# Analysis and Demonstration of the Quantum Dot Lasers

Haoyang Sun *

Department of Physics and astronomy, University of Sheffield, Sheffield, the UK

* Corresponding author: hsun50@sheffield.ac.uk

**Abstract.** Contemporarily, with the rapid development of laser techniques, various types of lasers have been invented covering almost all the visible wavelength and even near infrared or ultraviolet wavelength. However, the properties of laser can be boosted and enhanced with the state-of-art techniques to fulfill the needs for advanced applications. With the invention and realization of quantum dots, it is feasible to enhance the performance of the laser feature (e.g., spread, efficiency, luminosity) based on the dose of the quantum dots. This study will discuss the realization of the quantum dot lasers and demonstrate the different types of ways as well as performances. Specifically, lasers based on self-assembled quantum dots, colloidal quantum dots, and carbon quantum dots will be discussed. According to the analysis, the features and construction methods as well as drawbacks of different types of quantum dots laser are clarified.s Overall, these results shed light on guiding further exploration of quantum dot lasers as well as implementations of quantum dots.

**Keywords:** Laser, keywords covered, quantum dots.

## 1. Introduction

Quantum dot (QD) is a structure that can confine electrons in a very small range in three spatial dimensions. The size of this range is on the same order of magnitude as the De Broglie wavelength of the electron. Quantum size effects arise when electrons are confined in such a small area [1]. The energy bands of electrons will split, and the width will become very narrow, forming energy levels similar to the electrons in atoms. Therefore, quantum dots can be also called artificial atoms. This structure brings many excellent physical properties to quantum dots. The size of a quantum dot is strongly related to the frequency of photons its excited. In addition, due to the narrow electronic energy band of quantum dots, the frequency range of photons generated by their transitions is also very small. Therefore, quantum dots have many advantages in making optoelectronic devices, especially lasers.

In 1982, Arakawa and Sakagi proposed that the "multidimensional quantum well" laser can prominently increase the characteristic temperature. Shortly thereafter, Asada predicted high material gain and low threshold current density can be shown on quantum dots laser device [2]. Luminescence of individual quantum dots was first demonstrated in the laboratory in the mid-nineties. In 1996, lasing of quantum dots at room temperature was achieved. After that, people gradually stimulated electromagnetic waves with a wavelength from 1000um to 1300um in the laboratory [1]. In recent years, it has been possible to fabricate quantum dots that excite electromagnetic waves of shorter wavelengths [1].

There are currently many studies in this area, all of which have achieved noteworthy results in different aspects. This paper will summarize these studies and give an outlook on future quantum dot laser research. The purpose of this article is to summarize the existing research, analyse the advantages and limitations of various quantum dot lasers, and look forward to providing a useful reference for future researchers. This study will first analyse the physical properties of quantum dots themselves, explain how to use these physical properties, and analyse the advantages and disadvantages of using them to make lasers. Then, this paper will classify quantum dot lasers into three categories by three different ways of making quantum dots and discuss their respective advantages and disadvantages. Finally, this paper evaluates these three quantum dot lasers against these advantages and disadvantages, discuss their respective limitations, and give an outlook for future research.

## 2. Physical Properties of Quantum Dots Lasers

The most important physical form of a quantum dot for a laser is that it produces an energy level distribution similar to that of an isolated atom. Due to its narrow bandwidth, photons of defined energy are produced. In addition, since its size is strongly related to the wavelength of photons generated by excitation, the photon wavelength can be adjusted by adjusting the size. In addition, compared with quantum wells, quantum dot lasers have several significant advantages: higher temperature operation, lower linewidth enhancement factor and reduced linewidth, reduced reflection sensitivity, improved mode-locking and reduced sensitivity to defects.

Quantum dots can also be regarded as three-dimensional quantum wells, so their structures are also made of materials with different bandwidths. Therefore, the fabrication method of the quantum dot structure is to embed a very small narrow bandgap material into a wide bandgap material. The most common and well-studied material for fabricating quantum dots is InAs/GaAs, which are usually embedded on a platform composed of InGaAs [1]. Due to the extremely small size of quantum dots, realizing this structure is not simple. There are currently two main strategies for fabricating quantum dots: physical vacuum-based methods and wet chemical methods [3]. This study will divide quantum dots into three categories through different manufacturing methods of quantum dots, namely: lasers based on self-assembled quantum dots, colloidal quantum dots, and carbon quantum dots.

## 3. Lasers Based on Self-assembled Quantum Dots

Quantum well structures are formed by epitaxial growth of one material on another along the normal direction, and a similar process can be used to grow quantum dots [4]. The difference is that the fabrication of quantum dots requires significantly different lattice constants of the two materials. When the lattice constants of the two materials are different, dislocations are created when they are bonded, and then quantum dots with an "island" shape are created at the bonding point. For example, quantum dot structures made of In (Ga)As/GaAs and InAs/InP are made by this method, and these two materials are the most studied and developed quantum dot materials [5, 6]. Such structures are known as self-assembled quantum dots. However, this structure has an inherent drawback that he will generate quantum dots randomly leading to an uncontrollable microstructure of the material (seen from Fig.1). An improved fabrication method for them is Droplet epitaxy, which is essentially the crystallization of metal droplets prefabricated on the surface of the substrate material [6]. This method can significantly improve the control over the nanostructure on the material.

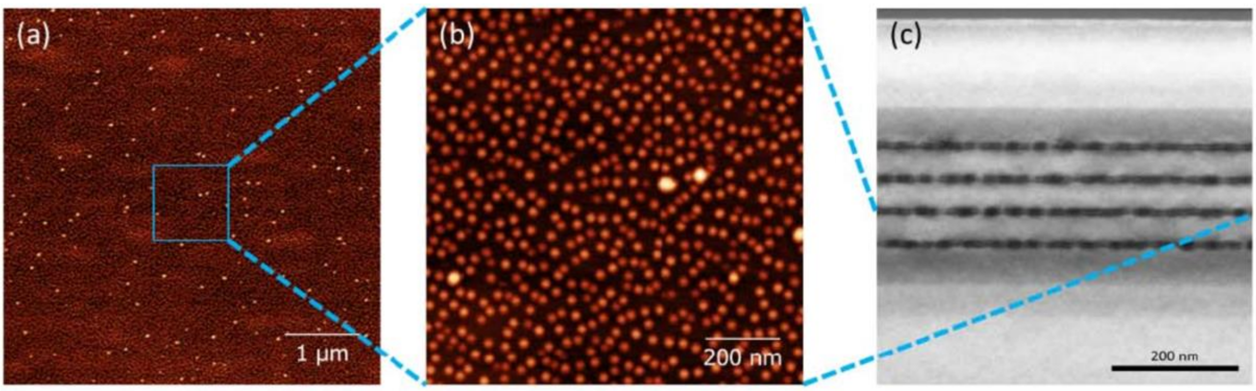


**Figure1.** Microstructure of the material for quantum dots.

The resulting quantum dot materials have many excellent properties. There are many enhancements in the laser gain region of quantum dots compared to quantum well materials [5]. In addition, the inhomogeneous distribution of quantum dots running independently on the material leads to high stability of quantum dot lasers compared to quantum well lasers and low sensitivity to material defects [5]. Moreover, quantum dot lasers have lower threshold currents as well as higher operating temperatures. Further, the linewidth enhancement factor in quantum dots is significantly smaller than in quantum well lasers owing to the more symmetric gain function in quantum dot lasers [6]. This is of great benefit for the fabrication of high-performance lasers [6]. However, it is bad news for fabricating quantum dot dynamic lasers due to the weak fast response in quantum dot lasers [6]. Several research groups have focused on solving this problem and scattering carrier lifetime engineering is one of their proposed solutions [4].

Self-assembled quantum dots are randomly distributed in the material. Moreover, the dimensions of the generated quantum dots are also random due to their self-assembly process [5]. These fluctuations in size give rise to a number of quasi-state bands which are superimposed to form a broadening as shown in Fig. 2 [5]. The $\Delta E_{inh}$ in the figure is the energy change due to the illustration of inhomogeneous. This broadening does not cause the overlap of different energy levels within the quantum dot because its width is much smaller than the gap between energy levels [5]. The width of this broadening is determined by the growth conditions of the crystal, which further enhances the tunability of the quantum dot material [4]. In addition, this broadening is of great benefit for broadband applications such as tunable lasers, and mode-locked lasers [4].

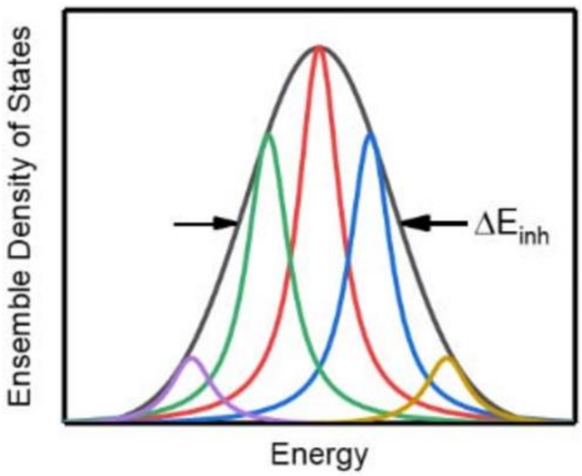


**Figure 2.** A sketch of energy broadening.

The wy to expand the spectral range of quantum dot lasers is also an important research direction. For InP-based quantum dot lasers, a spectral emission of 1550-2000 nm has been achieved [6]. For higher wavelength ranges, such as spectra larger than 2000 nm, challenges still exist [6]. In addition to this, earlier quantum dot lasers were performed at low temperatures due to the influence of phonons within the quantum dots on the results. This has been somewhat overcome in new studies, such as quantum dot lasers of In (As)Sb grown on p-InAs substrates, which have been able to emit lasers around 3000 nm and operate at temperatures up to 120 K [6].

In addition to this, the new research has led to a reduction in the threshold current density of quantum dot lasers. Earlier, the threshold current density would reach 7.6 $kAcm^{-2}$ [6]. In contrast, some newly reported quantum dot lasers have been able to achieve very low threshold current densities of 26 $Acm^{-2}$ [6]. Some studies have even proposed theories to reduce the threshold current density to below 10$Acm^{-2}$.

## 4. Colloidal Quantum Dot Laser

Colloidal quantum dots are attached to the platform after being made in chemical reagents. It's very significant advantage is that it is easy to manufacture, can be used for mass production and can be attached to a variety of materials. Colloidal quantum dots are low cost because they can be processed from solution [7]. In addition, colloidal technology has the advantage of being easily scalable and easy to manipulate the properties of quantum dots [8]. In addition, colloidal quantum dots retain the low optical gain threshold and high temperature stability of the luminescence properties of conventional quantum dots [9]. Some colloidal quantum dot structures successfully combine the excellent optical properties of quantum dot structures with the high chemical flexibility of molecular systems [9]. The fabrication of colloidal quantum dots came from the study of nanocrystals. The initial studies were carried out by generating precipitates in molten glass to prepare nanocrystals. Subsequently, the study of colloidal chemical methods for the fabrication of semiconductor particles led to methods for controlling the structure of the material at the nanoscale [8]. A drawback of colloidal quantum dots is their poor stability at high current densities, which leads to their not being susceptible to high intensity DC excitation [9].

A great breakthrough in the manipulation of the optical-gain properties of colloidal quantum dots has been reported in a previous study [8]. This has been of great benefit to the research on quantum dot lasers, such as the successful development of developing optically pumped continuous-wave (cw) lasers. Besides, some excellent quantum dot materials have been mentioned, such as CdSe-based nanostructures. these nanocrystals are suitable for applications in the visible wavelength range because of their large band gap (1.75 eV) [8]. For electromagnetic waves in the infrared band, the structures based on PbS and PbSe crystals exemplify the best performance. Previous studies revealed that an obvious drawback of this material is that it exhibits a high optical-gain threshold, but subsequent studies have shown that this problem can be solved by using heavily doped quantum dots [8].

Further studies have shown that the performance of colloidal quantum dots can be enhanced by halide chalcogenides, and quantum-tuned colloidal quantum dots have been combined into quantum dots in chalcogenide solids (QDiP). Several new QDiP systems have been synthesized and applied to optoelectronic devices. The main structure is to grow quantum dots on a halide substrate and wrap them around it. This material can combine the advantages of colloidal quantum dots and halide cladding materials. The optical properties of QDiP are related to the nature of the constituent colloidal quantum dots, chalcogenides and their interfaces. In contrast to conventional cqd, where properties are tuned by controlling size, exposed surface and surface ligands, QDiP systems can also be tuned by the choice of cladding materials. This brings a new dimension to quantum dot tuning due to the diversity of candidate materials. In the current study, some material choices can lead to longer carrier lifetime, more carrier migration to colloidal quantum dot, and better quantum dot photoluminescence. In addition, in some applications, QDiP systems extend the emission range of LEDs and improve the performance of photodetectors. The drawback of QDiP systems is the lack of material stability due to halogenated chalcogenides [7].

## 5. Carbon Quantum Dot Laser

Charcoal quantum dots are microscopic particles less than 10 nm in diameter [2]. Unlike the quantum dot materials mentioned above, charcoal quantum dots are not formed by a certain compound, but can be synthesized by charring various organic substances or even food [2]. Because of this, charcoal quantum dots are less toxic and more chemically inert [10]. These characteristics lead to charcoal quantum dots being well suited for biological and medical research. Also, because it contains a quantum dot structure, it possesses excellent optical properties as mentioned before. In particular, its excellent photoluminescence properties, and electroluminescence properties give carbon quantum dots a wide range of applications [2].

An example of the application of carbon quantum dots is in wastewater treatment [10]. In this study carbon quantum dots exhibit many excellent properties, but one only focuses on their aspect as lasers. It was shown that carbon quantum dots can be used as excellent spectral converters and exhibit good absorption of the visible spectrum. In addition, carbon quantum dots have a good performance in the emission of band wavelengths, i.e., high energy photons [10]. This structure provides a huge performance improvement over the conventional semiconductor photocatalysts. A sketch of the laser system is illustrated in Fig. 3 [11].

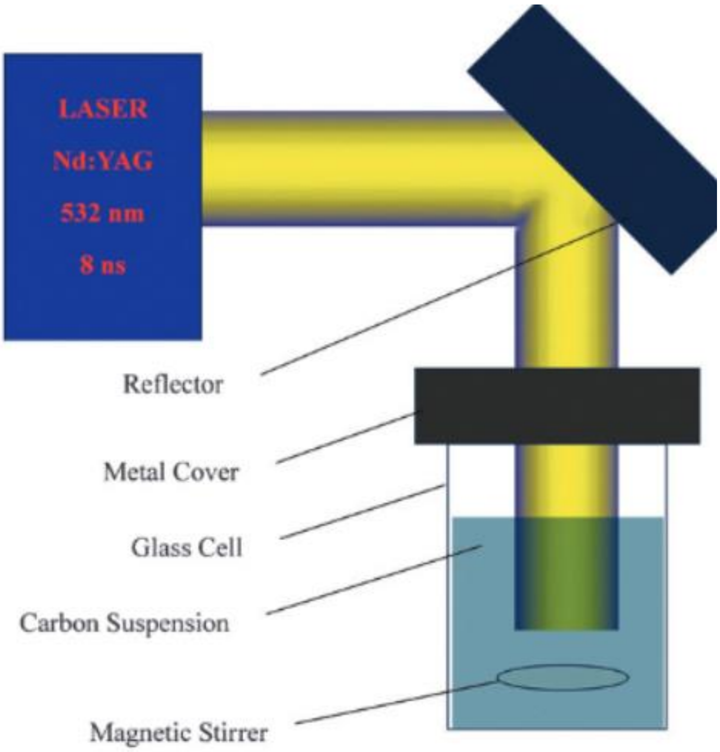


**Figure 3.** A sketch of carbon quantum dots laser.

## 6. Limitation & Prospects

As mentioned above, the research on quantum dot lasers has achieved remarkable results. However, the current research still has some shortcomings. First, quantum dot lasers are still not effective enough for high temperature operation and long wavelength luminescence. Secondly, for structures containing compounds such as the colloidal quantum dot lasers described in this paper, although there are many studies, there is still a large gap in the materials studied. In addition, most of the quantum dots with high quality performance are still too harsh to be manufactured or used under conditions that make them difficult to be realized outside the laboratory, and they cannot be mass produced. Finally, there is the problem of random growth of quantum dots during fabrication. Although there are some solutions to some extent, it is difficult to overcome random growth if self-assembly is chosen. Most of the quantum dot materials that have good performance and are easy to fabricate have self-assembly fabrication. Since quantum dot lasers have excellent performance in theory and their principles are not complicated. Therefore, the main challenge of the research is to smooth out the gap between theory and practice. Today's research has made good progress, and as the number of studies increases, the gap with theory will be closed.

## 7. Conclusion

In summary, the energy level distribution of quantum dots similar to that of isolated atoms brings excellent optical properties. This optical property makes quantum dots suitable to be used as components of lasers. This paper presents quantum dot lasers fabricated based on three representative fabrication methods. Self-assembled quantum dots have the best properties, are the most dominant quantum dot laser, and are easy to fabricate, but possesses large growth uncontrollability. Colloidal quantum dot lasers are based on self-assembled quantum dots with the addition of compound materials to combine the high quality material properties with the excellent optical properties of quantum dots. The research on colloidal quantum dot lasers is mainly focused on experimenting with different materials in the hope of obtaining excellent structures. Finally, a carbon quantum dot is a quantum dot material made by physical or chemical methods after carbonization of organic matter.

The high affinity of carbon quantum dot lasers for the environment and living organisms makes them suitable for use as medical or biological materials. Finally, direct hit manufactured quantum dot lasers possess some gaps with the properties of the theoretical quantum dot model. Current research is gradually closing this gap. Overall, these results offer a guideline for further exploration of quantum dots laser.

## References

[1] Norman J C, Mirin R P, Bowers J E. Quantum dot lasers—History and future prospects. Journal of Vacuum Science & Technology A: Vacuum, Surfaces, and Films, 2021, 39 (2): 020802.

[2] Das R, Bandyopadhyay R, Pramanik P. Carbon quantum dots from natural resource: A review. Materials today chemistry, 2018, 8: 96 - 109.

[3] García de Arquer F P, Talapin D V, Klimov V I, et al. Semiconductor quantum dots: Technological progress and future challenges. Science, 2021, 373(6555): eaaz8541.

[4] Zhou W, Coleman J J. Semiconductor quantum dots. Current Opinion in Solid State and Materials Science, 2016, 20 (6): 352 - 360.

[5] Norman J C, Jung D, Zhang Z, et al. A review of high-performance quantum dot lasers on silicon. IEEE Journal of Quantum Electronics, 2019, 55 (2): 1 - 11.

[6] Wu J, Chen S, Seeds A, et al. Quantum dot optoelectronic devices: lasers, photodetectors and solar cells. Journal of Physics D: Applied Physics, 2015, 48 (36): 363001.

[7] Chen H, Pina J M, Hou Y, et al. Synthesis, applications, and prospects of quantum-dot-in-perovskite solids. Advanced Energy Materials, 2022, 12 (4): 2100774.

[8] Park Y S, Roh J, Diroll B T, et al. Colloidal quantum dot lasers. Nature Reviews Materials, 2021, 6(5): 382 - 401.

[9] Jung H, Ahn N, Klimov V I. Prospects and challenges of colloidal quantum dot laser diodes. Nature Photonics, 2021, 15 (9): 643 - 655.

[10] Sharma S, Dutta V, Singh P, et al. Carbon quantum dot supported semiconductor photocatalysts for efficient degradation of organic pollutants in water: a review. Journal of Cleaner Production, 2019, 228: 755 - 769.

[11] Li X, Wang H, Shimizu Y, et al. Preparation of carbon quantum dots with tunable photoluminescence by rapid laser passivation in ordinary organic solvents. Chemical Communications, 2010, 47 (3): 932 - 934.