Rate-equation analysis for an integrated coupled-cavity laser with multi-mode interference anti-phase coupler
Lenstra, D.

Published in:
25th International Semiconductor Laser Conference (ISLC2016, 23-25 September 2016, Kobe, Japan),

Published: 14/09/2016

Document Version
Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:
• A submitted manuscript is the author's version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

Citation for published version (APA):
Rate-Equation Analysis for Integrated Coupled-Cavity Laser with Multi-Mode Interference Anti-Phase Coupler

Steady-state analysis

\[ E_j = \sqrt{P_j} \varphi_j (P_j \text{ photon number}, \varphi_j \text{ phase in laser } j; \varphi_{21} \equiv \varphi_2 - \varphi_1) \]

\[ \frac{P_j}{P_0} = \frac{2|\psi_j|^2 \cos(\varphi_j + \varphi_{21})}{\xi_j N_j}; \quad \frac{P_j}{P_0} = \frac{2|\psi_j|^2 \cos(\varphi_{21} + \varphi_j)}{\xi_j N_j} \]

\[ \varphi_1 = \omega_10 - \frac{\pi}{2} \sqrt{1 + \alpha_2^2 \sin(\theta_1 + \varphi_{21} - \Delta \alpha \tau_1)} \]

\[ \varphi_2 = \omega_20 - \epsilon |\psi_2|^2 \sqrt{1 + \alpha_2^2 \sin(\theta_2 - \varphi_{21} - \Delta \alpha \tau_2)} \quad (\epsilon \equiv |P_2|/P_2) \]

\[ \varphi_{21} = \omega_{21} + \sqrt{C^2 + D^2 \sin(\varphi_{21} + \psi)} \quad (C, D, \psi \text{ given in } [1]) \]

Stable mutual locking: \( \varphi_{21} = \text{Asin} \left( \frac{\omega_{21}}{\sqrt{C^2 + D^2}} \right) - \psi + \pi \)

Conclusion

- Rate equation theory adequately describes single-mode CW operation of CCL with MMI anti-phase coupler
- Self-consistent numerical iteration method demonstrates stable frequency and phase locking under flexible conditions
- Sizeable detuning interval for locking ~ 5.7 GHz allows easy fine tuning (as was observed in the experiment) [2]
- Due to coupling inversions clamp at lower values than without coupling
- Operation frequency substantially lower (~3.5 GHz) than in uncoupled situation due to \( \alpha \) (linewidth enhancement parameter) ~ 2.5

References

[1] D. Lenstra: Int. J. of Science and Techn., accepted

Theoretical (details in [1]): \( \omega_{jk} = \omega_j - \omega_k; j, k = 1, 2 \)

\[ E_1(t) = \omega_{110}E_1(t) + \frac{1}{2} (1 + i \alpha_1 \xi_1 N_1(t)) E_1(t) + \kappa_1 E_2(t), \]

\[ E_2(t) = \omega_{220}E_2(t) + \frac{1}{2} (1 + i \alpha_2 \xi_2 N_2(t)) E_1(t) + \kappa_2 E_2(t), \]

\[ \kappa_j = -|k_j| e^{i\theta_j}; \theta_j \equiv \frac{1}{2} \xi_j \xi_0 N_j \tau_j + \omega_{00} \tau_j; |k_j| \equiv \frac{C_{bar}}{\tau_j} \]

\[ N_1 = \Delta \tau_1 + N_k - \xi N_1 \tau_1 - \Gamma_1 P_1, \]

\[ N_2 = \Delta \tau_2 + N_k - \xi N_2 \tau_2 - \Gamma_2 P_2. \]

Since each \( \kappa_j \) depends on the inversion in laser \( j \) the coupling is a complex selfconsistent problem.

Abstract

A rate-equation theory is derived for a laser consisting of two Fabry-Perot cavities coupled via self-imaging in a multi-mode interference reflector. Stable single-mode anti-phase operation is demonstrated and locking ranges are calculated. The shapes of output-intensity curves agree well with measured curves.

Numerical Results

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha_1 )</td>
<td>2.5</td>
</tr>
<tr>
<td>( \xi_1 )</td>
<td>( 3.10 \times 10^{10} \text{ s}^{-1} )</td>
</tr>
<tr>
<td>( \tau_1 )</td>
<td>( 2.46 \times 10^{-11} )</td>
</tr>
<tr>
<td>( \tau_2 )</td>
<td>( 2.52 \times 10^{-11} )</td>
</tr>
<tr>
<td>( T )</td>
<td>( 1.0 \times 10^{14} )</td>
</tr>
<tr>
<td>( \Gamma_1 )</td>
<td>( 5.27 \times 10^{3} )</td>
</tr>
<tr>
<td>( \Gamma_2 )</td>
<td>( 5.02 \times 10^{3} )</td>
</tr>
<tr>
<td>( C_{bar} )</td>
<td>0.75</td>
</tr>
<tr>
<td>( C )</td>
<td>-0.18</td>
</tr>
<tr>
<td>( \psi )</td>
<td>0.7</td>
</tr>
<tr>
<td>( \tau )</td>
<td>( 1.1 \times 10^{15} \text{ s}^{-1} )</td>
</tr>
<tr>
<td>( \tau )</td>
<td>( \times 48 \text{ mA} )</td>
</tr>
<tr>
<td>( \text{Value} )</td>
<td>( \Gamma ) Photon decay rate of cavity 1</td>
</tr>
<tr>
<td>( \text{Value} )</td>
<td>( \Gamma ) Photon decay rate of cavity 2</td>
</tr>
<tr>
<td>( \text{Value} )</td>
<td>( C ) Cross-coupling coefficient of MMI-reflector</td>
</tr>
<tr>
<td>( \text{Value} )</td>
<td>( \psi ) Reflection coefficient of mirrors</td>
</tr>
</tbody>
</table>

Steady-state analysis

\[ E_j = \sqrt{|F_j|^2 (\varphi_j P_j \text{ photon number}, \varphi_j \text{ phase in laser } j; \varphi_{21} \equiv \varphi_2 - \varphi_1) \}

\[ \varphi_1 = \omega_10 - \frac{\pi}{2} \sqrt{1 + \alpha_2^2 \sin(\theta_1 + \varphi_{21} - \Delta \alpha \tau_1)} \]

\[ \varphi_2 = \omega_20 - \epsilon |\psi_2|^2 \sqrt{1 + \alpha_2^2 \sin(\theta_2 - \varphi_{21} - \Delta \alpha \tau_2)} \quad (\epsilon \equiv |P_2|/P_2) \]

\[ \varphi_{21} = \omega_{21} + \sqrt{C^2 + D^2 \sin(\varphi_{21} + \psi)} \quad (C, D, \psi \text{ given in } [1]) \]

Stable mutual locking: \( \varphi_{21} = \text{Asin} \left( \frac{\omega_{21}}{\sqrt{C^2 + D^2}} \right) - \psi + \pi \)