Mode-locking and frequency beating in compact semiconductor lasers

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• Pulsed lasers
• Mode-locking basics
• Semiconductor MLLs
• Harmonic Mode-Locking
• Tunable mode-beating and stabilisation
Light and Lasers: a brief history

• Demonstrated for the first time >50 years ago
  • Creates beams of light where all the photons are “in-phase”
  • “A solution looking for a problem”

• 10 Nobel prizes later...
• Surgical tools
• CD/DVD/Blu-ray players
• Telecommunications
• Industrial machining
• Precision metrology
• Adaptive optics for astronomy
• Electronics Lithography
• Particle cooling
• Laser wake acceleration
The laser zoo

• Vast range of laser technologies and performance

• Gain material
  – Solid-state (crystal)
  – Gas
  – Dye
  – Fibre
  – Semiconductor
  – Plasmonic
  – Micro-fluidic

• Pumping
  – Optical
  – Electrical

• Cavity
  – Fabry-Perot
  – Ring
  – DBR and DFB
  – VCSEL
  – VECSEL
The laser zoo

- Vast range of laser technologies and performance

- Power
  - nW - PW

- Size
  - μm - metres

- Wavelength
  - X-ray - cm
Temporal characteristics

- Many lasers are used in Continuous Wave (CW) operation
- Alternatively, we may want to use **Pulsed** laser sources
  - Data communications
  - Higher optical peak powers for non-linear processing
  - Probing ultrafast physics of devices and biological systems
  - Time of flight ranging
Semiconductor pulsed lasers

- Often we want many device properties together:
  1. Compact size
  2. High peak power
  3. Ease of use (i.e. drive electronics)
- Semiconductor lasers offer an attractive solution

- There are a number of different ways to generate laser pulses
- Typically we generate trains of pulses, with two key metrics:
  - $\Delta \tau$, the temporal width of the pulse
  - $\nu$, the repetition frequency of the pulse train
- Each method operates with a characteristic time-scale and repetition rate
Direct modulation

- The laser is simply switched on and off
  - A population inversion must be generated for each pulse generated
  - Limited by pulse chirping and availability of high speed drive electronics

External Modulation

- A CW laser beam can be attenuated periodically
  - Acousto-optic and electro-optic modulators
  - DC-GHz rates (>ns pulse durations)
Q-Switching

• A variable output loss is applied to the laser cavity
• Carriers are built up in the gain medium while the output loss is high
• When cavity loss is reduced a short pulse is created depleting the stored carriers
• Pulses are typically 100’s of ps for semiconductor lasers
Why mode-locking?

- We want to generate pulses with durations shorter than can be created using electronic modulation schemes.
- The shorter the pulse, potentially, the higher the peak power we can generate.
- We also create the potential for very high repetition-rate sources.
- Simple cavity geometries.
- Low cost driver requirements.

- Simple Fourier Transform argument:
  - Pulse duration vs Laser bandwidth.
Time-bandwidth

Single frequency CW laser

Temporal impulse
In reality we will have a bandwidth limited by:
- Gain material bandwidth
- Dispersion
- Pulse formation mechanisms

A limited bandwidth in the frequency domain leads to a limited pulse-width in the temporal domain.

A so-called ‘transform limited’ pulse
Pulsed operation from multiple modes

- Make use of multiple longitudinal modes of a laser cavity
- Giving much higher output peak power than a single colour laser
- Pulse travels around cavity at the group velocity
- Not limited to a FP laser
  - Ring lasers
  - DBR lasers
The beat length of the interfering modes is proportional to the round-trip time of the cavity.

i.e. the pulse travels around the cavity.

Hence each round-trip a pulse is emitted.

So in time, the laser emits a train of periodically spaced pulses.
Spectral and temporal combs

- Optical mode frequency spacing is equal to the repetition rate of the laser
- Optical bandwidth is the transform of the pulse width
Multi-mode but not mode-locked

- Mode-locking requires the active modes to be phase-locked
- If modes are not in a constant phase relationship, pulses will not be generated
- OSA’s are slow and may actually show mode-hopping
Measuring ultra-short pulse lasers

- Three key measures for characterising mode-locked operation
  - Optical Spectrum (Easy)
  - RF Spectrum (Need a fast detector)
  - Temporal trace (Difficult)

Optical Spectrum Analyser
- Time average
- Can’t discern between multimode and mode-locked

RF Spectrum Analyser
- Periodic amplitude modulations are clear
- No higher harmonics for 10’s GHz MLLs
- Beating still no guarantee of phase locking

Temporal Analyser (Osc.)
- fs resolution
- Low average input powers (<mW)
Measuring time traces

- Ultra-short optical pulses are the shortest events we create in the lab, so how can we measure them?
- We can use the pulse itself as a ‘ruler’
- We need an effect by which the pulse can gate itself with a response time faster than the pulse duration
- Optical non-linearities (2\textsuperscript{nd} order, 3\textsuperscript{rd} order)
Phase resolved pulse measurement techniques

- FROG, SPIDER, GRENOUILLE, ….
General measurement setup
HOW TO MAKE A MODE-LOCKED LASER
Semiconductor MLLs

- Gain
- Resonant cavity (with many modes)
- How do we get the modes to phase lock?
- Transients (hit the table!)
- Saturable Absorber

- Passive mode-locking
- Active mode-locking
- Hybrid mode-locking
Saturable absorption

- Phase-locking is only one solution for the multi-mode laser
- We can introduce additional loss to the laser to favour the pulsed regime
- Saturable absorbers have lower loss for high intensity fields
Monolithic integration

- Can we fabricate a gain section and SA on a single compact semiconductor laser chip?
  - Yes

- In forward bias the diode acts as an electrically pumped gain region
- In reverse bias the diode acts as an photodiode, or absorber
- How can we make such an absorber saturable?
Monolithic integration

- Ridge waveguide confines the light
- Forward bias gain section
- FP cavity formed between cleaved bar facets

- Short reverse bias section acts as a saturable absorber
- Absorber length critical to the operation characteristics of the laser
- Round-trip time of the cavity defines the repetition rate of the laser

\[ \nu = \frac{c}{2n_g L} \]
Technology options

- Single III-V wafer fabrication
  - Simple fabrication
  - Good heat sink

- Active\Passive III-V
  - Very low loss in passive sections
  - Potential for long cavity lengths and low rep-rates

- III-V on Silicon
  - As above
  - Integration with SOI photonic circuits fully on-chip

Tahvili et al., Opt Lett., 36 (13), 2011
2 Section Semiconductor MLLs

Optical Spectrum

$\Delta \lambda \sim 10\text{nm}$

Intensity Autocorrelation

$\lambda_{\text{drift}} \sim 8\text{nm}$ over 50mA

$\tau \sim 900\text{fs}$
2 Section Semiconductor MLLs

- Sub-picosecond pulses
- Up to 100’s of mW average power
- 3dB bandwidths ~10nm
- Large peak wavelength drift with $I_{inj}$
- Spectral characteristics are less than ideal
- Why?
Gain and Absorption Spectra

- Band-filling effects give blue-shift with increasing current density
- Increasing reverse bias on the absorber gives a red band-edge shift due to the Quantum Confined Stark Effect
Spectral considerations

- Slowly varying spectral envelope
- Poor pulse behaviour
- Well defined pulses
- Large spectral jumps
DBR Semiconductor MLLs

Optical Spectrum

$\Delta \lambda \sim 0.6\text{nm}$

Wavelength Map

$\lambda_{\text{drift}} < 1\text{nm}$

over 80mA

Intensity Autocorrelation

$\tau \sim 6\text{ps}$
Dependence on filter wavelength

- DBR gratings fabricated with $\lambda_B$ across bandwidth
- Passive filter bandwidth ~2.5nm
- Absorber ~4%

Passive filter response
- Strong dependence on central wavelength
- 1520nm < Pulse formation < 1570nm
- Single mode lasing otherwise
DBR Mode-locking regions

- DBR’s force the lasing wavelength
- Can improve output power
- Degraded spectral and temporal limits compared with free-running MLLs

Strain et al., IEEE PTL., 25, 2013
Spectral control

- Can we control wavelength without losing bandwidth and inducing chirp?
- Spectral and dispersion control on-chip

Tahvili et al., IEEE PTL., 25 (5), 2013
Fully on-chip dispersion compensation

- $\kappa \sim 70\text{cm}^{-1}$
- Passive filter bandwidth of $\sim2.5\text{nm}$
- Mode-locked bandwidth of $\sim0.6\text{nm}$

- $\kappa \sim 150\text{cm}^{-1}$
- Passive filter bandwidth of $\sim4\text{nm}$
- Mode-locked bandwidth of $\sim1\text{nm}$
Chirped DBR MLLs

- Linearly chirped gratings fabricated
- Constant spatial period
- Control necessary over both waveguide width and recess depth

\[ \kappa \approx 70-180 \text{cm}^{-1} \text{ allowing bandwidths in the order of } 10^0-10^1 \text{nm} \]
Chirped Bragg Grating Response

- Chirped gratings:
  - Increase reflectivity bandwidth
  - Create dispersion across reflection bandwidth
Chirped DBR MLLs

- $\kappa \sim 70\text{cm}^{-1}$
- Passive filter bandwidth of $\sim 5.5\text{nm}$
- Mode-locked bandwidth of $\sim 2.6\text{nm}$

Strain et al., IEEE JQE., 47 (4), 2011
Sonogram Measurements

Unfiltered pulse

Filtered pulse

DELAY

Spectral filtering

Beam splitter

Variable delay

Nonlinear detector
## Effects of grating chirp rate

<table>
<thead>
<tr>
<th>Chirp rate (μm/nm)</th>
<th>DBR bandwidth (nm)</th>
<th>ML bandwidth % of DBR</th>
<th>Pulse-width (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2.5</td>
<td>24</td>
<td>5.5</td>
</tr>
<tr>
<td>0.016</td>
<td>3.2</td>
<td>44</td>
<td>2.2</td>
</tr>
<tr>
<td>0.032</td>
<td>5.5</td>
<td>47</td>
<td>1.5</td>
</tr>
</tbody>
</table>

### Graphs

1. **Pulse Intensity (a.u.)**
   - X-axis: Delay (ps)
   - Y-axis: Pulse Intensity (a.u.)
   - Two lines represent different chirp rates: 0.016 nm/μm and 0.032 nm/μm.

2. **Pulse Group Delay (ps)**
   - X-axis: Wavelength (nm)
   - Y-axis: Pulse Group Delay (ps)
   - Two lines represent different chirp rates: 0.016 nm/μm and 0.032 nm/μm.
DBR Mode-locking regions

Strain et al., IEEE PTL., 25, 2013
Q-switched mode-locking

- ps pulse widths
- GHz repetition rates
- $P_p/P_{av} \sim 120$
HARMONIC MODE-LOCKING AND MODE-BEATING
Colliding pulse mode locked lasers

- <50GHz repetition rates are reasonable for mm long semiconductor laser cavities
- To increase repetition rates a new cavity geometry can be considered
- Colliding pulse mode-locked lasers (CPMLLs)

- Overlapping pulses have higher peak power so can trigger SA
- Alternatively an intra-cavity reflector can have a similar effect
CPMLLs

\[ x = \frac{L}{M} \]

M: order of higher-harmonic mode-locking

- The first few HH’s can be reached using a single, asymmetrically placed SA
- For higher frequencies the sub-cavity length becomes critically sensitive to fabrication tolerances
Double Interval CPMLLs

\[ M = \frac{L^2}{xy} \]

- HH frequency is determined by the lowest common integer multiple of \( x \) and \( y \)
- Should be able to generate 100’s of GHz repetition rates using a standard mm-cavity with fundamental freq. \( \sim 40\text{GHz} \)
CPMLLs

- **M=2**, 70GHz

- **M=3**, 105GHz

- **M=7**, 240GHz
THz mode beating

- Only 2 cavity modes in phase-locked condition
- More like mode beating than mode-locked laser operation
- Still exhibits 10’s MHz linewidths (without external stabilisation)
- Is there a better way to do this?
Mode-beating

- 2 unrelated laser sources will produce a beat frequency.
- Coherence time is related to the individual laser linewidths.
- Random phase jumps are uncorrelated between sources.

We want narrow linewidth mm-THz sources with tunability.
- Phase-locking the beating signals should help.
Photo-mixing

- Beating of two semiconductor laser sources on a high-speed photodetector

**Laser 1**

**Laser 2**

**Non-Linear Element**

**Optical signals** @ $\nu_1$ and $\nu_2$

**Optical to electrical conversion**

**CW electrical signal** @ frequency difference

$\nu_{RF} = |\nu_1 - \nu_2|$

😊 Easy tunability, scalable

😭 Poor spectral purity

Uncorrelated optical signals $\rightarrow$ broad linewidth electrical signal

Optical domain

Electrical domain
Photomixing assisted by mutual injection locking and Four Wave Mixing

- Three lasers can be locked via mutual injection assisted by a Four-Wave-Mixing process that takes place in a third auxiliary laser.

\[ \nu_3 = \frac{\nu_1 + \nu_2}{2} \]

- Frequency fluctuations of the three lasers are correlated:
  \[ \Rightarrow \text{Narrow linewidth RF signal generation} \]
DFB lasers for Single mode operation, high SMSR, easy wavelength tunability

Different coupling values (evanescent-field, MMI coupler, direct injection)

SOA/Attenuators to achieve further tuning of injected power

Tapered output waveguides to collect the generated optical signals

Scheme of the integrated devices
DFB lasers – single mode operation

Uniform grating

$\lambda/4$ Phase shifted grating

Grating spectral response (stop band)

Lasing mode

Reflection (a.u.)

$\Delta \lambda$

Wavelength (nm)

1.545
1.550
1.555

0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

0
0.2
0.4
0.6
0.8
1.0

1.540
1.545
1.550
1.555
1.560
DFB laser characteristics

- CW operation @ room temperature
- Output power up to 3 mW in air
- $\lambda \sim 1552$ nm
- SMSR up to 59 dB
- $\Delta \nu$ spacing accuracy better than 5GHz by fabrication (i.e. no current tuning necessary)
mm-wave signal generation

- DFB-1 and DFB-2 pumped at a fixed current
- DFB-3 current fine tuned to reach the locking condition

$$\nu_3 = \frac{\nu_1 + \nu_2}{2}$$

| $$|\nu_1 - \nu_3| \neq |\nu_3 - \nu_2|$$ | $$\rightarrow$$ | UNLOCKED |
|-------------------------------------------------|---------------------------------|
| $$|\nu_1 - \nu_3| = |\nu_3 - \nu_2|$$ | $$\rightarrow$$ | LOCKED !!! |
mm-wave signal generation

\[ |v_1 - v_3| \neq |v_3 - v_2| \]

UNLOCKED

\[ |v_1 - v_3| = |v_3 - v_2| \]

LOCKED
mm-wave signal generation

- Beating linewidth narrows as the locking condition is achieved
- Unlocked linewidth = 25 MHz
- Minimum Locked linewidth = 2.0 MHz
mm-wave signal frequency tunability

- Tuning of the RF signal simply by tuning the DFB-1 and DFB-2 currents
- Continuous fine tunability
- Tunability range from a few GHz to hundreds of GHz
Summary

• Many applications require compact ultra-short pulsed laser sources
• Semiconductor mode-locked lasers use phase locking between many spectral cavity modes to generate temporal pulses
• Sub-ps pulse durations
• GHz-THz repetition rates
• Narrow-linewidth mode-beating can be achieved using mutually injecting semiconductor lasers
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