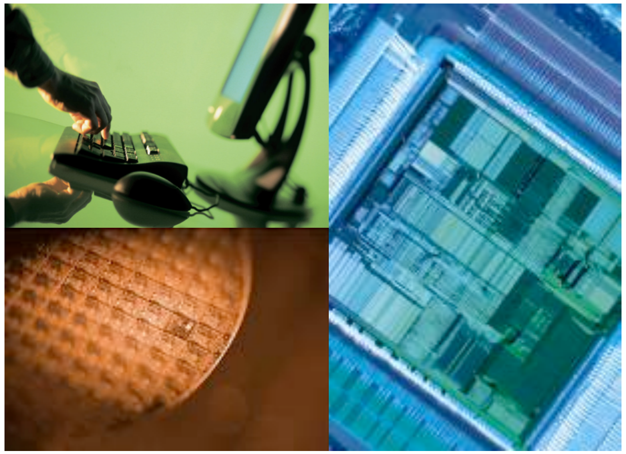
Large-Signal Modeling on Device Level:

Intermodulation Distortion and Eye-Diagrams of Semiconductor Lasers



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ETH Zürich

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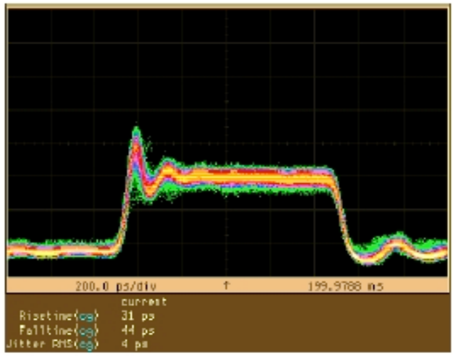
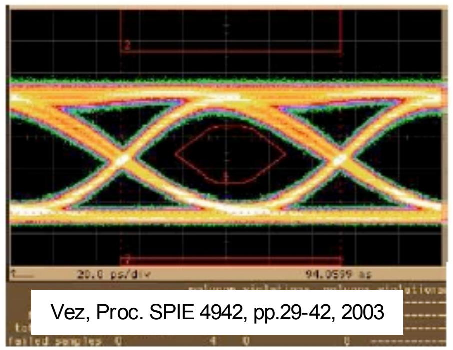
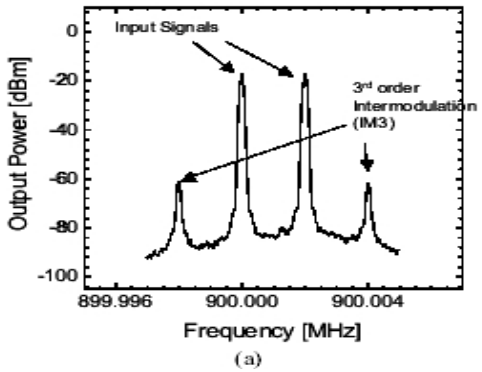
Large-Signal Characteristics

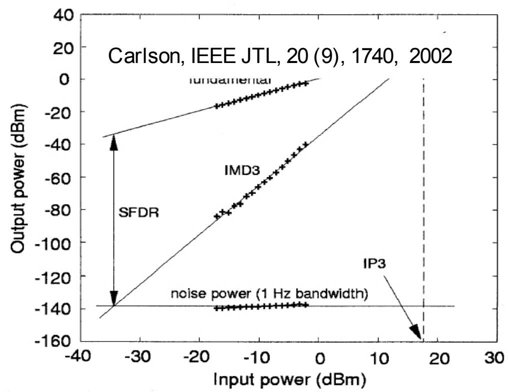




Digital Applications:

- Resonance Overshoot
- Eye-Diagram





Analog Applications:

- Intermodulation Distortion
- Spurious Free Dynamic Range

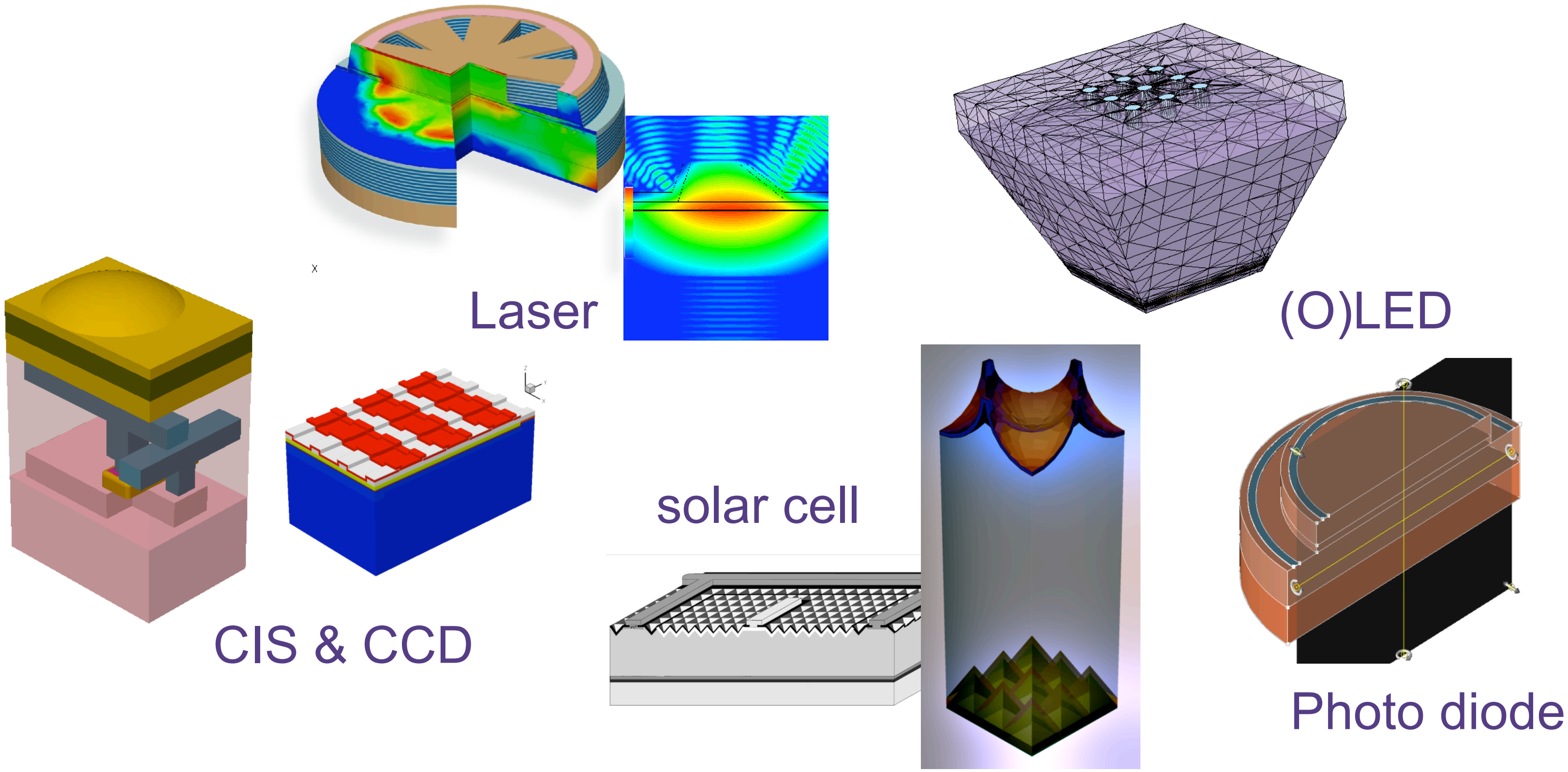
Large-Signal Modeling:

- So far, theoretical description on 0-dimensional rate-equation-models, “device-level” link missing
- This work: **Larg-Signal modeling on device level using harmonic balance method**

Content

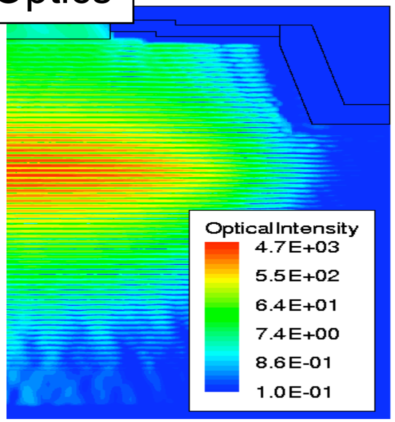
- Introduction
  - Optoelectronics and Multi-dimensional VCSEL Simulation
- Multi-Tone Harmonic Balance Method
  - Introduction
  - Single vs Multi-Tone
  - Performance: transient vs. HB
- Application Examples
  - Analog: Intermodulation distortion
  - Digital: Eye Diagram
- Conclusion

Synopsys Sentaurus Device: Optoelectronic Applications

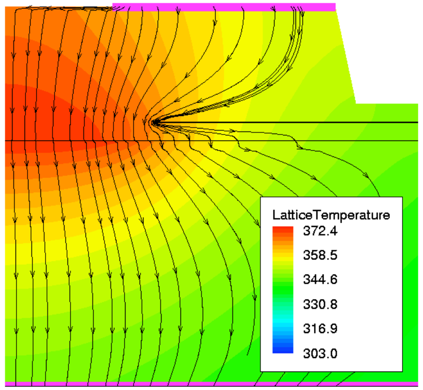


VCSEL Simulation

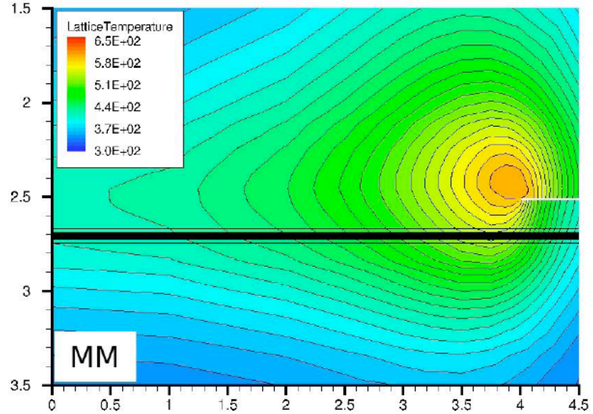
Optics



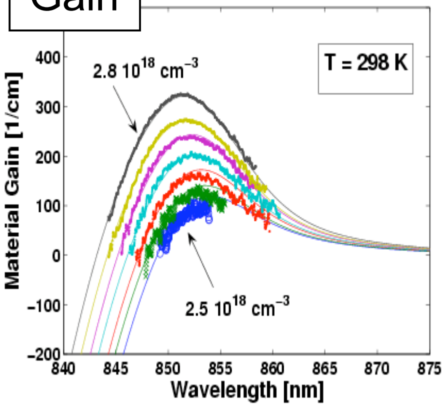
Electro-Thermal



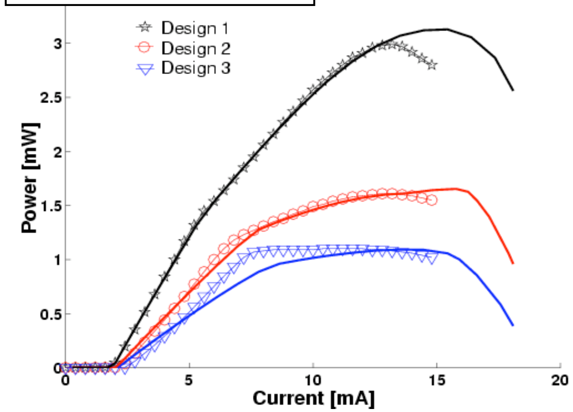
Transient Heating



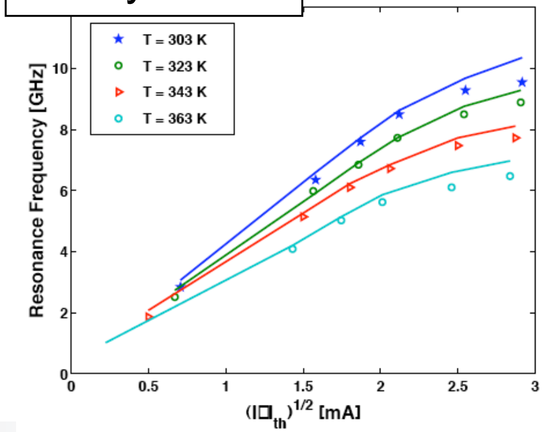
Gain



Mode Stability



SS Dynamics



Harmonic Balance Method

Assume a system of nonlin. Equations in the following form

$$\partial_t \mathbf{q}\left(\mathbf{x}(t)\right) + \mathbf{y}\left(\mathbf{x}(t)\right) - \mathbf{w}(t) = 0$$

Expand the source w(t) and solution x(t) into **Fourier series**

$$\mathbf{w}(t) = \sum_{k=-K}^{K} \mathbf{W}_k \exp\left(i\,\omega_k\,t\right) \qquad \mathbf{x}(t) = \sum_{h=-H}^{H} \mathbf{X}_h \exp\left(i\,\omega_h\,t\right)$$

And solve the system in the **frequency domain** for the Fourier coefficients Xh of the solution vector

$$i\Omega\mathbf{Q}\left(\mathbf{X}\right) + \mathbf{Y}\left(\mathbf{X}\right) - \mathbf{W} = 0$$

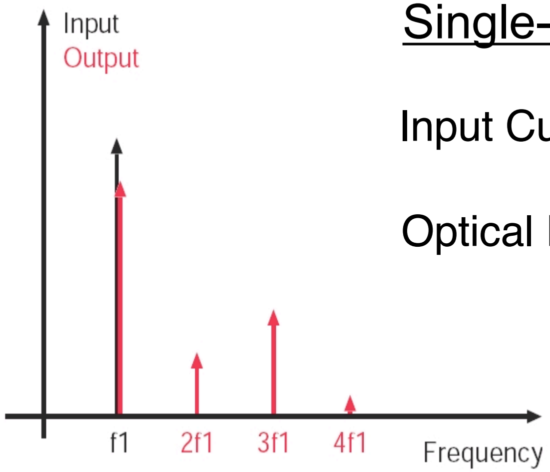
Note: The system to solve is O(H^2) bigger than the DC system → memory consumption!!

HB for Electro-Thermal Laser Model

$$\partial_t \mathbf{q}\big(\mathbf{x}(t)\big) + \mathbf{y}\big(\mathbf{x}(t)\big) - \mathbf{w}(t) = 0$$

- Poisson: $\nabla \cdot \epsilon \nabla V = -q\left(p - n + N_D^+ - N_A^-\right)$
- El./Hole DD: $\nabla \cdot \mathbf{j}_n = q\left(R^{sp} + R^{nr} + \partial_t n\right) + F_n(t)$
  $-\nabla \cdot \mathbf{j}_p = q\left(R^{sp} + R^{nr} + \partial_t p\right) + F_p(t)$
- Heat Diff.: $-\nabla \cdot \mathbf{S} = H + c_{th} \partial_t T_L$
- Phot. Rate: $\partial_t S_\nu = \left(G_\nu - L_\nu\right) S_\nu + T_\nu^{sp} + F_{S_\nu}(t)$
- Phot. Phase $\partial_t \Phi_\nu = \Xi_\nu + F_{\Phi,\nu}(t).$

Single-Tone vs. Multi-Tone HB

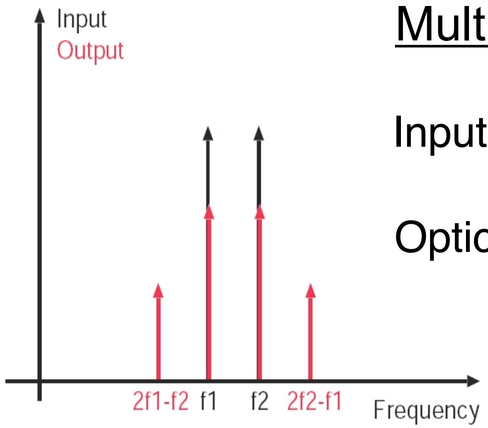


Single-Tone

Input Current: $I(t) = I_0 + I_1 \sin(\omega t)$

Optical Power: $P(t) = P_0 + P_1 \sin(\omega t) + P_2 \sin(2\omega t) + P_3 \sin(3\omega t) + \ldots$

Presented at NUSOD 2006



Multi-Tone

Input Current: $I(t) = I_0 + I_1 \sin(\omega_1 t) + I_1 \sin(\omega_2 t) + \ldots.$

Optical Power:

$$P(t) = P_0 + P_1 \sin(\omega_1 t) + P_2 \sin(\omega_2 t)$$
$$+ P_{-12} \sin([2\omega_2 - \omega_1]t) + P_{2(-1)} \sin([2\omega_1 - \omega_2]t)$$
$$+ P_{20} \sin(2\omega_1 t) + \ldots$$

NEW in Synopsys Sentaurus Device 2007.03

Transient vs. Harmonic Balance

Feature	transient	HB
Implementation aspects	simple	difficult
Memory consumption	medium	high
Performance/runtime efficiency	low	very high**
Analog modulation performance	very low*	very high**
Digital modulation performance	medium	very high**

* 2-tone example with f1=1GHz and Δf=1KHz requires >>f1/ Δf=1e6 time steps for a single point.
** HB schemes allow to “ramp/sweep” modulation signal parameters such as frequencies or amplitudes.

Application Example

- VCSEL GaAs/AlGaAs
  - 2-D simulation domain
  - Electro-opto-thermal
  - Many-body Gain Model
- Analog Modulation: Intermodulation Distortion
- Digital Modulation: Eye-Diagram

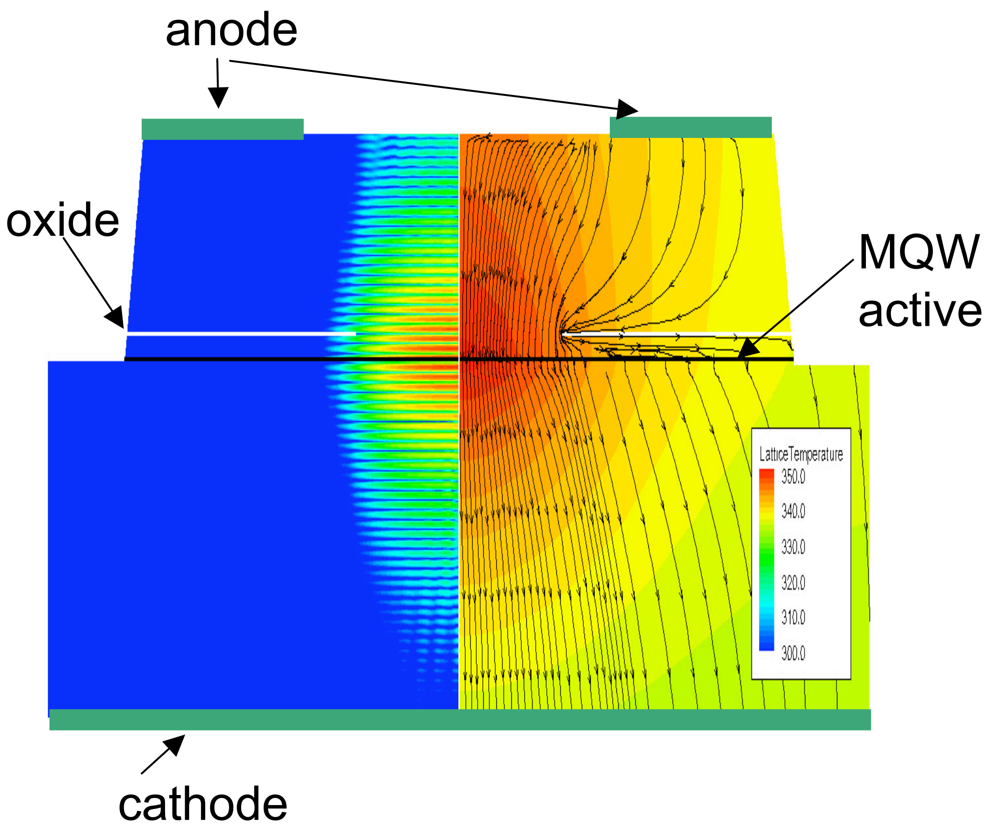
MQW AlGaAs VCSEL

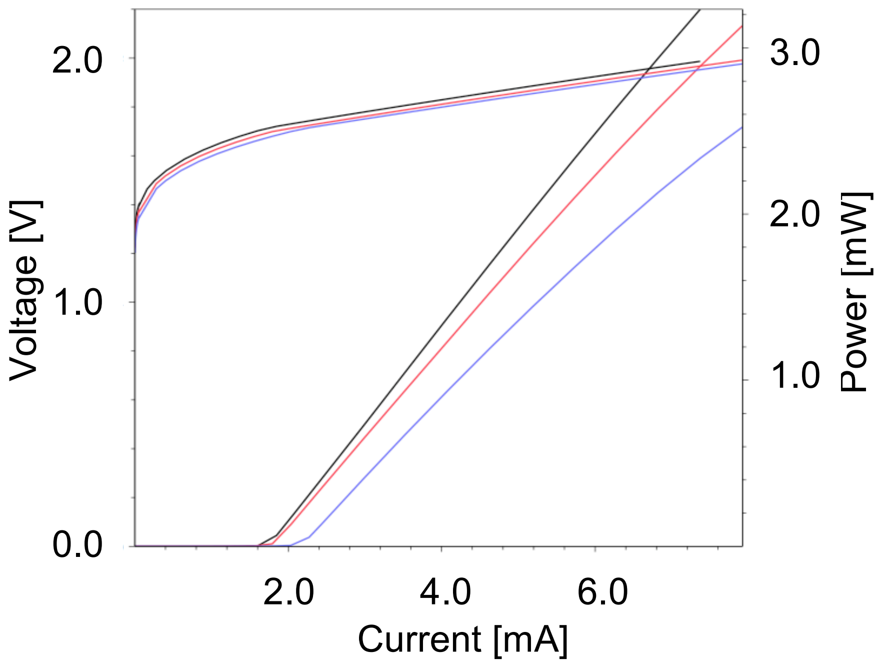
I_{th} ~ 2.0 mA

λ ~ 850 nm

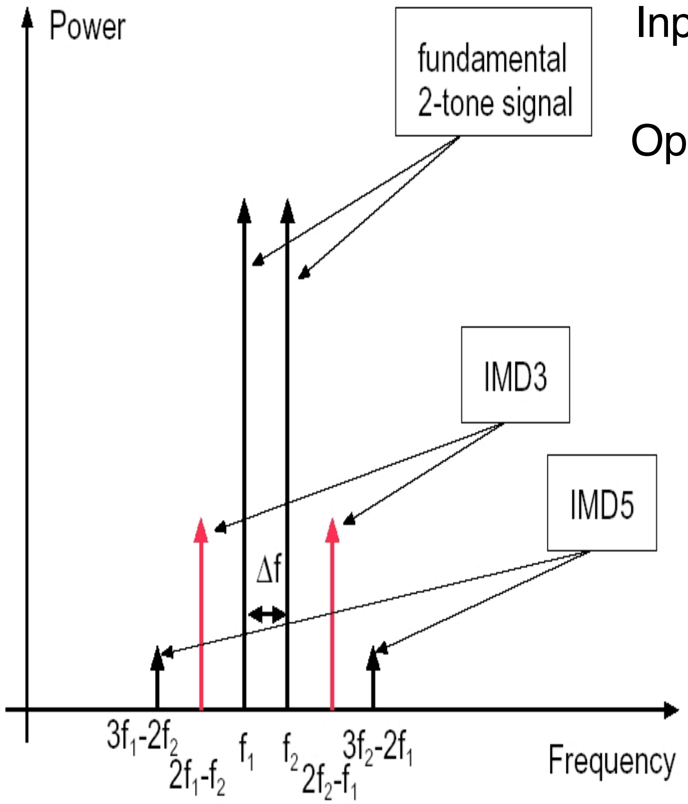
Iop = 6 mA (T=300 K)

Pop = 2.5 mW





Analog: Intermodulation Distortion



Input Current: $I(t) = I_0 + I_1 \sin(\omega_1 t) + I_1 \sin(\omega_2 t) + ...$

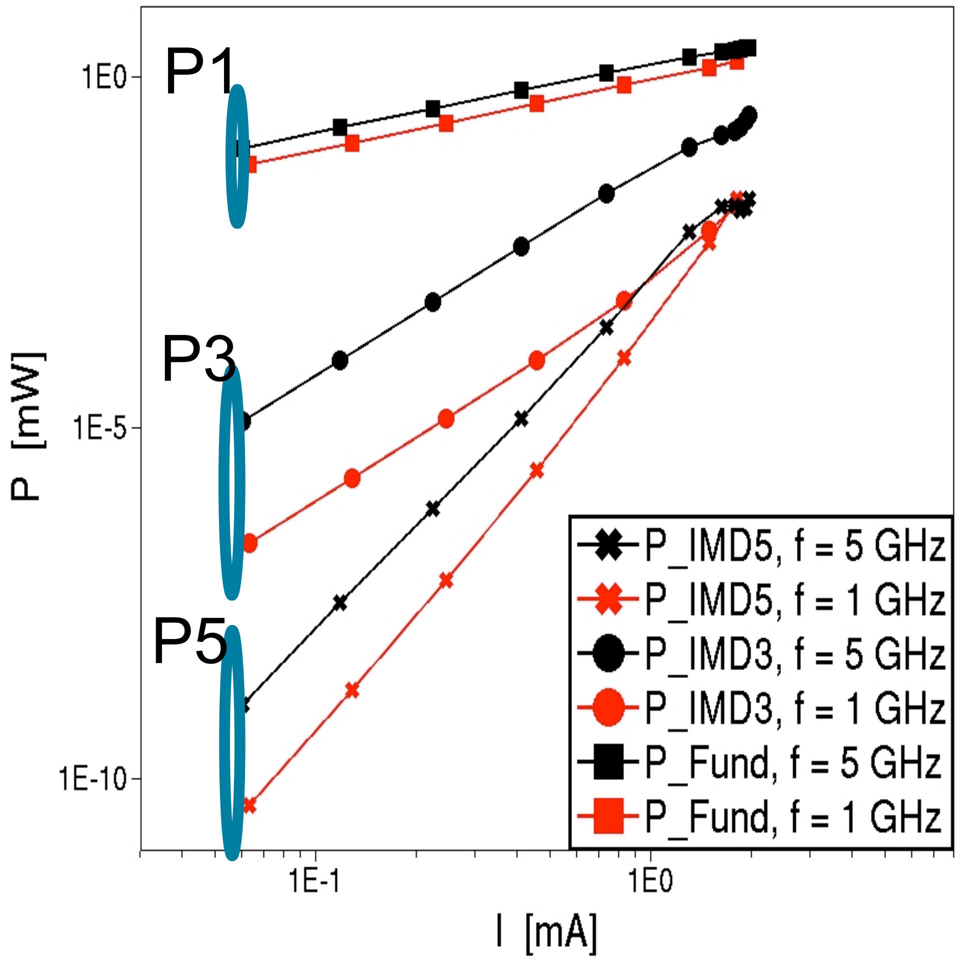
Optical Power:
$$P(t) = P_0 + P_1 \sin(\omega_1 t) + P_2 \sin(\omega_2 t)$$
$$+ P_{-12} \sin([2\omega_2 - \omega_1]t) + P_{2(-1)} \sin([2\omega_1 - \omega_2]t)$$
$$+ P_{20} \sin(2\omega_1 t) + ...$$

Analog Modulation schemes have closely spaced channels (Δf ~ kHz)

Non-linearities introduce cross-talk (IMD3,IMD5)

→ IMD3 and IMD5 should be as low as possible

Analog: Intermodulation Distortion



MQW AlGaAs VCSEL

Iop = 6 mA

Δf = 2 kHz

Two cases:

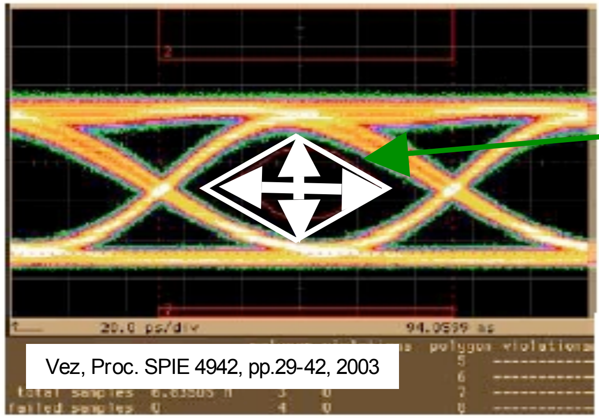
f1=5.0 GHz,

f1=1.0 GHz

For the higher modulation frequency, the power in the higher harmonics is strongly enhanced.

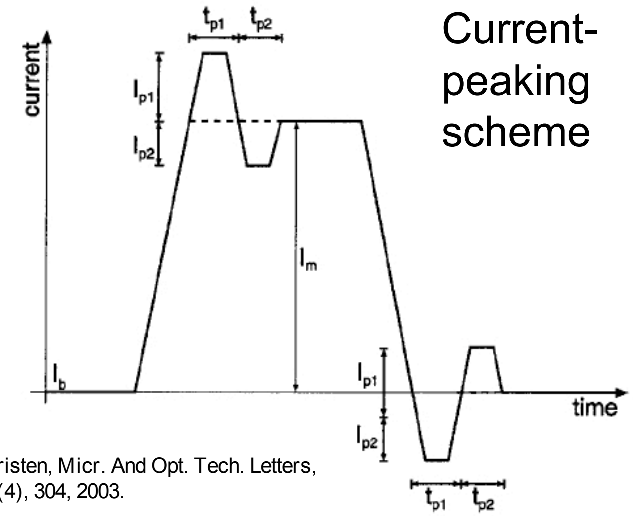
(reason: resonance effects, fr~6 GHz at I=6mA)

Digital Modulation: Eye-Diagram



Vez, Proc. SPIE 4942, pp.29-42, 2003

The eye-diagram is the most important laser characteristic in digital modulation applications.



Current-peaking scheme

Christen, Micr. And Opt. Tech. Letters, 38 (4), 304, 2003.

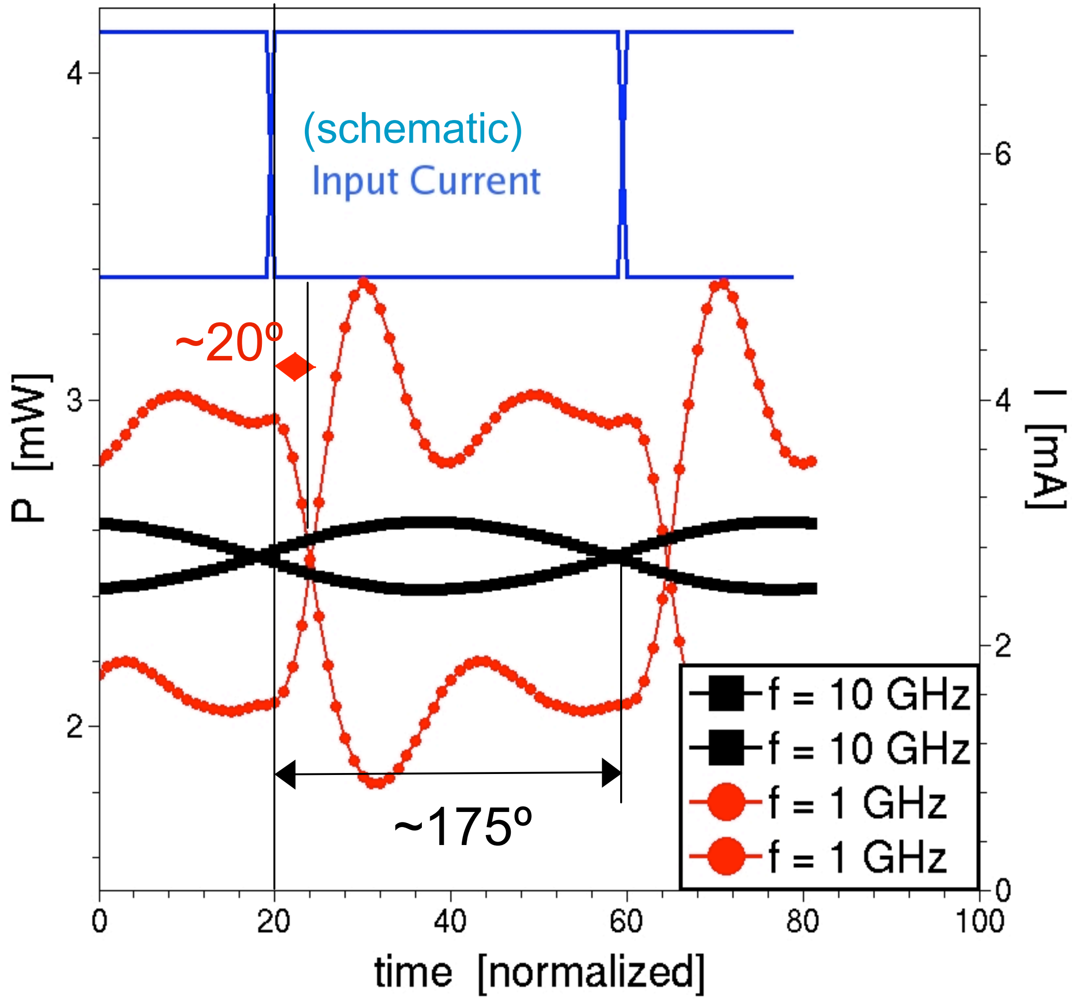
In order to obtain a “open eyes”, the input signal may be designed using advanced current-peaking schemes, in addition to device design.

In this work, we chose a simple rectangular input signal and approximate it with a finite Fourier series using 20 coefficients.

Note that the Harmonic Balance method is even better suited to support current peaking schemes do to it’s periodic nature.

Predictable Success

Eye-Diagram (without jitter and noise)



Modulation with 1 GBit/s

$f < f_{res}$

→ Strong overshoots

→ "Open Eye"

Modulation with 10 GBit/s

$f > f_{res}$

→ Closed eye

→ Large phase delay (~175º)

Fourier coefficients for internal densities, potentials etc. can be analyzed!

Summary

- Harmonic Balance Method for simulation of Large-Signal characteristics
- Consistent link between “System Specs” and microscopic description on device level using **Synopsys Sentaurus Device** framework
- Investigation of Analog and Digital modulation schemes possible
- VCSEL Application examples
  - Analog Modulation: Intermodulation distortion
  - Digital Modulation: Eye-Diagrams

Outlook:

Systematic investigation of eye-diagrams on device level including noise and jitter, physics of Fourier coefficients of microscopic quantities

Backup

Figure of Merit of Non-Linearities: Intercept Points

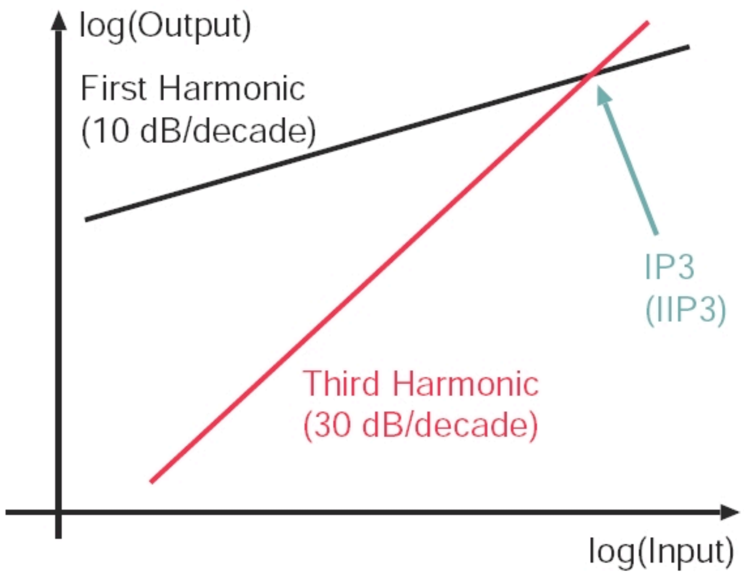


Figure 2. Schematic of third-order intercept point, which is defined by the extrapolated crossing point of the fundamental first and third harmonics of the output signal.