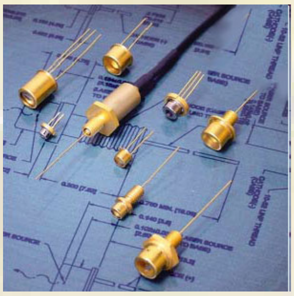
Полупроводниковые лазеры
и ре~~в~~олюция света

Г.С. Соколовский



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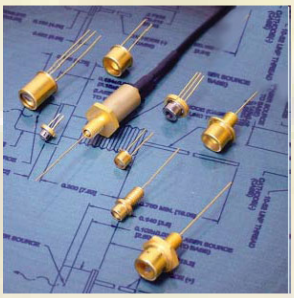
Laser diodes

Grigorii Sokolovskii[1,2]



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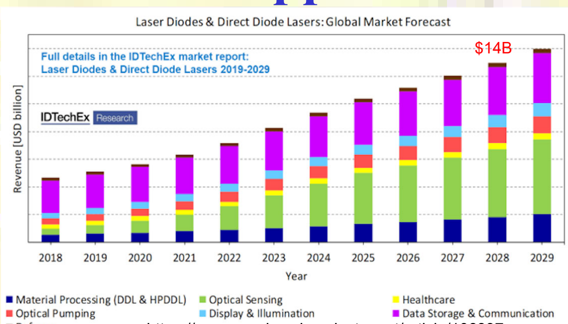
Outline

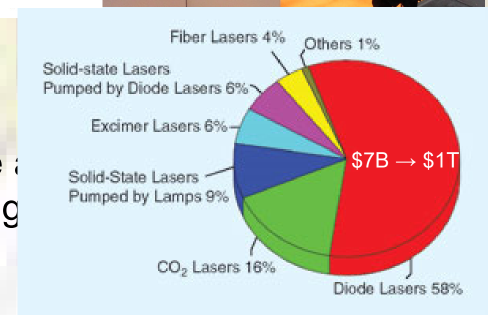
- Applications of semiconductor lasers. ‘Revolution’ of light.
- Basic principles of laser operation (only to remind).
- Absorption and gain in semiconductors, inversion of population and conditions for it's achievement.
- Rate equations. Lasing threshold. Laser efficiency.
- Modulation of the laser signal. Gain clamping.
- Fiber-optical applications. DFB and DBR lasers. VCSELs and VECSELS
- Waveguide in LD structure. Modes of the waveguide.
- Beam-propagation (‘beam-quality’) parameter M^2 and how to measure it. Achieving maximum power density with LDs.
- Interference focusing of LD beams.
- What’s next? New applications and problems to solve.

Applications of LDs

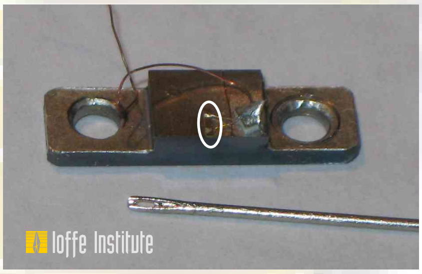


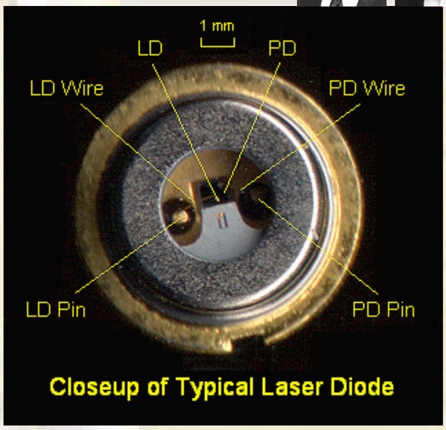
https://compoundsemiconductor.net/article/106837

- Telecoms
- Data reading/recording
- Laser printing
- Pumping of the solid-state
- ‘Direct’ applications: cutting
- Biology and medicine



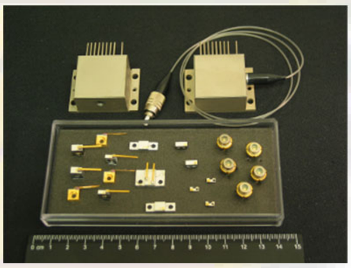
Applications of LDs

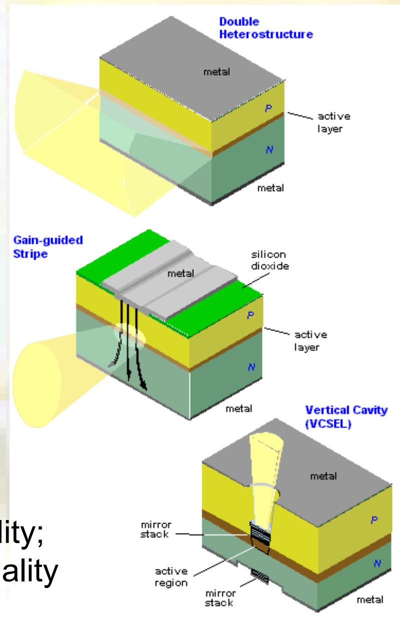




- Telecoms
- Data reading/recording
- Laser printing
- Pumping of the solid state and fiber lasers
- ‘Direct’ applications: drilling/cutting etc
- Biomedicine

Types of LDs





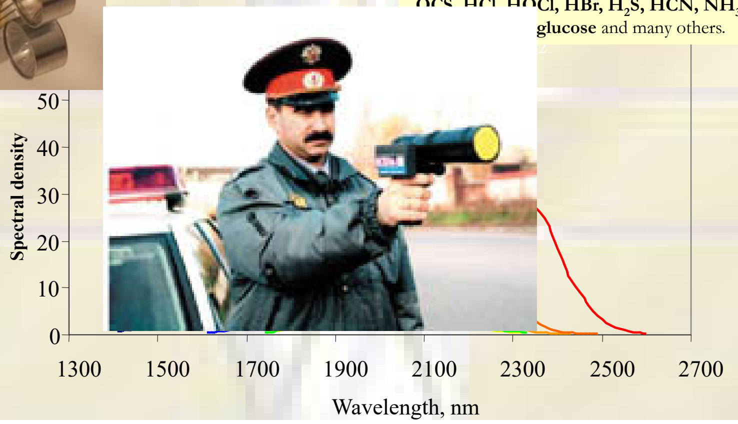
1. Surface and edge-emitting (e.g. VCSELs, VECSELs, GCSELs, etc and ‘striped’ LDs)

2. Broad and narrow area
Broad: high power, poor beam quality;
Narrow: low power, better beam quality

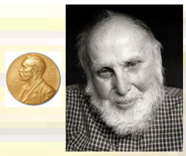
LDs for Mid-IR (1600-5000 nm)

In Mid Infrared spectral range 1600-5000 nm lies strong absorption bands of such important gases and liquids as:

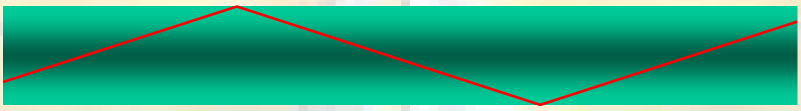
CH_4, H_2O, CO_2, CO, C_2H_2, C_2H_4, C_2H_6, CH_3Cl, OCS, HCl, HOCl, HBr, H_2S, HCN, NH_3, NO_2, glucose and many others.



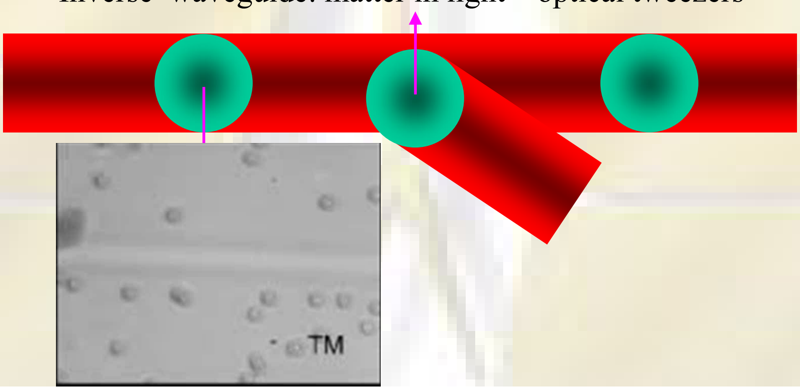
Optical tweezers



Waveguide: light in matter



'Inverse' waveguide: matter in light – optical tweezers

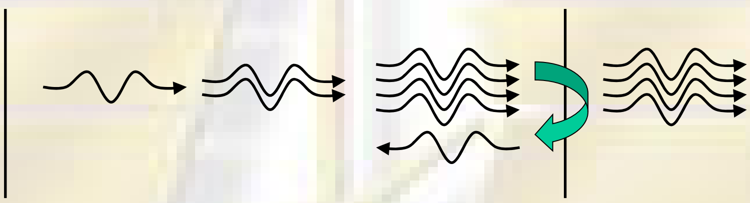


Laser projectors

no focus adjustment!

Basic principles of laser operation

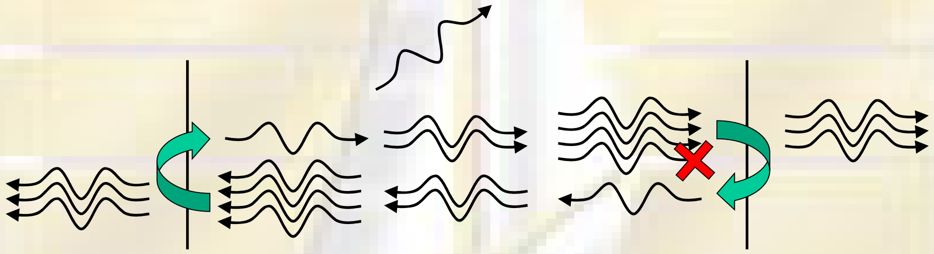
Gain + Feedback



$$S(x) = S_0 e^{\alpha x}$$

Basic principles of laser operation

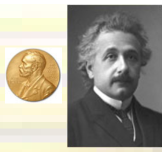
Lasing threshold



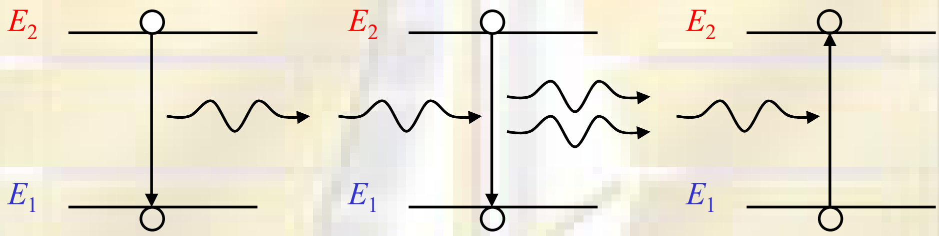
$$S(x) = S_0 e^{\alpha x} \qquad S(2L) = R^2 S_0 e^{2\alpha L} = S_0$$

$$\alpha_{out} = \frac{1}{L} \ln R \qquad \alpha_{threshold} = \alpha_{out} + \alpha_{in}$$

Basic principles of laser operation



Spontaneous and stimulated emission

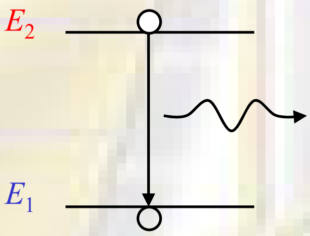


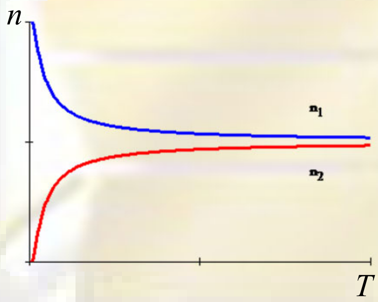
Spontaneous	Stimulated	Absorption
$\frac{dS}{dt} = An$	$\frac{dS}{dt} = BSn$	$\frac{dS}{dt} = -BSn$

Basic principles of laser operation

Gain: inversion of population

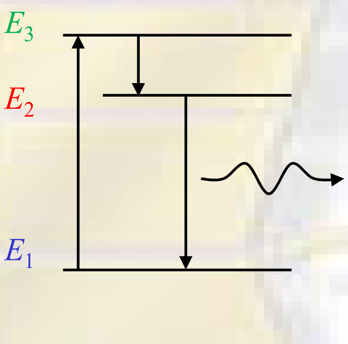
$$\frac{n_2}{n_1} = e^{-\frac{\Delta E}{kT}}$$

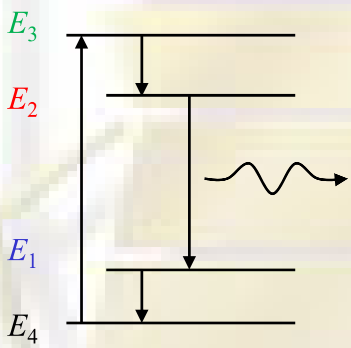




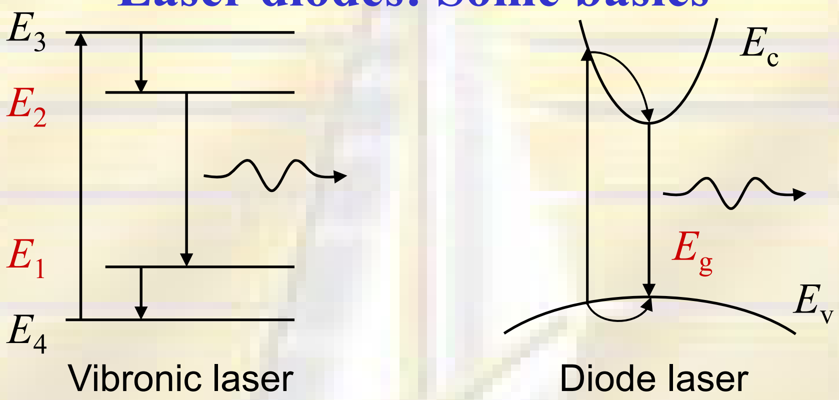
'Negative' temperature

3- & 4-level systems



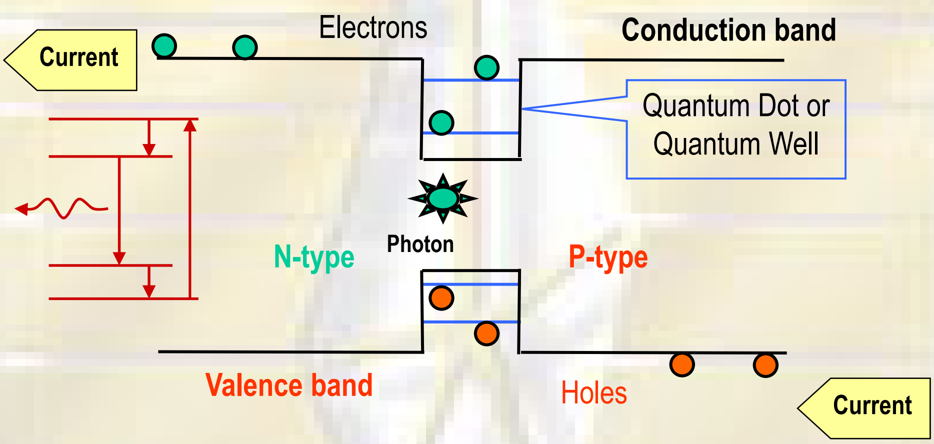


Laser diodes: Some basics



E_c – conduction band
E_v – valence band
E_g – energy gap

Laser diodes: Some basics



QWs and QDs are the ‘artificial atoms’ :)

Light generation and absorption in semiconductors

'Golden' rule of Quantum mechanics: $W = \frac{2\pi}{\hbar}\left|\langle f|H|i\rangle\right|^2 \rho_f$

Absorption probability: $W_{absorbtion} = B|M|^2 S\rho(E) f_v (1-f_c)$

Radiation probability: $W_{radiation} = B|M|^2 (S+1)\rho(E)(1-f_v) f_c$

The total radiation probability:

$$W = W_{radiation} - W_{absorption} = B|M|^2 \rho(E) f_c (1-f_v) + SB|M|^2 \rho(E)(f_c - f_v)$$

$$W(E) = r_{sp}(E) + Sr_{st}(E)$$

$$r_{sp}(E) = B|M|^2 \rho(E) f_c (1-f_v)$$

$$r_{st}(E) = B|M|^2 \rho(E)(f_c - f_v)$$

Light generation and absorption in semiconductors

What is the condition for stimulated emission? $r_{st}(E) > 0$

$$r_{st}(E) = B|M|^2 \rho(E)(f_c - f_v) > 0$$

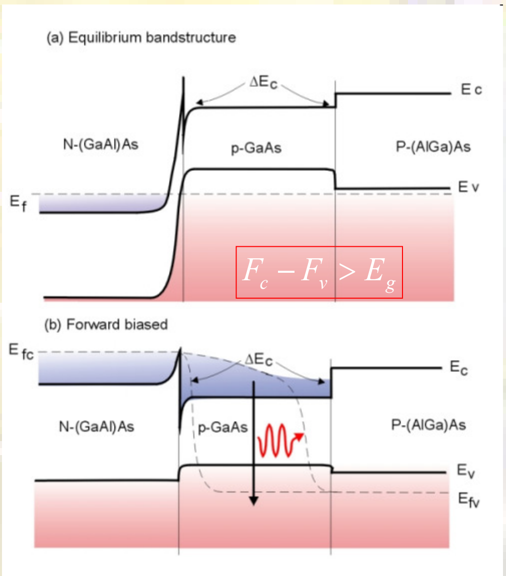
$$f_c - f_v > 0 \quad \Leftrightarrow \quad \frac{1}{1+\exp\left(\frac{E_c - F_c}{kT}\right)} - \frac{1}{1+\exp\left(\frac{E_v - F_v}{kT}\right)} > 0$$

$$F_c - F_v > E_c - E_v \geq E_g$$

Inversion of population:

$$\boxed{F_c - F_v > E_g}$$

Inversion of population



http://britneyspears.ac/physics/fplasers/fplasers.htm

Forward-biased p-n-junction is both the source for the inversion of population and for the name of the "laser diodes"

Stimulated and spontaneous emission rate: 3D

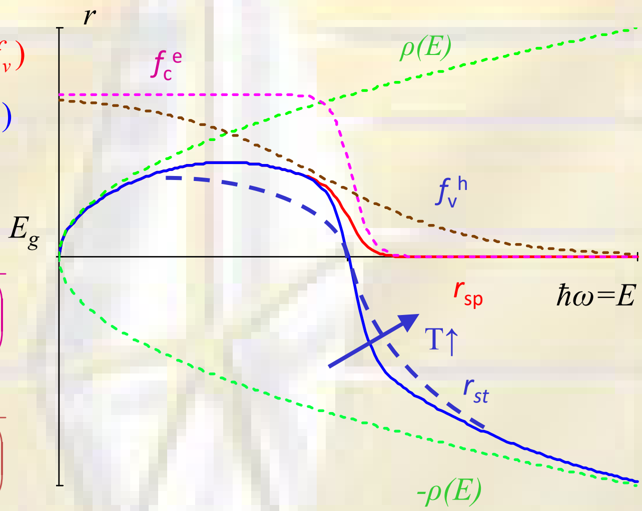
$$r_{sp}(E) \sim \rho(E) f_c (1 - f_v)$$

$$r_{st}(E) \sim \rho(E)(f_c - f_v)$$

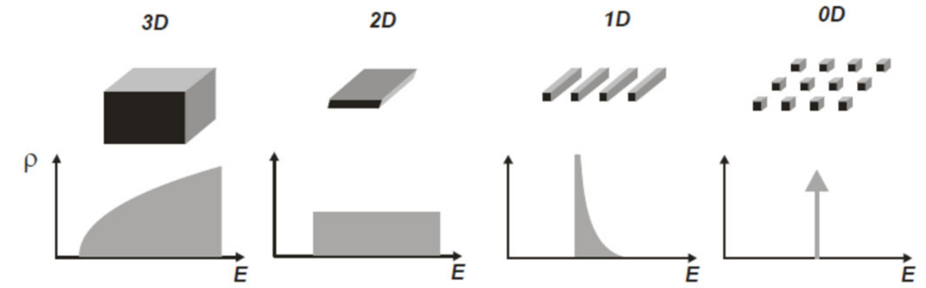
$$\rho(E) \sim \sqrt{E - E_g}$$

$$f_c = \frac{1}{1 + \exp\left(\frac{E_c - F_c}{kT}\right)}$$

$$f_v = \frac{1}{1 + \exp\left(\frac{E_v - F_v}{kT}\right)}$$



Density of states: Low-Dimensional vs 3D



Bulk semiconductor	Quantum Well	Quantum Wire	Quantum Dot

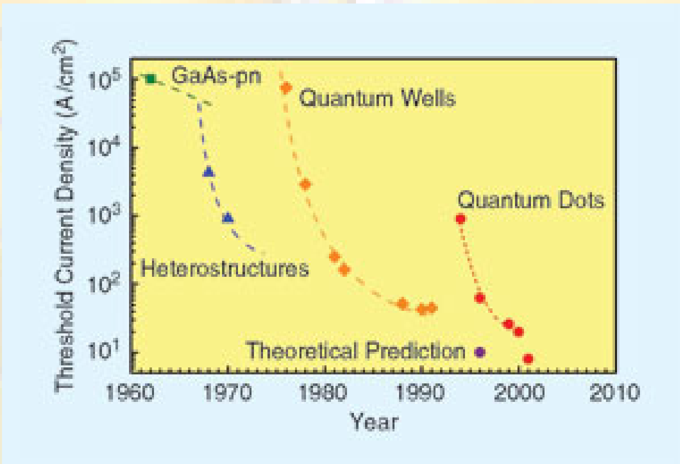
$$\rho_{3D}(E) = \frac{d}{2\pi^2}\left(\frac{2m}{\hbar^2}\right)^{3/2}\sqrt{E-E_g}$$

$$\rho_{2D}(E) = n_{QW}\frac{m}{\pi\hbar^2}h(E-E_0)$$

$$\rho_{1D}(E) = \frac{n_{QWW}}{2\pi}\left(\frac{2m}{\hbar^2}\right)^{1/2}\frac{1}{E-E_0}$$

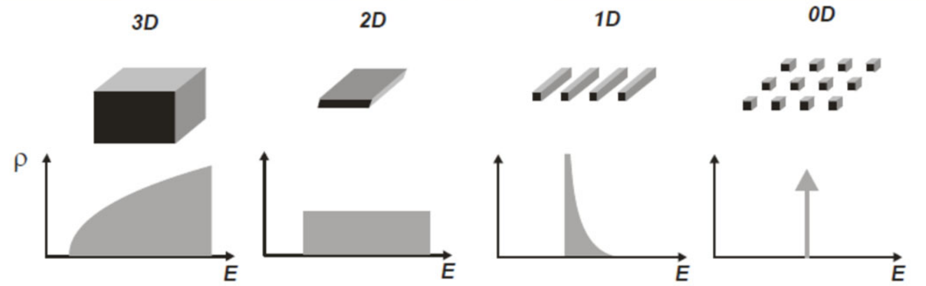
$$\rho_{0D}(E) = 2n_{QD}\delta(E-E_0)$$

Evolution of the threshold current density: from 3D to Low-Dimensional



[D.Bimberg, IEEE Phot. Soc. Newsletter 6, 3 (2013)]

Density of states: Low-Dimensional vs 3D



Bulk semiconductor	Quantum Well	Quantum Wire	Quantum Dot
~1 kA/cm^2	~100 A/cm^2	???	~10 A/cm^2

QDs vs 3D

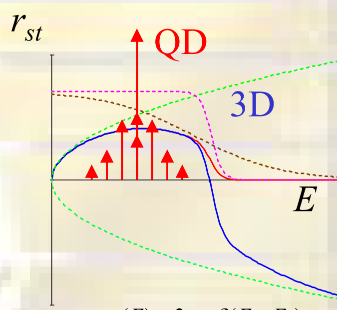
Lower threshold

But: at low QD density threshold may NOT be reached

Lower temperature dependence of the laser parameters

Narrow spectrum for IDENTICAL QDs

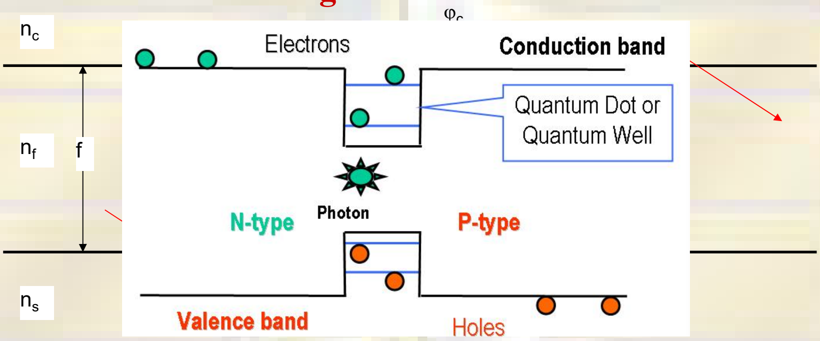
But: broad spectrum for inhomogeneously broadened QDs



$$\rho_{QD}(E) = 2n_{QD}\delta(E - E_0)$$

Laser diodes: The waveguide

$E_g \downarrow \leftrightarrow n\uparrow$

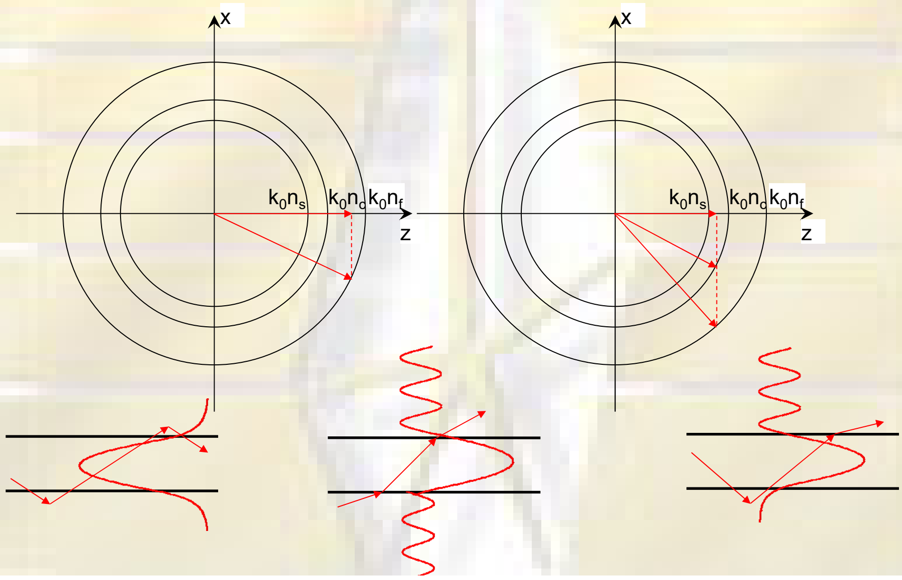


$$k_x^2 + k_z^2 = k_0^2 n_f^2 \qquad 2k_x f + \varphi_s + \varphi_c = 2\pi m$$

$$k_z^{(m)} = \sqrt{k_0^2 n_f^2 - \left(k_x^{(m)}\right)^2} = k_0 N_m$$

$$n_s, n_c < N_m < n_f$$

Modes of the waveguide



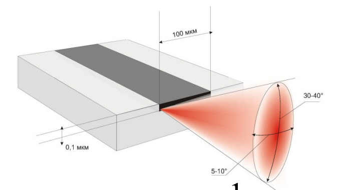
Composing Rate Equations

The simplest model

J is the average pump current density
n is the average carrier concentration in the active region
S is the average photon concentration (average intensity)

Carriers, steady-state:

Pump rate = Recombination rate $\frac{J}{ed} = r$



Carriers, time-dependent:

$$\frac{dn}{dt} = \frac{J}{ed} - r \qquad \frac{dn}{dt} = \frac{J}{ed} - r_{sp} - Sr_{st}$$

$$r_{sp} = Bn^2 = \frac{n}{\tau_s}, \quad \tau_s = \frac{1}{Bn}$$

$$\frac{dn}{dt} = \frac{J}{ed} - \frac{n}{\tau_s} - \frac{c}{N_{eff}} g(n)\, S \qquad r_{st} \sim gain \quad r_{st} = \frac{c}{N_{eff}} g(n)$$

Composing Rate Equations

Photons, steady-state:

Total radiation probability = Recombination rate $\frac{S}{\tau_p} = r$

Photons, time-dependent:

$$\frac{dS}{dt} = r - \frac{S}{\tau_p} \qquad \frac{dS}{dt} = \Gamma\left(r_{sp} + Sr_{st}\right) - \frac{S}{\tau_p}$$

$$\frac{dS}{dt} = \Gamma \frac{c}{N_{eff}} g(n)\, S + \Gamma\beta \frac{n}{\tau_s} - \frac{S}{\tau_p}$$

$$\begin{cases} \frac{dS}{dt} = \Gamma A(n - n_t)\, S + \Gamma\beta \frac{n}{\tau_s} - \frac{S}{\tau_p} \\ \frac{dn}{dt} = \frac{J}{ed} - \frac{n}{\tau_s} - A(n - n_t)\, S \end{cases}$$

Γ - confinement factor
β - spontaneous emission factor
n_t - transparency concentration
A - linear gain coefficient
τ_s - spontaneous recomb. time
τ_p - photon lifetime

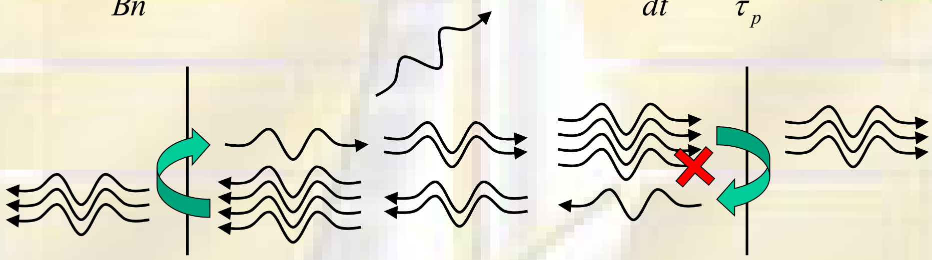
Lifetimes

Spontaneous:

$$\tau_s = \frac{1}{Bn} \qquad \tau_s \sim 1 \text{ ns}$$

Photon lifetime:

$$\text{if } n \sim n_t \text{, then: } \frac{dS}{dt} \approx -\frac{S}{\tau_p} \Rightarrow S = S_0 e^{-t/\tau_p}$$



$$t_r = \frac{2LN_{eff}}{c} \qquad S(t_r) = S_0 e^{-\frac{2LN_{eff}}{c\tau_p}} = S_0 e^{-2L\alpha_{in}} R^2$$

$$\frac{1}{\tau_p} = \frac{c}{N_{eff}}\left(\alpha_{in} + \frac{1}{L}\ln\frac{1}{R}\right) \qquad \tau_p \sim 1 \text{ ps}$$

$L \uparrow \rightarrow \tau_p \uparrow$
$\alpha_{in} \uparrow \rightarrow \tau_p \downarrow$
$R \uparrow \rightarrow \tau_p \uparrow$

Rate Equations for QD LD

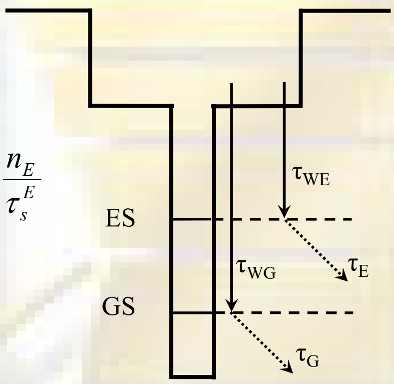
$$\frac{\partial n_W}{\partial t} = \frac{J}{ed} + \gamma\frac{n_E}{\tau_E} f_W' - \frac{n_W}{\tau_E^0} f_E' - \frac{n_W}{\tau_s^W}$$

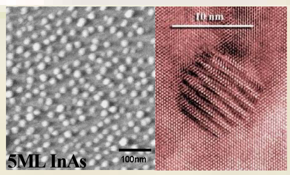
$$\frac{\partial n_E}{\partial t} = \gamma\frac{n_W}{\tau_0^E} f_E' - \frac{n_E}{\tau_E} f_W' - \frac{n_E}{\tau_0^E} f_G' + \frac{n_G}{\tau_G} f_E' - \frac{n_E}{\tau_s^E}$$

$$\frac{\partial n_G}{\partial t} = \frac{n_E}{\tau_0^G} f_G' - A(n_G - n_{tr})S - \frac{n_G}{\tau_G} f_E' - \frac{n_G}{\tau_s^G}$$

$$\frac{\partial S}{\partial t} = \Gamma A(n_G - n_{tr})S + \Gamma\beta\frac{n_G}{\tau_s^G} - \frac{S_p}{\tau_p}$$

…where f is the filling factor





Y. Wu, L.V. Asryan, JAP 115, 103105 (2014)
https://doi.org/10.1063/1.4868472

Steady-state solution of the Rate Eqs

$$\begin{cases} \dfrac{dS}{dt} = \Gamma A(n-n_t)\,S + \Gamma\beta\dfrac{n}{\tau_s} - \dfrac{S}{\tau_p} = 0 \\ \dfrac{dn}{dt} = \dfrac{J}{ed} - \dfrac{n}{\tau_s} - A(n-n_t)\,S = 0 \end{cases}$$

$$\begin{cases} \Gamma A(n-n_t)\,S = \dfrac{S}{\tau_p} - \Gamma\beta\dfrac{n}{\tau_s} \\ A(n-n_t)\,S = \dfrac{J}{ed} - \dfrac{n}{\tau_s} \end{cases}$$

$\Gamma\beta\frac{n}{\tau_s} \rightarrow 0$

$$\begin{cases} S = \Gamma\tau_p\left(\dfrac{J}{ed} - \dfrac{n}{\tau_s}\right) \\ \Gamma A(n-n_t)\,\tau_p\left(\dfrac{J}{ed} - \dfrac{n}{\tau_s}\right) = \dfrac{J}{ed} - \dfrac{n}{\tau_s} \end{cases}$$

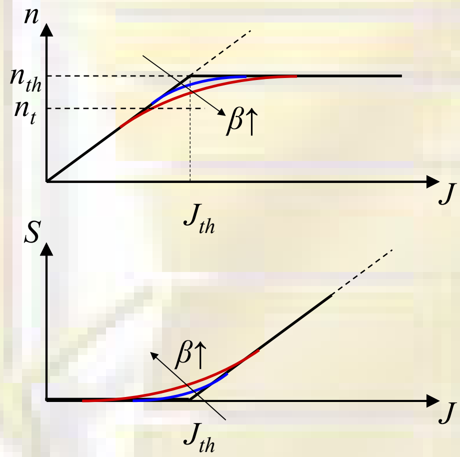
$$\left[\begin{array}{l} n = \dfrac{J\tau_s}{ed} \\ n = n_t + \dfrac{1}{\Gamma A\tau_p} \end{array} \right.$$

$$\left[\begin{array}{l} S = 0 \\ S = \dfrac{\Gamma\tau_p}{ed}\left(J - \dfrac{ed}{\tau_s}\left(n_t + \dfrac{1}{\Gamma A\tau_p}\right)\right) \end{array} \right.$$

Steady-state solution of the Rate Eqs

$$\left[\begin{array}{l} n = \dfrac{J\tau_s}{ed} \\ n = n_t + \dfrac{1}{\Gamma A\tau_p} \end{array} \right.$$

$$\left[\begin{array}{l} S = 0 \\ S = \dfrac{\Gamma\tau_p}{ed}\left(J - \dfrac{ed}{\tau_s}\left(n_t + \dfrac{1}{\Gamma A\tau_p}\right)\right) \end{array} \right.$$

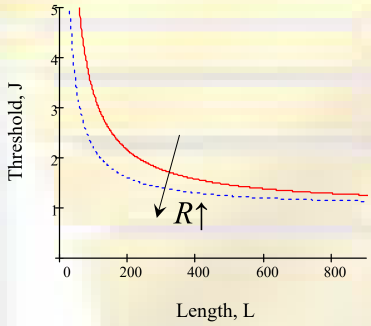


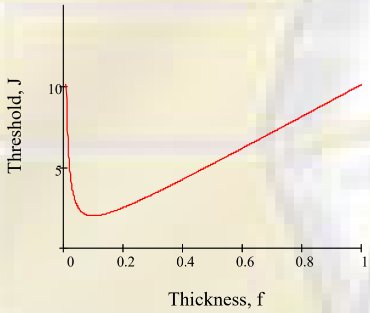
$$J_{th} = \frac{ed}{\tau_s}\left(n_t + \frac{1}{\Gamma A\tau_p}\right) = \frac{ed}{\tau_s} n_{th} \qquad n_{th} = n_t + \frac{1}{\Gamma A\tau_p}$$

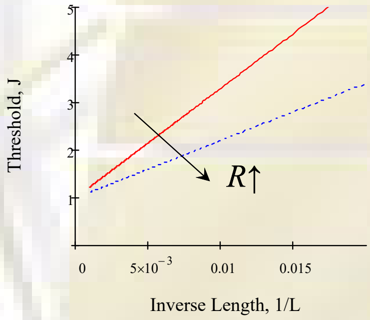
Lasing Threshold

$$J_{th} = \frac{ed}{\tau_s}\left(n_t + \frac{1}{\Gamma A \tau_p}\right) = \frac{ed}{\tau_s} n_{th}$$

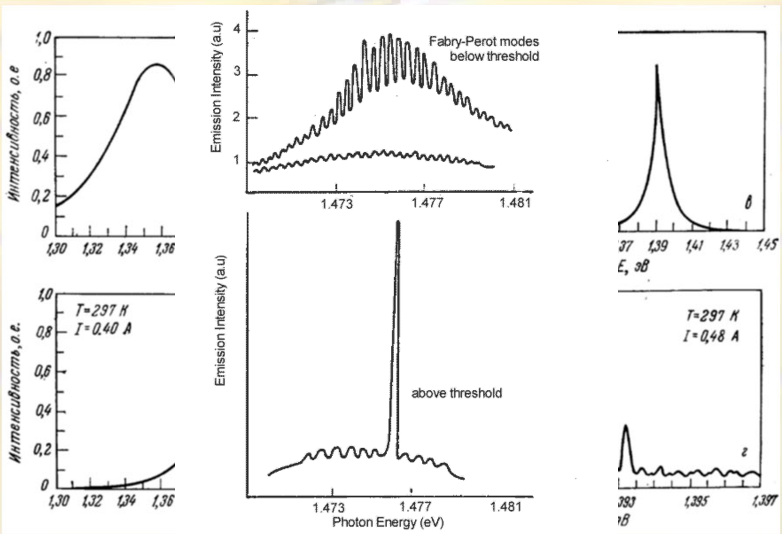
$$\frac{1}{\tau_p} = \frac{c}{N_{eff}}\left(\alpha_{in} + \frac{1}{L}\ln\frac{1}{R}\right)$$







Lasing Threshold

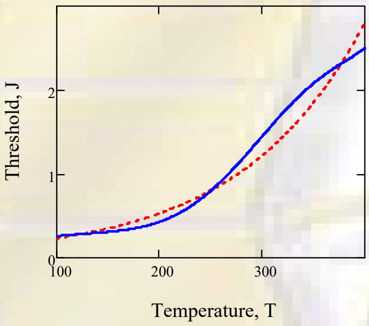


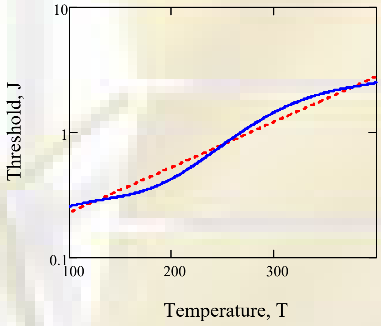
http://britneyspears.ac/physics/fplasers/fplasers.htm

Threshold vs Temperature

$$J \sim \exp\frac{T}{T_0}$$

$$T_0 = f(T)$$





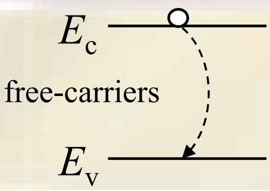
Laser efficiency

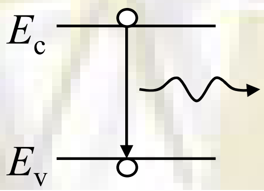
$$J \rightarrow J\tilde{\eta}\eta_i \quad \Rightarrow \quad S = \tilde{\eta}\eta_i\Gamma\frac{\tau_p}{ed}\left(J - J_{th}\right)$$

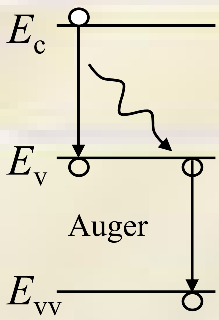
$\tilde{\eta} = \dfrac{J_{active}}{J_{total}}$ Pumping efficiency

$\eta_i = \dfrac{\sum photons}{\sum electrons}$ Internal quantum efficiency

$$\eta_i = \frac{Bn^2}{An + Bn^2 + Cn^3}$$







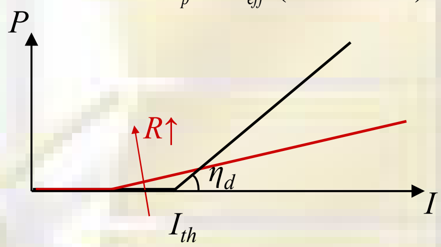
Laser efficiency

$$S = \tilde{\eta}\eta_i\Gamma\frac{\tau_p}{ed}(J - J_{th}) \qquad P^{(1/2)} = \frac{1}{2}S\hbar\omega\frac{c}{N_{eff}}\frac{V}{\Gamma}\frac{1}{L}\ln\frac{1}{R}$$

$$P^{(1/2)} = \frac{1}{2}\hbar\omega\frac{c}{N_{eff}}\frac{V}{\Gamma}\frac{1}{L}\ln\frac{1}{R}\;\tilde{\eta}\eta_i\Gamma\frac{\tau_p}{ed}(J - J_{th}) \qquad \frac{1}{\tau_p} = \frac{c}{N_{eff}}\left(\alpha_{in} + \frac{1}{L}\ln\frac{1}{R}\right)$$

$$I = JWL = J\frac{V}{d}$$

$$P^{(1/2)} = \frac{1}{2}\tilde{\eta}\eta_i\frac{\hbar\omega}{e}\frac{\frac{1}{L}\ln\frac{1}{R}}{\alpha_{in} + \frac{1}{L}\ln\frac{1}{R}}(I - I_{th})$$

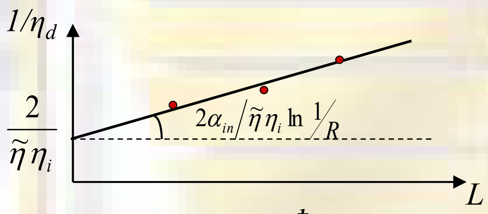


differential efficiency: $$\eta_d = \frac{P^{(1/2)}}{\frac{\hbar\omega}{e}(I - I_{th})} = \frac{1}{2}\tilde{\eta}\eta_i\frac{\frac{1}{L}\ln\frac{1}{R}}{\alpha_{in} + \frac{1}{L}\ln\frac{1}{R}} = \frac{1}{2}\frac{\tilde{\eta}\eta_i\alpha_{out}}{\alpha_{in} + \alpha_{out}}$$

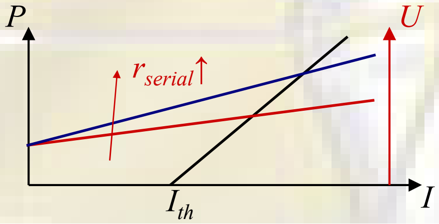
Laser efficiency

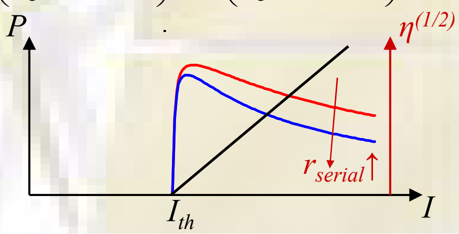
Measuring IQE:

$$\frac{1}{\eta_d} = \frac{2}{\tilde{\eta}\eta_i}\left(1 + \frac{\alpha_{in}L}{\ln\frac{1}{R}}\right)$$



Lasing efficiency: $$\eta^{(1/2)} = \frac{P^{(1/2)}}{I\left(\frac{\hbar\omega}{e} + Ir_{serial}\right)} = \frac{\eta_d\frac{\hbar\omega}{e}(I - I_{th})}{I\left(\frac{\hbar\omega}{e} + Ir_{serial}\right)}$$





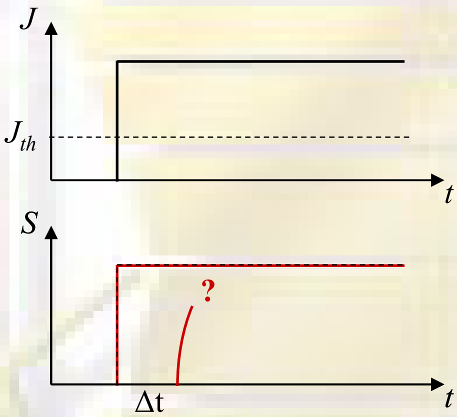
Turn-on delay

$$\begin{cases} \cancel{\frac{dS}{dt} = \Gamma A(n-n_t)S + \Gamma\beta\frac{n}{\tau_s} - \frac{S}{\tau_p}} \\ \frac{dn}{dt} = \frac{J}{ed} - \frac{n}{\tau_s} \cancel{- A(n-n_t)S} \end{cases}$$

$$n(t) = \frac{J\tau_s}{ed}\left(1 - e^{-t/\tau_s}\right)$$

$$n(\Delta t) = n_{th}$$

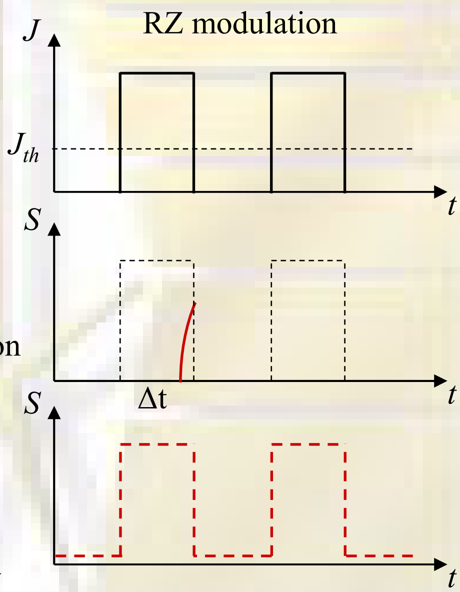
$$\Delta t = \tau_s \ln\left(\frac{J}{J - J_{th}}\right) \approx \tau_s \frac{J_{th}}{J}$$



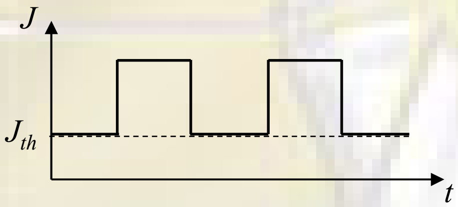
Turn-on delay

$$\Delta t = \tau_s \ln\left(\frac{J}{J - J_{th}}\right) \approx \tau_s \frac{J_{th}}{J}$$

If $J = 2J_{th}$, $\tau_s = 1$ ns: $\Delta t = 0.7$ ns



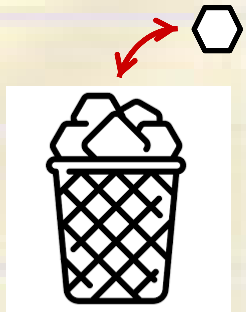
Non-return-to-zero (NRZ) modulation



Turn-on delay of QD LDs

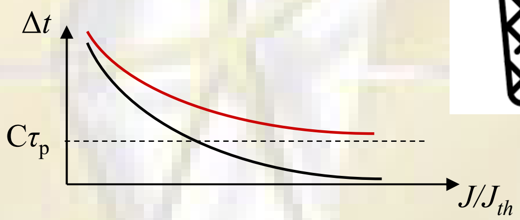
Non-QD laser diode:

$$\Delta t = \tau_s \ln\left(\frac{J}{J - J_{th}}\right) \approx \tau_s \frac{J_{th}}{J}$$



QD LD:

$$\Delta t \approx \tau_s \frac{J_{th}}{J} + C\tau_p$$



Small-signal moduation

$$\frac{dn}{dt} = \frac{J}{e\,d} - \frac{n}{\tau_s} - \frac{c}{N_{eff}} g(n)\,S$$

$$\frac{dS}{dt} = \Gamma \frac{c}{N_{eff}} g(n)\,S - \frac{S}{\tau_p} + \Gamma\beta \frac{n}{\tau_s}$$

$$J(t) = J_0 + \delta J(t), \quad J_0 >> \delta J(t)$$

$$S(t) = S_0 + \delta S(t), \quad S_0 >> \delta S(t)$$

$$n(t) = n_0 + \delta n(t), \quad n_0 >> nJ(t)$$

$$\begin{cases} \Gamma \frac{c}{N_{eff}} g(n)\,S + \Gamma\beta \frac{n}{\tau_s} - \frac{S}{\tau_p} = 0 \\ \frac{J}{ed} - \frac{n}{\tau_s} - \frac{c}{N_{eff}} g(n)\,S = 0 \end{cases}$$

$$\delta \dot{n} = \frac{\delta J}{e\,d} - \frac{\delta n}{\tau_s} - \frac{c}{N_{eff}} (g_0\,\delta S + g'\,S_0 \delta n)$$

$$\delta \dot{S} = \Gamma \frac{c}{N_{eff}} (g_0\,\delta S + g'\,S_0 \delta n) - \frac{\delta S}{\tau_p} + \Gamma\beta \frac{\delta n}{\tau_s}$$

Small-signal moduation

$$\delta \dot{n} = \frac{\delta J}{ed} - \frac{\delta n}{\tau_s} - \frac{c}{N_{eff}}(g_0\,\delta S + g'\,S_0\delta n)$$

$$\delta \dot{S} = \Gamma\frac{c}{N_{eff}}(g_0\,\delta S + g'\,S_0\delta n) - \frac{\delta S}{\tau_p} + \Gamma\beta\frac{\delta n}{\tau_s}$$

$$\delta J(t) = j\exp(i\omega t)$$

$$\delta n(t) = a(\omega)\exp(i\omega t)$$

$$\delta S(t) = b(\omega)\exp(i\omega t)$$

$$\left(i\omega + \frac{1}{\tau_s} + \frac{c}{N_{eff}}g'S_0\right)a + \frac{c}{N_{eff}}g_0\,b = \frac{j}{ed}$$

$$-\left(\Gamma\frac{c}{N_{eff}}g'\,S_0 + \Gamma\frac{\beta}{\tau_s}\right)a + \left(i\omega + \frac{1}{\tau_p} - \Gamma\frac{c}{N_{eff}}g_0\right)b = 0$$

$$\gamma = \frac{1}{\tau_s} + AS_0, \quad A \equiv \frac{c}{N_{eff}}g' \qquad \Delta = \frac{1}{\tau_p} - \Gamma\frac{c}{N_{eff}}g_0 \qquad \omega_0^2 = \frac{AS_0}{\tau_p}$$

Amplitude-freq. response of photons

$$\left(i\omega + \frac{1}{\tau_s} + \frac{c}{N_{eff}}g'S_0\right)a + \frac{c}{N_{eff}}g_0\,b = \frac{j}{ed}$$

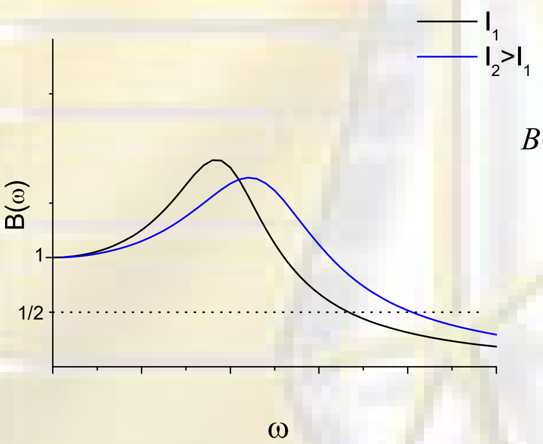
$$-\left(\Gamma\frac{c}{N_{eff}}g'\,S_0 + \Gamma\frac{\beta}{\tau_s}\right)a + \left(i\omega + \frac{1}{\tau_p} - \Gamma\frac{c}{N_{eff}}g_0\right)b = 0$$

$$b(\omega) \approx \frac{\Gamma j\tau_p}{ed}\,\frac{\omega_0^2}{\omega_0^2 - \omega^2 + \gamma i\omega} = \frac{j}{ed}B(\omega)\exp(i\phi_B(\omega))$$

$$B(\omega) = \frac{\omega_0^2}{\sqrt{(\omega_0^2 - \omega^2)^2 + \gamma^2\omega^2}} \qquad \phi_B(\omega) = arctg\left(-\frac{\gamma\omega}{\omega_0^2 - \omega^2}\right)$$

$$\gamma = \frac{1}{\tau_s} + AS_0, \quad A \equiv \frac{c}{N_{eff}}g' \qquad \Delta = \frac{1}{\tau_p} - \Gamma\frac{c}{N_{eff}}g_0 \qquad \omega_0^2 = \frac{AS_0}{\tau_p}$$

Amplitude-freq. response of photons

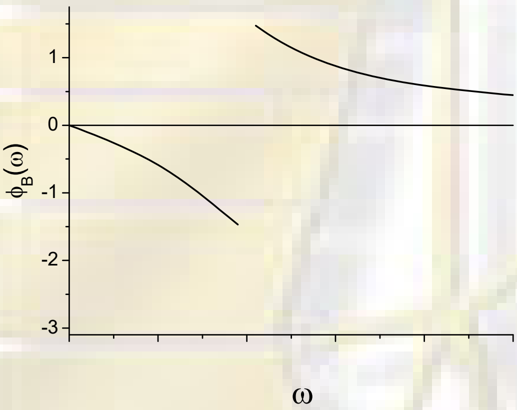


$$B(\omega) = \frac{\omega_0^2}{\sqrt{(\omega_0^2 - \omega^2)^2 + \gamma^2\omega^2}}$$

$$\gamma = \frac{1}{\tau_s} + AS_0$$

$$\omega_0^2 = \frac{AS_0}{\tau_p}$$

Phase-frequency response of photons



$$\phi_B(\omega) = arctg\left(-\frac{\gamma\omega}{\omega_0^2 - \omega^2}\right)$$

$$\gamma = \frac{1}{\tau_s} + AS_0$$

$$\omega_0^2 = \frac{AS_0}{\tau_p}$$

Amplitude-freq. response of carriers

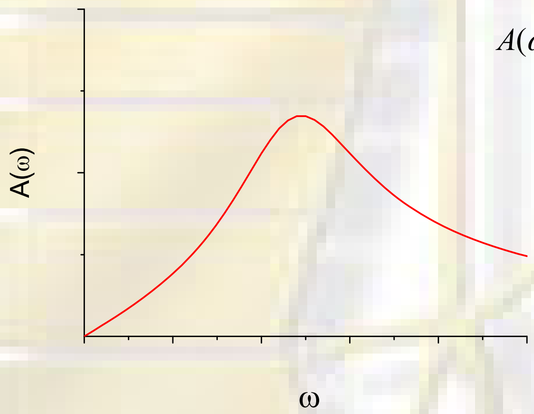
$$\left(i\omega+\frac{1}{\tau_s}+\frac{c}{N_{eff}}g'S_0\right)a+\frac{c}{N_{eff}}g_0\,b=\frac{j}{ed}$$

$$-\left(\Gamma\frac{c}{N_{eff}}g'S_0+\Gamma\frac{\beta}{\tau_s}\right)a+\left(i\omega+\frac{1}{\tau_p}-\Gamma\frac{c}{N_{eff}}g_0\right)b=0$$

$$a(\omega)\approx\frac{j}{ed}\,\frac{-i\omega}{\omega_0^2-\omega^2+\gamma i\omega}=\frac{j}{ed}A(\omega)\exp(i\phi_A(\omega))$$

$$A(\omega)=\frac{\omega}{\sqrt{(\omega_0^2-\omega^2)^2+\gamma^2\omega^2}}\qquad \phi_A(\omega)=arctg\left(-\frac{\gamma\omega}{\omega_0^2-\omega^2}\right)-\frac{\pi}{2}$$

Amplitude-freq. response of carriers

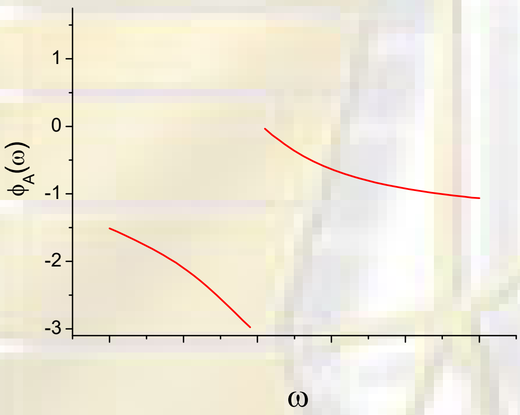


$$A(\omega)=\frac{\omega}{\sqrt{(\omega_0^2-\omega^2)^2+\gamma^2\omega^2}}$$

$$\gamma=\frac{1}{\tau_s}+AS_0$$

$$\omega_0^2=\frac{AS_0}{\tau_p}$$

Phase-frequency response of carriers

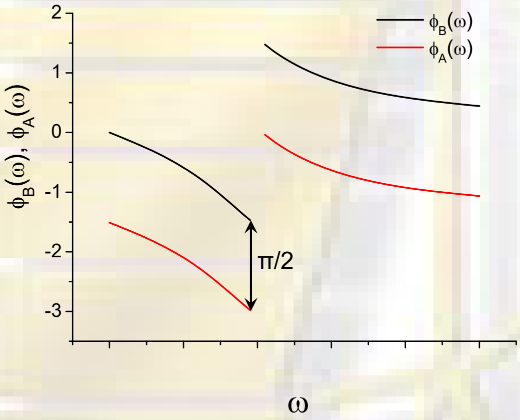


$$\phi_A(\omega) = arctg(-\frac{\gamma\omega}{\omega_0^2 - \omega^2}) - \frac{\pi}{2}$$

$$\gamma = \frac{1}{\tau_s} + AS_0$$

$$\omega_0^2 = \frac{AS_0}{\tau_p}$$

Phase-frequency response

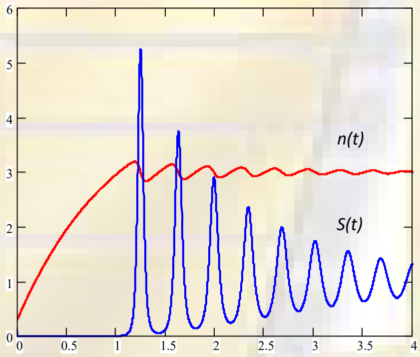


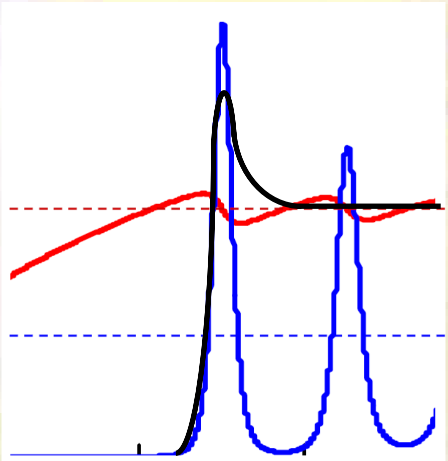
$$\phi_A(\omega) = arctg(-\frac{\gamma\omega}{\omega_0^2 - \omega^2}) - \frac{\pi}{2}$$

$$\phi_B(\omega) = arctg(-\frac{\gamma\omega}{\omega_0^2 - \omega^2})$$

π/2 shift in the phase-frequency responses means the energy flow between the photons and carriers (similar to the kinetic and potential energy in pendulum) which is called 'relaxation oscillations'.

Relaxation oscillations

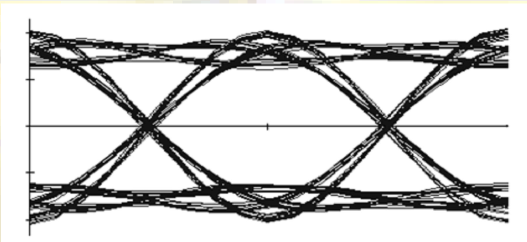


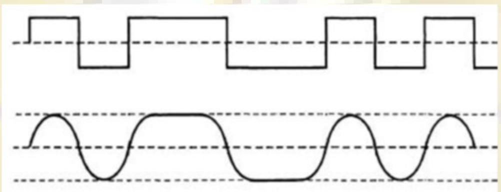


NB: no relaxation oscillations in QD lasers!

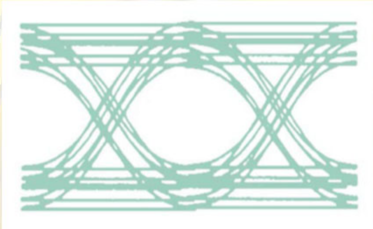
Typical explanations: 1) QD LDs are too fast; 2) QD LDs are too slow

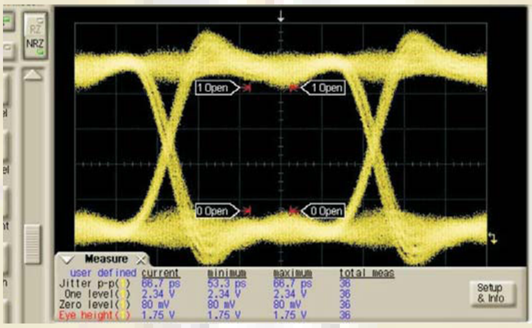
Eye-diagram





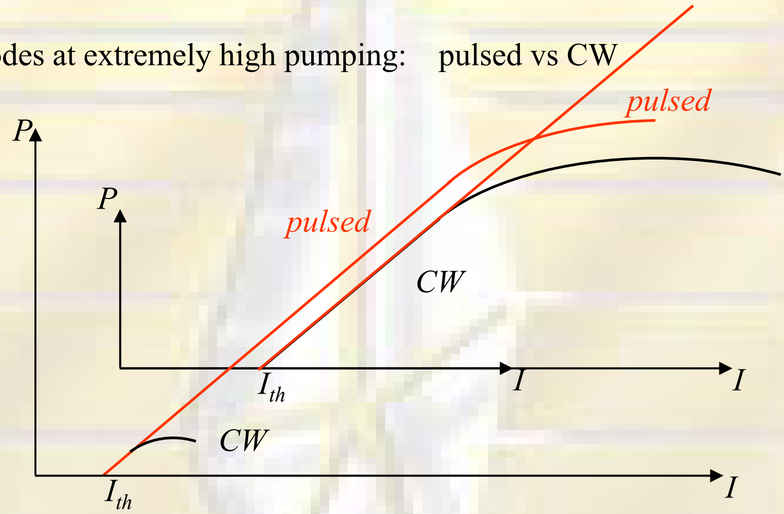
Eye-diagram





Gain clamping (gain saturation)

Laser diodes at extremely high pumping: pulsed vs CW

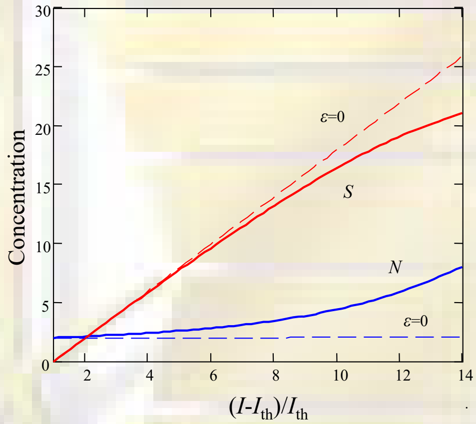


Gain clamping

$$\begin{cases} \dfrac{dN}{dt} = \dfrac{J}{ed} - A(N - N_{tr})S(1-\varepsilon S) - \dfrac{N}{\tau} \\ \dfrac{dS}{dt} = \Gamma A(N - N_{tr})S(1-\varepsilon S) + \dfrac{\Gamma \beta N}{\tau} - \dfrac{S}{\tau_p} \end{cases}$$

Quasi-analytical:

$$\begin{cases} N = N_{th} + \dfrac{1}{\Gamma A \tau_p}\dfrac{\varepsilon S}{1-\varepsilon S}, \quad N_{th} = N_{tr} + \dfrac{1}{\Gamma A \tau_p} \\ S = \dfrac{\Gamma \tau_p}{ed}\left(J - J_{th} - \dfrac{ed}{\Gamma A \tau \tau_p}\dfrac{\varepsilon S}{1-\varepsilon S}\right), \quad J_{th} = \dfrac{N_{th} ed}{\tau} \end{cases}$$



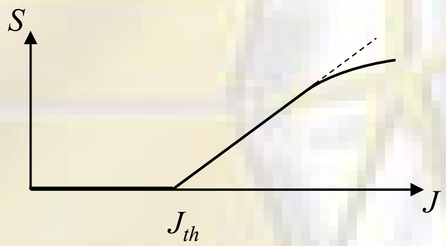
Asymptotical:

$$N = N_{th} + \frac{\tau}{ed}\frac{\varepsilon}{A\tau + \varepsilon}(J - J_{th}) + \frac{\Gamma A^2 \tau \tau_p}{A\tau + \varepsilon}\left[\frac{\tau}{ed}\frac{\varepsilon}{A\tau+\varepsilon}(J - J_{th})\right]^2$$

Gain clamping

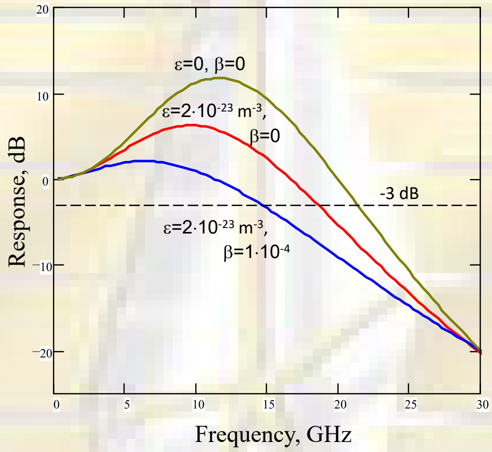
$$\frac{dn}{dt} = \frac{J}{e\,d} - \frac{n}{\tau_s} - \frac{c}{N_{eff}} g(n)\, S(1-\varepsilon S)$$

$$\frac{dS}{dt} = \Gamma \frac{c}{N_{eff}} g(n)\, S\,(1-\varepsilon S) - \frac{S}{\tau_p} + \Gamma \beta \frac{n}{\tau_s}$$



$$\omega_p \approx \sqrt{{AS_0}/{\tau_p}\left(1-\varepsilon S_0\right)}$$

Gain clamping



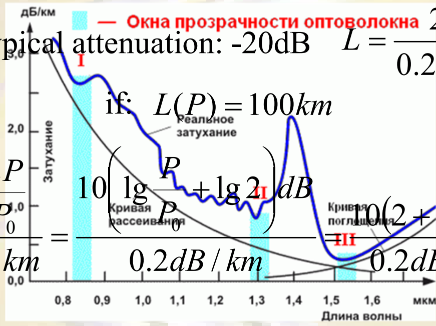
$$\omega_p \approx \sqrt{\frac{AS_0}{\tau_p}\left(1-\varepsilon S_0\right)}$$

Application to the fiber optical communications

Application to the fiber optical communications

Double power: Double distance?

$dB = 10\lg\frac{P}{P_0}$ Typical attenuation: -20dB $L = \frac{20dB}{0.2dB/km} = 100km$

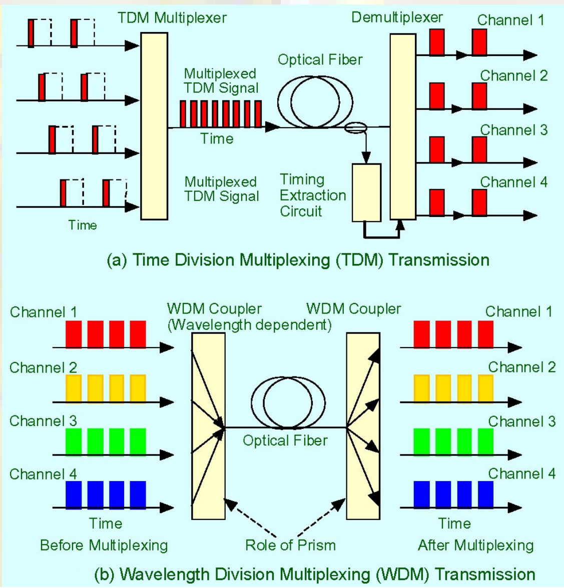


if: $L(P) = 100km$

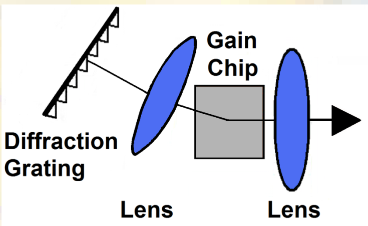
$$L(2P) = \frac{10\lg\frac{2P}{P_0}}{0.2dB/km} = \frac{10\left(\lg\frac{P}{P_0} + \lg 2\right)dB}{0.2dB/km} = \frac{10(2+0.3)dB}{0.2dB/km} = 115km$$

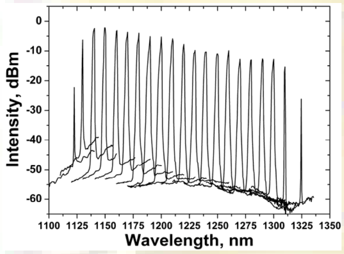
$L(100P) = 200km$

Wavelength / Time Division Multiplexing



Wavelength Selection

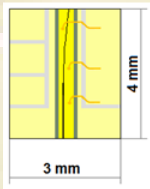




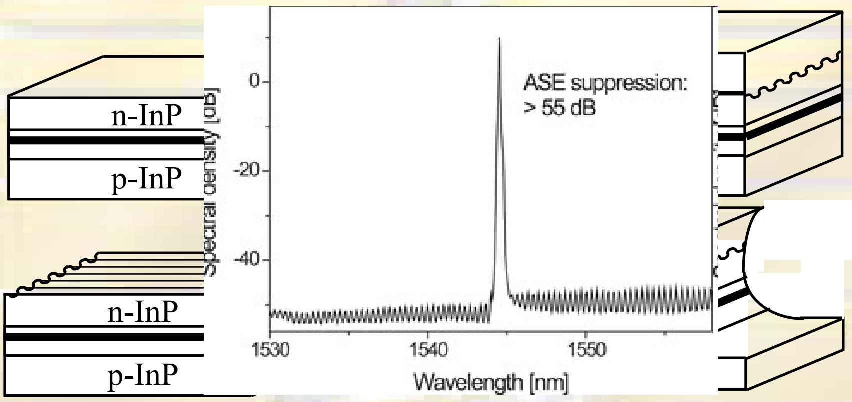
<u>Gain Chip:</u>

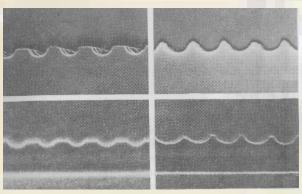
- 4mm length, 5μm wide waveguide
- 10 layers InAs QDs, grown on GaAs substrate
- waveguide angled at 5°
- facets AR coated: $R_{angled} < 10^{-5}$

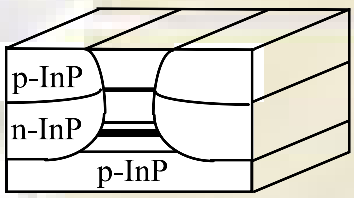
  $R_{front} \sim 2 \cdot 10^{-3}$



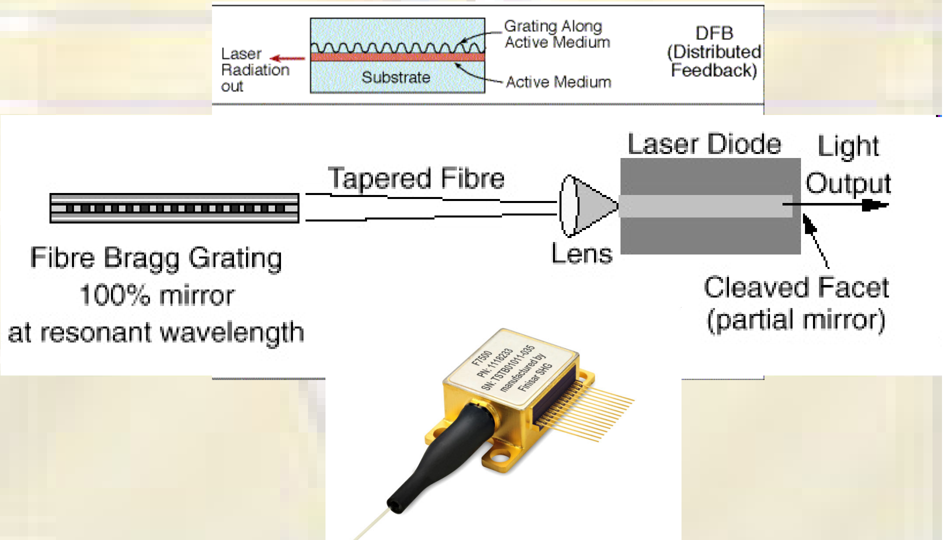
Distributed feedback (DFB) laser diodes





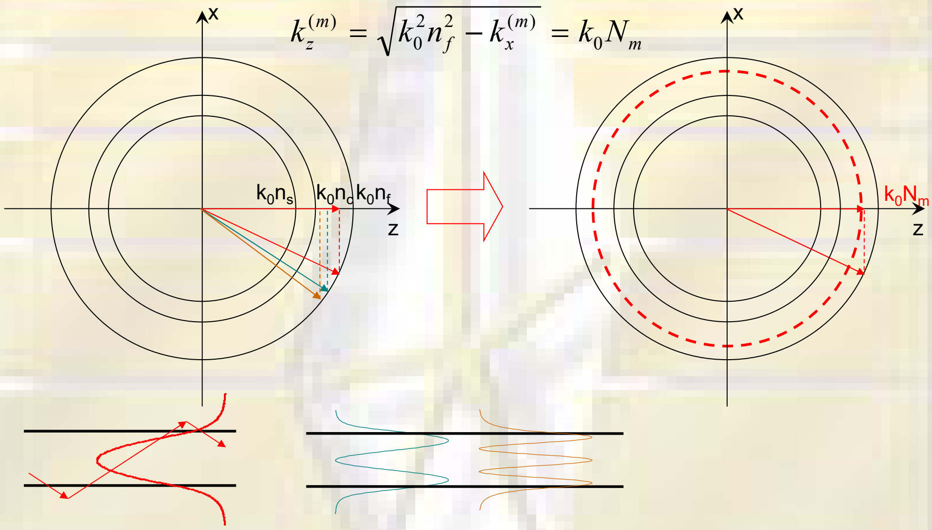


Distributed Bragg reflector (DBR) LDs

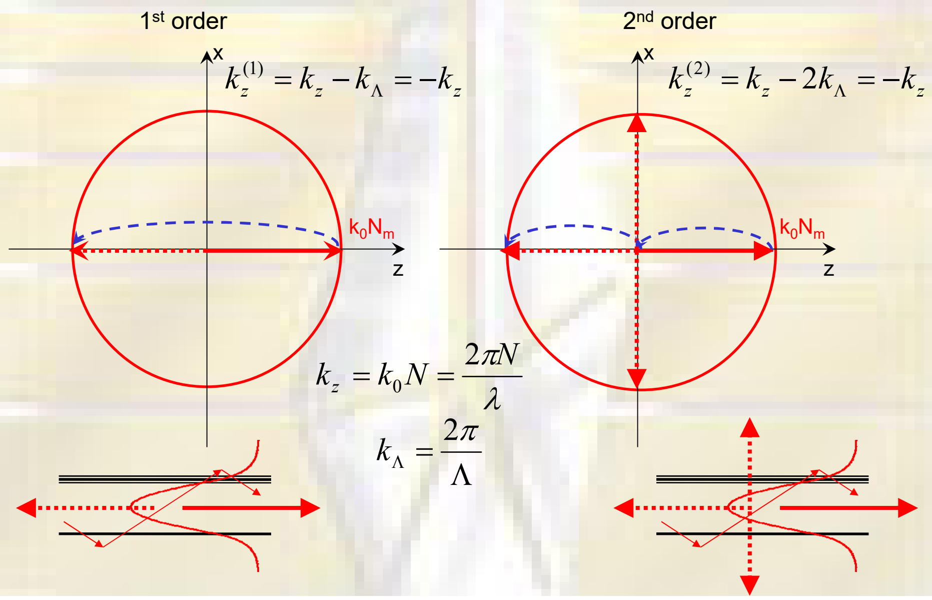


Diffraction grating in a waveguide

$$k_z^{(m)} = \sqrt{k_0^2 n_f^2 - k_x^{(m)}} = k_0 N_m$$



Diffraction grating in a waveguide



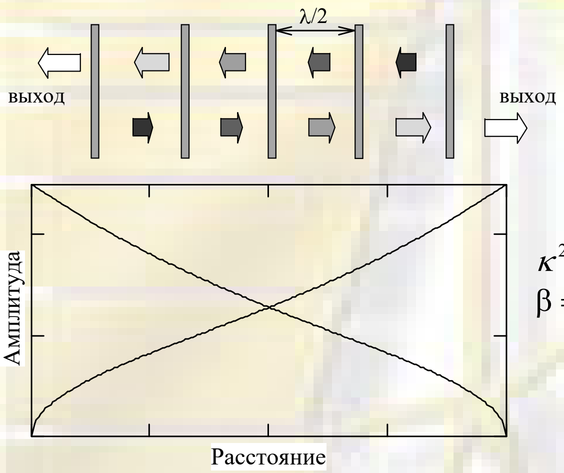
$$k_z^{(1)} = k_z - k_\Lambda = -k_z$$

$$k_z^{(2)} = k_z - 2k_\Lambda = -k_z$$

$$k_z = k_0 N = \frac{2\pi N}{\lambda}$$

$$k_\Lambda = \frac{2\pi}{\Lambda}$$

Distributed feedback



$$\delta = (\beta^2 - \beta_0^2)/2\beta \qquad \beta - \beta_0 = n(\omega - \omega_0)/c$$

$$\frac{\partial^2 E}{\partial z^2} + \kappa^2 E = 0$$

$$\alpha(z) = \alpha + \alpha_1 \cos(2\beta_0 z)$$
$$n(z) = n + n_1 \cos(2\beta_0 z)$$

$$\beta_0 = n\omega_0 / c \approx n\omega / c$$

$$\kappa^2 = \beta^2 + 2i\alpha\beta + 4k\beta\cos(2\beta_0 z)$$

$$\beta = n\omega/c \qquad k = \pi n_1/\lambda_0 + i\alpha_1/2$$

$$E(z) = R(z)e^{-i\beta_0 z} + S(z)e^{i\beta_0 z}$$

$$-\frac{dR}{dz} + (\alpha - i\delta)R = ikS$$

$$\frac{dS}{dz} + (\alpha - i\delta)S = ik^* R$$

Р.Ф.Казаринов, Р.А.Сурис, ФТП, 1972, т.6(7), с. 1359-1365.
H.Kogelnik, C.V.Shank, Journal of Appl. Phys, 1972, v.43(5), pp.2327-2335.

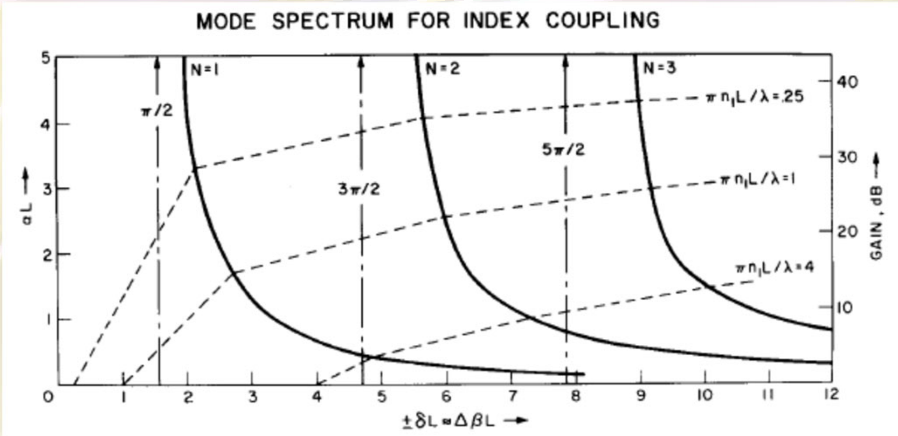
Distributed feedback

$$-\frac{dR}{dz}+(\alpha-i\delta)R=ikS$$

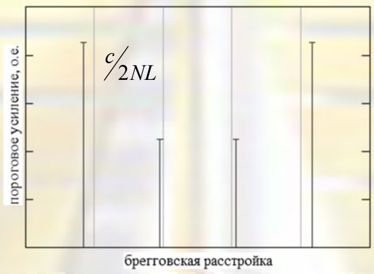
$$\frac{dS}{dz}+(\alpha-i\delta)S=ik^{*}R$$

$$\delta=\frac{(\beta^2-\beta_0^2)}{2\beta}\qquad \beta-\beta_0=\frac{n(\omega-\omega_0)}{c}$$

$$k=\pi n_1/\lambda_0+i\alpha_1/2$$

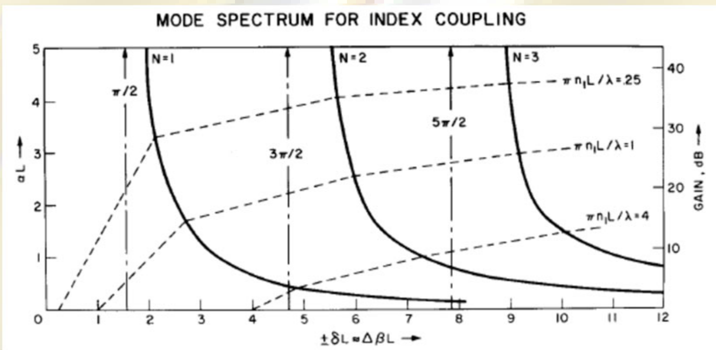


Distributed feedback

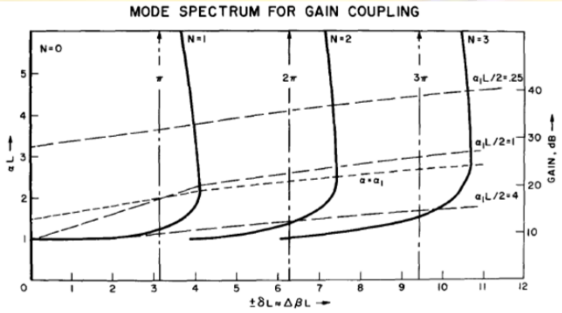


$$\delta=\frac{(\beta^2-\beta_0^2)}{2\beta}$$

$$k=\pi n_1/\lambda_0+i\alpha_1/2$$



Distributed feedback

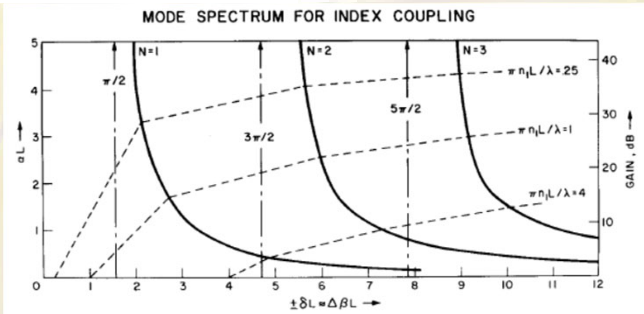


Связь по усилению

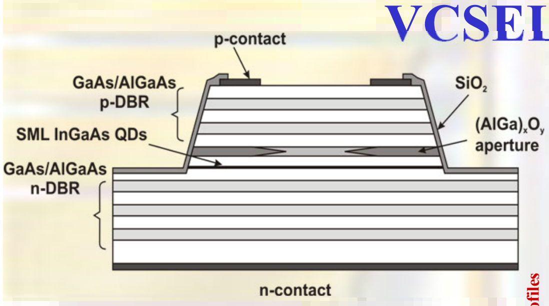
$$k = \pi n_1/\lambda_0 + i\alpha_1/2$$

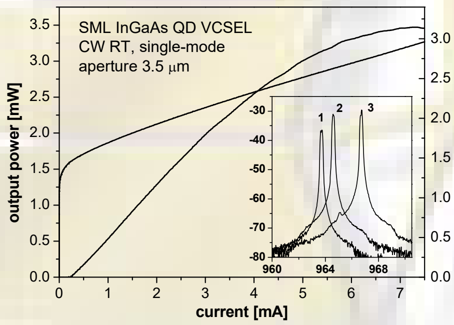
Связь по коэф. преломления

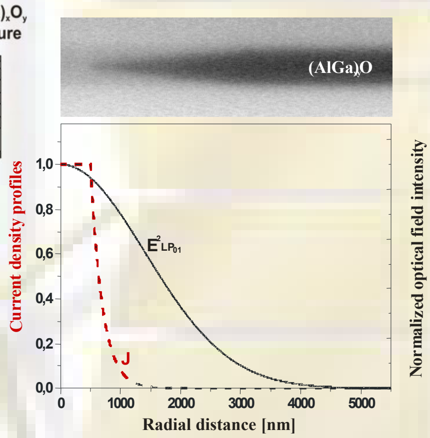
$$k = \pi n_1/\lambda_0 + i\alpha_1/2$$



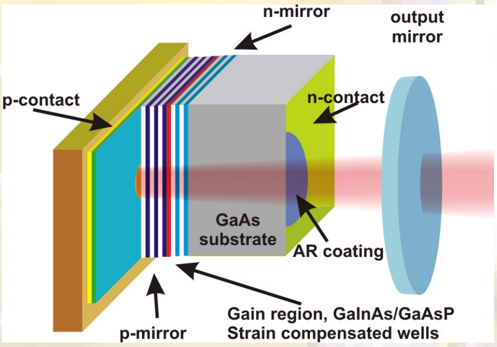
Vertical-cavity surface-emitting lasers VCSELs

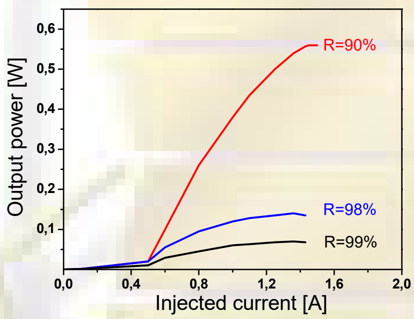






Vertical-extended-cavity surface-emitting lasers (VECSELs)





A.Mooradian, "High brightness cavity-controlled surface emitting GaInAs lasers operating at 980 nm", Proceedings of the Optical Fiber Communications Conference, 17-22 March 2001

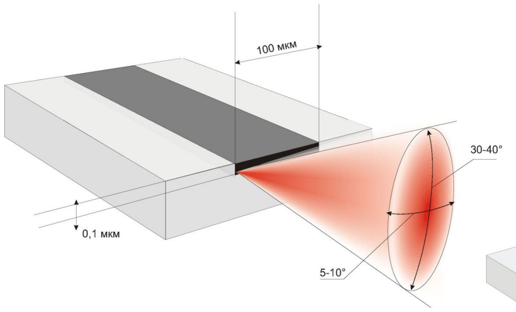
Problems of LDs

- Power
- Beam quality

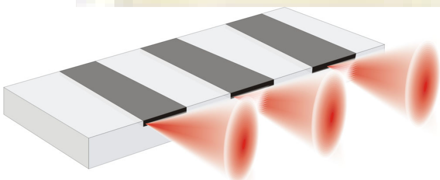
} Power density &intensity gradient

- ~~Spectral quality~~

Broad-stripe LD

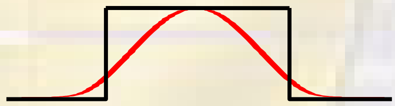


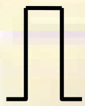
LD 'bar'



Optical confinement

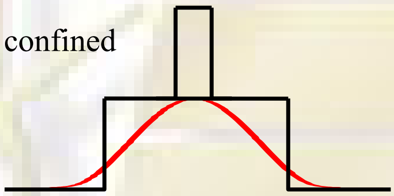
Double confined





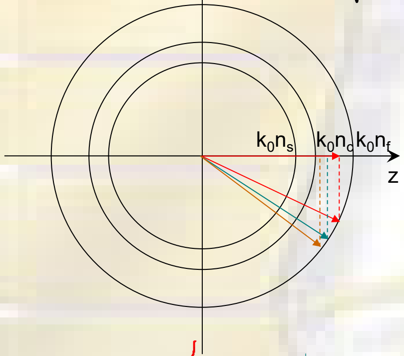
$$\Gamma = \frac{\int_0^f |E(x)|^2 \, dx}{\int_{-\infty}^{+\infty} |E(x)|^2 \, dx}$$

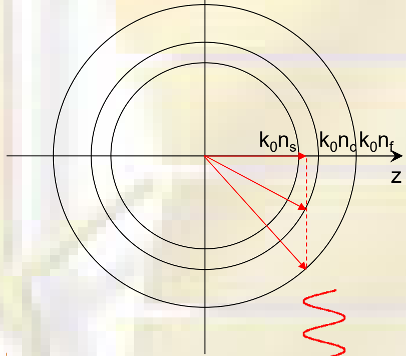
Separately confined

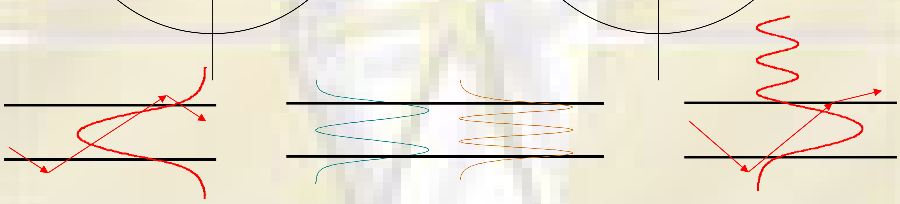


Modes of the waveguide

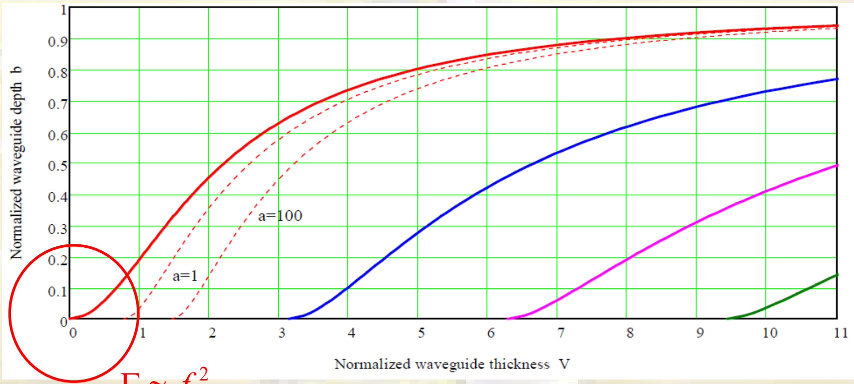
$$k_z^{(m)} = \sqrt{k_0^2 n_f^2 - k_x^{(m)}} = k_0 N_m$$





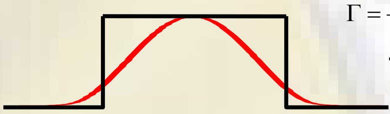


Optical confinement

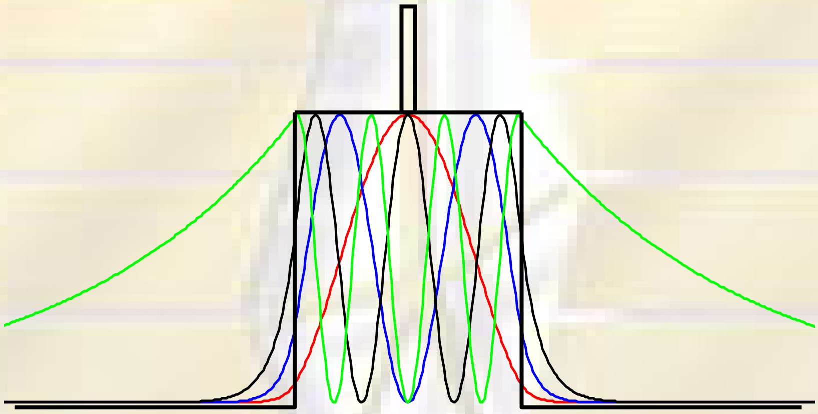


$\Gamma \approx f^2$

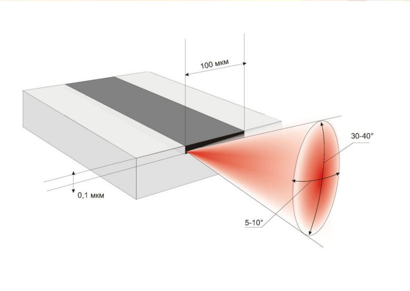
$$\Gamma = \frac{\int_0^f |E(x)|^2 dx}{\int_{-\infty}^{+\infty} |E(x)|^2 dx}$$



Managing mode structure with optical confinement



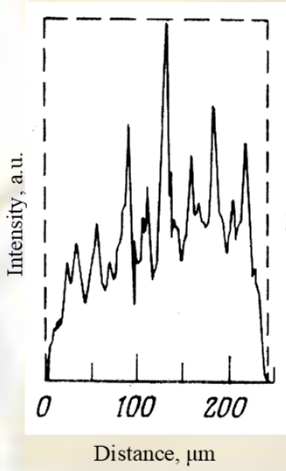
Power density and LD power



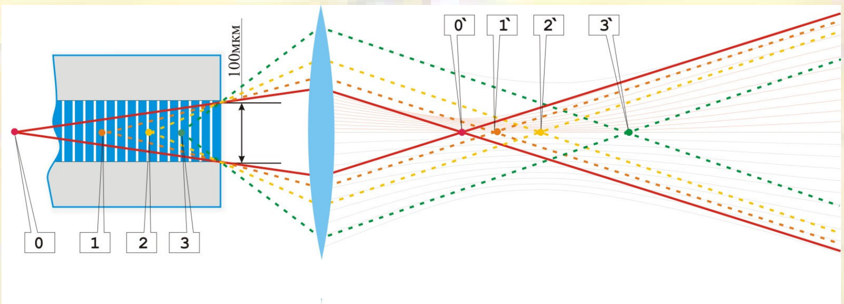
Higher power:
- Higher modes
- Spots (filaments)
- Astigmatism

Higher power does not mean higher power density… :(

'Not impossible' near-field distribution of the broad-stripe LD

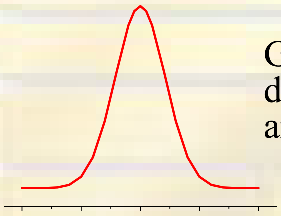


Multimode LDs



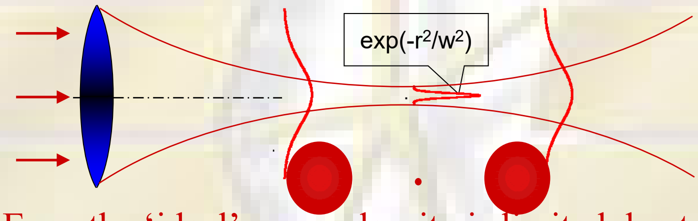
Multi-moded and 'spotted' (filamented) radiation is difficult (and sometimes impossible) to focus!

Gaussian beams



Gaussian exp(-r^2/w^2) is the most dense distribution. Therefore, Gaussian beams are the beams of the highest 'quality'.

Propagation of the Gaussian beam



Even the 'ideal' power density is limited due to the quantum mechanical uncertainty principle ΔpΔx=h

Gaussian beams

$$w_0 = \frac{\lambda}{\pi\, NA}$$

Beam waist size on the level of 1/e^2 (13.5%)

$$w(z) = w_0\sqrt{1+\left(\frac{\lambda z}{\pi w_0^2}\right)^2}$$

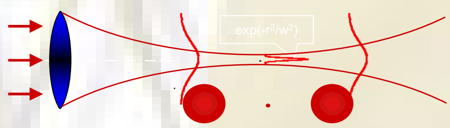
Propagating beam size (beam diameter)

$$R(z) = z\left[1+\left(\frac{\pi w_0^2}{\lambda z}\right)^2\right]$$

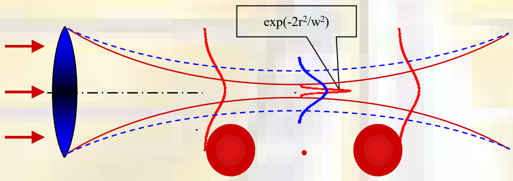
Wavefront curvature

$$z_R = \frac{\pi w_0^2}{\lambda}$$

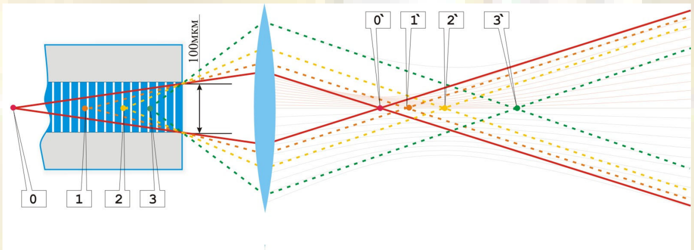
Rayleigh range (distance of √2-fold increase of diameter of the beam)

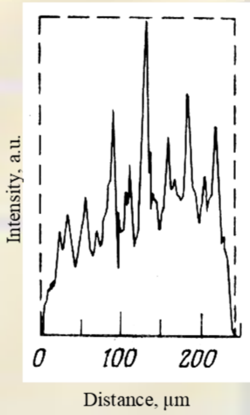


LD beams:
From multi-mode to quasi-Gaussian



M^2 – beam propagation parameter





Second moment properties

Definition of the second moment (or variance):

$$\sigma_x^2 = \frac{\int_{-\infty}^{\infty} (x-x_0)^2 I(x,y)dxdy}{\int_{-\infty}^{\infty} I(x,y)dxdy}$$

Applied to a zero-order Gaussian beam yields:

$$\sigma_x^2 = \frac{\int_{-\infty}^{\infty} x^2 \exp\left(-x^2/w_x^2\right)dx}{\int_{-\infty}^{\infty} \exp\left(-x^2/w_x^2\right)dx} = \frac{w_x^2}{2}$$

This leads to a parabolic propagation rule:

$$\sigma_x^2(z) = \sigma_{x0}^2 + \sigma_\theta^2 (z-z_0)^2$$

$$w^2(z) = w_0^2 + \left(\frac{\lambda}{\pi w_0}\right)^2 (z-z_0)^2 = w_0^2 \left[1 + \left(\frac{z-z_0}{z_R}\right)^2\right]$$

A.E.Siegman / Proc. SPIE 1868, 2 (1993)

Second-moment-based beam width definition

Therefore for arbitrary real beams similar beam width definitions can be adopted:

$$w_x = \sqrt{2}\sigma_x$$

These second-moment-based beam widths will propagate exactly quadratically with distance in free space. For any arbitrary beam (coherent or incoherent), one can then write using the second-moment width definition

$$w_{x,y}^2(z) = w_{0x,y}^2 + M_{x,y}^4 \left(\frac{\lambda}{\pi w_{0x,y}}\right)^2 (z - z_0)^2$$

With $M^2 \geq 1$ being 'times diffraction-limited' factor for an arbitrary real beam compared to the zeroth-order Gaussian beam

$$M^2 \equiv \frac{\pi w_0 w(z)}{z\lambda}$$

A.E.Siegman / Proc. SPIE 1868, 2 (1993)

Basic properties of the M^2 parameter

M^2 is a 'times-diffraction-limited' parameter based on measured near and far field second-moment beam widths

$$M^2 = \frac{w_{measured}}{w_0}$$

M^2=1 for a zero-mode Gaussian beams

Arbitrary real beam width can then be fully described by 6 parameters:

$$w_{0x},\ w_{0y},\ z_{0x},\ z_{0y},\ M_x^2,\ M_y^2$$

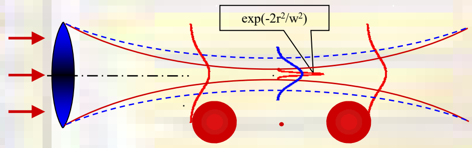
Requires time-averaged intensity measurements only.
NO phase or wavefront measurements!

- Can develop such a universial propagation rule only for the second-moment beam width definition
- Actually holds true for propagation through arbitrary paraxial optical systems as well

A.E.Siegman / Proc. SPIE 1868, 2 (1993)

Focusing of the quasi-Gaussian beams

$$\lambda \rightarrow M^2\lambda$$

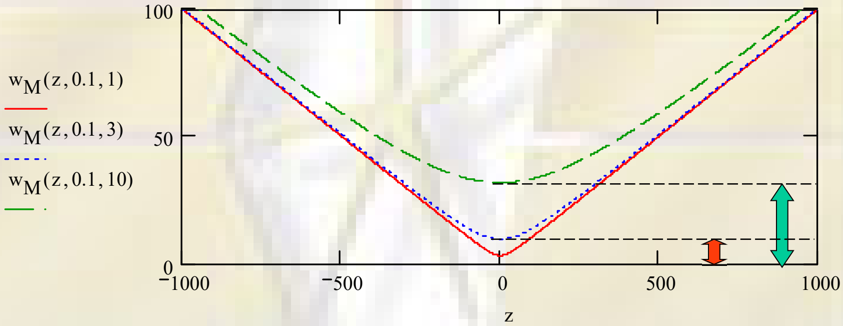


$$w_{M^2} = \frac{M^2\lambda}{\pi\, NA}$$

Beam waist size on the level of $1/e^2$ (13.5%)

$$w(z) = w_{M^2}\sqrt{1+\left(\frac{M^2\lambda z}{\pi w_{M^2}^2}\right)^2}$$

Propagating beam size



How to measure M² parameter?

Measurable: beam diameter as a function of propagation length:

$$w^2(z) = w_{M^2}^2 + NA^2(z-z_0)^2 = w_{M^2}^2 + z_0^2NA^2 - 2zz_0NA^2 + z^2NA^2 = A + B_1z + B_2z^2$$

$$A = w_{M^2} + z_0^2NA^2$$

$$B_1 = -2z_0NA^2$$

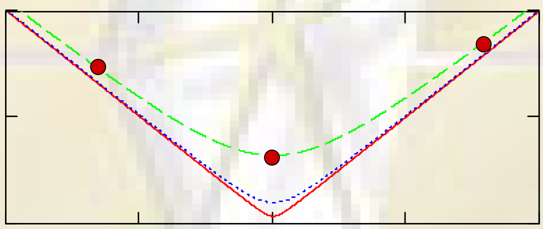
$$B_2 = NA^2$$

with $w_{M^2} = \frac{M^2\lambda}{\pi\, NA}$ follows:

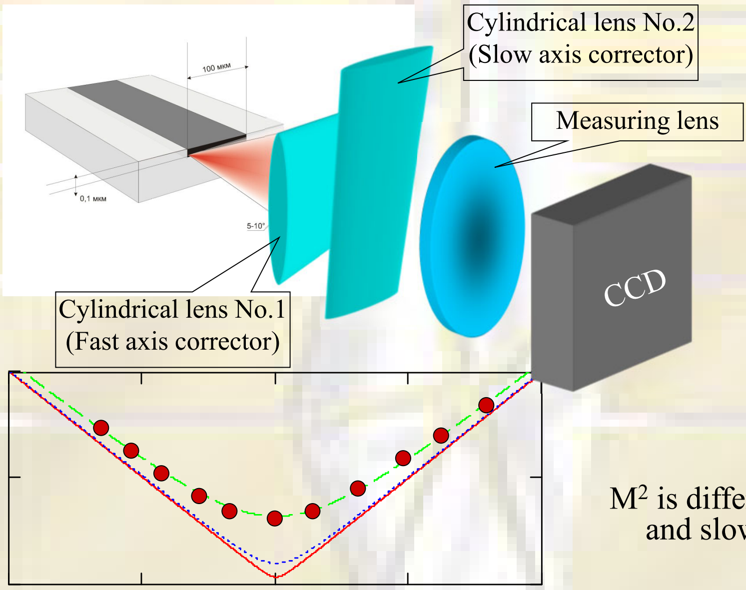
$$NA = \sqrt{B_2}$$

$$z_0 = -B_1/2B_2$$

$$M^2 = \frac{\pi}{\lambda}\sqrt{AB_2 - B_1^2/4}$$



How to measure M^2 parameter?



M^2 is different at fast and slow axis!

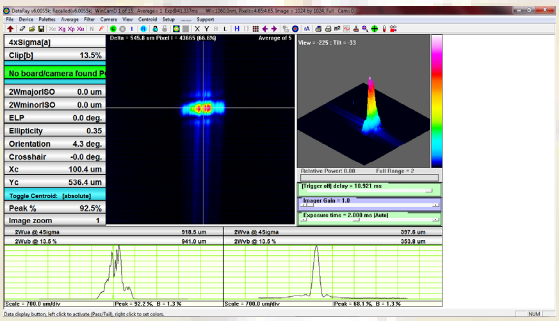
How to measure M^2 in your lab?

1. Use house-built setup with any CAL or CAD software (e.g. MicroCal Origin)

Approx. time for one laser: 3 hrs (when you've got some experience)

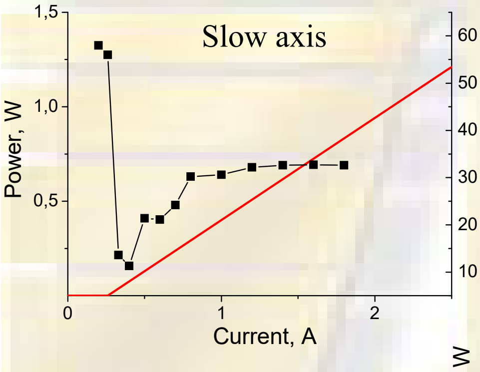
2. Use specialist hard- and soft-ware (e.g. DataRay)

Approx. time for one laser: 15 mins



Standard: ISO 11146

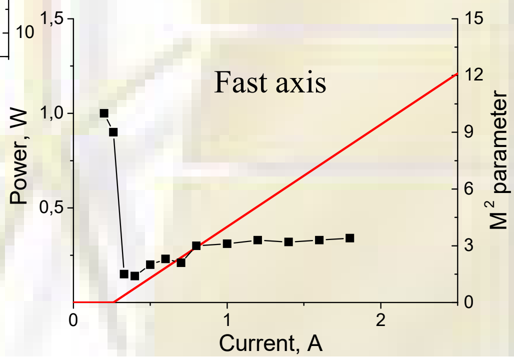
Measuring M^2 parameter



100 um high-power LD, 1.06 um

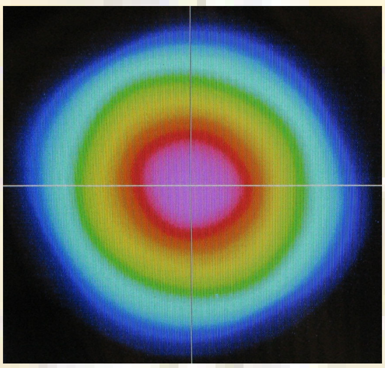
M^2 varies with current!

M^2 can be NOT measurable!



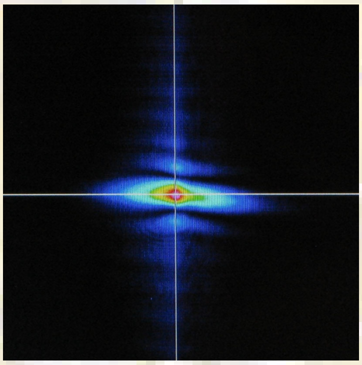
For broad-stripe laser diodes, M^2 at slow axis is an order of magnitude higher comparing to that at slow axis…

Don’t call it ‘Gaussian’ before you are sure…



Light emitting diode Lumiled, 0.63 um 350 mA, M^2=500

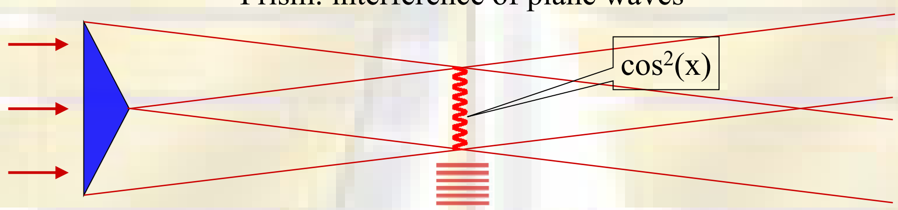
Don't overestimate the M^2 parameter of the 'nasty' LD beams…



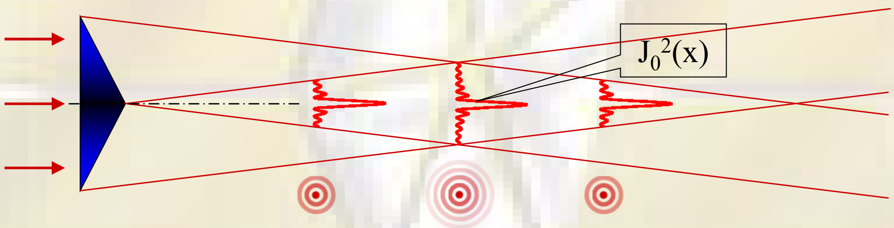
Narrow stripe LD, 1.06 um, 100 mA, M^2=4

Interference focusing (Generation of Bessel beams)

Prism: interference of plane waves

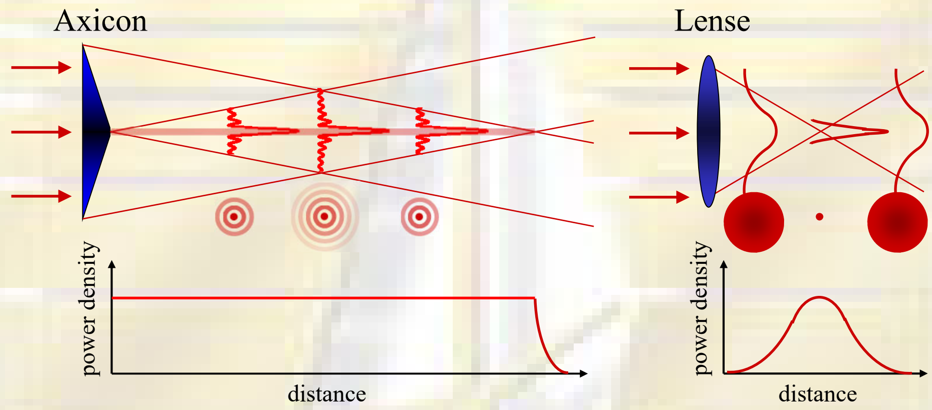


Conical lens (axicon): interference of conical waves



J. Durnin // J. Opt. Soc. Am. 1987, A 4, P. 651-654
B.Ya.Zel'dovich, N.F.Pilipetskii // Izvestia VUZov, Radiophysics, 1966, 9(1), P.95-101

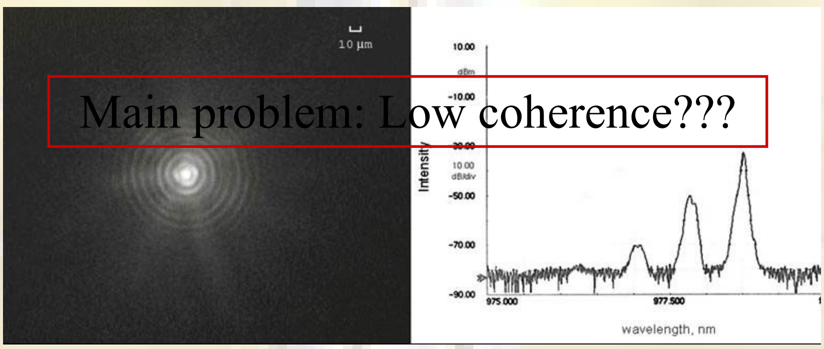
Bessel beams vs Gaussian beams



Bessel beams are ideal for optical tweezers, micromanipulation and lab-on-a-chip applications

Bessel beams are typically generated with vibronic lasers

Interference focusing with Laser Diodes



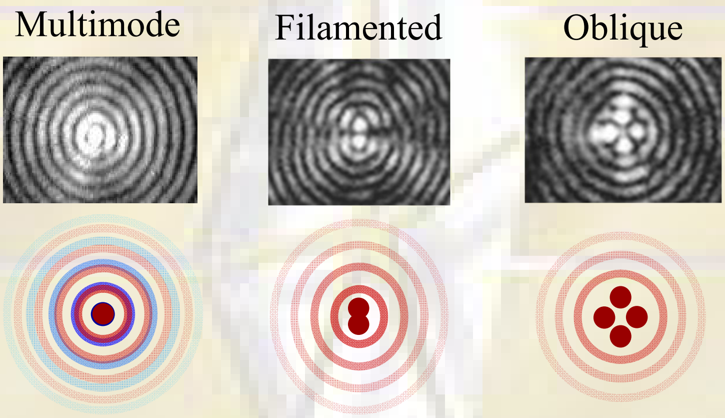
Main problem: Low coherence???

VCSEL DO-701d, Innolume GmbH, axicon 170^{0}, I=1 mA

G.S.Sokolovskii et al. // Tech Phys Lett, 2008, 34(24) 75-82

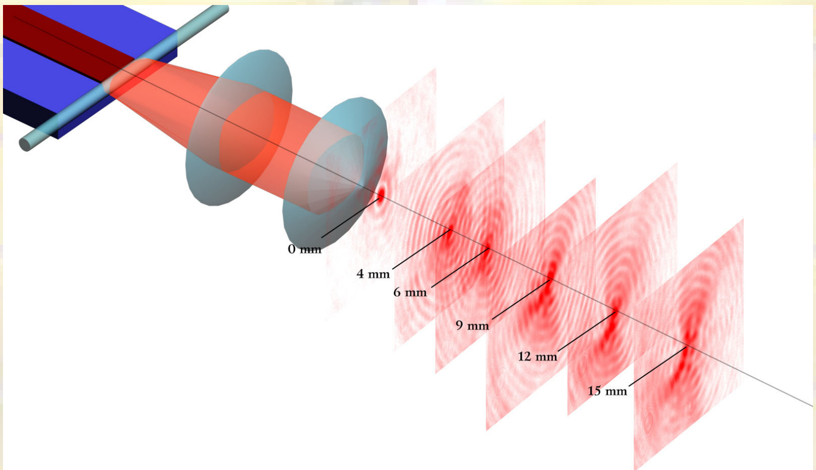
Interference focuing
with High-power Laser Diodes

Main problem: Poor beam quality



Radiation wavelength λ = 1.06 µm. Axicon apex angle 170^0. Central lobe size d_0 = 10 µm.

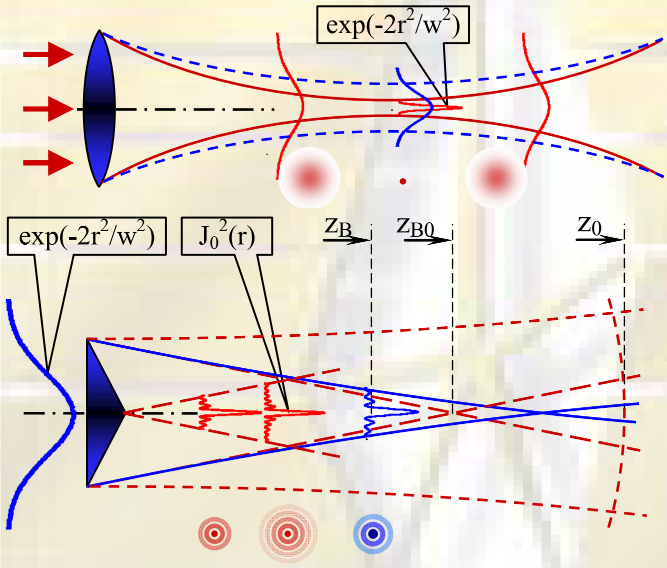
Bessel beams from the broad-stripe LD



Axicon apex angle 170^0

G.S.Sokolovskii et al. // Tech Phys Lett, 2010, 36(1) 22-30

Propagation length of Bessel beams generated from Laser Diodes

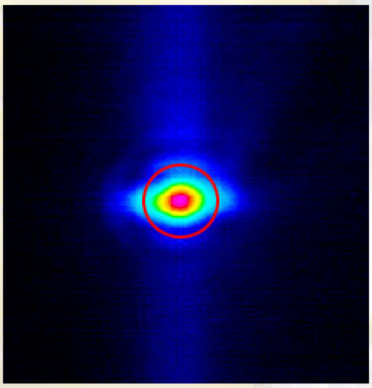


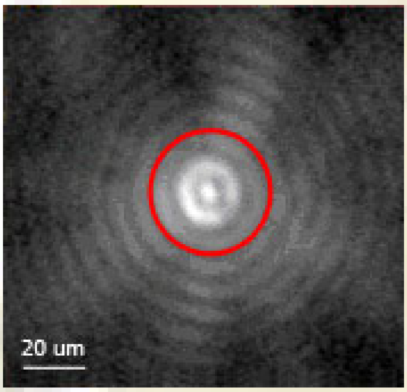
$$\lambda \rightarrow M^2\lambda$$

$$\Delta = \frac{M^2\lambda}{\pi\, NA}$$

M^2_{LD}=10-50
M^2_{LED}=200-500

Achieving ‘non-achievable’ intensity gradients with broad-stripe LDs



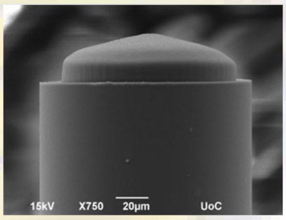


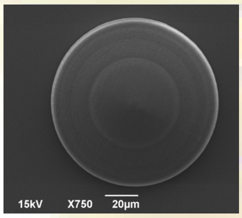
Broad-stripe LD 1.06 um, M^2=22, interference focal spot dia = 4 um

LED 0.63 um, M^2=200, interference focal spot dia = 6 um

Fiber axicons

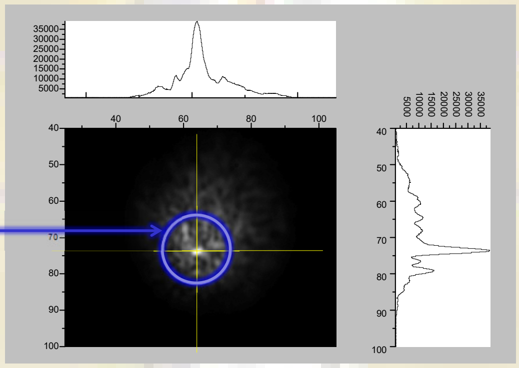
(Fiber axicons manufactured by Maria Farsari and colleagues, FORTH)



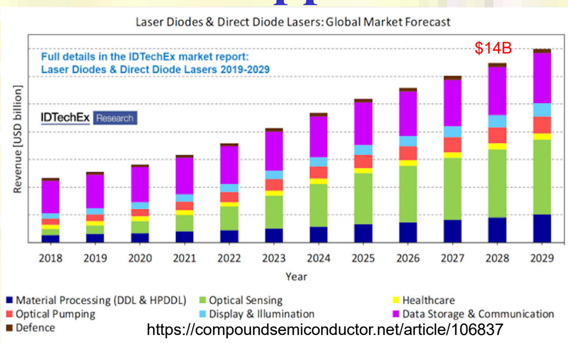


$$\Delta = \frac{M^2\lambda}{\pi \, \text{NA}}$$

1

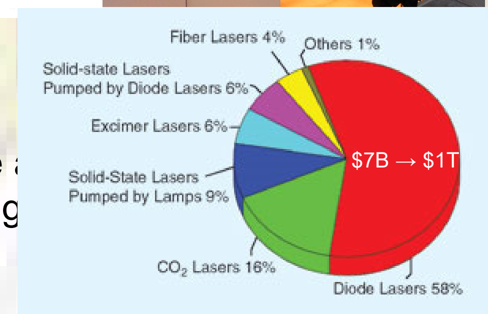


Applications of LDs



https://compoundsemiconductor.net/article/106837

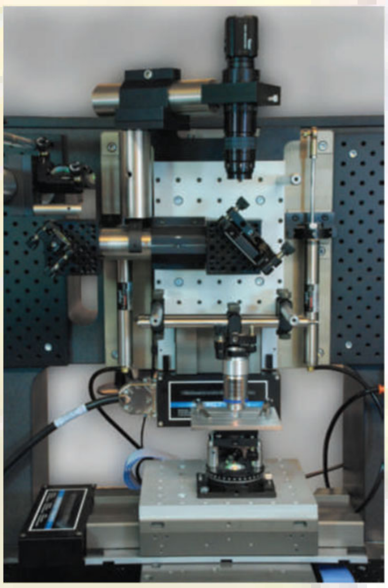
- Telecoms
- Data reading/recording
- Laser printing
- Pumping of the solid-state
- 'Direct' applications: cutting
- Biology and medicine

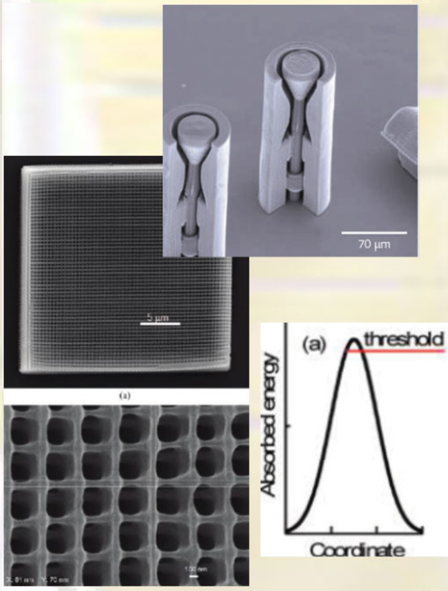


Laser projectors: Green Light?

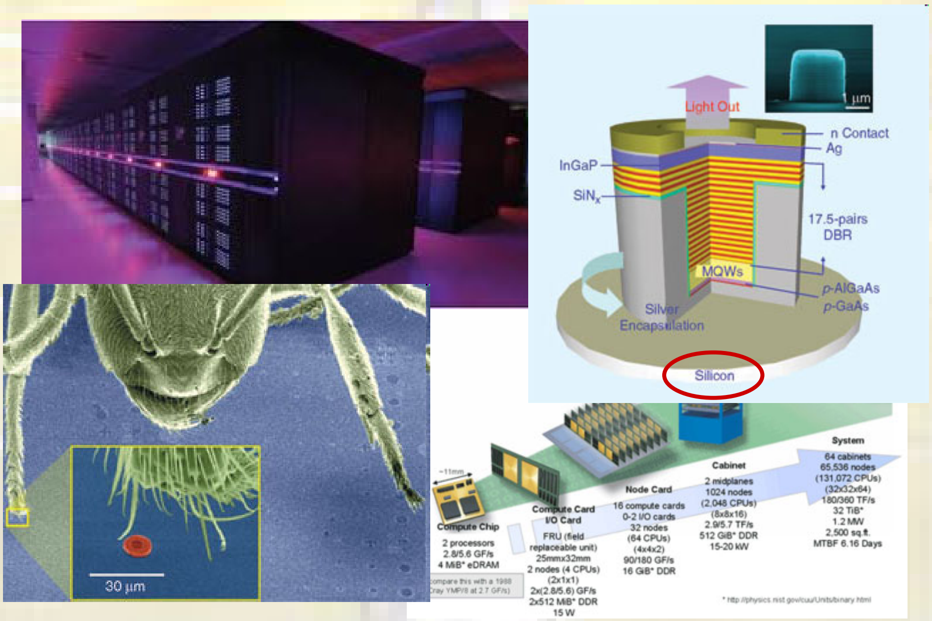
no focus adjustment!

From laser printers to 3D printing





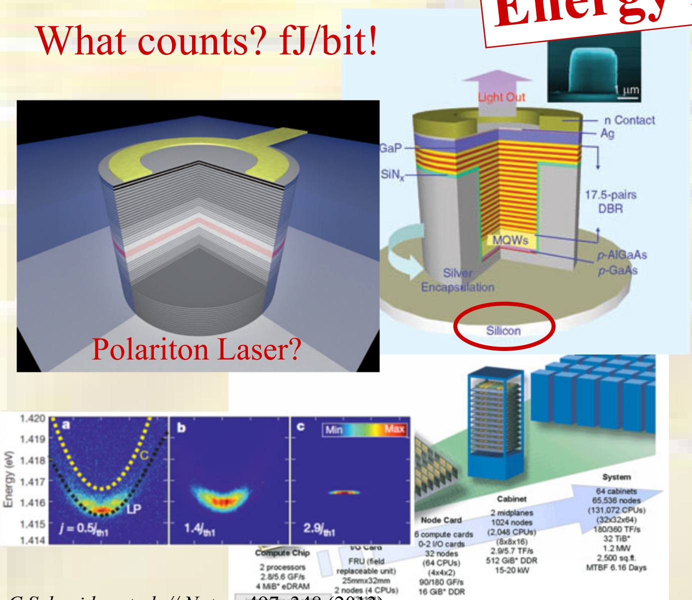
Telecoms/Datacoms: Silicon Photonics?



On-chip Datacom

Energy matters!

What counts? fJ/bit!



C.Schneider et al. // Nature 497, 348 (2013)

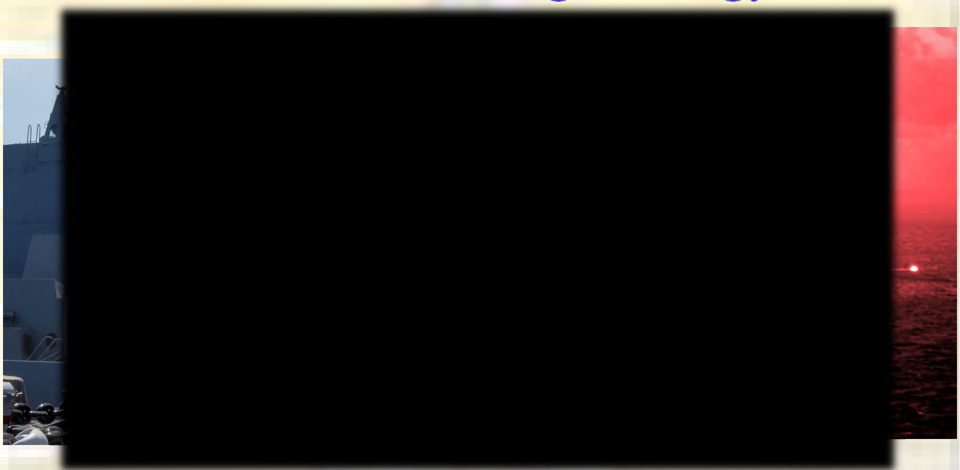
Automotive applications: laser ignition?

US Army first laser weapon

Offers lethality against unmanned aircraft systems (drones) and rockets, artillery and mortars

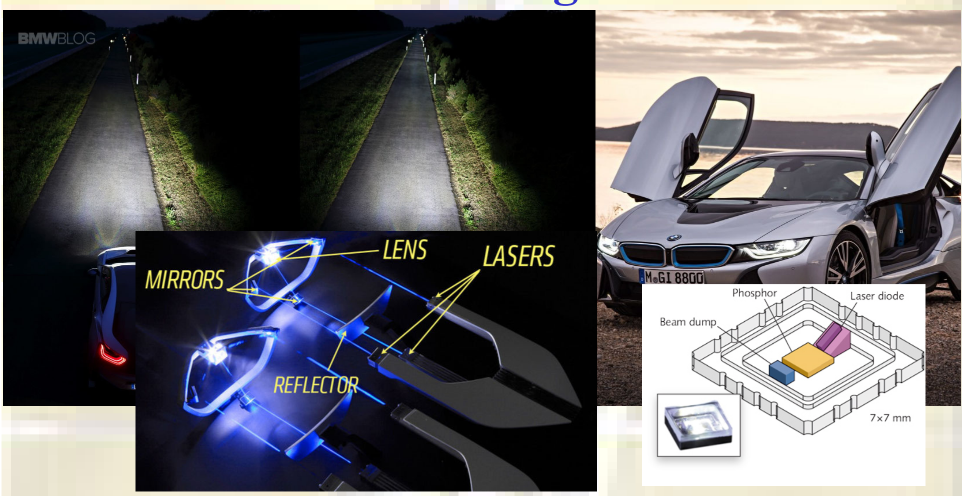
Citadel Defense has been awarded a sole source contract for $6M from US DoD to build and deploy an AI-powered counter drone solution. The system will be deployed at “sensitive government locations” and operated by non-specialist military personnel and first responders.

USS Portland tests high-energy laser



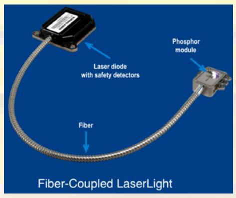
Solid State Laser aboard USS Portland successfully engages a static surface training target. Portland previously tested the LWSD in May 2020 when it successfully disabled a small unmanned aerial system while operating in the Pacific Ocean.

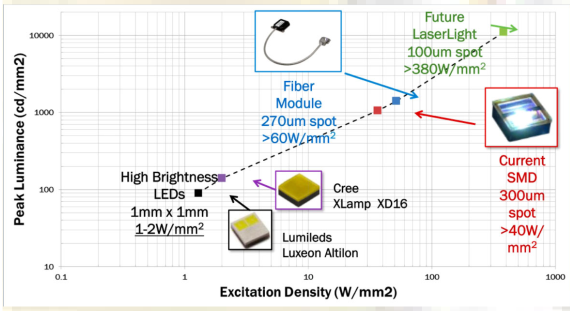
Automotive applications: laser headlights?

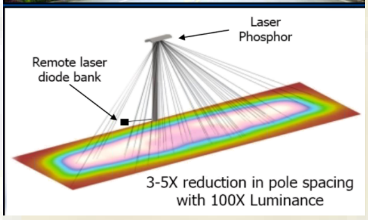


www.bmw.com 'In the laser headlight, the beams of light are bundled together to attain a luminous intensity that is ten times greater than conventional light sources such as halogen, xenon or LED. BMW Laserlight has a visual range of up to 600 metres, twice that of a headlight with conventional light technology.'

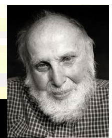
Laser lighting?



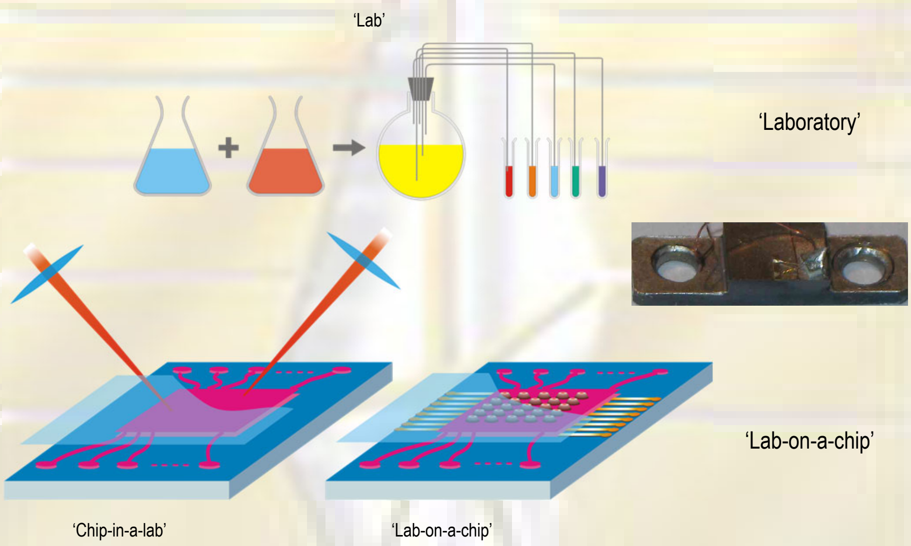




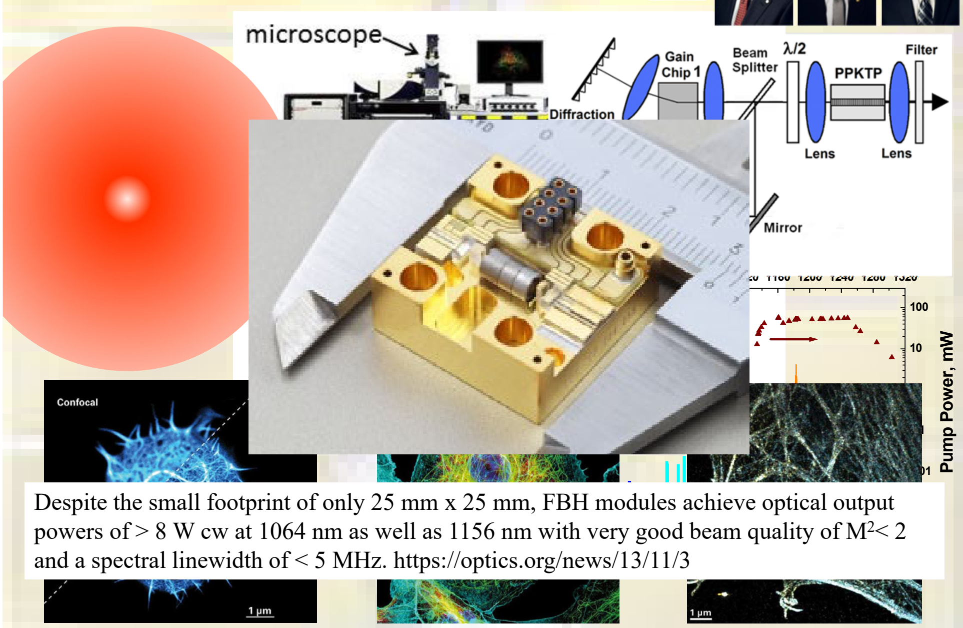
Optical tweezers: lab-on-a-chip?



Lab-on-a-chip

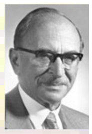


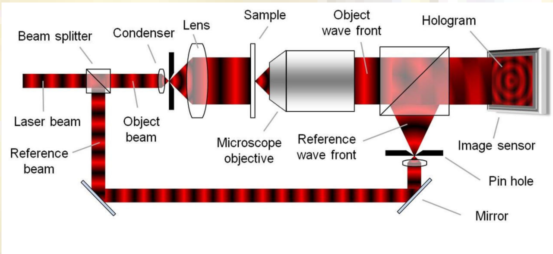
Fluorescent microscopy

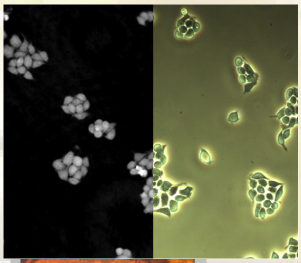


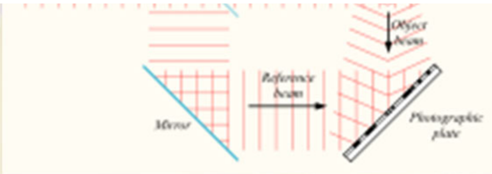
Despite the small footprint of only 25 mm x 25 mm, FBH modules achieve optical output powers of > 8 W cw at 1064 nm as well as 1156 nm with very good beam quality of $M^2 < 2$ and a spectral linewidth of < 5 MHz. https://optics.org/news/13/11/3

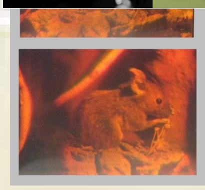
Lensless microscopy











Generation of Heat-Shock Proteins and Ceramides with Laser Diodes

Extracellular heat shock proteins (Hsp70) and ceramides are known to possess high adjuvant activity for cancer vaccines and low-immunogenic vaccines against dangerous infections. Hsp70 and ceramide can activate receptors of the innate immunity (TLR4) and boost protective immune response reactions against abiotic stress factors and biopathogens.

Pulse duration 100 ns
Frequency 10 kHz
Wavelength 1060 nm

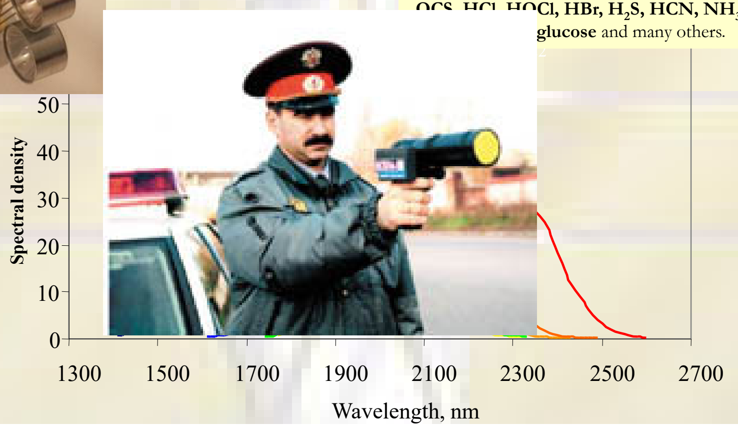
Quantum time standards and gyroscopes

[P. Porsandeh Khial et al, Nature Photonics, 12 (11), 671, 2018]

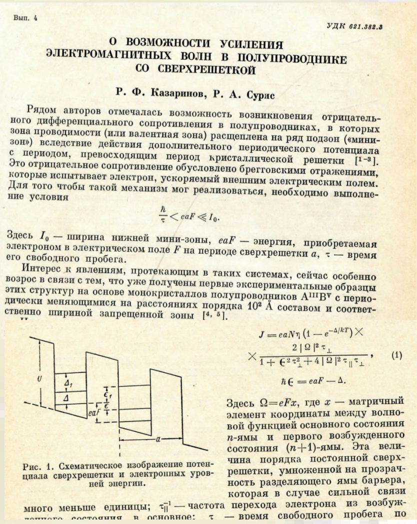
LDs for Mid-IR (1600 nm - 16 μm)

In Mid Infrared spectral range 1600-5000 nm lies strong absorption bands of such important gases and liquids as:

CH_4, H_2O, CO_2, CO, C_2H_2, C_2H_4, C_2H_6, CH_3Cl, OCS, HCl, HOCl, HBr, H_2S, HCN, NH_3, NO_2, glucose and many others.



Quantum-cascade lasers



Вып. 4

УДК 621.382.3

О ВОЗМОЖНОСТИ УСИЛЕНИЯ ЭЛЕКТРОМАГНИТНЫХ ВОЛН В ПОЛУПРОВОДНИКЕ СО СВЕРХРЕШЕТКОЙ

Р. Ф. Казаринов, Р. А. Сурис

Рядом авторов отмечалась возможность возникновения отрицательного дифференциального сопротивления в полупроводниках, в которых зона проводимости (или валентная зона) расщеплена на ряд подзон («мини-зон») вследствие действия дополнительного периодического потенциала с периодом, превосходящим период кристаллической решетки [1-3]. Это отрицательное сопротивление обусловлено брегговскими отражениями, которые испытывает электрон, ускоряемый внешним электрическим полем. Для того чтобы такой механизм мог реализоваться, необходимо выполнение условия

$$\frac{\hbar}{\tau} < eaF \ll I_0.$$

Здесь I_0 — ширина нижней мини-зоны, eaF — энергия, приобретаемая электроном в электрическом поле F на периоде сверхрешетки a, τ — время его свободного пробега.

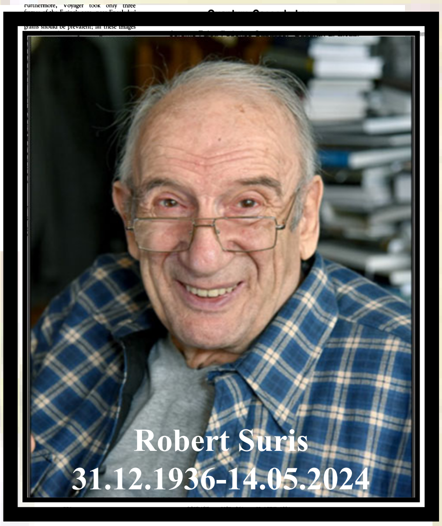
Интерес к явлениям, протекающим в таких системах, сейчас особенно возрос в связи с тем, что уже получены первые экспериментальные образцы этих структур на основе монокристаллов полупроводников $A^{III}B^{V}$ с периодически меняющимися на расстояниях порядка 10^2 Å составом и соответственно шириной запрещенной зоны [4, 5].

$$J = eaN\eta\,(1 - e^{-\Delta/kT}) \times \frac{2\,|\Omega|^2\,\tau_\perp}{1 + \epsilon^2\tau_\perp^2 + 4\,|\Omega|^2\,\tau_\parallel\tau_\perp}, \quad (1)$$

$$\hbar\epsilon = eaF - \Delta.$$

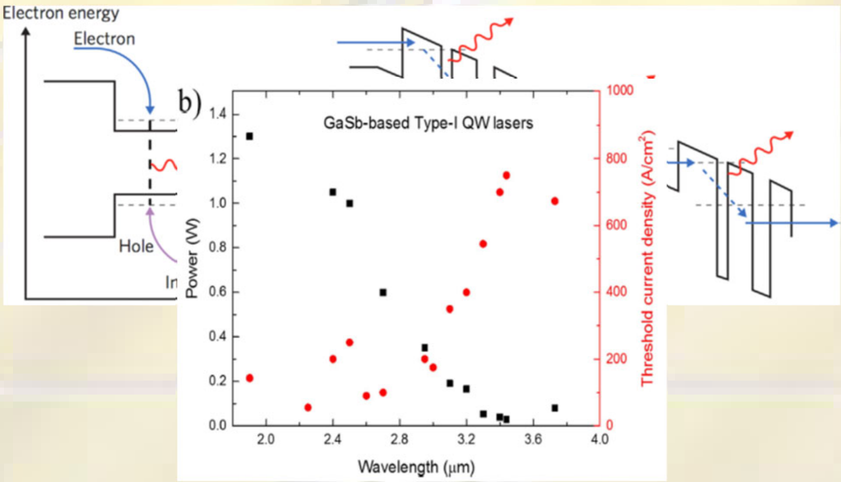
Рис. 1. Схематическое изображение потенциала сверхрешетки и электронных уровней энергии.

Здесь $\Omega = eFx$, где x — матричный элемент координаты между волновой функцией основного состояния n-ямы и первого возбужденного состояния $(n+1)$-ямы. Эта величина порядка постоянной сверхрешетки, умноженной на прозрачность разделяющего ямы барьера, которая в случае сильной связи много меньше единицы; $\tau_\parallel^{-1}$ — частота перехода электрона из возбужденного состояния в основное; $\tau_\perp$ — время свободного пробега по



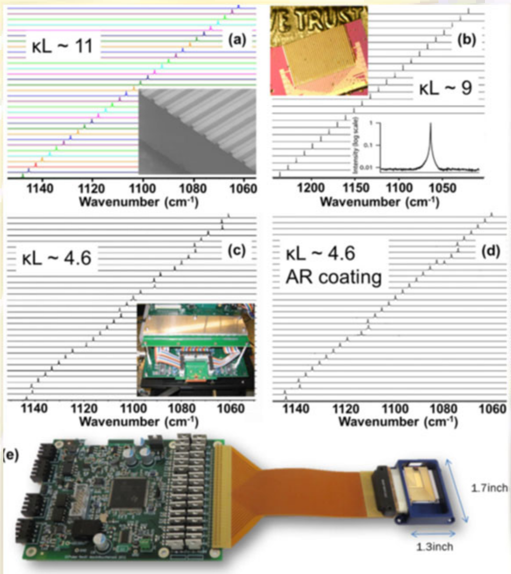
[R.F.Kazarinov, R.A.Suris, Semiconductors 5, 797 (1971)]
[J.Faist, F.Capasso et al., Science 264, 553 (1994)]

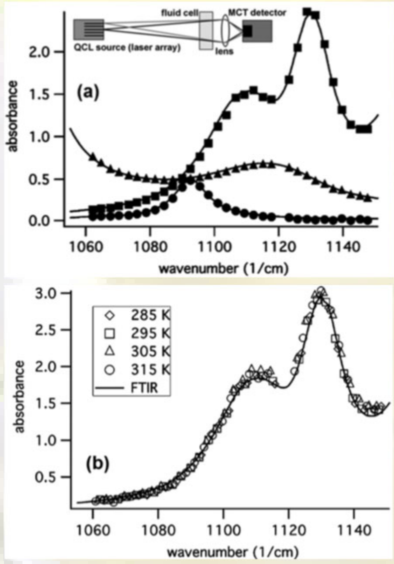
Quantum cascade lasers: End of E_g slavery



[G. Taubes, 'A new laser promises to put an end to band gap slavery' Science 264, 508 (1994)]
[D. Jung et al. / J of Optics 19, 123001 (2017)]

QCL arrays for spectroscopy





[P.Rauter, F.Capasso/Laser Phot.Rev. 9, 452 (2015)] [B. G. Lee et al./IEEE PTL 21, 914 (2009)]

Thank you for your attention!

- Applications of semiconductor lasers. 'Revolution' of light.
- Basic principles of laser operation (only to remind).
- Absorption and gain in semiconductors, inversion of population and conditions for it's achievement.
- Rate equations. Lasing threshold. Laser efficiency.
- Modulation of the laser signal. Gain clamping.
- Fiber-optical applications. DFB and DBR lasers. VCSELs and VECSELS
- Waveguide in LD structure. Modes of the waveguide.
- Beam-propagation ('beam-quality') parameter M^2 and how to measure it. Achieving maximum power density with LDs.
- Interference focusing of LD beams.
- What's next? New applications and problems to solve.

Thank you!
Questions?
gs@mail.ioffe.ru

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