ENHANCED KNOWLEDGE IN SCIENCES AND TECHNOLOGY
e-ISSN: 2773-6385

EKST

Vol. 4 No. 2 (2024) 509-519
https://publisher.uthm.edu.my/periodicals/index.php/ekst

The Study of Nonlinear Optical Properties of Curcumin Dye Using Z-Scan Method.

Mas Iezaty Mukhtar[1], Nurul Nadia Adnan[1*], Ganesan Krishnan[2]

[1] *Department of Physics and Chemistry, Universiti Tun Hussein Onn Malaysia Kampus Cawangan Pagoh, Hab Pendidikan Tinggi Pagoh, KM 1, Jalan Panchor, 84600 Pagoh, Muar, Johor, MALAYSIA*
[2] *Laser Center, Ibnu-Sina Institute for Scientific and Industrial Research (ISI-SIR), Universiti Teknologi Malaysia (UTM), Johor Bahru, 81310, Johor, MALAYSIA*

*Corresponding Author: nadia@uthm.edu.my
DOI: https://doi.org/10.30880/ekst.2024.04.02.056

Article Info

Received: 27 December 2023
Accepted: 12 January 2024
Available online: 12 December 2024

Keywords

Curcumin, Nonlinear absorption, Nonlinear refractive index, Z-scan method.

Abstract

Curcumin, a prominent component in Curcuma longa's rhizome, manifests as a vibrant orange-yellow crystalline compound. This research uses the Z-scan technique to characterise the nonlinear refractive (NLR) and nonlinear absorption (NLA) of Curcumin dye solutions. Employing open and closed aperture in Z-scan measurements, we investigate the relationship between laser diode input fluences (150 milliwatts) at five different dye concentrations (0.1 millimolar, 0.2 millimolar, 0.3 millimolar, 0.4 millimolar, and 0.5 millimolar). The results show that nonlinear refractive (NLR) and nonlinear absorption (NLA) were observed starting at 0.1 millimolar and going up to 0.5 millimolar. The result indicates the emergence of NLR and NLA properties from 0.01 millimetre, with a reduction in NLR value observed as concentrations increased. This underscores Curcumin dye's potential as an optical limiter in photonics applications.

1. Introduction

Curcumin, a primary constituent of Turmeric's rhizome, scientifically known as Curcuma longa, constitutes about 77% of the three main compounds present in Turmeric, collectively referred to as curcuminoids [1]. Curcumin has garnered attention for its potential use in photonics, particularly in optical limiting and related applications. Additionally, it has been subjected to in-depth investigations concerning its nonlinear optical properties despite the significant progress made in nonlinear optics. Curcumin presents itself as a crystalline compound with a vibrant orange-yellow hue, offering the possibility of intriguing nonlinear reactions when analyzed using techniques like the Z-scan method.

The Z-scan method represents a powerful experimental approach for assessing the nonlinear optical characteristics of materials. It plays a crucial role in advancing our comprehension of nonlinear optics, aiding in material characterization, optimizing device performance, and supporting the development of novel materials and applications [2]. The Z-scan technique, originally introduced by Sheik-Bahae et al., is widely employed to measure the nonlinear optical properties of materials due to its simplicity and high sensitivity [3].

Hence, using the solvent extraction method to prepare Curcumin allows for the comprehensive characterization of its nonlinear optical properties through the Z-scan technique. This approach enables the determination of nonlinear absorption (α), nonlinear refractive index (n2), and third-order nonlinear properties (X^3) [5]. Consequently, a better understanding of how Curcumin responds to intense light can be achieved, opening possibilities for its utilization in various rapidly evolving fields, including nonlinear optics, signal processing, and light modulation applications [4]. In summary, this study aims to bridge the existing knowledge gap by thoroughly examining Curcumin's nonlinear optical properties via Z-scan measurements.

1.1 Nonlinear Optical Characterization.

The Z-scan technique is employed to measure the third-order nonlinear optical (NLO) parameters, including the (n2), nonlinear absorption coefficient (β), and third-order nonlinear susceptibility ($X3$). This measurement used a 532 nm continuous-wave (CW) diode-pumped solid-state (DPSS) laser with a repetition rate of 10 Hz as the laser source [5].

Two Thorlabs photodetectors, PD1 and PD2, were utilized in the experiment. A quartz cuvette with a 1 mm path length held the dye solutions and was mounted on a computer-controlled, motorized stage with a 20 cm displacement. This cuvette was moved parallel to the laser beam's direction. Subsequently, the laser beam was split into two arms using a 50:50 beam splitter. An aperture was positioned in front of PD1 for the first arm (closed-aperture Z-scan), while PD2 was placed in front of the second arm without any aperture (open-aperture Z-scan). Simultaneously, the signals from PD1 and PD2 were recorded by an oscilloscope, which would later be analyzed to determine the nonlinear absorption (NLA) and nonlinear refractive (NLR) responses.

$\Delta T_{P\text{-}V}$ is known as the normalized peak-to-valley transmittance and can be determined from the closed-aperture Z-scan method [8]. Another change in $\Delta T_{P\text{-}V}$ is a function of the on-axis phase shift represented by $|\Delta\phi_0|$where $\Delta T_{P\text{-}V} = 0.406(1 - S)0.25|\Delta\phi_0|$where S is the linear transmittance of the aperture, r_0 represents the radius of the aperture, and ω_0 represents the radius of the beam located at the aperture with the function $S = 1^{-(-2r0\omega0)}$ [9]. From these considerations, the expression for the nonlinear refractive index (n2) can be determined as:

$$n_2 = \frac{\Delta\phi_0\lambda}{2\pi L_{eff} I_0} \tag{1}$$

where λ is the wavelength of the laser, Leff the effective thickness of the sample, and I0 is the laser intensity at the focus.

Effective thickness, L_{eff} where α is the linear absorption coefficient and L is the thickness of the sample. Additionally, the NLA coefficient (β) can be estimated from the open aperture Z-scan data using the relationship:

$$\beta = \frac{2\sqrt{2}\,\Delta T}{I_0 L_{eff}} \tag{2}$$

where ΔT is the value of one- valley from the curve of open aperture

$$X^3 = ReX^3 + \mathrm{Im}X^3 \tag{3}$$

The real part of X^3 can be obtained from evaluating the nonlinear refractive index (n2) derived from a closed aperture Z-scan experiment. The behaviour of the transmission minimum valley before the focus and the behaviour of the transmission maximum peak after the focus contributes to determining the real part of the susceptibility ReX^3. Conversely, the imaginary part of ImX^3 is determined from the nonlinear absorption coefficient (β) obtained from the aperture Z-scan experiments. As the sample approaches the laser beam, the detected transmittance either increases or decreases, forming valley and peak features. Therefore, a normalized transmission plot is generated, which correlates with the sample deviation (Z-shift).

$ReX^3$and imaginary ImX^3 can be evaluated with their relationship are defined as follows:

$$ReX^3 = 10^{-4}\frac{\varepsilon_0\, c^2 n_0^2}{\pi} n_2 \tag{4}$$

$$\mathrm{Im}X^3 = 10^{-2}\frac{\varepsilon_0 c^2 n_0^2 \lambda}{4\pi^2}\beta \tag{5}$$

where ε_0 represents the vacuum permittivity, and c is the speed of light in a vacuum.

2. Materials and methods.

2.1 Preparation of Curcumin Dye solution

Curcumin dye was sourced from a local supermarket. Curcumin dye was acquired from a local supermarket, and the sample preparation method employed was solvent extraction method (6). The Curcumin dye preparation process initiates by meticulously slicing and drying turmeric rhizomes to eliminate moisture. Concurrently, an acetone solution is formulated with a precise 1:10 ratio of pulverized turmeric to acetone. Following the thorough mixing of distilled water and acetone, a specific volume is measured, and 5 grams of turmeric are introduced, leading to a noticeable change in color to a vibrant yellow.

After thorough stirring and allowing a resting period, the solution undergoes a transformation, turning a striking scarlet hue. Subsequently, the solution is meticulously filtered through a micron sieve and filter paper to yield a refined Curcumin solution. This process is repeated with varying quantities of turmeric to attain distinct concentrations suitable for optical analysis. Additionally, the option to adjust hue intensity through dilution with distilled water is available as needed. Ultimately, the resulting Curcumin pigment extract is stored in a cold, dark environment to preserve its color and prevent deterioration.

A series of five Curcumin dye solutions were meticulously prepared to create the required concentrations, with concentrations of 0.1 mM, 0.2 mM, 0.3 mM, 0.4 mM, and 0.5 mM. The solvent used for these solutions comprised a mixture of distilled water and acetone, with their preparation involving a sequence dilution process, as per the following eq. 6 below:

$$C_1V_1 = C_2V_2 \tag{6}$$

Where the C_1 is the initial concentration of acetone, V_1 is the initial volume of acetone. C_2 is the final concentration of acetone and V_2 the final volume of the mixture.

Each solution was placed above the surface of FTIR device to facilitate the Z-scan analysis. Fourier transform infrared (FTIR) spectroscopy was employed to characterize the dye solutions, providing valuable insights into their chemical composition and properties.

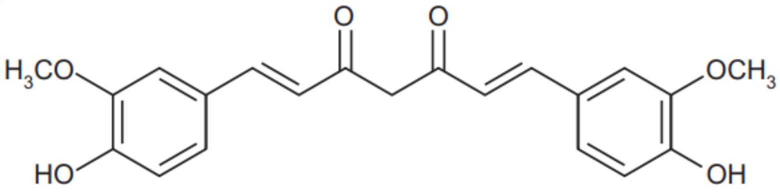


Fig. 1 *The chemical structure of Curcumin dye [1]*

2.2 Z-Scan technique

The experimental setup utilizes a diode laser source that emits electromagnetic radiation with a wavelength of 532 nm, falling within the range between microwave and infrared wavelengths. Fig. 2 provides a schematic representation of the Z-scan experiment configuration.

In this setup, two Thorlabs PDA 55 photodetectors, namely PD1 and PD2, are employed. The Curcumin dye solution is contained within a quartz cuvette with a path length of 1 mm. This cuvette is positioned on a computer-controlled motorized stage capable of moving 20 cm along a linear path parallel to the laser beam [5].

To split the laser beam into two paths, a beam splitter is used, and these paths form a 50° angle as they traverse the dye solution [7]. In the first path, there is an aperture in front of PD1, resulting in a Z-scan with a closed aperture configuration. In contrast, the second path includes a lens without a gap in front of PD2. Signals from PD1 and PD2 are simultaneously recorded by an oscilloscope, enabling the examination of nonlinear absorption (NLA) and nonlinear refraction (NLR) responses.

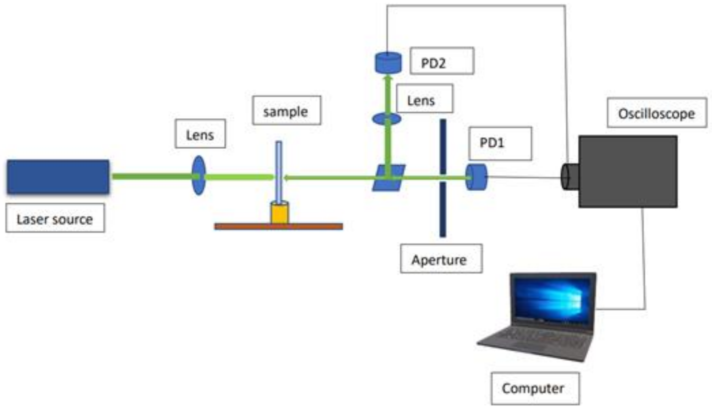


Fig. 2 *Schematic diagram of experiment setup of Z-Scan*

Table 1 *Parameters of Z-Scan experiment*

Parameters	Value
Wavelength, λ	532 nm
Aperture radius, r0	1.9 mm [5]
Focal length, (f)	200 mm [5]
Rayleigh range, (Z_R)	0.0041 m
Beam waist, (ω_0)	2.64×10-5 m

3. Result and Discussion

3.1 Fourier transform infrared (FTIR)

Fig. 3 shows the Fourier transform infrared spectroscopy (FTIR) was employed to analyze the Curcumin dye solution, allowing to identify its bonding structure and functional groups by generating a corresponding spectrum. During the FTIR measurement, Table 3 was compiled to help assign peaks based on the FTIR spectrum.

A significant peak at 3351.02 cm^{-1} can be attributed to the O-H stretching vibration. This peak signifies the presence of phenolic groups within Curcumin. These phenolic groups are renowned for their antioxidant properties, underscoring their importance in Curcumin's biological functions [1].

Two additional peaks detected at 1696.87 cm^{-1} and 1639.59 cm^{-1} are associated with C=O stretching vibrations, indicating the coexistence of ketonic and enolic forms within the Curcumin structure. This dual structural nature is significant because it plays a crucial role in determining the stability and reactivity of Curcumin, which are pivotal factors in its biological activities [8].

The peak observed at 1422.02 cm-1 corresponds to C-C stretching within the aromatic ring of Curcumin. This feature is fundamental to the Curcumin molecule, as it consists of two aromatic rings connected by a seven-carbon linker. Furthermore, two peaks at 1370.61 cm-1 and 1237.94 cm-1 can be attributed to C-O stretching vibrations, indicating the presence of ether linkages. These ether linkages are a distinctive characteristic of the Curcumin molecule [9].

It's worth noting that these FTIR results align with previous research on Curcumin's thermal nonlinearities, as reported in a study that investigated three curcuminoids measured by diffraction ring patterns and Z-scan under visible continuous-wave (CW) laser illumination [9].

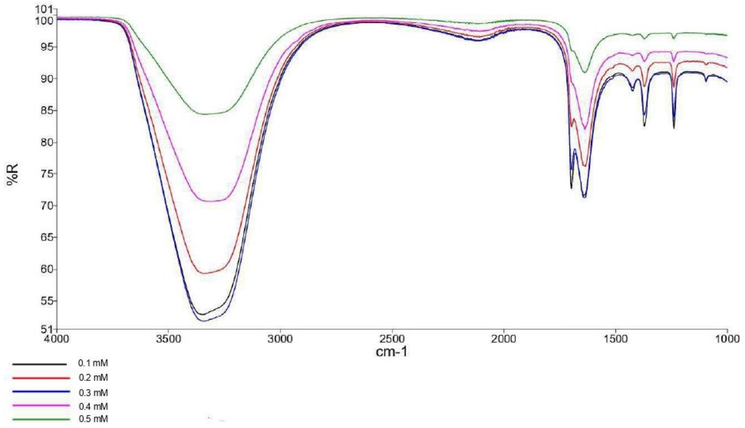


Fig. 3 *FTIR spectra of Curcumin with different concentrations*

Table 2 *FTIR analysis of Curcumin with different concentrations*

Sample	O-H (cm^{-1})	C=O (cm^{-1})	C-C (cm^{-1})	C-O (cm^{-1})
Curcumin (0.1mM)	3351.02	1696.87 1639.59	1422.04	1370.61 1237.94
Curcumin (0.2mM)	3350.46	1696.95 1639.20	1422.29	1370.68 1237.94
Curcumin (0.3mM)	3350.66	1696.80 1639.53		1370.86 1238.22
Curcumin (0.4mM)	3339.21	1696.14 1639.15		1370.98 1238.42

3.2 UV-Vis spectroscopy

In Fig. 4, the absorption spectrum obtained using UV-Vis spectroscopy for the Curcumin solution in an acetone solvent is presented. The results reveal a prominent absorption spectrum peak located just above 460 nm, with an absorbance value slightly below 5.5. This finding implies that the substance exhibits a substantial level of light absorption at this specific wavelength.

The samples were tested across the visible wavelength range, spanning from 460 nm to 660 nm, in the presence of acetone within the Curcumin solution. It's worth noting that acetone plays a crucial role in UV-Vis spectroscopy, primarily due to its high transparency within this particular spectral region [10]. This transparency is vital as it allows for accurate and precise absorption measurements to be conducted.

Curcumin, on its own, has inherent absorption peaks within the UV-Vis spectrum. However, the introduction of acetone into the solution may influence the solubility of Curcumin and alter its molecular environment. Consequently, this can lead to shifts in absorption peaks or modifications in absorption intensity [11].

In summary, the UV-Vis spectroscopy analysis revealed a distinct absorption peak for the Curcumin solution in acetone, centered just above 460 nm, with a relatively high absorbance value. This indicates significant light absorption by Curcumin at this specific wavelength. Furthermore, the presence of acetone, known for its spectral transparency, facilitated precise absorption measurements. However, it's essential to consider that the introduction of acetone could potentially affect the solubility and molecular environment of Curcumin, potentially leading to changes in its absorption characteristics [12].

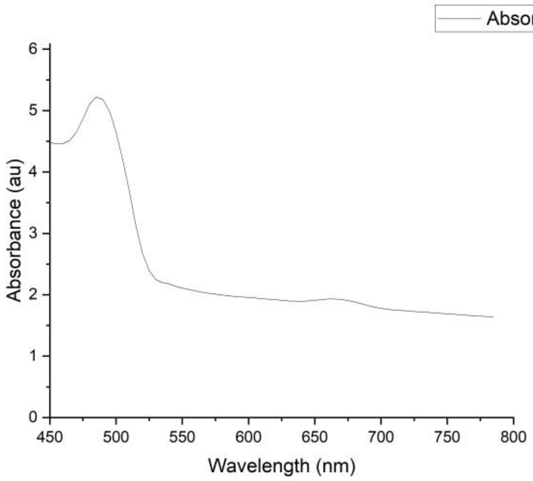


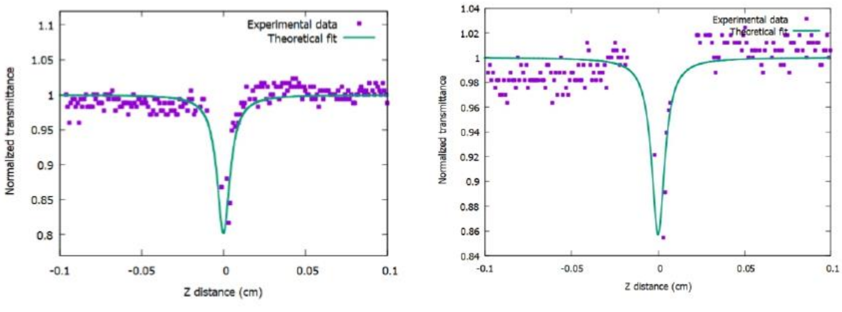
Fig. 4 *The absorption spectrum of Curcumin using UV-Vis Spectroscopy*

3.3 Nonlinear absorption (β) by Open aperture of Z-scan.

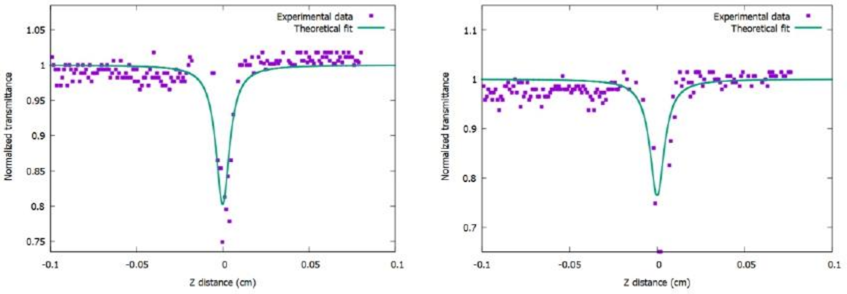
In Fig. 5 (a) to (e), initially, there were no discernible signs of nonlinearity as the samples were positioned at a considerable distance from the beam waist. However, noticeable changes in transmission, primarily attributed to nonlinear absorption, occurred as the samples traversed the nonlinear regime. At an excitation laser power of 150 mW, a phenomenon known as Reverse Saturable Absorption (RSA) became evident as the concentration of the Curcumin dye increased from 0.1 mM to 0.5 mM. RSA is characterized by a reduction in the transmittance signal when the sample passes through the focal point (where z-displacement = 0) within the nonlinear regime [13]. Reverse Saturable Absorption, which is a non-linear optical phenomenon observed in materials with high concentrations of absorbing molecules. RSA is characterized by a decrease in the absorption coefficient with increasing incident light intensity, which is the opposite of saturable absorption [19].

Upon examining Figure 5 (a) to (e), the (NLA) response indicates that RSA occurs due to the aggregation of dye molecules, facilitating Two-Photon Absorption (TPA) [14]. The substantial absorption observed in these high-concentration Curcumin dye solutions may result from the combined effects of TPA and Excited State Absorption (ESA), contributing to the RSA process. Table 3 presents the NLA coefficient, β.

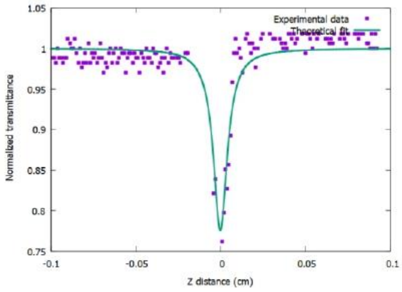
In Fig. 6 below, a noticeable trend emerges with the positive sign of β increasing as the dye concentration rises. This positive sign of β signifies an enhancement in RSA, primarily attributed to the ESA phenomenon [15]. The increasing aggregation of dye molecules can elucidate this as the concentration escalates. This aggregation is linked to the benzene rings connected by seven-carbon chains in the Curcumin solution [16]. As previously mentioned, this aggregation leads to dimerization between the molecules, causing energy splitting from singlet to triplet energy states.



(a) 0.1mM (b) 0.2mM



(c) 0.3mM (d) 0.4mM



(e) 0.5 mM

Fig. 5 *The result of an open aperture of the Z-scan curve of Curcumin dye at concentrations of (a) 0.1 mM, (b) 0.2 mM (c) 0.3 mM (d) 0.4 mM and (e) 0.5 mM.*

Table 3 *The result of nonlinear absorption(▯) optical properties of Z- scan measurement*

Sample with different concentrations (mM)	β ($\times 10^{-5}$)
0.1	1.14856
0.2	1.32671
0.3	1.44718
0.4	1.49152
0.5	1.56881

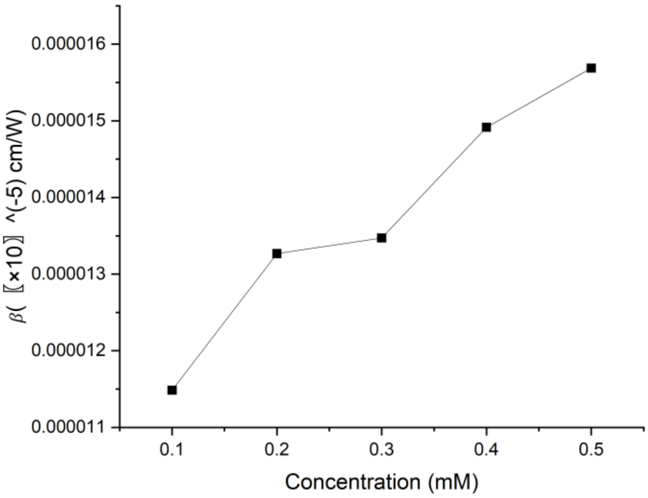
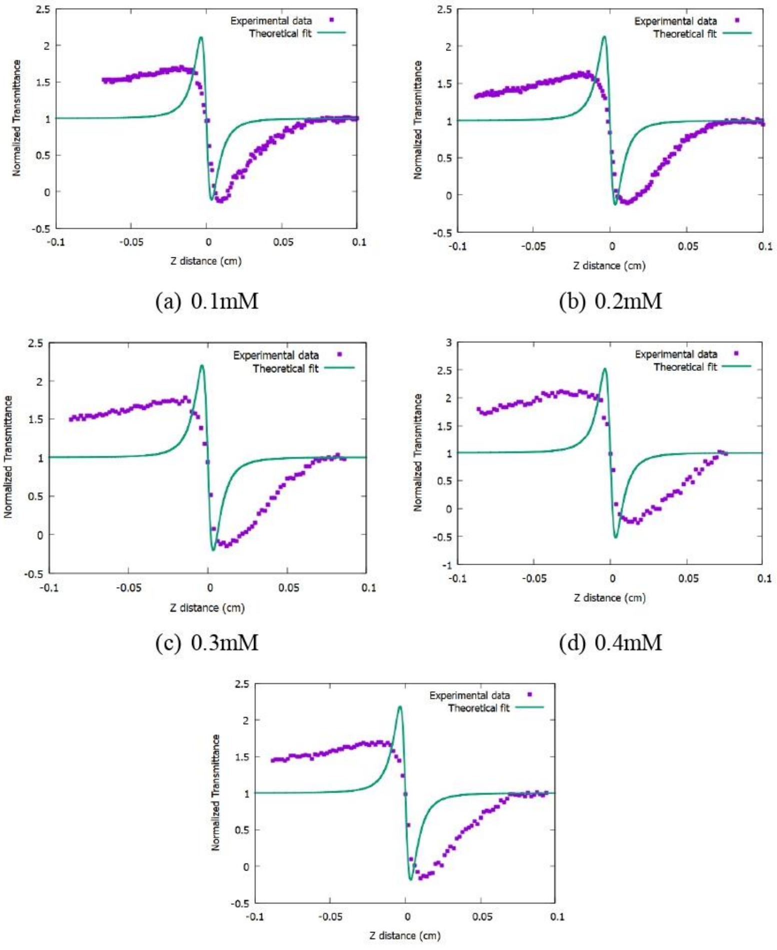


Fig. 6 *The results of varying concentrations of dyes towards the nonlinear absorption, values*

3.4 Nonlinear Refractive Index (n2) by Closed aperture of Z-Scan.

Fig. 7 (a) to (e) displays the closed-aperture z-scan transmission curves for Curcumin dye solutions at varying concentrations. These figures reveal that the peak-valley normalized transmission, denoted as ΔT_{P-V}, indicates negative nonlinear refraction, also known as the self-defocusing effect, stemming from irradiance divergence [17].

By utilizing the measured ΔTP− V values, the nonlinear refractive index, n2, can be calculated using Eq. (1). As presented in Table 4, the calculated n2 values are found to be 10^{-12} cm^2/W. In contrast to (NLA), (NLR) exhibits a different trend as the dye concentrations increase under the same input power of 150 mW, as shown in Figure 7. As the concentration increases, the n2 values for these dye solutions decrease within the range of 1.826-1.152 × 10^{-12} cm^2/W. This trend aligns with the peak values of these transmission curves, which fall within the range of 1.5–2.0, and the valley transmittance, which is around 0.3–0.2 [18]. Fig. 8 illustrates that, the highest n2 value was recorded at the lowest concentration of 0.5 mM. However, as the concentration increases, it leads to a decrease in the n2 value. This trend suggests that the NLR of the material weakens due to population redistribution during the Excited State Absorption (ESA), and it can be speculated that the thermal lens effect may impact the dye molecules as the concentration increases [19].



(a) 0.1mM (b) 0.2mM

(c) 0.3mM (d) 0.4mM

(e) 0.5mM

Fig. 7 *The result of closed aperture of Z-scan curve of Curcumin dye at concentrations of (a) 0.1 mM, (b) 0.2 mM (c) 0.3 mM (d) 0.4 mM and (e) 0.5 mM*

Table 4 *The result of the samples' nonlinear refractive index (n2)*

Sample with different concentrations (mM)	n2 ($\times 10^{-12}$)
0.1	-2.462
0.2	-1.180
0.3	-1.126
0.4	-1.489
0.5	-1.827

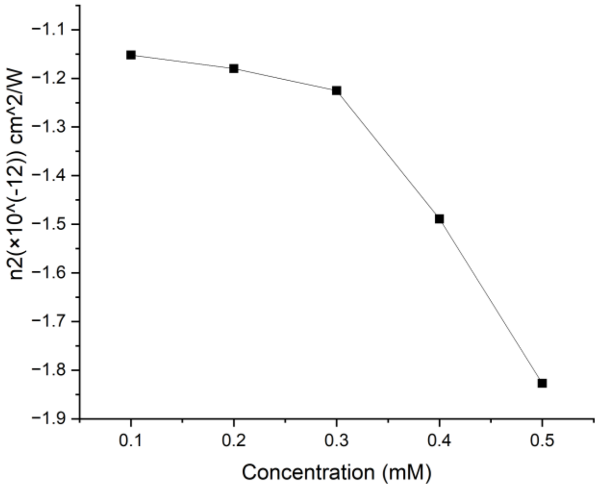


Fig. 8 *The results of varying concentration of dyes towards the nonlinear refractive index, n2 values*

4. Conclusion

In this study, we conducted an in-depth investigation into the nonlinear optical properties of Curcumin dye solutions using the Z-scan method. The results obtained shed light on the intriguing optical behavior of Curcumin and its potential applications in various fields.

In the closed-aperture Z-scan experiments, we observed self-defocusing effects in the Curcumin dye, characterized by consistently negative n2 values. Notably, these self-defocusing effects demonstrated a tendency to diminish as the concentration of Curcumin increased [20]. On the other hand, the open-aperture Z-scan experiments revealed a Reverse Saturable Absorption (RSA) effect at higher concentrations of the dye. This effect indicated a non-linear relationship between β values and the concentration of Curcumin [19]. The discovery of these non-linear optical attributes in Curcumin solutions holds great promise. Beyond its potential as an optical limiter for safety applications, Curcumin emerges as a fascinating candidate for utilization in the realms of optoelectronics and advanced photonics [21]. Its unique optical properties, as unveiled in this study, open doors to exciting possibilities in the development of innovative optical devices and technologies [22].

In summary, our investigation into the nonlinear optical properties of Curcumin dye solutions has provided valuable insights into its behavior under different conditions. These findings not only contribute to the fundamental understanding of Curcumin's optical characteristics but also offer a promising avenue for practical applications across various scientific and technological domains. The potential of Curcumin as a versatile and effective component in optical systems is a significant outcome of this research, paving the way for future exploration and utilization of its remarkable optical properties.

Acknowledgement

This research was supported by Universiti Tun Hussein Onn Malaysia (UTHM) through Tier 1 (Vot Q407). Special thanks from the author to the Faculty of Applied Sciences and Technology (FAST) of Universiti Tun Hussein Onn Malaysia, giving full support in instruments. The authors express their gratitude to the Laser Centre at the Institute for Scientific and Industrial Research, Universiti Teknologi Malaysia (UTM) as well.

Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design, data collection, methodology, analysis and interpretation of results:*** *Mas Iezaty Mukhtar, Nurul Nadia Adnan and Ganesan Krishnan. All authors reviewed the results and approved the final version of the manuscript.*

References

[1] M. L. A. D. Lestari and G. Indrayanto, “Curcumin,” in Profiles of Drug Substances, Excipients and Related Methodology, 2014, pp. 113–204. doi: 10.1016/b978-0-12-800173-8.00003-9.

[2] R. Fathima and A. Mujeeb, "Plasmon enhanced linear and nonlinear optical properties of natural curcumin dye with silver nanoparticles," Dyes and Pigments, vol. 189, p. 109256, May 2021, doi: 10.1016/j.dyepig.2021.109256.

[3] M. Vaziri, F. Hajiesmaeilbaigi, and M. H. Maleki, "Generalizing theZ-scan theory for nonlocal nonlinear media," Journal of Optics, vol. 15, no. 2, p. 025201, Dec. 2012, doi: 10.1088/2040-8978/15/2/025201.

[4] Sakshi, N. K. Pathak, B. C. Swain, and U. Tripathy, "Analyzing nonlinear trends in curcumin: A comparative study," Optics and Laser Technology, vol. 121, p. 105822, Jan. 2020, doi: 10.1016/j.optlastec.2019.105822.

[5] A. Awalludin, A. Syuhada, M. I. Rosli, M. Abdullah, M. Duralim, and M. S. Aziz, "The study of nonlinear optical properties of aqueous acid fuchsin dye and its optical power limiting using Z-Scan method," Optical Materials, vol. 112, p. 110540, Feb. 2021, doi: 10.1016/j.optmat.2020.110540.

[6] P. Manasa, A. D. Kamble, and U. Chilakamarthi, "Various extraction techniques of Curcumin—A Comprehensive Review," ACS Omega, vol. 8, no. 38, pp. 34868–34878, Sep. 2023, doi: 10.1021/acsomega.3c04205.

[7] R. S. Elias, Q. M. A. Hassan, H. A. Sultan, A. S. Al-Asadi, B. A. Saeed, and C. A. Emshary, "Thermal nonlinearities for three curcuminoids measured by diffraction ring patterns and Z-scan under visible CW laser illumination," Optics and Laser Technology, vol. 107, pp. 131–141, Nov. 2018, doi: 10.1016/j.optlastec.2018.05.012.

[8] E. A. R. Ismail, D. Y. Sabry, H. A. Mahdy, and M. Khalil, "Synthesis and Characterization of some Ternary Metal Complexes of Curcumin with 1,10-phenanthroline and their Anticancer Applications," Journal of Scientific Research, vol. 6, no. 3, pp. 509–519, Aug. 2014, doi: 10.3329/jsr.v6i3.18750.

[9] R. S. Elias, Q. M. A. Hassan, H. A. Sultan, A. S. Al-Asadi, B. A. Saeed, and C. A. Emshary, "Thermal nonlinearities for three curcuminoids measured by diffraction ring patterns and Z-scan under visible CW laser illumination," Optics and Laser Technology, vol. 107, pp. 131–141, Nov. 2018, doi: 10.1016/j.optlastec.2018.05.012.

[10] W. Lee et al., "Two-Photon absorption and nonlinear optical properties of octupolar molecules," Journal of the American Chemical Society, vol. 123, no. 43, pp. 10658–10667, Oct. 2001, doi: 10.1021/ja004226d.

[11] D. S. Venables and C. A. Schmuttenmaer, "Spectroscopy and dynamics of mixtures of water with acetone, acetonitrile, and methanol," The Journal of Chemical Physics, vol. 113, no. 24, pp. 11222–11236, Dec. 2000, doi: 10.1063/1.1328072.

[12] P. Tahay, Z. Parsa, P. Zamani, and N. Safari, "A structural and optical study of curcumin and curcumin analogs," Journal of the Iranian Chemical Society, vol. 19, no. 7, pp. 3177–3188, Feb. 2022, doi: 10.1007/s13738-022-02522-x.

[13] A. Volpi, J. Kock, A. R. Albrecht, M. P. Hehlen, R. I. Epstein, and M. Sheik‐Bahae, "Open-aperture Z-scan study for absorption saturation: accurate measurement of saturation intensity in YLF:Yb for optical refrigeration," Optics Letters, vol. 46, no. 6, p. 1421, Mar. 2021, doi: 10.1364/ol.419551.

[14] M. Falconieri, "Thermo-optical effects in Z -scan measurements using high-repetition-rate lasers," Journal of Optics, vol. 1, no. 6, pp. 662–667, Sep. 1999, doi: 10.1088/1464-4258/1/6/302.

[15] C. Beryl, N. Reji, and R. Philip, "Optical limiting behavior of the natural dye extract from Indigofera Tinctoria leaves," Optical Materials, vol. 114, p. 110925, Apr. 2021, doi: 10.1016/j.optmat.2021.110925.

[16] J. Santos, P. E. Abreu, and J. Marques, "Aggregation patterns of curcumin and piperine mixtures in different polar media," Physical Chemistry Chemical Physics, vol. 25, no. 29, pp. 19899–19910, Jan. 2023, doi: 10.1039/d3cp00096f.

[17] A. Tognazzi et al., "Z-Scan theory for thin film measurements: Validation of a model beyond the standard approach using ITO and HfO2," Optical Materials: X, vol. 19, p. 100242, Jul. 2023, doi: 10.1016/j.omx.2023.100242.

[18] P. Prabhakaran, T. Kim, and K. S. Lee, "Polymer photonics," in Elsevier eBooks, 2012, pp. 211–260. doi: 10.1016/b978-0-444-53349-4.00207-7.

[19] C. Beryl, N. Reji, and R. Philip, "Optical limiting behavior of the natural dye extract from Indigofera Tinctoria leaves," Optical Materials, vol. 114, p. 110925, Apr. 2021, doi: 10.1016/j.optmat.2021.110925.

[20] A. Gaur, P. Gaur, D. Sharma, D. Sharma, N. Singh, and B. P. Malik, "Study of transmittance dependence closed-aperture Z-scan curves in the materials with nonlinear refraction and strong absorption," Optik, vol. 123, no. 17, pp. 1583–1587, Sep. 2012, doi: 10.1016/j.ijleo.2011.08.038.

[21] Y. Erez, R. Simkovitch, S. Shomer, R. Gepshtein, and D. Huppert, "Effect of acid on the Ultraviolet–Visible absorption and emission properties of curcumin," The Journal of Physical Chemistry A, vol. 118, no. 5, pp. 872–884, Jan. 2014, doi: 10.1021/jp411686d.

[22] A. M. Al-Roumy et al., "Nonlinear optical properties and all optical switching of curcumin derivatives," Journal of Fluorescence, May 2023, doi: 10.1007/s10895-023-03257-5.