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Iodine crystals spectral, nonlinear optical properties and optical limiting using green laser beam

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ABSTRACT

Two distinct Z-scanning approaches were utilised in order to get the nonlinear refractive index (NORX) and the nonlinear absorption coefficient (NACO) for the iodine crystals that were suspended in chloroform, at the same laser wavelength of 532 nm. These techniques were open aperture (OPR) and closed aperture (CPR). According to the measurements, the NORX demonstrates that the iodine crystal solvent has a negative nonlinearity, and the value of n_2 = - $22.5 \times 10^{-8}\ cm^2/W$. In addition, we see a shift in NORX as the concentrations continue to rise. $\beta = 18.17 \times 10^{-4}\ cm/W$ is the value that is measured for the NACO. Iodine crystals have been subjected to an investigation utilising a green laser beam in order to determine their optical limiting characteristic.

Keywords: Iodine crystals, chloroform, Z-scanning, laser wavelength

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INTRODUCTION

Since the beginning of the twenty-first century, nonlinear optics (NLRO) has been gaining traction as a potentially fruitful topic that has significant applications in the fields of photoelectronic modulation and photonics sensors [1,2]. Through the use of NLRO materials, optical signals may be manipulated by telecommunication systems as well as other applications that include optical signal processing [3,4]. It is generally believed that organic materials are among the most significant groups of third-order nonlinear optical materials. This is due to the fact that organic materials display large and rapid nonlinearities, and they are also simple to produce and incorporate into optical systems [5-7]. In addition, the NLRO characteristics of organic compounds may be fine-tuned by the application of reasonable modifications to the chemical structure [8]. Applications have been found for a wide variety of optical areas, including high sensitive optical sensors, optical communications, all-optical switching, and limiting behaviour, among others. In order to discover the third-order NLO features of a wide range of materials, including both inorganic and organic materials, researchers have put in a significant amount of effort [9-15]. Organic materials, which are well-known for their impressive optical nonlinearities, have a wide range of applications in the field of photonics due to the benefits they offer in terms of ultrafast response [16,17]. As a consequence of this, these materials have been the focus of much experimental and theoretical research over the past several years [18-20], with the goal of determining the third-order NLRO properties of a variety of organic materials. The preparation of iodine crystals of superior quality and the investigation of its optical characteristics are the primary objectives of the researchers conducting this study. The optical properties approach was utilised in order to estimate the optical characteristics of the iodine crystals. Additionally, the Z-scan methodology was utilised in order to investigate the nonlinear properties of the sample, namely the NORX and the NACO. The continuous-wave laser that was utilised had a wavelength of 532 nm.

EXPERIMENT

Figure 1 depicts the chemical structure of iodine crystals in their crystallised form. The iodine crystals were dissolved in chloroform (CHRO), which was used to dissolve the solution sample.

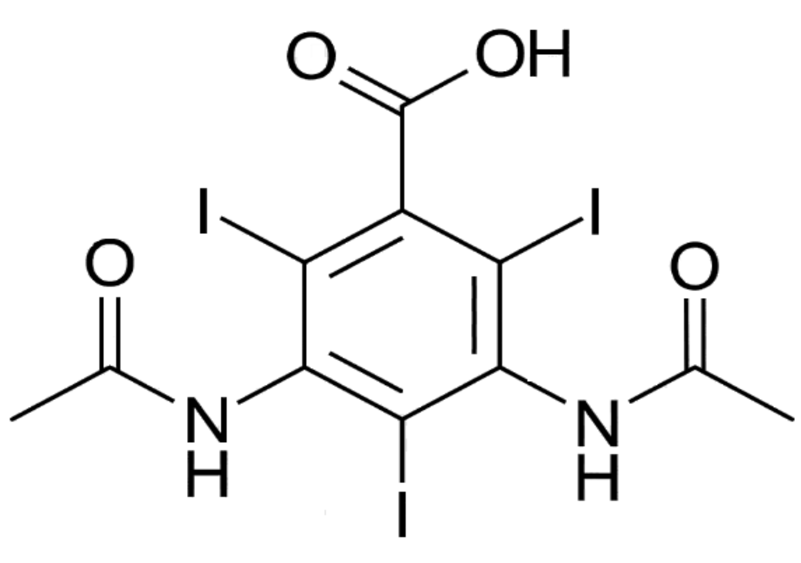

Figure 1. Perspective view of the crystal structure of iodine.

The iodine crystals solution has a concentration of 0.05 mM. A Cecil Reflected-Scan CE 3055 was utilised in order to record the ultraviolet-visible (UV-Vis) absorption spectra of the sample while it was in the CHRO solvent. As can be observed in Figure 2, the optical absorption of the iodine crystals solution exhibits absorption peaks precisely at 541 nm.

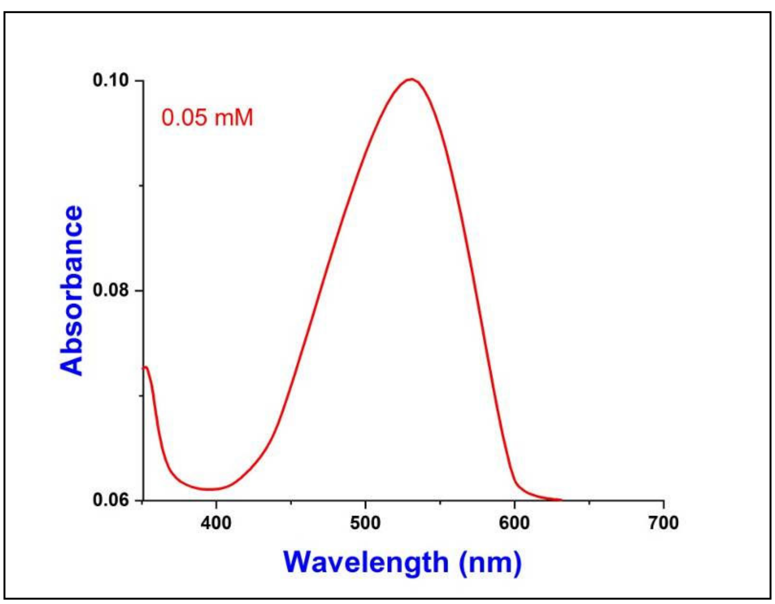

Figure 2. absorption spectra of the iodine crystals.

An analysis of the absorbance data was performed in order to determine the spectrum of the optical absorption. Through the use of the relation [21-24], the absorption coefficient was directly determined from the absorbance curves that were plotted against the wavelength curves.

(1) $$\alpha_{OP} = \frac{2.303\ Abs.}{Th}$$

Where *Th* is the iodine crystals thickness and *Abs.* is the iodine crystals absorbance. The values of α_{OP} at 532nm of iodine crystals in CHRO solvent is 2.303 cm^{-1}. The Z-scan method was utilised in order to carry out the measurements of the nonlinear optical features of the samples that were under investigation. A positive focal length lens with a focal length of five centimeters was used to concentrate an SDL laser beam that had a wavelength of 532 nm and a laser power of 15mW. The laser beam waist, denoted as $\omega_{\circ}$, is measured to be 27.04 µm at the focus, while the Rayleigh length($Z_{Ryl} = r\omega_{\circ}^2/\lambda$ [25,26]) , expressed as Z_{Ryl} = 4.31mm, is measured. One of the most essential requirements for the Z-scan approach is that it must be greater than the thickness of the iodine crystals. The laser beam propagates along the axial direction, translating a 0.1cm-thick optical cell containing the iodine crystals in CHRO across the region. We measured the beam's transmission through an aperture by feeding a photo detector to a digital power meter. A diverging lens was employed to gather the whole laser beam that was sent through the sample in order to perform the open aperture Z-scan. This lens was meant to replace the aperture. When doing the Z-scan approach, the same laser was utilised in order to investigate the limiting impact of the iodine crystals solution. A demonstration of Z-scan is provided in Figure 3, which depicts the experimental setup for the presentation. We keep a 0.1cm quartz cell containing iodine crystals solvient at the position where the transmitted intensity shows a valley in the CPR Z-scan curve. We used a variable beam splitter (VBS) to vary the input power. We systematically vary the input laser power, and the photodetector measures the corresponding output laser intensity values.

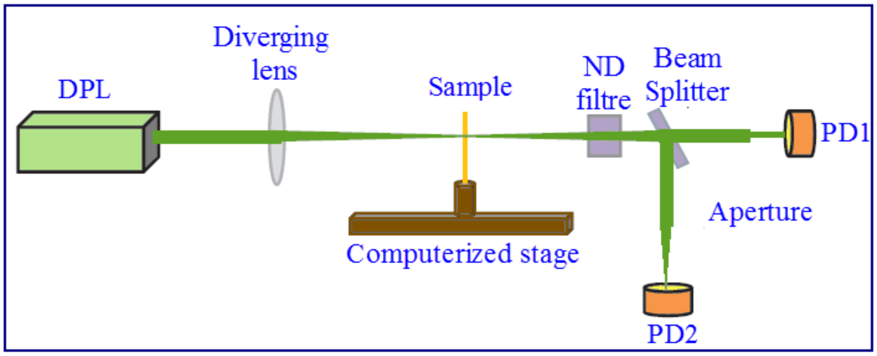

Figure 3. Z-scan and optical limiting setup

RESULTS AND DISCUSSION

Data obtained from the Z-scan method of iodine crystals in CHRO solvent are shown in Fig.4, which shows the OPR data. For the sample solution, the data regarding the CPR Z-scan were split by the data about the OPR Z-scan. As shown in Fig.5, the iodine crystals exhibit revised saturation absorption (RSA) behavior when they are located a considerable distance away from the focus [27–29].

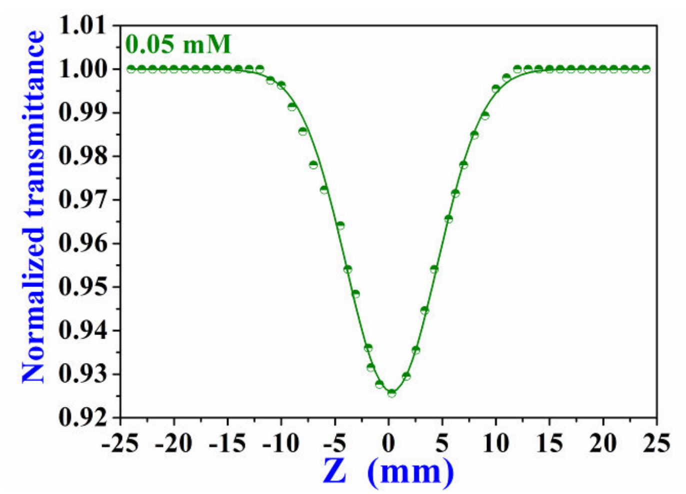

Figure 4. Normalized open aperture data.

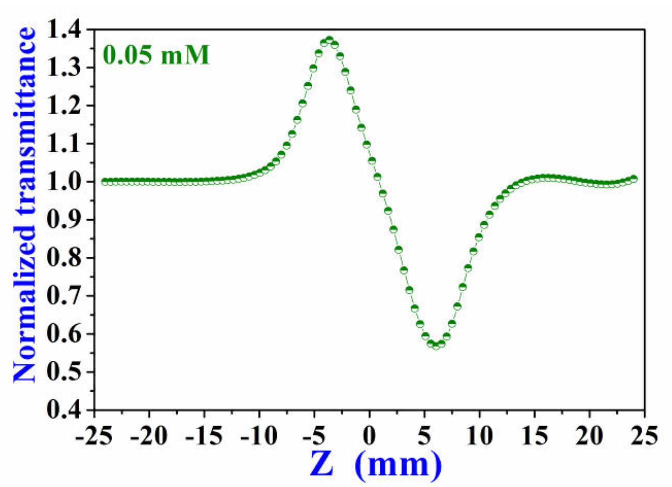

Figure 5. Pure z-scan data.

Additionally, as the intensity of the light rises (increases), the transmission beam at the focus gets smaller (decreases). Because of the development of a peak followed by a valley after a CPR z-scan (self-defocusing), the nonlinearity is negative. It is possible to consider that continuous-wave (CW) pumping is a significant factor that results in the emergence of third-order nonlinearities.

For example, a thermal in nature sample may be attributed to linear absorption, which obtains energy from a focused laser beam. An alteration in the heating is brought about by this energy, which is then followed by a temperature gradient. Because of the thermal lens effect, the phase of the beam that was propagating was distorted, and this occurred. Δ_{P-V} may be determined by determining the difference between the highest normalised transmittance and the minimum, and the relationship between the quantity of $T\Delta_{P-V}$ and $\Delta\Theta$ is shown as follows: [30-32]

$$\Delta T_{P-V} = 0.406\,(1-S)^{0.25}\,|\Delta\Theta| \qquad (2)$$

S is the linear transmittance of the aperture, which is described as $S = 1 - EXP(-2r_a^2 / w_a^2)$ [33-35]. r_a is the radius of the aperture, which is 2.5 millimetres, and w_a is the radius of the beam at the aperture, which was determined to be 2.45 millimetres. A determination of the NORX may be made based on the following relation [36,37]:

$$n_2 = \frac{\Delta\Theta\,\lambda}{2\pi L_{efct} I_\circ} \qquad (3)$$

In this equation, λ represents the wavelength, $I_\circ$ represents the intensity of the laser beam at the focal point (Z = 0), and $L_{efct} = (1-\exp(-\alpha_{OP} L))/\alpha_{OP}$ [38,39] indicates the effective thickness of the iodine crystals. The NACO , β , can be determined from the OPR Z-scan data as shown in the following relation [40–42]:

$$\beta = \frac{2\sqrt{2}\Delta T}{I_\circ L_{efct}} \qquad (4)$$

where ΔT represents the difference transmission of one valley. For a laser input power of 15 mW ($I_\circ = 1.306\ W/cm^2$). With the assistance of Figs. 4 and 5, the NACO , β , and NORX , n_2 , can be investigated and are shown in Table 1.

Table 1: Nonlinear coefficient, linear properties and enhancement factor of sample.

Concentration (mM)	$n_2 \times 10^{-7}$ (cm^2/W)	$\beta \times 10^{-3}$ (cm/W)	α_{OP} (cm^{-1})	Δn $\times 10^{-3}$	$\Delta\Theta$	W	dn/dT_{ther} $(\times 10^{-5} K^{-1})$
0.05	-2.25	1.81	2.303	0.29	3.11	2.4	6.27

It is necessary to guarantee that the figure of merit W is met for the 2π phase shift in order to determine its employment in optical devices [43,44]:

$$W = \frac{\Delta_{\max}}{\alpha_{OP}\lambda} > 1 \quad (5)$$

In the presence of an excitation wavelength of 532 nm, the value of W is more than one, which signifies that the nonlinear optical characteristics of iodine crystals are enough for use in all different kinds of optical switching technologies. Iodine crystals compound is promising for application in all-optical switching devices because to the high value of the figure of merit, which can be found in Table 1. In conclusion, the NORX value that is acquired from the Z-scan trace may be used to estimate the thermally generated on-axis NORX of the iodine crystals in a CHRO solvent. This can be done by applying the following equation [45-47]:

$$\frac{dn}{dT_{ther}} = \frac{4n_2 K_{TH}}{\alpha_{OP}\omega_\circ^2} \quad (6)$$

where $\frac{dn}{dT_{ther}}$ represents the change in refractive index with temperature, also known as the thermo-optic coefficient, and K_{TH} represents the thermal conductivity of the CHRO solvent. Finally, we found the $\frac{dn}{dT_{ther}}$ of iodine crystals in CHRO solvent to be $6.27\times10^{-5}K^{-1}$ by using Eq.6 with K_{TH} equal to $0.117\ Wm^{-1}K^{-1}$ [48].

OPTICAL LIMITING BEHAVIOR

In order to investigate the characteristics of the optical limiting (OPTL) behaviour of the iodine crystals solution, a solid-state-laser-type (SODL) with 532 nm was utilised. The apparatus that was used for the experimental investigations into the characteristics of OPTL behaviour is depicted in Figure 6.

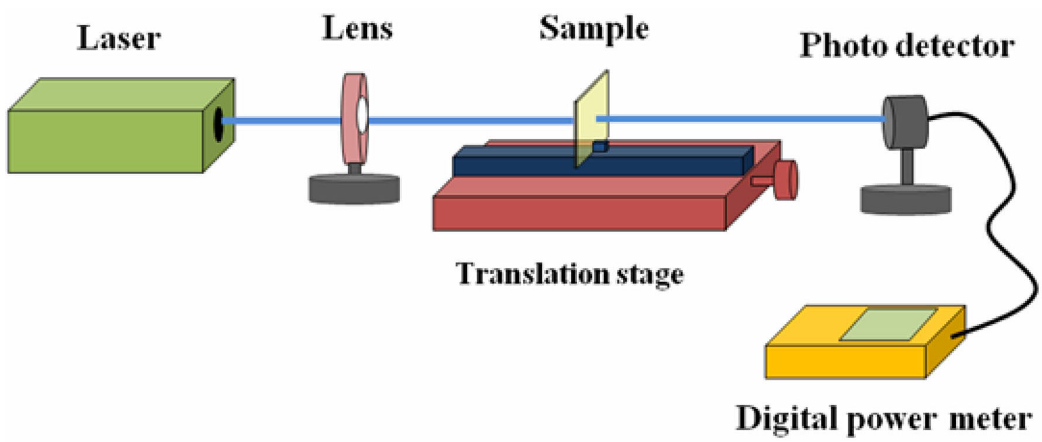

Figure 6. Experimental arrangement of OPTL.

The laser beam is initially focused on a quartz cell with a thickness of 1 mm, which is subsequently filled with the iodine crystals solution. This is accomplished by passing the laser beam via an attenuator beam (A) that has a focal length of greater than 5 centimetres. Following the focal length, the sample was positioned behind it. It is the photodetector that is connected to the power meter that will be responsible for measuring the beam that is transmitted from the iodine crystals. The OPTL behaviour was investigated by altering the laser input in order to make observations on the laser output power. To determine the OPTL property of iodine crystals, the limiting threshold (LTH) is an essential metric to consider. It is possible to define the LTH as the input power at which the transmittance equals fifty percent of the linear transmittance [49-51]. An illustration of the linear fluctuation of the output at low input power may be found in Figure 7. The rise in input laser power will be observed until the limiter's threshold when the output will begin to depart from the linear relationship. In addition, we will notice the increase in laser power via the limiter. Even though we were still seeing a rise in input power, we attained the saturation condition of output power. Moreover, identical behavior was documented in the recordings. An example of the LTH value can be shown in Figure 8.

After conducting the necessary measurements, we determined that the threshold power, which is defined as the incident input power at which the transmission decreases by 50%, is 10.63 mW. People typically think that optical limiters with lower limiting threshold values are more effective.

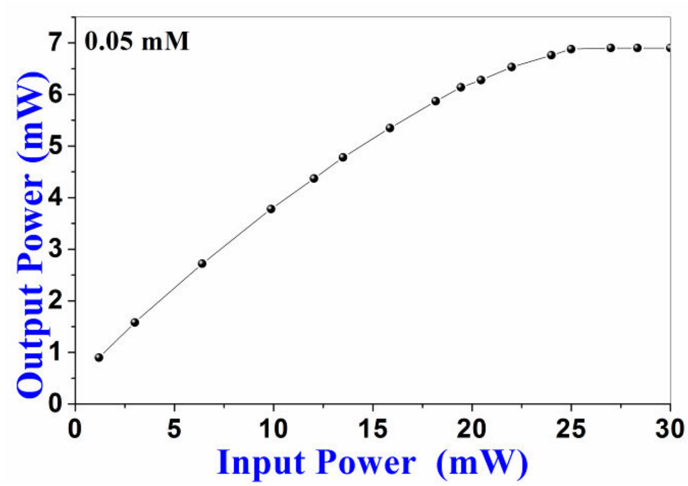

Figure 7. OPTL carve of iodine crystals solution

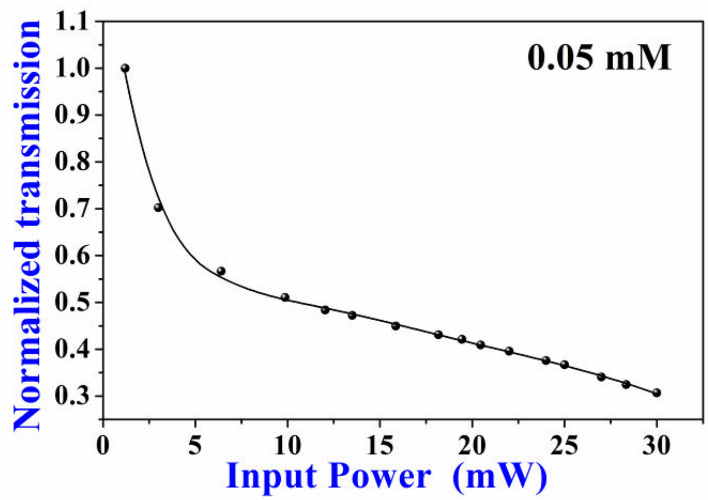

Figure 8. LTH power of iodine crystals solution

CONCLUSIONS

We have utilised the Z-scan approach with a 532 nm SODL laser in order to determine the NORX , n_2 , and NACO , β , values for iodine crystals that were dissolved in chloroform as a solvent at a concentration of 0.05 mM. According to the findings of the Z-scan, the samples exhibit a significant amount of optical nonlinearity in comparison to other optical materials; the NORX and NACO for the iodine crystals is on the order of $10^{-7}\ cm^2/W$ and $10^{-3}\ cm/W$, respectively. At a wavelength of 532 nm, the iodine crystals have a favourable OPTL behaviour. Each and every one of these experimental findings demonstrates that materials of this kind have the potential to be utilised in nonlinear optical systems.

References

[1] R. W. Boyd. Nonlinear Optics, Academic Press, San Diego, CA, 1992.

[2] J. Zyss . Molecular Nonlinear Optics: Materials, Physcis and Devices, Academic Press, New York, 1994.

[3] S. P. Karna, A.T.Yeates. Nonlinear Optics Material, American Chemical Society, Washington,DC,1996.

[4] K. Ogawa, T. Zhang, K. Yoshihara and Y. Kobuke, *J. Am. Chem. Soc*., 124 (2002) 22.

[5] J. L. Bredas, C. Andant, P. Tackx, A. Petersoons and B. M. Pierce, *Chem. Rev*. 94 (1994) 243.

[6] R. R. Tykwinski, U. Gubler, R. E. Martin, F. Diederich, C. Bosshard and P. Gunter, *J. Phys. Chem. B* 102 (1998) 4451.

[7] U. Gubler, C. Bosshard, K. S. Lee, Polymers in Photonics Applications, Springer Berlin, 2002.

[8] G. Dela Torre, P. Vazquez, F. Agullo-Lopez, T. Torresm, *Chem. Rev*. 104 (2004) 3723.

[9] C. Gayathri, A. Ramalingam, Z-scan determination of the third-order optical nonlinearities of an azo dye using diodepumped Nd: Yag laser. *Optik* 119 (2008) 409–414

[10] M. Zhang, Z.M. Su, Y.Q. Qiu, X.M. Pan, I. Zhao, Y. Zhao, Y. Liao, C.S. Qin. Calculated UV-Vis spectra and third-order nonlinear optical properties of heteroaromatic derivatives of stilbene inserted with 1,3-squaraine. *Synth. Met.* 137 (2003) 1525–1526

[11] S.S. Chu, F.M. Li, H.Z. Tao, H. Yang, S.F. Wang, C.G. Lin, X.J. Zhao, Q.H. Gong. SbS3 enhanced ultrafast third-order optical nonlinearities of Ge–S chalcogenide glasses at 820nm. *Opt. Mater* 31, (2008) 193–195

[12] Z.Y.Tian, W.T.Huang, D.B.Xiao, S.Q.Wang, Y.S.Wu, Q.H.Gong, W.S.Yang, J.N.Yao. Enhanced and size-tunable thirdorder nonlinearity of nanoparticles from an azo metal chelate. *Chem. Phys Lett.* 391 (2004) 283–287

[13] J. B. Han, H. J. Zhou, Q. Q. Wang. Conductivity and optical nonlinearity of Sb doped SnO_2 films. *Mater*. *Lett*. 60 (2006) 252–254

[14] X.B. Chen, J.J. Zhang, H.B. Zhan, Z.H. Jiang, G. Shi, Y.B. Li, Y.L.Song. Preparation and nonlinear optical studies of a novel thermal stable polymer containing azo chromophores in the side chain. *Dyes Pigments* 77(2008) 223–228

[15] H.Y. Xu, S.C. Yin, W.J. Zhu, Y.L. Song, B.Z. Tang. Synthesis and optical properties of three novel Functional polyurethanes bearing nonlinear optical chromophoric pendants with different p electron conjugation bridge structure. *Polymer* 47 (2006) 6986–6992

[16] J.J. Rodrigues Jr., C. H. T. P. Silva, S. C. Zilio, L. Misoguti, C. R. Mendonca. Femtosecond Z-scan measurements of nonlinear refraction in amino acid solutions. *Opt. Mater.* 20 (2002)153–157

[17] H. A. Badran, K. Abd, A.L. Aladil, H.G. Lazim, A.Y. Al- Ahmad, Thermal blooming and photoluminescence characterizations of sol-gel CdO-SiO_2 with different nanocomposite. *J Mater. Sci: Mater. Electron.* 27 (2016) 2212-2220 https://doi.org/10.1007/s10854-015-4013-0

[18] R. D. Present. Chapman-enskog method in chemical kinetics. *J. Chem. Phys.* 48 (1968) 4875

[19] J. Ross, P. Mazur. Some deductions from a formal statistical mechanical theory of chemical kinetics. *J. Chem. Phys.* 35 (1961) 19

[20] B. Shizgal, M. Karplus. Nonequilibrium contribution to the rate of reaction. III. Isothermal multicomponent systems. J. Chem. Phys. 54 (1971) 4357

[21] R.K.F Alfahed, H. A.Badran, Abu TYA, A.S. Noor, Investigation of third order nonlinearity of Ethidium bromide doped deoxyribonucleic acid (DNA). *J Phys Conf Series* 1963 (2021) 012136. https://doi.org/10.1088/1742-6596/1963/1/012136

[22] H. A.Badran, Abu TYA, R.K.F. Alfahed. Study the Effect of Concentration on the Evolution of Far Field Diffraction Patterns of Bromocresol Purple and Congo Red Solution. *J Phys Conf Series*, 1963 (2021) 012013. https://doi.org/10.1088/1742- 6596/1963/1/012013

[23] H. A. Badran, A.Y. Taha, A.F. Abdulkader, C.A. Emshary. preparation and study of the electrical and optical properties of a new azo dye (4-acetaminophenol-[2-(4-azo)]- 4- amino dipheyl sulfone). *J Ovonic Res* 8 (2012) 161–70.

[24] H. A. Badran, Study on Optical Constants and Refractive Index Dispersion of Neutral red Doped Polymer Film. *Am J Appl Sci* 9 (2012) 250–253. https://doi.org/10.3844/ajassp.2012.250.253

[25] R.K.F. Alfahed, I. Abdulameer, M.S. Majeed, H. A.Badran. Photoluminescence characterizations and nonlinear optical of PM-355 nuclear track detector film by alpha- particles and laser irradiation. *Phys Scr* 95 (2020) 075709 (8 pp) https://doi.org/10.1088/1402-4896/ab7e33

[26] A.T. Fadhil, T.O. Mohammed, Alyaa A J, H. A. Badran, T.A. Alaridhee. Effect of gamma ray on self-induced diffraction patterns of organic compound Poly (methyl-methacrylate films. *Results in Physics* 52 (2023)106858. https://doi.org/10.1016/j.rinp.2023.106858

[27] H. G. Lazim, K. I. Ajeel, H. A. Badran. The photovoltaic efficiency of the fabrication of copolymer P3HT: PCBM on different thickness nano-anatase titania as solar cell. *Spectrochim. Acta Part A Mol. Biomol Spectrosc* 145 (2015) 598-603. http://dx.doi.org/ 10.1016/j.saa.2015.02.096

[28] B. Kadem, R. K. F Alfahed, A. S. Alasadi, H. A. Badran. Morphological, structural, optical, and photovoltaic cell of copolymer P3HT: ICBA and P3HT:PCBM. *Optik* 204 (2020) 164153. https://doi.org/ 10.1016/j.ijleo.2019.164153

[29] R.K.F.Al-Fahed, A.R.Alaa, S.M.Munaf, H. A. Badran. Chemical Polymerization Method to Synthesize Polyaniline as a Novel Anode Catalyst in Microbial Fuel Cell, *Polymer Science, Series B*, 63 (2021) 773-780. https://doi.org/ 10.1134/S1560090421060026

[30] H.A. Al-Hazam, R.K.F. Al-fahad, A.M. Imran, H. A.Badran, H.S. Shaker, A. Alsalihi, K.I. Ajeel. Preparation and optoelectronic studies of the organic compound [2-(2,3 dimethyl phenylamino)-N–Phenyl benzamide doped (PMMA)]. *J. Mater. Sci.: Mater. Electron*. 30 (2019) 10284. https://doi.org/ 10.1007/s10854-019-01365-2

[31] H. A. Badran. Z-scan measurement for the thermo-optic coefficient and transmitted beam profile of 1.8-dihydroxynaphthalin- 3,6 (disulfonic acid-[2-(4-azo)]-N-5-methyl-3- isoxazolyl)-benzene sulfonamide. *Adv. Phys. Theor. Appl.* 26 (2013) 36

[32] H. A.Badran, K. I. Ajeel, H.G. Lazim. Effect of nano particle sizes on the third-order optical non linearities and nanostructure of copolymer P3HT: PCBM thin film for organic photovoltaics. *Mater Res Bull* 76 (2016) 422–430. http://dx.doi.org/10.1016/j.materresbull.2016.01.005

[33] Fadhil AT, H. A. Badran, H. A.Hasan, R. Ch. Abul-Hail. Azimuthal angle scan distribution, third order response, and optical limiting threshold of the Bismarck Brown Y:PMMA film. *Current Optics and Photonics* 7 (2023)721-731. https://doi.org/10.3807/COPP.2023.7.6.721

[34] R.F.Alfahed, A.S.Al-Asadi, H.A.Badran, K.I.Ajeel. Structural, morphological, and z-scan technique for a temperature-controllable chemical reaction synthesis of zinc sulfide nanoparticles. *Appl Phys B* 125 (2019) 48. https://doi.org/10.1007/s00340-019-7154-7

[35] H.A. Badran, Hanan AH, R.K.F. Alfahed, K. I.Ajeel. Second order hyperpolarizability and nonlinear optical properties of novel organic compound-doped poly (O- methoxyaniline) polymer film. *J Mater Sci: Mater Electron* 32 (2021)14623–14641. https://doi.org/ 10.1007/s10854-021-06021-2

[36] A.Y. AL-Ahmad, M.F. AL-Mudhaffer, H.A. Badran, C.A. Emshary. Nonlinear optical and thermal properties of BCP:PMMA films determined by thermal self-diffraction. *Opt Laser Technol* 54 (2013) 72–78. https://doi.org/ 10.1016/j.optlastec.2013.05.009.

[37] H.A. Al-Hazam, R.K.F Alfahed, A. Imran, H.A. Badran, S. H. Shaker, A.A. Alsalihi. Preparation and optoelectronic studies of the organic compound [2-(2,3-dimethyl phenylamino)- N-Phenyl benzamide] doped PMMA. *J Mater Sci Mater Electron* 30 (2019) 10284-92. https://doi.org/ 10.1007/s10854-019-01365-2.

[38] H. A. Badran. Thermal lens and all optical switching of new organometallic compound doped polyacrylamide gel. *Results in Physics*, 4 (2014) 69-72 http://dx.doi.org/10.1016/j.rinp.2014.05.004

[39] R.K.F.Alfahed, A.S. Al-Asadi, M.F. Al-Mudhaffer, H. A.Badran. Synthesis, morphological and optical characterizations of the poly (O-toluidine)- LiCl networks thin film. *Opt Laser Technol*. 133 (2021) 106524. https://doi.org/10.1016/j.optlastec.2020.106524

[40] A. Al-Salihi, R.D. Salim, R.K.F. Alfahed, H. A. Badran. Effect of Solar radiation induced and alpha particles on Nonlinear behavior of PM-355 film, *IOP Conf. Series: Materials Science and Engineering* 928 (2020) 072056. https://doi.org/10.1088/1757-899X/928/7/072056

[41] H. A.Badran, A.A. Al-Fregi,R.K.F. Alfahed, A.S. Al-asadi. Study of thermal lens technique and Third order nonlinear susceptibility of PMMA base containing 5′,5′′dibromo-o cresolsulfothalein. *J. Mater. Sci.: Mater. Electron.* 28 (2017) 17288. https://doi.org/10.1007/s10854-017-7661-4

[42] H. A. Hasan, A.H.A. Nadia, H. A. Badran, Raeed K A, K. I.Ajeel. The influence of temperature on structural and third order nonlinear properties of cadmium sulfide nanoparticle films prepared by chemical reaction method, *Material Research Bulletin* 170 (2024) 112554. https://doi.org/10.1016/j.materresbull.2023.112554

[43] F. A. Tuma, A. A. Jari, H. A. Hasan, H. A. Badran. Synthesis, Surface Morphology, Gas Sensor, DSC Technique and Third- Order Behavior of Conducting Polymer, Journal of Fluorescence, (2023) https://doi.org/10.1007/s10895-023-03448-0

[44] R. K. Fakher Alfahed, A. Imran, H. A. Badran, A. Al-Salihi, Synthesis, optical limiting behavior, thermal blooming and nonlinear studies of dye doped polymer films, *J Mater Sci: Mater Electron*, 31 (2020) 13862–13873. https://doi.org/10.1007/s10854-020-03946-y

[45] K. Abd AL-Adel, H.A. Badran, Optical nonlinear properties and optical limiting effect of congo red dye under CW Laser. *Misan J. Acad. Stud.* 11, 1–9 (2012)

[46] H.A. Sultan, H.A. Badran, A.Y. Al-Ahmad, C.A. Emshary. Experimental and theoretical study of the laser induced diffraction rings pattern in Acid Orange 10 dye: Polyacrylamide gel. *J. Basrah Res. (Sciences) A* 39 (2013)1–12

[47] H.A. Badran, A.Y. AL-Ahmad, M.F. AL-Mudhaffer, C.A. Emshary. Nonlinear optical responses and limiting behavior of sulfadiazine-chromotropic acid azo dye. *Opt Quant Electron.* 47, 1859–1867 (2015) https://doi.org/10.1007/s11082-014-0051-8

[48] H. A.Badran, A. Al-Maliki, R.K.F. Alfahed, B.A. Saeed, A.Y. Al-Ahmad, FA Al- Saymari, RS Elias. Synthesis, surface profile, nonlinear reflective index and photophysical properties of curcumin compound. *J. Mater. Sci.: Mater. Electron.* 29 (2018) 10890-10903. https:// doi.org/10.1007/s10854-018-9167-0.

[49] MA Rajaa, H. A. Badran, R. Ch. Abul-hall. Electrical, Thermal Lens and Optical Study of Fluorescein Film for Application as Organic Photovoltaic Devices, *Journal of Fluorescence*,34 (2024) 549-560 https://doi.org/10.1007/s10895-023-03299-9

[50] K. Abd AL-Adel, H.A. Badran. χ^3 measurements and optical limiting in Bismarck Brown Y dye. *Int. J. Emerg. Technol. Comput. Appl. Sci.* (IJETCAS) 8 (2014) 64–68

[51] N. Al-Huda S.Yakop, H. A. Badran. Single-Beam Z-Scan Measurement of the third-order optical nonlinearities of Ethidium Bromide, *Int. J.of Engineering Research and Applications* 4 (2014)727-731