet. Also, the absorbance of chloroform was compared to water in Figure 8(b) to evaluate how much of the chloroform microdroplets remained in the water.

Figure 8(b) shows that the absorption of chloroform microdroplets is higher than that of water. Furthermore, it showed that chloroform microdroplets were present in the water. Thus, the chloroform microdroplet was stable in water for 1 hour of observation time. This finding helps estimate how long chloroform microdroplets can sustain in water.

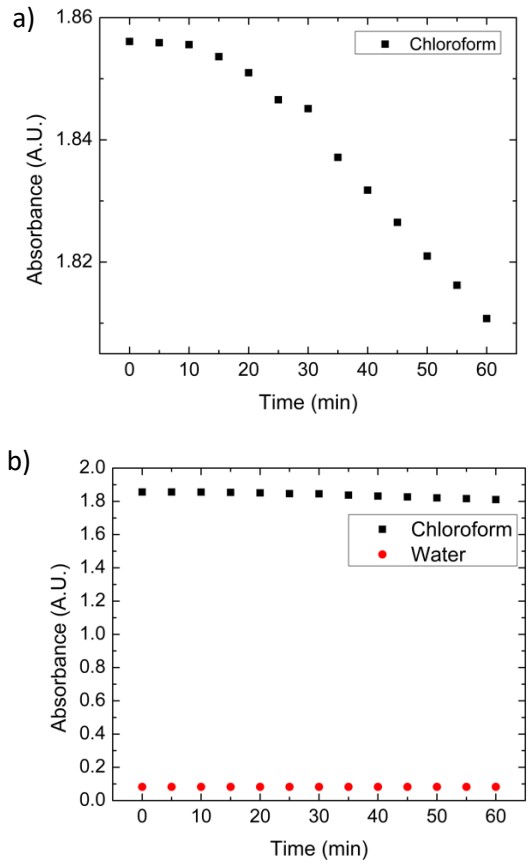


Figure 8 The graph of peak (λ = 198 nm) versus time in Figure 7. absorbance against time (a) chloroform, (b) chloroform, and water

3.3 ptical Trapping of a Single Chlorofom Microdroplet in Water

A higher index of refractive for the desired object to be trapped than its environment is one of the crucial factors for successful trapping [20]. However, even though ethanol has this property, its solubility in water makes it impossible to optical trapping (see Table 1). Therefore, solubility in water is another vital factor in optically trapping an object in the liquid phase.

The optical trapping of chloroform microdroplets was performed at increasing laser powers from 1.1 MW/cm2 to 7.3 MW/cm^2 and monitored by a CCD camera. Figure 9 shows a series of snapshots of the optical trapping of a single chloroform microdroplet at a selected laser power density.

Based on the observation shown in Figure 9, a chloroform microdroplet could be stably trapped at a low laser power density of 1.1 MW/cm^2 up to 7.3 MW/cm^2. Indeed, these chloroform microdroplet were stably trapped for more than an hour.

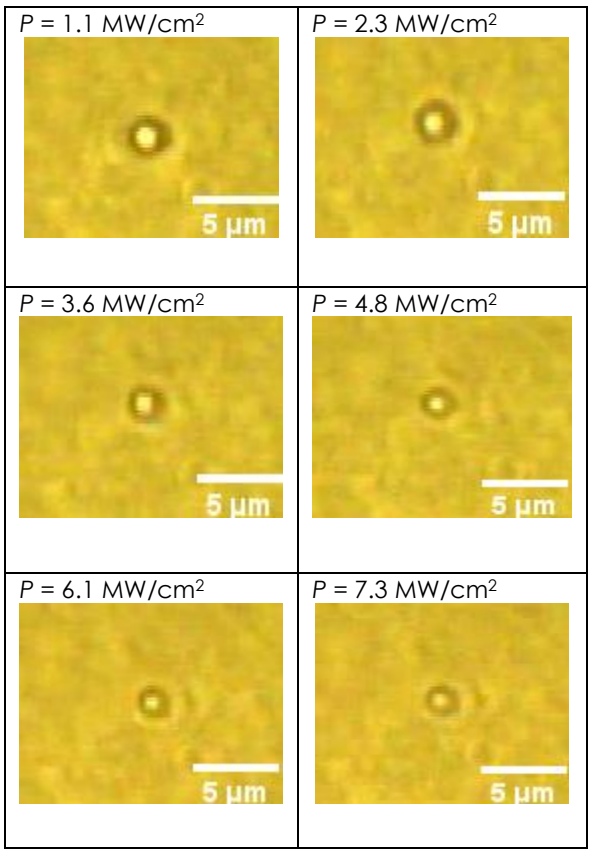


Figure 9 Snapshots of a single chloroform microdroplet optical trapping at specific laser power densities

The study of optical trapping of a single chloroform microdroplet was further investigated to observe the physical change of microdroplet size for 1 hour of monitoring time. Figure 10 shows the image of the trapped single chloroform microdroplet of different size and laser power for 1 hour. The microdroplet of the initial radius of 1.5 µm and 1.3 µm were trapped at 3.6 MW/cm^2 and 4.8 MW/cm^2, respectively. A graph of normalized radius change $\Delta = (r_o - r_t)/r_o$, where r_o is the initial radius and r_t is the radius at time t) against the trapping time is plotted to describe the observed microdroplet radius change, as shown in Figure 11. The observed size of the chloroform microdroplet decreased as optical tweezers held it for 1 hour. As the time was elapsing, the change in the trapped microdroplet radius Δ increased up to 20% in an hour. The possible reasons for the microdroplet shrink are due to the combined heating effect caused by the focused lased on the chloroform microdroplet and its water environment and the chloroform volatility, knowing that the boiling point of the chloroform is 61°C [22]. Therefore, although the optical tweezers could stably trap the chloroform microdroplet, its physical size shrinks over time.

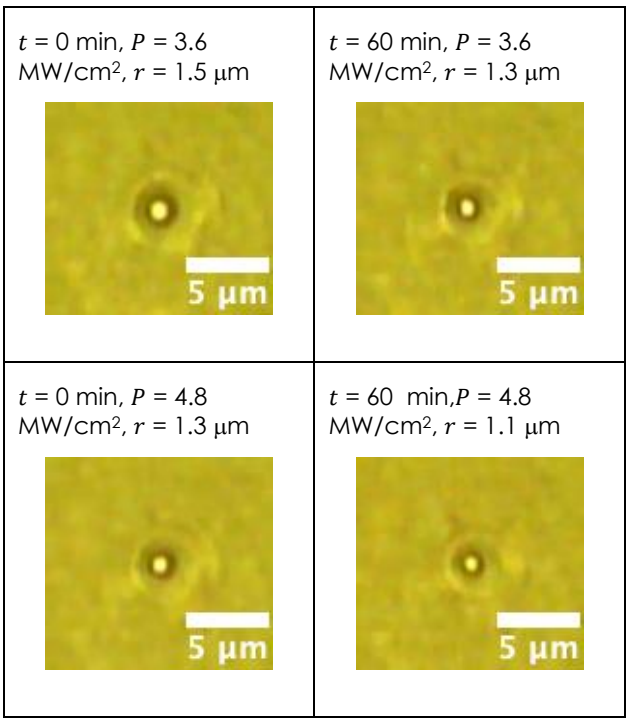


Figure 10 The observation images of the trapped chloroform microdroplet for 1 hour at different laser power and size.

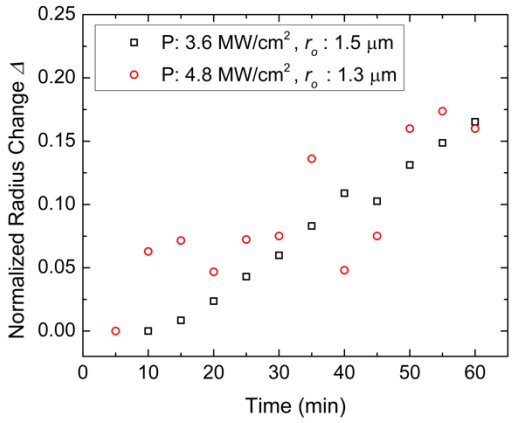


Figure 11 The graph normalized radius change against time

4.0 CONCLUSION

In summary, with a sonication time of fewer than 10 minutes, the finding shows no significant reduction in the average radius of the chloroform microdroplets. However, if the sonication time is extended beyond 10 minutes, the size of the microdroplet is significantly shrunk and narrows the average size distribution. The number of chloroform microdroplets suspended in water also decreases with time. The chloroforms microdroplet in the water can be stably trapped with suitable laser density. The trapping is possible due to the difference in refractive index between the medium and chloroform. These findings offer the possibility of extending the trapped chloroform microdroplet for various applications. For example, the optically trapped microdroplet can act as a carrier to contain active molecules or a platform for a microreactor.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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