Review Article

Recent Developments of Quantum Science in Laser Technologies, a Mini-Review

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Abstract

Nowadays, quantum science plays an important role in the development of various applications and systems one of the main ones being quantum lasers. InAs and Ge/GeAs material systems are among those that are of interest in the development of Quantum Cascade Lasers. Also, laser pointers based on quantum lasers are of interest and the development of quantum dot laser diodes is also discussed and developed. Due to the importance of this issue, in this research, in the form of a mini-review, the general aspects of quantum lasers and the latest advancements have been examined and analyzed. It is worth mentioning that lasers play an effective role in the development of various quantum dots, including carbon quantum dots. The purpose of this research is to summarize the latest research in the field of quantum lasers and also to review some of their applications in the development of various types of quantum dots, especially carbon quantum dots.

Keywords:Quantum Laser, Quantum Cascade Laser, Quantum Dots, Laser Diodes.

1. Introduction

Today, the development of quantum materials has been given attention in various sectors due to their special capabilities. These materials are mainly semiconductor nanocrystals with nanometer size, which have different optical, electronic and fluorescent properties compared to larger particles due to the effects of quantum mechanics [1-3]. These materials, which are in the form of quantum dots, have unique applications in various fields, including the construction of modern solar cells [4, 5], quantum bio-imaging [6], drug delivery to cells [7], manufacturing the advanced sensors [8, 9] and quantum computers [10].
Among the various applications of quantum materials, special attention has been paid to quantum lasers. In this way, the development of quantum cascade lasers, and the use of quantum dots in diode lasers and laser pointers are proposed, and quantum technology has various roles in the application of these technologies. In the current research, the theory, applications, and some of the latest achievements in this field are specifically reviewed, and suggestions for future research are presented to the researchers[11].

2. Quantum Cascade Laser

The theory of quantum cascade laser (QCL) was first proposed in 1971 by Kazarinov and Suris [12] and experimented in 1994 by Faist et al [13].

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After that, extensive research has been done in the field of this technology. Today, research in this field is still ongoing, so Razeghi has mentioned about the importance of Indium Phosphide (InP) in the development of quantum cascade laser in her research. Results of this research showed by choosing the right parameters, WPE (wall-plug efficiency) and thermal efficiency can be recorded up to 38% and 84%, respectively. Also Room temperature continuous-wave (CW) output power will improve significantly with the improvement of WPE [14]. Also, in this way, Douglas J. Paul investigated terahertz quantum cascade lasers on silicon substrates. The results of his investigations showed that it is possible to obtain silicon-based QCL, and he presented examples of p-type Si/SiGe quantum cascade designs and also presented some n-type Si-based designs [15].
Quantum cascade lasers are used today as sources in the mid to far-infrared spectral range, which are unipolar semiconductors whose performance depends on multiple quantum well (QW) structures [12, 16]. To develop QCL lasers, InAs/AlSb material systems have been focused by Baranov and Teissier [16], and the results show that the use of this system can create successful results in the development of QCLs and the shift of the short wavelength frontier of QCL to 2.63 μm has been reduced. Also, this material system (InAs/AlSb) is suitable for the use of far-infrared QCLs. In another study, Baranov et al again demonstrated the CW regime for quantum QCLs at room temperature for the first time for InAs material system [17].

In confirmation of the positive application of the InAs/AlSb material system, positive results from the development of QCL were reported by Loghmari et al [18]. Also, in another study, Loghmari et al. mentioned the development of QCL with the InAs/AlSb material system, which was grown on a silicon substrate. The results of this research also showed that the threshold current density was up to 22% compared to reference QCLs with the same design grown on native InAs substrate [19]. Finally, similar results have been mentioned by Kinjalk et al. in the use of the InAs-based system in QCL [20].

The material systems used in the development of QCLs are not limited to InAs material systems and the Ge/GeSi material system has been considered. Oriented n-type Ge/GeSi structures use L-valley intersubband transitions and therefore have provided promising results in the development of QCLs [21, 22]. Positive results were also reported from the use of n-type Ge/Si0:15Ge0:85 material system by Stark et al [23].

Also, the use of a special type of diamond thin-film waveguide in the development of graphene-enabling surface-enhanced quantum cascade lasers has also attracted the attention of researchers in recent years. The results of the research conducted in the application of beverage quality analysis and also in biomedical assays have been favorable [24].

Table. 1. shows the final classification of QCLs with some of their applications. In order to complete the research, it is suggested that in the future, researchers focus more on the selection and investigation of other quantum materials such as graphene in the development of QCLs. It is also suggested to investigate and analyze the role of quantum diamonds in the development of QCLs.

3. Laser Diodes

A laser diode is a semiconductor that has similarities with a light-emitting diode and an electric current is directly introduced into it and laser conditions are provided at the junction of the diode [34]. Laser diodes have various applications in telecommunications [35, 36], spectroscopy [37] and 3D-laser printers [38]. Also, their various uses in medicine are evident. Their medical applications are especially evident in dentistry [39, 40].

Quantum science is also used in the development of laser diodes. Among the mentioned cases, there are colloidal quantum dots (CQDs lasers) that create different characteristics and lead to the emission of light in a wide range of wavelengths, which has a potential impact on the application of laser diodes [41, 42]. Of course, it should be noted that the realization of such devices has challenges such as optical gain decay that occurs due to the poor stability of QD solids, and in this regard, research has been conducted that has led to the development of devices with an electric pump that can greatly increase the current density [43]. In addition to the above point, the use of the type of quantum dots is also effective on the optical structures of CQDs lasers. In this regard, Ahn et al. pointed to the CdSe/CdxZn1- xSe cg-quantum dots. The results showed that the wavelength will be equal to 615 nm [44]. Similar results were reported by Prasad et al. in the combination of CdSe/ZnS quantum dots, a laser with a spectral width of 1 nm and adjustable from 510 to 630 nm was obtained [45]. Similar results were reported by Kozlov et al [46] and Table. 2. summarizes some types of quantum dots and their respective wavelengths in CQDs lasers.

Table. 1. classification of QCLs with some of their applications.

Material System	Feature / Application	Ref.
InAs/AlSb	High-conduction band offset.	[16]
	Emitting 2.75 μm at 80 degrees Celsius.	[25]
	Emitting 2.97 μm near room temperature.	[25]
	Maximum operating temperature is 373 ºK.	[26]
InAs	Waveguide emitting near 3 µm or even below.	[27]
	Threshold current density as low as 730 A/cm^2.	[17]
	Threshold current density is as low as 630 A/cm^2 at room temperature.	[28]
	9.1 µm in pulse mode and up to 160 ºK.	[29]
Ge/GeSi	Ge/GeSi structures have the best performance at 3 and 4 THz.	[22]
	These materials are widely used in optical devices.	[30]
	Most promising material for the realization of a THz QCL.	[31]
Graphene	For biomedical applications where the particles are very small.	[24]
	Bio-imaging and sensing applications.	[32]
	Modification of the optical response of Plasmonic resonances.	[33]

Table. 2. Summarizes some types of quantum dots in CQDs lasers.

Type of Quantum Dots	Wavelength	Ref.
CdSe/CdxZn1- xSe cg-QDs	628 nm	[46]
CdSe/CdS/ZnS	610 nm	[47]
CdSe/ZnS quantum dots in the submicron-sized silicon disk.	594 nm	[48]
InP/ZnS	616 nm	[49]
CdSe/ZnCdS	610 / 575 nm	[50]
ZnS:Mn QDs	603 nm	[51]

4. Quantum laser pointer

Limited research has been done in this field, and in general, the goal of the research conducted in the field of quantum laser pointer (QLP) is to detect the direction of the beam more accurately than conventional lasers [52, 53]. The research shows that the use of carbon nanotubes can be an accessible source for hand-held lasers and pointers. Carbon nanotubes have quantum behavior due to their geometry and can play a role in the development of pointers in the future [54].
Although less attention has been paid to quantum laser pointers, researchers are suggested to pay more attention to this field.
Light-induced generation of free electrons is important for a wide range of applications, especially electronic devices that work in a vacuum. For this reason, the development of various quantum dots such as graphene, carbon or other quantum dots in different forms and 2D or 3D dimensions can be a way to develop new QLPs.

5. Applications and Perspective

One of the applications of Pulsed laser fragmentation in liquid (PLFL) is in the development and production of high-purity carbon quantum dots (CQDs), which are used to measure glucose. Since CQDs have low toxicity, it is very important to use this method to prepare CQDs with high purity. The results show the good sensitivity of this method for the detection of glucose with a concentration of 0.165 to 8 mM, and its use is of particular importance [55].
Also, Carbon dots (CDs) play an effective role in the development of modern lyres. The results show that these CDs play an effective role in the development of miniaturized lasers due to their special fluorescent properties and also the presence of carbon-hybrid nanostructure [56].
It is worth mentioning that because the CQDs are stable after death in the cell, they are considered a suitable way to store cell information for a long time [57]. Also, the method of assembling QD lasers on silicon photonic circuit with flip chip bonding is of interest to researchers, which should be further investigated in the future [58].

6.Conclusion

Today, quantum science and QDs play a very effective role in the development of modern technologies, and laser manufacturing technologies are no exception. In the current research, an attempt was made to summarize the policy and some of the latest achievements in the field of quantum in the development of laser technologies. What was observed in the present review was more focus on CdSe, Ge and ZnS quantum dots, and less attention was paid to graphene and carbon quantum dots in the field of quantum lasers, considering the positive effects of graphene quantum dots on equipment such as solar cells [59] and sensors [60], Researchers should pay more attention to experiments and research related to quantum lasers, in which quantum dots of graphene or two- and three-dimensional states of Nano-carbons are used. Of course, it should be noted that research in the field of CdSe, ZnS, InP and ZnS/Mn quantum dots still needs further investigation.

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