Modulation Energy Efficiency of VCSEL and Coupled-Cavity VCSEL

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Abstract: We measure the energy per bit (EPB) for the 25-Gb/s implanted holey VCSEL and 12-Gb/s coupled-cavity VCSEL, and discuss the possibilities for the VCSEL to achieve a lower EPB for data center and interconnect applications.

OCIS Codes: (142.7260) Vertical cavity surface emitting lasers (060.4080) Modulation (140.9560) Semiconductor lasers

The VCSEL is widely used in short-distance optical communication. For emerging applications such as data centers and chip-level interconnects, however, the VCSEL can become a suitable laser source only if it can operate with sufficiently low energy [1]. Although high modulation bandwidth of the VCSEL has been achieved from different perspectives [2-5], the energy per bit (EPB) is not necessarily minimized. In this work, we measure the EPB for the VCSELs and coupled-cavity VCSELs (or composite-resonator vertical-cavity laser, i.e. CRVCL), and discuss their potential to become a future on-chip laser. Specifically, (1) we measure the power consumption of a 25-Gb/s implanted holey VCSEL, and discuss the possibility to reduce the EPB using a micro thermoelectric cooler (TEC); (2) we calculate the EPB for the CRVCL using four different modulation approaches, showing the CRVCL can achieve a lower EPB by exploiting the modulation format and the cavity detuning. An example of this is shown using a 12-Gb/s CRVCL.

A conventional implant-confined VCSEL can achieve high-speed operation and low current density simultaneously by etching a holey structure into its top Bragg reflector [5]. Fig. 1 illustrates the measured data rate versus power consumption for a 25 Gb/s implanted holey VCSEL. Note that at each data rate the bit error ratio of $<10^{-8}$ is attained. The lowest EPB achieved is 1.08 pJ/bit (i.e. 27 mW at 25 Gb/s). The data rate can be related to the square root of the power consumption (indicated by the blue curve in Fig. 1). This agrees with the laser modulation theory that increasing laser speed requires quadratically increasing injection current and operation power [6], which is nevertheless the greatest challenge for the EPB scaling. Alternative approaches are thus desired to circumvent this challenge. One possibility found is that, when combining with a TEC, the same 25 Gb/s VCSEL can operate >30 Gb/s [7]. Although additional operation power must be spent on the TEC, the overall EPB can be reduced even with the operation power scaling of the commercially available single-stage TECs [8]. To qualitatively illustrate the energy scaling, Fig. 1 includes two points calculated assuming a smaller size (i.e. 2.5×2.5 mm^2) of the same TEC as in [7] is used. The TEC used in [7] has a size of 40×40 mm^2, and the TEC power consumption is expected to decrease linearly with its size [8].

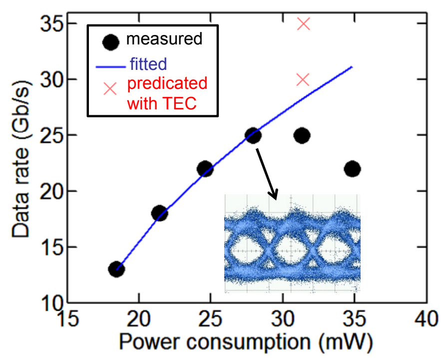

Fig. 1: Data rate vs. power consumption for a 25-Gb/s VCSEL. Inset shows the measured eye at 25 Gb/s.

In addition to a conventional VCSEL, the CRVCL has also exhibited potential to achieve higher modulation bandwidth owing to its flexibility to modulate laser using different approaches [9-10]. Fig. 2(a) compares the laser frequency responses with four different modulation approaches. These responses are obtained using the same photon density and the same static power. The direct modulation of the CRVCL is assumed to have the same response as a conventional VCSEL [10]. Without spending additional energy, the other three modulation approaches increase the -3 dB bandwidth from 20 GHz to 50 GHz, thus reducing the EPB. In Fig. 2(b) the EPB is plotted versus the -3 dB bandwidth for these modulation approaches, assuming the direct modulation consumes 1 pJ/bit; the measured EPB for the 25 Gb/s holey VCSEL is also plotted as reference. For simplicity the -3 dB bandwidth is mapped to the maximum data rate, e.g. 20 GHz bandwidth produces a 20-Gb/s operation. Note that other parameters such as the extinction ratio and electrical parasitic effects should be also considered for more accurate EPB calculation.

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Similar to Fig. 2(a), the cavity detuning provides another knob to improve the laser modulation bandwidth [10], and thus it can reduce the EPB. This concept is demonstrated using a 12-Gb/s CRVCL. Fig. 3(a) shows the -3 dB bandwidth of 12 GHz (6 GHz) is achieved, when only the top (bottom) cavity of this CRVCL is directly modulated. We can estimate from the fitted curves that 80% (20%) of the optical field is confined in the top (bottom) cavity. Assuming the cavity symmetry [10], a modulation response equivalent to the red curve can be also obtained by only modulating the top cavity, when 20% (80%) of the optical field is confined in the top (bottom) cavity. Therefore, if we were able to modify the cavity detuning (i.e. optical field distribution) from the CRVCL epitaxy, we would achieve all the modulation responses indicated by the calculated curves in Fig. 3(a) by only directly modulating the top cavity. Fig. 3(b) illustrates the EPB decreases as we vary the cavity detuning to increase the optical field confined in the top cavity. The minimum EPB measured for this CRVCL is 5.4 pJ/bit at 12 Gb/s, which is expected to decrease further with device optimization.

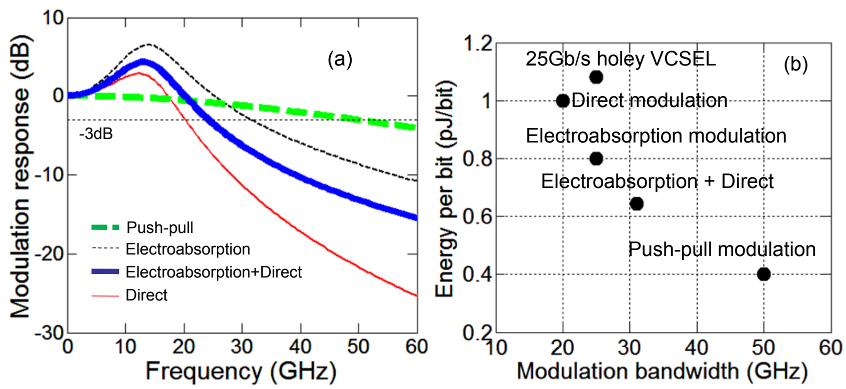

Fig. 2: Calculated (a) modulation responses and (b) energy per bit of the CRVCL using four different modulation approaches.

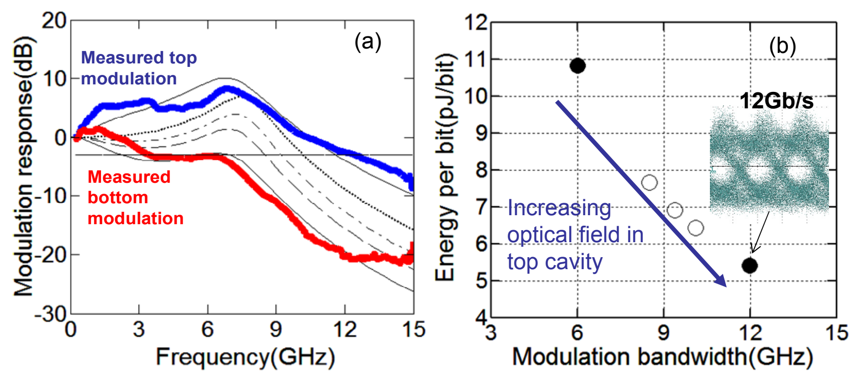

Fig. 3: (a) Measured (colored line), fitted (solid line) and calculated (broken line) modulation responses, and (b) measured (solid circle) and calculated (open circle) energy per bit for the 12 Gb/s CRVCL. Inset shows the measured eye at 12 Gb/s.

In summary, we measure the EPB for the 25-Gb/s implanted holey VCSEL and 12-Gb/s CRVCL, and we discuss the potential of the VCSEL and CRVCL to reduce the EPB for future data center and interconnect applications. Integrated with a TEC, the VCSEL may circumvent the inherent laser relation governing the data rate and power consumption so as to achieve a lower EPB. The CRVCL can also reduce the EPB by exploiting the modulation format and the cavity detuning.

References:

[1] D. Miller, *Proc. IEEE*, vol. 97, no. 7, pp. 1166-1185, 2009.
[2] Y. Chang, C. Wang, and L. Coldren, *Electron. Lett.*, vol. 43, no. 19, 2007.
[3] R. Johnson and D. Kutcha, CLEO 2008.
[4] P. Westbergh, et al., *J. Sel. Topics Quantum Electron.*, vol. 15, no. 3, pp. 694–703, 2009.
[5] C. Chen, Z. Tian, K. Choquette and D. Plant, *Photon. Technol. Lett.*, vol. 22, no. 7, 2010.
[6] L. Coldren and S. Corzine, *Diode Lasers and Photonic Integrated Circuits*. New York: Wiley, 1995.
[7] Z. Tian, C. Chen, K. Choquette and D. Plant, CLEO 2010.
[8] http://www.marlow.com/thermoelectric-modules/single-stage/
[9] V. Shchukin, et al., *Proc. SPIE*, vol. 6889, 2008.
[10] C. Chen and K. Choquette, *J. Lightwave Technol.* vol. 28, no. 7, 2010.