Ultrafast Narrow-Band Modulation of VCSELs

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Outline

- Introduction (application and generation)
- Model and Equations
- Coupled VCSELs
- Multi-Transverse Mode Dynamics
- Modulation of Multimode VCSELs
- Extension of Bandwidth
- Conclusion

Introduction: Application

High-Frequency: $\Omega >> \omega_0$
Narrow Band: $\Delta\Omega << \Omega$
(digital application: $\omega_0 - \Delta\omega$)
- Microwave, millimeter-wave photonics
- Narrow-band communications
- All-optical clock generation and recovery
- Digital communication, if bandwidth $\Delta\Omega$ expanded

Introduction: Generation

- Modulation of mode-locked (-coupled) lasers at 100GHz (theory, Lau 1988, 1990)
- Resonant enhancement by feedback (experiment, Lau and Yariv 1985) or by external cavity (Nagendra et al. 1993)
- Push-pull modulated DFB lasers (theory, Marconet al. 1994)
- Detuned DFB lasers (theory, Feste 1998)
- 2-Section DFB lasers (theory and experiment, Kjebne et al 1997, Nahbiser et al 2000)
- Coupled VCSELs (theory, Ning and Goorjian, 2001)

Common features:
- Generating a second resonance in addition to the RO oscillation either through external cavity, feedback or multimode beating
- Using multi-section DFB or DFB lasers or needing external cavity or feedback

Model and Equations

\[
\begin{align*}
\frac{\partial E}{\partial t} &= \frac{1}{c} \nabla^2 E - kE + \frac{i\omega}{2\omega_0} P + i\delta(x,y) K E \\
\frac{\partial N}{\partial t} &= \nabla \cdot (\nabla N - \nabla \xi) - \frac{f(x,y,t)}{e} \frac{i\omega}{8\alpha} (P^*E - PE^*) \\
\frac{\partial P}{\partial t} &= (\Gamma_1(N) + \Gamma_2(N) \delta(N))P - i\epsilon_0 A_j(N) E \\
\end{align*}
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Coupled VCSELs: 40GHz Modulation

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**Mode Dynamics**

Averaged Intensity Patterns (Index Guided)

Near-field intensity output: half and full facet

Multi-Transverse Mode Dynamics

Near-field intensity output: half and full facet
Multimode relaxation oscillations and mode beating

Near-field intensity output: half and full faces

Optical Spectrum

Modulation of Multimode VCSELs

Higher beating frequency with smaller device

Extension of Bandwidth
Conclusion

Multimode beating greatly enhanced by taking output from part (e.g., half) of output facet.

- Simpler sources of microwave, millimeter wave of various frequencies generated by varying VCSEL diameter in a single multimode VCSEL or coupling of a few VCSELs.
- Breathing frequency in multi-mode operation affects modulation response and bandwidth.
- Optimizing RO frequency and mode beating frequency could potentially expand bandwidth suitable for wide band digital communication.