# Tunable optical group delay in quantum dot vertical-cavity surface-emitting laser at 10 GHz

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This investigation experimentally demonstrates tunable optical group delay in a 1.3 µm quantum dot vertical-cavity surface-emitting laser (QD VCSEL). The QD VCSEL is fabricated on a GaAs substrate. Tunable delays are achieved by varying the bias currents, and the maximum delay of 42 ps at 10 GHz has been demonstrated at room temperature.

*Introduction:* Vertical-cavity surface-emitting lasers (VCSELs) are now very attractive for optical communication applications. VCSELs fabricated on GaAs-based materials have been expected to realise high-performance and low-cost light sources. The large conduction band offset improves temperature performance over that of general InP-based materials. The most promising materials at long-wavelength semiconductor lasers on GaAs-based materials are GaInAsN and InAs quantum dots (QDs). Recently, there has been significant progress in the development of monolithically singlemode QD VCSELs [1, 2].

Variable optical delay lines and buffers will be crucial components in optical communication, phased array antennas, and signal processing systems. Recently, tunable optical group delay in a quantum well Fabry-Perot laser has been reported [3]. Tunable delays of 14 ps for 2 GHz sinusoidal signal have been demonstrated. Moreover, tunable optical group delay in a quantum well VCSEL fabricated on InP-based materials also has been reported [4]. The modulation frequency of a probe signal between 1–3 GHz was presented. However, tunable optical group delay in a QD VCSEL has not yet been addressed. Moreover, the relationship between the signal power and the tunable optical group delay also has not been studied in detail.

In this Letter we report tunable optical group delay in a QD VCSEL for the first time. The QD VCSELs are grown by molecular beam epitaxy (MBE) with fully doped *n*- and *p*-doped AlGaAs distributed Bragg reflectors (DBRs). Tunable optical group delay can be achieved by adjusting the bias current.

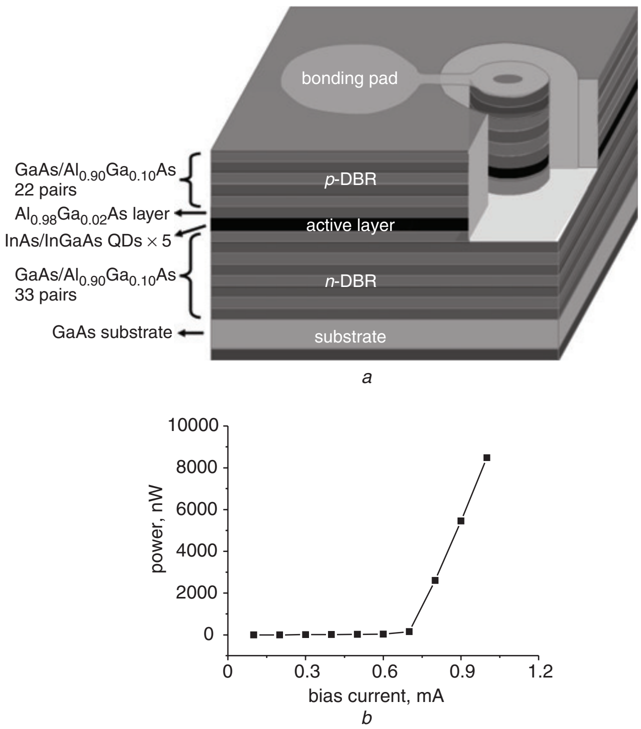


**Fig. 1** *Schematic diagram of QD VCSEL and light-current characteristics*

*a* Schematic diagram
*b* Light-current characteristics

*Experiment and results:* Fig. 1*a* shows the schematic diagram of the monolithically singlemode QD VCSEL. The structure is grown on a GaAs (100) substrate using MBE by NL Nanosemiconductor GmbH (Germany). The fabrication method has described in our previous works [2, 5]. In addition, the QD VCSEL is hermetically sealed by a standard TO-Can package with a built-in lens. The TO-Can packaged QD VCSEL and the singlemode fibre are assembled by laser welding technique. Fig. 1*b* shows the light-current characteristics of the QD VCSEL. The threshold current is about 0.7 mA. Fig. 2 shows the experimental setup for measuring the optical group delays in the QD VCSEL. A probe signal is generated by a tunable laser modulated with an electro-optical modulator. The signal power is controlled by a variable optical attenuator at the output of the electro-optical modulator. The polarisation of the probe signal is adjusted to reach the maximum time delay in the QD VCSEL. An optical circulator is used to couple the probe signal into the QD VCSEL.

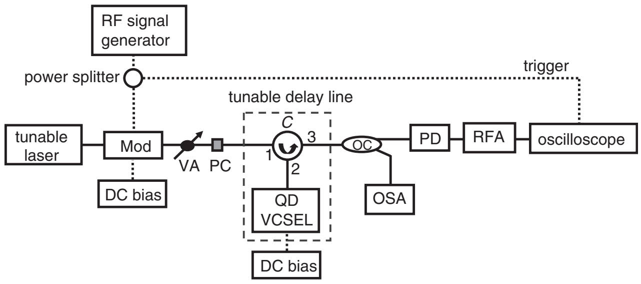


**Fig. 2** *Experimental setup for measuring optical group delays in QD VCSEL*

Mod: electro-optic modulator; VA: variable optical attenuator; C: optical circulator; OC: optical coupler; PC: polarisation controller; RFA: RF amplifier; PD: photodetector; OSA: optical spectrum analyser

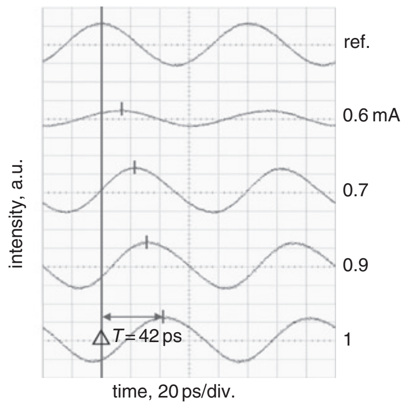


**Fig. 3** *Measurements of time delay for 10 GHz probe signal at various bias currents of QD VCSEL*

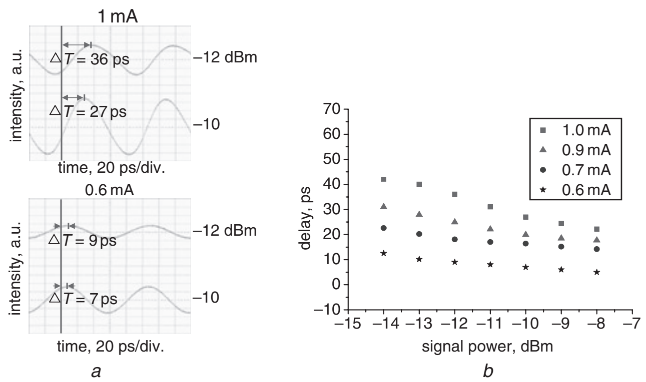


**Fig. 4** *Waveform at different powers of probe signals; time delays against bias currents of QD VCSEL and optical power of probe signal*

*a* Waveform at different powers of probe signals
*b* Time delays against bias currents of QD VCSEL and optical power of probe signal

Fig. 3 shows the measurements of time delay for a 10 GHz probe signal at the various bias currents of the QD VCSEL. The probe signal is tuned to the resonance of the QD VCSEL cavity, and the signal power is −14 dBm. Increasing the bias current of the QD VCSEL can increase the time delay of the probe signal. The maximum group delay of 42 ps is observed, and the driving current is at 1 mA. Fig. 4*a* shows the waveform at different powers of probe signals when the bias current of the QD VCSEL are at 1 and 0.6 mA. The time delays are 36 and 27 ps for −12 and −10 dBm, respectively, when the bias current is at 1 mA. In addition, the time delays against bias currents of the QD VCSEL and the optical power of probe signal are shown in Fig. 4*b*. We observe that the time delay increases as the signal power decreases.

*Conclusion:* We have experimentally demonstrated tunable optical group delay in a 1.3 μm QD VCSEL at room temperature for the first time. The monolithic QD VCSEL based on GaAs substrate is the fully doped structure. Tunable delays of 42 ps for 10 GHz are achieved by varying the bias current.

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