Long-Wavelength VCSELs: Devices and Applications

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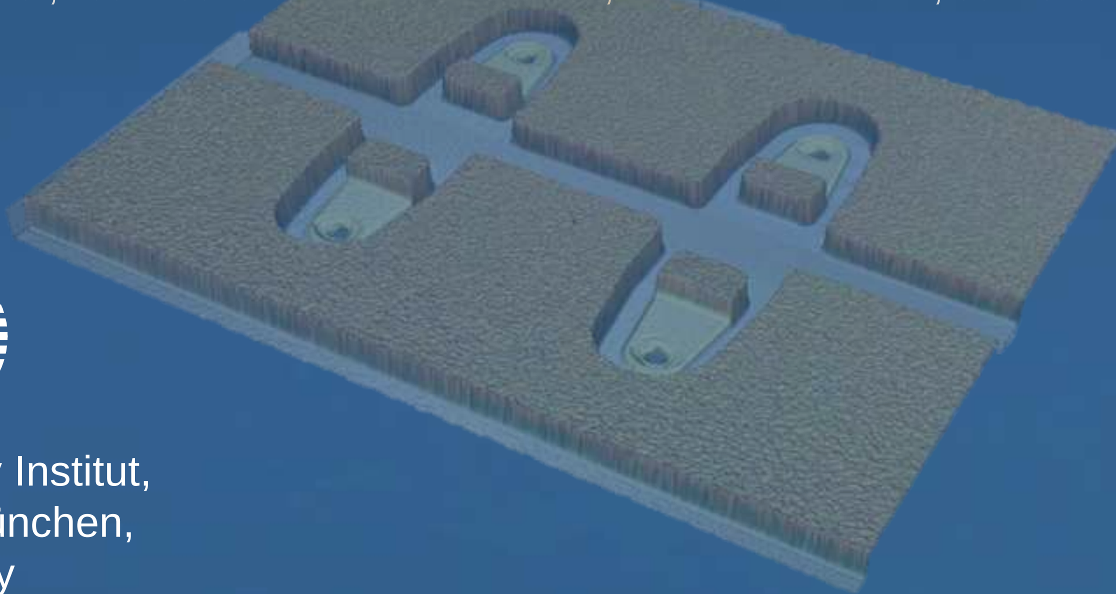

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Germany

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Outline

I. Motivation

II. Device Concept: **B**uried-**T**unnel **J**unction VCSEL (BTJ-VCSEL)

III. 1.55-µm VCSELs for High-Speed Applications
   – Stationary Characteristics
   – Dynamic Characteristics

IV. InP- and GaSb-based VCSELs for Sensing Applications (Approaching the Mid-Infrared)

V. Conclusion

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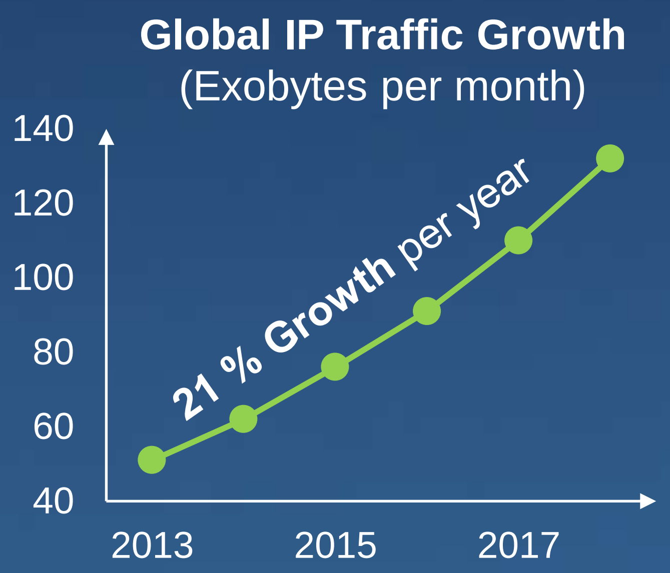
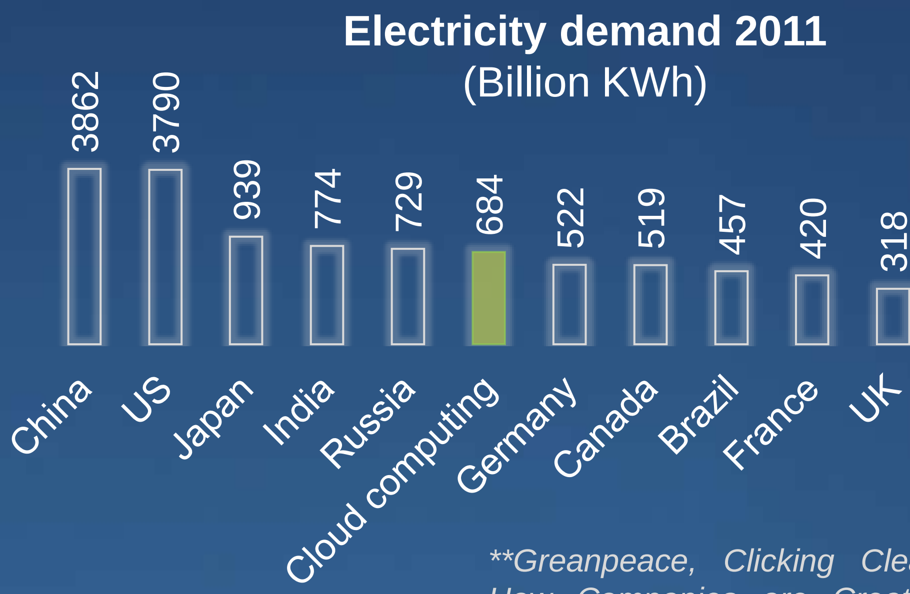
NIR-VCSELs for High-Speed Applications



***Cisco VNI Global IP Traffic Forecast, 2013 - 2018*

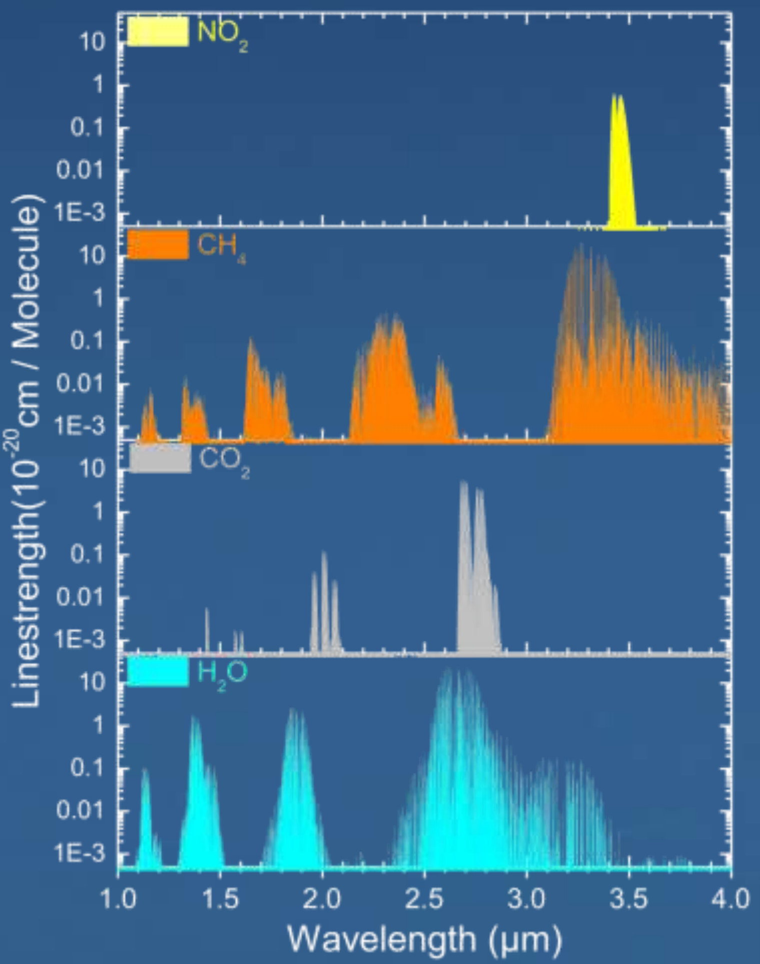


***Greenpeace, Clicking Clean: How Companies are Creating the Green Internet, 2014*

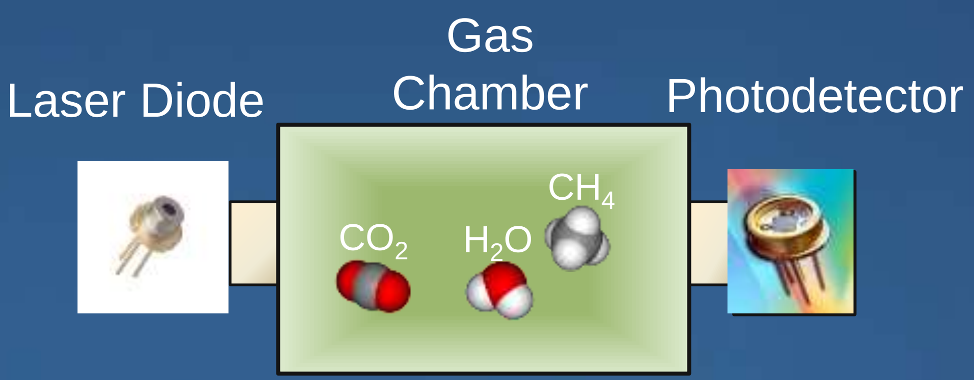
Optical interconnects

- Low cost
- Power Efficiency
- High temperature operation (up to 60°C)

Reasons for developing **M**id **I**nfrared **R**ange laser sources:

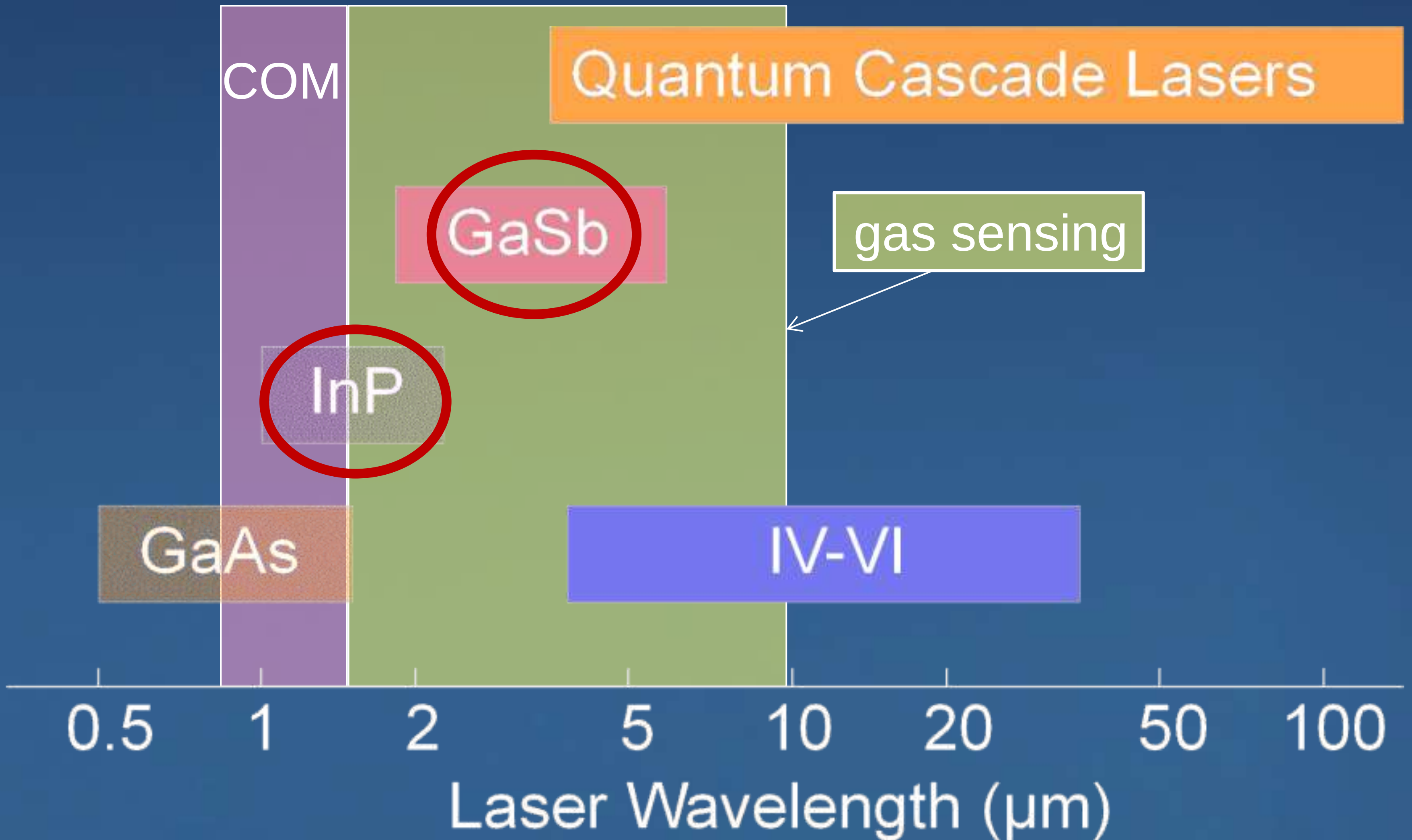


Gas Sensing (TDLAS)



Contactless, ultra-sensitive, rapid sensing method

Wavelengths & Semiconductor Laser Materials



An early 5µm Vertical-Emitting Laser (InSb)

Volume 6, Number 3 APPLIED PHYSICS LETTERS 1 February 1965

LONGITUDINAL INJECTION-PLASMA LASER OF InSb

Ivars Melngailis
Lincoln Laboratory,[1] Massachusetts Institute of Technology
Lexington, Massachusetts
(Received 28 December 1964)

(10°K; 0–21kG longitudinal to current; E)

We have obtained coherent emission in n^+pp^+ InSb structures parallel to the direction of the diode current, as illustrated in Fig. 1. Large-volume luminescence and coherent emission was previously obtained in similar n^+pp^+ InSb structures, but the coherent beam was emitted perpendicular to the direction of current,[2] as in all other existing semiconductor lasers. However, the large active regions of these InSb diodes in which lifetimes of 10^{-7} to 10^{-6} sec permit population inversion in regions of the order of 100 μ away from the injecting contacts are naturally suited for laser oscillations longitudinal to the current, provided that a suitable Fabry-Perot cavity can be constructed in that direction and provided that lasing in the perpendicular direction is inhibited. Such lasers are free from some of the structural restrictions of the perpendicular lasers. For example, they can be more readily constructed in arrays. They also promise to emit coherently over large areas—hence with small beam angles—and they should be suited for large power outputs.

As shown in Fig. 1 the laser is mounted on a copper heat sink over a small hole. An n^+ layer is grown on a (100) plane of the p-type base ($N_A - N_D \approx 3 \times 10^{13}$ cm^{-3} at 77°K) by a solution-regrowth technique similar to that developed by Nelson[3] for GaAs and Ge, and a p^+ layer is formed by Zn diffusion. The laser cavity consists of an optically flat polished sur-

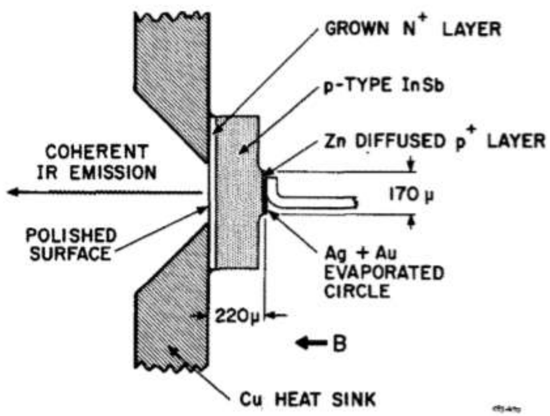
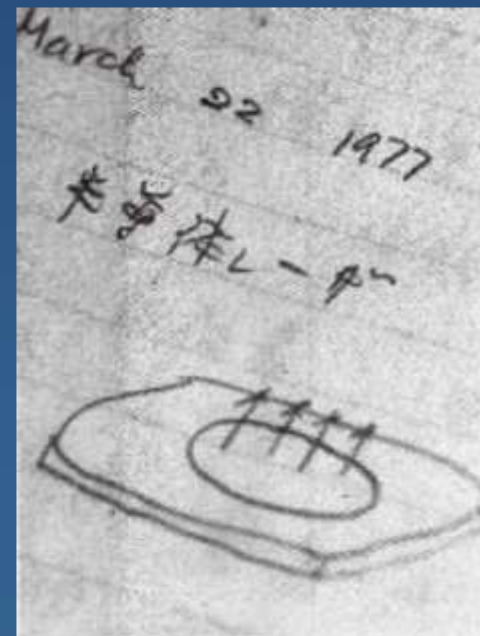


Fig. 1. InSb n^+pp^+ structure with a Fabry-Perot cavity designed for coherent emission parallel to the current.

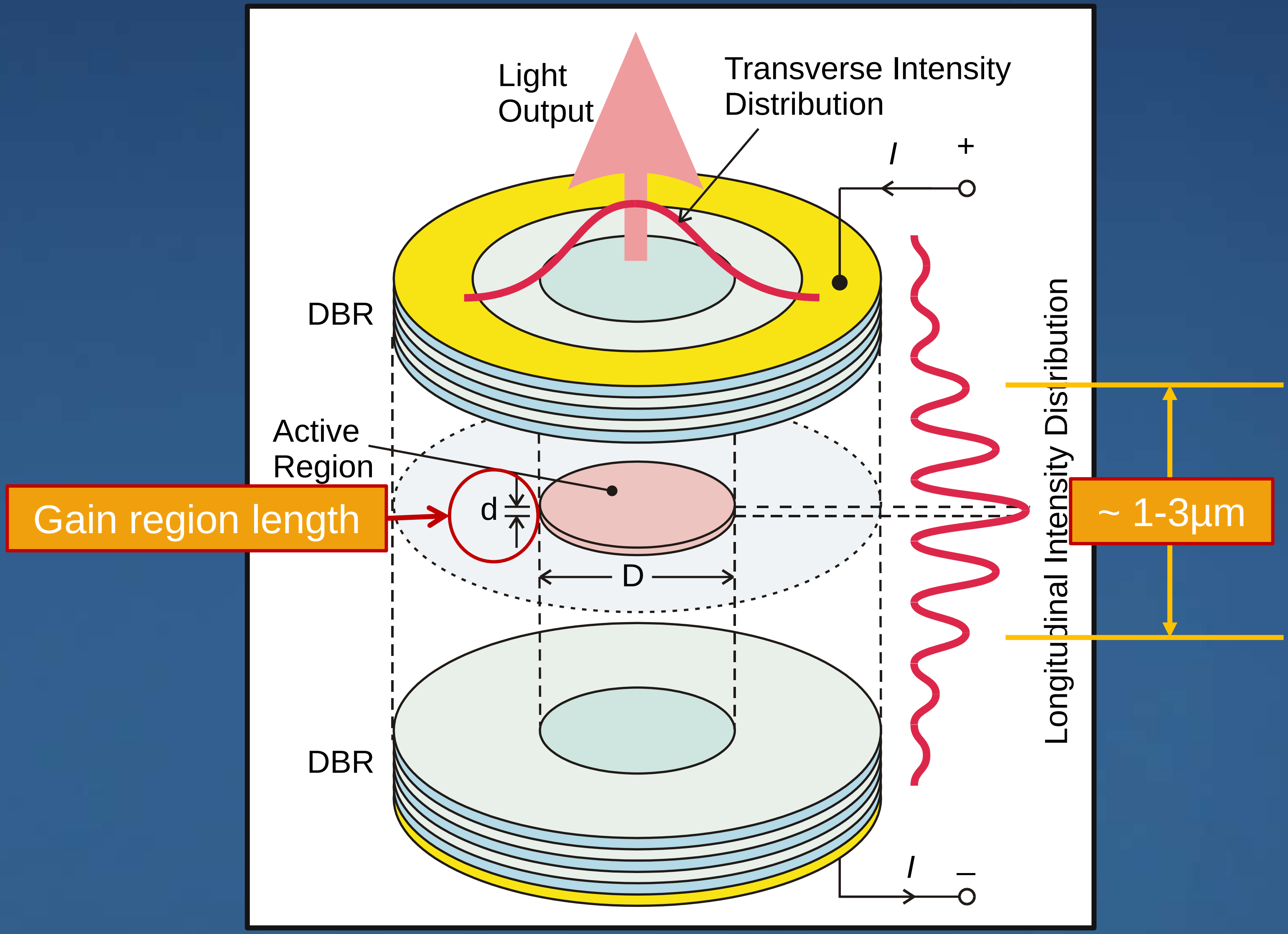
The Invention of the VCSEL

Kenichi Iga
(Tokyo Institute of Technology



Laboratory Notebook Entry
March 22, 1977

Basic VCSEL Structure



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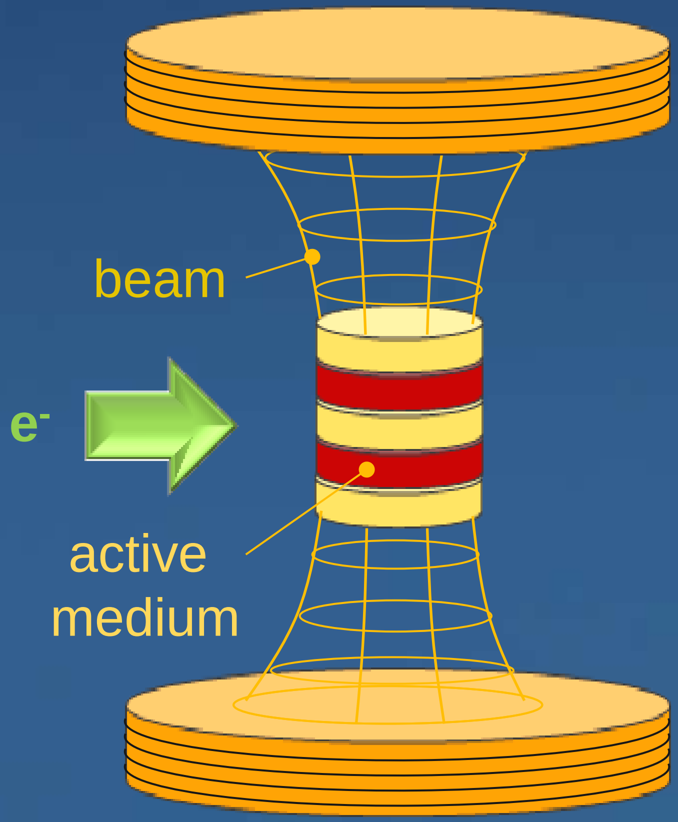
Current and photon confinement in VCSEL

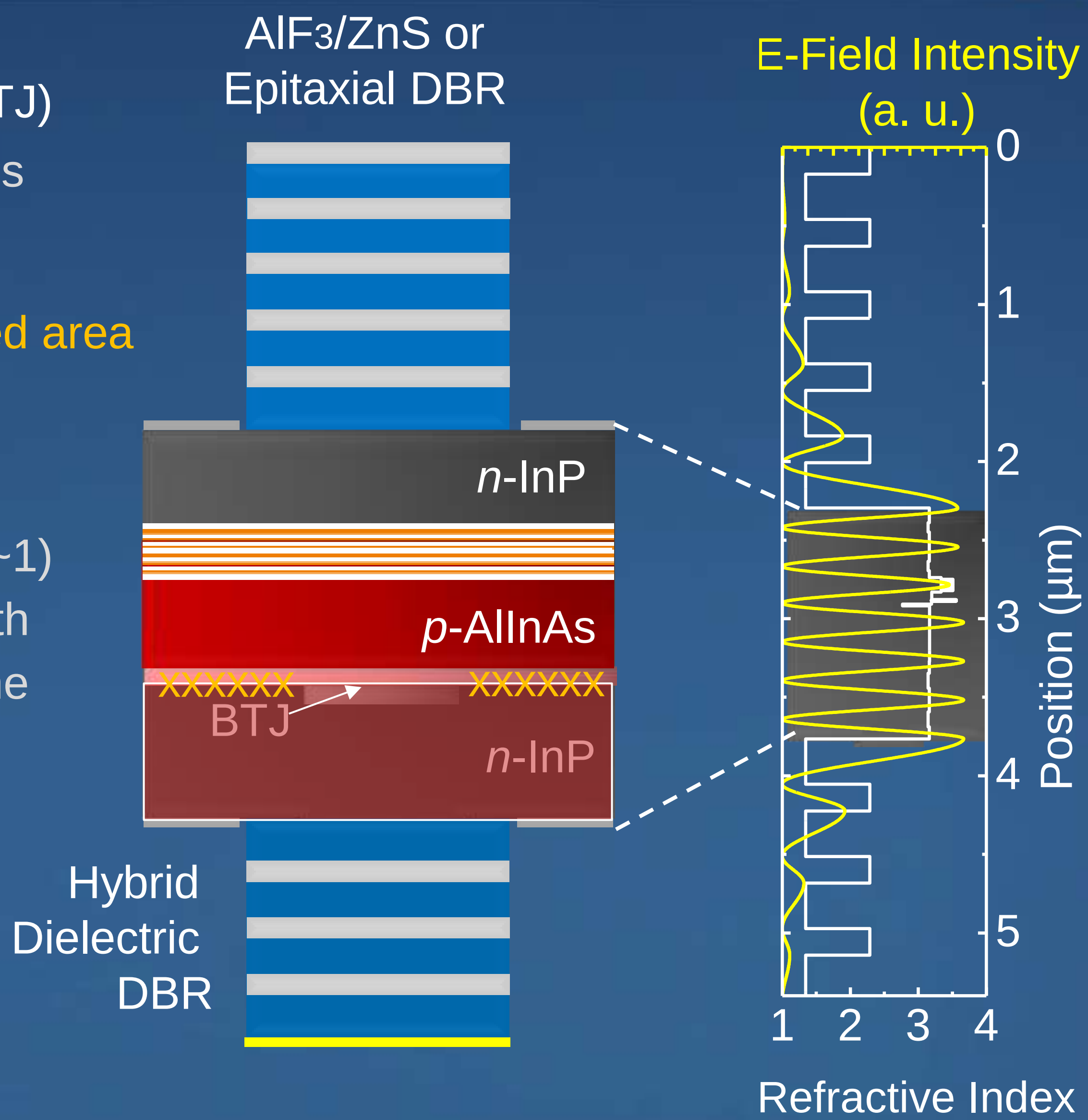


BTJ-VCSEL Structure

- Buried Tunnel Junction (BTJ)
  - ⇒ reduced internal losses
  - ⇒ current confinement

⇒ ‚reduces‘ p-doped area

- Dielectric mirrors
  - ⇒ large index contrast (~1)
  - ⇒ small penetration depth
  - ⇒ reduced photon lifetime
  - ⇒ larger bandwidth



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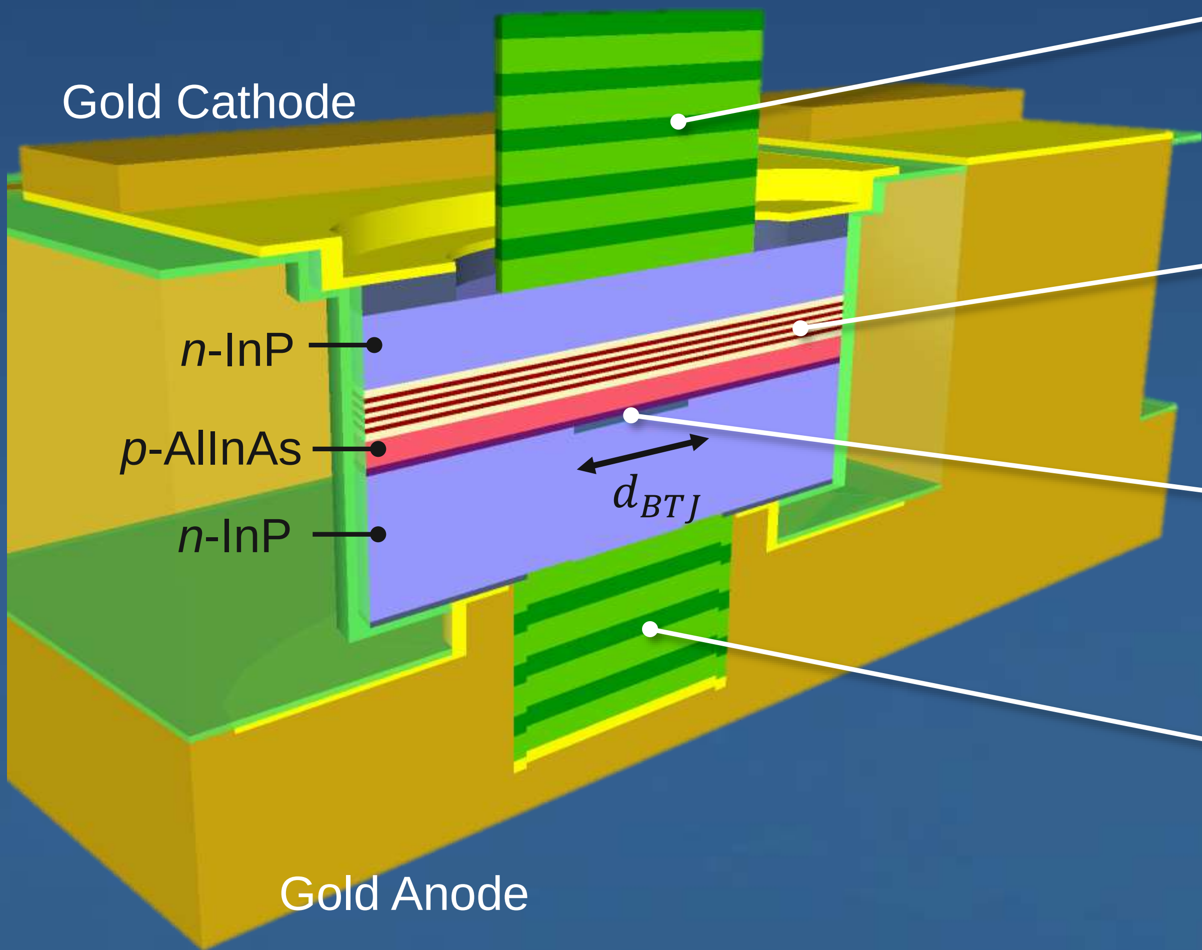
VCSEL Design



Top Dielectric DBR

- 5 pairs AlF_3/ZnS
- $\mathrm{R} = 99.3\ \%$

Active Region

- AlGaInAs
- 1.2% Compressive Strain

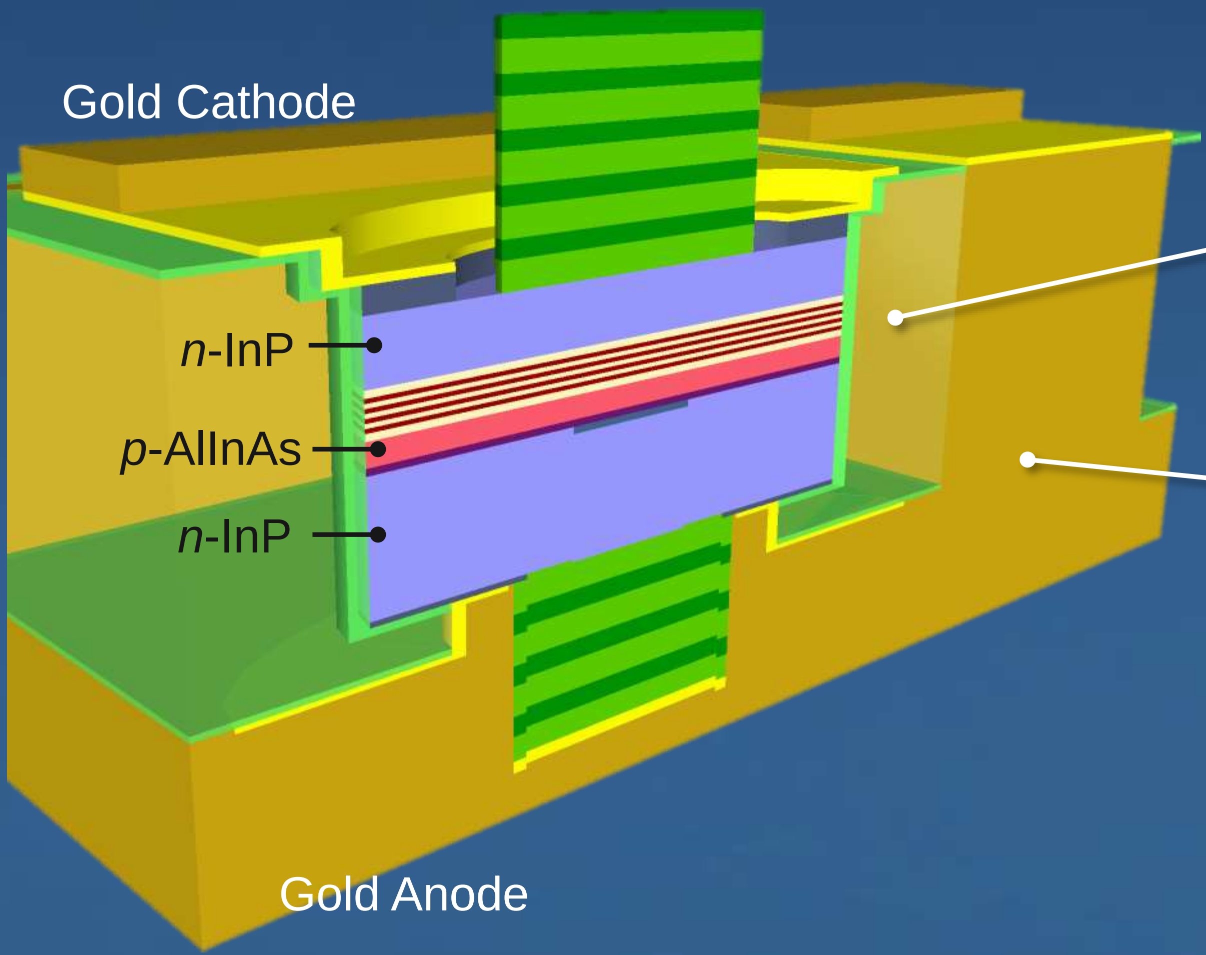
Burried Tunnel Junction (BTJ)

- Electrical confinement
- Optical confinement

Bottom Hybrid Dielectric DBR

- 3.5 pairs AlF_3/ZnS + Au
- $\mathrm{R} = 99.9\ \%$

VCSEL Design



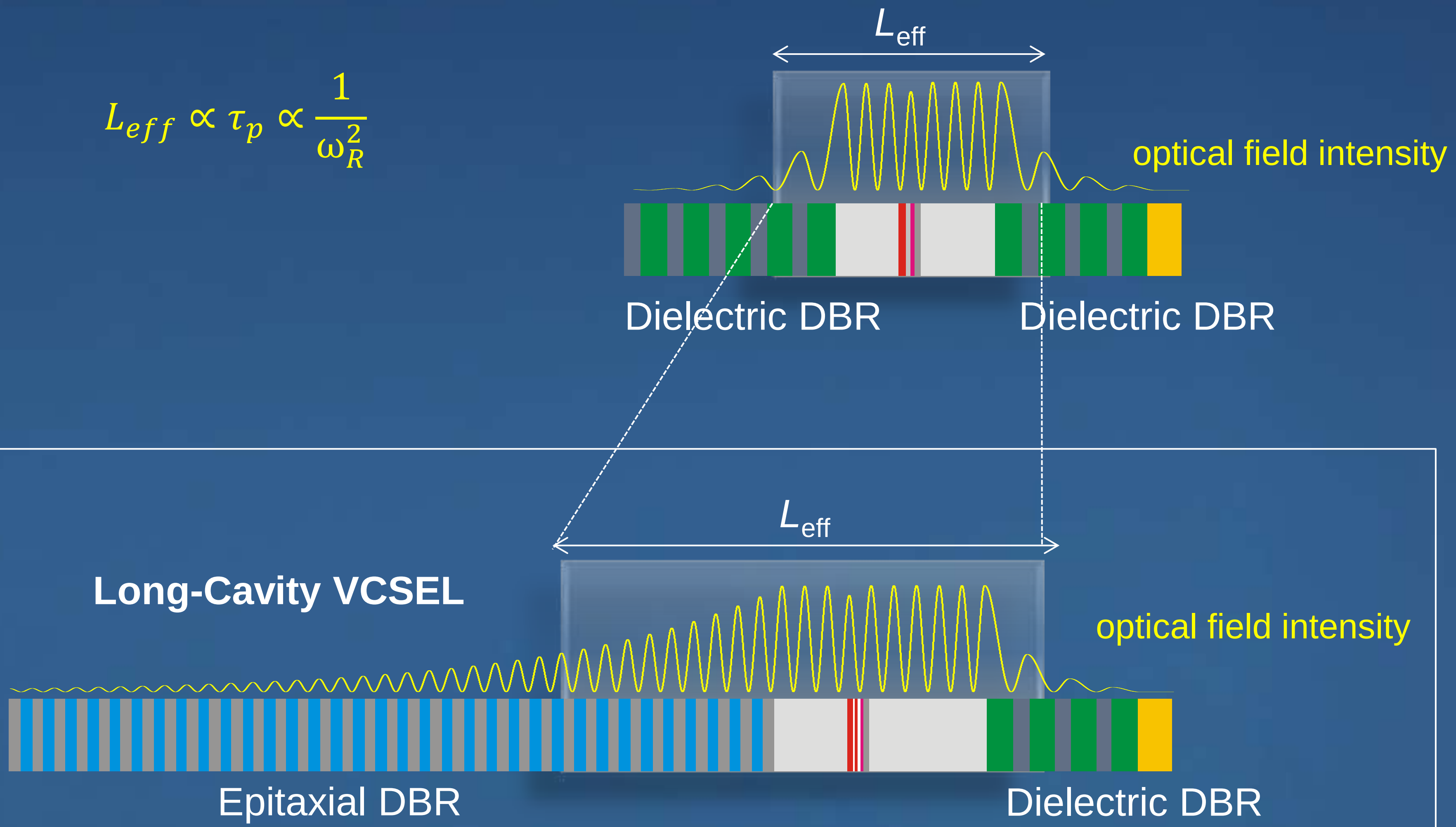
Passavation (BCB)
- reduced pad parasitic

Integrated Au heat sink
- good heat management

Photon Life Time

Short-cavity concept

$$L_{eff} \propto \tau_p \propto \frac{1}{\omega_R^2}$$



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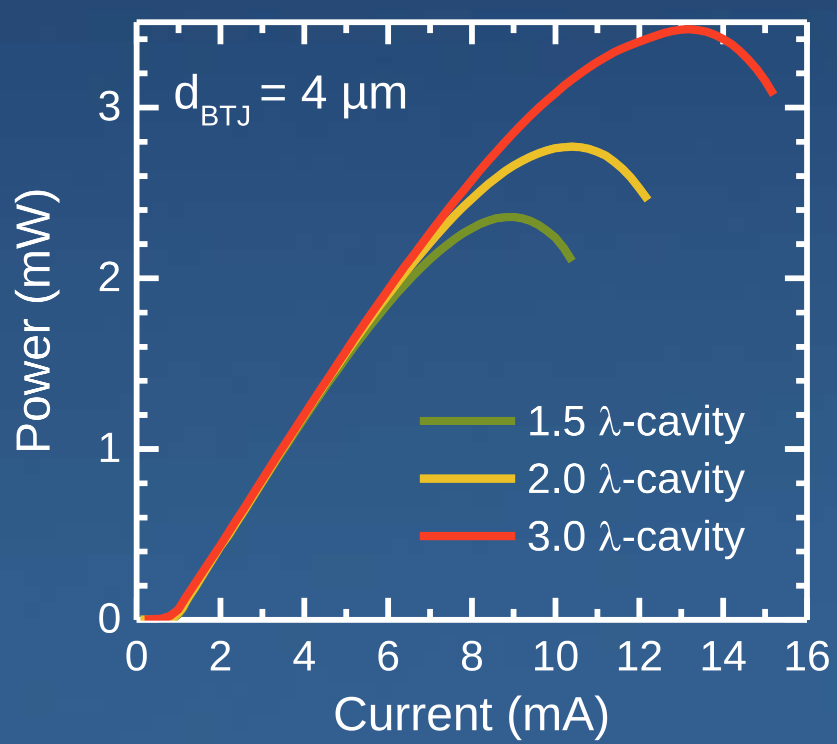
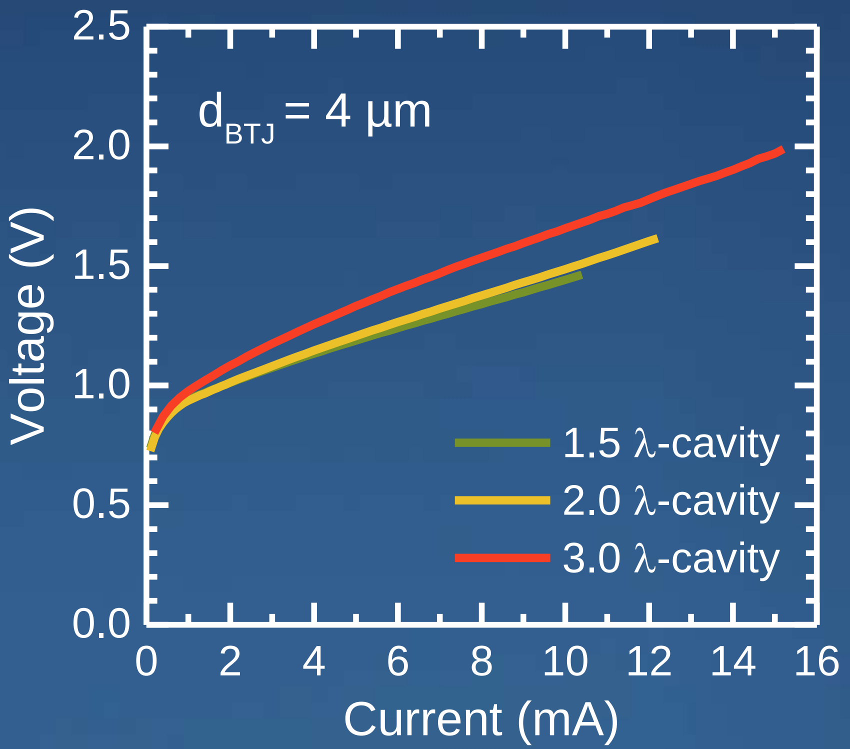
Stationary Characteristics

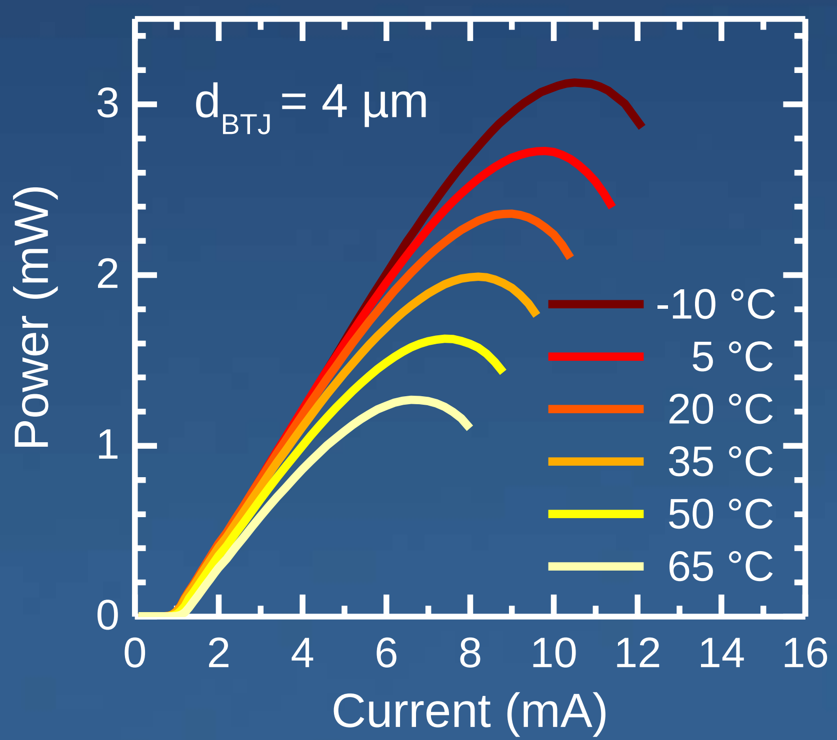


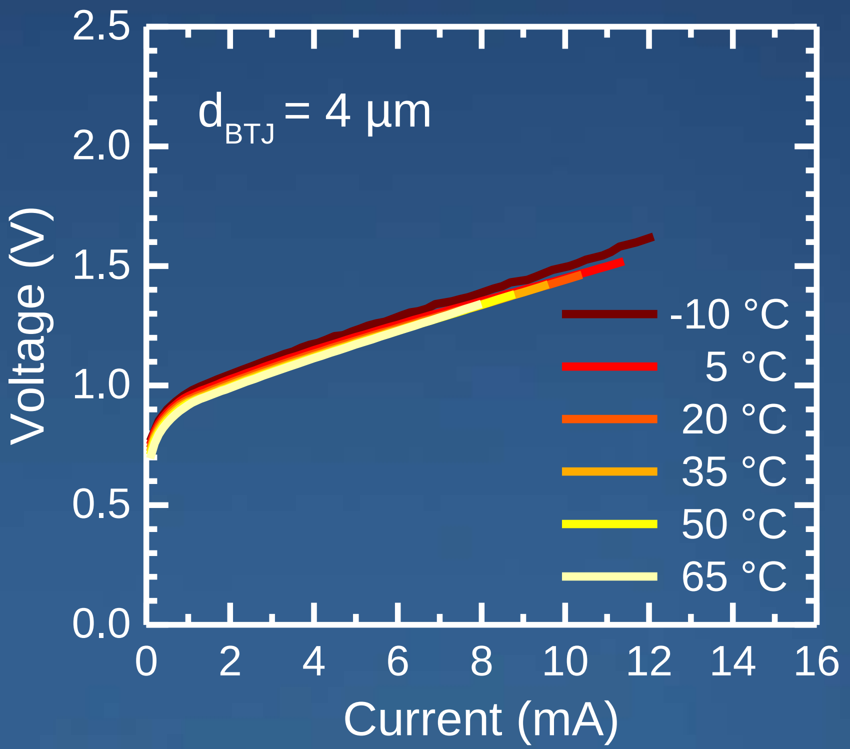


- Maximum Output Power 3.5 mW
- Threshold of 0.9 mA @ 20°C

- 50 Ω matched
- No increase in spreading resistance

Stationary Characteristics

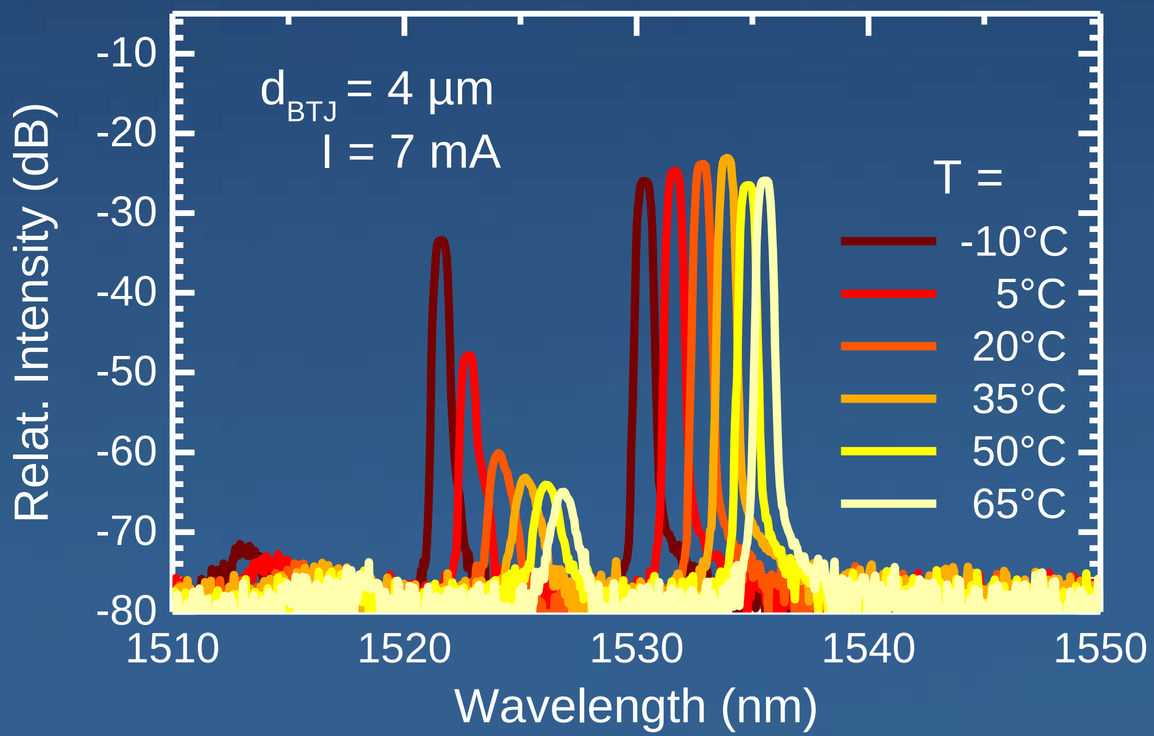




- Operation above 65°C
- Threshold between 0.8 and 1.2 mA

- 50 Ω matched

Stationary Characteristics



- Single-Mode Operation at High Temperatures

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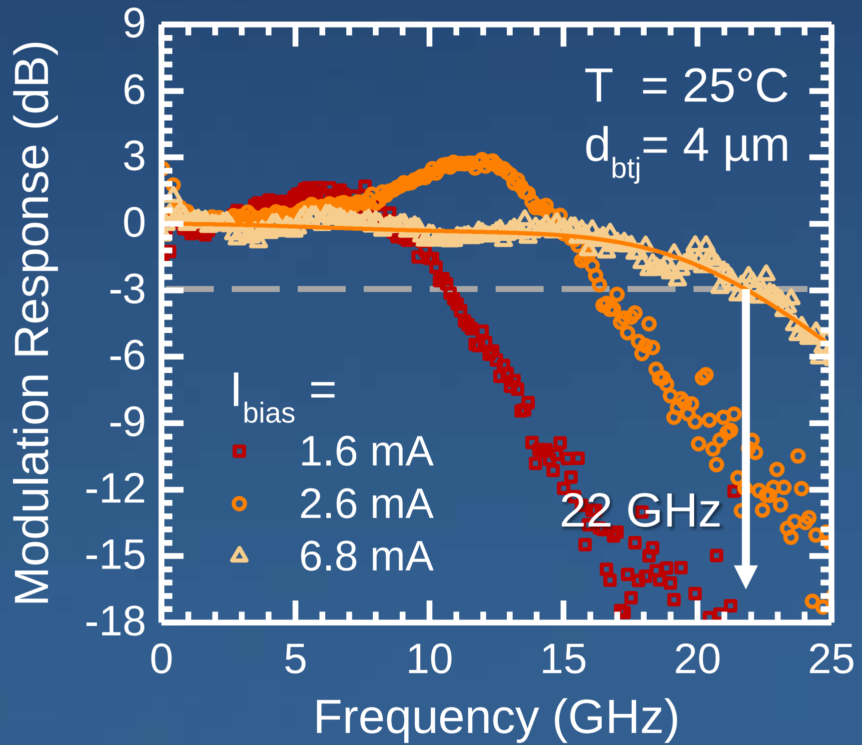
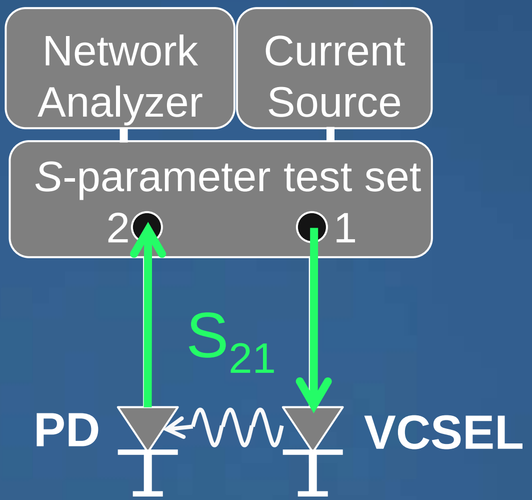
Dynamics Characteristics



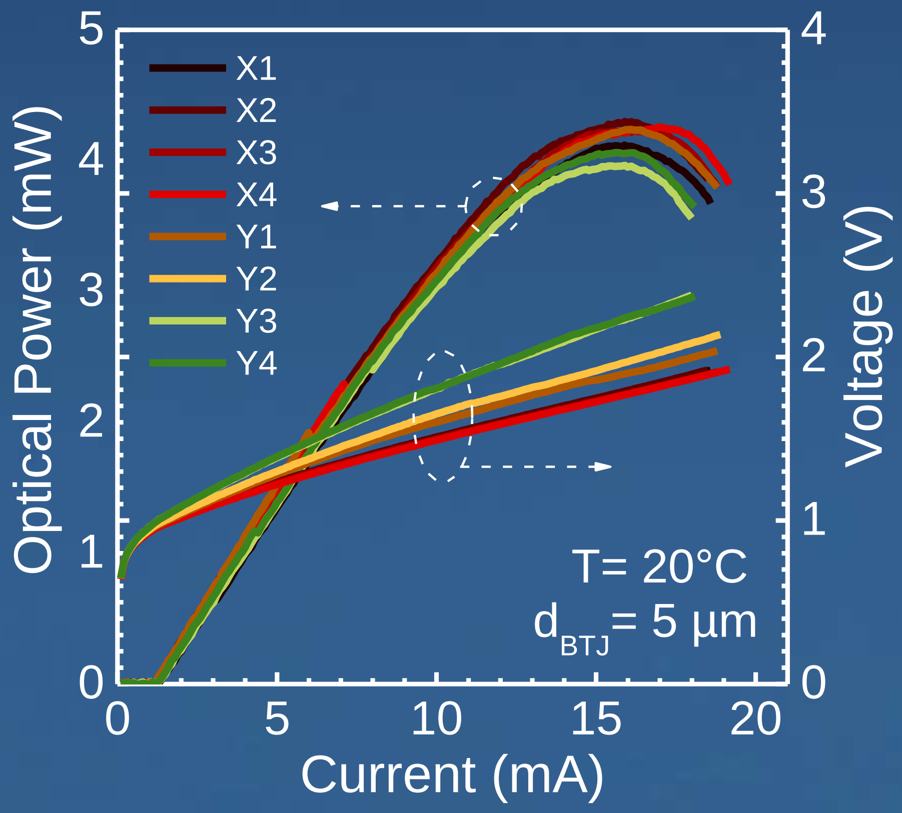
Parasitic Intrinsic

$$H(f) \propto \left| \frac{1}{1 + j\frac{f}{f_p}} \frac{f_R^2}{f_R^2 + j\frac{\gamma}{2\pi} f - f^2} \right|^2$$

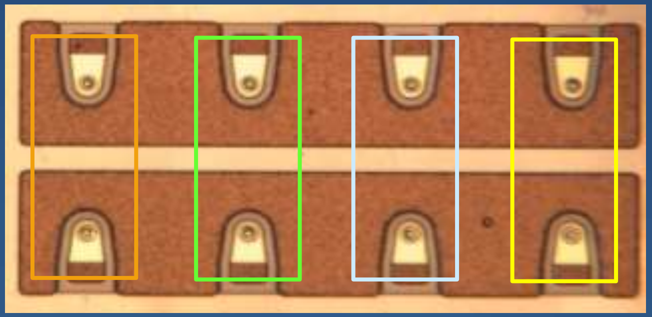


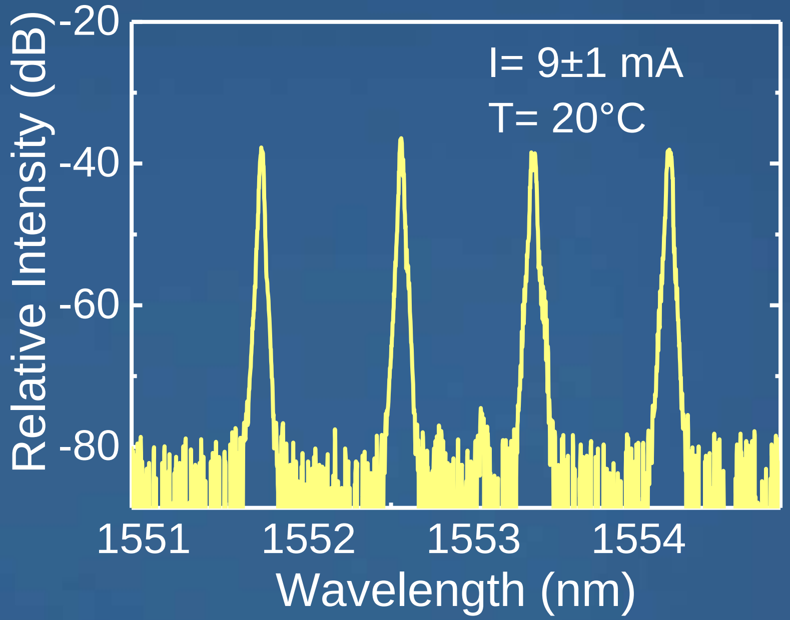
- Record high small-signal bandwidth of 22 GHz @ 1.5 µm
- DC Power Consumption of 9 mW

LIV and Spectrum



Ch1: λ_1 Ch2: λ_2 Ch3: λ_3 Ch4: λ_4

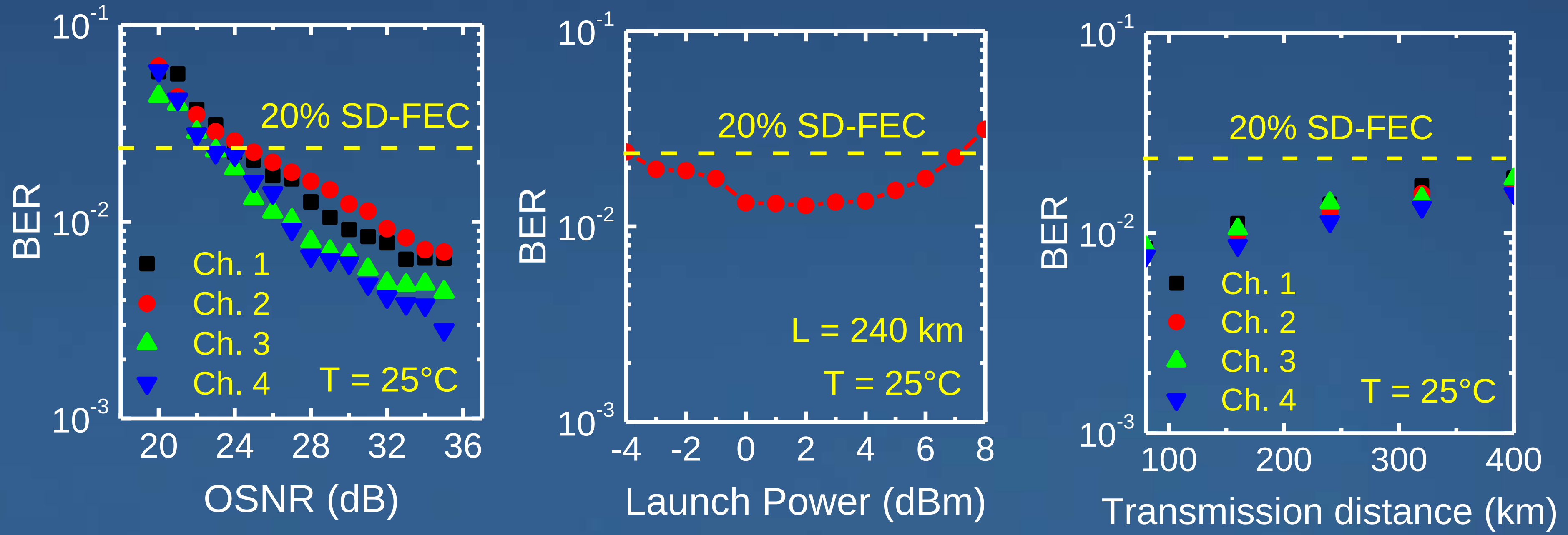




Experimental Results

Channel: 100Gb/s

Transmission Link: 400Gb/s over 400 km



** Xie, C.; Spiga, S.; Dong, P.; Winzer, P.; Bergmann, M.; Kogel, B.; Neumeyr, C.; Amann, M., "**400-Gb/s PDM-4PAM WDM System Using a Monolithic 2×4 VCSEL Array and Coherent Detection**" *Lightwave Technology, Journal of* , vol.33, no.3, pp.670,677, Feb.1, 1 2015

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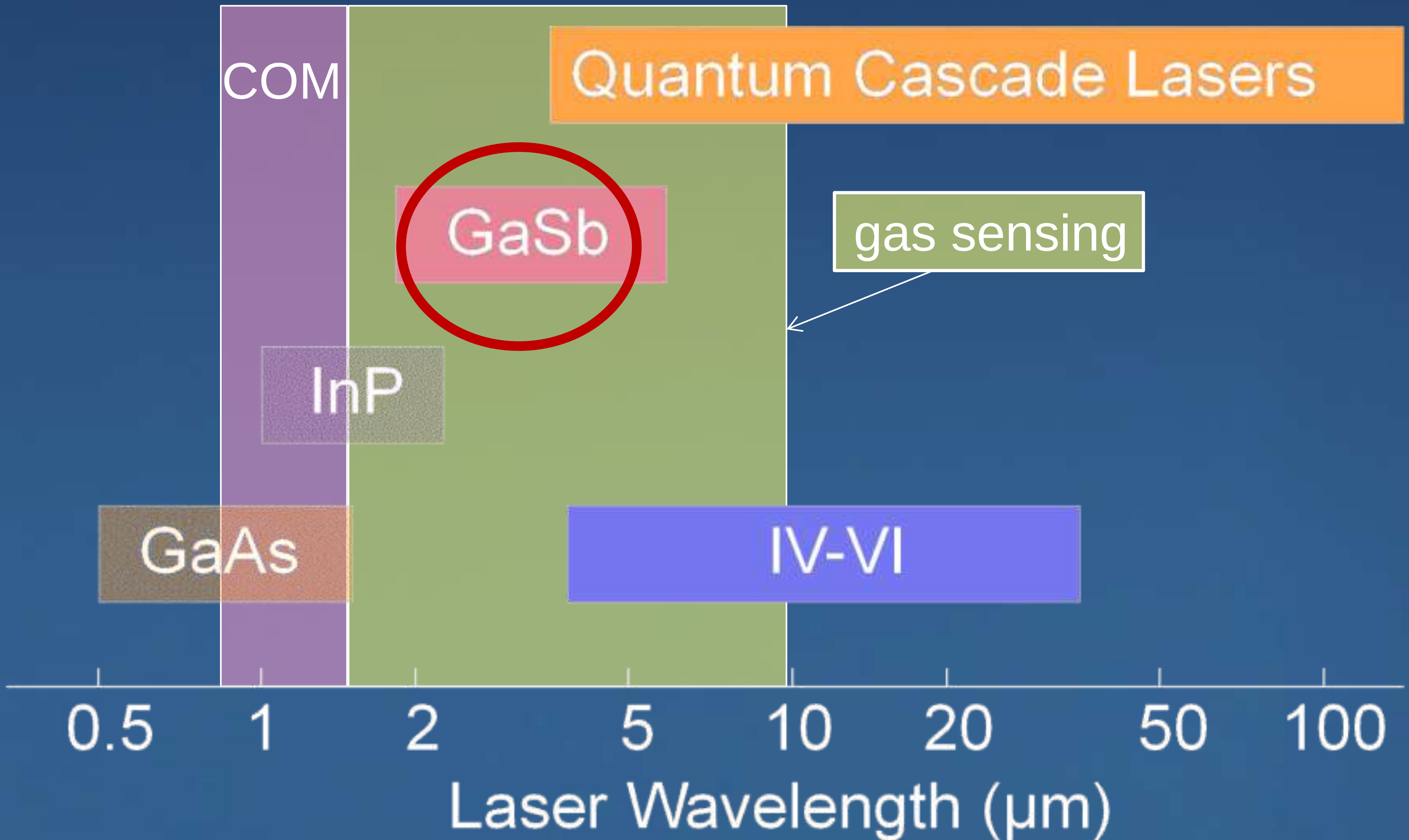
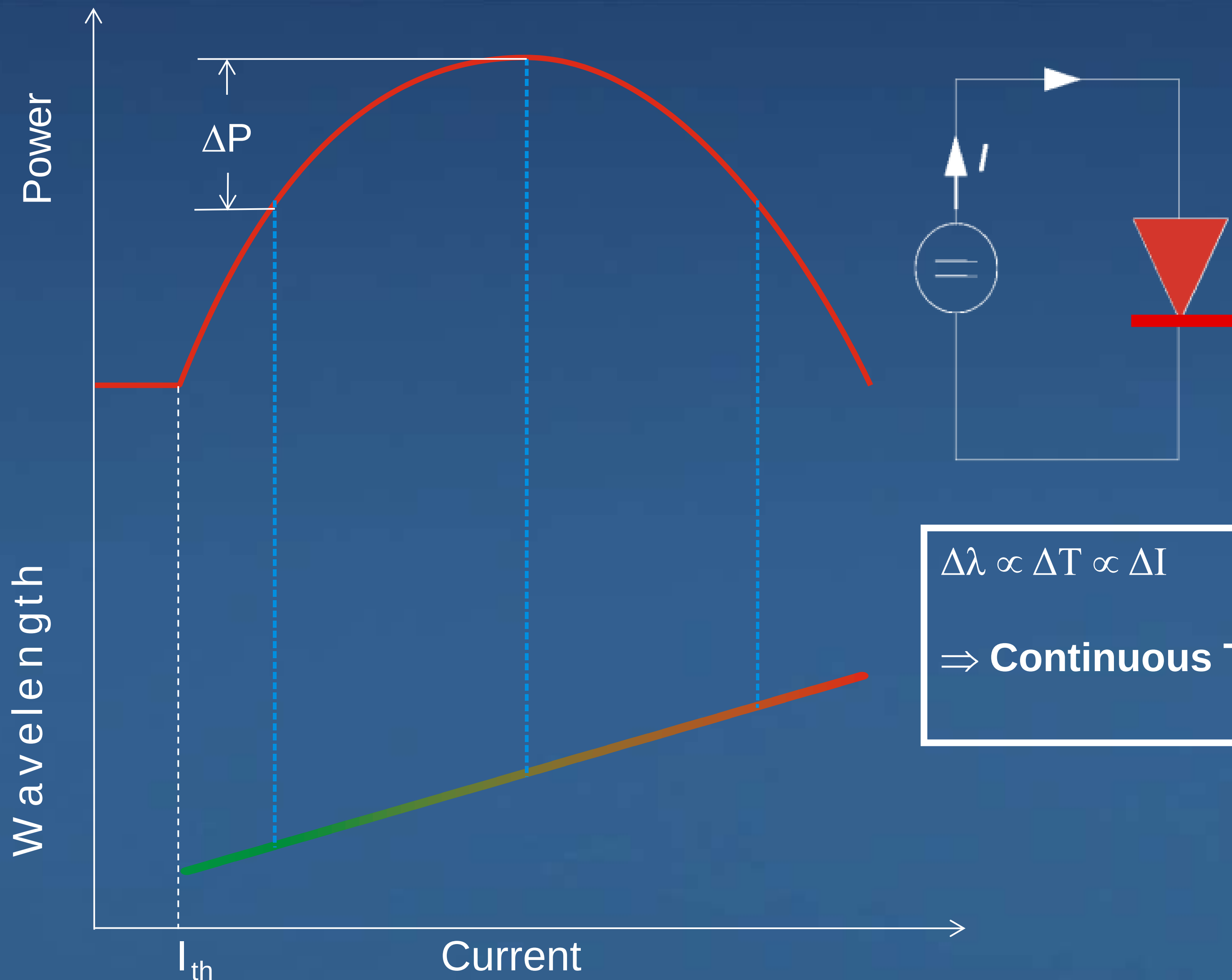
Wavelengths & Semiconductor Laser Materials



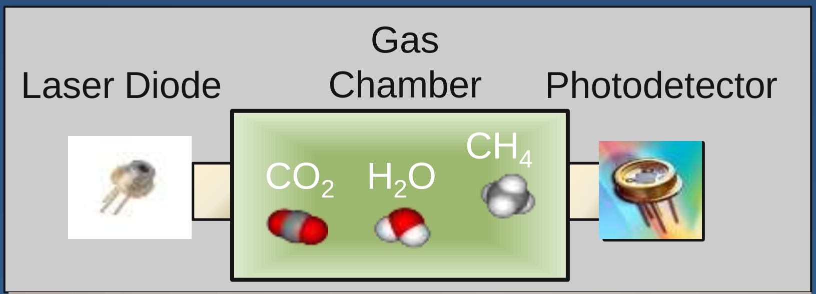
Electro-Thermal Tuning of a VCSEL

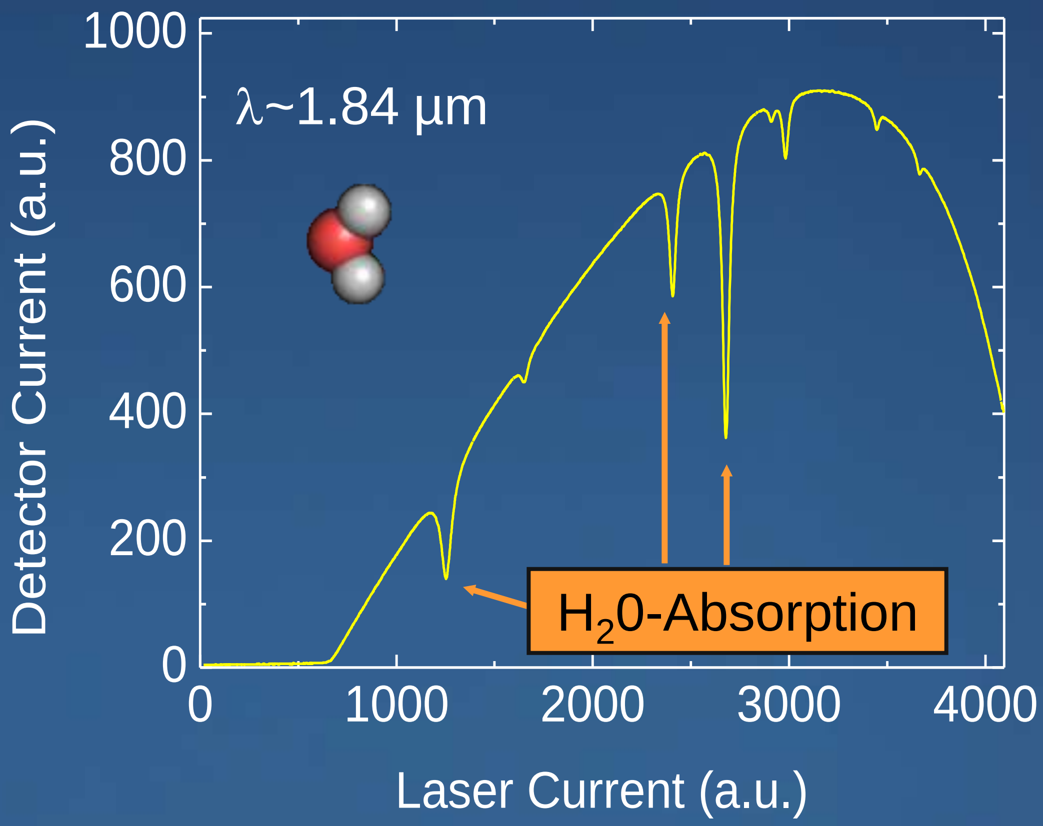


$\Delta\lambda \propto \Delta T \propto \Delta I$

$\Rightarrow$ **Continuous Tuning**

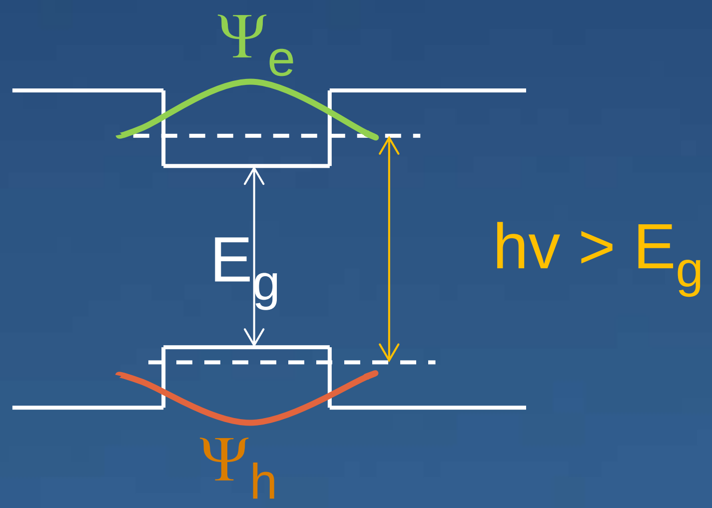
Electro-Thermal Tuning of 1.8µm VCSEL (InP)



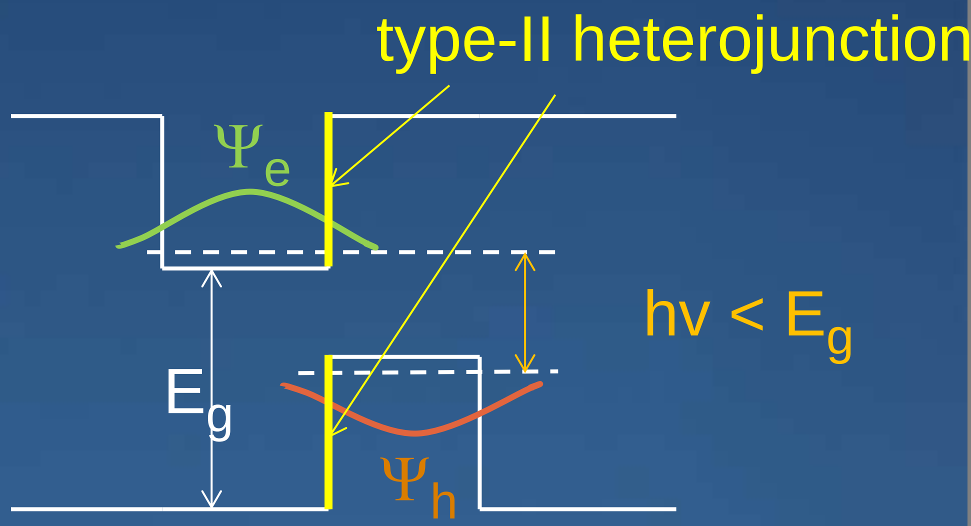


Type-I and Type-II Band-Band Transisitons

Type-I



Type-II



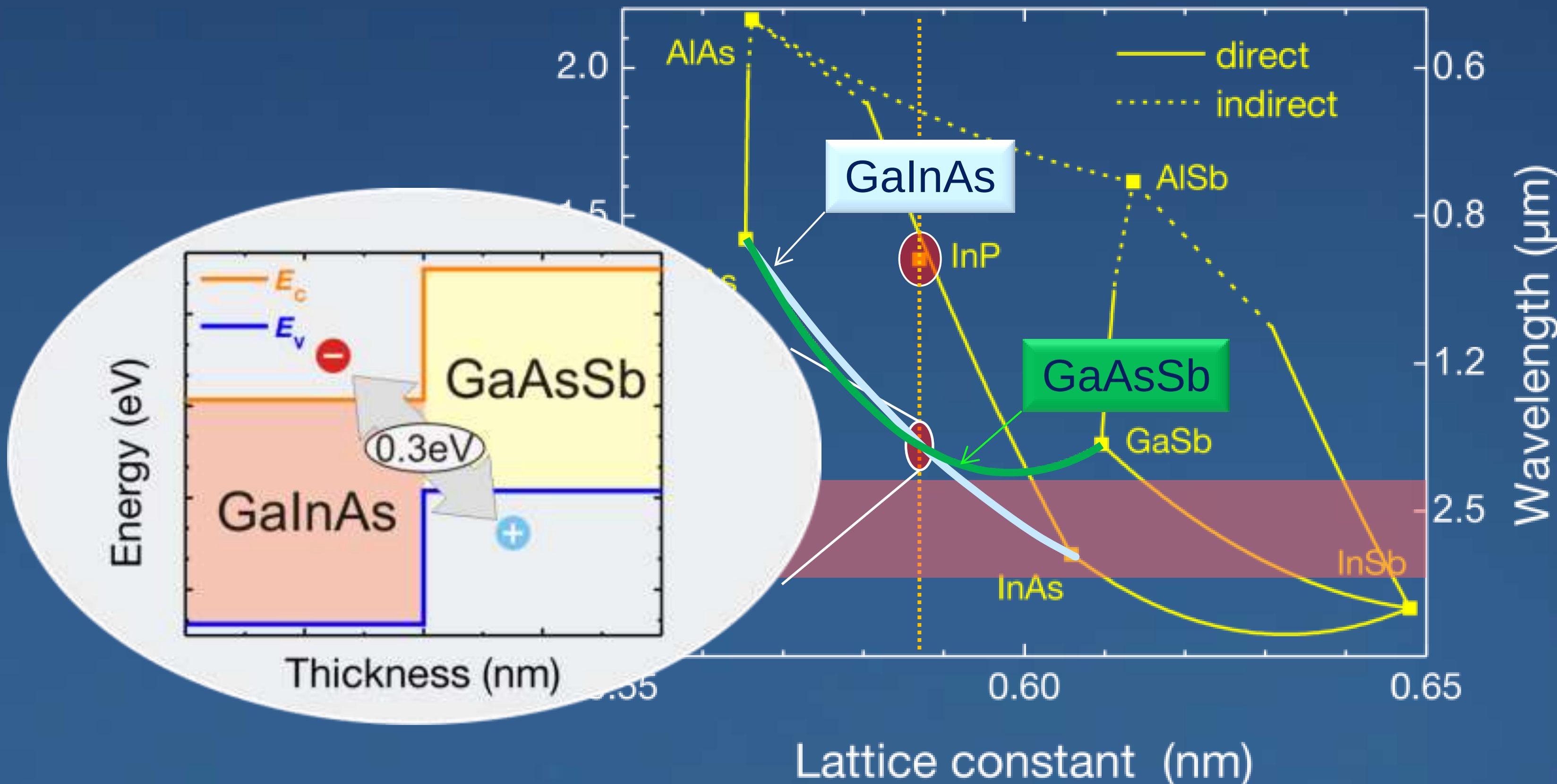
large hv → short wavelength vs. small hv → long wavelength

$$\left|\int \Psi_e \Psi_h \, dz\right|^2 \cong 0.8 - 1$$

$$\left|\int \Psi_e \Psi_h \, dz\right|^2 \cong 0.3 - 0.7$$

large overlap → high gain vs. small overlap → low gain

InP Type-II Lasers: Target Material System

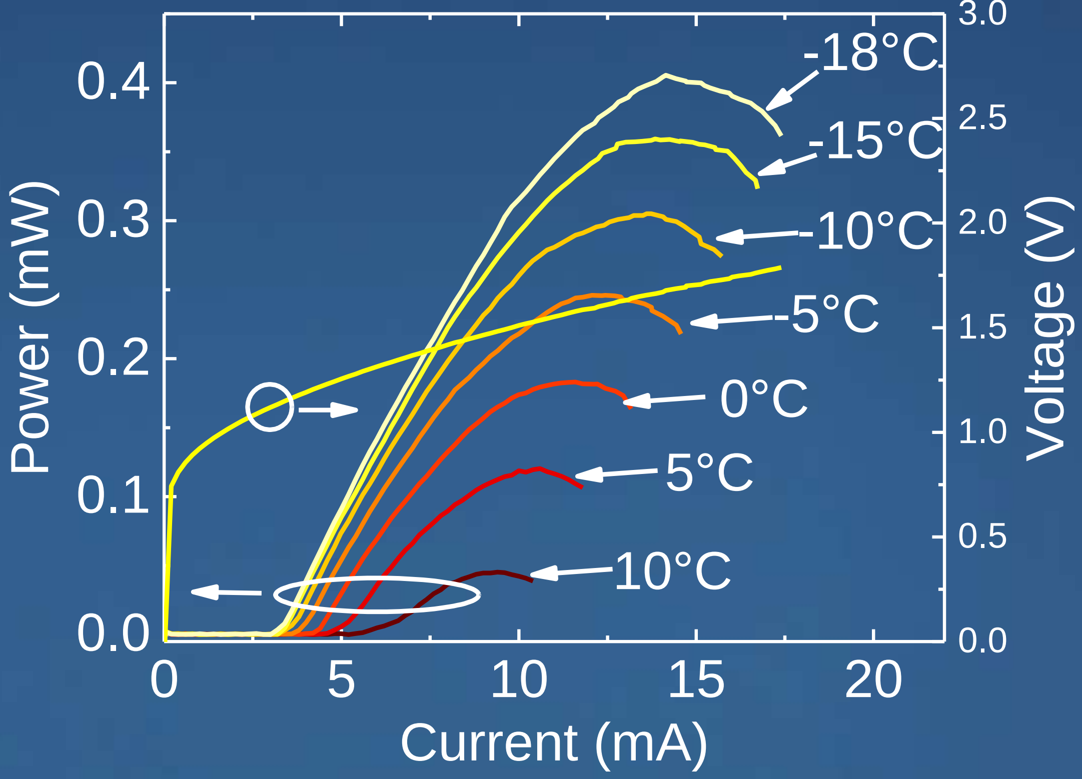


- **Aim: expand accessible wavelength range into MIR by using type-II QWs**

InP type-II VCSEL

First demonstration of InP-based VCSEL with type-II QWs

- λ = 2.49 µm
- D_{BTJ} = 7.5 µm
- T_{CW} =...10°C
- I_{th} = 3.2 mA (-18°C)
- P_{out} = 0.40 mW (-18°C)



InP type-II VCSEL

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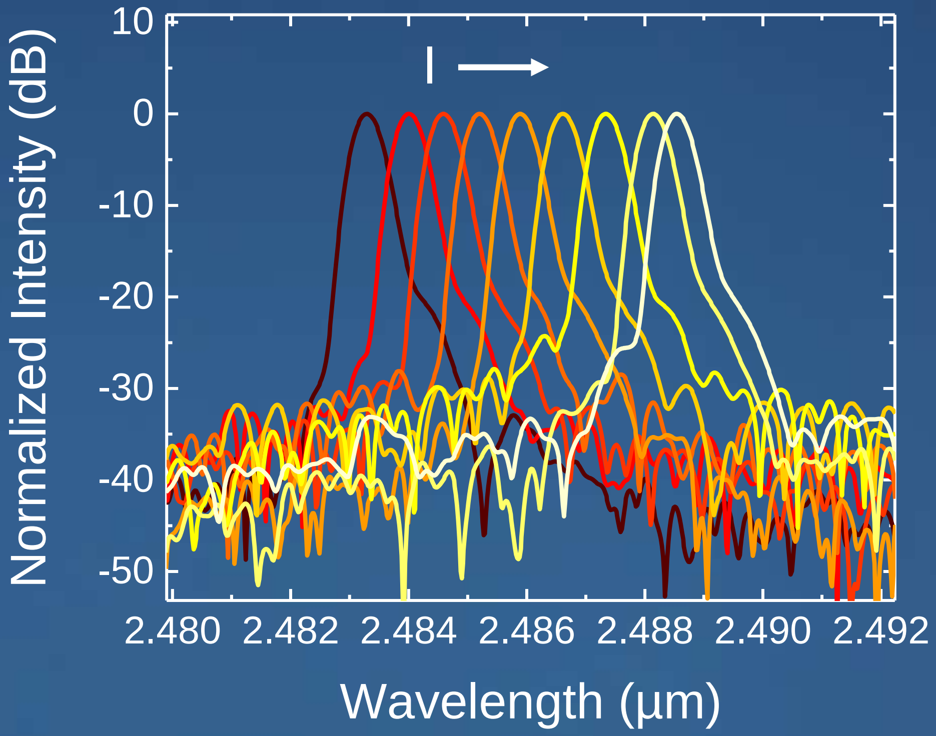
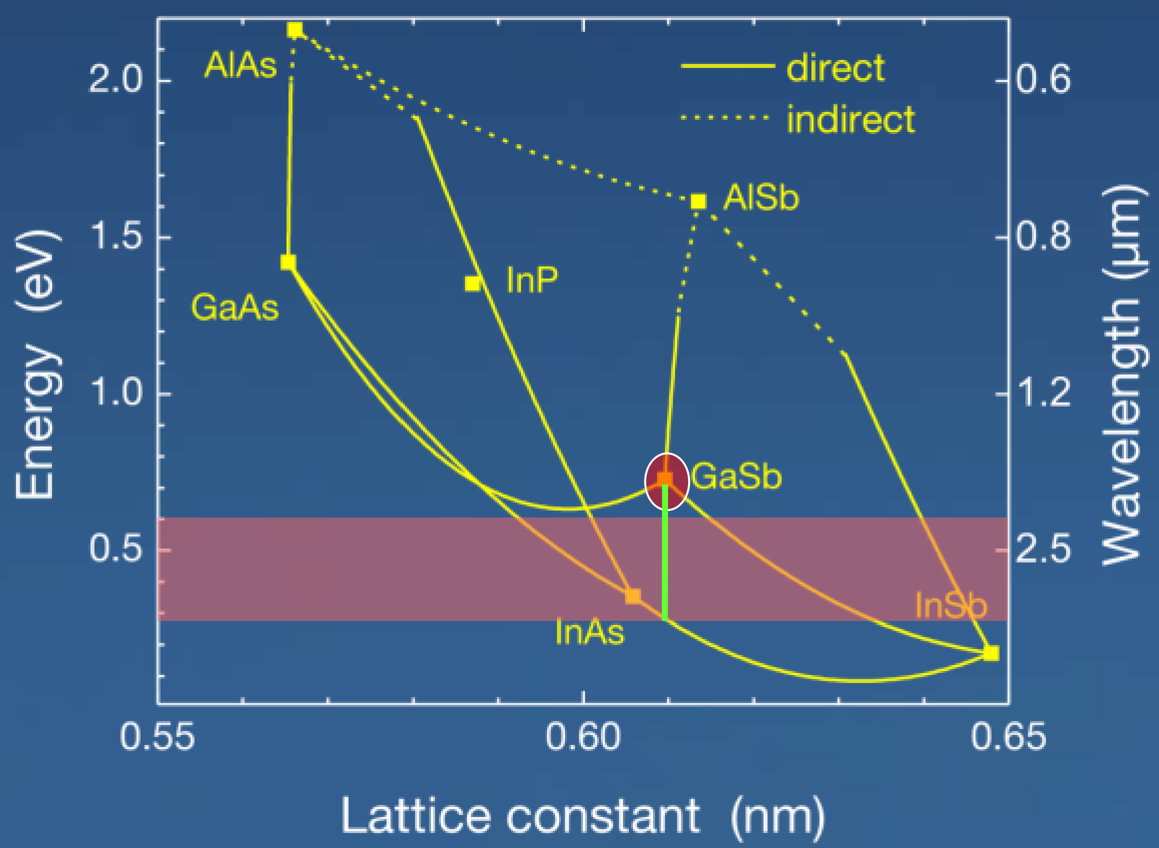
- $D_{BTJ} = 7.5$ µm
- T_{CW} =...10°C
- $I_{th} = 3.2$ mA (-18°C)
- $P_{out} = 0.40$ mW (-18°C)
- Tuning range > 5 nm (-20°C)



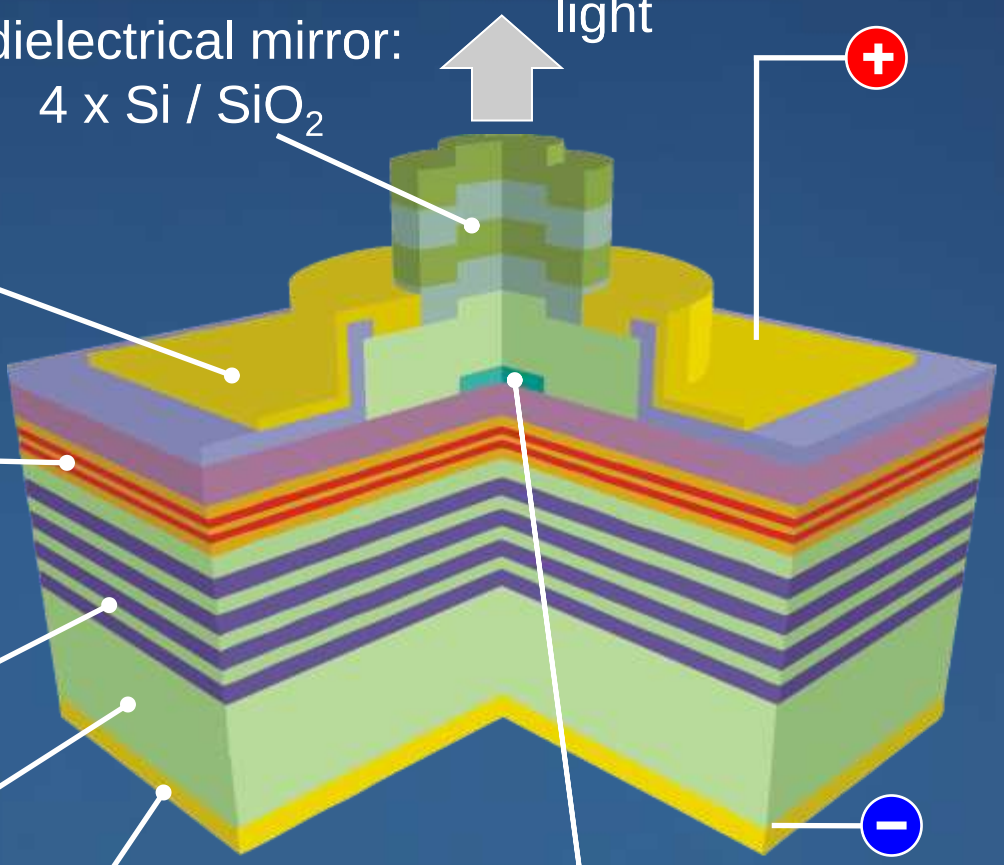
GaSb Based VCSELs



GaSb-based alloys are primary choice for MIR Laser diodes

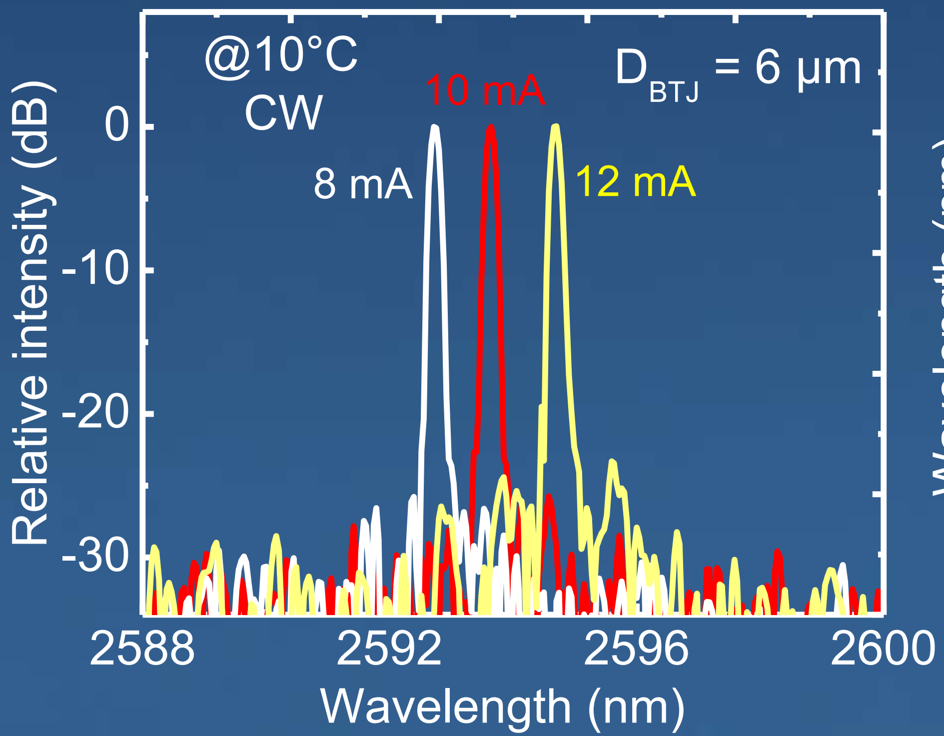
GaSb Based VCSELs

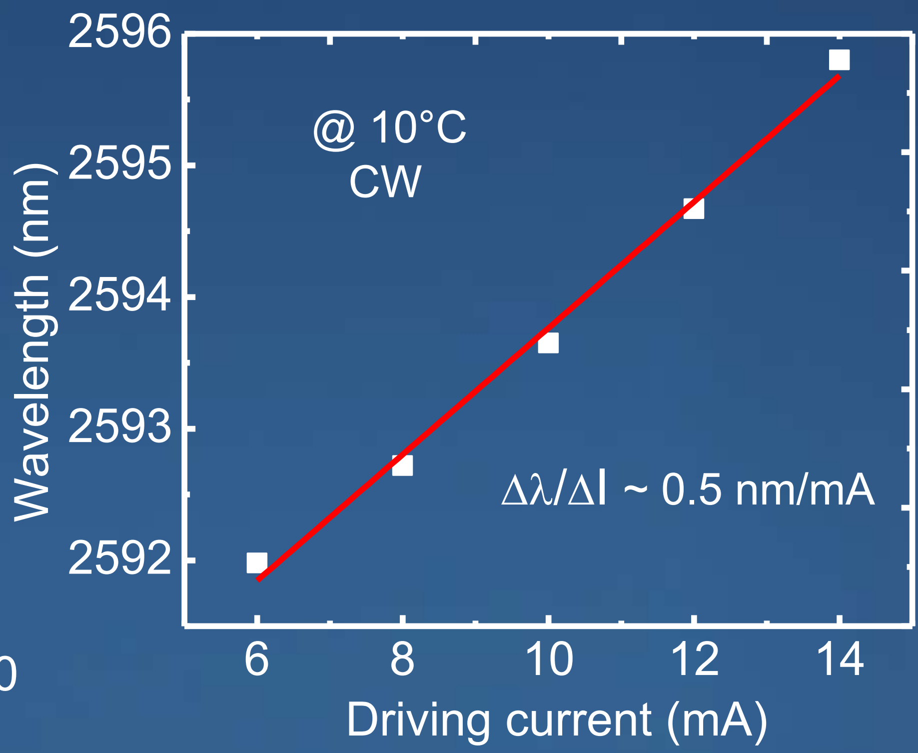
VCSEL Design



GaSb Based VCSELs

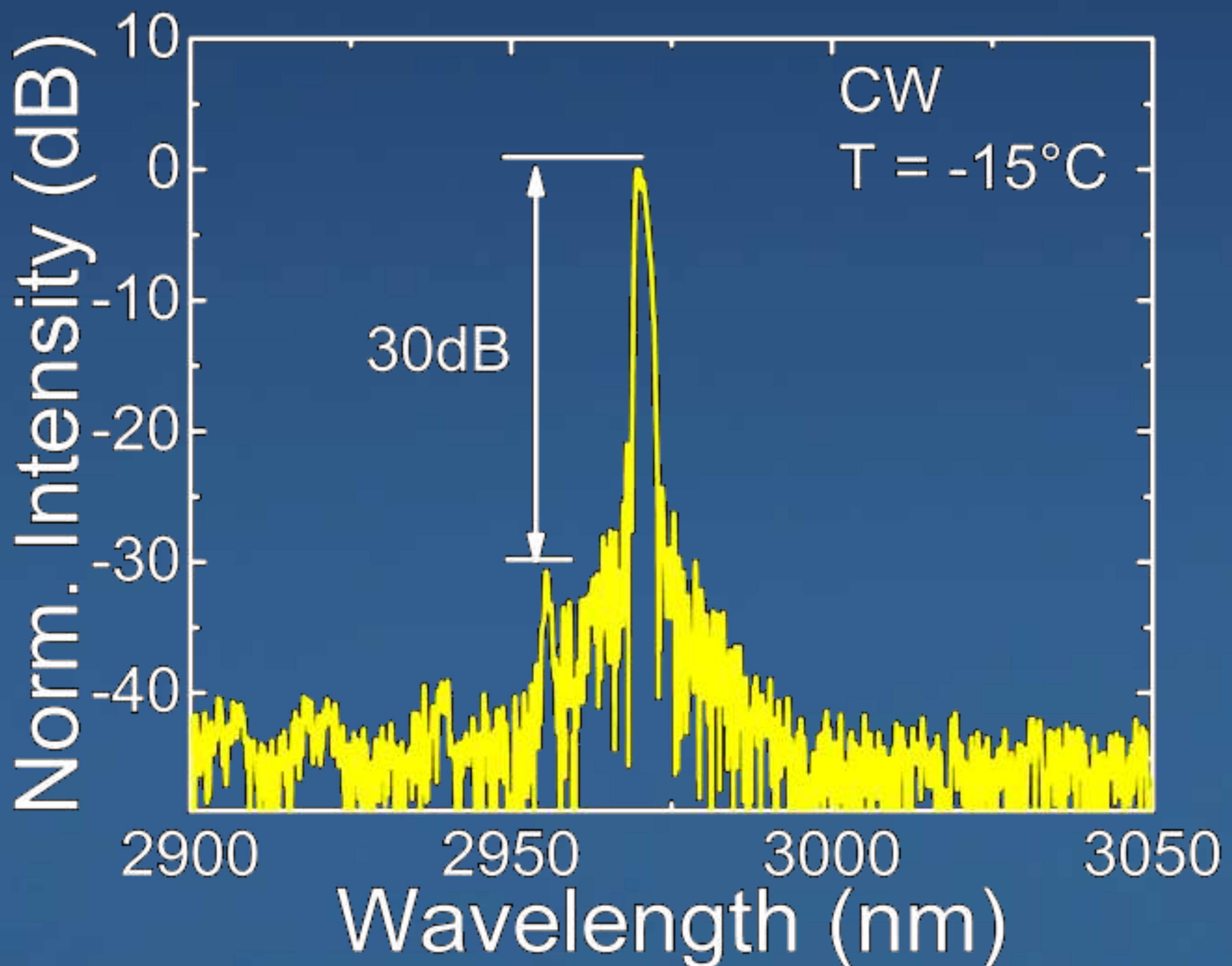
Tunability by current at 2.6 µm





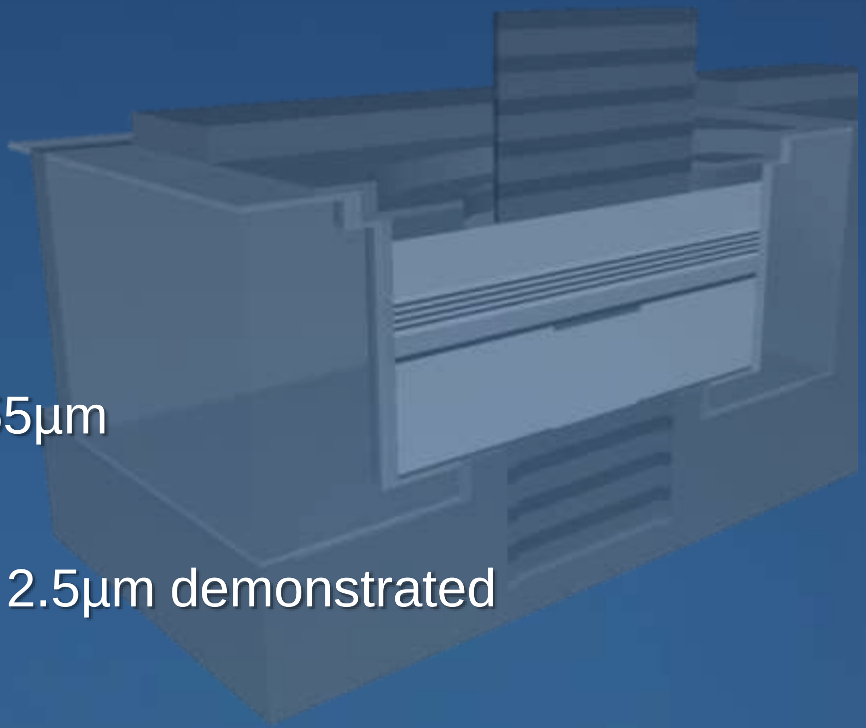
- Tuning range: $\Delta\lambda = 4$ nm
- Tuning coefficient: $\Delta\lambda / \Delta I = 0.5$ nm / mA

First 3µm VCSEL



Conclusion

- Demonstration of High-Performance BTJ-VCSELs in 1.3-3µm range
  - low threshold
  - single-mode
  - tunable



- Record bandwidth of 22 GHz at 1.55µm
- InP-VCSELs for wavelengths up to 2.5µm demonstrated
- GaSb-VCSELs for wavelengths up to 3µm demonstrated
- Outlook: GaSb Type-II Heterostructure VCSELs for 3-5µm MIR range

Thanks for your attention