Reconfigurable Functionalities of Coupled-Cavity VCSELs Using Digital Modulation

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Abstract: The coupled-cavity VCSEL under digital modulation can be configured to perform different functionalities for data communications. 10 Gb/s pulse amplitude modulation up to 4 levels, and 34 ps optical pulse generation are demonstrated in this work.

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The vertical-cavity surface-emitting laser (VCSEL) is a dominant laser source for short-haul optical communication networks. Recently the VCSEL consisting of two optical cavities has demonstrated abilities to achieve higher speed modulation [1-4], as well as to provide additional functionalities for optical communications [5-7]. Specifically, the VCSEL with an optically coupled-cavity structure is known as the composite-resonator vertical-cavity lasers (CRVCLs). In this work, 10 Gb/s operation and bit error measurements of a CRVCL are demonstrated for the first time, when one optical cavity is directly modulated. In addition, the CRVCL can be reconfigured to generate 10 Gb/s three- or four-level pulse amplitude modulation (PAM) signaling, or an optical pulse train with the minimum pulse width of 34 ps, by applying digital modulation to both optical cavities simultaneously, and adjusting the amplitude and phase difference between two modulation signals. These unique functionalities make the CRVCL attractive for the future optical systems, especially when combined with a digital circuit whose logic can be reconfigured.

Fig. 1(a) illustrates the device structure of the CRVCL. The CRVCL consists of a monolithic bottom p-type distributed Bragg reflector (DBR) with 35 periods, a middle n-type DBR with 12.5 periods, and an upper p-type DBR with 22 periods. The middle DBR mirror separates two optical cavities, each of which contains five $GaAs/Al_{0.2}Ga_{0.8}As$ quantum wells. An 8×8 μm² implant and 4×4 μm² oxide aperture are formed in the upper and bottom mesa, respectively. The ground-signal-signal-ground coplanar contacts are deposited on polyimide surface to reduce parasitic capacitance and facilitate high-speed signaling to both cavities. Fig. 1(b) shows the light-current (LI) characteristics of the CRVCL at room-temperature with different dc currents in the bottom cavity. The threshold current decreases and the light power increases, when a large dc current and thus higher gain are available in the bottom cavity. Fig. 1(b) inset shows the optical spectrum taken when the top and bottom cavity current are 6 mA and 4 mA, respectively, at which the 10 Gb/s CRVCL modulation is performed.

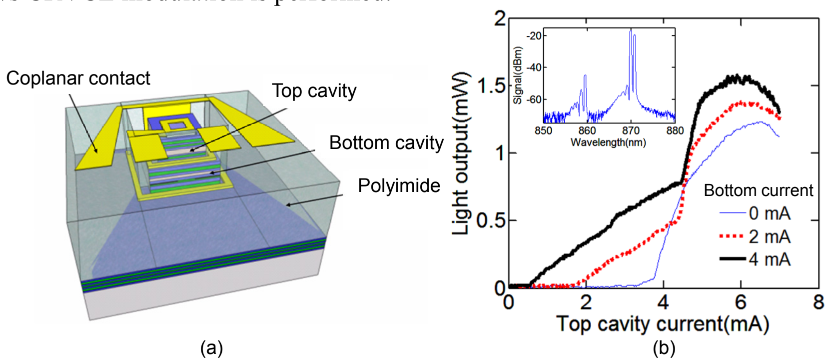

Fig. 1: (a) Schematic and (b) LI characteristics and optical spectrum of the CRVCL used in this study.

For large-signal digital modulation, a lensed 50/125-μm graded-index (GI) multimode fiber (MMF) and a 25 GHz photodetector are used to collect output light from the CRVCL. The modulation voltages for the both cavities are supplied by two identical pattern generators, with which the relative amplitude and delay between two modulation signals can be adjusted. Note that these two pattern generators work essentially as a digital circuit with a reconfigurable logic. The eye diagrams are measured with a 20 GHz electrical sampling oscilloscope using a nonreturn-to-zero pseudorandom bit sequence of 2^7-1. The bit-error-ratio (BER) measurement is taken with an error detector, and two stages of broadband electrical amplifiers are used following the 25 GHz photodetector.

Fig. 2 shows the eye diagrams of the CRVCL operating at three different data rates for a back-to-back transmission, when direct modulation is applied to the top cavity only. A peak-peak modulation voltage of 2.5 V (the maximum voltage from a pattern generator) is used to open up the eyes, due to the large differential series resistance of 760 Ohm from the ion implantation. The extinction ratio is 3.2 dB for both the eyes at 5 Gb/s and 10 Gb/s. However, the degradation of the eye diagram becomes apparent when the CRVCL operates at 12.5 Gb/s. The small-signal measurement is also performed for this particular CRVCL. The -3 dB bandwidth at the same dc biases is 9 GHz, limiting the maximum data rate the CRVCL can support. Fig. 3 illustrates the BER versus the received optical power for a back-back transmission. The lowest BER the CRVCL can achieve is 2.96×10^{-9} and 1.27×10^{-7} for the 5 Gb/s and 10 Gb/s operation, respectively.

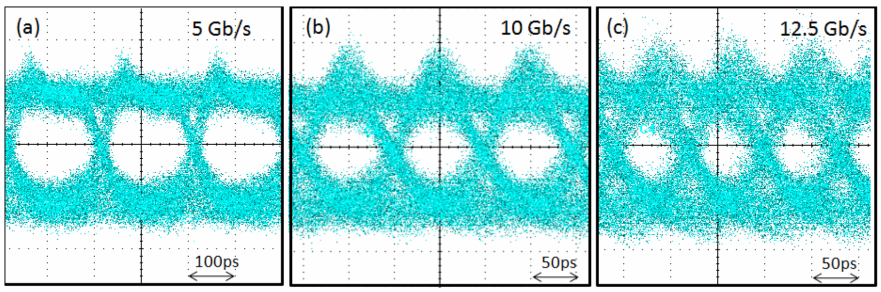

Fig. 2: Eye diagram of the CRCVL at a data rate of (a) 5 Gb/s (b) 10 Gb/s and (c) 12.5 Gb/s.

In addition to direct modulation using a single optical cavity, the CRVCL has the unique ability to manipulate its light output by modulating both optical cavities simultaneously. The overall modulation response of the CRVCL was found to be the summation of the modulation response from each individual cavity, which enables to produce PAM-4 signaling by combining two binary signaling in the coupled cavities [6]. Fig. 4 illustrates that the CRVCL generates two different patterns of PAM-4 signaling at 10 Gb/s, only by decreasing the modulation voltage in the top cavity from 2.5 V to 1.7 V. In Fig. 4 (b), two intermediate amplitude levels (i.e. level 10 and 10) coincide, producing the three-level PAM signaling. Note that the same dc biases are used as in Fig. 2, and the peak-peak modulation voltage in the bottom cavity is 2.5 V.

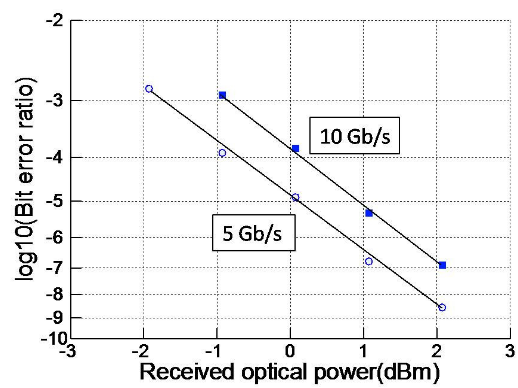

Fig. 3: BER versus received optical power at 5 Gb/s and 10 Gb/s for a back-to-back transmission.

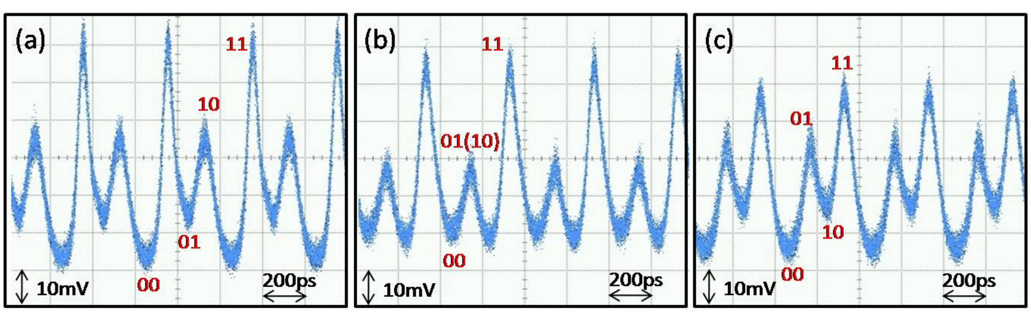

Fig. 4: 10 Gb/s PAM signaling when the modulation voltage in the top cavity is (a) 2.5 V, (b) 2 V and (c) 1.7 V.

Lastly, the CRVCL under simultaneous digital modulation enables a novel approach to generate and tailor short optical pulses. This is different from the conventional approach, in which the pulse generation relies on a sinusoidal current modulation near the laser threshold [8-9]. However, with the CRVCL, the same digital circuit for the PAM signaling can be used for the optical pulse generation. Fig. 5 illustrates the pulse generation mechanism. The CRVCL is dc biased with the top and bottom cavity current of 6 mA and 2 mA, respectively. When direct modulation is applied to the bottom cavity only, an extraordinarily large relaxation oscillation (RO) peak appears on the rising edge (see Fig. 5 (a)), owing to the enhanced modulation response near the RO frequency when the cavity lifetime modulation is associated with the current modulation [4]. This large RO peak can be extracted to form a short optical pulse (see Fig. 5(c)), by simultaneously applying an out-of-phase modulation to the top cavity of the CRVCL to suppress the signal following the RO peak. In Fig. 5(c) the pulse width and repetition rate are 34 ps and 1.5 GHz, respectively. Fig. 6 shows the measured pulse width at different top cavity currents, while the bottom cavity current is held at 2 mA. The pulse width is inversely proportional to the dc current and thus the photon density. The minimum pulse width of 34 ps is limited by the photon density in the CRVCL. The RF spectrum of the optical pulse is also measured, and it can be approximated by a Gaussian function, indicating the optical pulse has a Gaussian shape in the time domain. Additionally, the pulse shape can be further tailored by varying the delay between two modulation signals.

In conclusion, we have demonstrated that with the same digital circuit (i.e. the pattern generators in this work), the CRVCL can be configured to provide different functionalities, which includes the generation of the PAM signaling and the optical pulse train. This unique ability makes the CRVCL a promising laser source for the future optical systems where rapid reconfiguration among multiple functionalities is desired.

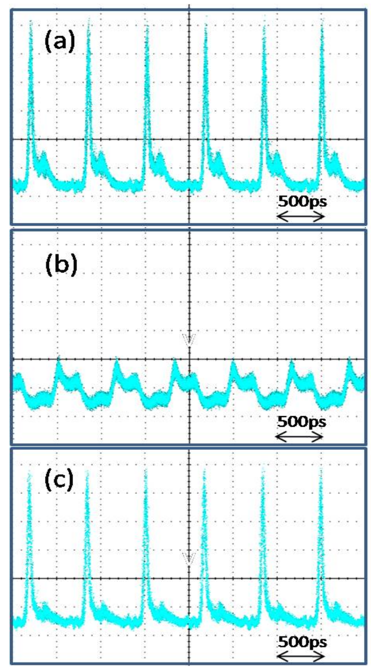

Fig. 5: Optical signal when digital modulation is applied to the (a) bottom cavity, (b) top cavity and (c) both cavities.

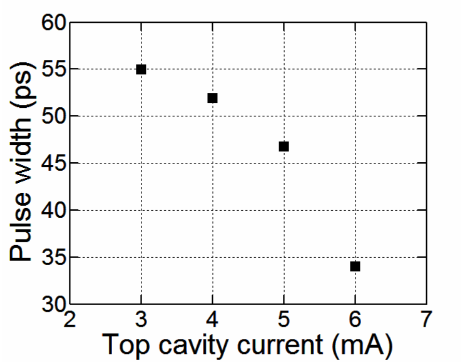

Fig. 6: Measured pulse width versus top cavity current.

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