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Wavelength Switching Based on Quantum-Dot Vertical-Cavity Surface-Emitting Laser[1]

P. C. Peng[a, *], H. Y. Wang[a], R. L. Lan[a], H. H. Lu[a, b], G. R. Lin[c], G. Lin[d], and J. Y. Chi[e]

[a] Department of Electro-Optical Engineering, National Taipei University of Technology, Taipei, Taiwan, R.O.C.
[b] Department of Information Technology and Communication, Tungnan University, New Taipei City, Taiwan, R.O.C.
[c] Graduate Institute of Photonics and Optoelectronics and Department of Electrical Engineering, National Taiwan University, Taipei, Taiwan, R.O.C.
[d] Department of Electronics Engineering, National Chiao Tung University, Hsinchu, Taiwan, R.O.C.
[e] Department of Electrical Engineering, National Chung Hsing University, Taichung, Taiwan, R.O.C.
*e-mail: pcpeng@ntut.edu.tw

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Abstract—This study investigates, for the first time, static and dynamic wavelength switching characteristics of the 1.3 μm quantum-dot vertical-cavity surface-emitting laser (QD VCSEL). The free-running QD VCSEL with λ1 and λ2 state innately is injected by a laser source with λ1 state. When the injection power exceeds the threshold power, the dominant state of the QD VCSEL changes from λ2 to λ1 state. Results of this study demonstrate that the wavelength switching based on a 1.3 μm QD VCSEL has a simpler and more cost-effective configuration than those of previous systems.

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1. INTRODUCTION

Wavelength switching and tuning schemes are necessary optical devices for optical communication systems and optical switching applications [1–18]. Wavelength switching schemes using quantum well semiconductor lasers have received considerable attention, owing to their compactness, simple of operation, low cost, and low power consumption [14–18]. However, increasing the wavelength selectivity requires use of tunable bandpass filters or the bandpass filters, possibly increasing system costs.

Recent studies have demonstrated that semiconductor lasers containing quantum dots (QDs) structure in their active region exhibit excellent technological characteristics, including a low chirp, high differential gain, high quantum efficiency and high temperature stability [19–22]. Besides, vertical-cavity surface-emitting lasers (VCSELs) have attracted substantial attention in recent years because they provide various advantages in optical communication systems, such as low power consumption, high-speed modulation, high beam quality, low manufacturing cost, and low threshold current [23–29]. Recently, substantial progress by our group has been made in the development of 1.3 μm QD VCSEL [30–34]. The frequency response, linewidth enhancement factor, and intermodulation distortion have been described. However, the wavelength switching of 1.3 μm QD VCSELs has not yet been studied.

This study describes wavelength switching based on a 1.3 μm QD VCSEL with external light injection. The

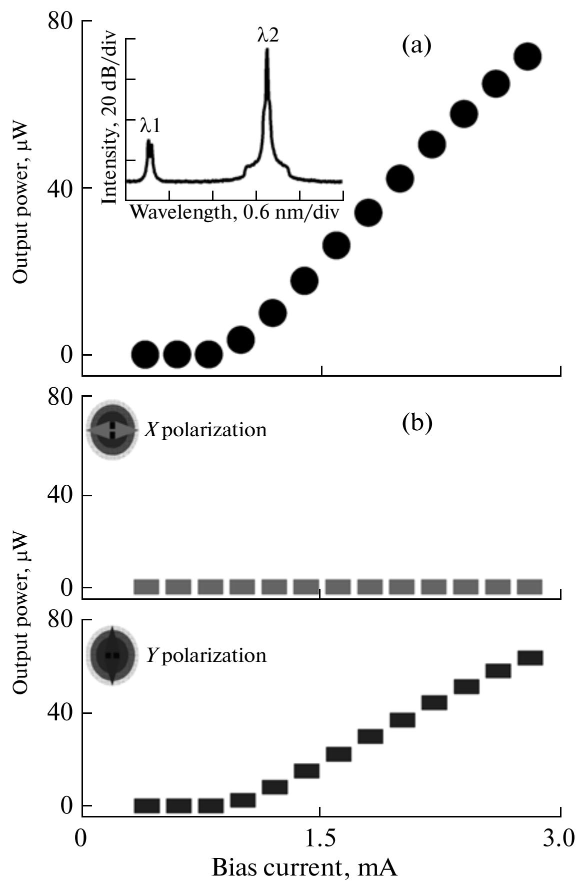

Fig. 1. (a) Light–current characteristics and (b) optical polarization characteristics of QD VCSEL.

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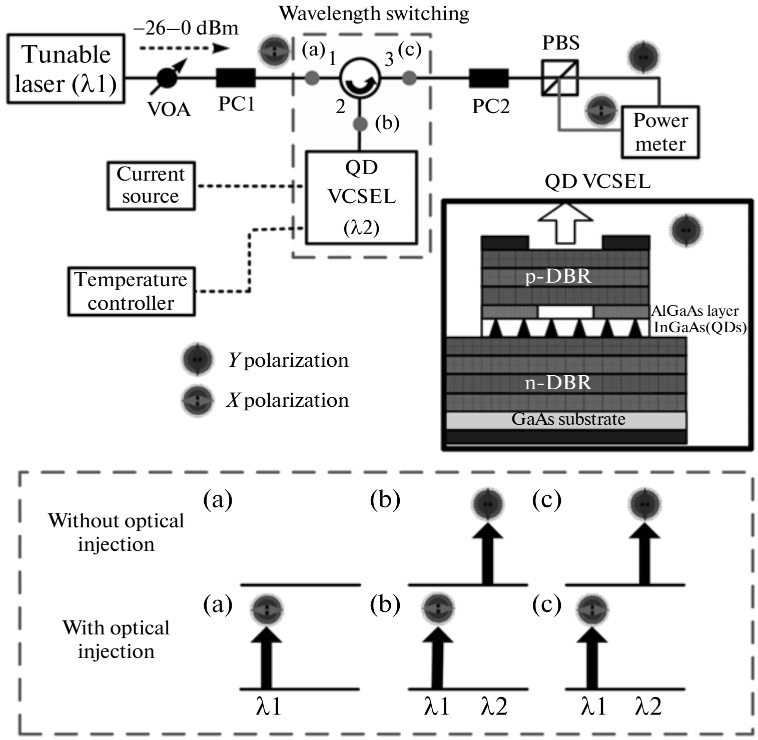

Fig. 2. Experimental setup for evaluating the optical wavelength characteristics of QD VCSEL with external light injection (VOA: variable optical attenuator; C: optical circulator; PBS: polarization beam splitter; PC: polarization controller).

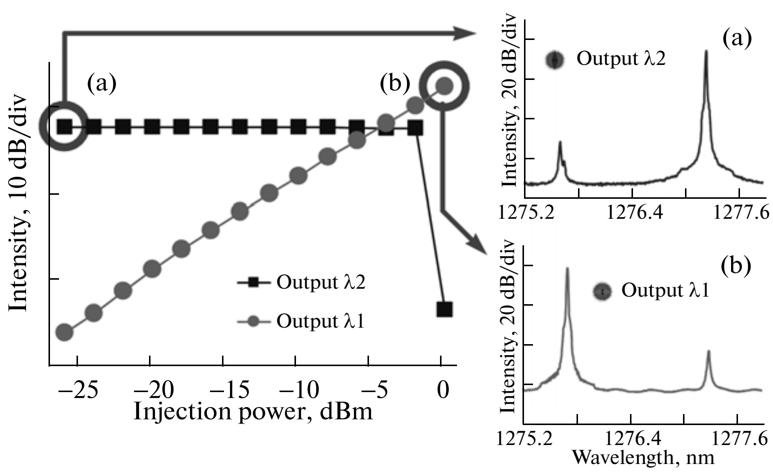

Fig. 3. Measuring the power of QD VCSEL for output λ1 and λ2. Figures 3a–3b depict the optical spectrum of output λ2 and λ1 when the power of optical injection is –26 and 0 dBm, respectively.

QD VCSEL has two wavelength states λ1 and λ2 innately. Injection of the external light source λ1 to that of the free-running VCSEL allows us to observe wavelength switching. When surpassing the threshold value, injection power λ1 possesses the dominant λ1 state. Also, side-mode suppression ratio (SMSR) surpasses 42 dB when the injection power is 0 dBm. This study also investigates the waveforms and the eye diagrams with 2.5 Gb/s signals. Furthermore, the wavelength switching system based on a 1.3 μm QD VCSEL without tunable bandpass filters or the bandpass filters is simpler and more economic than previous systems.

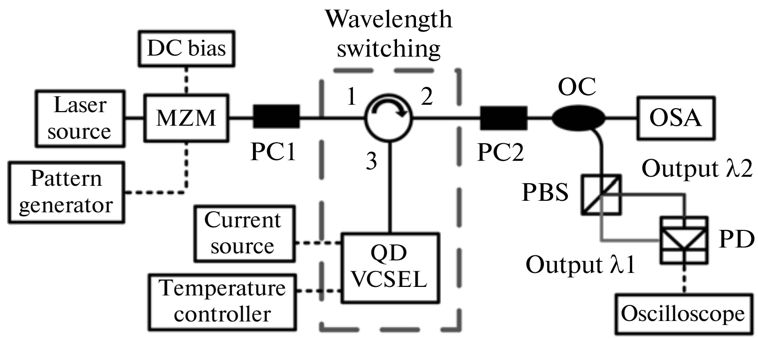

Fig. 4. Experimental architecture for wavelength switching based on the QD VCSEL (OC: optical coupler; OSA: optical spectrum analyzer).

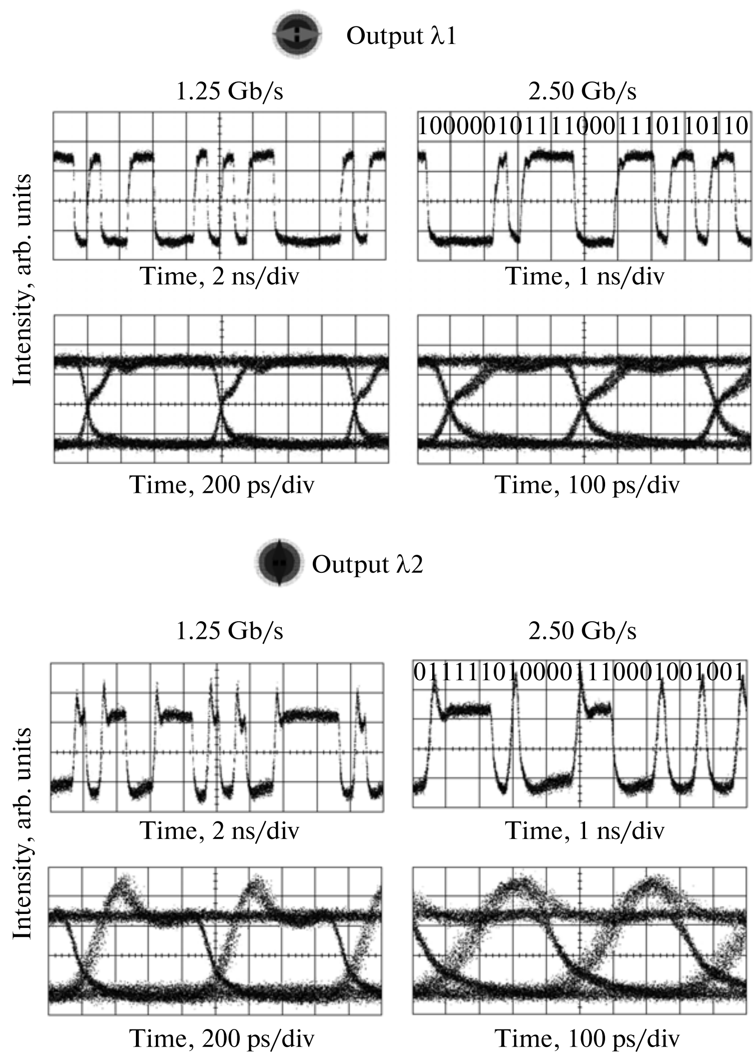

Fig. 5. 1.25 and 2.50 Gb/s data waveforms and eye diagrams.

2. EXPERIMENTAL SETUP AND RESULTS

The 1.3 μm InAs–InGaAs QD VCSEL is grown on a GaAs substrate using molecular beam epitaxy. Our earlier studies have described the fabrication method of fabrication has been described in our earlier works [31, 32]. The InAs QD VCSEL is hermetically sealed using a TO-Can laser package. The InAs QD VCSEL TO-Can package and the single-mode fiber are assembled by laser welding. Figure 1a displays the Light–current characteristics at room temperature. The threshold current of the laser is approximately 0.9 mA and the slope of the output power over the bias current is around 0.038 mW/mA. The inset in Fig. 1a shows the optical spectrum of free-running QD VCSEL. Moreover, the side mode λ1 and the main mode λ2 are 1277.25 nm and 1275.62 nm, respectively. Additionally, the polarization of the QD VCSEL output is linear and is *Y* polarization while *X* Polarization is orthogonal to the *Y* polarization, as shown in Fig. 1b. Notably, the QD VCSEL without external light injection exhibits no polarization switching.

Figure 2 displays the setup for evaluating the wavelength switching by using the QD VCSEL with external light injection. Injection power ranging from –26 to 0 dBm is controlled by a variable optical attenuator (VOA) at the output of the tunable laser, which causes wavelength switching. Polarization of the tunable laser is then adjusted by using a polarization controller (PC1). The laser light in the QD VCSEL is coupled using an optical circulator (C). The output light from the QD VCSEL is guided through the same optical circulator, which is attached to the polarization controller (PC2). Next, the static wavelength switching behavior of QD VCSEL is examined by using a polarization beam splitter (PBS), an optical power meter and an optical spectrum analyzer (OSA).

The inset in Fig. 2 presents the operation of wavelength switching in the QD VCSEL. The wavelength switching is achieved by optical injection. The main mode λ2 in the free-running QD VCSEL is at a higher output power then λ1, while the side mode λ1 is relatively at a low output power. When side mode λ1 of the QD VCSEL is injected by external light λ1, the power of side mode λ1 is gradually increased linearly while the power of main mode λ2 is reduced. The process can be reversed by reducing the injection light power.

Figure 3 displays the optical spectra of the QD VCSEL biased at 2.8 mA with various injection powers. When the injection power exceeds –4 dBm, the λ2 state transforms into the λ1 state. Figures 3a–3b show the optical spectrum of output λ2 and λ1 at the injection power of –26 and 0 dBm, the SMSR is 45.24 and 42.17 dB, respectively. Based on the above results, the QD VCSEL with external light injection is verified to demonstrate the feasibility of wavelength switching.

The dynamic wavelength switching behavior of the QD VCSEL is investigated as shown in Fig. 4. The probe light is externally modulated with NRZ PRBS signals by Mach–Zehnder modulator (MZM) and injected through an optical circulator into the QD VCSEL. Additionally, the output light from the VCSEL is guided through the same optical circulator and is coupled to the PBS. Moreover, output signals λ1 and λ2 are examined using an oscilloscope.

Figure 5 illustrates the evaluated 1.25 and 2.50 Gb/s data waveforms and eye diagrams. Dynamic wavelength switching was successfully performed based on the QD VCSEL with modulated NRZ PRBS signals. However, the relaxation oscillation of the VCSEL appears apparently degrades the eye diagram of the Y polarization λ2 signal. The modulation bandwidth of the VCSEL limits the switching speed.

3. CONCLUSIONS

This study elucidates the first static and dynamic wavelength switching of the 1.3 μm QD VCSEL with external light injection. The QD VCSEL is biased above the threshold current, and the wavelength bistability can be observed by external light injection. Wavelength switching between two wavelength states λ1 and λ2 in the 1.3 μm QD VCSEL is achieved by adjusting the injection power. The SMSR exceeds 42 dB at an injection power of 0 dBm. This study also examines the waveforms and eye diagrams for a 2.5 Gb/s signal. Therefore, wavelength switching based on a 1.3 μm QD VCSEL without tunable bandpass filters or the bandpass filters has a simpler and more cost-effective configuration than those in previous systems, and can be applied to dynamically route signals, regenerate data, avoid wavelength blocking, and ease wavelength management.

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