High-Speed Potential of Field-Induced Charge-Separation Lasers for Short-link Applications

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Abstract – Novel three-terminal FICSLs in VCSEL form were designed and fabricated for direct gain modulation, which by analysis introduces an additional zero to the modulation transfer function and promises modulation bandwidth enhancement.

OCIS codes: (140.7260) Vertical cavity surface emitting lasers; (140.3430) Laser theory; (060.4080) Modulation

I. Introduction

As the microprocessor performance scales and the number of cores in supercomputers increases, high-speed, high-efficiency VCSELs have become more and more attractive for applications ranging from chip-to-chip to box-to-box optical links. Over the recent years, state-of-the-art diode VCSELs have demonstrated above 35 Gbit/s operation and above 20 GHz bandwidth at different lasing wavelengths [1-3]. These breakthroughs were made possible by enhancing the modulation bandwidth, which is limited by the double-pole roll-off of the relaxation resonance response as well as carrier transport effects [4].

II. Modulation Bandwidth Enhancement via Direct Gain Modulation

Arising from the interaction between carrier and photon rate equations, relaxation resonance frequency plays an important role in laser performance. As illustrated in Fig. 1, the modulation transfer function can be characterized with the relaxation resonance frequency ω_R and the damping factor γ. Hence, all diode lasers have a 40 dB/decade roll-off when operated at the high frequencies. According to the expression for relaxation resonance frequency, there are several possible ways to increase the relaxation resonance frequency.

Modulation transfer function

$$\frac{P_{ac}(\omega)}{P_{ac}(0)} = H(\omega) = \left(\frac{\omega_R^2}{\omega_R^2 - \omega^2 + j\omega\gamma}\right)$$

Relaxation resonance frequency

$$f_R = \frac{\omega_R}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{v_g a}{qV_p}\eta_i (I - I_{th})}$$

v_g	Group velocity
a	Differential gain
η_i	Injection efficiency
V_p	Optical volume
I_{th}	Threshold current

Fig. 1. Modulation transfer function and relaxation resonance frequency of lasers.

Firstly, we can increase the differential gain a. Common ways to increase the differential gain include introducing delta or modulation p-doping into the quantum well barriers, and increasing the strain in the quantum wells, such as adding more indium in the InGaAs/GaAs quantum well system [5]. In addition, active region composed of quantum dots can be an alternative candidate to provide high differential gain [6].

Secondly, we can reduce the optical mode volume V_P. Selective oxidation is a common way to confine the optical mode laterally, and tapered oxide apertures have been shown to reduce the mode volume effectively without introducing extra loss [7]. It is also possible to further reduce the optical mode volume in the longitudinal direction by utilizing high-reflectance mirrors such as high-contrast grating (HCG) reflectors [8].

Last and perhaps the easiest way is just increasing the bias current I, as the modulation bandwidth can be steadily enhanced by increasing the current above threshold. However, there will be a point that the damping effect and thermal limitations start to dominate. Also, operating VCSELs at high current densities can be detrimental to the device lifetime.

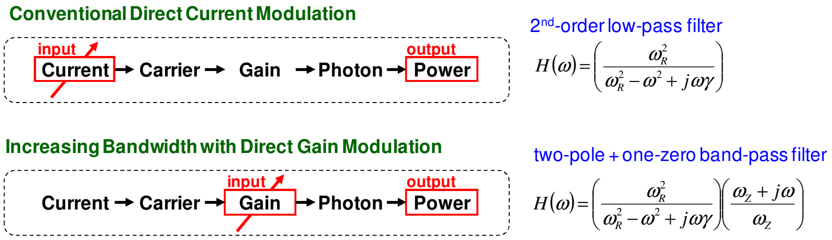

Fig. 2. Modulation chain effects and transfer functions of conventional current-modulated lasers (upper) and gain-modulated lasers (lower).

The conventional current-modulation can be characterized with a “C2GP2” chain, as shown in upper part of Fig. 2. The laser driver modulates the current, which populates the active region with carriers. Carriers provide gain to the optical mode and generate photons, part of which comes out of the cavity as the output power. The result is the double-pole or 2^{nd}-order low-pass filter type of frequency response. If we can find a way modulate the gain directly, this chain effect will be shortened, as shown in the lower part of Fig. 2. From our analysis, the shortened chain effect adds an additional zero, which we defined as ω_Z, to the original two-pole transfer function. The result is a two-pole, one-zero band-pass filter type of frequency response for the gain-modulated lasers. As we are going to show in the next section of this paper, ω_Z plays an interesting role for modulation bandwidth enhancement.

III. Field-Induced Charge-Separation Laser (FICSL)

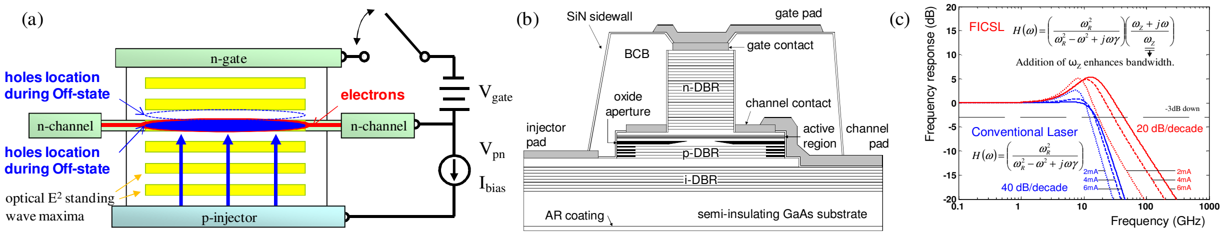

Fig. 3. (a) FICSL operation mechanism. (b) Cross-sectional schematic of a FICSL. (c) Modeled small-signal response comparison of a conventional laser and a FICSL with the same parameters and reduced carrier lifetime. Bias current I_{bias} was 2mA, 4mA and 6mA.

To realize direct gain modulation, the field-induced charge-separation laser (FICSL) was built by adding a third terminal to a convention dual-intracavity-contacted diode VCSEL, as shown in Fig. 3a. Electrons are injected laterally into the active region from the upper intracavity n-contact, which we also defined as the **n-channel**. Holes are injected from the bottom intracavity p-contact, which we defined as the **p-injector**. Electrons and holes overlap and recombine radiatively at one of the optical standing wave maxima. The modal gain is maximized and the carriers can recombine radiatively and provide gain to the optical mode. This is the On-state of the FICSL.

To turn off the laser, a negative bias is applied to the third terminal, which we defined as the **n-gate**. Driven by the external electric field, the holes will be pulled toward the gate, and the electrons will be pushed away from the gate. The two types of charges are separated and the modal gain is reduced, therefore the laser output is also reduced. One can clearly see that with the application of gate voltage, the gain can be modulated directly without changing the bias current. Devices were designed and fabricated with details described in ref. [9] and the schematic is illustrated in Fig. 3b.

Fig 3c compares the frequency response of FICSLs versus conventional diode lasers. Unlike the 2^{nd}-order low-pass filter response of conventional diode lasers, the FICSL response ramps up around the additional zero frequency ω_Z, peaks around the relaxation resonance ω_R, and then features a 20dB roll-off at the high-frequencies. Consequently, with the same relaxation resonance frequency and damping factor, FICSLs will have a much higher 3dB cutoff frequency than conventional diode lasers.

Furthermore, the 3dB cutoff frequency of FICSLs scales with the bias current almost linearly, while the 3dB cutoff frequency of a conventional diode laser saturates regardless of bias current increase, as shown in Fig 4a. For more accurate modeling, thermal limitations and parasitic effects have to be considered. In this case, the 3dB cutoff frequency of FICSLs will be lower than what Fig 4a predicts but still higher than that of conventional diode lasers.

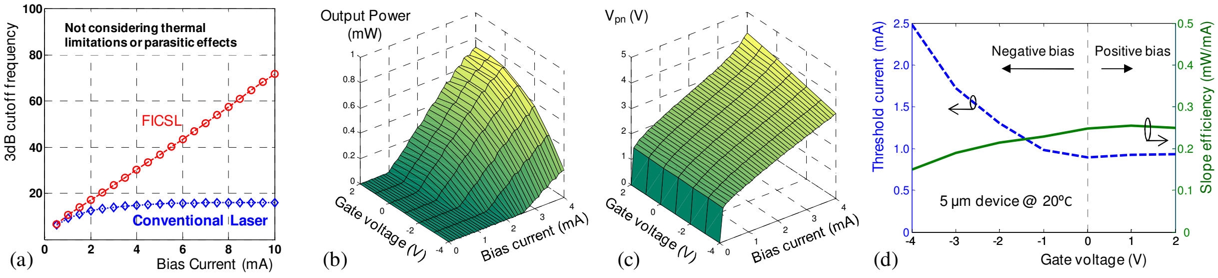

Fig. 4. (a) Modeled 3dB cutoff frequency comparison a conventional laser and a FICSL assuming no thermal limitations or parasitic effects. (b) L-I_{bias}-V_{gate} plot. (c) I_{bias}-V_{pn}-V_{gate} plot. (d) Threshold current and slope efficiency as a function of gate voltage.

IV. Experimental Results

To verify the gain modulation effect, the device was tested by DC L-I-V setup with different gate voltage applied. The results are summarized in Fig. 4b-4d. When there was a positive voltage on the n-gate, the threshold current and the slope efficiency did not changed significantly. If we put a negative bias on the n-gate, an increase of the threshold current, a reduction of the slope efficiency and a reduction of the output power could be observed. Direct modulation with the gate voltage was demonstrated. However, the required voltage swing was around 4V peak-to-peak, much higher than expected. This indicated that the fabricated FICSLs had very large resistance in the n-DBR which consumed a large voltage drop. The large n-DBR resistance also limited the small-signal bandwidth to be around 11GHz [9]. The parasitic time constant determined by the n-DBR resistance and the junction capacitance became a limiting factor to prevent good observation of the high frequency roll-off.

V. Conclusion

We have demonstrated the novel theory of direct modulation via field-induced charge-separation in FICSLs. Analysis showed an addition of zero to the conventional two-pole transfer function. Simulation showed that due to the additional zero, FICSLs were promised to have much higher modulation bandwidth than conventional diode VCSELs. Experimental results verified the physics of field-induced modulation, but the high resistance in the n-DBR increased the voltage required for modulation, and limited the RF performance.

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