Broadband Quantum-Dot/Dash Lasers

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Outline

• Introduction

• InGaAs/GaAs Quantum-dot Broadband laser ($\lambda = 1200\text{nm}$)

• InGaAlAs/InAs Quantum-dash broadband laser ($\lambda = 1600\text{nm}$)

• Towards Ultra-broadband semiconductor laser

• Summary
Applications of Broad Gain Material & Broadband Laser

**Optical Telecommunications**
- Ultra-broadband components
  - tunable laser, SOA, EA modulator, detector, etc
- Ultrafast pulse generation
  - Optical clocking, OTDM, etc

**Spectroscopy & Sensing**
- Molecular spectroscopy (1450-1650nm)
  - Strong overtone spectra of CO, C2H2, and NH3
- Atmospheric and planetary gas sensors
  - CH4, CO, CO2, H2S, HCl, NH3, C2H4, C2H2, C2H6, C6H6, etc
- General Spectroscopy
  - Material absorption, transmission, luminescence, etc

**Metrology**
- Optical test and measurements, etc
- Optical time domain reflectrometry (OTDR)

**Imaging**
- Bio-imaging (Optical Coherence Tomography)
- Ultra-short pulse imaging, etc

**Others**
- High efficiency pump source e.g., Cr:ZnSe, Cd:CdSe solid state mid-IR lasers.
- High sensitive fiber gyroscope
- Instrumentation, etc
Existing technologies:
- Photonic crystal fiber (PCF)
- Incandescent lamp
- Amplified spontaneous emission (ASE) source
- Semiconductor broadband emitters:
  - Light-Emitting Diode (LED) & Superluminescent Diodes (SLD)
  - Broadband intersub-band Quantum Cascade Laser (QCL)
Prior Work in SLDs

1550nm Quantum-Well SLED:
- **Performance**: Bandwidth 60nm, output power >20mW
- US Patent 6,617,188, granted : 9 September 2003

850nm Quantum-Well SLED
- **Performance**: Bandwidth: 65nm, ripple:<0.1dB
- USA Patent Application, submitted October 2005

1200nm & 1600nm Quantum-Dot SLEDs:
- 1200nm SLED: Bandwidth: 135nm, ripple: 0.3dB, 10s μW
- 1600nm SLED: Bandwidth: 110 nm, ripple: 0.3 dB, power: 2 mW
Intersub-band Broadband QCL concept

**Ultra-broadband semiconductor laser**

Claire Gmachl, Deborah L. Sivco, Raffaele Colombelli, Federico Capasso & Alfred Y. Cho

Bell Laboratories, Lucent Technologies, 600 Mountain Avenue, Murray Hill, New Jersey 07974, USA

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- Intersub-band cascade → mid-IR
- Quantum band engineering:
  - 36 different active regions
- Covering 6-8 μm emission
- Low wall-plug efficiency at RT (<0.1%)
- Side-mode-supression-ratio : ~20 dB
- Material challenge for near-IR region!

Inhomogeneous QD gain media

Ideal QD gain media

So far...

Inhomogeneous QD
Large energy spacing
DISCRETE-transition band
→ Dual-state lasing action

Now...

Highly inhomogeneous QD
Narrow energy separation
QUASI-transition band
→ Broadband interband laser


Ref: Djie et al., Optics Letters, vol. 32 (2), 1 Jan 2007
Broadband Semiconductor Laser

Short wavelength (1300nm) InGaAs/GaAs Quantum-Dot laser
InGaAs/GaAs inhomogeneous QD growth

Grown by Molecular Beam Epitaxy on (100) GaAs substrate
Cycled monolayer deposition (CMD) → self-limiting mechanism
- highly inhomogeneous QDs with controllable energy spacing.
InGaAs/GaAs QD characterization

- Comparison with typical 1300 nm InAs/GaAs QDs by Stranski-Krastanow (SK) mode in MBE.
- Photoluminescence (PL) at room temp. (RT) is much broader in CMD-QDs.
- Power-dependent PL at 77 K reveals QUASI-transition band in CMD-QDs.
InGaAs/GaAs QD laser performance

Gain-guided laser without facet coating:
- $T = 20^\circ C$, Total power = 0.6 W, wavelength = $\sim 1.15 \, \mu m$, $T_o = 40.3 \, K$, GS modal gain = 20.6 cm$^{-1}$, $\eta_{int} = 91\%$, $\alpha = 4.5 \, cm^{-1}$, $J_{inf} = 84 \, A/cm^2$ per dot layer.
Progressive blue-shift in transition energy as increased injection level.
Bandwidth broadening with flat-top profile.
Wavelength coverage > 40 nm (with corresponding power of 0.4 W)
SMSR > 25 dB, ripple < 3dB (within 10 nm span)
The origin of broadband laser emission

Different cavity lengths under constant injection level $J = 2x J_{th}$
- Long cavity (>1000 µm) $\rightarrow$ GS lasing line
- Short cavity (< 600 µm) $\rightarrow$ ES1 lasing line
- Intermediate cavity (700 – 900 µm) $\rightarrow$ GS+ES1 lasing lines

Single state linewidth is ~10 nm, which is broader than typical SK (4 nm). Simultaneous lasing at comparable modal gain for confined states.
The effect of gain broadening in QD laser

- The calculated lasing spectra change with injection levels in two different systems of small and large inhomogeneous broadening.

- The measured (upper) and calculated (lower) lasing spectra change with injection levels.

- The effect of gain broadening (large inhomogeneous system and retarded increment of homogeneous broadening at excited state) contribute to this changes.
Broadband Semiconductor Laser

Long wavelength (1600nm)
InAs/InGaAsAs quantum-dash-in-well laser
InGaAlAs/InAs DWELL growth

- Grown by Molecular Beam Epitaxy on (100) InP substrate.
- Elongated dots along (0-11) → dash or wire
- Dashes is within quantum-well → DWELL configuration.
InGaAlAs/InAs DWELL characterization

- Carrier confinement in 2D across y- and z- directions. Due to the dispersion effect in size and composition, the QDash structures possess the DOS spreading over the energy and forms the quasi-continuous interband transition.
- Power dependent PL from InAs/InP QDs and InAs/InAlGaAs QDashes revealing the systematic filling of quantized states.
- ASE from the 300 µm long device, and the lasing spectra from E0, E1 and E2 states from lasers with cavity length $L$ of 1000, 300, and 150 µm, respectively.
InGaAlAs/InAs Broadband Laser Characterization

- Gain-guided laser without facet coating:
  - Total power = 0.35 W, wavelength = 1.63 µm, $\eta_{\text{int}} = 90\%$, $\alpha = 10.5 \text{ cm}^{-1}$, $J_{\text{inf}} = 420 \text{ A/cm}^2$ per layer.

- Bandwidth broadening with supercontinuum profile at high injection level.

- Simultaneous quantized states (GS+ES1) in QDash gain media.
  - Wavelength coverage > 50 nm
Ultra-Broadband Semiconductor Laser

Inhomogeneous quantum-dot/dash + intermixing
Quantum-well Intermixing (QWI)

**QWI principle**: thermal/defect/impurity induced interdiffusion of constituent atoms through the QW heterointerface.

**Advantages**:
- Postgrowth level  \(\rightarrow\) cost-effective
- Planar process
- Improved device performance, i.e. carrier confinement
- Excellent mode matching  \(\rightarrow\) negligible joint-reflection \(R < 10^{-6}\)

**Conventional bandgap engineering approaches**:
- growth and regrowth
- selective area epitaxy
- evanescent coupling

![Diagram showing the QWI principle and its advantages](image-url)
Various Techniques for Monolithic Quantum Well Intermixing

Dielectric cap

\[ \frac{W}{W_0} \]


Ion implantation


Laser irradiation

Quantum-Dot Intermixing

- QD on GaAs and InP platforms has been annealed using various dielectric caps producing different magnitude of bandgap blue-shifts.
- The intermixing is enhanced for the area under SiO₂ cap and suppressed for the area under SiₓNᵧ cap.¹
- The large tunability covering the emission:
  - InGaAs QDs on GaAs substrate: 800-1100 nm
  - InAs QDs on InP substrate: 1100-1600 nm.

²B.S. Ooi, Optics East 2005 (invited talk);
**Large Spatial Selectivity Quantum Dot Intermixing**

- High bandgap selectivity (96 nm) observed from InAs/InAlGaAs dot-in-well laser structure using Si$_x$N$_y$ and SiO$_2$ technique.$^1$

- Temperature assisted ion implantation using As and P ions for selective QD intermixing.$^2$

- Differential blue shift of ~126 meV observed from the P$^+$ intermixed and the Si$_x$N$_y$ capped InGaAs/GaAs QDs.$^3$

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N-implantation enhanced DWELL intermixing

N-implant: neutral, light ion \(\rightarrow\) deeper penetration at \(\sim 2\ \mu m\) (\(E=1500\text{keV}\)):
- a lower annealing activation & wider temperature range
- larger bandgap shift.

QD shift >> QW shift \(\rightarrow\) larger surface to volume ratio.
Intermixing activation is lower by 50-100ºC than dielectric cap annealing.

High-quality bandgap-tuned DWELL laser

Direct-implant to DWELL: comparable $J_{th}$ and slope of efficiency.

Shallow implant to cap layer: $J_{th} \uparrow$ and slope of efficiency $\downarrow$.
- dopant alteration at highly doped cap $\rightarrow$ serial resistance $\uparrow$ (20%)

Proximity implant: $J_{th} \downarrow$ and comparable slope of efficiency
- reduced free-carrier absorption at shorter wavelength (?)
- improved dash imhomogeneity after intermixing $\rightarrow$ larger gain

Broadband lasing emission: Potential bandwidth extension using intermixing
Summary

- Broadband, supercontinuum interband short & long-wavelength QD lasers operating at 300K have been demonstrated.

- The quasi-transition was obtained by engineering the confined states and dot inhomogeneity.

- The emission is formed from the simultaneous laser lines from ground and excited states whenever the net modal gains at certain injection are comparable.

- The devices exhibit the broad wavelength coverage (40 nm and 60 nm for GaAs- and InP-based QD, respectively), high optical power of hundreds mWs & ripple of 3 dB.

- Ultra-broadband laser with wavelength spans from 1450-1650nm can potentially be obtained from intermixed multiple laser structure.

THANK YOU!