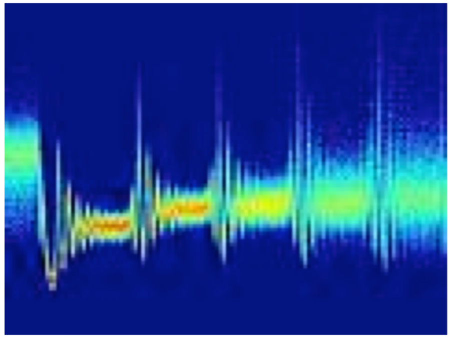
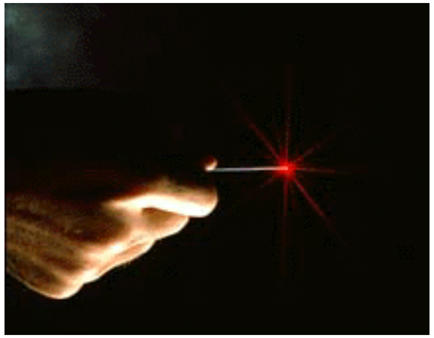
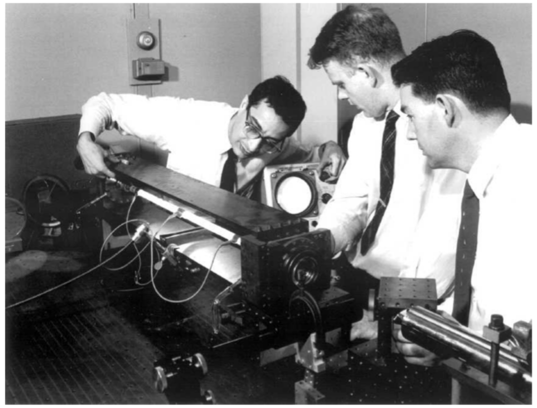
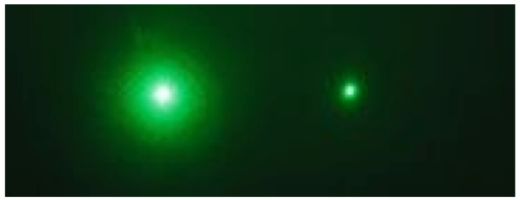
# Chapter 2

# Ultra-fast Laser Diodes in Fiber Optics Communications









# Introduction

- The most important application of ultra-fast diode lasers is the field of **optical fiber communications**

- **Bit rate-distance product** is the product of the number of bits transmitted per second by the repeater spacing

- The performance of optical fiber communication systems depends on the parameters of the **optical fiber (dispersion and loss) and of the laser diode**

- **Modulation bandwidth and spectral purity** of the laser emission play a crucial role and affect considerably the the bit rate-distance product

- Minimum loss in conventional silica fibers ~1.55 μm + zero-dispersion ~1.3 μm
$\Rightarrow$ **InGaAsP lasers are the most promising candidates**

# Modulation

- Semiconductor lasers can be **directly modulated by the device current**

⇒ **amplitude (AM) and frequency (FM) modulations**

- This comes from the **refractive index variations** in the laser at the same time when the **optical gain changes as a result of the carrier density variations**

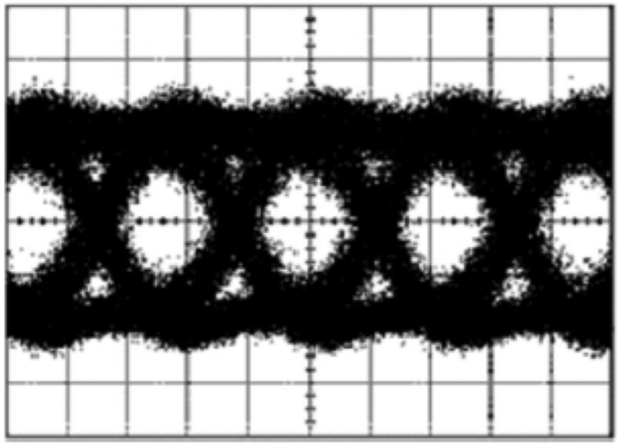


FIGURE 12.20 Eye diagram of a 40-Gb/s bit pattern from an external modulator.

- The interdependence between AM and FM modulations are governed by the **linewidth enhancement factor ($\alpha_H$-factor)**

# Rate Equations

- Rate equations describe the interplay between the carrier density N(t) in the active layer and the photon density S(t) in the cavity

$$\frac{dN}{dt} = \frac{I(t)}{eV} - \frac{N(t)}{\tau_e} - g_0(N - N_t)S$$

$$\frac{dS}{dt} = \Gamma g_0(N - N_t)S - \frac{S}{\tau_p} + \frac{\beta \Gamma N}{\tau_e}$$

- Small-signal analysis

$$N(t) = N_0 + \delta N(t)$$

$$S(t) = S_0 + \delta S(t)$$

$$P(t) = P_0 + \delta P(t)$$

$$I(t) = I_0 + \delta I(t)$$

- $N_0$, $S_0$, $P_0$ et $I_0$ are the **steady-state (average) values of carrier, photon densities, power and current respectively**

- Small-signal variations are such that $\delta I(t) \ll I_0$, $\delta S(t) \ll S_0$, $\delta P(t) \ll P_0$ and $\delta I(t) \ll I_0$

# Response

- The small-signal solution of the rate equations give the **intrinsic frequency response**

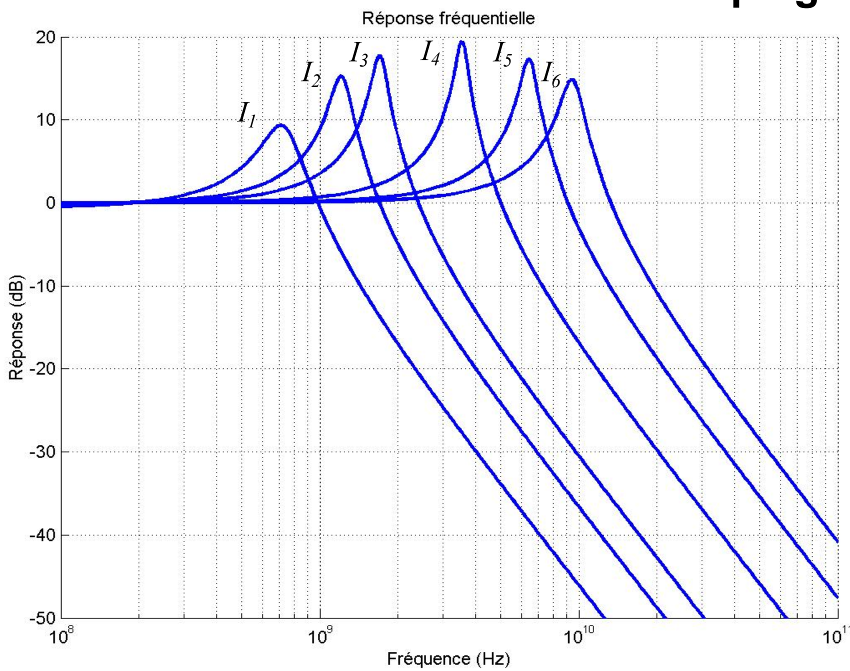
$$M(j\omega) = \frac{\delta \widetilde{S(\omega)}}{\delta \widetilde{I(\omega)}} \qquad R_{int} = \left| \frac{M(j\omega)}{M(0)} \right| \qquad R_{int} = \frac{\omega_r^4}{(\omega^2 - \omega_r^2)^2 + \omega^2 \gamma^2}$$

Damping

$$\omega_r^2 = \frac{g_0 S_0}{\tau_p}$$ **Relaxation frequency**

- **Relaxation oscillation** depends on spontaneous emission factor, carrier diffusion and carrier transport effects

- Above the resonance peak, the magnitude of the intrinsic response approaches **asymptotically a slope of -40dB/decade**



# Response

- The parameter $f_{3dB}=\omega_{3dB}/2\pi$ is referred to as the **modulation bandwidth of the laser**
- **Universal relation** between the resonant frequency and the damping rate

$$\gamma = K f_r^2 + \gamma_0 \qquad \text{with} \qquad K = 4\pi^2 \tau_p$$

- K-factor is a **figure of merit for high-speed laser diodes** since the maximum possible intrinsic modulation bandwidth $f_{max}=8.88/K$
- Small K-factor required for high-speed operations
- K-factor depends not only on the photon lifetime but is significantly affected by **nonlinear gain effects and carrier transport effects**
- Typical values range from **0.2 to 0.4 ns leading to modulation bandwidths as wide as 20-40 GHz**

# Improvements?

❑ **How to increase the relaxation frequency and the modulation bandwidth?**

❑ **Increasing the photon density** via a better confinement of the optical field in the active layer or by biasing the laser at a higher pump current

⇒The relaxation frequency increases with an increasing output power until the power levels when heating and catastrophic mirror damage can occur

❑ **Increasing the differential gain** coefficient by cooling the device, doping active areas or by using quantum well, quantum dot structures

❑ An additional enhancement can be obtained with the inclusion of **strain in the active layer**

❑ **Reducing the photon lifetime** by decreasing the laser-cavity length

# Parasitic

❑ Bandwidth is usually limited by **RC parasitic, device heating and maximum power-handling capability of the laser facets**

❑ Overall modulation response is $R=R_{int}.R_e$

$$R_e = \eta^2 \frac{1}{1+\left(\frac{\omega}{\omega_{RC}}\right)^2} \frac{1}{1+\left(\frac{\omega}{\omega_{pn}}\right)^2}$$

⇒ $\eta$ represents the **low-frequency modulation efficiency** caused by the sublinearity of the power-current curve

⇒ $\omega_{RC}$ and $\omega_{pn}$ describe the **high-frequency roll-off** caused by **the series resistance and the diffusion capacitance of the pn junction**

❑ **Package parasitic**: bond-wire inductance and a capacitance between the input terminals (decreased by the monolithic integration)

❑ **Chip parasitic**: resistance associated with the semiconductor material surrounding the active region and stray capacitance

# Nonlinear Gain

- Additional **nonlinear dependence of the gain** with the photon density in the cavity is observed
- At high photon densities, the gain is reduced or suppressed in comparison to the threshold gain or the gain at low photon densities
  $\Rightarrow$ **spectral hole burning, spatial hole burning and carrier heating**
- **Spectral hole** refers to a slight reduction in gain around the spectral region at the lasing wavelength due to the finite intra-band relaxation time of carriers
- **Carrier heating**: fast carrier thermalization maintains electrons and holes in thermal equilibrium with each other at temperatures that are higher than that of the lattice
- The carrier heating is brought by **stimulated emission and free-carrier absorption**
- Electron-hole plasma loses its **energy to the lattice by a combination of relaxation processes**

# Nonlinear Gain

- Analytical expression of the nonlinear gain

$$g(N,S) = \frac{g_0(N-N_t)}{(1+\epsilon S)^m}$$

with ε the **nonlinear gain coefficient**, S the photon density and m a fitting constant

- m=-1 directly related to the **third-order nonlinear susceptibility** of a semiconductor
- m=1 results from a **two-level-atom treatment for laser diodes**.
- m=1/2 is derived from a more rigorous solution using an approximation for the **density of states function**

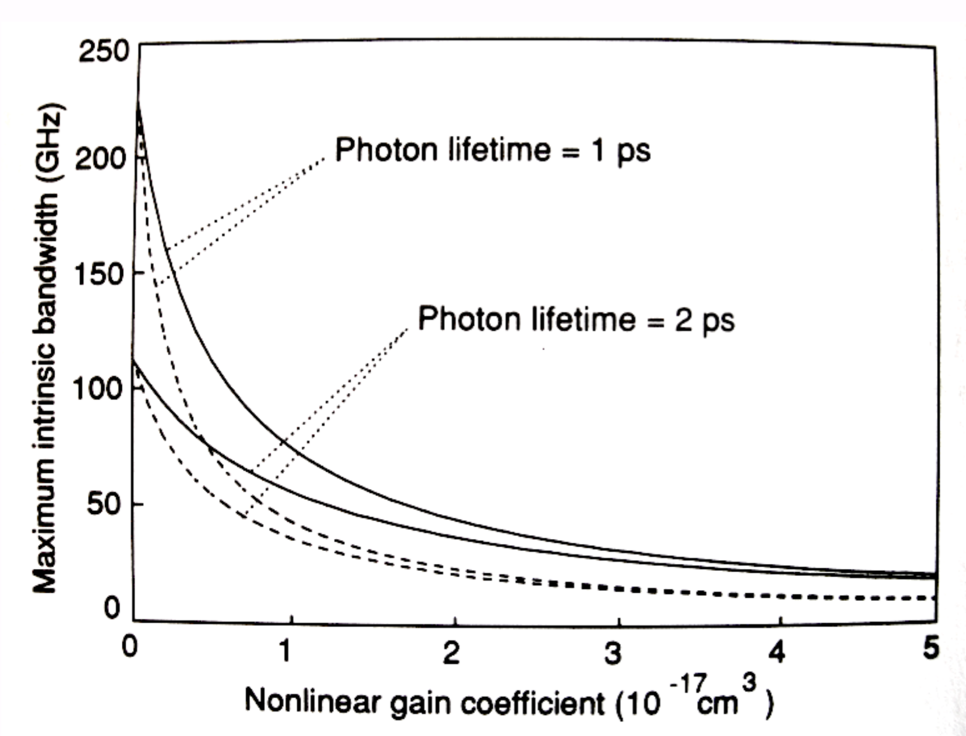
- When nonlinear gain effects are included the **relaxation frequency as well as the K-factor of the laser are modified**

$$K = 4\pi^2\left(\tau_p + \frac{\epsilon}{g_0}\right) \qquad \omega_r^2 = \frac{g_0 S_0}{\tau_p(1+\epsilon S_0)}$$

# Nonlinear Gain

❑ Because of the quantum confinement of electrons, **nonlinear effects are enhanced in QW lasers**

❑ QW lasers with thinner quantum-well thickness have the **larger nonlinear gain coefficient at the constant linear bulk gain**




❑ Frequency $f_{max}$ is strongly dependent on the gain compression coefficient

$\Rightarrow$ **low values of $\varepsilon$, $f_{max}$ is primarily determined by $\tau_p$**

$\Rightarrow$ **large values of $\varepsilon$, $f_{max}$ is affected by $g_0$ only**

# Microwave Analysis

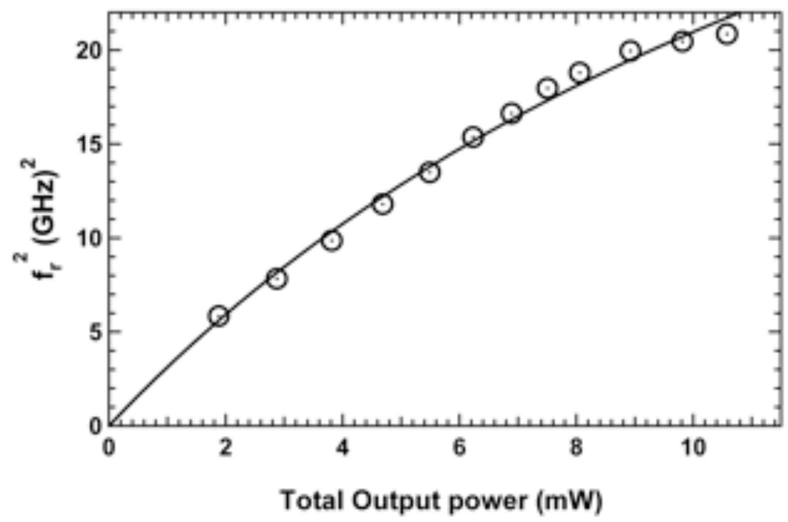


- The experimental dependence of the **relaxation oscillation frequency deviates from the expected linear dependence**

$$\boxed{f_r^2 = \frac{AP}{1+\frac{P}{P_{sat}}} = \frac{AP}{1+\varepsilon_P P}}$$

**$\varepsilon_P$: gain compression coefficient related to the output power**

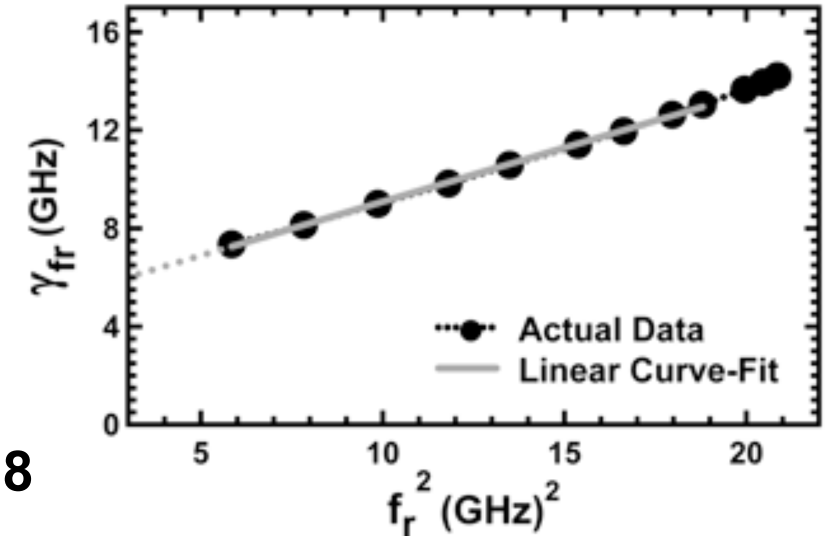
$$\boxed{\varepsilon_P P = \varepsilon_S S}$$




- Curve-fitting results: **$P_{sat}$ ~ 17mW, $\varepsilon_P$= .06mW$^{-1}$** and $\omega_{rmax}=(AP_{sat})^{1/2}$ ~7.6GHz.

- The evolution of the damping rate against the relaxation frequency squared leads to a **K~.45ns** as well as an effective carrier lifetime of **.16ns**

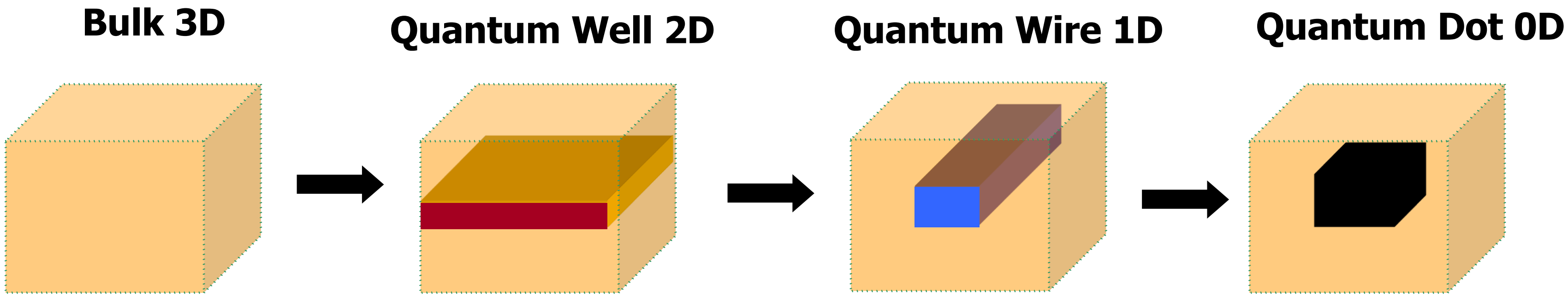
**Grillot *et al.*, 2008**

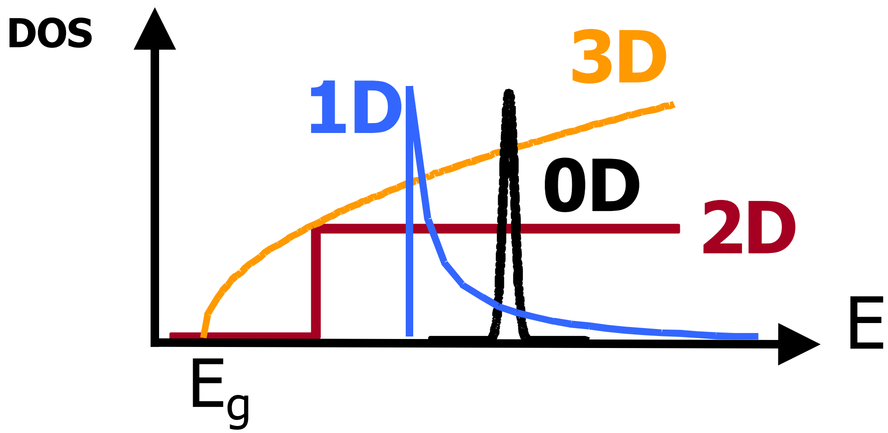


# Quantum Dots



- Improved charge carrier confinement in three spatial dimensions




$$\rho_{3D}(E) \propto \sqrt{E - E_g}$$

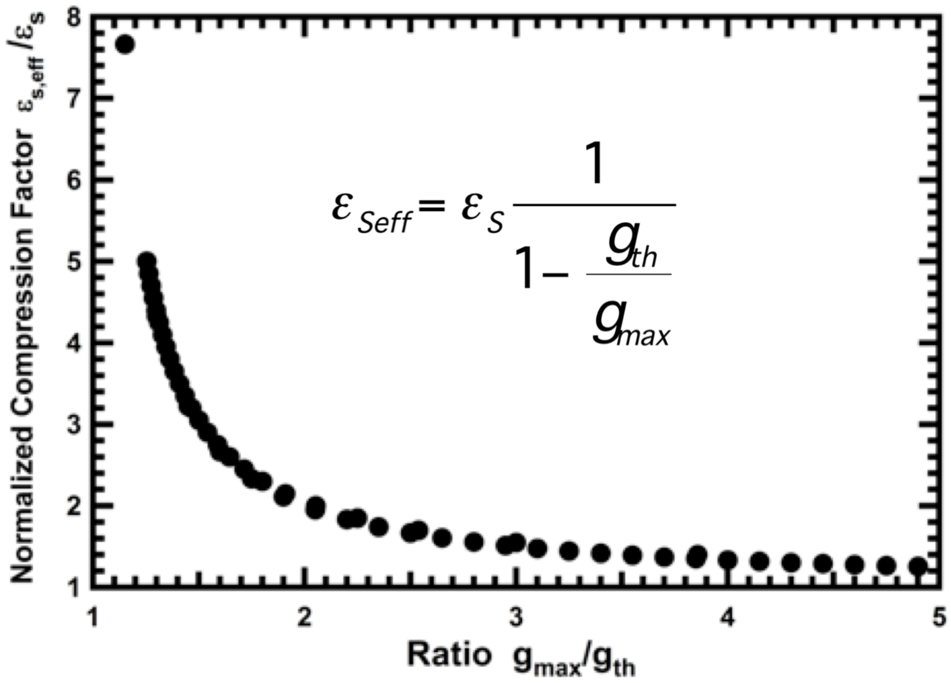
$$\rho_{0D}(E) \propto \delta\left(E - \left(E_g + E_{n,x} + E_{n,y} + E_{n,z}\right)\right)$$

# Quantum Dots

- In QD based devices **the gain compression is found to be enhanced due to gain saturation by a factor of $g_{max}/(g_{max}-g_{th})$**

- **Spatial hole burning** occurs as a result of the standing wave nature of the optical modes. Increased lasing power results in decreased carrier diffusion efficiency
$\Rightarrow$ **the stimulated recombination time becomes shorter relative to the carrier diffusion time**

- Carriers are therefore **depleted faster at the crest of the wave causing a decrease in the modal gain**



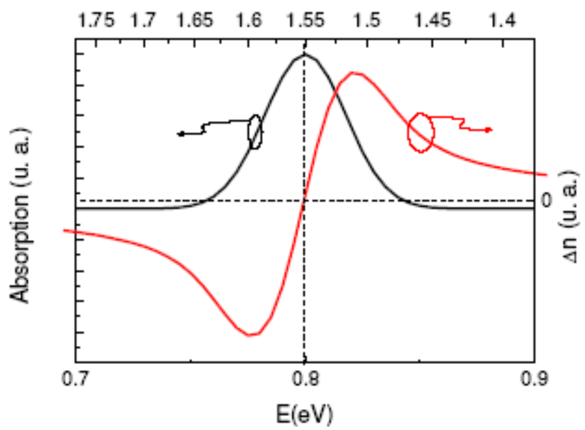

**Grillot et al., 2008**

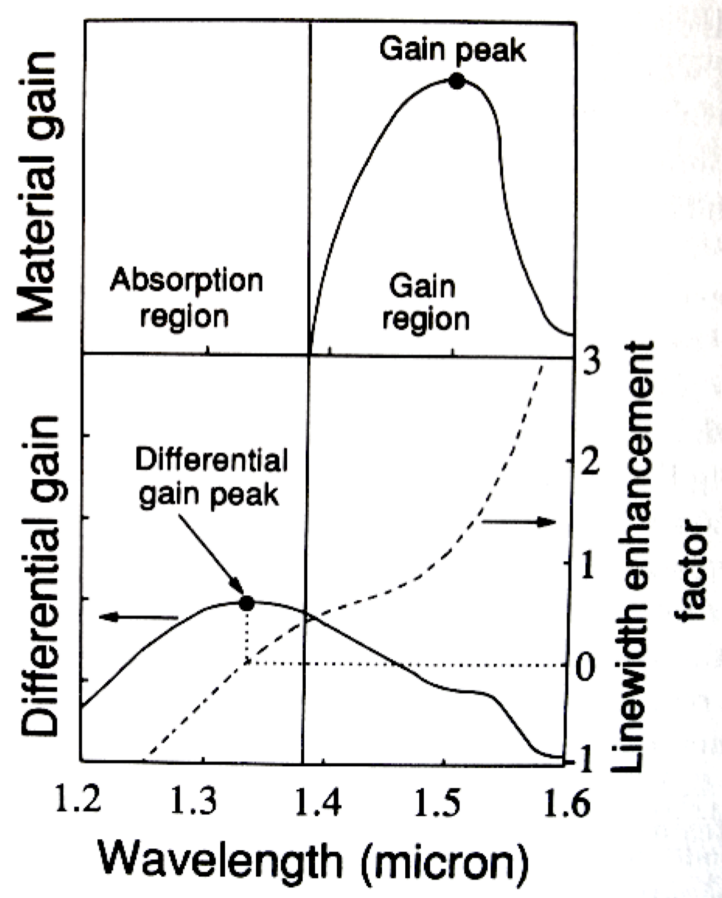
# The $\alpha_H$-factor

- The $\alpha_H$-factor influences several fundamental aspects of semiconductor lasers, such as the **linewidth or the laser behavior under optical feedback**

$$\alpha_H = -\frac{4\pi}{\lambda}\frac{dn/dN}{dg/dN} = -\frac{4\Gamma\pi}{\lambda}\frac{dn/dN}{dG_{net}/dN}$$

- In the case of QD lasers, several models at the early stages have predicted a **near-zero $\alpha_H$-factor due to the discrete density of states**



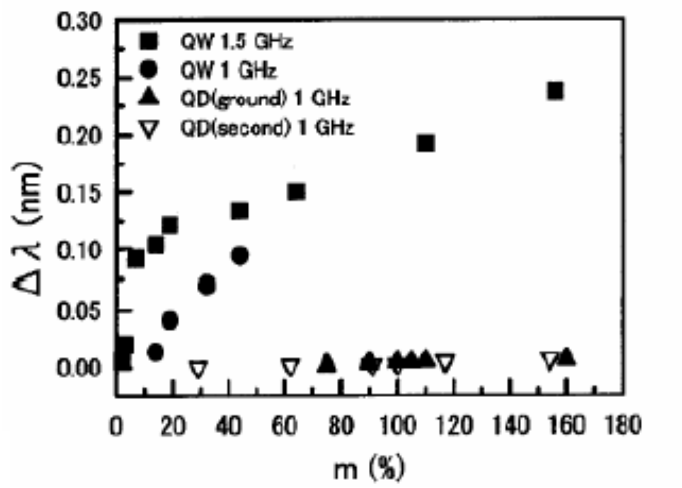



# The $\alpha_H$-factor

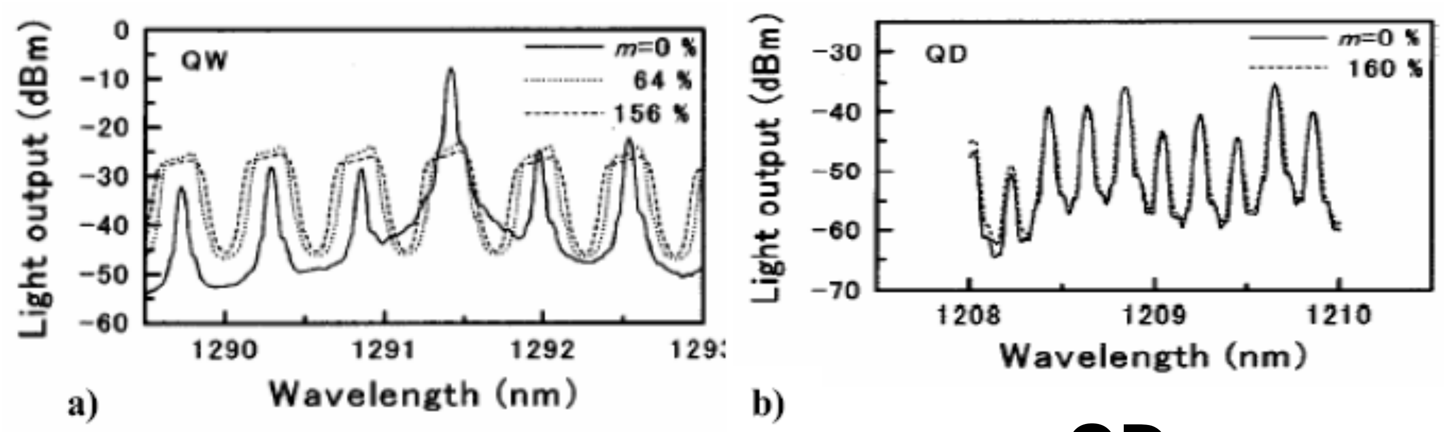
- Lower $\alpha_H \Rightarrow$ **narrower laser linewidth**

$$\boxed{\Delta\nu \propto \sqrt{1+\alpha_H^2}}$$

**C. H. Henry (1982)**




- Direct modulation at 2GHz on an InAs/InP QD laser




**QWs** **QDs**

**Saito et *al.* (2000)**

# The $\alpha_H$-factor

- **Hakki-Paoli:** this method is of straightforward implementation. Critical points concern the resolution of the OSA for the case of closely spaced longitudinal modes, and the fact that the thermal peak-shift drift occurring in CW measurements shall be subtracted to reveal the net carrier effect

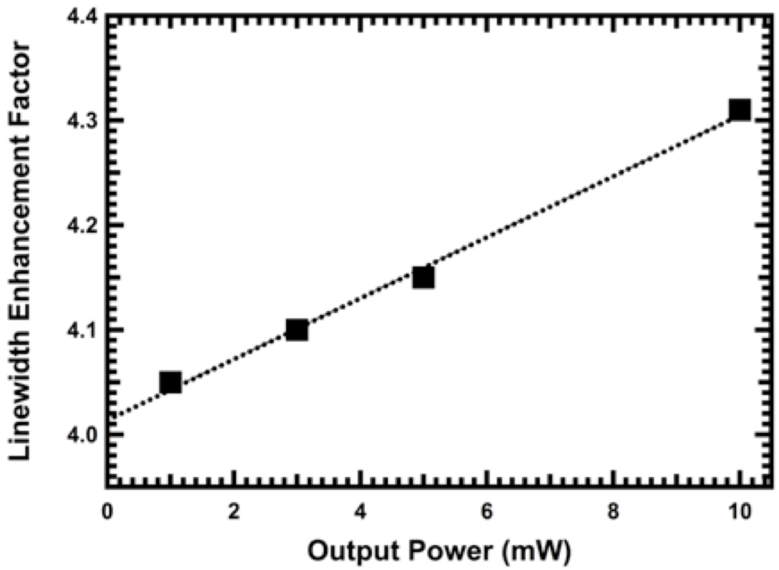
- **Modulation frequency**: This method relies on high frequency SL current modulation which, according to theory, generates both amplitude (AM) and optical frequency (FM) modulation. The ratio of the FM over AM components gives a direct measurement of the $\alpha_H$-factor

- **External optical feedback**: The $\alpha_H$-factor is determined from the measurement of specific parameters of the resulting interferometric waveform, without the need for the measurement of feedback level. The measured value for the $\alpha_H$-factor is the effective value in operating conditions, and nonlinear effects could be revealed at high power

- **Injection locking**: injection of light from a master SL into a slave SL causes locking of the slave optical oscillation frequency to that of the master. Typically, the locking region is characterized in terms of the injection level and frequency detuning, showing an asymmetry in frequency due to the non zero $\alpha_H$-factor

# The $\alpha_H$-factor

❑ In QW lasers, which are made from a homogeneously broadened gain medium, the carrier density and distribution are clamped at threshold. As a result, **the change of the $\alpha_H$-factor is due to the decrease of the differential gain from gain compression**




$$\alpha_H = \alpha_0 (1 + \varepsilon_P P) + \beta \varepsilon_P P \frac{1 + \varepsilon_P P}{2 + \varepsilon_P P}$$

**with $|\beta|<1$ a parameter related to the slope of the linear gain**

❑ The effective $\alpha_H$-factor **linearly increases with the output power**

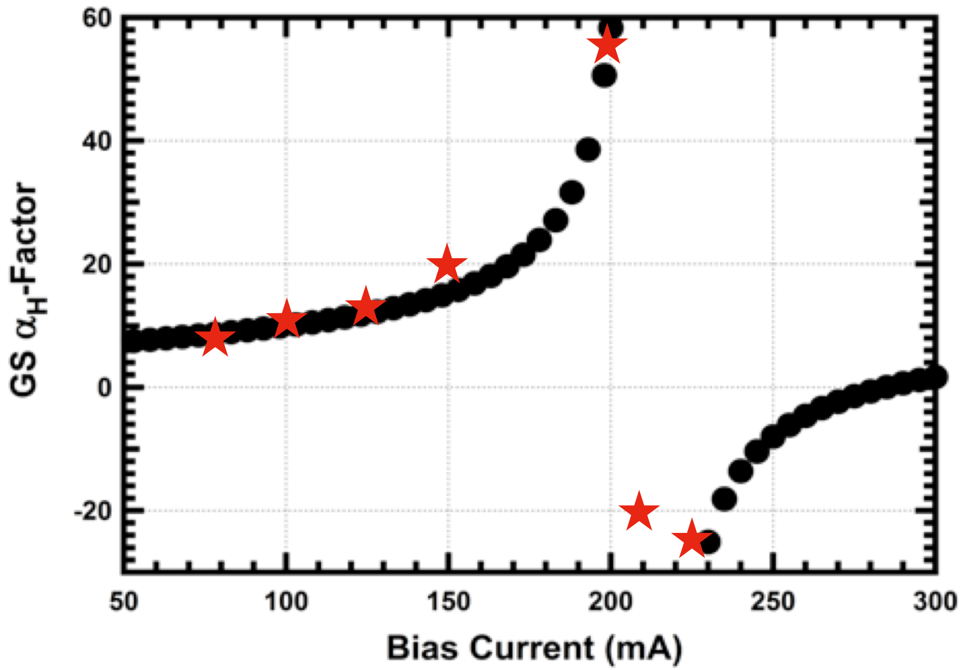
❑ Compare to QD lasers, **the gain compression coefficient is much lower** since the enhancement of the effective $\alpha_H$-factor is not significant over the range of power

# The $\alpha_H$-factor

- In QD lasers, **the carrier density and distribution are not clearly clamped at threshold** because the inhomogeneous broadening gain is more predominant
- **The filling of the ES inevitably increases the $\alpha_H$-factor of the GS introducing an additional dependence with the injected current**

$$\alpha_H(P) = \alpha_g(1+\varepsilon_P P) + \frac{\alpha_0}{1 - \dfrac{g_{th}}{g_{max} - g_{th}}\varepsilon_P P}$$

**Grillot *et al.*, 2008**



# The $\alpha_H$-factor

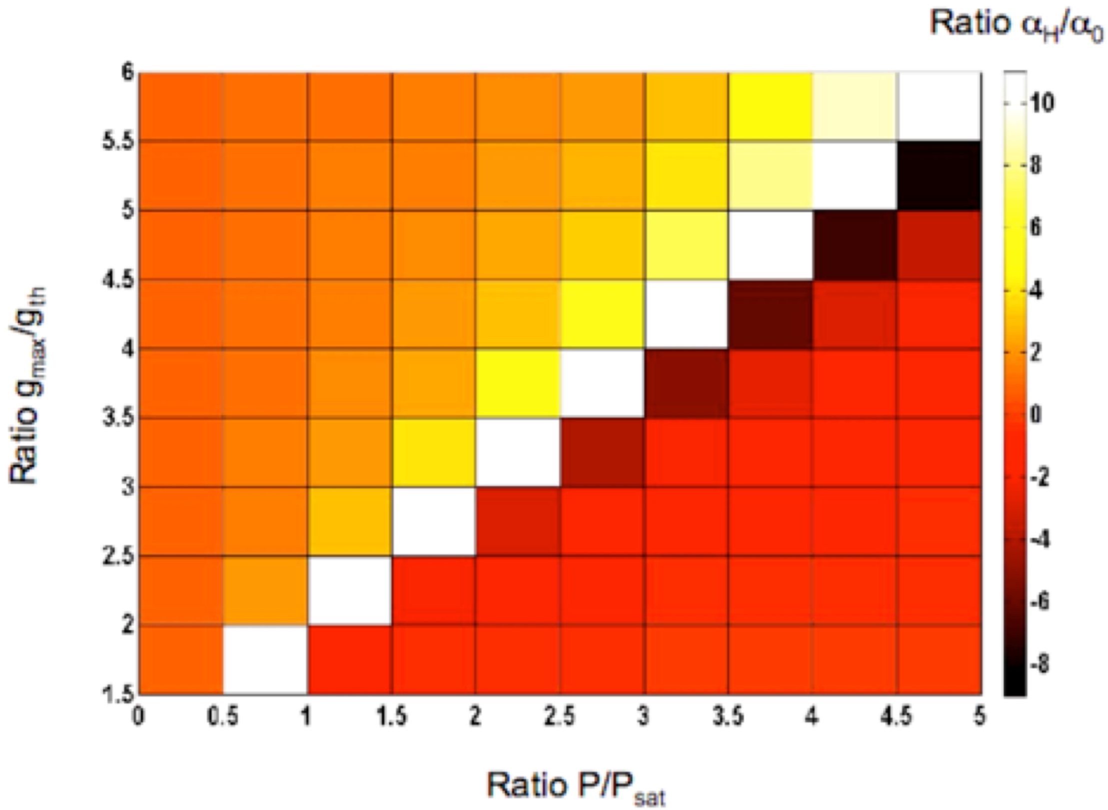
- The $\alpha_H$-factor can be controlled by properly choosing the ratio $g_{max}/g_{th}$

$\Rightarrow$ **the lower $g_{th}$, the higher $g_{max}$, the smaller the $\alpha_H$-factor**

- Both $g_{th}$ and $g_{max}$ should be considered simultaneously so as to properly design **a laser with a high differential gain and limited gain compression effects**

$$\alpha_H(P) = \frac{\alpha_0}{1 - \dfrac{g_{th}}{g_{max} - g_{th}} \varepsilon_P P}$$

**Grillot *et al.*, 2008**

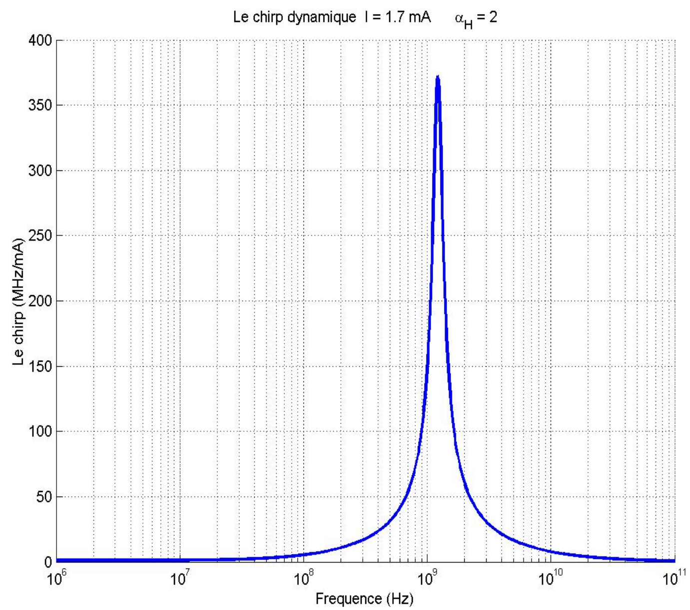


# Laser Chirp

❑ The enhanced linewidth and frequency chirp under the direct current modulation originate from **variations in the carrier density and from the finite difference in carrier density between the laser on and off states**

❑ The $\alpha_H$-factor plays a major role in obtaining **low-chirp emission from high-speed directly modulated lasers**

$$\Delta\nu(t) = \frac{\alpha_H}{4\pi}\left(\frac{d\ln P(t)}{dt} + \frac{2\Gamma\epsilon P(t)}{V\eta\hbar\omega}\right)$$




❑ **Chirpless lasers:**

⇒ Strained QW lasers

⇒ P-type modulation of QWs

⇒ chirp can be controlled by detuning the lasing wavelength with respect to the gain peak (increase the differential gain)

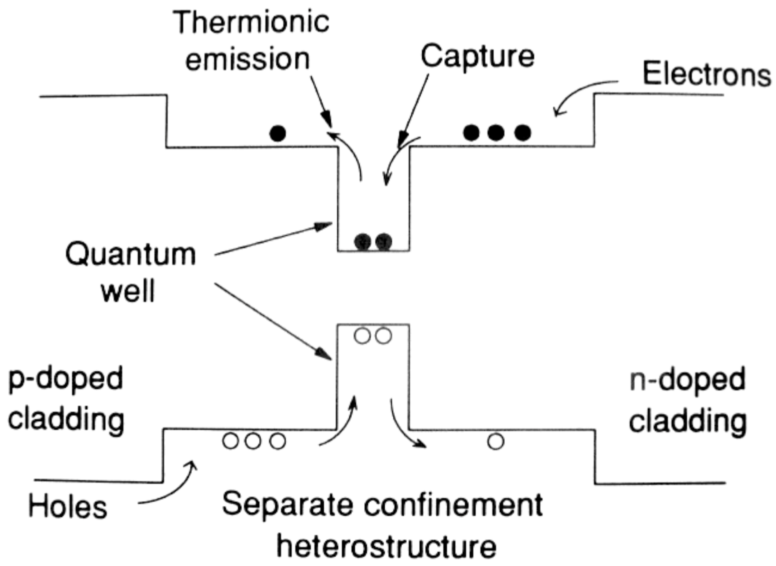
# Carrier Transport

- QW lasers lead to considerable improvement in the **modulation response of laser diodes mainly due to the enhanced differential gain**
- Unlike the bulk lasers, QW ones have a very small active areas and **carrier-transport effects have to be considered**

$$\frac{dN_W}{dt} = -\frac{G(N_W)S}{1+\epsilon S} - \frac{N_W}{\tau_e} - \frac{N_W}{\tau_{n2}} + \frac{N_B}{\tau_{tr}}\frac{V_{SCH}}{V_W}$$

$$\frac{dS}{dt} = \frac{\Gamma G(N_W)S}{1+\epsilon S} - \frac{S}{\tau_{ph}} + \frac{\beta\Gamma N_W}{\tau_{n2}}$$

$$\frac{dN_{SCH}}{dt} = \frac{I(t)}{eV_{SCH}} - \frac{N_{SCH}}{\tau_{tr}} - \frac{N_{SCH}}{\tau_{n1}} + \frac{N_W}{\tau_e}\frac{V_W}{V_{SCH}}$$



# Carrier Transport

- Analytical approximations for the relaxation frequency and damping rate

$$\omega_r^2 = \frac{(g_0/\chi)S_0}{\tau_{ph}(1+\epsilon S_0)}\left(1+\frac{\epsilon}{g_0\tau_n}\right)$$

$$\gamma = \frac{(g_0/\chi)S_0}{(1+\epsilon S_0)} + \frac{\epsilon S_0}{\tau_{ph}(1+\epsilon S_0)} + \frac{1}{\chi\tau_n}$$

$$\gamma = 1 + \frac{\tau_{tr}}{\tau_e}$$

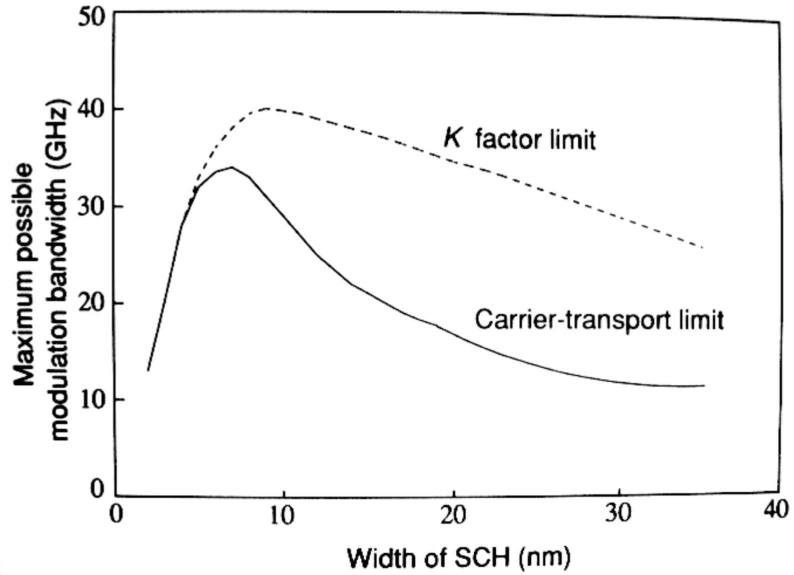
$$K = 4\pi^2\left(\tau_p + \frac{\epsilon}{g_0/\chi}\right)$$

- The first **effect of the carrier transport consists of a parasitic-like roll-off** in the modulation response (finite transport time across the SCH)
- Reduction of the effective differential gain by a factor of $\chi$

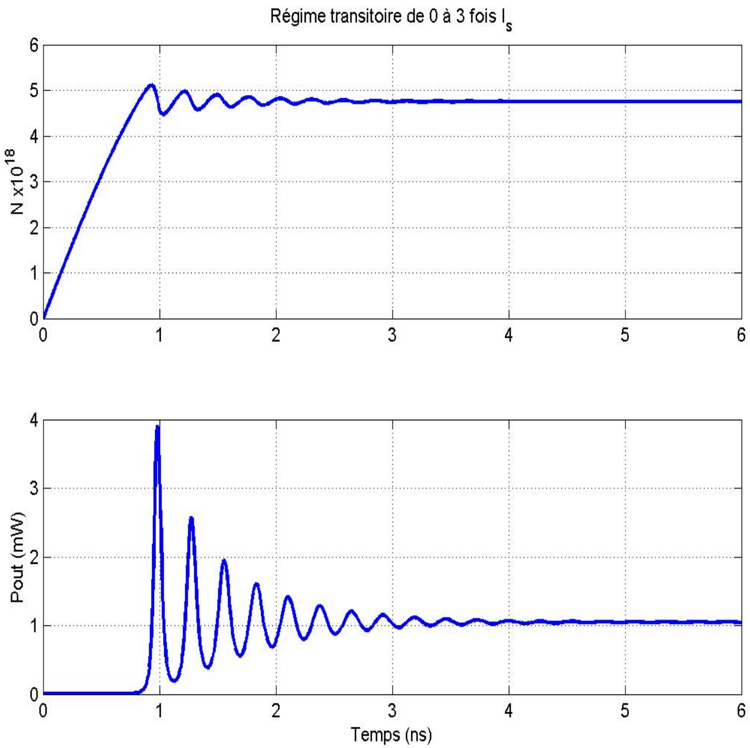
**⇒reduction of the relaxation frequency**

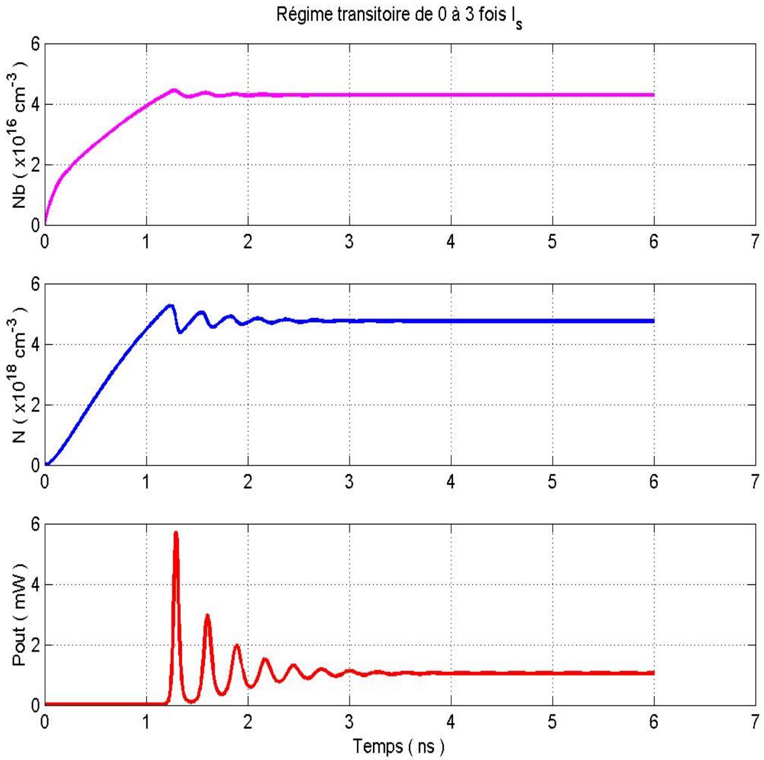
- **Gain compression remains unmodified**
- Optimization the high-speed performance of QW lasers

**⇒ transport time across the SCH must be minimized**



# Transient Time




$$\frac{dN}{dt}=\frac{I(t)}{eV}-\left(AN(t)+BN(t)^2+CN(t)^3\right)-v_g a\left(N(t)-N_{tr}\right)S(t)$$

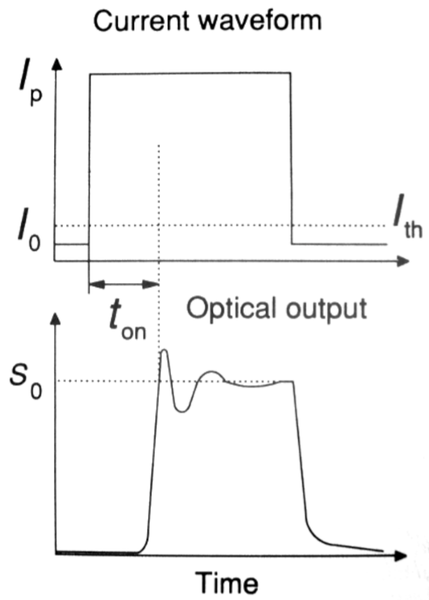
$$\frac{dS}{dt}=\left[\Gamma v_g a\left(N(t)-N_{tr}\right)-\frac{1}{\tau_p}\right]S(t)+\Gamma\beta_{sp}\left(BN(t)^2+CN(t)^3\right)$$

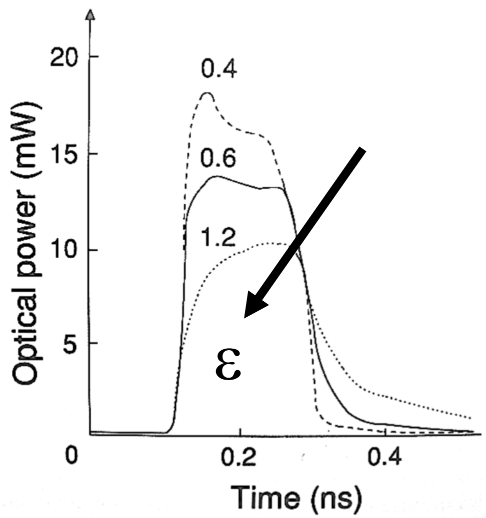
$$\frac{dN_B}{dt}=\frac{I(t)}{eV_{SCH}}-\frac{N_B(t)}{\tau_s}+\frac{N(t)}{\tau_e}\frac{V}{V_{SCH}}$$

$$\frac{dN}{dt}=\frac{N_B(t)}{\tau_s}\frac{V_{SCH}}{V}-\frac{N(t)}{\tau_e}-\left(AN(t)+BN(t)^2+CN(t)^3\right)-v_g a\left(N(t)-N_{tr}\right)S(t)$$

$$\frac{dS}{dt}=\left[\Gamma v_g a\left(N(t)-N_{tr}\right)-\frac{1}{\tau_p}\right]S(t)+\Gamma\beta_{sp}\left(BN(t)^2+CN(t)^3\right)$$

# Large-Signals




- Small-signal e.g. **modulation depths of the drive current and optical output <1**
- Large signal modulation when **biasing the laser close to the threshold and modulation with current pulsed of large amplitude**
- The **large-signal modulation response is generally worse compared to the small-signal one**
- The **turn-on-time** of the laser $t_{on}$ is an important parameter that **affects the maximum achievable bit rate in digital systems**
- The frequency of **damped relaxations oscillations equals the relaxation frequency**
- The **damping is affected** by spontaneous emission that contributed to the laser mode, carrier diffusion and nonlinear gain effects

# Limitations

- **Power Limitation**: The power available is expressed as the ratio of the power launched into the fiber and the minimum power required by the receiver to maintain a certain bit-error ration (BER)

- **Dispersion limitation** will occur when the pulse spreading causes adjacent pulses to overlap so that errors result (inter-symbol interference). It is well-known that the pulsewidth increases with distance due to dispersion

- **Timing jitter limitation** may result in power penalties or enhanced BER floors. If the timing jitter is large enough, additional errors originate from the uncertainty in a pulse position over a significant fraction of the bit period. The origin of the power penalty due to jitter can be explained through the turn-on and turn-off fluctuations of optical pulses