

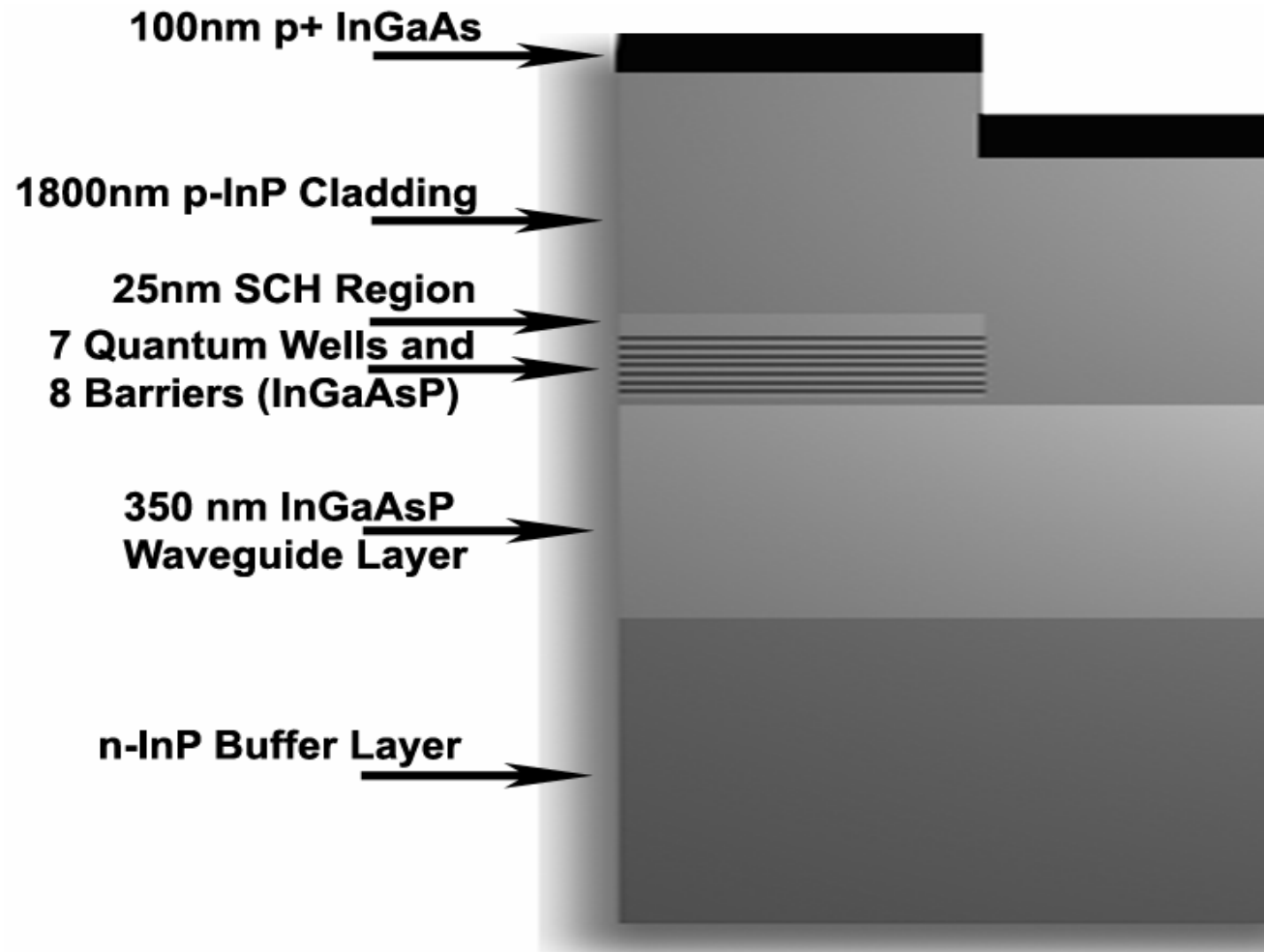
Broadband Rate-Equation Model including Many-Body Gain for WDM Traveling-Wave SOAs

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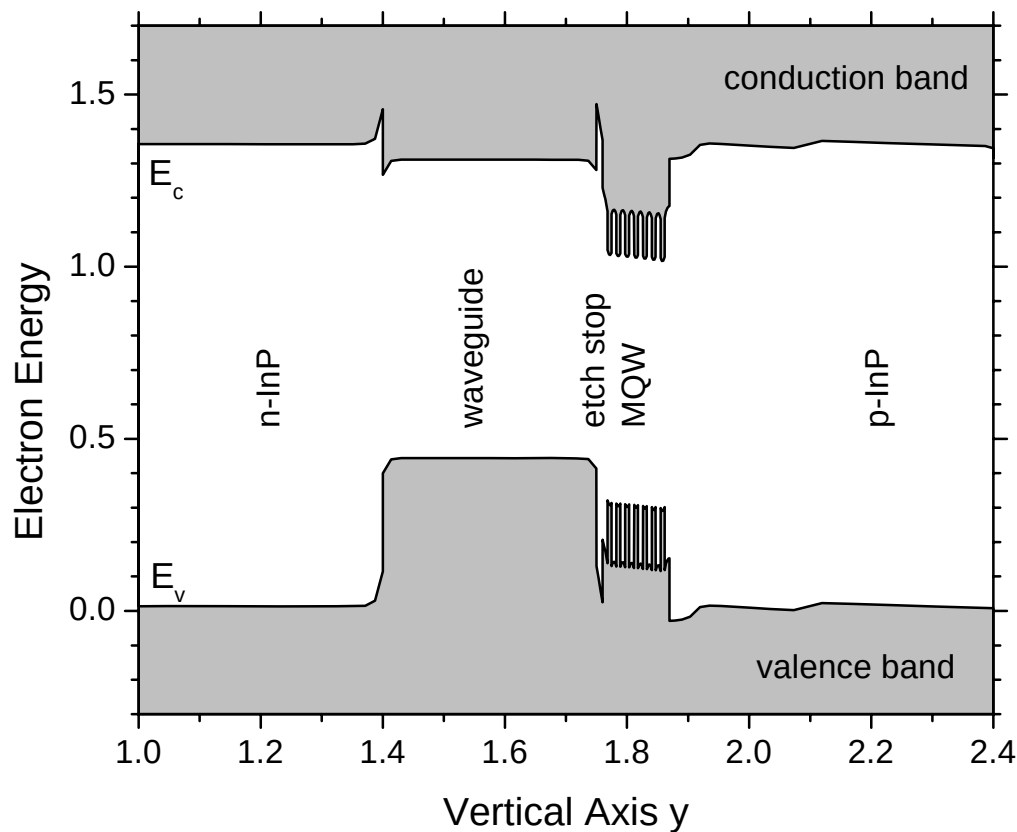
funding: Semiconductor Research Corp. & Intel Corp.

1. Introduction
2. Quantum Well Gain Models
3. Rate Equation Model
4. Comparison to Measurements
 - Unsaturated SOA Gain
 - SOA Saturation Power
5. Conclusion

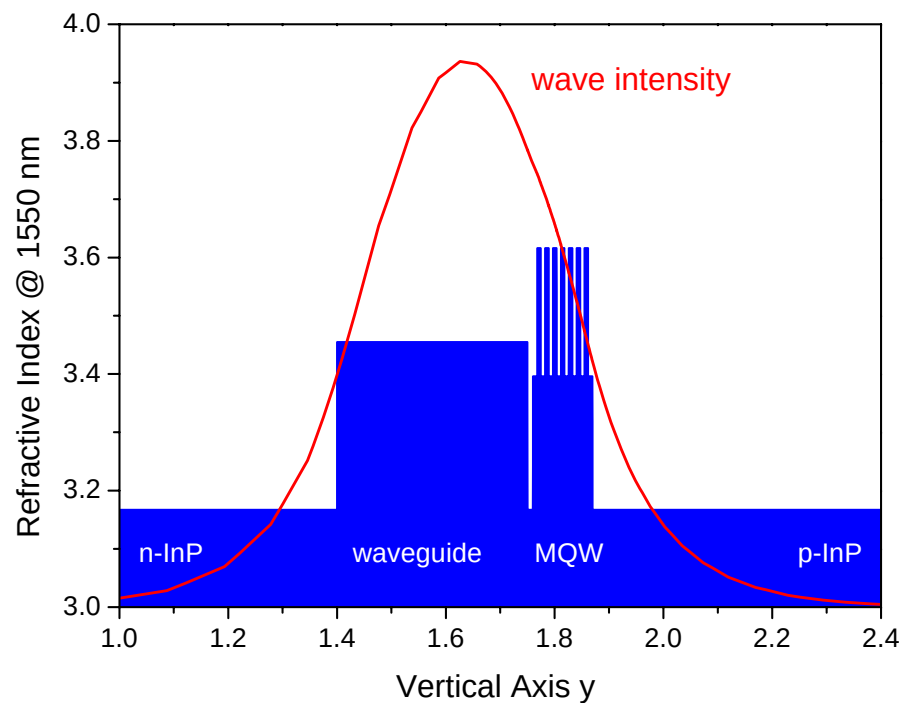


Quantum Well Region

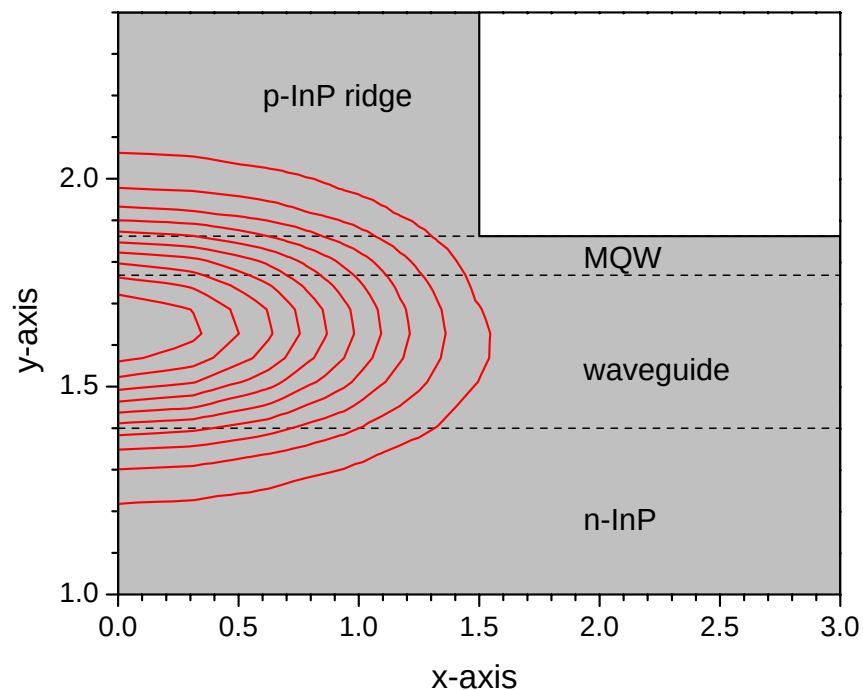
Energy Band Diagram



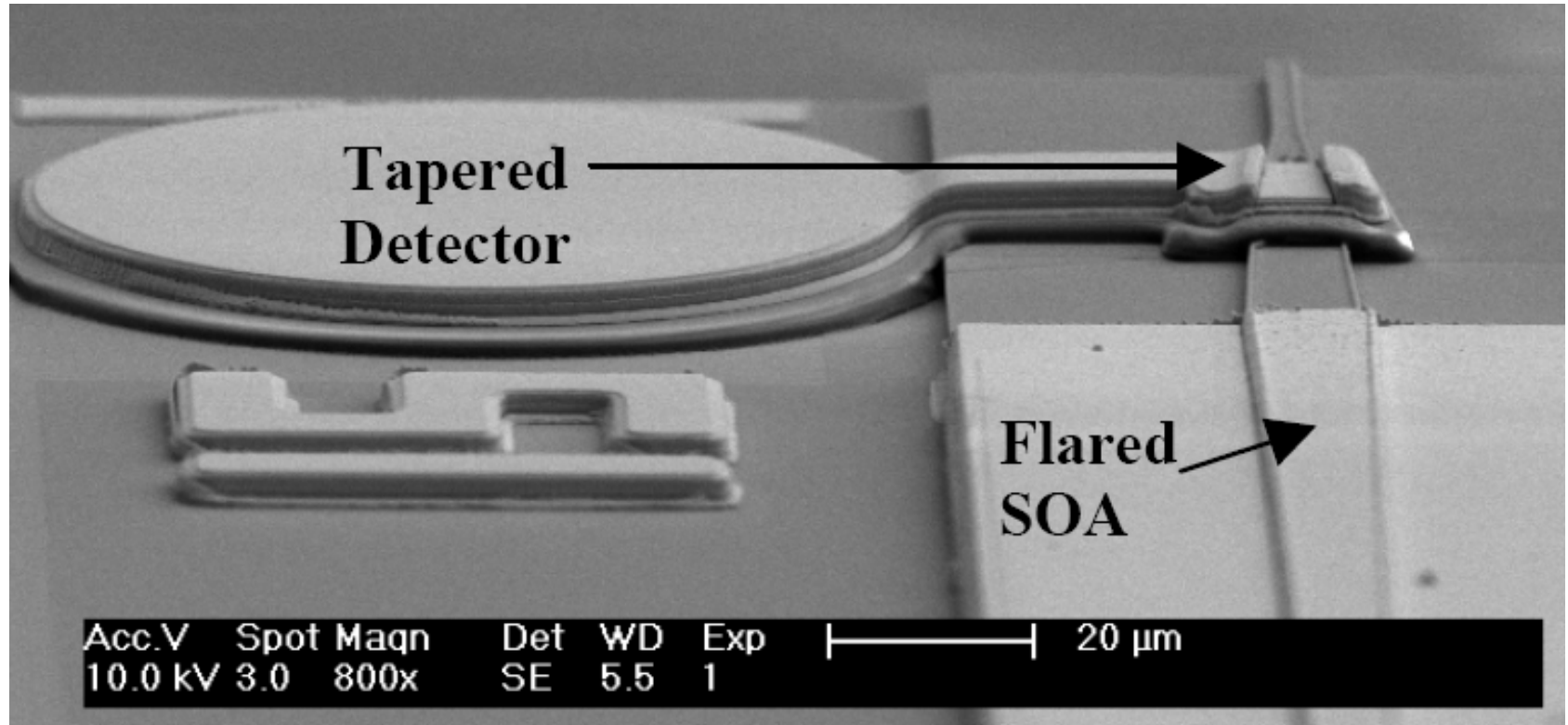
Vertical Index Profile



2D Mode Profile



Integrated SOA & Detector



Here: straight SOA ridge, $W_{\text{SOA}} = 3 \mu\text{m}$, $L_{\text{SOA}} = 400 \mu\text{m}$

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X-Ray Diffraction

Well (0.59% compressive strain)

6.5 nm $\text{In}_{0.685}\text{Ga}_{0.315}\text{As}_{0.864}\text{P}_{0.136}$

Barrier (0.3% tensile strain)

8 nm $\text{In}_{0.685}\text{Ga}_{0.315}\text{As}_{0.595}\text{P}_{0.405}$

many-body model fit parameter:

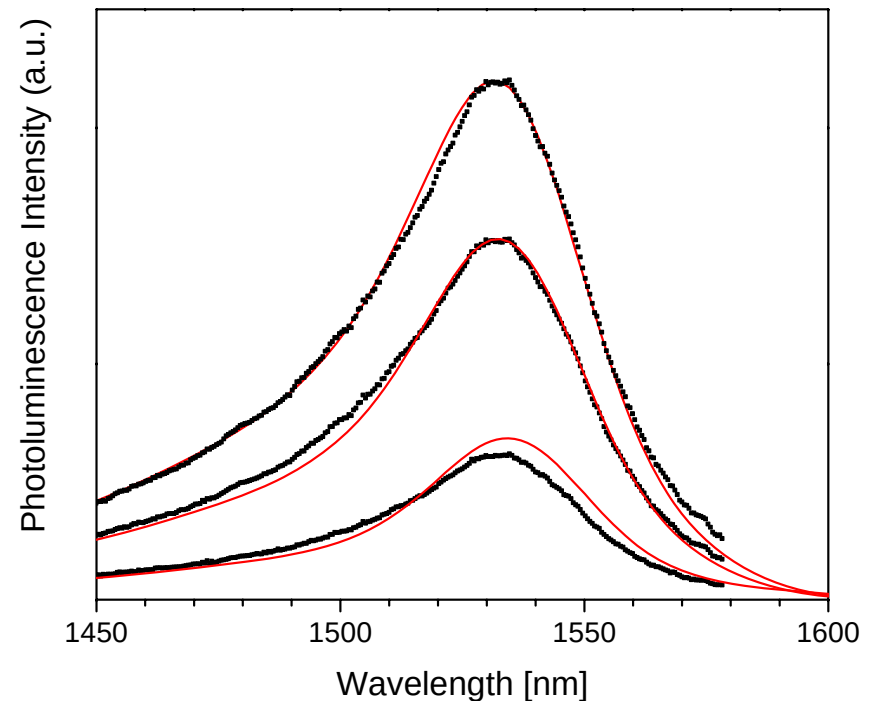
inhomogeneous broadening

due to QW imperfections = 14 meV

Photoluminescence (PL)

dots: measurements

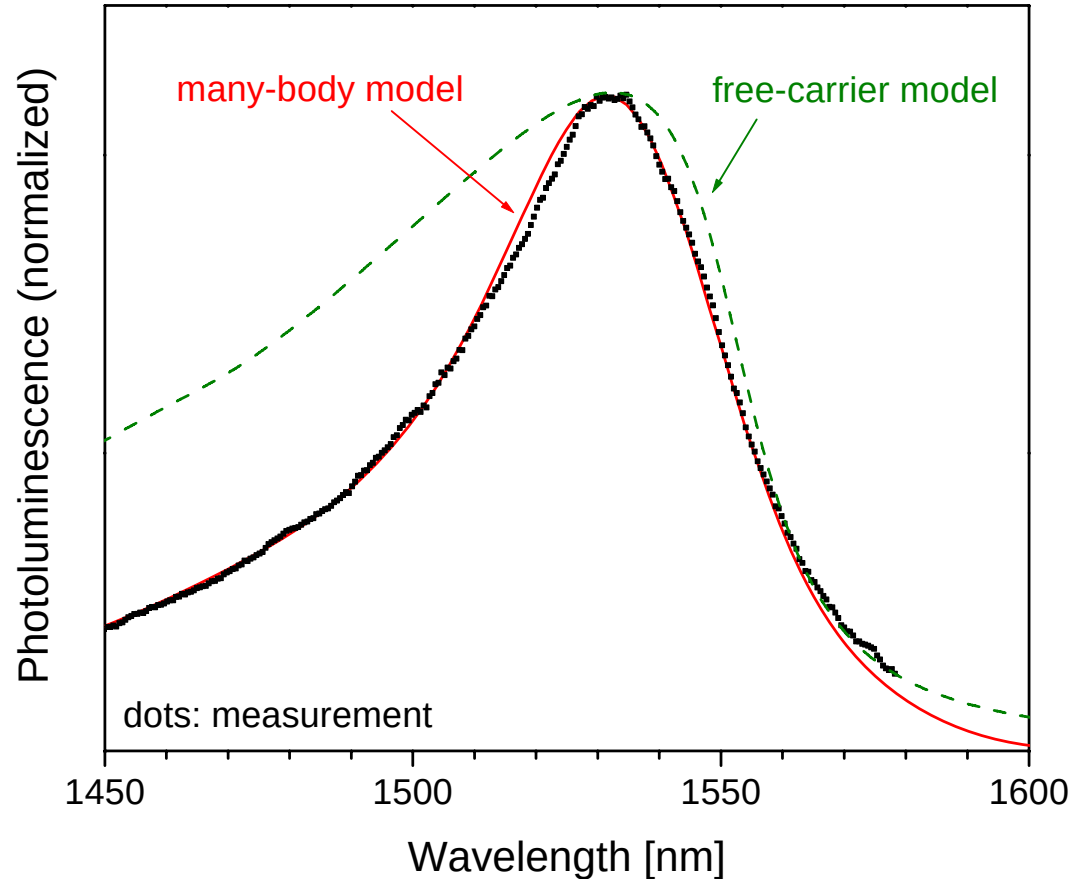
lines: many-body calculations



many-body model & supercomputer calculations by

Nonlinear Control Strategies, Inc., Tucson, AZ (J. Hader, S. Koch, J. Moloney)

PL Model Comparison

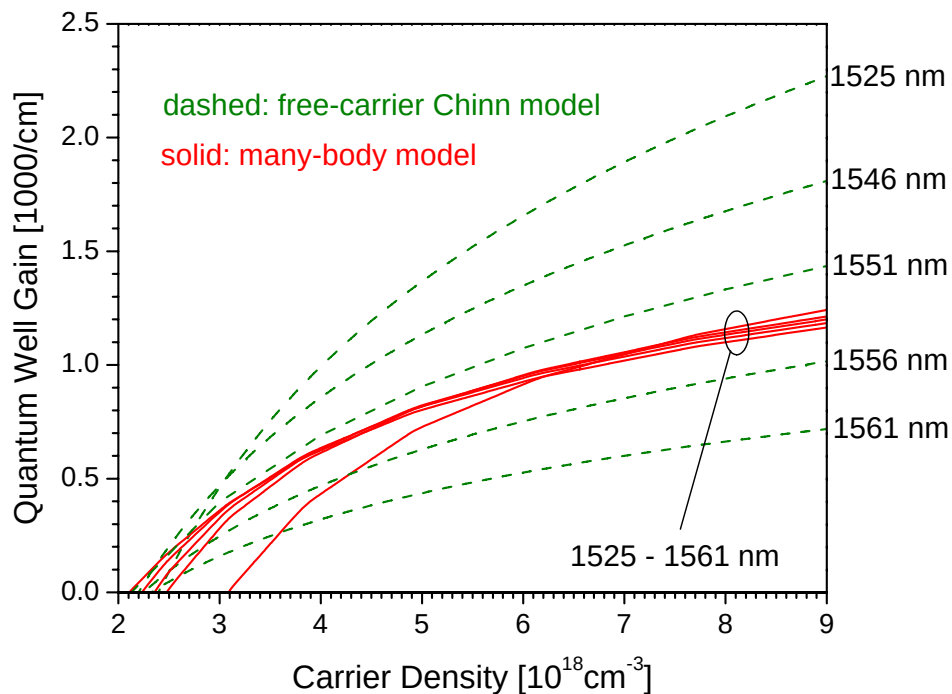
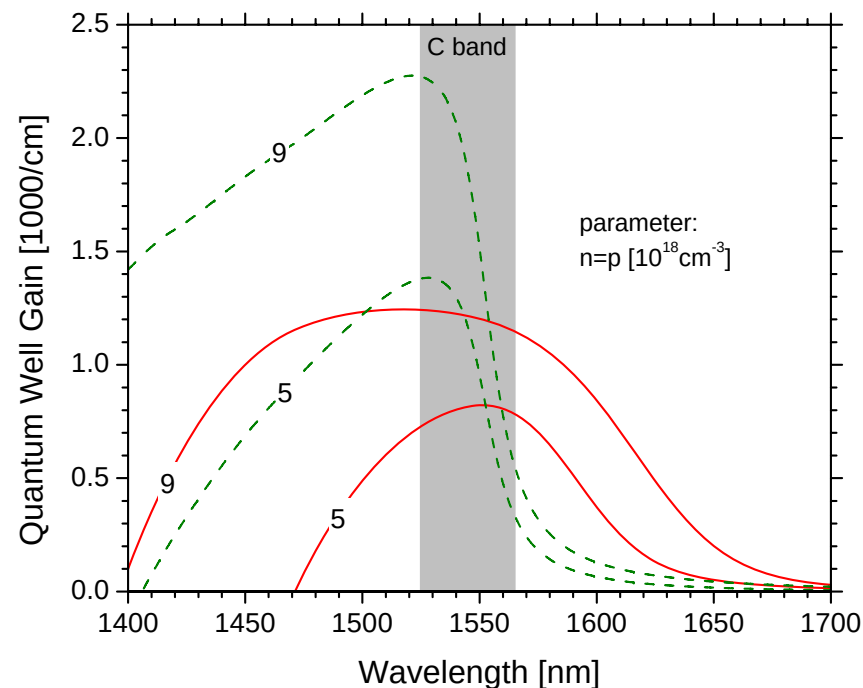


details on gain models:

Chow & Koch, "Semiconductor Lasers", Springer, New York, 1999

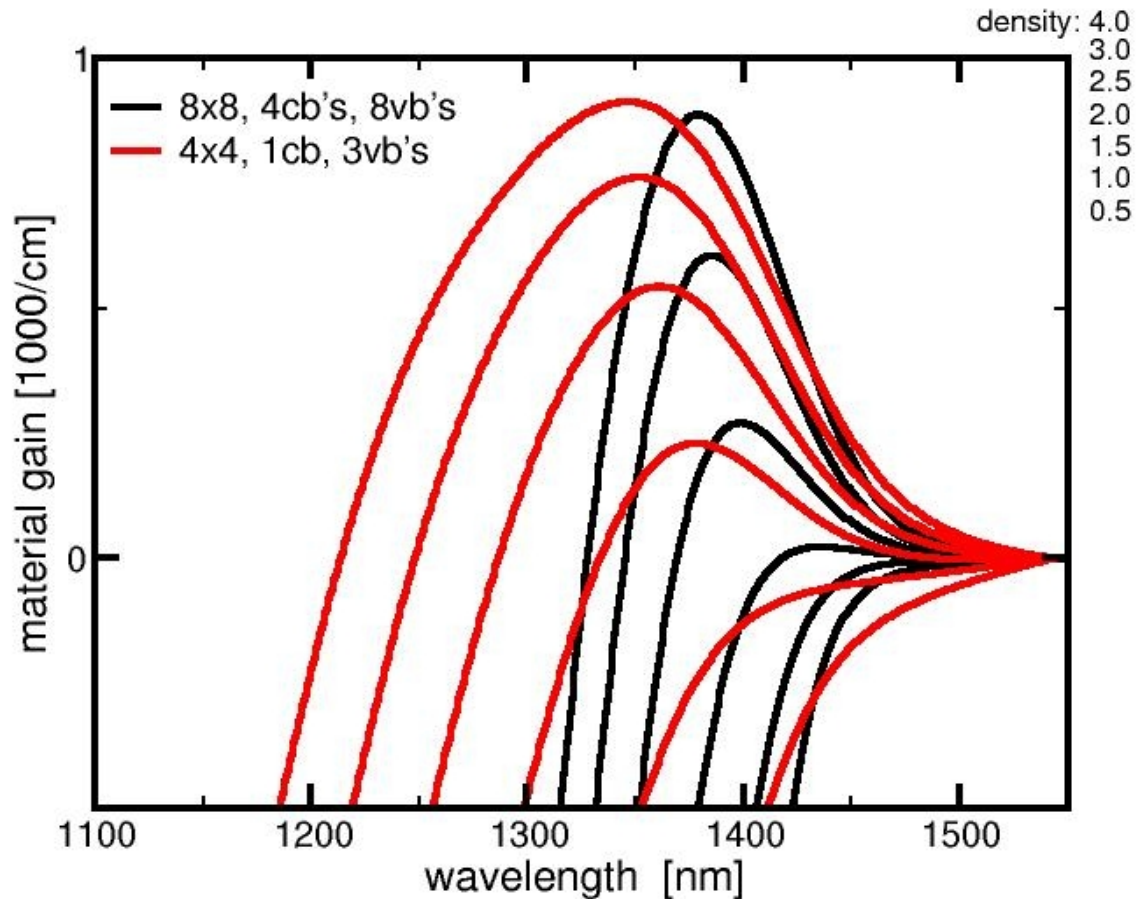
Gain Model Comparison

important: correct wavelength dependence

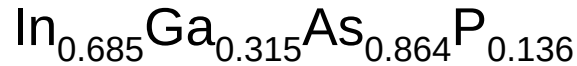


Bandstructure Effects

4 x 4 kp gives lower density of states and higher band filling



Dipole Matrix Element



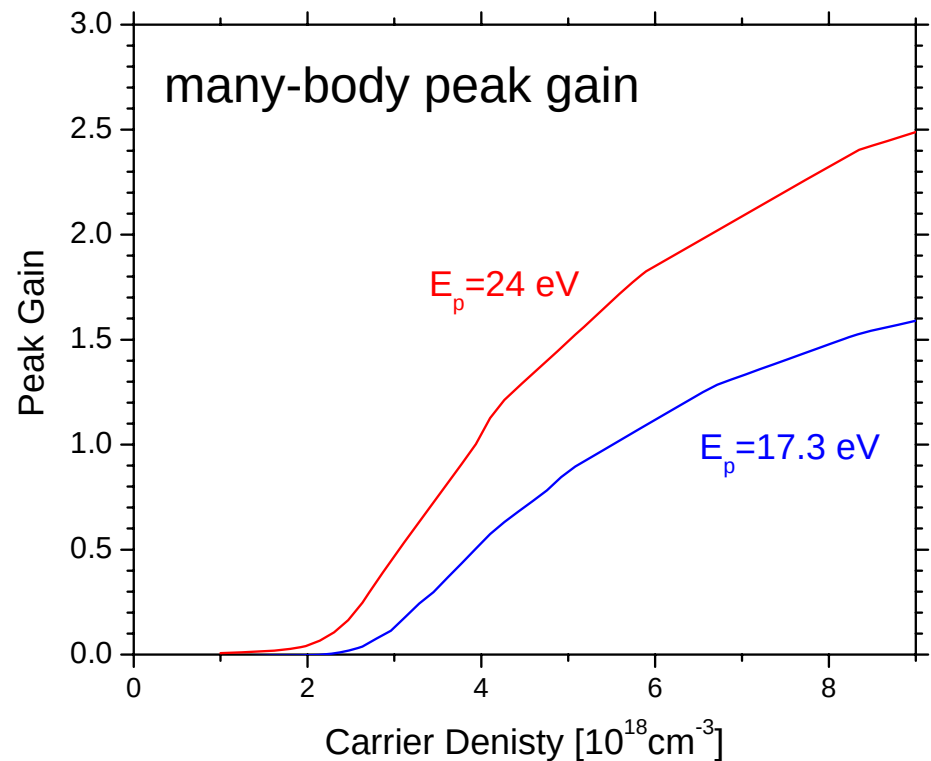
- no direct measurements
- interpolation scheme ?

Linear Interpolation:

$$E_p = 17.3 \text{ eV}$$

Non-linear Interpolation:

$$E_p = 24 \text{ eV}$$



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Dynamic Rate Equations

$$\frac{\partial N(z,t)}{\partial t} = \frac{\eta_i J}{qd} - (AN + BN^2 + CN^3) - \frac{\Gamma}{wd\hbar} \left[\sum_k \frac{g(N, \omega_s)}{\omega_s} P_s(z,t) + \int \frac{g(N, \omega)}{\omega} (P^{ASE+} + P^{ASE-}) d\omega \right]$$

$$\frac{1}{v_g} \frac{\partial P_s^\pm}{\partial t} \pm \frac{\partial P_s^\pm}{\partial z} = [\Gamma g(N, \omega_s) - \alpha_i] P_s^\pm \quad \forall k$$

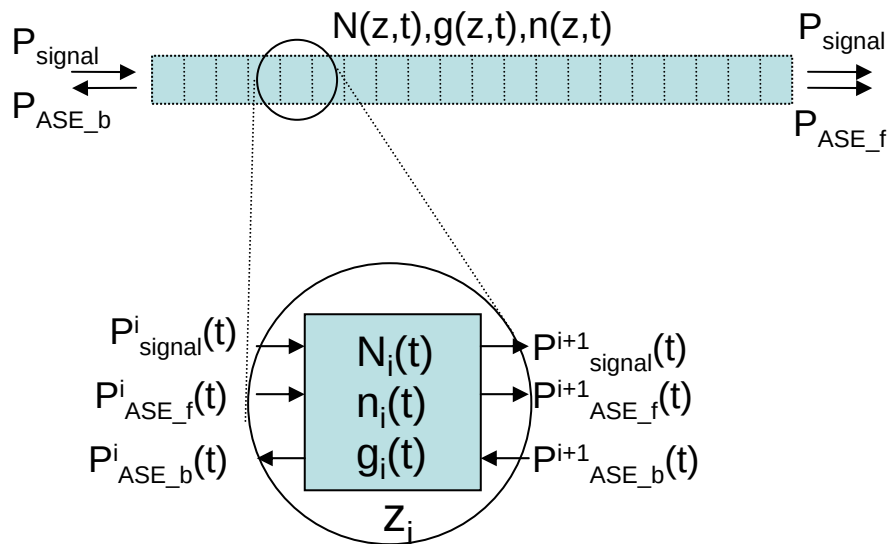
$$\frac{1}{v_g} \frac{\partial P^{ASE\pm}}{\partial t} \pm \frac{\partial P^{ASE\pm}}{\partial z} = [\Gamma g(N, \omega) - \alpha_i] P^{ASE\pm} + \beta R_{sp}(N, \omega) A \hbar \omega \quad \forall \omega$$

N electron density ($N=n=p$)
 η_i injection efficiency
 d thickness of the active region
 w active region width
 A, B, C recombination parameters for the material.
 Γ overlap of the optical mode with the active material
 P_s input signal power
 ω_s signal frequency
 g material gain at carrier density N and frequency ω

$P^{ASE+/-}$ ASE power spectral density
 J current density
 v_g signal group velocity
 β spontaneous emission factor
 R_{sp} spontaneous emission rate

Multi-Section Model

accounting for longitudinal non-uniformity



- Carrier Density: $N(z,t)$
- Gain: $g(z,t)$
- Index: $n(z,t)$
- signal power: $P_{\text{signal}}(t)$
- ampl. spont. emission: $P_{\text{ASE}}(t)$

from measurements:

modal loss $\alpha_i = 10 / \text{cm}$

from 3D device simulation:

injection efficiency $\eta_i = 82\%$

optical confinement factor $\Gamma = 6\%$

estimated:

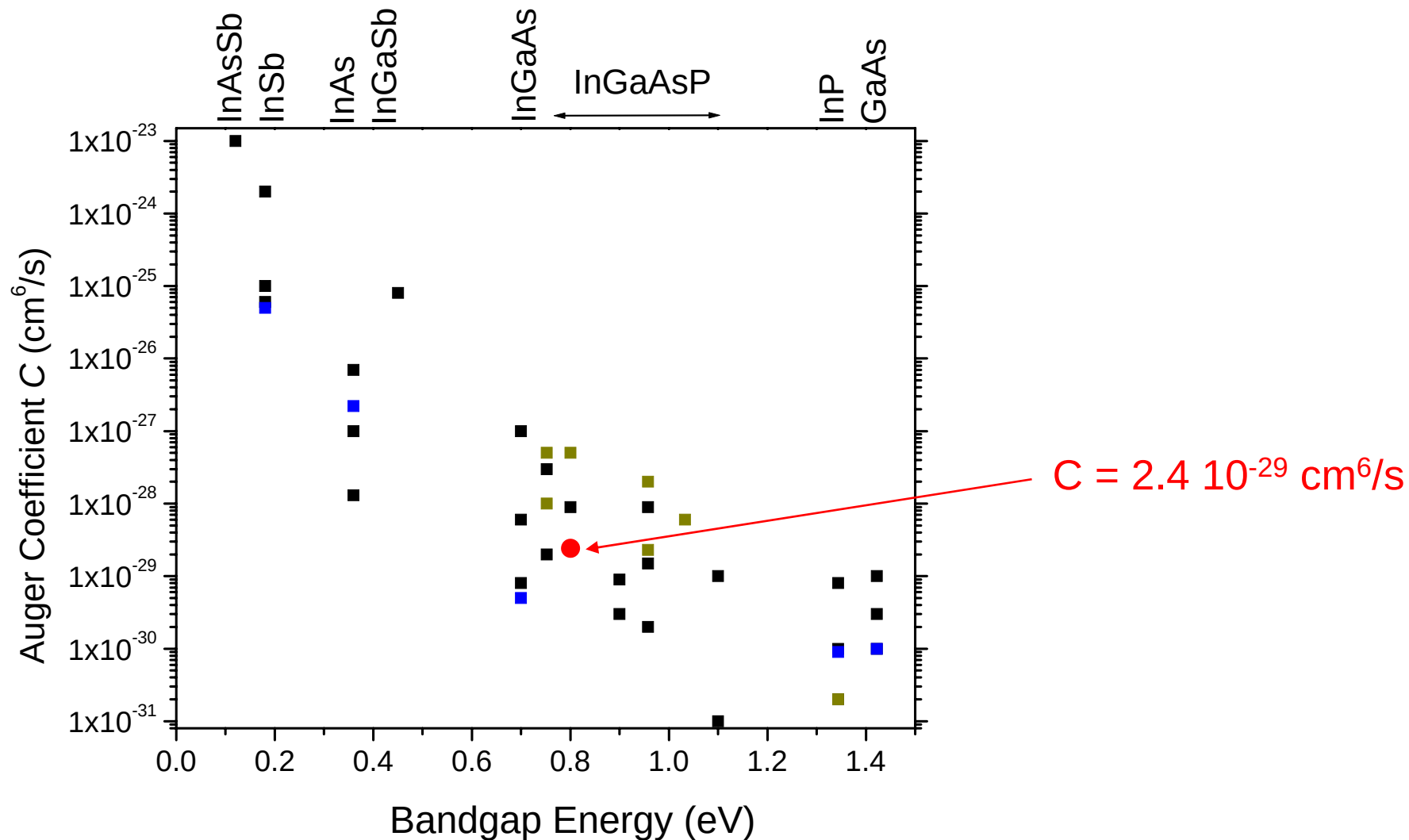
defect recombination lifetime $\tau_{\text{SRH}} = 20 \text{ ns}$

spontaneous recombination coeff. $B = 0.8 \cdot 10^{-10} \text{ cm}^3/\text{s}$

fit parameter:

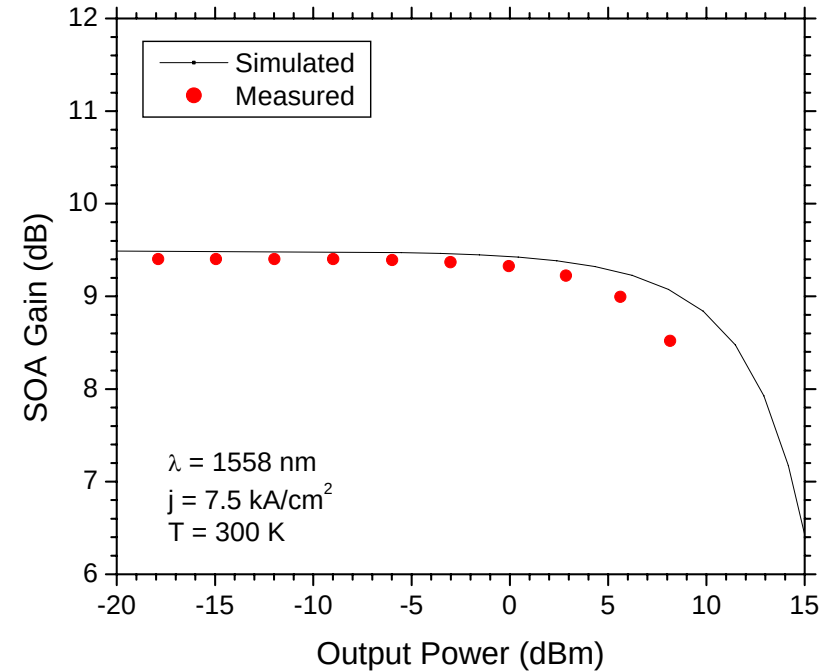
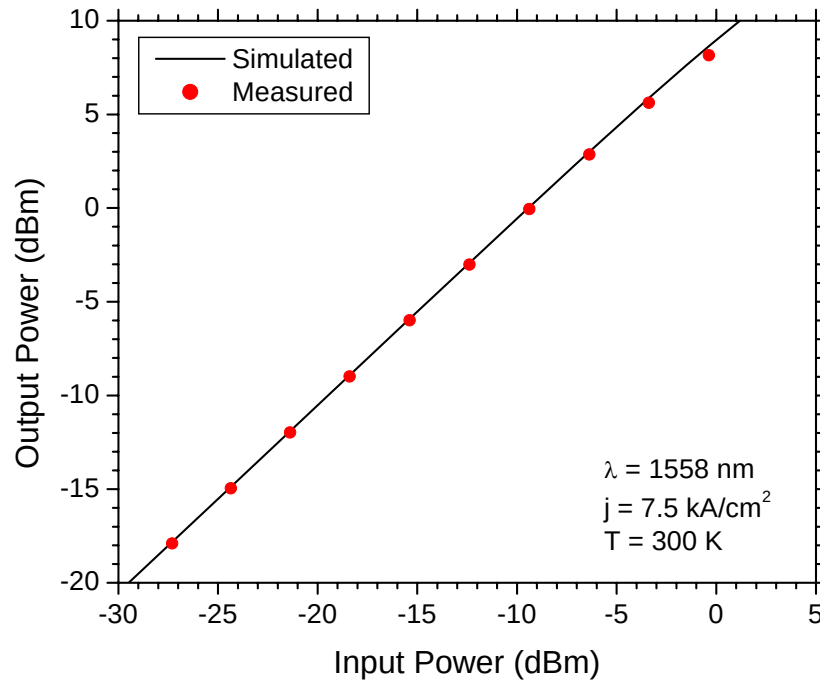
Auger coefficient $C = 2.4 \cdot 10^{-29} \text{ cm}^6/\text{s}$

Auger Coefficient



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Saturation

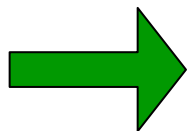
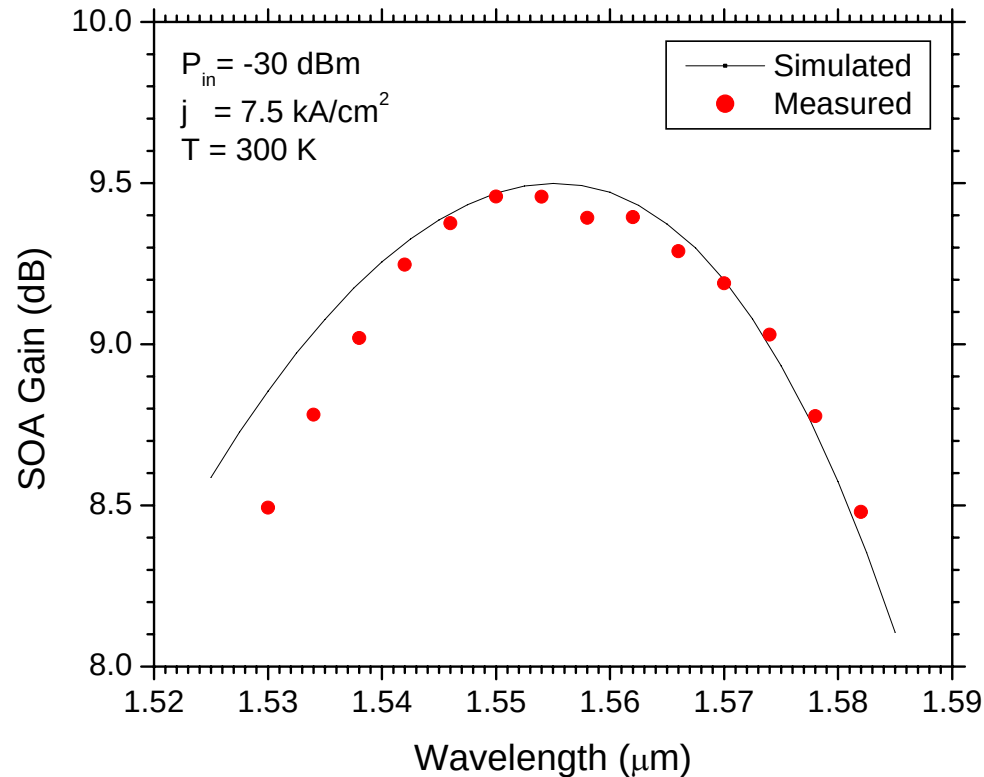


experimental saturation power somewhat lower

possible reasons:

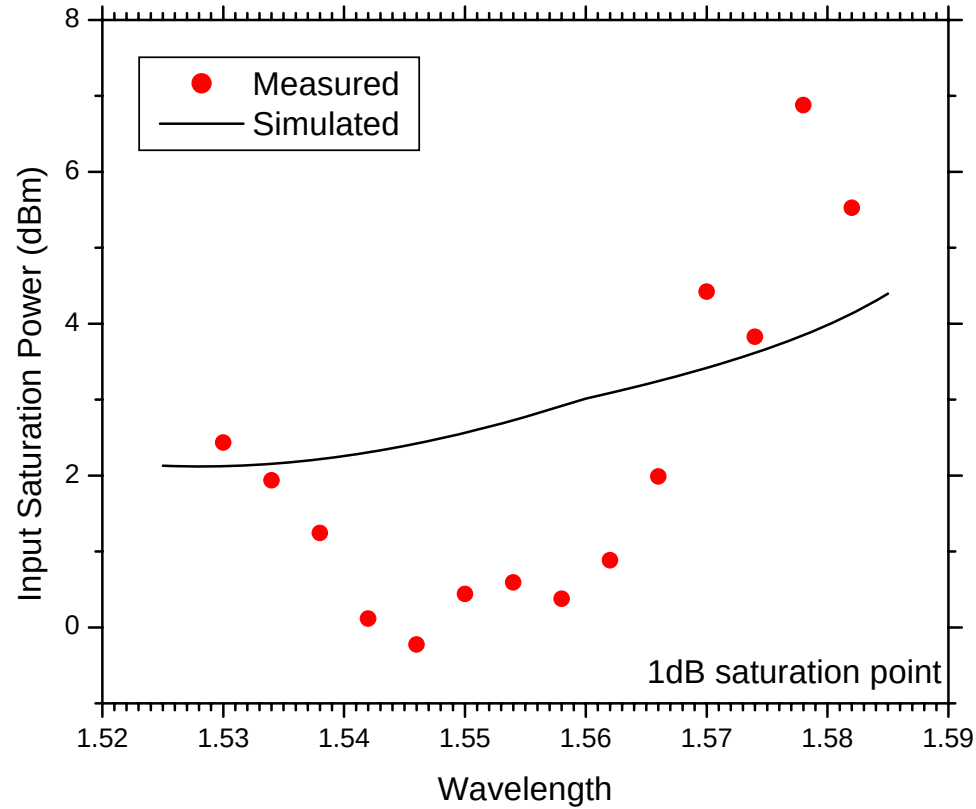
- real QW gain somewhat higher than in many-body theory
- Auger coefficient depends on carrier density

Unsaturated Gain Spectrum



- many-body gain spectrum close to reality
- quantum well recombination dominates performance
- carrier transport & distribution effects are less important

Saturation Power Spectrum



- spectral deviation at low carrier densities
- saturation spectrum fit gives deviations for unsaturated gain (higher density)

- inclusion of many-body theory in rate equation model
- good fit with unsaturated gain measurements across wide wavelength spectrum
- deviations from reality: $g(N)$ and/or $C(N)$

Layer Structure

	Thickness (nm)	Doping ($1/\text{cm}^3$)	Mobility (n/p) (cm^2/Vs)
<i>p</i> -InGaAs contact	100	3×10^{19}	100/20
<i>p</i> -InP cladding	1600	1×10^{18}	2200/70
<i>p</i> -InP cladding	200	3×10^{17}	2800/100
<i>i</i> -InP doping setback	50	—	4300/160
<i>i</i> -In _{0.735} Ga _{0.265} As _{0.513} P _{0.487} barrier (7)	8	—	4300/160
<i>i</i> -In _{0.735} Ga _{0.265} As _{0.845} P _{0.155} well (7)	6.5	—	4300/160
<i>i</i> -In _{0.735} Ga _{0.265} As _{0.513} P _{0.487} barrier	8	—	4300/160
<i>i</i> -InP etch stop	10	—	4300/160
<i>n</i> -In _{0.612} Ga _{0.338} As _{0.728} P _{0.272} waveguide	350	1×10^{17}	3300/130
<i>n</i> -InP cladding	1400	1×10^{18}	2200/70
<i>n</i> -InGaAs contact	100	1×10^{18}	2200/70
<i>i</i> -InP buffer	1000	—	4300/160