ECEN689: Special Topics in Optical Interconnects Circuits and Systems
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Lecture 12: Laser Sources

Sam Palermo
Analug & Mixed-Signal Center
Texas A&M University
Announcements

• Preliminary Project Report Due Apr. 20
  • Email me one report per group

• Exam 3 is on Apr. 24
  • Covers through Lecture 12

• Reading
What is a Laser?

- **Light Amplification by Stimulated Emission of Radiation**
- **Light Oscillation by Stimulated Emission of Radiation**
- Lasers are optical oscillators that emit coherent light through the process of stimulated emission
- 3 Elements in all lasers
  - Amplifying Medium
  - Pumping Process
  - Optical Feedback (Cavity)
Agenda

• Fabry-Perot Lasers

• Distributed-Feedback (DFB) Lasers

• Hybrid Silicon Lasers

• Comb Lasers
Fabry-Perot Interferometer

- In order to “lase” or be an optical oscillator

\[ \beta G = 1 \quad \text{where} \quad \beta = r_1 r_2 \]

\[ G = e^{(g-\alpha)2L} e^{-ik2L} \]

- Gain Condition: \( \beta G = 1 \Rightarrow g = \alpha + \frac{1}{2L} \ln \left( \frac{1}{r_1 r_2} \right) \)

- Round-trip gain must equal cavity losses & mirror transmission

\[ \frac{E_t}{E_i} = \frac{G}{1 - \beta G} \]

\( r \) = mirror reflectivities (field)

\( g \) = gain coefficient \( \left( \frac{1}{m} \right) \)

\( \alpha \) = loss coefficient

\( L \) = optical cavity length

\( k = \frac{2\pi n}{\lambda} \) (field wavevector)
Fabry-Perot Interferometer (2)

Phase Condition:  

\[ e^{-ik2L} = 1 \Rightarrow k2L = m2\pi \]

\[ L = \frac{m\lambda}{2n} \]

Phase condition makes this an “optical bandpass filter” – wavelengths transmitted correspond to an integer number of \( \lambda/2 \) in a length \( L \)

Transmitted Wavelength:  

\[ \lambda = \frac{2Ln}{m} \]

Frequency:  

\[ f = m\left(\frac{c}{2Ln}\right) \]

The transmitted wavelengths/frequencies are called the longitudinal modes of oscillation

Mode Spacing:  

\[ \Delta\lambda = \frac{\lambda^2}{2Ln} \]

\[ \Delta\nu_{ax} = \frac{c}{2Ln} \]
Fabry-Perot Laser

- Laser gain medium formed by a forward-biased p-n junction
- Carriers electrically “pump” the active region such that an incoming photon can stimulate electron-hole pair recombination to produce another identical photon
- Long cavity length (300μm) results in multiple-longitudinal modes and large spectral linewidths
  \[ \text{Typical } \Delta \lambda_S = 3\text{nm} \]
- While FP lasers typically have multiple-longitudinal modes (wavelengths), they can still be designed to have a single transversal mode to couple efficiently into a single-mode fiber
10Gb/s Fabry-Perot Laser Example

- Typically used in uncooled applications, where tight wavelength control is not necessary
- Used primarily at 1310nm where dispersion is low

**Table: 10Gb/s Fabry-Perot Laser Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Condition</th>
<th>Min</th>
<th>Typ</th>
<th>Max</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Temperature</td>
<td>$T_{op}$</td>
<td>-</td>
<td>-40</td>
<td>+25</td>
<td>+95</td>
<td>°C</td>
</tr>
<tr>
<td>Optical Output Power</td>
<td>$I_{op}$</td>
<td>+25°C, Ith+30mA, +95°C, Ith+30mA</td>
<td>7</td>
<td>9</td>
<td>9</td>
<td>mA</td>
</tr>
<tr>
<td>Threshold Current</td>
<td>$I_{TH}$</td>
<td>+25°C, +95°C</td>
<td>8</td>
<td>17</td>
<td>12</td>
<td>mA</td>
</tr>
<tr>
<td>Slope Efficiency</td>
<td>$\eta$</td>
<td>+25°C, +95°C</td>
<td>0.20</td>
<td>0.12</td>
<td>0.31</td>
<td>mW/mA</td>
</tr>
<tr>
<td>DC Resistance</td>
<td>$R$</td>
<td>+25°C</td>
<td>10</td>
<td>12</td>
<td>12</td>
<td>Ω</td>
</tr>
<tr>
<td>Operating Voltage</td>
<td>$V_{op}$</td>
<td>-</td>
<td>1.3</td>
<td>1.6</td>
<td>-</td>
<td>V</td>
</tr>
<tr>
<td>Central Wavelength</td>
<td>$\lambda$</td>
<td>At Ith+20mA</td>
<td>1290</td>
<td>1310</td>
<td>1320</td>
<td>nm</td>
</tr>
<tr>
<td>Temperature Dependence of Central Wavelength</td>
<td>$\Delta\lambda/\Delta T$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>nm/°C</td>
<td></td>
</tr>
<tr>
<td>Beam Divergence Angle, Vertical</td>
<td>$\theta_v$</td>
<td>Full Width, Half Max</td>
<td>32</td>
<td>40</td>
<td>48</td>
<td>deg</td>
</tr>
<tr>
<td>Beam Divergence Angle, Horizontal</td>
<td>$\theta_h$</td>
<td>Full Width, Half Max</td>
<td>12</td>
<td>20</td>
<td>28</td>
<td>deg</td>
</tr>
<tr>
<td>Laser Reverse Voltage</td>
<td>$V_r$</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>V</td>
</tr>
<tr>
<td>Continuous Operating Current</td>
<td>$I_{op}$</td>
<td>+25°C</td>
<td>-</td>
<td>-</td>
<td>120</td>
<td>mA</td>
</tr>
<tr>
<td>Spectral Width</td>
<td>$\Delta \lambda$</td>
<td>Ith+30mA</td>
<td>-</td>
<td>-</td>
<td>2.4</td>
<td>nm</td>
</tr>
<tr>
<td>Modulation Bandwidth</td>
<td>$f_{3dB}$</td>
<td>+25°C, Ith+30mA</td>
<td>10</td>
<td>-</td>
<td>-</td>
<td>GHz</td>
</tr>
<tr>
<td>Rise/Fall Time</td>
<td>$t_r / t_f$</td>
<td>20/80%</td>
<td>-</td>
<td>-</td>
<td>45</td>
<td>ps</td>
</tr>
</tbody>
</table>
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Bragg Reflections

Figure 1.43 The incident wave $E_{in}$ travels through $N$ partially (and weakly) reflective mirrors. At each mirror, the wave is partially transmitted and partially reflected.

$E_{r1}(0) = E_{in}(0) \cdot r; \quad E_{r1}(0) = E_{in}(0) \cdot t$

$E_{r2} (\Lambda) = E_{r1}(0) \cdot r \cdot e^{-j\beta\Lambda}; \quad E_{r2} (\Lambda) = E_{r1}(0) \cdot t \cdot e^{-j\beta\Lambda}$

$E_{r3} (2\Lambda) = E_{r2} (\Lambda) \cdot r \cdot e^{-j\beta\Lambda}; \quad E_{r3} (2\Lambda) = E_{r2} (\Lambda) \cdot t \cdot e^{-j\beta\Lambda}$

$\vdots$

$E_{rN} [ (N - 1)\Lambda] = E_{r(N - 1)} [(N - 2)\Lambda] \cdot r \cdot e^{-j\beta\Lambda};$

$E_{rN} [ (N - 1)\Lambda] = E_{r(N - 1)} [(N - 2)\Lambda] \cdot t \cdot e^{-j\beta\Lambda}$

$E_{rtot}(0) = rE_{in}(0) \cdot \frac{1 - M^N}{1 - M}$

where $M \equiv t^2 e^{-2j\beta\Lambda}$

The condition for strong reflections (Bragg condition)

$2\Lambda = m\lambda$
Distributed-Feedback (DFB) Laser

- DFBs have a grating etched throughout the cavity, except for a quarter-wavelength shifted section which forces a single longitudinal mode.
- This results in a very narrow linewidth. Typical $\Delta \lambda_s < 1 \mu m$.
- With direct modulation, the linewidth broadens due to the AM sidebands and chirp.
- Since DFB lasers have overlapping gain and grating sections, when the current changes both the output power and frequency change simultaneously, causing chirp.
10GHz DFB Laser Example

- Very tight linewidth, 1MHz at 1550nm is 8fm!!
- As the lasing wavelength is sensitive to temperature (~0.1nm/°C), DFB lasers often include thermal control
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Laser Integration Strategy

- With the rise of silicon photonic integrated circuits, there are various approaches to laser integration

- Stand-alone laser
  - Laser is separate from the silicon PIC
    - Enables testing before integration
    - Requires separate assembly of each laser

- Hybrid laser
  - Involves the bonding of a III-V gain material onto a silicon waveguide
    - Allows for wafer-scale processing
    - Lasers can’t be tested before assembly
DFB Hybrid Silicon Laser

- Optical gain provided by III-V (InAlGaAs) bonded onto silicon waveguide
- Should enable high coupling efficiency with subsequent modulators on the same PIC
- Achieved a wall-plug efficiency of \(~2\%\) 😞

[Zhang Opt Exp 2014]
External-Cavity Hybrid Silicon Laser

- External reflective semiconductor optical amplifier (RSOA) provides gain
- Heating the ring reflector provides 8nm tuning range
- Achieves a wall-plug efficiency of 12.2%

[Lee Opt Exp 2015]
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A dense wavelength-division multiplexed (DWDM) system requires the integration of many DFB lasers that have accurate channel spacing. A single “comb” laser can produce these wavelengths with stable channel spacing. An attractive solution is to use a comb laser with ring modulators that provide inherent wavelength multiplexing.
Quantum Dot Fabry-Perot Comb Laser

- 80GHz channel spacing
- 1.5-1.8mW per channel
- Requires ~70mA current