Analysis of Resonant-Cavity Light-Emitting Diodes

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Contents

- About RCLED.
- Crosslight’s model.
- Example of an InGaAs/AlGaAs RCLED with experimental verification.
- Example of a VCSEL-like RCLED of GaAs/AlGaAs MQW.
- RCLED with detuned DBR.
- RCLED with long cavity.
- Conclusions.

About RCLED

- RCLED takes advantage of microcavity effects to enhance spontaneous emission.
- Narrower spectrum linewidth.
- Superior directionality of emission with better LED-fiber coupling.
- Potential as light source for recent plastic optical fiber (POF)-based local area networks.

Crosslight RCLED model

- Self-consistent calculation of material spontaneous emission rate based on rigorous quantum well/dot spectrum theories coupled with 2/3D simulation of current injection from the Crosslight APSYS drift-diffusion solver.
- Coupling of spontaneous emission with microcavity modes based on theory of C. H. Henry (1986) [1].
- Henry's theory has been extended from waveguide to RCLED by proper accounting of mode densities in a quasi-2D/3D emission situation.
- Photon recycling effects taken into account by accurate determination of photon power density inside the RCLED and self-consistent model of material gain/loss of the quantum wells/dots.

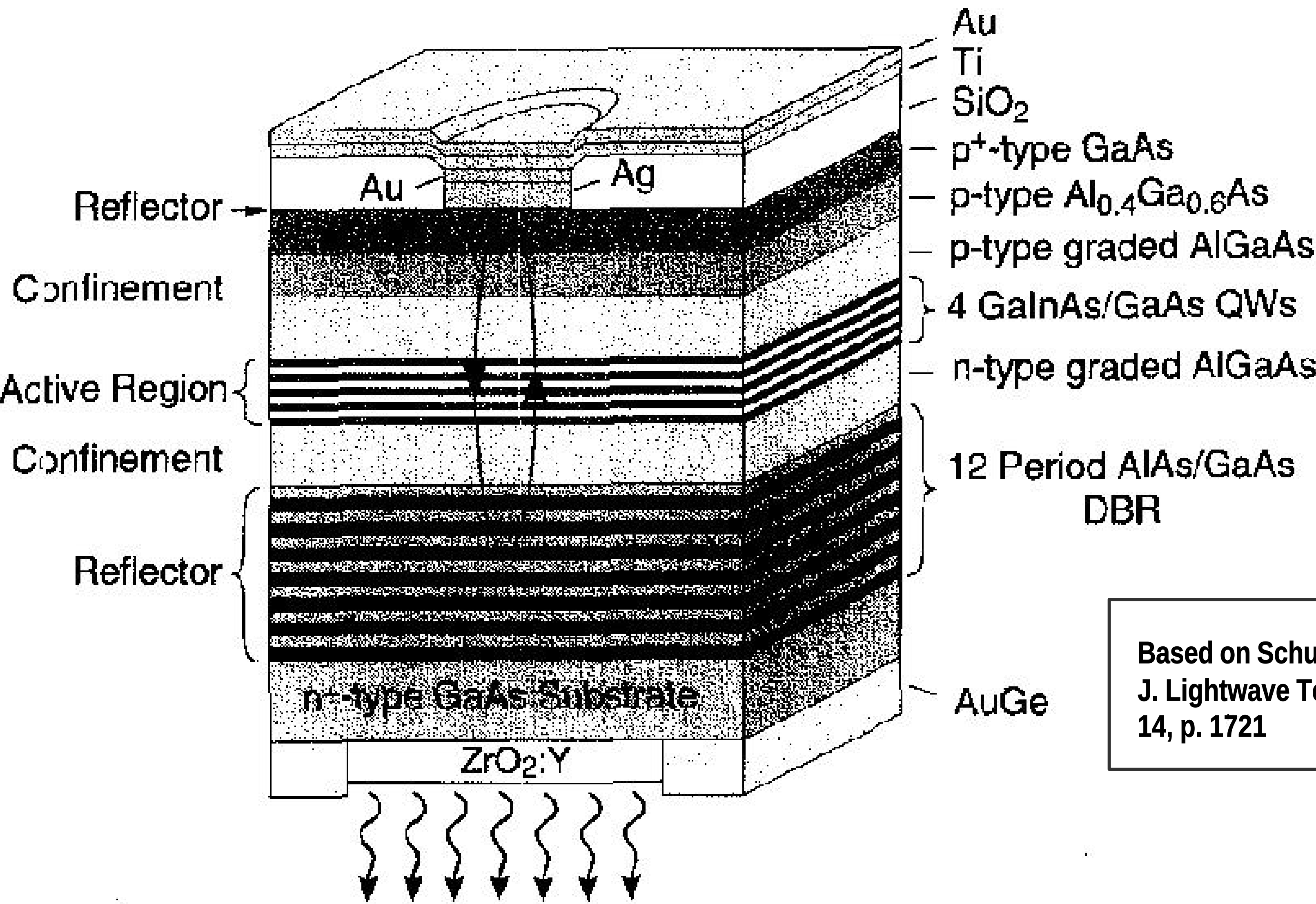
[1] C. H. Henry, "Theory of spontaneous emission noise

in open resonators and its application to lasers and optical amplifiers,"

J. Lightwave Technol., vol. LT-4, pp. 288--297, March 1986.

Contents

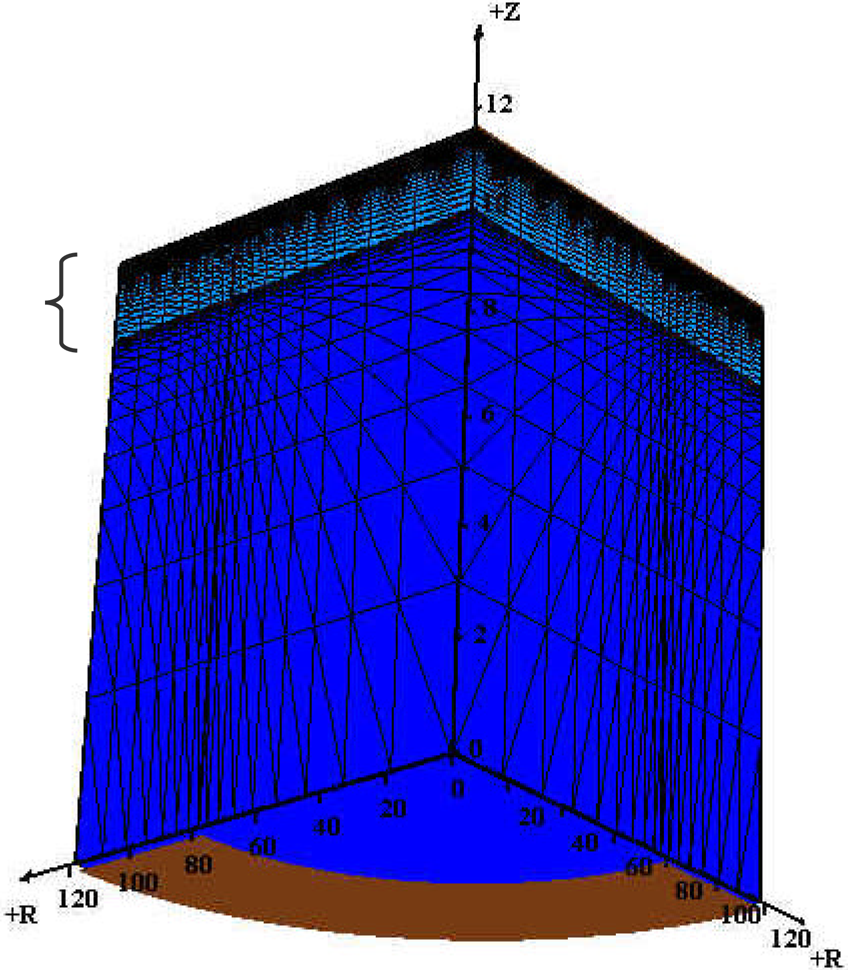
Structure



Based on Schubert et. al, J. Lightwave Technol., vol. 14, p. 1721

Simulation Mesh

MQW and Optical Region



File Name : rc.std_0004
File Type : APSYS

Variable Name :
Material Number

3D Cube Contour Parameters :
X Range : 0 - 118
Y Range : 0 - 11.6044
Z Range : 0 - 0

X Cut Line Num : 20
Y Cut Line Num : 20
Z Cut Line Num : 20

Material Number

- algaas(x=0.4)
- algaas(x=graded)
- algaas(x=graded)
- ingaas(x=0.14), InGaAs.
- algaas(x=graded)
- algaas(x=graded)
- algaas(x=0.5)
- algaas(x=0)

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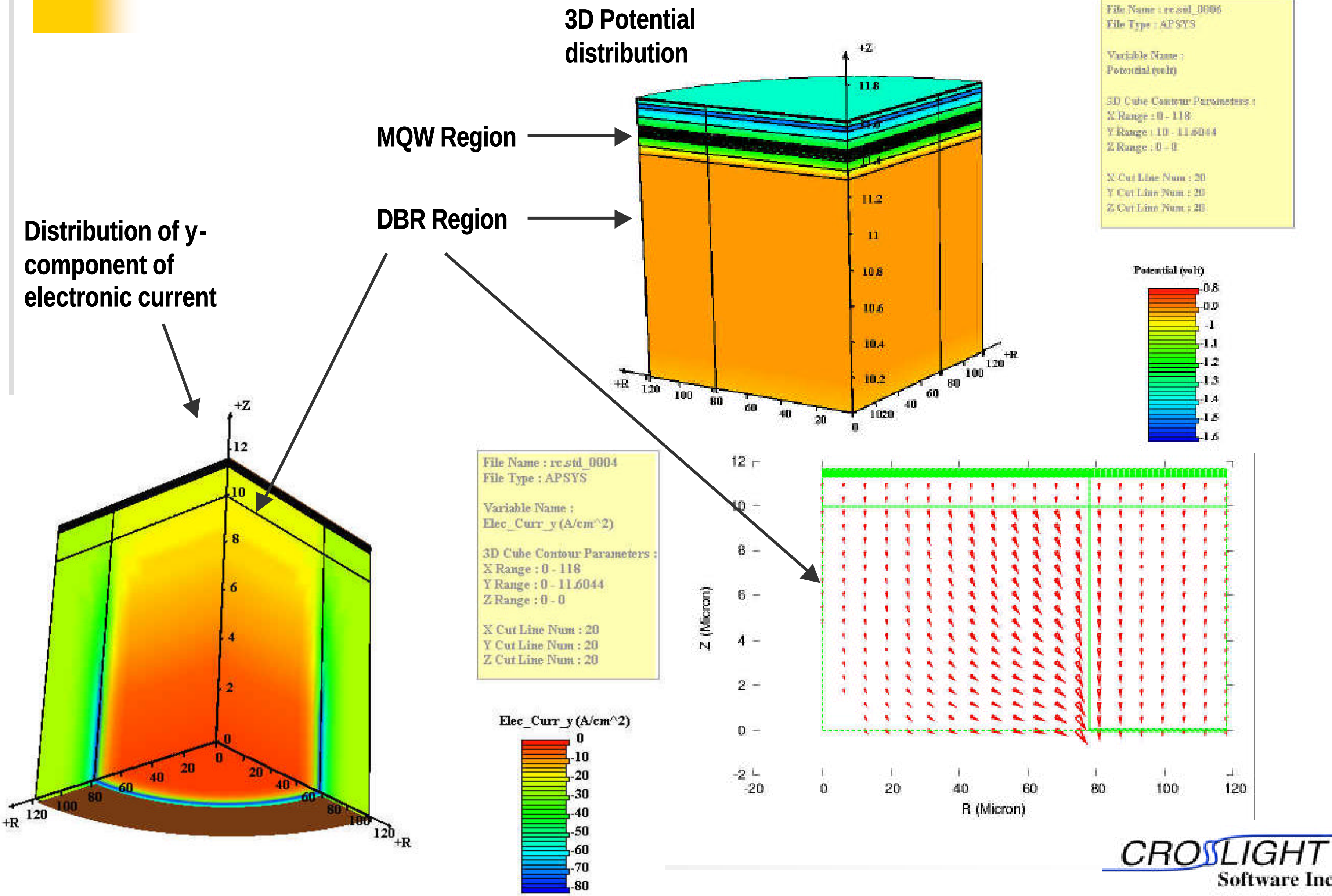
2/3D Drift-Diffusion Model



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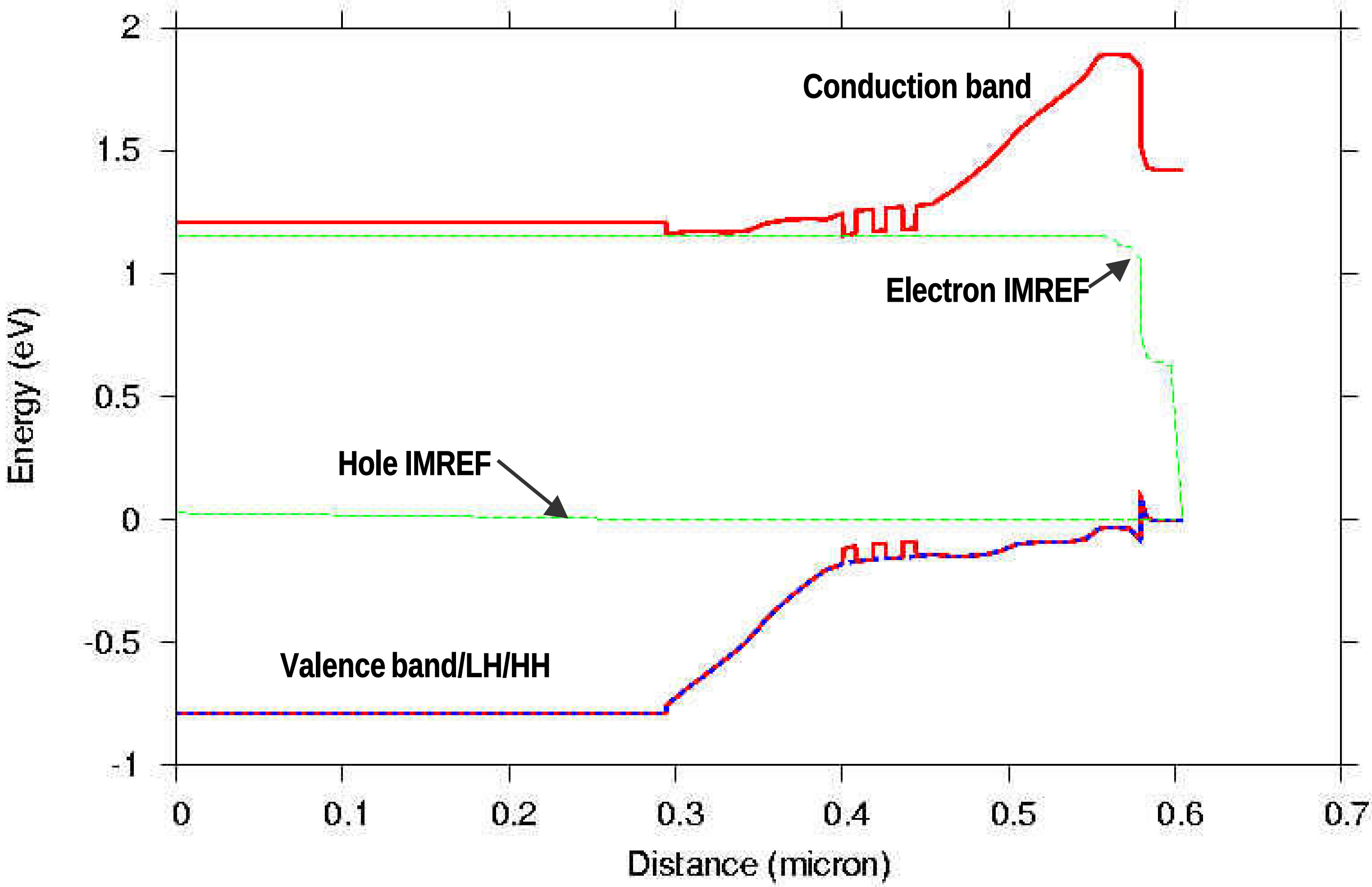
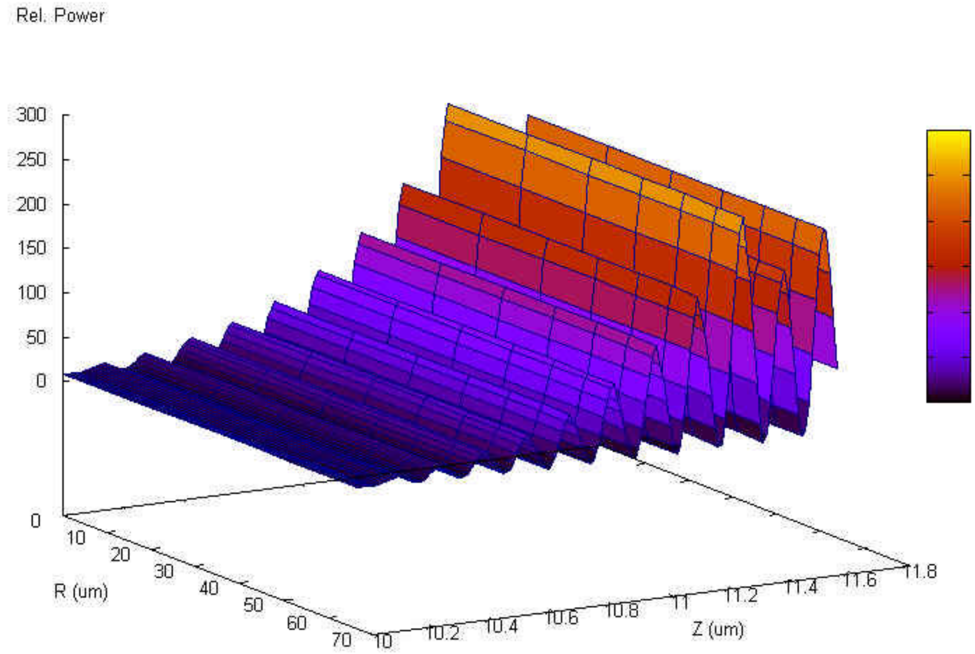
True Physical Simulation in 3D

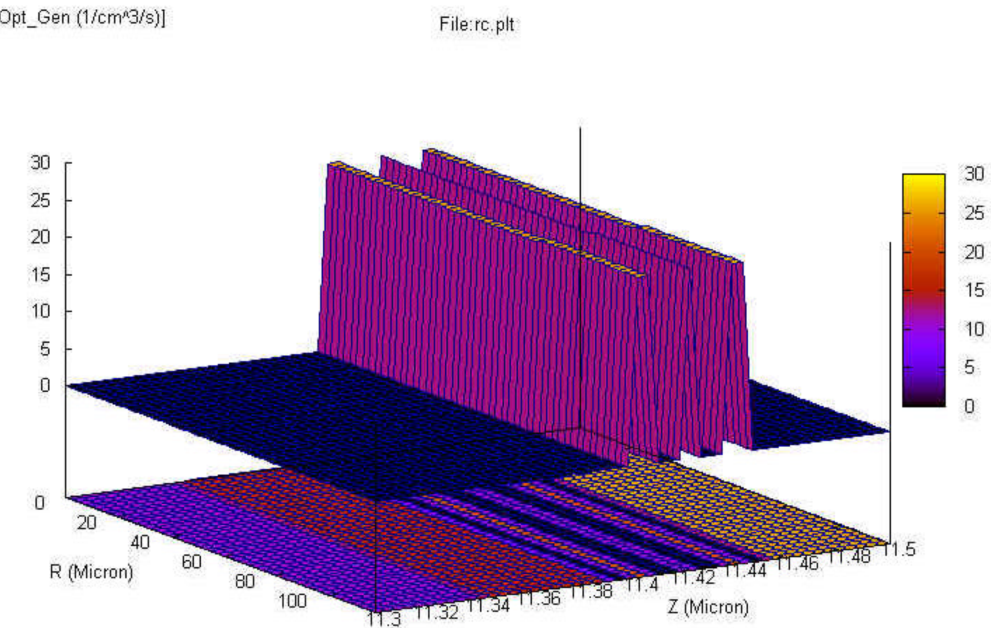


True 3D simulation of band structure physics including MQW strain effects. Current flow and self-heating may be included self-consistently in 3D.

Standing Wave and Carrier Generation

Power density relative to spontaneous emission power in z-direction





Carrier generation rate due to high optical power within the LED cavity. Absorption at MQW calculated self-consistently using interband transition models.

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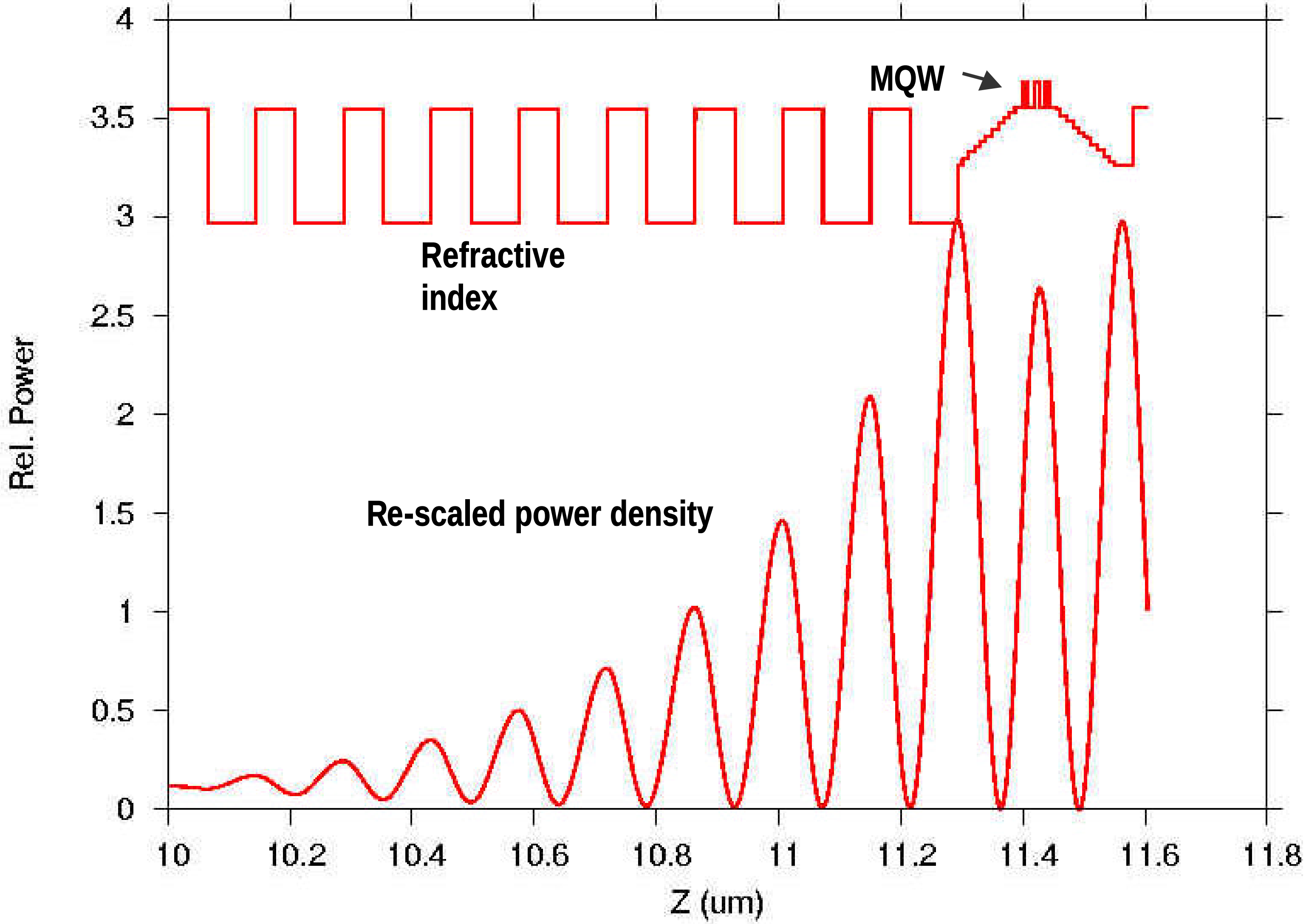
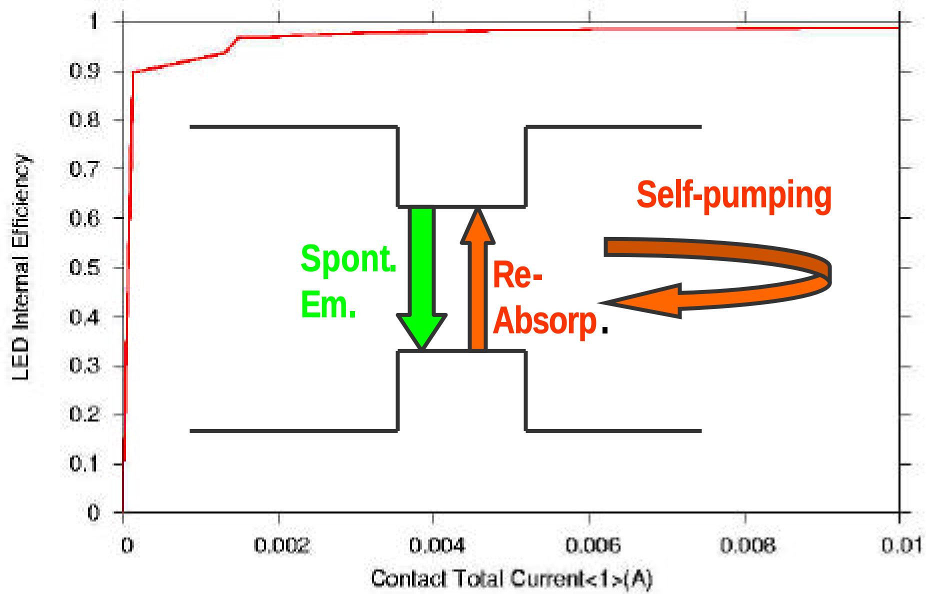
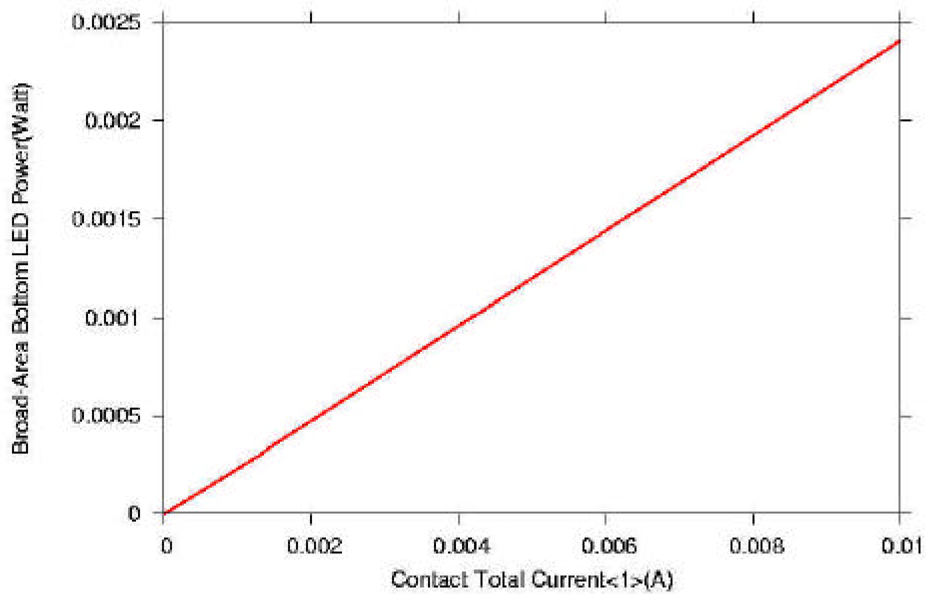
Standing Wave and Index



Remark: The reflection phase of the Ag. Mirror is adjusted so that antinode of standing wave aligns with the MQW region.

Photon Recycling and IQE





- High mirror reflectivity → higher photon density in cavity under resonant condition.
- Re-absorbed photons → higher photo carrier densities (self-photo-pumping).
- Higher carrier concentration → more photon emission by spontaneous emission (enhanced by microcavity resonance).
- Actual spontaneous emission rate substantially higher than current injection rate.
- IQE calculation = spontaneous emission rate subtracting photon absorption rate, dividing current injection rate.

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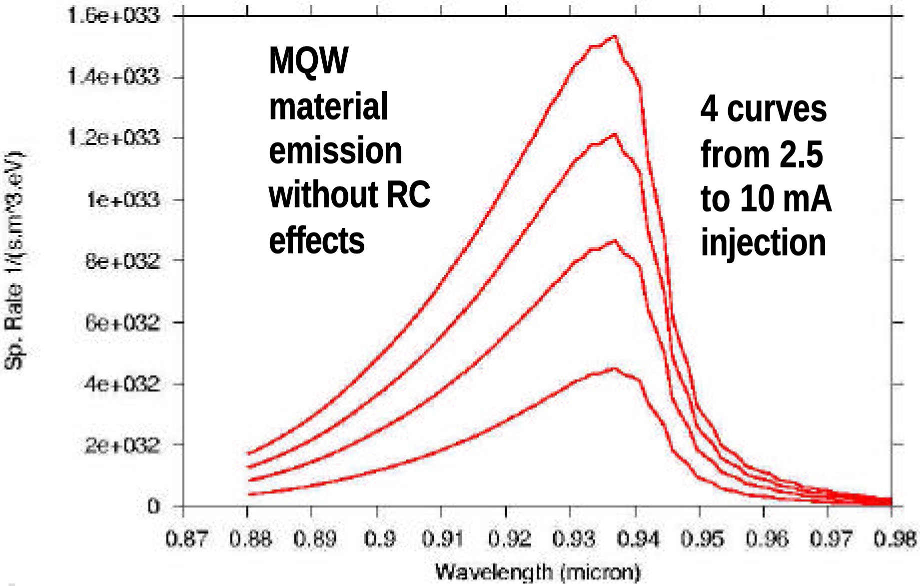
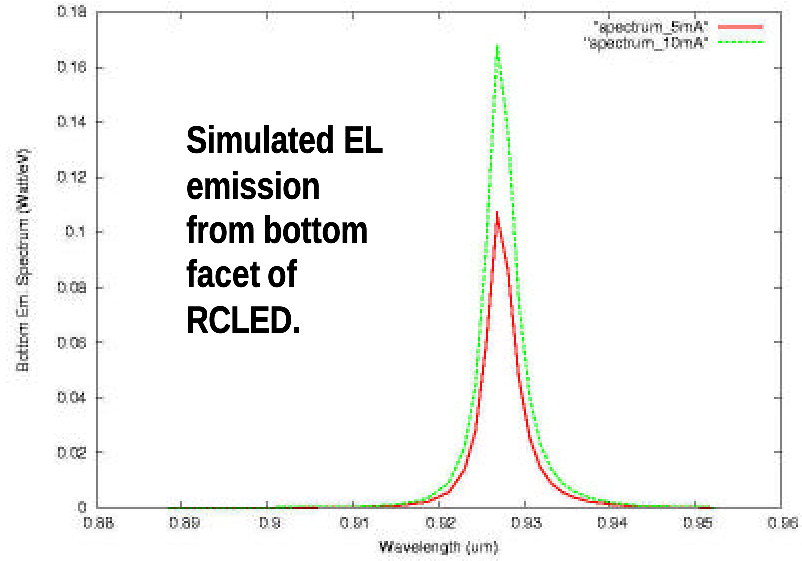
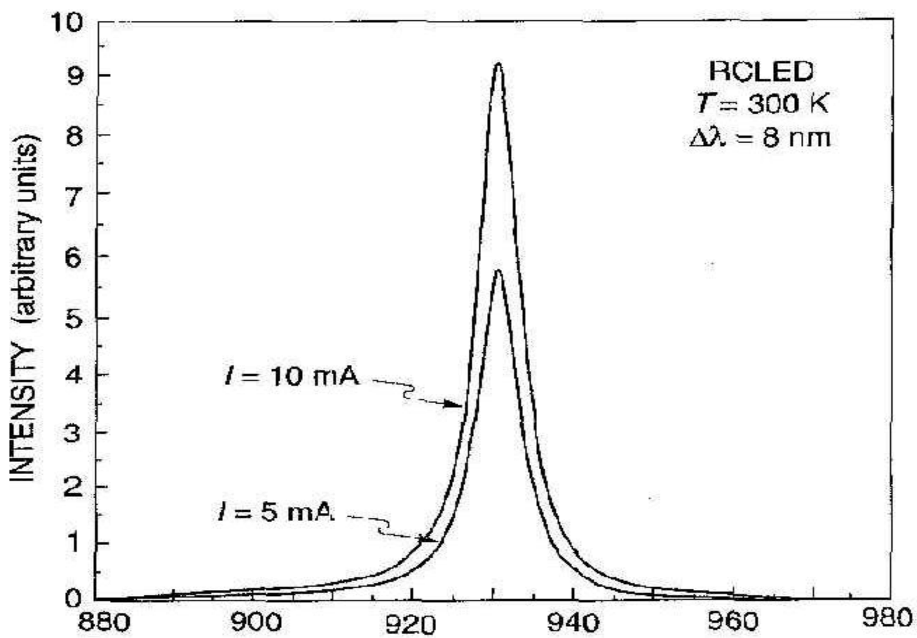
Improvement in Spectrum Linewidth







Experimental Data taken from Schubert et. al, J. Lightwave Technol., vol. 14, p. 1721

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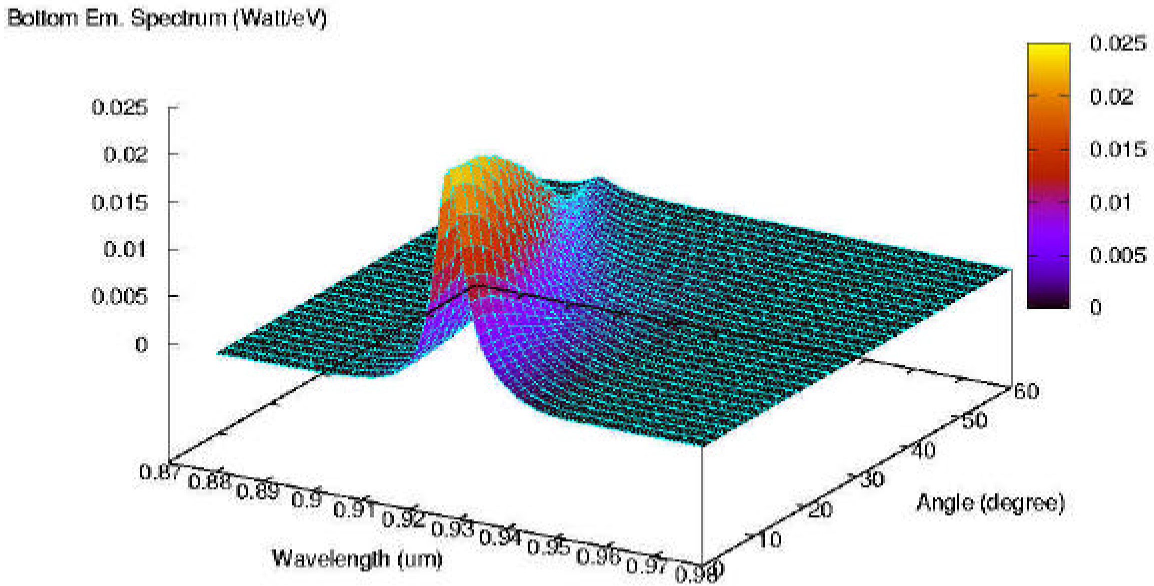
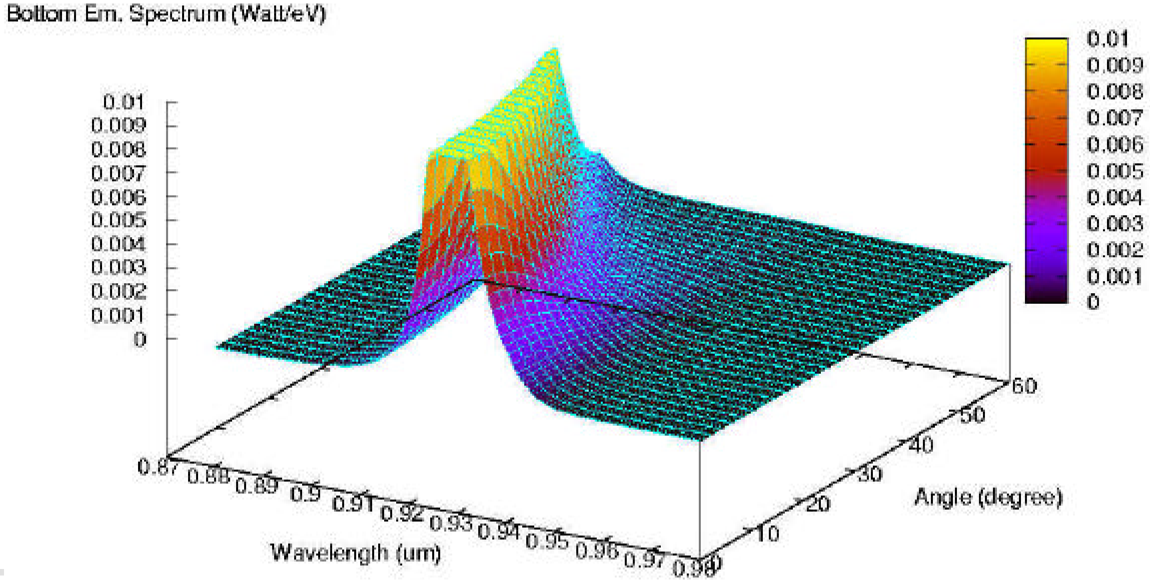
Angle Dependence in EL Spectrum



Remark: For well tuned DBR /cavity-length and high Q cavity, only a single emission peak at normal direction is significant.



More details near low intensity region

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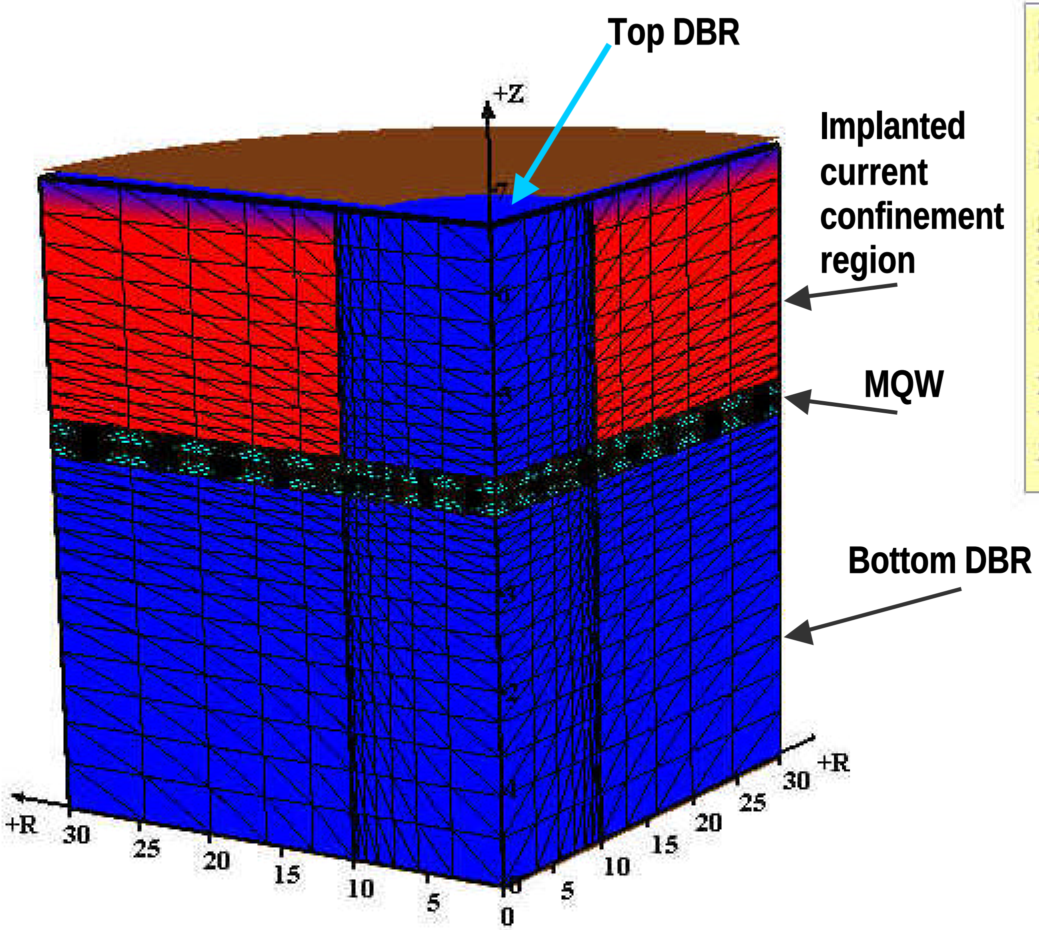
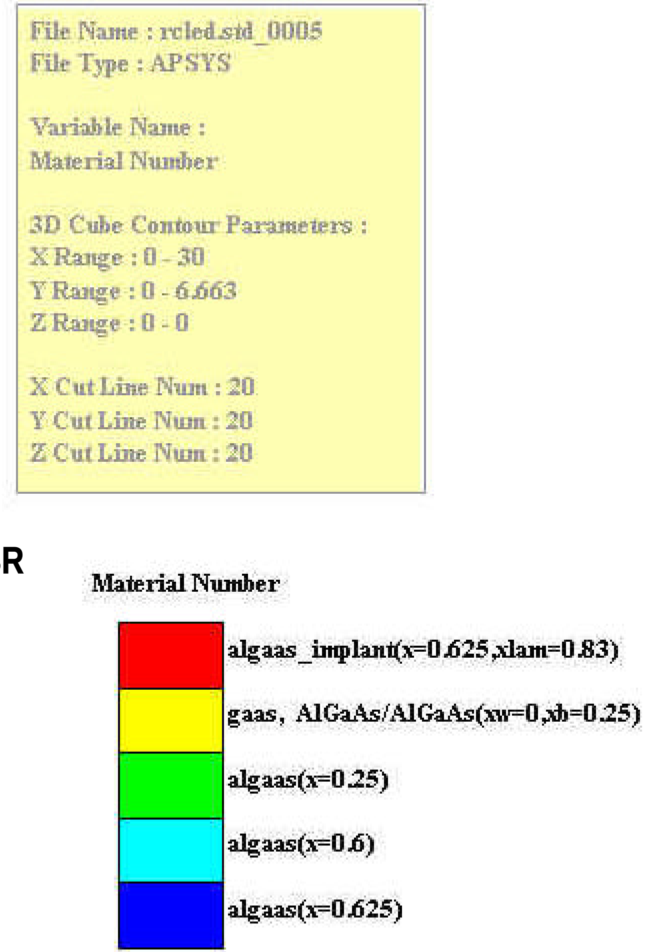
Structure of AlGaAs RCLED





A VCSEL-like structure with fewer layer pairs in top DBR to help power extraction. Ion implantation is used to form current confinement.

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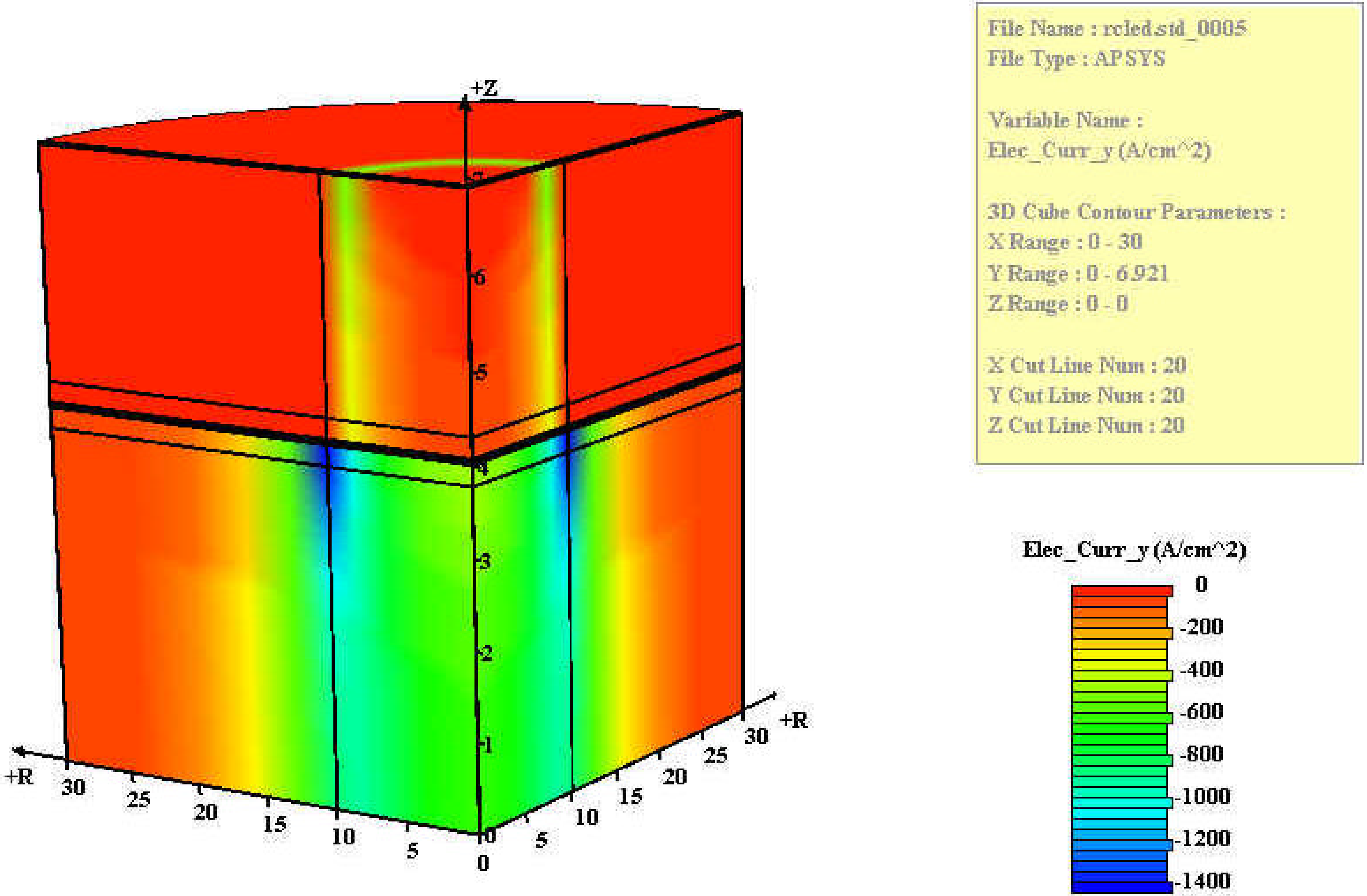
2/3 Dim Drift-Diffusion Model



Y-component of electron current distribution in RCLED. Please note the strong (blue) current crowding area which causes optical gain to help amplify the optical waves there.

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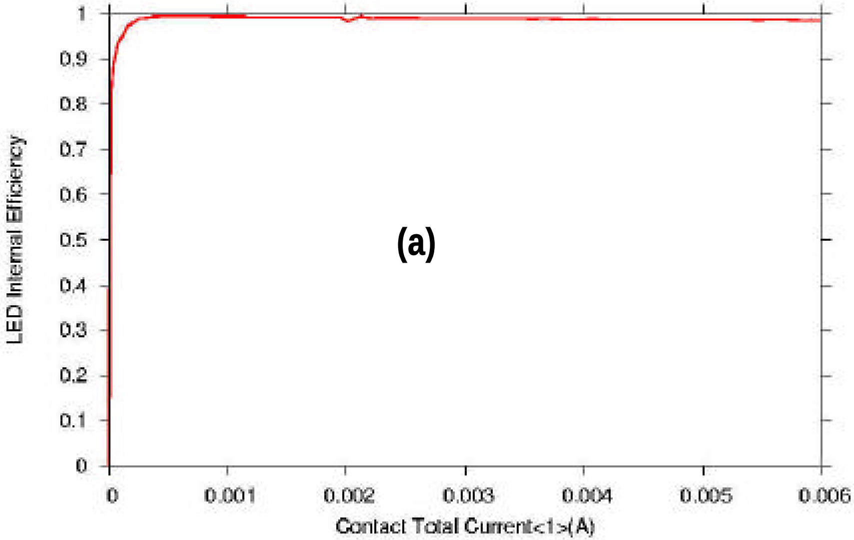
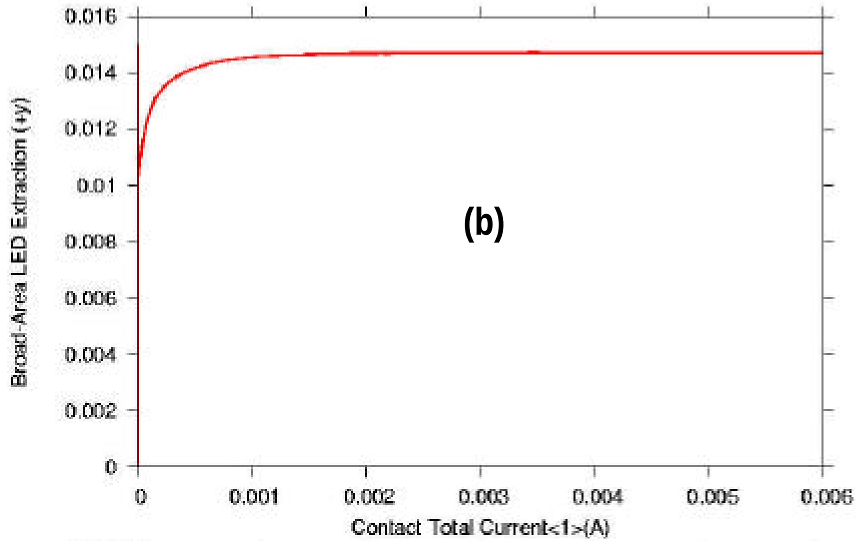
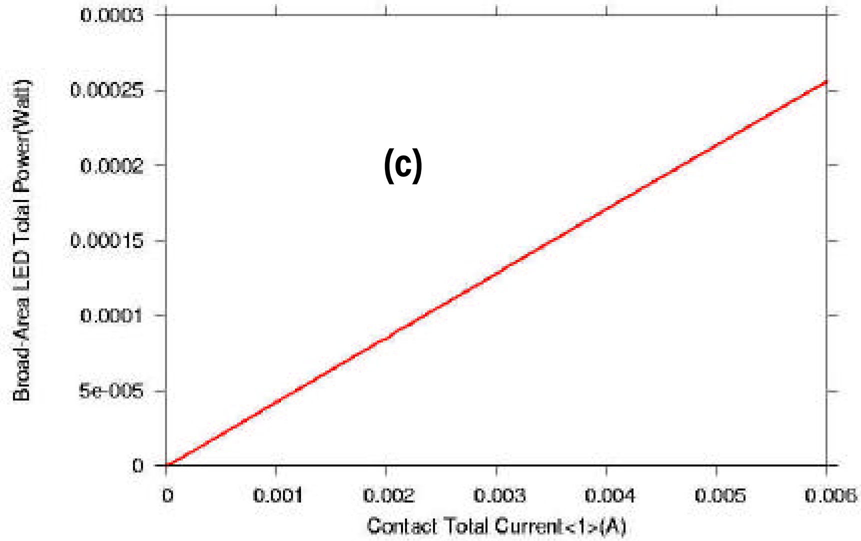
RCLED Performance

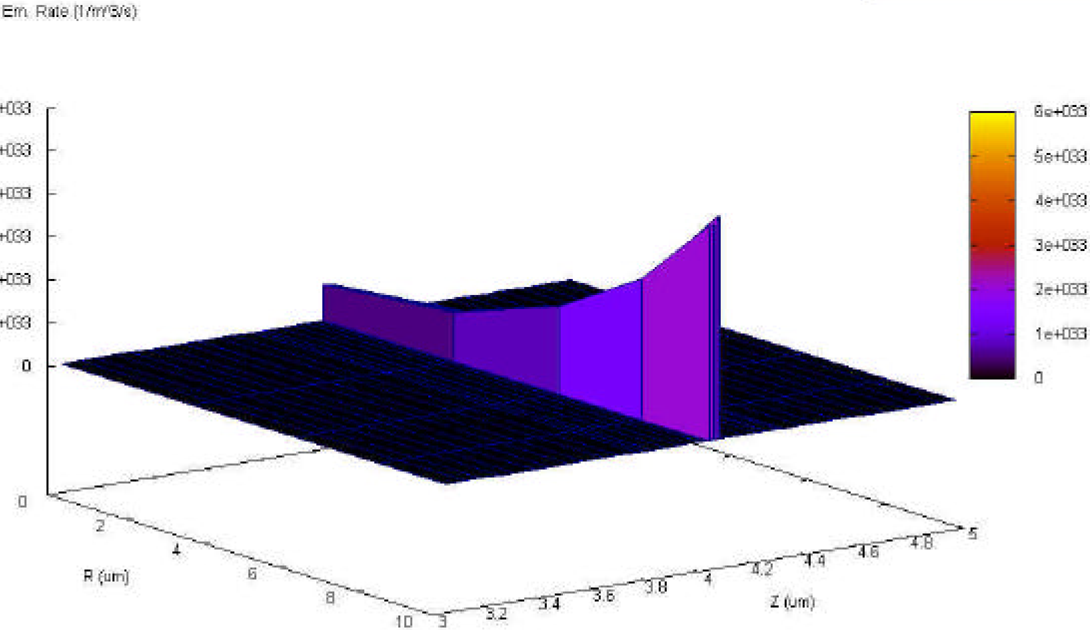






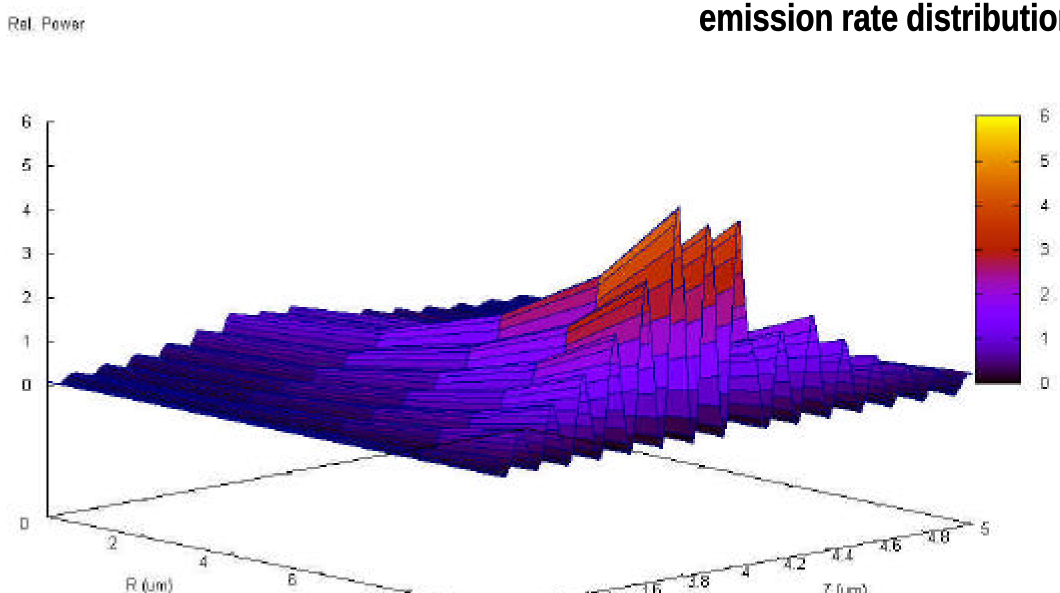
- **(a) Internal efficiency of near unity.**
- **(b) Extraction efficiency from top facet.**
- **(c) Total EL power versus injection current.**

Current Crowding Effects



MQW spontaneous emission distribution under top aperture. Lateral distribution is due to current crowding.

Standing wave shows strong lateral variation due to gain/'spontaneous emission rate distribution.



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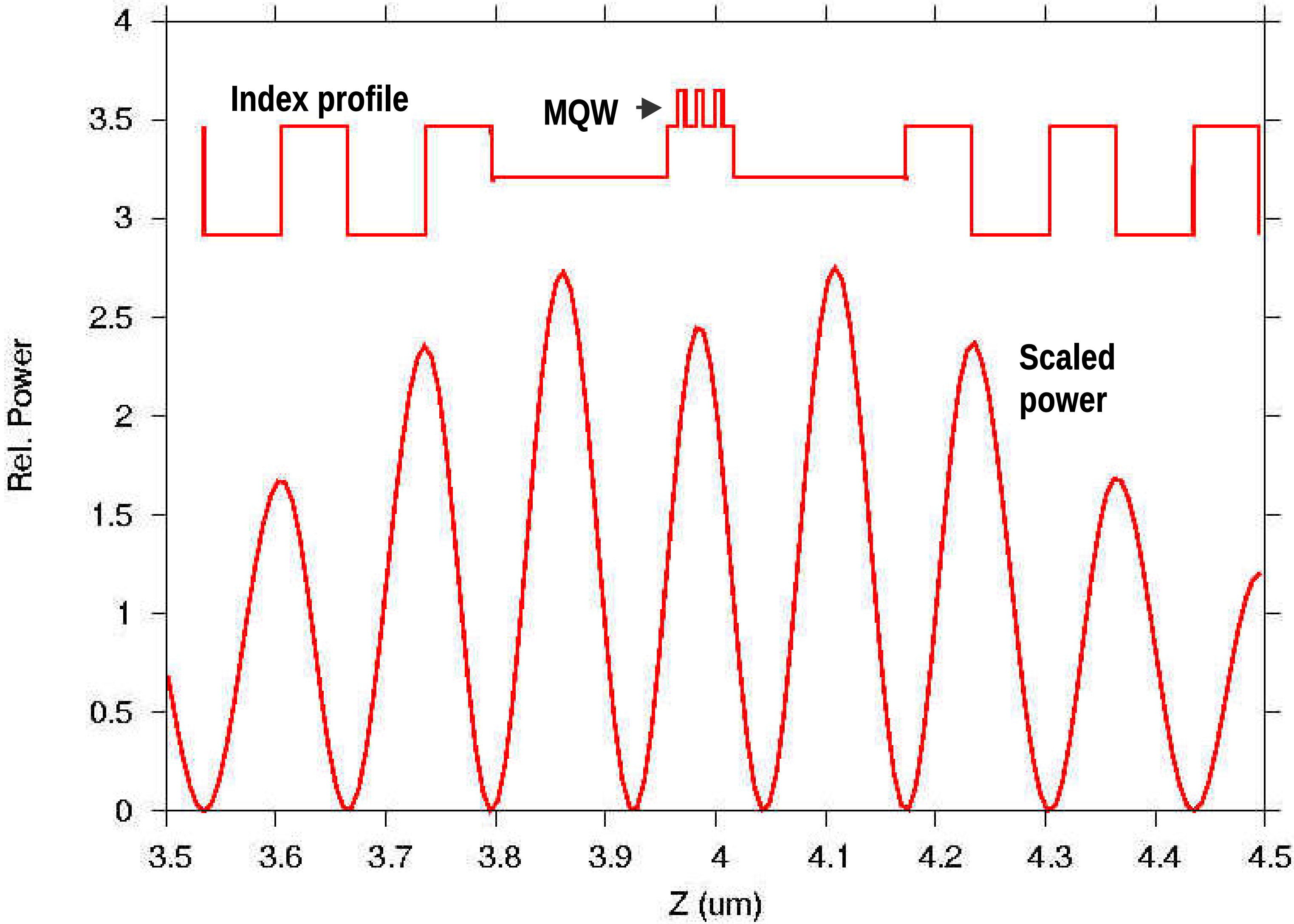
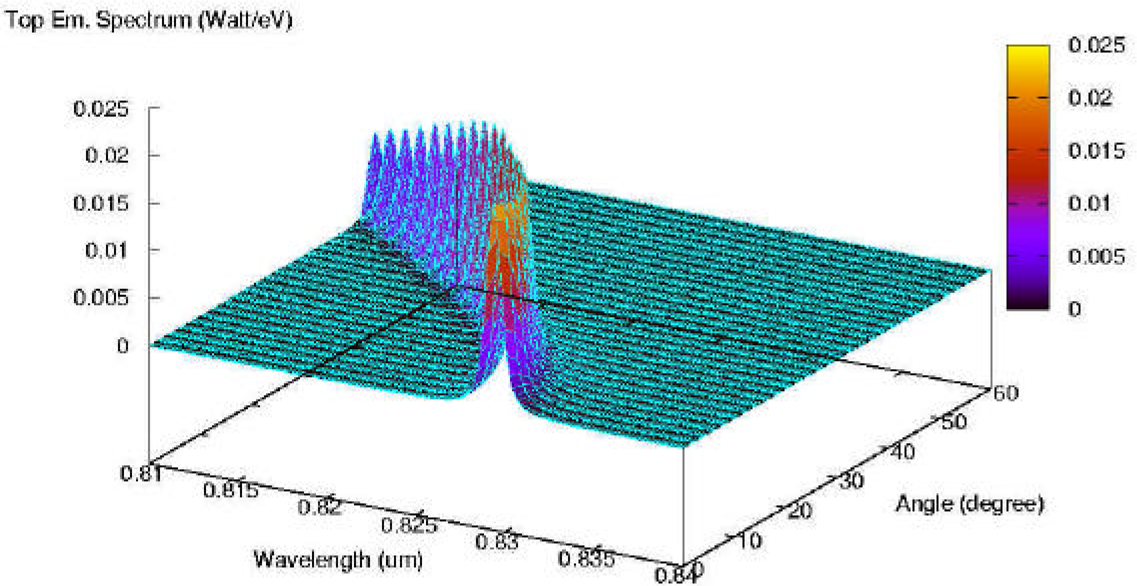
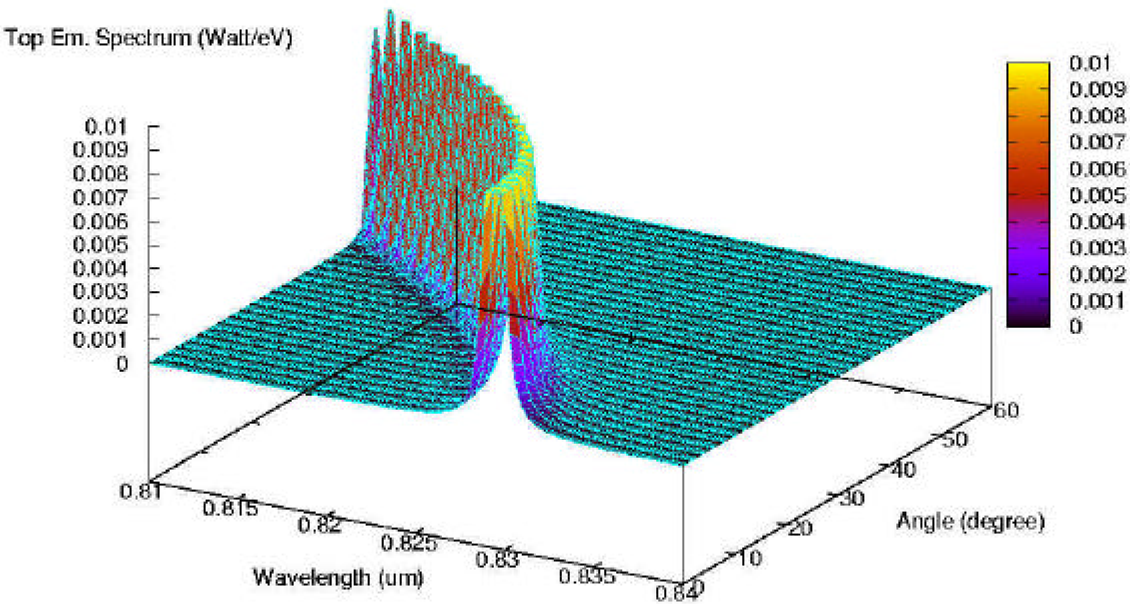
Standing Wave Alignment



Remark: Effective cavity length near the MQW should be (n+1/2) wavelength to ensure antinode of standing wave aligns with MQW.

Angular dependence of EL spectrum





Detailed view of lower power regime of the above

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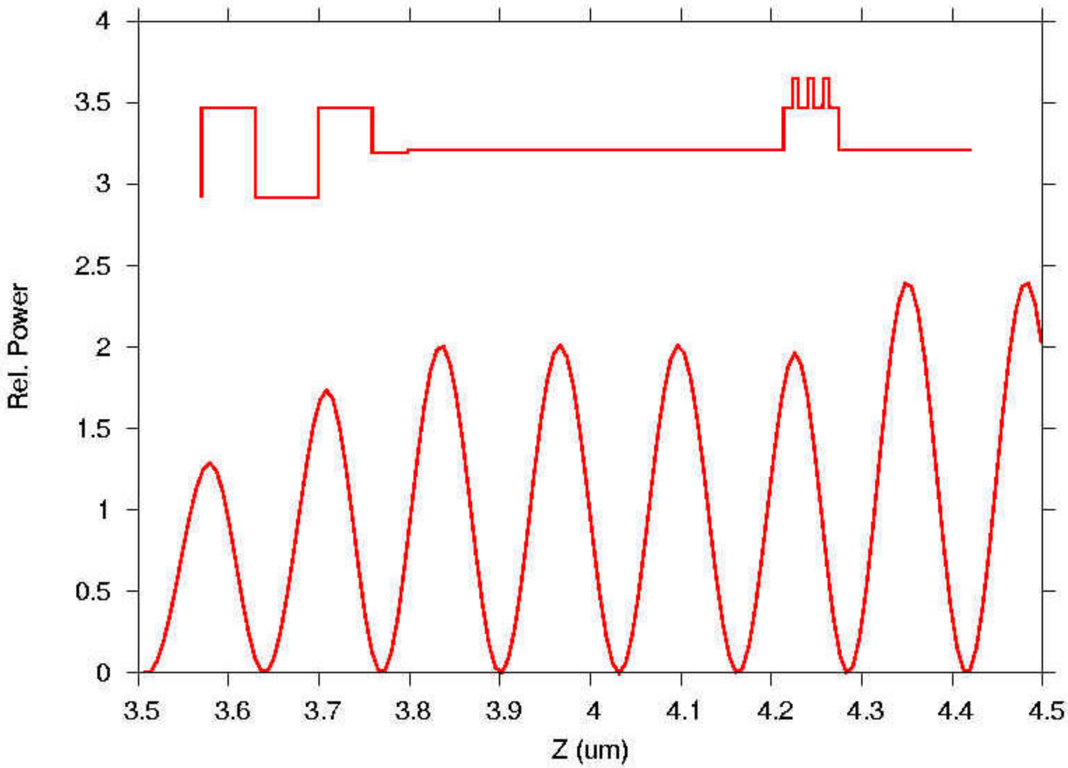
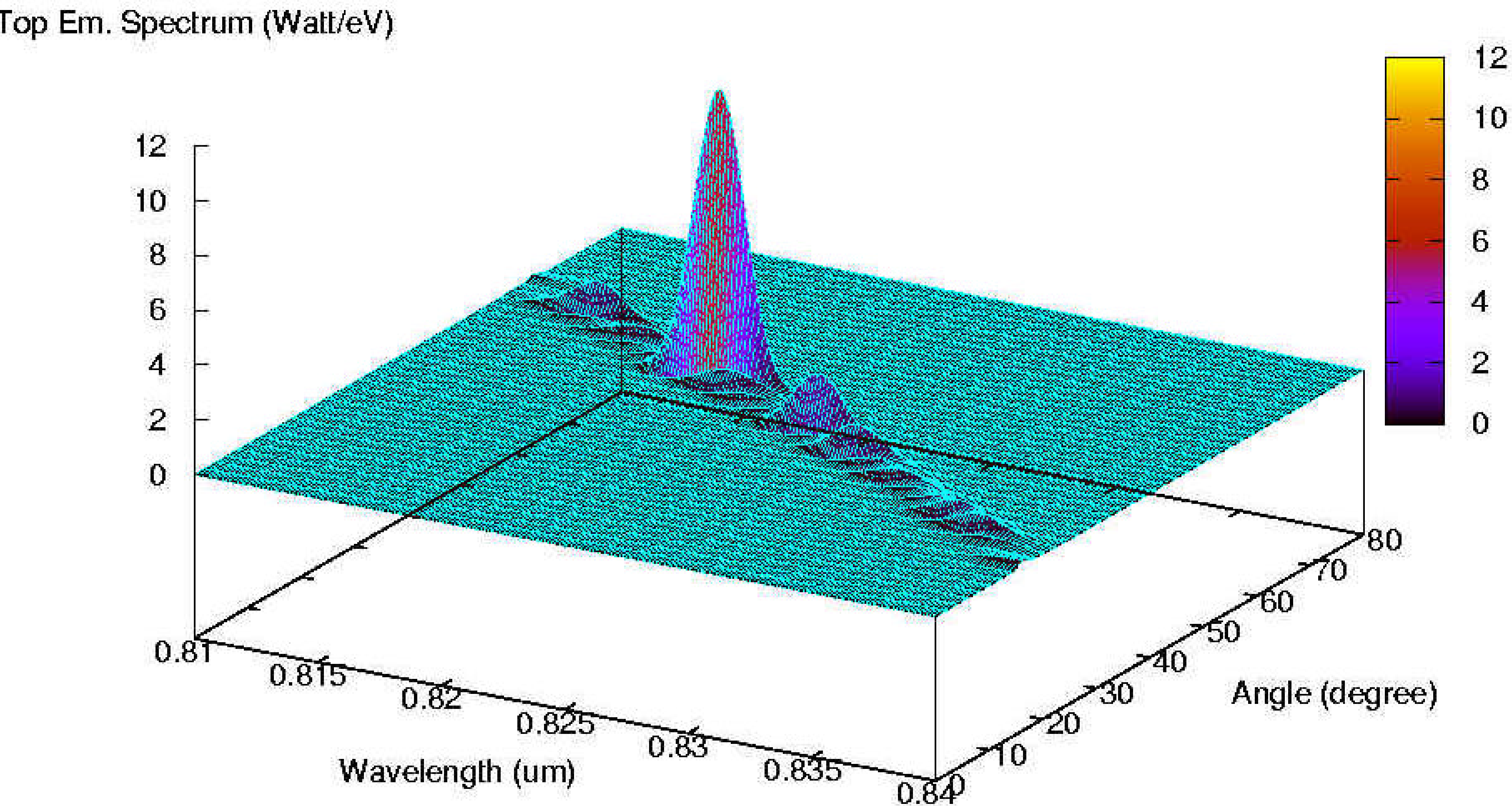
Detuning DBR/Cavity



Alignment of wave at oblique maximum power direction with refractive index profile.

- There may be applications of RCLED to control the direction of major resonant peak at an oblique angle.
- Take similar VCSEL-like structure with longer cavity and slightly reduced DBR periods.
- Detuning at normal direction.

Engineering the Emission Angle

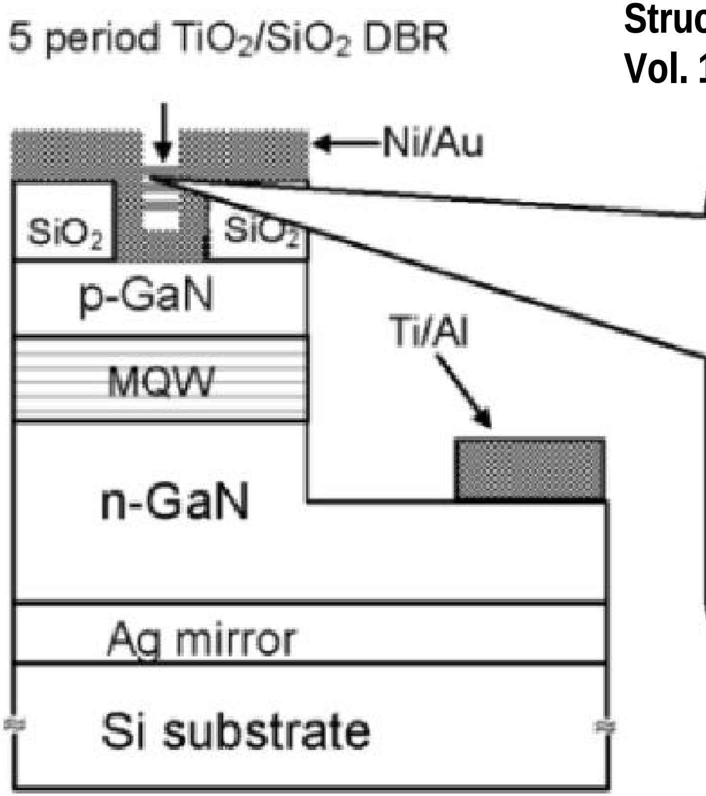


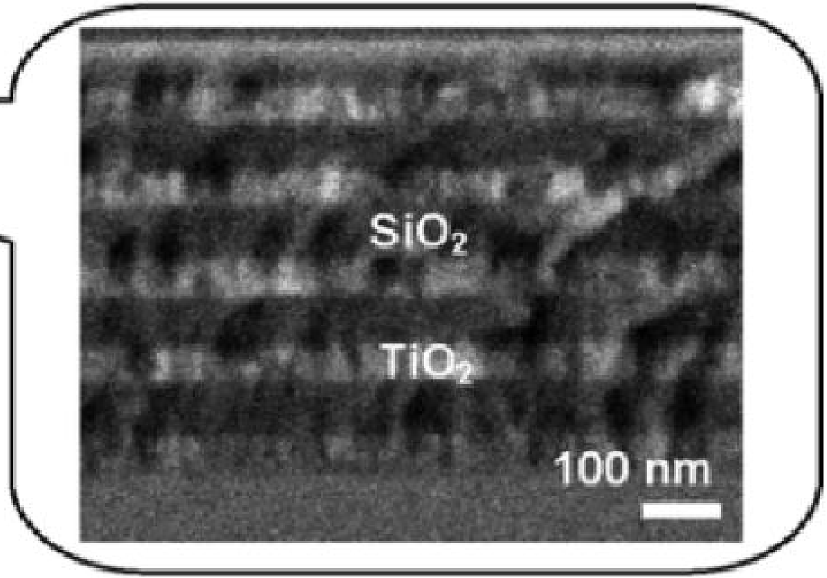
Remark: Major emission at an oblique angle means ring-like emission pattern in real space.

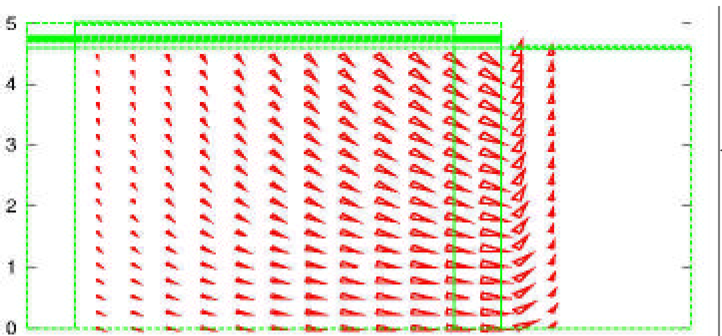
Contents

InGaN LED Structure

Structure taken from: Horng et. al. IEEE Photonic Tech. Lett., Vol. 18, p. 457, 2006

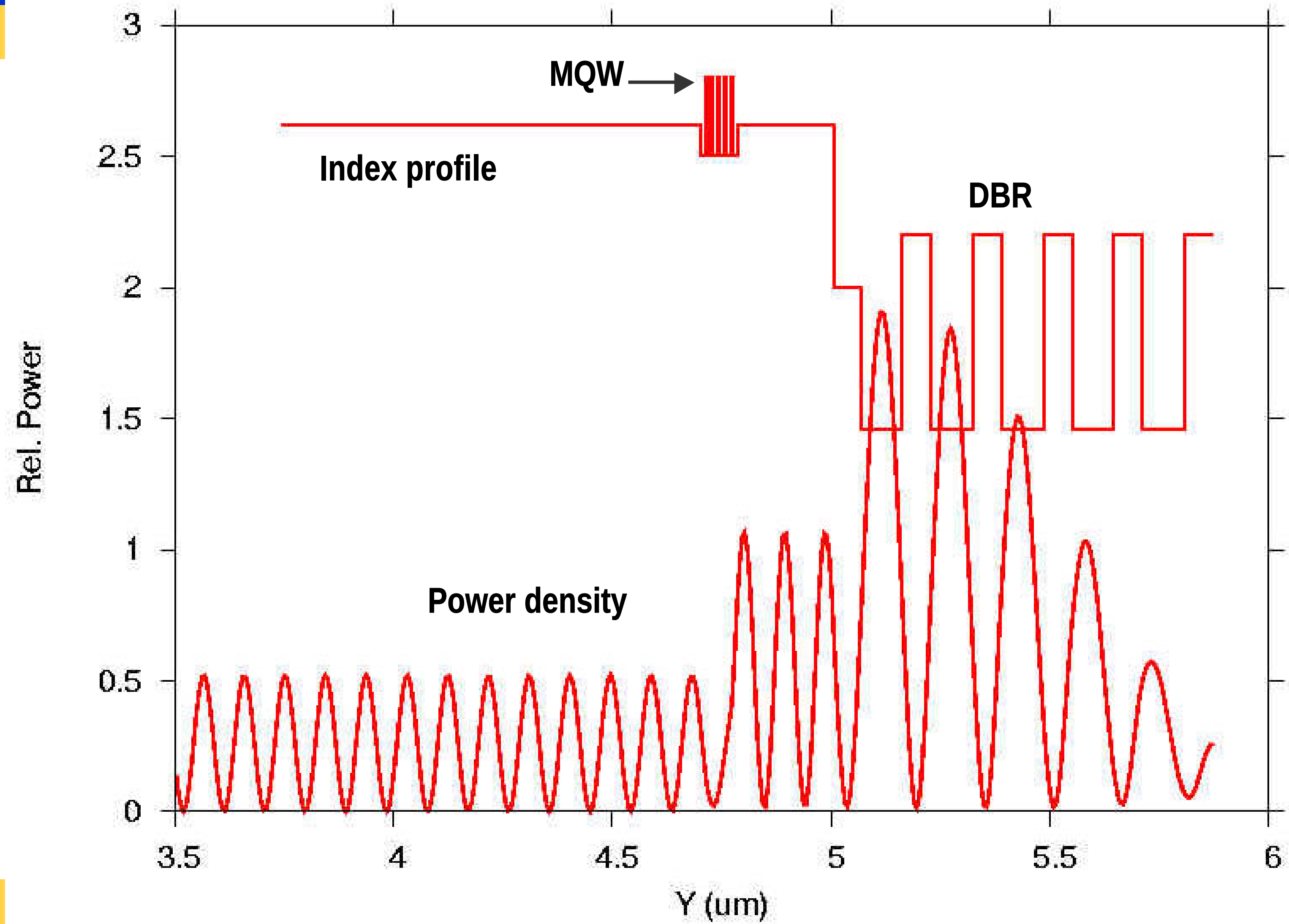






Simulated electron current flow pattern.

Standing Wave at Normal Direction



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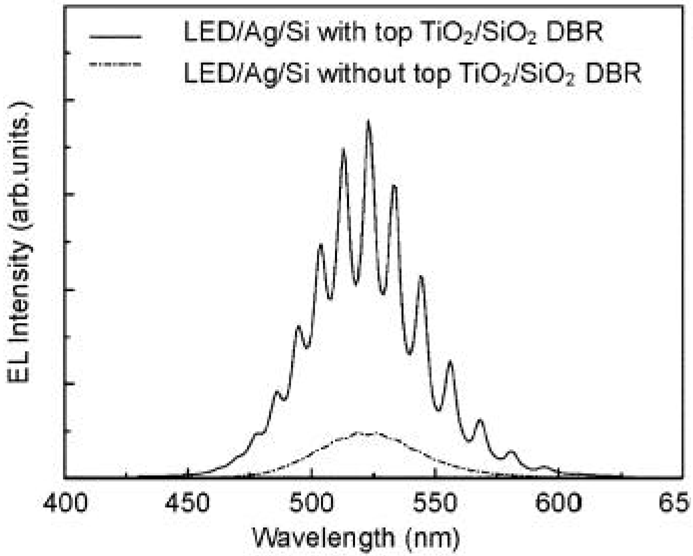
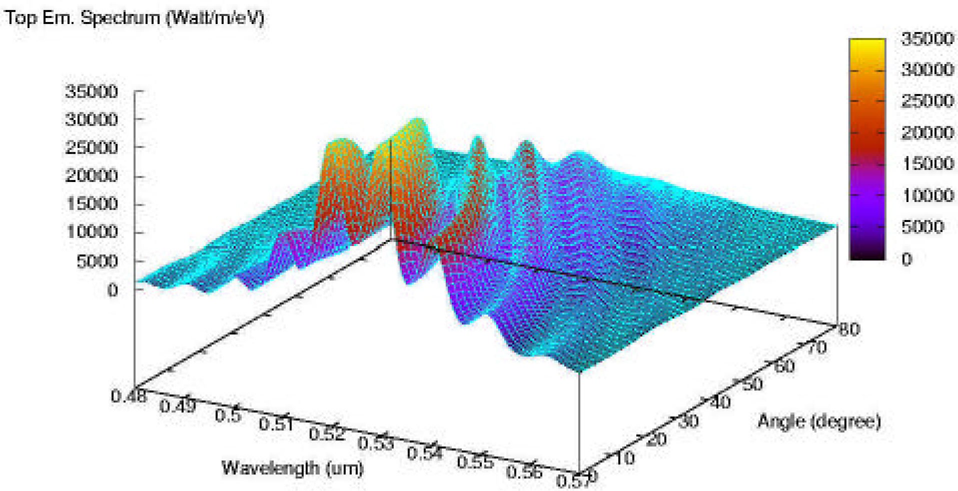
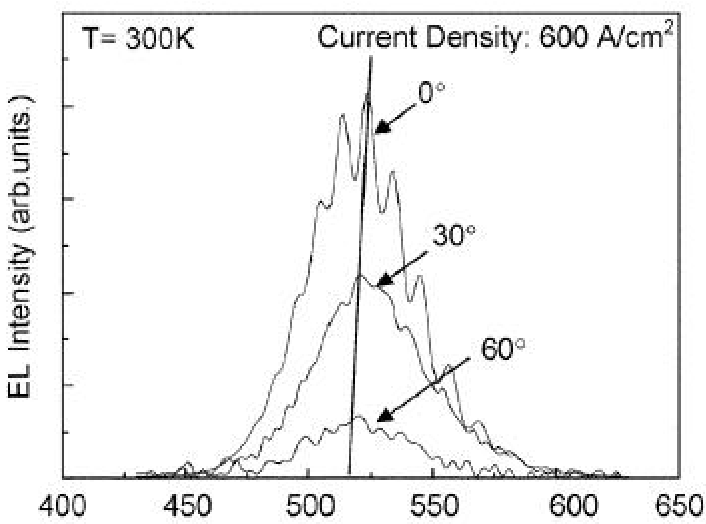
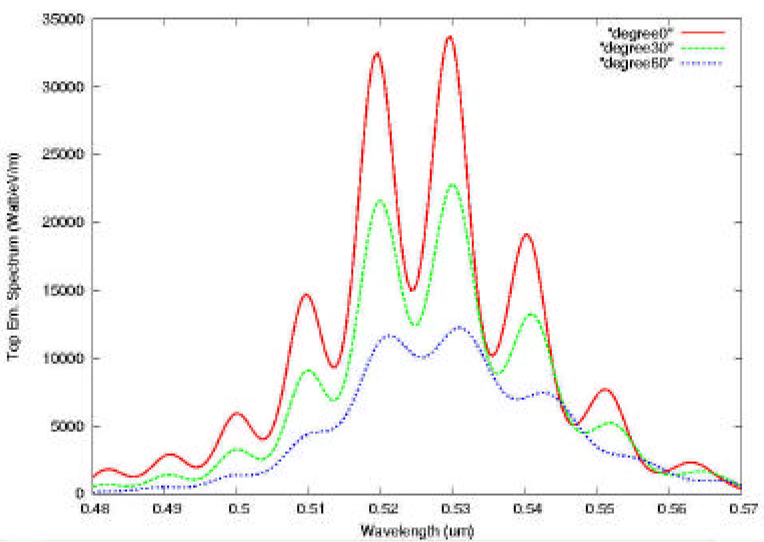
Multiple Resonance Peaks as Compared with Experiment







Angle-resolved EL spectrum of InGaN RCLED sample.



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Conclusions

- A comprehensive physical model of resonant cavity has been incorporated into Crosslight's APSYS/LED modules.
- Based on rigorous theory describing interaction of spontaneous emission spectrum with microcavity modes.
- Resonant effects in spatial, spectral and angular dimensions have been obtained in reasonable agreement with experiments.
- Self-consistent integration with the main APSYS simulator enables all-in-one analysis and design approach.