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29GHz-bandwidth monolithically integrated EAM-VCSEL

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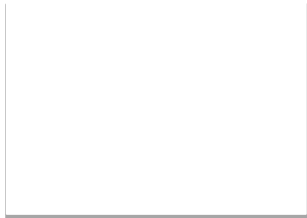
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* *Now with II-VI Laser Enterprise*

> VCSEL modulation speed increase



Datacenters



High performance computing



Consumer electronics

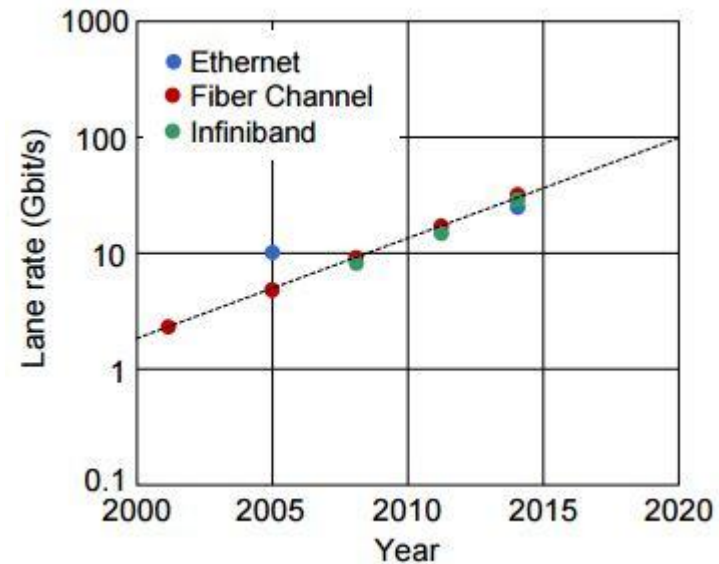
Pluggable transceiver



Active optical cable



Mid-board optical module



Next generation : 100 Gb/s

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

> VCSEL modulation speed increase

Direct modulation

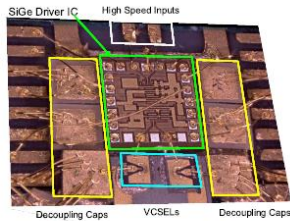
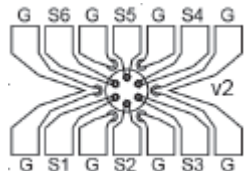


Fig. 1. Photograph of transmitter showing driver IC, VCSELS, decoupling capacitors and printed circuit board traces.

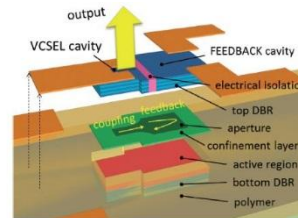
71 Gb/s NRZ modulated VCSEL
 30 GHz Chalmers - 2015,
 33 GHz Berlin - 2016



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

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

Lateral integration



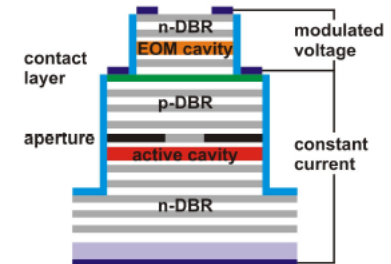
EAM laterally integrated
 > 30 GHz
 Tokyo Inst. Technol. - 2015



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

- ✓ Less chirp
- ✗ Modulation depth
- ✗ Feedback

Vertical modulation



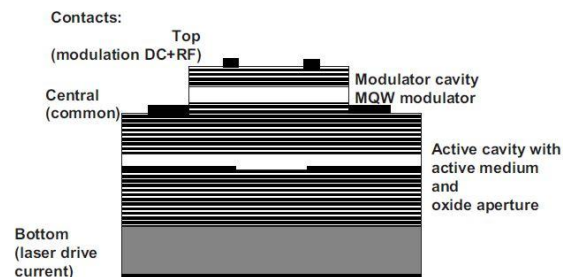
EO modulation of VCSEL
 >35 GHz T. U. Berlin - 2008
 23 GHz ECE Illinois - 2010

Electro-refractive effect:
 Modif. of the top DBR properties

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

> VCSEL modulation speed increase

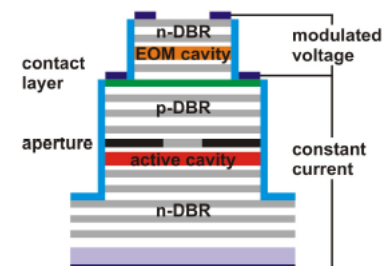
Vertical modulation



EAM - VCSEL
20 GHz Univ. Albany - 2010

Electro-absorption effect:
Absorption in the modulator cavity

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



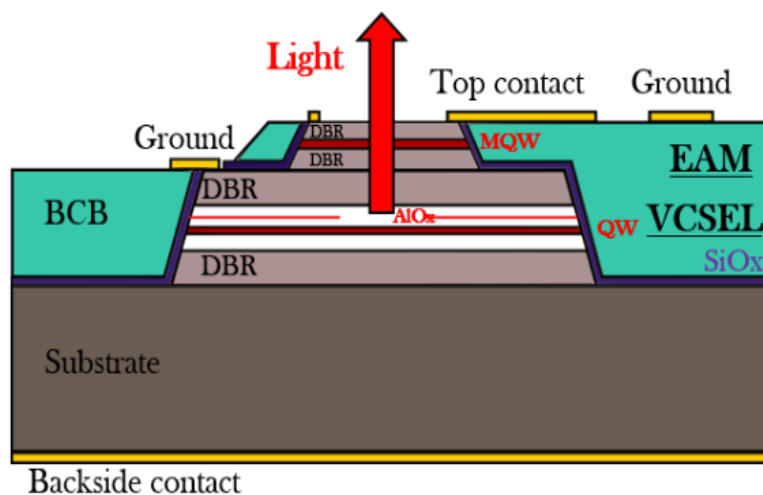
EO modulation of VCSEL
>35 GHz T. U. Berlin - 2008
23 GHz ECE Illinois - 2010

Electro-refractive effect:
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:

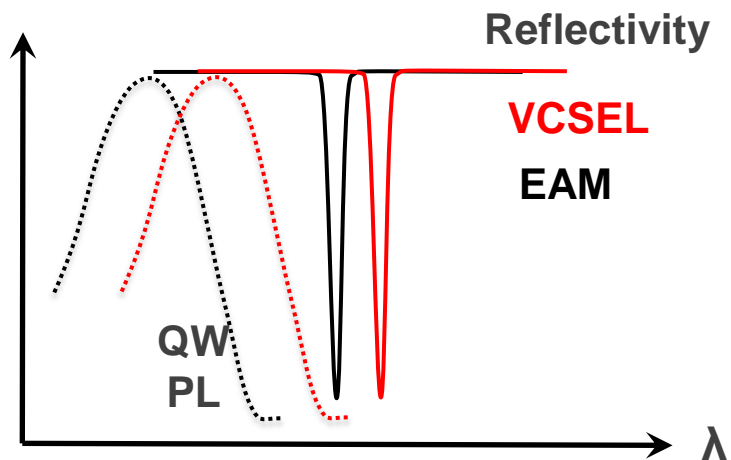
- Optical optimization (shared DBR and modulator MQW)
- Impact of temperature on modulator
- RF Design for high-speed electrical injection
- Epitaxial growth
- Technological integration

[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

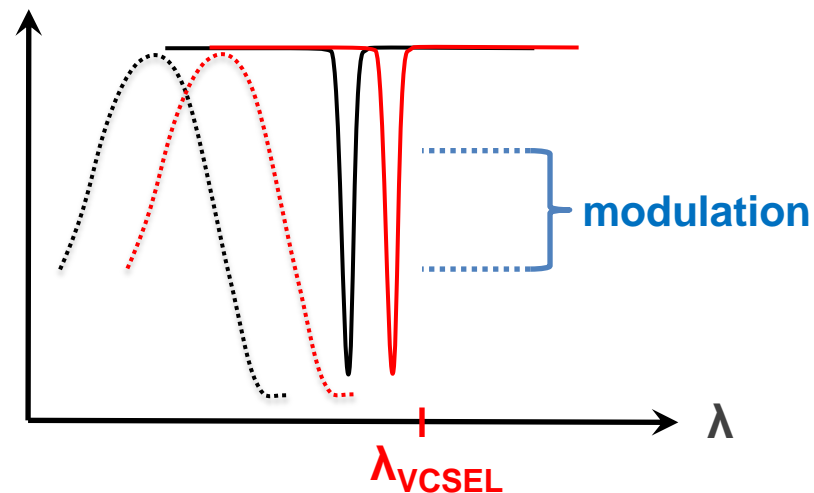
[2] V. V. Nikolaev and E. A. Avrutin, « Photocarrier Escape Time in Quantum-Well Light-Absorbing Devices: Effects of Electric Field and Well Parameters », JoQE, 2003

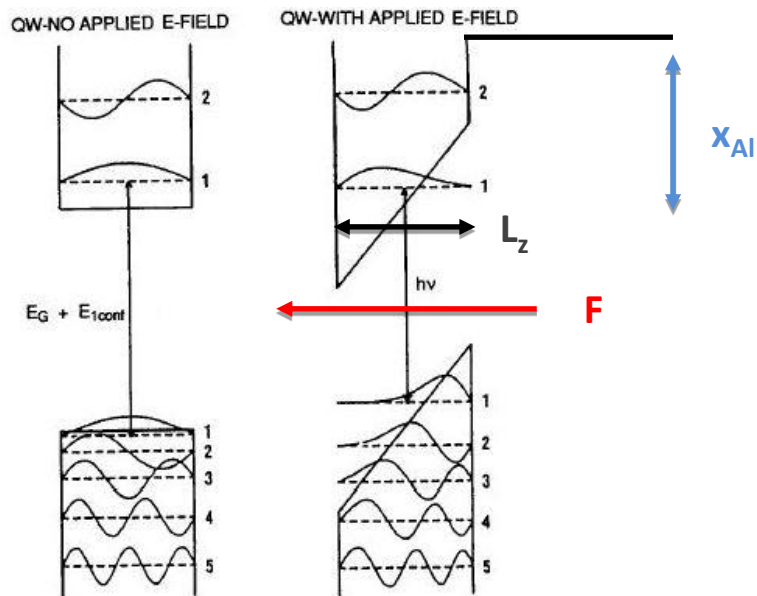
- > Main challenge : optimum detuning between both cavities

Room Temp. - without field



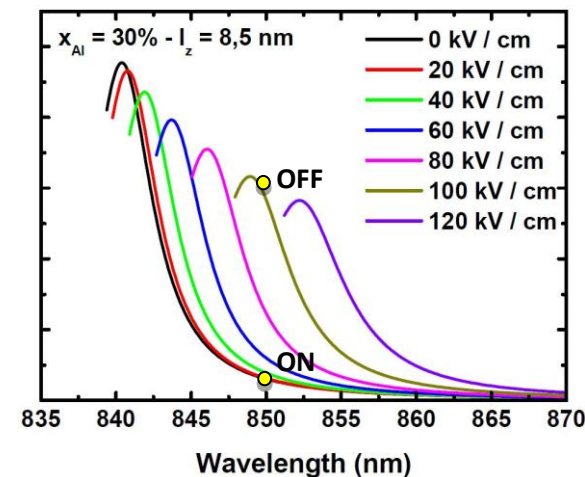
VCSEL operation (50°C)
Electric field applied to EAM





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)

Proposed figure of merit :

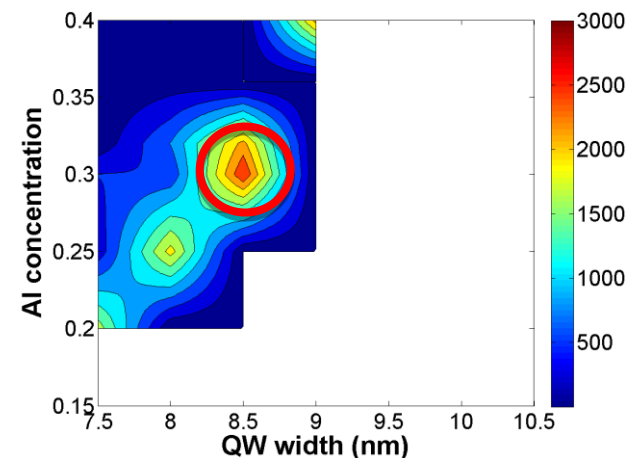
$$M = (\Delta\alpha/\alpha_0) \cdot (\Delta\alpha/(\Delta F)^2)$$

to be maximized

Optimization for :

- $7.5 \text{ nm} < L_z < 10.5 \text{ nm}$
- $15 \% < x_{Al} < 40 \%$
- $F_{ON} \ 0 \rightarrow 80 \text{ kV/cm}$
- $F_{OFF} \ 20 \rightarrow 100 \text{ kV/cm}$

M for ΔF range 80-100 kV/cm ($\Delta V=5.6V$)



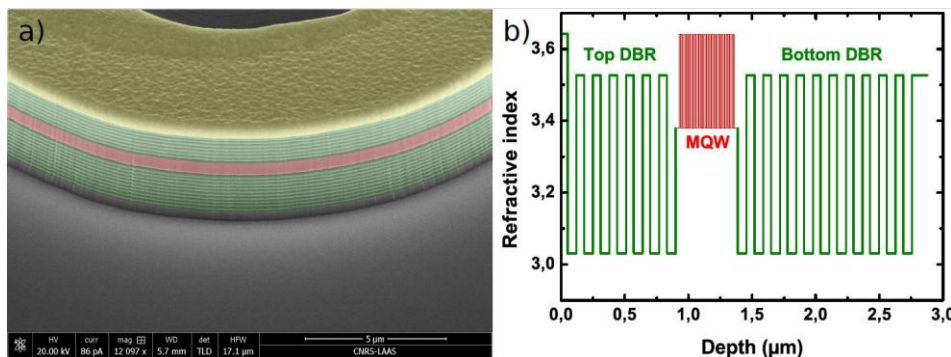
MQW embedded in an asymmetric Fabry-Perot structures (ASFP)

6-period top DBR
25 QWs

$$x_{Al} = 30\%$$

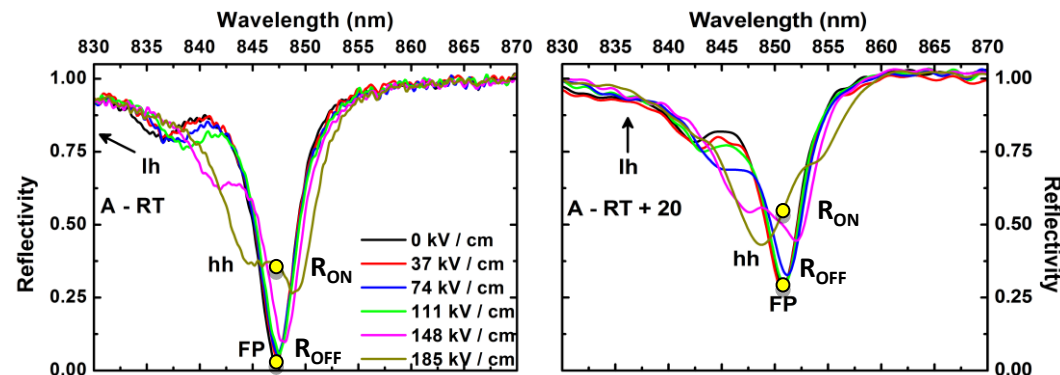
$$L_z = 8.5 \text{ nm}$$

10-period bottom DBR

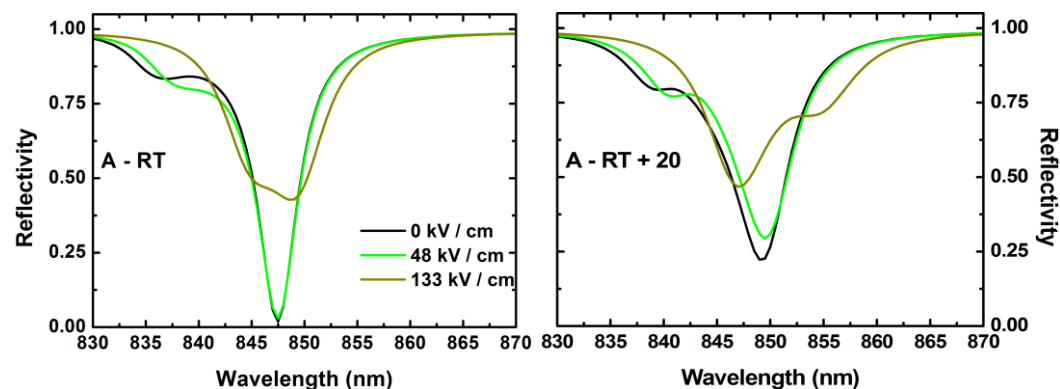


SEM crossview of a EAM mesa

Experimental measurements (by hyperspectral imaging setup)



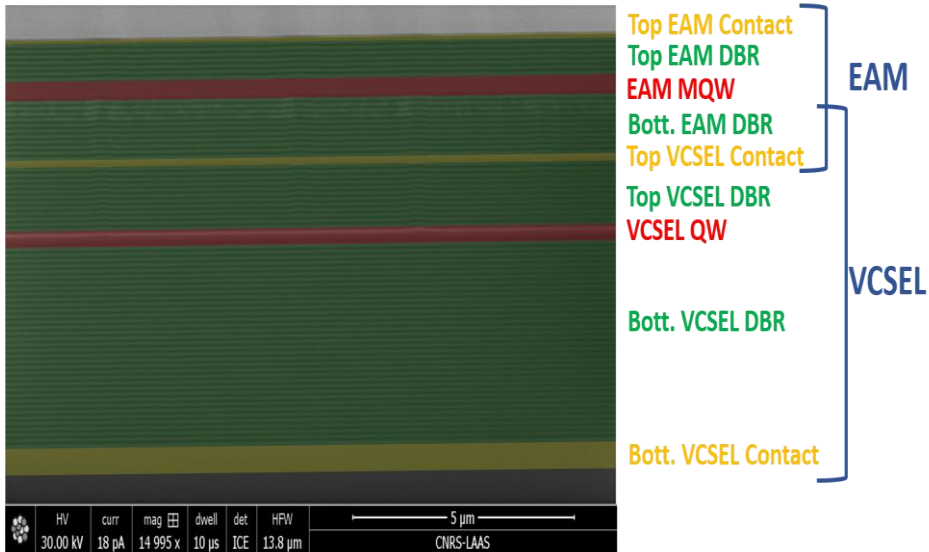
ASFP Modelling (Lengyel EA model - JQE 1990)



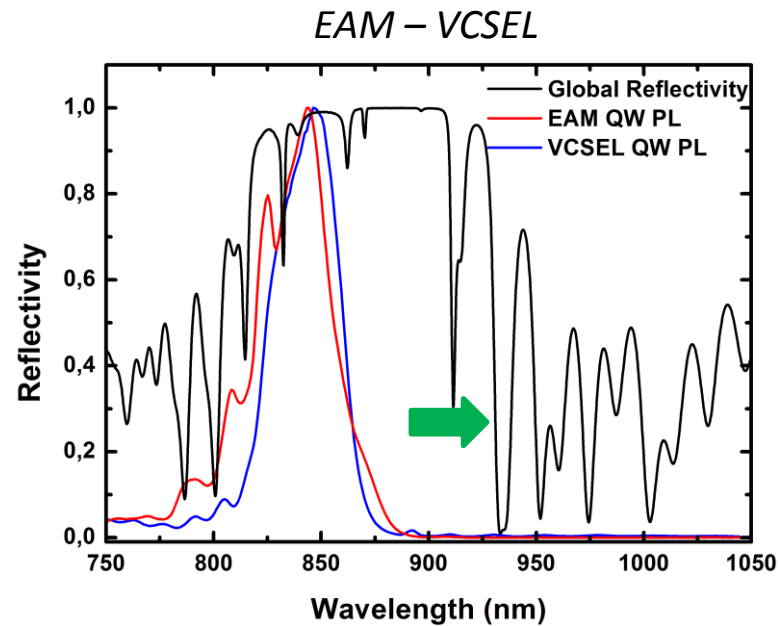
Very good agreement measurement / simulation

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

- **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.)

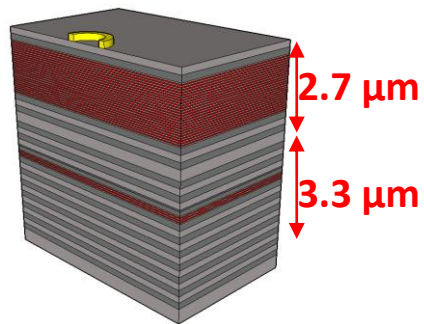


SEM crossview of a EAM – VCSEL grown by Molecular Beam Epitaxy in the LAAS-CNRS cleanroom

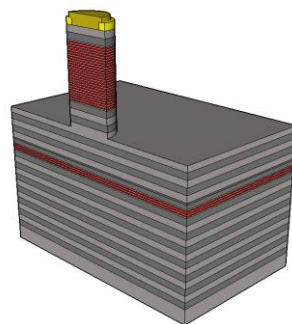


EAM - VCSEL cavities :

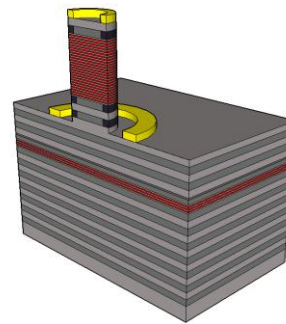
- EAM absorption and VCSEL gain blueshifted w/ cavities
- FP cavity modes : $\lambda_{VCSEL} > \lambda_{EAM}$



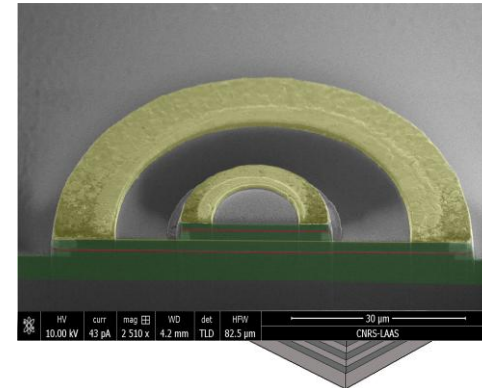
EAM top contact



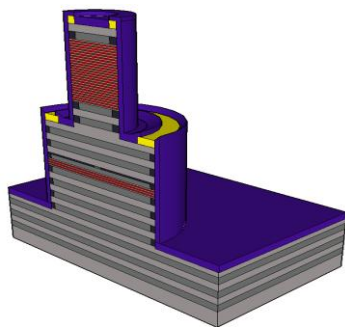
EAM etch



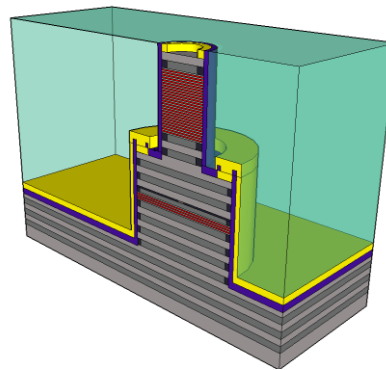
EAM bottom contact



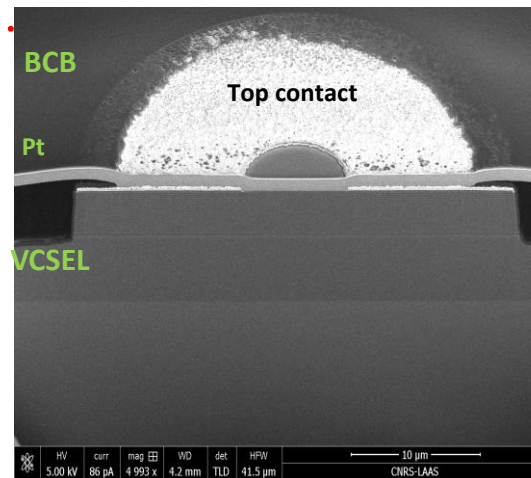
EAM passivation + VCSEL etch
+ oxidation



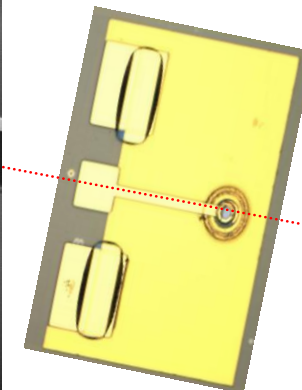
VCSEL passivation



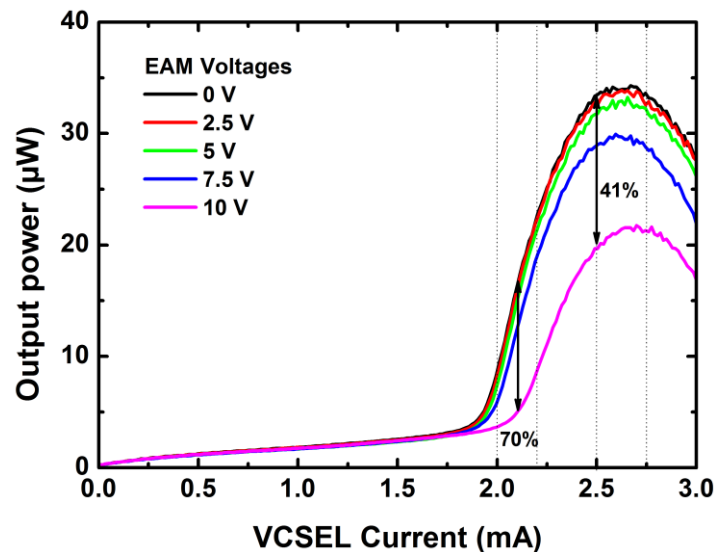
Contact report +
BCB planarization



GSG contacts



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



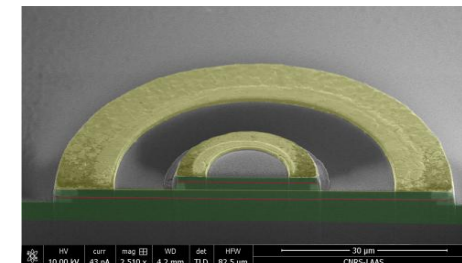
Very small oxide aperture (1 µm)

⇒ High temperature

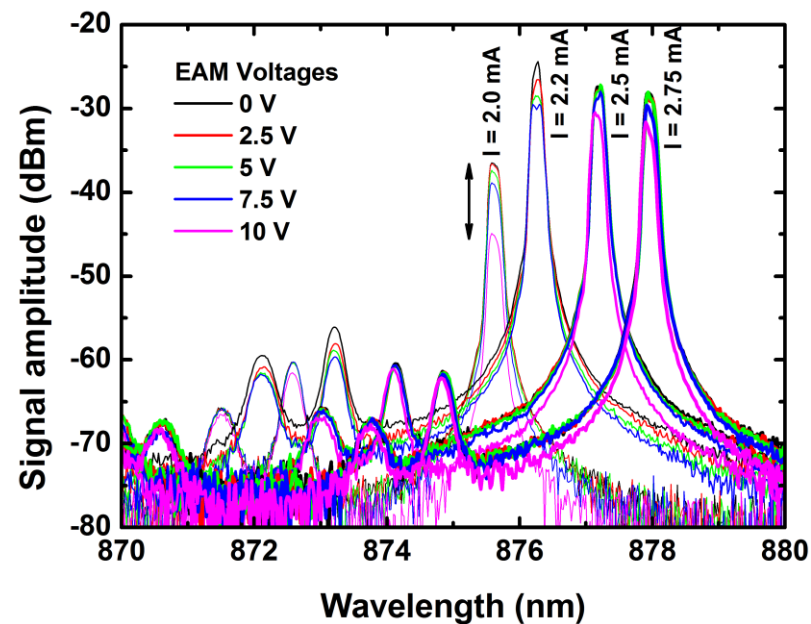
⇒ High voltage (around 10V)

⇒ Low reliability

⇒ Low output power



Modulation > 40 %
Chirp ≤ 0.08 nm



Experimental hurdles :

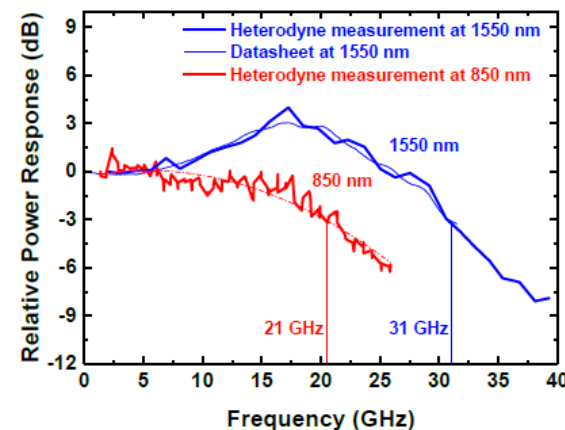
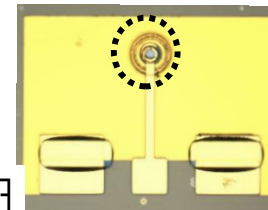
- Optical alignment between SM fiber ($\varnothing < 10\mu\text{m}$) and EAM ($\varnothing 18 - 27 \mu\text{m}$)

>>> Lock-in amplifier assisted alignment

- Photodiode HF response for calibration/normalization

>>> InGaAs HF response at 850nm \neq 1550nm

>>> Measured by heterodyne beating technique @ 850nm

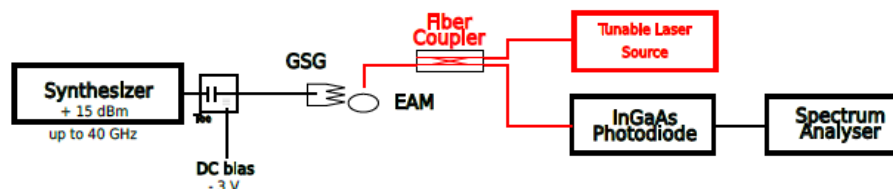
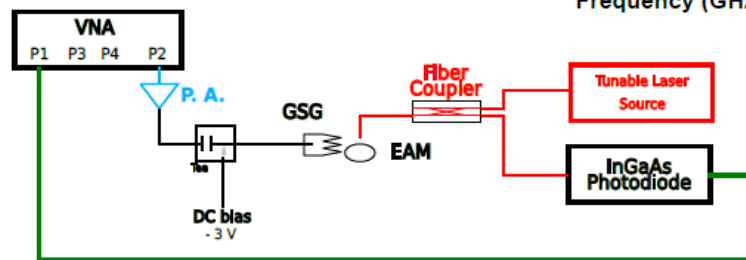


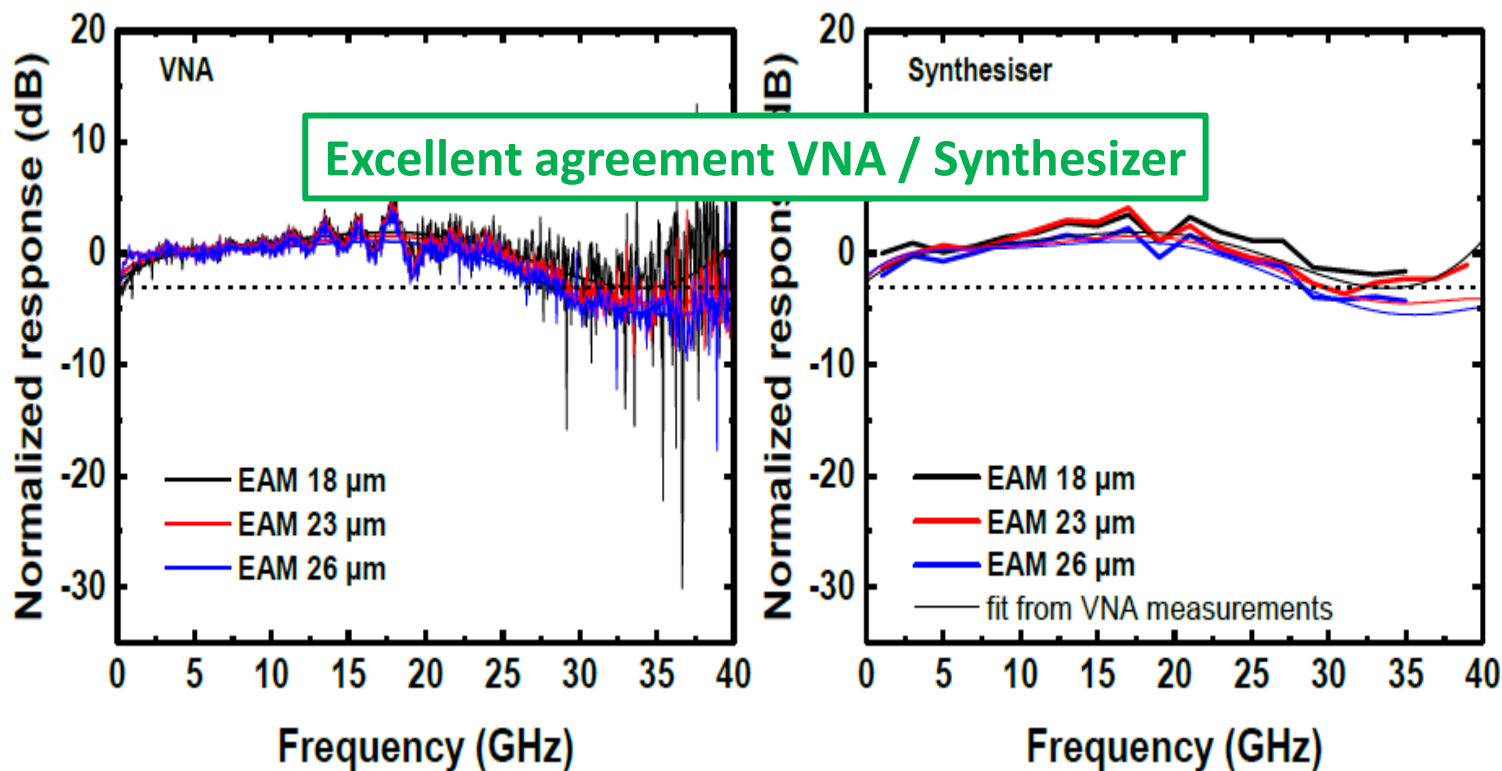
- Significant modulation contrast :

>>> 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

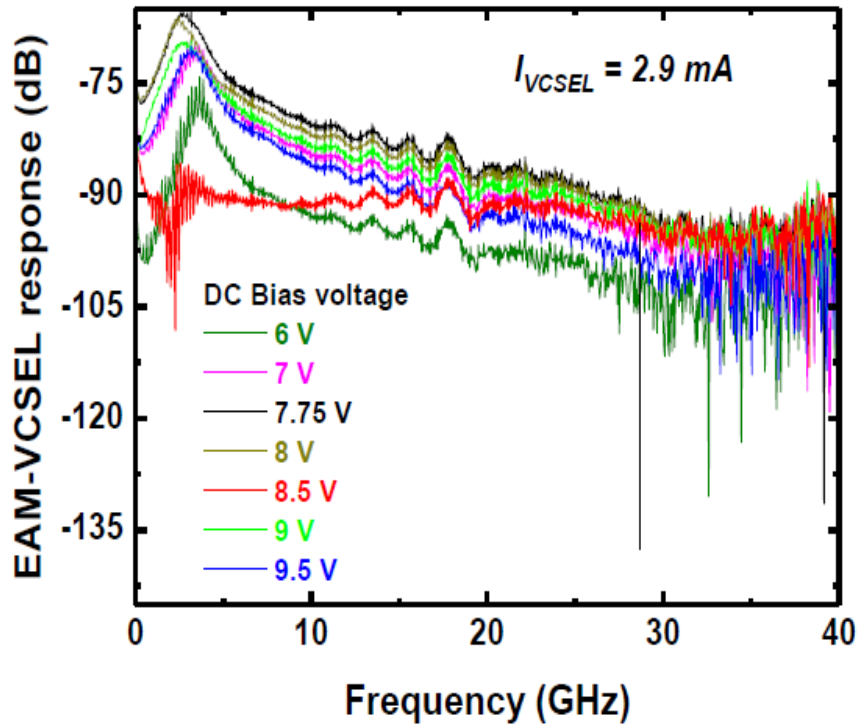




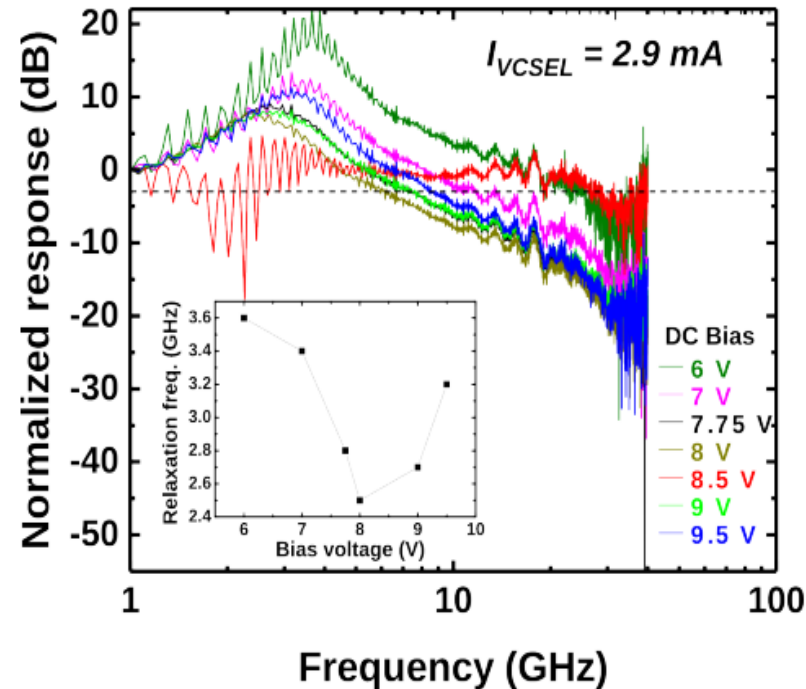
Physical parameters :

- ✓ **Diameter:** $f_{-3dB} = 28, 29$ and 32 GHz for $\varnothing=26, 23$ and $18 \mu\text{m}$
- ✓ **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**



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

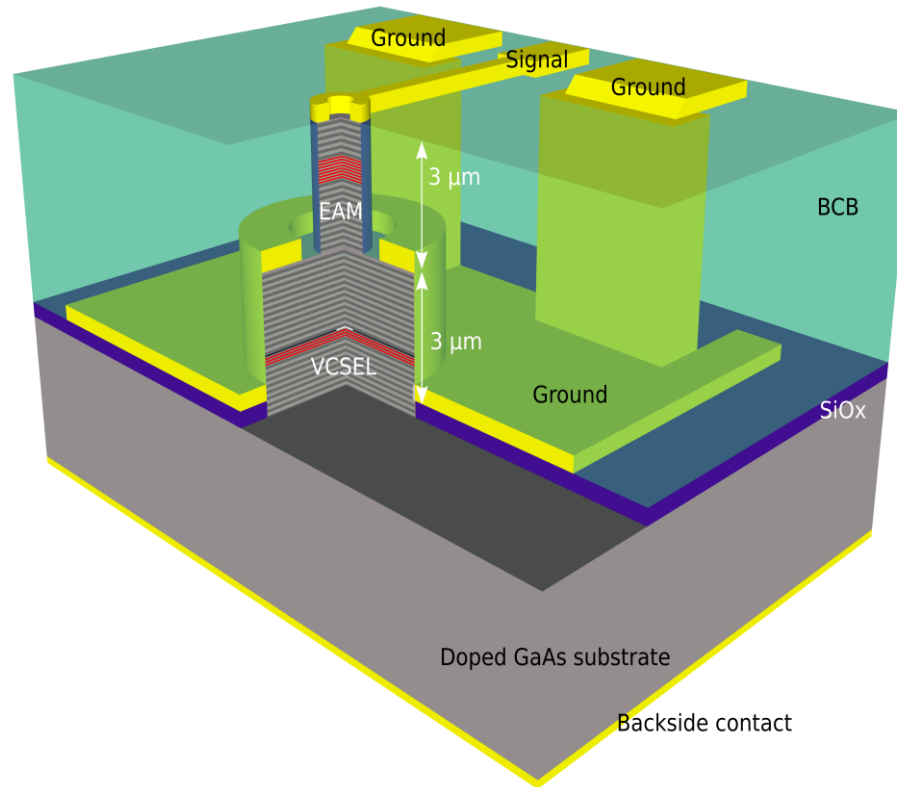


Very pronounced resonance around 3 GHz

For $V_{EAM} = 8.5 \text{ V}$ and $I_{VCSEL} = 2.9 \text{ mA} \gg \gg f_{3dB} = 29 \text{ GHz}$
Highest modulation for the vertical integration of an EAM onto a VCSEL
 (previous 20 GHz)

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}

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