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參展科別 物理與天文學

作品名稱 Studies of spatial self-phase modulation of the laser beam passing through the olive oil

得獎獎項 二等獎

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關鍵詞 Gaussian beam、Spatial self-phase modulation、Olive oil

作者簡介

我們是吳子謙和張夏睿，就讀嘉義高中數理資優班。就讀數理資優班後，有幸在李文堂老師和林芳妃老師的指導下，對物理有更深入的了解，並對物理研究產生更多熱忱。

在實驗的過程中，我們必須對實驗不斷的做出修正，並強化相關的理論知識和實驗技巧，在不斷的自我修正以及老師們辛苦的指導下，這段時間我成長了很多，謝謝兩位老師。

摘要

橄欖油含有葉綠素-a，葉綠素 b，和胡蘿蔔素等高熱吸收率的物質；高斯光束照射橄欖油時，橄欖油吸收的熱量，使橄欖油產生溫度梯度和折射率梯度，並產生熱透鏡(Thermal lens)和自調相(Self-phase modulation)現象。

以雷射光照射盛橄欖油水平置放的方型盒時，中央軸的照度最大，橄欖油的溫度最高，折射率和密度最小。由於對流作用的影響，使得光束照射到的橄欖油的上半部折射率梯度小於下半部；光束通過橄欖油後，在屏幕上出現的繞射圖樣呈現上半部的亮帶半徑小於下半部。

將橄欖油改置圓柱筒中，雷射光由上向下照射，可以消除熱對流現象。用不同功率的雷射，照射不同液柱高度，和不同熱吸收率的橄欖油；探討功率、液柱高度、和熱吸收率對:繞射亮帶最大半徑、繞射亮帶半徑隨時間的變化、和亮帶數目的影響。

Abstract

Olive oil contains substances with high heat absorption coefficient. These substances are chlorophyll-a, chlorophyll-b, and carotenoids. When a Gaussian beam irradiates olive oil, the olive oil absorbs a large amount of heat, which leads to an increase in its temperature and a change in the refractive index. Such a change makes the olive oil behave like a lens, and produces a spatial self-phase modulation on the olive oil. Spatial self-phase modulation produces a set of interference that displays a dark and light pattern of rings when illuminated onto a screen.

When a laser beam passes through a container containing olive oil horizontally, there are three characteristics that happen in the central axis of the beam: the intensity is the largest, the temperature of the olive oil is the largest, and the refractive index and density are the smallest. Due to the influence of thermal convection, the refractive index gradient of the olive oil is smaller than that of the lower half, which can be seen the screen by irradiating a laser beam through the olive oil. The radius of the diffraction pattern is smaller in the upper half than the lower half.

However, when the olive oil is placed in a cylinder, and the laser beam is irradiated vertically from top to bottom, the phenomenon of thermal convection can be eliminated. The study uses lasers of different powers to irradiate olive oil with different absorption coefficients at different depths. The substances with high heat absorbability, the lack of convection, and the different depths of olive oil influences the radii of the outermost ring of the diffraction pattern, the temporal evolution of the radii of the outermost ring, and number of the diffraction rings.

A self-made apparatus is used to easily show spatial self-phase modulation in olive oil and the far-field diffraction pattern. Results show that thermal convection and liquids with high heat absorbability will greatly influence the number of rings, the radii, and temporal evolution of the diffraction pattern shown on the screen.

1. Introduction

When a Gaussian beam passes through olive oil, part of the energy is absorbed by the liquid, which locally heats the liquid. Since the energy of the light presents a Gaussian distribution, where the temperature is the hottest in the middle of the beam, and gradually disperses from the middle outwards, it is accompanied by a refractive index gradient. When a Gaussian beam passes through olive oil, there are two phenomena that can be examined - plane waves become spherical waves due to the thermal lens effect [1] ; and spatial self -phase modulation creating diffraction patterns[2].

We have designed a setup of apparatus which requires components that are commonly available in high school labs. It is used to easily show spatial self-phase modulation in olive oil and to show the far-field diffraction pattern, and the thermal convection affect the diffraction pattern.

2. Theoretical background

2.1. Gaussian beam

The laser we used to do the experiment have a beam called a Gaussian beam, with a mathematical expression of the Gaussian intensity $I = I_0 e^{-\frac{y^2}{\omega^2}} \cdots (1)$ where I_0 is the intensity on the propagation axis (y=0), and $y = \omega$ is the radial distance at which the intesity decreased to 1/e of its axis value. Fig. 1 shows the 2D intensity distribution of a Gaussian beam. For a Gaussian beam passing through a sample of absorbing medium, more energy absorption occurs at the central axis of the transmission path. The temperature of the medium is the highest at the central axis of the beam and decreases radially outward, forming a temperature gradient dT/dy in the medium.

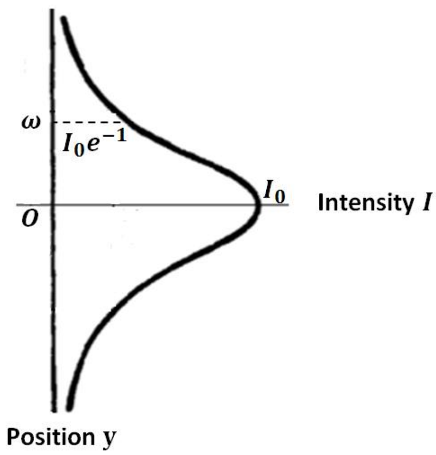


Fig 1. A 2D plot of the intensity of a Gaussian beam varied with position.

2.2. Thermal lens

It is experimentally observed that a change in temperature in the sample leads to a change in the refractive index of the sample [3]. As shown in Figure 2, as the Gaussian beam passes through the the transparent sample, the temperature of the sample decreases from the central axis outward, and the refractive index increases outward, forming a refractive index gradient dn/dy.

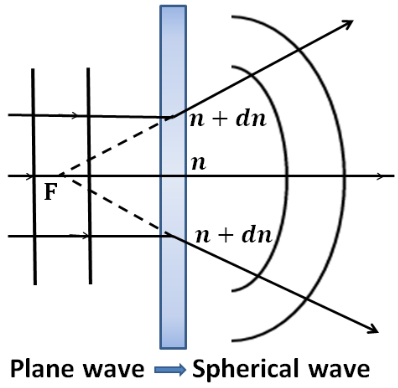


Fig 2. A plane wave forms a spherical wave after passing through a medium with a refractive index gradient. The incident ray parallel to the central axis diverges from point F, and the medium is equivalent to a concave lens.

The wavefront of the beam is a plane wave. Once the laser beam reaches sample, the ray on the central axis passes through the sample in which the refractive index is n, and the velocity of light is $v_1 = \frac{c}{n}$, where c is the light velocity in vacuum. However, the refractive index of the adjacent rays passing through the liquid is n + dn, and the velocity of light is $v_2 = \frac{c}{n+dn}$. Since $v_1 > v_2$, the wavefront of the beam passing through the sample changes from plane waves to spherical waves.

The outgoing ray is perpendicular to the wave front of the spherical wave and diverges from point F. This sample is equivalent to a concave lens, which is called a thermal lens [1]. It creates a diverging lens with a focal point F.

2.3. Spatial self-phase modulation

As shown in Figure 3, the Gaussian beam of radius *r* irradiates a thin sample of thickness ℓ with a refractive index gradient in the sample. Ray A is the central axis of a Gaussian beam passing through a liquid that has an index of refraction of n.; and rays B are the edges of the Gaussian beam passing through the same liquid, but the index of refraction is $n + \Delta n$. Rays A and B are separated by a distance *r*.

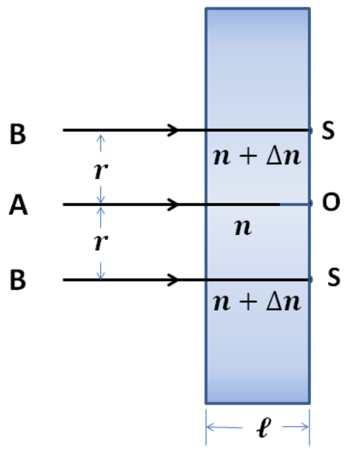


Fig 3. A diagram of how Rays A and B go through a thin sample that has an index of refraction gradient.

The time t_1 for the central axis ray A to pass through the liquid inside the container is the length of the liquid medium ℓ divided by the velocity of light in a vacuum c over the index of refraction n; and the time t_2 for rays B is the same, except that the index of refraction is $n + \Delta n$. The formulae for these are:

$t_1 = \frac{\ell}{c/n}$, $t_2 = \frac{\ell}{c/(n+\Delta n)}$, respectively.

The time difference Δt of the two rays passing through the thin sample is

$\Delta t = t_2 - t_1 = \frac{\ell \Delta n}{c}$. The phase difference is $p = \frac{\Delta t}{T} = \frac{\ell \Delta n}{\lambda} \cdots (2)$

When a Gaussian beam irradiates a sample, the sample produces a refractive index gradient. When different rays of light in the beam pass through the sample with different refractive indices, a phase difference occurs at the excit plane of the thin sample. This phenomenon is called spatial self-phase modulation [2].

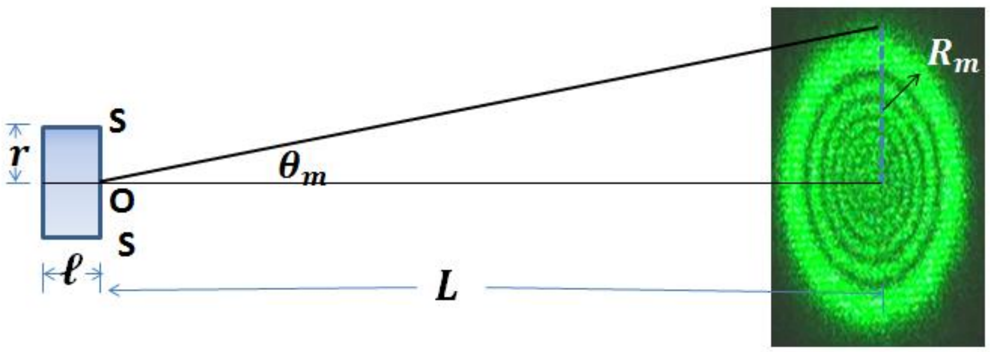


Fig 4. A diagram showing the maximum deflection angle of the laser beam θ_m and the radius of the outmost diffraction ring appearing on a screen R_m when the laser beam goes through a distance L.

When a laser beam interacts with the sample, an added phase shift and the far-field diffraction pattern are obtained. The far-field diffraction ring is caused by the interference of several rays of the laser beam, which come out with difference phases after crossing the sample that has a refractive index gradient. If the thermal refractive index change is practically independent of the propacation coordinate (thin sample approximation), the maximum deflection angle θ_m can be determined. As shown in figure 4, L is the distance between the container and the screen, R_m is the radius of the outmost ring, θ_m is the maximum deflection angle of the beam. Thus, the formulae for the maximum deflection angle of the beam and the radius of the outmost ring are: $\theta_m = \frac{(\frac{dn}{dT})\ell P\alpha}{\lambda\rho C_p} \cdots (3)$, $R_m \approx L\theta_m = \frac{L(\frac{dn}{dT})\ell P\alpha}{\lambda\rho C_p} \cdots (4)$, where $\frac{dn}{dT}$ is the thermal optical coefficient of the olive oil, P is the power of laser, ρ density of the olive oil, C_p is the molar specific heat capacity at constant pressure [4]. After the laser beam passes through the sample, the maximum number of diffraction rings N will appear on the screen. The formula for the maximum number of diffraction is $\mathrm{N} = p = \frac{\ell\Delta n}{\lambda} \cdots (5)$ [5].

For a Gaussian beam of radius r, the power P of the beam is related to the on-axis intensity by $\mathrm{P} = I_0\pi r^2/2 \cdots (6)$, I_0 is the intensity on the propagation axis (y=0), as shown in Figure 1. The refraction index difference Δn of the sample between the edge and the central axis of the beam is $\Delta\mathrm{n} = n_2 I \cdots (7)$, n_2 is called the nonlinear refractive index, I is the incident indencity of the beam. The maximum number of diffraction is $\mathrm{N} = \frac{2n_2\ell}{\lambda\pi r^2}P \cdots (8)$.

2.4. Olive oil with high heat absorbability

1. Beer-Lambert Law: A common and practical expression of the Beer–Lambert law relates to the optical attenuation of a physical medium containing a single attenuating medium of uniform concentration. The intensity of light passing through the medium can be found as $I_2 = I_1 e^{-A} \cdots (6)$, where I_1: the intensity of the incidence of light, and A: absorbance. The absorbance can be found using $A = \alpha \ell C \cdots (7)$, where C: the molar concentration of the medium, ℓ: the optical path length through the medium, and α: attenuation coefficient of the medium.

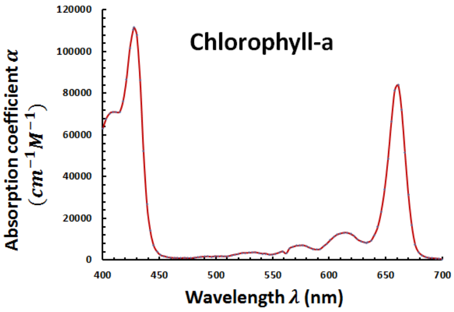


Fig 5. Attenuation coefficient vary with wave length of irradiate light.

2. At a wavelength of λ = 427nm from a violet light beam, the thermal attenuation coefficient of chlorophyll-a is $\alpha = 1.12 \times 10^5 cm^{-1}M^{-1}$. The attenuation coefficient is about a million times that of ethanol. At a wavelength of λ = 532nm from a green light, beam, $\alpha = 3.72 \times 10^3 cm^{-1}M^{-1}$. For λ = 633nm from a red light beam, $\alpha = 8.30 \times 10^3 cm^{-1}M^{-1}$ [6]. The commercially available chlorophyll-a is extracted from spinach leaves. The price is 700 US dollars per mg, and it is not easy to store. The price is too expensive, and it is not within budget.

4. The concentration of chlorophyll-a in olive oil ranges from 1.8 ppm to 10.6 ppm for those that come from Italy. Olive oil that comes from Spain have concentrations that ranges from 4.2 ppm to 18.3 ppm [7].
5. (1) By irradiating a laser light beam through the olive oil that comes from Italy, which contains at least 1.8 ppm of chlorophyll-a, the molar concentration is $C = 2.0 \times 10^{-6} M$. If the length of the oil is $\ell = 10cm$, (a) the attenuation coefficient for the violet light beam is $\alpha = 1.12 \times 10^5 cm^{-1}M^{-1}$, the absorbance is $A = \alpha \ell C = 2.4$, and the intensity of light passing through the olive oil is $I_2 = 0.09 I_1$; (b) for the red light beam, $I_2 = 0.85 I_1$; and (c) $I_2 = 0.92 I_1$ for the green light beam.
   (2) By irradiating a laser light beam through the olive oil that comes from Spain, (a) the intensity of light passing through olive oil is $I_2 = 3.56 \times 10^{-3} I_1$ for the violet light beam; (b) $I_2 = 0.68 I_1$ for the red light beam; and (c) $I_2 = 0.84 I_1$ for the green light beam.

6. Olive oil contains three substances with high

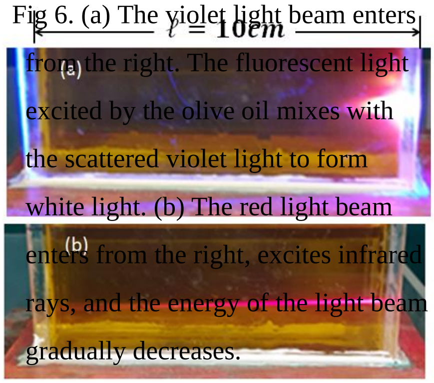


Fig 6. (a) The violet light beam enters from the right. The fluorescent light excited by the olive oil mixes with the scattered violet light to form white light. (b) The red light beam enters from the right, excites infrared rays, and the energy of the light beam gradually decreases.

heat attenuation coefficient, which are chlorophyll-a, chlorophyll-b, and carotenoids [9]. The concentration of those substances in olive oil depends on several factors, such as the maturity of olives before oil production, the cultivar, and the geographic origin of olives. Olive oil contains so many substances with high heat absorption coefficient, which is very suitable for high school students to do this experiment.

7. The container is filled olive oil with a length $\ell = 10$ cm. When the olive oil is irradiated by a laser light beam, part of the energy is absorbed by chlorophyll-a, chlorophyll-b, and carotenoids, which excite fluorescence and generate heat.
(a). As shown in Figure 5 (a), the violet light beam enters from the right and is absorbed by the three substances in olive oil, which excites the different colors of florescent light. This mixes with the scattered violet light to form white light. The energy of the light beam decreases rapidly. It seems that no violet light can pass through the container.
(b) The red light beam enters from the right and is absorbed by the three substances inside olive oil. The red light beam excites infrared rays, and the energy of the light beam gradually decreases as it goes through the length of the olive oil. Only part of the illuminated red light can pass through the container.

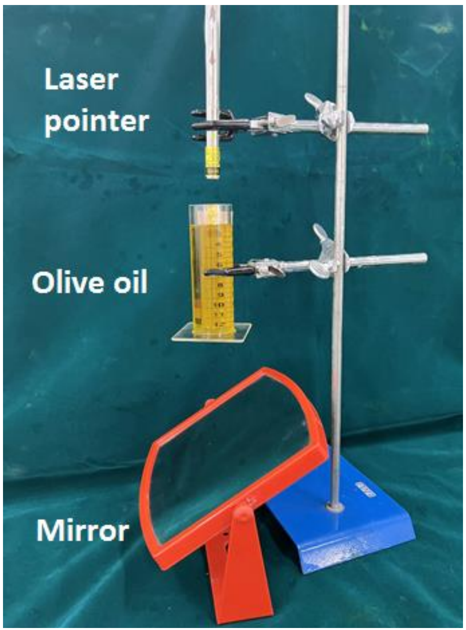
3. Apparatus

a. Rectangular container 10 cm × 5.0 cm × 7.0 cm.

b. Cylindrical container radius 3.0 cm, length 12 cm.

c. Laser pointer, 532 nm and 100mW

d. Laser pointer, 532 nm and 20mW



e. Mirror.
f. Screen (distance from container to screen is
L=544 cm.
g. Camera, Kmplayer software.
h. Microsoft Excel.
i. Olive oil (Spain) (Extra virgin olive oil, 23 US dollars/L)
j. Olive oil (Italy) (Virgin olive oil, 9.7 US dollars/L)

Fig 6. Picture of apparatus.

4. Experiment 1 (horizontal light beam)

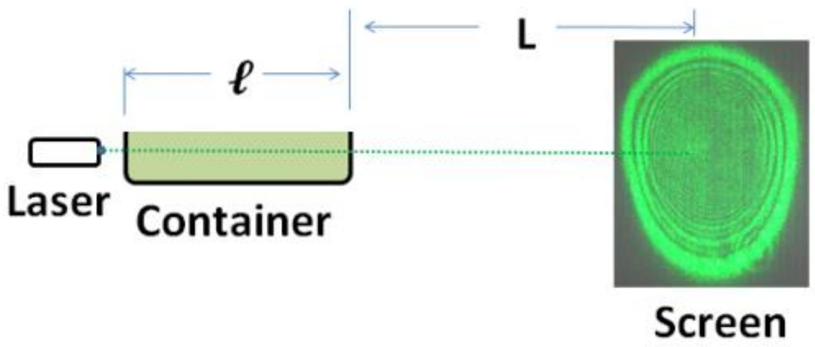


Fig 7. Schematic side view of a horizontal laser beam going through olive oil.

4. 1. Procedure

a. Place the rectangular container containing the liquid to be tested at the exit of the laser pointer. Turn on the laser, and a diffraction pattern will appear on the screen.
b. Turn on the camera to face the screen. Adjust the aperture, so the camera can capture the clearest diffraction pattern.
c. Turn on the camera to record the moving diffraction pattern.
d. Take the video to collect the data of the diffraction pattern progressing with time.
e. Plot data into Microsoft Excel to see the data quantitatively.

4. 2. Results and discussion

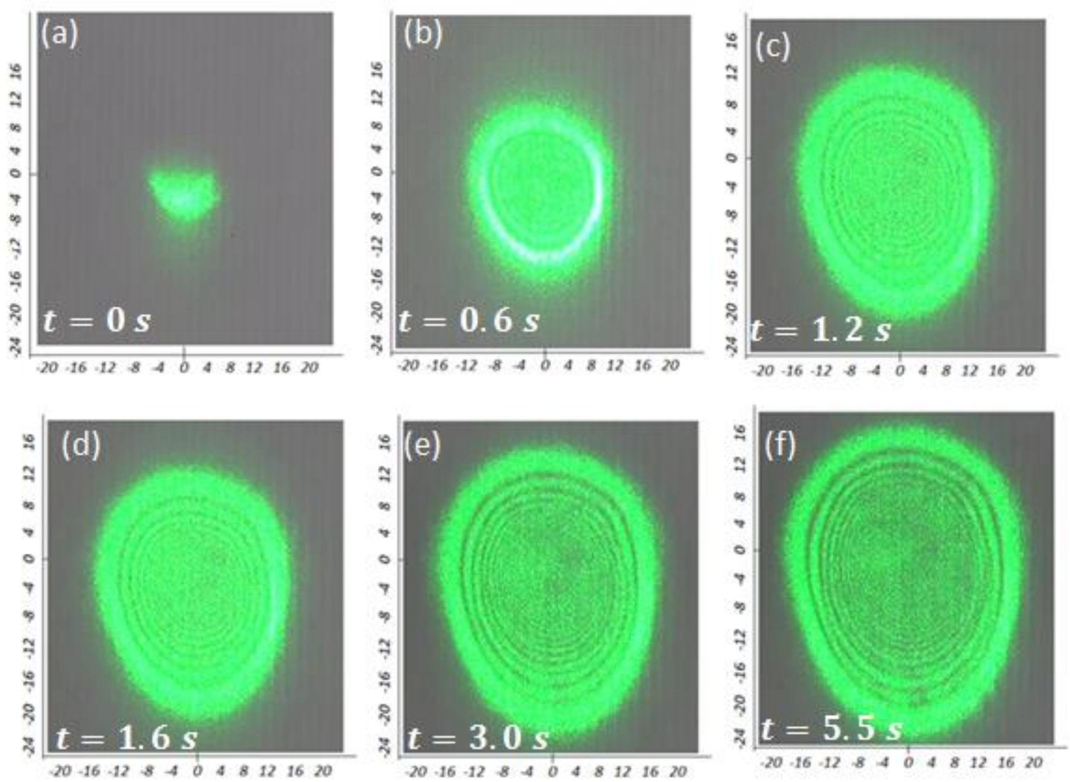
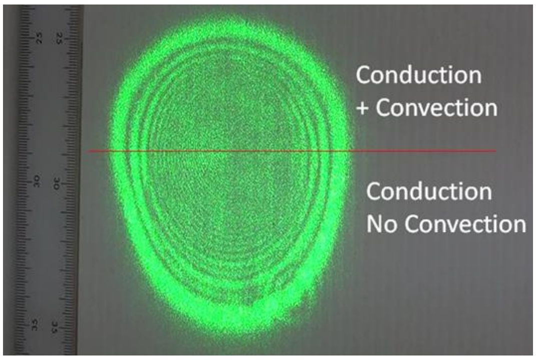


Fig 8. Images of the diffraction patterns of a horizontal laser beam going through olive oil (Spain). Coordinate axis units are in cm.

a. In the experiment, a Gaussian beam of laser at 532 nm and 100 mW is irradiated in a container filled with olive oil (Spain) that has a length ℓ of 10 cm. After the beam passes through the liquid, the beam began to diverge into diffraction patterns, which illuminate the screen. The screen is mounted in front of the container at a distance of L = 544 cm. The images of the diffraction patterns are recorded by a digital camera with an exposure time of 1/32 second.

b. When the laser beam passes through the olive oil, the diffraction patterns are formed on the screen varied with time. Figure 8 (a)-(f) are frames taken out from the recorded video. Figure 8 (a) shows a bright spot appearing on the screen at the initial time, the size of which is the penetration of the laser beam. After passing through olive oil, the area of the bright spot increases rapidly from t = 0s to t = 3.0s. From t = 3.0s to t = 5.5s, the spot increased in size, but at a much slower pace.

c. At t = 0.6s, the spot on the screen starts to have diffraction rings appearing. At t = 1.6s, there are 6 visible diffraction dark rings; at t = 3.0 s, there are 8 visible diffraction dark rings; at t = 5.5s, there are 16 clear diffraction dark rings. The maximum radius R_m occurs at this time.



d. There are two stages shown through the development of these diffraction rings. The first is self-modulation with thermal conduction, which will make the diffraction pattern look more circular. The second stage is thermal convection, which flattens the diffraction patterns and makes the radius shorter from the center. This can be seen on the top half of the diffraction pattern.

(1) When a Gaussian beam passes through olive oil, which has high absorbability, partial light energy is absorbed along the path of the beam. In this process, light energy is absorbed by the oil. There is more energy absorption occurring at the central axis of the transmission path. Therefore, the temperature gradient accompanies a refractive index gradient.

Fig 9. The top half of the diffraction pattern has a lower radius than the lower part. This is due to the difference in convection as the laser passes through olive oil in a horizontal manner.

(2) If the oil is an initially quiescent liquid, absorption of energy near the beam causes a density gradient in the oil. The temperature is a maximum at the central axis and the density is at the minimum. This causes an upward liquid current, as the less dense oil from the center flows to the top, and the denser oil from the top flows downwards towards the center. The lower half, however, is not affected by the natural convection currents as severely as the upper portion, and the upper portion of the oil reduces the refractive index gradient. Figure 9, shows that the radius of the diffraction pattern is smaller in the upper half than the lower half.

From equation (4) $R_m - R_0 \approx L\theta_m = \frac{L\ell\Delta n}{r}$, the difference of refraction index Δn of the upper half is less than the lower half, so the radius of the outmost ring R_m is less than the lower half.

(e) The radius of the diffractions rings increases with time as shown in Figure 10. In the lower half, the olive oil goes through process of heat conduction. The radius of the outermost ring increases with time. After a period of time, the radius reaches a stable maximum value. On the other hand, the olive oil goes through the process of heat conduction and heat convection in the upper half, and the radius of outermost ring reaches a maximum size and then decreases to a stable value which is smaller than the size of the former. The time for the upper half to reach its maximum radius is also less than the former.

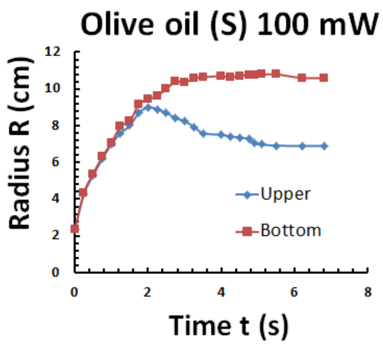


Fig 10. Radius of the outermost ring of the diffraction pattern as a function of the exposure time for a 100 mW laser. Upper Half (Conduction + Convection), Bottom Half (Conduction + No Convection).

5. Experiment 2 (vertical light beam)

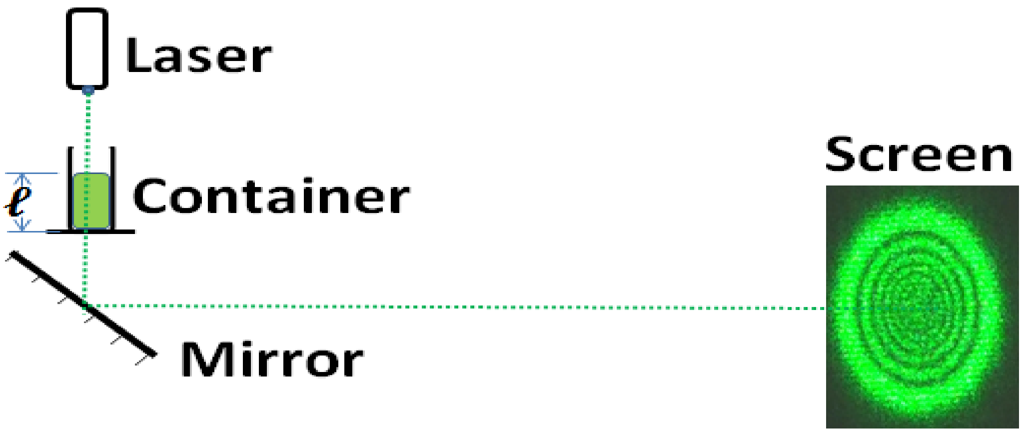


Fig 10. Schematic side view of a vertical laser beam going through olive oil.

5. 1. Procedure

5.1.A.

a. Place the cylindrical container containing olive oil (Spain) with a depth of 10 cm at the exit of a 100 mW, 532nm laser pointer. Place a mirror below the container that has an incline of 45° with the horizontal plane.

b. Turn on the laser, and the moving diffraction patterns will appear on the screen.

c. Change the depth of olive oil and repeat the procedure from Experiment 1.

5.1.B.

Change the 100 mW, 532 nm laser pointer to a 20 mW, 532 nm laser pointer, and repeat the procedure from Experiment 5.1.A.

5.1.C.

Follow the procedure again from Experiment 5.1.A. using a 60 mW, 532 nm laser pointer.

5.1.D.

Change the olive oil (Spain) to olive oil (Italy), and repeat the procedure from Experiment A, B, and C.

5.2. Results and discussion

5.2.A. Vertical light and horizontal light

a. The cylindrical container is filled with olive oil (Spain) with a depth of $\ell = 10$ cm. It is then irradiated with a 100 mW, 532 nm green laser. The light path from the bottom of the container to the screen is L = 544 cm. All the conditions are the same as Experiment 1. The only difference is that the former experiment is illuminated horizontally, while the latter experiment is illuminated vertically.

b. Figure 11 (a)-(f) are frames taken out from the recorded video. Figure 11 (a) shows a bright spot appearing on the screen at the initial time, the size of which is the penetration of the laser beam. After passing through olive oil, the area of the bright spot increases rapidly from t = 0s to t = 1.6s. At t = 3.0s there are 16 clear, dark diffraction rings.

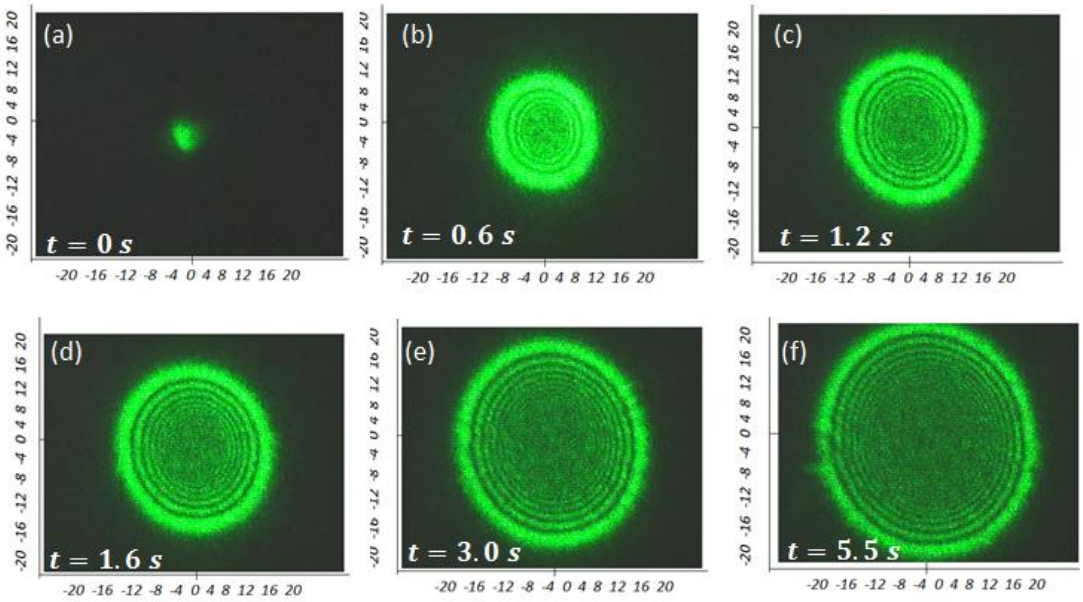


Fig 11. Images of the diffraction patterns of a vertical laser beam going through olive oil (Spain). Coordinate axis units are in cm.

c. The radii of the outermost ring are shown in Figure 12.

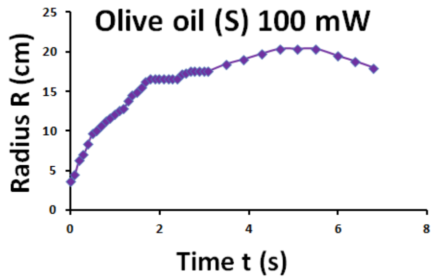


Fig 12. Radii of the outermost ring of the diffraction pattern as a function of the exposure time for a 100 mW laser.

d. Comparison of Horizontal and Vertical Experiments:

The laser beam used was of the same power (100 mW); the length of the liquid that the light passed through was also the same ($\ell = 10$cm); the distance from the container to the screen was L = 544cm; and the olive oil used was the same.

1. The former container is placed horizontally. Due to the influence of thermal convection, the diffraction pattern on the screen is not a perfect circle. The refractive index gradient of the liquid in the upper half is smaller than the lower half. The radius of the outermost ring of the upper half is therefore smaller than the lower half. The diameter of the outermost ring is $\mathrm{D} = 20.4\mathrm{cm} + 18.2\mathrm{cm} = 38.6\mathrm{cm}$.

2. The latter container is placed vertically, and the Gaussian beam irradiates the liquid from top to bottom. The refractive index of the liquid gradually increases from the central axis of the beam to the outside, forming a gradient of refractive index. The self-phased beam generates a far-field diffraction, creating concentric circles on the screen. The diameter of the outermost ring is $\mathrm{D} = 20.4\mathrm{cm} \times 2 = 40.8\mathrm{cm}$.

(c). The formula for the maximum number of diffraction rings is $N = p = \frac{\ell \Delta n}{\lambda} \cdots (5)$.

In this experiment, N = 16, $\ell = 10$ cm, $\lambda = 5.32 \times 10^{-5}$ cm. Thus, we can get Δn by using $\Delta n = 8.5 \times 10^{-5}$. In other words, when a 100 mW, 532 nm laser beam passes through a container filled with $\ell = 10$cm of olive oil (Spain), the maximum refractive index difference at the outlet of the container is $\Delta n = 8.5 \times 10^{-5}$.

5.2.B. Comparison between Olive oil (Spain) and Olive oil (Italy)

a. The cylindrical containers are respectively filled with olive oil (Spain), indicated as Olive oil (S), and olive oil (Italy), indicated as Olive oil (I) with a depth $\ell = 10$ cm, and irradiated with a 100 mW, 532nm green laser. The light path from the bottom of the container to the screen is L = 544 cm.

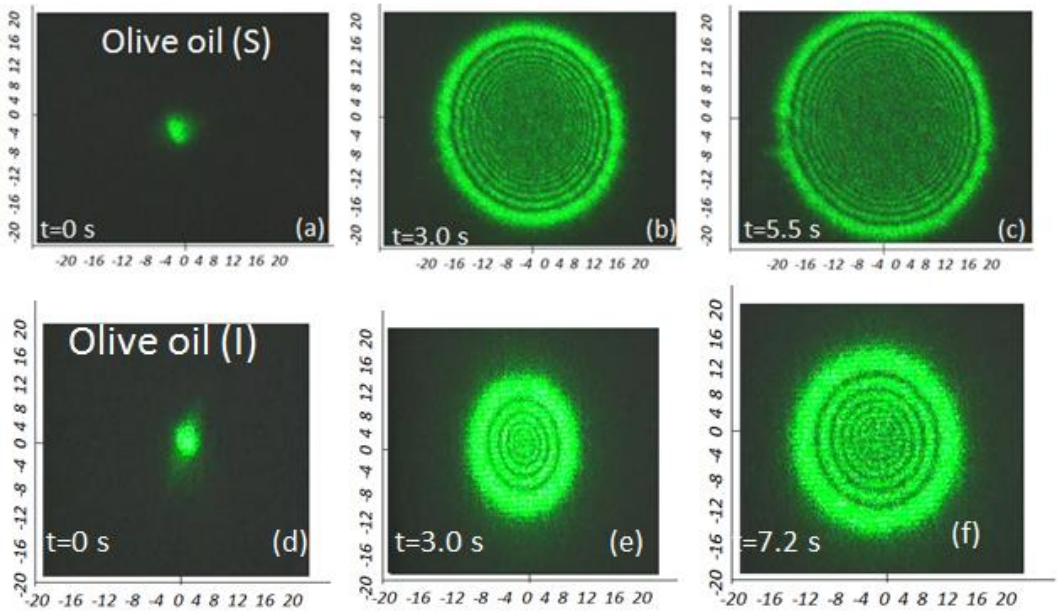


Fig 13. Comparison of Olive oil (S) in row 1 and Olive oil (I) in row 2. Images of these diffraction patterns are created by using a 100 mW, 532 nm laser beam going through olive oil vertically. Coordinate axis units are in cm.

b. For Figures 13 (a)-(c), the screen shows diffraction rings as the laser light irradiates olive oil (S), and they are captured as a set of video frames. Figure 13 (c) shows that there are 16 clear dark diffraction rings at t = 5.5 s; and the maximum radius of the outermost ring is $R_m = 20.4\ cm$. For Figures 13 (d)-(f), the screen shows diffraction rings as the laser light irradiates olive oil (I). Figure 13 (f) shows that there are 6 clear dark diffraction rings at t = 7.2 s; and the maximum radius of the outermost ring is $R_m = 16.8\ cm$.

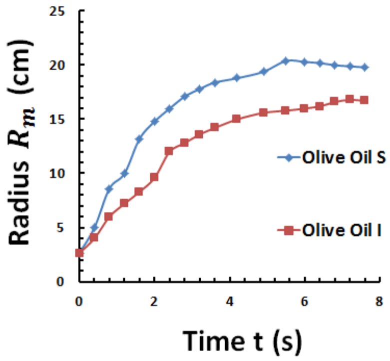


Fig 14. Comparison of the radii of the outermost ring of the diffraction pattern as time progresses for a 100 mW laser going through olive oil from Spain and Italy.

c. The temporal evolution of the radii of the outermost ring is shown in Figure 14.

d. The formula for the maximum number of diffraction rings is $N = p = \frac{\ell \Delta n}{\lambda} \cdots (5)$.

In this experiment: (1) For olive oil (S), N = 16, $\ell = 10$cm, and $\lambda = 5.32 \times 10^{-5} cm$. Thus, we can get $\Delta n = 5.3 \times 10^{-5}$. (2) For olive oil (I), N = 6, $\ell = 10$cm, and $\lambda = 5.32 \times 10^{-5} cm$, thus $\Delta n = 3.2 \times 10^{-5}$. In other words, when a 100 mW, 532 nm laser beam passes through a container filled with $\ell = 10$cm of olive oil (S), the maximum refractive index difference at the outlet of the container is $\Delta n = 5.3 \times 10^{-5}$, and $\Delta n = 3.2 \times 10^{-5}$ for olive oil (I).

e. Olive oil (S) is extra virgin olive oil, and Olive oil (I) is virgin olive oil. The former contains three more substances that have a high heat absorption coefficient. These substances are chlorophyll-a, chlorophyll-b, and carotenoids [9].

f. Olive oil that has a high heat absorption coefficient make the radius of the outermost ring R_m, the maximum number of diffraction rings N, and the refraction index difference between the edge and the central axis of the beam Δn larger, and the time to reach the maximum radius is relatively short.

5.2.C. Special thermal diffusivity of Olive oil

a. The cylindrical containers are respectively filled with olive oil (Spain) with a depth ℓ = 1cm, 5cm, 6cm, 7cm, 10cm separately, and irradiated with a 100 mW, 532nm green laser. The light path from the bottom of the container to the screen is L = 544 cm.

b. The temporal evolution of the radii of the outermost ring are shown in Figure 15 and Figure 16.

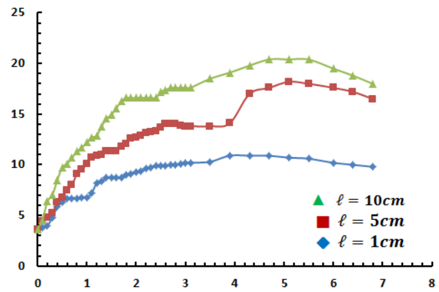


Fig 15. Radii of the outermost ring of the diffraction pattern as time progresses. Olive oil (S), 100 mW, 532 nm laser at different depths.

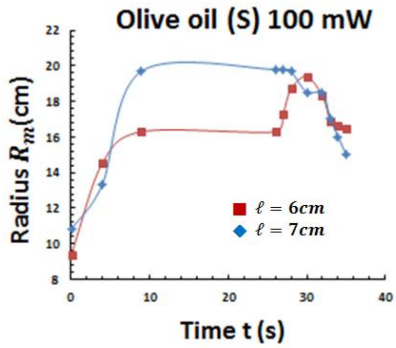


Fig 16. The radii of the outermost ring of the diffraction pattern experiences a quick expansion and shrinkage at a depth of 6 cm. The diffraction pattern experiences only a sharp shrinkage at a depth of 7 cm. Olive oil (S), 100 mW, 532 nm laser.

c. Thermal diffusion [1]:

When the material is homogeneous and isotropic, the heat equation is

$\frac{\partial T}{\partial t} = D\frac{\partial^2 T}{\partial y^2} \cdots$ (8), where T : temperature of the material, D: Thermal diffusivity, and y: distance from the central axis of a Gaussian beam (as shown in Figure 1). The temporal evolution of the radii of the outermost ring is shown in Figure 17.

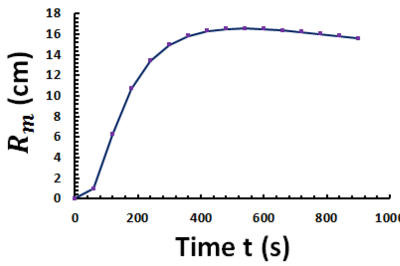


Fig 17. The temporal evolution of the radii of the outermost ring follows the thermal diffusion equation.

d. (a) As shown in Figure 15, the temporal evolution of the radii of depths ℓ = 1 cm and ℓ = 10 cm is very close to Figure 17. When ℓ = 5 cm, the radius of the outmost ring R_m stops changing for 1.32 s between t = 2.54 s and t = 3.86 s.

(b) As shown in Figure 16, when ℓ = 6cm, R_m does not change up to 16.17 seconds between t = 9.86 s and t = 26.03 s. When ℓ = 7cm, the R_m only gradually shortens by 1.98 cm for around 20.12 s, then suddenly shrinks by 3.98 cm after 29.33 s between t = 9.21 s and t = 29.33 s.

(c) From equations $I_2 = I_1 e^{-A}$ and $A = \alpha\ell C$, it is known that the heat absorption of olive oil is closely related to the depth of the liquid ℓ. It is worthy studying whether the heat absorbed by olive oil causes a special change in the thermal diffusivity of olive oil when ℓ is close to 5 cm.

5.2.D. Number of diffraction rings

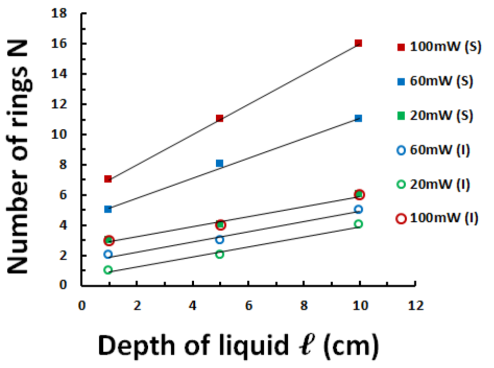
a. Olive Oil (S)

(1) The cylindrical containers are individually filled with olive oil (S) with a depth $\ell = 1$cm, 5cm, and 10cm. Olive oil (S) is separately irradiated with a 100 mW, a 60 mW, and a 20 mW, 532nm green laser.

b. Olive Oil (I)

(1) Repeat the same procedure and change olive oil (S) to olive oil (I).

c. The number of the diffraction rings from different depths of olive oil ℓ, and different kinds of olive oil are listed in Figure 18.



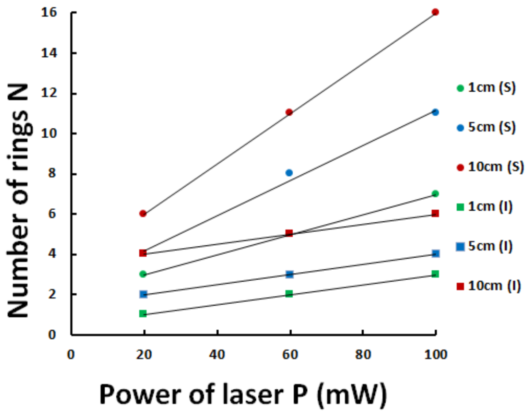


Fig 18. Number of diffraction rings N varied with the depth ℓ of olive oil, illuminated by different powers of green laser.

Fig 19. Number of diffraction rings N varied with the power P of the laser. All measurements are the depths of olive oil.

d. Figure 19 illustrates the number of rings as a function of incident power for two kinds of olive oil. In the same figure, linear fittings of data are also shown. It is possible to observe the linear trend of the number of rings N as a function of power P of the laser. The linear coefficient β obtained from the fittings allowed us to obtain the nonlinear refractive index n_2 of the olive oil. As shown in table 1.

e. Equation (8) $N = \frac{2n_2\ell}{\lambda\pi r^2}P = \beta P$. The linear coefficient $\beta = \frac{2n_2\ell}{\lambda\pi r^2}$. Thus, $n_2 = \frac{\lambda\pi r^2}{2\ell}\beta$.

Table 1. Value of the nonlinear refractive index n_2 for two kinds of olive oil

Olive oil	Liquid depth ℓ	Linear coefficient β (W^{-1})	$n_2(\times 10^{-10}m^2W^{-1})$
Olive oil (I)	$\ell = 1$cm	25.0	188
	$\ell = 5$cm	25.0	37.5
	$\ell = 10$cm	25.0	47.0
Olive oil (S)	$\ell = 1$cm	50.0	375
	$\ell = 5$cm	87.5	131
	$\ell = 10$cm	125	93.8

f. Previously, we are able to find Δn using equation (5). Using the data from 5.2.B., the cylindrical containers are respectively filled with olive oil (S) and olive oil (I) with a depth $\ell = 10$cm, and irradiated with a 100 mW, 532 nm green laser.

   From equation (5) $\mathrm{N} = p = \frac{\ell \Delta n}{\lambda}$.

   (1) For olive oil (S), N = 16, $\ell = 10$cm, $\lambda = 5.32 \times 10^{-5} cm$, thus, $\Delta\mathrm{n} = 5.3 \times 10^{-5}$.

   (2) For olive oil (I), N = 6, $\ell = 10$cm, $\lambda = 5.32 \times 10^{-5} cm$, thus, $\Delta\mathrm{n} = 3.2 \times 10^{-5}$.

g. After getting n_2 from Equation 8, we are able to use Equation (7) to get Δn, which is $\Delta\mathrm{n} = n_2\mathrm{I}$. We use this calculation to compare with Equation (5).

   (1) For olive (s) $\ell = 10$cm, $n_2 = 93.8 \times 10^{-10} m^2 W^{-1}$,

   $\mathrm{I} = \frac{P}{\pi r^2} = 3.54 \times 10^3 W m^{-2}$, thus, $\Delta\mathrm{n} = n_2\mathrm{I} = 3.32 \times 10^{-5}$

   (2) For olive (I) $\Delta\mathrm{n} = n_2\mathrm{I} = 3.54 \times 10^3 \times 47.0 \times 10^{-10} = 1.67 \times 10^{-5}$

h. The Δn of Equation (5) and (7) should be the same. However, results show that the Δn from Equation (7) to be lower. We suggest that the lower number is caused by olive oil's natural ability to create florescence and scattering when absorbing the laser beam, as seen on Fig 6.

5.2.E. Calculating μ by using the radius of the outermost diffraction ring

(a) (1) The cylindrical containers are respectively filled with olive oil (S) with a depth $\ell = 1$cm, 1.5cm, 2cm, 2.5cm, and 3cm. Olive oil (S) is irradiated with a 100 mW, and a 20 mW, 532nm green laser. (2) Repeat the same procedure and change the olive oil (S) to olive oil (I).

(b) The radius of the outermost ring R_m from different depths of olive oil ℓ, and kinds of olive oil are listed in Figure 22. It is possible to observe the linear trend of the radius of the outermost ring R_m as a function of the depth of olive oil ℓ. The linear coefficient γ obtained fom the fittings allows us to obtain the absorption coefficient μ of the two kinds of olive oil.

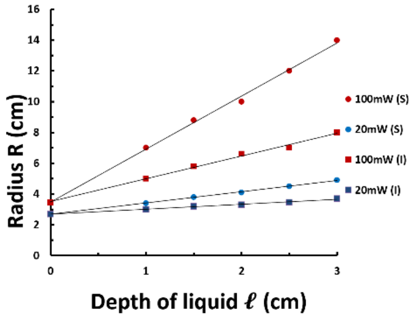


Fig 22. The radius of the outmost ring R_m vary with the depth of liquid ℓ .

Table 2. Value of the absorption coefficient μ for two kinds of olive oil

Olive oil	Power (W)	Linear coefficient γ	$\mu(\times 10^{-4} m^{-1})$
Olive oil (I)	P = 0.02W	0.30	3.3
	P= 0.10W	1.47	3.2
Olive oil (S)	P = 0.02W	0.72	7.8
	P = 0.10W	3.46	7.5

(c) From equation (4) $R_m = \frac{L\left(\frac{dn}{dT}\right)P\mu}{\lambda\rho c_p D}\ell + R_0 \rightarrow R_m = \gamma\ell + R_0,$

the linear coefficient $\gamma = \frac{L\left(\frac{dn}{dT}\right)P\mu}{\lambda\rho c_p D}$.

In this experiment L=5.44 m,

$\frac{dn}{dT} = -7.4 \times 10^{-4} K^{-1},\ \lambda = 5.32 \times 10^{-7}\ m,$

$\rho = 916\ K_g m^{-3},\ c_p = 1.8 \times 10^3 J K_g^{-1} K^{-1},$ and $D = 10 \times 10^{-8} m^2 s^{-1}.$

The linear coefficient γ obtained from the fittings allowed us to obtain the absorption coefficient μ for two kinds of olive oil as shown in Table 2.

(d) Two kinds of the olive oil contain almost the same molar absorption coefficient α, just in different molar concentration C [7]. From Table 2. It can be calculate that the absorption coefficient μ of olive oil (S) is 2.4 times of olive oil (I). From equation (10) $A = \alpha\ell C = \mu\ell$, it can be judged that the heat absorbability olive oil (S) is 2.4 times of the olive oil (I).

6. Conclusion

In this study we used a self-made apparatus to show:

1. The high thermal absorbability of olive oil forms a large temperature gradient and a refractive gradient when a low-power laser irradiates the olive oil. This causes a spatial self-phase modulation and a diffraction pattern will be produced on the screen.
2. Olive oil containing more chlorophyll-a, chlorophyll-b, and carotenoids will have a higher thermal absorbability. The higher the thermal absorbability, the larger the number of diffraction rings, the maximum radius of the diffraction pattern, and the shorter the time to reach the maximum radius.
3. When the laser light irradiates olive oil in the horizontal direction, the refractive index gradient of the upper half of the olive oil is smaller than that of the lower half, and the radius of the upper half of the diffraction pattern is also smaller than the lower half. This phenomenon happens due to thermal convection.
4. When the liquid depth is small, the maximum radius of the diffractive pattern and the number of diffraction rings are proportional to the liquid depth. In other words, the deeper the liquid depth, the larger the diffraction rings and the maximum radius.

7. References

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