The Effect of Gain/Loss-Coupling on Mode Beatings in Weakly Coupled Two-Section DFB Lasers

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Introduction

• DFB Self-pulsating devices reported in the literature –
  Two Section: Index- Coupled, Partially gain-coupled.
  Three Section: Three DFB sections, Two DFB sections and a center phase section.
• Application include –
• All-optical clock recovery, Wireless Fiber Links, Terahertz generation.
• Motivation –
  Having Predicted Symmetrical and Asymmetrical mode-beating in partially gain-coupled DFB lasers
  – In the symmetrical mode beating case, does the modal dynamics differ from that of Index-coupled DFB lasers?
  – What about Loss-coupled DFB lasers?
Complex-Coupled Two-Section DFB Lasers

- **Index-coupling**
  \[ n(z) = n_{eff,0} + \Delta n_{eff} A_n \cos\left(\frac{2\pi z}{\lambda} + \phi_g\right) \]

- **Loss-coupling**
  \[ \alpha(z) = \alpha_0 + \Delta \alpha_0 A_L \cos\left(\frac{2\pi z}{\lambda} + \phi_g\right) \]

- **Gain-coupling**
  \[ g(z) = g_0 + \Delta g_0 A_g \cos\left(\frac{2\pi z}{\lambda} + \phi_g\right) \]

\[ \kappa = \frac{\pi}{\lambda} A_n \Delta n_{eff} + \frac{j}{4} \left( A_g \Delta g_0 - A_L \Delta \alpha_0 \right) \]

Reflectivity Spectra

Index-coupled  Loss-coupled  Gain-coupled
Nonlinear Coupled Differential Equations of TS-DFB Lasers

Forward wave
\[ \frac{\partial F(z,t)}{\partial z} + \frac{1}{v_g} \frac{\partial F(z,t)}{\partial t} = \frac{1}{2} G(z,t)F(z,t) + i\kappa B(z,t) + s_f(z,t), \]

Backward wave
\[ \frac{\partial B(z,t)}{\partial z} - \frac{1}{v_g} \frac{\partial B(z,t)}{\partial t} = -\frac{1}{2} G(z,t)B(z,t) - i\kappa F(z,t) + s_b(z,t), \]

Carrier density
\[ \frac{\partial N(z,t)}{\partial t} = \frac{I_{A,B}}{qV} - \frac{N(z,t)}{\tau} - \left[ \frac{g_n(N(z,t) - N_0)}{1 + \varepsilon P(z,t)} - 2f_s(z,t) \right] v_g P(z,t), \]

\[ f_s(z,t) = \kappa_g \left( e^{i\varphi_g} F(z,t)B^*(z,t) + c.c \right) / P(z,t), \]

Only gain-coupled
The inclusion of Wavelength Tuning

\[
G(z, t) = \Gamma_x g_n (N(z, t) - N_0) \frac{1}{1 + \varepsilon P(z, t) - i\alpha} - \Gamma + i\Delta\beta(z),
\]

\[
\delta = \delta_s + \delta_I + \delta_c,
\]

\[
\delta_s = \beta_B(A) - \beta_A(B) = \frac{\pi}{\Lambda_A} - \frac{\pi}{\Lambda_B},
\]

\[
\delta_I = \frac{\delta\beta_B}{\delta I} \Delta I,
\]

\[
\delta_c = \frac{2\pi}{\lambda} (\bar{n}_{\text{eff}}(A) - \bar{n}_{\text{eff}}(B)) = \alpha\Gamma g_n (\bar{N}_A - \bar{N}_B),
\]

\[
\Delta\beta_c^a \quad \Delta\beta_c^b
\]

Section a  Section b
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L$</td>
<td>Section Length</td>
<td>400 μm</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>Coupling Constant</td>
<td>50 cm$^{-1}$</td>
</tr>
<tr>
<td>$N_0$</td>
<td>Carrier density at transparency</td>
<td>1.5×10$^{18}$ cm$^{-3}$</td>
</tr>
<tr>
<td>$g_n$</td>
<td>Differential gain</td>
<td>3×10$^{-16}$ cm$^2$</td>
</tr>
<tr>
<td>$\Gamma_x$</td>
<td>Confinement factor</td>
<td>0.068</td>
</tr>
<tr>
<td>$\lambda_n$</td>
<td>Free space wavelength</td>
<td>1.55×10$^{-4}$ cm</td>
</tr>
<tr>
<td>$\Gamma$</td>
<td>Cavity loss</td>
<td>20 cm$^{-1}$</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Linewidth enhancement factor</td>
<td>3</td>
</tr>
<tr>
<td>$\tau$</td>
<td>Carrier lifetime</td>
<td>1.25 ns</td>
</tr>
<tr>
<td>$\varphi$</td>
<td>Nonlinear gain coefficient</td>
<td>1×10$^{-17}$ cm$^3$</td>
</tr>
<tr>
<td>$n_{sp}$</td>
<td>Spontaneous emission factor</td>
<td>2</td>
</tr>
<tr>
<td>$n_{ef}$</td>
<td>Effective refractive index</td>
<td>3.7</td>
</tr>
<tr>
<td>$n_g$</td>
<td>Group refractive index</td>
<td>3.55</td>
</tr>
<tr>
<td>$\delta\beta/\delta(I/I_0)$</td>
<td>Temperature induced shift in Bragg condition</td>
<td>-30 cm$^{-1}$</td>
</tr>
</tbody>
</table>
Predicted Modes vs Static Detuning

-10%
\(\kappa_i = -5\%\), \(\delta_{\text{min}} = 13\, \text{cm}^{-1}\)

0%
\(\kappa_i = 0\%\), \(\delta_{\text{min}} = 7\, \text{cm}^{-1}\)

5%
\(\kappa_i = 5\%\), \(\delta_{\text{min}} = 35\, \text{cm}^{-1}\)

10%
\(\kappa_i = 10\%\), \(\delta_{\text{min}} = 61\, \text{cm}^{-1}\)

15%

\(15\%\)
Minimum Static Detuning vs. $\kappa_i \%$

![Graph showing minimum static detuning vs. $\kappa_i \%$]
Minimum Static Detuning LC, IC and GC

<table>
<thead>
<tr>
<th>Detuning</th>
<th>Detuning Value</th>
<th>Frequency Shift</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa_i = -5%$</td>
<td>$\delta s = 13 \text{ cm}^{-1}$</td>
<td></td>
</tr>
<tr>
<td>$\kappa_i = 0%$</td>
<td>$\delta s = 7 \text{ cm}^{-1}$</td>
<td></td>
</tr>
<tr>
<td>$\kappa_i = 5%$</td>
<td>$\delta s = 35 \text{ cm}^{-1}$</td>
<td></td>
</tr>
</tbody>
</table>
Minimum Static Detuning at $\kappa_i = 2.5\%$, $\delta s = 4 \text{ cm}^{-1}$
Mode Profiles and Carrier Distribution

Minimum detuning range.

Minimum self-pulsation frequency
\[ \kappa_i=-5\% \delta_s=175 \text{ cm}^{-1} \]
\[ \kappa_i=0\% \delta_s=175 \text{ cm}^{-1} \]
\[ \kappa_i=5\% \delta_s=173 \text{ cm}^{-1} \]
\[ \kappa_i=10\% \delta_s=171 \text{ cm}^{-1} \]
Tuning Range and Modulation Index

Self-pulsation frequency as a function of $I_a$ with $I_b=3I_{tr}$, (b) index of the forward wave at the facet of section B, (c) Modulation and the modulation index of the backward wave at the facet of section A (Top - $\delta_s=80 \text{ cm}^{-1}$, Bottom $\delta_s=170 \text{ cm}^{-1}$).
Temporal Response Loss-Coupled

Backward Wave (a.u.)

ns

0 3 5 8 10

20 dB/Div.

50 GHz/Div.

2.12 GHz mode spacing

$I/I_{tr}=6.4$

$I/I_{tr}=6.3$
Carrier Response Loss-Coupled
Modes Profiles ($\delta = 80 \text{ cm}^{-1}$)

IC

LC

GC

$\frac{I_a}{I_{tr}} = 3$

$\frac{I_a}{I_{tr}} = 5.5$

$\frac{I_a}{I_{tr}} = 7.2$

$\frac{I_a}{I_{tr}} = 3$

$\frac{I_a}{I_{tr}} = 5$

$\frac{I_a}{I_{tr}} = 6.3$

$\frac{I_a}{I_{tr}} = 3$

$\frac{I_a}{I_{tr}} = 4$

$\frac{I_a}{I_{tr}} = 4.43$

$I_a/I_{tr} = 3$

$I_a/I_{tr} = 5.5$

$I_a/I_{tr} = 7.2$

$I_a/I_{tr} = 3$

$I_a/I_{tr} = 5$

$I_a/I_{tr} = 6.3$

$I_a/I_{tr} = 3$

$I_a/I_{tr} = 4$

$I_a/I_{tr} = 4.43$
Modes Profiles ($\delta_s=170$ cm$^{-1}$)

IC

LC

GC

Mode Profiles (6dB/Div.)

$\mu$m

Section A Section B

N/N$_0$

$\mu$m

Section A Section B

N/N$_0$

$\mu$m

Section A Section B

$\mu$m
Reflectivity Spectra

Lasing Modes

Index-coupled  Loss-coupled  Gain-coupled
Modal Dynamics

• Loss-coupled DFB lasers – When the current of section A is increased, mode B is also increased – Mode B is the dominant mode.

• Index-coupled DFB lasers – The dominant mode depends on the static detuning parameter.

• Gain-coupled DFB lasers – Mode A is the dominant mode.
Conclusion

• For 10% gain-coupled DFB laser - above 90% modulation index is predicted for self-pulsations between 34 and 123 GHz.
• For 5% loss-coupled DFB laser - above 50% modulation index is predicted for self-pulsations between 27 and 155 GHz.
• When the difference in current levels is large the self-pulsation become pulsed for loss-coupled DFB lasers
• The carrier levels are least sensitive to current levels in the case of gain-coupled DFB lasers.