

Size effect on all-optical switching of CdSe/ZnS quantum dots

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Our research will investigate the effect of quantum dots (QDs) sizes of Cadmium Selenide (CdSe) on the all-optical switching phenomena. The study was carried out using two continuous wave lasers, a pump green laser ($\lambda = 532$ nm) and a probe red laser ($\lambda = 635$ nm). The results of our work have shown that the size of CdSe QDs effect has a strong influence on the all-optical switching phenomena. The size of the QDs effect is used as an efficient way to control the all-optical switching processes. Our results show that a strong pump beam can modify the low-power probe beam by generating diffraction ring patterns, which confirms the possibility of changing and modifying the probe's laser beam signal standardise as OFF/ON through nonlinear optical switching processes.

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1. Introduction

The fast development of the semiconductor market and the increasing demand for photoelectronic devices has presented a major challenge in the nonlinear optical (NLO) materials that have high sensitivity and fast nonlinear optical response times [1]. Semiconductor nanocrystals, or what are known as quantum dots, are currently receiving widespread attention within many scientific fields, especially on the field of optoelectronic devices, because they provide the possibility of controlling the band gap over a wide spectral range [2, 3]. Semiconductor quantum dots (QDs) have a radius comparable to the exciton Bohr radius of the exciton system, making them of great interest due to their optical and physical-chemical properties. When, the diameter of nanocrystals is smaller than the Bohr exciton radius, it is called quantum confinement effect [4]. Quantum confinement effects in semiconductor QDs make them efficient and promising NLO materials in the near future [5, 6]. Studies on QDs have achieved great success since their fabrication began in the 1980s [7-9]. So, the semiconductor QDs can be used in basic materials' science, nonlinear photonic and biological applications [10]. Recently, Cadmium Selenide (CdSe) nanocrystals have received great attention in a number of medical fields, biological and pharmaceutical applications, as well as in making new optical devices, owing to their size-dependent nonlinear optical properties and fast response [11].

The bulk of Cadmium Selenide (CdSe) has a band gap of 1.74 eV and possesses a Bohr exciton radius of about 5.6 nm [12]. However, the effect of quantum confinement is smaller than the delocalization length of the material in the bulk state. Therefore, the CdSe QDs will play an important role in modification and change of NLO properties compared to CdSe in the bulk state [12-14].

The all-optical-switching (AOS) effect has been studied using many materials including: MoS₂ graphene oxide and MoS₂/TiO₂ QDs [15, 16], ZnS [17], CdSe [18], and CdTe [19]. A pump-probe laser beam technique is used to study the all-optical switching mechanism, which is considered an optical-optical system to control the interaction of light with NL medium. A high-power laser beam is used to perform an all-optical switching and modification process for another low-power laser beam, where a light-light interaction is performed through a nonlinear medium [20-23]. Zhang et al. demonstrated a prototype of new 2D materials such as SnSe for using in the all-optical switching process and proposed a new all-optical switching mechanism [20]. Also, a study of the all optical-switching effect of two-dimensional materials, including graphene and organometallic compounds has been investigated elsewhere [24-26].

This work aims to study the AOS effect of CdSe/ZnS QDs using pump-probe laser beam technique based on the concept of spatial cross phase modulation (SXPM). The novelty of this work is important to understand the interaction mechanism between the laser beam and CdSe/ZnS QDs at two different sizes providing a new approach for the development of a future photonics application, such as bio-labeling, quantum information processing, optical computing and all-optical device applications.

2. Experimental techniques

Samples of CdSe/ZnS QDs with diameters of 2.6 and 3.2 nm were obtained from Evident Technologies, which are typically synthesized by colloidal methods in solution. Usually, the surface of these particles is coated with organic

molecules such as polymers or a surfactant attached (ZnS) to the surface to prevent aggregation (optical stability) and to control the size and shape of the particles. The surface particles are called capping material [27,28]. In our samples, the capping material is ZnS.

The CdSe/ZnS QDs samples were dissolved in toluene solvent with a concentration of 10^{-3} M. Fig. 1 shows the ultraviolet-visible absorption spectra of CdSe/ZnS QDs with two different sizes using a Shimadzu UV-3101PC spectrophotometer.

Fig. 2 shows the experimental setup used with a pump-probe laser beam technique, where a green CW DPSS laser ($\lambda=532$ nm) was used as a high-power pumping beam, and a red CW Diode laser with a Gaussian beam ($\lambda=635$ nm) was used as a low-power probe beam (1mW). Both beams are directed to a 10 cm convex lens to be focused at the center of stationary sample cell (2 mm quartz cell thickness). Fig. 2 (a) shows the experimental arrangement in order to study

the all-optical modulation based on the phenomenon of DRs pattern formation in the far field, for each of the green laser beam, based on the concept of spatial self-phase modulation (SSPM) and the red laser beam, based on the concept of spatial cross phase modulation (SXPM), in a circular shape on a white screen located behind the cell at a distance of about 100 cm, and using a digital camera, the resulting green and red DRs were recorded.

Using the experimental arrangement shown in Figure 2 (b), both of the passed pump beam (green) and probe beam (red) signals are monitored and recorded using two silicon photo-detectors, PD₁ and PD₂ (Thorlab, DET-110 model), which were connected to a digital oscilloscope (Tektronix). TDS 3054B model, a pulse generator was used to control the green pump beam, beam profiler was used to determine the beam waist (ω_0) and all the experimental components were computer controlled.

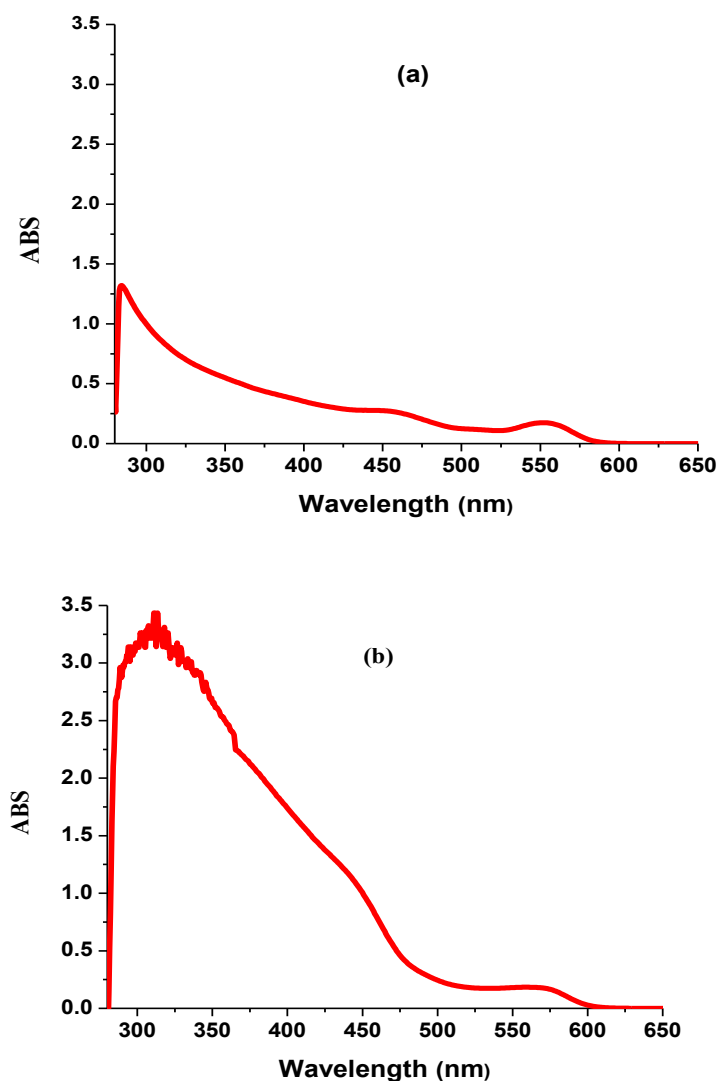


Fig. 1. (a) Absorption spectrum of CdSe QDs with size of 2.6 nm, (b) Absorption spectrum of CdSe QDs with size of 3.2 nm (colour online)

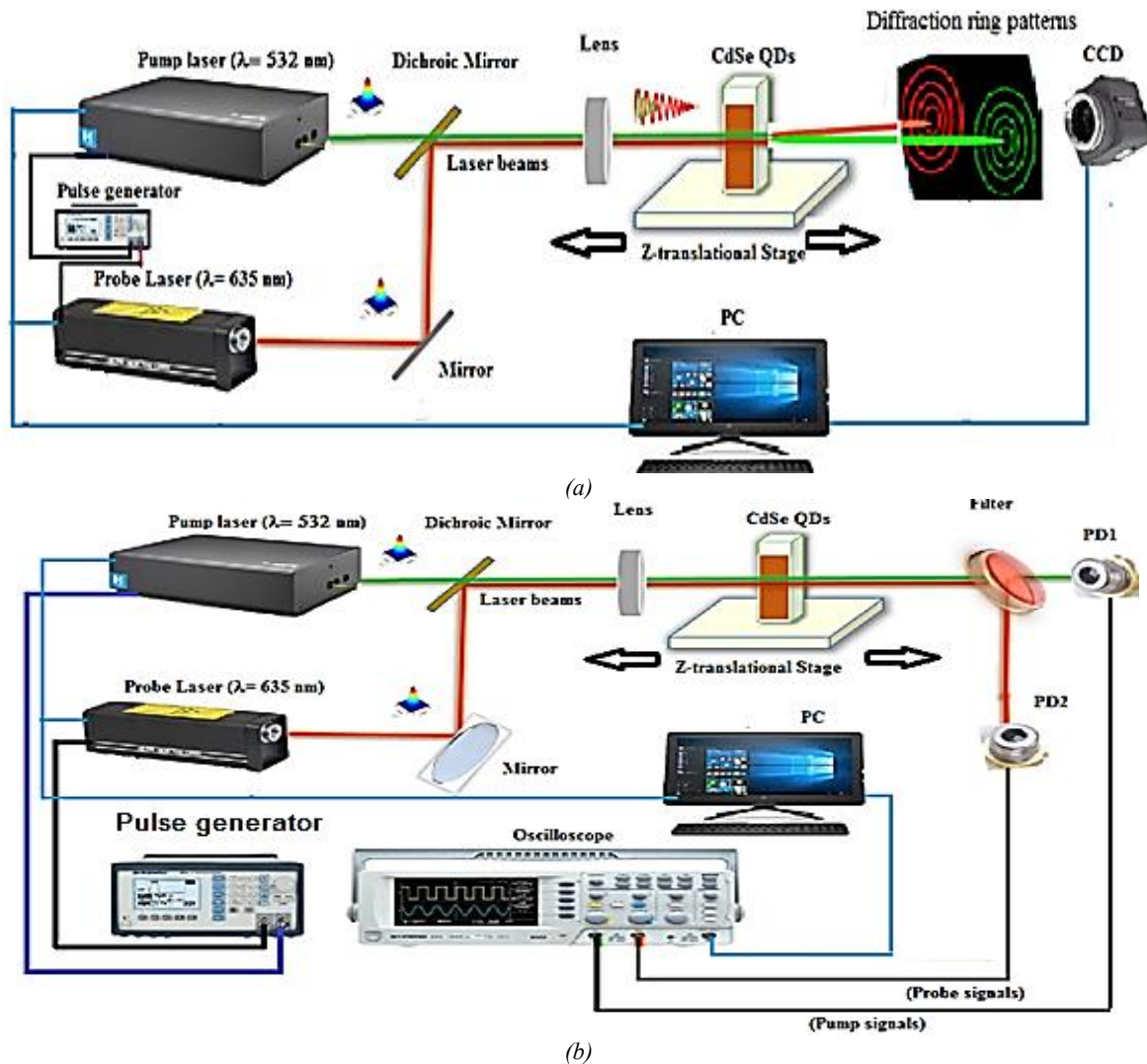


Fig. 2. Experimental setup of AOS technique (a) for observing diffraction rings, (b) for tracing the output signals (colour online)

3. Results and discussion

Using the samples, “CdSe QDs with sizes of 2.6 nm or 3.2 nm”, we observed the red laser ($\lambda = 635 \text{ nm}$) spot without the green laser, and then the green laser ($\lambda = 532 \text{ nm}$) DR pattern was observed at power of 5 mW. It was very clear the power of the red laser is below the excitation threshold to create any DR patterns, and then, the green laser power is enough to create the diffraction ring patterns, as seen in Fig. 3.

The AOS effect of the red laser beam controlled by the green laser was performed using the experimental setup shown in Fig. 2(a). Fig. 4 shows the overlapping of DR patterns formed for the green and red laser beams, where the power of the probe beam was set to 1 mW ($I = 18 \text{ W/cm}^2$) and the pump intensities were increased gradually as follow: $I = 194, 388, 777, 1165, 1553 \text{ W/cm}^2$ which are corresponded to powers of 5, 10, 20, 30, 40 mW, respectively. The obtained measurements were taken using

two different sizes of CdSe/ZnS QDs (2.6 and 3.2 nm). It is noted that the size and number of DRs of the red probe beam increased significantly in proportion to the increase in the power of the green pump beam for both sizes of CdSe/ZnS QDs (2.6 and 3.2 nm), and this is explained by relying on the phenomenon of spatial cross phase modulation (SXP), meaning that the green pump beam spatially modified the phase shift of the low power probe red beam by passing it with a solution of CdSe/ZnS QDs (2.6 and 3.2 nm) [29]. Fig. 5 shows the size and numbers of the red DR patterns were also increased with the enhancement of the green laser powers (5 to 40 mW). When red laser beam passes through the CdSe/ZnS QDs, the changed reflective index enhanced by the green laser beam would also cause a phase shift on the red laser beam and the red laser beam is diffracted into ring patterns. We can say that our obtained results confirmed that the light-control-light effect worked well in all the phase states by using CdSe/ZnS QDs (2.6 and 3.2 nm) [29].

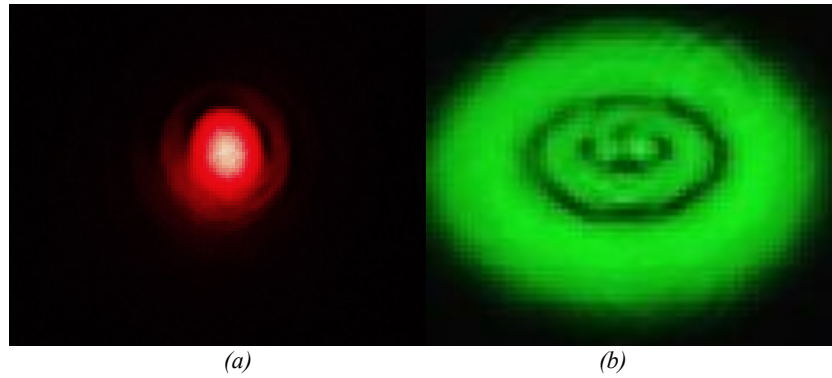


Fig. 3. (a) Red laser spot (1mW) without green laser, (b) Green laser DRs at power of 5 mW (colour online)

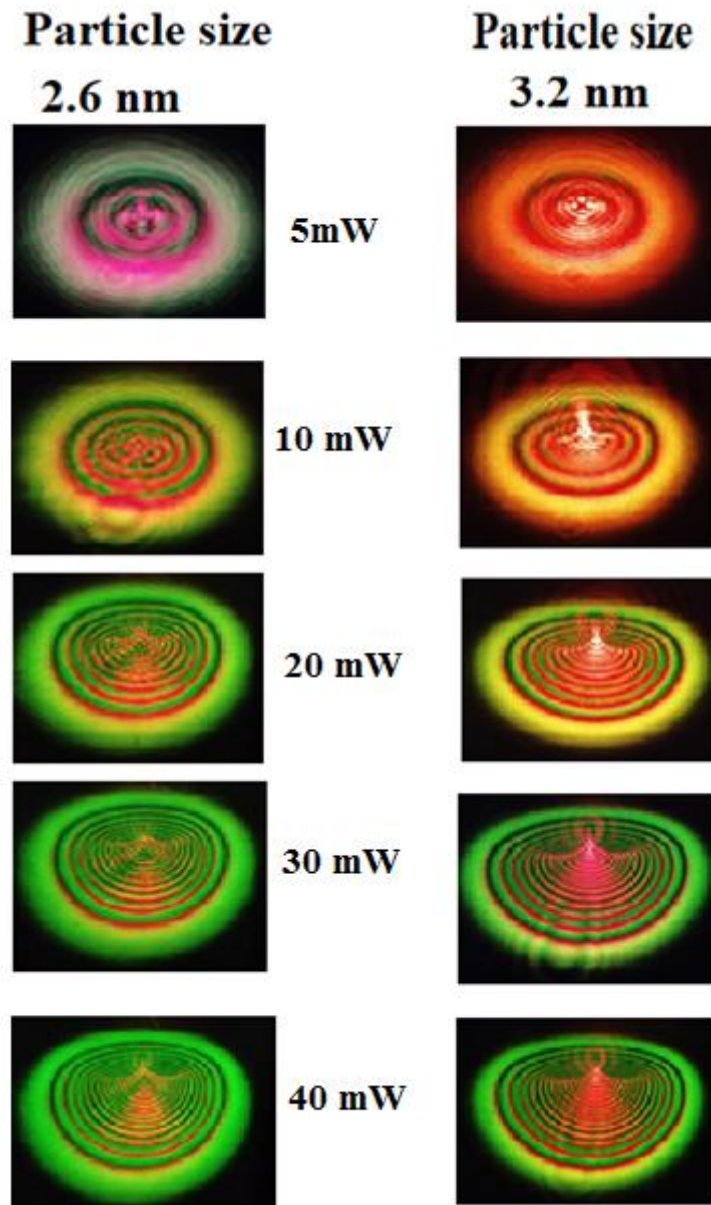


Fig. 4. AOS images of the overlapped DR patterns of the green beams and the red beam passing the CdSe/ ZnS QDs with two sizes of 2.6 and 3.2 nm under the excitation of the green laser beam with pump intensities of $I= 194, 388, 777, 1165, 1553 \text{ W/cm}^2$ correspond to powers of 5, 10, 20, 30, 40 mW, respectively (colour online)

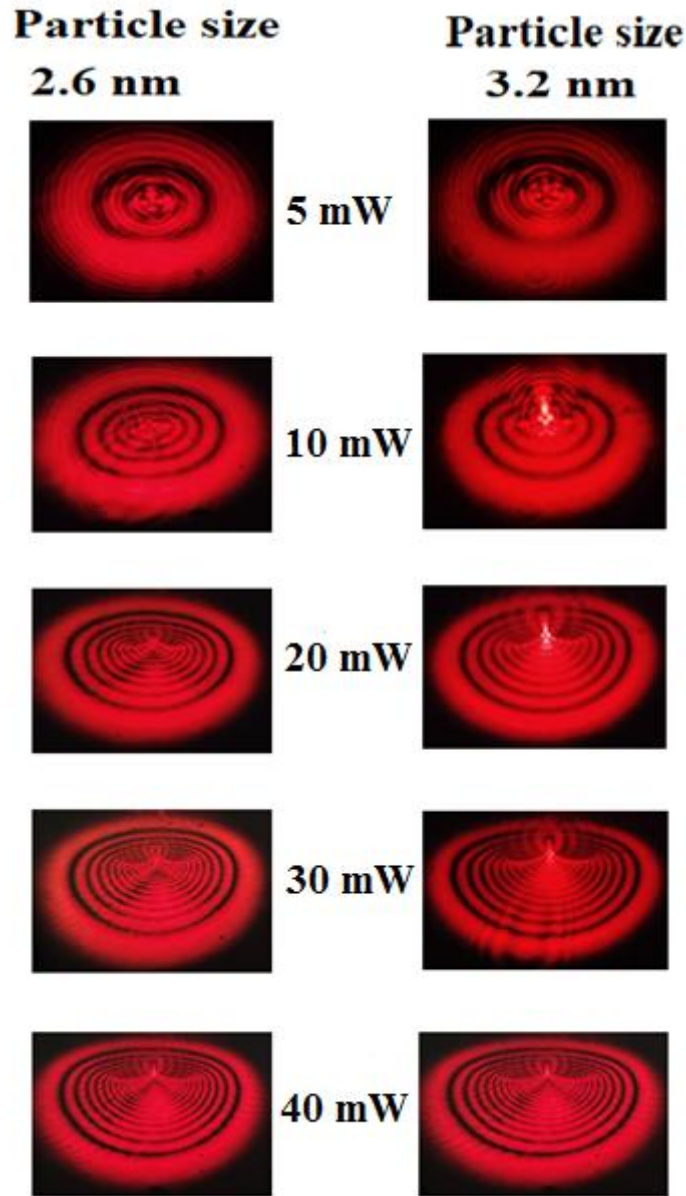


Fig. 5. AOS images of the red laser DRs passing CdSe/ZnS QDs with two sizes of 2.6 and 3.2 nm, under the excitation of the green laser beam at different pump beam powers (5, 10, 20, 30, 40 mW) (colour online)

As can be seen in Figs. 4 and 5, the shapes of the DRs were symmetrical (circular) at powers of 5 and 10 mW, which indicates that thermal conduction currents were responsible for reducing the heat generated by the green pump beam within the CdSe/ZnS QDs solution, but at higher powers (20, 30 and 40 mW), the shape of the DRs is asymmetrical (distortion). The distortion of the DR patterns suggests that convection currents contribute to compressing the formed ring under the effect of gravity [27]. The experimental geometrical configuration suggested that thermal lensing and convection are the primary mechanisms for this distortion, because the laser beam interacts with the sample in vertical way not come from underneath the sample [21].

By analyzing the obtained results relating to the DR patterns for both the green and red laser beams with two

sizes of CdSe/ZnS QDs (2.6 and 3.2 nm), we can recognize that there are differences in the number, sizes and the brightness of the DR patterns. The number of DRs is increased with the smaller diameter of the CdSe/ZnS QDs (2.6 nm), as well as the number of red DRs with two sizes of 2.6 and 3.2 nm increased with increasing of the green laser powers [30], as shown in Figure 6. It was found that there is a linear relationship between the number of DRs formed (red and green) and the power of the green pump laser beam. The physical link between the QD size and the enhancement of the spatial cross-phase modulation effect is due to the energy band gap (E_g). As the size of the QDs gets smaller, the E_g and oscillator strength become larger, this led to higher nonlinearity (increasing the number of DRs). It should be mentioned that the observed nonlinear optical response is dominated only by thermal effects, not purely

electronic Kerr effect, as CW laser beam was used as pump laser beam [31].

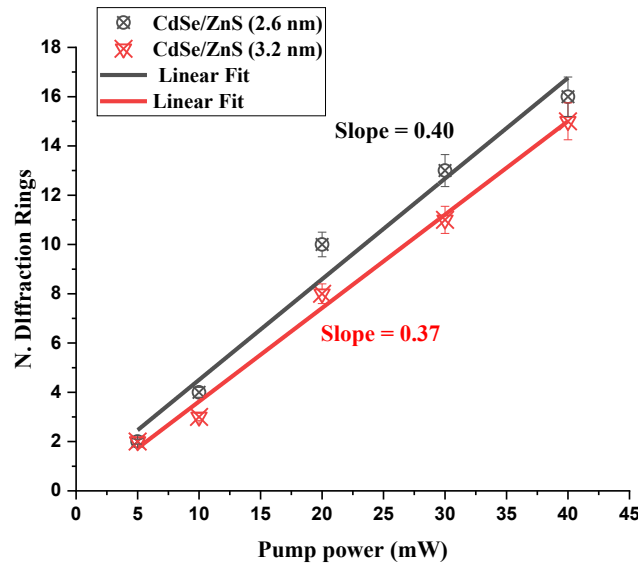


Fig. 6. Number of red DRs for CdSe/ZnS QDs with diameters of 2.6 and 3.2 nm as a function of green pump power (colour online)

The NL refractive index n_2 of CdSe/ZnS QDs (2.6 and 3.2 nm) can be determined using the following equation [32]:

$$n_2 = \frac{\pi \omega_0^2 \lambda}{2L_{eff}} \frac{N}{p} \quad (1)$$

where N is number of DRs, P is the pump power, λ is the laser wavelength, ω_0 is the beam waist and $L_{eff} = [1 - e^{(-\alpha_0 L)}]/\alpha_0$ is the effective thickness.

The value of the slope (N/P) was deduced from Fig. 6. Then, the values of n_2 for each CdSe/ZnS QD sizes of 2.6 and 3.2 nm were calculated using equation 1. All the experimental values of linear absorption coefficient α_0 , and NL refraction index n_2 are listed in Table 1. As, the difference between n_2 at 2.6 nm and 3.2 nm is small due to the small range is not significant.

Table 1. Experimental results of CdSe/ZnS with Particle sizes (2.6 and 3.2 nm): linear absorption coefficient (α_0), and nonlinear index of refraction (n_2) for green laser beam ($\lambda = 532$)

CdSe/ZnS with Particle sizes	Present work		Ref.[36]
	α_0 (cm ⁻¹)	n_2 (cm ² /W)	n_2 (cm ² /W)
2.6 nm	0.83	-3.46×10^{-9}	-6.33×10^{-20} (Size 2.84nm)
3.2 nm	0.65	-3.23×10^{-9}	-3.06×10^{-20} (Size 3.04nm)

The value of α_0 can be calculated as follow: using Beer-Lambert law, where $L = 2$ mm (the sample thickness) and the ratio between the incident (I_0) and transmitted (I) intensities were measured at low laser powers (for more than 5 values), then α_0 can be deduced.

Regarding, the uncertainties in Table 1, the linear refractive index (α_0) is about $\pm 0.3\%$, the beam waist (ω_0) is $\pm 0.4\%$ and the nonlinear refractive index (n_2) is about $\pm 0.5\%$.

The time response behavior of the AOS effect was studied by placing silicon photodetectors (PD₁, PD₂) in front of the green laser beam and the red beam, respectively. These detectors are connected to a digital oscilloscope in order to record the signals of the two beams and study the optical-switch effect. The experimental arrangement has been shown in Fig. (2b), which is based on the concept of SXPM [33]. As mentioned previously, a pulse generating device was used to control the firing of a green laser beam in the status of opening and closing (ON/OFF). When the green laser beam is closed, that is, in the OFF position, it was noticed that the red laser beam remained as it was (red spot), it did not form any type of diffraction ring. However, when the green laser beam (pump laser) is turned ON, i.e. the ON position, it is observed that diffraction rings begin to form for the red laser beam, and both signals were recorded using optical detectors. Fig. 7 shows the recorded signals by the digital oscilloscope for both the pump and probe beams, and we have noticed the contrast in the signals. The experiment was performed using the frequency of the pump beam 0.5 Hz, the power of the pump beam is 10 mW, and the power of the probe beam is 1 mW. The rise and fall time of the probe beam are shown in Table 2.

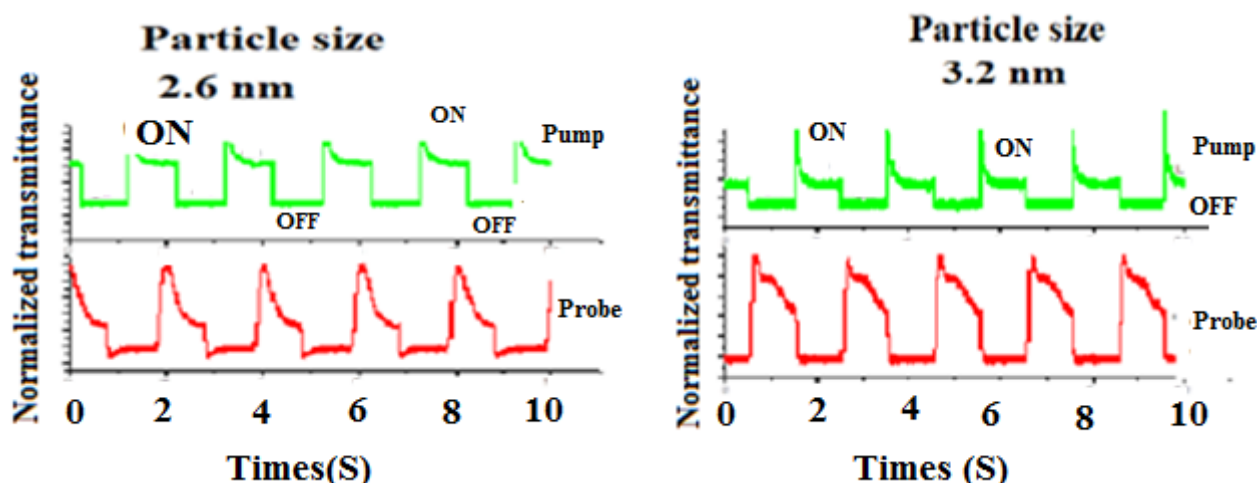


Fig. 7. Time response behavior of the AOS effect at frequencies of 0.5 Hz, pump beam (upper curve), probe beam (lower curve), for the 10 mW pump beam, and 1 mW probe beam for CdSe/ZnS QDs with two sizes of 2.6 and 3.2 nm (colour online)

Table 2. The rise and fall time of the probe beam at 1mW

	Particle size (2.6 nm)	Particle size (3.2 nm)
Rise time	124 ms	67 ms
Fall time	713 ms	840 ms

This feature can be explained as follows: when the pump laser beam passes the CdSe/ZnS QD (ON state), the transmitted probe laser beam will be in the OFF state due to the start of the formation of diffraction rings for the probe beam [34]. When the pump beam is in the OFF state, the intensity of the transmitted probe laser beam will begin to increase, and it will be in the ON state. The adjustment time ranges from within microseconds. Fig. 7 shows the size dependent behavior of AOS effect when the green pump laser switches from on to off at a frequency of 0.5Hz. The light intensity and the time width can be observed for both of the two particle sizes of samples with 2.6 and 3.2 nm, during the on and off cycles at 0.5Hz. Our present work on the size effect of CdSe/ZnS QDs of AOS can be compared to that described in [29], AOS in InP QDs [35] and CdSe QDs [36]; it can be concluded that the obtained results agree with the similar works. Through the results of our study, we have noted that there is a relationship between the sizes of the CdSe/ZnS QDs samples and its NLO properties, and thus the possibility of improving the NLO properties of the sample by controlling its size and making it nano-sized, and benefiting from it in the manufacture of all-optical switching devices.

4. Conclusion

The red laser beam modified by the green laser beam based on the concept of SXPM using CdSe QDs with sizes of 2.6 and 3.2 nm. The DRs of the red probe beam obtained when the sample irradiated with the green pump beam. It observed that the size of CdSe QDs at 2.6 nm contributed to increase the number of red DRs and both of the red and green DRs increased linearly with the increase in the power of the green laser beam. The optical control system was

studied based on the SXPM concept, where the weak probe beam was controlled and modified by a strong pump beam. This can be used to manufacture optical modulators and convert optical information.

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