OPTOELECTRONIC WORKSHOPS

XXVII

SEMICONDUCTOR LASERS AND THEIR APPLICATIONS

December 17, 1990

sponsored jointly by

ARO-URI Center for Opto-Electronic Systems Research
The Institute of Optics, University of Rochester
**REPORT DOCUMENTATION PAGE**

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<tr>
<td>Govind Agrawal and C. Ward Trussell</td>
<td>The Institute of Optics University of Rochester Rochester, NY 14627</td>
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<td>Optoelectronic workshop; semiconductor; lasers</td>
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OPTOELECTRONIC WORKSHOPS

XXVII

SEMICONDUCTOR LASERS AND THEIR APPLICATIONS

December 17, 1990

sponsored jointly by

ARO-URI Center for Opto-Electronic Systems Research
The Institute of Optics, University of Rochester
OPTOELECTRONIC WORKSHOP
ON
SEMICONDUCTOR LASERS AND THEIR APPLICATIONS

Organizer: ARO-URI - University of Rochester
and CECOM Center for Night Vision and Electro-Optics

1. INTRODUCTION
2. SUMMARY -- INCLUDING FOLLOW-UP
3. VIEWGRAPH PRESENTATIONS

CECOM Center for Night Vision and Electro-Optics
Organizer -- C. Ward Trussell

ARO-URI Center for Opto-Electronic Systems Research
Organizer -- Govind Agrawal

Welcome and Overview
C. Ward Trussell, CCNVEO

Dynamics of Semiconductor Lasers and Amplifiers
Govind Agrawal, ARO-URI

Laser Diode Array Research at Night Vision Lab
David Caffey, CCNVEO

MBE Growth for Visible and Near-Infrared Lasers
Gary Wicks, ARO-URI

Intensity-Phase Coupling in Semiconductor Lasers
Thomas Brown, ARO-URI

High-Power Laser Diode Array Measurements
Vernon King, CCNVEO

Intensity and Phase Noise in Semiconductor Lasers
George Gray, ARO-URI

Diode-Pumped Solid-State Laser Amplifiers
Richard Utano, CCNVEO

Quantum-Well Dynamics
Mark Biermann, ARO-URI

4. LIST OF ATTENDEES
1. INTRODUCTION

This workshop on "Semiconductor Lasers and Their Applications" represents the twenty-seventh of a series of intensive academic / government interactions in the field of advanced electro-optics, as part of the Army sponsored University Research Initiative. By documenting the associated technology status and dialogue it is hoped that this baseline will serve all interested parties towards providing a solution to high priority Army requirements. Responsible for program and program execution are Dr. Nicholas George, University of Rochester (ARO-URI), and Dr. Rudolf Buser, CCNVEO.
2. SUMMARY AND FOLLOW-UP

The workshop on "Semiconductor Lasers and Their Applications" was organized jointly by Prof. Govind Agrawal of the University of Rochester and Dr. C. Ward Trussell of CECOM Center for Night Vision and Electro-Optics. It was held on December 17, 1990 at Fort Belvoir and was attended by 20 people, including 9 from the University of Rochester. The agenda consisted of 9 technical presentations of about 20-25 minutes with about 10 minutes devoted to scientific discussions at the end of each presentation. A final 30-minute session was devoted to a general discussion aimed at finding areas of potential collaborations.

Dr. C. Ward Trussell opened the workshop with an overview of the laser-diode programs at the CCNVEO. The talk was particularly useful to the scientists from the University of Rochester as it gave a clear indication of the objectives and the thrust behind the laser-diode research at CCNVEO.

The presentation by Prof. Govind Agrawal focused on the dynamic performance of semiconductor lasers. He presented the details of a model based on the generalized rate equations. The model takes into account both interband and intraband gain saturation and is particularly suited for a fundamental understanding of the limitations on the output power under current modulation. Dr. Trussell indicated that the model can be useful for the 1.5 μm laser program at CCNVEO.

The research on laser-diode arrays at CCNVEO was summarized by Mr. David Caffey. He indicated the program goals and discussed the current status. Basic steps behind the fabrication of laser diode arrays were presented in a clear way. He also mentioned the research on external-cavity lasers as it can be used to combine the output of multiple diodes coherently with a narrow spectrum.

Prof. Gary Wicks reviewed the status of the growth of III-V materials and devices by using the molecular-beam epitaxy (MBE) machine at the University of Rochester. The CCNVEO group was particularly interested if we were able to grow InGaAsP material in the wavelength range 1.5-1.6 μm. There is a possibility of future collaboration in this field.

The next talk by Prof. T. G. Brown discussed the intensity-phase coupling in semiconductor lasers. Such a coupling is governed by the linewidth enhancement factor. The emphasis of the presentation was to study how the linewidth enhancement factor may depend on the device structure and geometry, particularly in the case of distributed feedback lasers.

Mr. Vernon King presented the measurement techniques and the data used to quantify the material and device characteristics of laser diode arrays. The light-current curves, the near and far fields, and the optical spectrum were among the many measurements made to characterize such arrays.
The noise characteristics of semiconductor lasers were discussed by Dr. George Gray of the Institute of Optics. He mentioned how spontaneous emission leads to intensity and phase fluctuations in semiconductor lasers. The issues discussed were the relative intensity noise, mode-partition noise, frequency noise, and the laser linewidth. The laser linewidth was found to be considerably enhanced by the presence of a weak side mode due to cross-saturation effects.

Mr. Richard Utano of CCNVEO discussed how diode pumping can be used to produce high-efficiency Q-switched lasers and amplifiers. He presented the data on several diode-pumped Nd-ion lasers with different host materials. The role of fluorescence lifetime on the storage efficiency was considered and issues related to its optimization were discussed.

The final presentation of the workshop by Mr. Mark Biermann of the Institute of Optics focused on the quantum-well devices. In particular, he discussed how the subband structure is affected when two narrow quantum wells are brought closer. He has developed a sophisticated computer model to analyze the electrical and optical properties of coupled quantum-well devices.

After the formal presentations a concluding session followed in which all participants discussed various aspects of semiconductor lasers and their use for pumping solid-state lasers. The purpose of this technical discussion was to identify the follow-up items. Three possible areas were identified.

The material research related to the growth of InGaAsP material in the wavelength region 1.5-1.6 μm is of considerable interest to CCNVEO because of its applications in laser radars and range finders. Prof. Gary Wicks of the University of Rochester and Dr. Dave Caffey of CCNVEO will follow-up on this topic. The numerical modeling capability of Prof. Agrawal’s group is of interest to CCNVEO for the purpose of exploring the power limitation on 1.5-μm InGaAsP lasers imposed by interband and intraband gain saturation. Prof. Agrawal of the University of Rochester and Dr. Trussell of CCNVEO intend to follow-up on this topic. There is some interest in the work on semiconductor-laser noise since it may relate to the coherent laser radar. Further technical discussions will continue to explore this topic.

The workshop ended at about 3:30 pm and was followed by a tour of various laboratories in the Lasers and Photonics Division.
LASER DIODE PROGRAMS
OVERVIEW

Dr. C. Ward Trussell
Directed Energy Team
Laser Division

U. S. Army CECOM
Center for Night Vision & Electro-Optics
DIRECTED ENERGY TEAM
MAJOR PROJECTS

- LASER MATERIALS RESEARCH
- LASER DIODE ARRAYS
- DIODE PUMPED SOLID STATE LASERS
- FREQUENCY CONVERSION
- EYESAFE LASERS
LASER DIODE ARRAY PRODUCIBILITY PROGRAM

• JOINT ARMY, NAVY, AIR FORCE PROGRAM

• FUNDED BY BALANCED TECHNOLOGY INITIATIVE

• OBJECTIVE IS LOW COST, HIGH PERFORMANCE LASER ARRAYS FOR PUMPING SOLID STATE LASERS

• PRIMARY THRUST-STACKED ARRAYS-PHASE I
  1. Spectra Diode Laboratories
  2. McDonnell Douglas
  3. Advanced Optoelectronics

• SECONDARY THRUSTS - (SERVICE FUNDED)-PHASE I
  1. 2-D MONOLITHIC ARRAYS - TRW
  2. MBE GROWTH - NESI

• PHASE II - AWARDED AUGUST 1990 - SDL & AO
# LASER DIODE ARRAY PRODUCIBILITY
## PHASE I RESULTS

<table>
<thead>
<tr>
<th>COMPANY</th>
<th>EFFICIENCY *</th>
<th>DELIVERIES</th>
<th>HIGHLIGHTS</th>
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<tbody>
<tr>
<td>Spectra</td>
<td>32% to 40%</td>
<td>2 20-bar</td>
<td>High Duty Factor, Low Cost Package</td>
</tr>
<tr>
<td>Diode Lab</td>
<td>36% Ave</td>
<td>8 10-bar</td>
<td>High Yield</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5 5-bar</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>8.7 KWatt total</td>
<td></td>
</tr>
<tr>
<td>McDonnell Douglas</td>
<td>34% to 47%</td>
<td>7 25-bar</td>
<td>High Efficiency</td>
</tr>
<tr>
<td></td>
<td>42% Ave</td>
<td>7 4-bar</td>
<td>High Uniformity</td>
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<tr>
<td></td>
<td></td>
<td>10 KWatt total</td>
<td>Low Cost Package</td>
</tr>
<tr>
<td>Advanced Optoelect.</td>
<td>16% to 38%</td>
<td>1 20-bar</td>
<td>Great Progress in Phase I</td>
</tr>
<tr>
<td></td>
<td>27% Ave</td>
<td>20 4-bar</td>
<td>High Vol. Potential</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5 KWatt total</td>
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*Arrays tested by CNVEO*
LDA PRODUCIBILITY
PHASE II PROGRAM

- FABRICATE 150 BARS - 807 nm - SDL, AO
- FABRICATE 150 BARS - 785 nm - SDL, AO
- DESIGN PACKAGE FOR 785 nm ROD PUMP - SDL, AO
- ADVANCED ARRAY ANALYSIS FOR 20% DUTY - SDL, AO
- FABRICATE ARRAY TO VALIDATE DESIGN
- BACK COOLED CW ARRAY ANALYSIS - SDL
- FABRICATE ARRAY TO VALIDATE DESIGN
- IMPROVE YIELD, PERFORMANCE, THROUGHPUT - SDL
- OPTION FOR 1000 EACH 785 nm BARS - SDL
# Laser Diode Arrays for Solid State Laser Pumping

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>Material</th>
<th>SS Laser</th>
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<tr>
<td>785 nm.</td>
<td>GaAlAs QW</td>
<td>Tm:YAG</td>
</tr>
<tr>
<td>795 nm.</td>
<td>GaAlAs QW</td>
<td>Nd:YLF</td>
</tr>
<tr>
<td>808 nm.</td>
<td>GaAlAs QW</td>
<td>Nd:YAG/Glass</td>
</tr>
<tr>
<td>970 nm.</td>
<td>GaInAs SL QW</td>
<td>Er:Glass/YAG</td>
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Figure 1. GRIN-SCH diode epitaxial structure (not to scale). The actual indium concentration in the quantum well is estimated to be 22%.
EFFICIENCY OF END/DIODE PUMPED ER LASER

900327, 97.9\%R, 50cm/\text{mJ}, Energy

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<th>REFLECTIVITY OF OUTPUT COUPLER (%R)</th>
<th>99.4</th>
<th>97.9</th>
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<tr>
<td>ENERGY EFFICIENCY</td>
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<tr>
<td>DIFFERENTIAL (SLOPE) EFFICIENCY (%)</td>
<td>2.6</td>
<td>7.1</td>
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<tr>
<td>THRESHOLD (mJ @ 982nm)</td>
<td>0.88</td>
<td>0.90</td>
</tr>
<tr>
<td>PEAK POWER EFFICIENCY</td>
<td></td>
<td></td>
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<tr>
<td>DIFFERENTIAL (SLOPE) EFFICIENCY (%)</td>
<td>2.7</td>
<td>7.7</td>
</tr>
<tr>
<td>THRESHOLD (mW @ 982nm)</td>
<td>69</td>
<td>75</td>
</tr>
<tr>
<td>Er\textsuperscript{3+} \textsuperscript{4}_\textsubscript{11/2} FLUORESCENCE</td>
<td>7.58ms</td>
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Dynamics of Semiconductor Lasers and Amplifiers

Govind P. Agrawal
The Institute of Optics
University of Rochester

- Introduction
- Semiconductor Laser Dynamics
- Nonlinear Gain
- Modified Rate Equations
- Modulation and Noise Characteristics
- Semiconductor Optical Amplifiers
- Concluding Remarks
INTRODUCTION

- Electrical pumping through p-n junction
- Population inversion through high carrier density in the active region ($\sim 10^{18} \text{ cm}^{-3}$)
- Spontaneous and stimulated emission through electron-hole recombination
- Clamping of carrier density above laser threshold (interband gain saturation)
- Optical field can modify carrier distribution within the band at high intensities
- Intraband gain saturation affects laser dynamics
SEMICONDUCTOR LASER DYNAMICS

- **Carrier lifetime** $\tau_c \sim 1-3$ ns
  - radiative recombination (electron-hole recombination)
  - nonradiative recombination (impurities, Auger effects)
- **Photon lifetime** $\tau_p \sim 1-2$ ps
  - Small cavity length ($L = 0.2-0.3$ mm)
  - High loss (facet reflectivity $R \sim 30\%$)
- **Polarization relaxation time** $\tau_{\text{m}} \sim 0.1$ ps
  - Intraband carrier scattering
- **Rate-equation approximation**

  \[
  \frac{dP}{dt} = \left( G - \frac{1}{\tau_p} \right) P + R_{\text{np}}
  \]

  \[
  \frac{dN}{dt} = \frac{I}{q} - \frac{N}{\tau_c} - GP
  \]

  with \( G(N) = G_N (N-N_0) \)
AMPLITUDE-PHASE COUPLING

- A change in electron population $N$ changes not only the gain but also the refractive index.
- Changes in the amplitude of the optical field produce simultaneous changes in the phase (via $S_N$).
- Rate equation for the optical phase

$$\frac{d\phi}{dt} = \Delta \omega(t) = \frac{1}{2} \chi_0 \left( G - \frac{1}{2} \right)$$

Where

$$\chi_0 = \frac{\partial \chi_r / \partial N}{\partial \chi_i / \partial N} \quad (\chi = \chi_r + i \chi_i)$$

- Consequences of amplitude-phase coupling
  - frequency chirp under modulation
  - broadening of the laser linewidth

$\chi_0$ - linewidth enhancement factor
Semiconductor-Laser Rate Equations

\[
\frac{dP}{dt} = \left( G - \frac{1}{\tau_p} \right) P + R_{sp}
\]

\[
\frac{dN}{dt} = \frac{I}{q} - \frac{N}{\tau_c} - GP
\]

\[
\frac{d\phi}{dt} = \frac{1}{2} \alpha_0 \left( G - \frac{1}{\tau_p} \right)
\]

where \( G = G_N (N - N_0) \).

- How good are the rate equations?

\[
I(t) = I_b + I_m f(t)
\]

\( I_b \) — Bias current

\( I_m \) — Modulation current

\( f(t) \) — Current pulse shape

Super-Gaussian pulse shape

\[
f(t) = \exp \left[ - \left( \frac{2t}{T_b} \right)^{T_b/T_r} \right]
\]

\( T_b = \frac{1}{b} \) — Pulse duration

\( T_r \) — Rise or fall time (\( T_b/5 \))
**LARGE-SIGNAL MODULATION**

- Multiple optical pulses due to relaxation oscillations
- The predicted behavior is far from the experiments
**NONLINEAR GAIN**

- Intensity-dependent gain
  \[ G = G_N (N - N_o) (1 - \varepsilon_{NL} P) \]

- For InGaAsP lasers
  \[ \varepsilon_{NL} \approx 0.01 \text{ mW}^{-1} \]
  (1% gain reduction at 1 mW output power)

- Laser dynamics affected significantly

- Relaxation oscillations heavily damped
  Small-signal analysis:
  \[ \Gamma' = \frac{\Gamma_{sp}}{P} + \varepsilon_{NL} P \frac{1}{\tau_P} \]

- For \( \tau_P \approx 1 \text{ ps} \), \( \varepsilon_{NL} P \approx 0.01 \),
  damping time \( \Gamma'^{-1} \approx 100 \text{ ps} \)

- \( \Gamma'^{-1} \approx 1-3 \text{ ns} \) without the nonlinear gain
Effect of Nonlinear Gain

\[ \epsilon_{NL} = 0.01 \text{ mW}^{-1} \]

\[ I_p = I_{th} \]

\[ I_m = 3 I_{th} \]

- Optical pulse shape in agreement with experiments
- Nonlinear gain must be included in the rate equations
NONLINEAR GAIN AT HIGH POWERS

- Phenomenological model

\[ G = G_N (N - N_0) \left(1 - \epsilon_{NLP}\right) \]

Valid only at low powers (\( \epsilon_{NLP} << 1 \))

- What is the functional form of the nonlinear gain?

- Two-level atom analogy

\[ G(N, P) = \frac{G_N (N - N_0)}{1 + P/P_0} \]

- Validity for semiconductor lasers questionable!

- What is the physical origin of nonlinear gain?

  - Gain saturation due to electron-hole recombination
    is already included in the rate equations

- **Answer:** Intraband gain saturation
**GAIN SATURATION**

- Two distinct saturation processes
  - Stimulated emission changes the electron and hole populations as a result of electron-hole recombination. The gain saturation is due to interband processes. The rate equation

\[
\frac{dN}{dt} = \frac{I}{q} - \frac{N}{\tau_e} - GP
\]

includes interband gain saturation (the last term).

- The optical field can change the distribution of electrons within the conduction band. Intraband relaxation processes try to restore the equilibrium distribution at a time scale \(\tau_{in} \sim 0.1\) ps.

- At high intensities \(\Omega \tau_{in} \sim 1\), the gain is reduced since electron distribution is modified significantly. This is **intraband gain saturation**. It is not included in the rate equations.
GAIN and INDEX NONLINEARITIES

\[ \chi_{NL} = 2\eta \left( \Delta \eta_{NL} - i \frac{g_{NL}}{2k_{0}} \right) \]

\[ \Delta \eta_{NL} = \frac{\beta g_{L}}{2k_{0}} \frac{I}{1 + \sqrt{1 + I}} \]

\[ g_{NL} = -\frac{g_{L} I}{\sqrt{1 + I} (1 + \sqrt{1 + I})} \]

Total Gain

\[ g = g_{L} + g_{NL} = \frac{g_{L}}{\sqrt{1 + I}} \]

- Modification in the rate equations:

\[ G = \Gamma V g = \frac{G_{0} (N - N_{0})}{\sqrt{1 + P/P_{s}}} \]

Saturation photon number

\[ P_{s} = \frac{\epsilon_{0} n n_{g} V}{\hbar \omega_{0} \Gamma} I_{s} \]

- Include \( \Delta \eta_{NL} \) in the phase equation
**MODIFIED RATE EQUATIONS**

\[
\frac{dP}{dt} = \left( \frac{G_N(N-N_0)}{\sqrt{1+P/P_o}} - \frac{1}{\tau_p} \right) P + R_{in}
\]

\[
\frac{dN}{dt} = \frac{I}{q} - \frac{N}{\tau_c} - \frac{G_N(N-N_0)P}{\sqrt{1+P/P_o}}
\]

\[
\frac{d\phi}{dt} = \frac{\alpha}{2} \left( G_N(N-N_0) - \frac{1}{\tau_p} \right) - \frac{\beta}{2} \frac{G_N(N-N_0)P/P_o}{1 + \sqrt{1+P/P_o}}
\]

- **Small-signal modulation**
  - relaxation oscillations
  - 3-dB modulation bandwidth

- **Large-signal modulation**
  - pulse shape, rise and fall times
  - frequency chirp, gain switching

- **Noise characteristics**
  - Laser linewidth
  - Relative intensity noise
RELAXATION OSCILLATIONS

- Linear stability analysis of the modified rate equations
- Oscillatory approach to the steady state

- Power dependence of the relaxation-oscillation frequency

(a) \[ G(N, P) = \frac{G_N(N-N_0)}{\sqrt{1 + P/P_d}} \]

(b) \[ G(N, P) = \frac{G_N(N-N_0)}{(1 + P/P_d)} \]
DAMPING RATE OF RELAXATION OSCILLATIONS

\[ \Gamma'_R \approx \frac{1}{4 \tau_p} \frac{P/P_s}{(1 + P/P_s)^{3/2}} \]

\begin{align*}
(a) \quad G(N, P) &= \frac{G_N(N - N_s)}{\sqrt{1 + P/P_s}} \\
(b) \quad G(N, P) &= \frac{G_N(N - N_s)}{1 + P/P_s}
\end{align*}

\[ \Gamma'_{\max} \approx \frac{1}{10 \tau_p} \quad (\tau_p \sim 1 - 2 \beta \varepsilon) \]
SMALL-SIGNAL MODULATION

- Solve the modified rate equations with
  \[ I(t) = I_b + I_m \exp(i\omega_m t), \quad I_m \ll I_b - I_b \]

- Modulation Response
  \[ S_P(W_m) = \frac{G_N P (\Gamma_m/g_0) (1 + P/R_0)^{-1/2}}{(\Omega_R - i\Gamma_R + W_m) (\Omega_R + i\Gamma_R - W_m)} \]

- 3-dB modulation bandwidth \( f_{3dB} \)
  \[ \frac{S_P(f_{3dB})}{S_P(0)} = \frac{1}{2} \]
  \[ f_{3dB} = \frac{1}{2\pi} \left\{ \Omega_R^2 - \Gamma_R + 2 \left[ \Omega_R^2 (\Omega_R^2 + \Gamma_R^2) + \Gamma_R^2 \right]^{1/2} \right\}^{1/2} \]

- In the absence of intraband gain saturation
  \[ f_{3dB} \propto \sqrt{P} \]

- In the presence of intraband gain saturation \( f_{3dB} \) saturates
  \[ f_{3dB}^{max} = \frac{1}{2\pi} \left( \frac{3}{2} \frac{G_N P_S}{\tau_p} \right)^{1/2} \]
  \[ f_{3dB}^{max} = \left[ \frac{3e \eta \eta_g \hbar^2 v G_N}{8\pi^2 \hbar \omega_m} \right]^{1/2} \]
MODULATION BANDWIDTH

- $f_{3dB}$ depends on the bias power and other device parameters

\[ G_N P_s = 5 \times 10^{10} \text{s}^{-1} \]

\[ \frac{G_N P_s}{P_s} = 2 \times 10^{10} \text{s}^{-1} \]

\[ \frac{G_N P_s}{P_s} = 1 \times 10^{10} \text{s}^{-1} \]

\[ \frac{G_N P_s}{P_s} = 5 \times 10^9 \text{s}^{-1} \]

- $\tau_p = 1 \text{ps}$

\[ f_{3dB}^{\text{max}} \sim 20 - 40 \text{ GHz} \text{ for InGaAsP lasers} \]

- Can be enhanced for quantum-well lasers ($G_N$ larger)
- Direct current modulation ($I_b = I_{th}$)

$$I(t) = I_b + I_m f(t)$$

- Rise and fall times increase when $P_{out} \sim P_{sout}$
- Intersymbol interference in communication systems
**LASER LINEWIDTH**

- Add Langevin noise sources to the modified rate equations.
- Solve the stochastic rate equations by linearizing them around the steady-state average values.
- Calculate the spectrum by taking the Fourier transform of the autocorrelation function.
- Lorentzian spectrum with FWHM

\[
\Delta \nu = \frac{R_{sp}}{4\pi P} (1 + \alpha_{eff}^2)
\]

\[
\alpha_{eff} = \alpha_0 \sqrt{1+I} + \beta \frac{I(1+I)}{(2+I)}
\]

where \( I = \frac{|E|^2}{I_s} = \frac{P}{P_s} \)

- In the absence of intraband gain saturation \( \alpha_{eff} = \alpha_0 \) and \( \Delta \nu \propto 1/P \).
- Linewidth saturates to a limiting value (~1-10 MHz) because of intraband gain saturation.
SPECTRAL LINEWIDTH

\[ \frac{\Delta V}{\Delta V_s} \]

\[ \frac{P}{P_s} \]

\[ \alpha_0 = 5 \]

\[ \beta = 1 \]

\[ 0 \]

\[ -1 \]


- Broadening of the linewidth can occur for lasers oscillating away from the gain peak because of index nonlinearities \((\beta \neq 0)\).
SEMICONDUCTOR LASER AMPLIFIERS

- Traveling-wave amplifier
  AR facet coatings (< 10^{-3} reflectivity)

- Rate equations must include
  spatial variation of the optical field

\[
\frac{\partial A}{\partial z} + \frac{i}{\gamma_g} \frac{\partial A}{\partial t} = \frac{1}{2} (1-i\alpha) g A - \frac{1}{2} \alpha_{int} A
\]

- Gain dispersion

\[
\tilde{g}(\omega) = g_p [1 - T_2^2 (\omega - \omega_0)^2]
\]
\[
g = g_p [1 + T_2^2 \frac{\partial^2}{\partial t^2}]
\]

- Peak gain

\[
g_p = \gamma a (N - N_0) / (1 + |A|^2 / P_s)^{1/2}
\]

\[
\frac{\partial N}{\partial t} = \frac{I}{qV} - \frac{N}{\tau_e} - \frac{g_p |A|^2}{\varepsilon_{sat}}
\]

interband saturation energy \( \varepsilon_{sat} = \hbar \omega_0 (\sigma / a) \)

- Gain dispersion leads to carrier-induced index dispersion

- Gain saturation leads to self-phase modulation
Carrier-Induced Group-Velocity Dispersion

\[ \frac{\partial A}{\partial z} + \frac{1}{v_g} \frac{\partial A}{\partial t} = \frac{1}{2} (1 - i \alpha) g_b (A + T_2 \frac{\partial^2 A}{\partial t^2}) \]

Define \( \tau = (t - z/v_g)/T_0 \)

\[ \frac{\partial A}{\partial z} - \frac{1}{2} (1 - i \alpha) g_b \left( \frac{T_2}{T_0} \right)^2 \frac{\partial^2 A}{\partial z^2} = \frac{1}{2} (1 - i \alpha) g_b \]

Dispersion length \( L_D = \frac{T_0^2}{\beta_2^\text{eff}} = \frac{T_0^2}{\alpha g_b T_2^2} \)

GVD parameter \( \beta_2^\text{eff} = \alpha g_b T_2^2 \)

- Pulse broadening and compression

\[ A(0, \tau) = A_0 \exp \left[ - (1 + i C) \frac{\tau^2}{2} \right] \]

\[ A(L, \tau) = \frac{A_0 \exp \left[ (1 - i \alpha) g_b L / 2 \right]}{(1 + \alpha)^{1/2}} \exp \left[ - \frac{1 + i C}{1 + i \alpha} \frac{\tau^2}{2} \right] \]

\[ \alpha = (\frac{T_2}{T_0})^2 g_b L (1 - i \alpha) (1 + i C) \]

- Pulse broadening for \( C > 0 \)
- Pulse compression for \( C < 0 \)
Broadening Factor for Chirped Gaussian Pulses

- Amplifier gain 30 dB

- Pulse compression possible for $C < 0$
- $C$ is negative for pulses emitted by semiconductor lasers
Carrier-Induced Nonlinearity

- Refractive index in semiconductor laser amplifiers depends on the injected carrier density.
- Gain saturation leads to intensity-dependent variations in the carrier density.
- Refractive index becomes intensity dependent as a result of gain saturation.
- Self-phase modulation due to carrier-induced nonlinearity.
- Amplified pulse develops a nearly linear frequency chirp.
- Chirped pulse can be compressed by passing through a dispersive-delay line.
- Significant chirp can occur for input pulse energies as small as 0.1 pJ.
SPM-INDUCED SPECTRAL DISTORTION

Gaussian input pulse: \( P_{in}(\tau) = P_0 \exp\left(-\frac{\tau^2}{\tau_0^2}\right) \)

- Spectral red shift and broadening
- Asymmetric multipeak structure
Concluding Remarks

- Rate equations can model the laser dynamics quite well.

- Intraband gain saturation must be considered for a realistic description of semiconductor lasers.

- Nonlinear gain limits the modulation bandwidth of semiconductor lasers in the neighborhood of 30 GHz.

- Carrier-induced dispersion is important for semiconductor optical amplifiers. It can lead to pulse compression under certain conditions.

- Spectrum of the amplified pulse is considerably modified by gain-induced self-phase modulation.
LASER DIODE ARRAY

Internal Program

David Caffey
Vernon King
Neal Bambha
Bill Lyndon, SAIC
PROGRAM GOALS

- Support BTI producibility program
- Develop low-cost, high performance arrays
- Support in-house research
- Improve performance of basic device
SOURCES OF WAFER MATERIAL

- University of New Mexico 785nm
- NIST 970nm
- Advanced Optoelectronics 808nm
- NESI 808nm
BASIC FABRICATION STEPS

1. Coat epi-side of wafer with SiO2
2. Pattern SiO2 using PR
3. Metallize epi-side
4. Thin wafer
5. Metallize n-side
6. Cleave wafer into bars
7. Coat cleaved facets
8. Bond bars to heatsinks
785 nm. LASER DIODE ARRAYS
STATUS

• Bar Bonder (SEC) set up and operating
• New fixtures developed for bar AR/HR coatings
• High Density bar process developed
• Indium coating improved using new vacuum system
• New 785 nm. wafers ordered from U. New Mexico
  2 - GRINSCH single quantum well
  2 - GRINSCH SQW narrow divergence
  1 - GainAlAs quantum well
Phase II SBR Goals

STARTED 05/89

- Re-growth process
- Post-growth processing
- Window liquid structures
- High power arrays

ORTEL, INC.
SUPPORT IN-HOUSE RESEARCH

- Provide pump arrays at 785, 808, 970nm for end-pumped and microchip lasers

- Provide specialized devices for external cavity operation
<table>
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<tr>
<th>WAVELENGTH</th>
<th>MATERIAL</th>
<th>SR LASER</th>
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<tr>
<td>785 nm.</td>
<td>GaAlAs QW</td>
<td>Tm: YAG</td>
</tr>
<tr>
<td>795 nm.</td>
<td>GaAlAs QW</td>
<td>Nd: YLF</td>
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<tr>
<td>808 nm.</td>
<td>GaAlAs QW</td>
<td>Nd: YAG/Glass</td>
</tr>
<tr>
<td>970 nm.</td>
<td>GaInAs SL QW</td>
<td>Er: Glass/YAG</td>
</tr>
</tbody>
</table>
External Cavity Laser Diode

- Spectral narrowing $\Delta v = \Delta v_0 \frac{1}{\sqrt{1+\text{feedback ratio}}}$
- Diffraction limited output
- Ability to combine multiple diodes coherently in one cavity
File Name: M204E3P.DTA
File Date: 03-Apr-90

Device Size: 1 junction(s)
Length: 630 µm
Active Width: 800 µm
Pulse Width: 200 µS
Rep. Rate: 50 Hz
Wavelength: 779 nm
Current Min.: 2 Amps
Power Max.: 4 Watts

Thresh. = 1.64 Amps
J(θh) = 325 A/cm²
Slope = 0.843 W/A
Slope/Jct = 0.843 W/A
Resistance = 0.1131 Ohms
Resist./Jct = 0.1131 Ohms
Diff. Q.E. = 52 %
V(e) = 1.672 Volts
Water Temp: 20 °C
Printed: 10/12/90
### File Name: N206K1P.DTA
File Date: 01-Mar-90
Device Size: 1 junction(s)
Length: 650 μm
Active Width: 100 μm
Pulse Width: 200 μS
Rep. Rate: 50 Hz
Wavelength: 785 nm
Current Min.: 0.3 Amps
Power Max.: 1 Watts

| Threshold | 0.249 Amps |
| Slope | 383 A/cm² |
| Slope/Jct | 1.052 W/A |
| Resistance | 0.3224 Ohms |
| Resist./Jct | 0.3224 Ohms |
| Diff. Q.E. | 66 % |
| V(c) | 1.663 Volts |
| Water Temp. | 23 °C |
| Printed: 10/11/90 |
IMPROVE PERFORMANCE OF BASIC DEVICE

- Device power is limited by COD to facets

APPROACH

- Use PL to characterize new facet coatings
- Work with NIST and UNM on advanced laser structures
Run 582 Structure
576

\[ h = 1 \times 10^{-3} \]
\[ P = 1 \times 10^{-6} \]

- 0.5 m Grass
- Buoy

\[ X_{A1} \]

1 2 3 4 5 6 7

1 782
2 783
3 783
4 782
5 781
6 782
7 781

\[ \bar{X}_{B1} = 782 \text{ nm} \]
1.5μm High Power InGaAs/InGaAsP MQW Lasers

- High Power - 55 mW CW Per Facet, Index-Guided Ridge Guide Structure
- >200 mW CW from Broad Stripe (30μm) Ridge Structure
- High External Diff. Quantum Eff. from Multiple Quantum Well (MQW) Structure
- 1.5μm Eyesafe Wavelength
- High Reliability InGaAsP Materials
III-V Materials and Devices

Gary W. Wicks

I. FACILITIES AT UR

• MOLECULAR BEAM EPITAXY (MBE)
  BEAMS AVAILABLE: III: Al, Ga, In
  V: As₄, P₂
  Dopants: Si, Be

  MATERIALS: GaAs/AlGaAs/GaInAs on GaAs
              GaInP/AlInP on GaAs
              (GaInAs/AlInAs on InP)
              (III-V’s on Si substrate)

• CHEMICALLY ASSISTED ION BEAM ETCHING
  Dry Etching of GaAs

• RAPID THERMAL ANNEALERS
  Annealing of GaAs and Si

• OPTICAL CHARACTERIZATION
  Raman Spectroscopy
  Photoluminescence
  Photoluminescence Excitation spectroscopy
  Waveguide endfiring

• DEVICE PROCESSING EQUIPMENT (D. HALL)
  Evaporators
  Photolithography
Ill-V Materials and Devices

Gary W. Wicks

II. RESEARCH AREAS

• **III-V MATERIALS STUDIES**
  – Vertical Superlattices/Quantum Wires
  – GaInP/AlInP on GaAs Substrates
  – (111) Quantum Wells

• **OPTO-ELECTRONIC EFFECTS AND DEVICES**
  – Quantum Well Lasers
    • visible (λ ≤ 660 nm) AlGaInP materials
    • IR (720 nm ≤ λ ≤ 1.1 μm) AlGaAs/GaInAs
    • dry etching of laser mirrors for integration
  – Optical Modulators
    • new electrooptic effects
      – enhanced e/o effects in {111} quantum wells
      – field induced ionization of excitons in QW's
      – coupled quantum wells
    • MQW modulators in mismatched materials
      – AlGaAs/GaAs on Si
      – AlGaAs/GaInAs on GaAs
Best Reported Quantum Well Laser Results

Threshold Current Density (A/cm²)

Wavelength (nm)

- CNRS—250μm
- Sharp—250μm
- CNRS—500μm
- Sharp—500μm
- U.Rochester—500μm
- Sharp [111]—490μm
Ill-V Compounds Lattice-matched to GaAs Substrates

Bandgap Energy (eV) vs. Aluminum Content, x

- Efficient
- Lasing

Indirect gap
Direct gap

Bandgap Wavelength (nm)

Random \((\text{Al}_{x}\text{Ga}_{1-x})_{0.51}\text{In}_{0.49}\text{P}\) (MBE)
Ordered \((\text{Al}_{x}\text{Ga}_{1-x})_{0.51}\text{In}_{0.49}\text{P}\) (MOCVD)
AlGaAs
Conventional Solid Phosphorous Source

Problems:
- Small phosphorous charge
- Shutter clogging
- Loss of phosphorous during machine bake-out
- Beam stability/low operating temperature

Solutions:
- Phosphine Gas Source
  ➤ Solves above problems, but is toxic and expensive
- Valved Cracker
  ➤ Solves above problems, and is safe and inexpensive

Valved Solid Phosphorous Source
Electroabsorption in GaAs quantum wells

![Graph showing absorption spectra at different voltages](image-url)
Enhanced Electrooptic Effects on Quantum Wells Grown on \{111\} Substrates

**Heavy hole effective mass:**

→ in plane of QW: $m^*_{hh}(001) > m^*_{hh}(111)$

→ \perp to plane of QW: $m^*_{hh}(111) > m^*_{hh}(001)$

**Results** — increased oscillator strength in QW’s on {111} surfaces.

→ lasers: higher gain, lower threshold, higher speed
→ modulators: higher electroabsorption and electrorefraction, higher speed

**Piezoelectric effects**
Vertical Superlattice: Diagrams in real and reciprocal space.

For a substrate misorientation of $\alpha = 2$ degrees, the average terrace width $d$ is 84 A.

(Appl. Phys. Lett. 50 (13), March 30, 1987 - Takashi Fukui)
Concept:
Circular Grating Surface Emitting (CGSE) Laser:
A Special Case of a Circular Surface Emitting (CSE) Laser

- Circular Beam
- Large Emission Aperture
  - Well-collimated Beam
  - High Power
- Utilizes Planar Waveguide Modes
  - Light Confinement
  - Current Confinement
- 2 - Dimensional Array
- Equal Phase-Locking in Both Dimensions
- General CSE (Including CGSE and Vertical Cavity SE)
- Unique to Circular Grating Surface Emitting Laser
Possible Implementations
of a Circular Grating Surface Emitting Laser:

A Circular Distributed Feedback (DFB) Laser

A Circular Distributed Bragg Reflector (DBR) Laser
INTENSITY - PHASE COUPLING

IN

SEMICONDUCTOR LASERS*

T. G. BROWN

* L. CLIPSSON, GRAD. STUDENT

* SUPPORTED IN PART BY THE NEW YORK STATE CENTER FOR ADVANCED OPTICAL TECHNOLOGY
WHY STUDY INTENSITY-PHASE COUPLING?

1. Excess line broadening

2. Modulation-induced frequency chirp.

3. Reflection-induced intensity noise and coherence collapse
Importance of Laser Line width

- Optical Communications

\[ E(t) \rightarrow \quad \text{Optical frequency/phase info. is lost!} \]

\[ i(t) \sim |E(t)|^2 \]

\[ \phi(t) = \text{Dynamic Phase Difference} \]

\( E_s(t) \rightarrow \quad \text{How do we detect phase?} \)

\[ i(t) \sim |E_s + E_{\text{REF}}|^2 \]

\[ = |E_s|^2 + |E_{\text{REF}}|^2 + 2|E_sE_{\text{REF}}| \cos \phi(t) \]

"Beat" Signal
DIGITAL PHASE MODULATION - PHASE SHIFT KEYING

For accurate phase detection, we need low phase noise - narrow linewidth.
Spontaneous Emission

The spontaneous emission event perturbs both the intensity and phase of the optical signal.

\[ \Delta V \propto \sigma^2 \]
Influence of Laser Structure on Linewidth

- Waveguide Geometry
- Gain Medium
- Resonator

Generalized Resonators (Waveguide)

Fabric-Pepeot (2 facets)

Distributed Reflectors (DFB & DBR)
Using Periodic Corrugation

Aperiodic Structures
WEAKLY APERIODIC (CURVED) STRUCTURES

THE \{OSCILLATION FREQUENCY\} IS DETERMINED BY THE ROUND TRIP PHASE SHIFT.

CAN THIS BE MADE INDEPENDENT OF REFRACTIVE INDEX?

CHANGES IN \{ Temp. Current Carrier Density \} \rightarrow \Delta n

LOOK AT PASSIVE RESONATORS FIRST

Figure of Merit \alpha = \frac{\text{Re}\{\Delta n\}}{\text{Im}\{\Delta n\}} \rightarrow \text{Determinant Gain}
FUNDAMENTAL LOOK AT INTENSITY-PHASE

COUPLING: FIGURES OF MERIT

\[ \alpha_m = \frac{\Delta n'}{\Delta n''} \rightarrow \text{DISPERITIVE} \]
\[ \Delta n'' \rightarrow \text{ABSORPTIVE} \]

KRAMERS - KRONIG RELATIONS:

IDEAL TRANSITION

SEMICONDUCTOR
\( \alpha_{\text{eff}} = 2 \cdot \frac{\text{d} \phi}{\text{d} (\text{dt})} \rightarrow \text{PHASE PERTURBATION} \)

\( \frac{\text{d} (\text{dt})}{\text{d} (\text{dt})} \rightarrow \text{INTENSITY PERTURBATION} \)

**FULL CAVITY PICTURE:**

\[ \frac{\partial^2 E}{\partial z^2} + \beta^2 E = -4\beta K \cos(2\beta_0 z) E \]

**COUPLING CONSTANT**

(DISTRIBUTED FEEDBACK)

**COMPLEX PROPAGATION CONSTANT**
Active region
Grating

(a)

Corrugated gain region

(b) a(x)
INDEX COUPLING vs GAIN COUPLING

\[
\text{Re}\{k\} \rightarrow \text{INDEX COUPLING}
\]

\[
\text{Im}\{k\} \rightarrow \text{GAIN COUPLING}
\]

IF \( \theta_k = 0, \pi \) THEN

\[ d_m = d_{\text{eff}} \]

INTENSITY PHASE COUPLING IS INDEPENDENT OF THE LONGITUDINAL STRUCTURE!!
Phase of $\kappa$ (radians)

$|\alpha_{\text{eff}}|$
Carrier Scattering Parameter $Q$

$$Q \sim -\frac{\Delta K}{\Delta g} \text{ due to } \Delta N$$

$$\Delta N \rightarrow \Delta g \rightarrow \Delta \text{Im}(k)$$

$$\Delta N \rightarrow \Delta \text{Re}(k)$$

If $Q = 0$ then

$$\alpha_{\text{eff}} = \alpha_{m}$$

In general, $-1 \leq Q \leq 1$

$Q = 0 \rightarrow \text{Corrugation separated from gain region}$

$Q = 1 \rightarrow$
Is it possible for \( Q \) to be negative?

Yes, if \( k \) decreases with an increase in film index.
GAIN-COUPLED LASER STRUCTURES

1. Edge Emitters

   ACTIVE REGION

   LUO et al., APL 56, 1620 (1990)

2. Vertical Cavity Surface Emitters

   MQW Structure

   Resonant Periodic Gain

   Bragg Reflectors
MATERIAL CHARACTERISTICS

Wafer Uniformity
Internal quantum efficiency
Differential gain
Loss coefficient (alpha)
Transparency current
Wavelength
Lifetime

DEVICE CHARACTERISTICS

Wavelength
Threshold current
Threshold current density
Slope efficiency
Differential quantum efficiency
Series Resistance
Characteristic voltage
Temperature coefficient \( T_0 \)
Catastrophic mirror damage
Regression Report:

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<td>Std Y Est Error</td>
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<td>R Squared [0..1]</td>
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UNM #222,100um Phased, P-Up, (1 Stripe)
Ref'd P6063B, 6LC, HR/AR
U of New Mexico & C2NVEO

File Name: N222B4P.DTA
Date: 01-Mar-90
Length 660 µm
Width 100 µm
Pulse Width 200 µS
Rep. Rate 50 Hz
Wavelength 962 nm
End Points 0.50-2.50 Amps

Thresh. = 0.121 Amps
J(th) = 183 A/cm²
Slope = 0.996 W/A
Diff. Q.E. = 77%
Resistance = 0.6161 Ohm's
V(c) = 1.639 Volts
Temp. = 21 °C
Length: 600 μm  
Width: 900 μm  
File: NOZ2001.PWR  
Thresh. = 1.467 Amps  
J(th) = 271 A/cm²  
Slope = 0.471 W/A  
Diff Q.E. = 30 %  
Pulse Width: 100 μS

Rep. Rate: 20 Hz  
Wavelength: 795 nm  
End Points: 2-4.5 Amps  
Date: 10/14/88
WAVELENGTH CHANGE WITH REP RATE
1100 to 1200 Watts Peak Out (LDA 170W)
MDESC #1-007  25-bar array
50 Amps
200 μS pulses

24°C  21.5°C  20.5°C

10 Hz

20 Hz

30 Hz

40 Hz

"Temp. profile path"
Intensity Noise and Phase Noise
in Semiconductor Lasers

George R. Gray
The Institute of Optics
University of Rochester

* Introduction

* Langevin Rate Equations

* Intensity Noise and Mode-Partition Noise

* Frequency Noise

* Optical Spectrum and Laser Linewidth

* Conclusions
Sources of Noise

Intrinsic Noise Sources

- Spontaneous emission
- Shot noise

Extrinsic Noise Sources

- Pump fluctuations
- Environmental fluctuations

- Extrinsic noise dominates in most lasers.
- Noise in semiconductor lasers dominated by spontaneous emission.
Two-Mode Theory

* Nearly-Single-Longitudinal Mode Lasers

* Two orthogonal polarizations

* Two stripes of a laser array

* Two competing directions in external cavity ring laser
Spontaneous Emission Noise

- Each spontaneously emitted photon perturbs the coherent field established by stimulated emission.
- Rate of spontaneous emission is relatively high \( \approx 10^{12} \text{ s}^{-1} \) in semiconductor lasers.
- Phasor diagram shows induced intensity and phase fluctuations.

- Intensity and phase change randomly because of the uncertainty in phase of spontaneously emitted light.
Langevin Rate Equations

\[ \frac{dP_i}{dt} = \left[ G_i - \frac{1}{\tau_p} \right] P_i + R_{sp} + F_i(t) \]

\[ \frac{d\Phi_i}{dt} = \frac{\alpha}{2} \left[ G_i - \frac{1}{\tau_p} \right] + F_\Phi(t) \]

\[ \frac{dN}{dt} = \frac{1}{q} \cdot \frac{N}{\tau_e} - \sum_i G_i P_i + F_n(t) \]

- Langevin Noise Sources

\[ <F_i(t)> = 0 \]

\[ <F_i(t)F_j(t')> = 2D_{ij}\delta(t-t') \]

- Nonlinear Gain in Single Mode Lasers

\[ G(N,P) = \frac{G_N(N-N_0)}{\sqrt{1 + P/P_s}} \]

- Nonlinear Gain for Two-Mode Laser

\[ G_i(N,P_j) = G_N(N-N_0) - \beta_i P_i - \theta_{ij} P_j \]
Relative-Intensity Noise

\[
RIN(\omega) = \int_{-\infty}^{+\infty} \exp(-i\omega t) \frac{\langle \delta P(t) \delta P(t+\tau) \rangle}{\langle P \rangle^2} \, d\tau
\]

- RIN peaks at the relaxation-oscillation frequency \( \Omega_r \).

\[
\Omega_r = \sqrt{\frac{G_{NP}}{\tau_p}}, \quad \Gamma_r = \frac{P}{4P_s\tau_p}
\]

- Nonlinear gain saturates the SNR to about 30dB
Mode-Partition Noise

- Intensity noise of the main mode is enhanced due to the presence of a relatively weak side mode.

- Mode-suppression ratio: $\text{MSR} = \frac{\text{Main-mode power}}{\text{Side-mode power}}$

- Large increase in low-frequency noise (30-40 dB)
Increase in Total RIN due to Nonlinear Gain

- Cross Saturation by a weak side mode can also enhance the total low frequency RIN.

- If MSR degrades with increasing power, total SNR can actually worsen at high powers.
Phase Noise

- Frequency fluctuations: \( \delta f = \frac{1}{2\pi} \frac{d\phi}{dt} \)
- Frequency-noise spectrum (FNS)

\[
S_f(\omega) = \int_{-\infty}^{+\infty} \langle \delta f(t) \delta f(t+\tau) \rangle \exp(-i\omega \tau) \, d\tau
\]
Optical Spectrum

\[ S_E(\omega) = \int_{-\infty}^{+\infty} \langle \delta E(t) \delta E^*(t+\tau) \rangle \exp(-i\omega \tau) \, d\tau \]

- Relaxation oscillations appear as satellite peaks in the optical spectrum.

- Asymmetry in the side bands is related to amplitude-phase coupling (\( \alpha \)).

- Amplitude of side bands is \( \approx 1\% \) of main peak.
Laser lineshape at different powers

![Graph showing laser lineshape at different powers](image)
Laser Linewidth

- Single-mode lasers:

\[ \Delta v = \frac{R_{sp}(1+\alpha^2)}{4\pi P} \]

- In practice, \( \Delta v \) saturates at about 10 MHz (and often rebroadens) at power levels of 10-20 mW.

- Possible mechanisms: current fluctuations, 1/f noise, spatial hole-burning, intraband gain saturation, side-mode cross saturation
Side-Mode Cross Saturation

\[ G_i(N,P_j) = G_N(N-N_0) - \beta_iP_i - \theta_{ij}P_j \]

- Theory shows maximum rebroadening at particular side-mode power. For high power lasers, even a good MSR can allow for substantial side mode power.

\[ S = \sqrt{\frac{R_{sp}}{2(\theta-\beta)}} \]
Conclusions

- Noise in semiconductor lasers dominated by spontaneous emission
- Both laser intensity noise and phase noise can be strongly affected by side modes.
- Mode-partition noise can increase the main-mode RIN; Cross saturation can enhance the total RIN.
- Side-mode cross saturation can also lead to saturation and rebroadening of the laser linewidth.

Acknowledgements: Govind Agrawal
URI-ARO WORKSHOP

SEMICONDUCTOR LASERS FOR COMMUNICATIONS

AND DIODE PUMPING

17 DECEMBER 1990
MOTIVATION

HIGH EFFICIENCY, HIGH ENERGY
Q-SWITCHED LASERS

ARRAY PROPERTIES

- HIGH PEAK POWER
- NARROW BANDWIDTH
- HIGH EFFICIENCY

MATERIAL PROPERTIES

- LONG FLUORESCENT LIFETIME
- STORAGE EFFICIENCY
- INTERMEDIATE TO HIGH GAIN
- EXTRACTION EFFICIENCY
- LARGE BOULES
- HIGH DAMAGE THRESHOLD
## COMPARISON OF Nd LASER MATERIALS

<table>
<thead>
<tr>
<th>KEY FEATURES</th>
<th>YAG</th>
<th>YLF</th>
<th>G(S)GG</th>
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<td>SIZES (CM DIAMETERS)</td>
<td>1.0</td>
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<td>FLUORESCENCE LIFETIME (10-6 SECONDS)</td>
<td>232</td>
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<td>240</td>
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<td>2.4</td>
<td>1.8 (pl)</td>
<td>1.2</td>
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<td>INDEX OF REFRACTION</td>
<td>1.8</td>
<td>1.4</td>
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<td>THERMAL CONDUCTIVITY</td>
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BTI PRODUCIBILITY
SPECTRA DIODE LABS 10-BAR ARRAY # S032

C2NVEO DATA
REF'D DIR; 6LC; FIL. G; HP w/.0217
OUTPUT ENERGY AS A FUNCTION OF DIODE-ARRAY WAVELENGTH OR TEMPERATURE
INPUT ENERGY IS 100 MJ

Temperature (°C)

Energy Output (mJ)

Input Wavelength (nm)

LYAG

YAG

8% DEVIATION

8% DEVIATION
Nd: LYG ABSORPTION SPECTRUM

ABSORPTION COEFFICIENT (cm⁻¹)

WAVELENGTH (NM)
SIDE PUMPED YAG FLUORESCENT PROFILE

- 4 x 10 mm DIODE ARRAY
- 1/4 INCH DIAMETER YAG ROD
- BUTT COUPLED SIDE PUMPED
- AR/SILVERED ROD BARREL

DIODE ARRAY TEMP. = 20°C
WAVELENGTH = 811 NM

DIODE ARRAY TEMP. = 10°C
WAVELENGTH = 808 NM
Nd:GGG Rod

Reflectivity: 97.5% Curved

Input Energy (mJ)

Output Energy (mJ)

Old MD Array

MD#007 Array

*McDonnell Douglas Diode Arrays

FIGURE 11
<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>MEASURED SLOPE EFFICIENCY</th>
<th>ROUND-TRIP RESONATOR LOSS (FINDLAY-CLAY)</th>
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<tr>
<td>Nd:Lu:YAG ROD</td>
<td>50.3%</td>
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<td>Nd:YAG ROD</td>
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<td>Nd:YLF ROD</td>
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<td>Nd:GSGG ROD</td>
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<td>Nd:BZAG ROD</td>
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<td>Nd:YSAG ROD</td>
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<td>Nd:YAG SLAB</td>
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<tr>
<td>Nd:GSGG SLAB</td>
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<tr>
<td>Nd:Cr:GSGG SLAB</td>
<td>32.5%</td>
<td>10.2%</td>
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AMPLIFIER GAIN EXPERIMENT
STORAGE EFFICIENCY

STORAGE EFFICIENCY = PRODUCT OF INDIVIDUAL EFFICIENCIES

\[ \eta_s = \eta_{\text{stokes}} \times \eta_{\text{lifetime}} \times \eta_{\text{coupling}} \times \eta_{\text{absorption}} \times \eta_{\text{quantum}} \]

\[ \eta_{\text{stokes}} = \frac{\text{pump photon energy}}{\text{lasing photon energy}} \]

\[ \eta_{\text{absorption}} = \frac{\text{pump energy absorbed}}{\text{pump energy injected}} \]

\[ \eta_{\text{lifetime}} = \frac{\tau}{t} \left( 1 - e^{-\frac{t}{\tau}} \right) \]

\[ \eta_{\text{quantum}} = 1 - \text{loss from upper laser level} \]

\[ \eta_{\text{coupling}} = \frac{\text{pump energy into laser material}}{\text{incident pump energy}} \]
STORAGE EFFICIENCY ANALYSIS

Nd:YLF

ARRAY PULSE = 460 mJ IN 500μs

<table>
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<th>EFFICIENCY FACTOR</th>
<th>EXPERIMENTAL</th>
<th>OPTIMIZED</th>
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<td>COUPLING &amp; ABSORPTION</td>
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<td>.23</td>
<td>.34</td>
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MATERIAL COMPARISON

SMALL-SIGNAL SINGLE-PASS GAIN
PULSE DURATION 300 MICROSECONDS

GAIN (I/lo)

DIODE ENERGY (mJ)

LYAG  YAG  YLF (pi)
SUMMARY

● ALL MATERIALS EVALUATED PROVIDED >40% SLOPE EFFICIENCY IN LONG PULSE OSCILLATOR CONFIGURATION

● FOR HIGH PEAK POWERS, MATERIAL AND SPECTROSCOPIC PROPERTIES PLAY A MORE IMPORTANT ROLE FOR OBTAINING HIGH EFFICIENCIES

● Nd:YLF OUTPERFORMS OTHER MATERIALS FOR STORAGE EFFICIENCY DUE TO 2x LONGER UPPER STATE LIFETIME

● HIGH POWER ARRAYS PROVIDING 1.5KW/cm² WITH EFFICIENCIES OF 35% ARE READILY AVAILABLE

● HIGHER INTENSITY ARRAYS WOULD HAVE SIGNIFICANT IMPACT ON OVERALL LASER EFFICIENCY
FY 91 PLANS

• COMPLETE AMPLIFIER EXPERIMENTS TO IMPROVE DATA BASE FOR DIODE PUMPED DESIGN MODELS
  -measure absorption and coupling efficiencies of various materials with 5 and 10 bar arrays

• DIODE PUMP HEAD GEOMETRIES FOR PROVIDING UNIFORM PUMPING (NECESSARY FOR GOOD BEAM QUALITY) OVER A WIDE TEMPERATURE (TEMPERATURE INSENSITIVE)
  -look at fluorescent profiles and measure small signal gain at various material absorption strengths
DIODE PUMPED RODS

DIRECT COUPLED

NON-IMAGING

REFLECTIVE WAVEGUIDE

DIFFUSE
DIODE PUMPED SLAB LASER

ZIG-ZAG SLAB

LASER DIODE ARRAY
INHOUSE EXPERIMENTS

OSCILLATOR EXPERIMENTS - NINE Nd DOPED MATERIALS EVALUATED

- ALL MATERIALS SHOWED GOOD PERFORMANCE UNDER DIODE PUMPING
- ARRAY PUMP WAVELENGTH DOES NOT NEED TO BE ON PEAK ABSORPTION LINE
- DIODE WAVELENGTH WAS TUNED 6nm WITH ONLY 8% OUTPUT DEVIATION

AMPLIFIER EXPERIMENTS - PROVIDE DATA BASE FOR MODELING

- SHOWED EFFECTS OF ARRAY PEAK POWER ON EFFICIENCY
- SHOWED EFFECTS OF UPPERSTATE LIFETIME ON STORAGE EFFICIENCY
- MEASURE SMALL SIGNAL GAIN OF VARIOUS MATERIALS
Subband Structure for Narrow, Coupled Quantum Wells

Mark L. Biermann and C. R. Stroud, Jr.

University of Rochester

Also acknowledge the assistance of Christian Mailhiot
Theoretical Approach

1. Zone-center basis states from a pseudopotential calculation.
   *Use only material parameters and superlattice symmetry.
   *Effective masses are not assumed.

2. Use the $k \cdot p$ theory to calculate band structure.
   *Couple $\Gamma_1$ conduction and $\Gamma_{15}$ valence bands to spinor. Treat explicitly.
   *Treat neighboring states in Lowdin Perturbation Theory.
   *Use normal component of current density operator for interface matching of bulk eigenfunctions.

The System Studied:
Symmetric Coupled Quantum Wells, (SCQWs), well width \( W \) and barrier width \( B \), as seen below.

* Growth direction 100, room temperature

* Wells are GaAs layers ranging in width from 4 to 35 monolayers, 11.4 to 99.0 Å

* Barriers are Al\(_{0.3}\)Ga\(_{0.7}\)As layers, 4 to 6 monolayers, 11.4 to 17.0 Å, thick

* Fourth layer of periodic structure is a thick AlGaAs layer to isolate SCQWs

* 43% of bandgap offset goes to valence band
Valence Subband Energy Positions

The first three valence subbands are plotted against well width for fixed barrier widths of 4 and 6 atomic monolayers, 11.4 and 17.0 Å, respectively.

Hole Subbands, 11.4 Å barriers

* LH1 crosses under HH2 for narrow wells, less than 7 monolayers, 19.8 Å

*Crossover observed experimentally. Could be useful in Quantum Confined Stark Effect devices or experiments

valence subbands, cont.

Hole Subbands, 17.0 Å barrier

* HH1/HH2 splitting smaller due to thicker barrier

* LH1 crosses under HH2 at narrower well widths, less than 5 monolayers, 13.3 Å

* HH1 and HH2 are symmetric and anti-symmetric solutions arising from HH1 solution in single well

* HH1 and HH2 become degenerate for wide wells.
valence subbands, cont.

**Difference Between HH2 and LH1**

*Helpful to look at the difference between HH2 and LH1 in the crossover region*

*LH1 - HH2, Subband Separation*

*Crossover occurs for wider wells as the barrier width decreases*

*Amount of crossover, up to over 20 meV, can be large*
Conduction Subband Energy Positions

The first two conduction subbands are plotted against well width for fixed barrier width of 4 atomic monolayers, 11.4 Å.

Conduction Subbands, 11.4 Å barrier

*First two subbands are the symmetric and antisymmetric solutions arising from the single well C1 subband

*Splitting is greater than in hole cases: electrons more strongly coupled due to smaller effective mass
SCQW Subbands Compared to Single Well Case

The first two subbands in the SCQWs split about the first single well state.

Valence Subbands: 4 monolayers, 11.4 Å, barrier

Subbands HH1/HH2 with Single Well HH1

*Splitting is quite even about the single well state*
Single well comparison, cont.

Conduction Subbands: 4 monolayers, 11.4 Å barrier

Subbands C1/C2 with Single Well C1

- Solid: C1, Coupled Well
- Dashed: C1, Single Well
- Dotted: C2, Coupled Well

*Splitting is not even about single well state: cannot assume equal splitting

*Coupled Well C1 behavior could be due to bulk bandedge

* Assumption of equal splitting is okay for wide wells and barriers
Subband Behavior as a Function of Barrier Width

Plot the position of the first two valence and conduction subbands as a function of barrier width for a fixed well width of 11 atomic monolayers, 31.1 Å.

Valence and Conduction Subbands:

HH1/HH2 Splitting vs. Barrier Width
Barrier Width Behavior, cont.

C1/C2 Subband Splitting vs. Barrier Width

*Splitting is greater for the conduction states than for the valence states: follows from effective mass argument

*Functional form for both cases is quite simple: Use a simple fitting function?
Fitting Functions

It is seen that a simple function can be fit to the subband energy positions as a function of both well and barrier widths in SCQWs.

The functional form is:

\[ D = \frac{A}{x^2} + \frac{B}{x} + C \]

where
- \( D \) is the energy position
- \( x \) is the well or barrier width
- and \( A, B \) and \( C \) are system dependent parameters

*This function works well for the systems studied.

*It can also be applied to subband splittings since they are simply the difference between subband positions.
Fit to Valence Subbands

Plot the HH1 and LH1 subband energy positions for various well widths and a barrier width of 4 monolayers, 11.4 Å.

Hole States with Fits, 11.4 Å barriers

*Fit is excellent for both bands over entire region studied.*
Fit to Conduction Subbands

Plot the C1 and C2 subband energy positions for various well widths and a barrier width of 4 monolayers, 11.4 Å.

Conduction bands and Fit, 11.4 Å barrier

*Fit is quite good for the conduction bands also.
**Fit as a Function of Barrier Width**

The separation between the first two conduction states as a function of barrier width for a well width of 11 monolayers, 31.1 Å, is plotted along with the fit to it. The same functional form is used.

**C1/C2 Splitting vs. Barrier, with Fit**

*Yariv, et. al.,* found an exponential dependence on barrier width for the band splitting in a weakly coupled case. This case is strongly coupled.

Points to Note About Fitting Parameters

*The more strongly coupled subbands, conduction and light holes, have a larger inverse well width squared component.

*The more weakly coupled subbands, the heavy holes, are more linear in inverse well width.

*This is in agreement with the findings of Yariv et. al., who found a linear dependence on inverse well width for a weakly coupled case.

\[ D = \frac{A}{x^2} + \frac{B}{x} + C \]
Failure of the Fitting Function

The fit begins to fail in certain regions for the heavy holes. This can be explained in terms of a shift from the dominance of quantum confinement effects in determining subband location, to a region in which bulk material parameters play a larger role.

*Where quantum confinement is strong for all states, all subbands will have the same functional dependence.

*Heavy holes are the least strongly coupled due to large effective masses, so they should be the first to be more strongly affected by the bulk material.

*Fitting functions work well for light holes and electrons for well width of at least 100 Å, for these barriers, while the heavy holes go into a region where the bulk material effects are stronger: the fit begins to fail.
Summary

*Subband behavior for narrow, strongly coupled quantum wells is studied in detail.

*LH1 and HH2 subband crossover is seen at narrow well width: could be useful for Quantum Confined Stark Effect.

*Splitting of symmetric/antisymmetric states about single well state is not even for strongly coupled wells.

*Subband location and subband pair splitting can be given accurately using a simple fitting function.

*Fitting function has three system dependent parameters.

*Fitting function fails as quantum confinement gives way to the influence of the bulk material.
### 4. LIST OF ATTENDEES

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<tr>
<th>Name</th>
<th>Organization</th>
<th>Phone</th>
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<tr>
<td>Neil Bambha</td>
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<td>CCNVEO</td>
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