Quantum Dot Based Mode-locked Semiconductor Lasers And Applications

2010

Jimyung Kim
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In this dissertation, self-assembled InAs/InGaAs quantum dot Fabry-Pérot lasers and mode-locked lasers are investigated. The mode-locked lasers investigated include monolithic and curved two-section devices, and colliding pulse mode-locked diode lasers.

Ridge waveguide semiconductor lasers have been designed and fabricated by wet etching processes. Electroluminescence of the quantum dot lasers is studied. Cavity length dependent lasing via ground state and/or excited state transitions is observed from quantum dot lasers and the optical gain from both transitions is measured.

Stable optical pulse trains via ground and excited state transitions are generated using a grating coupled external cavity with a curved two-section device. Large differences in the applied reverse bias voltage on the saturable absorber are observed for stable mode-locking from the excited and ground state mode-locking regimes. The optical pulses from quantum dot mode-locked lasers are investigated in terms of chirp sign and linear chirp magnitude. Up-chirped pulses with large linear chirp magnitude are observed from both ground and excited states. Externally compressed pulse widths from the ground and excited states are 1.2 ps and 970 fs, respectively. Ground state optical pulses from monolithic mode-locked lasers e.g., two-section devices and colliding pulse mode-locked lasers, are also studied. Transformed limited optical pulses (~4.5 ps) are generated from a colliding pulse mode-locked semiconductor laser.

The above threshold linewidth enhancement factor of quantum dot Fabry-Pérot lasers is measured using the continuous wave injection locking method. A strong spectral dependence of the linewidth enhancement factor is observed around the gain peak. The measured linewidth
enhancement factor is highest at the gain peak, but becomes lower 10 nm away from the gain peak. The lowest linewidth enhancement factor is observed on the anti-Stokes side. The spectral dependence of the pulse duration from quantum dot based mode-locked lasers is also observed. Shorter pulses and reduced linear chirp are observed on the anti-Stokes side and externally compressed 660 fs pulses are achieved in this spectral regime.

A novel clock recovery technique using passively mode-locked quantum dot lasers is investigated. The clock signal (~4 GHz) is recovered by injecting an interband optical pulse train to the saturable absorber section. The excited state clock signal is recovered through the ground state transition and vice-versa. Asymmetry in the locking bandwidth is observed. The measured locking bandwidth is 10 times wider when the excited state clock signal is recovered from the ground state injection, as compared to recovering a ground state clock signal from excited state injection.
To my parents
ACKNOWLEDGMENTS

I would like to acknowledge Prof. Peter J. Delfyett for original ideas, guidance and support during my Ph.D study.

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<tr>
<th>Acronym</th>
<th>Abbreviation</th>
</tr>
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<tbody>
<tr>
<td>AR</td>
<td>Anti-Reflection</td>
</tr>
<tr>
<td>ASE</td>
<td>Amplified Spontaneous Emission</td>
</tr>
<tr>
<td>BPF</td>
<td>Band Pass Filter</td>
</tr>
<tr>
<td>BW</td>
<td>Bandwidth</td>
</tr>
<tr>
<td>DOS</td>
<td>Density of States</td>
</tr>
<tr>
<td>ECML</td>
<td>External Cavity Mode-locked Laser</td>
</tr>
<tr>
<td>EL</td>
<td>Electroluminescence</td>
</tr>
<tr>
<td>ES</td>
<td>Excited State</td>
</tr>
<tr>
<td>FP</td>
<td>Fabry-Pérot</td>
</tr>
<tr>
<td>GS</td>
<td>Ground State</td>
</tr>
<tr>
<td>HWP</td>
<td>Half Wave Plate</td>
</tr>
<tr>
<td>I</td>
<td>Isolator</td>
</tr>
<tr>
<td>LEF</td>
<td>Linewidth Enhancement Factor</td>
</tr>
<tr>
<td>LI</td>
<td>Light output Versus Current</td>
</tr>
<tr>
<td>ML</td>
<td>Master Laser</td>
</tr>
<tr>
<td>SL</td>
<td>Slave Laser</td>
</tr>
<tr>
<td>MOPA</td>
<td>Master Oscillator Power Amplification</td>
</tr>
<tr>
<td>PECVD</td>
<td>Plasma Enhanced Chemical Vapor Deposition</td>
</tr>
<tr>
<td>RIE</td>
<td>Reactive Ion Etching</td>
</tr>
<tr>
<td>RTA</td>
<td>Rapid Thermal Annealing</td>
</tr>
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</table>

xvii
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>SA</td>
<td>Saturable Absorber</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning Electron Microscope</td>
</tr>
<tr>
<td>SOA</td>
<td>Semiconductor Optical Amplifier</td>
</tr>
<tr>
<td>TBP</td>
<td>Time-Bandwidth Product</td>
</tr>
<tr>
<td>TEC</td>
<td>Thermo-Electric Cooler</td>
</tr>
<tr>
<td>QD</td>
<td>Quantum Dots</td>
</tr>
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</table>
CHAPTER 1: INTRODUCTION

Quantum dot structures have attracted strong attention over conventional semiconductor gain materials such as bulk and quantum well structures due to the predicted properties originating from carrier confinement in the quasi-zero dimensional structure. The superior physical properties are low temperature dependence of the threshold current [1-2], higher material and differential gain [3-4], high modulation bandwidth [5], and low chirp [6].

Quantum dot structures also offer advantages for mode-locking such as broad gain spectrum, low linewidth enhancement factor, and ultrafast gain/absorption recovery with low saturation energies. These advantages enable quantum dot based mode-locked lasers to be strong candidates for novel photonic devices leading to cost effective compact laser sources with low power consumption, low noise and near Fourier-transform-limited optical pulses at high repetition rate.

Recently, quantum dot based mode-locked lasers have been used to generate ultrafast pulses with high average power and upchirped pulses were reported from monolithic or external cavity lasers via the ground state transition [7-8]. Quantum dot semiconductor lasers do not exhibit gain clamping in the excited state transition after the lasing threshold of the ground state due to the finite intraband relaxation time and limited density of states. Fast gain recovery, higher differential gain, and a negative linewidth enhancement factor are observed from the excited state transitions [9-10]. Excited state mode-locking was demonstrated from a monolithic
two section diode laser by controlling the injection current with reverse bias [11]. A wide gain bandwidth of over 100 nm originating from ground and excited state transitions is extremely attractive for generating sub 100 fs pulses directly from a QD diode laser.

In this work, various kinds of semiconductor lasers including a Fabry-Pérot laser, a curved two section device, and a colliding pulse mode-locking device, employing a self assembled InAs/InGaAs quantum dot gain medium are studied. The fabrication process and optical characterization of these lasers are discussed. Optical pulses generated via ground and excited state transitions are investigated in terms of the chirp sign and magnitude. The spectral dependence of both linewidth enhancement factor and the pulse width is studied. Optical pulse injection locking is demonstrated for optical bandwidth combining and novel clock recovery.
References


[8] M. Choi, W. Lee, J. Kim, and P. J. Delfyett,”Ultrashort, high-power pulse generation from a master oscillator power amplifier based on external cavity mode locking of a quantum-dot two-


CHAPTER 2: FABRICATION OF QUANTUM DOT SEMICONDUCTOR LASERS

2.1 Quantum Dot Wafer

The QD were grown by molecular beam epitaxy on GaAS substrate by Innolume Inc. in Germany. A 10 layer stack of an InAs QD array covered by a In$_{0.15}$Ga$_{0.85}$As quantum well was used as the active region [1]. The QD wafer structure is shown in Table 2.1. Fabry-Pérot (FP) lasers, curved and monolithic two-section devices, and colliding pulse mode-locking (CPM) devices were fabricated from this quantum dot wafer.

Table 2.1: Quantum dot wafer structure.

<table>
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<th>Layer</th>
<th>Material</th>
<th>Repeat</th>
<th>Mole fraction (x)</th>
<th>Thickness (nm)</th>
<th>Type</th>
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<td>Al(x)Ga(1-x)As</td>
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2.2 The Photomask Design

Several photomasks are designed to fabricate different diode lasers. In this section, a photomask for a curved two section device is described. Two-section devices are designed by taking into the consideration the low facet reflectivity of the curved section and by carefully selecting the lengths of saturable absorber (SA) and gain medium.

To minimize the back reflection from the facet, a 7 degree angled and tapered waveguide is adapted in the curved two section device. Tapering the waveguide near the facet was first introduced to achieve a low facet reflectivity especially at 1.55 µm in a strongly index guided buried heterostructure [2]. The effective modal reflectivity is given by

\[ R = R_0 e^{-\left(\frac{\pi n W}{\lambda} \theta\right)^2} \]  

(2.1)

Where \( R_0 \) is the Fresnel reflectance, \( n \) is the effective refractive index of the waveguide, \( W \) is the mode width, \( \theta \) is the angle from the normal to the facet, and \( \lambda \) is the wavelength. The effective modal reflectivity can be reduced by increasing the waveguide angle and the modal width. When the fundamental mode reflects from the angled facet, higher order modes are generated due to the angle of the facet but suffer high transmission loss and less gain due to a smaller confinement factor. Also the effective modal reflectivity is reduced by tapering the waveguide which allows the modal width to increase.

For passive mode-locking, the saturation energy of the absorber, \( E_{\text{sat,abs}} \), must be less than that of the gain medium, \( E_{\text{sat,g}} \) because the loss must saturate faster than the gain:
\[ E_{\text{sat},\text{abs}} \equiv \frac{\hbar \omega A}{\partial a/\partial n} < \frac{\hbar \omega A}{\partial g/\partial n} \equiv E_{\text{sat},g} \quad (2.2) \]

where \( A \) is the optical mode cross-sectional area, \( \partial a/\partial n \) is differential loss of the absorber, \( \partial g/\partial n \) is the differential gain of the gain medium. Another condition for stable passive mode-locking is that the initial gain should be less than the initial loss. According to Haus’s approach, these conditions can be expressed in following equations, respectively [3].

\[ g_i \left( \frac{E_p}{E_{\text{sat},g}} \right)^2 < \alpha_i \left( \frac{E_p}{E_{\text{sat},\text{abs}}} \right)^2 \quad (2.2) \]

and

\[ g_i < 1 + \alpha_i \quad (2.3) \]

where \( g_i \) the initial gain just before the pulse arrival, \( \alpha_i \) is the initial value of the saturable loss normalized to the linear loss and \( E_p \) is pulse energy.

Several ratios between the gain and the saturable absorber length are considered. To find out the ratio which gives stable mode-locking, especially for the QD wafer used, two section devices whose ratio between the saturable absorber (SA) and device length varies from 5 % to 15 % are fabricated and their mode-locking performance is tested. A QD two section device whose SA ratio is 10 % - 12 % shows stable passive mode-locking performance. Curved two-section devices of lengths 2 mm, 2.5 mm, and 3 mm are fabricated. The above length ratios are also applied to design of the colliding pulse mode-locking devices.

The L-Edit program from Tanner EDA is used to the draw waveguides and metal patterns with an internal unit of 1nm. A C++ program is used with L-Edit to draw the curves and the
angles of waveguides and also metal pads. The GDSII format file generated from L-Edit is then used to make the photomask. The chrome patterns from PMMA coated sodalime substrates were generated by an electron beam lithography system (Leica EBPG5000) located in UCF/CREOL.

The detailed schematic and the parameters of the curved two-section device are shown in Figure 2.1 and Table 2.2. C++ code for the curved two-section waveguide can be found in Appendix A.

![Figure 2.1: Schematic and parameters of curved two-section waveguide.](image)

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<td>7</td>
<td>15</td>
<td>30</td>
<td>80</td>
<td>5</td>
<td>0</td>
<td>7°</td>
<td>70</td>
<td>30</td>
<td>7</td>
</tr>
</tbody>
</table>
Figure 2.2: Captured image of curved two section device from L-Edit. Waveguide (blue) and metal pad (green) are intentionally overlapped for visual aid.
2.3 Etching Study

The Fabry-Pérot (FP) waveguide width and etching ratio are studied for fundamental mode operation which is a horizontal transverse mode. The effective index of an active region is a function of the width of waveguide, the thickness from air to active region, and the refractive index and thickness of each layer [6-7]. The effective index of an active region will affect the confinement factor as well as the beam profile. The effective index in the horizontal direction is controlled by varying the width and the height of the ridge waveguide, while the vertical transverse modes are determined by the wafer structure itself. The ridge waveguide whose width is 5µm and height is 1.5 µm is empirically chosen for a single mode operation (TEM$_{00}$).

Three different wet etchants are explored to form the ridge waveguide structure from the QD wafer [8]. They are “H$_3$PO$_4$;H$_2$O$_2$;DI (1:2:50)”, “HCL:H$_2$O$_2$:DI (1:1:9)”, and “NH$_4$OH:H$_2$O$_2$:DI (1:5:60)”. The first two etchants are used to form the ridge waveguide structure and the third etchant,“NH$_4$OH:H$_2$O$_2$:DI”, is used to etch-out the hat formed in the first etching step.

For the etching study, the waveguide patterns are aligned along the minor flat <0-11> direction and the major flat <0-1-1> direction and then the waveguide is fabricated by the wet etchant, H$_3$PO$_4$;H$_2$O$_2$:DI (1:2:50). Figure 2.3 shows the facet images of the fabricated waveguide after the wet etching.
Figure 2.3: SEM images of QD FP lasers after wet etching by “H₃PO₄:H₂O₂:DI (1:2:50)” where the waveguide is along (a) a minor flat direction and (b) a major flat direction.

As observed, the etchant, “H₃PO₄:H₂O₂:DI (1:2:50)”, gives a mesa type ridge waveguide regardless of the waveguide direction and a hat is seen in the GaAs layer, implying that the etching ratios along <0-11> and <0-1-1> are the same in the case of the AlGaAs layer but
different in the GaAs layer. The hat in this case possibly led to metal pad discontinuity between waveguide and the contact point. As a second step, “NH₄OH:H₂O₂:DI (1:5:30)” is used successfully to remove the hat as shown in Figure 2.4.

Figure 2.5: SEM images of QD FP laser after wet etching by “HCL:H₂O₂:DI (1:1:9)” where waveguide is along (a) a minor flat direction and (b) a major flat direction.

Second, “HCL:H₂O₂:DI (1:1:9)” is used to form a ridge waveguide. “HCL:H₂O₂:DI (1:1:9)” gives a mesa type of a ridge waveguide when the waveguide is along <0-11> but gives a reverse mesa type of a ridge waveguide when the waveguide is along <0-1-1>, suggesting that “HCL:H₂O₂:DI (1:1:9)” has different etching ratios depending on the wafer direction. The SEM images after the wet etching are shown in Figure 2.5. Again a hat is observed with “HCL:H₂O₂:DI (1:1:9)”. The etchant, “NH₄OH:H₂O₂:DI (1:5:30)” is again used to remove the hat as shown in Figure 2.6.
Figure 2.6: SEM images of QD FP laser facet (a) before and (b) after the second wet etching NH₄OH:H₂O₂:DI (1:5:30).

Table 2.3: Etching characteristics of the QD wafer.

<table>
<thead>
<tr>
<th>Wet Etchant</th>
<th>Etching Rate</th>
<th>Waveguide</th>
<th>Direction</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₃PO₄:H₂O₂:DI (1:2:50)</td>
<td>170 nm/min</td>
<td>Minor &lt;0-11&gt;</td>
<td>Mesa</td>
<td></td>
</tr>
<tr>
<td>HCL:H₂O₂:DI (1:1:9)</td>
<td>200 nm/min</td>
<td>Minor &lt;0-11&gt;</td>
<td>Mesa</td>
<td></td>
</tr>
<tr>
<td>NH₄OH:H₂O₂:DI (1:5:30)</td>
<td>20 nm/sec</td>
<td>Major &lt;0-1-1&gt;</td>
<td>Reverse mesa</td>
<td></td>
</tr>
</tbody>
</table>
The reverse mesa type waveguide can more effectively confine the injected current in the active region than the mesa type waveguide due to the physical waveguide shape. But it may cause residual reflection in the gap between saturable absorber section and gain section in a two section device [9]. It should be mentioned that “H₃PO₄:H₂O₂:DI (1:2:50)” is chosen as the wet etchant in our study. However, the wet etchant, “NH₄OH:H₂O₂:DI (1:5:30)” is not used because the metal thickness is over 200 nm and there is an angle between the waveguide and metal source during metallization.
2.3 Fabrication Procedure

The brief overall fabrication steps are described below and files (prc) used in PECVD can be found in Appendix B.

**QD wafer cutting and cleaning**

- Cut wafer along crystal axis.
- Clean the wafer in acetone, methanol, and iso-propanol for 3 min each at 120 °C, respectively.

**SiN Deposition using PECVD**

- SiN_diff.prc for 20 min
- 200 nm thickness of SiN
- Deposition ratio is 10nm/min
Lithography

- Spin coat with S1805 @ 3500 rpm/40 sec
  - 500 nm thickness
- Pre-bake (120 °C / 4 min)
- UV Exposure @ 12 mW / 5.5 sec
- Develop in “351: DI = 10 ml: 70 ml” for 35 sec
- Post-bake (120 °C / 4 min)
  - Waveguide is located along major axis <0-1-1>
  - The wet etchant gives mesa ridge waveguide regardless of crystal axis

+ PR coating

Mask align & UV Expose

Developing
Etching of SiN using RIE

- Descum for 2 min
- Etchsin1.prc for 2min 30 sec
  - Etching ratio is 100nm/min

Positive photo resist removal

- Dip the sample RR2 @ 80°C for 5min
- Clean the sample with DI water
- prremove.prc for 10 min using PECVD

Wet etching

- H3PO4: H2O2: DI = 5 ml: 10 ml: 250 ml for 8 min.
  - Etching ratio is 160 nm / min ~ 180 nm / min
  - Thickness is 1.4 ~ 1.5 µm.
  - It should be noted that there is no stop layer.
**SiN Etching**

- etchsin1.prc for 3min using RIE
  - Etching ratio is 100nm/min

**BCB coating, curing, and etching**

- Spin coating of Adhesion Promoter (AP3000) @ 4000 rpm / 40 sec
- Spin coating of CYCLOTENE Advanced Electronics Resins @ 400 rpm / 40 sec
- Curing of Dry-Etch BCB in 250 °C for 1 hour in N₂ ambient
- RIE etching of Dry-Etch BCB for 9 min
- Etching ratio (O₂: CF₄ = 10 sccm: 5 sccm) is ~160 nm / min
- Soak wafer into ReziTM-28 (Ash residue remover) for 5min in room temperature
  - Properties of Cyclotene advanced electronics resins.
    - Low dielectric constant, loss at high frequency, and moisture absorption
    - High degree of planarization and optical clarity.
    - Good thermal stability and compatibility with various metallization systems.
    - Excellent chemical resistance and less than 5 % shrinkage during dure.
Lithography

- Spin coating of NR7-1000PY @ 4000 rpm / 40 sec
- Pre-baking @ 150 °C / 4 min
- UV Exposure @ 12 mW / 14 sec
- Developing in “351: DI = 10 ml: 70 ml” for 35 sec

De-oxidation

- H3PO4: DI = 6 ml: 180 ml during 2 ~ 5 sec.

- PR Coating

Mask Align / UV Expose

Chrome Mask

Developing

- PR(NR7-1000PY)
GaAs
AlGaAs / BCB
Active Region
GaAs
P-side metallization, lift-off and RTA

- Metal deposition: Ti (5nm) / Au (300nm)
- Lift-off in RR2 for 5 min ~ 30 min
- Rapid Thermal annealing @ 400 °C / 1 min

Gold (Purity of 99.99 % or better):
- High electrical conductivity \([45.2 \times 10^6 \text{ (s} \cdot \text{m}^{-1})]\).
- No reaction with oxygen, nitrogen, or carbon at any temperature.
- Resistance to attack by most acids.
- Interdiffuse into GaAs during rapid thermal annealing.
  - The electrical conductivity is reduced.
  - The Schottky barrier properties of the gold-GaAs interface is destroyed
- Poor adhesion to GaAs.

Titanium:
- Good adhesion to almost any surface.
- Higher thickness (200 Å ~ 1000Å nm) can be deposited for reliability.
Lapping and polishing

- Reduce wafer thickness to around 150 μm with aluminum oxide powder (5 μm size)
  
  ✓ The coefficient of thermal conductivity, $K_L$, for undoped GaAs at 300 K is approximately 0.55 W/cm-K
  
  ✓ Note that GaAs is a poor thermal conductor compared to silicon (1.5 W/cm-K)

- Shining n-side of the wafer with fine aluminum oxide powder (0.3 μm size)
  
  ✓ To prevent interference between substrate mode and guide, rough polishing can be tried.

---

N-side metallization

- Metal deposition: Ni (2nm) / Ge (20nm)/ Au (200nm)

---

RTA for n-side metallization

- Rapid Thermal annealing @ 400 °C / 1 min
Cleave the wafer.

**Scribing**

![Schematic diagram of laser fabrication layers](image)

- Ti / Au
- GaAs
- AlGaAs / BCB
- Active Region
- GaAs
- Ni / Ge / Au

**Figure 2.7**: SEM image of QD Fabry-Pérot laser after fabrication.
2.4 Fabricated Devices Types and Pictures

Figure 2.8: Fabry-Pérot laser.

Figure 2.9: Semiconductor Optical Amplifier.

Figure 2.10: Curved Two Section Device.

Figure 2.11: Monolithic Two Section Device.

Figure 2.12: Colliding Pulse Mode-locking Device.

Figure 2.13: Multiple Pulse Mode-locking Devices.
References


CHAPTER 3: OPTICAL CHARACTERISTICS OF QUANTUM DOT SEMICONDUCTOR LASERS

In this section, optical characteristics of fabricated devices, i.e., FP lasers, SOA, curved two-section device, are discussed. No high-reflection (HR) or antireflection (AR) coating was applied onto these devices.

3.1 Quantum Dot Fabry-Pérot Laser

3.1.1 Electroluminescence and Beam Profile

A ridge waveguide type QD FP laser, 1.9 mm long, is fabricated and mounted p-side up on a gold coated copper stud with cleaved facets. The QD FP laser is electrically pumped and the temperature of the laser is kept slightly below room temperature using a thermoelectric cooler. The optical output from one facet and the voltage across the junction are measured and shown in Figure 3.1. Current versus light output shows that the threshold current of the QD FP laser is around 35 mA, the slope efficiency is ~0.3 (W/A), assuming the output power of the other facet is the same. The slope efficiency becomes low after an injection current of 400 mA. Three possible mechanisms may contribute to the lower slope efficiency namely “leakage current”, “threshold current”, and “internal loss”, which increase with the increasing current [1-2]. Junction heating due to an increase of laser power will increase Auger recombination and reduce carrier-recombination time as result. The I-V curve shows a typical diode behavior and a turn on
A voltage of 0.72 V is measured.

Figure 3.1: Current versus optical power and voltage of a QD FP laser.

To measure the far field pattern, output power from the laser is collected by an aspheric lens (C230TM-C; Thorlab) and then measured using a Cohu 4400 TV camera. Far field patterns and corresponding electroluminescence (EL) with 0.01 nm resolution are shown in Figure 3.2. The transverse mode is evaluated from the beam profile in the far field pattern. The vertical transverse mode presents the light intensity distribution along the axes perpendicular to the active layer. The horizontal transverse mode exhibits the light intensity distributions along the axes parallel to the active layer. Single mode laser oscillation in vertical transverse mode can be achieved by controlling the normalized frequency which is a function of the refractive index of the guiding layer and the cladding and substrate layers, and the thickness of the guiding layer.
The horizontal transverse modes are controlled via index guiding by the ridge waveguide fabricated through wet etching. The fabricated ridge waveguide has width of 4 µm and height of 1.5 µm with 200 nm separation between the bottom of the waveguide and the active layer. A Gaussian beam profile is observed from a horizontal transverse mode. But a non-Gaussian profile is observed in the vertical transverse mode. It is interference pattern between guided mode and substrate mode [3].

![Image of Electroluminescence and Far Field Mode Pattern](image)

Figure 3.2: (a) Electroluminescence at 150 mA injection current (b) far field mode pattern of a 1.9 mm long QD FP laser.

3.1.2 Cavity Length Dependent Lasing Characteristics of QD FP Lasers

Lasing via ground state (GS) or excited state (ES) transitions or simultaneous two-state lasing from QD FP lasers has been reported and these optical characteristics are attributed to a
small density of states in the GS and the finite interband relaxation time [4-5].

Since the number of states in GS and ES is dependent upon the cavity length, the lasing via GS and/or ES can be varied by changing the cavity length with pumping current. For example, the laser only lases via the ES when the cavity is short as there are not enough number of states in the GS to overcome the cavity loss. Similarly the laser whose cavity length is long enough only lases in GS where there are enough number of states to overcome the cavity loss. Simultaneous two-state lasing is possible when the length of the cavity can support the right number of electronic states for both GS and ES to overcome the cavity loss.

QD FP lasers are fabricated and cleaved in different lengths and tested. Three devices which show ES, simultaneous two-state, and GS lasing are selected among them. They are 530 µm, 640 µm and 740 µm. Optical spectra of each laser with different pumping current are measured and showed in Figure 3.3.

As injection current increases in a 530 µm length device, amplified spontaneous emission (ASE) from GS is increased but saturates before reaching lasing due to small density of states. With higher injection current, ASE from ES starts to increase and finally reaches the threshold at a pumping current of 40 mA. As shown in Figure 3.3 (a), this short cavity FP (~530 µm) lases via only the ES transition. The longer cavity FP (~740 µm) lases via GS but ES lasing is also observed at high pumping current because injected electrons populate the ES after filling all states of the GS. The optical spectra are shown in Figure 3.3 (c). The cavity length of ~640 µm lases simultaneously via GS and ES transitions at injection current of 45 mA. The optical spectra are shown in Figure 3.3 (b). In this experiment, individual intensity from GS and ES are not
measured but it was reported that in the simultaneous lasing case, the integrated intensity of the GS transition saturates as the threshold of ES transition is reached and is suppressed while the integrated intensity of the ES transition increases [4].

Figure 3.3: Optical spectra of QD FP lasers whose length is (a) 528 µm (b) 637 µm and (c) 740 µm.

3.2 Quantum Dot Curved Two-Section Device

As described in Chapter 2, the curved two section device has an absorption section which
is linear and a gain section which has both linear and curved sections. Since the gain section is tapered and curved with $7^\circ$ to the facet, it can achieve a very low residual reflectivity ($\sim 10^{-6}$) without anti-reflection (AR) coating. The physical dimensions of several curved devices can be found in Table 2.2. A curved two section device of length 3 mm with SA length of 250 µm is fabricated. Electroluminescence from the curved gain section is measured with various pumping current and is shown in Figure 3.4. No strong FP modulation or lasing is observed from the curved two section device even with high pumping current due to the low reflectivity of the gain section and the loss in the absorber section. ASE from the first ES transition is observed after GS saturation. A large bandwidth of $\sim 100$ nm is observed by considering both the GS and ES transitions.

Figure 3.4: Electroluminescence from the gain section of a curved two-section device.

The tunable quantum dot laser is constructed by coupling a curved two section device with a grating (900 line/mm) in the Littrow configuration. Figure 3.5 shows the experimental
setup. The grating angle is tuned to achieve lasing via GS and ES transitions. Continuous tuning from GS to ES is achieved with injection current of 210 mA and reverse bias of 0 V. The continuous tuning range is around 124 nm. It should be mentioned that no HR/AR coating was applied to the facet of the device. Optical spectra for the continuous tuning are shown in Figure 3.6. The details of optical pulse characteristics are discussed in Chapter 4.

Grating Coupled \textit{ECML}

Figure 3.5: Grating coupled ECML, G: grating, and ECML: external cavity mode-locked laser.

Figure 3.6: Wavelength tuning over 120 nm from a grating coupled ECML.
3.3 Quantum Dot Semiconductor Optical Amplifier

To amplify optical energy, we fabricated a QD semiconductor optical amplifier (SOA) whose waveguide is tilted 7° to the facet and has a 1.8 mm long and 4 µm wide ridge waveguide. No HR/AR coating is applied to either facet of QD SOA. The electroluminescence from one facet is measured and shown in Figure 3.7. The QD SOA shows also the ES transition after saturation of GS transition around 100 mA. No lasing is observed even at high injection current.

![SOA](image)

Figure 3.7: Electroluminescence from the facet of 1.8 mm long QD SOA with different injection current.

The gain of the QD SOA is measured under the condition of optical pulse injection. An optical pulse train from the GS and ES transitions is generated through the QD ECML. Optical injection power to the QD SOA is controlled with a neutral density filter. The experimental setup for the gain measurement is shown in Figure 3.8. ES and GS gain of the QD SOA is measured as
function of injection current and it is shown in Figure 3.9. Pulse energy and duration of the injected pulses are not measured but the estimated pulse energy is sub pico-joule and pulse duration is over 10 ps. The measured small signal gain for ES and GS is approximately 18 dB and 12 dB, respectively.

Figure 3.8: Experimental setup for gain measurement of QD SOA, I: isolator, HWP: half wave plate, NDF: neutral density filter.

Figure 3.9: a) ES Gain and b) GS Gain of QD SOA with different injection current.
References


CHAPTER 4: PULSE CHARACTERISTICS OF PASSIVELY MODE-LOCKED QUANTUM DOT SEMICONDUCTOR LASERS

4.1 Introduction

Passive mode-locking is a self-starting process from initial weak noise. Pulses are formed from spontaneous fluctuations [1]. When the laser gain becomes equal to the cavity losses, spontaneous emission oscillates and builds up the initial intensity in the laser cavity. The noise is composed of cavity supported axial modes and their amplitude and phase are random and uncorrelated. As gain increases with pumping current, a single preferred noise spike gets an enough power to saturate the absorber. The saturable absorber turns transparent with saturation and the laser emits as long as the absorber is saturated, i.e., transparent. The pulse continues to build up its energy and make successive round trips. The optical pulse train is produced by interplay between time dependent saturable gain and absorber. Spontaneous emission cannot oscillate between pulses due to the faster recovery time of the absorber compared to that of the gain.

A GS optical pulse train from QD passively mode-locked diode laser had been demonstrated and studied [2]. An ES optical pulse train is generated by controlling pumping current and reverse bias [3].

In this section, we discuss the pulse characteristics of passively mode-locked QD lasers operating exclusively on the GS and the ES transitions in terms of pulse duration and the chirp
sign and magnitude. Also, the pulse characteristics from QD based monolithic laser diodes which are a two section device and colliding pulse mode-locked (CPM) devices are investigated together.

4.2 External Cavity of QD Mode-Locked Laser

To study the pulse characteristics from the different transition states, i.e. GS and ES, isolation and independent selection of the GS and ES is essential. A grating coupled external cavity is ideal to achieve stable passive GS and ES mode-locking and to study the pulses forming and nonlinear dynamics of each state, independently. The angle of the grating controls the external optical feedback in the cavity. It allows switching of the lasing wavelength between the GS and ES and prevents lasing competition between GS and ES transition.

The QD two-section device length and waveguide width are 2 mm and 4 μm, respectively. The length of the saturable absorber is 250 μm. The grating has a groove density of 300 line/mm and is coupled with the curved two-section device in a Littrow configuration. The grating coupled external cavity mode-locked laser is passively mode-locked with fundamental repetition rate of 2.7 GHz and the generated pulse train is amplified through an SOA whose length and waveguide width are 1.8 mm and 4 μm. The pulse train from the GS and ES is externally compressed to study the chirp sign and magnitude. The experimental setup is show in Figure. 4.1.
4.2.1 Pulses from the GS and ES Transitions

Stable GS passive mode-locking is obtained at current of 140 mA with reverse bias of ~5 V. Figure 4.2 shows the optical spectrum, the RF tones, the intensity autocorrelation signal, and the pulse width of the GS optical pulse train. Lasing wavelength of the GS is 1275 nm with a 3 dB optical bandwidth of 6 nm. The GS optical pulses are amplified through a QD SOA for diagnostic purpose. The GS optical pulse duration is decreased as reverse bias increases. Pulses from the GS transition are measured to be 14 ps with a time-bandwidth product (TBP) of 15.5, assuming a hyperbolic-secant-squared pulse shape. Large TBPs suggest that highly chirped optical pulses from the GS are being generated.
Figure 4.2: GS passively mode-locked (a) optical spectrum, (b) RF spectrum, (c) intensity autocorrelation signal, and (d) pulse width vs. reverse bias voltage.

ES passive mode-locking is achieved for pumping current of 240 mA with reverse bias of ~2V. The salient feature of ES mode-locking is that stable ES mode-locking is achieved for only lower reverse bias (< 2 V) while higher reverse bias (> 3 V) is preferred for the stable GS mode-locking. The optical spectrum, RF tones, intensity autocorrelation signal and pulse width with reverse bias are shown in Figure 4.3. The lasing wavelength is ~1193 nm with a 3 dB optical bandwidth of 4.25 nm and shows a 28 dB suppression of the GS ASE as shown in inset of Figure
4.3 (a). The measured pulse width is 10.8 ps and TBP is 9.7, assuming a hyperbolic-secant squared pulse shape, implying that highly chirped ES optical pulses are generated from the QD mode-locked laser.

Figure 4.3: ES passively mode-locked (a) optical spectrum, (b) RF spectrum, (c) intensity autocorrelation signal, and (d) pulse width vs. reverse bias voltage.

4.2.2 External Pulse Compression

To investigate the chirp sign and linear chirp magnitude of the GS and ES optical pulses,
the GS and ES pulse trains are amplified through a QD-SOA and then sent to a dual grating compressor. An internal telescope allows access to both positive and negative group velocity dispersion (GVD) regime [4].

Both GS and ES passively mode-locked pulses are maximally compressed in the negative group velocity dispersion region. Upchirped pulses are formed via GS and ES passive mode-locking. The compressed pulse width versus grating position (applied dispersion) and maximally compressed pulses are plotted in Figure 4.4 and 4.5 for GS and ES optical pulses, respectively. The ES pulses require more dispersion to achieve maximum compression as compared to the GS pulses and the rate of GS pulse broadening induced by applied dispersion is large due to the larger bandwidth of GS. The maximally compressed pulse widths are 970 fs with a TBP of 1.1 for the GS transition and 1.2 ps with a TBP of 1.1 for the ES transition, assuming a hyperbolic-secant-squared pulse shape.

Figure 4.4: (a) GS pulse width vs. the second grating position and (b) intensity autocorrelation signal of externally compressed pulses.
Figure 4.5: (a) ES pulse width vs. the second grating position and (b) intensity autocorrelation signal of externally compressed pulses.

Figure 4.6 shows GS and ES pulse characteristics in terms of pulse widths and linear chirp magnitude with respect to the reverse bias applied on the saturable absorber. The magnitude of the linear chirp is converted from the maximally compressed position of the second grating in the compressor using the following relationship [4].

\[ D = \frac{\omega}{\lambda l_e} \frac{d^2 \varphi}{d\omega^2} \]  
\[ \frac{d^2 \varphi}{d\omega^2} = -\frac{\lambda^3}{2\pi c^2 d^2 \cos \theta} l_e \]  

where \( D \) is the dispersion parameter (ps/nm cm), \( d^2 \varphi/d\omega^2 \) is the group velocity dispersion, \( l_e \) is twice the second grating distance from zero dispersion point, \( d \) is the groove spacing, and \( \theta \) is the emerging angle.
4.2.3 Summary

Stable passive mode-locking via GS and ES transitions are achieved from the grating coupled external cavity. Optical pulse train solitarily generated from the GS and ES are investigated and their pulses characteristics are studied and summarized in Table 4.1.
Table 4.1: Summary of pulse characteristics from QD mode-locked laser.

<table>
<thead>
<tr>
<th>Transition</th>
<th>Condition</th>
<th>Chirp Sign</th>
<th>Compressed Pulse Width</th>
<th>Linear Chirp Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>GS</td>
<td>DC: 140 mA, RB: 5V</td>
<td>Upchirped</td>
<td>970 fs (TBP: 1.1)</td>
<td>3.146 [ps/nm]</td>
</tr>
<tr>
<td>ES</td>
<td>DC: 240 mA, RB: 2V</td>
<td>Upchirped</td>
<td>1.2 ps (TBP: 1.1)</td>
<td>4.134 [ps/nm]</td>
</tr>
</tbody>
</table>
4.3 Monolithic QD Devices

A grating coupled QD external cavity mode-locked laser is suitable to study the chirp sign of generated pulses via the GS and ES transition. However, potentially higher insertion loss of external gratings and the possibility of working away from the gain peak ultimately lead to the use of higher injection current and thus additional chirp on the pulses. To reduce this excess chirp from carrier density effects, monolithic devices (two section device and colliding pulse mode-locking device) are fabricated.

4.3.1 QD Two Section Device

A monolithic QD two section device was fabricated from the same QD wafer. The length and waveguide width of the device are 2 mm and 5 μm, respectively. The length of the saturable absorber is 150 μm. The device length of this monolithic two section device is the same as that of the curved QD two section device used in the external cavity experiment. The passive mode-locking was performed on the device. The shortest optical pulses via the GS transition from the monolithic QD two section device are generated with injection current of 70 mA with an absorber bias of - 8 V with repetition rate of 20.3 GHz. The average output power is approximately 2.7 mW. It should be mentioned that even though higher saturable absorber bias is applied on the monolithic device compared to the curved two section device used in the external cavity, the injection current density is around 0.5 times that of the curved two section device.
The optical and RF spectra and intensity autocorrelation signal from the monolithic QD two section device are shown in Figure 4.7. The measured full width at half maximum (FWHM) of the spectral bandwidth and pulse width from the optical pulses are 2.9 nm and 2.4 ps assuming a Gaussian pulse shape, respectively, yielding a TBP of 0.915, which is about twice the Fourier transform limit. To investigate the chirp sign, the pulses are amplified through a QD SOA without any noticeable pulse broadening and then directed to the dual grating compressor. The
pulses do not experience compression in either the negative or positive GVD region, suggesting that the quadratic phase of the pulse is compensated by having low current density and high absorber bias of -8 V, since the grating compressor compensates for quadratic phase. As a result, the pulses have high order phase, i.e. cubic phase, quartic phase, quintic phase, etc. The plot for the pulse width vs. the 2nd grating position is shown in Figure 4.8.

![Figure 4.8: The pulse width vs. the second grating position.](image)

**4.3.2 Colliding Pulse Mode-Locked Device**

The colliding pulse mode-locking (CPM) technique is very attractive for high speed optical communication since harmonic mode-locking is used and can generate ultra short pulses without complicated architectures [5]. Since two pulses counter-propagate in a given round trip
time, the repetition rate of CPM is double of that of fundamental cavity. Higher harmonic CPM can be achieved by geometric configuration of the gain and the saturable absorber(s) [6]. Monolithic CPM design has several advantages over external cavity design, such as shorter pulse with higher repetition rate and mechanical stability, as well as compactness. The effects of the transient absorber gratings in a saturable absorber formed by counter propagating pulses were first studied in dye lasers to synchronize and shorten the pulses, and sub 0.1 ps pulse duration was reported [7]. The same principle has been used to generate shorter pulses from semiconductor lasers in external cavities or monolithic device [8]. When two pulses collide coherently in the semiconductor’s saturable absorber, a standing optical wave builds a carrier density absorption grating in which the rate of carrier generation is the highest at the peak of the standing wave and the lowest at the valley. Colliding two pulses coherently is an effective way to saturate an absorber rather than using one pulse (self-colliding), because less pulse energy is needed to reach transparency of the absorber and hence it also potentially avoids self-phase modulation (SPM). Optical pulses close to transform-limited were reported using QD CPM laser [9].

A CPM device is fabricated and the pulse width of the generated optical pulse train is measured. The length and waveguide width of the CPM device are 3 mm and 5 μm, respectively. The length of the saturable absorber is 150 μm and located in the middle of the device. Both facets are uncoated. Stable passive mode-locking is achieved with an injection current of 61 mA on the gain section and a reverse bias of 5.5 V on the saturable absorber section. The optical spectrum and intensity autocorrelator signal are shown in Figure 4.9. Every second FP
longitudinal mode is fully suppressed as shown in inset of Figure. 4.9 (a). The resolution of optical spectrum is 0.01nm. The measured FWHM of the lasing optical bandwidth and pulse width are 0.744 nm and 4.55 ps, assuming a Gaussian pulse shape. The calculated TBP of 0.442 shows that Fourier transformed limited pulses are generated from the QD CPM device.

Figure 4.9: (a) Optical spectra and (b) intensity autocorrelation signal from CPM device.
References


CHAPTER 5: SPECTRAL DEPENDENCE OF QUANTUM DOT MODE-LOCKED SEMICONDUCTOR LASERS

5.1 Spectral Dependence of Linewidth Enhancement Factor

One of most important physical parameter of semiconductor lasers is the linewidth enhancement factor (LEF). Henry first introduced the LEF, i.e. “α”, to explain the substantial linewidth broadening as compared to the Schawlow-Townes linewidth formula based on the fact that each spontaneous emission not only causes an instantaneous change of intensity and phase but also causes additional phase shift due to the refractive index dependence on carrier density [1]. The LEF affects linewidth, chirp, and filamentation as well as the overall semiconductor laser dynamics like noise and optical injection [2]. The LEF is defined by the coupling ratio between the carrier induced change of real and imaginary parts of susceptibility $\chi(N)$,

$$\text{LEF} \equiv -\frac{d[Re\{\chi(N)\}]/dN}{d[Im\{\chi(N)\}]/dN} = -2k_0 \frac{dn/dN}{dg/dN}$$ (5.1)

where $k_0$ is the free-space wave vector, $n$ is the refractive index, $g$ is the electronic gain per length, and $N$ is the electron concentration [1-3].

The LEF of a QD semiconductor laser above threshold is expected to be small because of the expected high differential gain and symmetric gain spectrum which arises from the delta like density of states of QDs. Lasing at the peak of a symmetric gain spectrum does not show the
carrier induced refractive index change due to the Kramers-Kronig relation. But the LEF above threshold is similar to that of quantum well lasers or can be substantially larger, ~57 [4-6]. It turns out that the LEF of a QD laser varies due to the inhomogeneous broadening caused by the size fluctuation of dots, the contribution of excited states, carrier induced refractive index change (free carrier and interband resonant transition), carrier temperature, etc [4-8].

In this section, LEFs above threshold are measured by the continuous wave injection locking method [9]. The locking bandwidth from the steady state solution of the rate equation can be obtained from [10-12]:

\[ \Delta \omega = \frac{c}{2n_e L} \sqrt{\frac{P_i}{P}} (\sin \theta - \alpha \cos \theta) \]  

(5.2)

where \( \Delta \omega = \omega_{master} - \omega_{slave} \), \( \alpha \) is the LEF, \( \theta \) is the phase difference between the master and slave laser, \( P_i \) is the injected optical power to the slave laser, \( P \) is the optical power of the slave laser, \( n_e \) is the refractive index of the slave laser, \( L \) is the cavity length of the slave laser, and \( c \) is the speed of light. By setting \( \theta_0 = \tan^{-1}(\alpha) \) with the restriction that \(- \pi/2 < \theta < \pi/2\) in (5.2), Equation (5.2) can be rewritten as

\[ -\frac{c}{2n_e L} \sqrt{\frac{P_i}{P}} (1 + \alpha^2) < \Delta \omega < \frac{c}{2n_e L} \sqrt{\frac{P_i}{P}} \]  

(5.3)

The phase and amplitude coupling yields an asymmetric locking bandwidth and maximum locking can be achieved for negative detuning for a given injection power. A simple illustration for Equation (5.3) is shown in Figure 5.1. Light from the master laser is injected to the slave laser (QD FP). The frequency (\( \omega_{inj} \)) of injection light has an offset with respect to a
target longitudinal mode \( (\omega_o) \) of the FP laser and the offset can be positive or negative. If the injection power is strong enough to lock the target longitudinal mode for a given offset, the injection frequency will dominate the gain and as a result the other FP modes cannot oscillate in the cavity. Locking for larger frequency offset requires increased injected optical power.

Figure 5.1: Illustration of a locking bandwidth of FP laser. (a) lower frequency detuning, (b) upper frequency detuning, and (c) an asymmetric locking bandwidth for negative and positive injection locking due to LEF.

For the locking bandwidth measurement, a QD FP laser is fabricated and the tunable laser is constructed by coupling a curved QD device with a grating (1200 line/mm) in the Littman/Metcalf configuration. The QD FP length of 734 μm is chosen for a high free spectral range (FSR) in the case of GS lasing because smaller QD FP lengths, i.e. 534 μm or 634 μm,
show lasing of only the excited state or two state lasing, as discussed in Chapter 3. The temperature of both QD lasers is controlled by thermo electric controllers (TEC) attached to the heat sink. The experimental setup is shown in Figure 5.2.

![Experimental Setup](image)

Figure 5.2: Experimental Setup. G: grating, M: mirror, I: isolator, NDF: neutral density filter, QD-FP: quantum dot Fabry-Pérot laser, OSA: optical spectrum analyzer.

A DC current of 45 mA ($2 \times I_{th}$) is injected to the QD FP and an output power of 5.5 mW is measured from one facet. The lasing wavelength is $\sim 1264$ nm. The FSR of the FP laser is measured to be 58 GHz with an injection current of 45 mA. Tuning of the master laser is achieved by introducing a very small change in the temperature of the gain medium using the TEC. A $100 \ \Omega$ change in the resistance of the temperature controller corresponds to a temperature change of $0.149 \ ^{\circ}C$ and causes a 3.2 GHz (0.017 nm) shift of FP modes. The wavelength tuning performance with respect to temperature is shown in Figure 5.3.

The LEF measurement is performed at five different wavelengths of the ground state, i.e., one around the gain peak ($\lambda_3 = 1264$ nm), where lasing occurs, and two each for the anti-Stokes ($\lambda_1 = 1254$ nm and $\lambda_2 = 1259$ nm) and the Stokes side ($\lambda_4 = 1269$ nm and $\lambda_5 = 1274$ nm) with respect to the gain peak as shown in Fig. 5.4 (a).
Figure 5.3: QD FP laser wavelength tuning with respect to temperature.

The injection power is controlled by a neutral density filter and injection locking is defined when side mode suppression is over 40 dB. Figure 5.4 (b) shows optical spectra of free running and injection locked QD F-P laser and a wide span of the injection locked optical spectrum is shown in Figure 5.4 (c). The measured locking bandwidth for each of the five different spectral regimes is shown in Figure 5.4 (d) - (h). The observed asymmetric locking bandwidth arises from phase and amplitude coupling which gives a wider locking bandwidth for negative detuning in factor of \((1+\alpha^2)^{1/2}\) for a given injection power \([10,12]\). The more asymmetric the slopes are, the larger the LEF. The ratio of the two slopes of locking bandwidth is power independent and is used to calculate LEF \([9]\). In Figure 5.4 (i), an absolute value of LEF is used since the sign of LEF could not be determined by the injection locking method. It is found that a considerable spectral dependence of the LEF above threshold is observed within ~20 nm rather than photon energy dependence or independence of the LEF under low injection
Figure 5.4: (a) Optical spectrum of a free running QD FP laser biased at 45 mA (5 arrows indicate measurement points for LEF), (b) optical spectrum of QD FP laser before and after injection locking, (c) wide span of optical spectrum of injection locked QD FP laser, (d) - (h) injection locking bandwidth with different lasing spectral points, and (i) LEF as function of wavelength.

Even though the LEF around the gain peak ($\lambda_3$) cannot be calculated from the locking
bandwidth due to the resolution limit of the OSA, it is obvious that its locking bandwidth is most asymmetric with respect to others and the value of the LEF is above 6. The LEF is significantly reduced (around 1) on the anti-Stokes side ($\lambda_1$ and $\lambda_2$) and also apparently reduced (around 4) on the Stokes side ($\lambda_4$ and $\lambda_5$) compared to the LEF around the peak gain. The observed low LEF above threshold on the anti-Stokes side is in agreement with theoretical work by Oksanen et al [8]. Oksanen et al predicted that, due to the shape of density of states, a low LEF can be achieved by detuning the laser operation to shorter wavelengths from the gain maximum, which is red shifted from the density of states maximum due to Fermi-Dirac statistics. The lower LEF on the Stokes side is not clearly understood and needs additional study. However, the carrier induced refractive index change on the Stokes side may play a role and will be discussed in the following section.

5.2 Spectral Dependence of Pulse Duration and Chirp

In the previous section, spectral dependence of the LEF from a QD laser is observed. The nonlinearity of the semiconductor gain medium affects the pulse forming mechanism. For example, if the optical pulse duration is longer than the carrier cooling time, optical pulses propagating in the semiconductor gain medium see a time varying refractive index due to the carrier depletion and hence experience temporal cubic phase. The time varying refractive index modifies the instantaneous frequency and produces a parabolic frequency sweep due to self-
phase modulation [14-15]. LEF can act as a pulse broadening mechanism through the carrier induced refractive index change that changes the carrier wavelength versus time.

The pulse duration and linear chirp are studied when pulses are formed for different spectral regimes. For this experiment, the grating coupled external cavity mode-locked laser used in Chapter 4 is employed to generate optical pulses of different spectral regimes. Passive mode-locking is performed on the cavity with injection current of 140 mA and reverse bias of 5 V. The fundamental cavity frequency is 2.5 GHz. The peak of the ASE from the saturable absorber section is around 1275 nm with a DC current of 140 mA. The time duration of the generated pulses is measured while the lasing wavelength is tuned by only changing the angle of the grating for fixed applied injection current and reverse bias. The tuning range of the lasing wavelength is from 1260 nm to 1285 nm within the given fixed operating conditions. During tuning, the cavity is carefully adjusted to have similar optical bandwidth for each different lasing wavelength. A lasing bandwidth of ~8 nm is achieved from the peak of ASE on the blue side (from 1275 nm to 1255 nm), however a lasing bandwidth of ~4.7 nm is achieved on the red side (from 1280 nm to 1285 nm) as shown in Figure. 5.5 (a). Figure 5.5 (b) and (c) show the intensity autocorrelation signal and pulse duration with respect to various lasing wavelengths of the passively mode-locked laser under the same operating conditions.

The measured FWHM of the autocorrelation signal varies with respect to the different lasing bands within 25 nm. The pulse duration of the optical pulse train is reduced from around 30 ps at 1275 nm to around 22 ps at 1260 nm for similar spectral bandwidths. For the Stokes side lasing, the pulse width is also reduced. To compare the magnitude of the linear chirp, the pulse
trains are sent to the dual grating compressor. The pulse trains generated at the different lasing wavelengths are compressed in the negative GVD regime but with a different magnitude of negative GVD as shown in Figure. 5.6.

Figure 5.5: (a) Optical spectra and (b) intensity autocorrelation signal, and (c) pulse width vs. lasing wavelength.

The impressed linear chirp magnitude is smaller for the blue side and larger for the red side. It is shown that less linear chirp is impressed on the pulse generated from the anti-Stokes side and a pulse width reduction of 26 % is observed by a 15 nm shift of the lasing wavelength.
from the peak of ASE towards the blue side.

Figure 5.6: (a) Plot for compressed pulse width vs. the second grating position and (b) plot for maximally compressed position and pulse width vs. wavelength.

Another curved two section device is fabricated and constructed into an external cavity mode-locked laser to confirm the reduction of pulse width and reduction of the linear chirp on the anti-Stokes side. The length of device and saturable absorber are 3 mm and 250 μm. Hybrid mode-locking was performed on the external cavity with an injection current of 130 mA and a reverse bias of 5 V. The fundamental cavity frequency is 3.5 GHz and similar experiments are performed. The cavity length, injection current, saturable absorber bias, and RF power for hybrid mode-locking are fixed during the measurement. The tuning range is from 1255 nm to 1280 nm and the cavity is also adjusted to have a similar lasing bandwidth for each lasing wavelength. Similar optical spectra of bandwidth ~6.3 nm are achieved from 1250 nm to 1275 nm but with ~4.2 nm on the long wavelength side. Less optical bandwidth of the lasing on the red side is
similar to the previous device.

Figure 5.7: (a) Optical spectra and (b) intensity autocorrelation signal, and (c) pulse width vs. lasing wavelength.

Figure 5.7 shows the optical spectra vs. center lasing wavelength and the intensity autocorrelation signal with the measured pulse duration, assuming a hyperbolic-secant-squared pulse shape. It is clearly shown that there is significant reduction of pulse duration when the hybrid mode-locked QD laser is operated on the anti-Stokes side. To find the magnitude of the
linear chirp of the generated pulse vs. the center lasing wavelength, the pulse trains are sent to the dual grating compressor.

![Graph showing compressed pulse width vs. the second grating position and maximally compressed position and pulse width vs. wavelength.](image)

Figure 5.8: (a) Plot for compressed pulse width vs. the second grating position, (b) plot for maximally compressed position and pulse width vs. wavelength.

Similar behavior is observed as in the case of passive mode-locking. The optical pulses generated from the short wavelength region have less linear chirp compared to the optical pulses generated from the long wavelength region as shown in Figure 5.8 (b).

These results show that the pulse width of the generated optical pulse is reduced from 11.6 ps at 1275 nm to 6.9 ps at 1255 nm, operating with similar spectral bandwidth. This corresponds to a 40 % reduction of the pulse width and a 33 % reduction of the linear chirp. A pulse width of 660 fs after compression is achieved at 1270 nm, assuming a hyperbolic-secant-squared pulse shape with TBP of 0.517. The autocorrelation signal is shown in Figure 5.9.
Figure 5.9: Intensity autocorrelation signal of externally compressed optical pulses formed at 1270 nm.

Table 5.1: Reduction of pulse duration and linear chirp by 20 nm wavelength tuning.

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>1255 nm</th>
<th>1275 nm</th>
<th>∆λ= 20 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse Duration</td>
<td>6.9 ps</td>
<td>11.6 ps</td>
<td>↓ 40 %</td>
</tr>
<tr>
<td>Linear Chirp</td>
<td>2.27 ps/km</td>
<td>3.39 ps/km</td>
<td>↓ 33 %</td>
</tr>
</tbody>
</table>

5.3 Summary

The spectral dependence of the LEF, the pulse duration and linear chirp are observed when QD lasers oscillate above threshold. The LEF, pulse width and linear chirp are lower on the anti-
Stokes side (around 10 nm to 15 nm blue shift from the peak of the gain), however pulses formed on the Stokes side (around up to 10 nm red shift from the peak of the gain) possess relatively large linear chirp. These experimental results suggest that QD lasers which operate on the anti-Stokes side of the gain peak, corresponding to a low nonlinear spectral regime, could potentially achieve lower chirp and shorter optical pulses.
References


In injection locking of semiconductor lasers has been considered as an effective technique to control lasers both in the optical frequency and time domains [1-7]. In this section, we explore optical pulse injection locking for two different applications, namely short pulse generation and optical clock recovery. We utilize the unique features of quantum dot gain media such as inhomogeneous broadening, and ground and excited state transitions.

### 6.1 Coherent Spectral Bandwidth Combining

Mode-locked lasers have been used to generate short pulse trains with high peak intensity. If there are $N$ phase locked modes of equal amplitude oscillating simultaneously in the cavity, the combined total amplitude of all of the modes can be expressed as

$$ E(t) = E_0 \sum_{n=0}^{N-1} e^{j(\omega_0 + n\Delta \omega) t} = E_0 e^{j\omega_0 t} \frac{e^{jN\Delta \omega t} - 1}{e^{j\Delta \omega t} - 1} $$

(6.1)

where $\Delta \omega$ is the axial mode spacing in frequency and the total intensity is

$$ I(t) = E_0^2 \frac{\sin^2(N\Delta \omega t/2)}{\sin^2(\Delta \omega t/2)} $$

(6.2)

The total intensity varies with time $t$ and the maximum value occurs at
\[ \frac{\Delta \omega t}{2} = 0, \pi, 2\pi, 3\pi, \ldots, n\pi \]  

(6.3)

If we evaluate Equation (6.2) at \( \Delta \omega t/2 = 0 \), the peak intensity becomes

\[ I(t)_{\text{max}} = \lim_{\Delta \omega t/2 \to 0} E_0^2 \frac{N^2(\Delta \omega t/2)^2}{(\Delta \omega t/2)^2} = N^2 E_0^2 \]  

(6.4)

So the peak intensity is proportional to the square of the number of longitudinal modes. Since \( \Delta \nu = 1/T \) where \( T \) is a round trip time, the intensity peak is produced at \( t=0, T, 2T, \) and so on. \( N-2 \) much weaker subsidiary peaks come in between the intensity peaks and FWHM pulse width given, roughly, by

\[ \Delta t_p \approx \frac{2\pi}{\Delta \omega N} = \frac{T}{N} \]  

(6.5)

The subsidiary peaks can be reduced or eliminated by amplitude shaping of longitudinal modes. According to Equation (6.4) and (6.5), the peak intensity increases and pulse duration is reduced with the number of longitudinal modes participating in the mode-locking process [8-9]

We perform a simple optical pulse injection locking experiment for coherent spectral bandwidth combining to generate shorter pulses by increasing the phase-locked longitudinal mode numbers. For this experiment, two external cavities operating as master and slave lasers are constructed. The grating coupled master laser is hybridly mode-locked and the pulse train from the master laser is injected into the slave laser, which is passively mode-locked. The cavity frequency of both mode-locked lasers is the same (~3 GHz) to ensure equally spaced longitudinal mode spacing. The phase of the longitudinal modes of the master laser is well organized due to hybrid mode-locking. The setup is shown in Figure 6.1.
Figure 6.1: Experimental setup for coherent bandwidth combining.

For the coherent spectral bandwidth combining, the optical spectrum of the master laser slightly overlaps with the optical spectrum of the slave laser. The output pulse train from the injection locked slave laser is amplified through a QD SOA for diagnostics. The results for the coherent bandwidth combining is shown in Figure 6.2.

The pulse widths of the optical train generated from the master and slave laser are measured to be around 15 ps assuming a Gaussian pulse shape. The measured 3 dB optical bandwidth of the master and slave lasers are 2.7 nm and 7.5 nm, respectively. When the slave laser is locked (when the phase of the slave laser follows the phase of the master laser) by induced optical pulse injection locking, the 3 dB optical bandwidth and the pulse width of the injection locked slave laser is 11.6 nm and 9 ps, assuming a Gaussian pulse shape, respectively, as shown in Figure 6.2. The 3 dB optical bandwidth is calculated by the second peak of the optical spectrum. The TBP of the slave laser does not significantly change before and after the injection locking as shown in Figure 6.2 (c).
Figure 6.2: (a) Optical spectra, (b) autocorrelation signal, and (c) autocorrelation FWHM of the master, the slave, and the injection locked slave laser.

The optical bandwidth of the slave laser is increased by 55 % due to the injection of optical bandwidth of 2.7 nm, which is ~35 % of the optical bandwidth of the slave laser. At the same time, a 43 % reduction in the pulse width of the injection locked slave laser is achieved. The reduction of the pulse duration by the increase of the optical bandwidth can be explained by an increase of the number of the phase locked modes participating in the pulse forming process.
in the slave laser, which is illustrated in Figure 6.3.

Figure 6.3 (a) and (b) present the phase-locked longitudinal modes by hybrid mode-locking and passive mode-locking, respectively. The mode set of the master laser is injected to the slave laser having a small spectral overlap. The small spectral overlap induces coupling between two different longitudinal mode sets in the slave laser. The amplitude and phase of the longitudinal modes of the injected optical pulses share and transfer not only energy but also their phase to the longitudinal modes of the slave laser. Finally, the phase of the slave laser follows the phase of the injected longitudinal modes, as shown in Figure 6.3 (c) and (d).

![Diagram](image.png)

Figure 6.3: Illustration of coherent spectral band combining. Optical spectrum of (a) master laser, (b) slave laser, (c) initial state of injected slave laser, and (d) injection locked slave laser.
This is a cost effective and simple technique compared to synthesized coherent optical pulses [10]. The inhomogeneous nature of QD semiconductor gain can be used to combine several spectral bands to generate even shorter optical pulses. The pulse trains from the injection locked slave laser are externally compressed in the negative GVD region. A pulse width of 770 fs is achieved after compression assuming a Gaussian pulse shape with TBP of 1.174, as shown, in Figure 6.4.

![Intensity autocorrelation signal](image)

Figure 6.4: Intensity autocorrelation signal of externally compressed pulses of the injection locked slave laser.

### 6.2 Interband Optical Pulse Injection Locking

Using QD mode-locked lasers for clock recovery is attractive for high speed all-optical
clock recovery due to their superior characteristics, such as low noise and fast gain recovery, as well as broad spectrum, which originates from the GS and the ES transitions.

In this section, we discuss the possibility of optical pulse injection locking between a master and a slave laser when the master and slave laser oscillate via different states, e.g., using either GS or ES transitions. This interband optical pulse injection locking will overcome the physical consideration of sharing the same spectral band between master and slave lasers for injection locking. As a result, one master laser can control different slave lasers whose finite lasing spectral band does not overlap with that of the master laser.

![Figure 6.5: Illustration of interband optical pulse injection locking experiment. (a) Case I: ES to GS injection and (b) Case II: GS to ES injection. (ML: master laser, SL: slave laser).](image-url)
The interband optical pulse injection locking experiment is carried out by considering two cases shown in Figure 6.5. In the first case, pulses from the ES transition of the master laser are injected to the slave laser oscillating via the GS transition. The second case examines pulses from the slave laser operating on the ES transition injected with pulses generated via GS transition from the master laser. Two grating coupled quantum dot external lasers (master and slave) were constructed such that each laser operated with a nominal pulse repetition frequency of 4 GHz. Hybrid mode-locking and passive mode-locking is achieved for the master laser and the slave laser, respectively. The lasing band selection of GS or ES is achieved through a grating (900 ln/mm) which is externally coupled to a QD curved 2-section device in the Littrow configuration.

6.2.1 ES Optical Pulse Injection to the Slave Laser Oscillating via GS Transition

For ES optical pulse injection to the slave laser oscillating via GS, a bias current of 134 mA to the gain section, a reverse bias of 0 V and an RF power of 15 dBm to the saturable absorber section enables the master laser to be hybridly mode-locked via the ES transition. The slave laser is passively mode-locked via the GS transition by applying a reverse bias of 5.7 V to the saturable absorber and a bias current of 37 mA to the gain section. Both mode-locked lasers nominally operate at the same 4 GHz repetition rate. Angle tuning of the externally coupled gratings enables the master and slave laser to lase via the ES transition (1186.5 nm) and GS transition (1267.5 nm), respectively. The corresponding optical spectra are shown in Figure 6.6.
Lasing via the ES transition is achieved through ES amplified spontaneous emission (ASE) generated after the saturation of GS ASE.

Figure 6.6: (a) ES optical spectrum of the hybridly mode-locked master laser, inset: wide span optical spectrum and (b) GS optical spectrum of the passively mode-locked slave laser, inset: wide span optical spectrum.

Figure 6.7 shows the interband optical pulse injection locking setup. An optical pulse train generated from the master laser oscillating via ES is injected into the saturable absorber of the slave laser oscillating via GS. The injection power level is controlled by a neutral density filter. The output of the slave laser is taken from the saturable absorber section. The partially reflected output of the slave laser by the pellicle is passed through an optical bandpass filter and it is amplified through a QD SOA. Since the optical bandpass filter allows only the spectral band of the slave laser to pass, only the spectral band of the interband optical pulse injected slave laser is detected and analyzed.

The average power of the injected signal is ~1 mW. A long pass filter whose transmission edge wavelength is 1250 nm is used as an optical filter. This filters the optical power of the master laser which is partially reflected from the facet of the slave laser, so only the optical pulse train generated from the slave laser is amplified through a QD SOA and is analyzed.
The injected interband optical pulses do not induce any noticeable change in the optical spectrum of the slave laser as shown in Figure 6.8 (a), where the resolution of the OSA is 0.01 nm. It should be noted that the ES pulse train is not supported in the slave laser due to an insufficient injected current level on the gain section of the slave laser and also due to the round trip losses experienced by the ES pulse from the externally coupled grating which only reflects the GS optical pulse back to the slave diode laser. As a result, the injected ES optical pulse train first saturates the ES band in the saturable absorber of the slave laser and is then attenuated through the slave oscillator.

![Figure 6.8](image)

Figure 6.8: (a) Optical spectrum, (b) RF power spectrum and (c) digital sampling scope trace of the passively mode-locked slave laser oscillating via GS transition before and after ES optical pulse train injection.

The phase and amplitude noise of the slave laser are reduced and an optical pulse train is observed after the injection of the interband optical pulses. As shown in Figure 6.8 (b) and (c), the noise reduction and stable optical pulse train generation of the slave laser shows that the
slave laser is locked to the master laser. The video and resolution bandwidth of RFSA are both 10 kHz.

The locking bandwidth of the slave laser is measured by changing the repetition rate of the master laser and varying the injection power. The pulse repetition rate of the master laser is achieved by changing the frequency of the signal generator used for the hybrid mode-locking. The repetition rate of the master laser is detuned from +500 kHz to –500 kHz with a noise suppression of 70 dB as shown in Figure 6.9 (a). The optical injection power level to the slave laser is controlled by a neutral density filter. Figure 6.9 (b) shows the RF spectrum of the slave laser at the maximum detuning of 500 kHz with an estimated 1 mW of injection power. It corresponds to $0.125 \times 10^{-3}$ fractional bandwidth [1].

![Figure 6.9: (a) Master laser repetition rate tuning and (b) locking range of the slave laser.](image)

Figure 6.9 (a) shows the locking bandwidth in terms of the injected optical power versus input pulse repetition rate. Locking is determined by observing a > 30 dB reduction of the
sideband noise from the fundamental tone of the RFSA and also by the optical pulse train shown from the digital sampling scope (DSS) triggered by the signal generator used for the master laser. Figure 6.10 (b) shows the total locking bandwidth as function of the injected interband optical power.

![Graph](image)

**Figure 6.10:** (a) Locking bandwidth and (b) total locking bandwidth of the interband optical pulse injected slave laser oscillating GS transition.

Injection locking of the slave laser for a given injection power (1 mW) is achievable at large values of positive detuning (4 GHz + 330 kHz) than for negative detuning (4 GHz – 170 kHz). The asymmetric locking bandwidth range can be explained by the causality of the saturable absorber and not by the carrier-induced refractive index change caused by the injected interband optical pulses. This is because the increase of index induced by the ES gain depletion in the slave laser will result in an increase of the effective cavity length of the slave laser and the slave laser would be locked to much lower injection repetition rate compared to the nominal
repetition rate of the slave laser [1].

6.2.2 GS Optical Pulse Injection to the Slave Laser Oscillating via ES transition

In the second experiment, a GS optical pulse train from the master laser is injected to the saturable absorber of the slave laser operating on the ES transition. The experimental setup is shown in Figure 6.11. Both the GS and ES bands in the saturable absorber of the slave laser are bleached at the same time by the injected GS optical pulse from the hybridly mode-locked master laser and the ES optical pulse from the passively mode-locked slave laser, respectively.

Figure 6.11: Schematic diagram of interband optical pulse injection locking experiment. (QD-

The GS master laser is hybridly mode-locked with a bias current of 75 mA to the gain section and a reverse bias of 0 V and RF power of 15 dBm to the saturable absorber. For the operation of the slave laser via the ES transition, a bias current of 115 mA and a reverse bias of 1.5 V are applied to the gain and the saturable absorber section, respectively. Both lasers are mode-locked at a fundamental cavity length of a 4 GHz and the lasing wavelengths are 1271 nm and 1191.8 nm for the master and slave laser, respectively, as shown in Figure 6.12.

Figure 6.12: (a) GS optical spectrum of the hybridly mode-locked master laser, inset: wide span optical spectrum and (b) ES optical spectrum of the passively mode-locked slave laser, inset: wide span optical spectrum.
To observe the dynamics of the interband optical pulse injected slave laser oscillating via the ES transition, the GS optical pulses, having an estimated average power of 1 mW, are injected into the slave laser. It should be noted that the injected GS optical pulse can experience gain in the slave laser diode itself owing to the large bias current needed to achieve a population inversion on the ES transition. This large bias current also creates a population inversion at the GS transition. Nonetheless, the injected GS optical pulses are not resonant in the slave laser cavity due to the externally coupled grating which allows only the ES optical pulses to feed back into the slave laser diode. An optical bandpass filter with center wavelength of 1200 nm and a full width at half maximum of 10 nm is inserted before QD SOA and the center wavelength of the optical bandpass filter is adjusted to 1192 nm by tilting the filter slightly. Since the filter blocks the GS optical pulse train partially reflected from the facet of the slave laser and only passes the ES optical band of the slave laser, we can investigate the dynamics of the GS optical pulse injected slave laser oscillating via ES transition. ES optical pulses of ~1 mW average power are injected into the slave laser oscillating through the GS transition. The slave laser does not lock, even though the master and slave laser both oscillate at the same repetition rate of 4 GHz. The optical band of the slave laser is reduced and also distorted after injection of the interband optical pulses. Figure 6.13 shows the optical and RF spectrum of the slave laser before and after an injection of the GS optical pulses.
To investigate how the slave laser oscillating via ES transition responds to the different injection rate of GS optical pulses, the pulse repetition rate of the hybridly mode-locked master laser is detuned from 3.991 GHz to 4.014 GHz by tuning the signal generator used for hybrid mode-locking. The performance of the detuned master laser is shown in Figure 6.14 (a). The locking dynamics of the slave laser is examined as the repetition rate of the master laser is tuned within the detuning range. First, as the injection rate is reduced compared to the nominal repetition rate of the slave laser, the slave laser does not lock to the interband optical pulse injection. The average repetition frequency of the slave laser is shifted to higher rates during the interband optical pulse injection rather than locked to the master laser, as shown in Figure 6.14 (d). On the other hand, at higher injection repetition rates than the nominal repetition rate of the slave laser, the repetition rate of the slave laser follows the master laser. As the repetition rate of
the interband optical pulse increases, the phase and amplitude noise decreases and the slave laser becomes locked to the master laser over the range of 4.0013 GHz to 4.008 GHz. Figure 6.14 (i) which shows the upper and lower limit of the recovered clock signal.

Figure 6.14: RF spectra. (a) the master laser tuning, (b) - (f) the interband optical pulse injected slave laser oscillating via ES transition. The cavity frequency offset of the slave laser with
respect to the master laser is (b) - 2 MHz, (c) - 1.5 MHz, (d) - 0.5 MHz, (e) 0 MHz, (f) + 0.5 MHz, (g) + 1 MHz, (h) + 1.2 MHz, and (i) above + 1.3 MHz.

The optical pulse train and optical spectrum of the locked slave laser during the interband optical pulse injection at a repetition rate of 4.004 GHz are shown in Figure 6. 15.

![Figure 6.15: (a) Optical pulse train and (b) optical spectra of the slave laser oscillating via ES transition before and after injection of GS optical pulse train of 4.004 GHz.](image)

The locking bandwidth of the interband optical pulse injected slave laser oscillating via the ES transition is measured in terms of the injected power and cavity frequency offset. The locking bandwidth is plotted in Figure 6.16. A large locking bandwidth of 6.7 MHz is achieved with an estimated 1 mW injection power, corresponding to $1.675 \times 10^{-3}$ fractional bandwidth. We should note here that the locking of the interband injected slave laser is determined not only by
the optical pulse train on the DSS but also by the sideband noise suppression of over 30 dB from the fundamental RF tone. Even though we observed optical pulses on the DSS, while the master laser was detuned above 4.009 GHZ, the sideband noise increased due to the large repetition rate offset between the master and slave laser. In that case, the sideband noise reduction from the fundamental tone was less than 30 dB in the RF spectrum.

![Graphs showing locking bandwidth and total locking bandwidth](image)

Figure 6.16: (a) Locking bandwidth and (b) total locking bandwidth of the interband optical pulse injected slave laser oscillating ES transition.

### 6.2.3 Summary

Clock recovery via interband optical pulse injection is achieved using a passively mode-locked quantum dot laser. The recovery of the clock signal (~4 GHz) is achieved by injecting an interband optical pulse train to the saturable absorber section. The ES (GS) clock signal is recovered through the GS (ES) transitions. An asymmetry in locking bandwidth is observed for
both cases. The measured locking bandwidth is 10 times wider when the excited state clock signal is recovered from the ground state injection, as compared to recovering ground state clock signal from excited state injection. Table 6.1 shows summary of the interband injection locking.

Table 6.1: Summary of the interband optical pulse injection locking.

<table>
<thead>
<tr>
<th>Injection</th>
<th>Injection Power</th>
<th>Locking Bandwidth</th>
<th>Fractional Bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>ES to GS (4 GHz)</td>
<td>1 mW</td>
<td>500 kHz</td>
<td>0.125×10^{-3}</td>
</tr>
<tr>
<td>GS to ES (4 GHz)</td>
<td>1 mW</td>
<td>6.7 MHz</td>
<td>1.675×10^{-3}</td>
</tr>
</tbody>
</table>

Interband optical pulse injection locking results due to the interplay between the saturable gain and saturable absorption dynamics of the slave laser. Further study is required to identify the mechanism that enables the clock signal to be recovered through the interband transition and why the slave laser oscillating via ES does not lock to GS pulse injection of the master laser at negative or zero detuning from the slave laser nominal repetition rate of 4 GHz.
References


CHAPTER 7: CONCLUSION

Self-assembled InAs/InGaAs quantum dot lasers and mode-locked lasers are designed, fabricated and studied in this dissertation.

Optical pulses are generated using different types of quantum dot mode-locked lasers such as a grating coupled external cavity with a curved two-section device, monolithic two-section devices and colliding pulse mode-locked devices. The generated optical pulses via GS and ES transitions are upchirped for all passively mode-locked laser cases studied. The optical pulses are highly chirped except for the cases of the monolithic two-section device with high reverse bias and the colliding pulse mode-locked device. High reverse bias and collision of counter propagating pulses in the saturable absorber with low injection currents reduce chirp of the optical pulses. The observed pulse duration and chirp from quantum dot mode-locked lasers are comparable with that from quantum well mode-locked lasers. Spectral dependence of the LEF, the pulse duration, and the chirp is observed in quantum dot mode-locked lasers due to inhomogeneous broadening. Smaller LEF and less linear chirp are observed on the anti-Stokes side (around 10 nm to 15 nm blue shift from the gain peak) from the continuous wave quantum dot lasers and the quantum dot mode-locked lasers fabricated, respectively. These experimental results suggest that quantum dot lasers, which have a lower threshold current density compared to quantum well lasers, are promising as sources of shorter pulses with low time-bandwidth products, when operated on the anti-Stokes side.

Novel clock recovery using interband optical pulse injection to a passively mode-locked quantum dot laser is demonstrated for the first time and an asymmetric locking bandwidth is
observed. This interband optical pulse injection locking overcomes the physical consideration of sharing the same spectral band between a master and slave laser for injection locking. As a result, one master laser can synchronize different slave lasers whose finite lasing spectral band does not overlap with that of the master laser.

These results are achieved from the current limits of quantum dot lasers rather than from the ideal one. But the achievements of this dissertation are worthwhile in understanding the potential advantages of quantum dot lasers and utilizing them for quantum dot based mode- locked lasers toward high speed, short pulse, low noise, and all optical clock recovery sources.
APPENDIX A
C++ CODE OF CURVED TWO-SECTION WAVEGUIDE
module waveguide {

#include "ldata.h" #include <stdlib.h> #include <math.h>

void WaveguideMacro ( void )
{
    LPoint Polygon [ 100 ];

    /*****General_Variables along x,y*****/

double X,Y,XE;

double Ltot, Wtot, Width, Lsa, Wsa, Lgap, Gap_Cen, Gap_Angle, Gap_Angle1,
    L1, L1tap, Le, Lcur, L2, L2tap, Wtap;  /***Wtap is Width after tapered***/

    /*****Start_Points(0,y)*****/

double y_start;

    /*****Torus_Variables*******/

double x_Torus, y_Torus, R, R_In, R_Out, Torus_Angle, Start_Angle, Stop_Angle,
    delta_x, delta_y, R2, R2_In, R2_Out, R5, R5_In, R5_Out;

    /*****"Taper+L1" Variables*******/

double Rotate,
    x0,y0,x1,x2,x3,x4,x5,x6,y1,y2,y3,y4,y5,y6,
    rot_x1,rot_x2,rot_x3,rot_x4,rot_x5,rot_x6,
    rot_y1,rot_y2,rot_y3,rot_y4,rot_y5,rot_y6;

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double Pi = 3.1415926535897938, hund = 100 * 1000, Tipsep = 150*1000;

double Add = 10*1000, Add_sa = 20*1000, Sep = 20*1000;

double Polygon_Points4, Polygon_Points6;

LCell Cell_Draw = LCell_GetVisible ( );

LFile File_Draw = LCell_GetFile ( Cell_Draw );

LPoint Translation = LCursorGetPosition ( )

LObject Torus, Torus1, Torus2, Torus3;

/********************************************************************/

if(LLayer_Find(File_Draw, "Grid Layer") == NULL)
{
    LDialog_AlertBox("There is no Grid Layer layer.\n
    \nMake sure Grid Layer is in the layer map!"); return;
}

if(LLayer_Find(File_Draw, "Layer 0") == NULL)
{
    LDialog_AlertBox("There is no Layer 0 layer.\n
    \nMake sure Layer 0 is in the layer map!"); return;
}
int i, j;  /* i is row, j is column */

#define k 8  /* k is how many row? i=k */

double array[k][14]= {

  /*************** QD TS(2.5mm) start*************** /

  /* (j=0) (j=1) Ltot(j=2) Lsa(j=3) w_sa(j=4) L_gap(j=5) L1(j=6) L1tap(j=7)
     Wg(j=8) Le(j=9) Angle(j=10) Ltap2(j=11) L2(j=12) w_tap(j=13) */

  { 0, 1, 2500, 280, 7, 15, 30, 80, 5, 0, 7, 70, 30, 7 },
  { 0, 2, 2500, 280, 7, 15, 30, 80, 5, 0, 7, 70, 30, 7 },
  { 0, 3, 2500, 280, 7, 15, 30, 80, 5, 0, 7, 70, 30, 7 },
  { 0, 4, 2500, 280, 7, 15, 30, 80, 5, 0, 7, 70, 30, 7 },
  { 0, 5, 2500, 280, 7, 15, 30, 80, 5, 0, 7, 70, 30, 7 },
  { 0, 6, 2500, 280, 7, 15, 30, 80, 5, 0, 7, 70, 30, 7 },
  { 0, 7, 2500, 280, 7, 15, 30, 80, 5, 0, 7, 70, 30, 7 },
  { 0, 8, 2500, 280, 7, 15, 30, 80, 5, 0, 7, 70, 30, 7 },

  /*************** QD TS(2.5mm) end*************** /

};
double v[14];

for (i=0; i<=k-1; i++) {
    for (j=0; j<=13; j++)
        { v[j]=array[i][j]; }

    Wtot = 600*1000;  Polygon_Points4 = 4;  Polygon_Points6 = 6;
    X = 1000*v[0];   Y = Wtot*( v[1] - 1 );       /* Column start point */


    Lgap = 1000 * ( v[5] );  Gap_Cen = Lsa + Lgap/2 ;

    Gap_Angle1 = 8 * (Pi/180);  Gap_Angle = 8 * (Pi/180);  /* 8 degree */

    L1 = 1000 * ( v[6] );  L1tap = 1000 * ( v[7] );  Width   = 1000 * ( v[8] );

    Le = 1000 * ( v[9] );

    Torus_Angle = (v[10])*(Pi/180); /***Equals to Lcur_Angle***/

    L2tap = 1000 * ( v[11] );  L2 = 1000 * ( v[12] );  Wtap = 1000 * ( v[13] );

    Lcur = Ltot-(Lsa+Lgap+L1+L1tap+Le+L2tap+L2);

    y_start = 200 * 1000);       /*SA(Center) [Start point i.e. (0,y)]**/

    R = Lcur/sin(Torus_Angle);   R_In = R - (Width/2);   R_Out = R + (Width/2);

    Start_Angle = 270;   Stop_Angle = Start_Angle + (Torus_Angle)*180/Pi;

    x_Torus = X + Lsa + Lgap + L1 + L1tap + Le;  y_Torus = Y + y_start + R ;
/************ "Ltap2+L2" and Its Rotation_Variables*************/

x0 = \text{x}_\text{Torus} + \text{Lcur}; \quad y0 = Y + y_{\text{start}} + R*(1-\cos(\text{Torus\_Angle}));

x1 = x0; \quad y1 = y0 - (\text{Width}/2); \quad x2 = x1 + \text{L2tap}; \quad y2 = y1 - (\text{(Wtap}\text{-}\text{Width})/2);

x3 = x2 + \text{L2} + \text{Add}; \quad y3 = y2; \quad x4 = x3; \quad y4 = y0 + \text{Width}/2 + (\text{(Wtap}\text{-}\text{Width})/2);

x5 = x2; \quad y5 = y4; \quad x6 = x1; \quad y6 = y0 + \text{Width}/2; \quad \text{Rotate} = \text{Torus\_Angle};

/*** translate from (x0,y0) to (0,0), rotate and then translate to (x0,y0)/***/

\text{rot\_x1} = ( (x1-x0)\ast\cos(\text{Rotate}) - (y1-y0)\ast\sin(\text{Rotate}) ) + x0;

\text{rot\_y1} = ( (x1-x0)\ast\sin(\text{Rotate}) + (y1-y0)\ast\cos(\text{Rotate}) ) + y0;

\text{rot\_x2} = ( (x2-x0)\ast\cos(\text{Rotate}) - (y2-y0)\ast\sin(\text{Rotate}) ) + x0;

\text{rot\_y2} = ( (x2-x0)\ast\sin(\text{Rotate}) + (y2-y0)\ast\cos(\text{Rotate}) ) + y0;

\text{rot\_x3} = ( (x3-x0)\ast\cos(\text{Rotate}) - (y3-y0)\ast\sin(\text{Rotate}) ) + x0;

\text{rot\_y3} = ( (x3-x0)\ast\sin(\text{Rotate}) + (y3-y0)\ast\cos(\text{Rotate}) ) + y0;

\text{rot\_x4} = ( (x4-x0)\ast\cos(\text{Rotate}) - (y4-y0)\ast\sin(\text{Rotate}) ) + x0;

\text{rot\_y4} = ( (x4-x0)\ast\sin(\text{Rotate}) + (y4-y0)\ast\cos(\text{Rotate}) ) + y0;

\text{rot\_x5} = ( (x5-x0)\ast\cos(\text{Rotate}) - (y5-y0)\ast\sin(\text{Rotate}) ) + x0;

\text{rot\_y5} = ( (x5-x0)\ast\sin(\text{Rotate}) + (y5-y0)\ast\cos(\text{Rotate}) ) + y0;

\text{rot\_x6} = ( (x6-x0)\ast\cos(\text{Rotate}) - (y6-y0)\ast\sin(\text{Rotate}) ) + x0;

\text{rot\_y6} = ( (x6-x0)\ast\sin(\text{Rotate}) + (y6-y0)\ast\cos(\text{Rotate}) ) + y0;

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/************************Device Size***************************/

Polygon [ 0 ] = LPoint_Set ( X + 0, Y + 0);
Polygon [ 1 ] = LPoint_Set ( X + Ltot, Y + 0);
Polygon [ 2 ] = LPoint_Set ( X + Ltot, Y + Wtot);
Polygon [ 3 ] = LPoint_Set ( X + 0, Y + Wtot);

LPolygon_New ( Cell_Draw, LLayer_Find ( File_Draw, "Grid Layer" ),
              Polygon, 1*Polygon_Points4);

/****************************SA******************************/

Polygon [ 0 ] = LPoint_Set ( X - Add_sa, Y + y_start - Wsa/2);
Polygon [ 1 ] = LPoint_Set ( X + Lsa - (Wsa/2)*tan(Gap_Angle1), Y + y_start - Wsa/2);
Polygon [ 2 ] = LPoint_Set ( X + Lsa + (Wsa/2)*tan(Gap_Angle1), Y + y_start + Wsa/2);
Polygon [ 3 ] = LPoint_Set ( X -Add_sa, Y + y_start + Wsa/2);

LPolygon_New ( Cell_Draw, LLayer_Find ( File_Draw, "Layer 0" ),
              Polygon, 1*Polygon_Points4);
Polygon [ 0 ] = LPoint_Set (X + Lsa + Lgap + (Wsa/2)*tan(Gap_Angle) , Y + y_start - Wsa/2);
Polygon [ 1 ] = LPoint_Set (X + Lsa + Lgap + L1,Y + y_start - Wsa/2);
Polygon [ 2 ] = LPoint_Set (X + Lsa + Lgap + L1 + L1tap,Y + y_start - Width/2);
Polygon [ 3 ] = LPoint_Set (X + Lsa + Lgap + L1 + L1tap,Y + y_start + Width/2);
Polygon [ 4 ] = LPoint_Set (X + Lsa + Lgap + L1,Y + y_start + Wsa/2);
Polygon [ 5 ] = LPoint_Set (X + Lsa + Lgap - (Wsa/2)*tan(Gap_Angle),Y + y_start + Wsa/2);
LPolygon_New ( Cell_Draw, LLayer_Find ( File_Draw, "Layer 0" ),

    Polygon, 1*Polygon_Points6);

Polygon [ 0 ] = LPoint_Set (X + Lsa + Lgap + L1 + L1tap,Y + y_start - Width/2);
Polygon [ 1 ] = LPoint_Set (X + Lsa + Lgap + L1 + L1tap + Le,Y + y_start - Width/2);
Polygon [ 2 ] = LPoint_Set (X + Lsa + Lgap + L1 + L1tap + Le,Y + y_start + Width/2);
Polygon [ 3 ] = LPoint_Set (X + Lsa + Lgap + L1 + L1tap,Y + y_start + Width/2);
LPolygon_New ( Cell_Draw, LLayer_Find ( File_Draw, "Layer 0" ),

    Polygon, 1*Polygon_Points4);
LTorusParams tParams;

    tParams.ptCenter.x = x_Torus;
    tParams.ptCenter.y = y_Torus;
    tParams.nInnerRadius = R_In;
    tParams.nOuterRadius = R_Out;
    tParams.dStartAngle = Start_Angle;
    tParams.dStopAngle = Stop_Angle;

Torus = LTorus_CreateNew(Cell_Draw, LLayer_Find ( File_Draw, "Layer 0" ), &tParams);
LTorus_GetParams(Torus, &tParams);

Polygon[0] = LPoint_Set ( rot_x1, rot_y1 );
Polygon[1] = LPoint_Set ( rot_x2, rot_y2 );
Polygon[2] = LPoint_Set ( rot_x3, rot_y3 );
Polygon[3] = LPoint_Set ( rot_x4, rot_y4 );
Polygon[4] = LPoint_Set ( rot_x5, rot_y5 );
Polygon[5] = LPoint_Set ( rot_x6, rot_y6 );
LPolygon_New (Cell_Draw, LLayer_Find (File_Draw, "Layer 0"),

Polyon, 1*Polygon_Points6);

}   // for loop end here;

LCell_MakeVisible (Cell_Draw);  LCell_HomeView( Cell_Draw);

}   // WaveguideMacro end here

void waveguide_macro_register ( void )

{ LMacro_BindToHotKey (KEY_F10, "QD_1Col_TS(2.5mm)_Curved_array",

"WaveguideMacro" ); }  

}   // module waveguide end here

waveguide_macro_register();
APPENDIX B
RECIPE FILES (PRC) OF PECVD
SiN_diff.prc

[_INI_HEADER_]
Version=1

[Step_001]
Description=Base Pressure, StepType=12004 INITIAL, Name=SIN_DIFF

DefaultPumps=0, InitPumpdown=1,

Temp1Out=0, Temp2Out=0, Temp3Out=250, Temp4Out=0

BasePressure=0.03, PressureExp=5, HoldTime=10, Chamber=0, LogConfig=

[Step_002]
Description=Flush, StepType=12005 PROCESS,

ChannelNames=SiH4,NH3,NO2,HE,N2,DE100, Channels=0,0,0,0,100,0

Pressure=300, PressureExp=0, ProcessPump=0, Terminate=0,

MaxStepTime=30, MaxEndTime=0,

OverEtch=0, OverEtchTime=0, OverEtchPercent=0,

RFControls=1,0, RFSetpoints=0,0,0,0,0, RFConfig=2, RFGenerators=0,0,0,0,

EndptMethod=0, HeliumCooling=0, Angstroms=0,

AMNMode=0, AMNTuneSetpoints=0, AMNLoadSetpoints=0, DepRate=
[Step_003]

Description=Purge, StepType=12006 PURGE

Pressure=900, PressureExp=0, Pump=0

PTime=10, RFConfig=2, RFControls=1,0, RFSetpoints=0,0,0,0,0,0

[Step_004]

Description=Evacuation, StepType=12007 EVAC

ProcessPump=1, PumpTime=10, BasePressure=0.03, PressureExp=5

[Step_005]

Description=Gas Stabilization, StepType=12005 PROCESS

ChannelNames=SiH4,NH3,NO2,HE,N2,DE100, Channels=120,4.5,0,0,400,

Pressure=900, PressureExp=0, ProcessPump=0, Terminate=0, MaxStepTime=30,

MaxEndTime=0, OverEtch=0, OverEtchTime=0, OverEtchPercent=0, RFControls=1,0

RFSetpoints=0,0,0,0,0,0, RFConfig=2, RFGenerators=0,0,0,0, EndptMethod=0

HeliumCooling=0, Angstroms=0,

AMNMode=0, AMNTuneSetpoints=0, AMNLoadSetpoints=0, DepRate=

[Step_006]

Description=Deposition, StepType=12005 PROCESS

ChannelNames=SiH4,NH3,NO2,HE,N2,DE100, Channels=120,4.5,0,0,400
Pressure=900, PressureExp=0, ProcessPump=0, Terminate=3, MaxStepTime=60
MaxEndTime=0, OverEtch=0, OverEtchTime=0, OverEtchPercent=0, RFControls=1,0
RFSetpoints=20,0,0,0,0,0, RFConfig=2, RFGenerators=0,0,0,0, EndptMethod=0
HeliumCooling=0, Angstroms=0
AMNMode=0, AMNTuneSetpoints=0, AMNLoadSetpoints=0, DepRate=

[Step_007]
Description=Purge, StepType=12006 PURGE
Pressure=900, PressureExp=0, Pump=0
PTime=10, RFConfig=2, RFControls=1,0, RFSetpoints=0,0,0,0,0,0

[Step_008]
Description=Evacuation, StepType=12007 EVAC
ProcessPump=1, PumpTime=10, BasePressure=0.03, PressureExp=5

[Step_009]
Description=Substrate cooling, StepType=12011 TEMP,
Temp1Out=0, Temp2Out=0, Temp3Out=25, Temp4Out=0, FlowPurge=0

[Step_010]
Description=End Step, StepType=12010 END
FinalPump=1, BasePressure=0.03, PressureExp=5, HoldTime=10, Vent=0
Etchsin1.prc

[_INI_HEADER_]

Version=1

[Step_001]

Description=, StepType=12004 INITIAL, Name=ETCHSIN1

DefaultPumps=0, InitPumpdown=1

Temp1Out=0, Temp2Out=0, Temp3Out=0, Temp4Out=0

BasePressure=0.05, PressureExp=5, HoldTime=10, Chamber=1, LogConfig=

[Step_002]

Description=Flush, StepType=12005 PROCESS

ChannelNames=BCL3,N2,O2,CHF3,HE,CF4, Channels=0,90,0,0,0,0

Pressure=500, PressureExp=0, ProcessPump=0, Terminate=0

MaxStepTime=60, MaxEndTime=0

OverEtch=0, OverEtchTime=0, OverEtchPercent=0

RFControls=1,0, RFSetpoints=0,0,0,0,0,0, RFConfig=1, RFGenerators=0,0,0,0

EndptMethod=0, HeliumCooling=0, Angstroms=0

AMNMode=0, AMNTuneSetpoints=0, AMNLoadSetpoints=0, DepRate=
[Step_003]

Description=, StepType=12007 EVAC

ProcessPump=1, PumpTime=300, BasePressure=0.05, PressureExp=5

[Step_004]

Description=Gas Flow Stabilization, StepType=12005 PROCESS

ChannelNames=BCL3,N2,O2,CHF3,HE,CF4, Channels=0,0,1,0,0,12

Pressure=75, PressureExp=0, ProcessPump=1, Terminate=0

MaxStepTime=120, MaxEndTime=0

OverEtch=0, OverEtchTime=0, OverEtchPercent=0

RFControls=1,0, RFSetpoints=0,0,0,0,0,0, RFConfig=1, RFGenerators=0,0,0,0

EndptMethod=0, HeliumCooling=0, Angstroms=0

AMNMode=0, AMNTuneSetpoints=0, AMNLoadSetpoints=0, DepRate=

[Step_005]

Description=SiN Etch, StepType=12005 PROCESS

ChannelNames=BCL3,N2,O2,CHF3,HE,CF4, Channels=0,0,1,0,0,12

Pressure=75, PressureExp=0, ProcessPump=1, Terminate=3

MaxStepTime=60, MaxEndTime=0

OverEtch=0, OverEtchTime=0, OverEtchPercent=0
RFControls=1,0, RFSetpoints=100,0,0,0,0,0, RFConfig=1, RFGenerators=0,0,0,0
EndptMethod=0, HeliumCooling=0, Angstroms=0
AMNMMode=0, AMNTuneSetpoints=0, AMNLoadSetpoints=0, DepRate=

[Step_006]
Description=, StepType=12007 EVAC
ProcessPump=1, PumpTime=300, BasePressure=0.05, PressureExp=5

[Step_007]
Description=, StepType=12006 PURGE
Pressure=1000, PressureExp=0, Pump=0, PTime=10
RFConfig=1, RFControls=1,0, RFSetpoints=0,0,0,0,0,0

[Step_008]
Description=, StepType=12010 END
FinalPump=1, BasePressure=0.05, PressureExp=5, HoldTime=300, Vent=0
**Prremove.prc**

```ini
[_INI_HEADER_]

[Step_001]
Description=, StepType=12004 INITIAL, Name=PRREMOVE

DefaultPumps=0, InitPumpdown=1

Temp1Out=0, Temp2Out=0, Temp3Out=0, Temp4Out=0

BasePressure=0.03, PressureExp=5, HoldTime=10, Chamber=1, LogConfig=

[Step_002]
Description=Gas Stablization, StepType=12005 PROCESS

ChannelNames=BCL3,N2,O2,CHF3,HE,CF4, Channels=0,0,50,0,50,0

Pressure=300, PressureExp=0, ProcessPump=0, Terminate=0

MaxStepTime=10, MaxEndTime=0

OverEtch=0, OverEtchTime=0, OverEtchPercent=0

RFControls=1,0, RFSetpoints=0,0,0,0,0,0, RFConfig=1, RFGenerators=0,0,0,0

EndptMethod=0, HeliumCooling=0, Angstroms=0, AMNMode=0

AMNTuneSetpoints=0, AMNLoadSetpoints=0, DepRate=

[Step_003]
```
Description=RF on, StepType=12005 PROCESS

ChannelNames=BCL3,N2,O2,CHF3,HE,CF4, Channels=0,0,50,0,50,0

Pressure=300, PressureExp=0, ProcessPump=0, Terminate=3

MaxStepTime=60, MaxEndTime=0,

OverEtch=0, OverEtchTime=0, OverEtchPercent=0

RFControls=1,0, RFSetpoints=100,0,0,0,0,0, RFConfig=1, RFGenerators=0,0,0,0

EndptMethod=0, HeliumCooling=0, Angstroms=0

AMNMode=0, AMNTuneSetpoints=0, AMNLoadSetpoints=0, DepRate=

[Step_004]

Description=, StepType=12007 EVAC

ProcessPump=0, PumpTime=10, BasePressure=30, PressureExp=2

[Step_005]

Description=, StepType=12006 PURGE

Pressure=1000, PressureExp=0, Pump=0, PTime=10

RFConfig=1, RFControls=1,0, RFSetpoints=0,0,0,0,0,0

[Step_006]

Description=, StepType=12010 END

FinalPump=0, BasePressure=50, PressureExp=2, HoldTime=10, Vent=0
Cyclotene.prc

[_INI_HEADER_]

Version=1

[Step_001]

Description=: StepType=12004 INITIAL, Name=CYCLOTEN

DefaultPumps=0, InitPumpdown=1

Temp1Out=0, Temp2Out=0, Temp3Out=0, Temp4Out=0

BasePressure=0.04, PressureExp=5, HoldTime=10, Chamber=1, LogConfig=

[Step_002]

Description=Flush, StepType=12005 PROCESS

ChannelNames=BCL3,N2,O2,CHF3,HE,CF4, Channels=0,90,0,0,0,0

Pressure=500, PressureExp=0, ProcessPump=0, Terminate=0

MaxStepTime=60, MaxEndTime=0

OverEtch=0, OverEtchTime=0, OverEtchPercent=0

RFControls=1,0, RFSetpoints=0,0,0,0,0,0, RFConfig=1, RFGenerators=0,0,0,0

EndptMethod=0, HeliumCooling=0, Angstroms=0

AMNMode=0, AMNTuneSetpoints=0, AMNLoadSetpoints=0, DepRate=
[Step_003]

Description=, StepType=12007 EVAC
ProcessPump=1, PumpTime=10, BasePressure=0.03, PressureExp=5

[Step_004]

Description=Gas Stabilization, StepType=12005 PROCESS
ChannelNames=BCL3,N2,O2,CHF3,HE,CF4, Channels=0,0,10,0,0,5
Pressure=50, PressureExp=0, ProcessPump=1
Terminate=0, MaxStepTime=60, MaxEndTime=0
OverEtch=0, OverEtchTime=0, OverEtchPercent=0
RFControls=1,0, RFSetpoints=0,0,0,0,0, RFConfig=1, RFGenerators=0,0,0,0
EndptMethod=0, HeliumCooling=0, Angstroms=0, AMNMode=0
AMNTuneSetpoints=0, AMNLoadSetpoints=0, DepRate=

[Step_005]

Description=Cyclotene Etch, StepType=12005 PROCESS
ChannelNames=BCL3,N2,O2,CHF3,HE,CF4, Channels=0,0,10,0,0,5
Pressure=50, PressureExp=0, ProcessPump=1, Terminate=3
MaxStepTime=60, MaxEndTime=0
OverEtch=0, OverEtchTime=0, OverEtchPercent=0
RFControls=1,0, RFSetpoints=100,0,0,0,0,0, RFConfig=1, RFGenerators=0,0,0,0
EndptMethod=0, HeliumCooling=0, Angstroms=0
AMNMode=0, AMNTuneSetpoints=0, AMNLoadSetpoints=0, DepRate=

[Step_006]
Description=, StepType=12007 EVAC
ProcessPump=1, PumpTime=10, BasePressure=0.04, PressureExp=5

[Step_007]
Description=, StepType=12006 PURGE
Pressure=1000, PressureExp=0, Pump=0, PTime=10
RFConfig=1, RFControls=1,0, RFSetpoints=0,0,0,0,0,0

[Step_008]
Description=, StepType=12010 END
FinalPump=1, BasePressure=10, PressureExp=2, HoldTime=10, Vent=0
Prremove.prc

[INI_HEADER_]
Version=1

[Step_001]
Description=, StepType=12004 INITIAL, Name=PRREMOVE
DefaultPumps=0, InitPumpdown=1
Temp1Out=0, Temp2Out=0, Temp3Out=0, Temp4Out=0
BasePressure=0.03, PressureExp=5, HoldTime=10, Chamber=1, LogConfig=

[Step_002]
Description=Gas Stablization, StepType=12005 PROCESS
ChannelNames=BCL3,N2,O2,CHF3,HE,CF4, Channels=0,0,50,0,50,0
Pressure=300, PressureExp=0, ProcessPump=0, Terminate=0
MaxStepTime=10, MaxEndTime=0
OverEtch=0, OverEtchTime=0, OverEtchPercent=0
RFControls=1,0, RFSetpoints=0,0,0,0,0, RFConfig=1, RFGenerators=0,0,0,0
EndptMethod=0, HeliumCooling=0, Angstroms=0
AMNMode=0, AMNTuneSetpoints=0, AMNLoadSetpoints=0, DepRate=

[Step_003]
Description=RF on, StepType=12005 PROCESS
ChannelNames=BCL3,N2,O2,CHF3,HE,CF4, Channels=0,0,50,0,50,0
Pressure=300, PressureExp=0, ProcessPump=0, Terminate=3
MaxStepTime=60, MaxEndTime=0, OverEtch=0, OverEtchTime=0, OverEtchPercent=0
RFControls=1,0, RFSetpoints=100,0,0,0,0,0, RFConfig=1, RFGenerators=0,0,0,0
EndptMethod=0, HeliumCooling=0
Angstroms=0, AMNMode=0, AMNTuneSetpoints=0, AMNLoadSetpoints=0, DepRate=

[Step_004]
Description=, StepType=12007 EVAC
ProcessPump=0, PumpTime=10, BasePressure=30, PressureExp=2

[Step_005]
Description=, StepType=12006 PURGE, Pressure=1000, PressureExp=0
Pump=0, PTime=10, RFConfig=1, RFControls=1,0, RFSetpoints=0,0,0,0,0,0

[Step_006]
Description=, StepType=12010 END
FinalPump=0, BasePressure=50, PressureExp=2, HoldTime=10, Vent=0