

Laser Diode Simulation



Semiconductor Laser Diode Simulation

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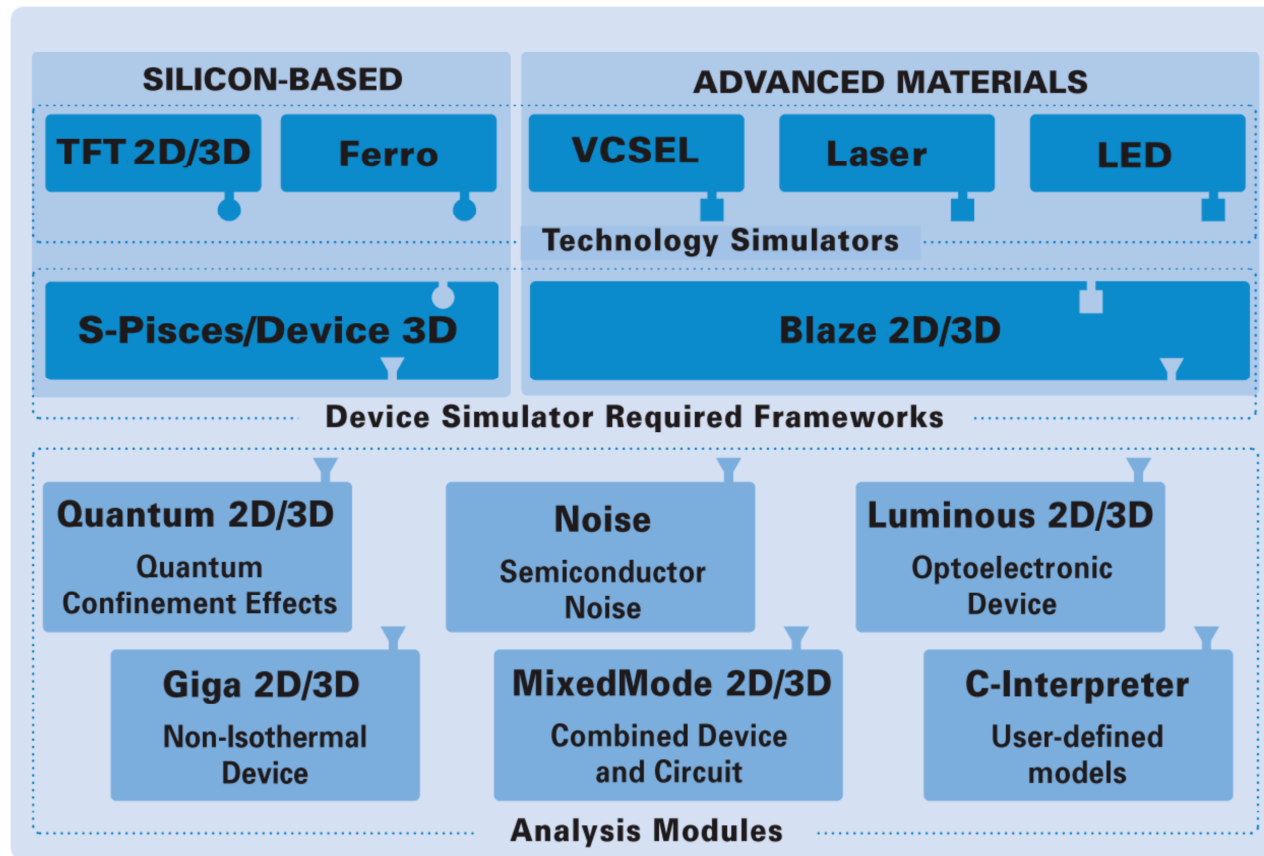
Laser as Part of the Atlas Framework



- Laser simulation is implemented as part of the Atlas device simulation framework
 - Atlas provides framework integration
 - Blaze provides III-V and II-VI device simulation
 - Laser provides optical emission capabilities for edge-emitting lasers
 - VCSEL provides optical emission capabilities for vertical-cavity surface emitting lasers

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Laser as Part of the Atlas Framework



Blaze as Part of a Complete Simulation Toolset



- III-V Device Simulation maturity has conventionally lagged behind silicon leading to many immature standalone tools with a low user base
- Users must ensure that the simulator they evaluate has all the necessary components
- Blaze shares many common components of the Atlas framework with the mature and heavily used silicon simulator, S-Pisces
- Blaze is able to take advantage of Atlas improvements in numerics, core functionality and analysis capabilities from Silicon users
- All of the features of Atlas are available to Blaze users
- Blaze is completely integrated with TonyPlot, DeckBuild and DevEdit
 - Blaze experiments can be run the Virtual Wafer Fab

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The 10 Essential Components of III-V Device Simulation



1 Energy Balance/Hydrodynamic Models

- Velocity overshoot effects critical for accurate current prediction
- Non-local impact ionization

2 Lattice Heating

- III-V substrates are poor conductors
- Significant local heating affects terminal characteristics

3 Fully Coupled Non-Isothermal Energy Balance Model

- Important to treat Energy balance and lattice heating effects together

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The 10 Essential Components of III-V Device Simulation (cont.)



4 Quantum Mechanical Simulation

- Schrodinger solver
- Quantum correction models
- Bohm Quantum Potential

5 High Frequency Solutions

- Direct AC solver for arbitrarily high frequencies
- AC parameter extraction
- Extraction of s-, z-, y-, and h-parameters
- Smith chart and polar plot output
- FFT for large signal transients

6 Interface and Bulk Traps

- Effect on terminal characteristics is profound
- Must be available in DC, transient and AC

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The 10 Essential Components of III-V Device Simulation (cont.)



7 Circuit Performance Simulation (MixedMode)

- For devices with no accurate compact model
- Verification of newly developed compact models

8 Optoelectronic Capability (Luminous/Laser)

- Ray tracing algorithms
- DC, AC, transient and spectral response for detectors
- Helmholtz solver for edge emitting laser diodes and VCSELs
- LED simulation

9 Speed and Convergence

- Flexible and automatic choice of numerical methods

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The 10 Essential Components of III-V Device Simulation (cont.)



10 C-Interpreter for interactive model development

- User defined band parameter equations
- Large selection of user defined models
- Mole fraction dependent material parameters
- Ideal for proprietary model development

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Material Parameters and Models



- Blaze uses currently available material and model coefficients taken from published data and university partners
- For some materials often very little literature information is available, especially composition dependent parameters for ternary compounds
- Some parameters (eg. band alignments) are process dependent
- Tuning of material parameters is essential for accurate results

Material Parameters and Models (cont.)



- Blaze provides access to all defaults through the input language and an ASCII default parameter file
- The ability to incorporate user equations into Blaze for mole fraction dependent parameters is an extremely important extra flexibility offered by Blaze
- The C-Interpreter allows users to enter model equations (or lookup tables) as C language routines. These are interpreted by Blaze at run-time. No compilers are required
- With correct tuning of parameters the results are accurate and predictive

Laser Diode Structure Creation

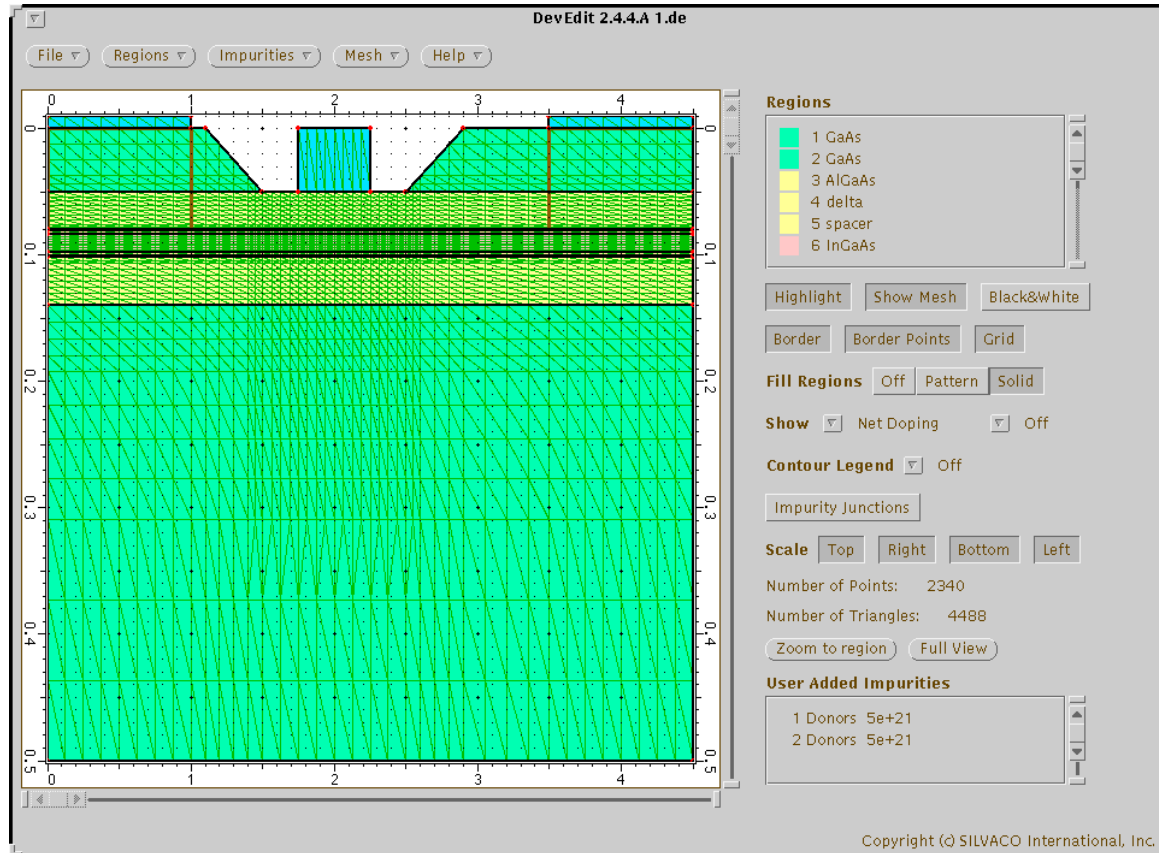


Three methods exist to create III-V device structures

- Process simulation
- Internal Atlas syntax
 - limited to rectangular structures
- Standalone device editor (DevEdit)
 - GUI to define structure, doping and mesh
 - batch mode for experimentation
 - abrupt and graded mole fraction definition
 - non-rectangular regions supported

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Structure Creation Using DevEdit



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Overview of Laser



- Laser works within the framework of Atlas and Blaze. Atlas provides the framework integration. Blaze provide electrical simulation of heterostructure devices and material models for common III-V and II-VI semiconductors
- Self-consistently solves the Helmholtz equation to calculate optical field and photon densities
- Accounts for carrier recombination due to spontaneous and stimulated emission using electronic band structure models based on the $k \cdot p$ method
- Calculates optical gain as a function of photon energy and quasi-Fermi levels/ carrier concentrations taking into account effects of strain and quantum confinement
- Predicts laser light output power and light intensity profiles corresponding to the fundamental and higher order transverse modes
- Calculates the light output and modal gain spectra for multiple longitudinal modes
- Finds laser threshold current and gain as a function of bias

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Features of Laser



- Devices with multiple insulators and electrodes
- Allows any material as the active layer
- Multiple quantum wells including strain effects
- Delta doped layers
- Standard Blaze III-V, II-VI and GaN materials supported
- Zincblende and Wurtzite crystalline structure
- DC and transient modes of operation
- Near field and far field patterns, spectra, I-V and LI curves

Laser Solution Methodology



- Laser solves the 2D Helmholtz equation to find the transverse optical field profile $E(x,y)$
 - $E(x,y)$ is found for the fundamental and higher order transverse modes
 - The Helmholtz equation may be solved for either
 - A single longitudinal mode of greatest optical power
 - Multiple longitudinal modes
- Laser has in-built models for
 - Complex dielectric permittivity
 - Optical gain models for $g(x,y)$

Laser Solution Methodology



- The central model in laser simulation is the optical gain model which is the ability of the semiconductor media to amplify light
- Laser contains two types of gain models
 - Empirically based models that have no frequency dependence and where gain is only a function of carrier concentrations
 - Physically based models taking into account actual band structure including effects of strain and quantum confinement

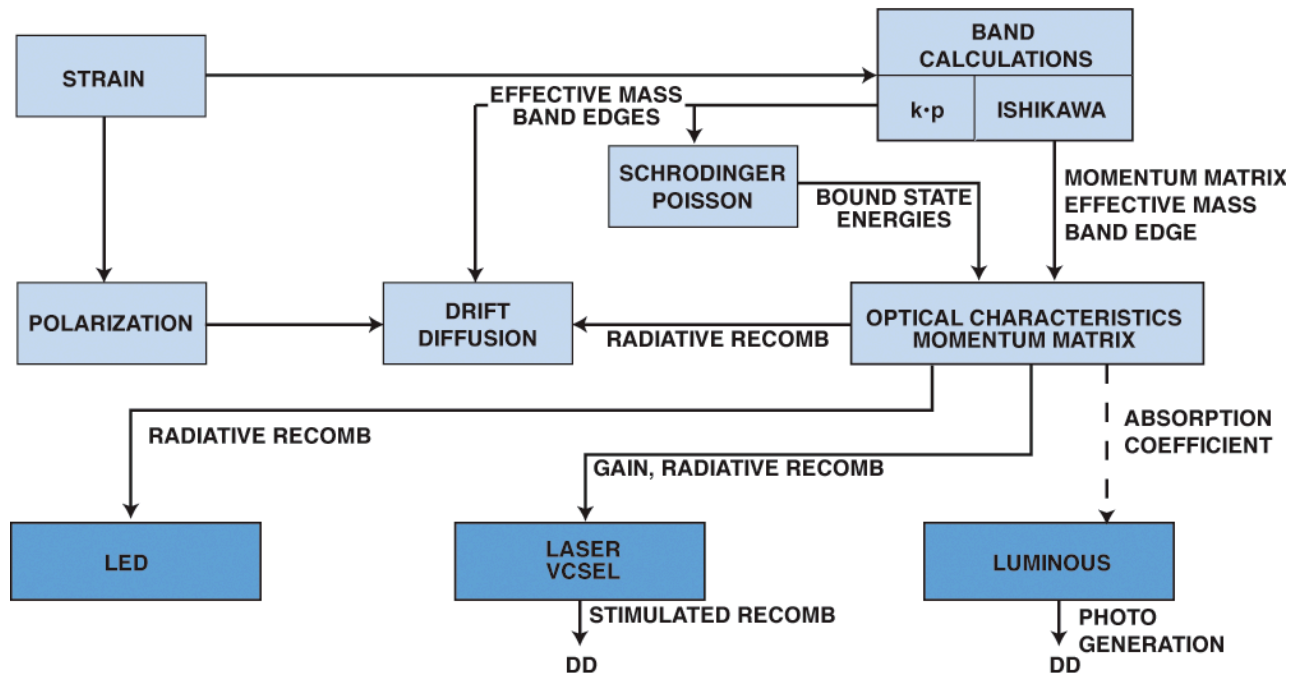
Empirical Models



- Blaze is used to obtain dc starting conditions by solving
 - Poisson equation
 - Electron continuity equation
 - Hole continuity equation
- Blaze includes:
 - Mobility models
 - SRH recombination
 - Auger recombination
 - Optical recombination (obtained in a self consistent manner from Laser)
- Laser empirical gain models:
 - Standard
 - Empirical
 - Tayamaya

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Physically Based Optoelectronic Models



Laser physical gain models:

- Yan
 - Li
 - Chuang
- } (Zincblende)
- (Wurtzite)

Laser Solution Methodology



- Laser uses $E(x,y)$ and $g(x,y)$ to solve the photon rate equation, to calculate the total photon density for each mode
- Blaze and Laser simulations are coupled in three areas
 - the optical gain $g(x,y)$ is a function of the band structure and carrier densities
 - the dielectric permittivity is a function of the optical gain $g(x,y)$
 - an additional optical recombination term is added to the RHS of the continuity equations and is a function of $g(x,y)$, $E(x,y)$ and the photon density

Application Notes for Laser



- The following items need to be defined for Laser simulations
 - A Laser mesh
 - The mesh must lie completely within the Blaze mesh
 - Limited to a rectangular mesh
 - Completely independent of the Blaze mesh
 - Length of laser cavity in z-direction
 - Laser loss (mirror loss, free carrier absorption loss and phase loss) coefficients
 - Quantum wells and their parameters
 - Optical gain parameters and line width broadening factor
 - Numerical solution tolerances

Application Notes for Laser



- Single Mode Parameters
 - The lasing frequency
 - Empirical or physical optical gain models may be used
- Multiple Mode Parameters
 - Photon energy range to be studied
 - Initial guess for photon density
 - Must use physically based optical gain model

Output from Laser



- Single mode operation
 - Optical intensity profile $E(x,y)$
 - Laser gain $g(x,y)$
 - Photon density
 - Optical power
 - Total optical gain
- Multiple mode operation
 - All single mode output but summed over all modes
 - Laser spectra file for each dc bias or transient solutions

Laser Application Examples



- Examples to be shown in the demonstration
 - InP/InGaAsP Laser Diode
 - Single mode operation
 - Forward biasing of diode
 - Calculation of light versus current characteristics
 - Spectral analysis of the InP/InGaAsP laser diode
 - Multiple mode operation
 - Calculation of I-V data, and laser spectra
 - Strip geometry GaAs/AlGaAs laser diode
 - Multiple transverse mode operation
 - Calculation of I-V data, and laser spectra
 - Transient laser simulation
 - Multiple quantum well laser

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Example Input Deck for Laser Simulation



```
go atlas
#
#     SILVACO International, 1993
#
#
Mesh           diag.flip           space.mult=1.0
#
x.mesh         loc =0.0             space=2
x.mesh         loc =8.0             space=0.5
x.mesh         loc =9.0             space=0.2
x.mesh         loc =11.0            space=0.2
x.mesh         loc =12.0            space=0.5
x.mesh         loc =20.0            space=2
#
y.mesh         loc =0.0             space=0.25
y.mesh         loc =1.0             space=0.25
y.mesh         loc =1.75            space=0.02
y.mesh         loc =1.90            space=0.02
y.mesh         loc =2.0             space=0.075
y.mesh         loc =2.5             space=0.1
y.mesh         loc =3.5             space=0.1
y.mesh         loc =4.5             space=0.2
y.mesh         loc =10.0            space=1.5
#
```

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Example Input Deck for Laser Simulation



```
region    num=1  material=InP  x.min=0.  x.max=20.0  y.min=0.0  y.max=1.0
#
region    num=2  material=InP  x.min=0.  x.max=9.0   y.min=1.0  y.max=2.5
#
region    num=3  material=InP  x.min=11.0 x.max=20.0  y.min=1.0  y.max=2.5
#
region    num=4  material=InP  x.min=9.0  x.max=11.0  y.min=1.0  y.max=1.75
#
region    num=5  material=InGaAsP  x.min=9.0  x.max=11.0  y.min=1.75 \
y.max=1.9  x.comp=0.25  y.comp=0.5
#
region    num=6  material=InP  x.min=0.0  x.max=9.0   y.min=2.5  y.max=3.5
#
region    num=7  material=InP  x.min=11.0 x.max=20.0  y.min=2.5  y.max=3.5
#
```

Example Input Deck for Laser Simulation



```
region      num=8  material=InP  x.min=9.0  x.max=11.0  y.min=1.9  y.max=3.5
#
region      num=9  material=InP  x.min=0.0  x.max=20.0  y.min=3.5  y.max=4.5
#
region      num=10  material=InP  x.min=0.0  x.max=20.0  y.min=4.5  y.max=10.0
#
elec        num=1  name=cathode  x.min=8.0  x.max=12.0  y.min=0.0  y.max=0.0
#
elec        num=2  name=anode    bottom
#
doping      uniform reg=1  n.type  conc=1.e18
doping      uniform reg=2  p.type  conc=2.e17
doping      uniform reg=3  p.type  conc=2.e17
doping      uniform reg=4  n.type  conc=1.e18
doping      uniform reg=5  p.type  conc=2.e15
doping      uniform reg=6  n.type  conc=2.e17
doping      uniform reg=7  n.type  conc=2.e17
doping      uniform reg=8  p.type  conc=1.e18
doping      uniform reg=9  p.type  conc=1.e18
doping      uniform reg=10 p.type  conc=2.e18
#
```

Example Input Deck for Laser Simulation



```
material material=InP      taun0=2.e-9  taup0=2.e-9  copt=1.5e-10  mun=2400.0  mup=80.0  align=0.6
#
material material=InGaAsP taun0=10.e-9 taup0=10.e-9 copt=1.5e-10 \
mun=4600.0 mup=150.0
#
models
models material=InP      fldmob  srh  optr  fermi  print
models material=InGaAsP fldmob  srh  optr  fermi  print
#

solve init
save outf=laserex02_0.str
tonyplot laserex02_0.str -set laserex02_0_str.set
#

method newton autonr trap
solve v2=0.01
solve v2=0.05
solve v2=0.1
solve v2=0.2
solve v2=0.4
solve v2=0.6
#
```

Example Input Deck for Laser Simulation



```
# LASER models
#
lx.m n=1 x=6.0
lx.m n=37 x=14.0
#
ly.m n=1 y=1.25
ly.m n=33 y=2.4
#
models material=InGaAsP fldmob srh optr fermi print laser gainmod=1 \
  photon_energy=1.025 spec.name=laserex02.log \
  lmodes las_einit=1.01 las_efinal=1.1 cavity_length=50
#
log outf=laserex02_1.log
#
solve v2=0.8
solve v2=0.9
solve v2=1.0
solve v2=1.1
#
output con.band val.band recomb u.srh u.aug u.rad flowlines
solve vstep=0.05 electr=2 vfinal=1.7
save outfile=laserex02_1.str
#
```

Example Input Deck for Laser Simulation



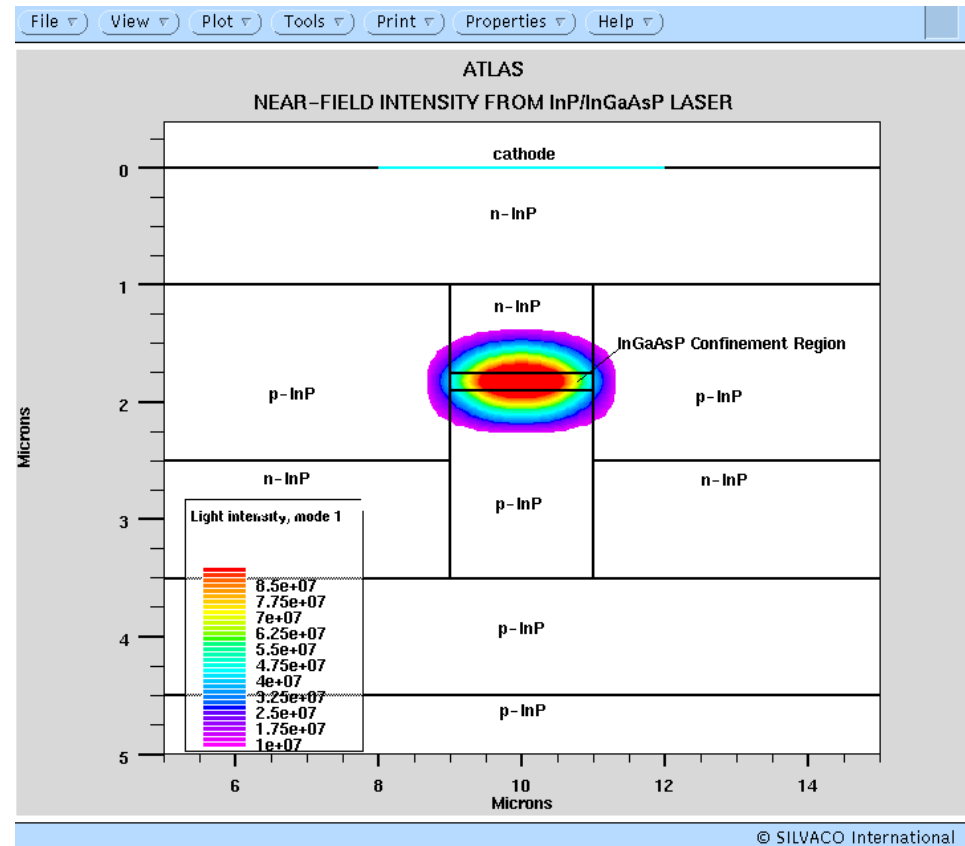
```
tonyplot -overlay laserex02_1.log laserex01_1.log -set laserex02_1_log.set
tonyplot -overlay laserex02.log6 laserex02.log14 laserex02.log18 -set
laserex02_2_log.set
tonyplot laserex02.log6 -set laserex02_3_log.set
tonyplot laserex02.log18 -set laserex02_4_log.set

quit
```

Near-Field Intensity from InP/InGaAsP Laser



- Cross section of a typical InP/InGaAsP laser diode. This represents the domain over which electrical solutions for the laser diode are obtained using Atlas/Blaze
- Optical solutions are obtained by Laser in a smaller domain around the active layer
- This figure shows the near field light intensity in the fundamental transverse mode

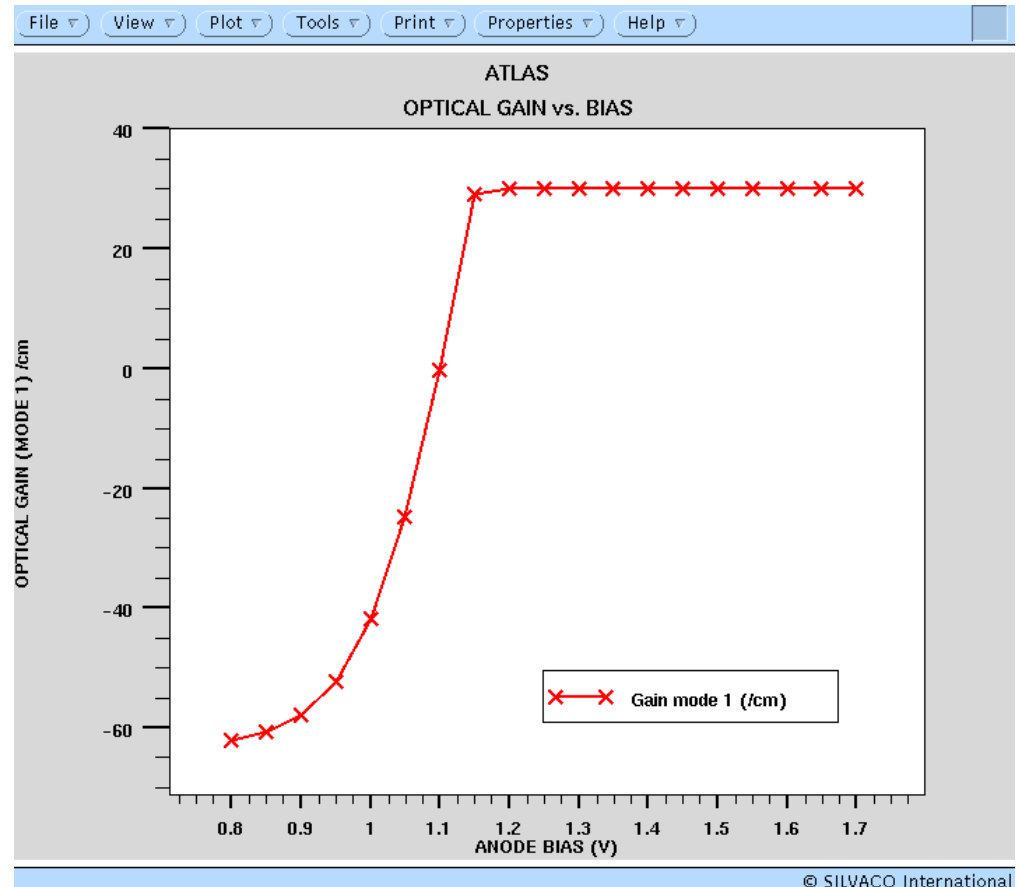


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Optical Gain vs. Bias



- Laser gain as a function of bias
- The gain rises until the laser threshold
- After the threshold the gain remains constant and equal to the laser losses

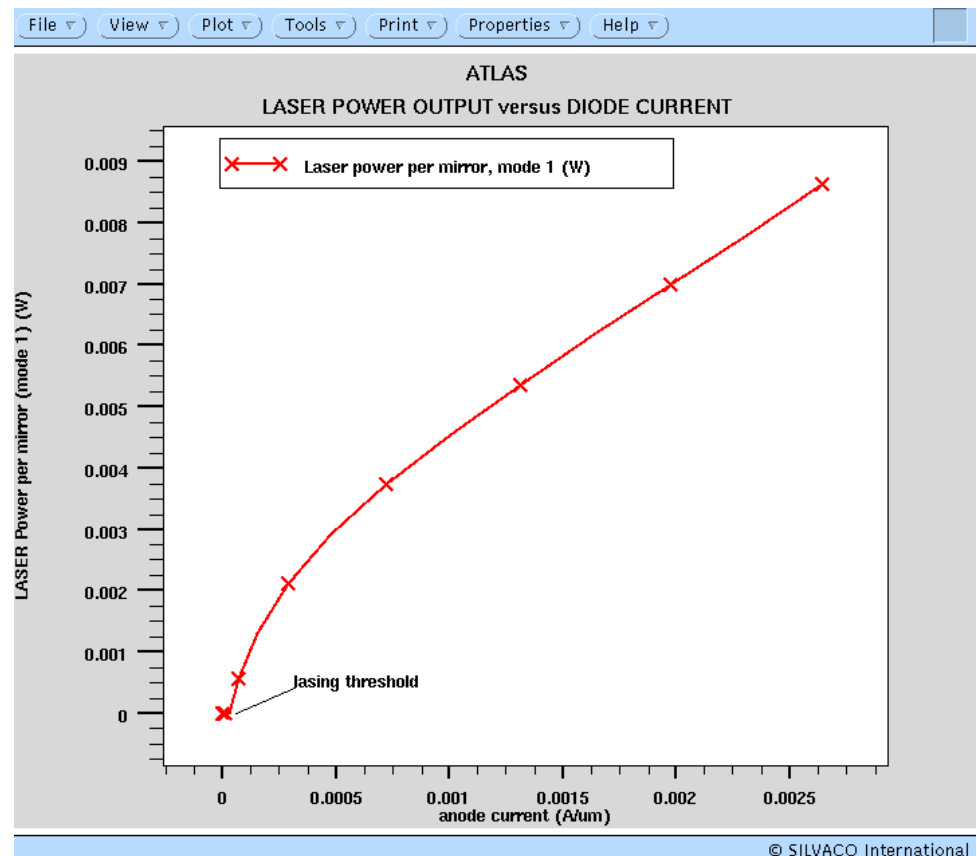


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Laser Power Output vs. Diode Current



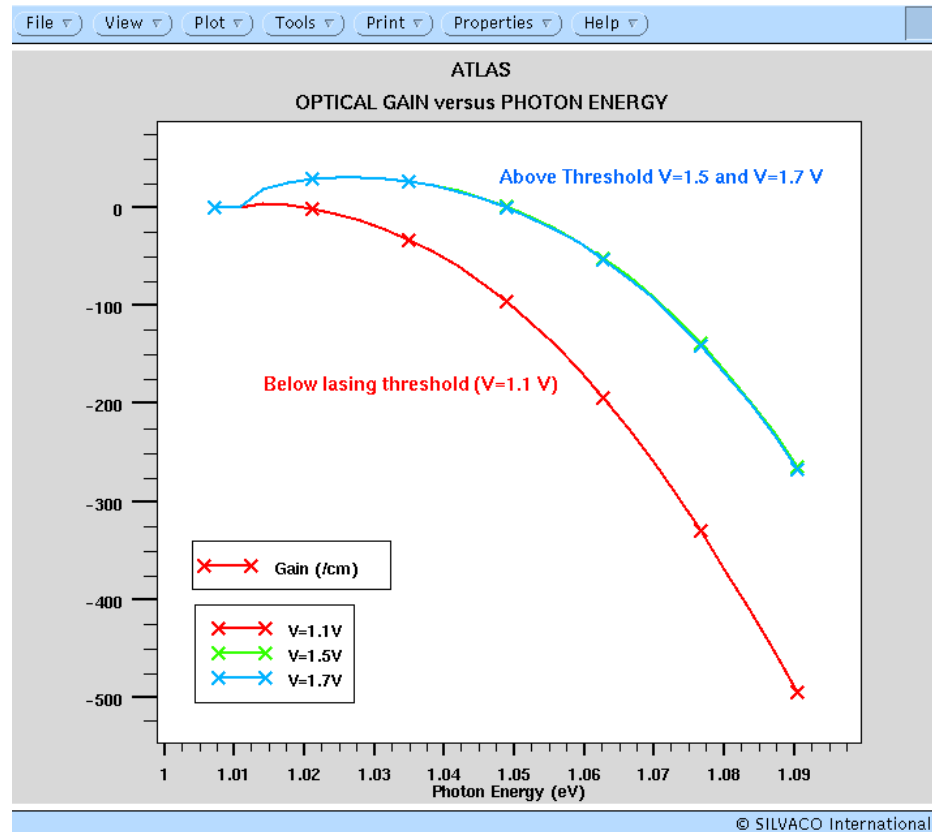
- This figure shows the simulated laser output power as a function of anode current for the InP/InGaAsP laser diode
- Important characteristics such as laser threshold current are readily extracted



Optical Gain vs. Photon Energy



- Comparison of the simulated gain spectra below and above lasing threshold for the InP/InGaAsP laser diode

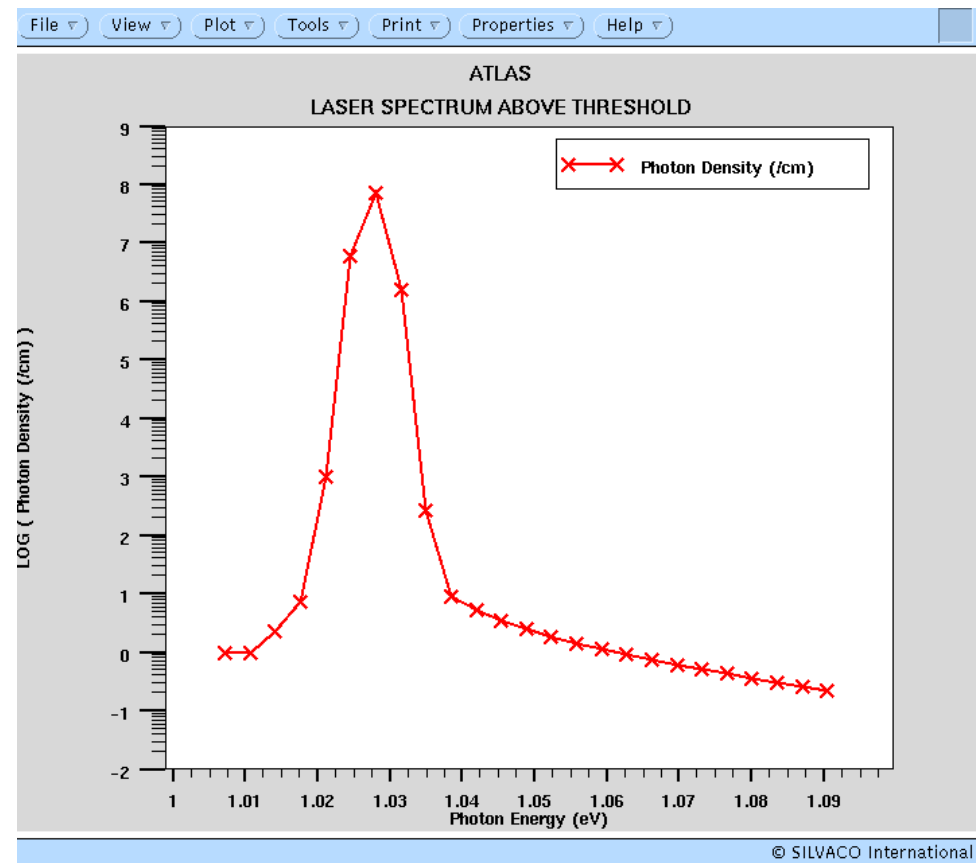


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Laser Spectrum Above Threshold



- Spectrum of the InP/
InGaAsP laser diode
above laser threshold

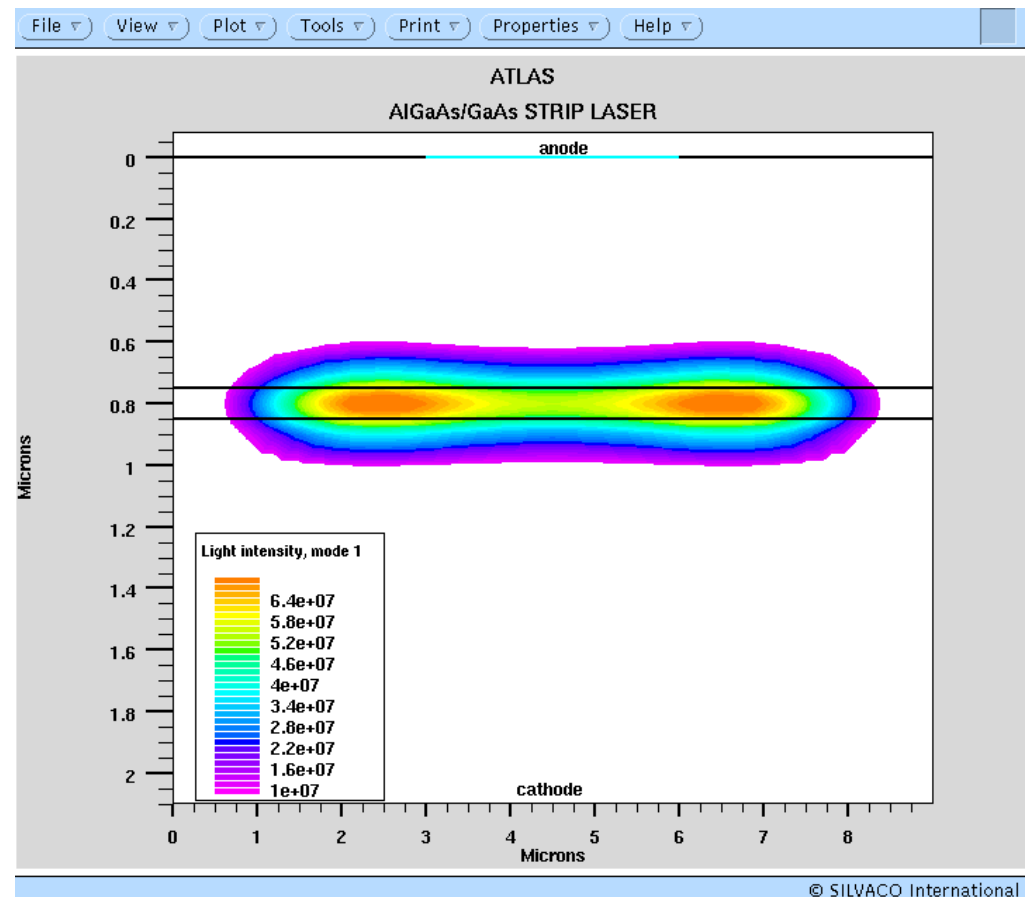


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AlGaAs/GaAs Strip Laser



- Light intensity from strip laser showing double spot
- The near field pattern is distorted due to spatial hole burning in the active layer

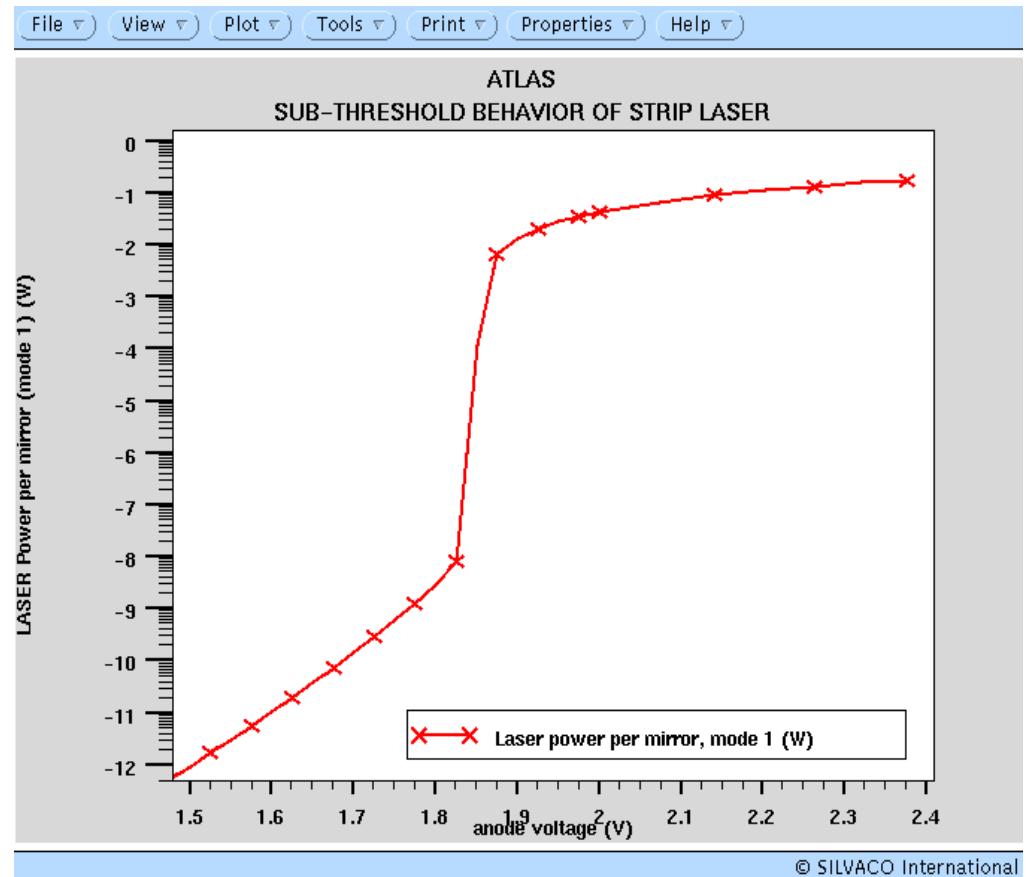


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Sub-Threshold Behavior of Strip Laser



- Laser response to a voltage sweep showing the threshold and subthreshold characteristics of the strip laser

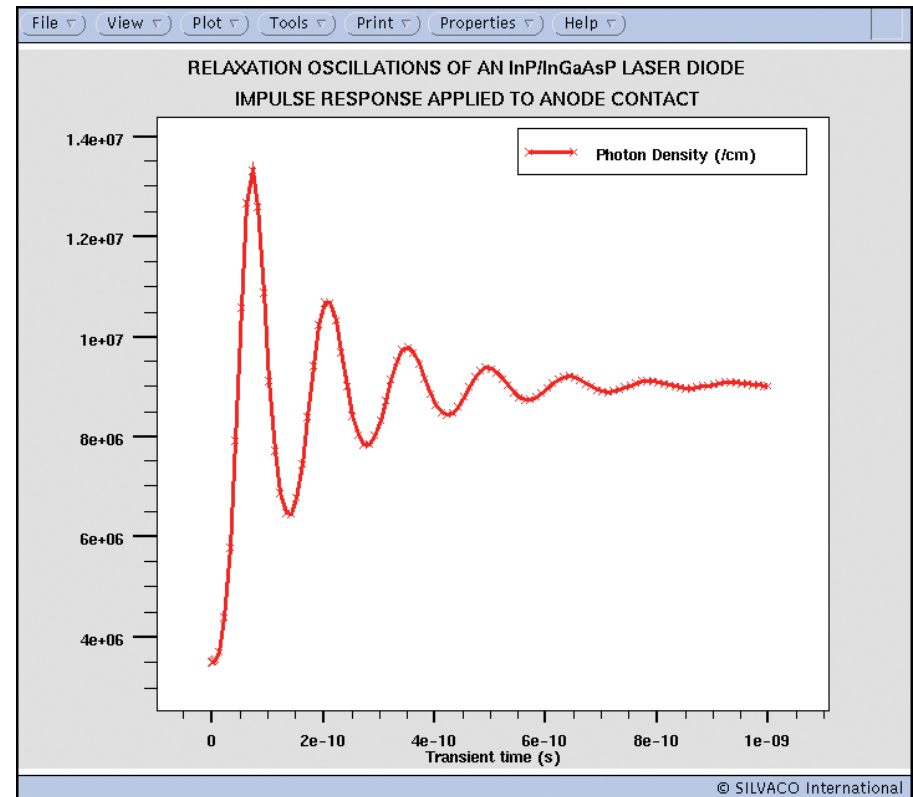


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Relaxation Oscillations of an InP/InGaAsP Laser Diode Impulse Response Applied to Anode Contact



- Laser incorporates the photon equation in its set of self-consistent equations
- This allows transient simulations to be preformed that accurately reproduce advanced behavior
- This figure shows the result of a small voltage perturbation to the anode voltage
- The transient simulation shows the resulting oscillations which are commonly referred to as relaxation oscillations

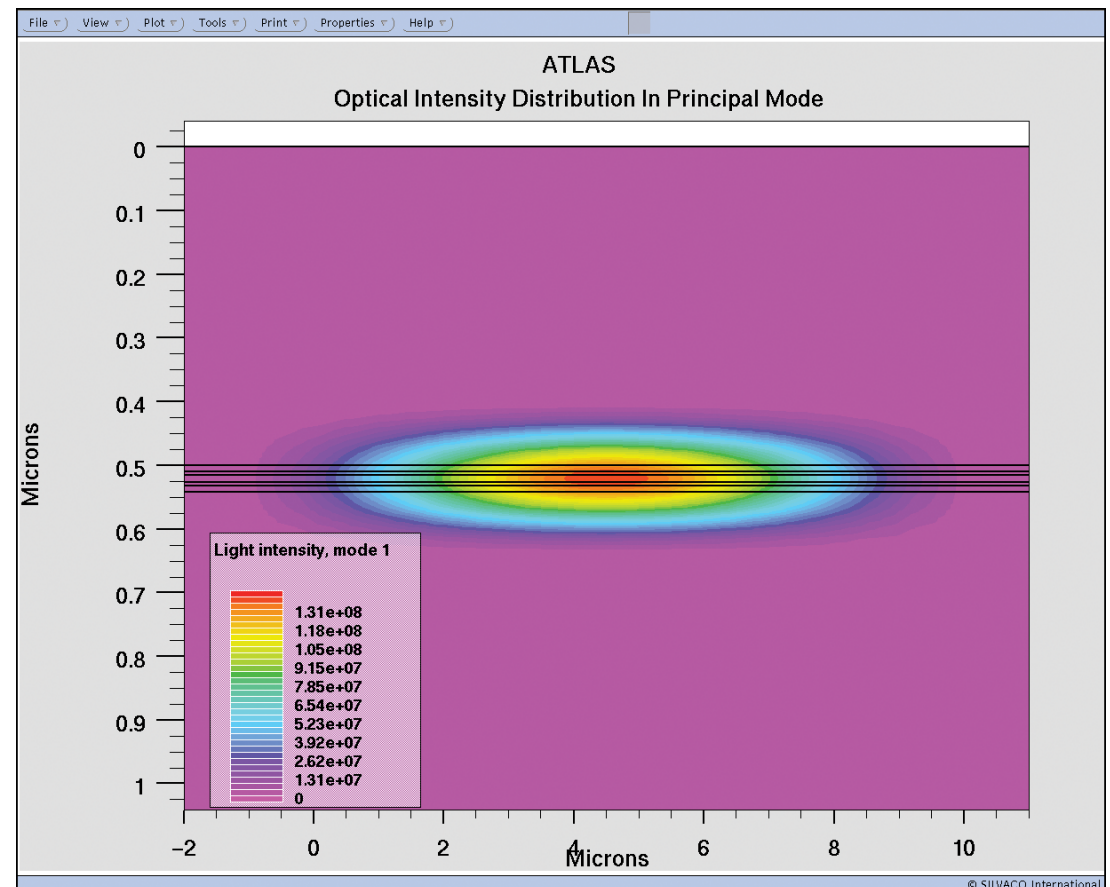


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Optical Intensity Distribution in Principal Mode



- This figure shows the optical intensity distribution of the principal optical mode at the operating bias

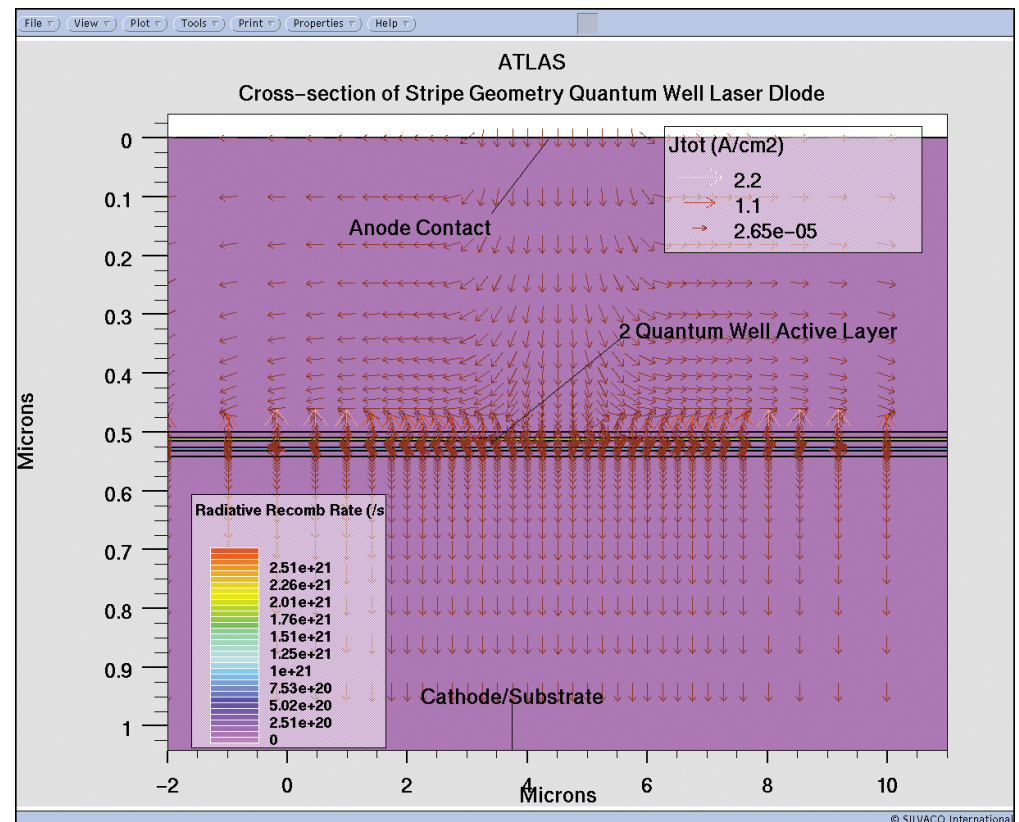


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Cross-Section of Stripe Geometry Quantum Well Laser Diode



- In this figure we see an overlay of the current vectors with contours of the radiative recombination rate in the wells

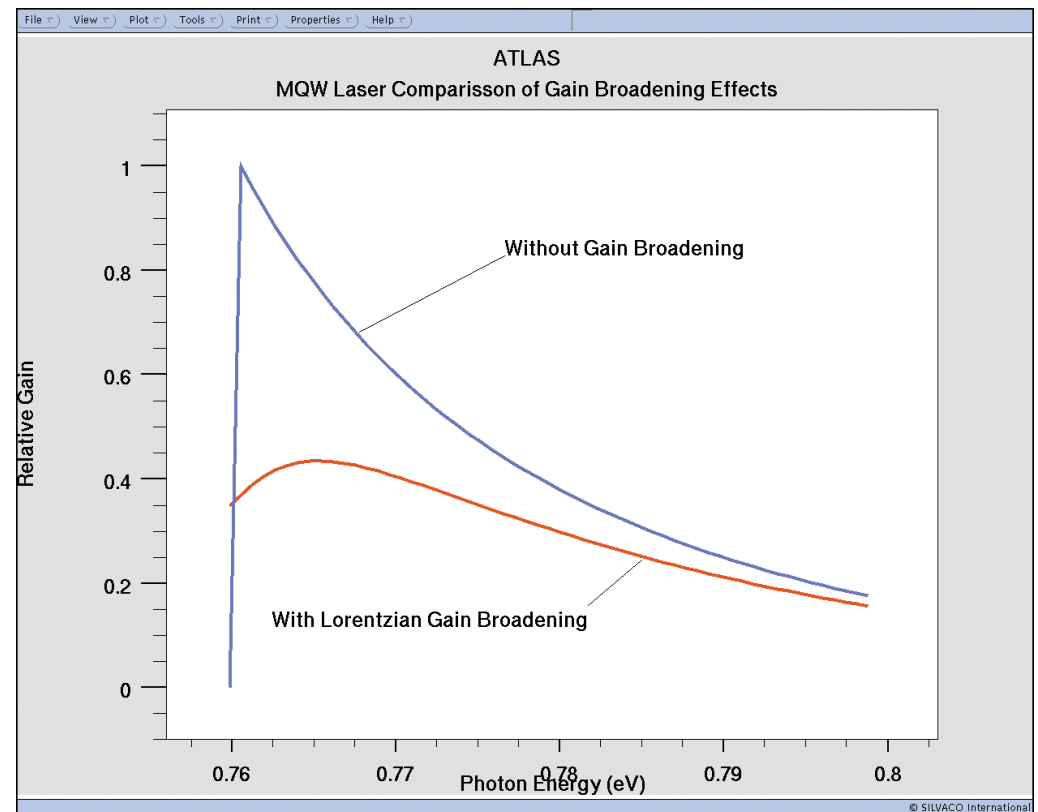


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MQW Laser Comparison of Gain Broadening Effects



- Laser models incorporate advanced effects such as Lorentzian line bordering in the gain curve as shown in the above figure



Background of Laser



References

- [1] D.P Wilt and A. Yariv, “A Self-Consistent Static Model of the Double-Hetrostructure Laser”, IEEE Journal of Quantum Electronics, vol. QE-17, No. 9, 1981, pp. 1941-1949.
- [2] K.B. Kahen, “Two-Dimensional Simulation of Laser Diodes in Steady State”, IEEE Journal of Quantum Electronics, vol. 24, No.4, April 1988.
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Future Development Plans for Laser



- Features under consideration for future implementation into LASER
 - TM optical models
 - 3D Helmholtz solver
 - Coupled cavity lasers
 - Distributed feedback lasers