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Diffraction ring patterns and z-scan measurements of nonlinear refractive index of khoba vegetable oil

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Abstract

The estimation of the nonlinear refractive index of khoba vegetable oil via diffraction ring patterns and Z-scan using continuous-wave (CW) visible, a single mode low power laser beam, is reported. Diffraction ring patterns are numerically obtained using Fresnel-Kirchhoff diffraction integral with good agreement. The khoba oil exhibited strong self-defocusing effect and the mechanism of optical nonlinearity in the low power regime is found to be predominantly of thermal origin. The optical limiting properties of khoba oil under CW illumination is investigated. Based on the obtained results, the khoba vegetable oil can be considered as a potential candidate for the use in photonic and nonlinear optical devices.

Keywords : Vegetable oil, Diffraction ring patterns, Z-scan, Nonlinear refractive index, Fresnel-Kirchhoff diffraction.

1. Introduction

Due to their potential applications in photonic devices, organic materials have been studied extensively from the point of view of their nonlinear properties [1-10]

such as their nonlinear refractive indexes. During the last years almost for the first time the present authors directed their efforts to study the nonlinear response of vegetables oils to CW visible low power laser lights

due to their high nonlinear refractive indexes [11-18]. According to the works of Abed Ali and Emshary [12-16], Hassan et al. [17] and Sultan et al. [18] vegetable oils proved to behave nonlinearly in response to laser lights in three wavelengths viz., 473 nm, 532 nm and 635 nm and high nonlinear refractive index ($\sim 10^{-6} \text{ cm}^2/\text{W}$) was obtained. Vegetable oils in general are nonpolar, do not dissolve in water, available everywhere as liquid and cheap substance. They have so many uses such as in soaps, skin products, perfumes, biodiesel, which can be used like conventional diesel, in medicine such as reducing the risk for developing heart diseases, etc.

In this work, the nonlinear refractive index of khoba oil is calculated experimentally via diffraction ring patterns and Z-scan techniques using visible, 473nm, CW laser light. The results indicate that khoba oil exhibits strong nonlinear refractive index. Moreover, the optical limiting behavior of the sample is studied. The mechanism leading to the observed nonlinear optical and optical limiting properties have also been investigated.

2. Experimental

2.1 UV- visible spectroscopic study

Khoba oil linear absorption spectrum in the UV-vis (Ultraviolet-visible)

measurement was carried out at room temperature using a UV-visible spectrophotometer (Jenway-England-6800) in the spectral range of 370 to 900 nm. Fig.1 shows the variation of absorbance (A) against wavelength of khoba oil. The absorption coefficient, α , was calculated at 473nm wavelength using Fig. 1 and the relation [19]

$$\alpha = 2.303 \frac{A}{d} \quad (1)$$

A and L are absorbance and thickness of the sample, respectively. For $d=1 \text{ mm}$, $\alpha = 59.14 \text{ cm}^{-1}$.

2.2 Diffraction ring patterns

The experimental set-up to obtain diffraction ring patterns is shown in Fig.2. It consists of CW 473 nm solid state laser of 0 to 66mW output, a 5cm focal length glass lens to focus the laser beam onto the sample cell, a sample glass cell of 1mm thickness and a 30×30 cm semitransparent screen placed 70 cm away from the cell to cast the ring patterns.

2.3 Z-scan technique

A closed aperture Z-scan experiment was carried out using the apparatus as shown in Fig.2 by fixing the sample cell on a moving stage. The screen was replaced with a photo detector fed to a digital power-meter to measure the transmitted power from the sample as a

function of the sample position z . The detector was covered with a 2 mm circular aperture. The open aperture Z-scan was carried out by removing the narrow aperture and using a lens to collect and measure the entire laser beam power transmitted through the sample.

2.4 Optical limiting technique

To obtain optical limiting, an experimental set-up similar to the two used

in the previous two sub-sections is used except that the sample is placed immediately behind the focal point of the lens. The input power of the laser beam and the corresponding output power through the aperture were detected by two photo detectors. A characteristic curve of the output power as a function of the input power can be obtained.

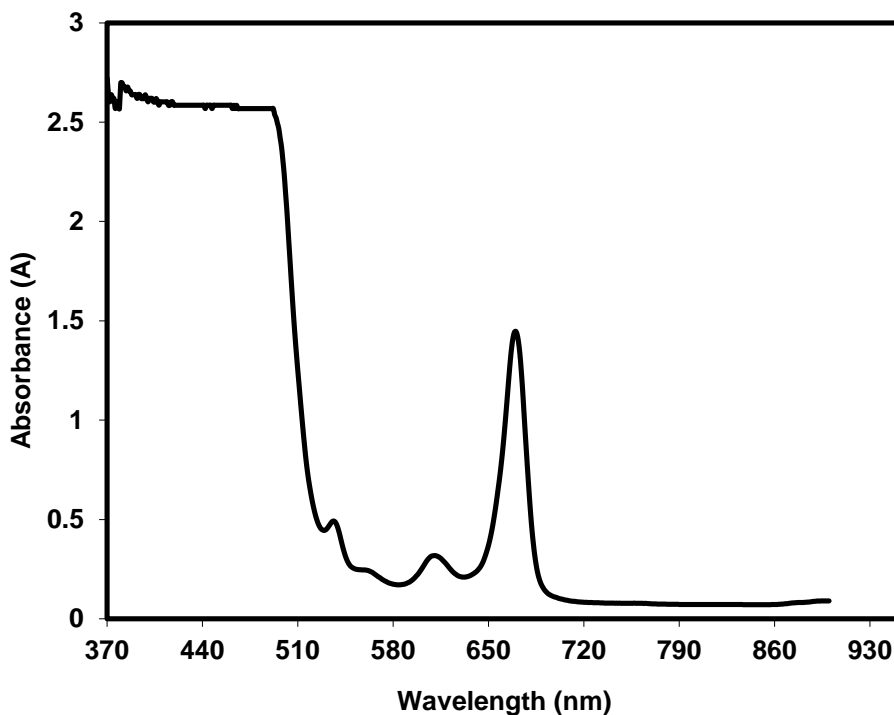


Fig. 1. The absorbance (A) spectrum of khoba oil.

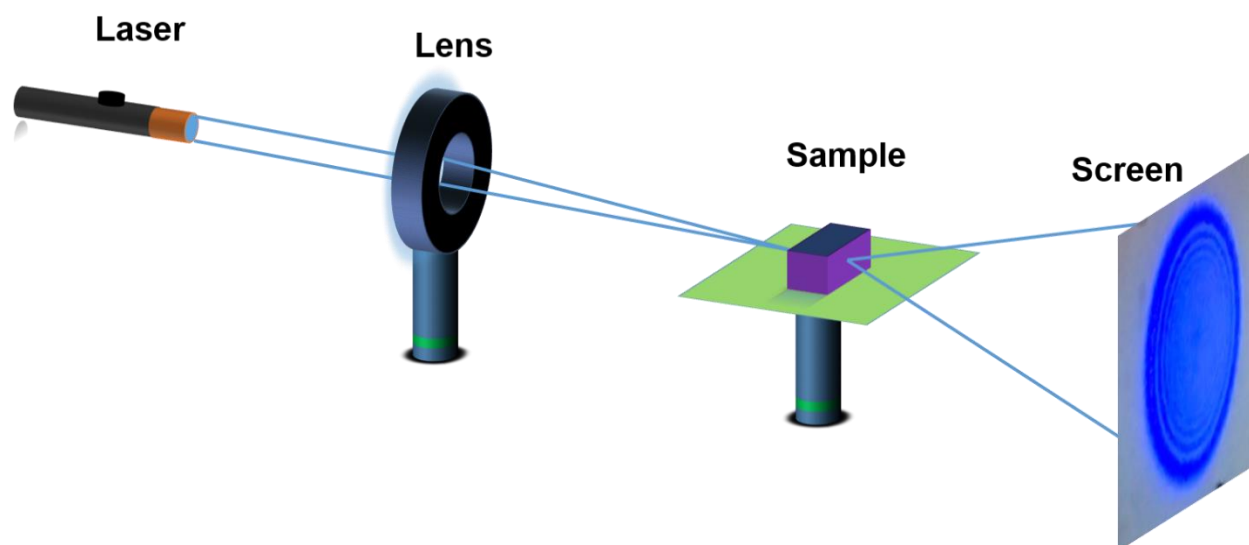


Fig. 2. Experimental set-up for the generation of diffraction ring patterns in khoba oil.

3. Results

3.1. Diffraction ring patterns measurement

Fig. 3 shows the variation of the number of rings per each pattern with increasing the input power (mW): 5, 21, 39, 51, 63. Fig. 4 shows the variation number of rings (N) and diameter (D) of the outer most ring in each pattern with the input power. As can be seen in Fig.4 that the number and diameter of outer most ring diameter in each pattern increase with the increase of input power, since the increase of input power lead to the increase of absorbed power by the oil hence an increase of nonlinear refractive index.

d is the sample cell thickness, λ is the laser beam wavelength, I is the laser beam intensity ($=2P/\pi\omega^2$, P is the input power and ω is the laser beam radius at the entrance of the sample cell, $\omega = 1.22\lambda f/\omega_0$), f is the lens focal length and ω_0 is the laser beam spot size as it leaves the laser output coupler= 1.5 mm). Based on the number of rings, the total change in refractive index, Δn , and the nonlinear refractive index, n_2 , can be obtained using the relations [20]

$$\Delta n = \frac{N\lambda}{d} \quad (2)$$

$$n_2 = \frac{\Delta n}{I} \quad (3)$$

3.2 Modeling the diffraction ring patterns

To obtain diffraction ring patterns numerically the Fresnel Kirchhoff diffraction integral [21] can be used based on the use of a laser beam with fundamental transverse mode, TEM_{00} , when the electric field at the entrance of the sample cell can be expressed by the following equation [21]

$$E(r, z) = E(0, z_0) \exp\left[-\frac{r^2}{\omega_p^2}\right] \exp\left[-\frac{ikn_0 r^2}{2R}\right] \quad (4)$$

r is the radial coordinate, z_0 is the medium coordinate position, k is the free space wave vector, n_0 is the air refractive index surrounding the medium, ω_p is the beam waist at the entrance of the medium and R is the radius of curvature of the beam wave-front in the position. The intensity of the beam traversing the khoba oil and falling on the screen which was 70 cm from the sample cell (see Fig. 5) can be obtained using the relation

$$I(\rho) = I_0 \left| \int_0^\infty J_0(k\theta(r)) \exp\left[-\left(\frac{r^2}{\omega_p^2}\right) - i\phi(r)\right] r dr \right|^2 \quad (5)$$

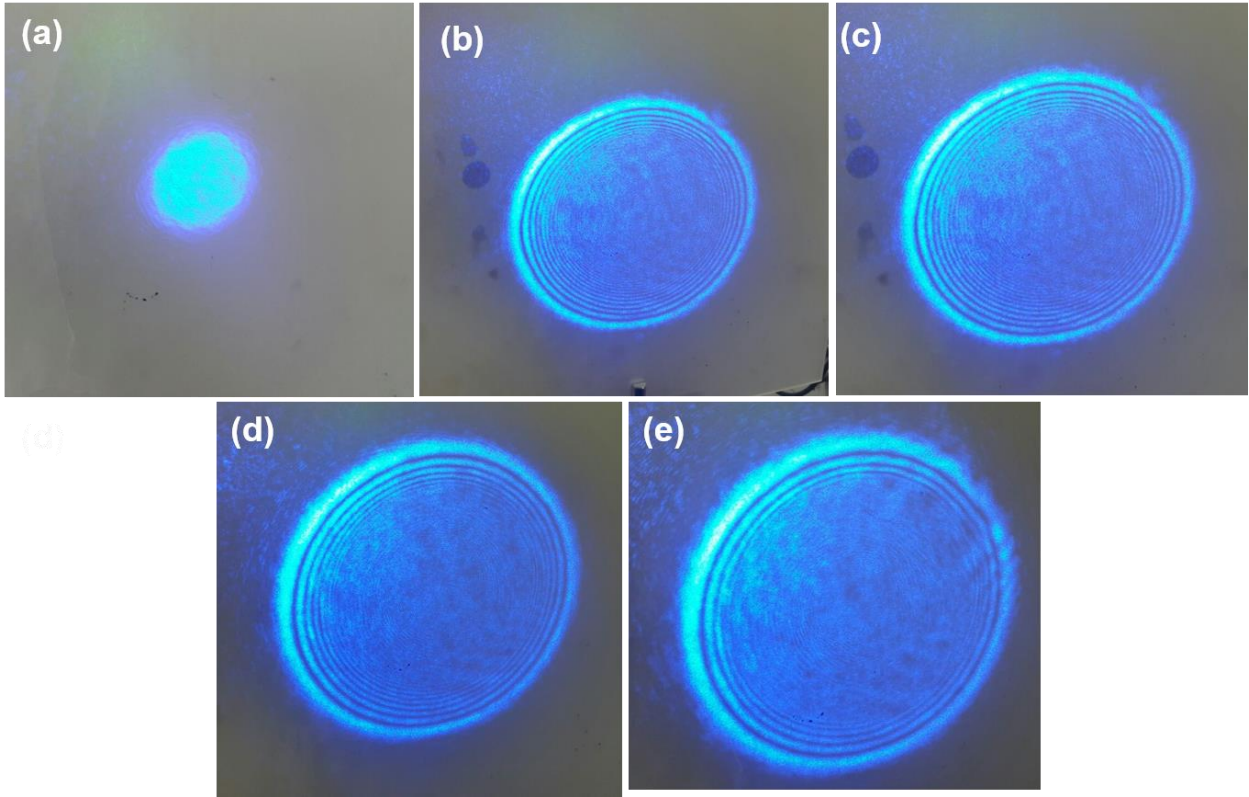


Fig.3: Images of the far field diffraction ring patterns at input laser power (mW) passing through the sample cell of (a) 5, (b) 21, (c) 39, (d) 51 (e) 63.

$J_0(x)$ is the zero order Bessel function of the first kind, θ is the far field diffraction angle, ρ is the radial coordinate in the far field plane, I_o is the laser beam intensity, and φ is the total phase shift that is added to the Gaussian beam.

Obvious agreement can be seen between the numerically obtained ring

patterns shown in Fig.6 and the experimental ones shown in Fig.3. Fig.7 shows (left column) 1D distributions and (right column) 3D distributions of laser beam on the screen passing through khoba oil.

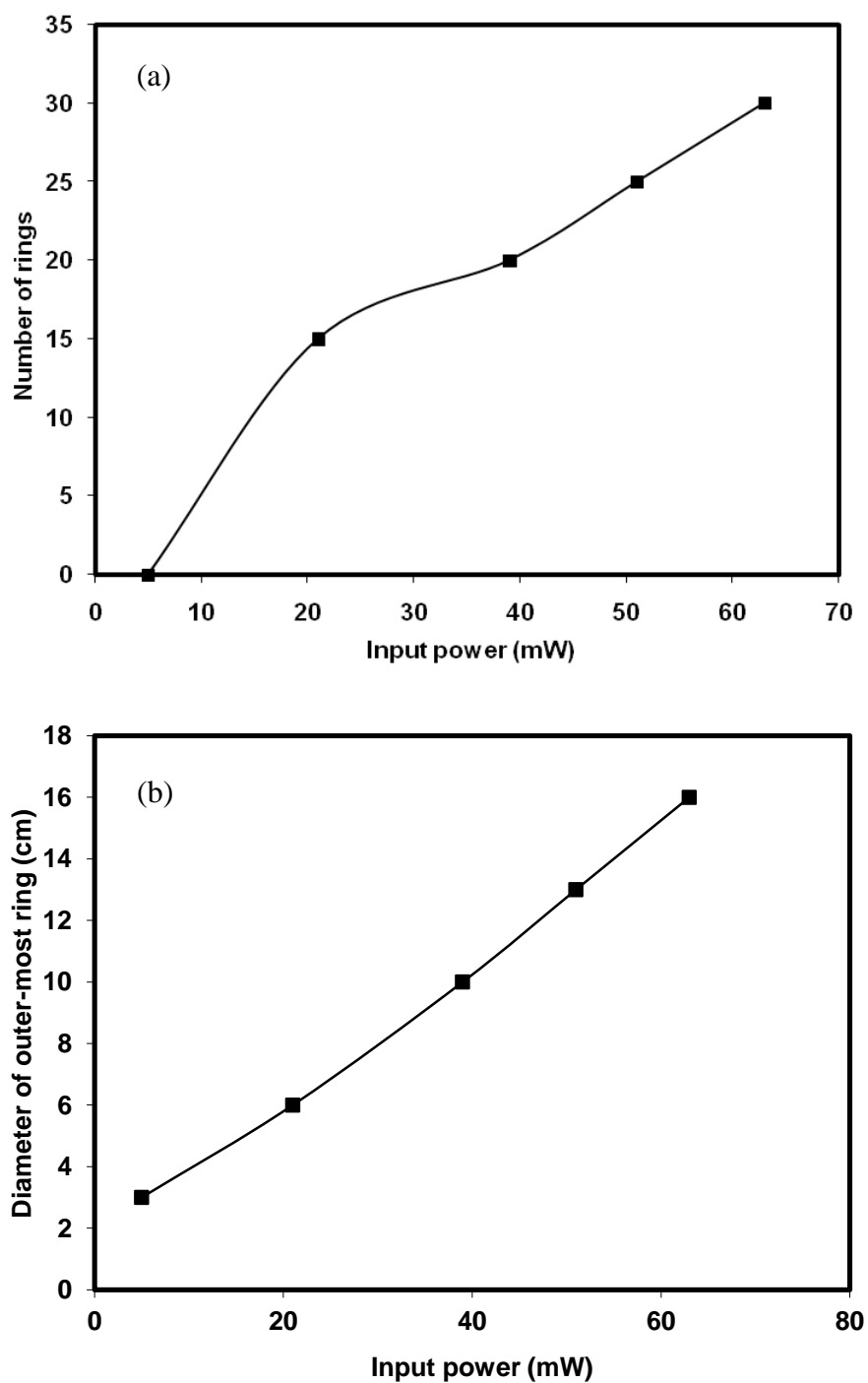


Fig.4. (a) Number of rings, N, and (b) diameter of outer-most rings for khoba oil against input power respectively at $\lambda=473$ nm.

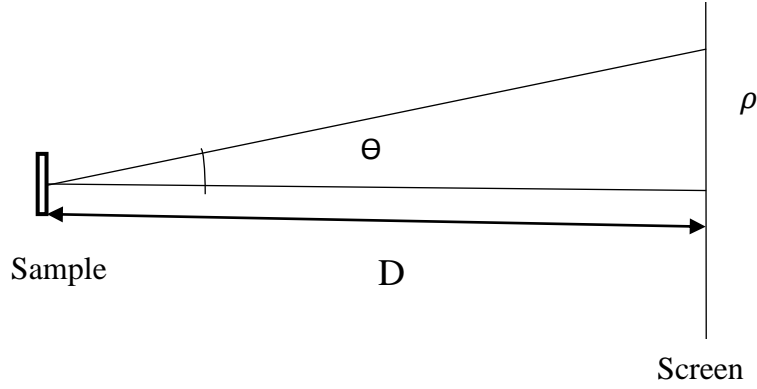


Fig. 5: Definition of experimental θ , D and ρ used in the theoretical analysis of the diffraction patterns.

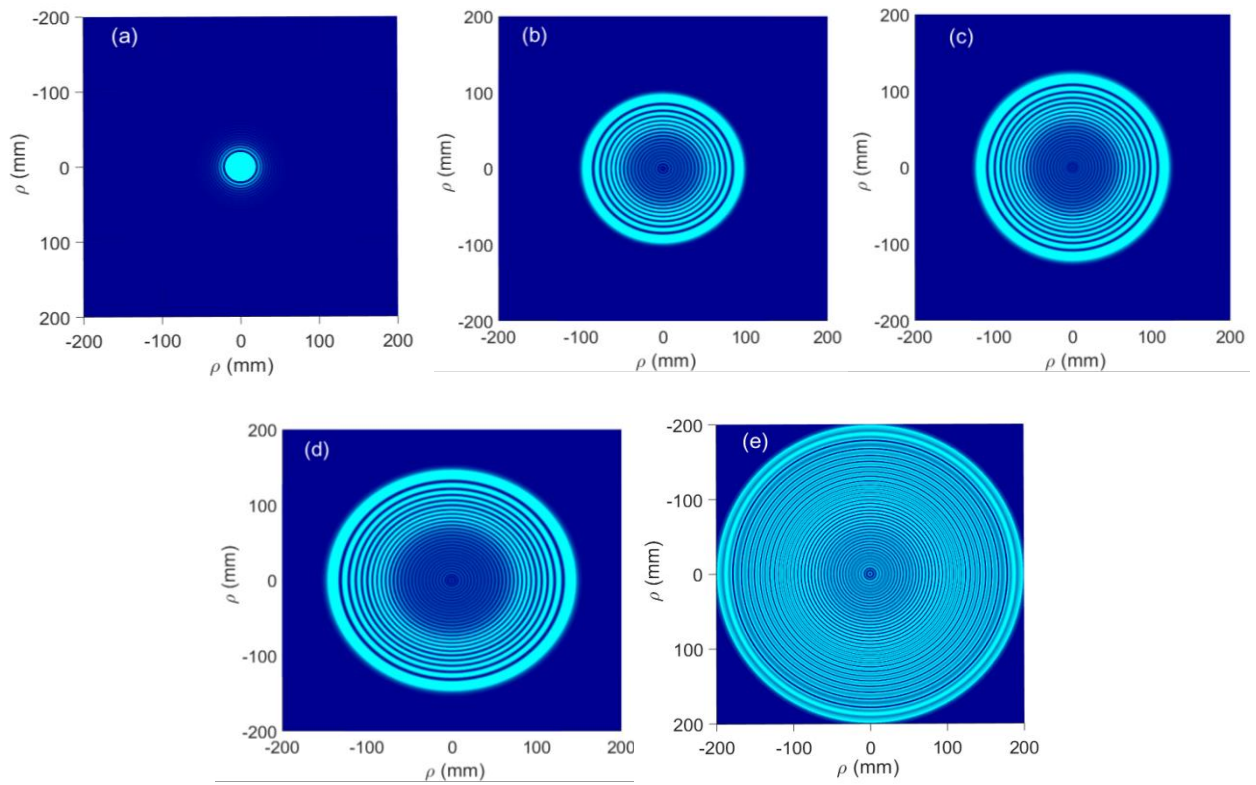


Fig.6: Numerically calculated diffraction ring patterns at input laser power (mW) passing through the sample cell of (a) 5, (b) 21, (c) 39, (d) 51 (e) 63.

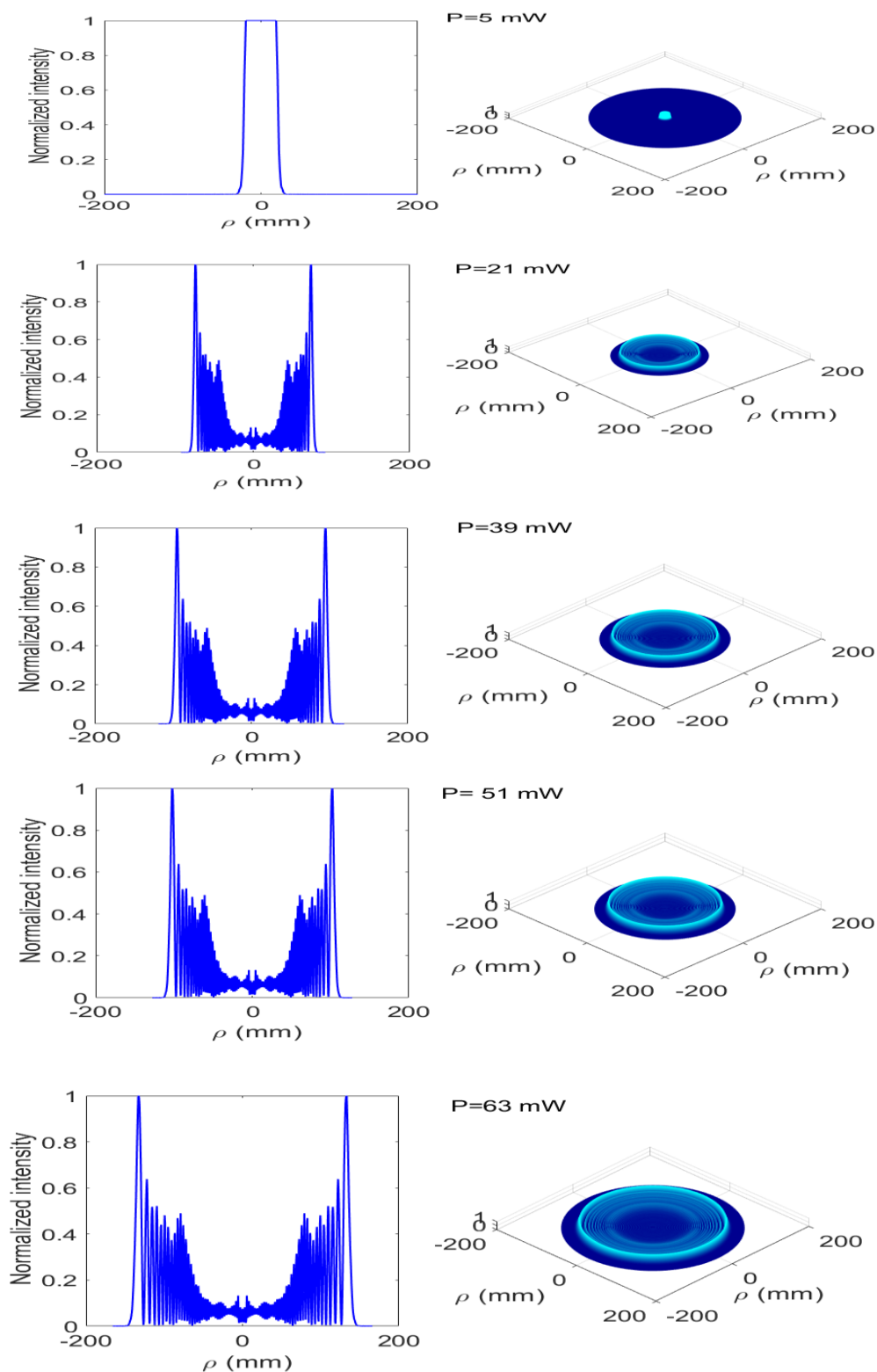


Fig. 7: Calculated far-field intensity distribution of laser beam passing through khoba oil, left column is one dimensional and right column is three dimensional distributions, of laser beam passing through khoba oil falling on the screen at different input power ranged from 5mW to 63 mW in ascending order from top to bottom.

3.3 Z-scan

To examine the optical nonlinearity of khoba oil, the closed aperture (CA) and open aperture (OA) Z-scans were used. It has been observed that the sample does not show any nonlinear absorption responses at this excitation laser wavelength with low laser intensity. The closed aperture Z-scan plot is shown in Fig. 8 for khoba oil. The graph clearly exhibits the presence of a peak followed by a valley, which indicates a negative value of nonlinear refraction (self-defocusing). The self-defocusing effect is due to local variation of refractive index with temperature, this lead to creation of a thermal lens that diverges the laser beam, resulting in the defocusing nature of the material.

In thermal lens model the difference in the transmittances, ΔT_{p-v} , at peak and

valley of the closed aperture Z-scan trace is related to the nonlinear refractive index, n_2 , by [22]

$$n_2 = \frac{\Delta T_{p-v} \lambda}{4\pi L I_0} \quad (6)$$

where λ is the wavelength of the laser and I_0 is the input intensity.

The nonlinear refractive index, n_2 , of the khoba oil is calculated via diffraction ring pattern using equations (2 and 3) and Z-scan using equation (6) and Fig.8, the obtained results are $1.3 \times 10^{-6} \text{ cm}^2/\text{W}$ and $1.26 \times 10^{-7} \text{ cm}^2/\text{W}$ respectively. These results are depicted in Table 1.

The order of magnitude difference of n_2 measured in diffraction ring pattern and Z-scan techniques is attributed to the order of magnitude difference between the input intensity used in both techniques.

Table 1: Nonlinear optical and optical limiting parameters for khoba oil by using diffraction ring patterns and Z-scan at $10.845 \text{ kW}/\text{cm}^2$ and $0.688 \text{ kW}/\text{cm}^2$ incident intensities, respectively.

Number of rings	Absorption coefficient $\alpha \text{ (cm}^{-1}\text{)}$	Diffraction rings $n_2 \times 10^{-6}$ (cm^2/W)	Z-scan $n_2 \times 10^{-7}$ (cm^2/W)	Limiting threshold (mW)
30	59.14	1.30	1.26	14.8

3.4 Optical limiting

There has been much interest in the development of optical limiting materials due to the development of laser technology. The optical limiter is a device used for the protection of human eyes and solid-state sensors against intense laser beams. An ideal limiter exhibits a linear transmission below threshold, and a constant transmission above threshold. Fig.9 shows the result of the optical limiting experiment where the output power is plotted as a function of the input power for the khoba oil. The experimental data shows that the sample exhibit an optical power limiting characteristic. As shown in Fig. 9, at low input power, the output power of sample increases linearly with the input power obeying the Beer–Lambert law but starts to deviate at high input power. With further increase of the input power, the output power reaches a plateau and is

saturated at a point defined as the limiting amplitude.

Transmittance responses versus input power for khoba oil is shown in Fig.10. In general, evaluation of optical limiting ability of the sample can be measured in term of limiting threshold, which is defined as the input power, at which the transmittance of the sample falls to half its linear transmittance. The threshold value for khoba oil, is found to be around 14.8 mW.

The mechanism of optical limiting can be explained as follows: In the case of continuous laser cw , this will result in a change in the refractive index of the material which causes spatial distortion of the Gaussian laser beam, thereby creating self-phase modulation (SPM). The SPM causes self- defocusing which leads to the reduction of transmittance at far field.

3.5 Comparative study

It is worth noting that the value of n_2 for khoba oil is larger than those of some representative nonlinear optical materials such as fast green FCF dye (acid blue 3) [23], azo dye [1-am ino-2-hydroxy naphthalin sulfonic acid-[3-(4-azo)]-4-amino diphenyl sulfone] [24], basic violet 16 dye [25], 10W30 oil [26], semiconductor

ZnS nanoparticles [27], Au and Ag colloids [28] , 2APS single crystal [29] , rose oil [18] ,cobalt (II) phthalocyanine [7] , epoxy resin doped carbon black [9] and parsley oil [30] .Their optical nonlinearities are listed in Table 2. These results suggest that the khoba oil may have potential applications in nonlinear optical devices.

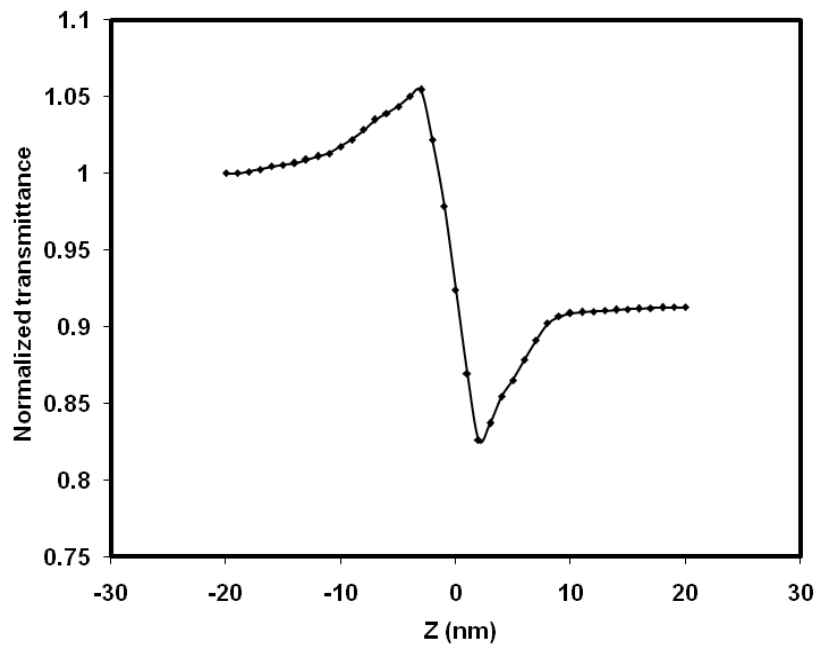


Fig.8: Closed aperture Z-scan data for khoba oil.

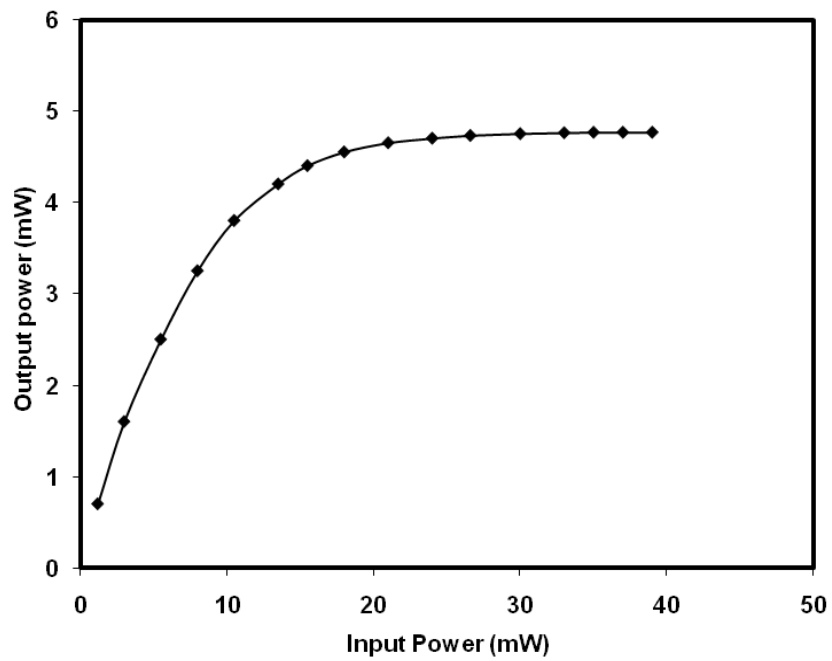


Fig.9: Optical limiting property of khoba oil.

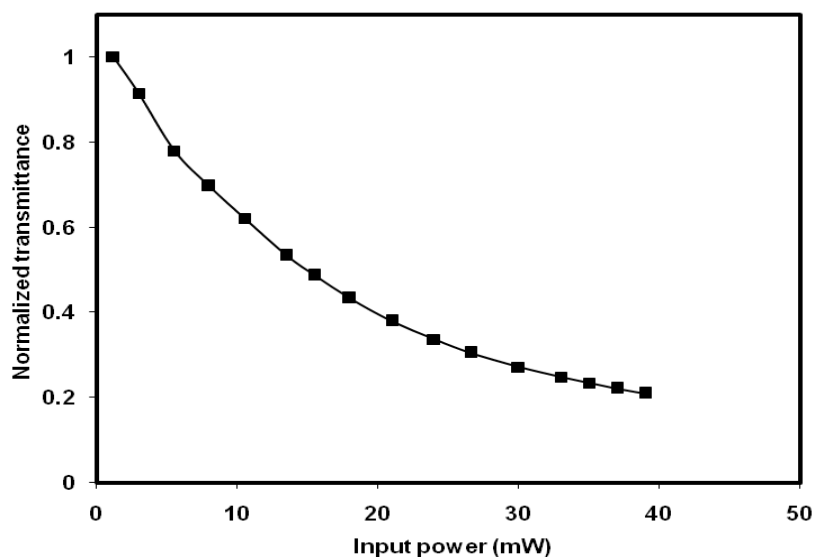


Fig.10: Normalized transmission curve of optical limiting for khoba oil.

Table 2. Table depicting the recently reported n_2 values of different materials

Materials	$n_2(\text{cm}^2/\text{W})$	Reference
khoba oil	1.26×10^{-7}	This work
Fast green FCF dye (acid blue 3)	3.2×10^{-8}	Ref.[23]
Azo dye dye[1-am ino-2-hydroxy naphthalin sulfonic acid-[3-(4-azo)]-4- amino diphenyl sulfone]	2.73×10^{-9}	Ref.[24]
Basic violet 16 dye	2.812×10^{-8}	Ref.[25]
10W30 oil	1.6×10^{-9}	Ref.[26]
Semiconductor ZnS nanoparticles	1.38×10^{-8}	Ref.[27]
Au and Ag colloids	2.23×10^{-8} , 1.6×10^{-8}	Ref.[28]
2APS single crystal	2.4189×10^{-8}	Ref.[29]
Rose oil	0.92×10^{-8}	Ref.[18]
Cobalt (II) phthalocyanine	7.79×10^{-9}	Ref.[7]
Epoxy resin doped carbon black	0.29×10^{-8}	Ref.[9]
Parsley Oil	3.9×10^{-8}	Ref.[30]

4. Conclusion

The passage of a single transverse mode, CW, visible and low power laser beam through khoba oil have led to diffraction ring patterns. Based on the ring patterns and the Z-scan techniques, the following nonlinear refractive index, n_2 , of the khoba oil are obtained viz., $1.3 \times 10^{-6} \text{ cm}^2/\text{W}$ and $1.26 \times 10^{-7} \text{ cm}^2/\text{W}$, respectively. Diffraction ring patterns successfully reproduced via the use of Fresnel-Kirchhoff diffraction integral

numerically. Due to the Z-scan results the sign of the nonlinear refractive index is found to be negative and the nonlinear phenomenon was due to self-defocusing process. The optical limiting characteristics of khoba oil is reported for the first time. The sample show good optical limiting behavior at 473 nm. The mechanism of optical limiting in the low power regime is found to be predominantly of a thermal origin.

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قياسات معامل الانكسار اللاخطي في زيت الخوبالنباتي مستعنيين بنماذج حلقات الحيود والمسح بالاتجاه Z

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الخلاصة

تم تقدير معامل الانكسار اللاخطي في زيت الخوبا النباتي بأستعمال نماذج حلقات الحيود والمسح بالاتجاه Z بأستعمال حزمة ليزر مرئية مستمرة ذات نمط مستعرض احادي واطئة القدرة. تم انتاج نماذج حلقات الحيود عدديا بالاستعانة بتكامل حيود فرنيل – كيرشهوف بتوافق جيد مع تلك المقاسة عمليا. أبدى هذا الزيت تأثير عدم التركيز الذاتي وبدا ان الالية الرئيسية المسؤولة عن اللاخطية البصرية ذات منشأ حراري. تم دراسة المحدد البصري في هذا الزيت وبدا ان له امكانية الاستعمال في الاجهزة البصرية اللاخطية.