# 29GHz-bandwidth monolithically integrated EAM-VCSEL

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# 29GHz-bandwidth monolithically integrated EAM-VCSEL

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* *Now with II-VI Laser Enterprise*

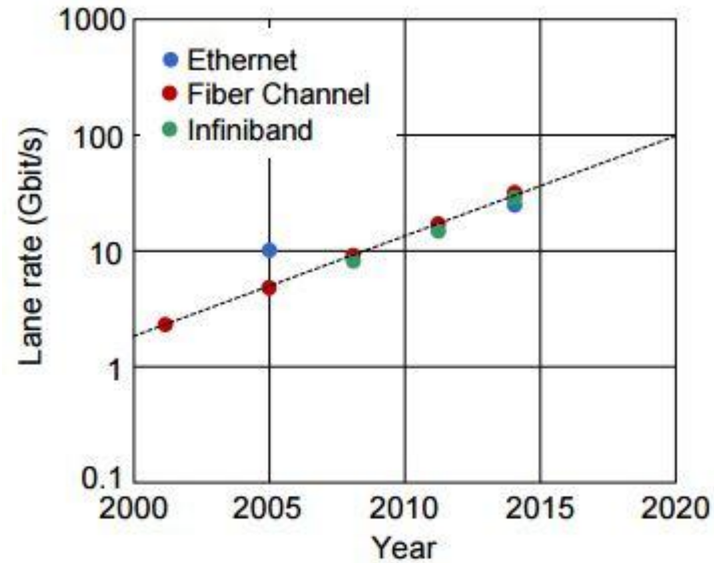
## > VCSEL modulation speed increase


Datacenters



Consumer electronics

High performance computing




*Pluggable tranceiver*


*Active optical cable*


*Mid-board optical module*


**Next generation : 100 Gb/s**

From A. Larsson presentation « VCSELs and Optical Interconnects », Chalmers, 2016

# Project context

## > VCSEL modulation speed increase

### Direct modulation

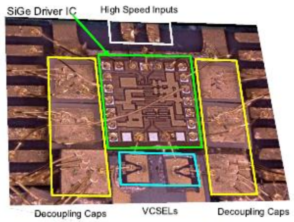
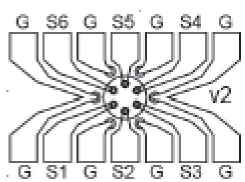



Fig. 1. Photograph of transmitter showing driver IC, VCSELs, decoupling capacitors and printed circuit board traces.

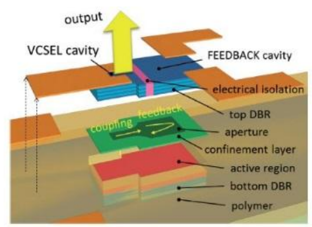
71 Gb/s NRZ modulated VCSEL
30 GHz Chalmers - 2015,
33 GHz Berlin - 2016



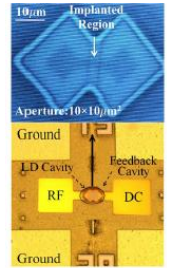

6x40Gb/s -> 240 Gb/s
Chalmers - 2015

- ✓ Standard approach
- ✓ Footprint
- ✘ High drive current
- ✘ Carriers dynamics limitation

### Lateral integration



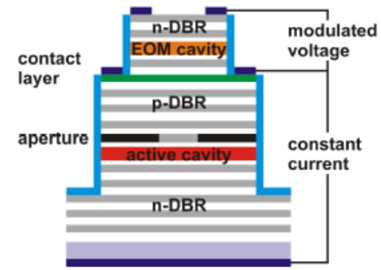

EAM laterally integrated
> 30 GHz
Tokyo Inst. Technol. - 2015




Transverse Coupled-Cavity VCSEL
10 GHz
Tokyo Inst. Technol. - 2014

- ✓ Less chirp
- ✘ Modulation depth
- ✘ Feedback

### Vertical modulation



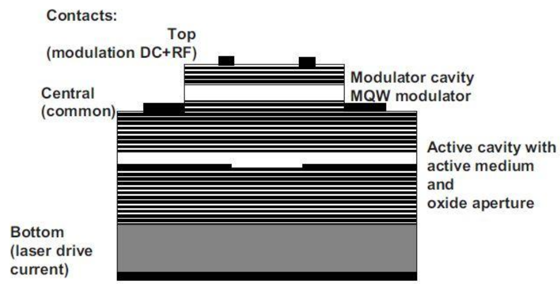

EO modulation of VCSEL
>35 GHz T. U. Berlin – 2008
23 GHz ECE Illinois - 2010

<u>Electro-refractive effect:</u>
Modif. of the top DBR properties

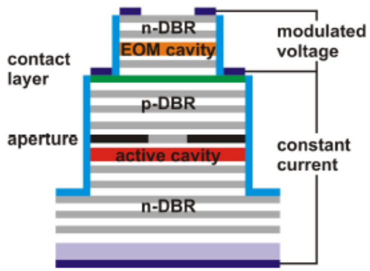
- ✓ Footprint
- ✓ Standard VCSEL technology
- ✓ Higher bandwidth
- ✘ Coupled cavities

## > VCSEL modulation speed increase

Vertical modulation




EAM - VCSEL
20 GHz Univ. Albany - 2010




EO modulation of VCSEL
>35 GHz T. U. Berlin – 2008
23 GHz ECE Illinois - 2010

<u>Electro-absorption effect:</u>
Absorption in the modulator cavity

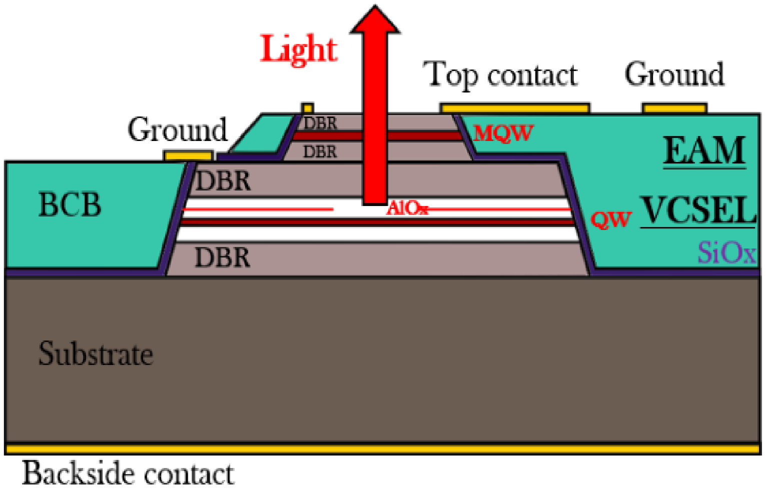
- ✓ Footprint
- ✓ Standard VCSEL technology
- ✓ Higher bandwidth
- • Weakly Coupled cavities

<u>Electro-refractive effect:</u>
Modif. of the top DBR properties

- ✓ Footprint
- ✓ Standard VCSEL technology
- ✓ Higher bandwidth
- ✘ Coupled cavities

## > Our approach

## Vertical integration of an Electro-Absorption Modulator




**Advantages:**

- Weakly coupled cavities
- Global consumption < 100 fJ/bit (estimation) **[1]**
- Optical absorption dynamics up to 300 GHz **[2]**

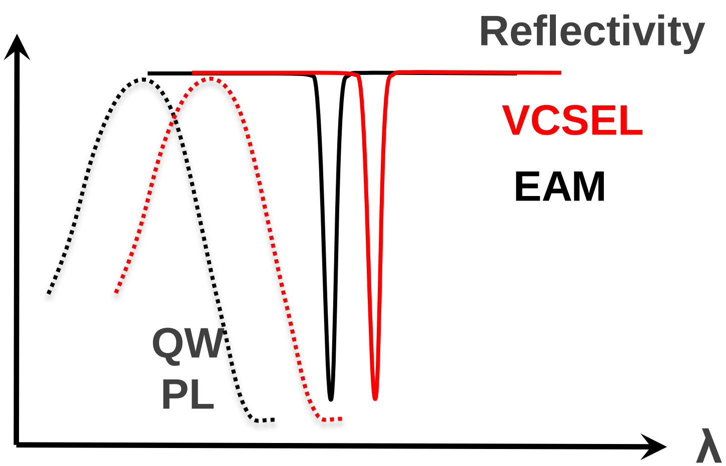
**Challenges:**

- Optical optimization (shared DBR and modulator MQW)
- Impact of temperature on modulator
- RF Design for high-speed electrical injection
- Epitaxial growth
- Technological integration


[1] X. Gu, T. Shimada, A. Matsutani and F. Koyama, « 35-µm Bragg Reflector Waveguide Modulator for High-Speed and Energy-Saving Operation », PTL, 2013
[2] V. V. Nikolaev and E. A. Avrutin, « Photocarrier Escape Time in Quantum-Well Light-Absorbing Devices: Effects of Electric Field and Well Parameters », JoQE, 2003

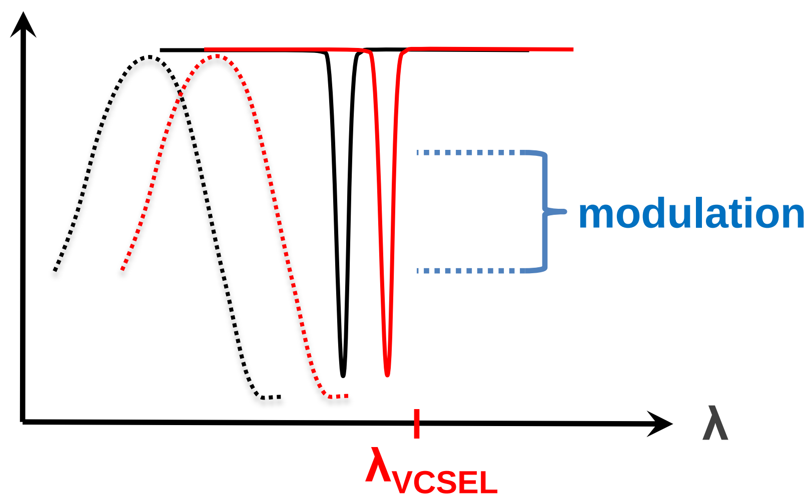
> **Main challenge : optimum detuning between both cavities**

**Room Temp. - without field**

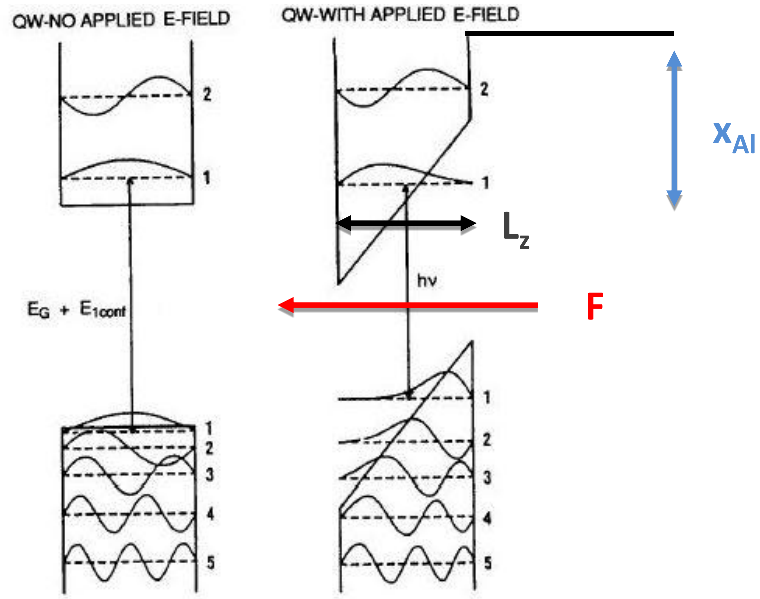



**VCSEL operation (50°C)**

**Electric field applied to EAM**

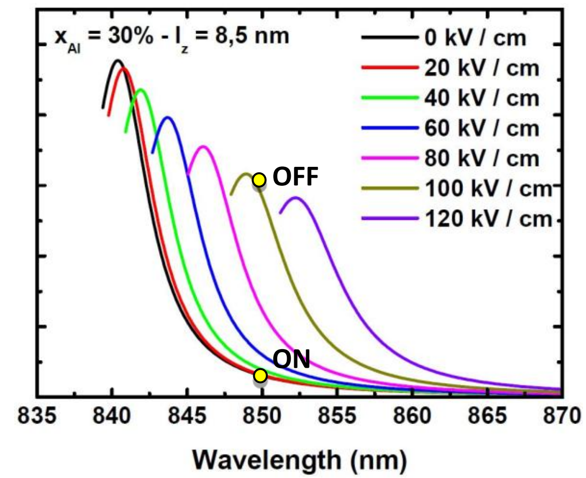


# Electro-Optical simulation




**Main QW physical parameters :**

- $x_{Al}$ = Al concentration in the barrier (%)
- $L_z$ = QW width (nm)
- F = electric field (kV/cm)




*Usual figures of merit* :

**$\Delta\alpha/\alpha_0$ (modulation depth)**

**$\Delta\alpha/(\Delta F)^2$ (mini. Electric field)**

*<u>Proposed figure of merit :</u>*

**$M = (\Delta\alpha/\alpha_0) . (\Delta\alpha/(\Delta F)^2)$**

to be maximized

*<u>Optimization for :</u>*

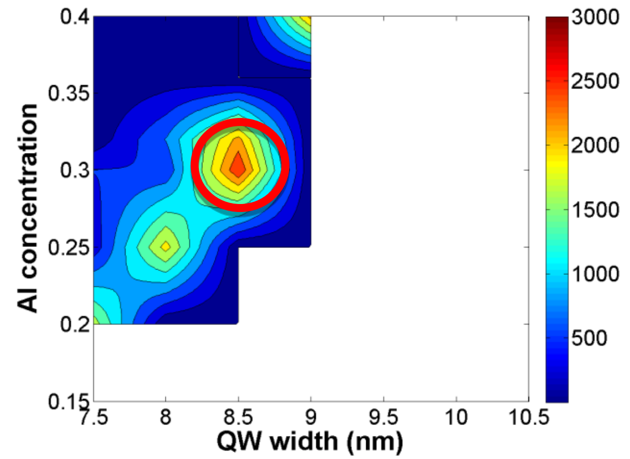
*7.5 nm < $L_z$ < 10.5 nm*

*15 % < $x_{Al}$ < 40 %*

*$F_{ON}$ 0 → 80 kV /cm*

*$F_{OFF}$ 20 → 100 kV /cm*

**M for ΔF range 80-100 kV/cm ( ΔV=5.6V)**




L. Marigo-Lombart et al. J. Phys. D: Appl. Phys. 51 (2018)

# EAM stand-alone (Undoped DBR)



**MQW embedded in**
**an asymmetric Fabry-Perot structures (ASFP)**

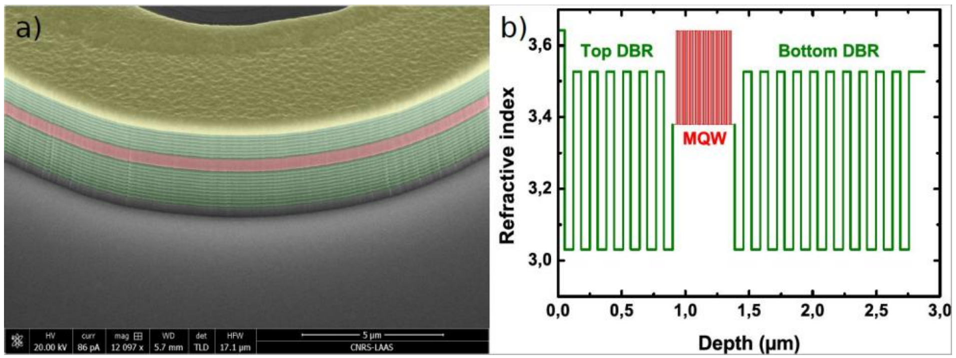
6-period top DBR

25 QWs

$x_{Al}$ = 30%

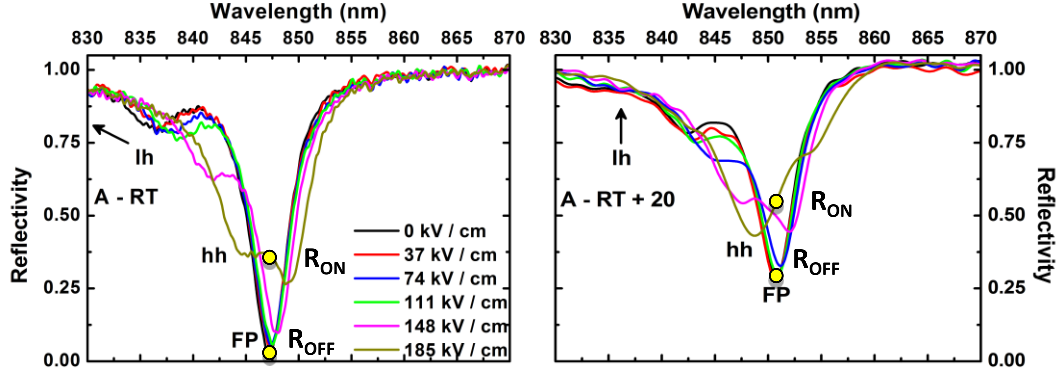
Lz = 8.5 nm

10-period bottom DBR

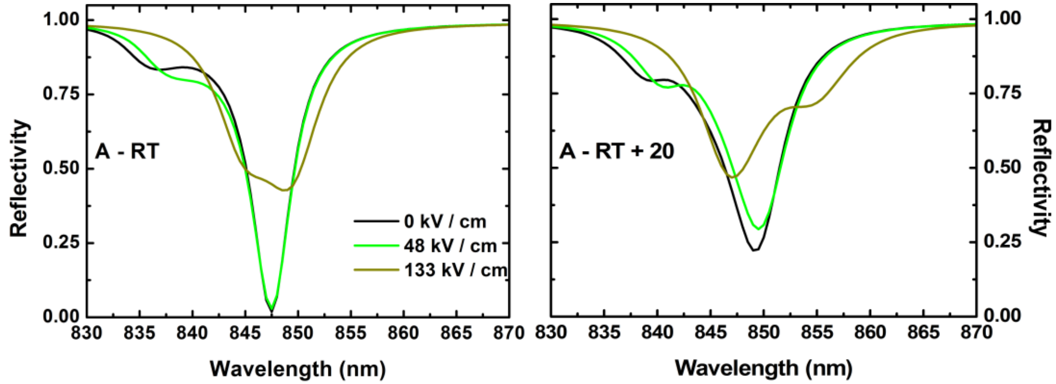



*SEM crossview of a EAM mesa*

*Experimental measurements (by hyperspectral imaging setup)*




*ASFP Modelling (Lengyel EA model - JQE 1990)*




***Very good agreement measurement / simulation***

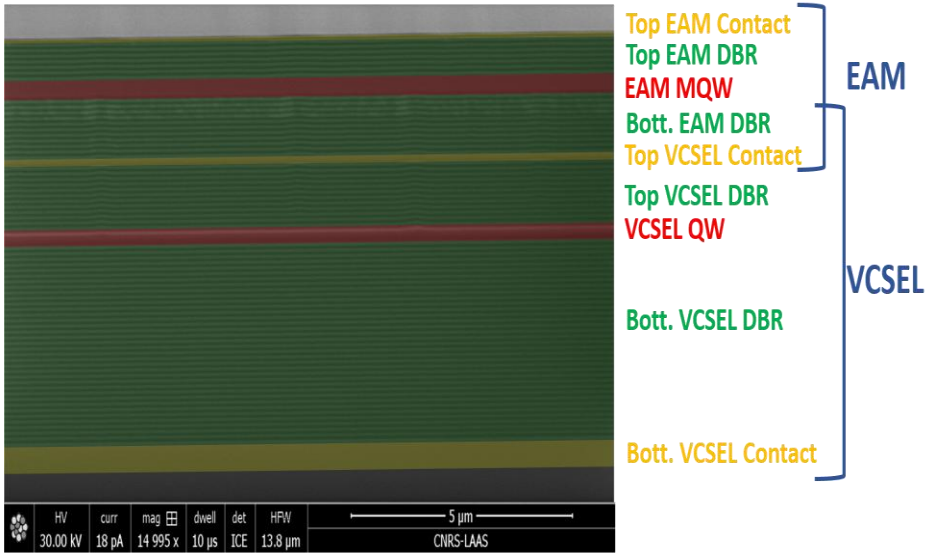
- Performance deterioration with the temperature
- Ideal EAM detuning => $\lambda_{\text{Excitonic peak}} < \lambda_{\text{Fabry-Pérot}}$

L. Marigo-Lombart et al. J. Phys. D: Appl. Phys. 51 (2018)

# Molecular Beam Epitaxy

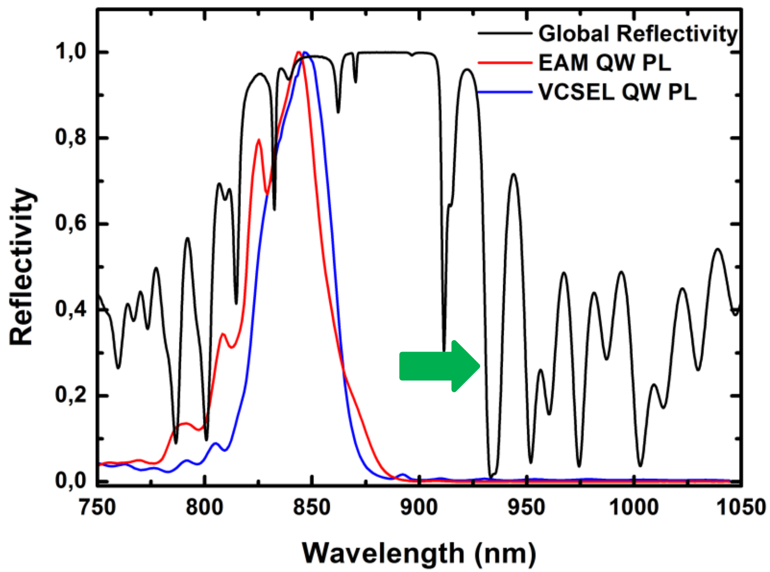


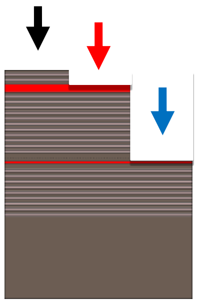
- **MBE Growth in-situ monitoring**
- Optical flux monitoring (Ga, Al effusion cells)
  *>>> LAAS Patent (A. Arnoult et al.)*
- Optical reflectometry
- *Wafer curvature (newly developed technique)*
  *>>> LAAS Patent (A. Arnoult et al.)*




SEM crossview of a EAM – VCSEL grown by Molecular Beam Epitaxy in the LAAS-CNRS cleanroom

*EAM – VCSEL*

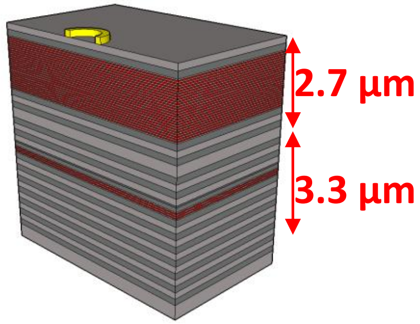


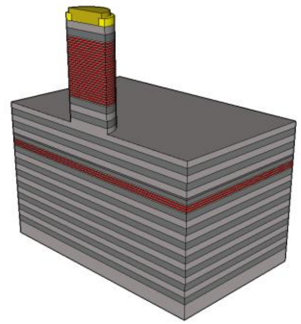
**EAM - VCSEL cavities :**

- EAM absorption and VCSEL gain blueshifted w/ cavities
- FP cavity modes : $\lambda_{VCSEL} > \lambda_{EAM}$

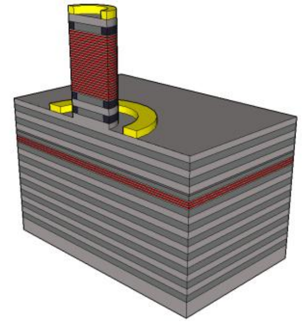
# Process flow – EAM-VCSEL fabrication



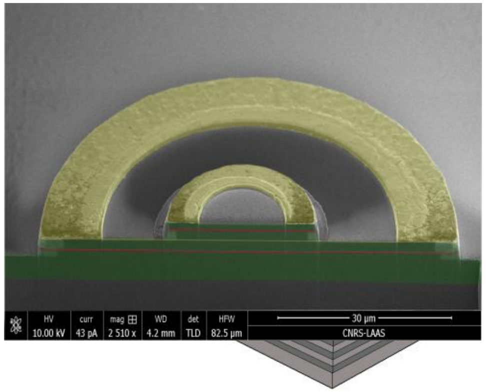

EAM top contact



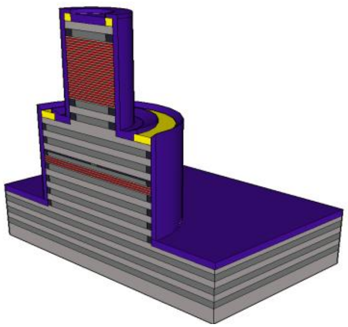
EAM etch



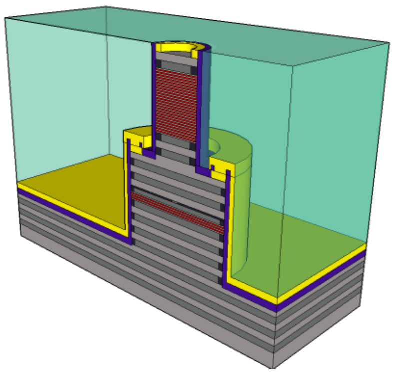
EAM bottom contact



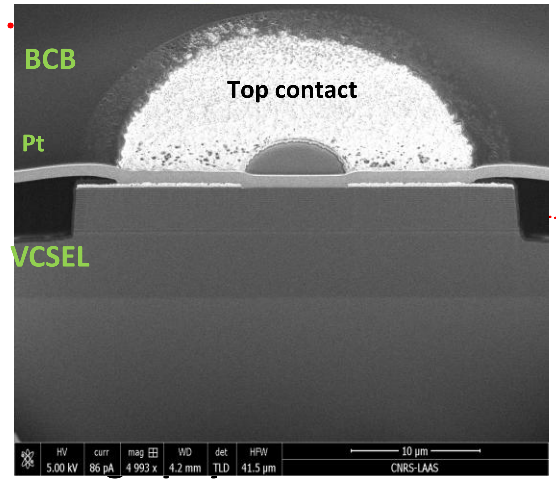

EAM passivation + VCSEL etch + oxidation

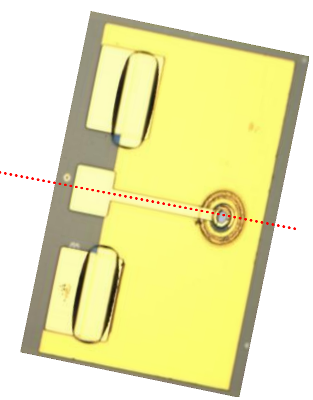


VCSEL passivation



Contact report + BCB planarization



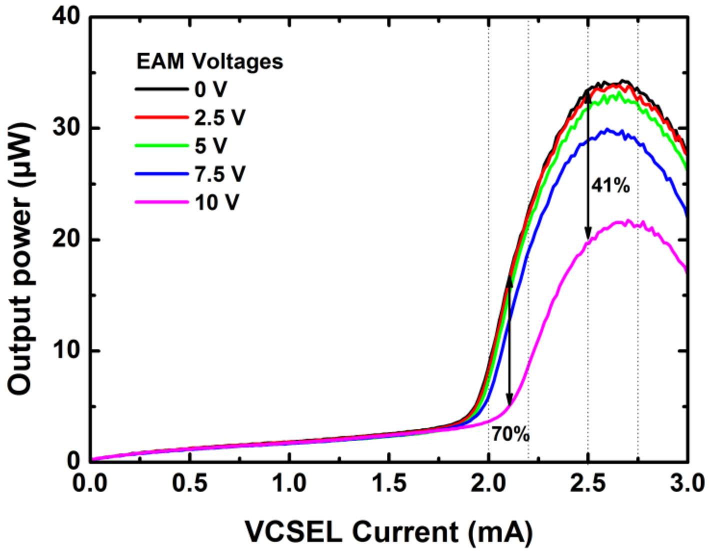



GSG contacts

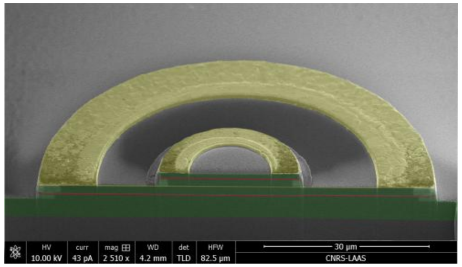
L. Marigo-Lombart et al., Proc. SPIE 9892, Semicond. Lasers and Laser Dyn. VII, 98921R, April 2016

# EAM – VCSEL : Static perf.

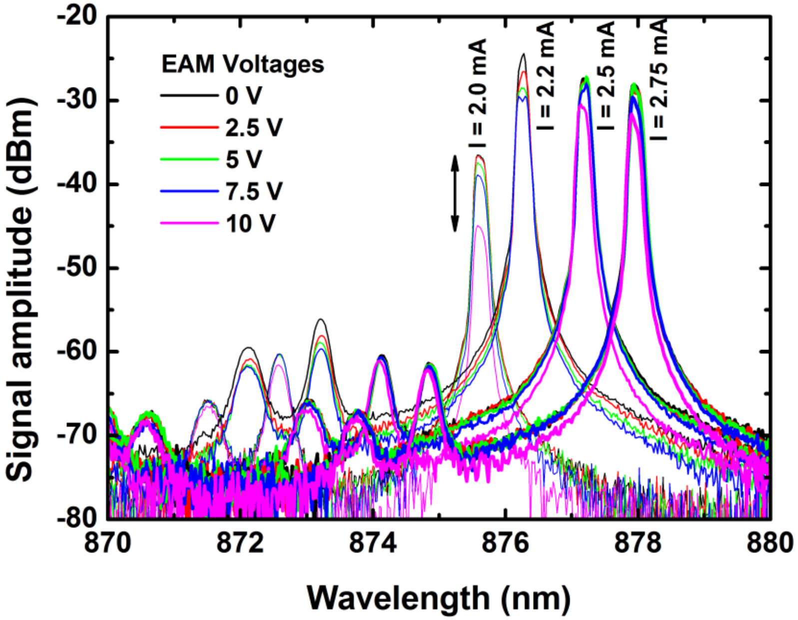





Very small oxide aperture ( 1 µm)
⇒ High temperature
⇒ High voltage (around 10V)
⇒ Low reliability
⇒ Low output power

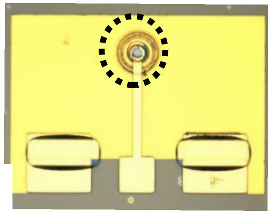



**Modulation > 40 %**
**Chirp ≤ 0.08 nm**



# High frequency perf. : EAM (doped DBR)





***Experimental hurdles :***

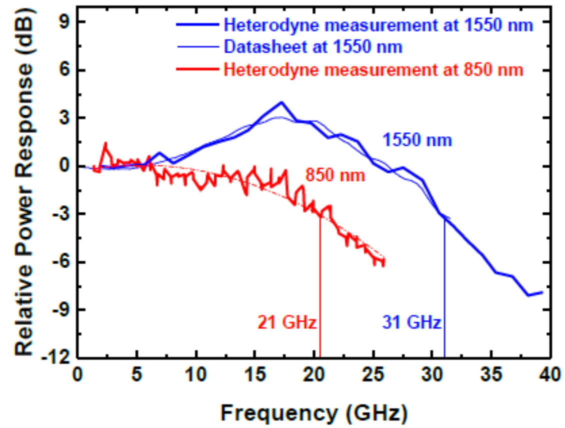
**- Optical alignment between SM fiber (Ø < 10µm) and EAM (Ø 18 - 27 µm)**

*>>> Lock-in amplifier assisted aligment*

**- Photodiode HF response for calibration/normalization**

*>>> InGaAs HF response at 850nm ≠ 1550nm*

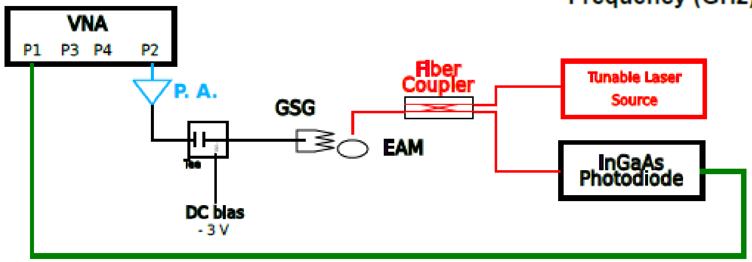
*>>> Measured by heterodyne beating technique @ 850nm*



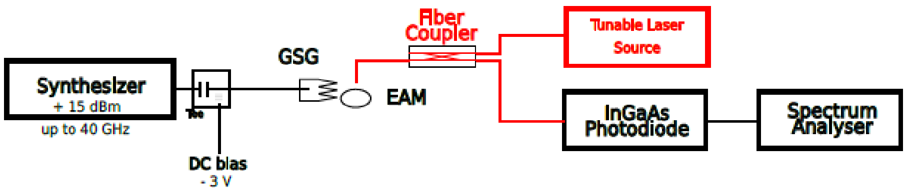

**- Significant modulation contrast :**

*>>> Two setups have been used :*

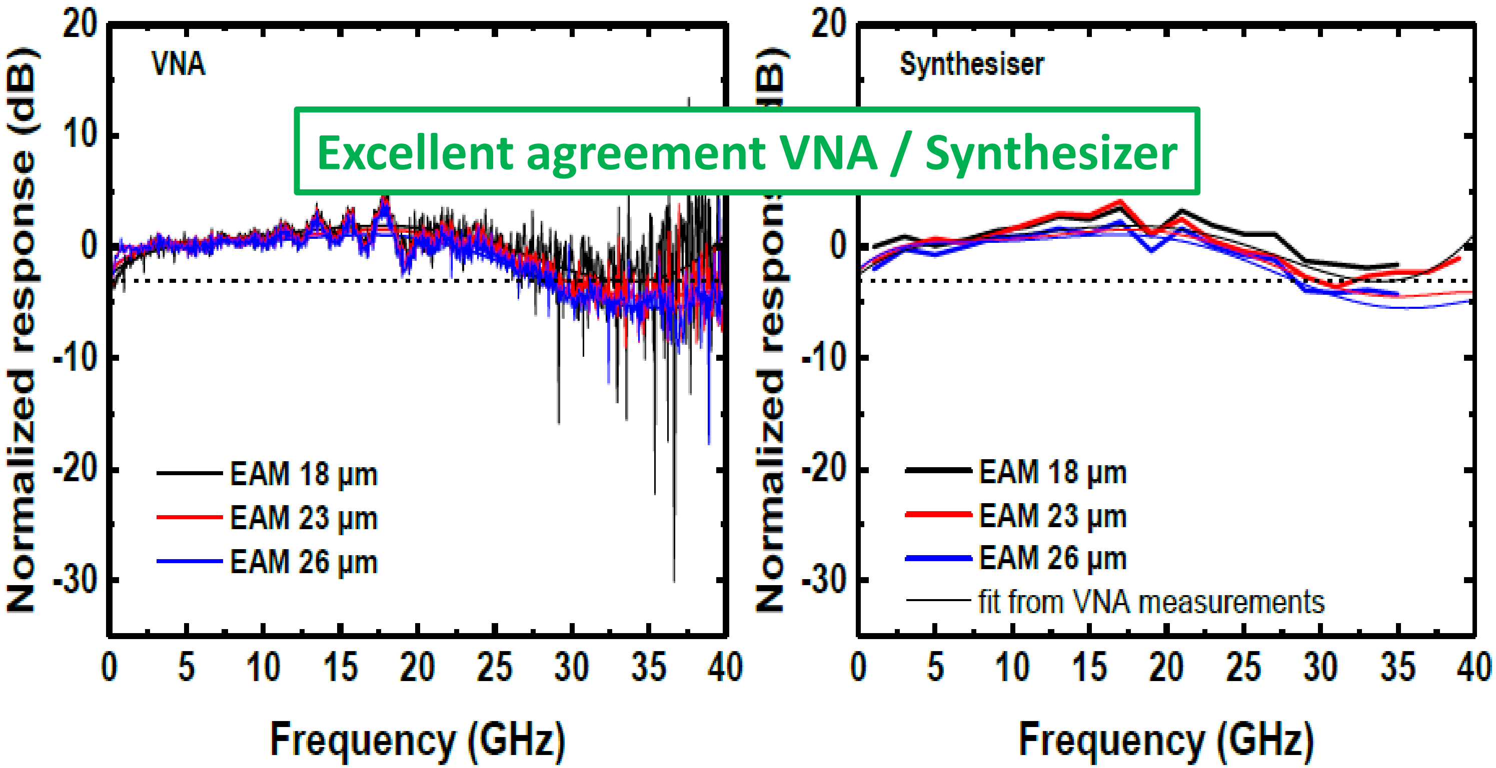
1) VNA (or PD) with power amplified output




2) RF synthesizer => possibility to apply a constant voltage on the EAM pads



# High frequency perf. : EAM (doped DBR)




**Excellent agreement VNA / Synthesizer**

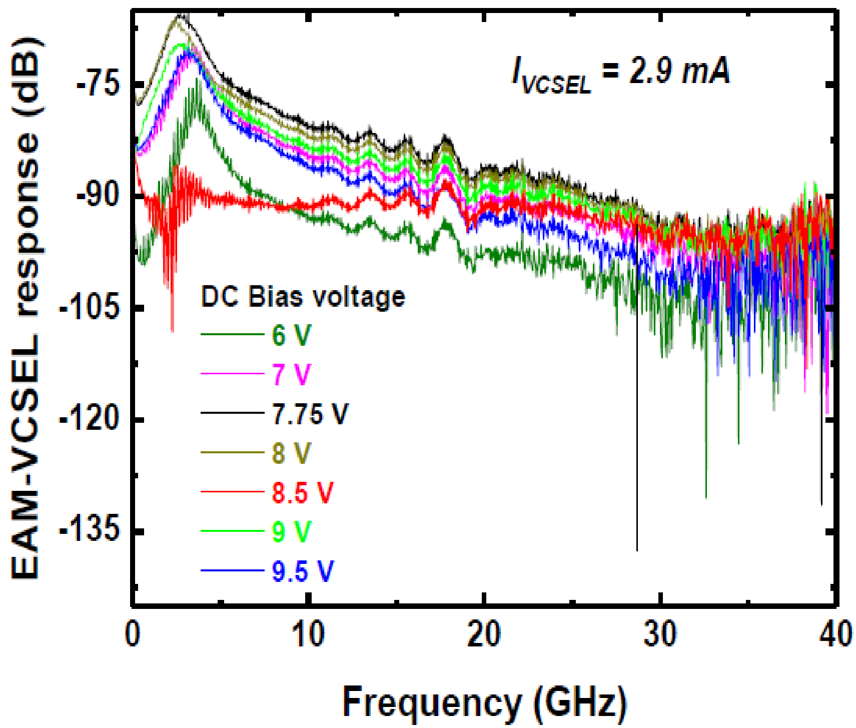
**Physical parameters :**

- ✓ **Diameter:** $f_{-3dB}$ = 28, 29 and 32 GHz for Ø=26, 23 and 18 µm
- ✓ **Temperature:** no impact (in the studied range)
- ✓ **Illumination wavelength:** no impact on $f_{-3dB}$ but amplitude modification
- ✓ **Bias voltage:** no impact on $f_{-3dB}$ but amplitude modification

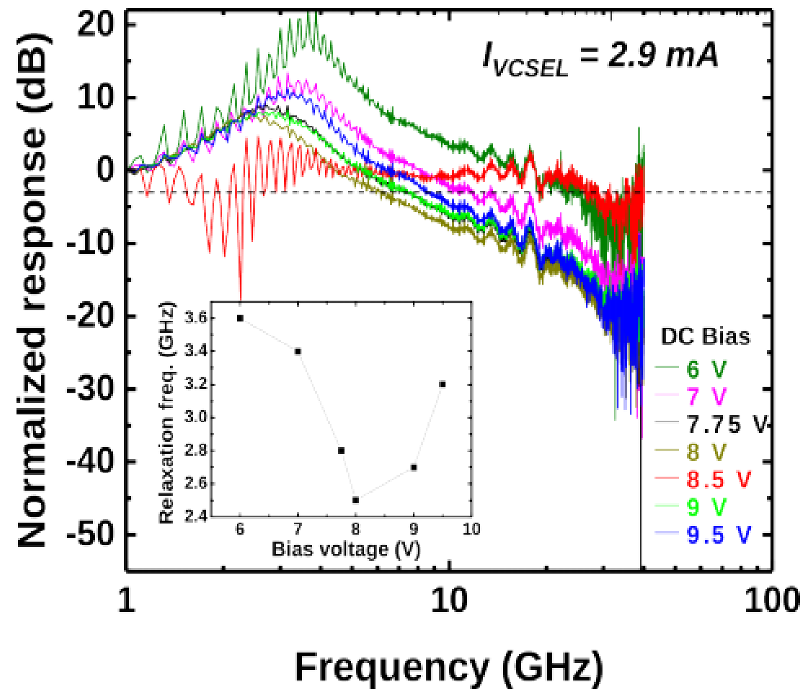
*- Study/optimization of the HF injection access*
*>>> Extraction of the EAM parasitics contribution*
***=> Electrical model developed***

# High frequency perf. : EAM-VCSEL






*L Marigo-Lombart et al, J. Phys. Photonics 1 02LT01 (2019)*




*Very pronounced resonance around 3 GHz*

For $V_{EAM}$ = 8.5 V and $I_{VCSEL}$ = 2.9 mA >>> **$f_{3dB}$ = 29 GHz**

Highest modulation for the vertical integration of an EAM onto a VCSEL (previous 20 GHz)

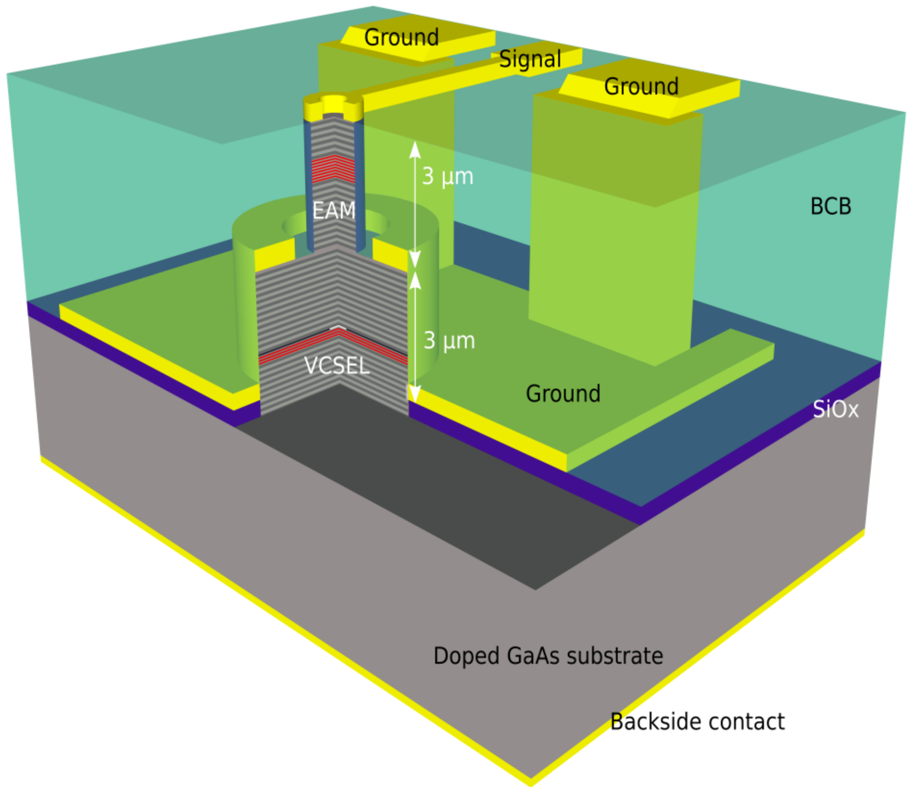
# Summary



**Stand-alone EAM**

- Modulation of 40 % with few volts
- Study of R (V,T)

- 30 GHz achieved
- Electrical model function of the diameter
- Study with T, V, λ




**EAM - VCSEL**

- Modulation > 40 % with few volts
- Chirp < 0.1 nm

- 29 GHz achieved
- Study with $V_{EAM}$, $I_{VCSEL}$