Harmonic Balance Analysis for Semiconductor Lasers under Large-Signal Modulation

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Outline

- Large-Signal Application and Characterization
- Simulation of Large-Signal Modulation
- Harmonic Balance Method
- Edge Emitter Example:
    - Distortion Analysis
    - Spatial Resolution

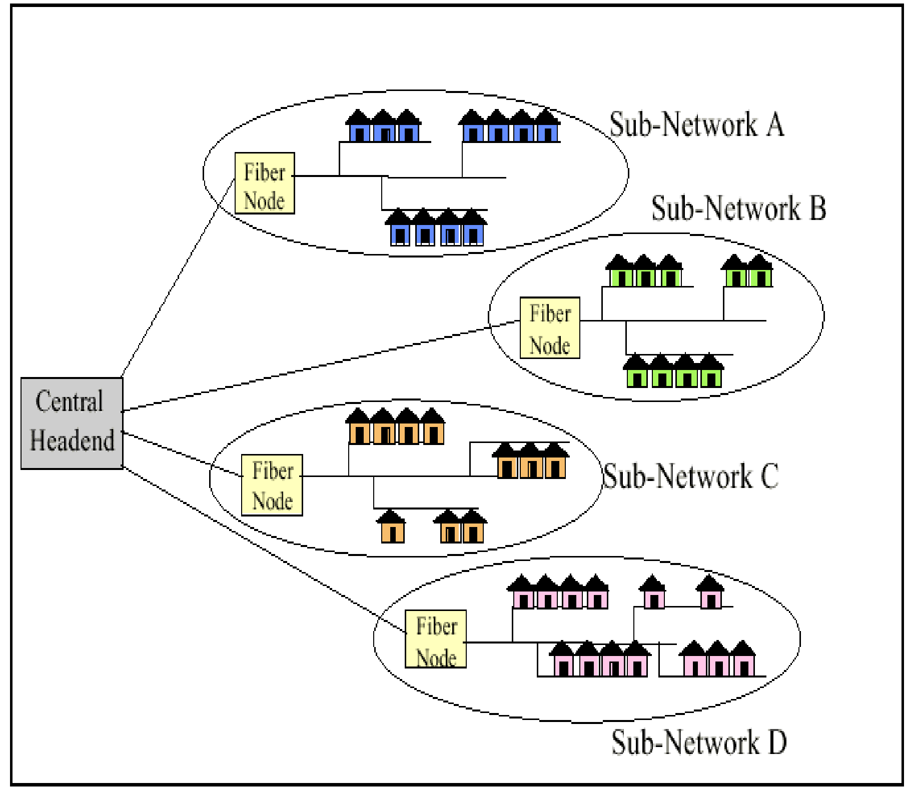
Large-Signal Modulation of SC Lasers

Analog CATV Systems:

- ➢ High linearity
- ➢ Low distortion

Digital Signal Transmission:

- ➢ Eye Diagram Masks
- ➢ Low BER



Sub-networks on an HFC Architecture

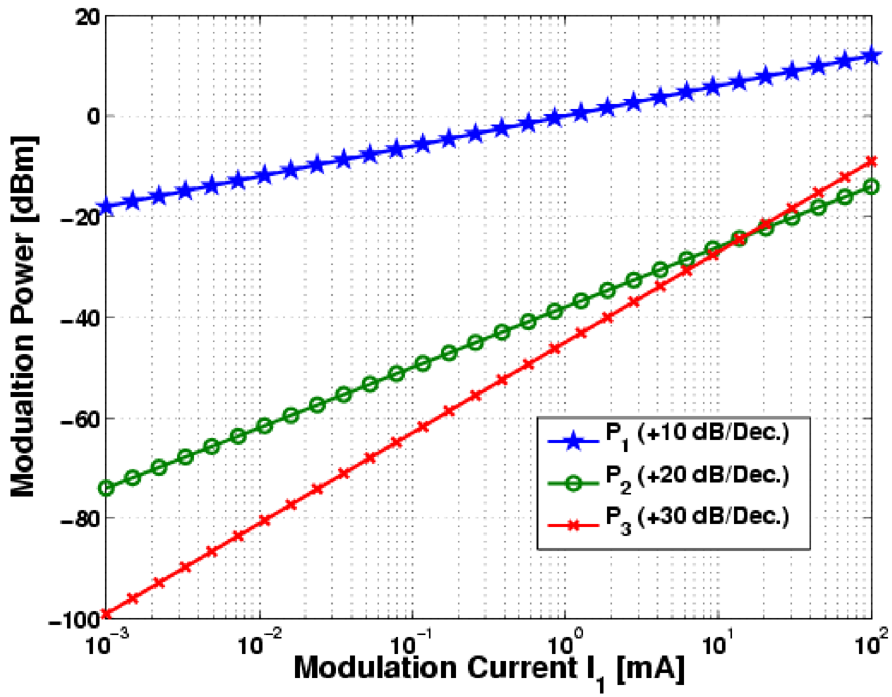
HFC = Hybrid Fiber to Coax

This Talk: Linearity/Distortion

Harmonic Distortion: Current Modulation

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

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



Harmonic Distortion:

$$\mathrm{SHD} = 10\log\left(\frac{P(2f)}{P(f)}\right)$$

Challenges for Device Simulation

Simulation under Large-Signal Conditions:

1) Time-Domain

   + simple

   - time consuming

   - dispersion

2) Mixed Frequency-/Time-Domain (Harmonic Balance HB)

   - complex

   + fast

   - memory consumption

Harmonic Balance Method

Assume a system of nonlin. Equations in the following form

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

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

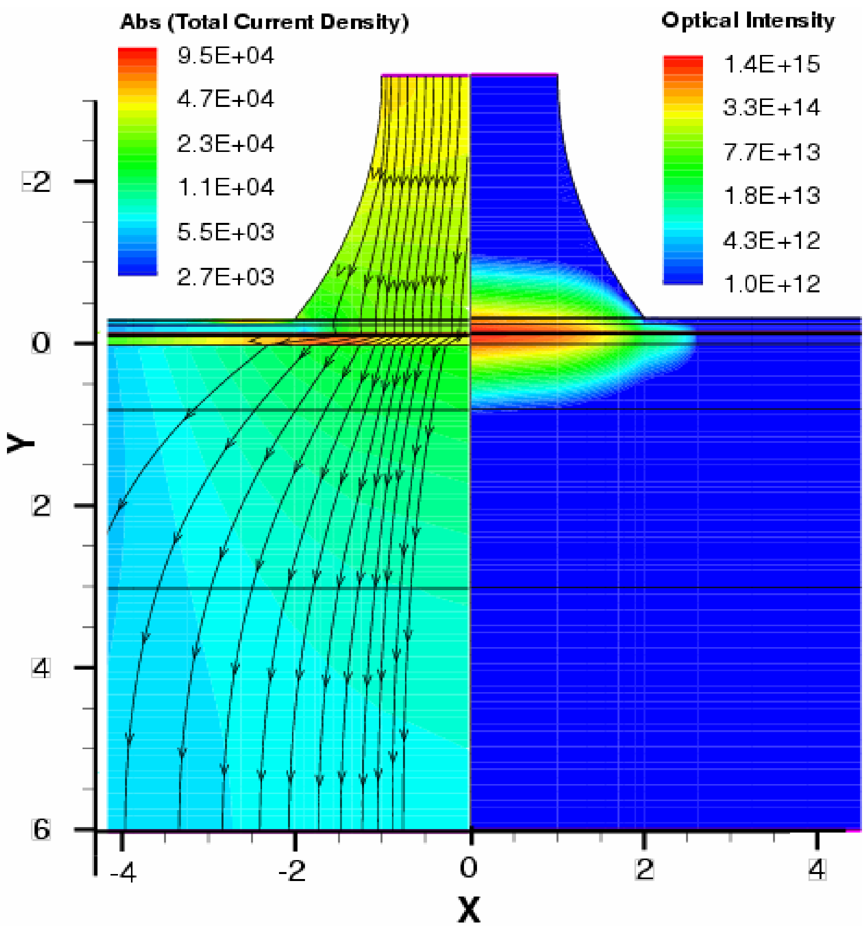
$$\mathbf{w}(t) = \sum_{k=-K}^{K} \mathbf{W}_k \exp\left(i\,\omega_k\,t\right) \qquad \mathbf{x}(t) = \sum_{h=-H}^{H} \mathbf{X}_h \exp\left(i\,\omega_h\,t\right)$$

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

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

B. Troyanovsky et al., Computational Methods in applied mechanics and engineering, Vol. 181, pp. 467-482, 2000.

Example
Generic (In,Al)GaAs Edge-Emitter



Single InGaAs QW

Length: 400 μm

$R_{1,2} = 0.3$

$I_{th} = 20$ mA

$\lambda = 980$ nm

Edge-Emitter Example
Performance Comparison

CPU/Memory requirements: (simulation mesh with 1500 elements)

DC with 40 points:	~ 2 min, 100 MByte
AC-SS with 40 frequency points:	~ 40 sec, 100 MByte
Distortion transient (10 mod-depths/20 freqs):	~ 200x2 h, 100 MByte
Distortion HB (10 mod-depths and 20 freqs):	~ 40 min, 20 GByte
(with GMRES* storage):	~ 20 min, 600 MByte

* Special vector-product storage concept of HB Jacobian to reduce memory consumption

Simulation Models

Laser Equations

Poisson:	$\nabla \cdot \epsilon \nabla V = -q\left(p - n + N_D^+ - N_A^-\right)$
Continuity (bulk):	$\pm\nabla \cdot \mathrm{J}_c^{3D} = q\left(C_{cap,c} + \partial_t c^{3D}\right) + F_{c^{3D}}(t)$
Continuity (QW):	$\pm\nabla \cdot \mathrm{J}_c^{2D} = q\left(R^{st} + R^{sp} + R^{nr} - C_{cap,c} + \partial_t c^{2D}\right) + F_{c^{2D}}(t)$
Thermodynamic:	$-\nabla \cdot \mathrm{S} = H + c_{th}\partial_t T_L$
Photon Rate:	$\partial_t S_\nu = \left(G_\nu - L_\nu\right) S_\nu + T_\nu^{sp} + F_{S_\nu}(t)$
Photon Phase:	$\partial_t \Phi_\nu = \Xi_\nu + F_{\Phi,\nu}(t)$

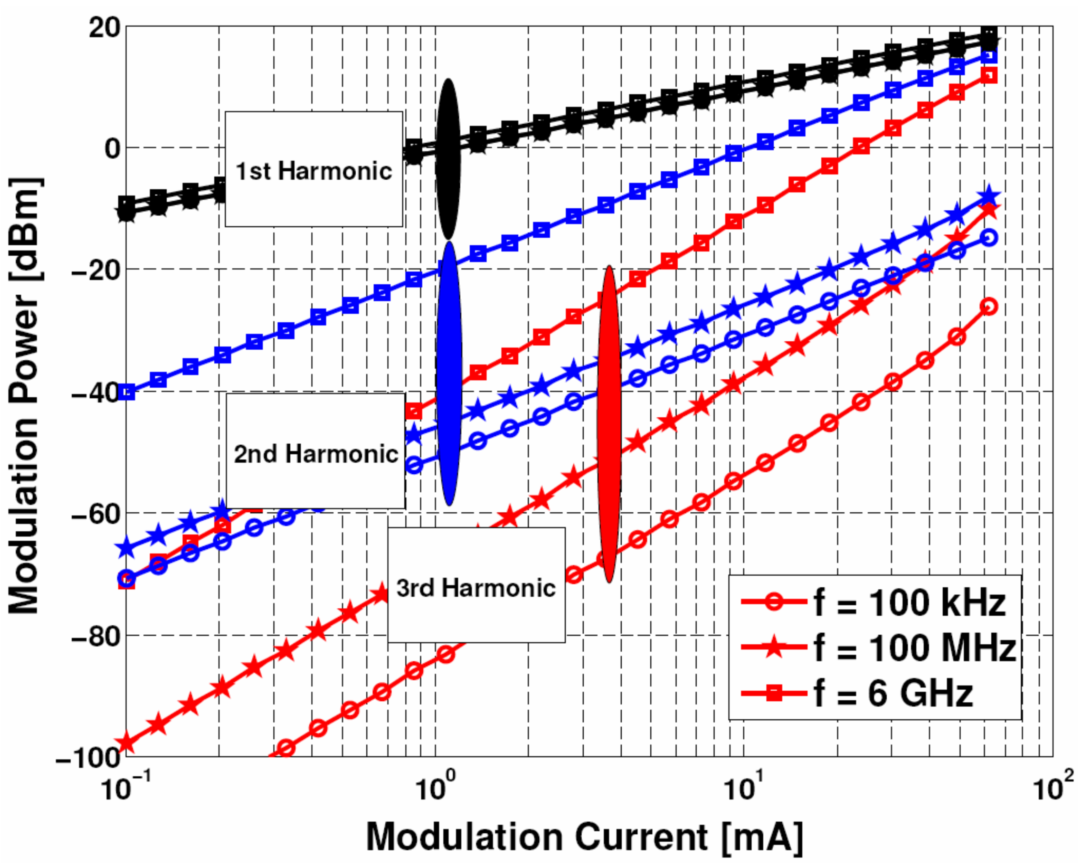
Helmholtz:

$$\nabla \times \nabla \times \Psi_\nu(r) - \frac{\omega_\nu^2}{c^2} n_{opt}^2(r)\Psi_\nu(r) = 0$$

Harmonic Distortion in Lasers:
Mechanisms

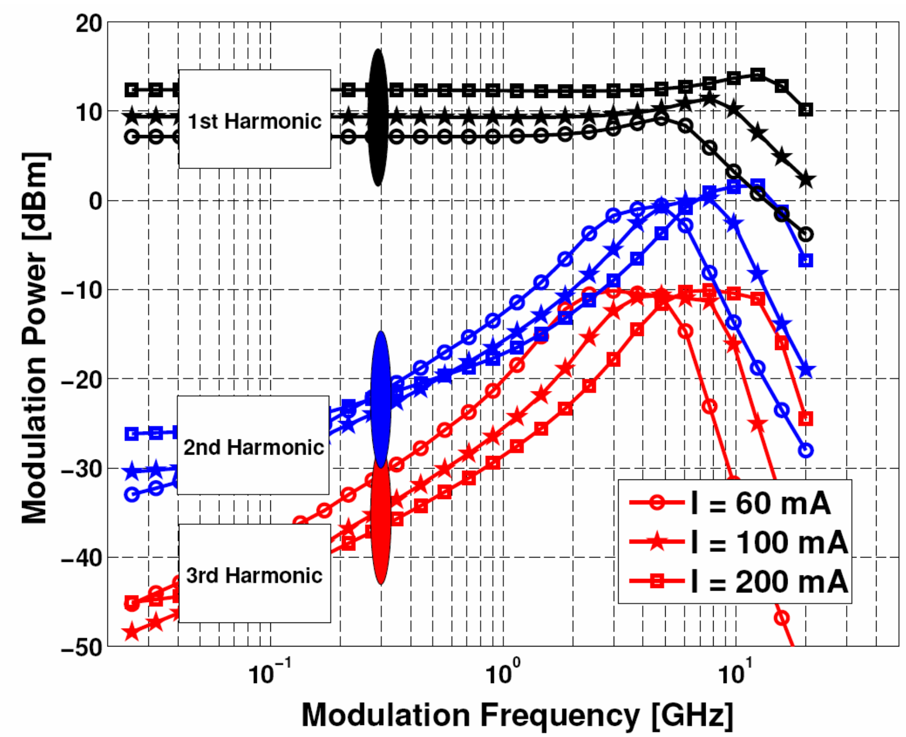
- Resonance Frequency Effects (G(N)*S-Term)
- Carrier Dependent Absorption (α_{FCA}(N)*S-Term)
- Leakage Current
- Gain Compression (G(S)*S-Term)
- Spatial Hole Burning

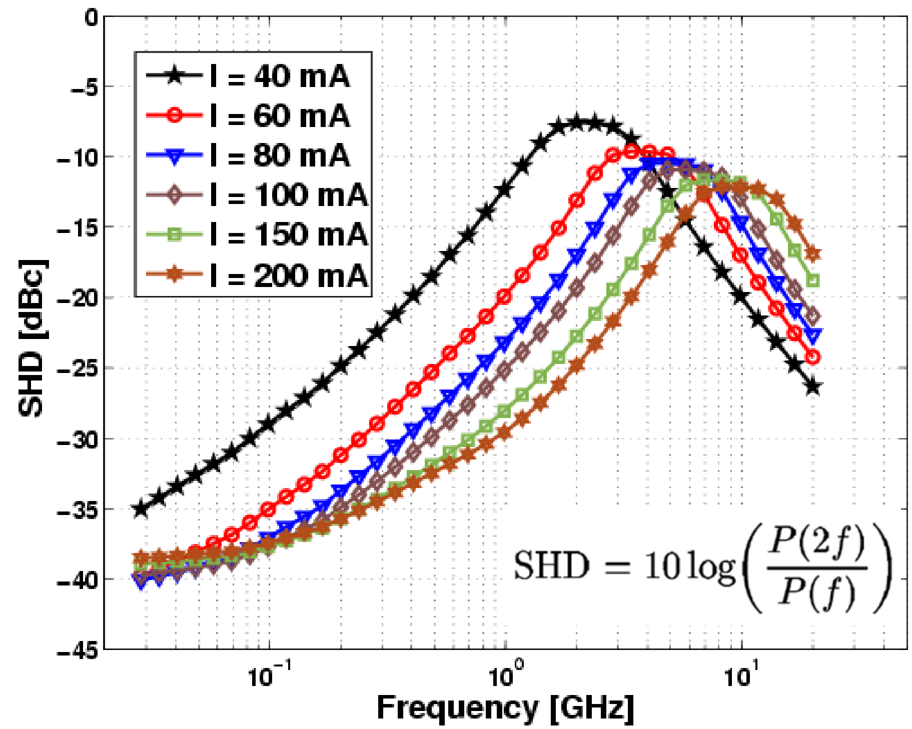
Edge-Emitter Example
Power vs. Modulation Current



- $P_{1/2/3}$= 10/20/30 db/dec.
- Compression insignificant
- I_{bias} = 100 mA
- α_{FCA} increases p_2 and p_3
- by approx. 10dB
- m=0.1

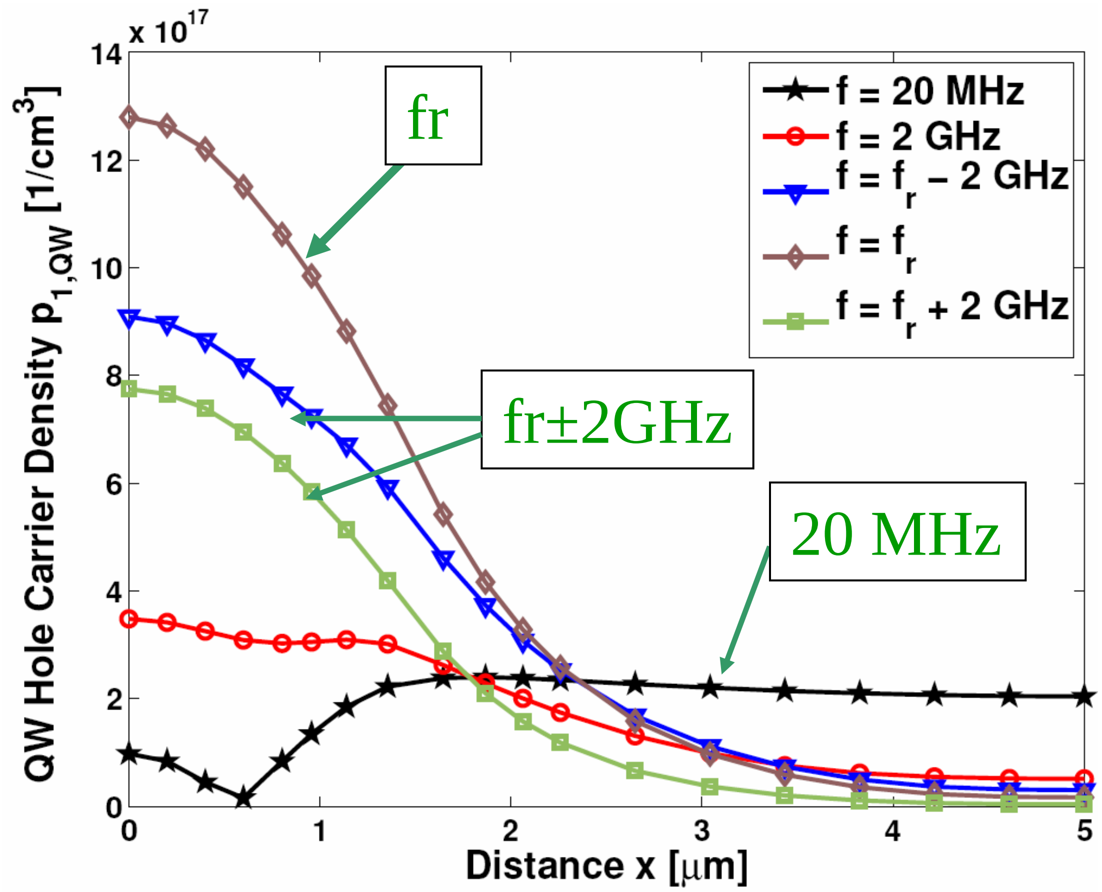
Edge-Emitter Example
Modulation Frequency





- Increasing distortion due to resonance effects (G(N,S)*S-term)
- Limit to Analog Transmission Rate
- Simulation Time: <10 minutes independent of f_{Mod}

Edge-Emitter Example
Large-Signal Response

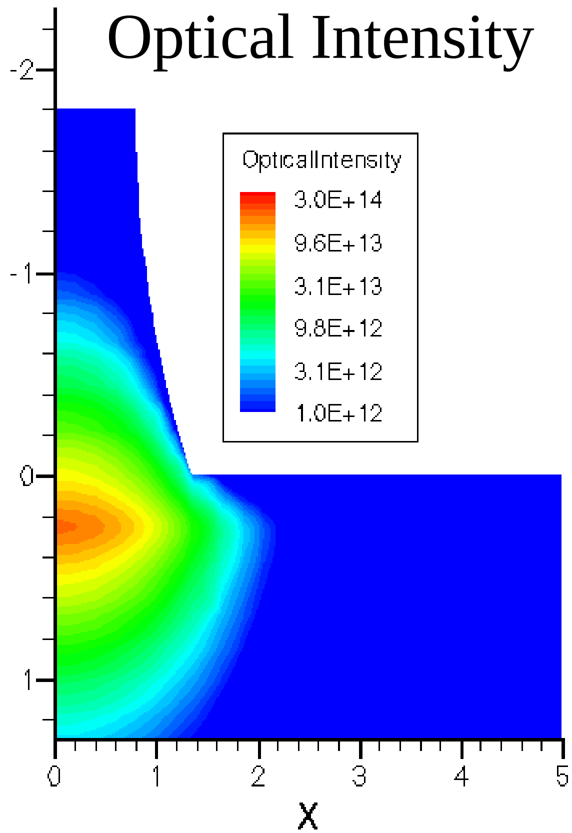


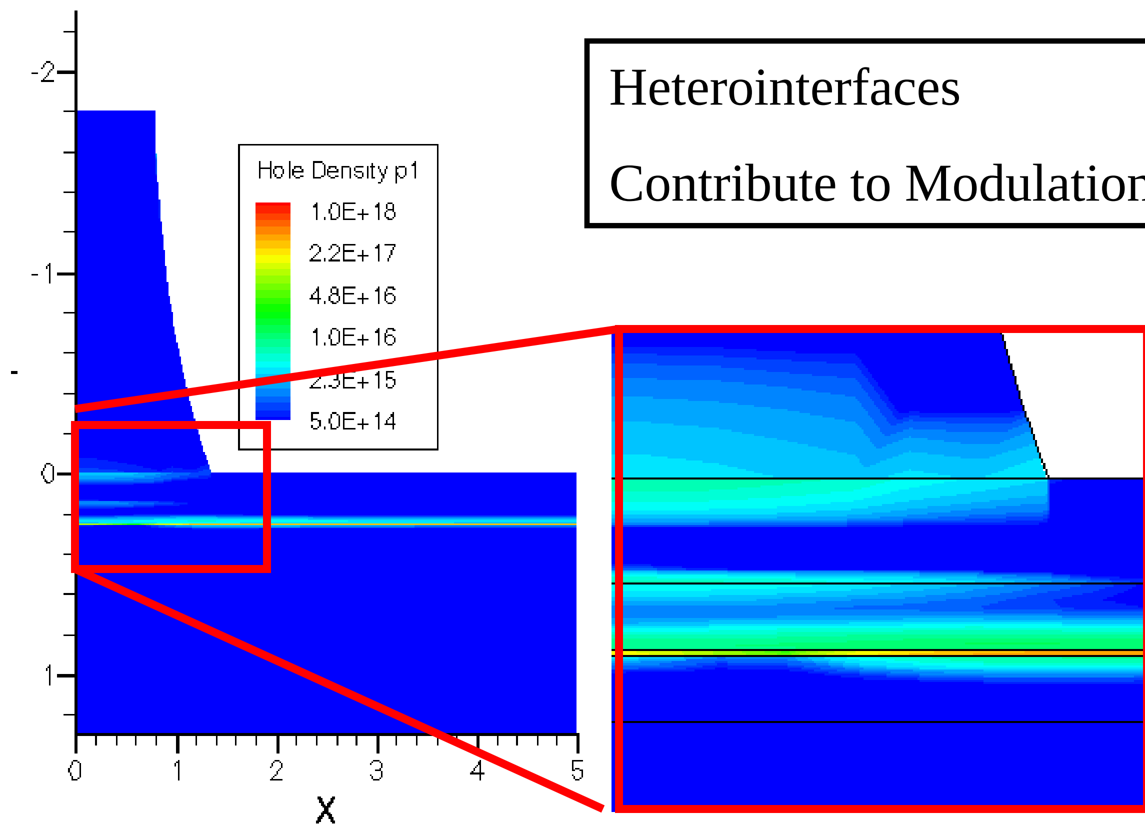
Hole Carrier Density p:

$$p(t) = p_0 + p_1 \sin(\omega t) + \dots$$

- Spatial Resolution of Harmonics (m=0.5)
- Low Frequency: Diffusion Currents
- High Frequency: Carrier-Photon Resonance

Edge-Emitter Example
Hole Density p1@ 20 MHz





Heterointerfaces

Contribute to Modulation

Conclusion & Outlook

- ❑ Harmonic Balance Model for Microscopic Laser Simulation
- ❑ Fast Computation of Nonlinear Large Signal Effects
- ❑ Microscopic Device Physics included: Leakage/Diffusion Currents, Defects, Gain Nonlinearities, Temperature, etc.
- ❑ Spatial Resolution of Harmonics => Analysis of Distortion Sources
- ❑ Example: Ridge Waveguide Edge Emitting Laser

Outlook:

- ❑ Multi-Tone and Eye-Diagram Simulations

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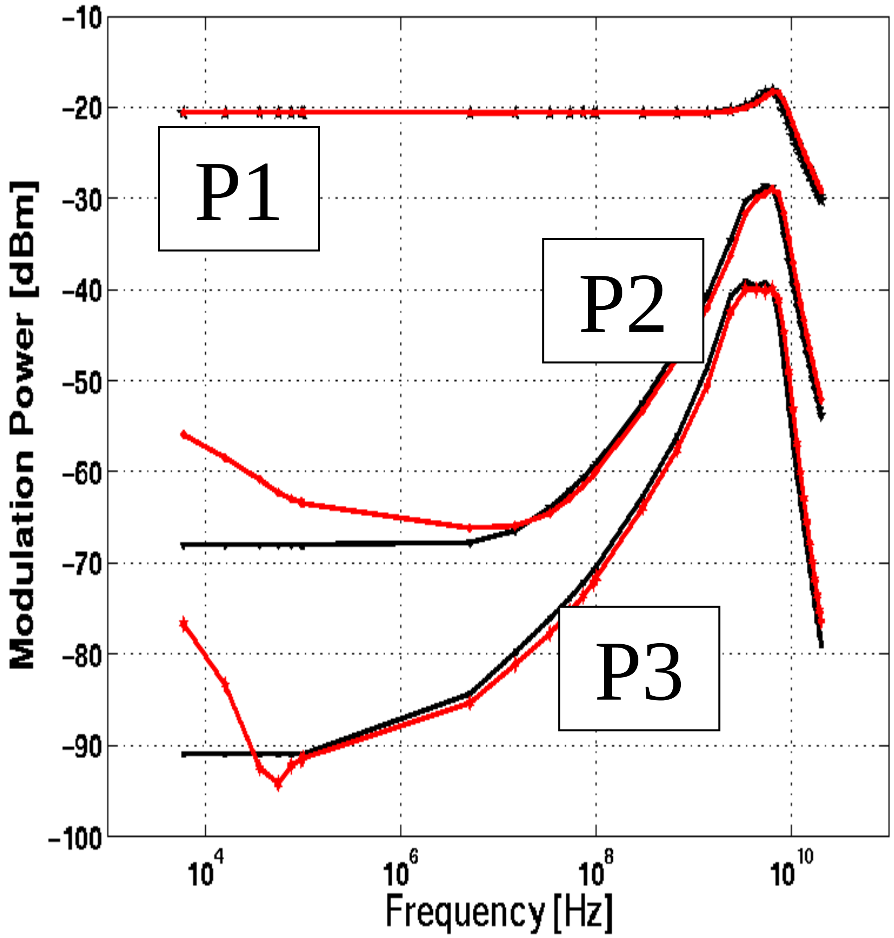
Temperature Effects



Temperature Effects at low Frequency only!

With Temperature
Without Temperature