Integrated High Speed VCSELs for Bi-Directional Optical Interconnects

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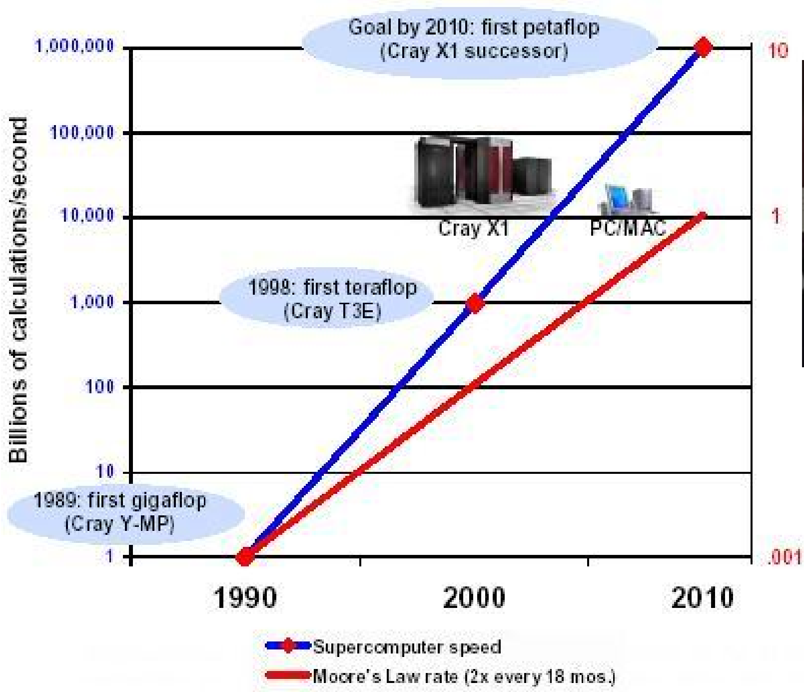
Outline

- Introduction
- Model description
- Structure optimization of VCSEL
- Conclusions

Computers: past, present and future



Cray1 1980s

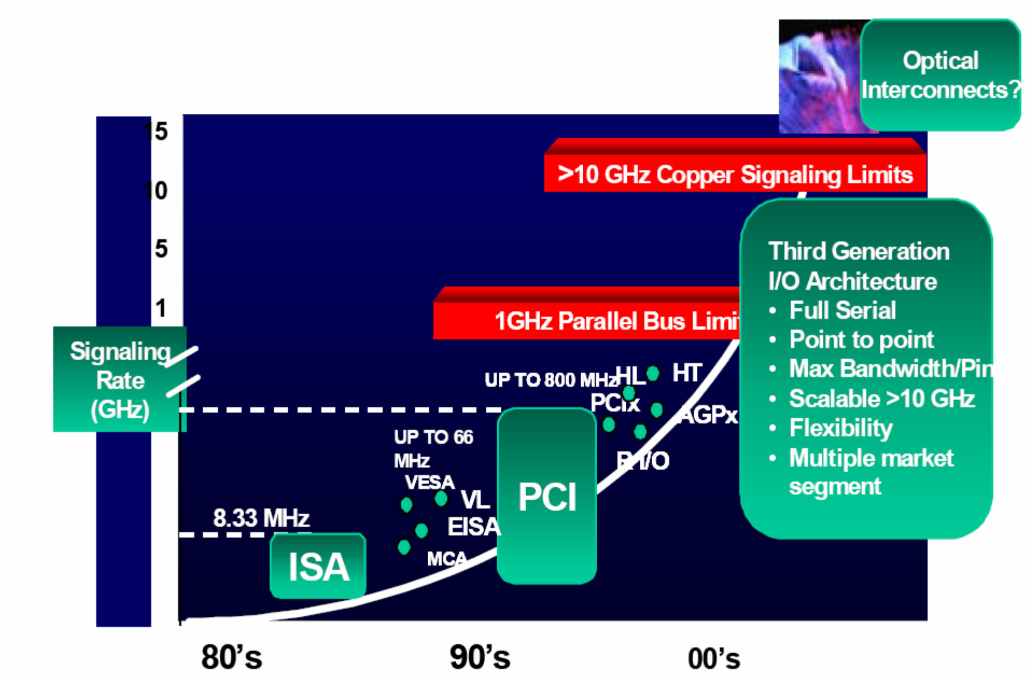
Pocket PC 2000s

Cray X1 2000s

?

PC 2020s

Computer I/O architecture history and I/O roadmap



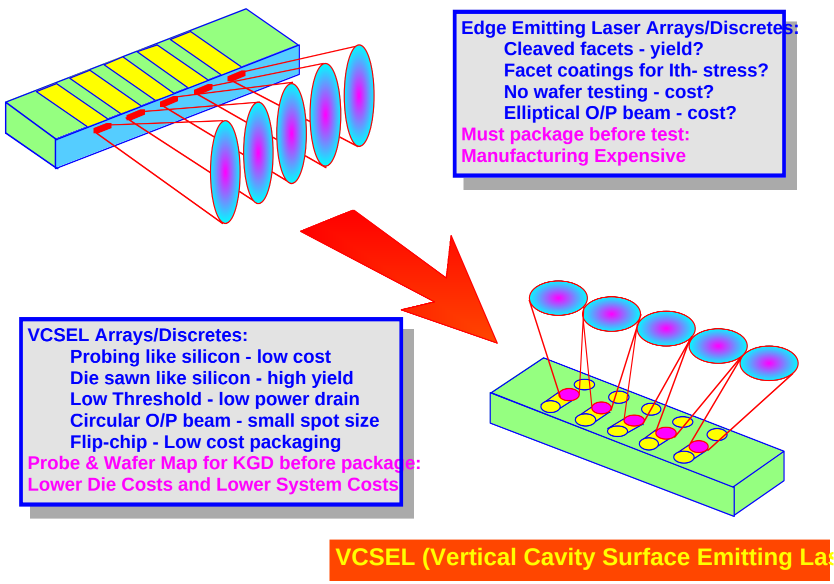
Beyond 10 GHz, copper interconnects, become bandwidth limited due to frequency-dependent losses such as
the skin effect in the conductors
and
the dielectric loss from the substrate material.

We need the optoelectronic devices with
• good performance (high-modulation bandwidth, low power consumption, high efficiency)
• manufacturing advantages (amenable to high-volume production, wafer-level testing, and ease of integration).

E. Mohammed et.al, Intel Technology Journal, V.8 N.2, 2004, pp. 115-127

VCSELs over Edge Emitter lasers

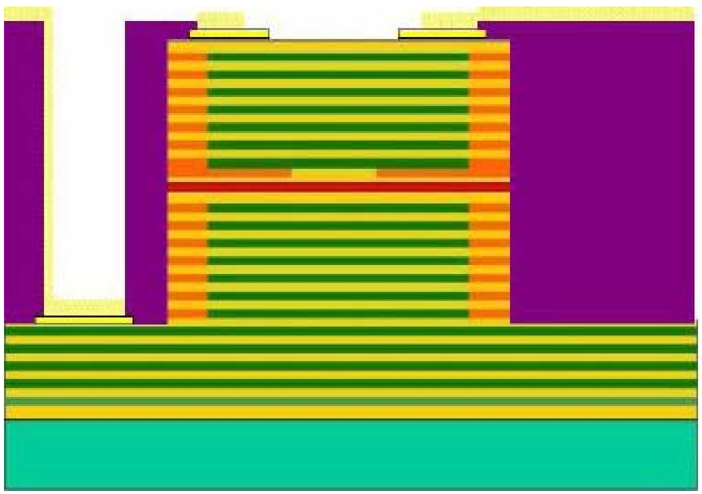
VCSELs Vs EEs (Arrays)

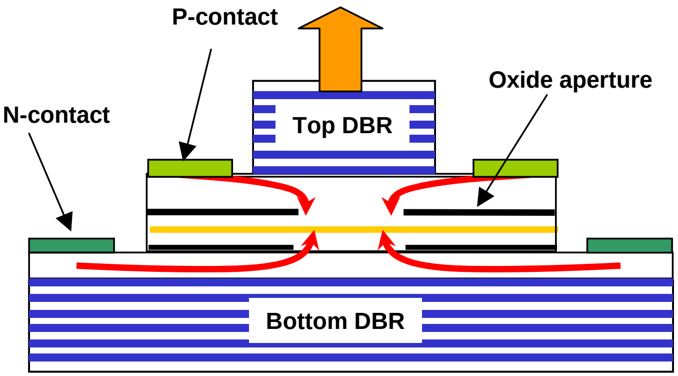


- <u>VCSELs are characterized by</u>:
- Low threshold Current.
- High power conversion efficiency.
- Less heating.
- Convenient operating wavelength.
- High speed of operation > 10 GHz.
- Surface normal light output.
- Circularly shaped, low NA output beams.
- Small size compared to other kinds of laser diodes.
- Very good potential for 2D arrays.
- Low cost wafer scale fabrication.

- <u>Important space applications:</u>
- High speed fiber optic networks.
- Free space optical communication.
- Optical interconnects.
- Optical storage systems.

Intracavity contacted VCSEL array

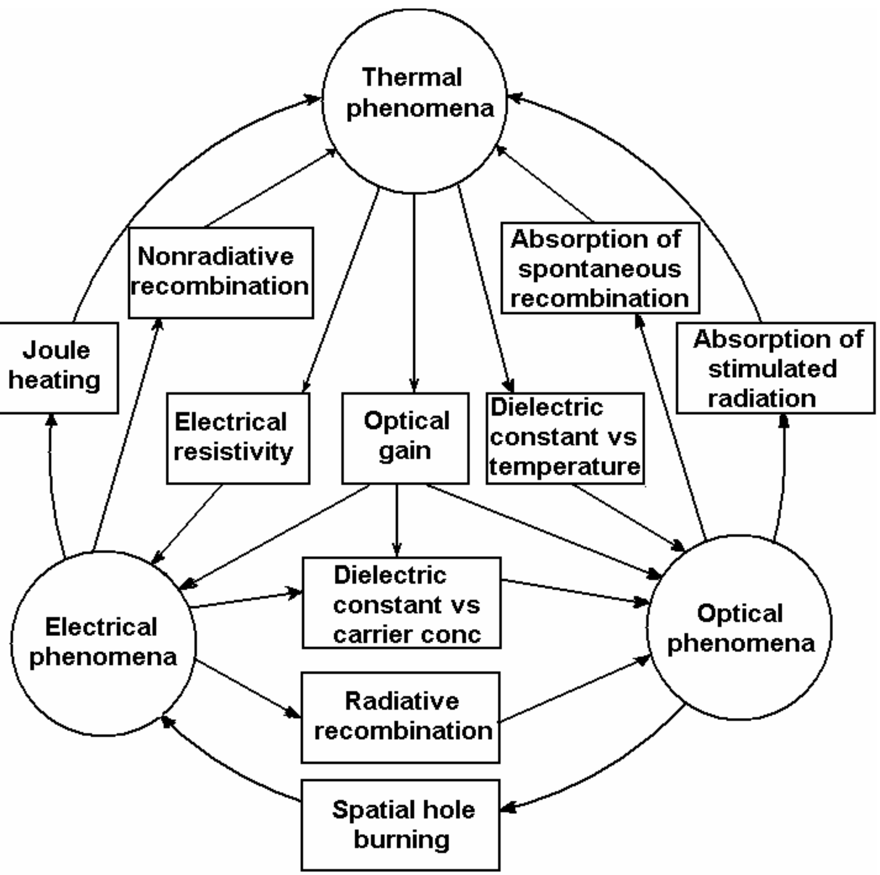


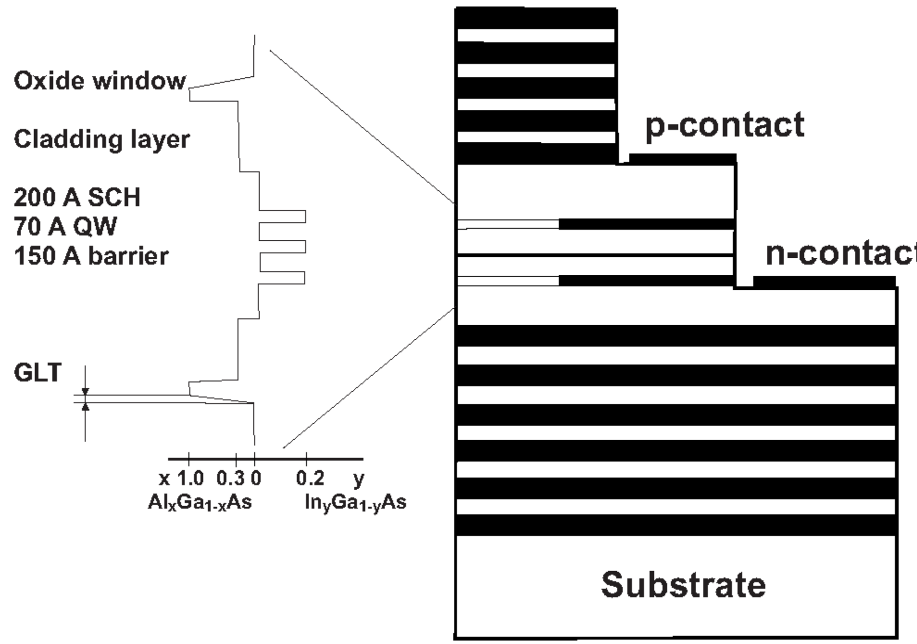


+ ***Bypass the current flow through mirrors***
  - ⇒ ***lowers the series resistance***
+ ***Use of undoped DBR mirror***
  - ⇒ ***reduce free carrier absorption***
  - ⇒ ***better reflectivity***
+ ***Co-planar contact***
  - ⇒ ***suitable for flip-chip bonding***

- Current crowding effect

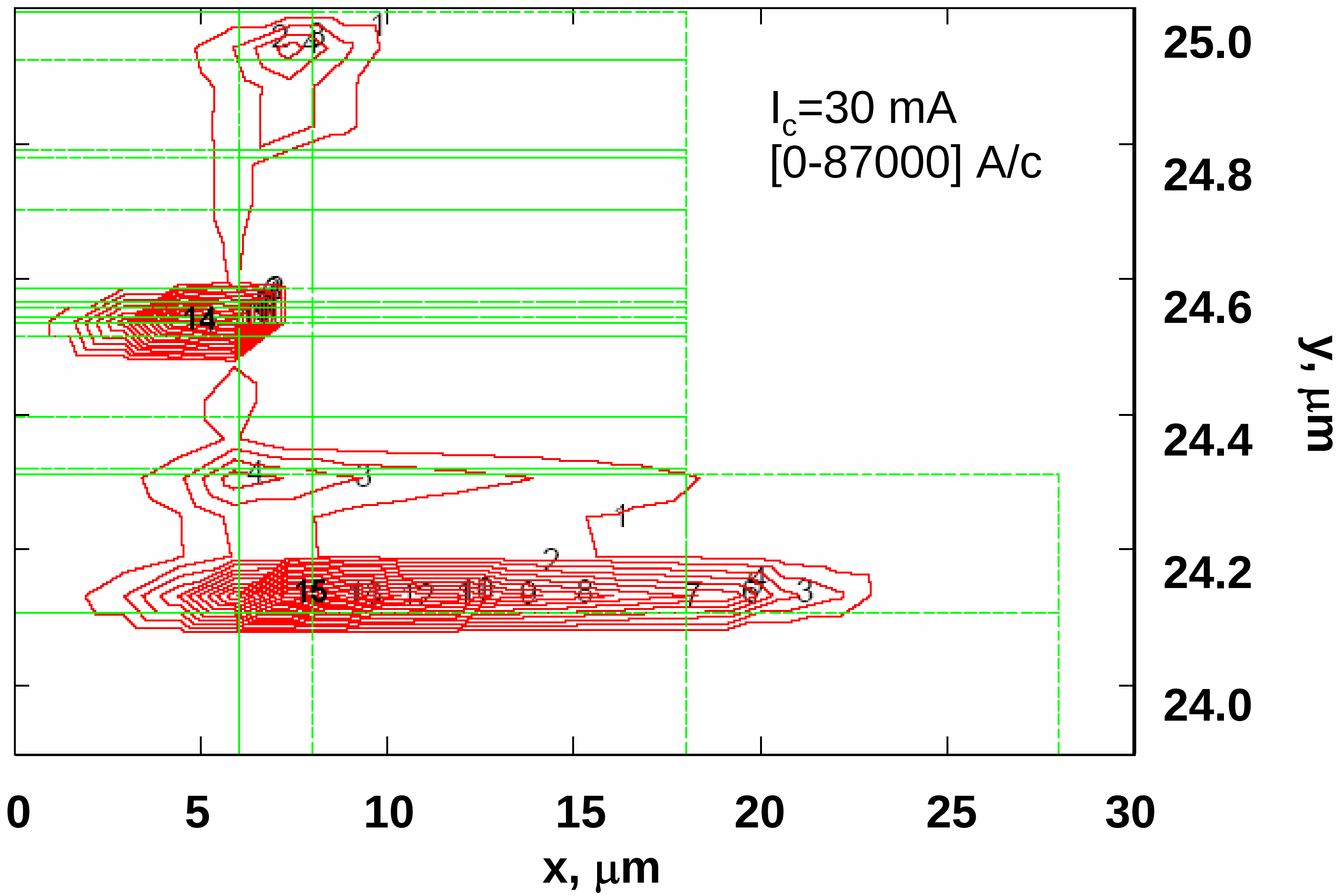
Interactions between physical processes in LD





PICS3D Crosslight program

Total current magnitude for different pumping currents



Thermal phenomena

Basic thermal equation

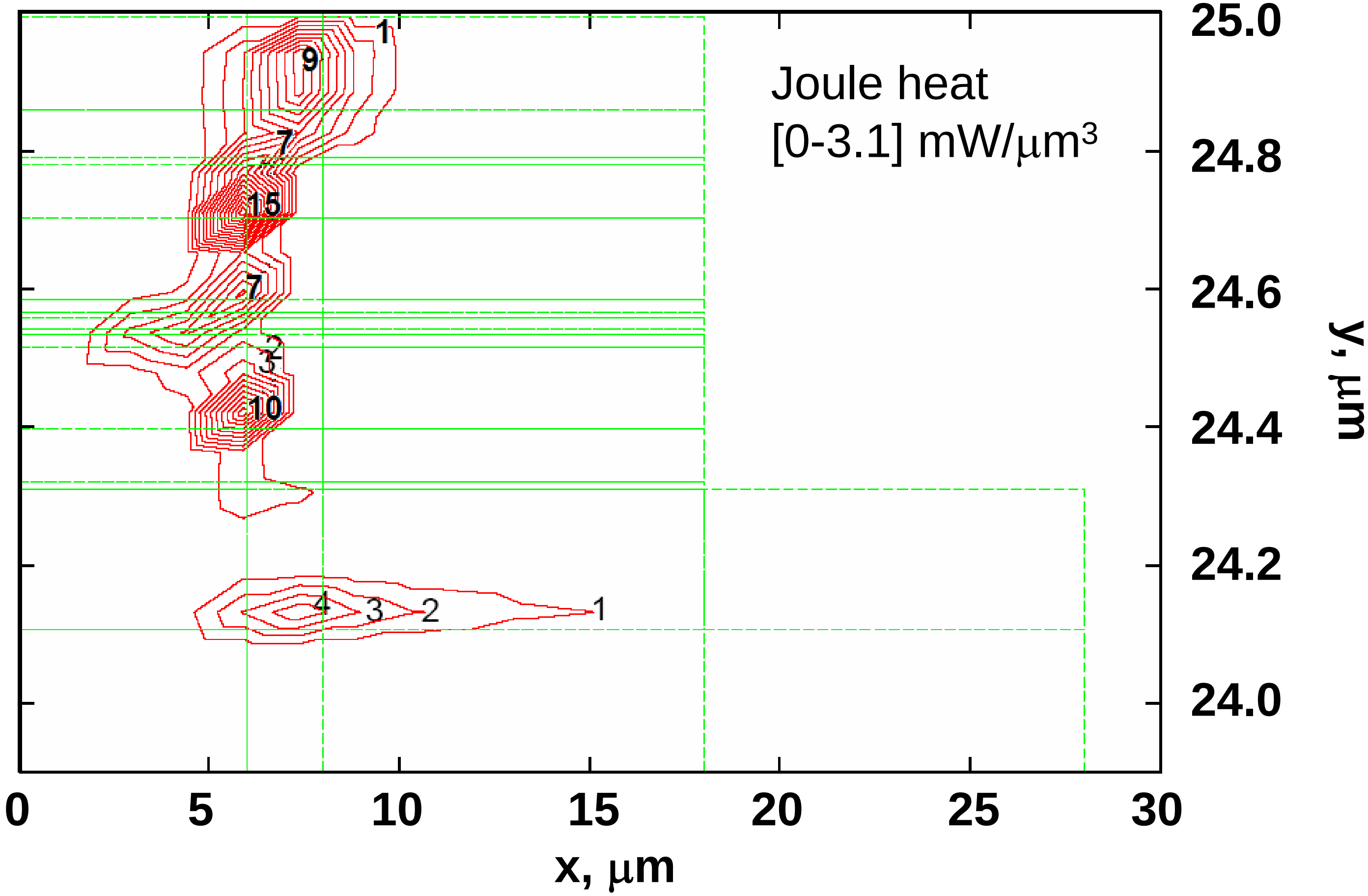
$$C_P \rho \frac{\partial T}{\partial t} = \nabla \cdot \kappa \nabla T + H$$

- C_P: Heat coefficient
- ρ: Material density
- κ: Thermal conductivity
- H: Heat sources

$$H = H_{Joule-dc} + H_{Joule-op} + H_{rec} + H_T + H_P$$

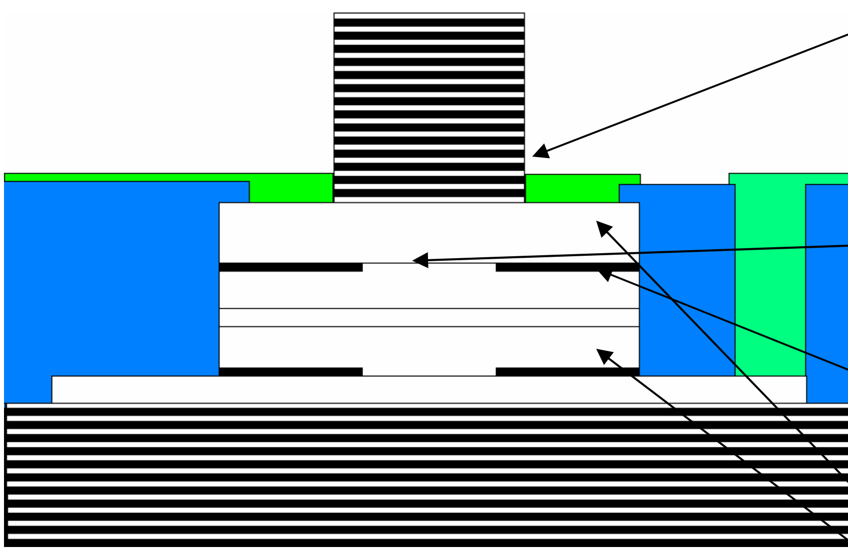
- $H_{Joule-dc}$ (~17 %): Steady-state Electrical field
- $H_{Joule-op}$ (~ 1 %): Optical wave absorption on loss semiconductors
- H_{rec} (80 %): Recombination heat
- H_T (0.001 %): Thomson heat
- H_P (~ 2 %): Peltier heat

Heat sources in ICOC VCSEL



Structure optimization

$$R_{ot} = \frac{d_{top\,mirror}}{d_{oxide\,window}}$$



$R_{ot}\uparrow$ $R_{tot}\uparrow$ $f_{3dB}\downarrow$

$R_{ot}\downarrow$ optic loss $\uparrow$ $f_{3dB}\downarrow$

Graded layer thickness

$t_{gr}\downarrow$ $R_{tot}\uparrow$ $f_{3dB}\downarrow$

$t_{gr}\uparrow$ $L_{pen}\uparrow$ $f_{3dB}\downarrow$

Oxide window diameter

$D_{ox}\downarrow$ $R_{tot}\uparrow$ $f_{3dB}\downarrow$

$D_{ox}\uparrow$ $V_{act}\uparrow$ $f_{3dB}\downarrow$

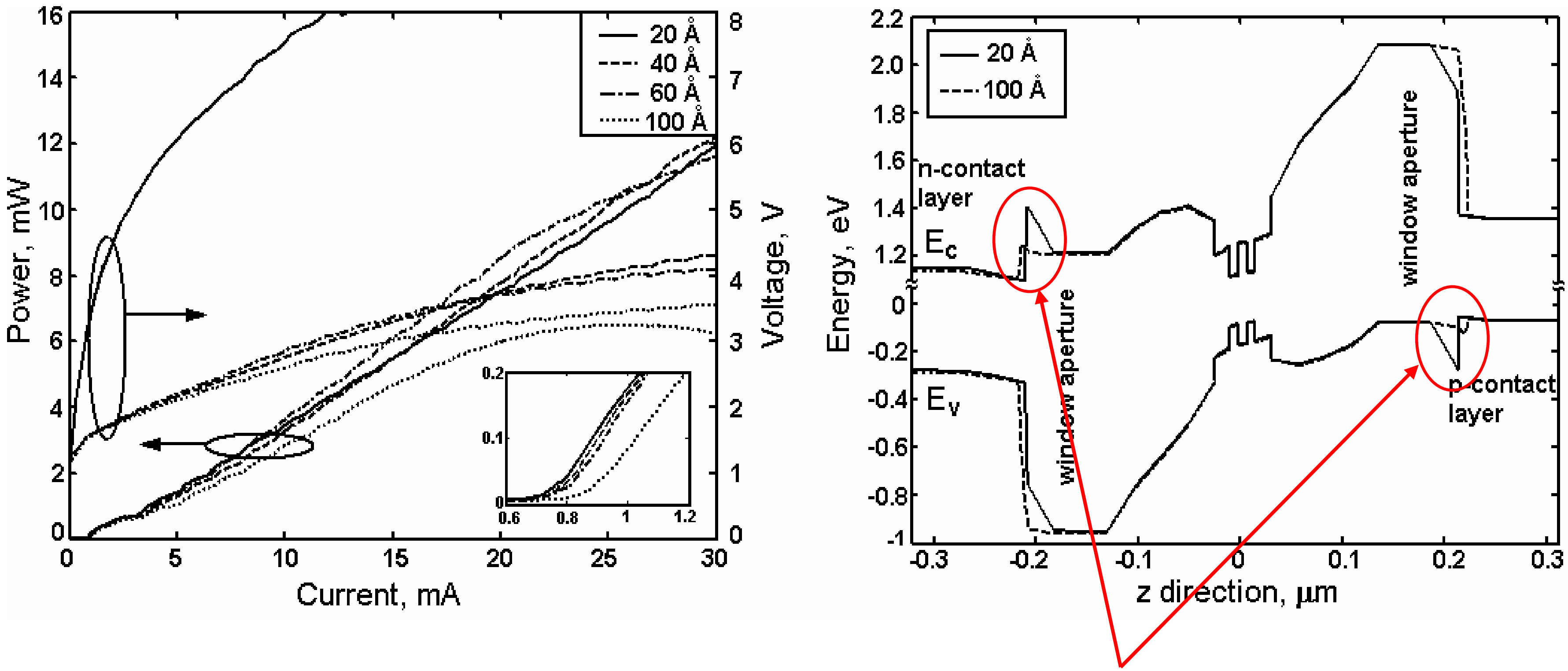
Contact layer thickness

$t_{cont}\downarrow$ $R_{tot}\uparrow$ $f_{3dB}\downarrow$

$t_{cont}\uparrow$ $L_{pen}\uparrow$ $f_{3dB}\downarrow$

Graded layer thickness I

I-L and I-V characteristics and energy band diagram in the center of structure for different values of **graded layer thickness** (GLT)

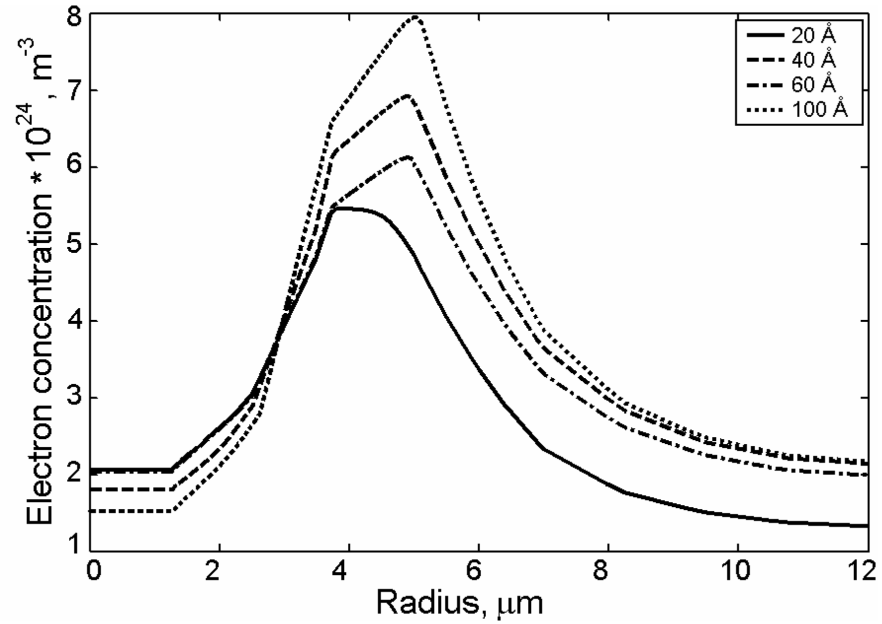


GLT↓→Energy "notches" ↑→R_{tot}↑

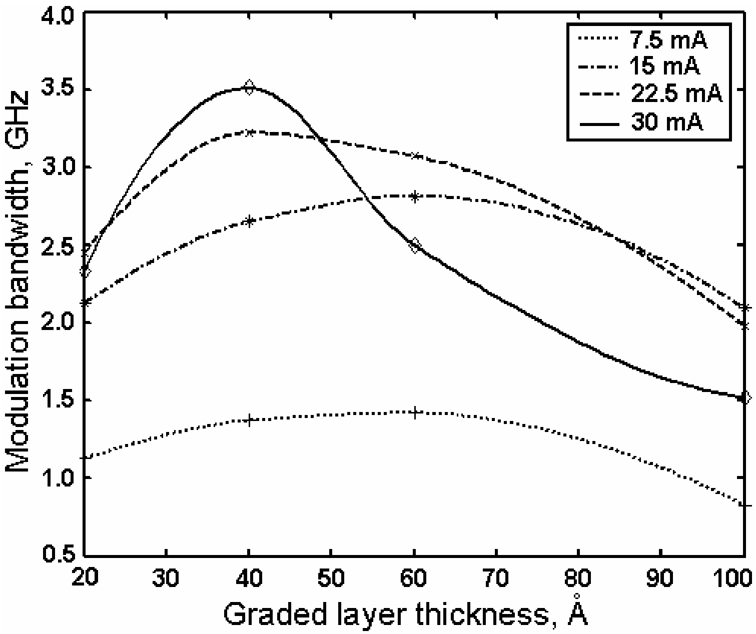
V. V. Lysak, et. al, Appl. Phys. Lett. 87 (2005), 231118 1-3

Graded layer thickness II

Radial distribution of electron concentration



f3dB bandwidth



GLT ↑→ current crowding effect↑

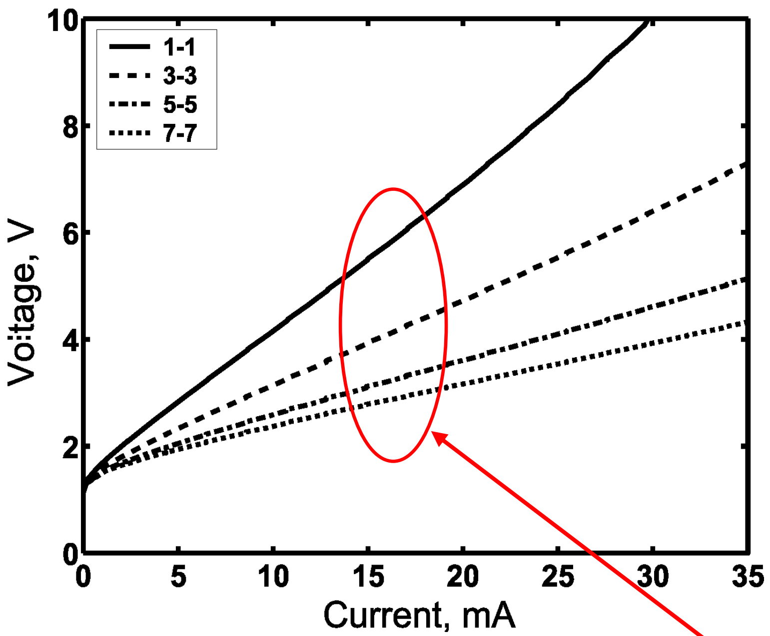
GLT↓→Rtot↑ → f3dB↓

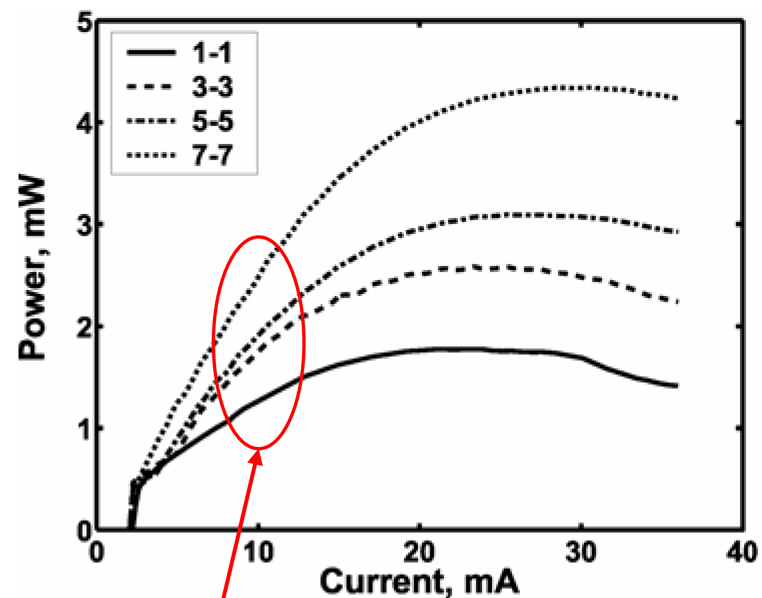
GLT ↑→Veff↑ + nonuniform current distribution → f3dB ↓

Contact layer thickness I

Contact layer is a part of DBR mirror → $d=(2k+1)\lambda/4n$

a) V-I and b) L-I characteristics for different values of n - and p - contact layer thickness of $\lambda/4n$ (solid lines), $3\lambda/4n$ (dashed lines), $5\lambda/4n$ (dash-dotted lines) and $7\lambda/4n$ (dotted lines)

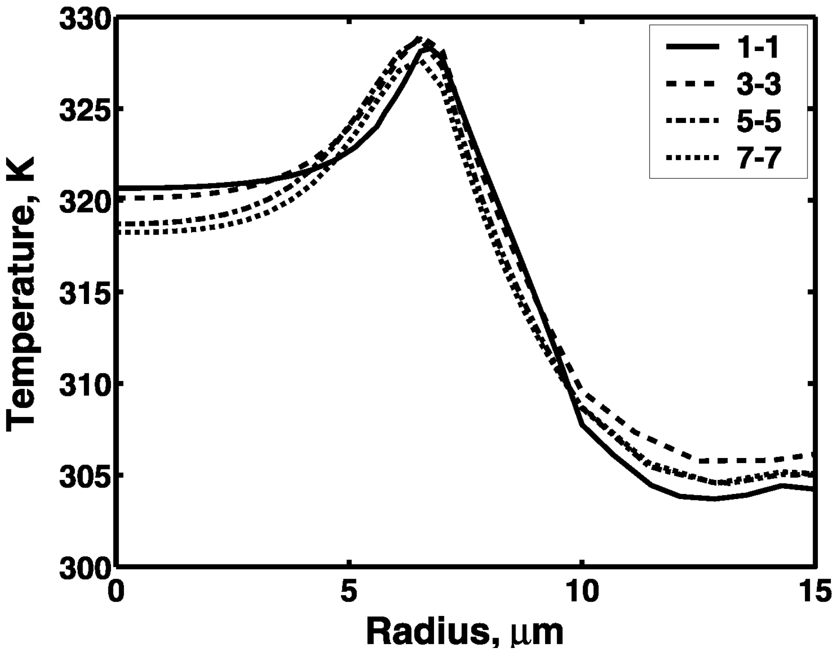




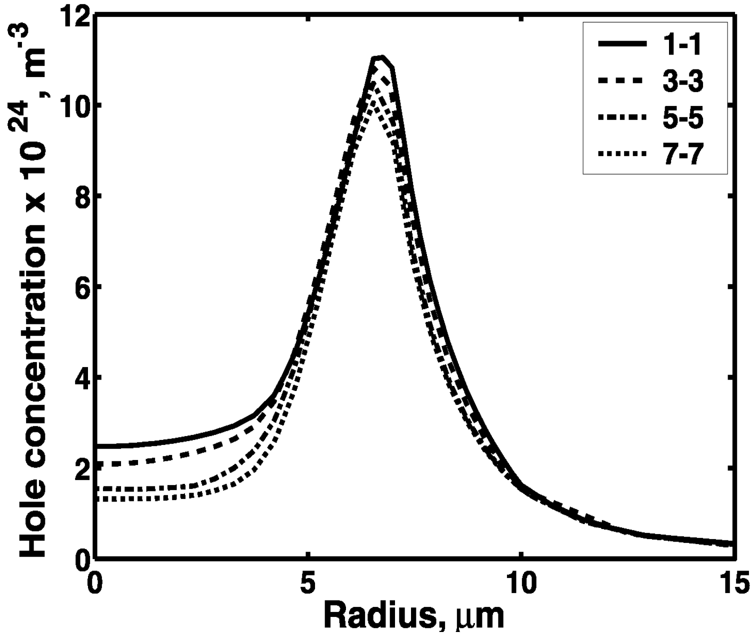
CLT↑ → R_{layer}↓ → R_{tot} ↓ → T_{active}↓ →Gain↑

Contact layer thickness II

Radial distribution of the lattice temperature in active layer

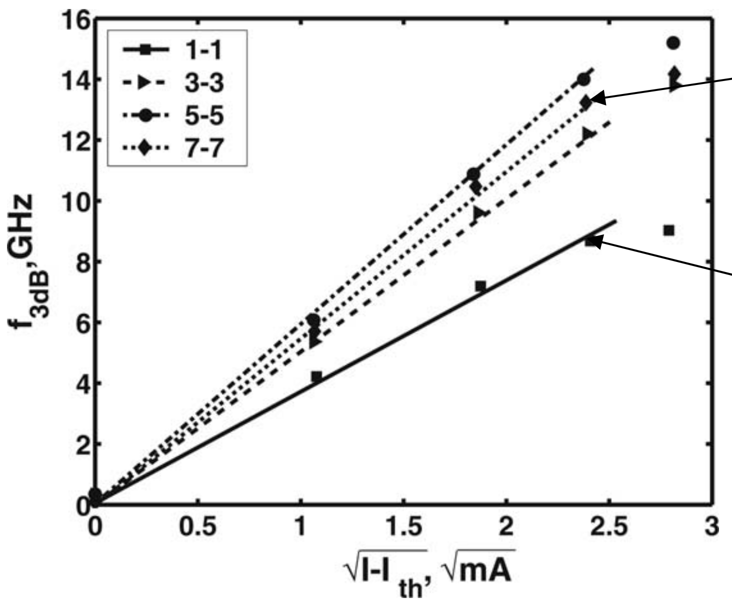


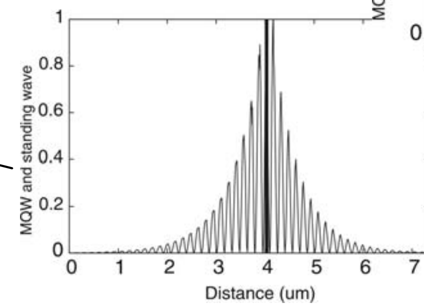
Radial distribution of the electron concentration

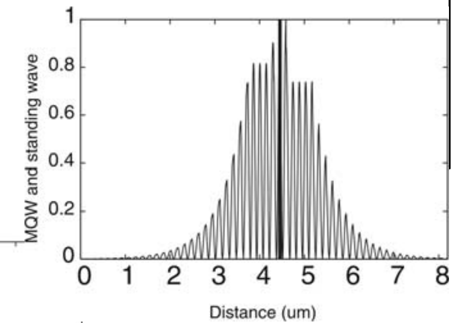


$CLT\uparrow \rightarrow R_{layer}\downarrow \rightarrow R_{tot}\downarrow \rightarrow T_{active}\downarrow \rightarrow Gain\uparrow$

Contact layer thickness III







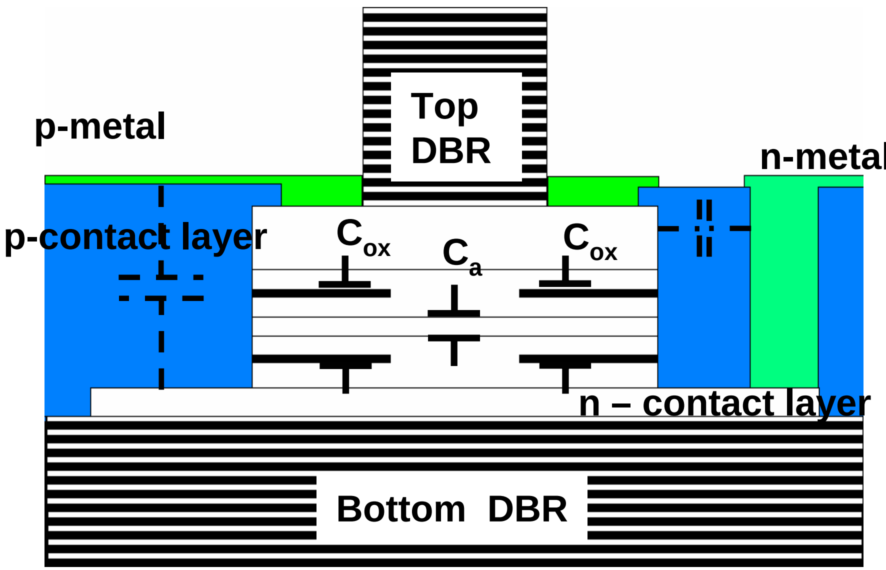
$$f_R = \frac{1}{2\pi}\sqrt{\eta_i \frac{\Gamma \xi v_g}{qV_{eff}} \frac{\partial g}{\partial N}\left(I - I_{th}\right)}$$

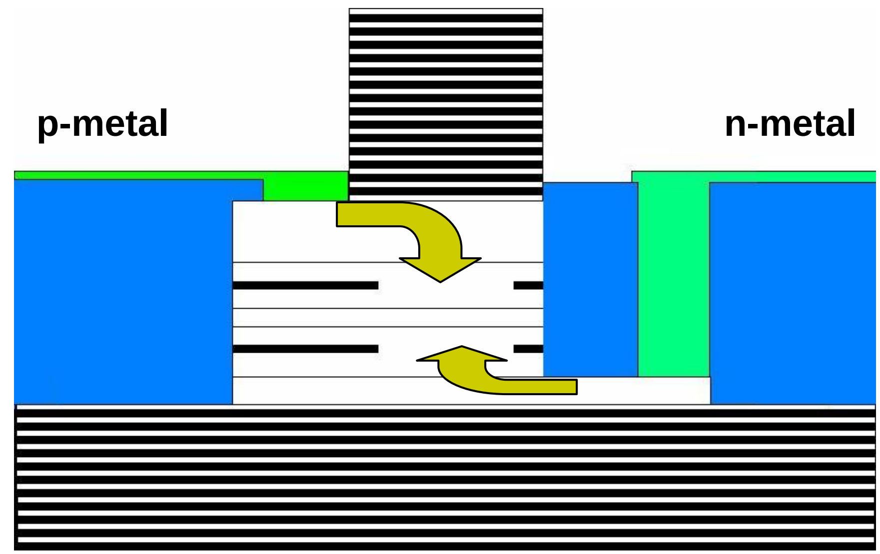
Decreasing the CLT increases the differential resistance (see V-I characteristics). On the other hand, increasing the CLT changes the parameters as follows:

increases the effective volume of resonator and decreases the gain enhancement factor due to increasing the penetration depths of DBR mirrors;

reduces differential gain from the current crowding effect

Capacitance management

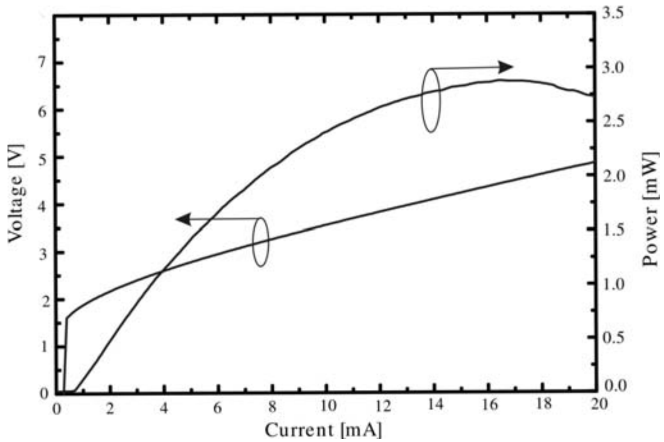


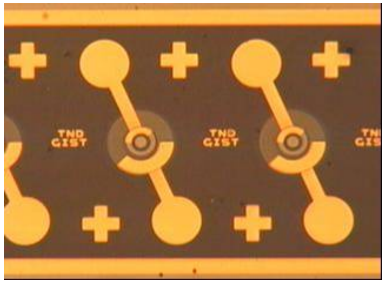


C_{ox} ↓ Counter-flowing paths for electrons and holes ⟶ asymmetrical contacts and suppress the conductivity

Experimental part

L-I-V characteristics

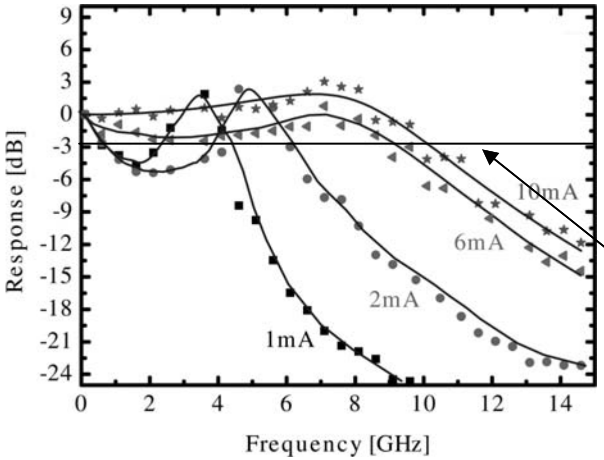




- Oxide aperture dia. : **5 μm**
- Threshold current : **0.7±0.05 mA**
- Threshold voltage : **1.7 V**
- Slope efficiency : **0.36±0.01 W/A @ I=2mA**
- Differential quantum efficiency:

  28.4±0.7 %@ I=2mA
- Differential resistance : **150 Ω @ I=6mA**

♦ small signal modulation



3dB bandwidth **10 GHz** at 10 mA

Conclusion

- we have analyzed the thermal, electrical, optical, and modulation properties of the 980 nm InGaAs ICOC VCSELs with different geometrical values
- devices with the optimal GLT of 40-60 Å have the highest output power and the widest modulation bandwidth due to compromise between the low resistance and more uniform radial carrier distribution in the active layer
- devices with the optimal CLT of $5\lambda/4n$ have the widest modulation bandwidth and the modulation conversion efficiency factor is approximately 5.92 GHz/(mA)$^{0.5}$ due to compromise between the effective volume of resonator, current crowding suppression and total resistance
- The VCSEL with 5 mm diameter oxide aperture has a threshold current of 0.7 mA, a threshold voltage of 1.7V and a maximum output power of 7mW. 0.36W/A slope efficiency at 6mA and 29% differential quantum efficiency were achieved at room temperature. A maximum 3dB modulation frequency at a bias current of 10mA reached 10 GHz.

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