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Characterization of Adsorption Processes in High-Temperature CO2 Sorbents

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Above Threshold Analysis of Quasi Guided Optical Waveguide VCSELs for Single-Mode High-Power Application

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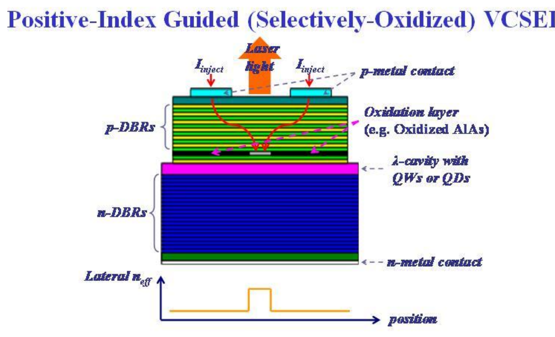
Research Objectives:

- ✓ To achieve novel vertical cavity surface emitting lasers (VCSELs) for high-power and single-mode operation
- ✓ Accomplish cold cavity analysis of the proposed Quasi-Guided Optical Waveguide (QGOW) VCSELs
- ✓ Develop and complete the above threshold analysis of the QGOW VCSELs for high injection current operation

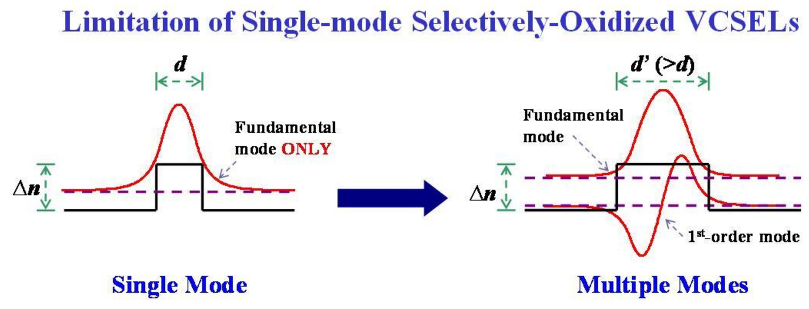
Positive-Index Guided (Selectively-Oxidized) VCSELs



- Selectively-Oxidized VCSELs [1] → Most-Widely Fabricated VCSELs
  - Small Aperture for Single-Mode → Low power
  - Aperture diameter (< 4 μm) → 5 mW [1,2]
  - Current Confinement provided by Oxidation Layer
  - Oxide Aperture → Positive Index Guiding
  - Lateral Transport leads to higher resistance in the p-DBRs.

1. K. L. Lear, K. D. Choquette, R. P. Schneider, Jr., S. P. Kilcoyne, and K. M. Geib, Electron. Lett., vol. 31, pp. 208-209, 1995.
2. C. Jung, R. Jäger, M. Grabherr, P. Schnitzer, R. Michalzik, B. Weigl, S. Müller, and K. J. Ebeling, Electron. Lett., 33, 1790 (1997).

Limitation of Single-mode Selectively-Oxidized VCSELs



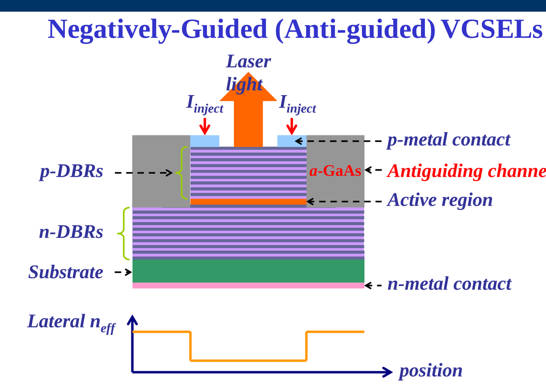
- High-Power Single-Mode VCSELs:
  - Large Aperture Diameter → High Power VCSELs
  - Single Lateral-Mode Control
- Limitation of Selectively Oxidized VCSELs:
  - Increase in Aperture Size → Multi-lateral Modes
  - Small Aperture → Limits Optical Power

Alternatives for High-Power Single Mode VCSELs

- External Mode Selectivity
  - Using the external cavity [1]
- Higher-Order Mode Suppression
  - Higher Mirror Loss for Higher Order Mode
  - Using the shallow surface relief [2]
- Lateral Mode Control
  - → Negative-Index-Guide VCSELs
    - Antiguided VCSELs [3]
    - S-ARROW VCSELs [4]
    - ARROW VCSELs [5]
  - → Photonic-Crystals VCSELs [6]
  - → Quasi-guided VCSELs (This Work)

1. B. J. Koch, J. R. Leger, A. Gopinath, Z. Wang, and R. A. Morgan, Appl. Phys. Lett., vol. 70, 2359 (1997).
2. H. Martinsson, J. A. Vukušić, and A. Larsson, IEEE Photon. Technol. Lett., vol. 12, pp. 1129-1131, 2000
3. T. A. Wu, C. J. Chang-Hasnain, and R. Nabiev, Electron. Lett., vol. 29, pp. 1861-1863, 1993
4. T.-W. Lee, S. C. Hagness, D. Zhou, L. J. Mawst, IEEE Photon. Technol. Lett., vol. 13, pp. 770-772, 2001
5. D. Zhou and L. J. Mawst, IEEE J. Quantum Electron., vol. 38, pp. 1599-1606, Dec. 2002
6. A. J. Danner, J. J. Raftery, N. Yokouchi, K. D. Choquette, Appl. Phys. Lett. Vol. 84, 1031 (2004), and A. J. Danner, et. al., APL, vol. 88, Art. 091114 (2006).

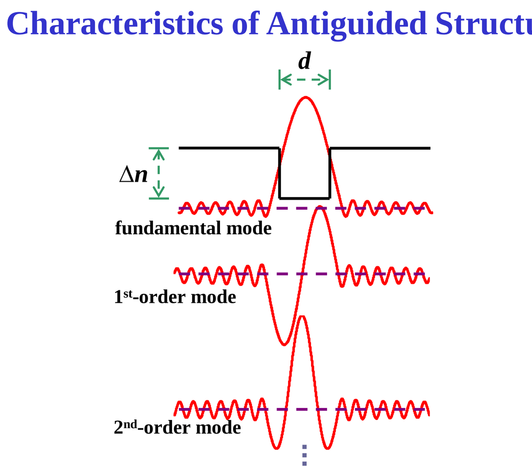
Negatively-Guided (Anti-guided) VCSELs



- Anti-guided Single Mode VCSELs
  - High α_{01} → High J_{th}
  - Above-threshold operation → Multi-lateral modes

1. B.-S. Yoo, H. Y. Chu, M.S. Park, H.-H. Park and E.-H. Lee, Electron. Lett., vol. 32, pp. 116-117, 1996

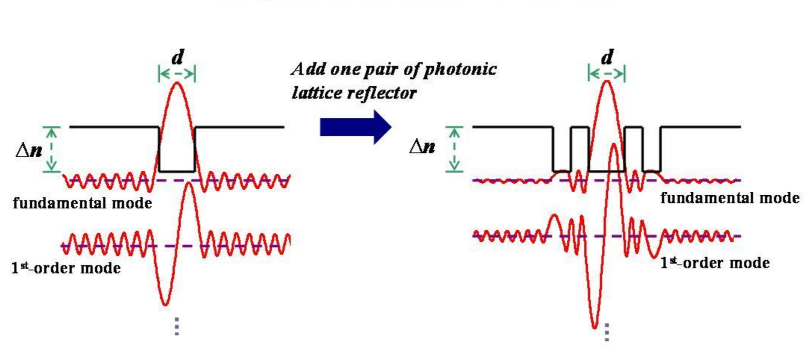
Characteristics of Antiguided Structure



Anti-Guided Structure Has Mode-Dependent Loss Mechanism!

- The loss of the fundamental mode decreases when the area increases
  - $\alpha_0 \sim 1/d^2$ (Area)
- The lateral radiation depends on the n^{th}-order of the mode
  - $\alpha_n \sim (n+1)^2\alpha_0$ (i.e. $\alpha_1 \sim 4\alpha_0$; $\alpha_2 \sim 9\alpha_0$)

Properties of ARROW VCSELs[1]

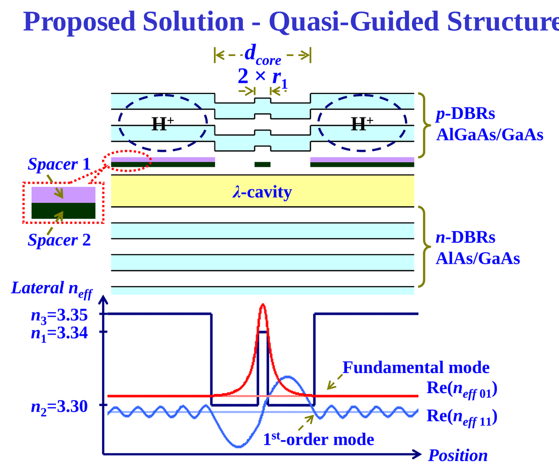


ARROW Structure[1] → Antiguided + one pair of photonic lattice reflector

- Significantly suppress the lateral radiation loss of the fundamental mode!
- Maintain the lateral radiation loss of the higher-order modes

1. D. Zhou and L. J. Mawst, IEEE J. Quantum Electron., vol. 38, pp. 1599-1606, Dec. 2002

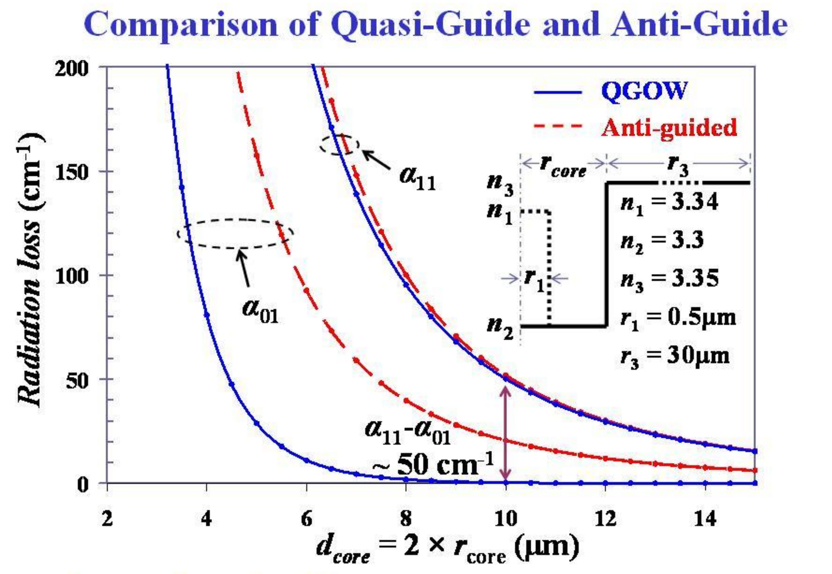
Proposed Solution - Quasi-Guided Structure [1]



- Proposed Solutions:
  - Quasi-guided VCSELs
    - Fundamental mode → Quasi-guided mode → low radiation loss
    - Higher-order modes → Anti-guided modes → high radiation loss

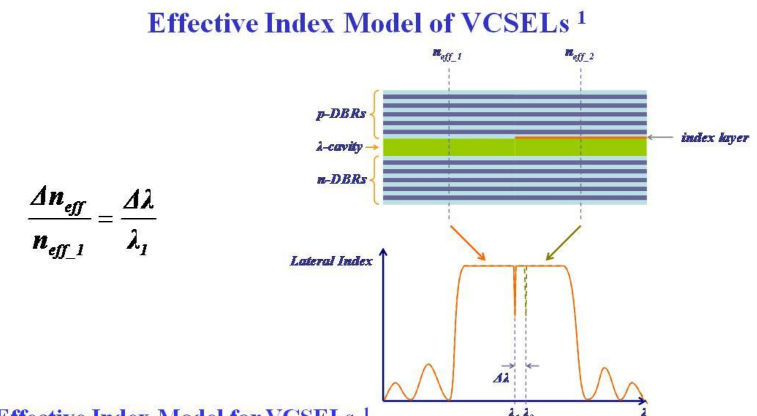
1. Z. Jin, R. S. Tummidi, Y. P. Gupta, D. M. Schindler, and N. Tansu, "Quasi-Guided-Optical-Waveguide VCSELs for Single-Mode High-Power Applications," in Proc. of the IEEE/OSA Conference on Lasers and Electro-Optics (CLEO) 2006, paper CWP7, Long Beach, CA, May 2006.

Comparison of Quasi-Guide and Anti-Guide



- α_{01} of quasi-guide
  - $\alpha_{01,quasi} << \alpha_{01,anti}$
  - e.g. $\alpha_{01,anti} - \alpha_{01,quasi} \sim 38$ cm^{-1} at $d_{core} = 8$ μm
- α_{11} of quasi-guide
  - $\alpha_{11,quasi} \approx \alpha_{11,anti}$

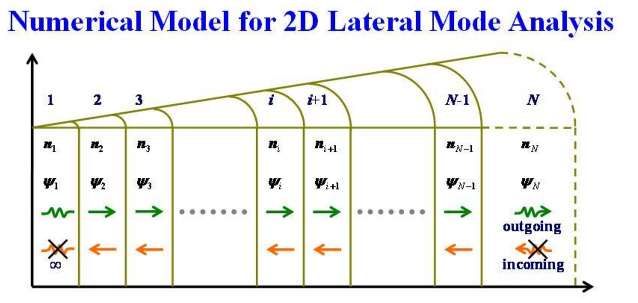
Effective Index Model of VCSELs [1]



- Effective Index Model for VCSELs [1]
  - Lateral Index Profile → Determined by Cavity Resonance [1]
  - Change $\Delta n_{Lateral}$ by Changing the $\Delta\lambda_{resonance}$
  - Standard and Widely-Used Approach for VCSELs modeling [1-5]

1. G. Ronald Hadley, Opt. Lett., vol. 20, No. 13, July 1995.
2. C. W. Wilmsen, H. Temkin, and L. A. Coldren, Vertical –Cavity Surface-Emitting Lasers, Cambridge Press, 1999
3. Yokouchi N, Danner AJ, Choquette KD, IEEE J. Sel. Top. Quantum Electron., vol. 9, pp. 1439-1445, 2003
4. D. Zhou and L. J. Mawst, IEEE J. Quantum Electron., vol. 38, pp. 1599-1606, Dec. 2002
5. Streiff M, Witzig A, Pfeiffer M, Royo P, Fichtner W, IEEE J. Sel. Top. Quantum Electron., vol. 9, pp. 879-891, 2003

Numerical Model for 2D Lateral Mode Analysis



- 2D Cylindrical Numerical Lateral Mode Analysis
- Applicable for Cylindrical Concentric Waveguide
  - Positive-Index VCSELs
  - Antiguided VCSELs
  - ARROW VCSELs
  - Quasi-Guided VCSELs
  - Photonic-Lattice VCSELs
- Analogous to transfer matrix in rectangular layered media[1]

1. Pochi Yeh, Optical Waves in layered Media, Wiley Interscience 1988

Numerical Model for 2D Lateral Mode Analysis

- Wave Equation (Bessel differential equation)

$$\frac{\partial^2\psi_i(r)}{\partial r^2}+\frac{1}{r}\frac{\partial\psi_i(r)}{\partial r}+\left[k_0^2\left(n_i^2-n_{eff}^2\right)-\frac{m^2}{r^2}\right]\cdot\psi_i(r)=0$$

- General Solutions ($\kappa_i=\sqrt{k_0^2 n_i^2 - n_{eff}^2}$)

Standing Wave

$$\psi_i(r)=F_m(\beta_i r)A_i+G_m(\beta_i r)B_i=\begin{cases}J_m(\kappa_i r)A_i^J+Y_m(\kappa_i r)B_i^Y\\ \text{or}\\ H_m^{(1)}(\kappa_i r)A_i^H+H_m^{(2)}(\kappa_i r)B_i^H\end{cases}$$

Traveling Wave

Numerical Model for 2D Lateral Mode Analysis

- Relationship of coefficients from i^{th} layer to i+1th layer :

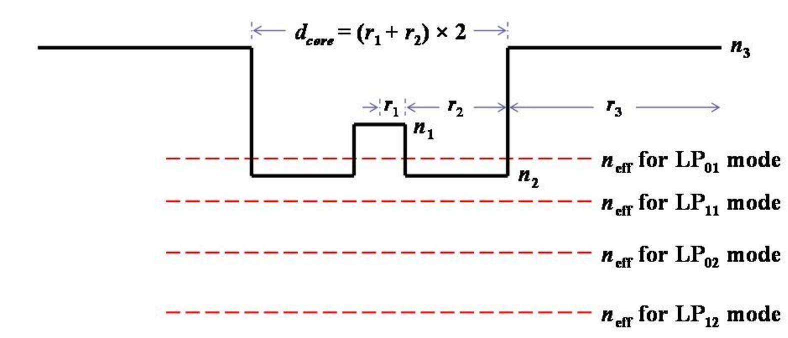
$$\begin{bmatrix}A_i\\B_i\end{bmatrix}=\begin{bmatrix}F_m(\beta_i r_i) & G_m(\beta_i r_i)\\ \frac{\partial F_m(\beta_i r)}{\partial r}\Big|_{r=r_i} & \frac{\partial G_m(\beta_i r)}{\partial r}\Big|_{r=r_i}\end{bmatrix}^{-1}\begin{bmatrix}F_m(\beta_{i+1} r_i) & G_m(\beta_{i+1} r_i)\\ \frac{\partial F_m(\beta_{i+1} r)}{\partial r}\Big|_{r=r_i} & \frac{\partial G_m(\beta_{i+1} r)}{\partial r}\Big|_{r=r_i}\end{bmatrix}\begin{bmatrix}A_{i+1}\\B_{i+1}\end{bmatrix}$$

- Relationship of coefficient from 1st layer to Nth layer:

$$\begin{bmatrix}A_1\\B_1\end{bmatrix}=\left[\prod_{i=1}^{N-1}TM_i\right]\begin{bmatrix}A_N\\B_N\end{bmatrix}\quad \text{where}\quad \prod_{i=1}^{N-1}TM_i=\begin{bmatrix}m_{00} & m_{01}\\ m_{10} & m_{11}\end{bmatrix}$$

- m_{ij} is the function of n_{eff}
- To compute the mode solutions in cylindrical-concentric VCSELs:
  - $B_1 = 0$ (Physically not allowed)
  - $B_N = 0$ (No external incoming wave)
  - → $m_{10} = 0$ → n_{eff}

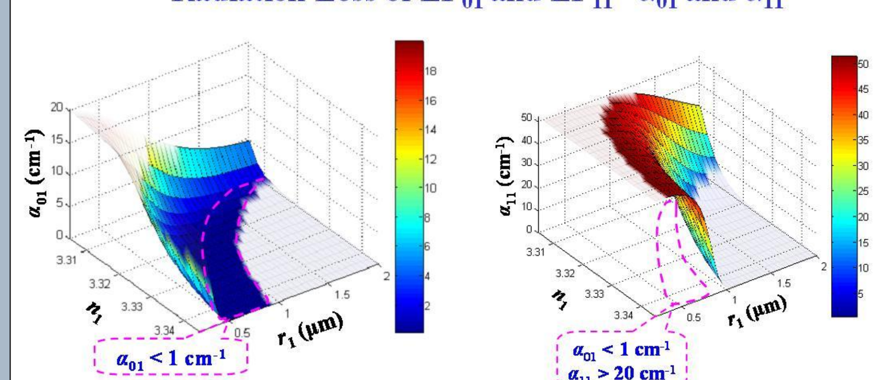
Quasi-Guided VCSELs - Simulation



Parameters of the simulated case:

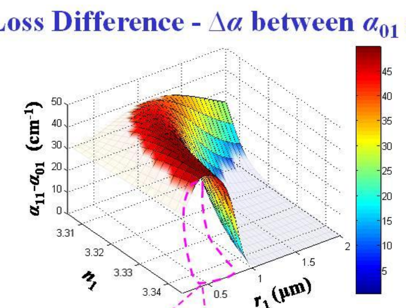
r_1 (μm)	Variable (0 – 2)
$r_{core} = r_1+r_2$ (μm)	5
r_3 (μm)	30
n_1	Variable (3.305 – 3.345)
n_2	3.3
n_3	3.35

Radiation Loss of LP$_{01}$ and LP$_{11}$ - α_{01} and α_{11}



- Radiation loss of fundamental mode (α_{01}):
  - Guided mode → Significantly low
  - α_{01} (Quasi-Guided) << α_{01} (ARROW)
- Radiation loss of 1st-order mode (α_{11}):
  - Antiguide mode → Significantly high

Loss Difference - $\Delta\alpha$ between α_{01} and α_{11}



- Loss difference between guided LP$_{01}$ and antiguided LP$_{11}$:
  - Minimum $\Delta\alpha$ > 10 cm^{-1}
  - Maximum $\Delta\alpha$ ~ 45 cm^{-1}
- Comparison – ARROW VCSELs (8μm diameter) [1]
  - α_{01} (ARROW) ~ 1 cm^{-1}
  - $\Delta\alpha$ (ARROW) ~ 7 cm^{-1}

1. D. Zhou and L. J. Mawst, IEEE J. Quantum Electron., vol. 38, pp. 1599-1606, Dec. 2002

Above Threshold Operation of QGOW VCSELs

- To achieve high power output one must increase the aperture size and injection current, however this leads to problematic effects:
  - **Thermal Lensing Effect**
    - Ohmic heating created from injection current causes an increase in temperature at the core of the VCSEL
    - Induces a graded refractive index change **with a guiding effect**
    - Focuses the fundamental mode in the VCSEL
  - **Spatial Hole Burning Effect**
    - Describes the injection current and the effect of optical mode on carrier concentration.
    - Stimulated emission in the active region of the VCSEL causes a non-uniform distribution of carriers
    - Induces a graded refractive index **with an anti-guiding effect**

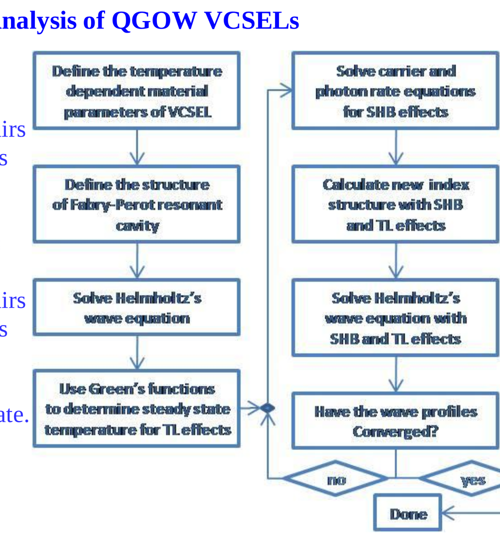
Above Threshold Analysis

✓requires complex and computing-intensive analysis of both the thermal lensing and spatial hole burning effects

Numerical Flow Chart for Above Threshold Analysis of QGOW VCSELs

Simulated Structure:

- 20 AlAs/GaAs p-DBR pairs
  - 4.3μm total thickness
- 3 InGaAsN / GaAs QWs
  - 61nm total thickness
- 30 AlAs/GaAs n-DBR pairs
  - 8.4μm total thickness
- DBRs tuned for 1.3μm emission on a GaAs substrate.



Thermal Profile in QGOW VCSELs – Green Function Method

- Thermal Lensing's Effect on QGOW
  - Thermal Lensing → *Positive* refractive index change: $\delta n_T = \frac{\partial n}{\partial T}\Delta T$
  - Temperature distribution solved using Green's Function Methods:

$$A_{mn}=\frac{1}{{k_m}^2+{L_n}^2}\int_0^H\int_0^W\frac{\sin(k_m z_a)J_0(L_n r)\,Q(r,z)}{\lambda(z)}rdrdz$$

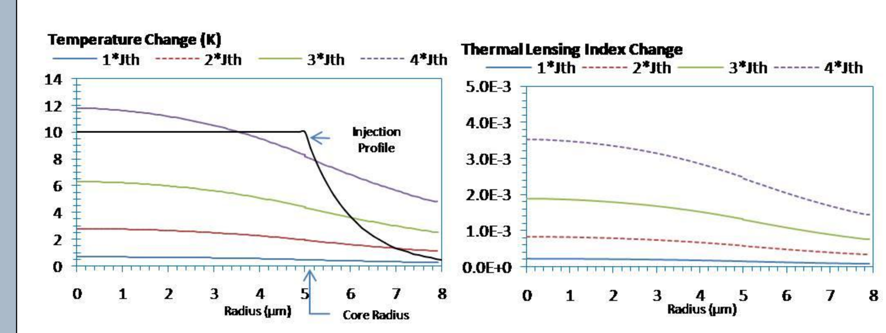
$$T(r)=T_0+\frac{4}{HW^2}\sum_m^{\infty}\sum_n^{\infty}\frac{A_{mn}\sin(k_m z_a)J_0(L_n r)}{J_0(L_n W)^2}$$

$$k_m=\frac{(2m-1)\pi}{2H}\qquad L_n=\frac{n_n}{2r_{core}}\qquad n_n=roots\,of\left\{J_1\left(\frac{rW}{2r_{core}}\right)\right\}$$

- VCSEL Material Parameters:

Region	Resistivity	Thermal Conductivity
p-DBR	$2.3 * 10^{-1}\Omega cm$	$0.035(W/cmK)$
active layer	$10^{-2}\Omega cm$	$0.25(W/cmK)$
n-DBR	$3.2 * 10^{-2}\Omega cm$	$0.08(W/cmK)$
substrate	$10^{-4}\Omega cm$	$0.44(W/cmK)$

Thermal Lensing Analysis of QGOW VCSELs



- Uniform injection current in core region
  - Employed 1μm diffusion length
  - Temperature decreases radially outward due to thermal conduction
- Refractive index change increases with higher injection current
  - Minimal $\Delta n_{thermal}$ for J = J_{th}
  - $\Delta n_{thermal}$ ~ 2-3.5x10^{-3} for J = 4xJ_{th}

Spatial Hole Burning in QGOW VCSELs

- Spatial Hole Burning → *Negative* index change:

$$\delta n_{SHB}=-\alpha_H\frac{\lambda}{4\pi}\Gamma_z\frac{g_{0N}}{N}\Delta N$$

- Carrier concentration distribution solved via FDTD on rate equations:
  - Carrier Rate Equation

$$\frac{\partial N}{\partial t}=\frac{J}{qd}+D_n\nabla^2 N-N\left(\frac{1}{t_n}+B_{sp}N+C_{aug}N^2\right)-v_g\sum_{v,h}GS_{v,h}$$

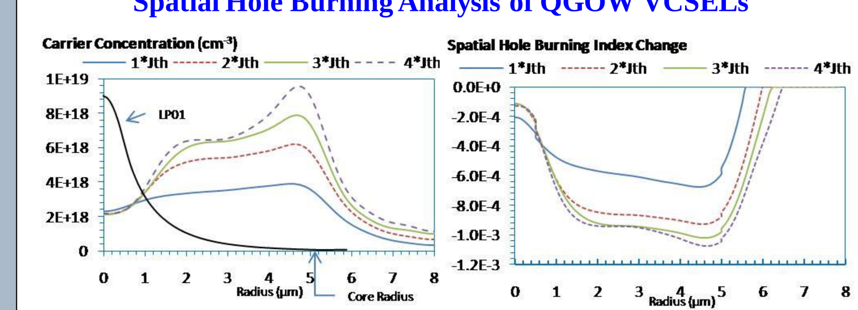
  - Photon Rate Equation

$$\frac{\partial S_{v,h}}{\partial t}=\left(\Gamma_z v_g\langle G\rangle-\frac{1}{t_p}\right)S_{v,h}+\beta B_{sp}\Gamma_z\langle N\rangle^2$$

- VCSEL Material Parameters:

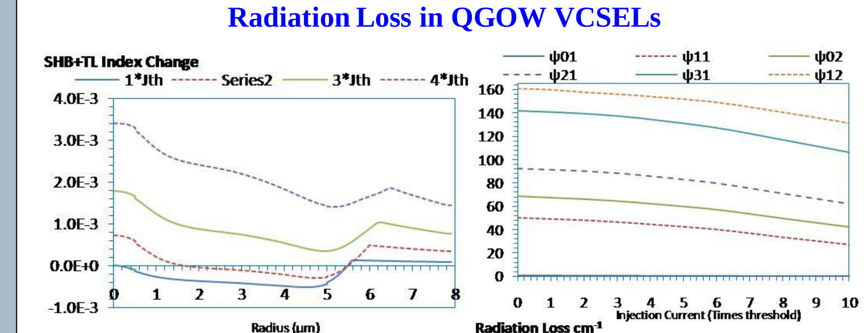
D_n	$1.04\,cm^2/s$	Diffusivity
β	10^{-5}	Spontaneous Emission Factor
α_H	2.2	Linewidth
g_{0N}	$1.32 * 10^3 cm^{-1}$	Gain Coefficient
Γ_z	0.045	Confinement Factor

Spatial Hole Burning Analysis of QGOW VCSELs



- Free Carrier depletion where LP$_{01}$ resides
  - Caused by LP$_{01}$ low loss and high confinement
- Carrier concentration increases at a decreasing rate
  - Occurs due to greater Auger recombination and spontaneous emissions
  - Decreasing LP$_{11}$ loss causes droop in carriers at r_1<r< r_2
- Magnitude of Refractive index change increases at decreasing rate
  - Negligible inner core index change Δn_{shb} < -2x10^{-4} at r< r_1
  - Large outer core index change Δn_{shb} ~ -1x10^{-3} at r_1<r< r_2 for J > 2xJ_{th}

Thermal Lensing and Spatial Hole Burning Effects on Radiation Loss in QGOW VCSELs



- Thermal Lensing index change dominates when J > 2xJ_{th}
  - Total index change is positive when J>J_{th}
  - Spatial hole burning primarily effects refractive index in the region r_1<r< r_2
- Radiation Loss for all modes decrease as injection current increases
  - α_{01}=(0.84 → 0.20) cm^{-1}, α_{11}= (50.2 → 27.0) cm^{-1} from cold cavity to 10xJ_{th}
  - RLM (α_{11}-α_{01}) of 50cm^{-1} at cold cavity decreases to 27cm^{-1} at J = 10xJ_{th}

QGOW VCSELs Summary

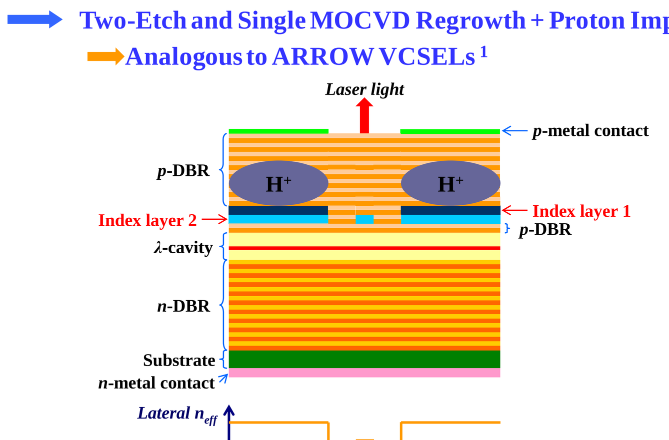
- **Quasi-Guided VCSELs for High-Power Single-Mode Operation**
  - ✓ LP$_{01}$ mode is **quasi-guided** → *Low* radiation loss (α_{01} < 1 cm^{-1})
  - ✓ LP$_{11}$ mode is **anti-guided** → α_{11} ~ 50 cm^{-1}, for 10-μm diameter VCSELs
  - ✓ Large $\Delta\alpha$ → Large tolerance for $\Delta\alpha$ > 20 cm^{-1}
  - ✓ Larger mode size can be achieved ~ 8μm diameter aperture
- **Comprehensive Above Threshold Analysis of QGOW VCSELs**
  - ✓ High fundamental mode confinement creates greater gain saturation for the lasing mode due to ***spatial hole burning*** in the region r< r_1.
  - ✓ At high injection currents the induced index change due to ***thermal lensing*** dominates the index profile in the core region, resulting in a decreasing RLM
  - ✓ QGOW VCSELs exhibited large RLM of 27cm^{-1} at J = 10xJ_{th}
    - ❖ Comparison: Single-mode ARROW VCSELs has RLM of 13cm^{-1}

QGOW VCSELs

- ***❖Provides stable single mode operation up to very high current injection level (10xJ_{th})***
  - ***✓With low fundamental loss (α_{01} < 1 cm^{-1})***
  - ***✓Large radiation loss margin (RLM > 27 cm^{-1})***

Future Works - QGOW VCSELs Fabrication Steps

- Two-Etch and Single MOCVD Regrowth + Proton Implantation
  - Analogous to ARROW VCSELs [1]



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