Multilevel Amplitude Modulation Using A Composite-Resonator Vertical-Cavity Laser

Chen Chen, *Student Member, IEEE*, and Kent D. Choquette, *Fellow, IEEE*

***Abstract*—Modulation characteristics of a composite-resonator vertical-cavity laser (CRVCL) can be engineered by modulating the carrier and photon densities in the two optically coupled cavities simultaneously. The total modulation response is a superposition of the individual modulation response from each cavity, when direct modulation is applied to both cavities. This property enables the CRVCL to produce multilevel signaling for optical communication. A demonstration of four-level amplitude modulation at 2.5 Gb/s is shown.**

***Index Terms*—Semiconductor lasers, vertical-cavity surface-emitting lasers (VCSELs).**

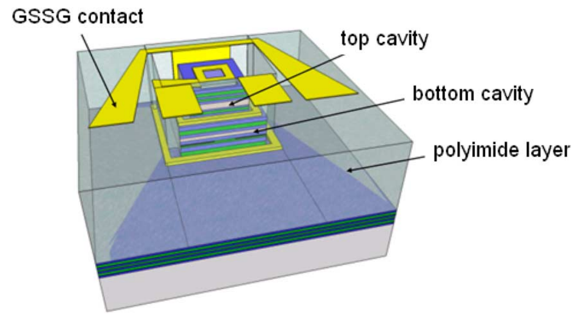

Fig. 1. Schematics of a CRVCL with a GSSG coplanar contact on the planarized surface.

I. Introduction

DRIVEN by the rapidly increasing information bandwidth required for the high-capacity communication network, a reliable, low-cost, high-speed laser source is important for optical communication. The vertical-cavity surface-emitting laser (VCSEL) is an ideal source for short to mid-haul optical communication network and optical interconnects. Today, 10-Gb/s VCSELs are commercially available, and the state-of-art VCSELs in laboratories have demonstrated modulation up to 35 Gb/s [1]–[3].

Recently, a VCSEL with two optically coupled and electrically independent cavities has exhibited potential to achieve higher speed operation [4]–[8]. This structure is often referred to as the composite-resonator vertical-cavity laser (CRVCL) [9], [10]. From the perspective of high-speed laser design, unique features of the CRVCL have been exploited, which include the ability to change the photon density by varying the gain or intracavity absorption in one cavity while fixing the current injection into the other cavity [4] [5], [7], [8], the ability to detune the optical cavity from epitaxial design or current injection [6], [7], and the ability to achieve wavelength multiplexing using its two longitudinal optical modes [11].

In this work, we demonstrate light modulation from a CRVCL when both of the coupled cavities are under direct modulation simultaneously. We observe that the total modulation response from a CRVCL is a superposition of the individual modulation response from each cavity. More importantly, by varying the relative amplitude between the modulation signals into the top and bottom cavity, the total modulation response can be tailored, and specifically the modulation bandwidth and relaxation oscillation (RO) peak can be engineered to achieve an optimal modulation response. These properties make the CRVCL a promising light source to generate multilevel amplitude modulation signals, which can increase the aggregate data transmission rate.

II. Experiment

Fig. 1 illustrates the device structure of the CRVCL used in this study. The CRVCL is fabricated from an epitaxial wafer consisting 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 mirrors separate two optical cavities, each of which contains five GaAs–$Al_{0.2}Ga_{0.8}As$ quantum well nominally lasing at 850 nm. A 40×40 μm^2 top mesa through the top cavity and a 90×90 μm^2 bottom mesa through the bottom cavity are formed using inductively coupled plasma reactive ion etching. An 8×8 μm^2 implant aperture and a 3×3 μm^2 oxide aperture are formed in the top and bottom mesa, respectively. In order to facilitate the high-speed signaling into both optical cavities, the CRVCL is planarized with polyimide and then a ground–signal–signal–ground (GSSG) coplanar contact is deposited.

The continuous-wave characteristics of the CRVCL are obtained at room temperature prior to the high-speed measurement. The bottom cavity is injected with current while we vary the dc current into the top cavity. Fig. 2(a) illustrates that the CRVCL light output increases and threshold current decreases, as a larger dc current is applied to the top cavity resulting in increasing laser gain [5]. The kinks in the light versus top cavity current curves indicates the onset of the longer wavelength longitudinal mode lasing. Fig. 2(b) illustrates the optical spectrum taken at the dc bias for the small-signal modulation.

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The authors are with Department of Electrical and Computer Engineering, University of Illinois at Urbana–Champaign, Urbana, IL 61801 USA (e-mail: chenchen@illinois.edu; choquett@illinois.edu).

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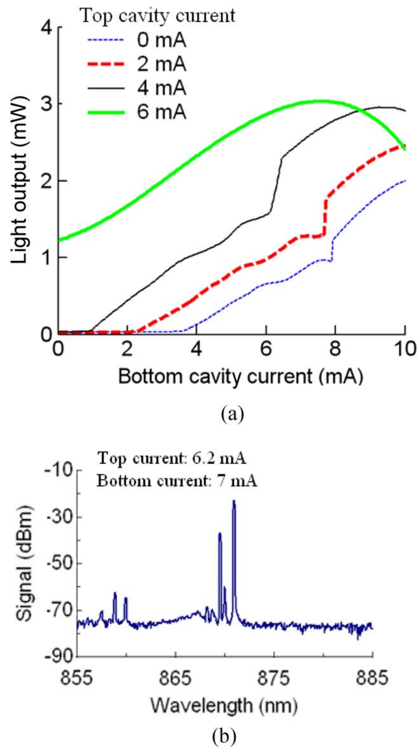

Fig. 2. (a) Light output versus bottom cavity current with different dc current into the top cavity. (b) Optical spectrum taken at the dc bias for the small-signal modulation.

The CRCVL emits predominately on the longer wavelength (∼870 nm) longitudinal optical mode due to a larger spectral overlap with the temperature-dependent material gain [12].

Small-signal modulation characteristics of the CRVCL are measured using a network analyzer. Large-signal modulation is performed using a pattern generator and an oscilloscope. A broadband power divider is used to split the modulation signal into both cavities of the CRVCL, and variable attenuators are used to control the relative amplitude between the modulation signals into both cavities. A cleaved 62.5-μm core graded-index multimode fiber and a high-speed photodetector are used to collect output light from the CRVCL under test.

III. Results

Fig. 3 illustrates that the total response varies, when the modulation amplitude in the bottom cavity is varied relative to that in the top cavity. The modulation responses in Fig. 3 are obtained at the fixed current (top and bottom cavity current fixed at 6.2 and 7 mA, respectively), and are normalized to their dc values. Note attenuators designed for radio frequency (RF) are used to vary the modulation amplitude. For a positive value of RF gain on the bottom cavity modulation in Fig. 3, the actual attenuation is applied to the modulation signal in the top cavity. On the other hand, for a negative value of RF gain, the attenuation is applied to the modulation signal in the bottom cavity. Evident from Fig. 3 is that the modulation responses have the same RO frequency (see arrow in Fig. 3), indicating they are operating with the same dc photon density. This condition cannot be achieved

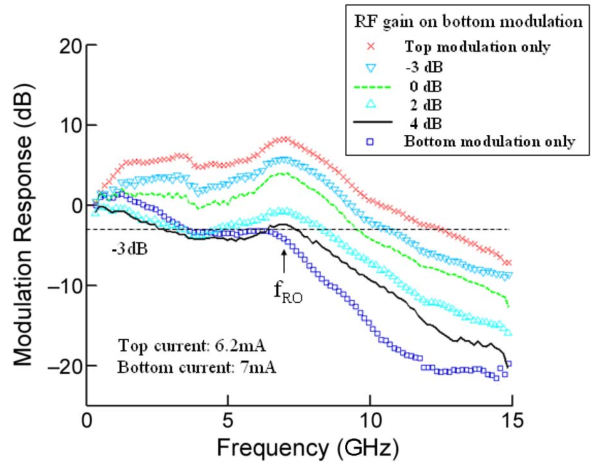

Fig. 3. CRVCL modulation responses as the relative modulation amplitude in both cavities varied by an attenuator.

using a conventional VCSEL, for which direct modulation response can only be varied by changing the injection current and thus the photon density. Additionally, the total response can be seen as a superposition of the modulation response from the top and bottom cavity, as it matches with the response calculated by adding the two individual modulation responses in phase over the measured frequency range.

It is desirable for a laser transmitter to attain a large modulation bandwidth and a small RO peak (or a flat response). In Fig. 3, a tradeoff can be made between a large modulation bandwidth and a small RO peak, by varying the relative amplitude between the modulation signals for both cavities. The −3-dB modulation bandwidth can be tuned between 5 and 12.5 GHz, and the height of the RO peak can be varied as the modulation response varies between the over- and under-damped regimes. The CRVCL modulation response can deviate from a conventional laser response due to asymmetry (for example, different longitudinal mode distribution or material gain) between the coupled cavities, resulting in increasing modulation response at frequencies below 3 GHz.

With the unique modulation characteristics shown in Fig. 3, the CRVCL has the ability to produce a four-level pulse amplitude modulation (PAM-4) optical signal by combining two binary amplitude modulation electrical signals in the coupled cavities. Fig. 4(a) illustrates the 125- and 62.5-MHz square-wave electrical signal to the top and bottom cavity, respectively. Note the square-wave signal is mixed with the dc bias in a bias tee before being applied to a CRVCL cavity. Fig. 4(b) shows the optical output signal consists of four amplitude levels, as a result of adding the individual modulation responses from the top and bottom cavities. The highest (lowest) amplitude level denoted as 11 (00) is achieved when both input signals are switched high (low). The intermediate levels 10 and 01 correspond to the individual modulation response from the bottom and top cavity, respectively. Fig. 5 illustrates this phenomenon at a higher data rate, where 2.5- and 1.25-GHz square-wave electrical signals are applied to the top and bottom cavities, respectively. The modulation speed is limited by our test equipment. Fig. 5(a) and (b) show the optical output signal when direct modulation is only

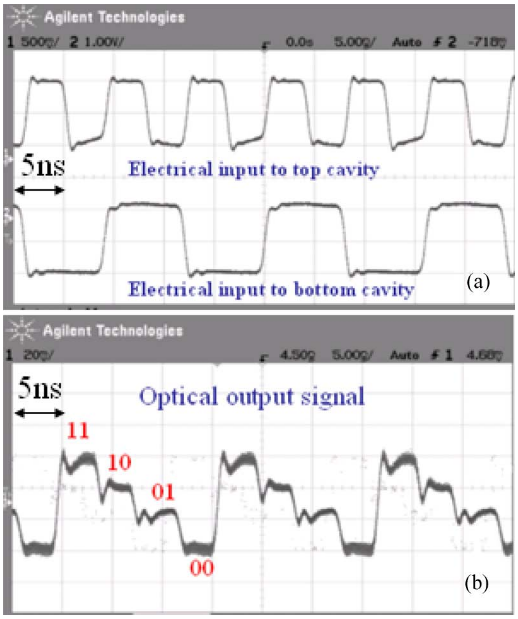

Fig. 4. (a) Electrical input signals to the top and bottom cavity of a CRVCL. (b) Resulting optical output signal measured from the CRVCL top facet.

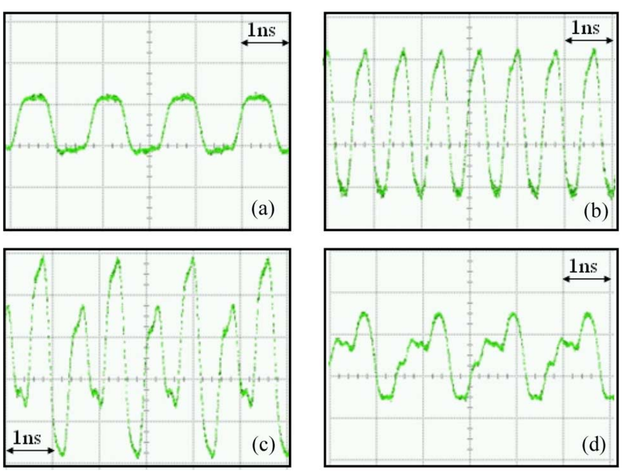

Fig. 5. Optical output signal when only the (a) bottom and (b) top cavity is under direct modulation. Optical output signal when (c) 0- and (d) 6-dB attenuation is applied to the top cavity, given that both cavities are under direct modulation simultaneously.

applied to the bottom or top cavity, respectively. When direct modulation is applied to both cavities, four amplitude levels can be observed in the optical output signal of the CRVCL [see Fig. 5(c)]. The optical waveform can be tailored, as the relative amplitude between the two input signals can be varied. Fig. 5(d) shows the optical waveform after applying 6-dB RF attenuation to the modulation signal to the top cavity, with the result that it becomes the same waveform as shown in Fig. 4(b). The relative amplitude for the intermediate levels 10 and 01 vary between Figs. 5(c) and (d), as the amplitude of the modulation response from the top cavity decreases with the RF attenuation. No effect from longitudinal mode switching on the PAM-4 waveforms is observed.

IV. Conclusion

The CRVCL can achieve light modulation by applying direct modulation to both coupled cavities simultaneously. It is found the total modulation response is a superposition of the individual response from the top and bottom cavities. Moreover, the total modulation response can be engineered by varying the relative amplitude between the modulation signals into both cavities, and thus the tradeoff between a large modulation bandwidth and a small RO peak can be made to achieve an optimal modulation response. These unique properties enable the CRVCL to produce a PAM-4 optical signal and improve the effective modulation bandwidth by a factor of two as compared to the conventional direct laser modulation. The new modulation functionalities may enable new applications for low-power high-performance data networks.

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