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Monolithically integrated 850-nm VCSEL / Electro-Absorption Modulator structures grown by MBE

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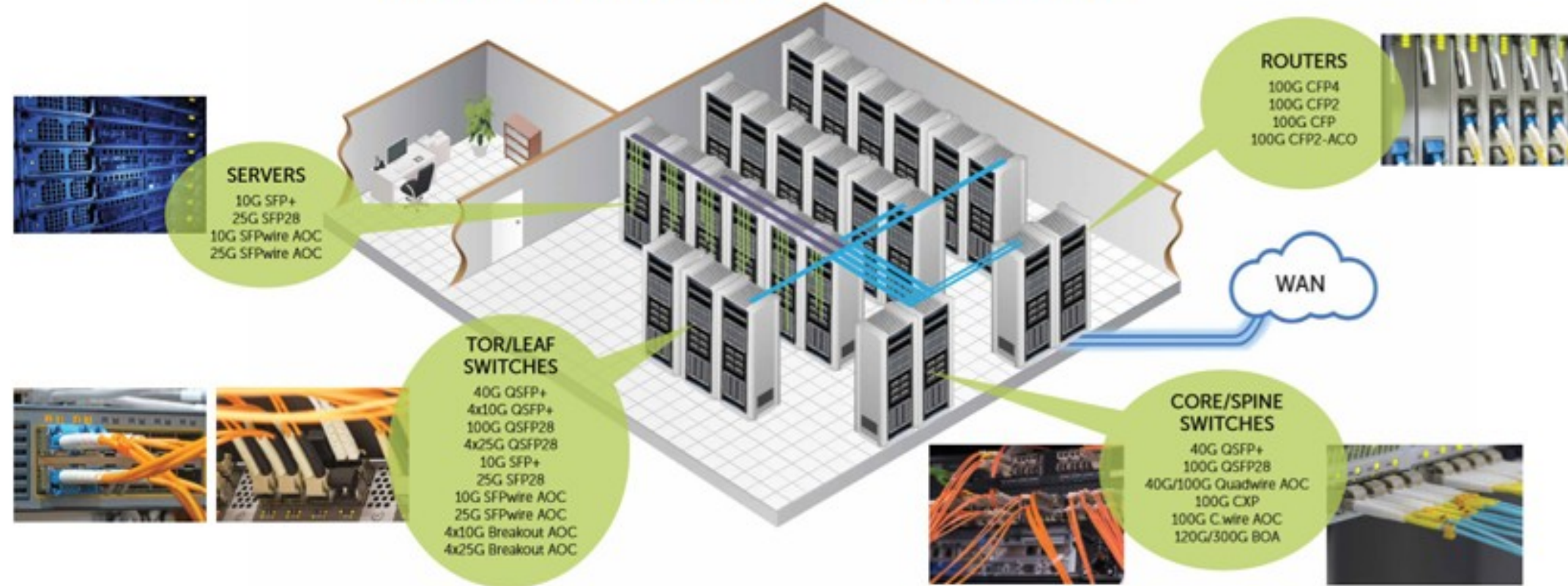
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High-Speed modulation with VCSELS

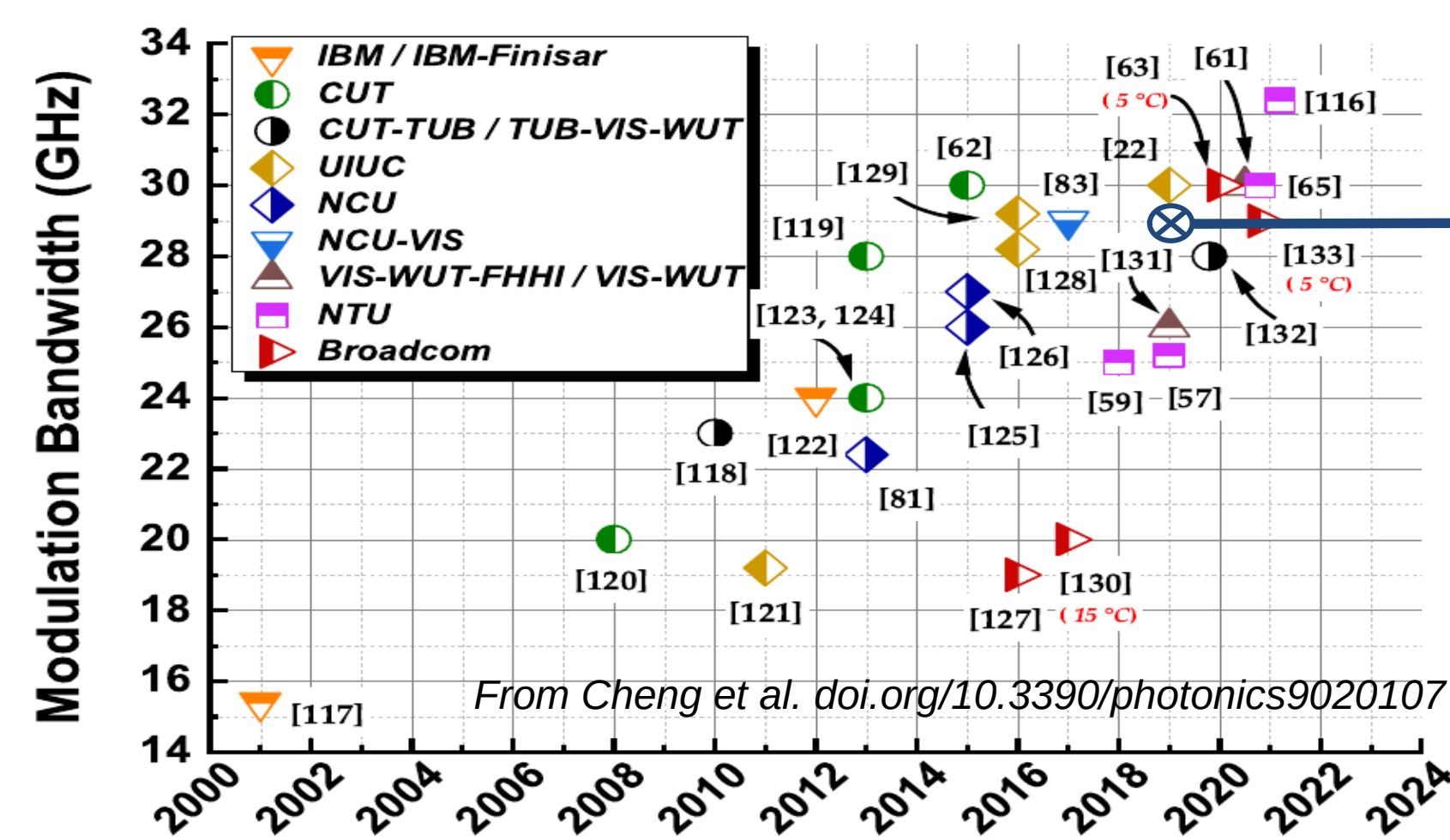
High speed VCSEL applications:

- Short-reach optical links in Datacenters, supercomputers,...
- LIDAR (3D imaging), mobiles >>> 940 nm-arrays
- Optical cables (USB, video)
- Wireless optical links (OWC)
- System on Chip (SoC)
- Quantum computing (Cryogenic readout circuit)

The Modern Highly-Interconnected Data Center



State-of-the-art



Data rate improvement requires:
 Increased intrinsic bandwidth (limited)
 Advanced modulation formats
 Wavelength or Frequency Demultiplexing

Our approach = Vertically Integrated Electro-Absorption Modulator on a VCSEL

First demo: $f_{3dB} = 29\text{GHz}$ in Marigo-Lombart et al. doi.org/10.1088/2515-7647/aa5af

- Splitting up Emission / Modulation: CW VCSEL emission + EA Modulation
- Electro-absorption modulator: Very high 3dB bandwidth > 65Ghz (Grillanda et al. 2019)
- High devices density, small footprint
- Solution not based on direct-current modulation: Not (intrinsically) limited by carriers/laser dynamics

Double microcavity resonant system:

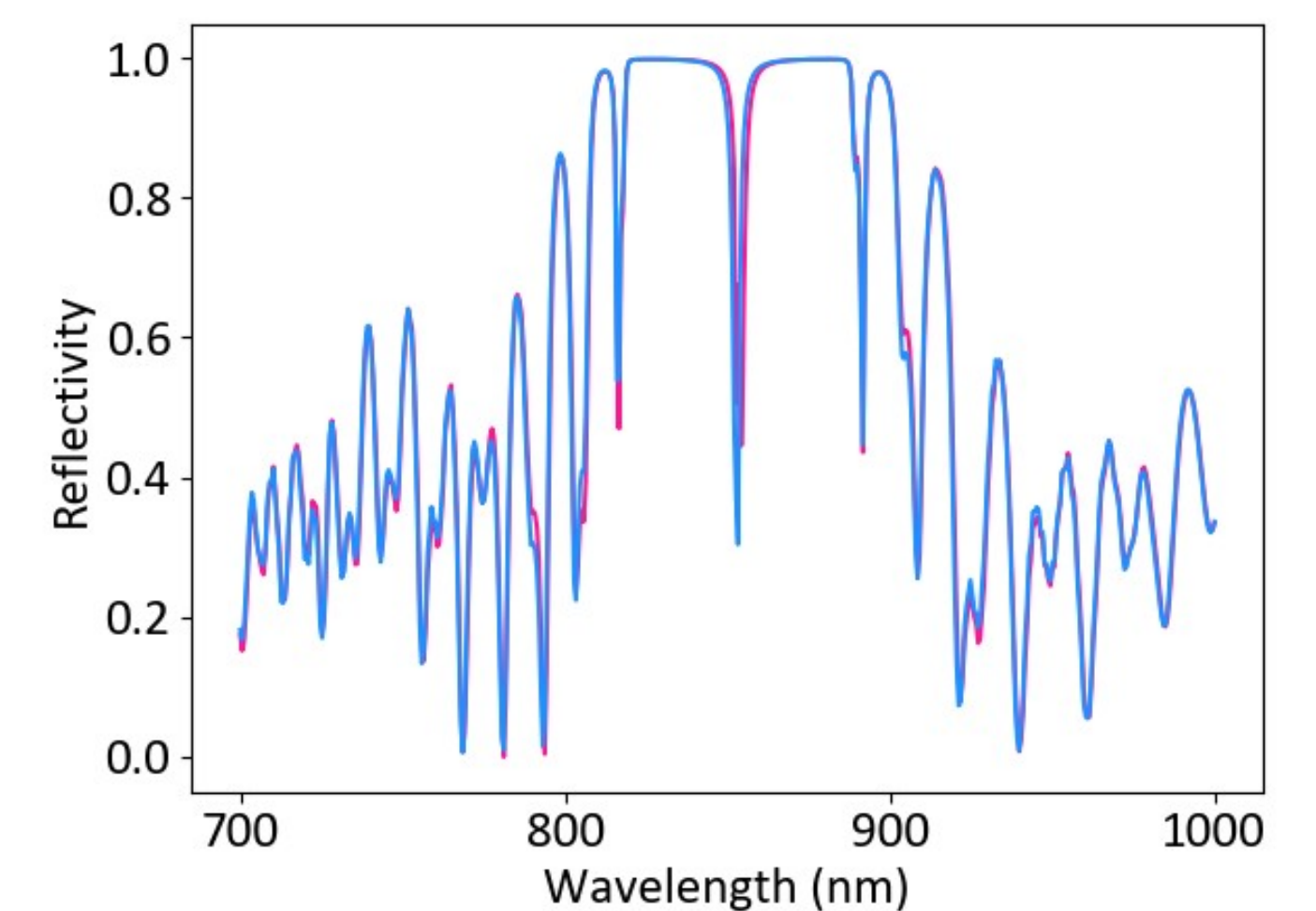
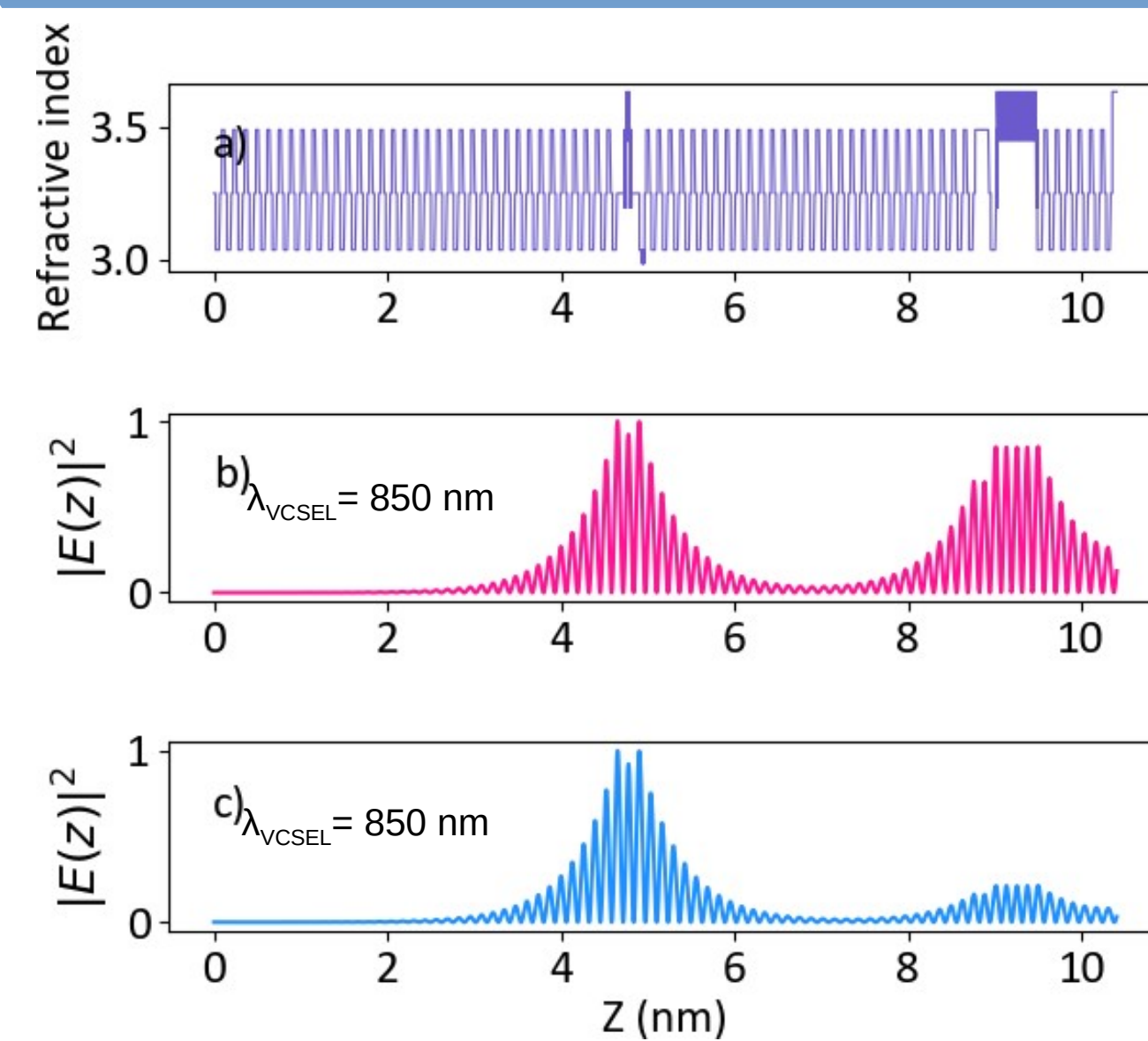
Frequency modulation response, is correlated to the optical coupling between VCSEL and EAM cavities (K. Panajotov et al. doi.org/10.3390/app10176128)

Strong coupling disrupts the VCSEL CW emission

Moderate coupling gives maximized frequency bandwidth

Weak coupling results in small modulation contrast

Modelisation & Design



Calculated reflectivity of the EAM-VCSEL structure

MBE growth

Growth on **RIBER 412 MBE reactor** on 4" GaAs wafer

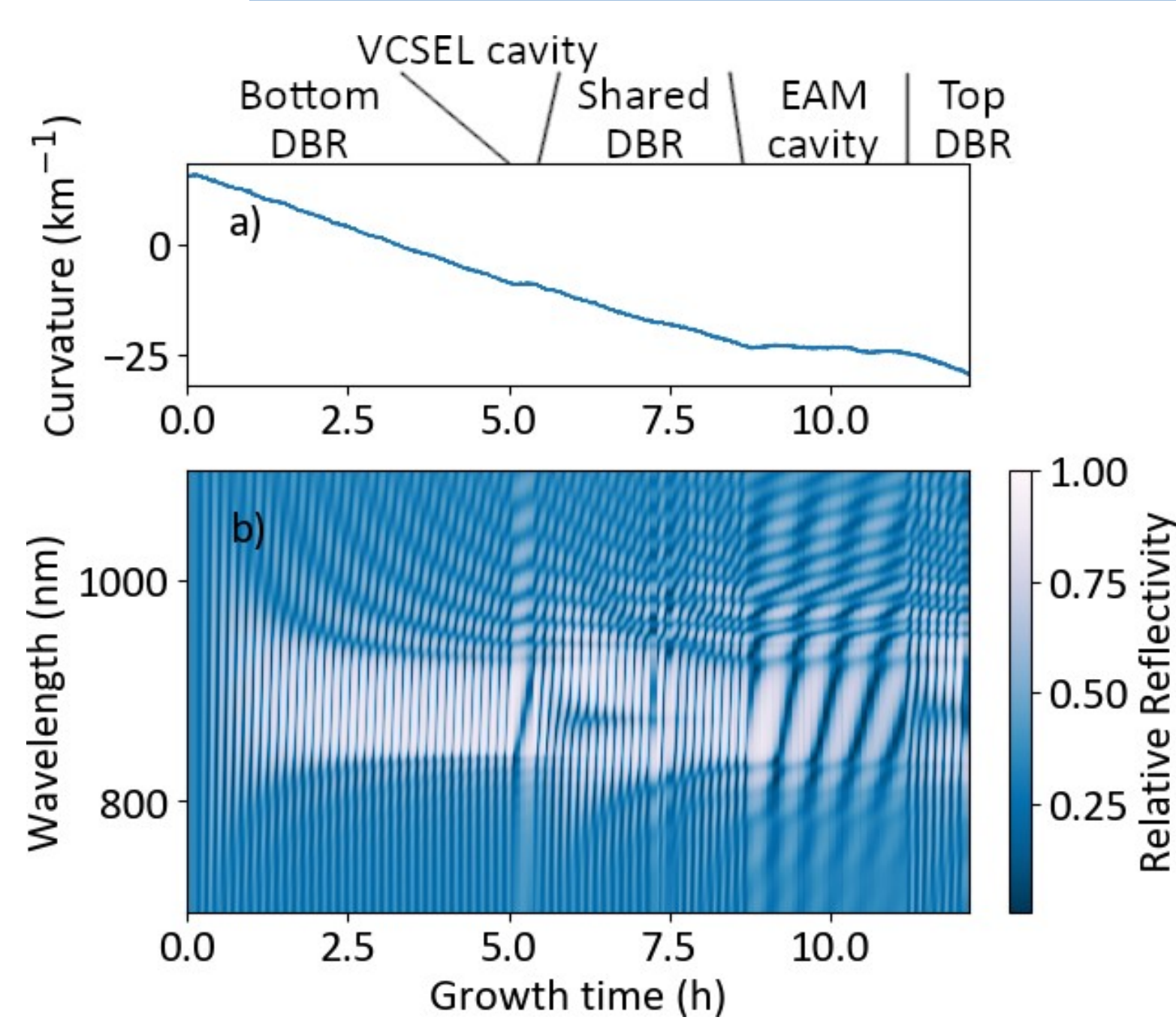
In-situ measurement methods implemented:

Wafer curvature by EZ-CURVE (LAAS patent)

Optical reflectometry 700-1100 nm range

Real-time reflectometry full spectrum allows to:

- Check the DBR central wavelength,
 - Track the VCSEL FP resonance,
 - Track and adjust the middle and top DBR wavelength
 - Track and adjust the EAM FP detuning
- **Fab yield increase**

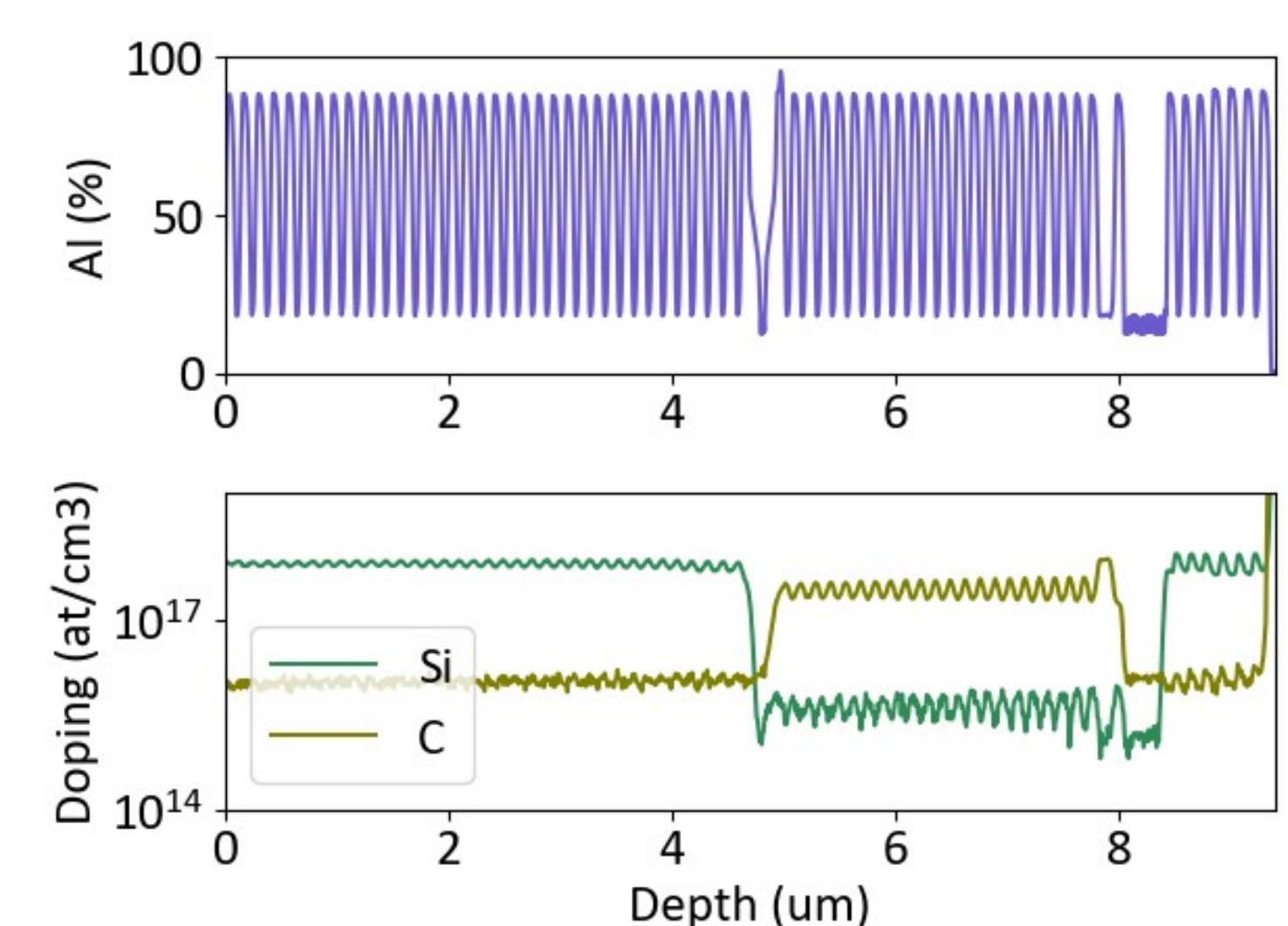


In-situ measurements during the EAM-VCSEL epitaxy:

- a) Wafer curvature
- b) Reflectometry



Scanning Electron Microscope cross-section view of the grown EAM-VCSEL structure



Secondary Ion Mass Spectrometry of the EAM-VCSEL structure

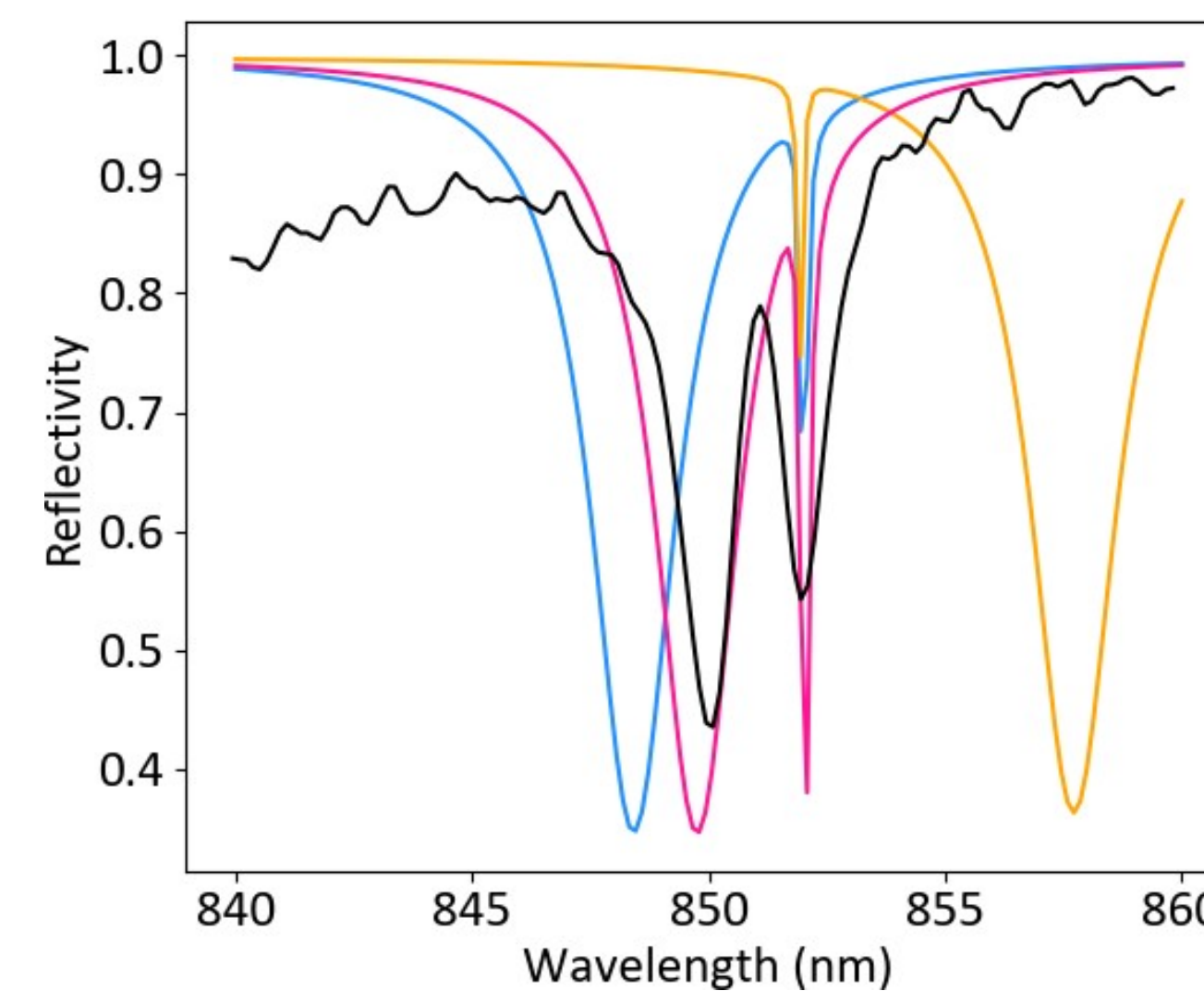
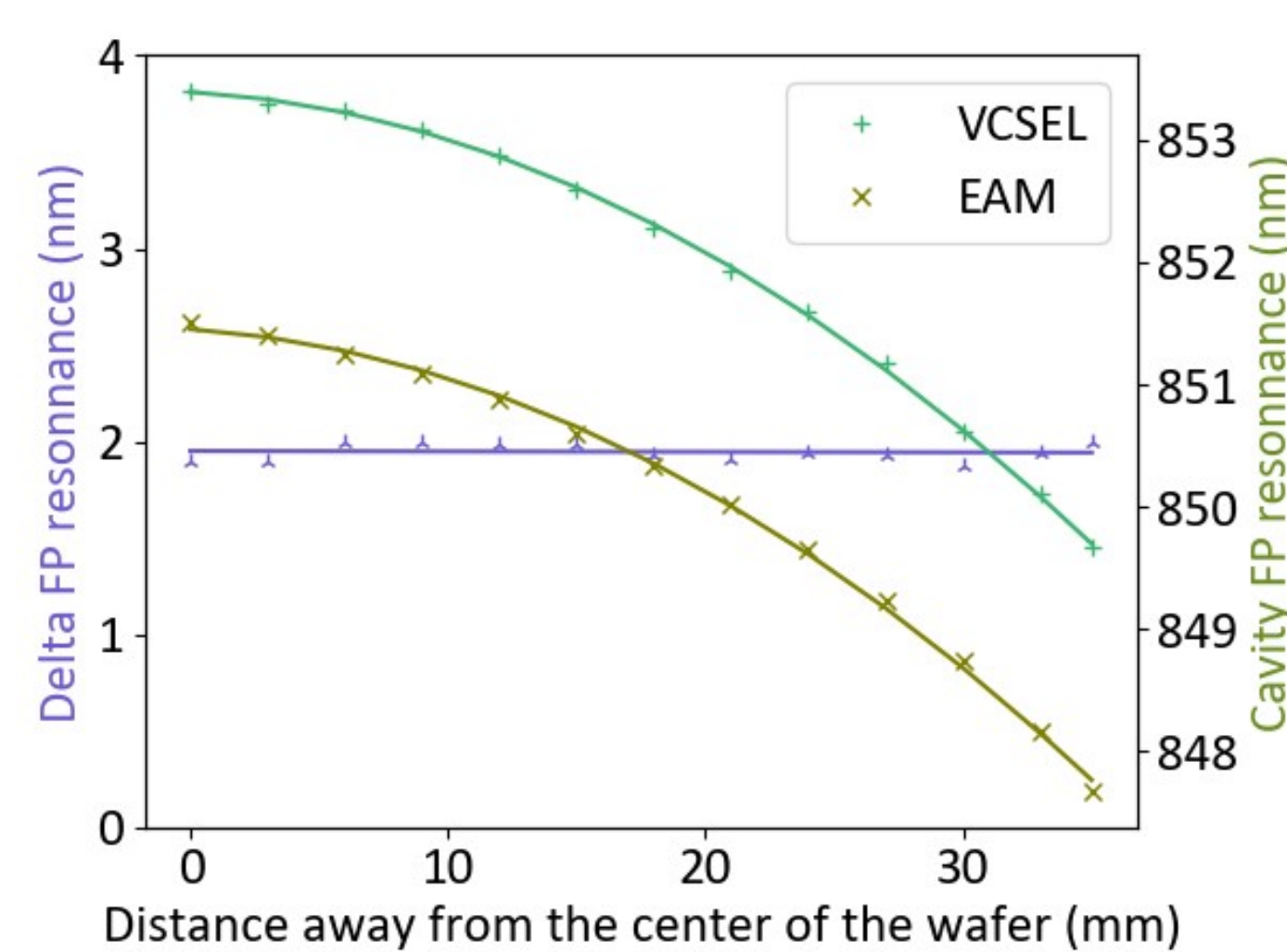
This result highlights that there is no time drift of the Al concentration

Optical results

Room temperature post-growth measurements of the cavities FP resonance by FTIR at different locations on the wafer

EAM cavity FP resonance ranges from 848 to 852 nm: best configuration possible

The difference of the two FP resonance wavelengths is constant → coupling is constant across the wafer



Room temperature post-growth FTIR reflectivity measurement of the grown EAM-VCSEL structure (black)

Numerical calculation of the reflectivity in the case of:

- Strong coupling (red)
- Moderate coupling (blue, EAM cavity deviation of -3nm)
- Overcoupling (orange, deviation of +7.5nm)

The grown structure exhibits a case of strong coupling

Achievements

- Vertically integrated VCSEL / Electro-absorber modulator (EAM): Original and efficient approach for overpass the limits of directly-modulated VCSELS
- Design/modelling of electro-optical behavior of the EAM-VCSEL
- MBE growth with *in-situ* monitoring: reflectometry + wafer curvature
- EAM-VCSEL growth requires high precision: Best performances (moderate coupling) requires an error of less than +/-0.5% on the EAM cavity thickness