

# Design of an Electro-absorption modulator for integration onto a VCSEL

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## 500 words:

VCSELs have become prevailing laser sources for many short optical link applications such as datacenter, active cables, etc. Actual commercialized VCSELs can provide 25 Gb/s data rates, but new solutions are expected to settle the next device generations towards 100 Gb/s. Indeed, directly modulated VCSELs have been extensively studied and their performances have evolved until reaching bandwidths currently in the range of 26-32 GHz [1,2] [Chalmers, TU Berlin]. However this evolution has been led at the price of increased applied current and thus reduced device lifetime. Furthermore, the relaxation oscillation limit still remain a insuperable boundary with this solution. Thus, to overpass this barrier, a very promising alternative would be to split the emission and the modulation functions as it has been successfully [3,4,5]. Here, we study the vertical integration of an Electro-Absorption Modulator (EAM) within a VCSEL, where the output light of the VCSEL is modulated through the EAM section. Based on this conceptual approach, we finely optimized the EAM design to maximize the modulation depth by implementing perturbative Quantum Confined Stark Effect (QCSE) calculations, with the aim of realizing the vertical integration of the EAM while benefiting from the best VCSEL static performances.

As a proof of concept, we have realized a complete optimization cycle from structure design, fabrication to devices characterization, and finally feedback analysis based on our model [6]. We will describe the design optimization of Multiple-Quantum-Wells electro-optical properties, subject to an applied electric field, integrated in an Asymmetric-Fabry-Perot structure to strengthen the absorption effect while minimizing the number of QWs. We used a perturbative quantum-confined Stark-effect based on a simple absorption model and transfer matrix calculations. Next, we carry out the fabrication of such vertical-cavity electro-optic modulators based on GaAs/AlGaAs system. The epitaxial growth by MBE of different EAM and EAM-VCSEL structures has been done, supported by intermediate optical measurements enabling to identify the EAM cavity and VCSEL cavity respective positions. Then, we demonstrate a very good agreement for both the effect of the applied field and the temperature on the excitonic peak position and the Fabry-Perot shift, when we compare the model results with the experimental static measurements such as reflectivity, LIV curves and photocurrent done on different EAM structures.

Finally, first static characterizations are done and demonstrate the expected modulation properties of the device. Thanks to these LIV curve and the absorption model described previously we are now able to predict the optimum EAM-VCSEL structure for a maximized absorption of the output power.

To aim for very high frequency efficient electrical injection we focused also on the BCB characterization up to 110 GHz and the injection scheme design specific to this triple electrode device. These measurements are of high interest for the optimum design of the access while considering the parasitic effects. We then compare coplanar and micro strip lines access, with a taper or not, to decrease the pad capacitance and so increase the cut-off frequency.

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[2] Hamad, W., Wanckel, S., et Hofmann, Werner HE. "Small-Signal Analysis of Ultra-High-Speed Multi-Mode VCSELs". *IEEE Journal of Quantum Electronics*, 2016, vol. 52, no 7, p. 1-11.

[3] Gu, X., Nakahama, M., Matsutani, A., Ahmed, M., Bakry, A., & Koyama, F. "850 nm transverse-coupled-cavity vertical-cavity surface-emitting laser with direct modulation bandwidth of over 30 GHz". *Applied Physics Express*, 8(8), 082702. 2015

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[5] Germann, T. D., Strittmatter, A., Mutig, A., et al. Monolithic electro-optically modulated vertical cavity surface emitting laser with 10 Gb/s open-eye operation. *physica status solidi (c)*, 2010, vol. 7, no 10, p. 2552-2554

[6] Marigo-Lombart, L., Calvez, S., Arnoult, A., Thienpont, H., Almuneau, G., Panajotov, K. "Vertical Electro-Absorption Modulator design and its integration in a VCSEL", in preparation.

**300 words:**

In this work, we have realized a complete optimization cycle from structure design, fabrication to devices characterization, and finally analysis based on our model of Asymmetric-Fabry-Perot vertical electro-absorption modulator. In order to achieve enhanced dynamic absorption effect with a minimized number of MQW, we used a perturbative quantum-confined Stark-effect based on a simple absorption model and transfer matrix calculations and optimize the modulation figures of merit as a function of different design parameters under varying applied electrical fields.

The epitaxial growth by MBE of different EAM and EAM-VCSEL structures has been done, supported by intermediate optical measurements enabling to identify the EAM cavity and VCSEL cavity respective positions.

Finally, first static characterizations are done and demonstrate the expected modulation properties of the device. A very good agreement of theoretical predictions for both the effect of the applied field and the temperature on the excitonic peak position and the Fabry-Perot shift experimentally measured on different fabricated EAM structures has been achieved. Thanks to this, we are now able to design an optimal VCSEL structure with integrated electro-absorption modulator.

To aim for very high frequency efficient electrical injection we focused also on the BCB characterization up to 110 GHz and the injection scheme design specific to this triple electrode device. These measurements are of high interest for the optimum design of the access while considering the parasitic effects. We then compare coplanar and micro strip lines access, with a taper or not, to decrease the pad capacitance and so increase the cut-off frequency.