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Investigation of Nonlinear Optical Properties of NiO Nanoparticles using the Z-Scan Technique

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Abstract

In this research, linear and nonlinear optical properties of NiO nanoparticles (NPs) dissolved in ethanol were investigated. Linear optical characteristics of NiO NPs were studied using a UV-Vis spectrophotometer. The linear absorption coefficient (α_0) was 0.88 and 0.57 cm^{-1} at 405 and 532 nm wavelengths, respectively. The band gap energy rose from 3.56 eV for a sample with a 10^{-7} g/ml concentration to 3.92 eV for the 10^{-3} g/ml concentration sample. Using the Z-scan technique, the nonlinear optical characteristics of the NPs were investigated. Two continuous wave laser diodes with 405 and 532 nm wavelengths and different powers were used. The Z-scan system with a closed aperture revealed that NiO NPs have a negative n_2 (self-defocusing effect) at various laser powers. n_2 increases as the power of the laser increases. The value of n_2 was found to be 0.51×10^{-4} cm^2/mW at a wavelength of 405 nm and a power of 0.33 mW. It improved as the laser power increased, reaching a maximum of 0.64×10^{-4} cm^2/mW at a laser power of 1.51 mW. For the laser with a wavelength of 532 nm, the n_2 value was 0.27×10^{-4} cm^2/mW for a laser power of 1.01 mW. This value increased to 0.76×10^{-4} cm^2/mW when the laser power increased to 6.2 mW. As measured by the Z-scan system with an open aperture, NiO NPs have a nonlinear absorption coefficient and display a two-photon absorption behavior.

Keywords: Nonlinear optical properties, Z-scan technique, NiO nanoparticles, two-photon absorption.

دراسة الخواص البصرية غير الخطية لجسيمات NiO النانوية باستعمال تقنية المسح بالبعذ الثالث

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الخلاصة

في هذا البحث تم دراسة الخصائص البصرية الخطية وغير الخطية للجسيمات النانوية NiO (NPs) المذابة في الإيثانول. تمت دراسة الخصائص البصرية الخطية لجسيمات NiO النانويه باستخدام مقياس الطيف الفوق البنفسجي والمرئي UV–Vis.و كان معامل الامتصاص الخطي 0/88 و $0/57\ cm^{-1}$ عند الأطوال الموجية 405 و 532 نانومتر على التوالي. ارتفعت فجوة الطاقة الضوئية من 3/56 eV لعينة بتركيز 10^{-7} g/ml إلى 3/92 eV لعينة بتركيز 10^{-3} g/ml. تم دراسة الصفات البصرية اللاخطية باستخدام تقنية المسح الضوئي Z–scan. تم استخدام ليزرين مستمرين نوع شبه موصل عند الطولين الموجيين 405 و 532 نانومتر وبقدرات مختلفة.اعطى نظام المسح Z–scan بالفتحة المغلقة أن جسيمات NiO النانويه تمتلك معمل انكسار لا خطي n_2 سالب(تأثير عدم تركيز ذاتي) عند قدرات مختلفه مختلفة.و يزداد n_2 مع زيادة قدره الليزر المختلفة. وكانت قيمة n_2 $0/51\times10^{-4}\ cm^2/mW$عند الطول الموجي 405 نانومتر وقدره 0/33 ملي واط. تم تحسينه مع زيادة قدره الليزر ، حيث وصلت بحد أقصى $0/64\times10^{-4}\ cm^2/mW$ عند قدره الليزر البالغة 1/51 ملي واط. ولليزرذو البطول الموجة 532 نانومتر ، كانت قيمة n_2 $0/27\times10^{-4}\ cm^2/mW$للقدره 1/01 ملي واط. ارتفعت هذه القيمة إلى $0/76\times10^{-4}\ cm^2/mW$ عندما زادت قدره الليزر إلى 6/2 ملي واط. اعطى نظام نظام المسح Z–scan بالفتحه المفتوحه ان جسيمات NiO لها معامل امتصاص غير خطي وتظهر سلوك امتصاص فوتونين.

1. Introduction

The study of nonlinear optical characteristics of materials is one of the most important fields at present due to its many applications in optoelectronic and photonic devices. Harmonic generation, optical computing, communications, laser printing, image processing, and sensors are nonlinear application fields [1]. The study of the optical properties of materials leads to a greater understanding of the fundamental nature of the strong interaction between light and matter, as well as a wide range of optical applications in all-optical systems. Since the invention of laser in 1961, the research of the nonlinear optical properties of several materials has been possible owing to the laser beam's unique benefits and qualities, such as monochromatic light, brightness, unidirectionality, and coherence [2]. With the advent of laser sources, it is now possible to determine the optical characteristics of a material that are dependent on laser intensity. Nonlinear optical responses start with the exposure of a material to a laser beam of high intensity. Nonlinear optics is thus the study of the nonlinear behavior of matter when it interacts with intense light [3]. The nonlinear optical response of materials is due to the change in their optical characteristics as a result of their interaction with intense electromagnetic pumping waves [4,5]. Peter Franken and colleagues performed the first experiment on Second Harmonic Generation (SHG) in 1961, achieving a nonlinear optical response [6]. The phenomena of SHG, a significant nonlinear process in which two photons of the same frequency combine to form a single photon with twice the frequency, has been studied extensively [7]. Crystals, amorphous materials, polymers, liquid crystals, semiconductors, organic materials, liquids, gases, and plasmas have all been used to investigate nonlinear optical phenomena from the far infrared to the extreme ultraviolet [8,9]. Certain materials are more susceptible to intense laser light than others, even though nonlinear optical interactions may be observed in a broad range of substances.

Nanoparticles (NPs) are of widespread interest due to their prospective use in optoelectronic devices and their notable nonlinear optical properties [6-8]. Because of their enormous optical nonlinearity and short reaction time, the study of the nonlinear optical characteristics of semiconductor NPs has received significant interest [10]. The NPs exhibit electrical, optical, and magnetic characteristics that are distinct from those of their bulk counterparts, making them more desirable [11]. Nonlinear optical properties for several nanomaterials, including TiO_2 NPs [12], ZnO NPs [13], Fe_3O_4 NPs [14], and MgO NPs [15], have been studied. NiO, a semiconductor with a significant band gap (around 4.0 eV), has been considered an attractive material for many technological applications [16]. It has been used as a transparent conducting material of the p-type in spin-valve devices [17] and electrochromic devices [18], as well as in photocatalysis, batteries, and chemical sensing [19]. Observed nonlinear optical effects include the electro-optical Kerr effect, the electro-optical Pokel effect, the Third Harmonic Generation (THG), the Second Harmonic Generation (SHG), self-focusing, nonlinear absorption, Two-Photon Absorption (TPA), Saturable Absorption (SA), and Reverse Saturable Absorption (RSA) [20]. There are several methods for measuring the nonlinear optical characteristics of materials, such as two-photon-induced fluorescence, self-phase modulation, four-wave mixing, pump-probe, and Z-scan methods [21]. The Z-scan technique, introduced by Sheik-Bahae *et al*. for the first time [22], is undoubtedly the most common, highly accurate method for characterizing the third-order nonlinear optical characteristics of samples. It is a reasonably straightforward method for determining both nonlinear refractive index and nonlinear absorption coefficient since it is based on a single measurement of beam distortion. The Z-scan consists of two parts: closed aperture and open aperture. Closed-aperture Z-scan measures the sign and magnitude of the materials' nonlinear refractive index. While the open aperture Z-scan measures the nonlinear absorption coefficient [23].

There are several reports on nanomaterials' nonlinear optical characteristics. Majlesara et al. investigated the nonlinear optical characteristics of PVP/TiO_2 nano-fibers containing AgNPs. They investigated the samples' nonlinear refractive and absorption indices at three different laser powers using the single-beam Z-scan technique with a He-Ne laser emitting a continuous wave at 632.8 nm. The sign of the nonlinear refractive index was negative according to closed aperture curves. They demonstrated that these nonlinearities are mostly attributable to the two-photon absorption procedure [24]. Saravanan et al. investigated the nonlinear optical absorption and optical limiting characteristics of cadmium ferrite ($CdFe_2O_4$). The optical nonlinearity of the samples was investigated by means of an open aperture Z-scan technique utilizing a Q-switched Nd:YAG (532 nm, 5 ns, 10 Hz) laser. The material's saturable absorption coefficient was attributed to a two-photon absorption process. Additionally, the materials demonstrated optically limiting features [25]. H. R. Humud investigated the nonlinear optical characteristics of pure polyaniline and Ag/polyaniline nanocomposite thin films deposited by a plasma jet on a glass substrate, utilizing an open and closed Z-scan approach with a 532 nm pulse second harmonic Nd: YAG laser. According to the obtained data, the sign of the nonlinear refraction coefficient

was negative for pure polyaniline thin films and positive for Ag/polyaniline nanocomposite thin films. The open Z-scan measurements revealed two photons absorption for Ag-doped polyaniline and saturation for pure polyaniline absorption [26]. Ganesh and coworkers studied the effect of Sn doping on the structural, morphological, and nonlinear optical characteristics of ZnO nanocrystalline thin films. The Z-scan approach was used to explore the third-order nonlinear optical characteristics; the nonlinear absorption coefficient, and nonlinear refractive index were determined. Observations indicated that Sn doping has a significant impact on the optical properties of the samples [27]. The impact of nitrogen doping on the nonlinear optical responses of NiO films was explained using the Z-scan method. In addition to their optical power limiting, the experimental findings revealed that these materials have the highest optical nonlinear absorption coefficient and optical nonlinear refraction index [28].

Since there is great interest in developing new materials for applications such as an optical limiter, optical switch, and signal processing, many techniques are needed to characterize materials for third-order nonlinear optical phenomena. This study has centered on the Z-scan technique, which is distinguished by its simplicity and precision in measurements. In this investigation, the linear and nonlinear optical properties of NiO NPs were investigated.

2. Z-scan technique

The Z-scan technique is a relatively simple and direct method to obtain nonlinear refractive index and nonlinear absorption coefficient. It is based on beam distortion measurement, which uses self-action at high-intensity levels [22]. The working principle is that the sample is scanned longitudinally through the focal point of a focused Gaussian beam. The nonlinear medium modifies the laser beam's intensity as the sample travels along the Z-axis, beginning at the focal point (z=0). The method is done by calculating the transmission of the laser through a sample as a function of the position (z) of the sample. There are two systems of optical scanning method; the first is a closed aperture system for detecting the nonlinear refractive index (n_2) and an open aperture system for detecting nonlinear absorption coefficient (β).

2. 1. Z-scan closed aperture system

As depicted in Figure 1, when the sample passes through the focal region of a laser beam, the detector measures the intensity transmitted through the sample passing through the aperture. The intensity incident on the detector will differ depending on the Kerr lens generated in the material by the intensity of the laser beam [29]. This system is used to demonstrate how the transmittance as a function of Z relates to the sample's nonlinear refractive index. The maximum transmittance (peak) followed by the minimum transmittance (valley) is evidence of a negative value of nonlinear transmittance (negative refractive index). While the Z-scanning curve (intensity versus location on the Z axis)of a valley followed by a peak characterizes a material with a positive nonlinear refractive index [30].

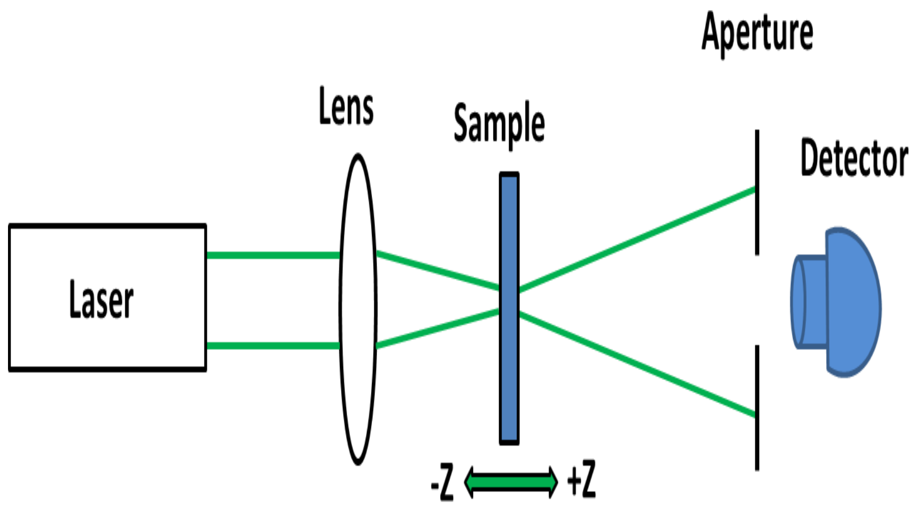

Figure 1: A schematic representation of the closed-aperture Z-scan setup**.**

4wwwThe magnitude of the nonlinear phase shift of the peak on the axis at the focal point can be determined from the following equation [22]:

$$|\Delta\Phi_0| = \frac{\Delta T_{P-V}}{0.406} \quad (1)$$

Where: ΔT_{P-V} represents the change in normalized transmittance between peak and valley and, equal to T_P-T_V. The nonlinear refractive index, n_2, can then be determined using the following equation [22]:

$$n_2 = \frac{\Delta\Phi_0}{I_0 L_{eff} K} \quad (2)$$

Where: I_0 is the incident laser light intensity, $\Delta\Phi_\circ$ is the nonlinear phase variation of the peak at the focal point, and *K* is the wave vector defined as:

$$K = \frac{2\pi}{\lambda} \quad (3)$$

Where: λ is the wavelength of the beam, L_{eff} is the effective length of the sample and it can be determined by the following relationship:

$$L_{eff} = \frac{1 - e^{-\alpha L}}{\alpha} \quad (4)$$

Where: L is the length of the sample and α is the linear absorption coefficient. To calculate the intensity at the focal point I_0, the following equation is used:

$$I_0 = \frac{2P_{Peak}}{\pi\omega_0^2} \quad (5)$$

Where: ω_0 is the radius of the laser beam at the focal point and P is the laser power.

2.2. Z-scan open aperture system

An open-aperture Z-scan measures the intensity change of a lens-focused beam in the far field at the detector, as shown in Figure 2, which captures the entire beam. In a Z-scan with an open aperture, the aperture is replaced with a lens. Therefore, the transmittance is insensitive to beam distortion, and Z-scan data is a function of nonlinear absorption. Usually, the change in intensity is caused by multi-photon absorption in the sample as it passes through the beam waist [31]. If nonlinear absorption, like two-photon absorption, is the dominating effect, then measurements at the focus point will reveal the lowest transmittance value [32]. The material exhibits saturated absorption when transmittance is high at position 0 (Z=0). The nonlinear absorption coefficients can easily be calculated from the transmittance [33]:

$$\beta(\frac{cm}{W}) = \frac{2\sqrt{2}}{I_0 L_{eff}} \Delta T \quad (6)$$

where: ΔT is the transmittance peak or valley at the open aperture Z-scan.

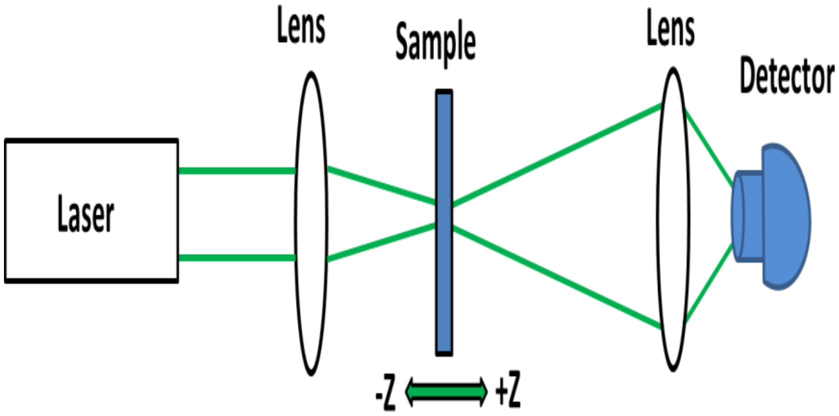

Figure 2: A schematic representation of the open-aperture Z-scan setup**.**

3. Experimental part

3.1. Materials used in the research

In this study, NiO NPs purchased from US nano (US3356) were utilized. The size of the NPs ranges between 10 and 20 nm, and their form is relatively spherical. NiO is a p-type semiconductor solid (insulator at room temperature) compound from the group (II-VI) of the periodic table. It has a density of 6.67 g/cm^3, a molecular weight of 8.4287 g/mol, and a melting point of 1984°C. It has a wide and direct energy gap of 3.4-4 eV [34] and is very important because of its excellent chemical stability in addition to its optical, electrical, and magnetic properties. It is one of the most critical electronic materials after tungsten oxide [35]. Samples with concentrations of 10^{-3}, 10^{-4}, 10^{-6} and 10^{-7} g/ml were prepared by dissolving different amounts of NiO NPs powder in ethanol solvent.

3.2. Absorption Spectrometry

The absorption spectrum was measured with a spectrometer (UV-Vis Spectrophotometer; CECIL CE 7200 double beam spectrophotometer, made in UK); the absorbance was measured within the range of (190-900 nm).

3.3. Z-Scan system

The Z-scan setup includes different continuous wave (CW) lasers with different wavelengths, lenses, and detectors; different optical filters to control the intensity of the laser beam falling on the sample; optical lenses with different focal lengths (8.5, 5 cm); and a laser beam splitter to divide the beam between the detectors. Utilizing connecting cables, signals were sent from the detectors to a controller device, which was then linked to a computer through a USB connection. The controller comprises two ports for connecting to the reagents and the regulator, which allows adjusting the sensitivity and gain of the reagents according to the sample's transmittance. Before beginning work, the sample was positioned before and after the focal point to determine the amount of beam amplitude influenced by the sample's nonlinearity.

4. Results and discussion

4.1. Linear Optical properties of NiO NPs

Figure 3 displays the transmittance and absorbance spectra of NiO NPs as a function of wavelength (at a range of 300-800 nm) for samples with different concentrations of 10^{-3}, 10^{-4}, 10^{-6}, and 10^{-7} g/ml. The NPs exhibit a high transmittance in the visible region and low ultraviolet (UV) transmittance at shorter than 360 nm wavelengths, where absorption occurs.

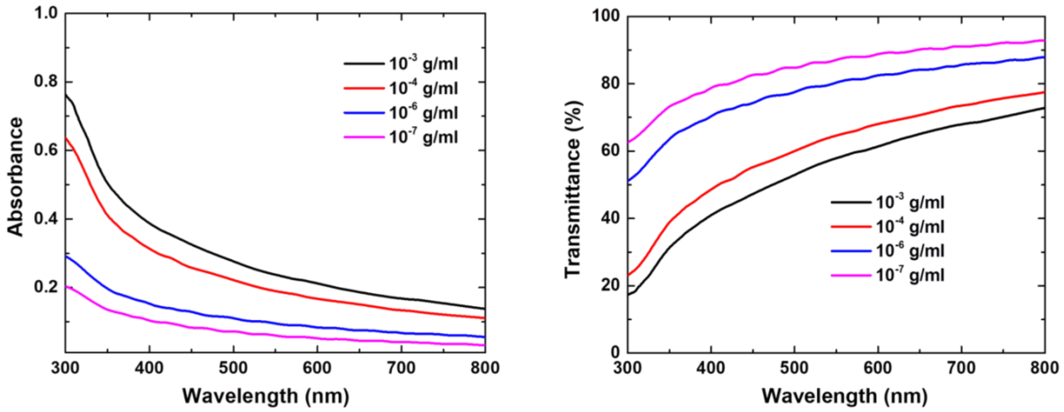

Figure 3: The absorbance and transmittance spectra for NiO NPs with different concentrations.

The linear optical absorption coefficient α_0 was calculated from the absorbance using the following equation [36]:

$$\alpha_0 = 2.303\frac{A}{d} \tag{7}$$

Where: A is the absorbance and d is the thickness of sample (quartz cell thickness: 1mm). Figure 4 represents the spectral variation of the linear optical absorption coefficient α_0 in the range of 300-800 nm for NiO NPs at different concentrations. The results showed a high absorption band (large absorption coefficient) in the UV region (300-360 nm). Then the absorption coefficient gradually decreases with the increase in the wavelength in the visible spectrum region (400-750 nm) because when the wavelength increases, the energy of the photon decreases, and the absorption decreases. These results are consistent with previous research [37]. The highest value of the linear absorption coefficient was about 1.727 cm^{-1} at a wavelength of 300 nm. The linear absorption coefficient in the visible spectrum region was about 0.8 and 0.5 cm^{-1} at wavelengths of 405 and 532 nm, respectively.

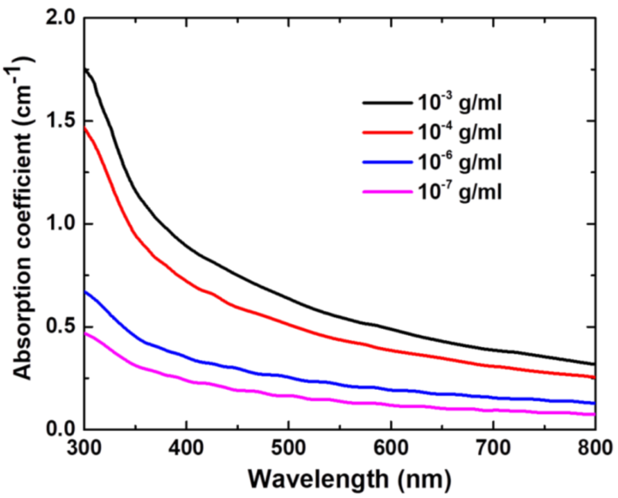

Figure 4: The linear absorption coefficient of NiO NPs with different concentrations

4.2. Linear refractive index

The linear refractive indices of pure NiO NPs were calculated using the following equation [38]:

$$n_0 = \frac{c}{v} = \left(\frac{1+R}{1-R}\right)^2 \tag{8}$$

Figure 5 represents the relation between the refractive index of NiO NPs at concentrations of 10^{-6} and 10^{-7} g/ml and wavelength at the range of 300-800 nm. For the sample with 10^{-6} g/ml concentration, at wavelengths of 405 and 532 nm, the linear refractive index was approximately 1.7 and 1.5, respectively.

4.3. Optical energy band gap

The optical energy band gap (E_g) for NiO NPs was calculated based on the optical absorption spectra method, known as Tauc method, using the following relation [39]:

$$\alpha_0 h\nu = \beta(h\nu - E_g)^n \quad (9)$$

Where: hν is the photon energy, E_g is the direct energy band gap, β is a constant, and n depends on the nature of the transition, for direct transitions, n = 1/2 or 3/2 and n = 2 or 3 for indirect transitions. Figure 6 represents $(\alpha_0 h\nu)^2$ as a function of the photon energy for NiO NPs. The energies band gap were 3.56, 3.75, 3.85, and 3.92 eV for samples with 10^{-7}, 10^{-6}, 10^{-4}, and 10^{-3} g/ml concentrations, respectively. The results obtained for varied concentrations of NiO NPs revealed that the value of the forbidden band gap energy increases with increasing concentration. The increase in the optical gap energy can be explained as due to a shift of the absorption edge towards high energies; when the levels near the conduction band are full of electrons, the electrons need more energy to the transition, so the band gap energy appears to increase.

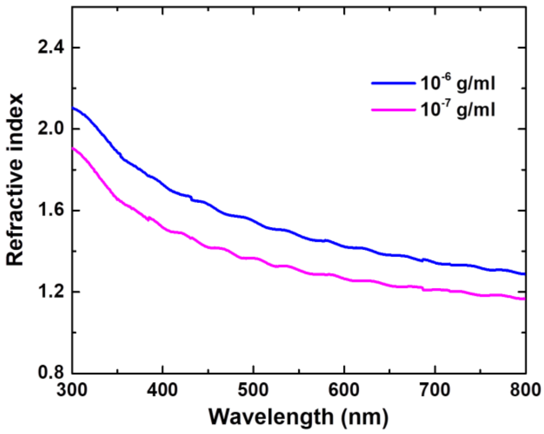

Figure 5: The linear refractive index spectrum for two NiO NPs concentrations of 10^{-6} and 10^{-7} g/ml.

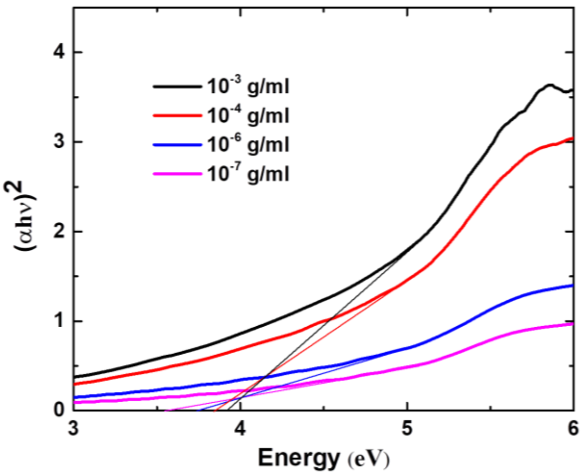

Figure 6: The direct optical energy band gap for different concentrations of 10^{-3}, 10^{-4}, 10^{-6}, and 10^{-7} g/ml for NiO NPs.

5. Nonlinear optical properties of NiO NPs

5.1. Nonlinear optical properties of NiO NPs for closed aperture at wavelength 405 nm

The nonlinear refractive index (n_2) of NiO NPs was measured by a continuous wave (CW) laser diode using the Z-scan system with a closed aperture. Diode laser emitted at a wavelength of 405 nm was focused using a lens of 8.5 cm focal length; the laser beam waist at the focal point (ω_o) was 5 mm. The laser beam propagated through the NiO NPs solution, which was in a quartz cell with a thickness of 1mm. Figure 7 illustrates the experimental results of the nonlinear transmittance through a closed aperture in the far field as a function of the sample location Z to the focal plane for NiO NPs with a concentration of 10^{-3} g/ml and for various laser powers of 0.33, 0.70, and 1.51 mW. n_2 was calculated from Equation 2. Table 1 shows the values of n_2 at different laser powers. The transmittance increased, and its value began to rise gradually from the –z-axis to the +z-axis, i.e. the beam width at the aperture became less. It has the highest value (peak) of 2.4 and the lowest value (valley) of 0.1 at 1.15 mW laser power. This behavior can be explained by the fact that the sample was affected by the focal lenses (thermal lenses). Then, the beam convergence increased as the rays passed through the sample towards the aperture, and the transmittance decreased. This effect can result from the thermal expansion of NiO NPs. As seen in Figure 7, the peak followed by a valley obtained from the closed aperture Z-scan data indicates that the sign of n_2 is negative, which results from a self-defocusing effect, and the NiO NPs work like a convex lens.

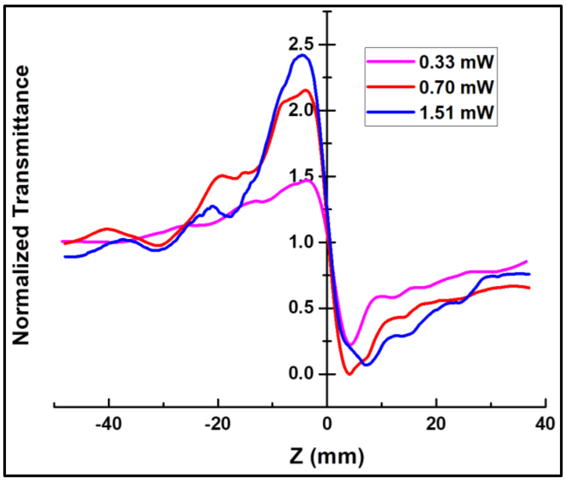

Figure7: Closed aperture Z-scan for NiO NPs concentration of 10^{-3} g/ml at 405 nm wavelength for different laser powers of 0.33, 0.70, and 1.51 mW.

Table 1: Nonlinear refractive index for NiO NPs at 405 nm with three different laser powers

Power (mW)	I_0 (mW/cm^2)	ΔT_{p-v}	$\Delta \phi_\circ$	n_2 (cm^2/mW)
0.33	3.82	1.20	2.95	**-0.51×10^{-4}**
0.70	5.60	2.05	5.04	**-0.59×10^{-4}**
1.51	6.62	2.30	5.66	**-0.64×10^{-4}**

5.2. Nonlinear optical properties of NiO NPs for closed aperture at wavelength 532 nm

The nonlinear refractive index was measured at a laser wavelength of 532nm using the closed aperture Z-scan system. Figure 8 shows the experimental results of the nonlinear transmittance as a function of the sample position Z, for the NiO NPs with a concentration of 10^{-3} g/ml, at 532 nm laser wavelength and for different laser powers of 1.01 1.13, 1.54, 3.30, and 6.20 mW. The transmittance first rises, and its value increases gradually but then decreases. For the 6.20 mW power, the transmittance curve has a maximum value (peak) of T_z = 2.3 and the lowest value (valley) of T_z = 0.2. The peak followed by a valley in the normalized transmittance from the closed aperture Z-scan data indicates that the sign of n_2 is negative. This is because of a self-defocusing effect, and the NiO NPs operate like a convex lens. Table 2 shows the values of the nonlinear refractive index. According to the obtained data, n_2 increased with increasing the laser power.

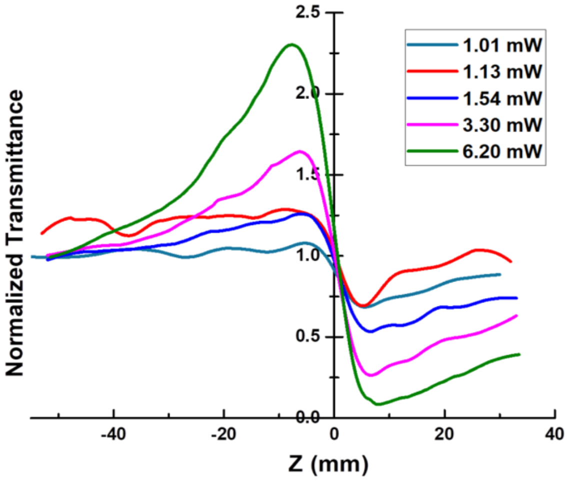

Figure 8: Closed aperture Z-scans for NiO NPs concentration of 10^{-3} g/ml at wavelength of 532nm for different laser powers.

Table 2: Nonlinear refractive index for NiO NPs at 532 nm for different laser powers

Power (mW)	I_0 (mW/cm^2)	ΔT_{p-v}	$\Delta\varphi_0$	n_2 (cm^2/mW)
1.01	1.91	0.25	0.60	**- 0.27×10^{-4}**
1.13	3.18	0.50	1.23	**- 0.33×10^{-4}**
1.54	3.84	0.70	1.72	**- 0.47×10^{-4}**
3.30	4.07	1.35	3.32	**- 0.71×10^{-4}**
6.20	5.80	2.10	5.17	**- 0.76×10^{-4}**

5.3. Nonlinear optical properties of NiO NPs for open aperture at 405 nm

The nonlinear absorption coefficient was determined using the open aperture Z-scan setup and a continuous wave diode laser with a wavelength of 405 nm. The laser was focused by a lens with a focal length of 8.5 cm, and the laser beam at the focal point had a waist of 5 mm. Figure 9 illustrates the nonlinear effect region that stretched from -40 mm to 40 mm, and a valley was observed for the various laser powers of 3.15, 6.40, and 12.96 mW, where the NiO NPs concentration was 10^{-3} g/ml. The nonlinear absorption coefficient was calculated from Equation 6. Table 3 shows the values of the nonlinear absorption coefficient at different laser powers. It can be seen that the transmittance of the open aperture is symmetric around the focal point (Z = 0), indicating a positive nonlinear absorption coefficient. The nonlinear response indicates a two-photon absorption, consistent with a previous report [40].

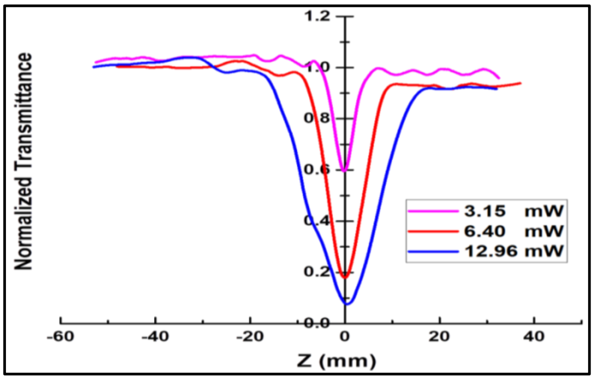

Figure 9: Open aperture Z-scans of NiO (normalized transmitted light versus distance) for different laser powers.

Table 3: The nonlinear absorption coefficient for NiO NPs at 405 nm for three different laser powers

Power (mW)	*I_0 (mW/cm^2)*	*L_{eff} (cm)*	*β (cm/W) ×10^{-5}*
3.15	1.528	0.0957	6.75
6.40	0.509	0.0957	5.75
12.96	0.254	0.0957	3.23

6. Conclusions

The linear and nonlinear optical characteristics of NiO NPs dispersed in ethanol were studied. The transmittance and absorbance spectra, absorption coefficient, linear refractive index, and optical band gap energy of NiO NPs dispersed in ethanol at various concentrations were investigated. In the visible spectrum region, the NiO NPs exhibited a high transmittance. The linear absorption coefficient for the sample with a concentration of 10^{-3} g/ml was 0.88 cm^{-1} at 405 nm and 0.57 cm^{-1} at 532 nm. The band gap energy increased from 3.56 eV for 10^{-7} g/ml sample concentration to 3.92 eV for 10^{-3} g/ml sample concentration. The nonlinear optical properties of the NPs' nonlinear refractive index and nonlinear absorption coefficient were studied using the Z-scan technique. Two diode lasers of 405 and 532 nm wavelengths and of varied powers were used. The Z-scan system with a closed aperture demonstrated that NiO NPs possess a negative n_2 (self-defocusing effect) at varying laser powers; n_2 rose as laser power increased. At a wavelength of 405 nm, n_2 increased from 0.51×10^{-4} cm^2/mW for 0.33 mW laser power to 0.64×10^{-4} cm^2/mW for 1.51 mW. For a laser with a wavelength of 532 nm and a power of 1.01 mW, the n_2 value was 0.27×10^{-4} cm^2/mW. This value increased to 0.76×10^{-4} cm^2/mW as the laser's power rose to 6.2 mW. NiO NPs exhibited a nonlinear absorption coefficient and a two-photon absorption behavior when measured by the Z-scan system with an open aperture.

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