行政院國家科學委員會專題研究計畫　期中進度報告

子計畫四：高速長波長(1.3,1.55μm)VCSELs 在都會 DWDM 之研究與實現(2/3)

計畫類別： 整合型計畫
計畫編號： NSC94-2215-E-009-020-
執行期間： 94 年 08 月 01 日至 95 年 07 月 31 日
執行單位： 國立交通大學光電工程學系(所)

計畫主持人： 郭浩中
共同主持人： 王興宗

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中　華　民　國 95 年 7 月 5 日

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中文摘要

在今年的計畫中，我們開發1.3 μm長波長量子點面射型雷射，並且研究其動態與高速特性。我們發現量子點面射型雷射在外部光源注入下其眼圖、頻率響應與調變失真都可以得以改善。除此之外，我們也成功製作出1.3 μm長波長量子點光子晶體面射型雷射，輸出的功率可以達到0.2mW，臨界電流為4.75mA，側模壓抑比 (Side-mode suppression ratio) 可以達到40dB。

Abstract

This investigation demonstrates the dynamic characteristics of quantum dot vertical-cavity surface-emitting lasers (QD VCSEL) without and with light injection. The QD VCSEL is fully doped structure on GaAs substrate and operates in the 1.3 μm optical communication wavelength. The eye diagram, frequency response, and intermodulation distortion are presented. We also demonstrate that the frequency response enhancement by light injection technique allows us to improve the performance of subcarrier multiplexed system. Furthermore, an quantum dot photonic crystal vertical-cavity surface-emitting laser (QD PhC-VCSEL) for fiber-optic applications is first demonstrated. Single fundamental mode CW output power of 0.2 mW has been achieved in the 1.3 μm range, with a threshold current of 4.75 mA. Side-mode suppression ratio larger than 40 dB has been observed over the entire thermally limited operation range.

Keywords: quantum dot, vertical-cavity surface-emitting lasers, photonic crystal

Introduction

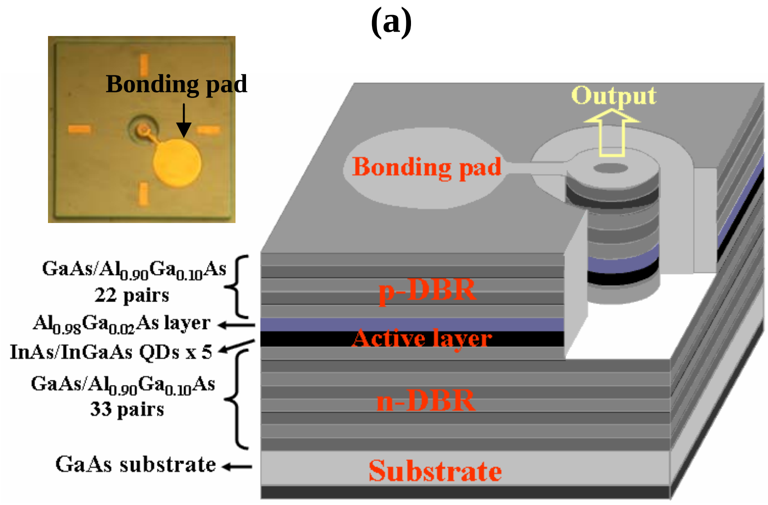
The advantages of vertical-cavity surface-emitting lasers (VCSELs) such as lower manufacturing cost, lower threshold current, and a circular output beam have led to an important application in optical communications. VCSELs fabricated on GaAs substrates have been expected to realize high-performance and cost-effective light sources. Semiconductor lasers containing quantum dots (QDs) in their active region has been proven to exhibit excellent characteristics, including low threshold currents, low chirp, high differential gain, and temperature insensitive.

In this report, we present the dynamic characteristics of 1.3 μm QD VCSEL without and with light injection. The QD VCSEL is grown by molecular beam epitaxy (MBE) with fully doped p- and n-doped AlGaAs distributed Bragg reflectors (DBRs). Significant frequency response enhancement in the QD VCSEL by light injection technique has been observed. Furthermore, we demonstrate that this frequency response enhancement allows us to improve the performance of subcarrier multiplexed (SCM) system. A 33 dB improvement in systems performance is obtained with a SCM system for a 7-GHz 50-Mb/s data signal. We also report the third-order intermodulation distortion (IMD3) of QD VCSEL with and without external light injection. We observed that the dynamic range of the QD VCSEL with light injection can be enhanced 15.1 dB for the IMD3.

Recently, a two-dimensional photonic crystal (2-D PhC) structure formed on the VCSEL surface has been investigated as a control method of lateral mode. Singlemode output was realised from larger aperture photonic crystal VCSELs (PhC-VCSELs). Singlemode operation of the QD VCSEL with PhC is yet to be realised. In this Letter, we report our results on the QD PhC-VCSELs in the 1.3 μm range. Single-lateral-mode operation with very high side-mode suppression ratio (SMSR) is demonstrated for the first time.

Experiments and Discussion

Figure 1(a) shows the schematic diagram of the QD VCSEL. The structure is grown on a GaAs (100) substrate using molecular beam epitaxy by NL Nanosemiconductor GmbH (Germany). The p- and n-doped DBRs is composed of 22 and 33.5 periods, respectively. The graded-index separate confinement heterostructure active region consist mainly of five groups of QDs active region embedded between two linear-graded $Al_xGa_{1-x}As$ (x = 0 to 0.9 and x = 0.9 to 0) confinement layers. Each group of QDs consists of three QDs layers and is situated around the antinode of a standing wave. The wafer is then processed into a VCSEL structure. The top view of the QD VCSEL is shown in the inset of Fig. 1(a). The fabrication method has been described in our previous works [11]. The QD VCSEL is hermetically sealed by a standard TO-Can laser package with a built-in lens. The QD VCSEL TO-Can package and the single-mode fiber are assembled by laser welding technique. Figure 1(b) shows the output spectra of the QD VCSEL. The lasing wavelength of QD VCSEL is around 1278 nm. The small signal response of QD VCSELs as a function of bias current is measured at room temperature using a vector network analyzer (8720ES from Agilent Technologies).



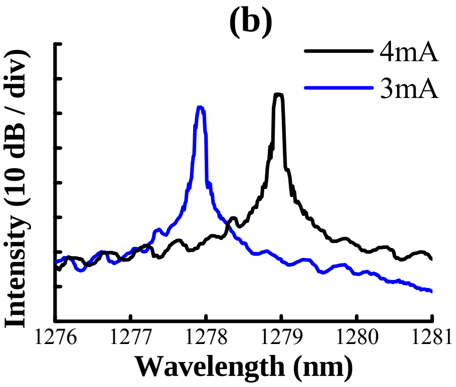


Fig. 1. (a) Schematic diagram of quantum dot VCSEL (b) Output spectra of quantum dot VCSEL.

Figure 2 shows the frequency response of QD VCSEL. The 3 dB frequency response is 1.75 GHz at operating bias of 4 mA. Modulation experiments on our present QD VCSEL are carried out at 625 Mb/s and 1.25 Gb/s with non-return-to-zero pseudo-random binary sequence (pattern length 2^{31}-1). The eye diagrams at room temperature are wide open, as shown in Fig. 2. The extinction ratios are over 6.7 dB.

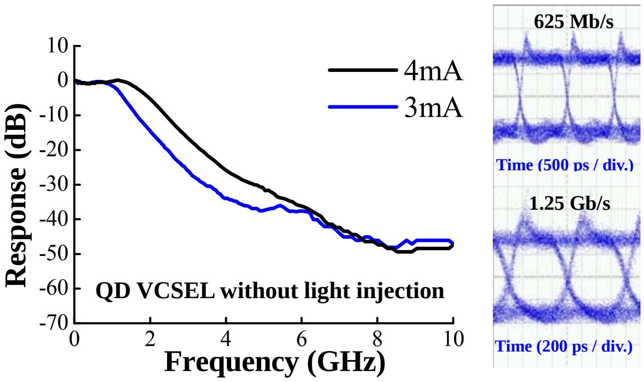


Fig. 2. Frequency response and eye diagram of quantum dot VCSEL.

The inset of Fig. 3 shows the experimental setup for the QD VCSEL with external light injection. A commercial DFB laser is used as the master laser in our experiments. The injection power is controlled by a variable optical attenuator at the output of the DFB laser. The polarization of the DFB laser is adjusted using a polarization controller before injecting into the QD VCSEL.

In the experiment, the polarization and the center wavelength of DFB laser are adjusted that the QD VCSEL has the most significant enhancement in the frequency response. An optical circulator is used to couple the DFB laser light into the QD VCSEL. The QD VCSEL is biased at 4 mA. Figure 3 shows the frequency response of the QD VCSEL with light injection. This figure clearly shows that external light injection can achieve a significant enhancement in frequency response. We also demonstrated that this enhancement of the frequency response can greatly improve the performance of SCM system based on direct modulation of QD VCSELs. Figure 4 shows the experimental setup for the injection locking of QD VCSEL in a SCM system. A 50 Mb/s non-return-to-zero (NRZ) pseudo-random binary sequence (PRBS) data with $2^{31} - 1$ pattern length from a pattern generator is mixed with a 7 GHz RF carrier. The resulting data signal is then used to directly modulate the QD VCSEL. Figure 5 shows the electrical spectra of QD VCSEL with and without light injection at point A. Light injection technique leads to 33 dB improvement in the SCM system. The 7-GHz 50-Mb/s is down converted using a mixer, where it is mixed with the same RF carrier generated by the signal generator. The variable phase shifter is used to adjust the carrier's phase. The corresponding eye diagrams are shown in Fig. 6. The improvement in system performance can be clearly seen when light injection technique is employed. The QD VCSEL without light injection cannot generate 7-GHz 50-Mb/s data due to the limited frequency response.

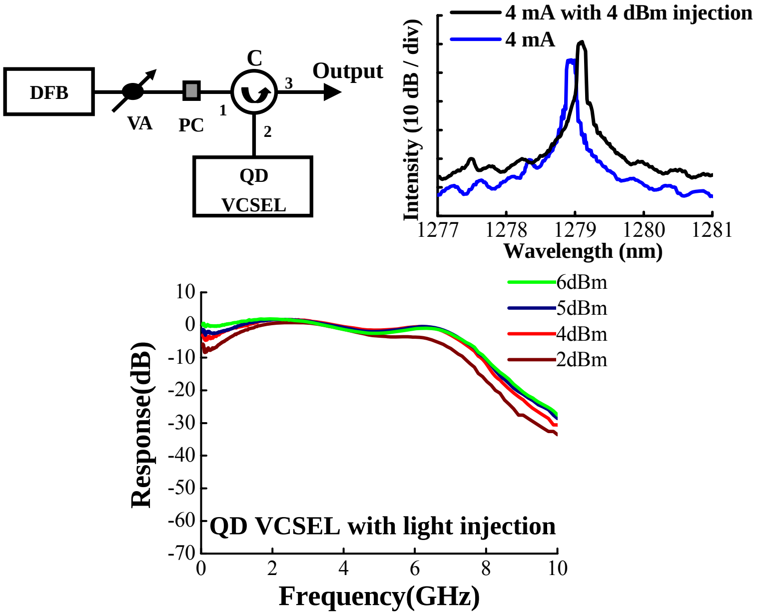


Fig. 3. Frequency response of quantum dot VCSEL with light injection. (DFB: DFB laser, VA: variable optical attenuator, C: optical circulator, PC: polarization controller)

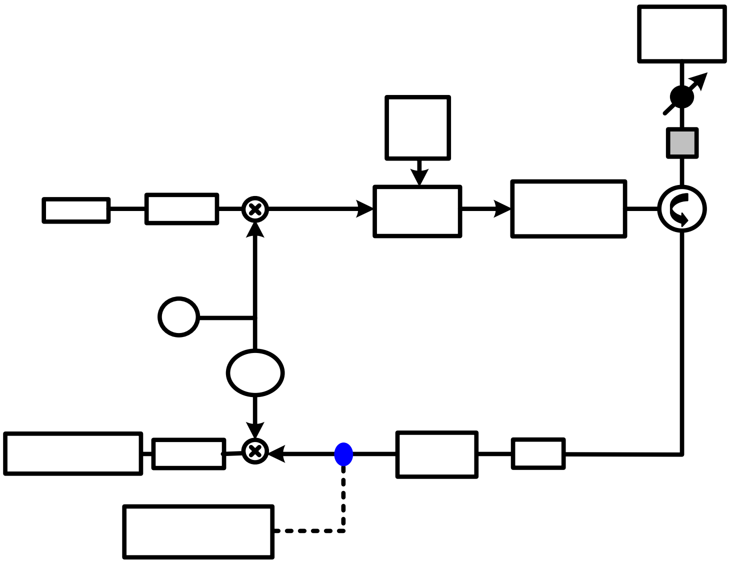


Fig. 4. Experimental setup for the quantum dot VCSEL without and with light injection in a subcarrier multiplexed system. (PG: pattern generator, LPF: low pass filter, RFA: RF amplifier, PD: photodetector)

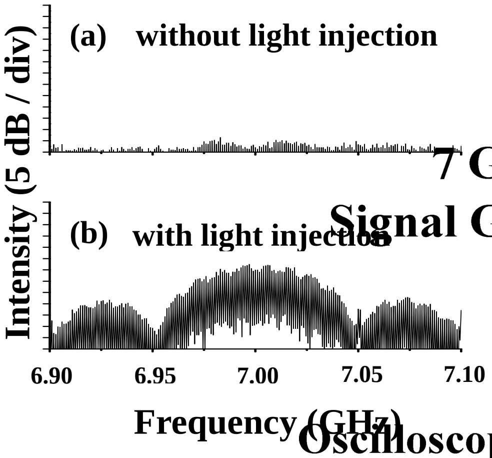


Fig. 5. 7-GHz 50-Mb/s data signal at point A (a) without light injection (b) with light injection.

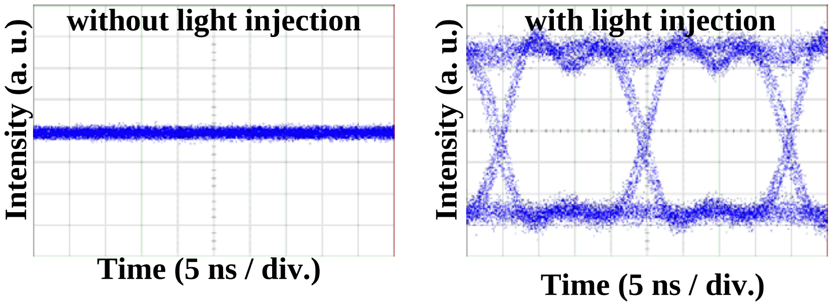


Fig. 6. Received eye diagrams of 50-Mb/s signal.

We also study the reduction of nonlinear distortion in the QD VCSEL by light injection technique. Nonlinear distortion of the laser is important consideration for SCM systems. It can be characterized by measuring third-order intermodulation distortion (IMD3). The IMD3 is caused by two closely subcarrier frequencies. For SCM systems, the IMD3 has the largest impact on performance degradation because of the IMD3 signal close to the original subcarrier frequencies [12]. Figure 7 shows the experimental setup for measuring the IMD3 of QD VCSEL with and without light injection. The two-tone frequencies are 1 and 1.01 GHz. The power of IMD3 of the QD VCSEL without and with light injection varied with the input RF power is shown in Fig. 8. The fundamental tone power increase of 4.5 dB and the distortion suppression of 10.6 dB are observed. As a result, the dynamic range of the QD VCSEL with light injection can be enhanced 15.1 dB for the IMD3.

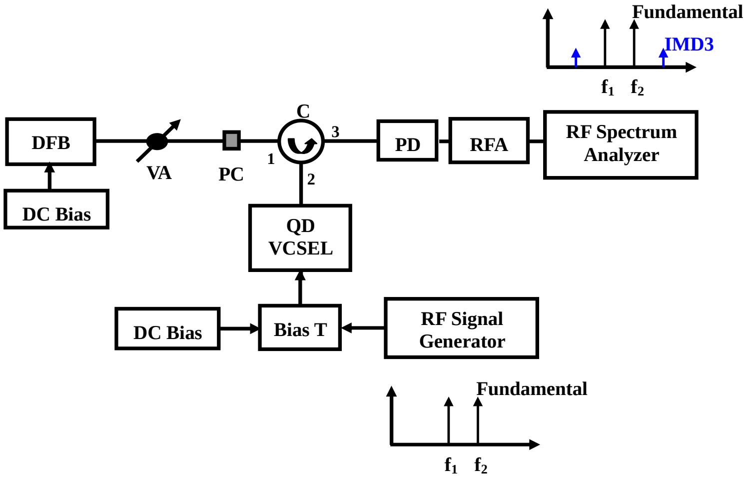


Fig. 7. Experimental setup for measuring the third-order intermodulation distortion (IMD3) of quantum dot VCSEL without and with light injection.

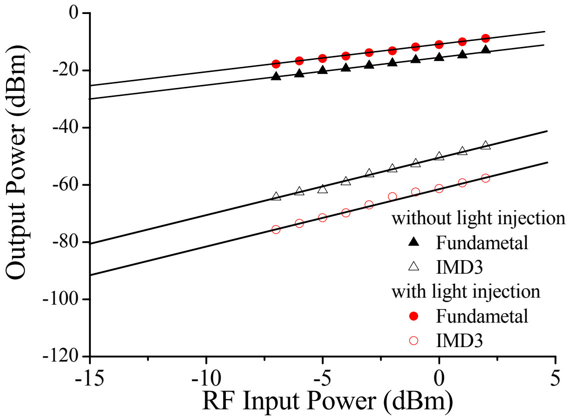


Fig. 8. IMD3 of quantum dot VCSEL without and with light injection.

A two-dimensional photonic crystal (2-D PhC) structure formed on the QD VCSEL surface has been studied. Triangular lattice patterns of photonic crystal with a singlepoint defect in the centre were defined within the p-contact ring using photolithography and etched through the p-type DBR using RIE. The lateral index around a single defect can be controlled by the hole diameter (a)-to-lattice constant (L) ratio and etching depth. This ratio (a=L) is 0.5; the lattice constant L is 5 mm in the PhC-VCSEL and the etching depth of the holes is about 18 pairs thick into the 23-pair top DBR layer. To ensure better current confinement of the device, proton implantation was carried out with a diameter of 12 mm, followed by an annealing at 430_C under N2 ambient. The implantation energy was 240 keV, with a dose of 6_1014 cm_2, to form an insulating region laying 10 DBR pairs above the active region. Higher implantation energy may introduce more defects in the lateral direction. The device structure is shown in Fig. 9. By using two types of apertures in this device, we decouple the effects of the current confinement from the optical confinement. The Ht implant aperture (12 mm) and the AlOx layer are used to confine the current flow, while the single-point defect (12 mm in diameter) photonic crystal is used to confine the optical mode. To clarify the effect of the photoniccrystal index-guiding layer, a VCSEL with Ht implant aperture (12 mm in diameter without PhC) was also fabricated for comparison.

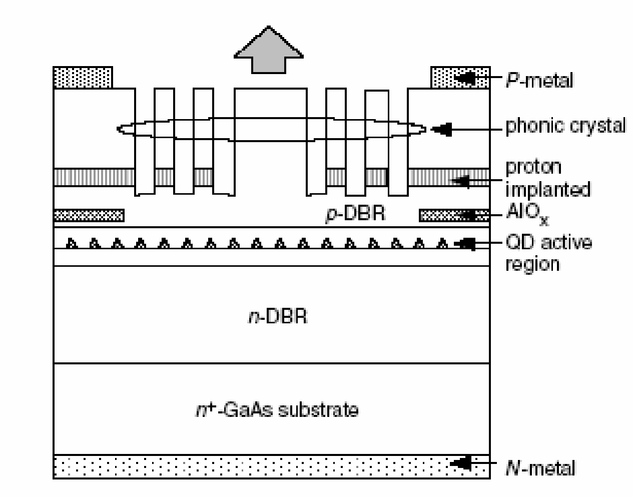


Fig. 9 Schematic of QD PhC-VCSEL Hole etching depth of PhC is 18 pairs out of the 23-pair top DBR having been etched off. The proton implantation position is 10 pairs of DBR layers above active region.

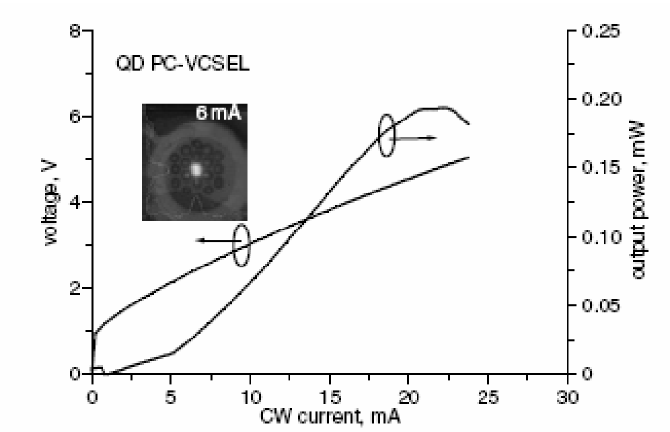


Fig. 10 CW L-I-V characteristics and near-field image (inset) of PhCVCSEL (ratio (a=L) is 0.5 and lattice constant L is 5 mm)

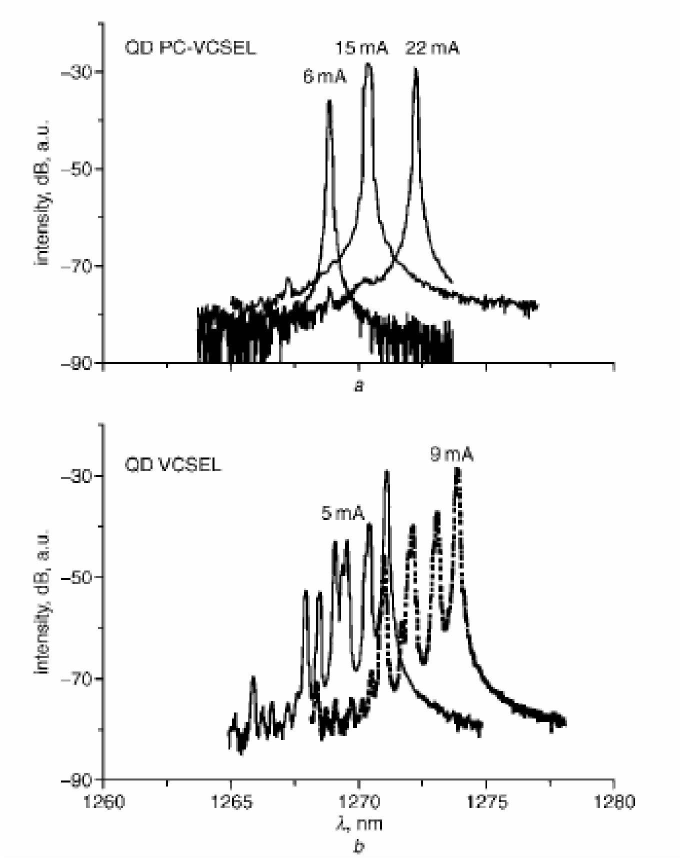


Fig. 11 Spectra of QD a PhC-VCSEL b VCSEL without PhC holes

Fig. 10 shows the CW light-current-voltage (L–I–V) output and near-field image operated at 6 mA (inset) of the PhC-VCSEL. The VCSEL emits 0.2 mW peak power and exhibits single modes throughout the current range of operation. The threshold current (Ith) of the PhC-VCSEL is 4.75mA. The I–V characteristics exhibit higher series resistance for the PhC-VCSEL, which should be mainly due to proton implantation through the p-ohmic contact of the device and blocking of the current flow in the region by photonic crystal holes. The differential series resistance is 170 O at 12 mA. The output power could be improved by reducing the series resistance of the PhC-VCSEL. Lasing spectra of the PhC-VCSEL is shown in Fig. 11a, confirming singlemode operation within the overall operation current. The peak lasing wavelengths are 1268 and 1272 nm at 6 and 22 mA, respectively. The PhC-VCSEL exhibits an SMSR > 40 dB throughout the current range. For comparison, a lasing spectra of a QD VCSEL without photonic crystal holes shows multiple mode operation as the driving current increased above 5 mA (Fig. 11b). The QD VCSEL showed multiple transverse mode characteristics over a broader wavelength span.

Conclusion

We report the dynamic characteristics of QD VCSEL without and with external light injection. The significant enhancement of frequency response by light injection technique has been studied. Moreover, this frequency response enhancement can improve the performance of SCM system. Experimental results show a 33 dB improvement in system performance. Furthermore, reduction of IMD3 in the QD VCSEL also has been observed. These results show that external light injection is a very powerful technique to upgrade QD semiconductor lasers. We also report a singlemode QD PhC-VCSEL with SMSR > 40 dB throughout the operation current range. The present results indicate that a VCSEL using a combined oxide layer with proton implantation for current confinement and photonic crystal for optical confinement is a promising approach to achieve singlemode operation of VCSELs.

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