Dynamic Characteristics and Linewidth Enhancement Factor of Quantum-Dot Vertical-Cavity Surface-Emitting Lasers

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***Abstract*—This study explores the relative intensity noise characteristics of quantum-dot vertical-cavity surface-emitting lasers (QD VCSELs). The resonance frequency and eye diagram are presented. The linewidth enhancement factor (α factor) of QD VCSEL is also investigated experimentally. The values of α factor were measured to be between 0.48 and 0.60. Moreover, a photonic RF phase shifter is examined using the QD VCSEL. A phase shifter with a total phase shift of 2π was demonstrated. These investigations and demonstrations will be useful in the field of QD VCSEL.**

***Index Terms*—Linewidth enhancement factor, quantum dot (QD), relative intensity noise (RIN), vertical-cavity surface-emitting laser (VCSEL).**

I. Introduction

VERTICAL-CAVITY surface-emitting lasers (VCSELs) are highly promising for optical communication applications. Among the merits of VCSELs include their circular output beam, low power consumption, and low manufacturing cost. VCSELs fabricated on GaAs substrates have been expected to be high-performance and cost-effective light sources [1], [2]. Semiconductor lasers whose active regions contain quantum dots (QDs) have been demonstrated to have excellent characteristics, such as low threshold currents, low chirp, high differential gain, and insensitivity to temperature [3], [4]. QDs can be used to fabricate 0.98-μm GaAs-based VCSELs [5], [6]. However, the relative intensity noise (RIN) characteristics of QD VCSELs have not been reported upon. The RIN peaks of a semiconductor laser are at the resonance frequencies of the small-signal modulation response of the laser [7]. The resonance frequency determines the modulation bandwidth of the semiconductor laser.

The linewidth enhancement factor, also known as the α factor, is an important parameter of semiconductor lasers. The α factor characterizes the chirp and linewidth broadening, which are detrimental to high-speed performance. The analysis of different material demonstrates that the α factor is generally smaller in quantum wells than in bulk, and it is even further reduced in strained materials, quantum wires, and QDs. Recently, the linewidth enhancement factor of quantum-well VCSEL with buried tunnel junction has been proposed [8]. The minimum value of linewidth enhancement factor is about 3.8 at low output power. Moreover, the linewidth enhancement factor of QD Fabry–Perot laser has also been reported. The linewidth enhancement factor of about 0.1 has been demonstrated [9]. Recently, significant progress has been made in the development of 1.3-μm QD VCSELs [10]. However, the linewidth enhancement factor of QD VCSEL has not yet been studied. In this paper, instead of measuring the below-threshold-amplified spontaneous emission spectra to determine the material differential refractive index versus differential gain as in conventional Hakki–Paoli method, the linewidth enhancement factor of 1.3-μm QD VCSEL was determined by the injection locking method [11].

Interest in the application of photonic technology to RF phase shifters for phased array antennas has been increasing recently. The advantage of the photonic RF phase shifter is its immunity to electromagnetic interference, excellent isolation, and its potential lightweight and small size [12]. Phase shifters and optical delay devices based on semiconductor lasers have become very attractive because of their inherent compactness, direct electrical controllability, and low power consumption [13], [14]. This paper presents a photonic RF phase shifter using the 1.3-μm QD VCSEL. A full 2π phase shift is achieved. The phase change is adjusted by controlling wavelength detuning ($\Delta\lambda = \lambda_{\rm probe} - \lambda_{\rm VCSEL}$), the difference between the wavelength of the probe signal and the lasing wavelength of QD VCSEL. The QD VCSEL can reduce the size and cost of an RF phase shifter used in microwave photonic systems.

The rest of this paper is organized as follows. Section II investigates the 0.98-μm QD VCSEL. Section III explores the linewidth enhancement factor of 1.3-μm QD VCSEL. Section IV examines the photonic RF phase shifter that is

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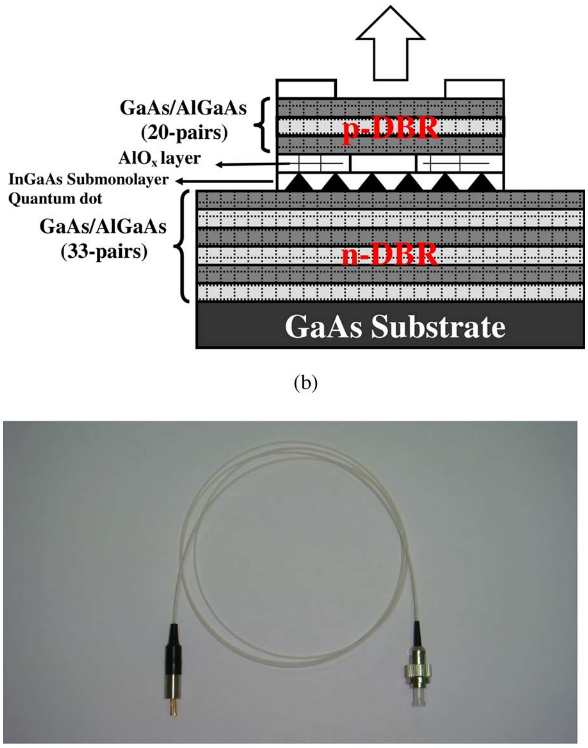

Fig. 1. (a) Schematic diagram of InGaAs submonolayer QD VCSEL. (b) TO-Can packaged QD VCSEL.

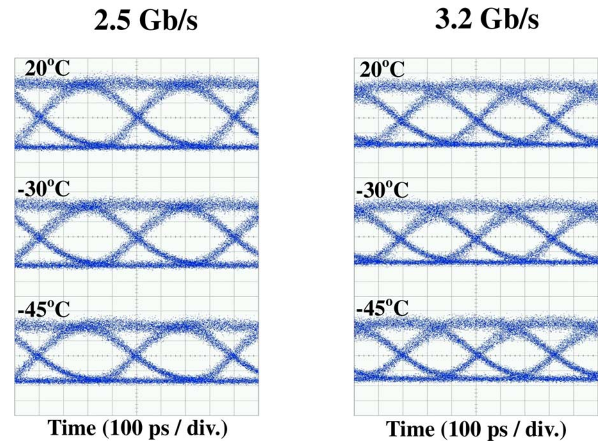

Fig. 2. Eye diagrams under 2.5- and 3.2-Gb/s modulation (20 °C, −30 °C, and −45 °C).

based on 1.3-μm QD VCSEL. Finally, Section V summarizes the research results.

II. 0.98-μm QD VCSEL

Fig. 1(a) schematically depicts the 0.98-μm QD VCSEL. The structure is grown on an n^+-GaAs (1 0 0) substrate by molecular beam epitaxy (MBE). The bottom distributed Bragg reflector (DBR) comprises a 33-pair n-doped GaAs–$Al_{0.9}Ga_{0.1}As$. The undoped 1λ cavity contains three InGaAs submonolayer QD layers, separated by GaAs barrier layers. Each of the InGaAs QD layers is formed by the alternate deposition of InAs and GaAs. The top DBR has a 20-pair p-doped GaAs–$Al_{0.9}Ga_{0.1}As$. The structure of the device, including the thicknesses and compositions of the layers, are designed for a resonance wavelength of 0.98 μm. The wafer is processed to form a VCSEL structure. The fabrication method has been described elsewhere [5]. The submonolayer QD VCSEL is hermetically sealed using a standard transistor outline (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, as displayed in Fig. 1(b). Modulation experiments on our present QD VCSEL are performed at 2.5 and 3.2 Gb/s with a nonreturn-to-zero pseudorandom binary sequence (pattern length $2^{31}-1$). The eye diagrams are wide open over a wide range of temperatures (−45 °C–20 °C), as displayed in Fig. 2. The extinction ratios are over 11 dB. Fig. 3 presents the RIN spectra. The RIN spectra are measured at various bias currents using an electrical spectrum analyzer. The inset in Fig. 3 plots the relationship between resonance frequency and driving current of the QD VCSEL. The maximum resonance frequency of the QD VCSEL is 5.85 GHz.

In this paper, we study the RIN peaks and eye diagram of 0.98-μm QD VCSEL at a wide range of temperatures (−45 °C–20 °C). The RIN peaks are the resonance frequencies of 0.98-μm QD VCSEL. The resonance frequency is approximated proportional to the square root of the injected current relative to threshold before saturation takes place. The previous investigation [15] revealed the lasing emissions of QD VCSELs via the ground-state transition at low temperature, while via the excited state transition at room temperature. At the lowest ambient temperature of −45 °C, the resonance frequency was observed to increase without saturation. The ground state lasing emission may contribute to the reduced damping in relaxation at low temperature under high current injection and is more resistant to the thermal effect as compared to that from excited state transition.

The frequency response of 1.3-μm QD VCSEL has been reported [10]. The RIN peaks of 1.3-μm QD VCSEL are around 1–2 GHz. The resonance frequency determines the intrinsic modulation bandwidth of QD VCSEL. The maximum modulation bandwidth for communication systems depends on the total frequency response of 0.98-μm TO-Can packaged QD VCSEL, including the intrinsic response of QD VCSEL (determined by the resonance frequency) and the response of laser package (determined by the TO-Can package). The maximum resonance frequency of the 0.98-μm QD VCSEL is 5.85 GHz. Therefore, the 0.98-μm QD VCSEL with high-speed package could be used for the over 5.85 Gb/s communication systems.

III. LINEWIDTH ENHANCEMENT FACTOR OF 1.3-μm QD VCSEL

The linewidth enhancement factor is measured using an injection locking approach [11]. Fig. 4 schematically depicts the InAs/InGaAs QD VCSEL. A QD VCSEL structure was grown on a GaAs substrate by MBE. The epitaxial structure was as follows (from bottom to top)—n^+-GaAs buffer, 33.5-pair n^+-$Al_{0.9}Ga_{0.1}As$/n^+-GaAs (Si-doped) DBR,

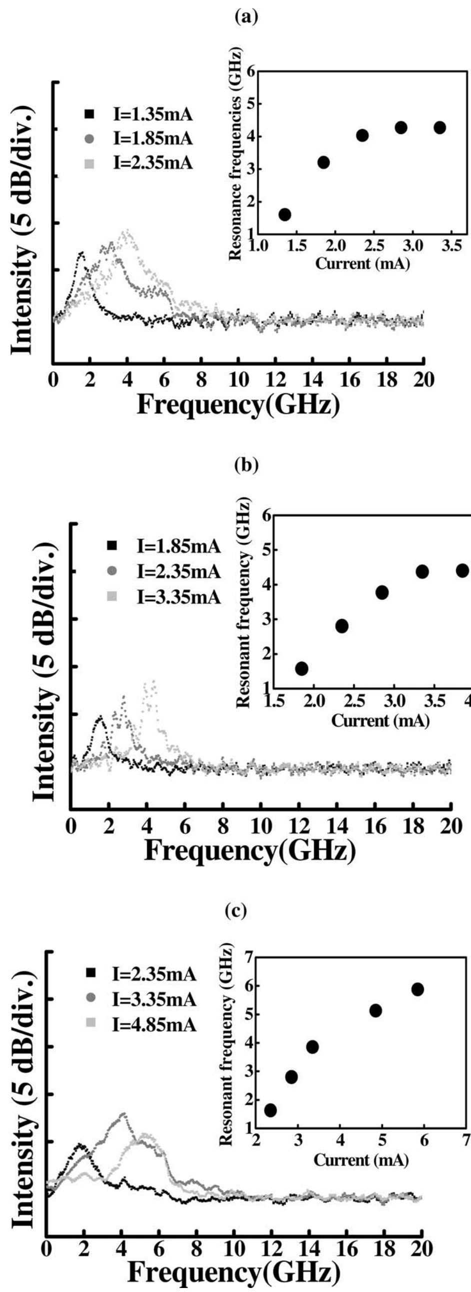

Fig. 3. RIN spectra at (a) 20 °C, (b) −30 °C, and (c) −45 °C.

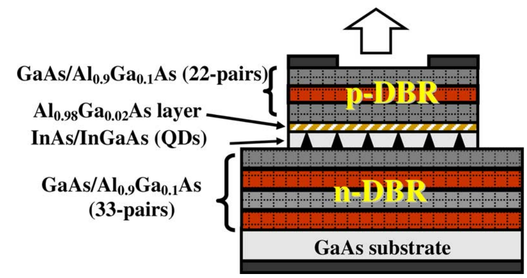

Fig. 4. Schematic diagram of InAs/InGaAs QD VCSEL.

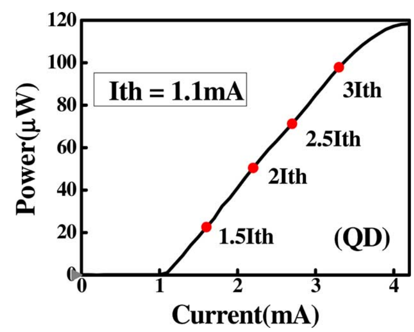

Fig. 5. Light–current characteristics of QD VCSEL.

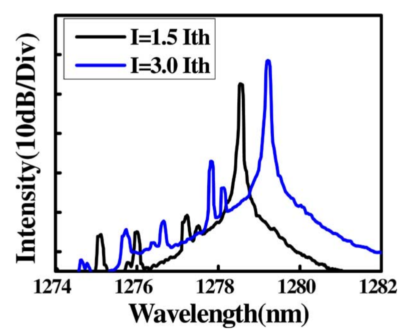

Fig. 6. Output spectrum of QD VCSEL.

undoped active region, p-$Al_{0.98}Ga_{0.02}As$ oxidation layer, 22-pair p^+-$Al_{0.9}Ga_{0.1}As/p^+$-GaAs DBR (carbon-doped), and p^+-GaAs (carbon-doped) contact layer. The graded-index separate confinement heterostructure (GRINSCH) active region primarily comprised five groups of QDs active region, embedded between two linearly graded $Al_xGa_{1-x}As$ ($x = 0$– 0.9 and $x = 0.9$–0) confinement layers. The thickness of the cavity active region was 3λ. Each group of QDs comprised three QD layers around the antinode of a standing wave. The wafer was then processed into a VCSEL structure.

Fig. 5 presents the light–current characteristics of the QD VCSEL. The threshold current is approximately 1.1 mA ($I_{\rm th}$ = 1.1 mA). The QD VCSEL is hermetically sealed using a TO-Can package. The TO-Can packaged QD VCSEL and the single-mode fiber are assembled by laser welding. Fig. 6 displays the output spectrum of the QD VCSEL. The lasing wavelength of the QD VCSEL is around 1279 nm at room temperature. The spiky spectrum to the left of the peak wavelength shows lasing in multiple transverse modes, which is the case for index-guided oxide-confined VCSELs without optimized oxide aperture [16]. Selective modal loss by surface-relief technique or implantation before oxidation was reported to achieve fundamental-mode operation with high side-mode suppression ratio (SMSR). Fig. 7 displays the experimental setup for measuring the linewidth enhancement factor. The VCSEL is employed as the slave laser, and a 1.3-μm tunable laser is used as the master laser. The optical power is varied using a variable optical attenuator (VA) at the output of the tunable laser. Fig. 10 plots the relationship between the driving current of QD VCSEL and the linewidth enhancement factor. The linewidth enhancement factor of QD VCSEL is varied from 0.48 to 0.60. Fig. 8 plots the light–current characteristics of a commercial quantum well (QW) VCSEL (InAlGaAs/InP QWs). The threshold current is about

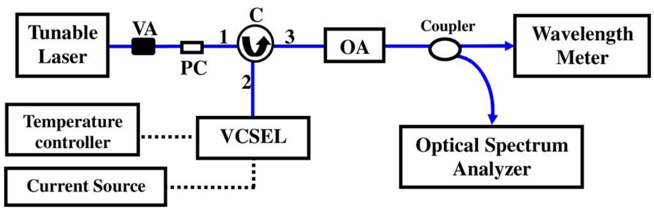

Fig. 7. Experimental setup for measuring the linewidth enhancement factor (VA: variable optical attenuator; PC: polarization controller; C: optical circulator; OA: optical amplifier).

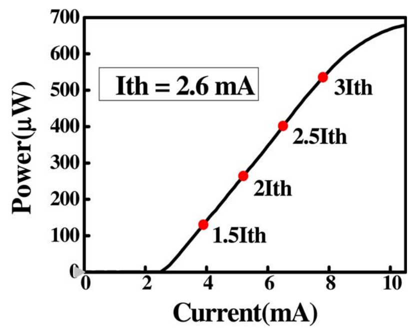

Fig. 8. Light–current characteristics of QW VCSEL.

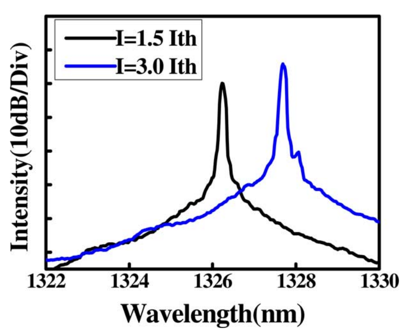

Fig. 9. Output spectrum of QW VCSEL.

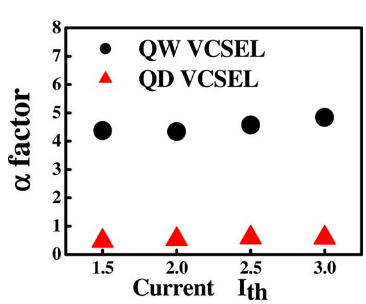

Fig. 10. Relationship between the driving current of VCSEL and the linewidth enhancement factor.

2.6 mA ($I_{\rm th} = 2.6$ mA). Fig. 9 displays the output spectrum of the QW VCSEL. The lasing wavelength of the QW VCSEL is about 1327 nm at room temperature. Fig. 10 plots the linewidth enhancement factor at various driving currents of the QW VCSEL. The linewidth enhancement factor of the QW VCSEL varies from 4.34 to 4.84 with the driving current of the QW VCSEL.

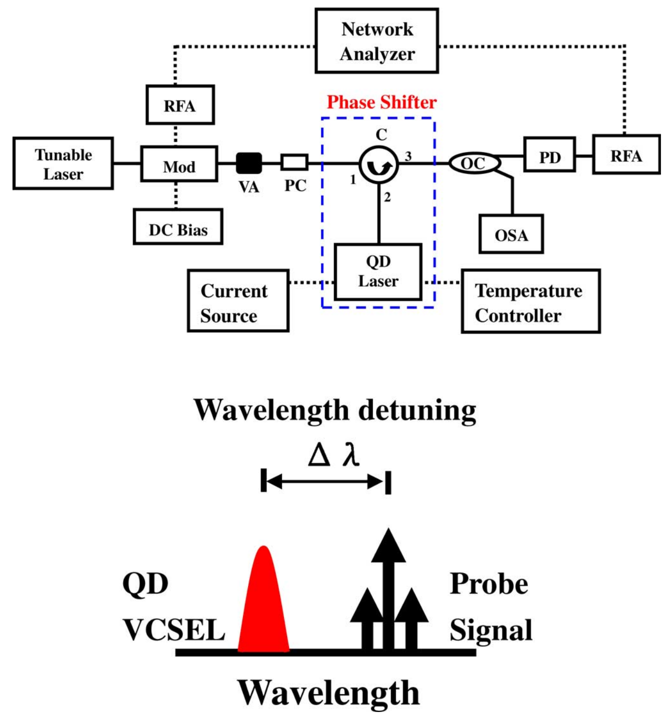

Fig. 11. Experimental setup for measuring the RF phase shift in the QD VCSEL (Mod: electrooptic modulator; PC: polarization controller; VA: variable optical attenuator; C: optical circulator; OC: optical coupler; OSA: optical spectrum analyzer; RFA: RF amplifier; PD: photodetector).

IV. RF Phase Shifter Using 1.3-μm QD VCSEL

Fig. 11 presents the experimental setup for measuring the RF phase shift in the QD VCSEL. A probe signal is generated using a tunable laser and then modulated using an electrooptical modulator. The electrooptical modulator is modulated using a network analyzer. The signal power is controlled using a VA at the output of the electrooptical modulator. The polarization of the probe signal is adjusted using a polarization controller. The probe signal is coupled into the QD VCSEL by using an optical circulator. Next, the output signal from port 3 of the circulator is split into two paths, which are sent to an optical spectrum analyzer and a photodetector, respectively. Finally, the amplitude and phase changes are measured using the network analyzer.

In the experiment, the power of the input probe signal is held constant as the wavelength of probe signal is varied. The power of the probe signal is -14 dBm, and the QD VCSEL is biased at 2.125 $I_{\rm th}$. Varying the power of the probe signal in the cavity of QD VCSEL will vary the available gain. The amplitude and phase change response indicates the locked amplitude and phase change, calibrated with reference to the unlocked values. Fig. 12 plots the amplitude and phase change response of the QD VCSEL at various wavelength detunings. Increasing wavelength detuning increases the frequency of the phase shift. A phase change of 2π is observed. The phase change can be tuned by adjusting wavelength detuning $\Delta\lambda$.

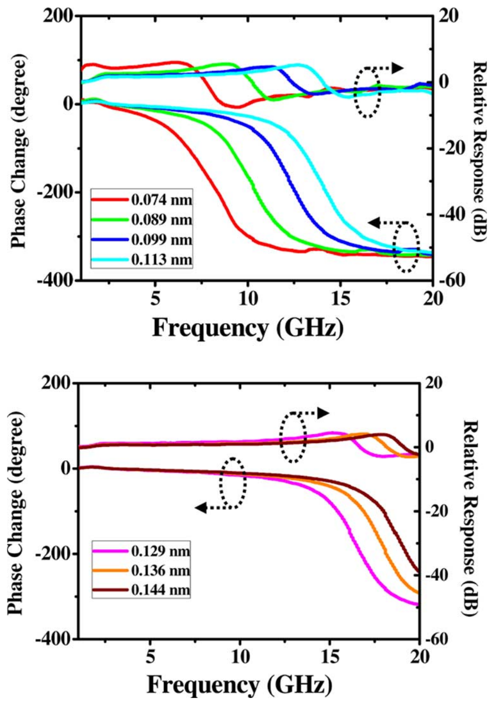

Fig. 12. Amplitude and phase change response of the QD VCSEL at various wavelength detunings.

V. Conclusion

This study describes the RIN characteristics of a QD VCSEL. The intrinsic resonance frequency and eye diagram of the QD VCSEL are presented. The linewidth enhancement factor of the QD VCSEL is also investigated. The α factor was measured to be 0.48–0.60. The linewidth enhancement factor of commercial QW VCSEL was also examined. A photonic RF phase shifter that is based on the QD VCSEL was demonstrated. A photonic RF phase shifter with a total phase shift of 2π was demonstrated. The relationship between the amplitude change response and the wavelength detuning was examined. The QD VCSEL has the potential to reduce the size and cost of the RF phase shifters used in a phased array antenna. Results of this study are useful in the field of QD VCSEL.

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