Polarization Characteristics of Quantum-Dot Vertical-Cavity Surface-Emitting Laser With Light Injection

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***Abstract*—This investigation explores experimentally the optical characteristics of long-wavelength quantum-dot vertical-cavity surface-emitting lasers (QD VCSELs). The InAs QD VCSEL, fabricated on a GaAs substrate, is grown by molecular beam epitaxy with fully doped distributed Bragg reflectors. The optical characteristics of QD VCSEL without and with light injection are studied in detail. The QD VCSEL has the potential to be used in all-optical signal processing systems.**

***Index Terms*—Quantum dots (QDs), vertical-cavity surface-emitting lasers (VCSELs).**

I. Introduction

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 [1]–[4]. The particular advantages of quantum-dot (QD) structures include high thermal stability, low threshold current, low chirp, high material gain, and high differential gain, making QD VCSELs potentially favored for use in optical communication systems [5]–[9]. Recently, substantial progress has been made in the development of 1.3-μm monolithic QD VCSELs [10], [11]. The eye diagram, frequency response, and intermodulation distortion of 1.3-μm monolithic QD VCSEL without and with external light injection have been described [11]. However, the optical polarization characteristics of 1.3-μm QD VCSELs with and without light injection have not yet been elucidated. Moreover, optical signal processing based on a QD VCSEL also has not been addressed.

This investigation experimentally explores the optical polarization characteristics of QD VCSEL with and without external light injection. The 1.3-μm InAs–InGaAs QD VCSELs are grown by molecular beam epitaxy (MBE) with fully doped p- and n-doped AlGaAs distributed Bragg reflectors and an AlAs layer to form a current and waveguide aperture. The optical injection power is adjusted to control the polarization of QD VCSEL. The polarization-mode suppression ratio is 29.6 dB at an injection power of -4 dBm.

II. Experimental Setup and Results

Fig. 1 depicts the structure of InAs QD VCSEL. The 1.3-μm InAs–InGaAs QD VCSEL is grown on an (100) n^+-GaAs substrate using MBE. The circular mesa with a diameter of 26 μm was defined by dry-etched circular trench for subsequent water vapor oxidation. The diameter of the oxide aperture was about $5 \sim 6$ μm. No intentional asymmetry was imposed during fabrication. The method of fabrication has been described in our earlier works [11]. 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. The inset in Fig. 1 displays the light–current characteristics of QD VCSEL at room temperature. The QD VCSEL has a threshold current of approximately 1 mA. The lasing wavelength of the QD VCSEL is around 1277.2 nm. Fig. 2 presents the experimental setup for measuring the polarization characteristics of QD VCSEL. The polarization of the QD VCSEL output is linear and is Y polarization. X polarization is orthogonal to the Y polarization. The QD VCSEL without external light injection exhibits no polarization switching. It is believed that stable linear polarization is attributed to the optical gain anisotropy of self-assembled QDs [12].

Fig. 3 displays the experimental setup for measuring the QD VCSEL with external light injection. The injection power is controlled by a variable optical attenuator (VA) at the output of the tunable laser. The polarization of the tunable laser is adjusted using a polarization controller (PC). An optical circulator (C) is adopted to couple the laser light in the QD

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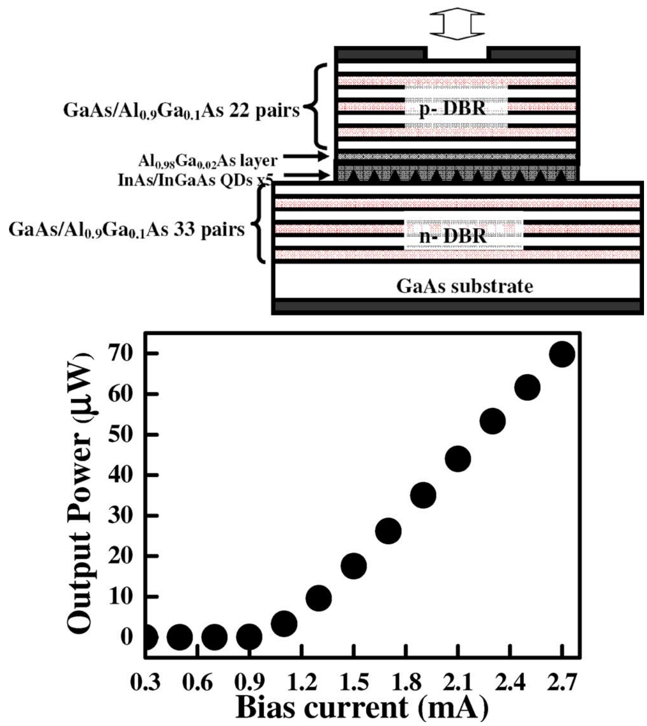

Fig. 1. Schematic diagram and light–current characteristics of InAs QD VCSEL.

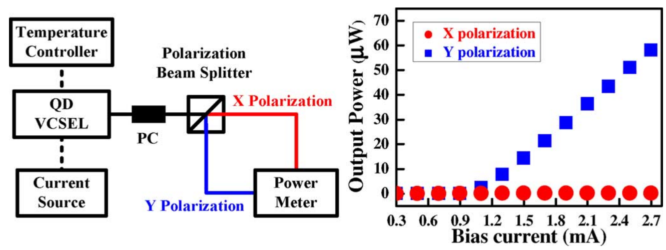

Fig. 2. Experimental setup for measuring the optical polarization characteristics of InAs QD VCSEL. (PC: polarization controller.)

VCSEL. The output light from the QD VCSEL is guided through the same optical circulator, which is attached to the PC. Polarization switching in the QD VCSEL is examined using a polarization beam splitter (PBS), an optical power meter, and an optical spectrum analyzer (OSA). The inset in Fig. 3 presents the operation of polarization switching in the QD VCSEL. The polarization switching is achieved by injection locking [13]. When external light (X polarization) is injected into the QD VCSEL, the X polarization power will increase while the Y polarization power will decline. If the injection light power is reduced, the process is reversed.

Fig. 4 displays the optical spectra of the InAs QD VCSEL biased at 2.7 mA and the measured X and Y polarization powers at various injection powers. The QD VCSEL exhibits single-mode lasing at 1277.2 nm. The sidemode suppression ratio is over 40 dB. The wavelength of the injected light is the same as the lasing wavelength of the QD VCSEL. Varying the injection power from -40 to -4 dBm causes polarization switching. When the injection power is -4 dBm, the polarization-mode suppression ratio exceeds 29.6 dB. Therefore, the InAs QD VCSELs can be used for an all optical inverter, as presented in Fig. 5. A probe signal is externally modulated by a 625-Mb/s

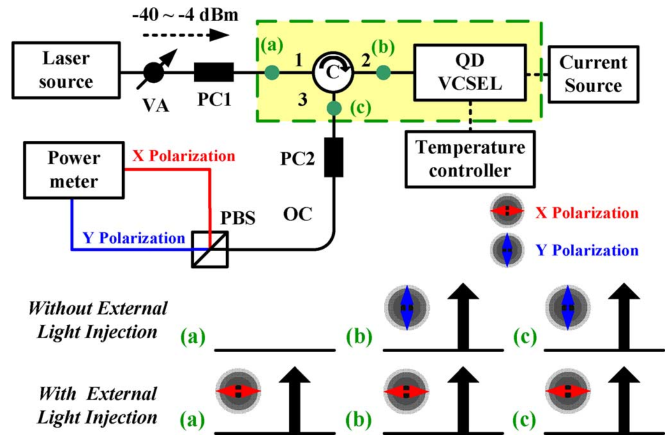

Fig. 3. Experimental setup for measuring the optical polarization characteristics of QD VCSEL with external light injection. (VA: variable optical attenuator; C: optical circulator; OC: optical coupler; PBS: polarization beam splitter; OSA: optical spectrum analyzer.)

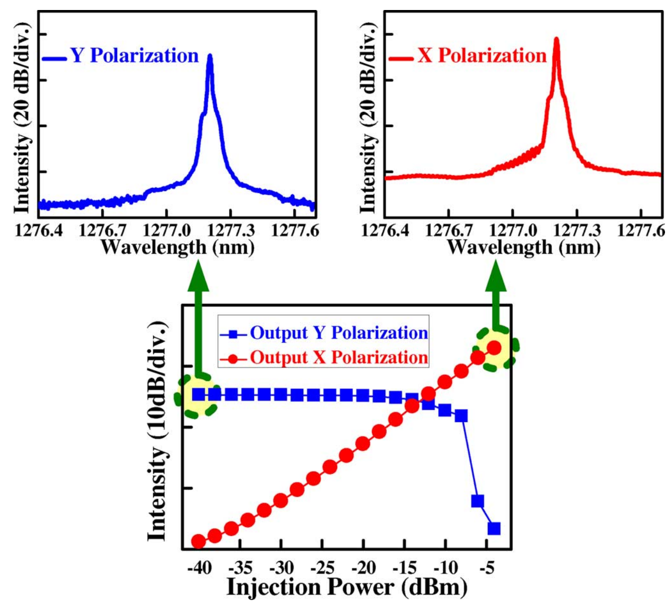

Fig. 4. Measuring the power of InAs QD VCSEL for X and Y polarization.

nonreturn-to-zero pseudorandom binary sequence. The polarization of the probe signal is X polarization. The QD VCSEL with external light injection has a threshold power between the X and Y polarization. When the injection light power exceeds the threshold power, the QD VCSEL begins to operate at X polarization. The X and Y polarization signal can be obtained using a PBS.

Fig. 6 shows the 625-Mb/s data waveforms ("0111001011010") and eye diagrams. An all-optical inverter using the InAs QD VCSEL was successfully obtained experimentally. Nevertheless, the relaxation oscillation of the VCSEL seems to degrade the eye diagram of the Y polarization signal. The modulation bandwidth of the VCSEL limits the inverter speed.

III. Conclusion

This work experimentally explores the optical characteristics of 1.3-μm InAs–InGaAs QD VCSEL without and with light in-

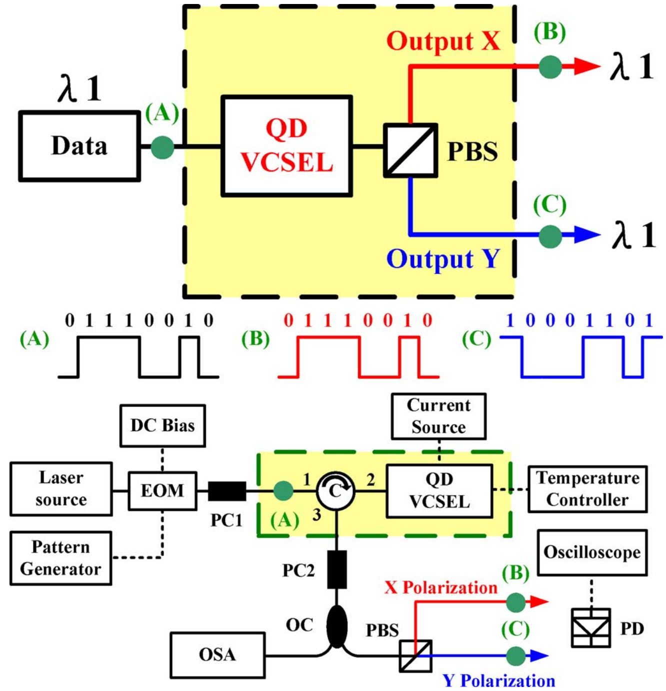

Fig. 5. Proposed architecture for optical signal processing system using InAs QD VCSEL. (PBS: polarization beam splitter.)

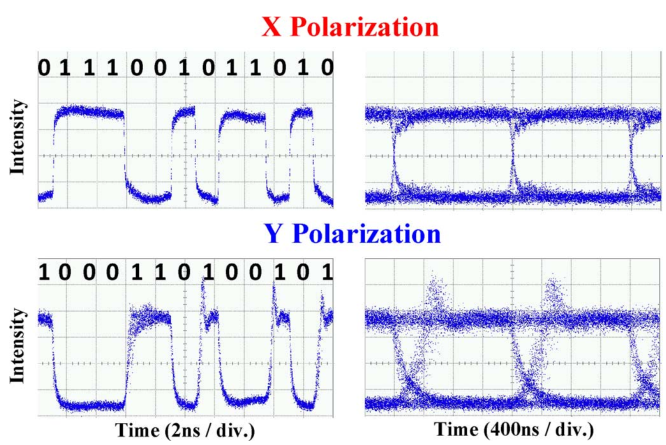

Fig. 6. 625-Mb/s data waveforms ("0111001011010") and eye diagrams.

jection. The 1.3-μm QD VCSEL is biased above the threshold current, and the polarization bistability is observed by external light injection. Polarization switching between two orthogonal polarizations in the QD VCSEL is achieved by adjusting the injection power. The suppression ratio between the two switched polarization modes exceeds 29.6 dB at an injection power of -4 dBm. The results of polarization switching in QD VCSEL demonstrate its applications in all-optical inverters and polarization modulators. Furthermore, the all-optical inverter can generate optical inverted and noninverted data signals at the same wavelength.

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