Dynamic characteristics of long-wavelength quantum dot vertical-cavity surface-emitting lasers with light injection

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Abstract: This investigation experimentally 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.

OCIS codes: (250.7260) vertical-cavity surface-emitting lasers; (140.5960) semiconductor lasers

References and links

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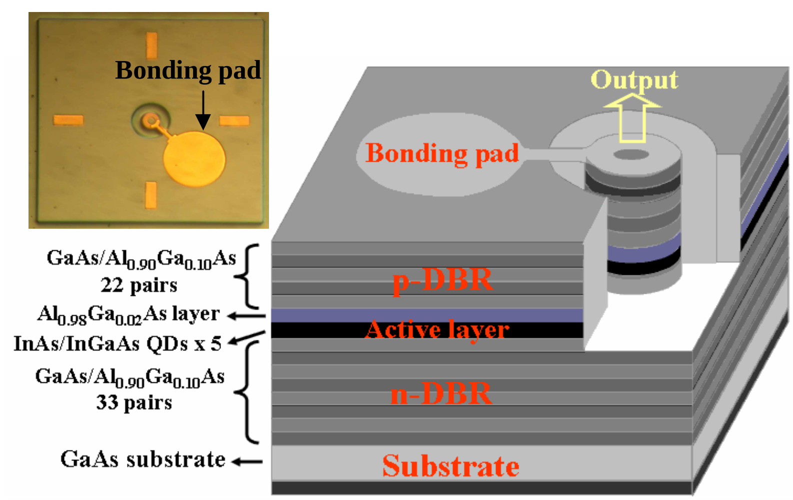
1. Introduction

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 [1-2]. 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. Recent progress revealed the quantum dots (QDs) can be used to fabricate long-wavelength GaAs-based VCSELs [3-6]. However, dynamic characteristics of QD VCSELs without and with light injection have not yet been addressed.

Recently, light injection technique has been reported to be effective for enhancing frequency response of quantum-well VCSELs [7]. In this paper, we report 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.

(a)



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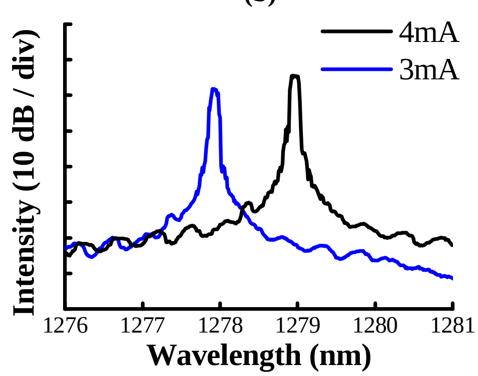

Fig. 1. (a) Schematic diagram of quantum dot VCSEL (b) Output spectra of quantum dot VCSEL.

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2. Experiment and results

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 [8]. 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). 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.

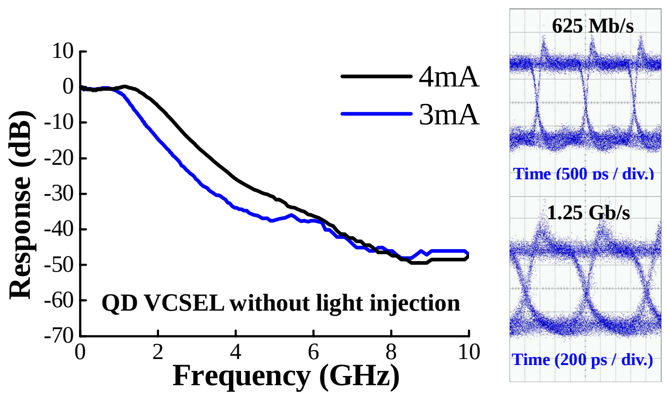

Fig. 2. Frequency response and eye diagram of quantum dot VCSEL.

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-

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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.

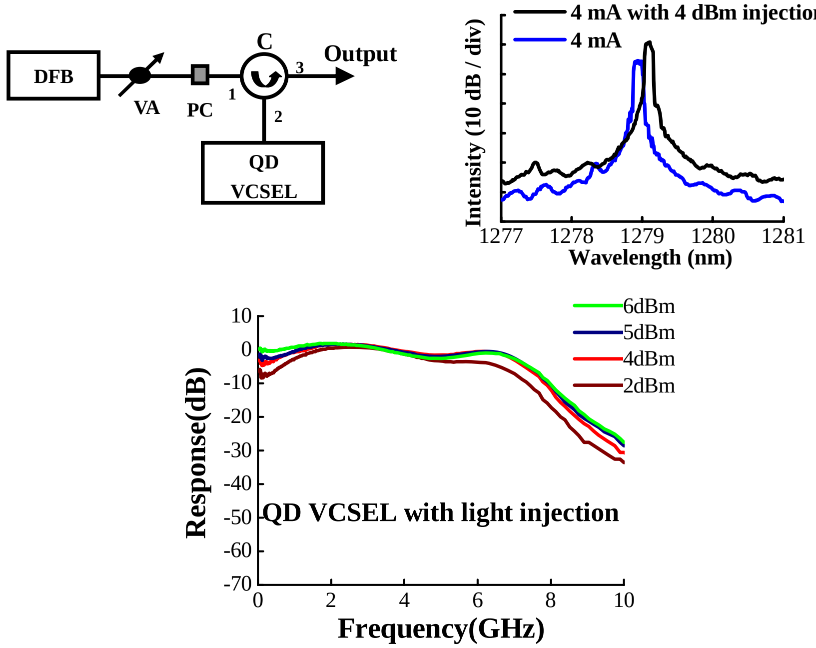

Fig. 3. Frequency response of quantum dot VCSEL with light injection. (DFB: DFB laser, VA: variable optical attenuator, C: optical circulator, PC: polarization controller)

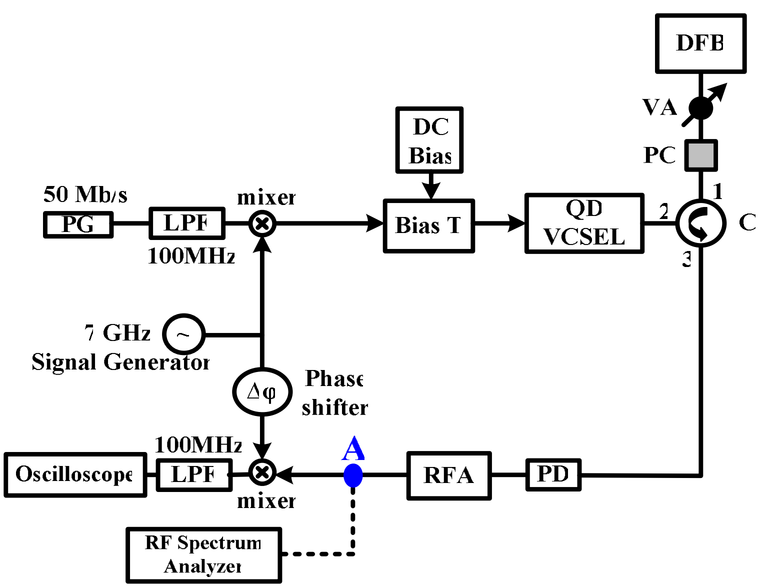

Fig. 4. Experimental setup for the quantum dot VCSEL without and with light injection in a subcarrier multiplexed system. (PG: pattern generator, LPF: low pass filter, RFA: RF amplifier, PD: photodetector)

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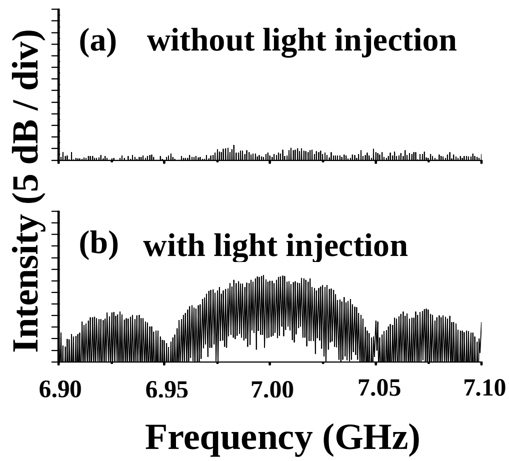

Fig. 5. 7-GHz 50-Mb/s data signal at point A (a) without light injection (b) with light injection.

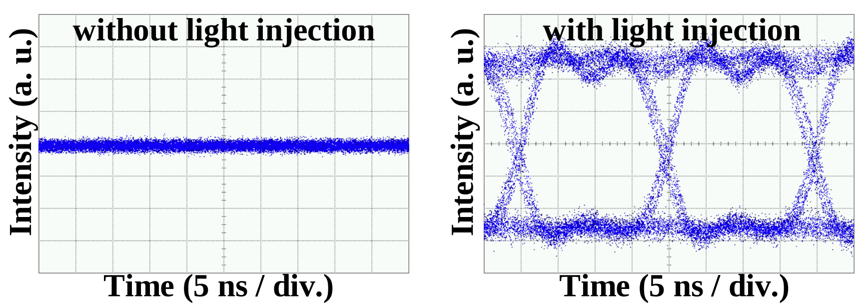

Fig. 6. Received eye diagrams of 50-Mb/s signal.

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 [9]. 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.

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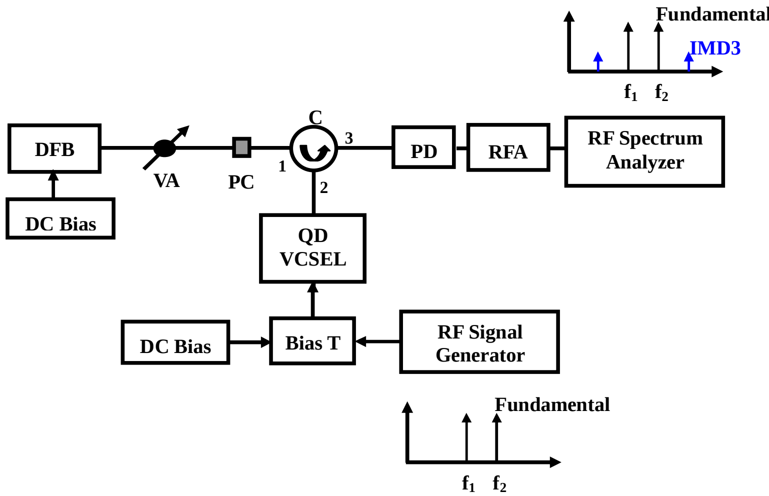

Fig. 7. Experimental setup for measuring the third-order intermodulation distortion (IMD3) of quantum dot VCSEL without and with light injection.

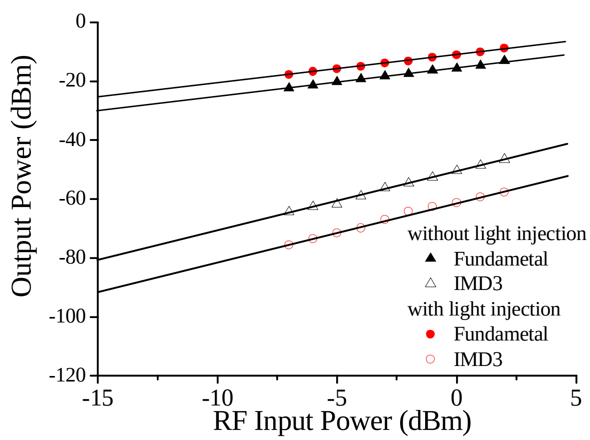

Fig. 8. IMD3 of quantum dot VCSEL without and with light injection.

3. 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.

Acknowledgments

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