ICTP SAIFR International Centre for Theoretical Physics
South American Institute for Fundamental Research

Semiconductor lasers: physics, dynamics & applications

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Outline

Part 1

1. Introduction to semiconductor lasers
2. Simplest model and dynamics with time-varying current parameter

Part 2

1. Applications of semiconductor lasers
2. More complicated models and nonlinear dynamics

Bibliography

- Saleh and Teich, *Fundamentals of photonics* (Wiley)
- J. Ohtsubo, *Semiconductor lasers: stability, instability and chaos* (Springer)
- J. M. Liu, *Photonic devices* (Cambridge University Press)

Survey

Who has taken a course on

- Optoelectronics/photonics/optical communications/lasers?
- Semiconductor physics/solid-state physics?
- Computing methods/ programming languages (C, Fortran)?
- Bifurcations/nonlinear dynamics/stochastic processes?

**Please feel free to interrupt me any time:
questions/comments welcome!**

Part 1: Introduction to SCLs

Main goals: acquire a basic knowledge of

- Historical development of SCLs & why they are important
- Types of SCLs & design goals
  - Cavity geometries: DFBs & DBRs; EELs & VCSELs, etc.
  - Gain medium: Bulk, QW, MQWs, etc

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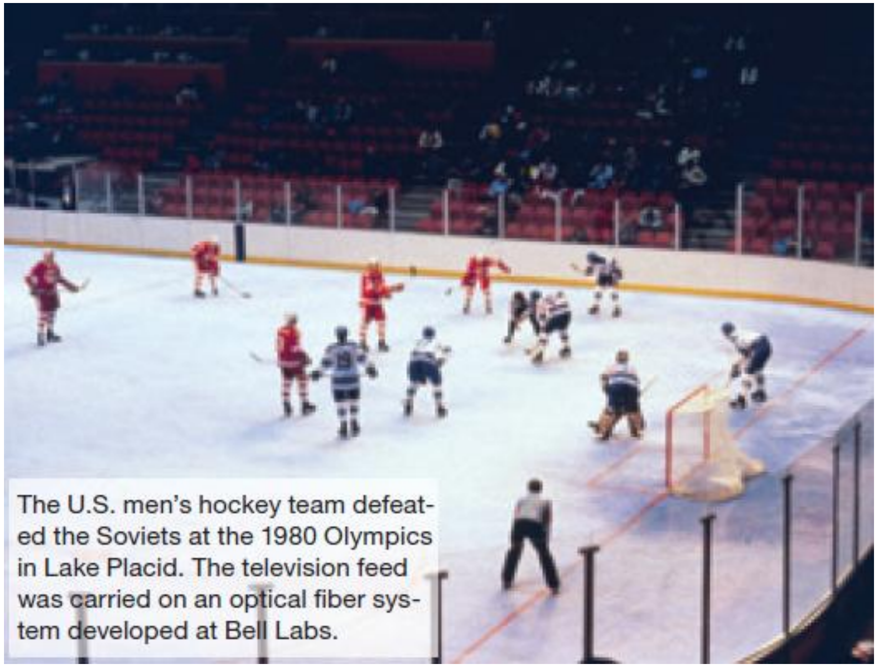
2012: 50th anniversary of the semiconductor laser (SCL)

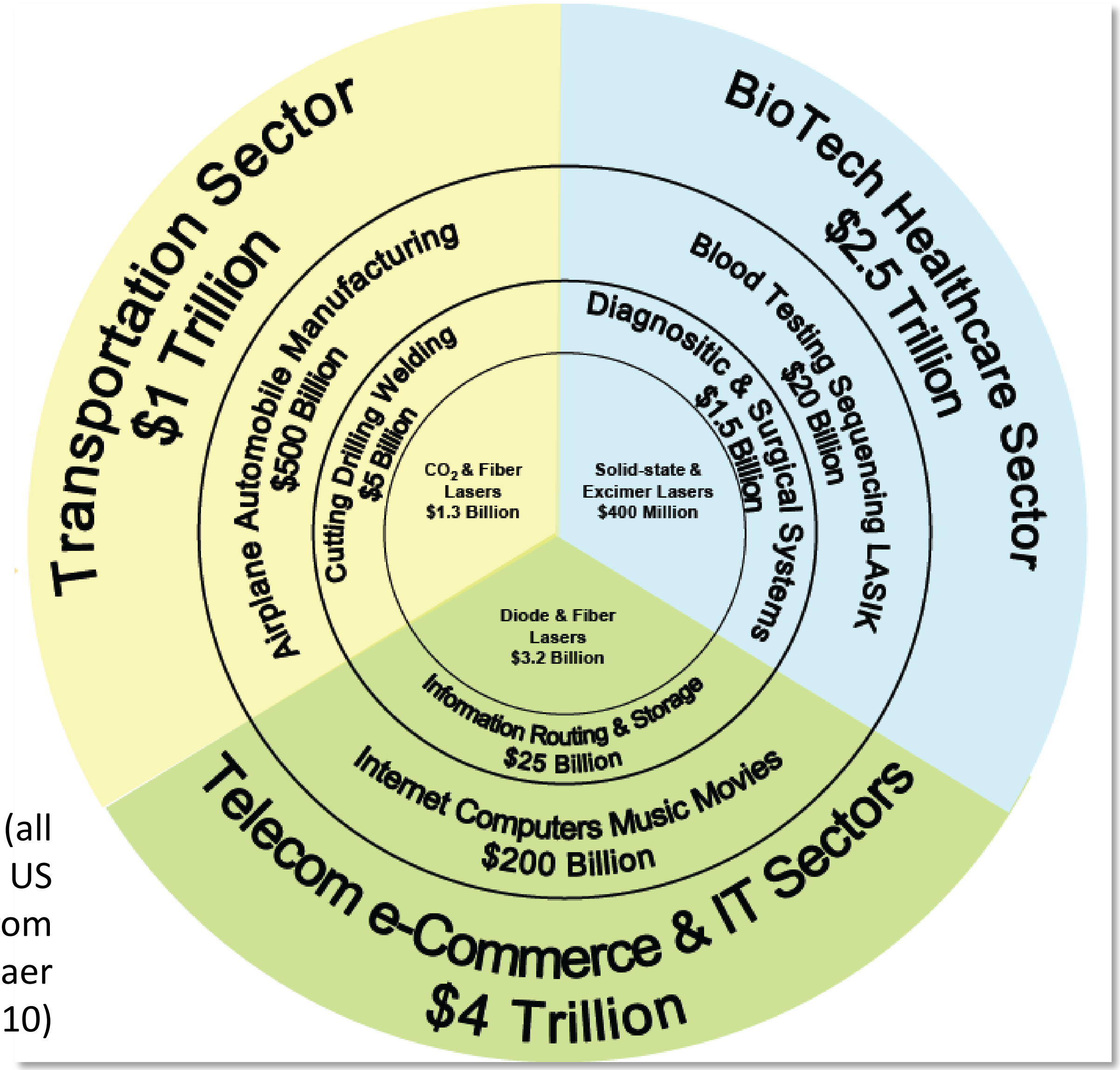
- First demonstration: **1962** (pulsed operation, cryogenic temperatures).
- cw RT emission: **1970**
- In the 60' & 70': SCLs where "**a solution looking for a problem**".
- The first practical application: February **1980**, an optical fiber system was used to **broadcast TV** (Winter Olympics, Lake Placid, US).



The U.S. men's hockey team defeated the Soviets at the 1980 Olympics in Lake Placid. The television feed was carried on an optical fiber system developed at Bell Labs.

Source: Optics & Photonics News May 2012

What are the applications of SCLs?



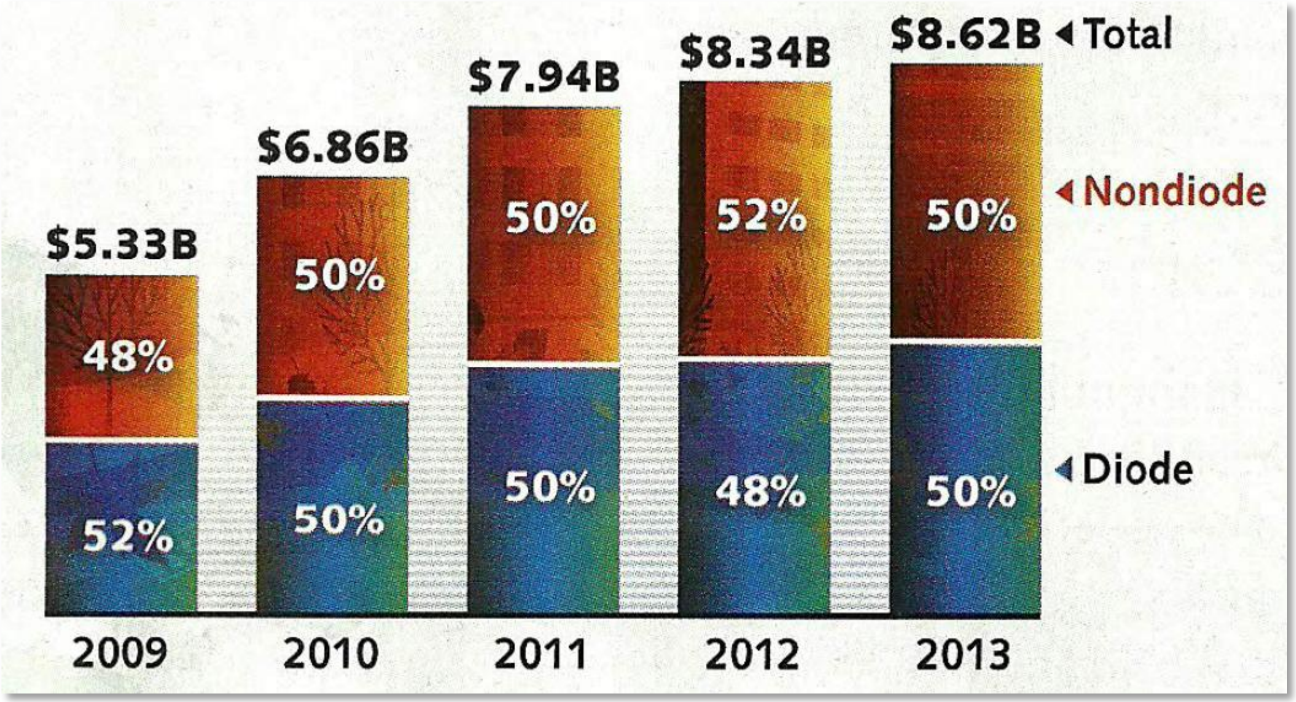
Impact of lasers (all types) in the US economy. Adapted from F. Schlachter & T. Baer (LaserFest 2010)

What is a diode laser?

- It is an **electrically pumped** semiconductor laser.
- As any laser, a diode laser requires a **gain medium** within an **optical cavity** (an exception to this are random lasers, which do not require a cavity).
- The semiconductor **band-gap** controls the emission **wavelength**.

Optical cavity

After 50 years diode lasers dominate the laser market



- They enable the development of key transformation technologies with **huge social impact**.

Source: Laserfocusworld.com

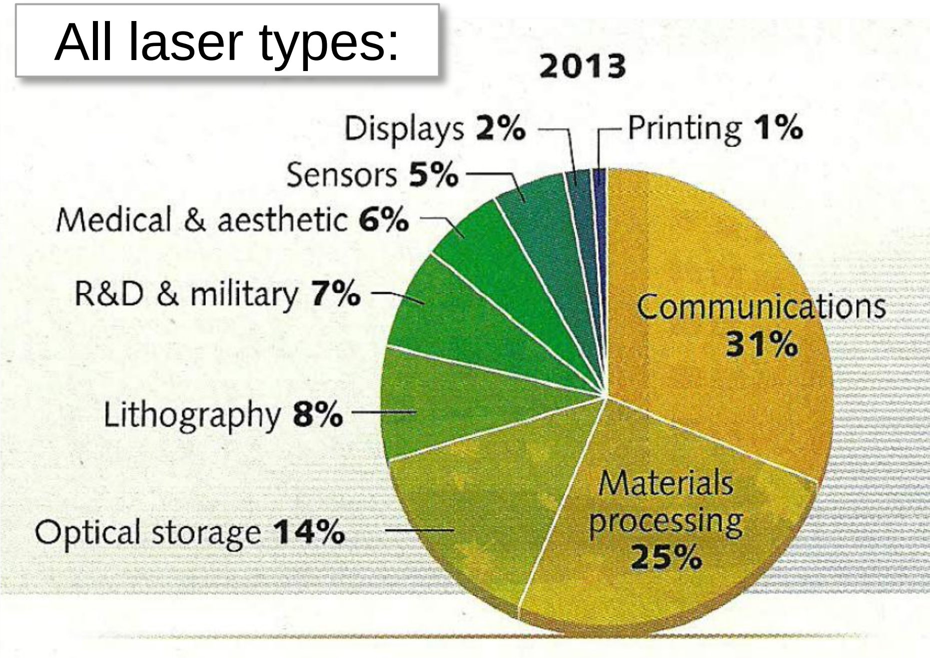
Main applications (more in Part 2)

- Optical fiber communications
- Optical storage

No diode laser

⇒ No internet!

All laser types:



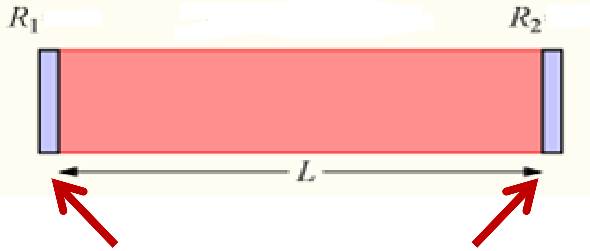
- But diode lasers are also widely used in printers, scanners, sensors, pumping of solid-state lasers, etc.
- A dramatic reduction of the fabrication price made possible these applications

The diode laser in a computer mouse costs about 10 US cents

Source: Laserfocusworld.com

Why are diode lasers so successful?

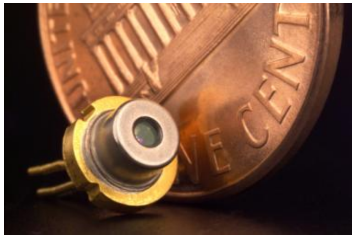
- The semiconductor medium has **huge gain** & do not require fragile enclosures or mirror alignment (the laser cavity is composed by the two facets of the semiconductor).



Cleaved facets

- **Low cost** fabrication because of existing semiconductor technology.

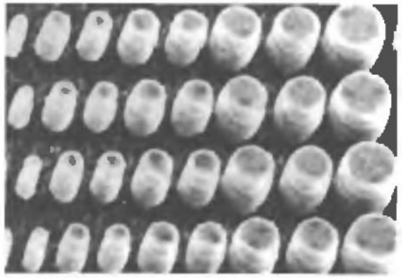
- Compared to other lasers, diode lasers are **very efficient** (nowadays 100% for the output photons with respect to the injected electrons).



- **Bright output** considering their **small size**.
- **Low threshold** current, **low energy consumption**.

Advantages for telecom applications

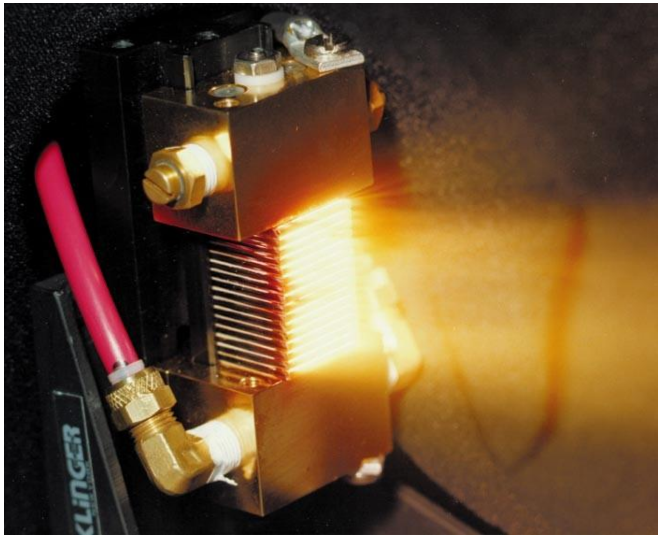
- Diode lasers can be **modulated at high speeds**: fast response to high-frequency information-modulated currents.
- Semiconductor materials provide a **wide range of wavelengths**. In particular, in the low-loss and low-dispersion regions of optical fibers.
- Easy integration in 1D & 2D arrays.



VCSELs with diameters between 1 and 5 μm. Adapted from Saleh and Teich

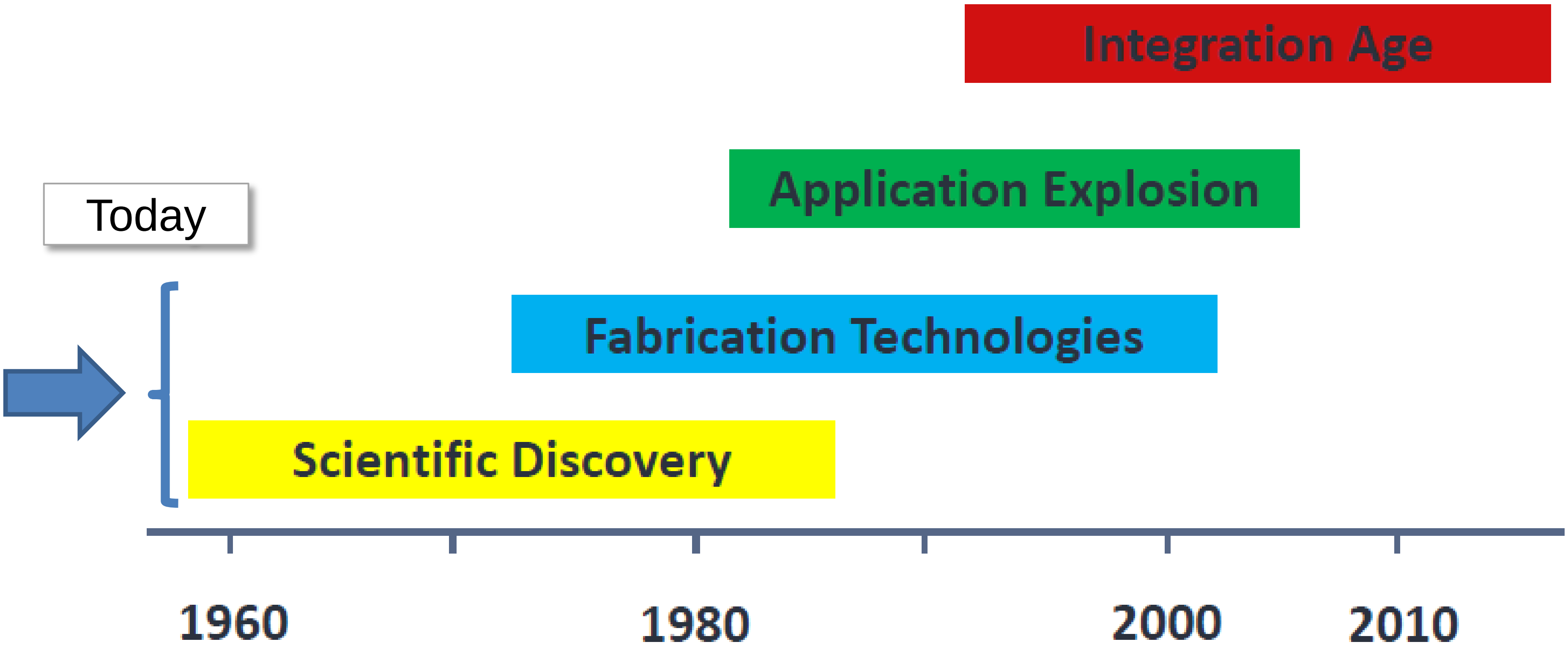
Diode lasers can also provide high output power

- Laser diode arrays produce > 1W, cw or pulsed.
- Diode lasers are used to pump **solid-state lasers**, such as the Nd:YAG. Laser diodes are tuned to the absorption band of the crystal providing efficient pumping.
- Also used to pump **Erbium Doped Fiber Amplifiers** (EDFAs), which are crucial for the amplification of signals in long distance fiber-optic links.



Source: Wikipedia

Laser Diode Evolution



Integration Age

Application Explosion

Today

Fabrication Technologies

Scientific Discovery

1960

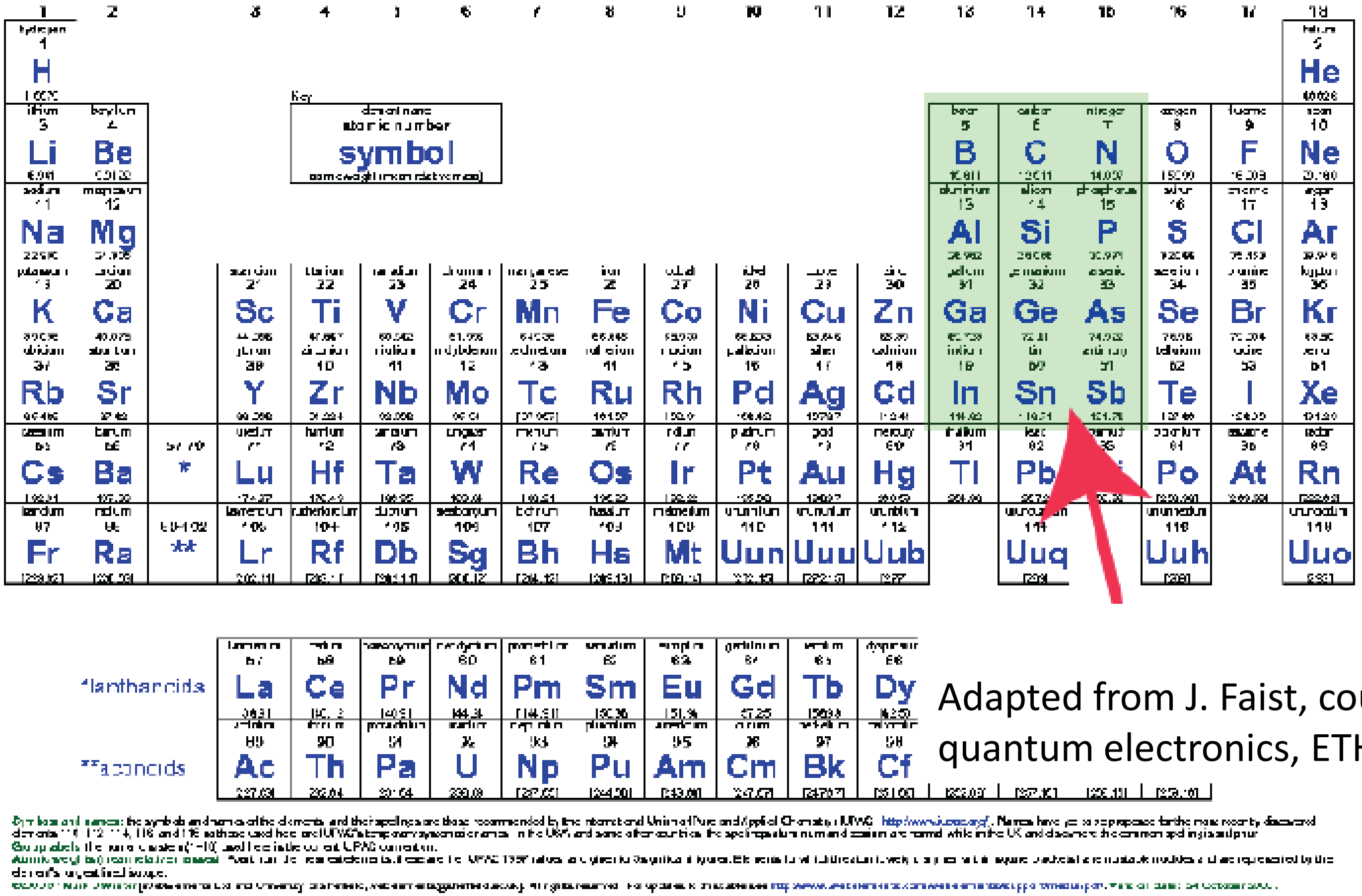
1980

2000

2010

Adapted from D. Welch, Infinera

Semiconductors

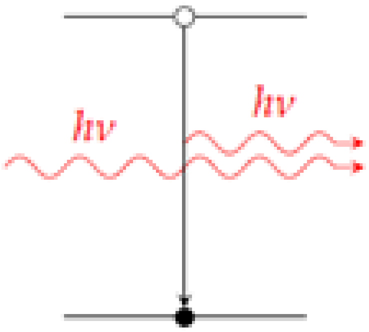


Adapted from J. Faist, course on quantum electronics, ETHZ)

Adapted from J. Faist, course on quantum electronics, ETHZ

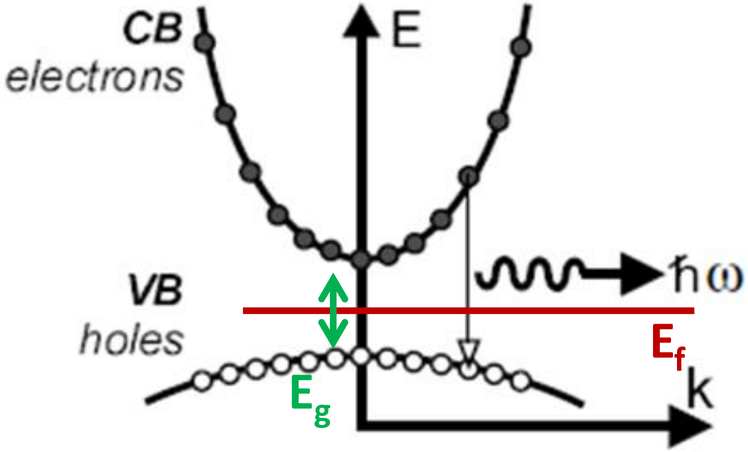
Which is the difference between a 2-level system and a semiconductor?

In a 2-level system: non interacting particles & individual energy levels



A particle in an excited state decays emitting a photon

In a semiconductor: electron/hole pairs & energy bands



An **electron** in the CB and a **hole** in the VB recombine emitting a photon

Conservation of momentum: $p_e \approx p_h$ ($p_{photon} \approx 0$) $\Rightarrow k_e \approx k_h$

$\Rightarrow$ Optical transitions are **vertical** in k space

Adapted from Saleh and Teich & W Coomans PhD thesis

Optical transitions in a semiconductor

Photo-detectors **LEDs** **Diode lasers & amplifiers**

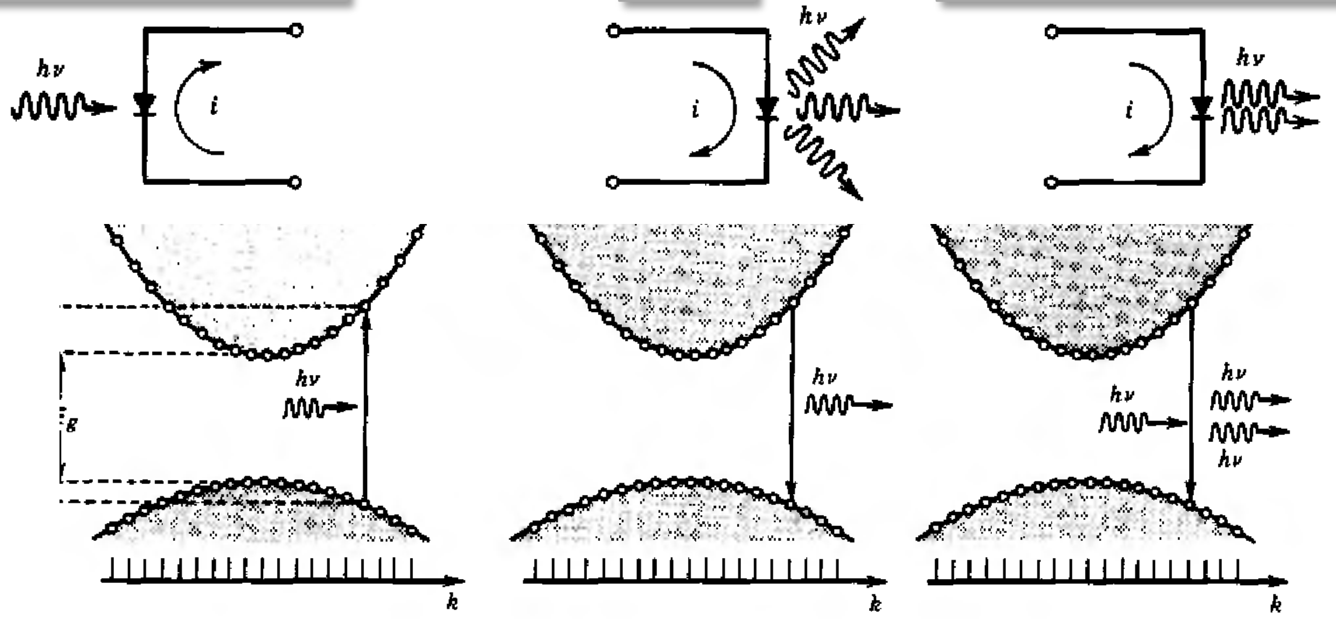
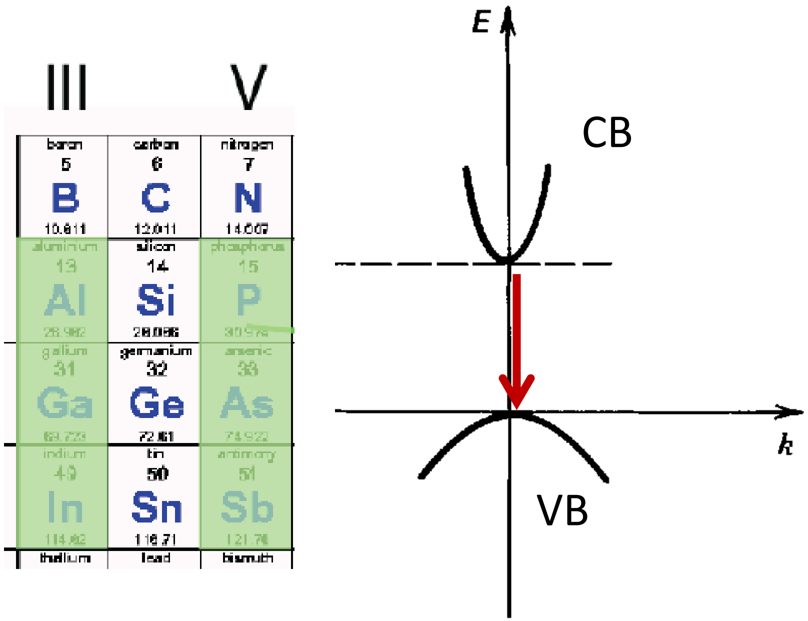


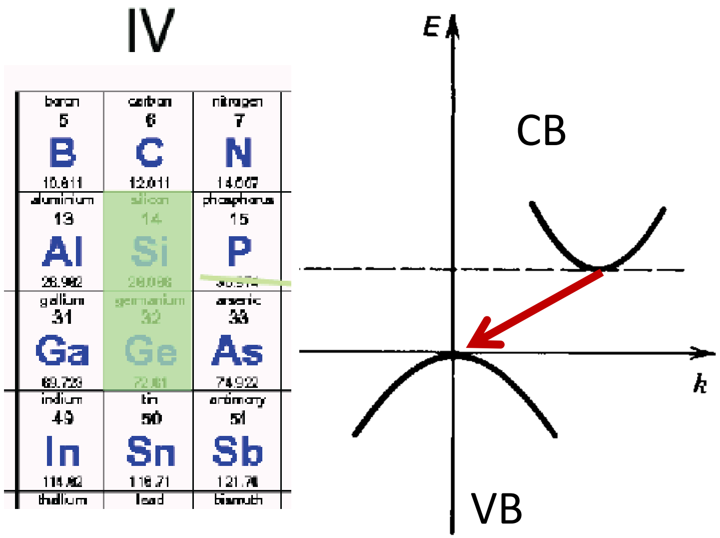
Figure 15.2-5 (*a*) The absorption of a photon results in the generation of an electron–hole pair. This process is used in the photodetection of light. (*b*) The recombination of an electron–hole pair results in the spontaneous emission of a photon. Light-emitting diodes (LEDs) operate on this basis. (*c*) Electron–hole recombination can be stimulated by a photon. The result is the induced emission of an identical photon. This is the underlying process responsible for the operation of semiconductor injection lasers.

Adapted from Saleh and Teich

Direct and indirect semiconductors



Direct optical transitions (GaAs): efficient photon sources



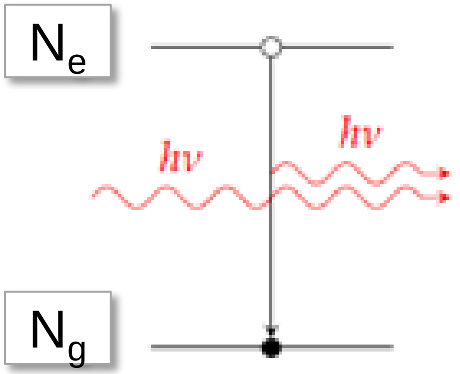
Indirect optical transitions (Si, Ge): inefficient photon sources (but efficient photo-detectors)

Almost all the III–V semiconductors can be used to fabricate semiconductor lasers

Adapted from J. Faist, course on quantum electronics, ETHZ

2-level system vs. a semiconductor

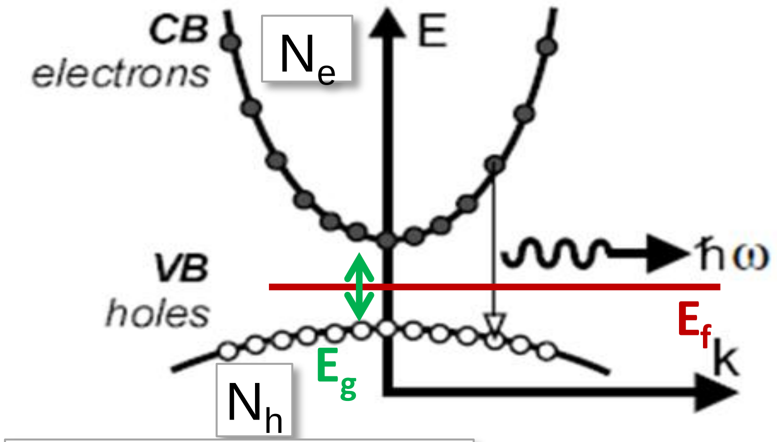
In a 2-level system:



For lasing we need **population inversion** ($N_e > N_g$)

In a semiconductor:

Charge neutrality $N_e \approx N_h = N$



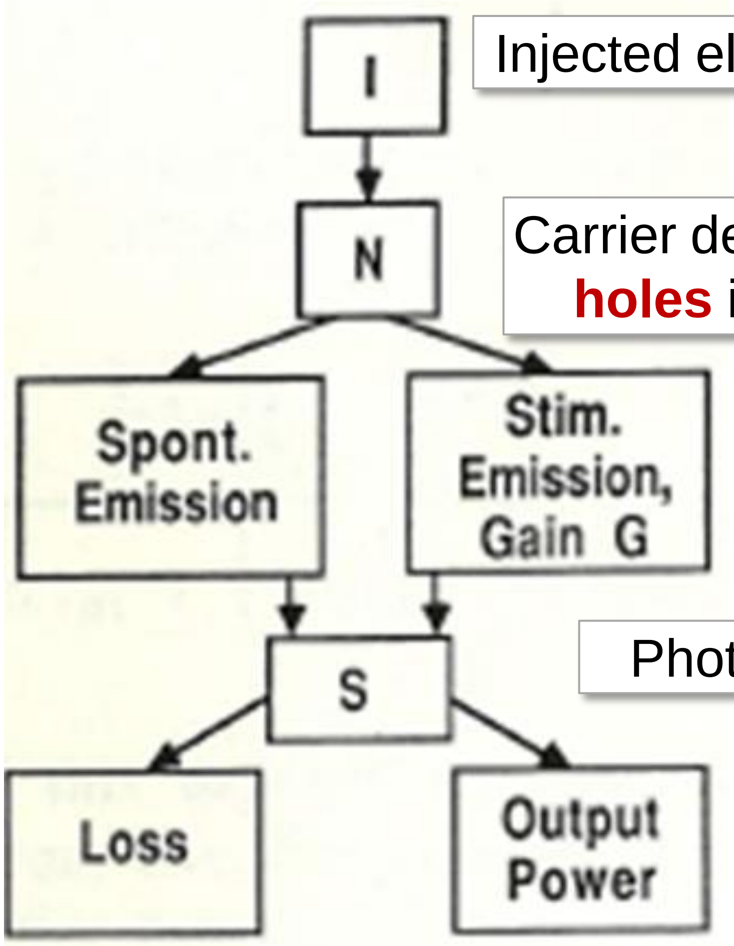
For lasing: $N > N_0$

carrier density

N_0= transparency value

Threshold value $N_{th} > N_0$

Diode lasers: electrical to optical power conversion



Injected electrical current

Carrier density: **electrons and holes** in the active region

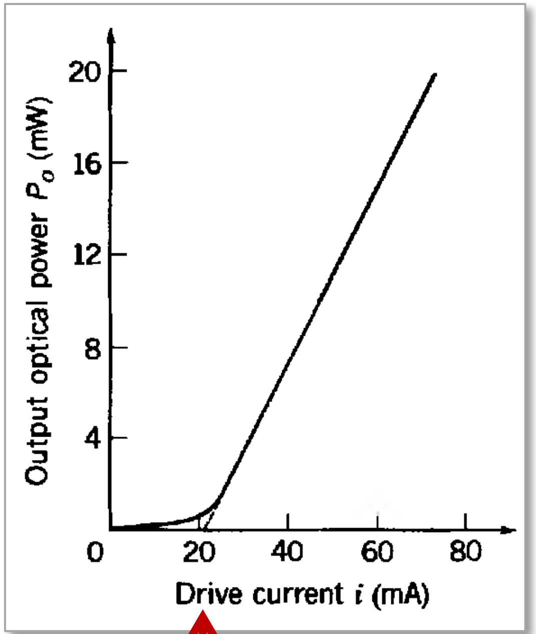
Photon density

In modern lasers the efficiency approaches one output photon for each injected electron

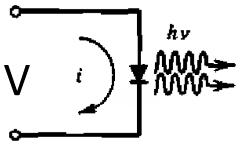
Light vs. Input (LI) current curve

- The laser efficiency in converting electrical power to optical power is determined by the **slope** of the LI curve, $\Delta P_0/\Delta I$
- Another measure: overall **quantum efficiency** (also called the power-conversion efficiency or wall-plug efficiency): the emitted optical power, P_0 / the applied electrical power, i V

LI curve



threshold current



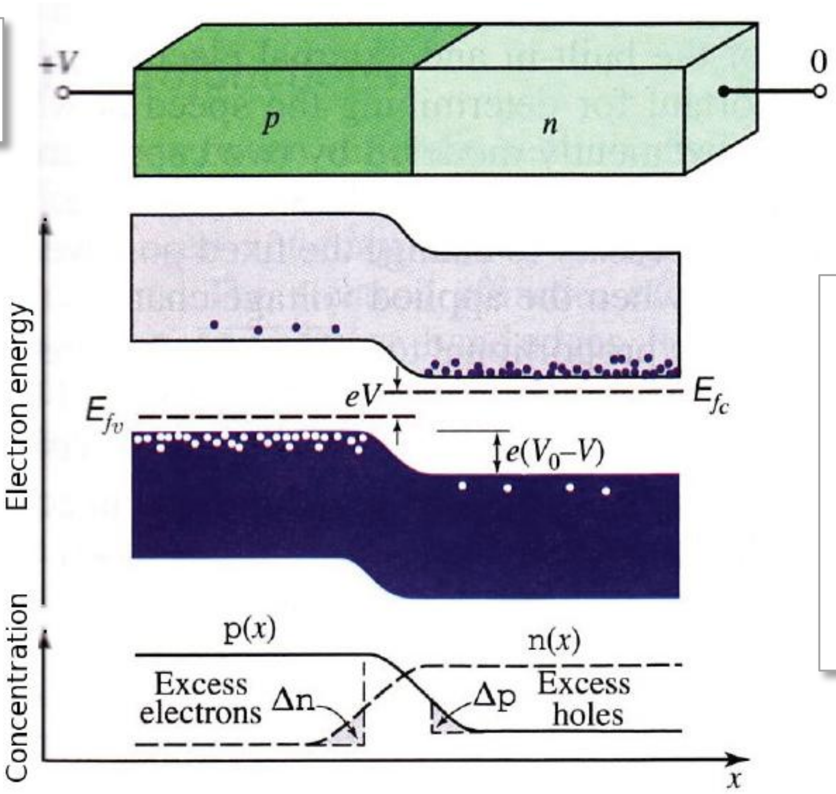
Nonlinearity at high currents leads to saturation (shown latter)

Adapted from Saleh and Teich

How does a diode laser work?

Homo-structure lasers (early lasers)

p doped:
extra holes



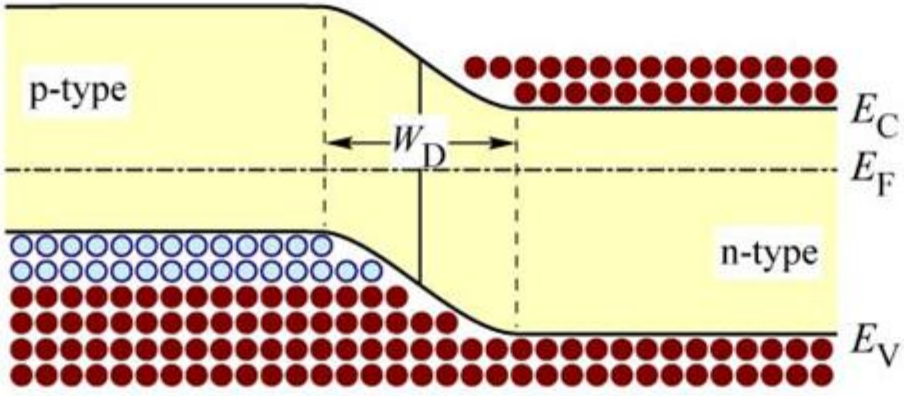
n doped:
extra electrons

The **diffusion** of electrons and holes creates the "**depletion layer**" (e/h are within the same region).

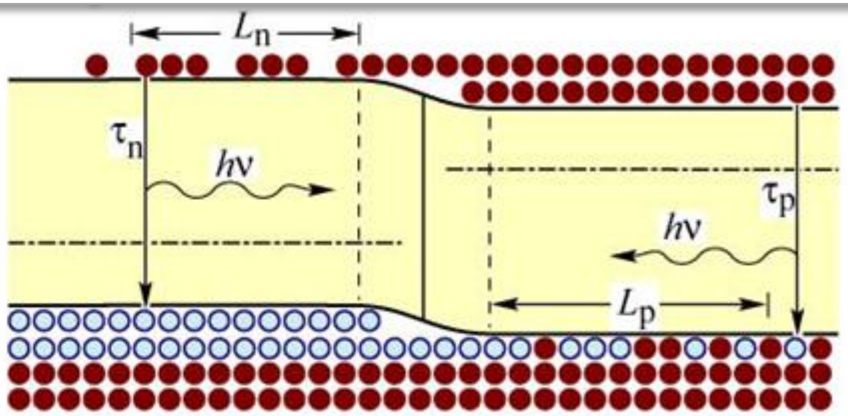
Adapted from Saleh and Teich

p-n junction

p-n junction under 0 bias



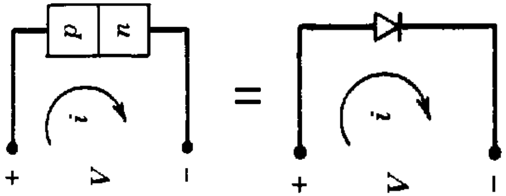
p-n junction under forward bias



L_n , L_p = diffusion lengths
τ_n , τ_p = recombination times

Forwards bias decreases the potential barrier; reverse bias increases the potential barrier

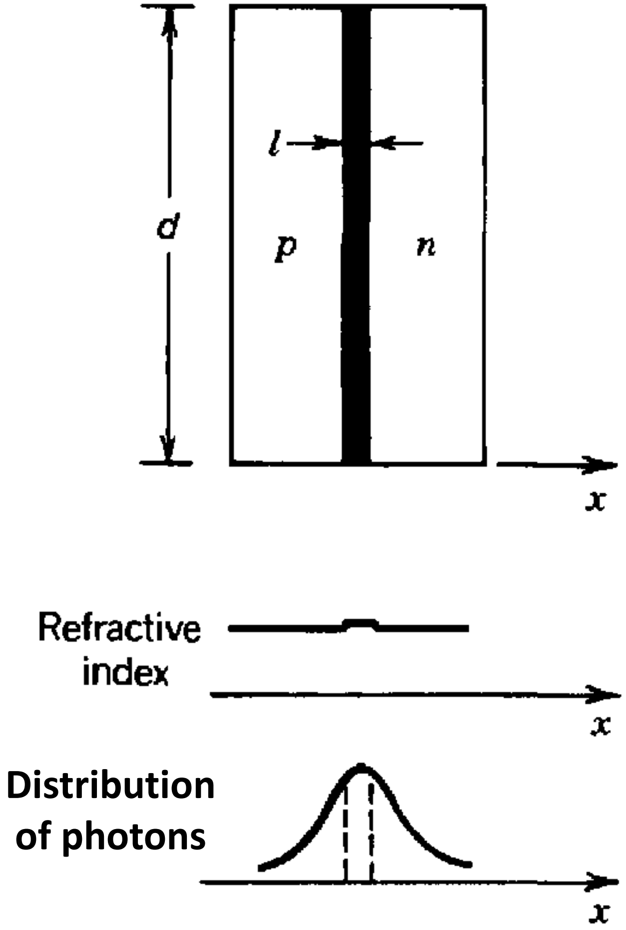
$\Rightarrow$ The p-n junction acts as a diode



Source: K. Kieu (University of Arizona)

The depletion layer is also a wave guide for the generated photons

The electron/hole concentration in the depletion layer modifies the refracting index, creating a **wave guide** that helps to confine the photons

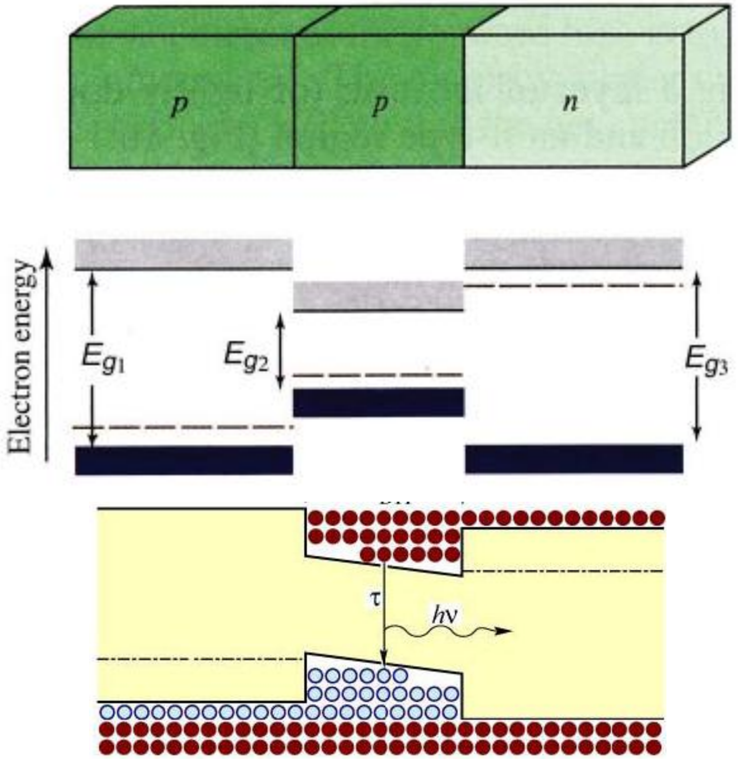


Adapted from Saleh and Teich

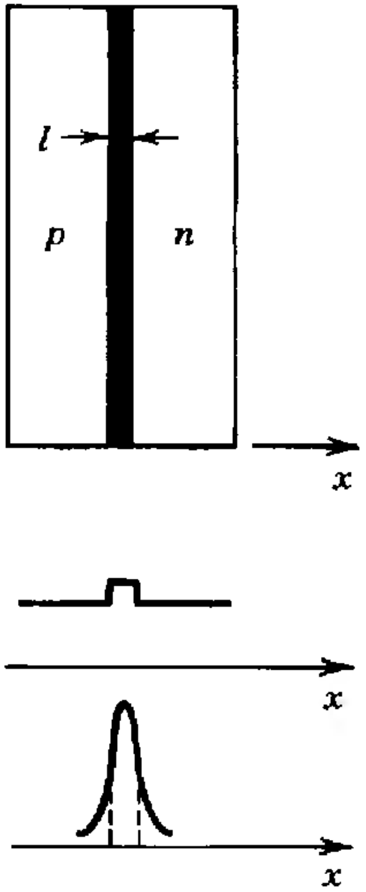
How to improve the gain & the optical confinement?

Hetero-structure lasers (2nd generation)

Semiconductors with different band-gaps: improved e/h confinement



From K. Kieu (University of Arizona)

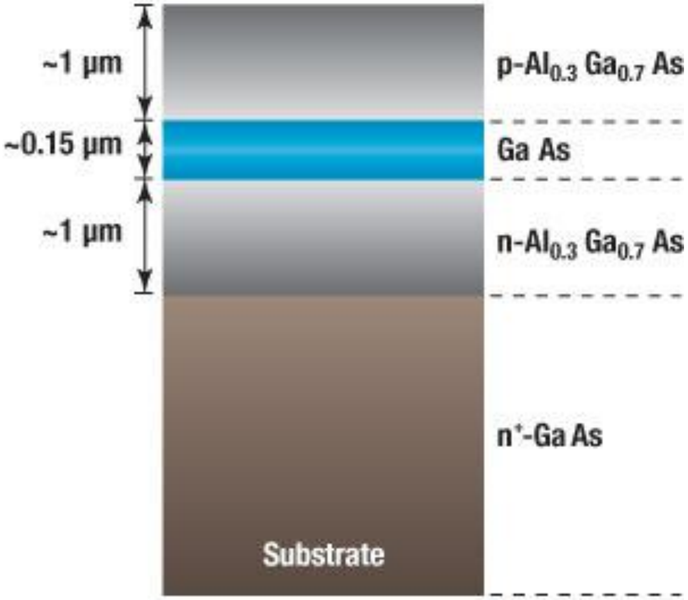


Improved waveguide because the semiconductors have different refractive index

From Saleh and Teich

Double Hetero-structure (DH) laser diodes

- **Improved photon confinement** in the GaAs active region due to the larger index of refraction of GaAs (n = 3.6) compared to the *p*- and *n*- cladding layers (n = 3.4).
- **Improved carrier confinement** in the GaAs active region due to the smaller band gap ($E_g \approx 1.5$ eV) of the GaAs compared to the *p*- and *n*- cladding layers ($E_g \approx 1.8$ eV).

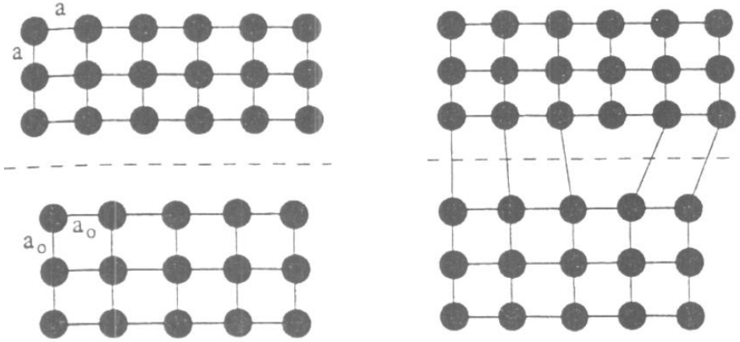


Source: Thorlabs tutorial

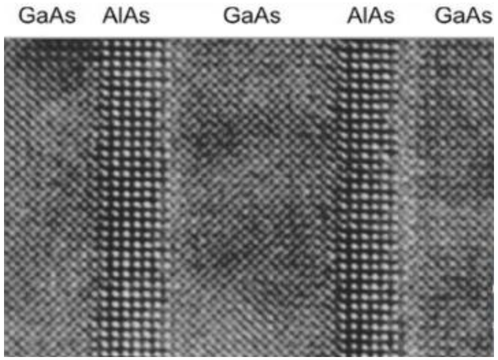
Drawback of DH lasers

More complicated to fabricate !

Require **strict matching** conditions between the two semiconductor layers (the **lattice constant** and the **thermal expansion coefficient**).



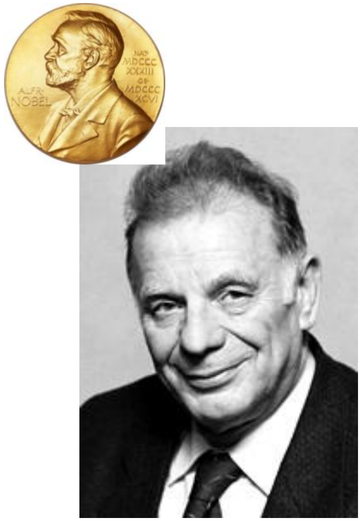
Adapted from Bhattacharya,
Optoelectronic devices



Adapted from D. Welch, Infinera

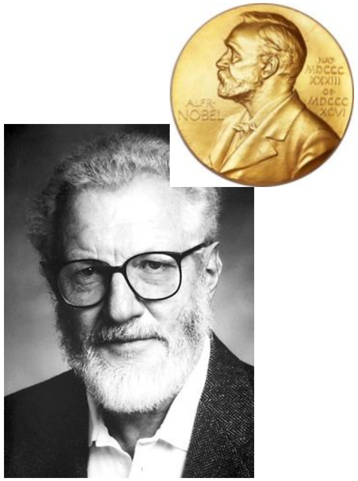
The 2000 Nobel Prize in Physics

The improved photon – electron/hole confinement of double hetero-structure lasers allowed for cw RT emission, enabling the development of technologies with huge social impact.



“For basic work on information and communication technology"

*“For developing **semiconductor heterostructures** used in high-speed opto-electronics"*



Zhores I. Alferov
Iaffe Physico-Technical Institute, St. Petersburg Russia

Herbert Kroemer
University of California
USA

Fabrication techniques

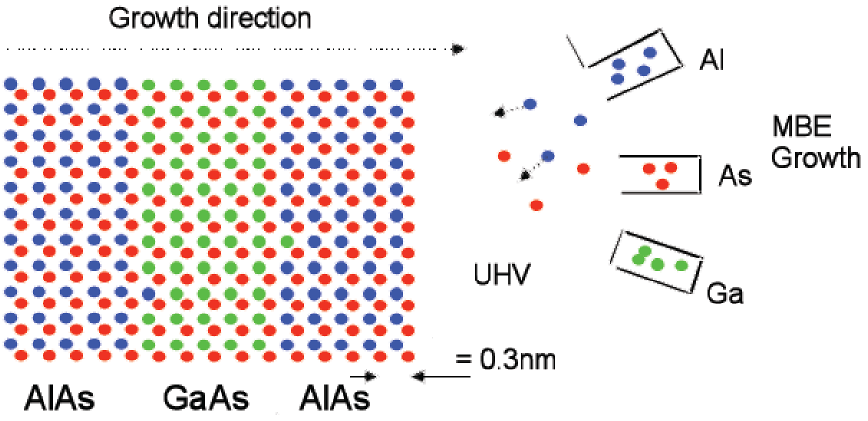
Heterostructures are grown **epitaxially**, as lattice-matched layers of one semiconductor material over another, by

- molecular-beam epitaxy (MBE) uses **molecular beams** of the constituent elements in a high-vacuum environment,
- liquid-phase epitaxy (LPE) uses the **cooling of a saturated solution** containing the constituents in contact with the substrate (but layers are thick)
- vapor-phase epitaxy (VPE) and metal-organic chemical vapor deposition (MOCVD) use **gases in a reactor**.

The performance of early laser diode was limited by manufacturing techniques

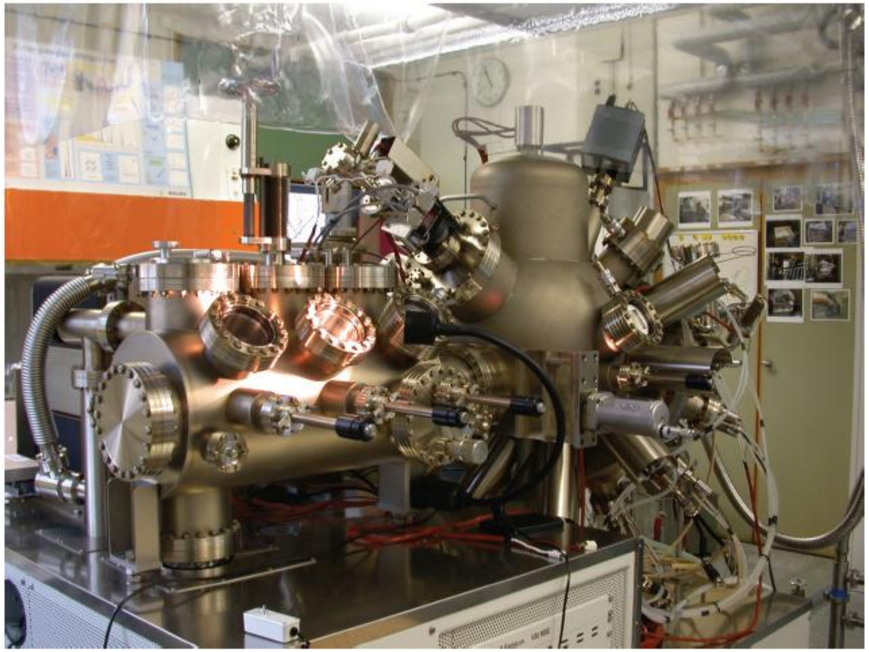
From Saleh and Teich

Molecular-beam epitaxy



The compositions and dopings of the individual layers are determined by **manipulating the arrival rates** of the molecules and the **temperature** of the substrate surface.

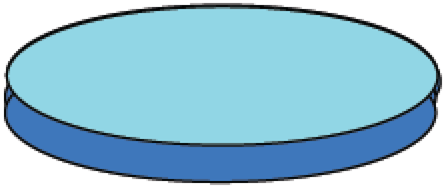
MBE growth reactor

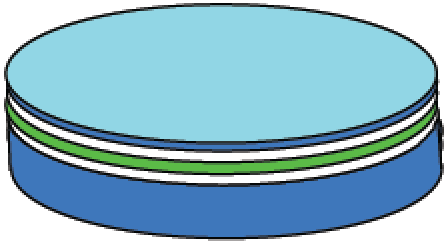


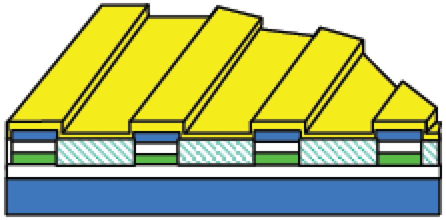
Individual layers can be made very thin (atomic layer accuracy)

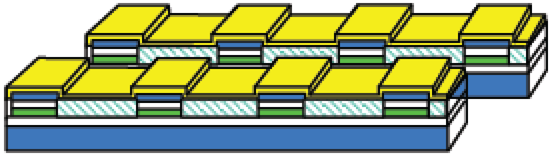
Adapted from J. Faist, ETHZ

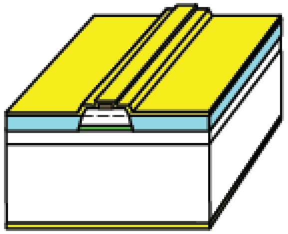
FABRICATION STEPS FOR A SEMICONDUCTOR LASER

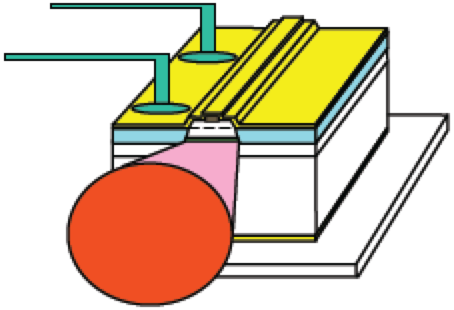

1- SUBSTRATE


2- EPITAXIE


3- LASER PROCESSING


4- FACETS CLEAVING

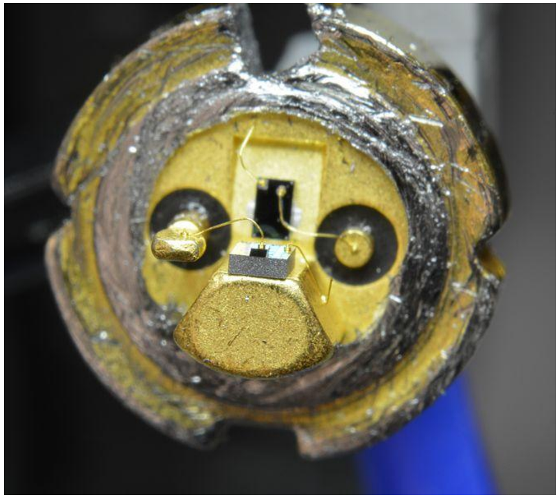

5- SINGLE CHIP
PREPARATION


6- MOUNTING, BONDING

Adapted from J. Faist, ETHZ

And the final step: packaging

- Packaging allows **integrating laser diodes in devices**
  - Mechanical and optical coupling to an optical fiber
  - Temperature stabilization
  - Photodiode for monitoring of the optical power, with respect to pump current level.
  - Optical Isolation (avoid back reflections from the fiber)
- But: significantly **increases the fabrication cost**.



A laser diode with the case cut away. The laser diode chip is the small black chip at the front; a photodiode at the back is used to control output power.

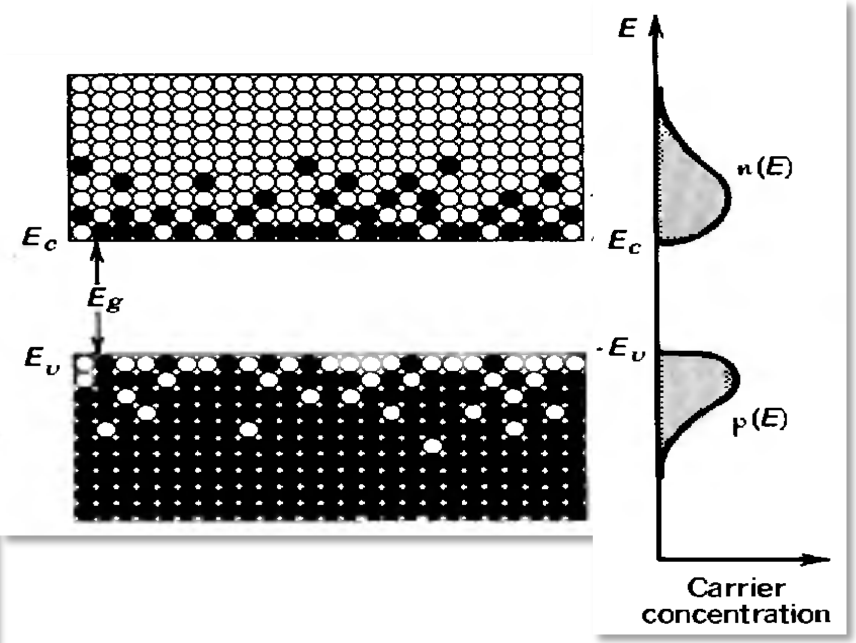
Laser diode: just the laser; **diode laser**: the complete system

Source: Wikipedia

How does a diode laser work? 1) gain

gain = rate of stimulated emission – rate of absorption.

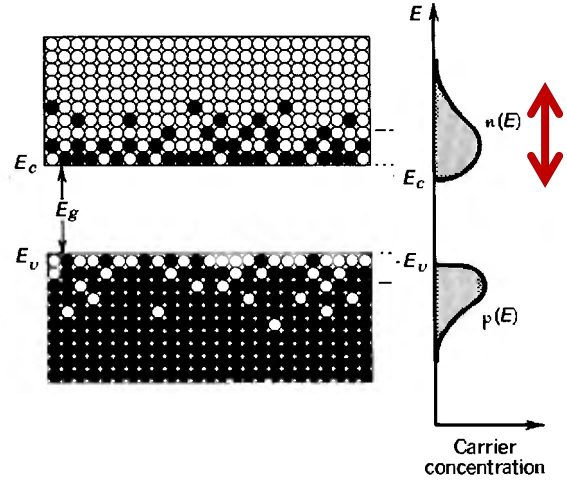
These rates can be calculated from first principles (Einstein theory) knowing the density of states in the CB & VB and their probability of occupancy.



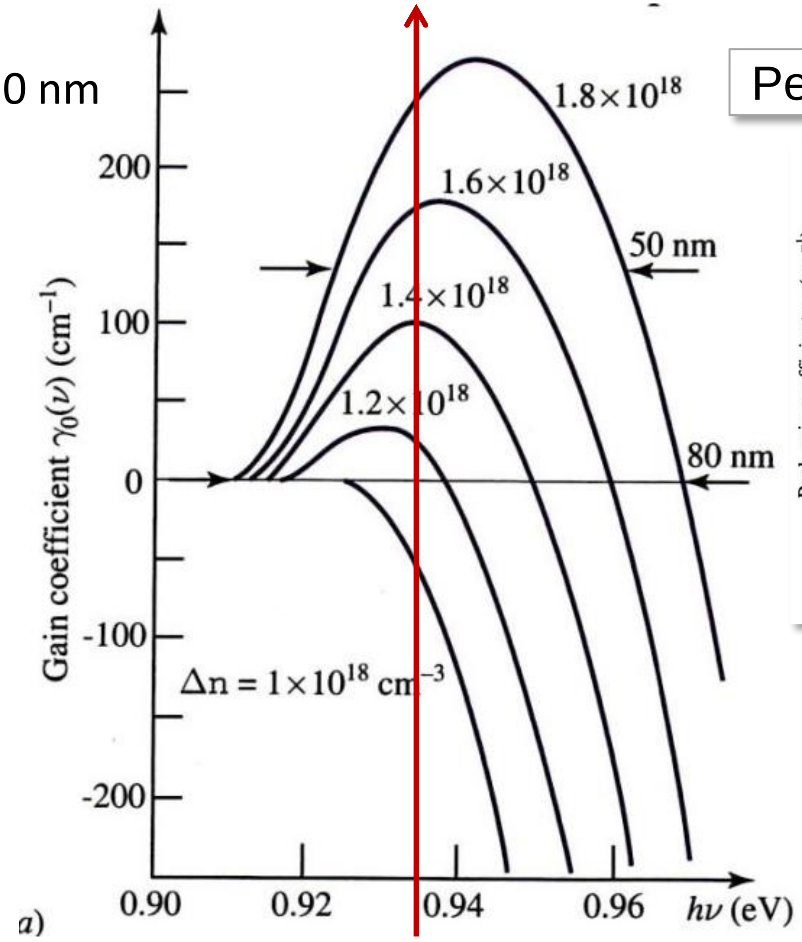
In diode lasers the gain is temperature-dependent

Adapted from Saleh and Teich

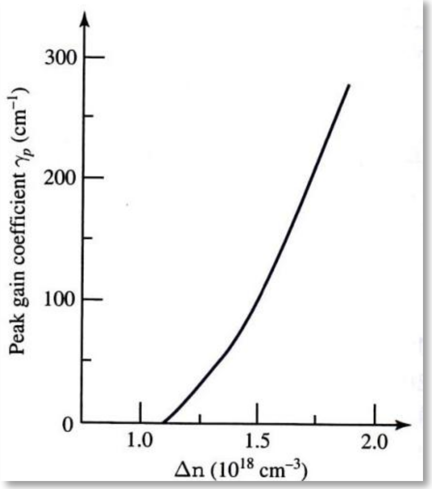
Semiconductor gain G(N,ν,T)



50 nm



Peak gain coefficient



The gain spectrum of the semiconductor is broad and increases with the carrier density (N) and the temperature.

RT InGaASP laser

Adapted from Saleh and Teich

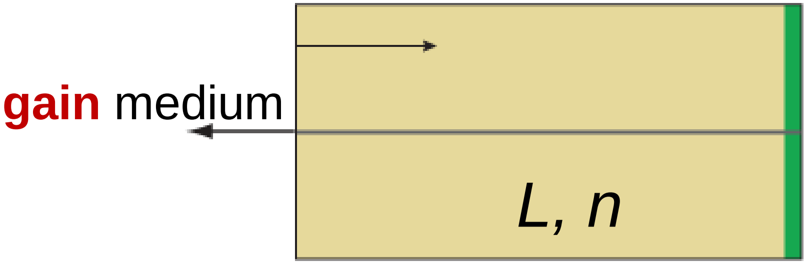
How does a diode laser work?
2) optical cavity

- The **simplest** cavity: Fabry-Perot (**FP**).
- Two parallel ends of the semiconductor are cleaved along the crystal axis, creating **mirrors** forming a FP cavity with the semiconductor as the **gain** medium.
- The laser emission is taken from the low-reflectivity front facet. High-reflectivity in the back facet reduces the cavity loss.

Longitudinal modes:

$\nu_m = m\,(c/n)/(2L)$

n: refractive index



low-reflectivity
front facet

high-reflectivity
back facet

How many modes?

- The gain spectrum of the semiconductor medium is broad $\Rightarrow$ **supports many longitudinal modes**.

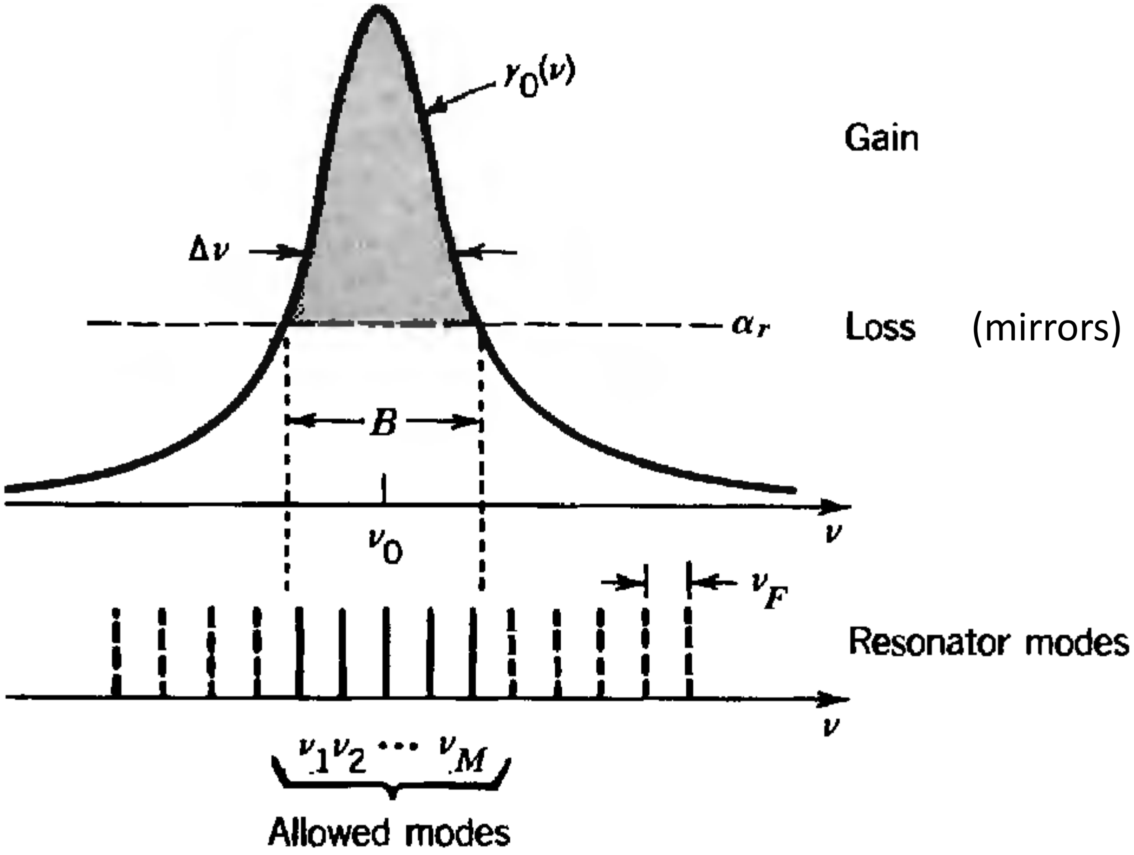
$\nu_m = m (c/n)/(2L)$

$\Delta\nu = c/(2nL)$

$\Delta\lambda = (\lambda_o)^2/(2nL)$

(free-space wavelength spacing, measured with an Optical Spectrum Analyzer)

$n = 3.5$, $L = 1$ mm:
$\Delta\lambda = 0.05$ nm @ 635 nm
$\Delta\lambda = 0.3$ nm @ 1550 nm

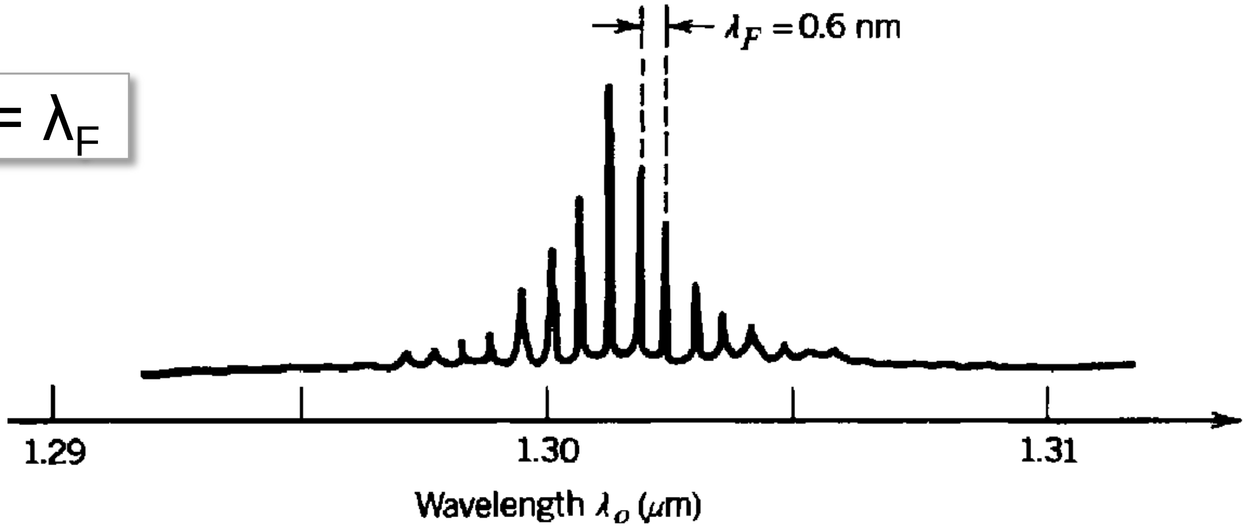


Adapted from Saleh and Teich

Example

EXAMPLE 16.3-4. ***Number of Longitudinal Modes in an InGaAsP Laser.*** An InGaAsP crystal ($n = 3.5$) of length $d = 400\ \mu$m has resonator modes spaced by $\nu_F = c/2d = c_o/2nd \approx 107$ GHz. Near the central wavelength $\lambda_o = 1.3\ \mu$m, this frequency spacing corresponds to a free-space wavelength spacing λ_F, where $\lambda_F/\lambda_o = \nu_F/\nu$, so that $\lambda_F = \lambda_o \nu_F/\nu = \lambda_o^2/2nd \approx 0.6$ nm. If the spectral width $B = 1.2$ THz (corresponding to a wavelength width of 7 nm), then approximately 11 longitudinal modes may oscillate. A

$L=d$, $\Delta\lambda = \lambda_F$

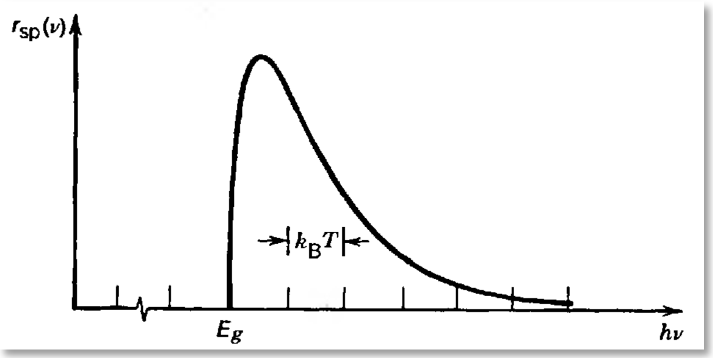


Adapted from Saleh and Teich

Optical spectra of Light Emitting Diodes (LEDs)

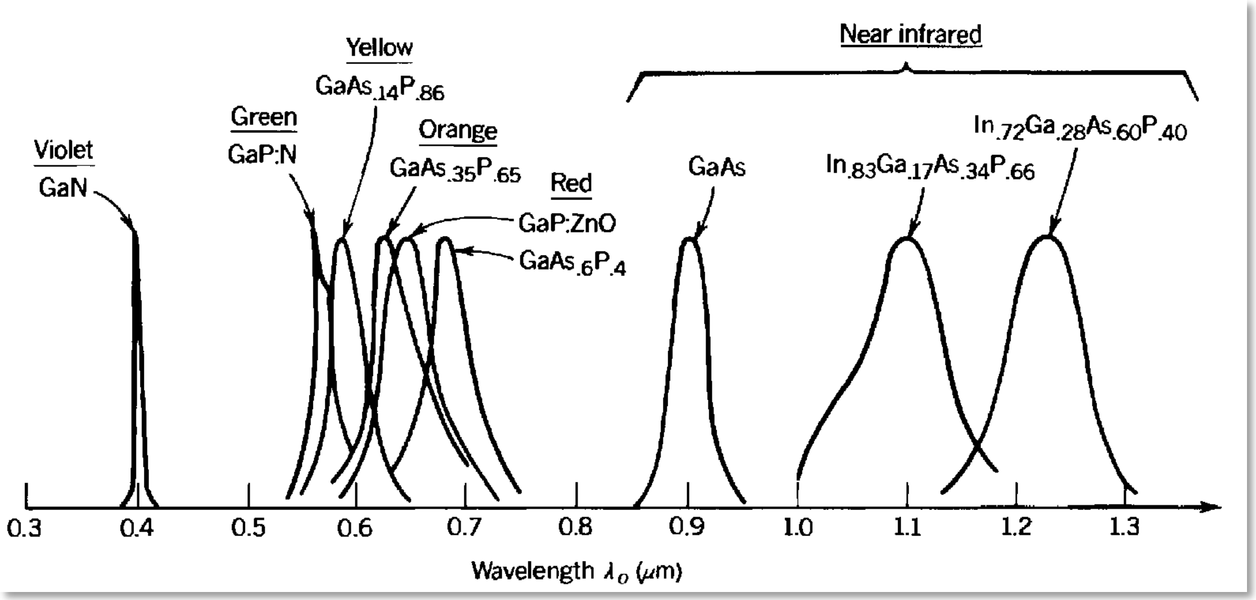
Spontaneous emission rate:

$$r_{\mathrm{sp}}(\nu) \approx D_0(h\nu - E_g)^{1/2} \exp\left(-\frac{h\nu - E_g}{k_B T}\right), \qquad h\nu \geq E_g$$



Line-width:

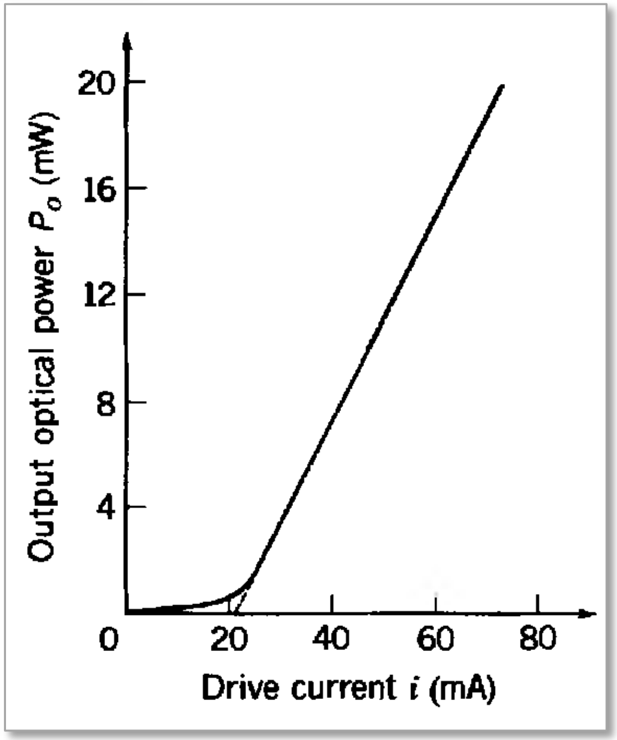
$$\Delta\lambda \approx 1.45\lambda_p^2 k_B T$$



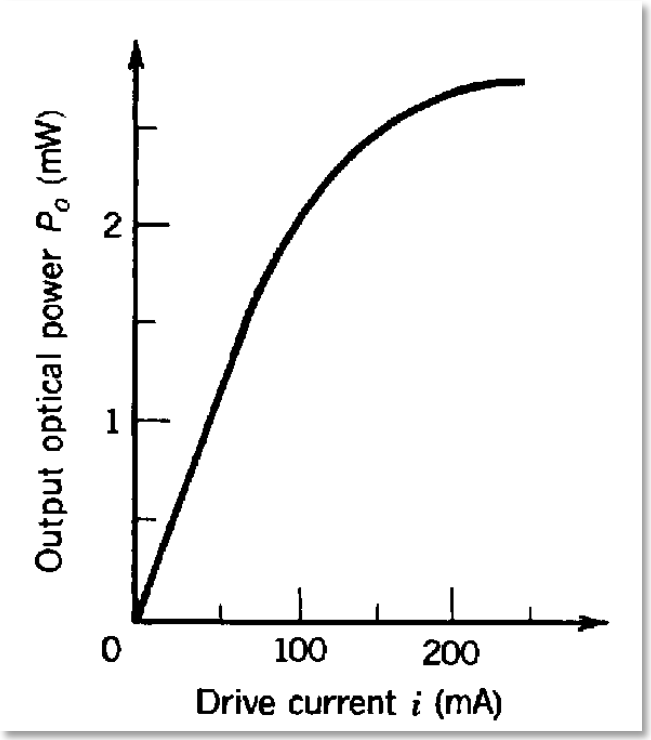
Adapted from Saleh and Teich

Comparing the LI curve of diode lasers and LEDs

Diode laser



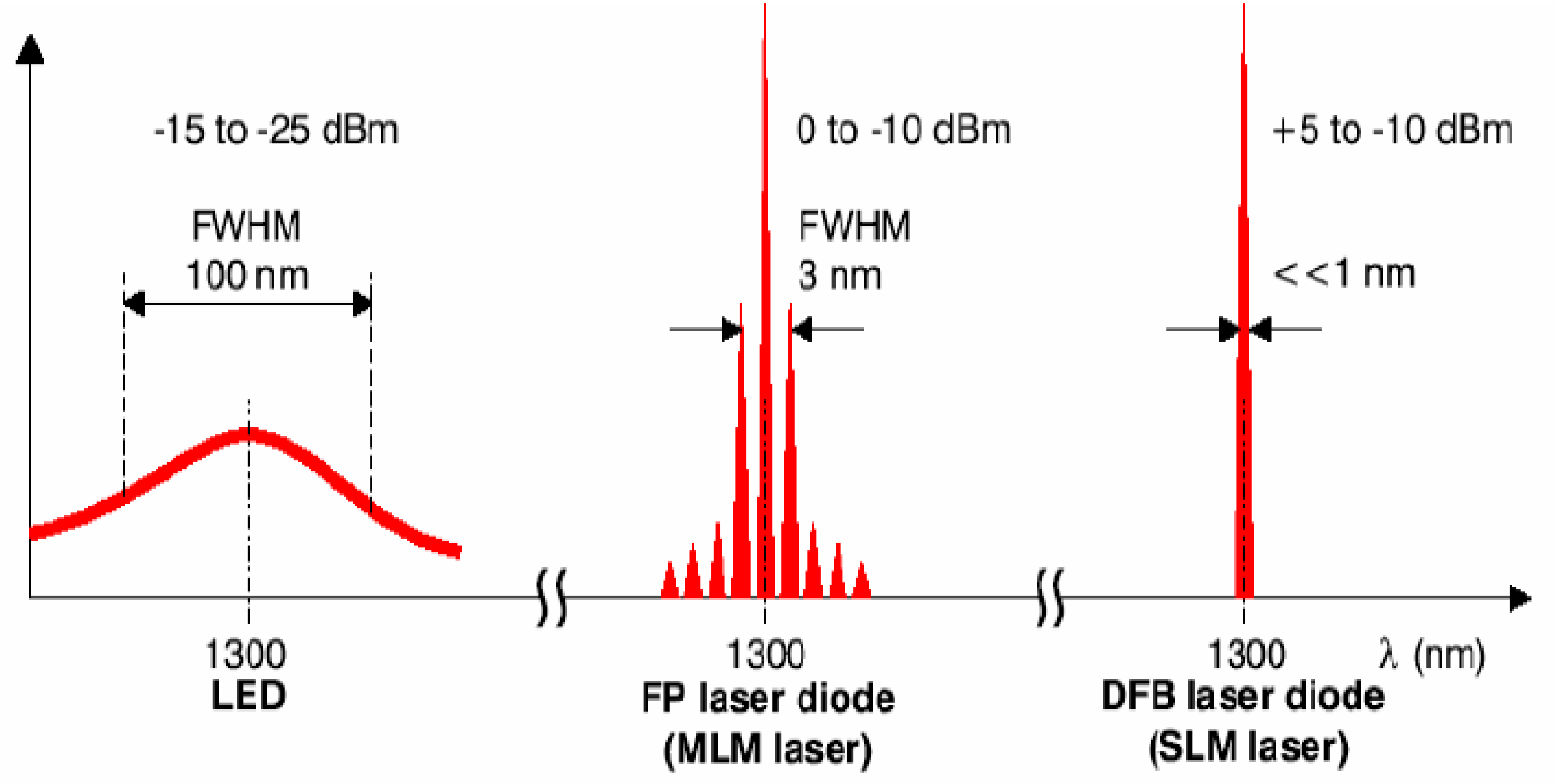
LED



Note the different scales

Adapted from Saleh and Teich

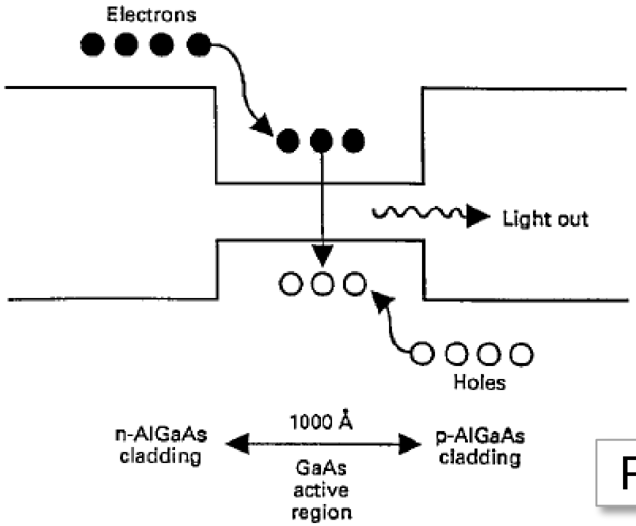
Comparing the optical spectrum



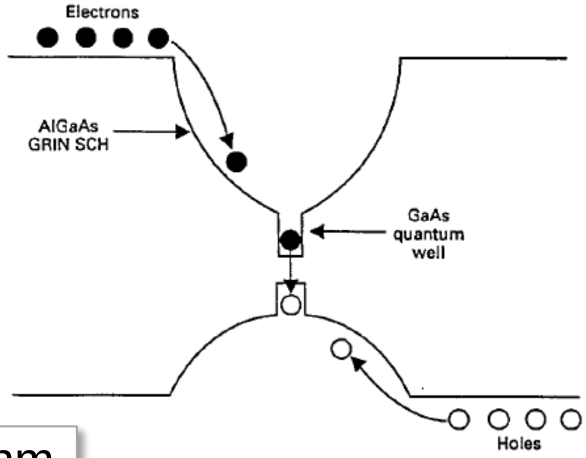
Early 1980s: moving the DH technology one step further to quantum-well lasers

QW lasers are DH lasers (DH are also referred to as “bulk” lasers) where the **thickness of the active layer is narrow** and the energy-momentum relation of bulk material (energy bands) does not apply.

Bulk:



QW:



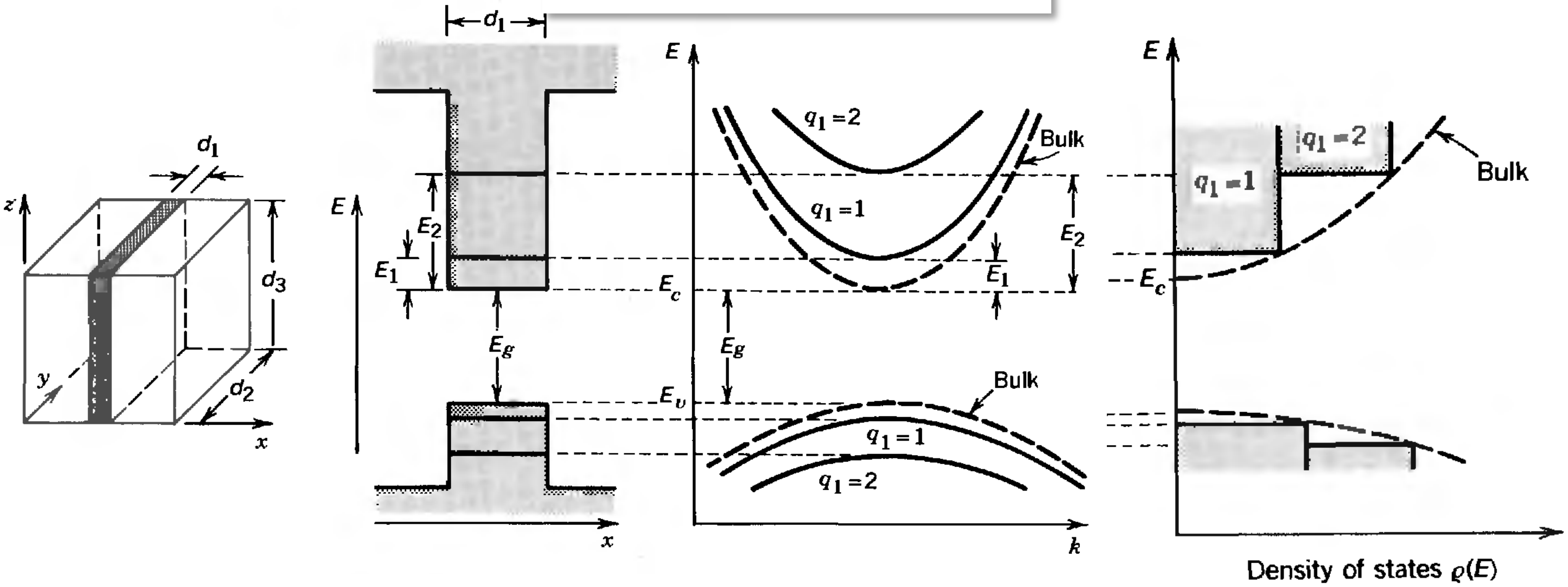
For GaAs λ_B = 50 nm

Adapted from Saleh and Teich

QW energy levels

1D infinite potential:

$$E_q = \frac{\hbar^2 (q\pi/d)^2}{2m}, \qquad q = 1, 2, \ldots$$

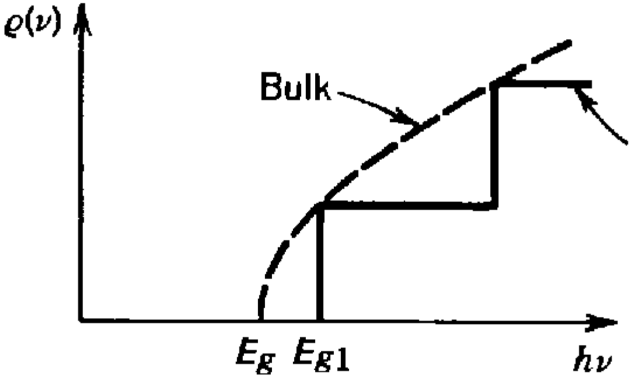


In a QW laser carriers are confined in the x direction within a distance d_1 (the well thickness). But, in plane of the active layer (the y—z plane), they behave as in bulk semiconductor.

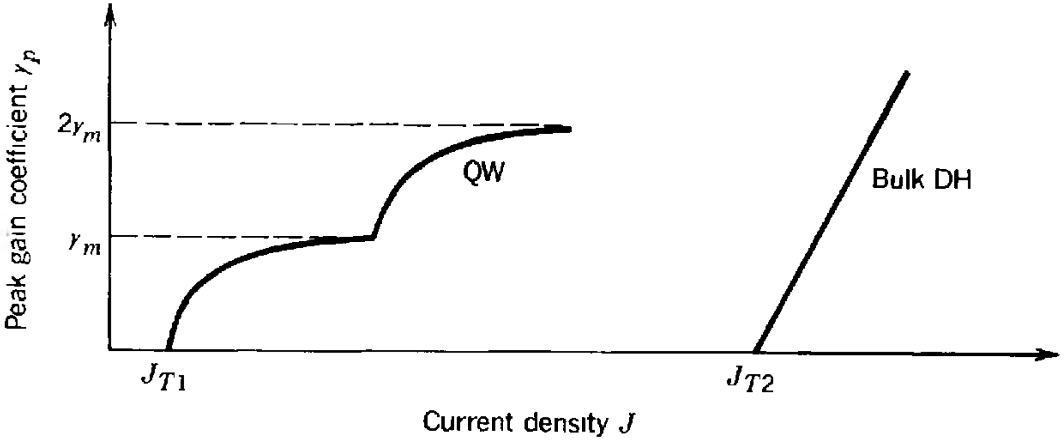
Adapted from Saleh and Teich

QW vs Bulk lasers

Density of states



Peak gain coefficient

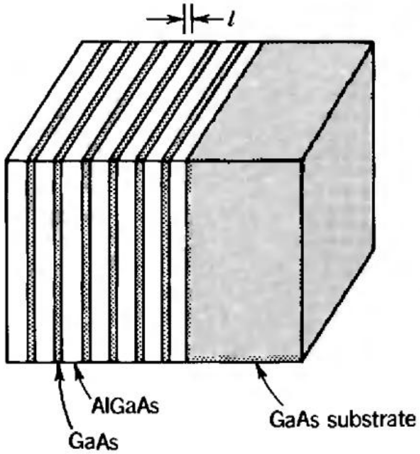


In QW lasers the threshold current is 4 - 5 time smaller than comparable DH lasers.

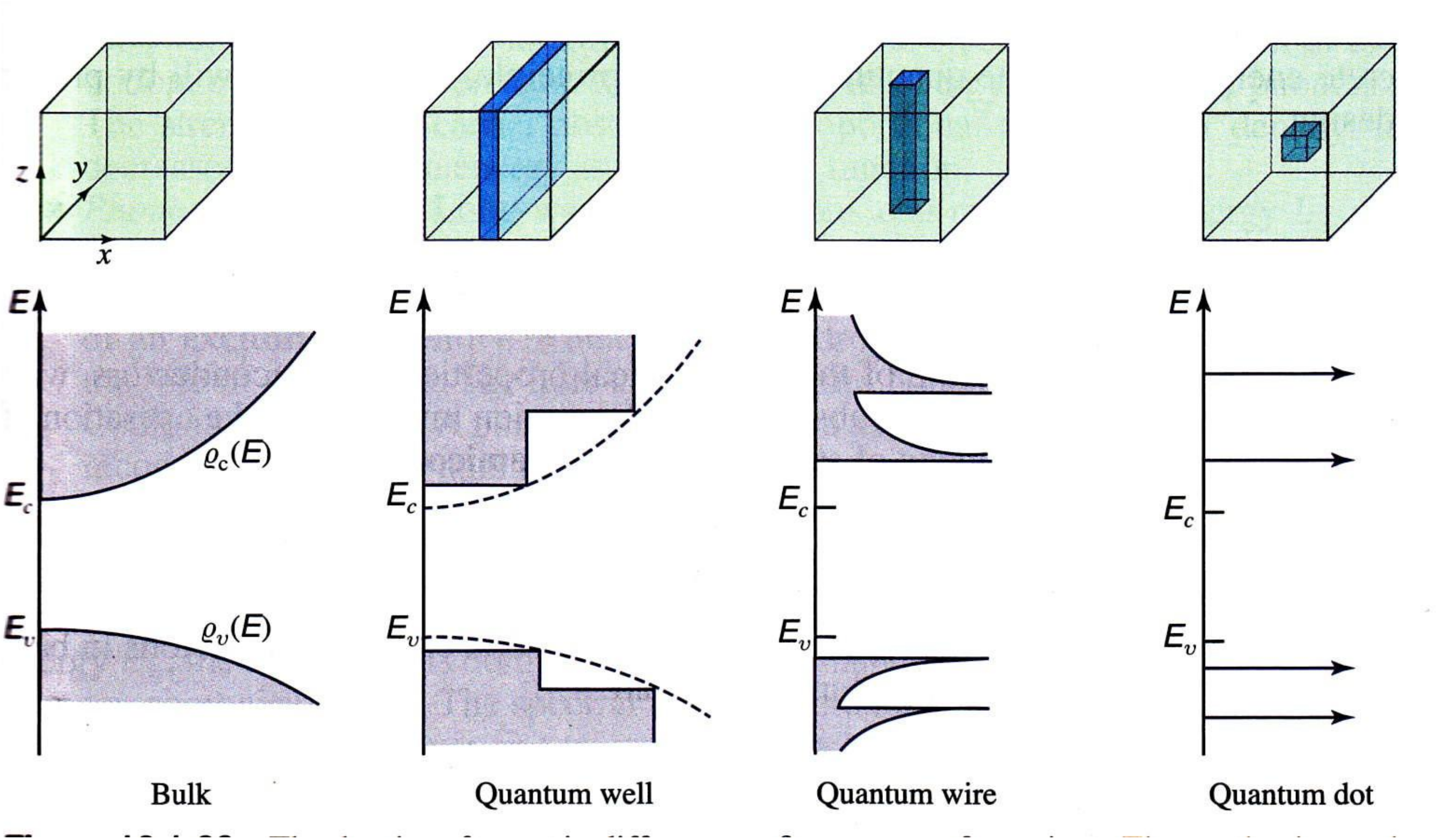
Adapted from Saleh and Teich

Multiple Quantum Well (MQW) lasers

- Alternating QW material (narrow band gap) with barrier material (high band gap).
- Advantages
  - Dramatic reduction in threshold current
  - Reduction in carrier loss
  - Reduced temperature sensitivity of threshold current
- Enable
  - Increase laser efficiency
  - Reduce thermal resistance
  - Higher output power



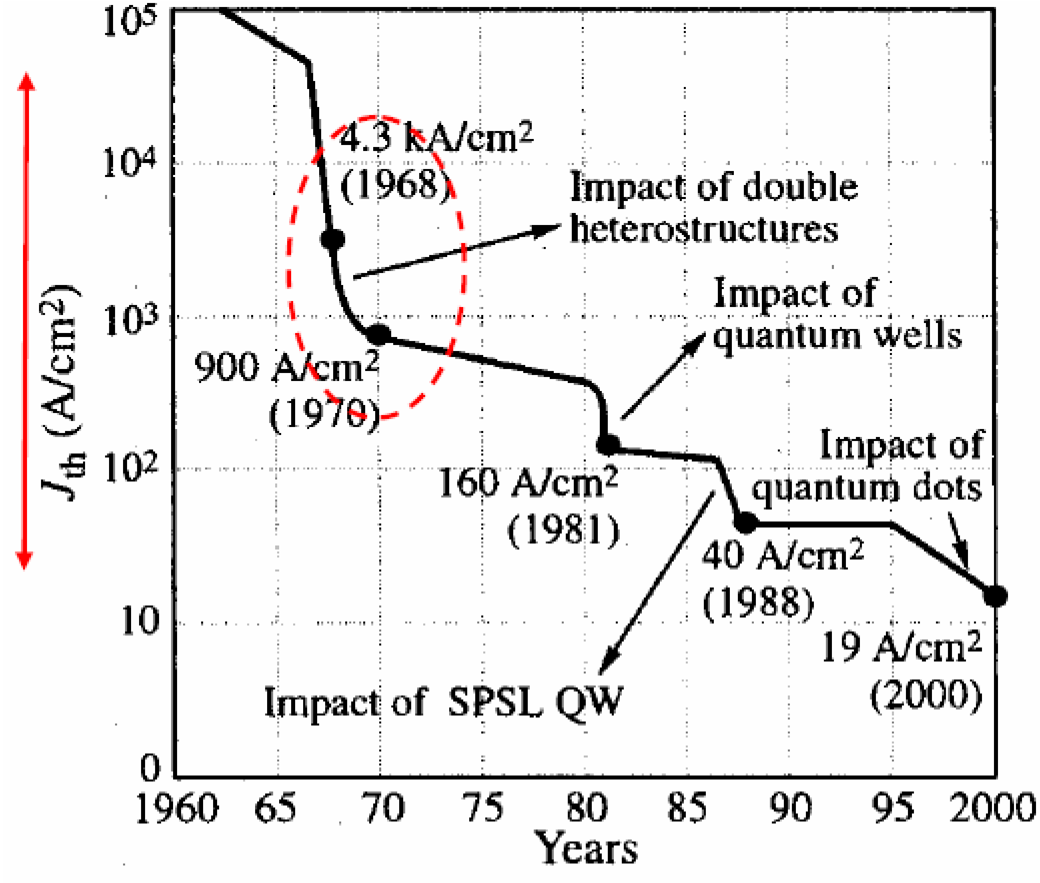
Novel lasers include quantum-wire, quantum-dash and quantum-dots



Adapted from Saleh and Teich

Threshold reduction: a long way from the beginning

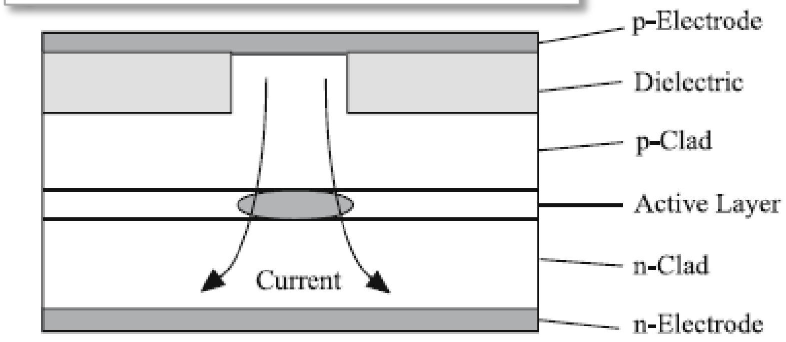
4 orders of magnitude



Adapted from H. Jäckel, ETHZ

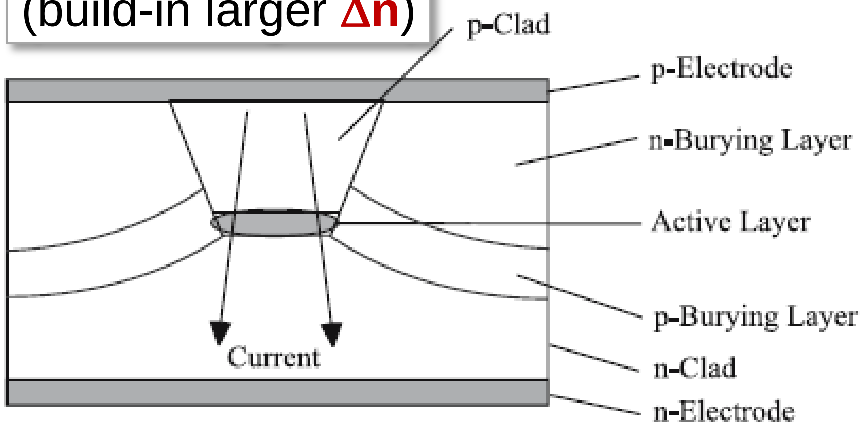
Further improving the confinement of photons and carriers: lateral waveguide

Gain guided
(carrier induced small **Δn**)

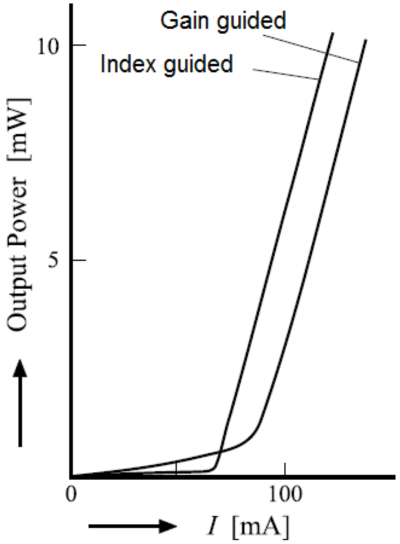


(a)

Index guided
(build-in larger **Δn**)



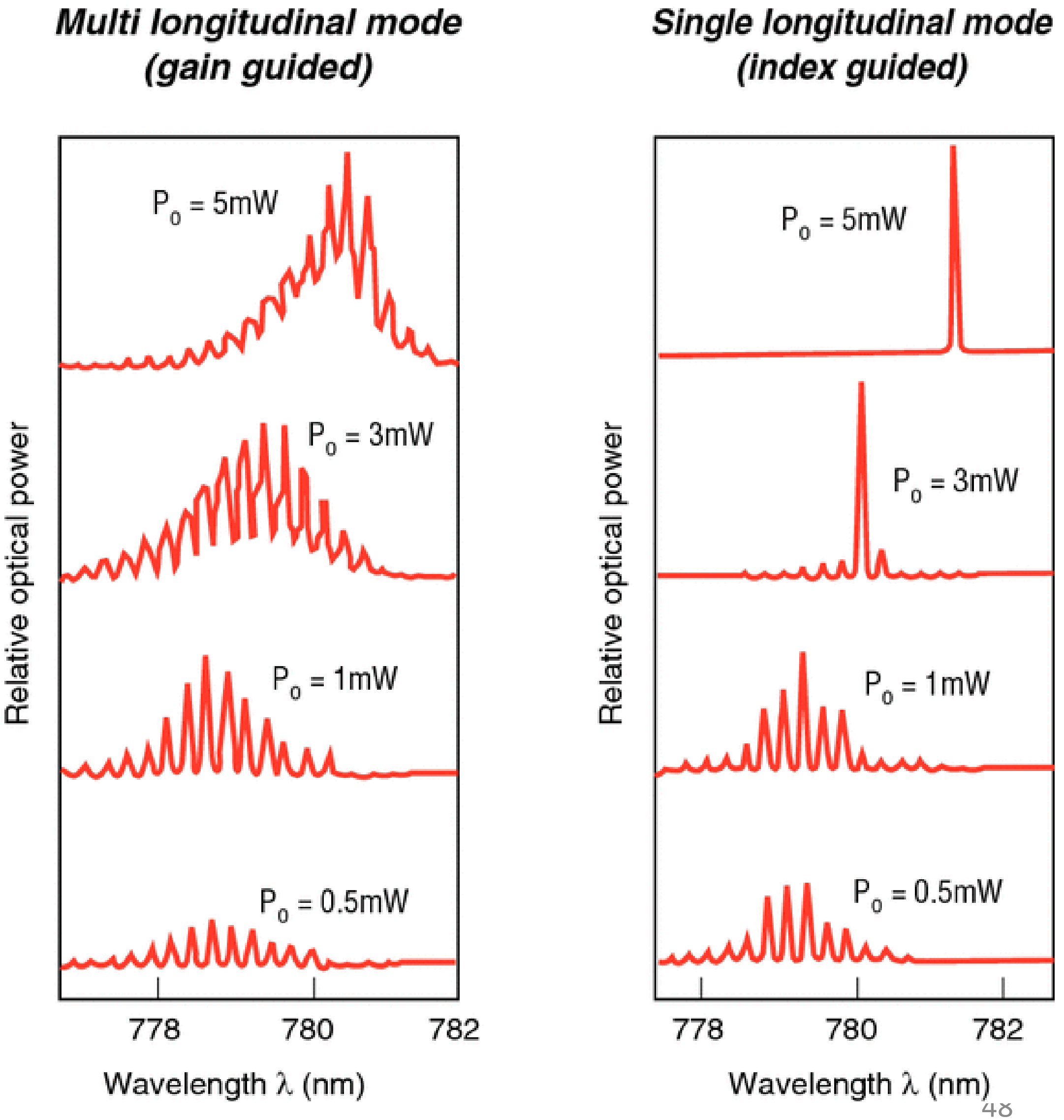
(b)



Adapted from J. Ohtsubo

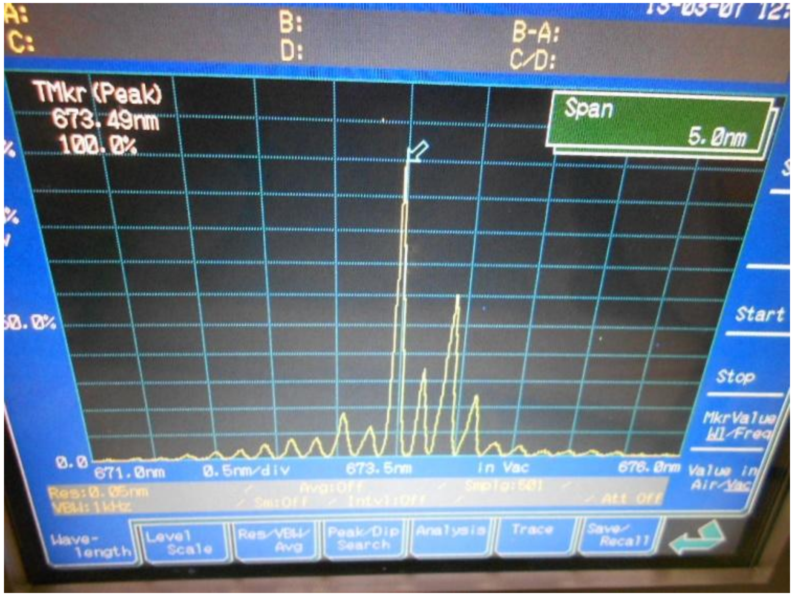
Gain + cavity determine the optical spectrum

- The number of lasing modes and their relative power depends on the type of laser, the current (I) and the temperature (T).
- It is often possible to adjust I and T for single-mode operation, but it can be achieved over a **limited** I and T range.

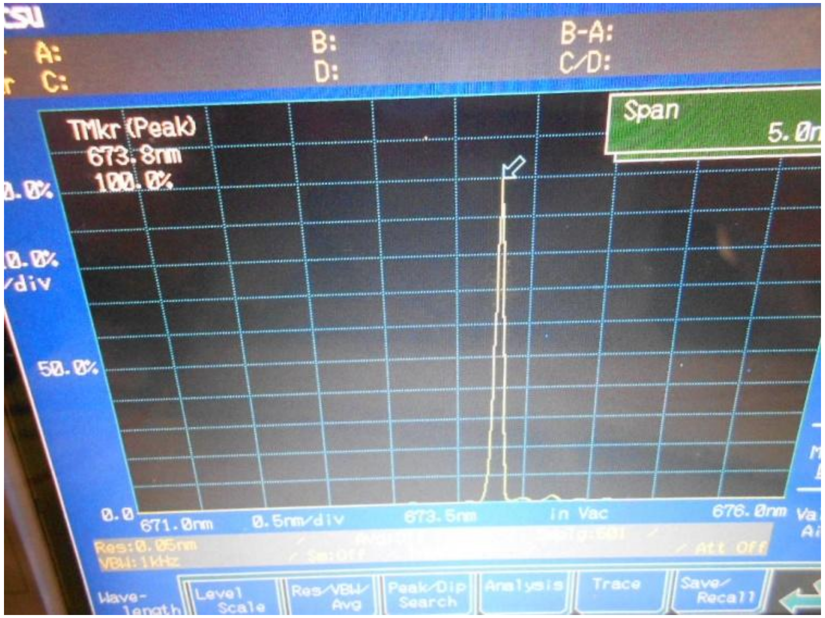


An example from our lab

Low pump current



High pump current



Courtesy of Andres Aragoneses,
UPC (Semiconductor laser lab, Terrassa, Spain)

Why do we need single-mode emission?

- High-data-rate optical fiber transmission requires the laser to emit single mode.

- This is because each mode travels with its own group velocity. Therefore, the optical pulses emitted by a multimode laser broaden with propagation distance, and the distinction between binary 'zero' and 'one' is gradually lost.

Can we fabricate stable single-mode lasers?

Dynamically stable?

Yes! Two main approaches using a **mode-selective cavity**

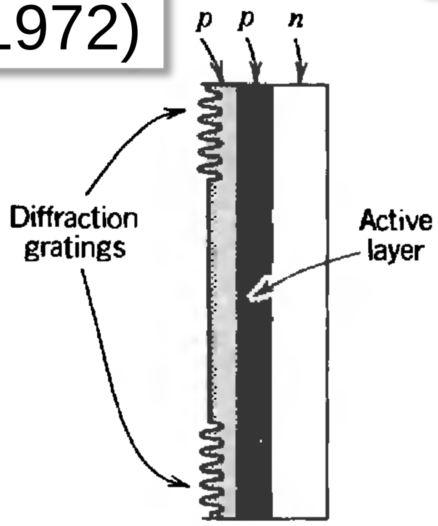
- A **Bragg-Grating** (BG) mirror
  - Distributed Feedback (DFB)
  - Distributed Bragg Reflector (DBR)
  - Vertical Cavity Surface Emitting Lasers (VCSEL)

- An **External** mirror – External Cavity Laser (ECL)

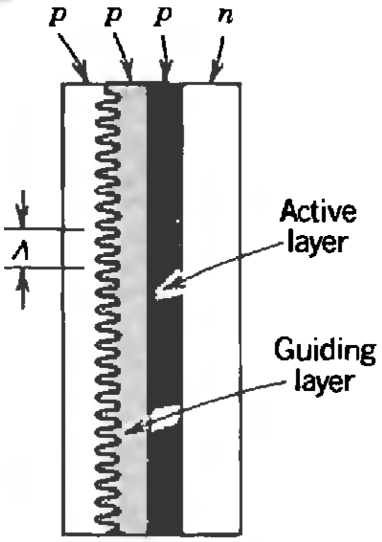
Bragg-Grating (BG) mirror

- Peak reflectivity for a particular frequency (the Bragg-frequency) via coherent addition of distributed reflections.

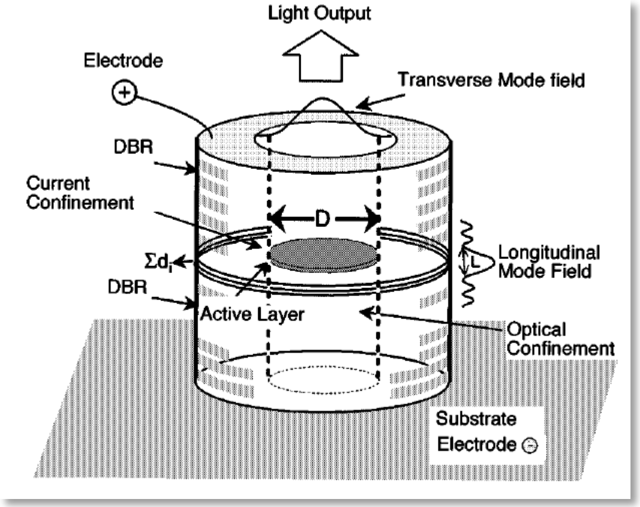
DBR
(1972)



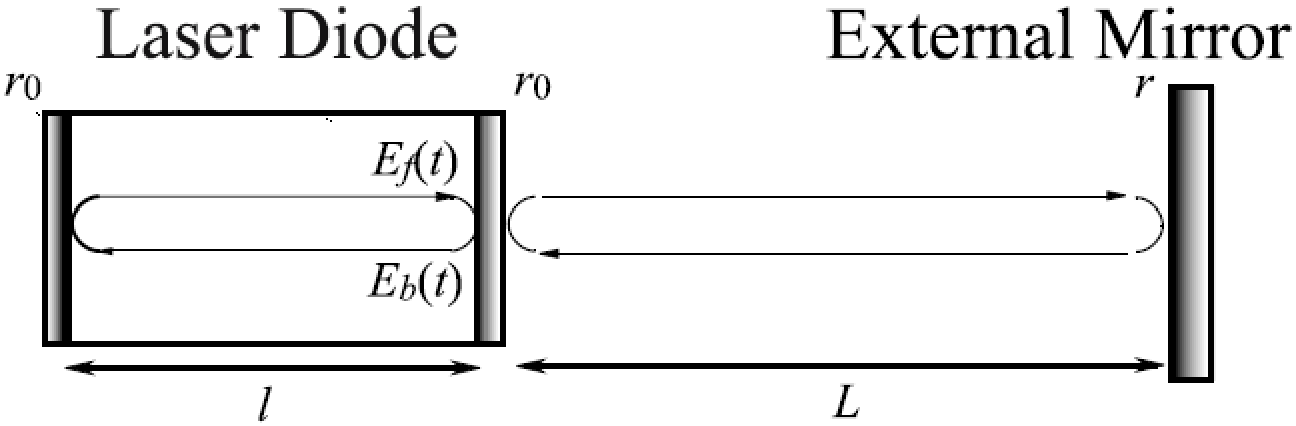
DFB



VCSEL
(mid 1980s)

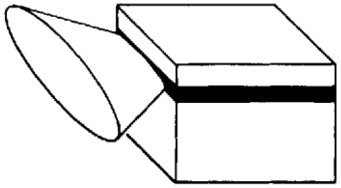


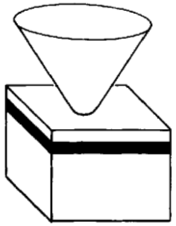
External Cavity Laser



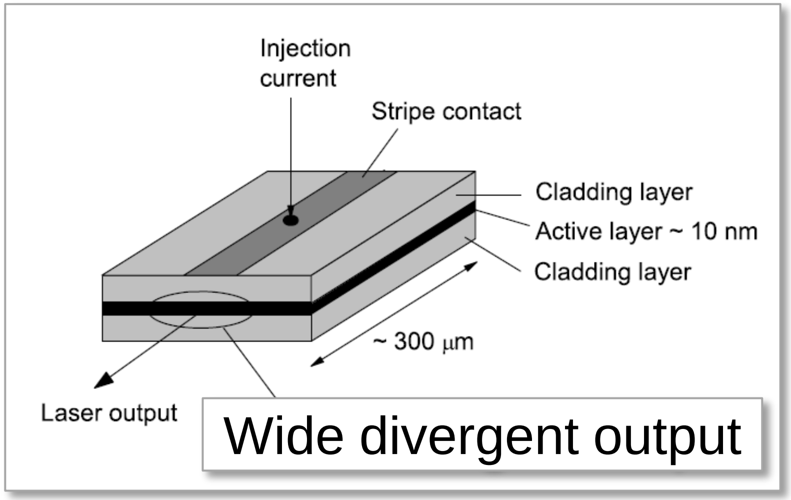
- With controlled feedback conditions the laser emission "locks" to one of the modes of the "compound" cavity.
  Additional advantages: decrease of the threshold current (reduced cavity loss) and reduced linewidth
- Drawback: uncontrolled feedback conditions can lead to **unstable** (and even **chaotic**) **output**.

EELs vs VCSELs





Edge-Emitting Laser (EEL)



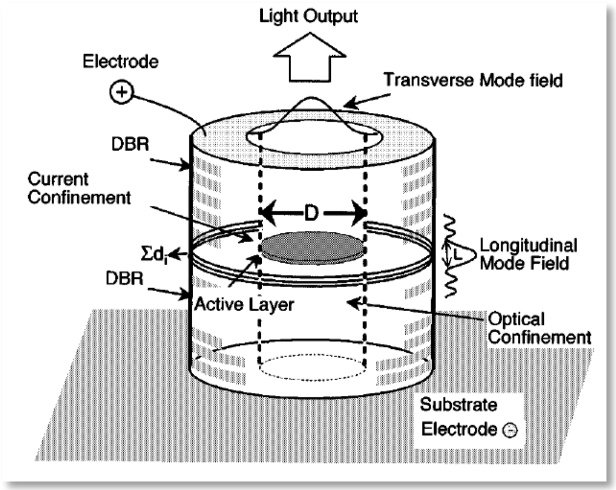
Wide divergent output

L≈ 300 μm

The semiconductor facets serve as mirrors

Adapted from J. Mulet, PhD thesis, Universitat de les Illes Balears (2002)

VCSEL



L=1-2 μm

Two DBRs serve as mirrors

$$\Delta\lambda = (\lambda_o)^2/(2nL)$$

$\Rightarrow$ VCSELs emit a **single-longitudinal-mode**.

Adapted from K. Iga, JSTQE 2000

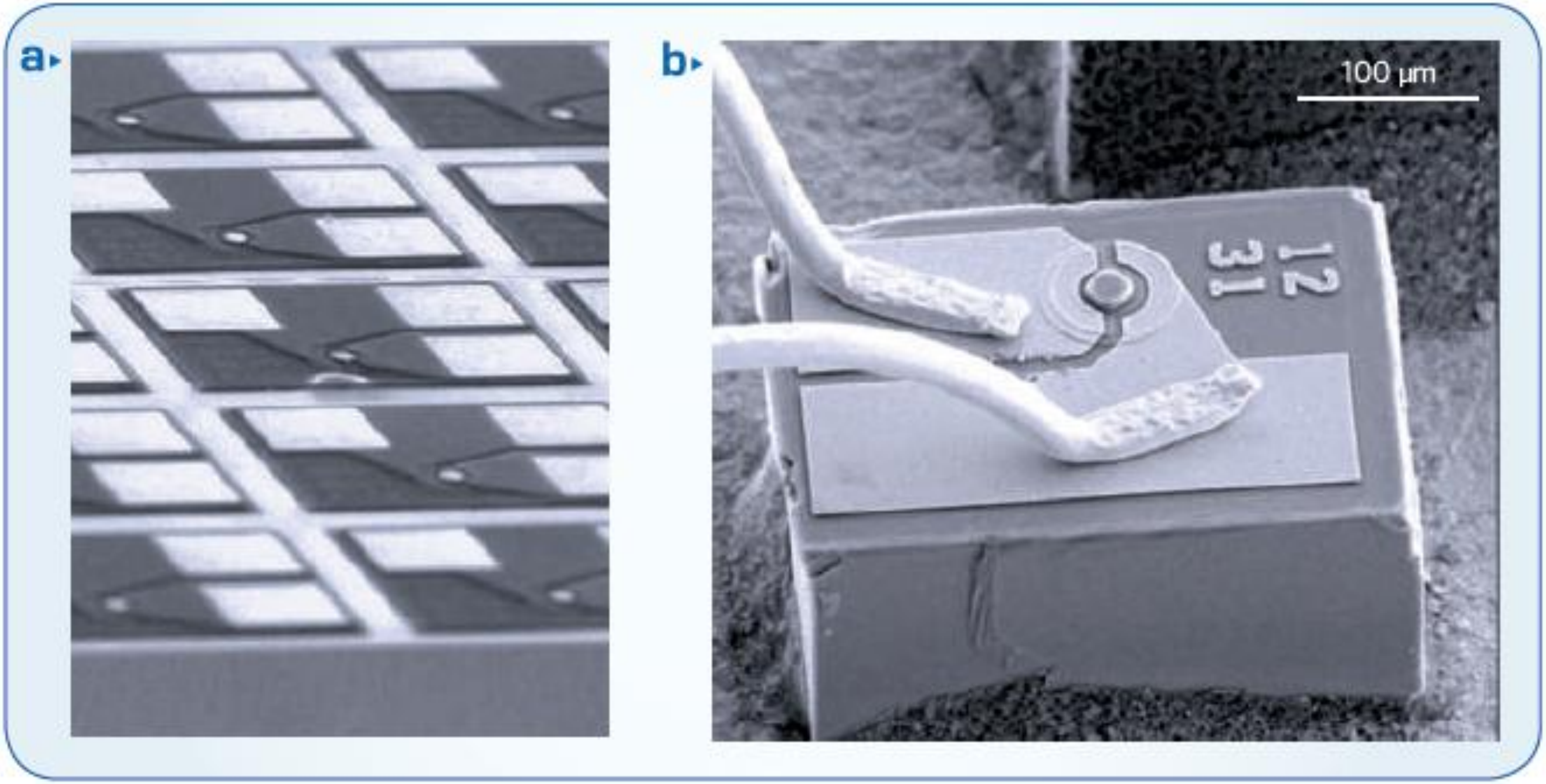
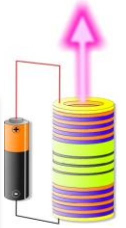


Figure 1 | Long-wavelength VCSELs. **a**, On a wafer. **b**, Individually. These have a lower power consumption than their edge-emitter counterparts at similar optical power level. In addition, their vertical-cavity design leads to better coupling to single-mode fibres (by a factor of 2–4) and enables on-wafer characterization, which greatly reduces manufacturing costs.

NATURE PHOTONICS | VOL 3 | JANUARY 2009 |

How does a VCSEL work?

The small cavity length requires highly-reflective DBRs, which are doped to facilitate the injection of electrons/holes



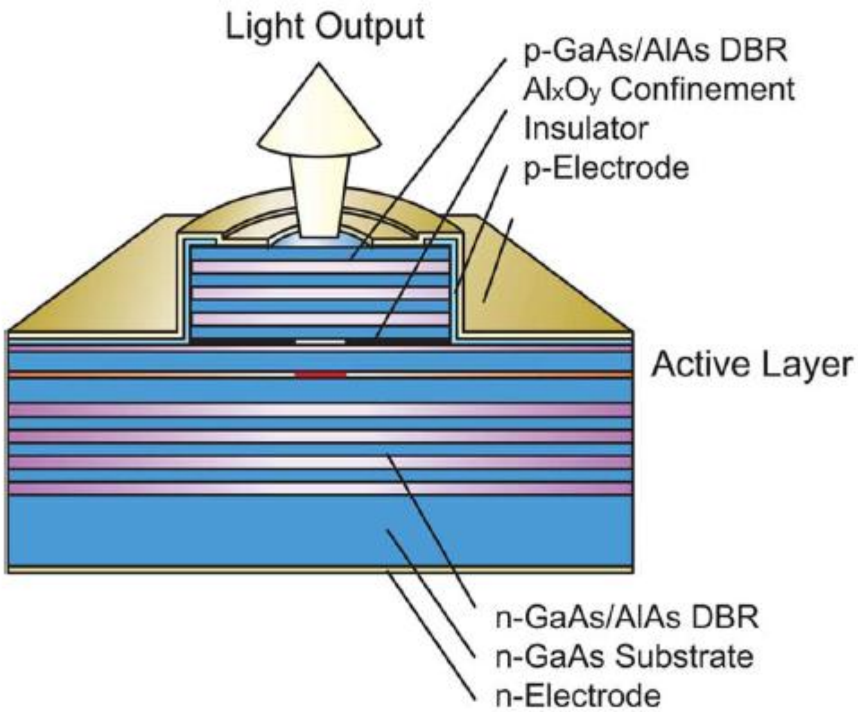
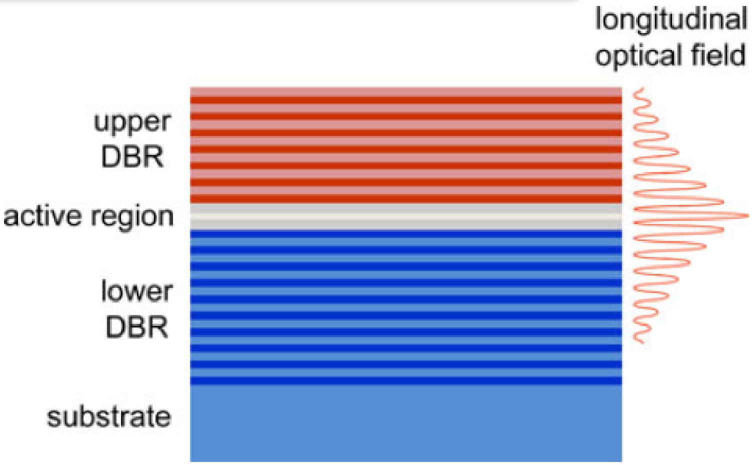


Fig. 6. Schematic structure of a typical VCSEL using GaAs/AlAs DBR and selective-oxidation technique. Various materials emitting wide wavelength ranges can be utilized as the active layer.



Blue indicates **n-type** material and **red** indicates **p-type**

Adapted from K. Iga, JLT 2008

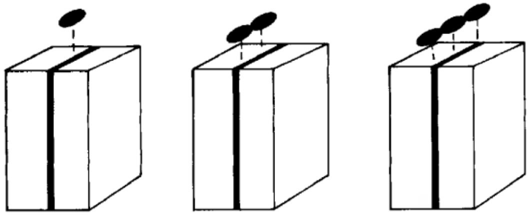
Adapted from A. Larsson, JSTQE 2011

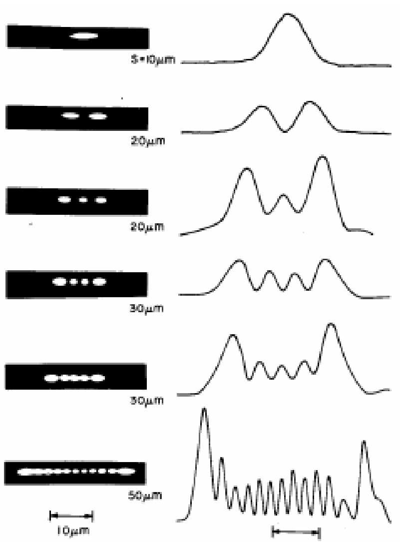
Spatial lateral/transverse modes

Solutions of the Helmholz equation

$$\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)\mathbf{E}(x,y)+(k^2n^2(\mathbf{r})-\beta^2)\mathbf{E}(x,y)=0$$

Edge-Emitting Lasers:

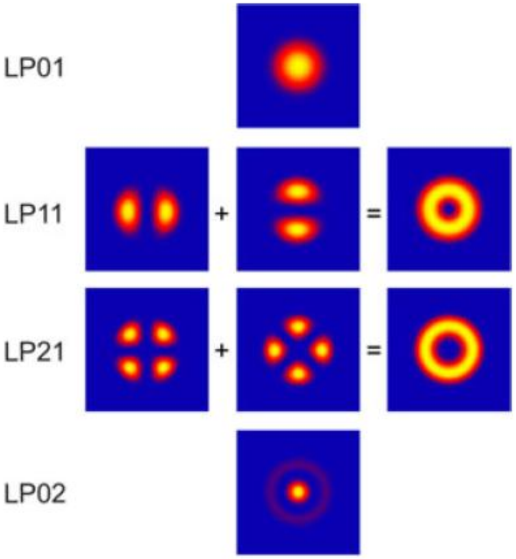




Adapted from Saleh and Teich

VCSELs:

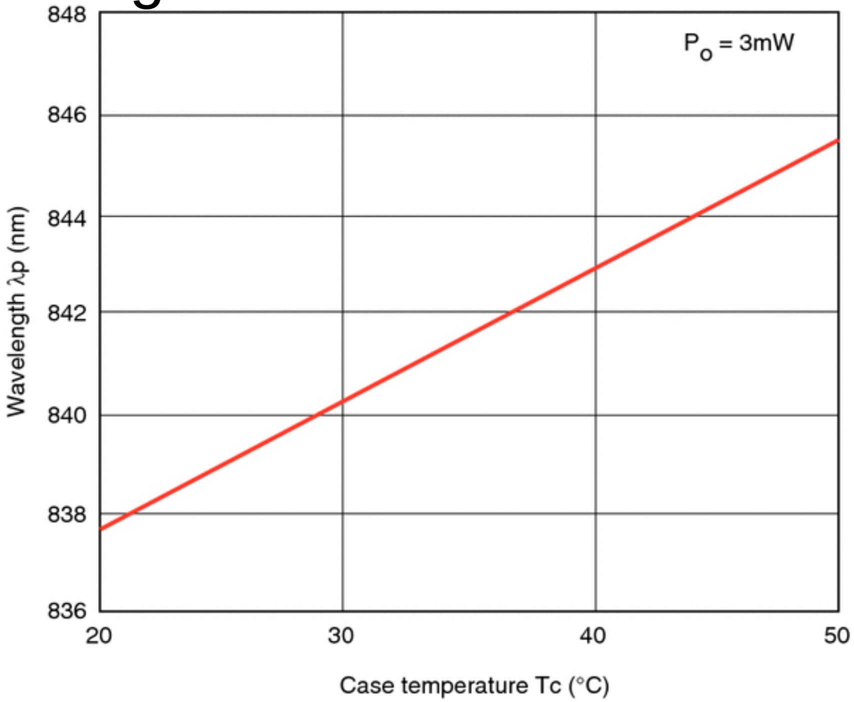
- The circular profile allows **easy coupling to an optical fiber**.
- But single-transverse mode emission **limited to few mW**.



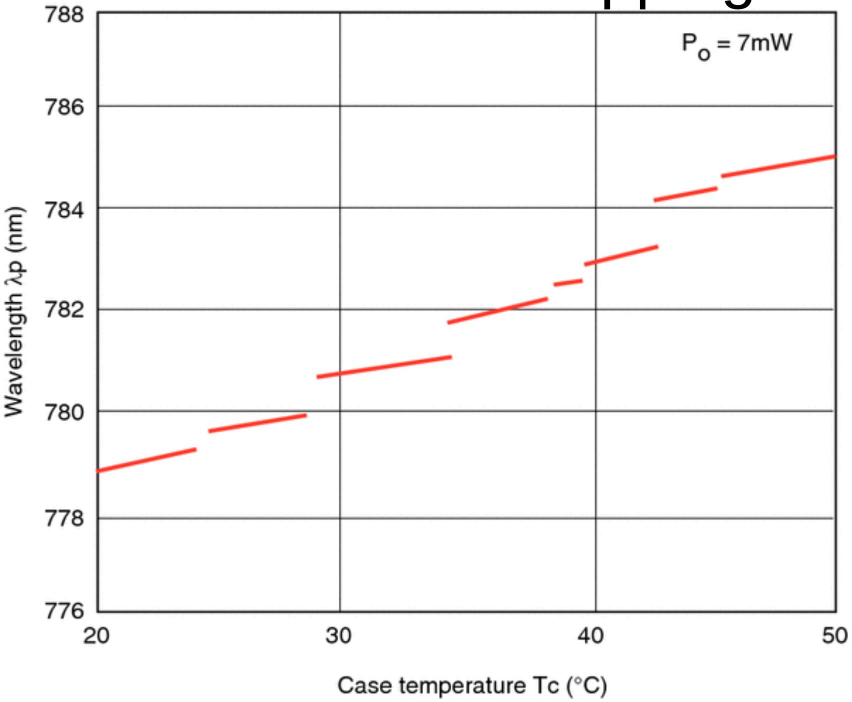
Adapted from A. Larsson, JSTQE 2011

Thermal properties of laser diodes: 1) variation of the center wavelength

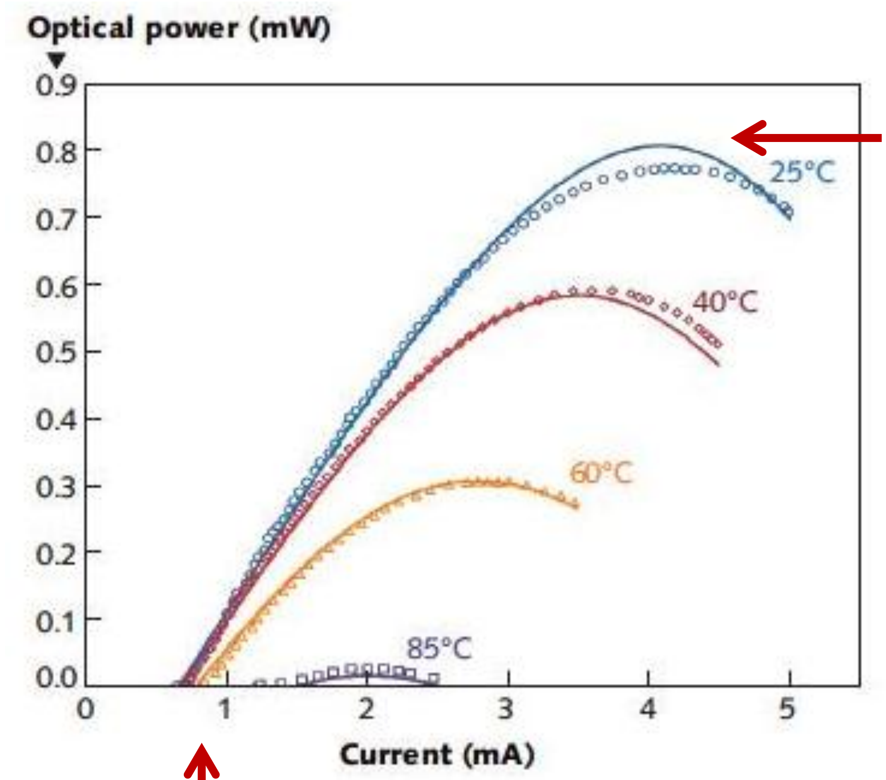
Single-mode laser



Multimode: Mode hopping



2) thermal effects in the LI curve



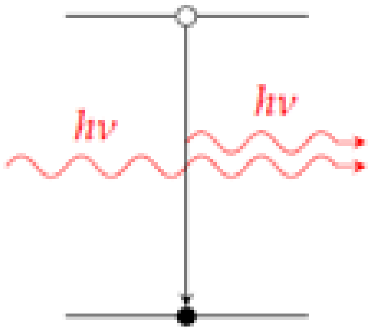
Thermal saturation

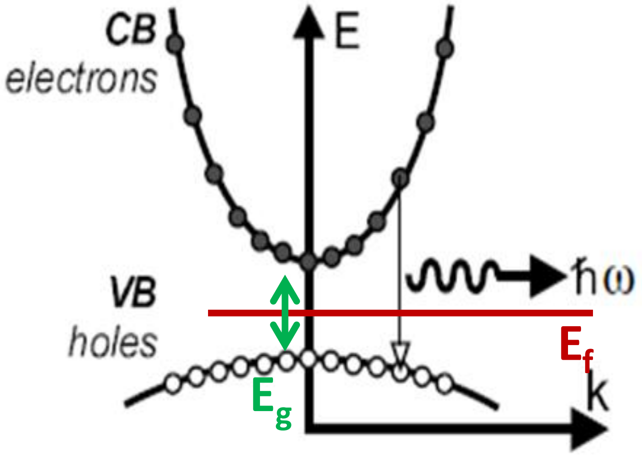
Threshold current

Source: Laser Focus World, sept. 2013

Why?

- The semiconductor is **not** a two level system.
- **Temperature affects the band-gap** of the semiconductor material, which determines the energy (and wavelength) of the emitted photons.
- With increasing temperature (**Joule heating**) E_g decreases and the emission frequency shifts to lower frequencies.





Band-gap energy and refractive index

A variation of the gain (due to a variation of N or T) causes a **change in the refractive index, n**, of the semiconductor (via the **Kramer-Kronig relation**), which results in a change of the optical cavity length, L, and thus, in a **change of the resonance frequencies** of the FP cavity.

GaAs

$$E_g = 1.5216 - \frac{5.405 \times 10^{-4} T^2}{T + 204} \text{ (eV)}$$

At 300 K:

$$n^2 = 8.950 + \frac{2.054\lambda^2}{\lambda^2 - 0.390}$$

$$\frac{1}{n}\frac{\mathrm{d}n}{\mathrm{d}T} = 4.5 \times 10^{-5} \text{ K}^{-1}$$

InP

$$E_g = 1.4206 - \frac{4.906 \times 10^{-4} T^2}{T + 327}$$

$$n^2 = 7.255 + \frac{2.316\lambda^2}{\lambda^2 - 0.3922}$$

$$\frac{1}{n}\frac{\mathrm{d}n}{\mathrm{d}T} = 2.7 \times 10^{-5} \text{ K}^{-1}$$

Adapted from J. M. Liu, Photonic devices

Summary of diode laser design goals

- To optimize carrier injection properties
- To optimize optical confinement
- To minimize optical loss and heating
- To obtain maximum gain at a given injection power
- To obtain a high-quality spatial profile and spectral purity

VF

✓ ❑ Si and Ge are important materials for photo-detectors but are not very useful for LEDs & SCLs.

✘ ❑ Both LEDs & SCLs have an emission threshold.

✘ ❑ Bragg-Grating lasers (DFBs and DBRs) emit a multimode spectrum.

✓ ❑ The goal of SCL design is to improve the confinement of photons and carriers, which allows lowering the threshold current.

✓ ❑ Thermal heating is responsible for the saturation of the LI curve and the shift of the emission wavelength with increasing current.

✘ ❑ QW lasers are as efficient as bulk lasers.

Outline

Part 1

1. Introduction to semiconductor lasers (SCLs)
2. Simplest rate-equation model and dynamics with time-varying current parameter

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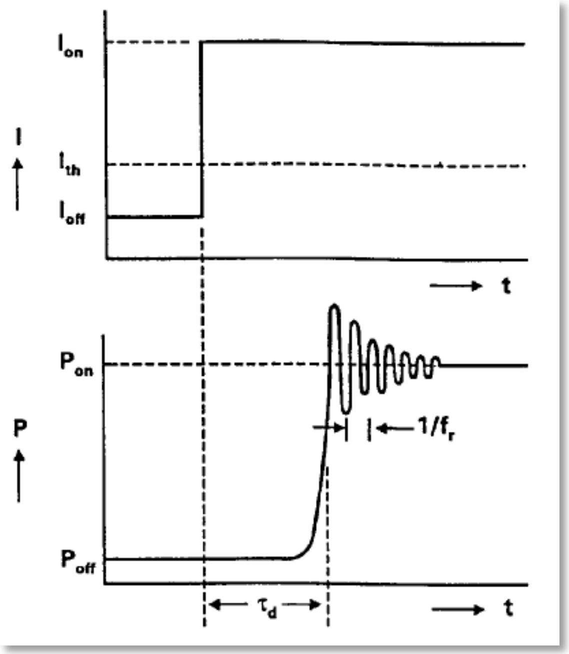
DE CATALUNYA
BARCELONATECH

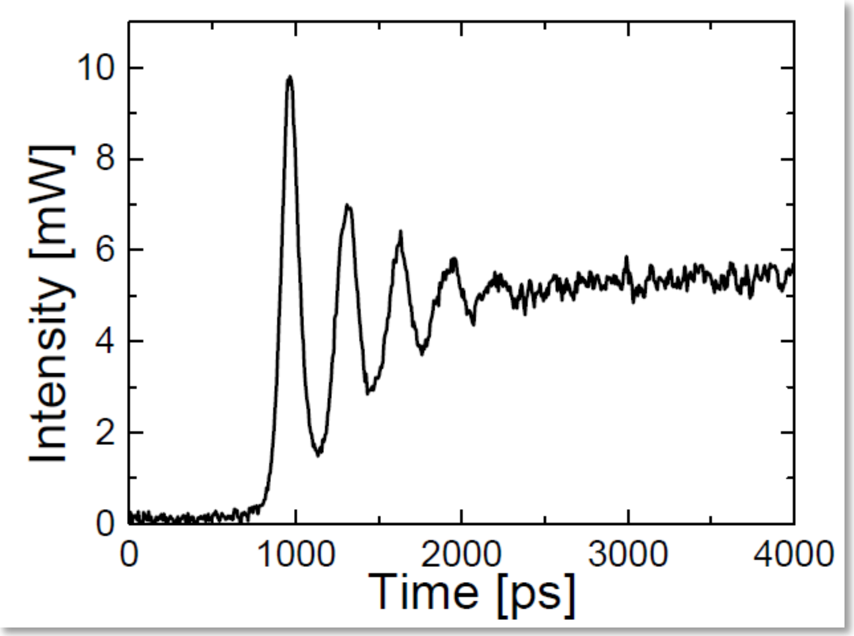
Main goals

Acquire a basic knowledge of

- The simplest rate equation model, the normalized equations, the meaning of the parameters and the steady-state solution.
- Perform simulations of deterministic dynamics with time-varying current parameter
  - **Turn on**: delay & relaxation oscillations
  - **LI curve**: dynamical hysteresis
  - Response to **current modulation**: understand the modulation bandwidth

Diode laser turn on ('gain switching'): delay and relaxation oscillations





Class B lasers only stable emission or periodic oscillations (more latter)

A simple model allows simulating the laser output intensity with time-varying injection current

From T. Heil, PhD thesis (Darmstadt 2001)

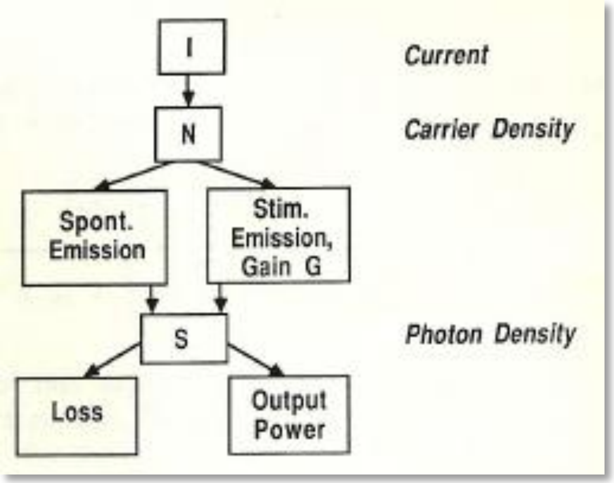
Rate equation for the photon density S

$$\frac{dS}{dt} = GS - \frac{S}{\tau_p} + \frac{\beta_{sp} N}{\tau_N}$$

Stimulated emission & absorption

Cavity losses

Spontaneous emission



τ_p : **Photon lifetime**. The optical cavity is a photon-reservoir where photons have a finite life-time before escaping. Typically τ_p is in the range of a few pico-seconds. $1/\tau_p = k$ is the cavity loss.

G (N,S) : **Gain** (stimulated emission – absorption)

β_{sp} : **Spontaneous emission rate**

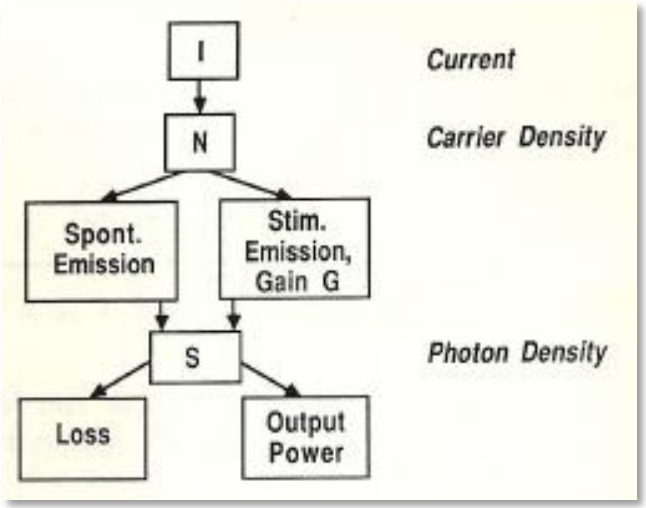
Rate equation for the carrier density N

$$\frac{dN}{dt} = \frac{I}{eV} - \frac{N}{\tau_N} - GS$$

Pump: injection of carriers

Recombination of carriers

Stimulated emission & absorption

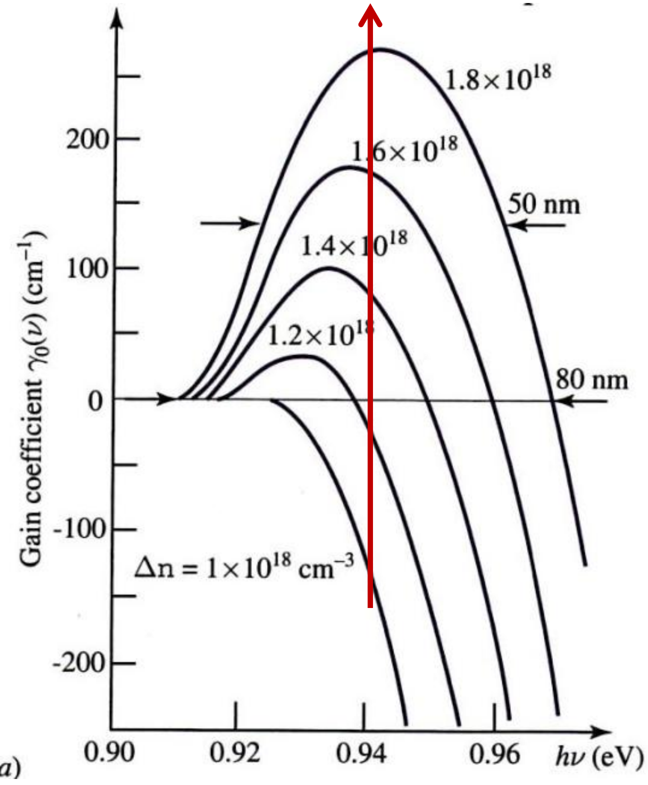


τ_N : **Carrier lifetime**. In the active region carriers (electron/hole pairs) are lost due to radiative recombination (spontaneous emission) and nonradiative recombination.

I : **Injection current** (I/eV is the number of electrons injected per unit volume and per unit time).

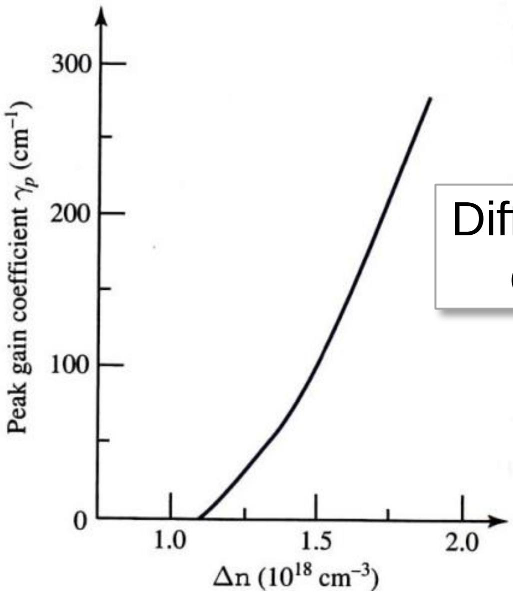
G (N,S) : **Gain**

The simplest expression for the semiconductor gain



ω_0

RT InGaASP laser



$$G = a(N - N_0)$$ DH

$$G = aN_0 \ln(N / N_0)$$ QW

Differential gain coefficient

Carrier density at transparency

We will assume single-mode emission at λ_0. The differential gain coefficient **a** depends on λ_0

Nonlinear coupled equations

$$\frac{dS}{dt} = GS - \frac{S}{\tau_p} + \frac{\beta_{sp} N}{\tau_N}$$

$$\frac{dN}{dt} = \frac{I}{eV} - \frac{N}{\tau_N} - GS$$

- Ordinary differential equations (spatial effects neglected!)
- Additional nonlinearities: carrier re-combination and gain saturation

$$\frac{1}{\tau_N} = \frac{1}{\tau_{nr}} + BN + CN^2$$

$$G = \frac{a\left(N - N_0\right)}{1 + \varepsilon S}$$

- These equations allow simulating the LI curve and the laser modulation response.
- To understand the intensity noise and the laser line-width (the optical spectrum), we need a stochastic equation for the <u>complex</u> field E ($S=|E|^2$).

Normalized equations

- Define the a-dimensional variable:

$$N' = \frac{N - N_0}{N - N_{th}}$$

Threshold carrier density: gain = loss

$$a\left(N_{th} - N_0\right) = \frac{1}{\tau_p}$$

$$\frac{dS}{dt} = \frac{1}{\tau_p}\left(N' - 1\right)S + \frac{\beta_{sp} N'}{\tau_N}$$

$$\frac{dN'}{dt} = \frac{1}{\tau_N}\left(\mu - N' - N'S\right)$$

Pump current parameter: proportional to I/I_{th}

- Normalizing the equations eliminates two parameters (a, N_o)
- In the following I will drop the " ' "

Initial conditions

$$\frac{dS}{dt} = \frac{1}{\tau_p}(N-1)S + \frac{\beta_{sp} N}{\tau_N}$$

- At t=0 there are no photons in the cavity: S(0) = 0

- Without noise (β_{sp}=0): if S=0 at t=0 $\Rightarrow$ dS/dt=0

  $\Rightarrow$ S remains 0 (regardless the value of μ and N).

- Without spontaneous emission noise the laser does not turn !

Steady state solutions

(Simple expressions if β_{sp} is neglected)

$$\frac{dS}{dt} = \frac{1}{\tau_p}(N-1)S$$

$$\frac{dN}{dt} = \frac{1}{\tau_N}(\mu - N - NS)$$

$$\frac{dS}{dt} = 0 \Rightarrow \begin{cases} S = 0 \\ N = 1 \end{cases}$$

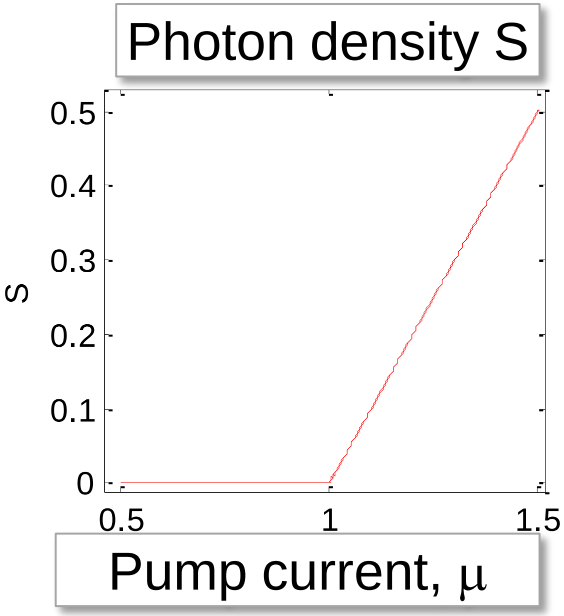
$$\frac{dN}{dt} = 0 \Rightarrow \begin{cases} S = 0 \rightarrow N = \mu \\ N = 1 \rightarrow S = \mu - 1 \end{cases}$$

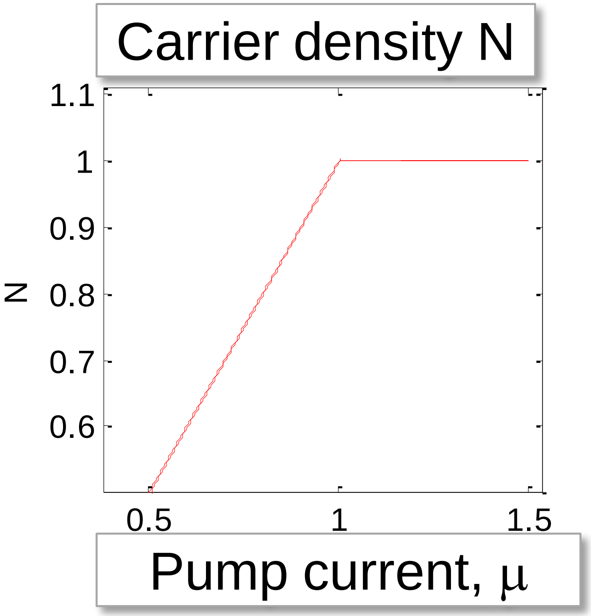
off

$S=0$

$N=\mu$

$\mu_{th} = 1$


Photon density S


Carrier density N

on

$S= \mu-1$

$N= 1$

The carrier density is "**clamped**" above threshold

Dynamics with time-varying pump current

$$\frac{dN}{dt} = \frac{1}{\tau_N}\left(\mu - N - NS\right)$$

μ (t)

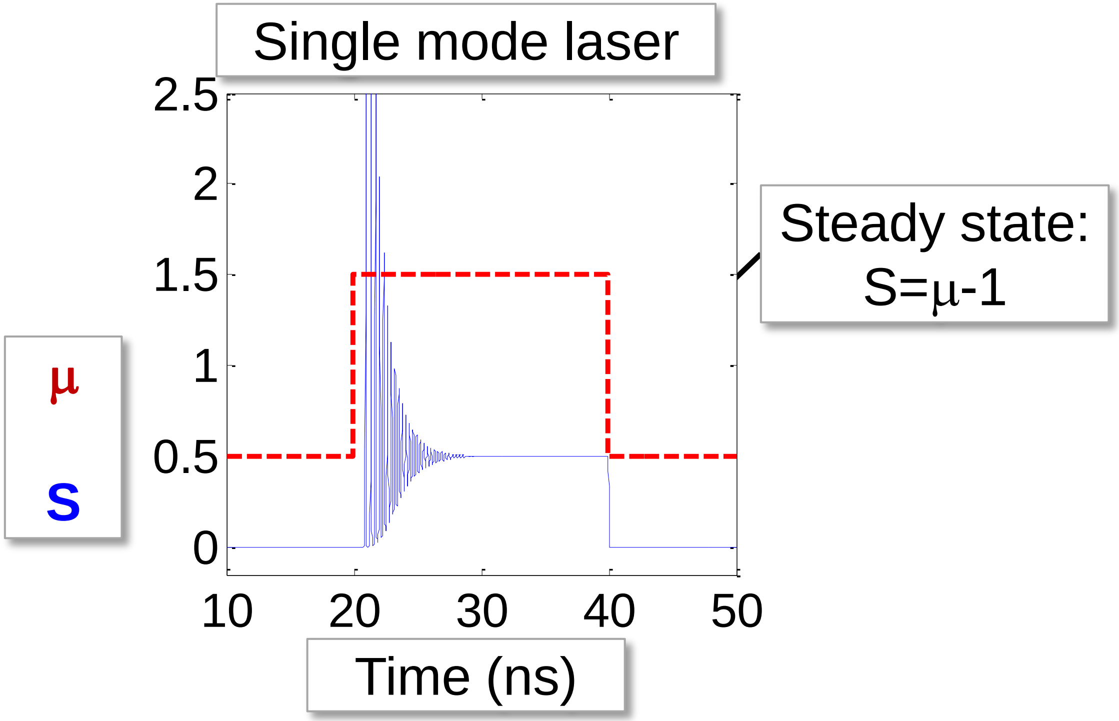
$$\frac{dS}{dt} = \frac{1}{\tau_p}\left(N - 1\right)S + \frac{\beta_{sp} N}{\tau_N}$$

- **Step** (laser turn on): μ_{off}, μ_{on}
- **Triangular** signal (LI curve): μ_{min}, μ_{max}, T
- **Sinusoidal** signal (modulation response): μ_{dc}, A, T_{mod}

Parameter values

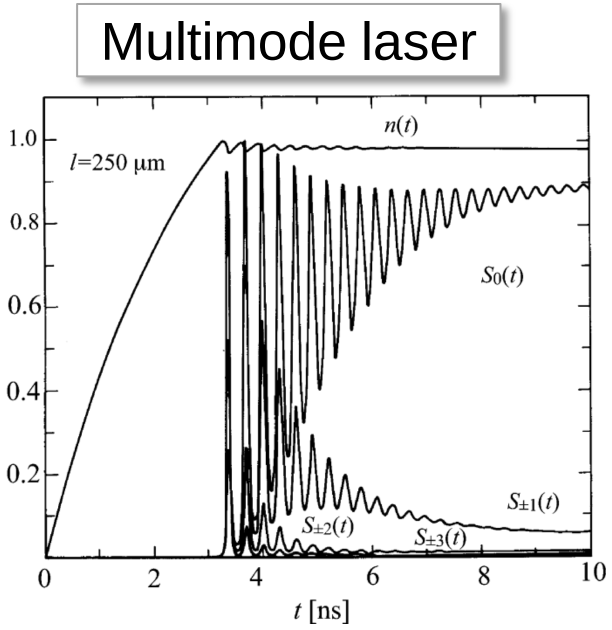
τ_p	1 ps
τ_N	1 ns
β_{sp}	10^{-4}

Current step: turn-on delay & relaxation oscillations


Single mode laser

Steady state: S=μ-1

Time (ns)

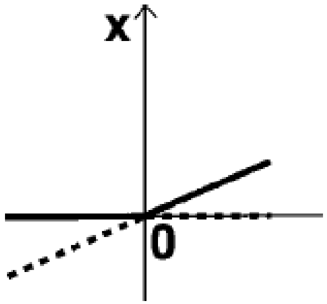

Multimode laser

A linear stability analysis of the rate equations allows calculating the RO frequency

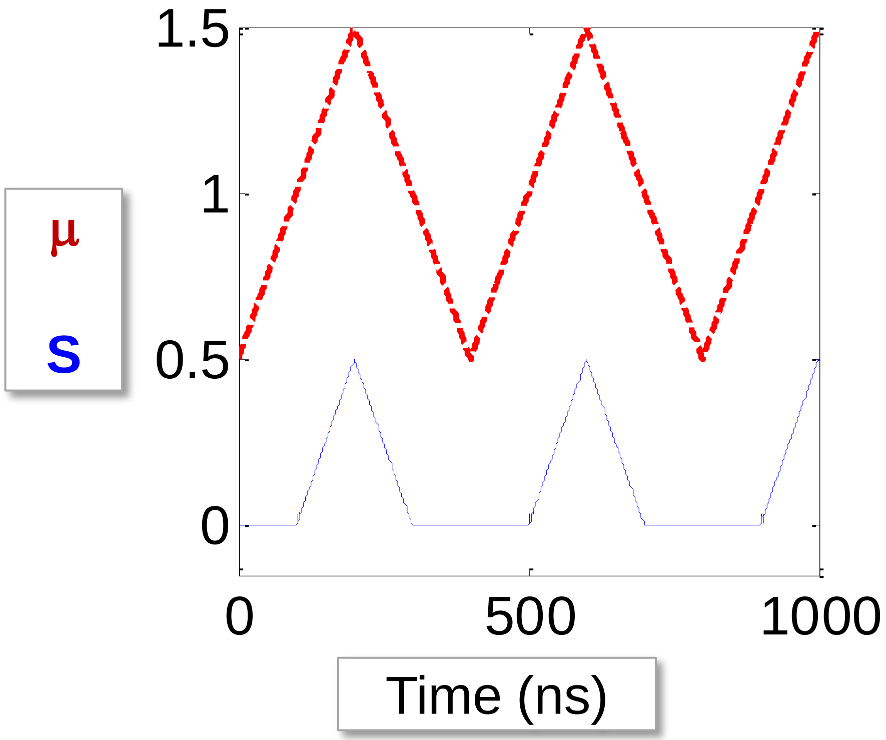
$$\omega_{RO} = \sqrt{\frac{\mu-1}{\tau_p \tau_N}}$$

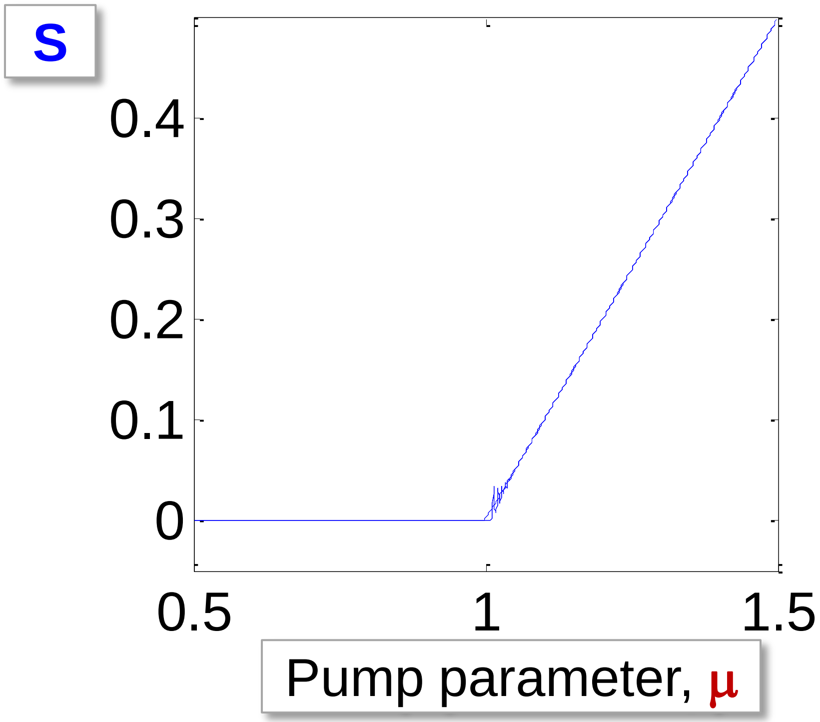
Adapted from J. Ohtsubo

Triangular signal: LI curve

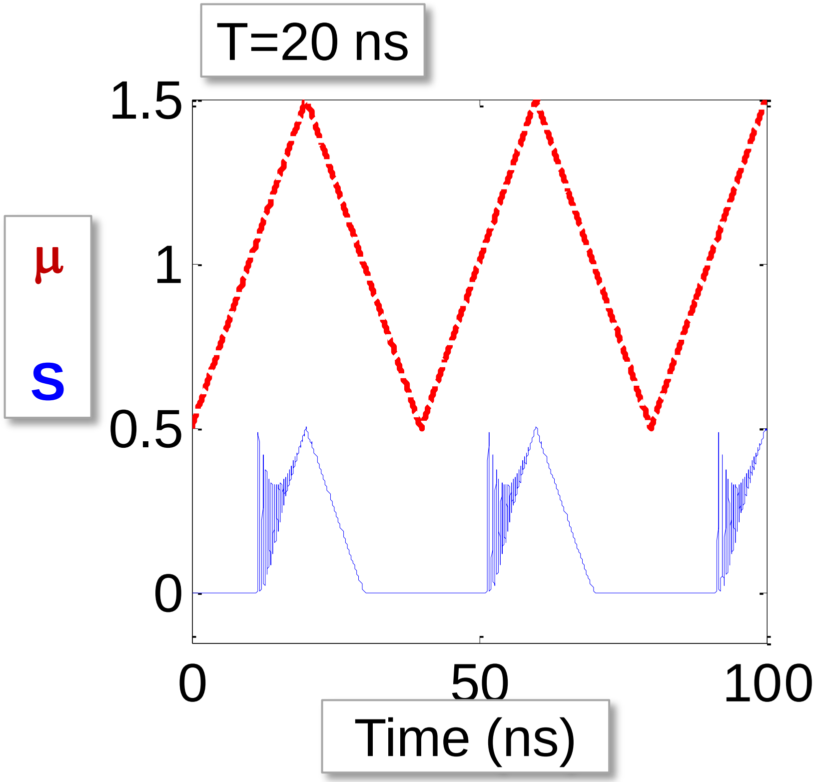


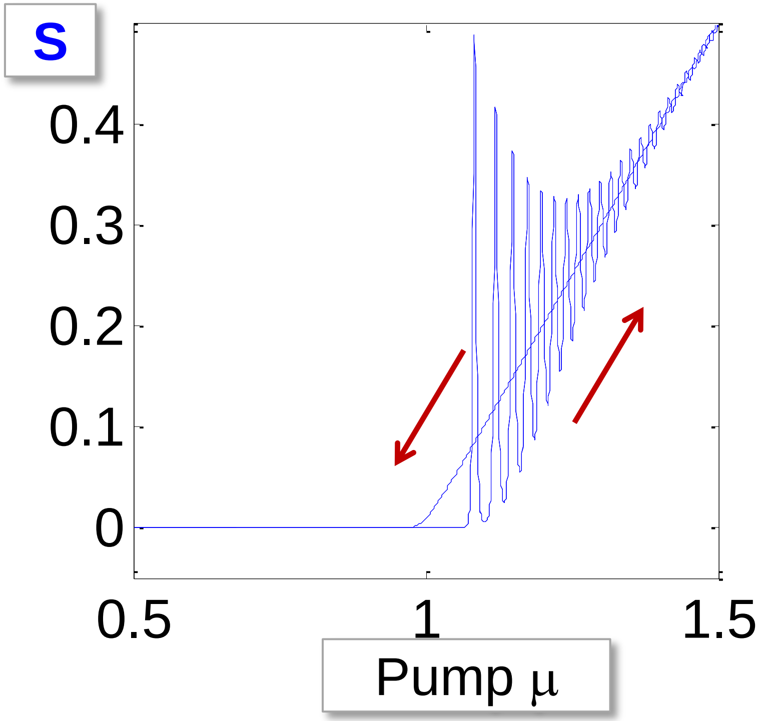
Slow “quasi-static” current ramp (T=200 ns)

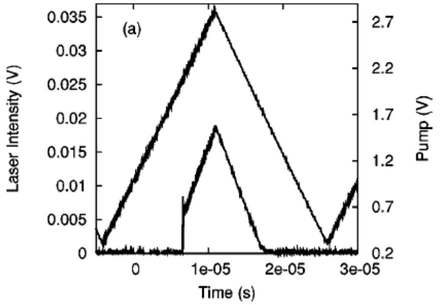


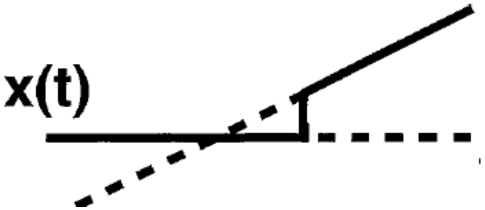


But with a “fast” ramp: dynamical hysteresis





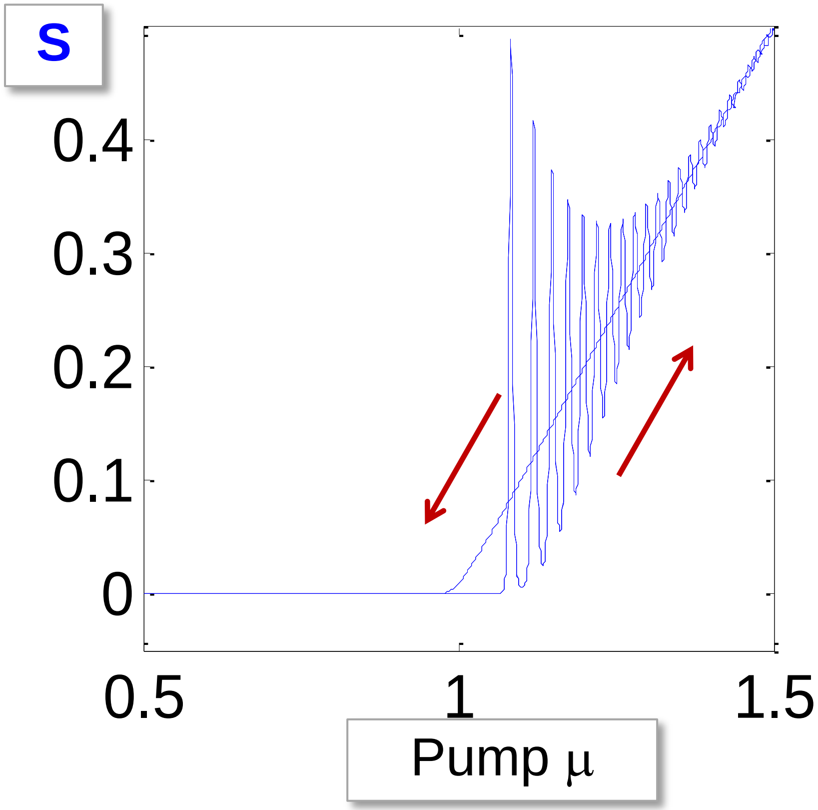




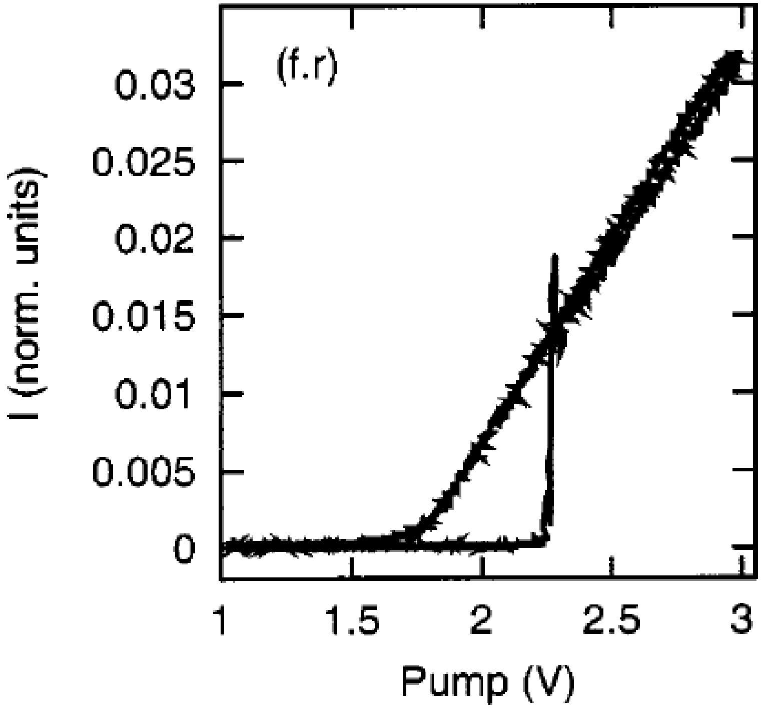
Tredicce et al, Am. J. Phys., Vol. 72, No. 6, June 2004

The laser threshold: a delayed dynamical bifurcation

Simulations



Experiments



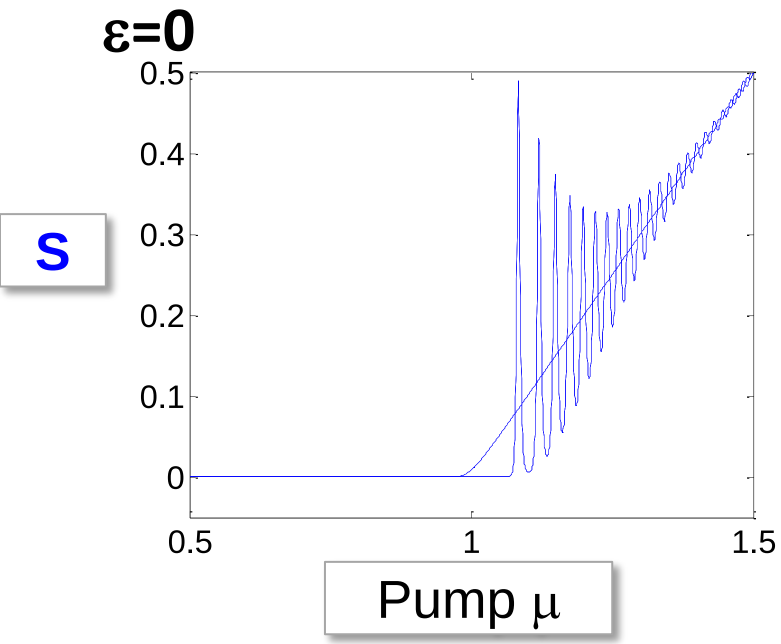
Tredicce et al, Am. J. Phys., Vol. 72, No. 6, June 2004

Relaxation oscillations: influence of gain saturation

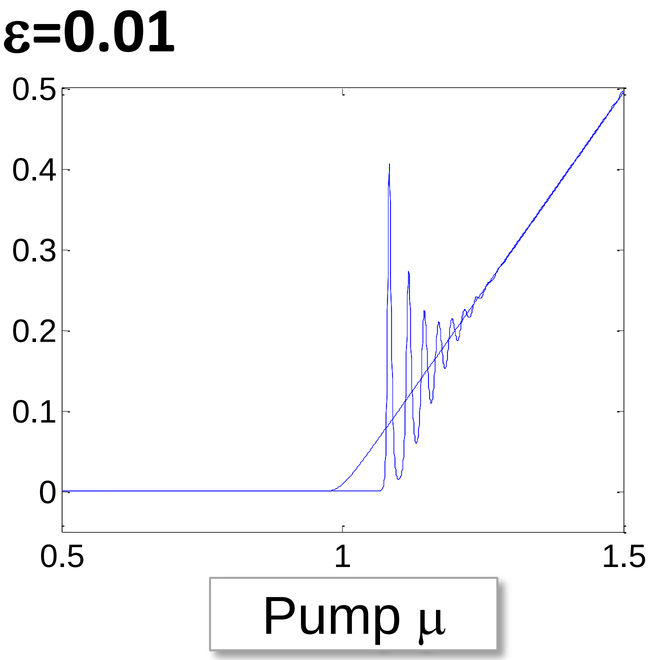
$$\frac{dS}{dt} = \frac{1}{\tau_p}(G-1)S + \frac{\beta_{sp}N}{\tau_N}$$

$$\frac{dN}{dt} = \frac{1}{\tau_N}(\mu - N - GS)$$

$$G(N,S) = \frac{N}{1+\varepsilon S}$$



ε=0

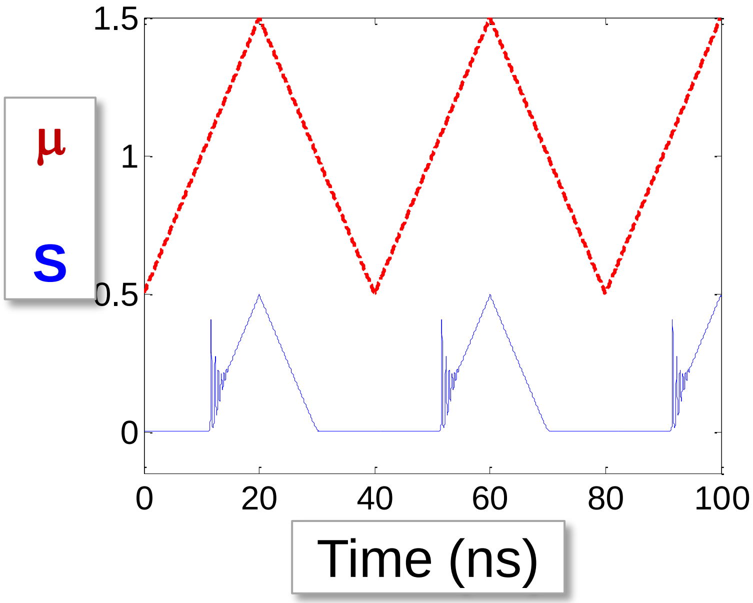


ε=0.01

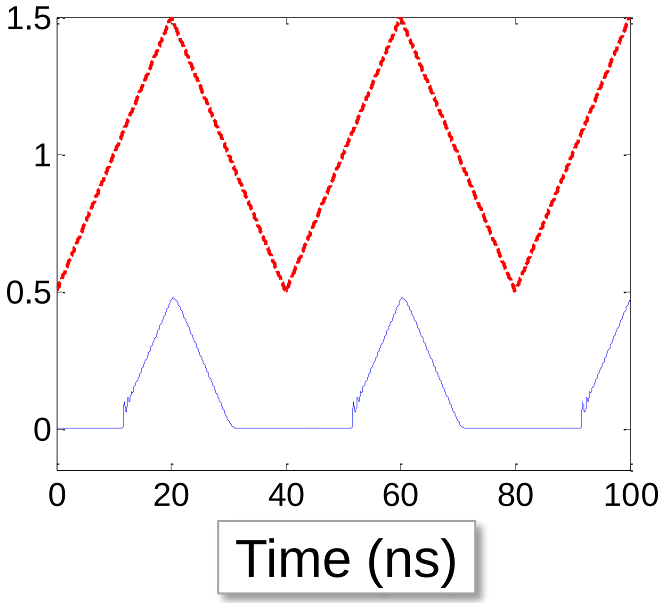
The gain saturation coefficient **ε** takes into account phenomenologically several effects (e.g., spatial and spectral hole burning)

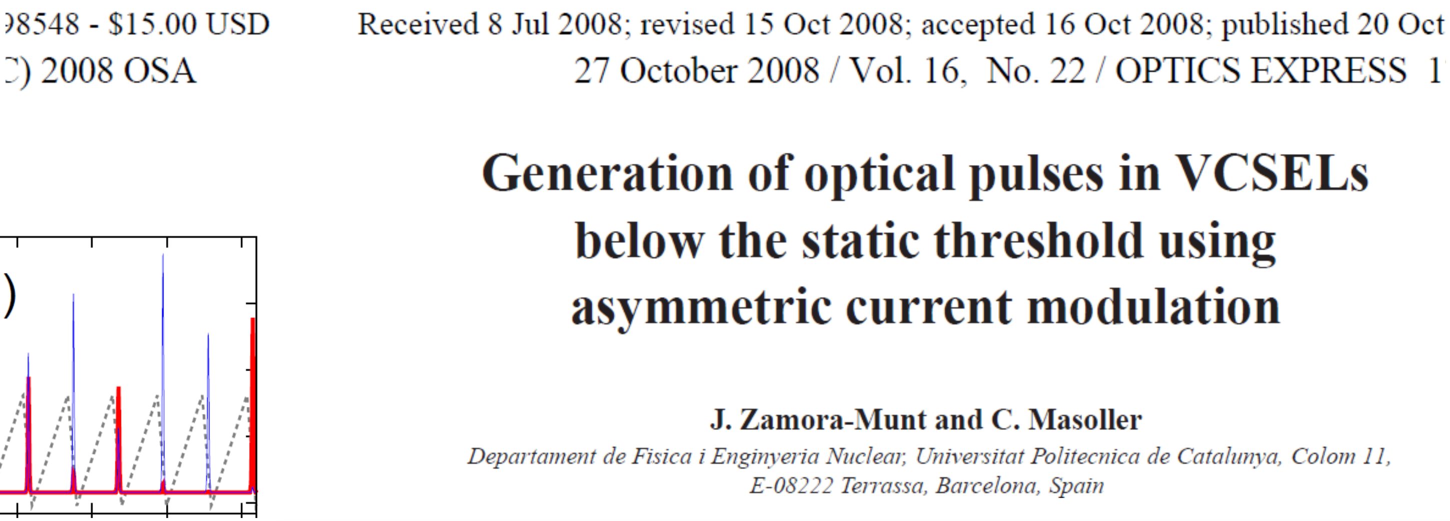
In the experiments: finite detection bandwidth ⇒ in the simulations: filter out the high frequencies by window averaging

No average



Averaging over 0.5 ns

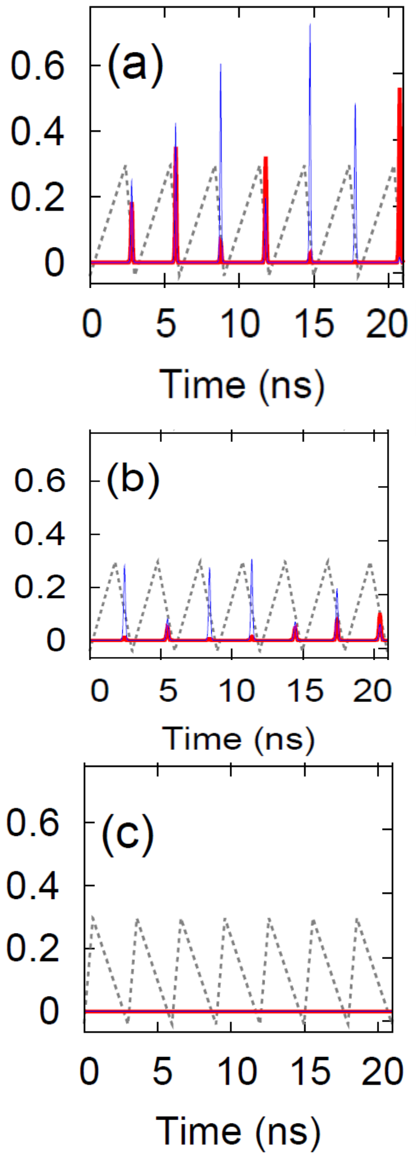




)8548 - $15.00 USD Received 8 Jul 2008; revised 15 Oct 2008; accepted 16 Oct 2008; published 20 Oct
C) 2008 OSA 27 October 2008 / Vol. 16, No. 22 / OPTICS EXPRESS 1

Generation of optical pulses in VCSELs below the static threshold using asymmetric current modulation

J. Zamora-Munt and C. Masoller
Departament de Fisica i Enginyeria Nuclear, Universitat Politecnica de Catalunya, Colom 11,
E-08222 Terrassa, Barcelona, Spain



“Ratchet” effect inspired by the work of Glorieux et al using a solid-state diode-pumped laser (Opt. Lett. 2006)

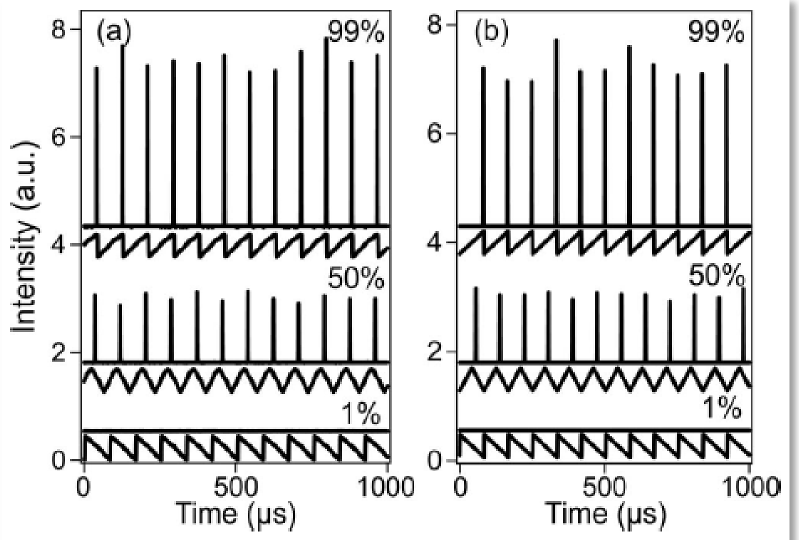
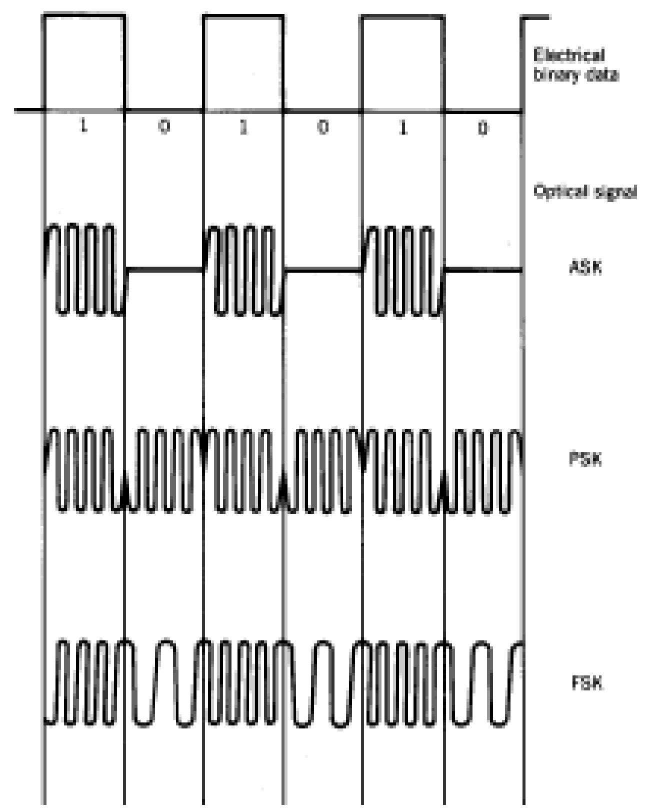


Fig. 1. Time evolution of the laser intensity (up) and of the pump power (down) for symmetry parameter α equal to 1%, 50%, and 99%. (a) Experiments, (b) simulations. Param-

Why current modulation is important?

Optical waves can be modulated in Amplitude, Phase and in Frequency in order to carry information



Electrical information signal

modulates the

Optical Amplitude: Amplitude Shift Keying

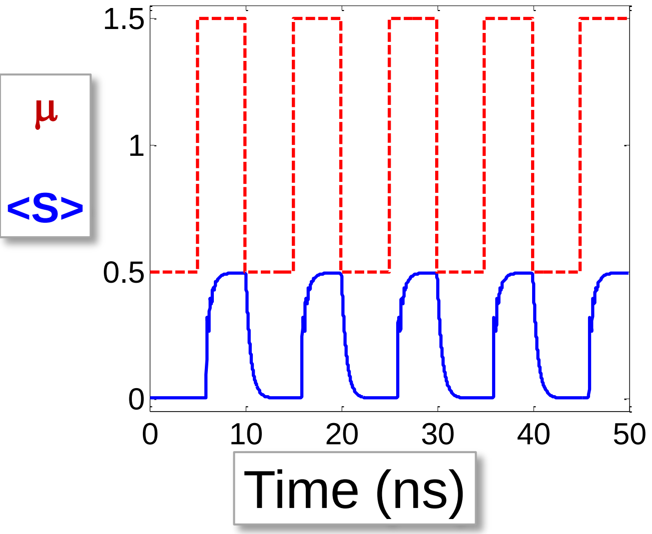
Optical Phase: Phase Shift Keying

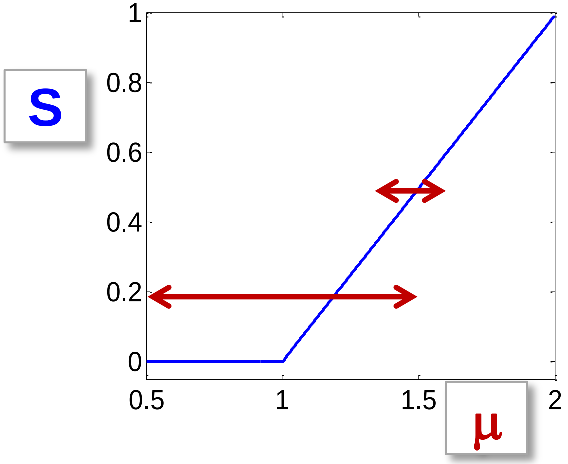
Optical Frequency: Frequency Shift Keying

Adapted from H. Jäckel, ETHZ

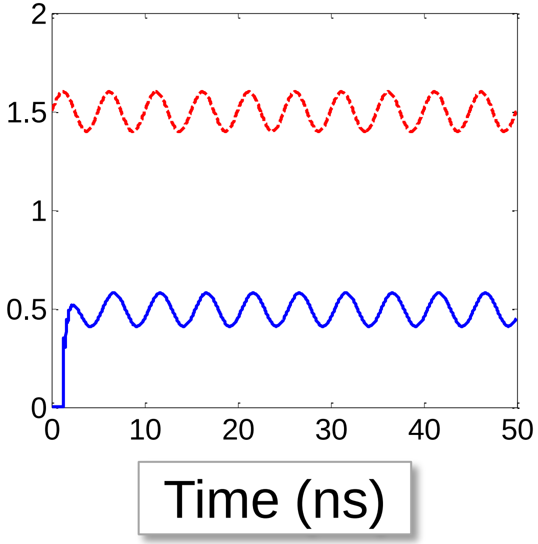
Digital vs analog current modulation

Digital





Analog

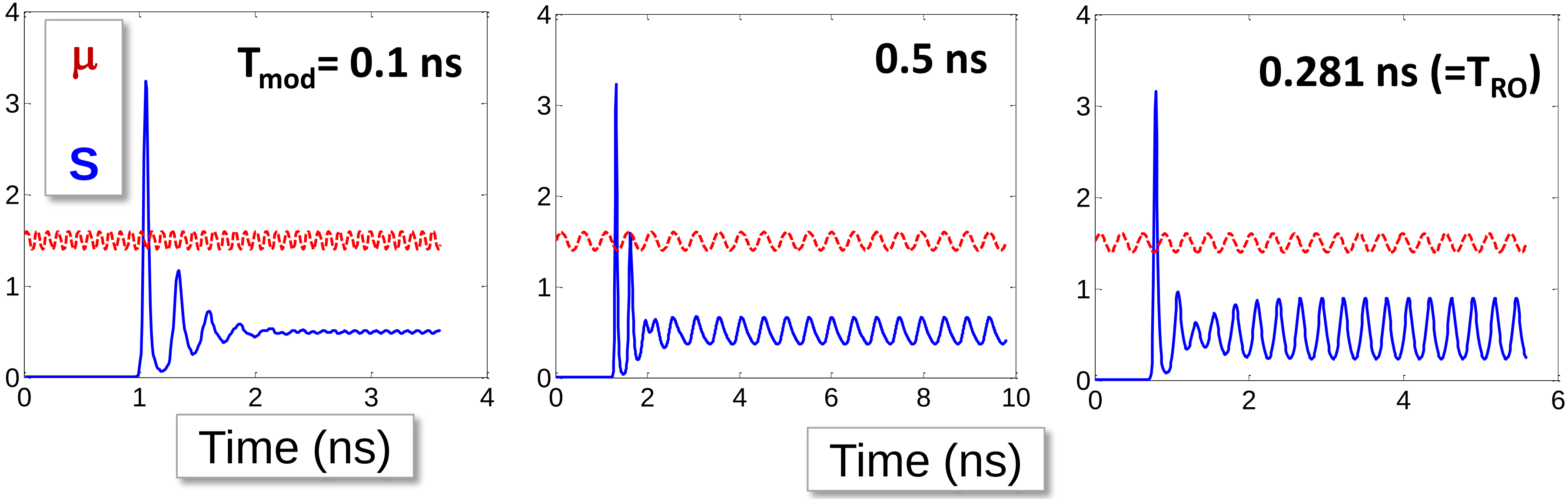


Weak sinusoidal modulation: influence of the modulation frequency

$\mu = \mu_{dc} + A \sin \omega_{mod} t$

$\mu_{dc} = 1.5$, $A=0.1$

For $\mu=1.5$: $\nu_{RO} = 3.56$ GHz

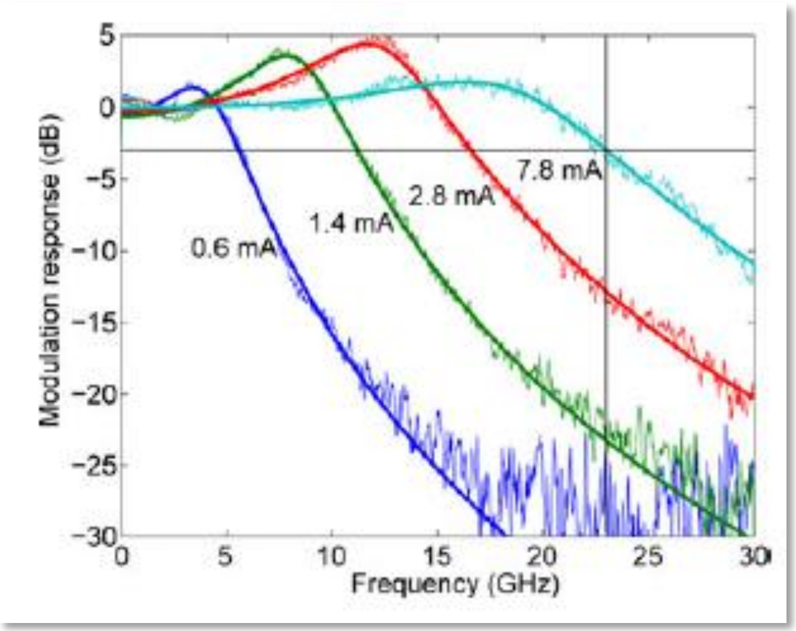


The laser intensity (**S** = photon density) is modulated at the same frequency of the pump current (**μ**), but the phase of the intensity and the current are not necessarily the same.

Modulation response: resonance at $\nu_{mod}=\nu_{RO}$

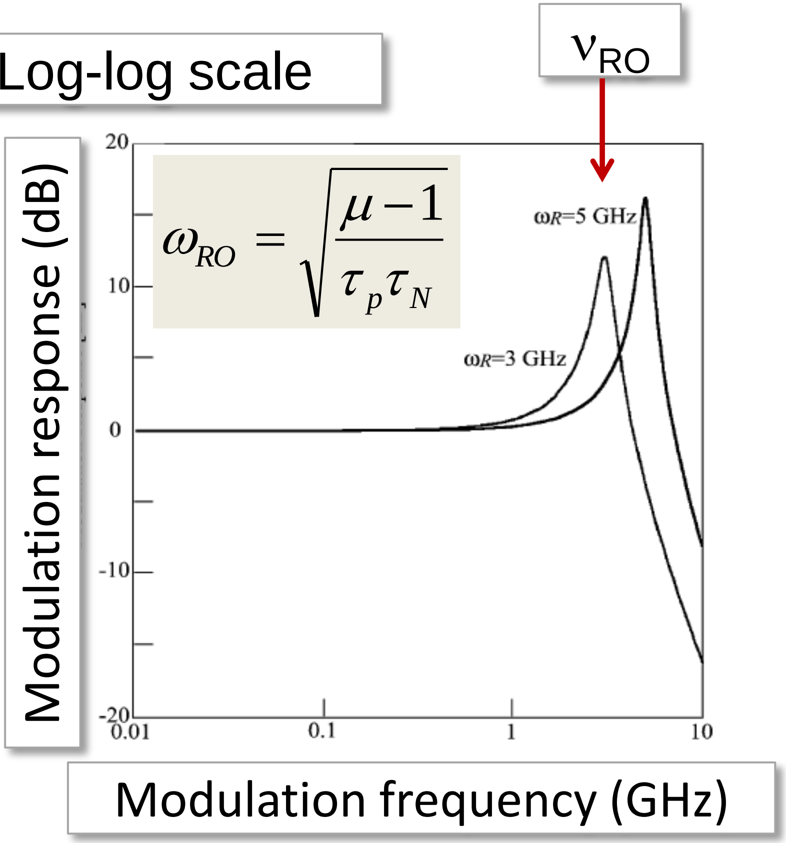
The modulation response can be analytically calculated by linearising the rate equations

Linear-log scale



Adapted from A. Larsson, JSTQE 2011

Log-log scale



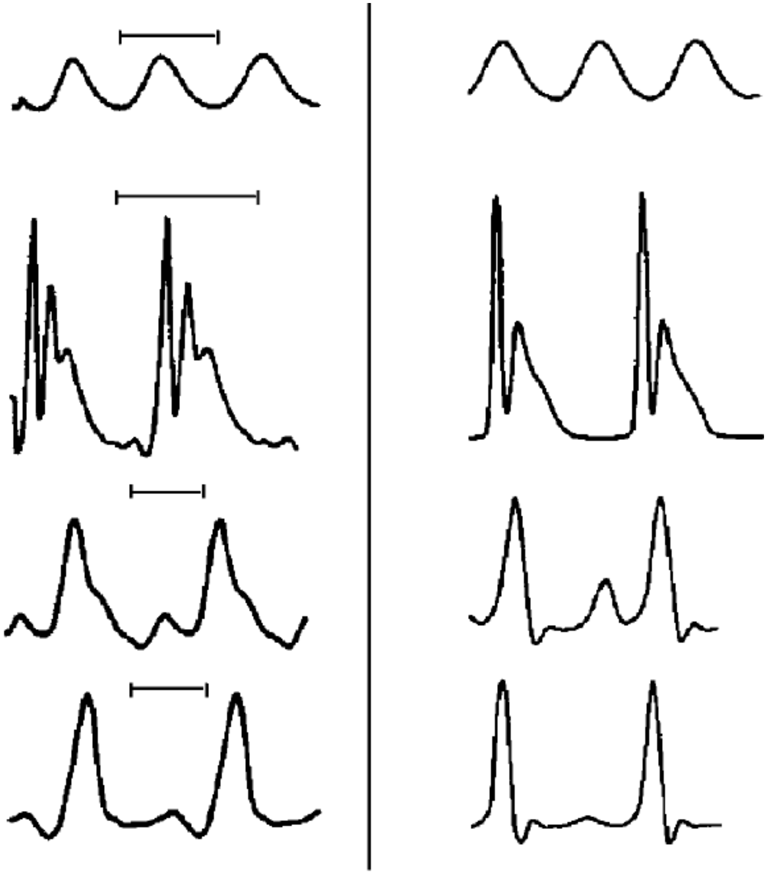
$$\omega_{RO}=\sqrt{\frac{\mu-1}{\tau_p\tau_N}}$$

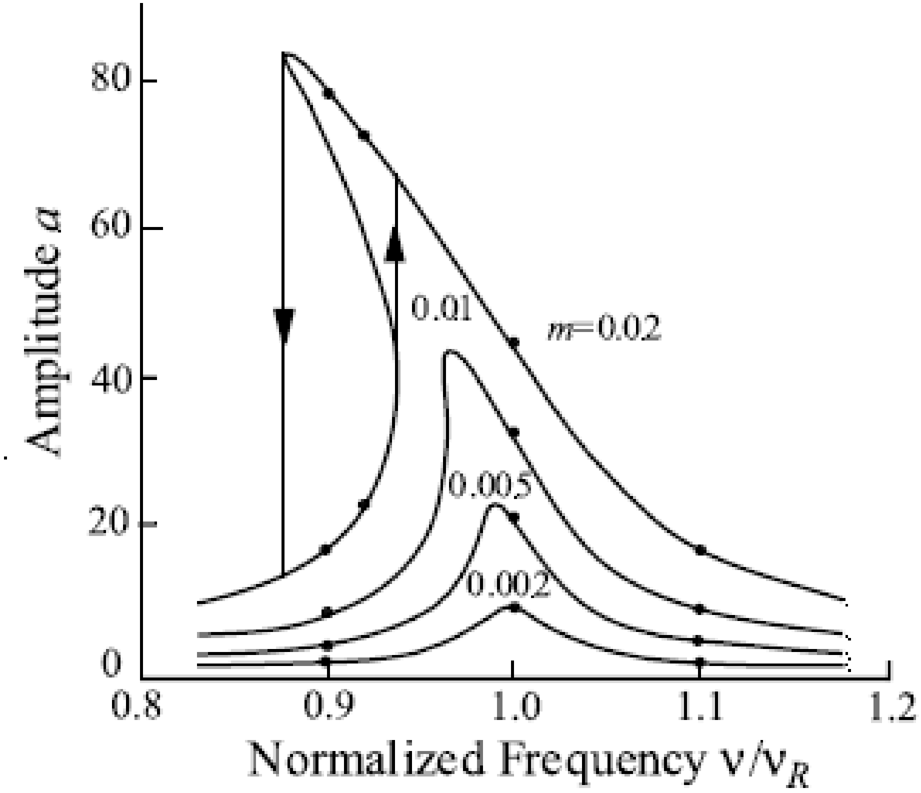
Adapted from J. Ohtsubo

Large-signal modulation response

Experiments

Simulations





Adapted from J. Ohtsubo

Summary

A simple rate equation model for the photon and carrier densities allows understanding the main features of the laser dynamics with time-varying injection current:

- The turn on (delay & relaxation oscillations)
- The LI curve (static & dynamic)
- The modulation response (small and large signal)

Outline

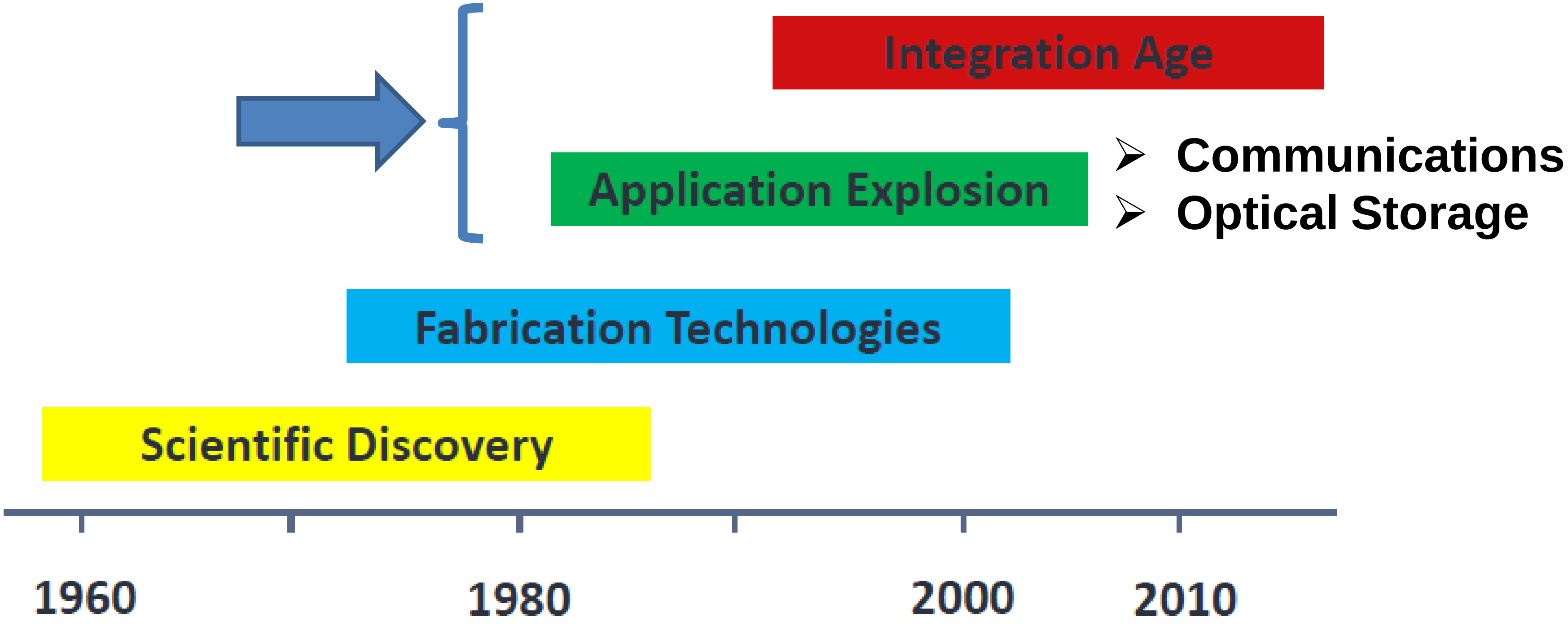
Part 1

1. Introduction to semiconductor lasers (SCLs)
2. Simplest model and dynamics with time-varying current parameter

Part 2

1. Applications of SCLs
2. More complicated model and dynamics with optical injection and polarization properties

Laser Diode Evolution



Integration Age

Application Explosion

- ➢ **Communications**
- ➢ **Optical Storage**

Fabrication Technologies

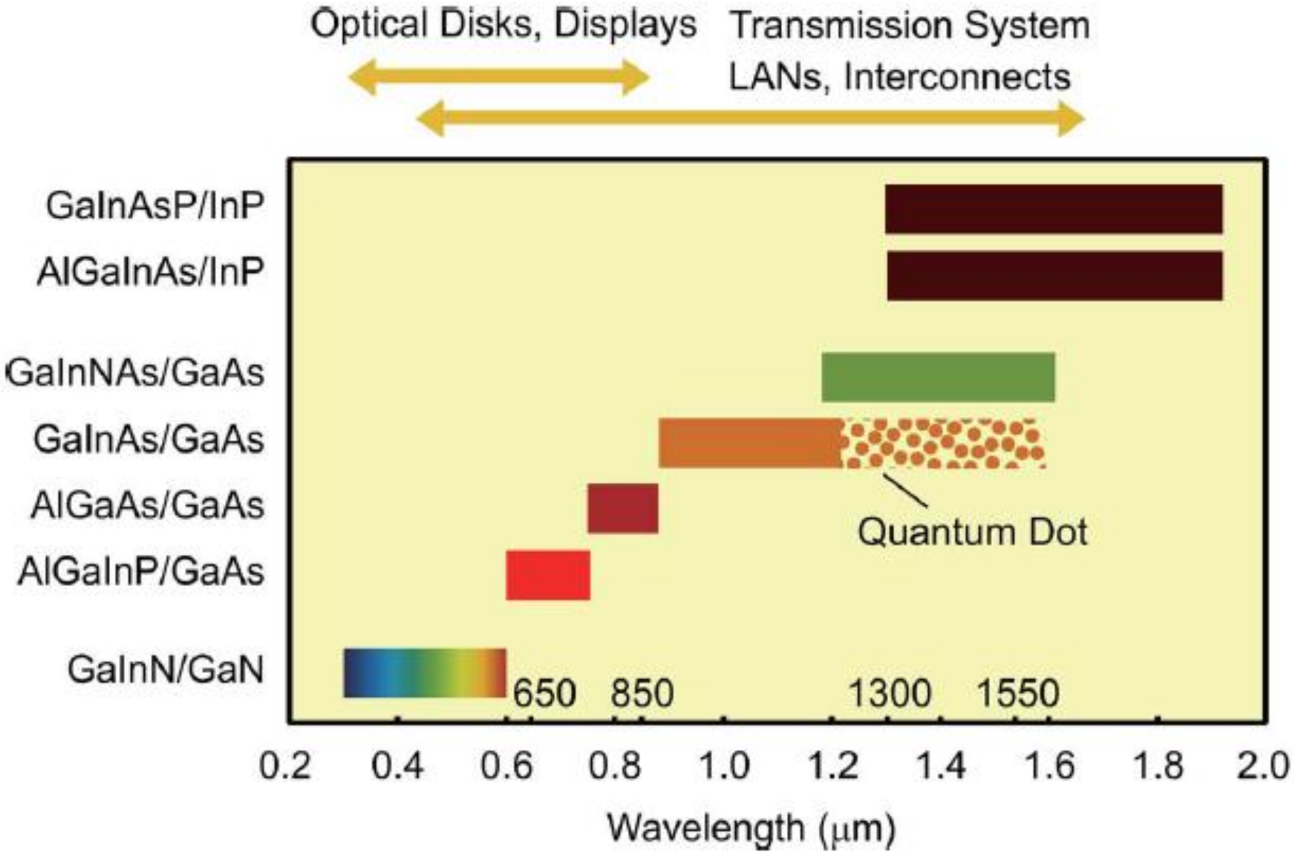
Scientific Discovery

Adapted from D. Welch, Infinera

Wavelengths for telecom & information storage

Short wavelength
Non telecommunications

Long wavelength
Telecommunications



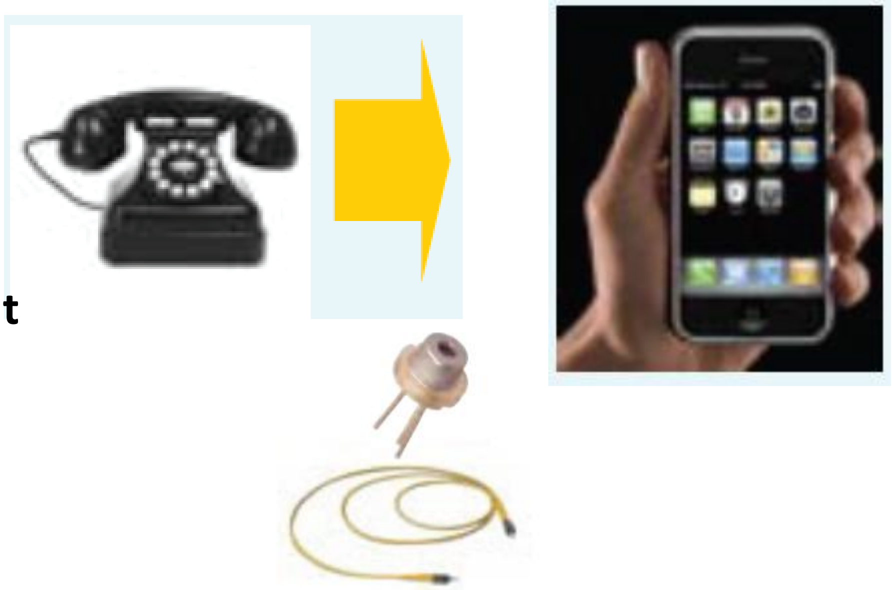
Source: SUEMATSU & IGA: SEMICONDUCTOR LASERS IN PHOTONICS, JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 26, 1132, 2008

Communications

The internet and communications over fiber-optic networks depend on diode lasers.
Diode lasers have created millions of jobs in the telecommunications industry

Instant news updates, television and movies, video conference, all depend on lasers.

Voice and data are encoded onto laser light and transmitted over fiber-optic networks



Adapted from: Fred Schlachter and Thomas Baer, www.laserfest.org

Optical communications: along way from the beginning

- The first optical transmission system operated **over 11 km of fiber at 45 Mbit/s**: in May 1977 optical fibers were used to connect three telephone central offices in downtown Chicago.

- In the late **1970s**, indium gallium arsenide phosphide (InGaAsP) lasers operating at longer wavelengths were demonstrated, enabling systems to transmit data at higher speeds and over longer distances.

- By the mid-**1980s**, transmission distances had increased to hundreds of kilometres and bit rates to 500 Mbit/s.

Nat. Phot. 4, 287 (2010)

Crucial development: optical amplifiers

- In the **1990s** the development of optical amplifiers allowed to compensate for the loss in optical fibers, enabling long transmission distances.
- Semiconductor lasers are efficient pump sources for optical amplifiers.
- In **1996: 5 Gbit/s transoceanic** systems spanning more than 6,000 km without the need for any optical-to-electronic conversion.
- Today, single fibers carrying signals at hundreds of different wavelengths can transmit **terabits/s** of information.

Nat. Phot. 4, 287 (2010)

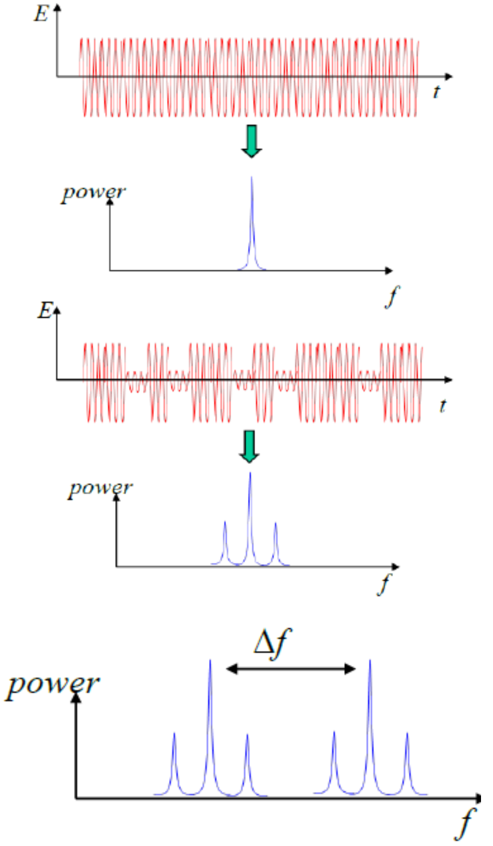
VCSELs for fiber optic communications

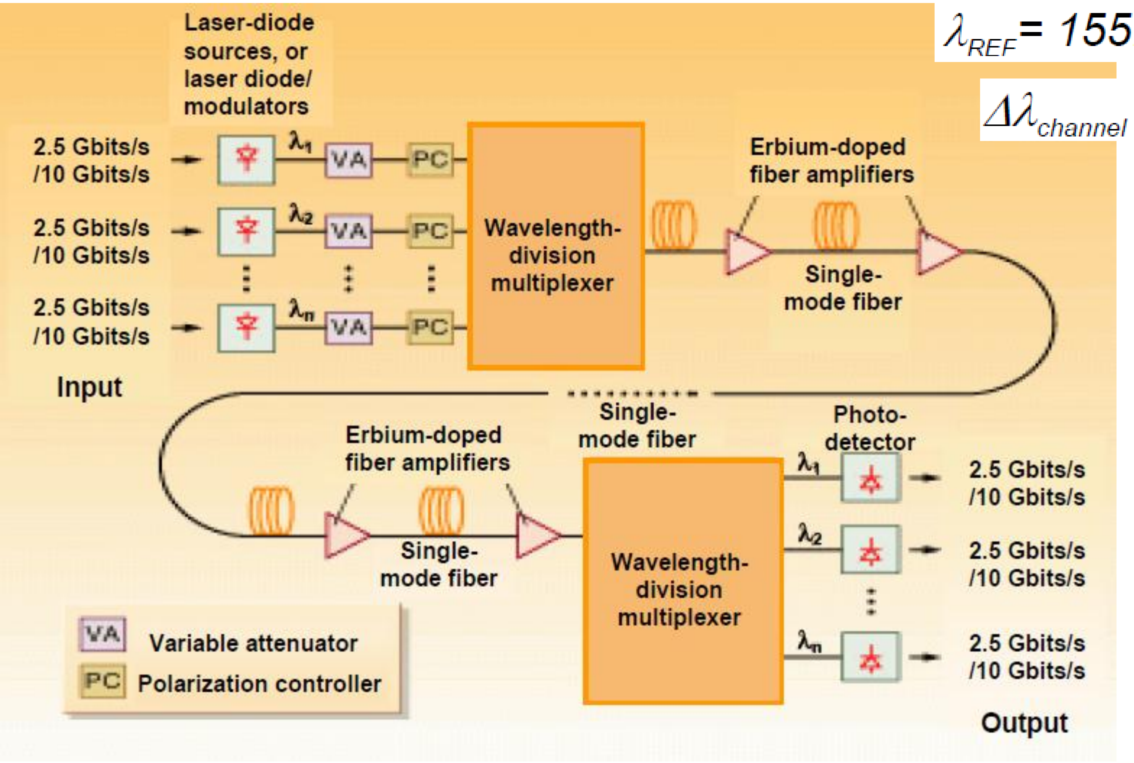
- VCSELs can be used at all levels of the optical communication network, **except for very long distance** transmission, where externally modulated DFBs are used to meet requirements of high power and low frequency chirp.
- VCSELs emitting in the 1310 and 1550 nm bands are used for medium distance communication (metro and access networks, which are based on single-mode optical fibers).
- Such VCSELs have to be **single mode** to enable efficient laser–fiber coupling and to prevent pulse broadening.

High-speed modulation and array integration allow for wavelength-division multiplexing (WDM)

Adapted from A. Larsson, JSTQE 2011

Wavelength-division multiplexing





λ_{REF} = 1552.52 nm

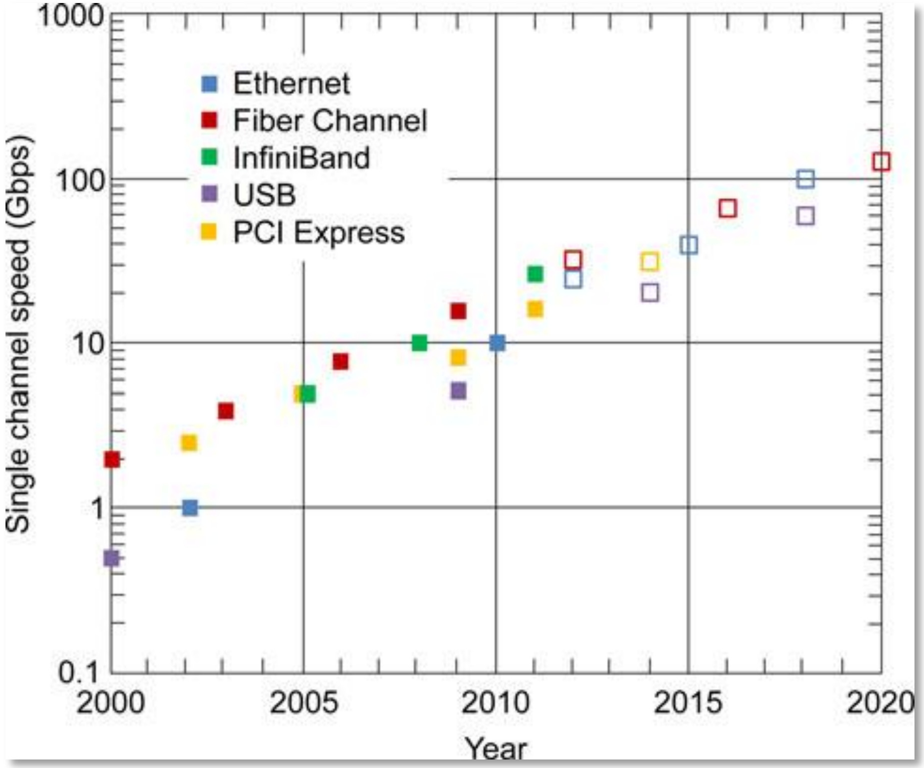
$\Delta\lambda_{channel}$ = 0.8 nm

- Channels need to be separated in frequency far enough such that the modulation sidebands of “neighboring channels” don’t overlap.
- The faster the modulation, the more difficult this becomes.

Adapted from D. Natelson, Rice University

VCSEL advantage: high speed modulation

The maximum single channel (per wavelength) speed is at **10 Gb/s (2011)**.
As the demand for higher data rates increases, 25 Gb/s are required for a 4 × 25 Gb/s 100G solution.



Adapted from A. Larsson, JSTQE 2011

But direct current modulation has drawbacks

- Limited modulation bandwidth.

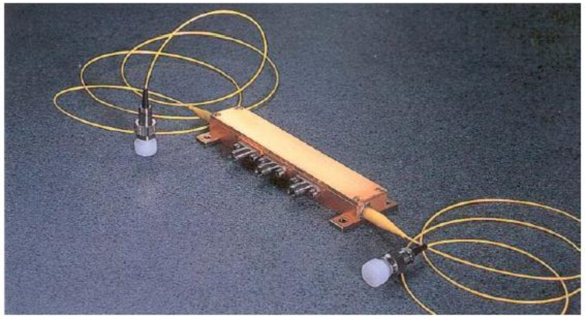
- Single mode lasers are expensive.

- Current modulation causes frequency chirping (due to a time-varying refractive index) that leads to pulse dispersion in long-distance optical fibers.

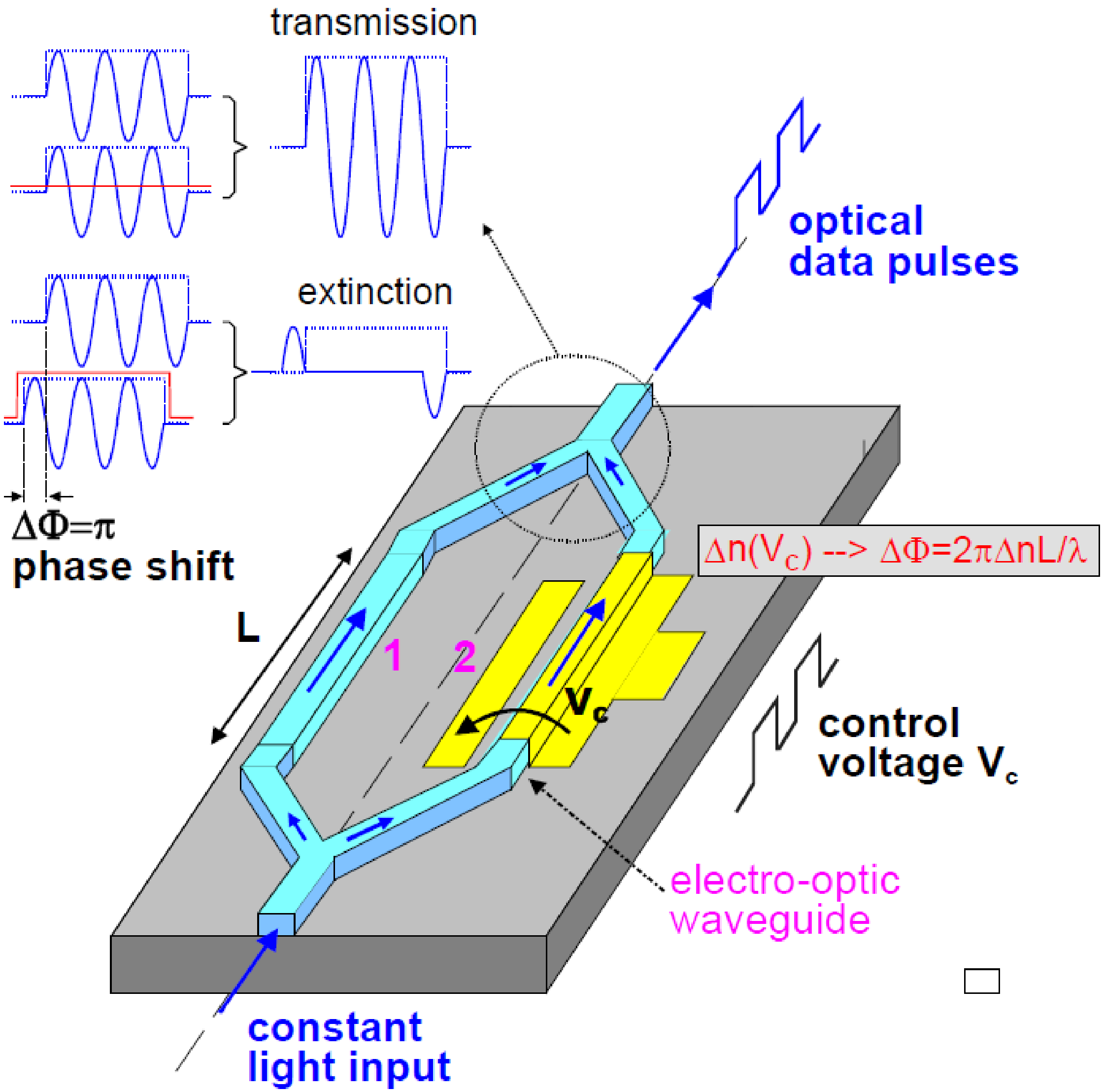
- At high data rates, modulating the laser directly consumes a lot of power.

Solution: external modulators

Based on the **electro-optical effect**: electrical modulation of the refractive index.



40 GHz Lithium-Niobat
Mach-Zehnder-Modulator (package)

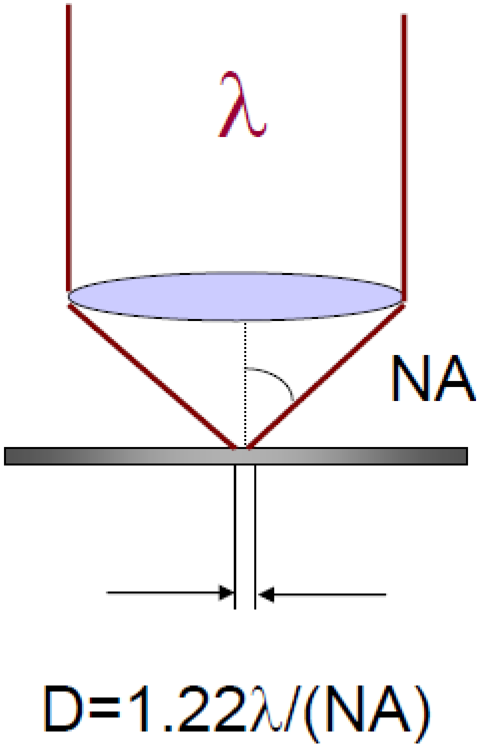


Adapted from H. Jäckel, ETHZ

Evolution of optical data storage systems

First generation (1980s): CDs

- The information is in a 2D surface of a recording medium and occupies less than **0.01 %** of the volume.
- λ =780 nm
- Due to the limitation of the recording wavelength and the numerical aperture (NA) of the recording lens, the storage capacity was **650-750 MB**.

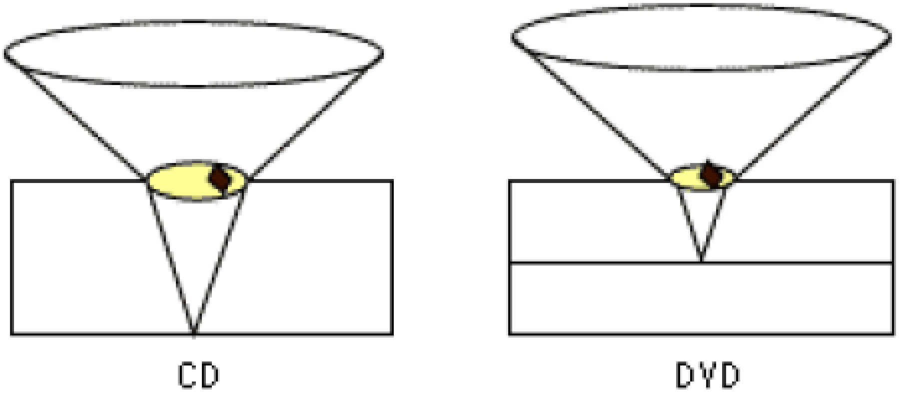


Diffraction-limited
Focused Spot

Next generations

Digital versatile disks (DVDs, 1995)

- λ=650 nm
- Storage capacity = 4.7 GB

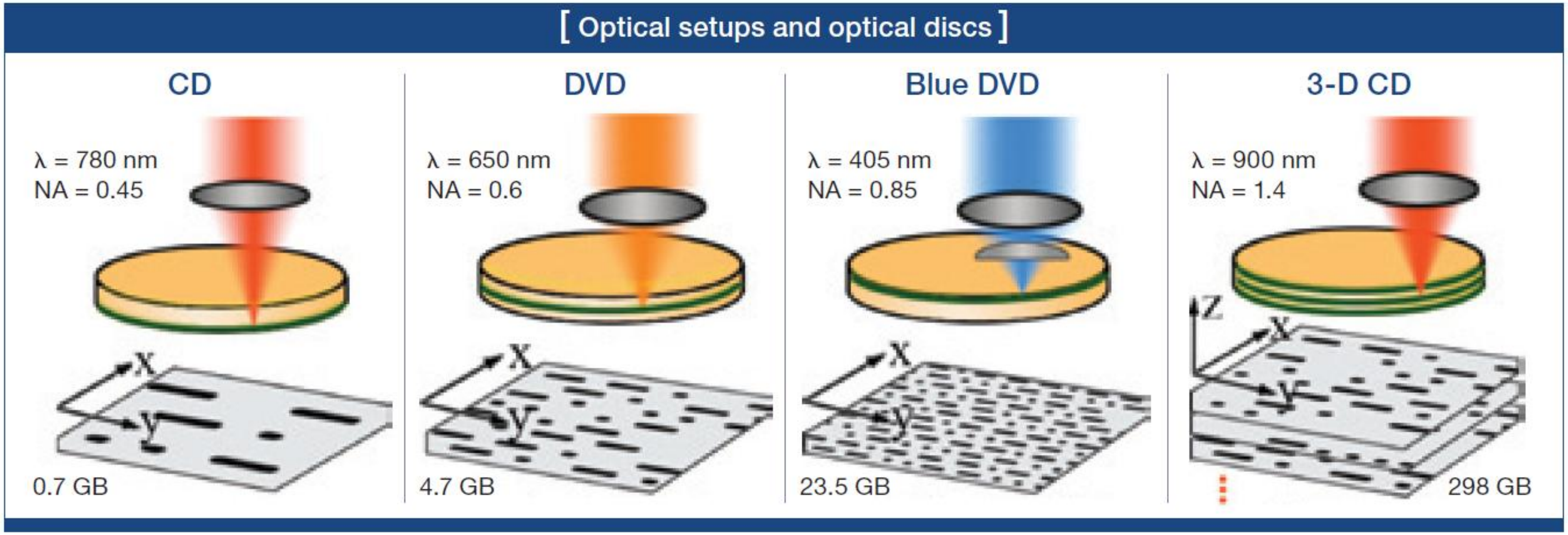


Blue DVDs (Blu-rays)

- λ=405 nm
- 23.5 GB/disc

- **What is next?**
  - 3D systems (via, e.g., 2-photon absorption to decrease depth of field for more layers)
  - shorter wavelengths (via nonlinear optics: frequency doubling)
  - supra-resolution imaging (stimulated emission depletion STED)
  - holographic data storage, etc.

Data storage: we are also a long way from the beginning

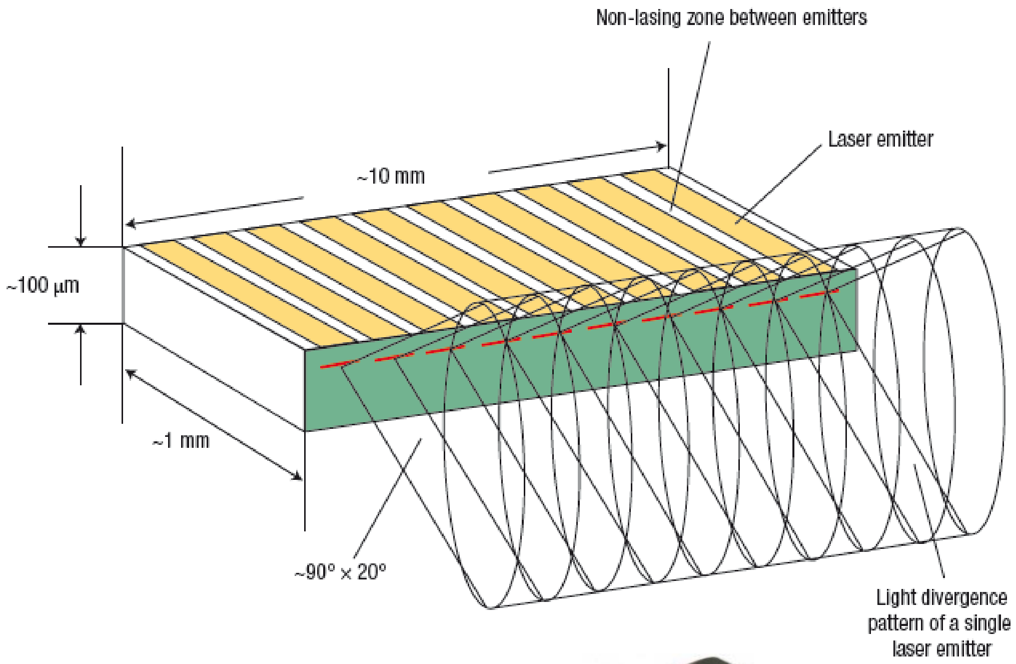


Storage capacity: about 0.01 byte / mm^2

(adapted from K. Tatebe)

Source: Optics and Photonics News July/August 2010

Laser arrays provide high output power for printing, material processing, etc.

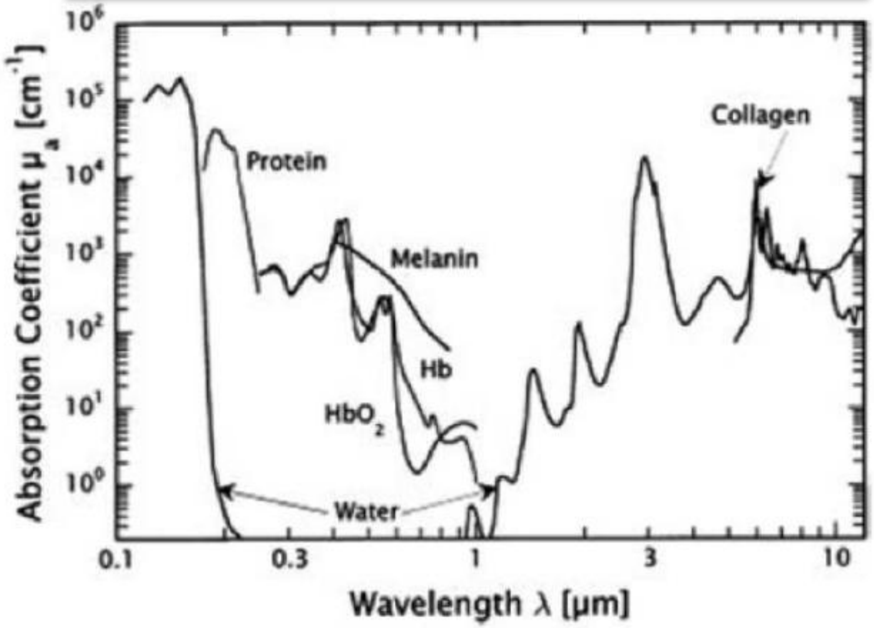


Source: Nat. Phot. Technology focus, July 2007

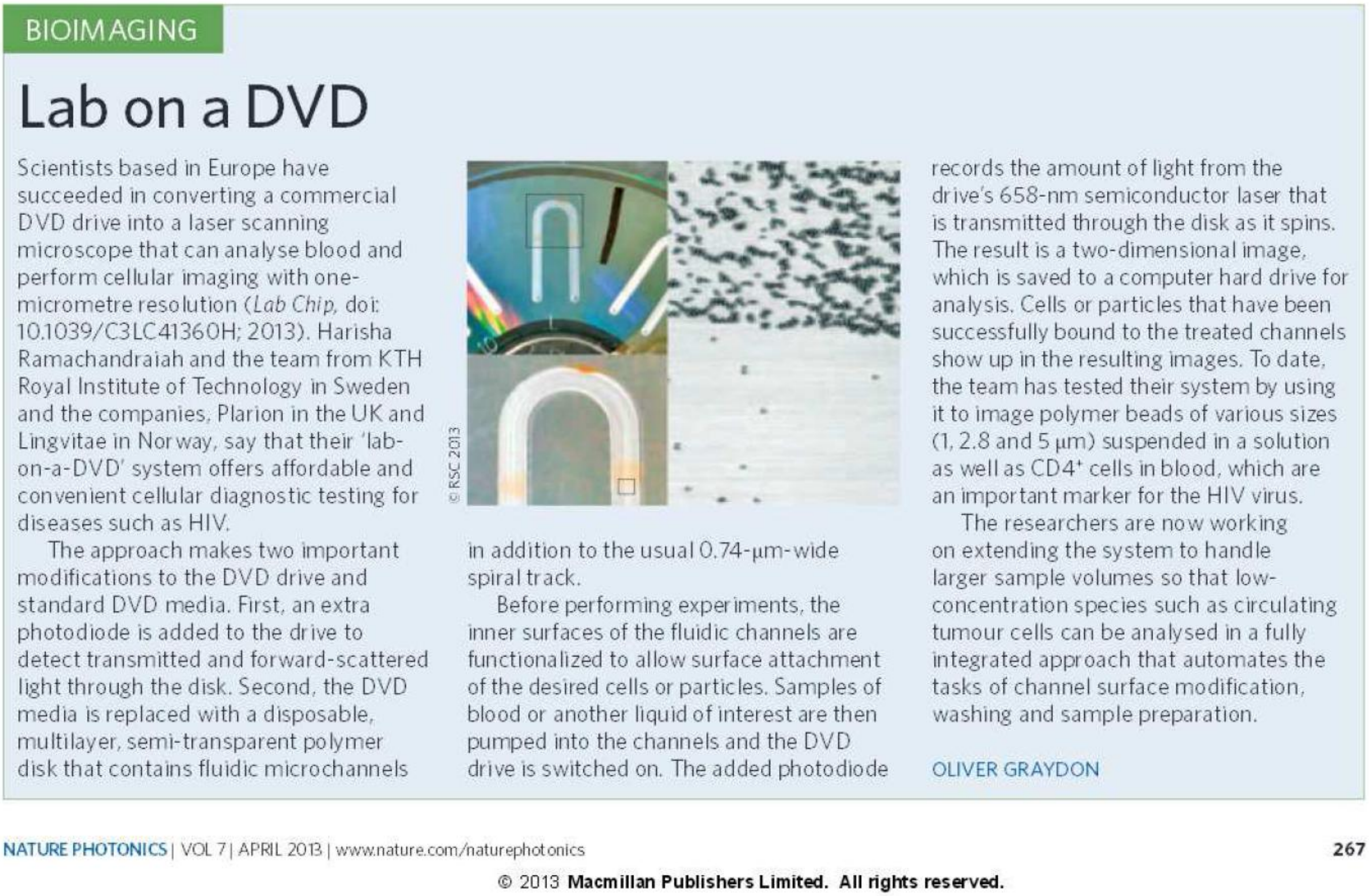
Wavelengths for biomedical applications

- Gallium arsenide (GaAs) yield **reds** (above 630 nm)
- Indium phosphide (InP) yields **blues** (375-488 nm)
- Indium gallium nitride (InGaN) yields **greens**: (515-536.6nm)
- Biomedical devices can combine multiple laser diodes for multiple wavelengths.

Absorption coefficients of the key components of tissue



Source: Mark May, Solving biomedical problems with laser diodes, BioOptics World, http://bit.ly/18NoouU



BIOIMAGING

Lab on a DVD

Scientists based in Europe have succeeded in converting a commercial DVD drive into a laser scanning microscope that can analyse blood and perform cellular imaging with one-micrometre resolution (*Lab Chip*, doi: 10.1039/C3LC41360H; 2013). Harisha Ramachandraiah and the team from KTH Royal Institute of Technology in Sweden and the companies, Plarion in the UK and Lingvitae in Norway, say that their 'lab-on-a-DVD' system offers affordable and convenient cellular diagnostic testing for diseases such as HIV.

© RSC 2013

The approach makes two important modifications to the DVD drive and standard DVD media. First, an extra photodiode is added to the drive to detect transmitted and forward-scattered light through the disk. Second, the DVD media is replaced with a disposable, multilayer, semi-transparent polymer disk that contains fluidic microchannels in addition to the usual 0.74-μm-wide spiral track.

Before performing experiments, the inner surfaces of the fluidic channels are functionalized to allow surface attachment of the desired cells or particles. Samples of blood or another liquid of interest are then pumped into the channels and the DVD drive is switched on. The added photodiode records the amount of light from the drive's 658-nm semiconductor laser that is transmitted through the disk as it spins. The result is a two-dimensional image, which is saved to a computer hard drive for analysis. Cells or particles that have been successfully bound to the treated channels show up in the resulting images. To date, the team has tested their system by using it to image polymer beads of various sizes (1, 2.8 and 5 μm) suspended in a solution as well as CD4$^+$ cells in blood, which are an important marker for the HIV virus.

The researchers are now working on extending the system to handle larger sample volumes so that low-concentration species such as circulating tumour cells can be analysed in a fully integrated approach that automates the tasks of channel surface modification, washing and sample preparation.

OLIVER GRAYDON

NATURE PHOTONICS | VOL 7 | APRIL 2013 | www.nature.com/naturephotonics 267

A few examples of biomedical applications that use laser diodes

Dental DNA analysis

- Take sample by swiping teeth with a toothpick like piece of paper.
- Placing the sample in a device that amplifies the DNA with the polymerase chain reaction (PCR) fluorescent labeling plus a laser diode and a photo-detector can identify 11 types of bacteria.
- Used to select the best antibiotic treatment.

Source: Mark May, Solving biomedical problems with laser diodes,
BioOptics World, http://bit.ly/18NoouU

Cancer treatment

- **Optical imaging for cancer detection**
  - Transmit light through the tissue
  - Then assess the results based on absorption and scattering
  - Laser-diode choice?
  - Near-infrared: 600–1000nm
  - Penetrates deeper because of low absorption by water.
  - By fiber-coupling the laser diode the light can be delivered directly to tissue.
- **Tumor ablation**
  - 590-1064 nm: maximum photo-thermal effect in human tissue
  - Laser diodes emitting in the 800-980nm range have been used for kidney and brain tumors ablation

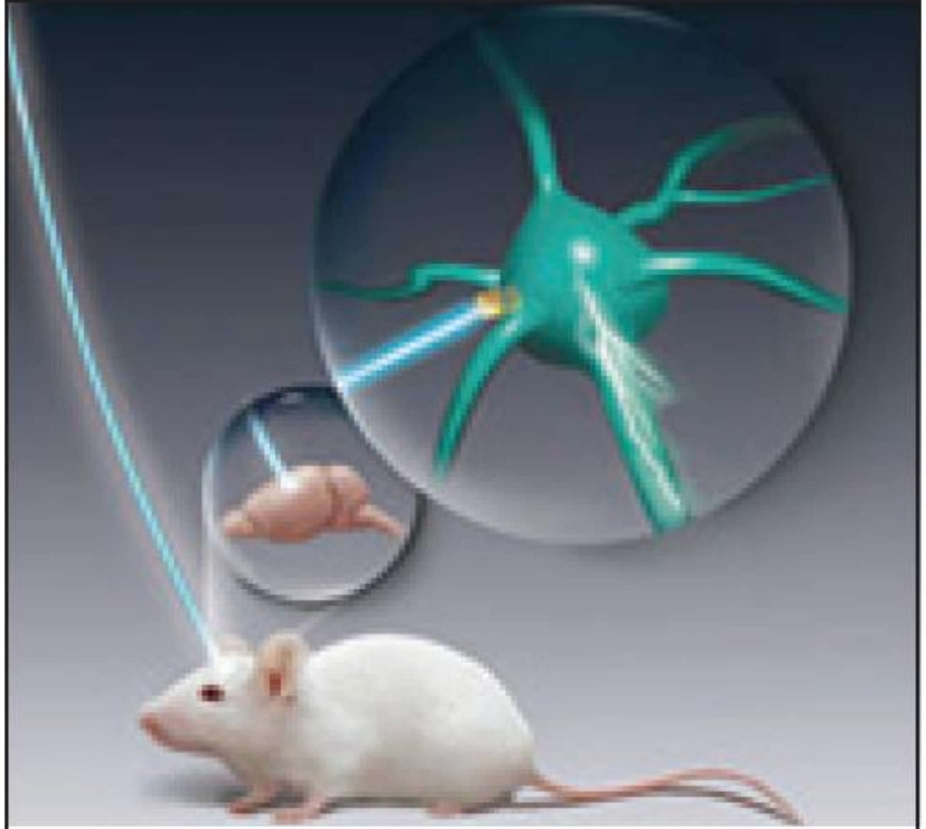
Source: Mark May, BioOptics World

Optogenetics

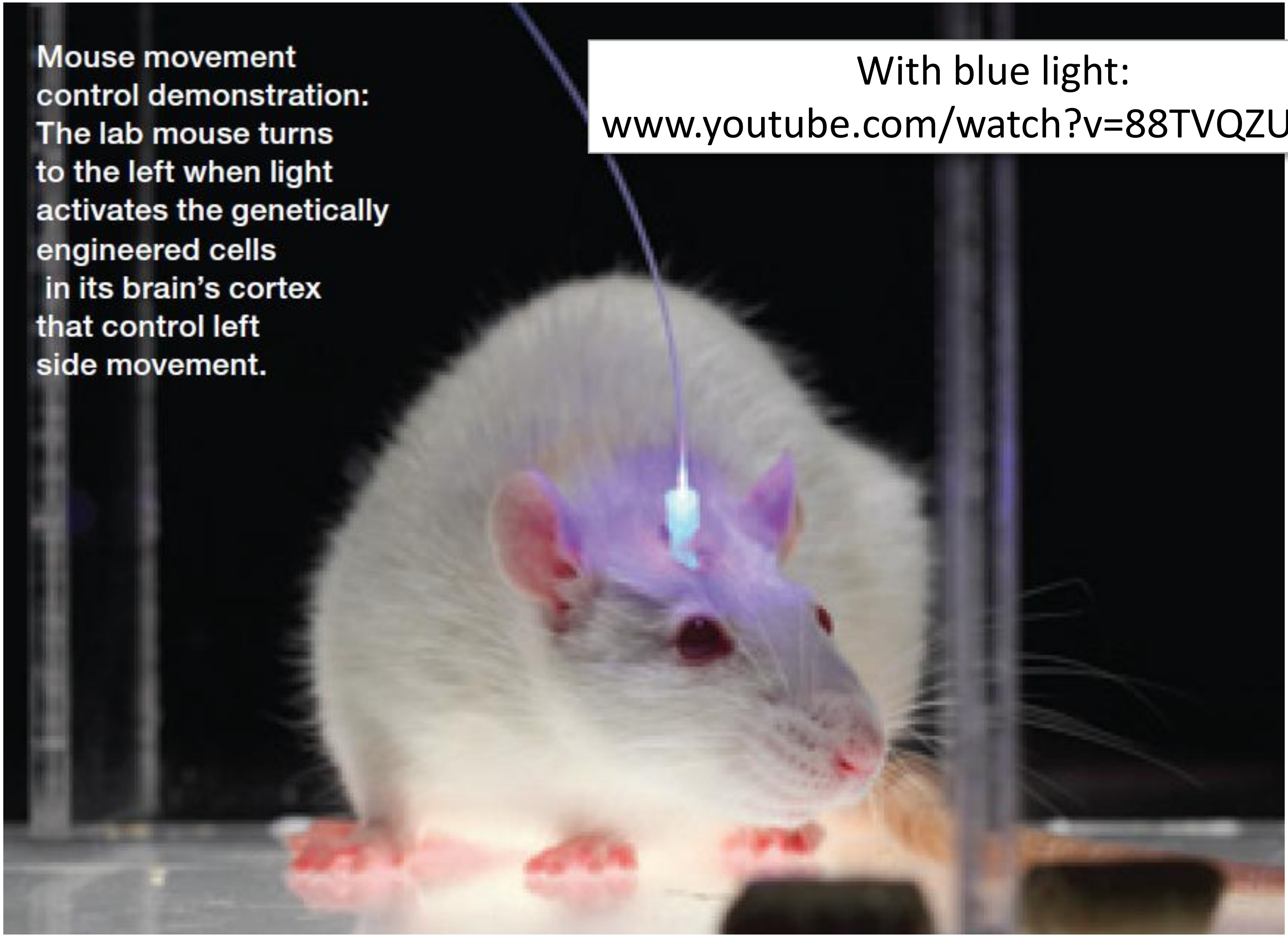
Two main approaches

- laser light inhibits or stimulates cells
- laser light triggers a drug effect

[Making neurons react to light]



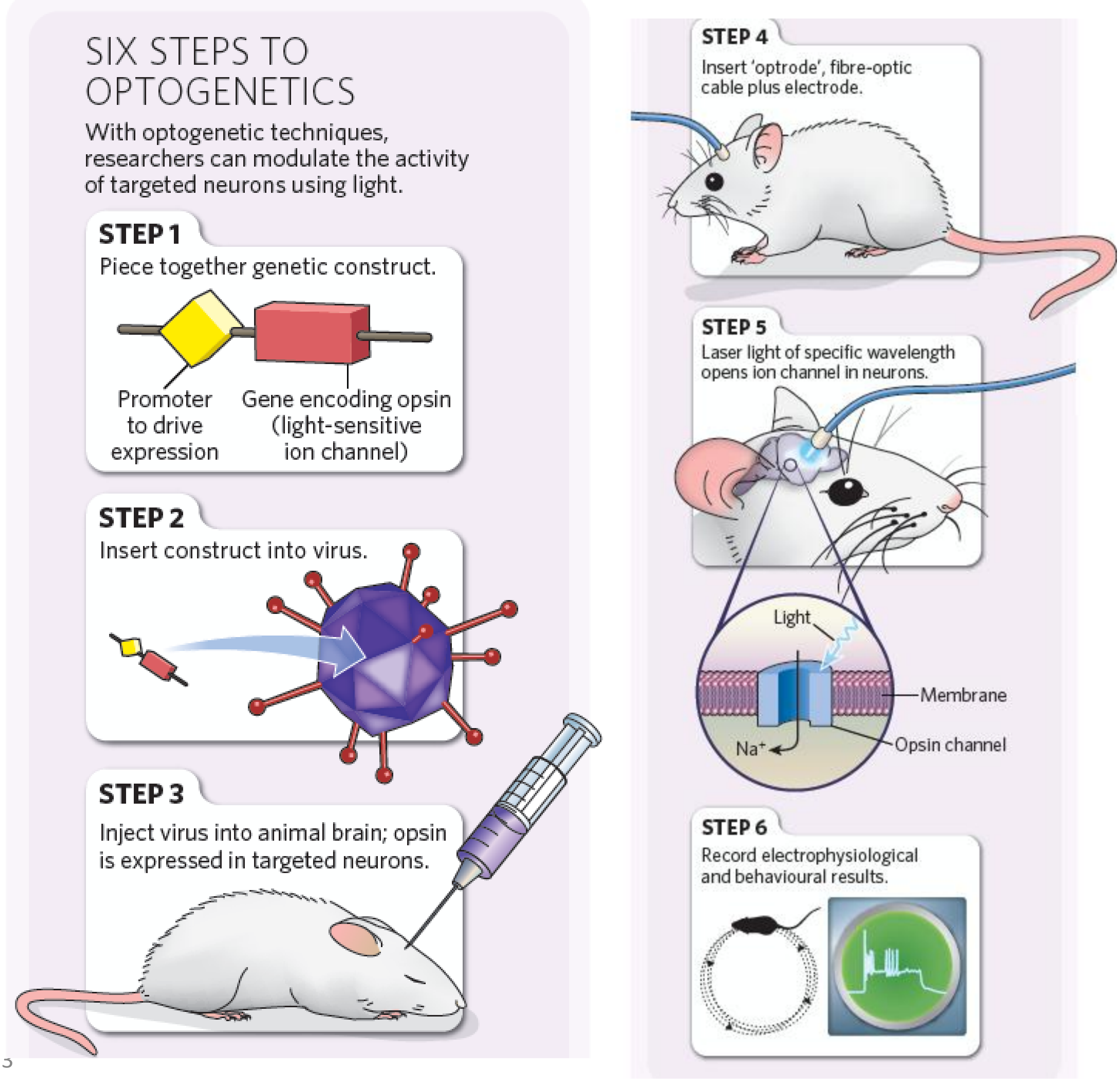
Neuroscientists insert opsin genes into brain cells with the help of engineered viruses. They can then trigger these cells on demand with pulses of light and observe the effects on experimental animals' behavior.



Mouse movement control demonstration: The lab mouse turns to the left when light activates the genetically engineered cells in its brain's cortex that control left side movement.

With blue light:
www.youtube.com/watch?v=88TVQZUfYGw

Nature Vol. 465, 6 May 2010,
Optics and Photonics News, August 2011



SIX STEPS TO OPTOGENETICS

With optogenetic techniques, researchers can modulate the activity of targeted neurons using light.

STEP 1
Piece together genetic construct.

STEP 2
Insert construct into virus.

STEP 3
Inject virus into animal brain; opsin is expressed in targeted neurons.

STEP 4
Insert 'optrode', fibre-optic cable plus electrode.

STEP 5
Laser light of specific wavelength opens ion channel in neurons.

STEP 6
Record electrophysiological and behavioural results.

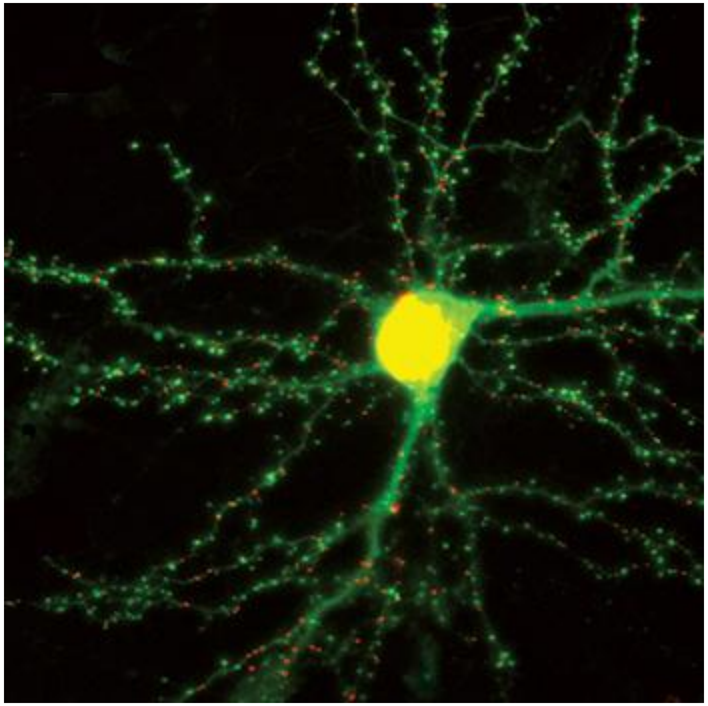
Which light source?

- Illuminating a small number of neurons in the brain requires a low-noise laser.
- In coarser applications, power fluctuations of the laser over micro- or milliseconds might not matter.
- Most users want a variety of laser wavelengths: one to excite cells and one to inhibit them.
- LEDs can also be used in optogenetics:
  - LEDs are more readily available in different colors than laser diodes, and
  - they are much cheaper.

Source: Mark May, BioOptics World

Fluorescing live synapses shed light on learning, memory formation

By using a green fluorescent protein (GFP), which glows brightly when exposed to blue light, researchers studied structural changes in the brain when we make a memory or learn something (and found that that gets changed is the distribution of synaptic connections).



G.G. Gross et al., *Neuron*, 78, 6, 971–985 (2013).

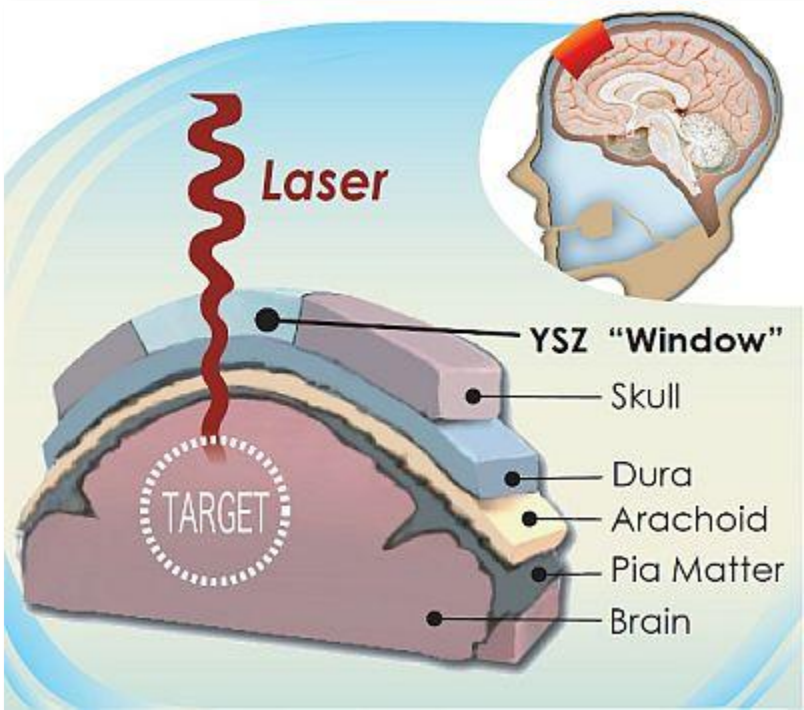
LED therapy boosts cognitive function following brain injury

- Two patients with chronic traumatic brain injury (TBI) were treated with transcranial LEDs.
- The patients showed significant improvement in concentration and memory.
- Light source: a LED console device, containing 52 near-infrared (870 nm) and nine red (633 nm) diodes for a total output power of 500 mW (±20%) continuous wave.
- But the patients' improvements vanished if they stopped the treatment.

Photomedicine & Laser Surgery (doi:10.1089/pho.2010.2814)

A transparent permanent window to the brain

- Yttria-stabilized-zirconia (YSZ) is a ceramic material, which is well tolerated and used in hip implants and dental crowns.
- It was modified to make it transparent.
- The modified YSZ prosthesis provide a permanent window through which doctors can aim light-based treatments for the brain without having to perform repeated craniectomies.



Y. Damestani et al, Nanomedicine: Nanotechnology, Biology and Medicine Volume 9, Issue 8 , Pages 1135-1138, November 2013

Big money

Is being invested in the US and in the EU in brain research:

- in the US: 100 M proposed by Obama for the BRAIN Initiative (Brain Research through Advancing Innovative Neurotechnologies)
- In the EU: 10 year Human Brain Project (54 M€ for the rump up phase, 2013-2016)

TheBrain Initiative

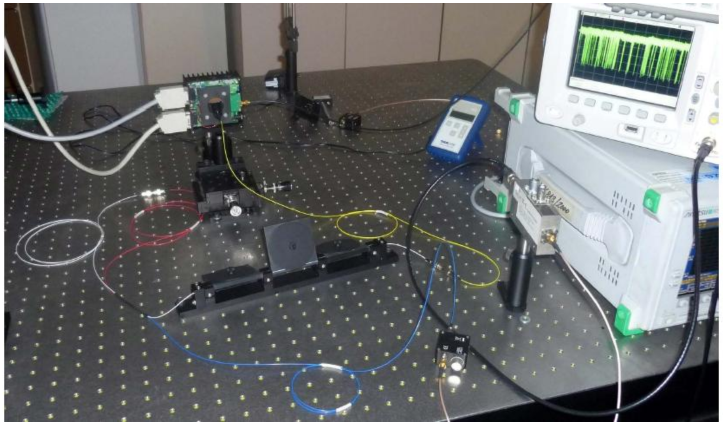
http://thebraininitiative.org

Human Brain Project

http://www.humanbrainproject.eu

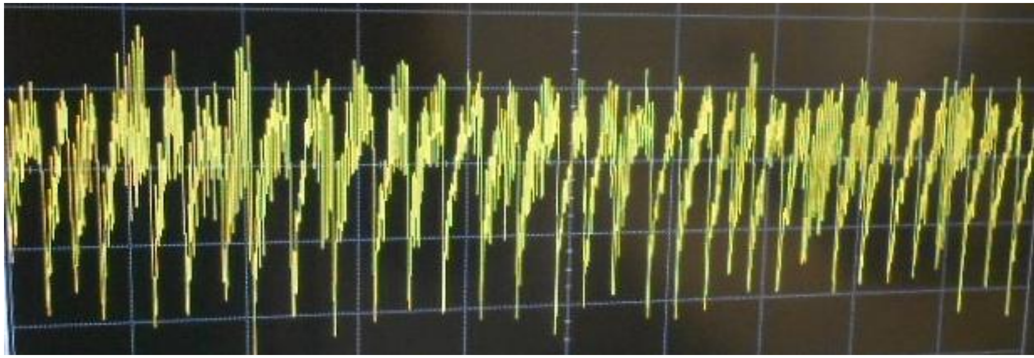
Research at our lab: from laser diodes to neurons and back

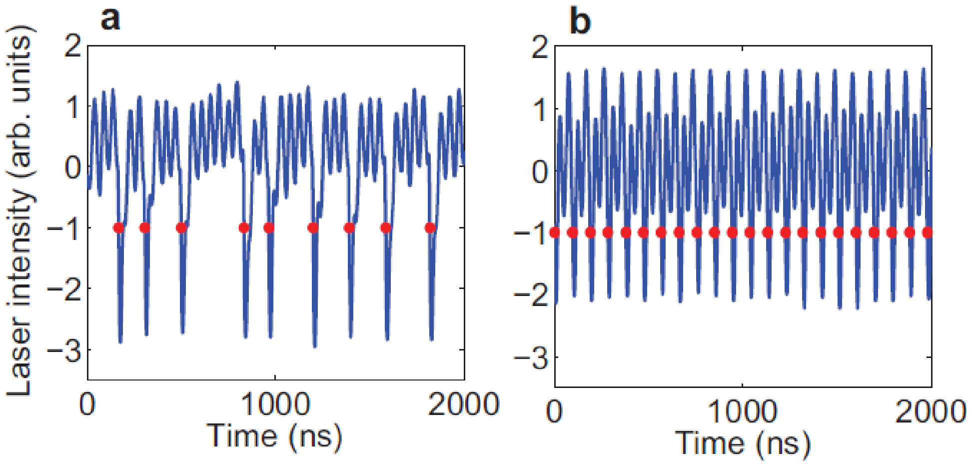
Experimental setup: a laser diode with optical feedback



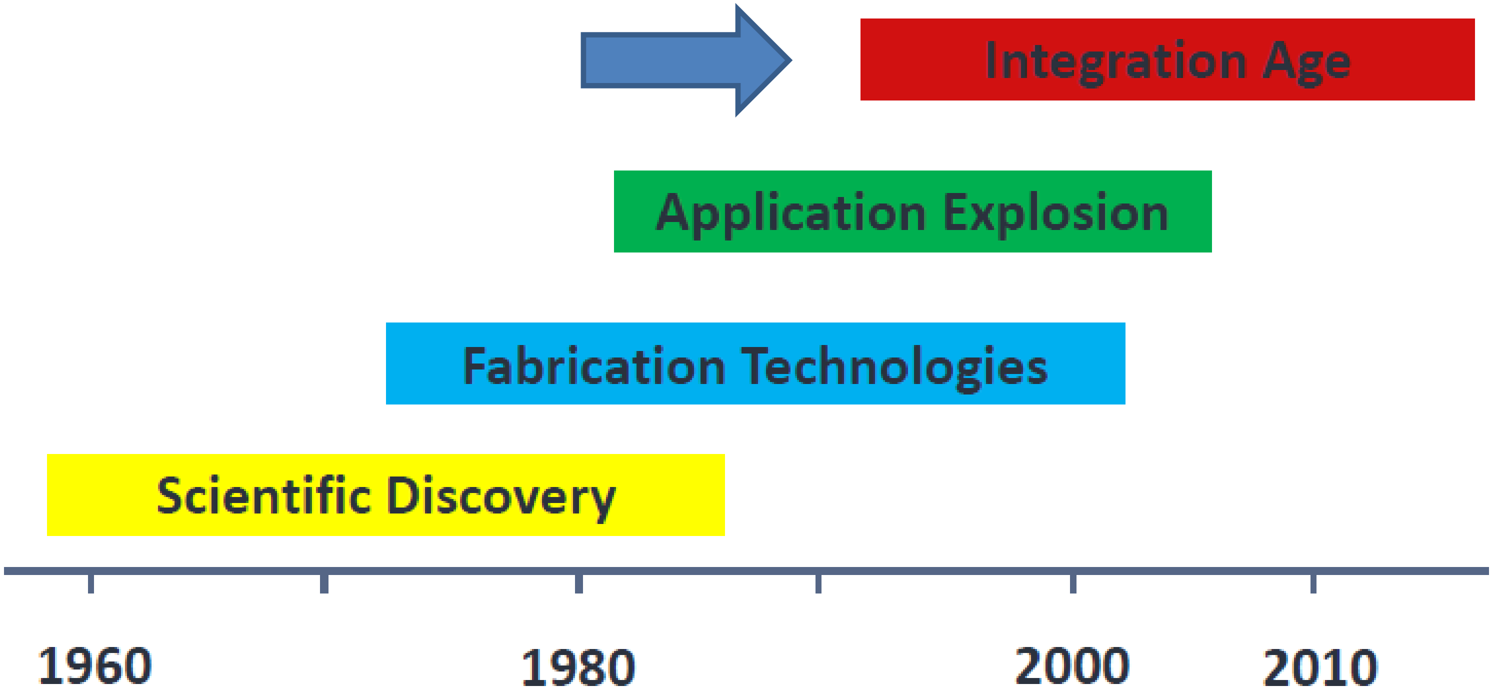
With current modulation: forced spike sequence

Optical spikes





Laser Diode Evolution



Integration Age

Application Explosion

Fabrication Technologies

Scientific Discovery

1960

1980

2000

2010

Adapted from D. Welch, Infinera

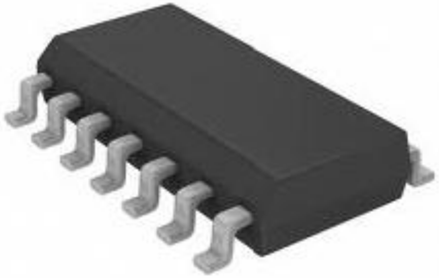
Why integrate?

In electronics:

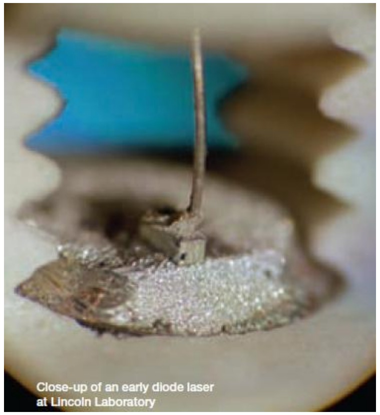
Vacuum tubes

Transistor

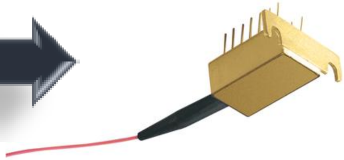
Integrated circuit



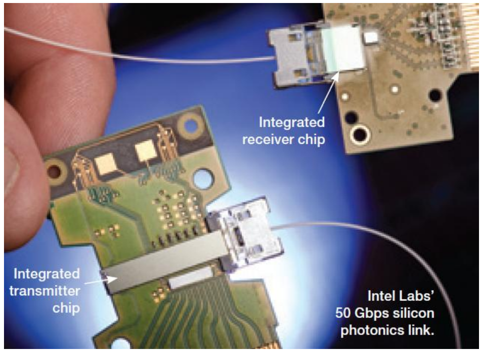
In photonics:



Diode laser

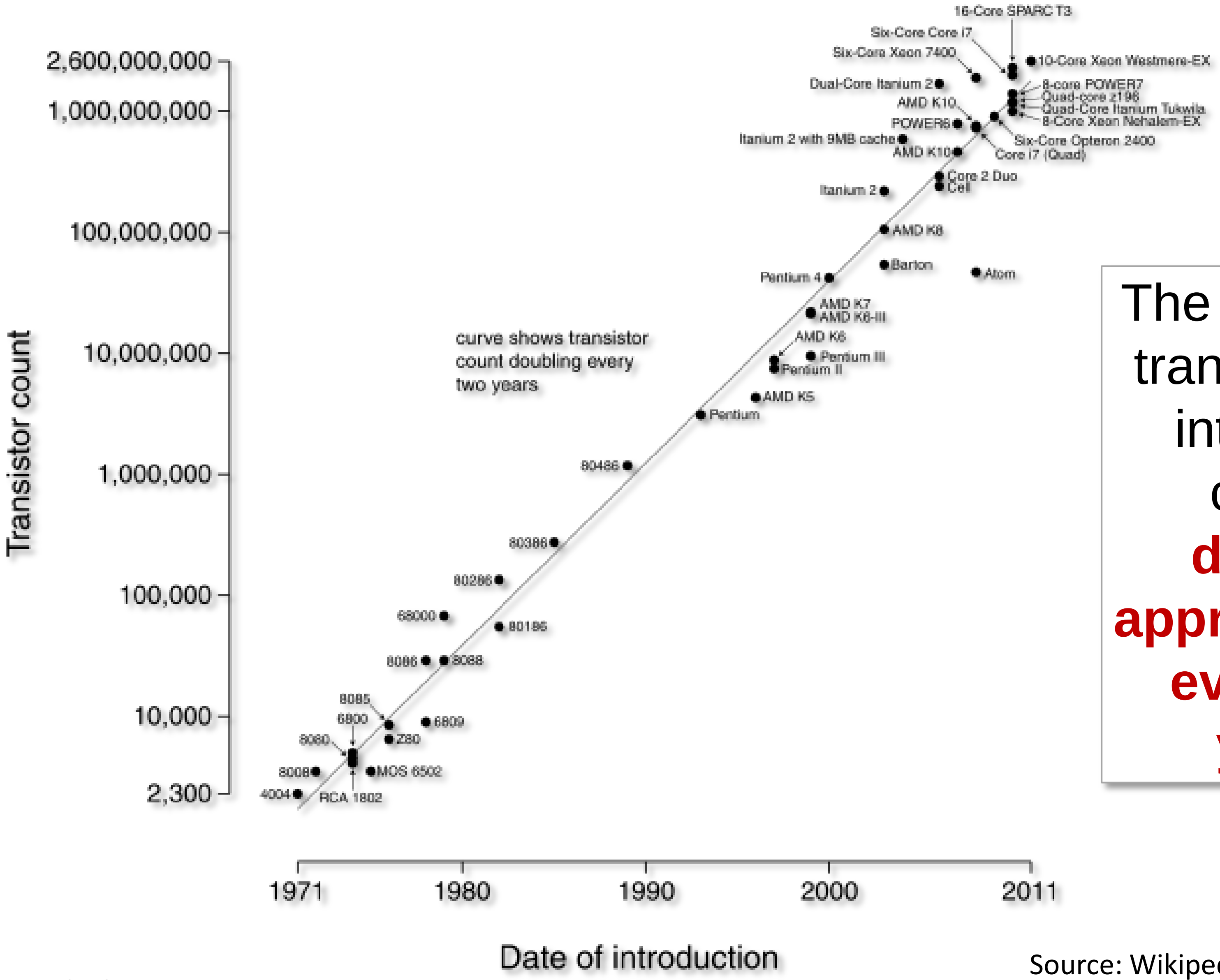


Photonic integrated circuit (PIC)



Adapted from Optics & Photonics News and D. Welch, Infinera

Microprocessor Transistor Counts 1971-2011 & Moore's Law



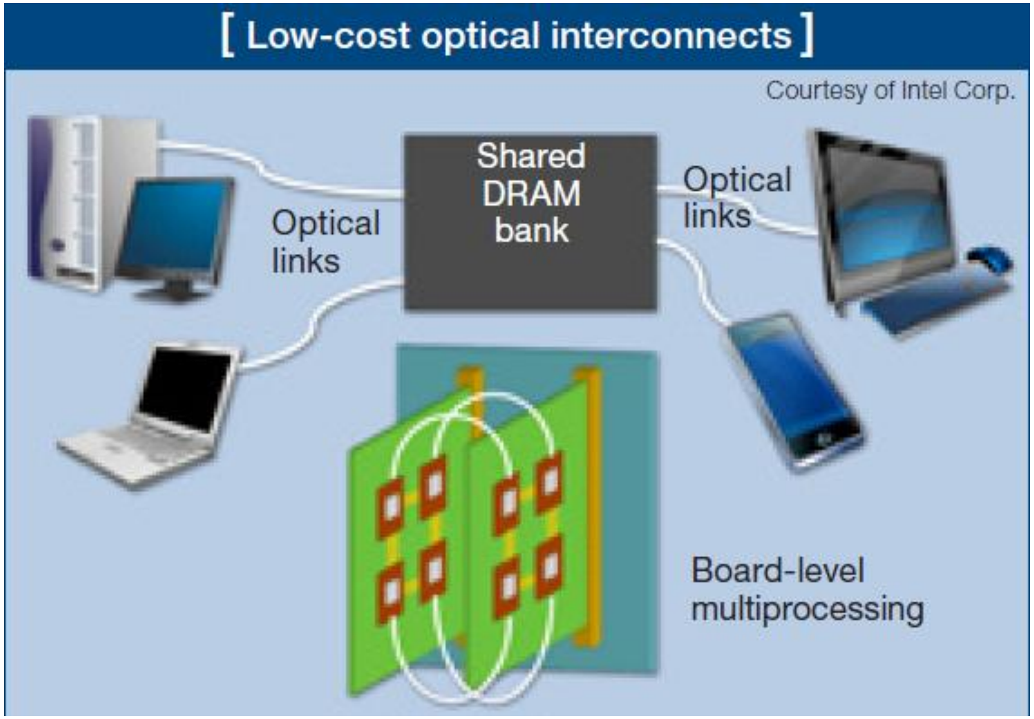
The number of transistors on integrated circuits **doubles approximately every two years**.

Source: Wikipedia

Big data

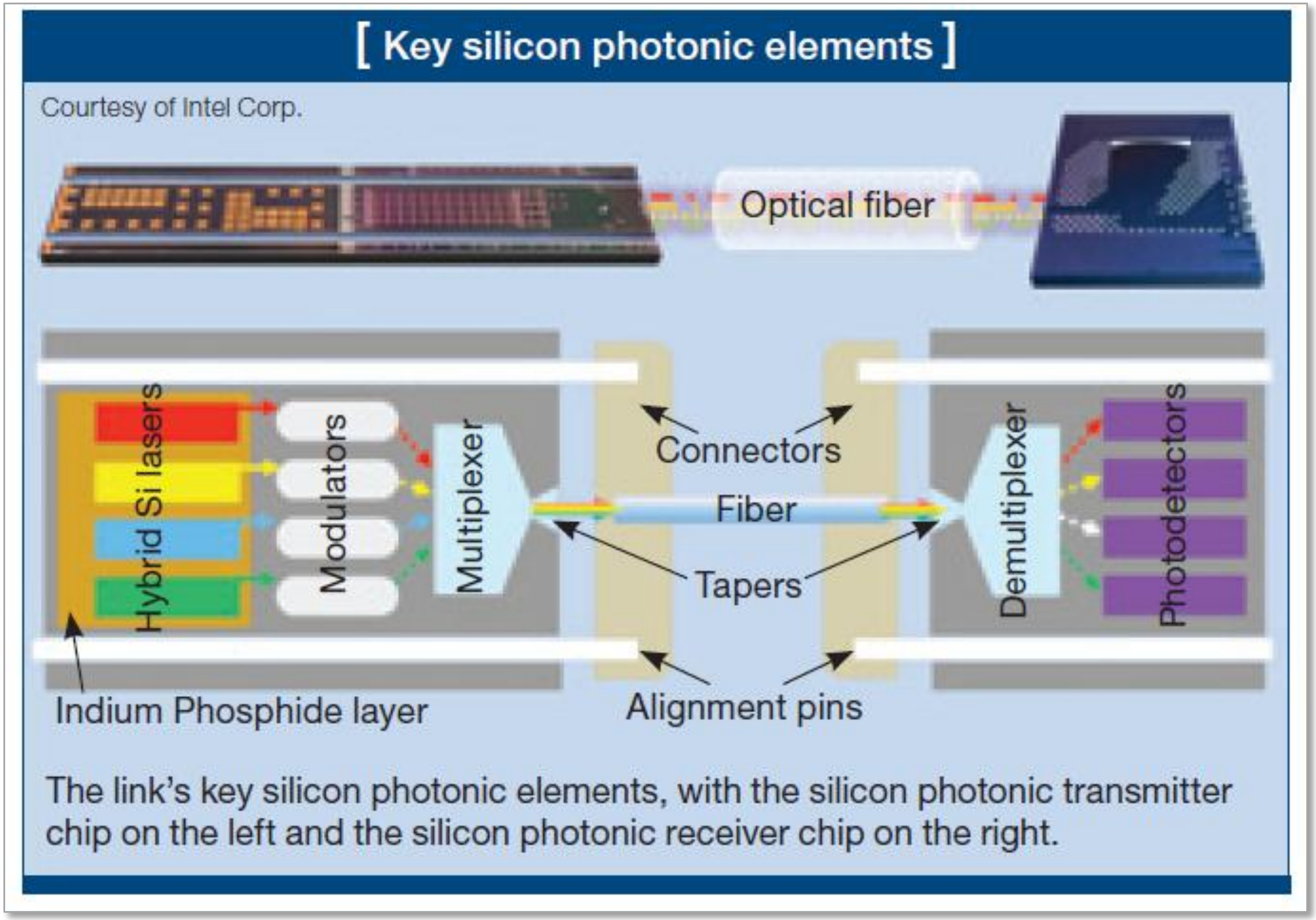
- In 2014, the Internet will be four times larger than it was in 2009.
- Companies and social networks contribute to the data explosion: huge databases, HDTV, video conferencing, etc.
- Multicore processors are packing more computing capability into smaller spaces. But these high-performance processors are constrained both electrically and physically.
- Can’t continue like this. The space is limited and the energy consumption is becoming unsustainable.

Solution: photonic integrated circuits (PICs)



Building lasers from silicon –the inexpensive core of computer chips– will allow to drastically increase the speed and capacity of data channels inside and between chips and computers.

Source: Optics and Photonics News, March 2011



[Key silicon photonic elements]

Courtesy of Intel Corp.

The link's key silicon photonic elements, with the silicon photonic transmitter chip on the left and the silicon photonic receiver chip on the right.

Goal: bonding lasers made with light emitting semiconductors to silicon chips.

Source: Optics and Photonics News, March 2011

Problem

- Silicon is optically transparent at telecom wavelengths (1,310 and 1,550 nm), so it can be used to create waveguides.
- But silicon lacks the necessary physical properties for active devices: the direct bandgap needed for light emission or the electro-optic effect used for modulation of light.
- Because of the different atomic structures of silicon and the semiconductors III-V that are efficient light emitters, growing those typically require temperatures in the range of 700^{o}C. Such temperatures destroy the other features on the chip.

nature photonics
FOCUS | PROGRESS ARTICLE
PUBLISHED ONLINE: 30 JULY 2010 | DOI: 10.1038/NPHOTON.2010.167

Recent progress in lasers on silicon

Di Liang* and John E. Bowers

Various ways of fabricating lasers on silicon are discussed.

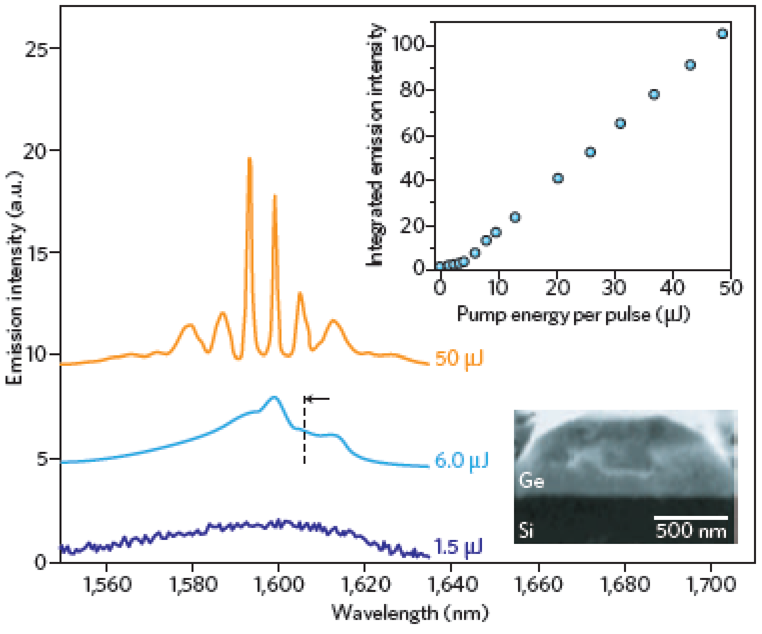


Figure 3 | Optically pumped Ge-on-Si laser demonstrating CW operation at room temperature. Edge-emission spectra of a Fabry–Pérot

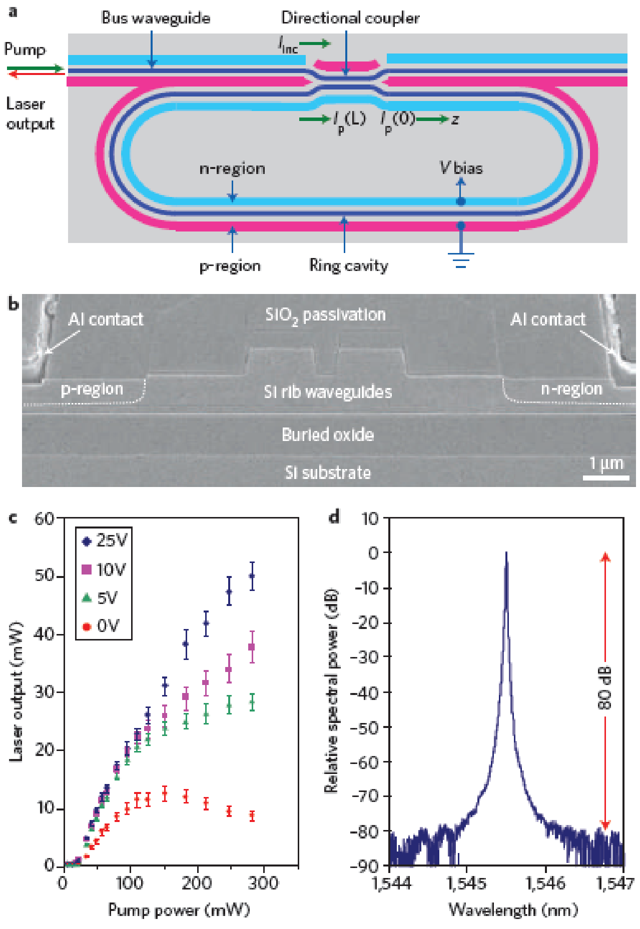
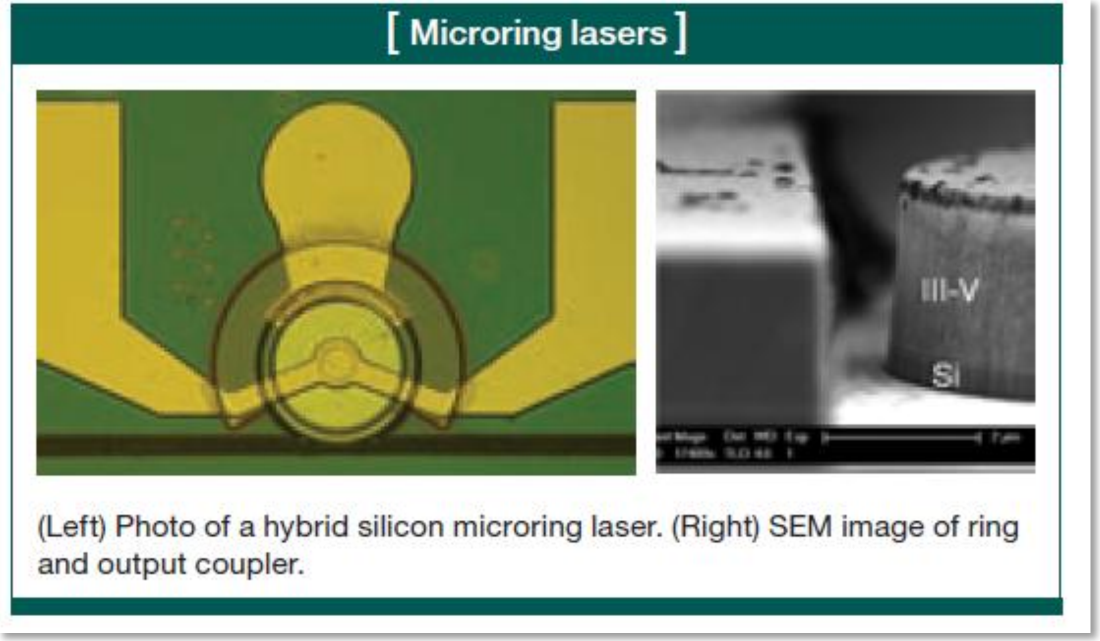


Figure 2 | Low-threshold Si Raman racetrack ring laser. a, Schematic of a device with a p-i-n junction design. $I_p(0)$ and $I_p(L)$ are the pump power at

John Bowers, Di Liang, Alexander Fang,
Hyundai Park, Richard Jones and Mario Paniccia

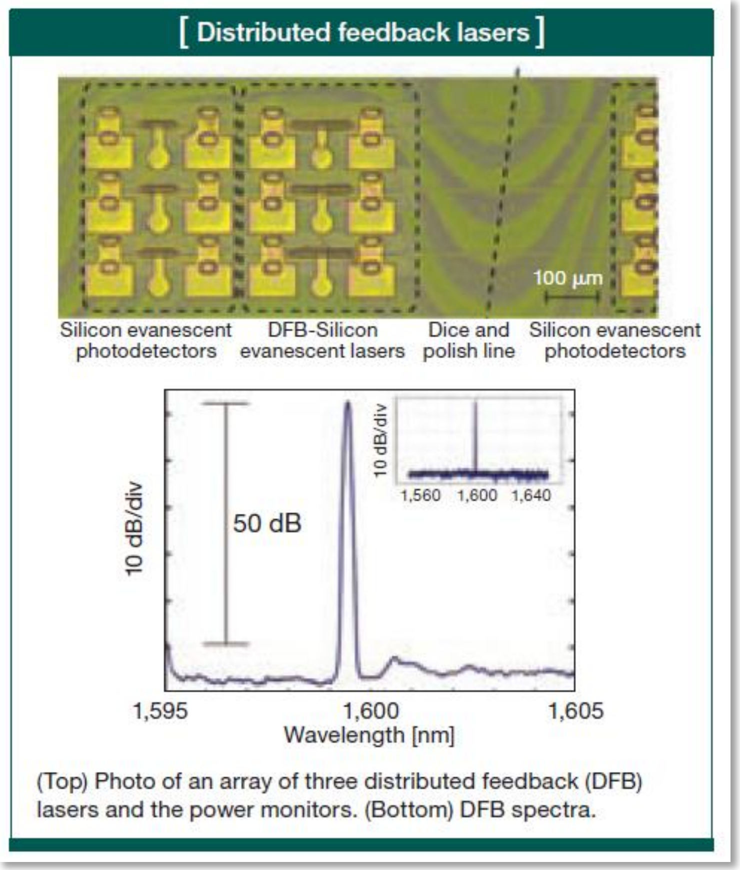
Hybrid Silicon Lasers

The Final Frontier to Integrated Computing



[Microring lasers]

(Left) Photo of a hybrid silicon microring laser. (Right) SEM image of ring and output coupler.



[Distributed feedback lasers]

(Top) Photo of an array of three distributed feedback (DFB) lasers and the power monitors. (Bottom) DFB spectra.

Optics and Photonics News, May 2010

How small can a laser be?

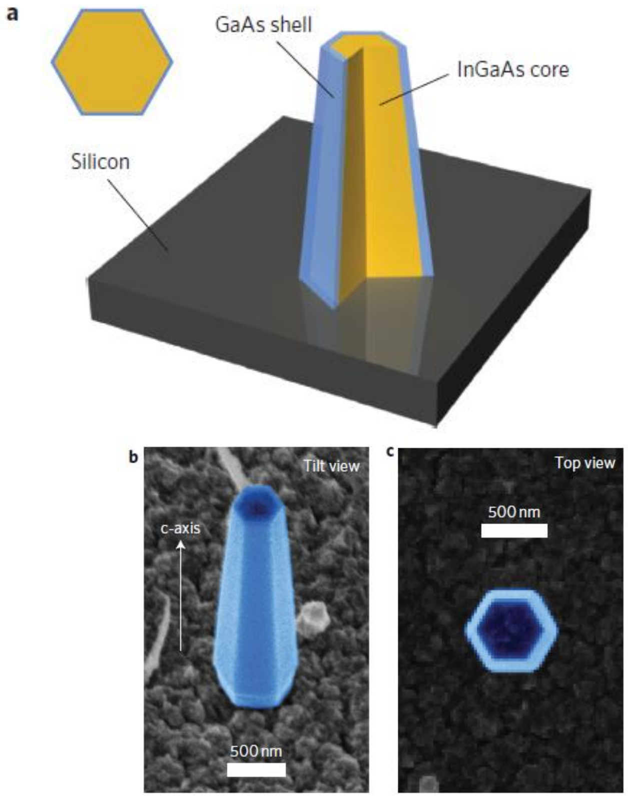
- **Diffraction** is the ultimate limit: the need to fit an optical mode inside a cavity ⇒ the cavity cannot be smaller than ~ 1/2 wavelength of the emitted light.
- However, **nanolasers** (first demonstrated in 2007) instead of confining optical energy in a cavity in the form of a conventional optical mode, it is confined with the help of **surface-plasmons** — free-electron oscillations that are bound to the interface between a metal and a dielectric.
- The great advantage of plasmons is not only that they can store optical energy on a very small dimension but they **are easy to excite by light and convert back into light**.

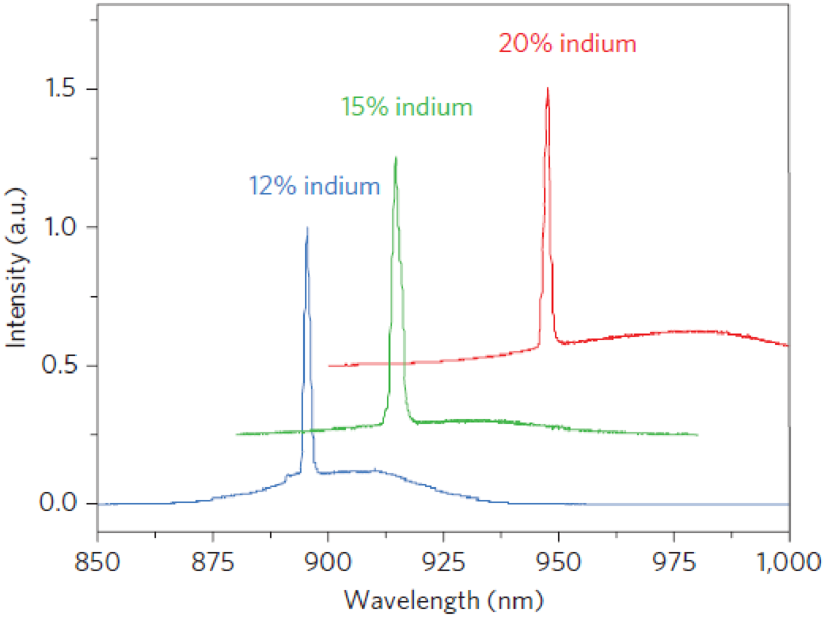
Noginov, M.A. et al.Nature 460, 1110–1112 (2009).
Oulton, R.F. et al. Nature doi:10.1038/nature08364

ARTICLES
PUBLISHED ONLINE: 6 FEBRUARY 2011 | DOI: 10.1038/NPHOTON.2010.315
nature photonics

Nanolasers grown on silicon

Roger Chen, Thai-Truong D. Tran, Kar Wei Ng, Wai Son Ko, Linus C. Chuang, Forrest G. Sedgwick and Connie Chang-Hasnain*

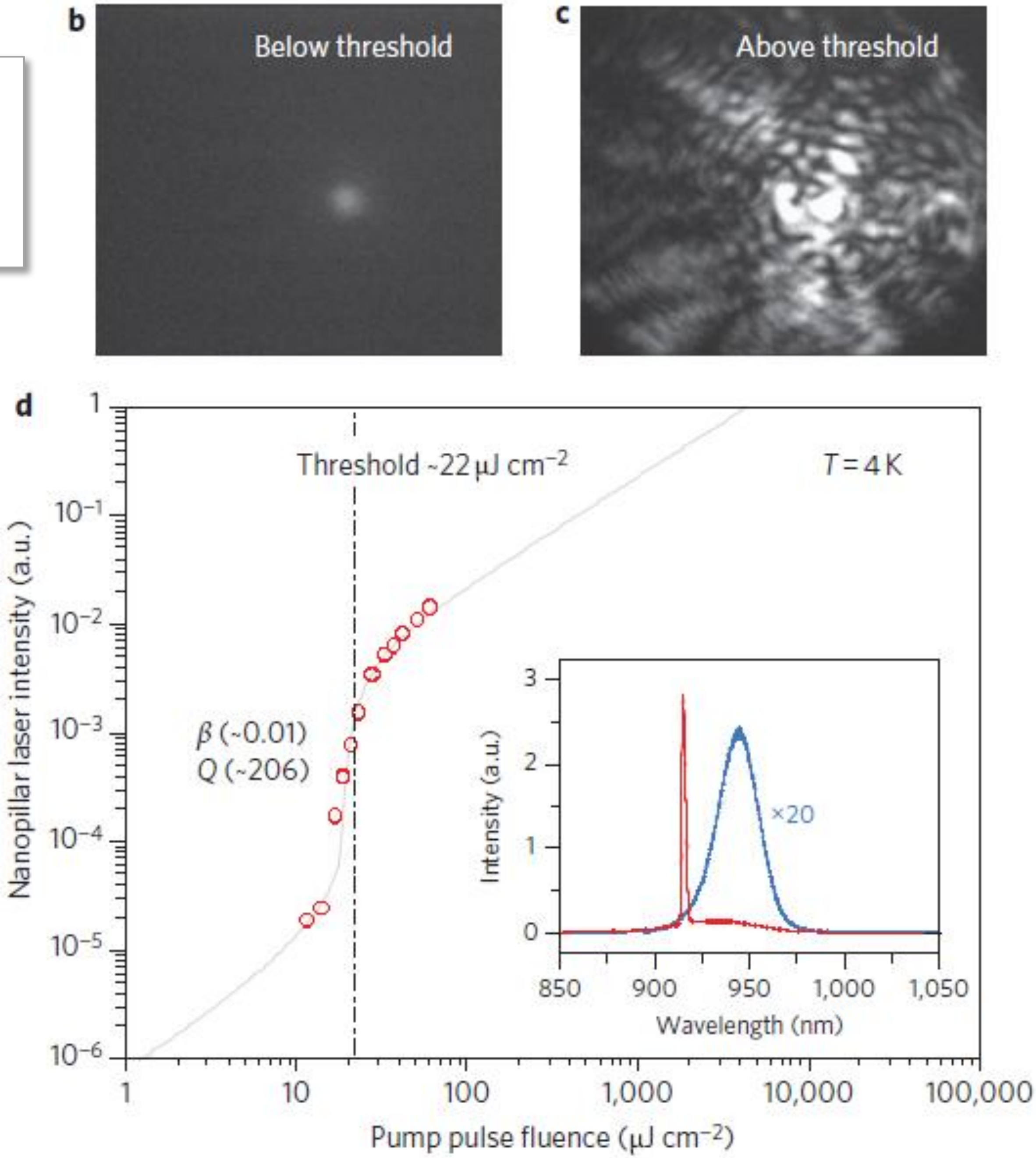




Wavelength tuning by composition variation

Optically pumped by using a mode-locked Ti:sapphire laser

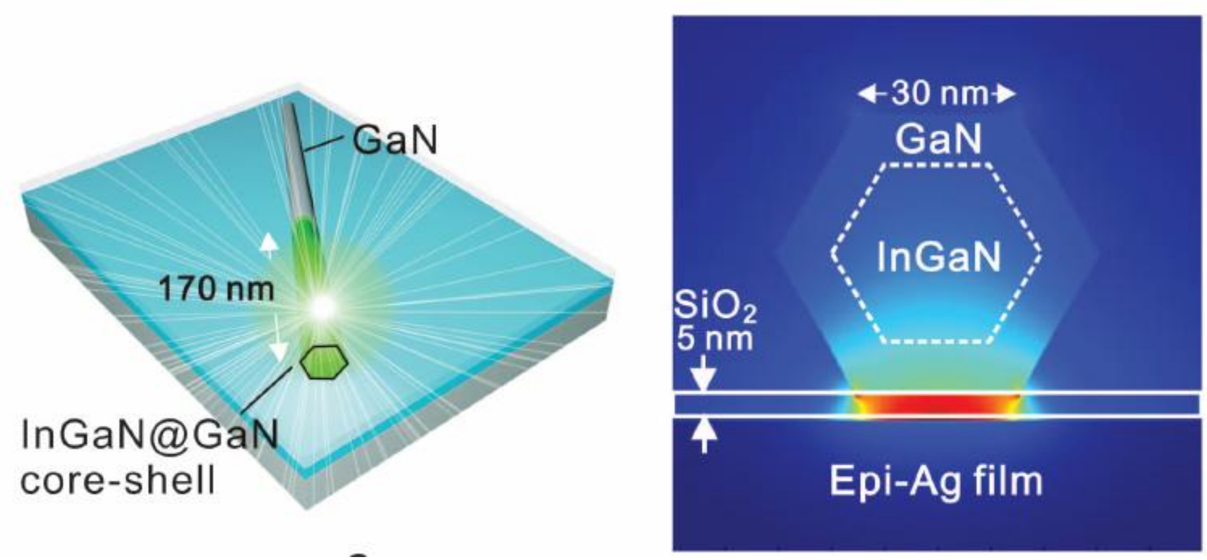
The lasing signature can be seen from the "kink" of the L-L plot and the linewidth narrowing.



The world’s smallest nanolaser?

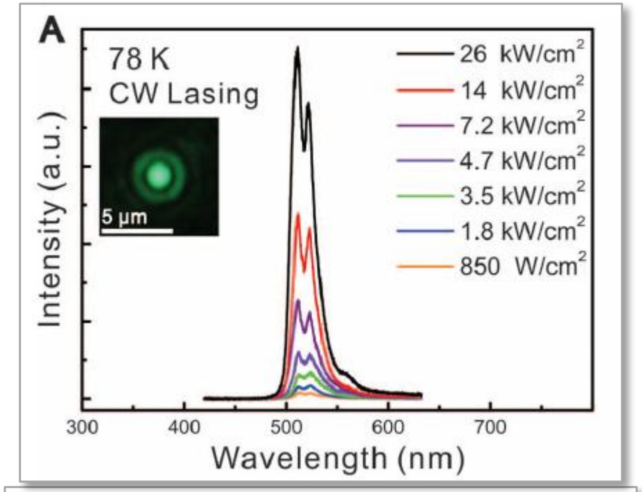
Plasmonic Nanolaser Using Epitaxially Grown Silver Film
Yu-Jung Lu *et al.*
Science **337**, 450 (2012);
DOI: 10.1126/science.1223504

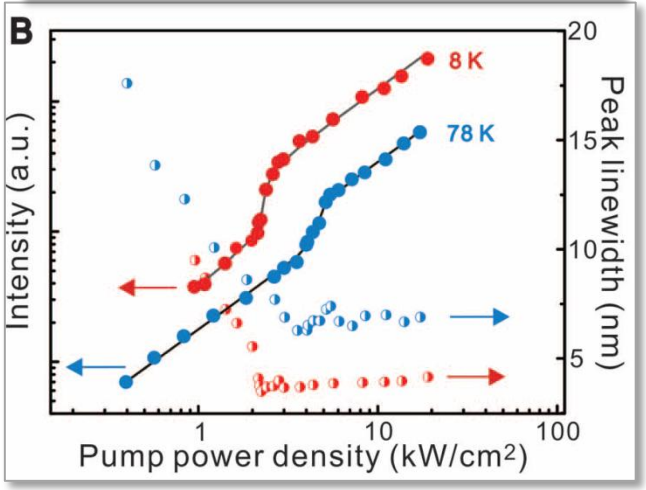
- Optically pumped by cw diode laser at 405 nm.
- Monolithically integrated plasmonics and Si-based electronics on a single platform.

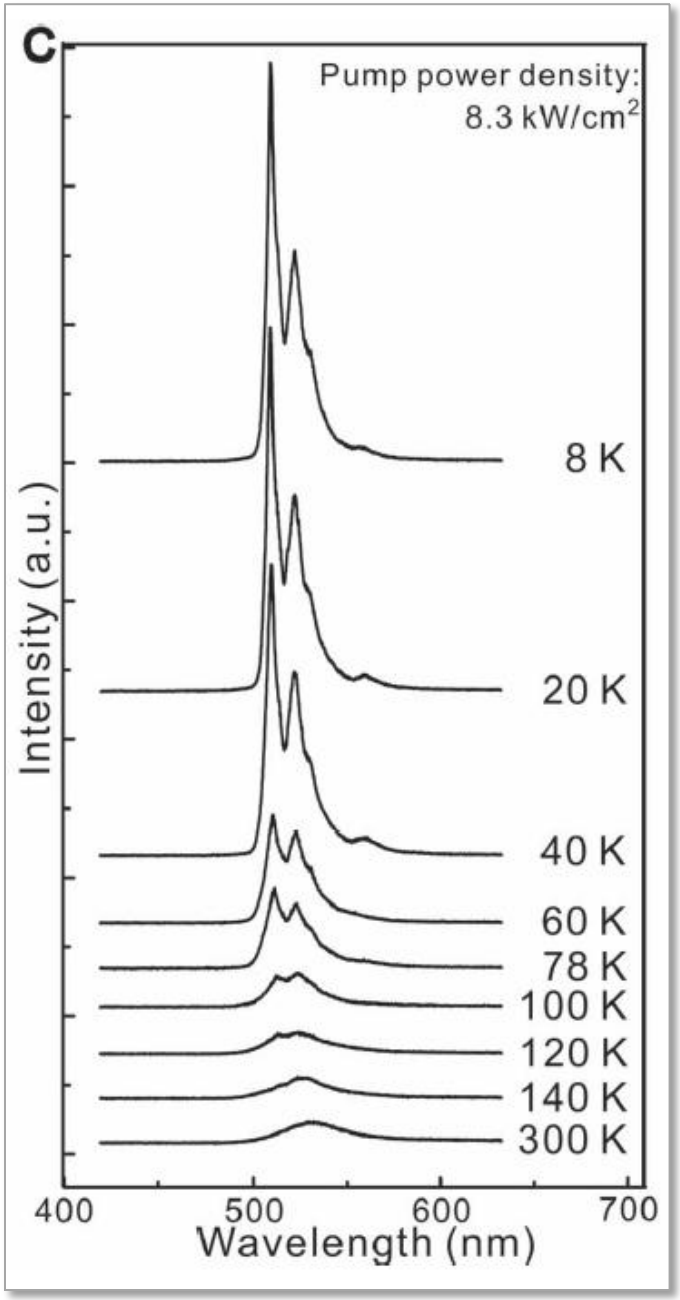


Schematic of device: a single InGaN@GaN core-shell nanorod on a SiO2-covered epitaxial Ag film (28 nm thick)

http://www.forbes.com/sites/tjmccue/2012/07/30/laser-diode-creates-worlds-smallest-semiconductor-laser-for-optical-computing/







"kink" of the L-L plot concurrent with linewidth narrowing

The challenge is whether nanolasers can be efficiently operated at RT.

Outline

Part 1

1. Introduction to semiconductor lasers (SCLs)
2. Simplest model and dynamics with time-varying current parameter

Part 2

1. Applications of SCLs
2. More complicated models, dynamics with optical injection and polarization properties

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BARCELONATECH

Reminder part 1: the rate equations for the photon and the carrier density

$$\frac{dS}{dt} = \frac{1}{\tau_p}(G-1)S + \frac{\beta_{sp}N}{\tau_N}$$

$$\frac{dN}{dt} = \frac{1}{\tau_N}(\mu - N - GS)$$

$$G(N,S) = \frac{N}{1+\varepsilon S}$$

- These are deterministic equations.
- Allow to understand the laser response to a time-varying pump current.
- But to understand the laser intensity noise and line-width we need an **stochastic** equation for the **optical field**.

Parameter values

τ_p	**1 ps**
τ_N	1 ns
β_{sp}	10^{-4}
ε	0.01

$\mu_{th} = 1$

Relative intensity noise (RIN)

The output intensity of a SCL is detected by a photo-detector, converted to an electric signal and sent to a RF spectrum analyzer. The relative intensity noise (RIN) is a measure of the relative noise level to the average dc power.

Log-log scale

FFT of S(t)

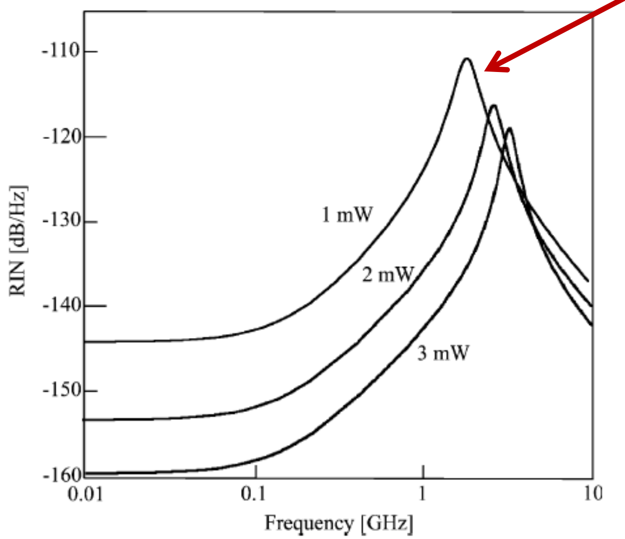


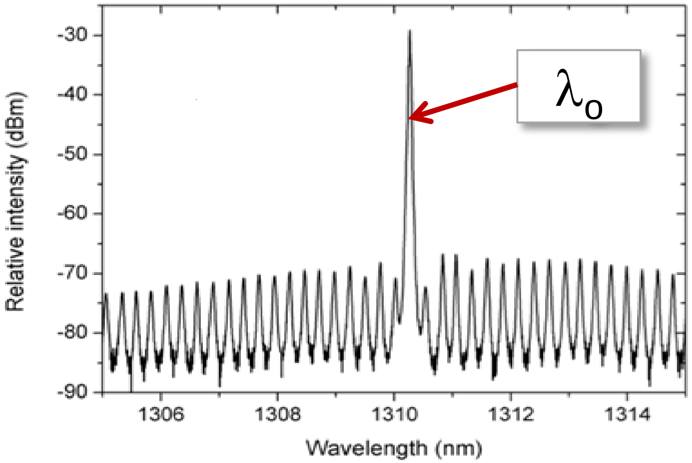
Fig. 3.3. Intensity noise spectrum for several power levels

$$\omega_{RO} = \sqrt{\frac{\mu - 1}{\tau_p \tau_N}}$$

Adapted from J. Ohtsubo

Laser linewidth

- The laser linewidth is due to spontaneous emission noise



- To compute the optical spectrum, we need a rate equation for the complex field E.

$$\mathrm{E}(t) = E(t)\, e^{i\,\omega_0\, t}$$

$\omega_0 = 2\pi c/\lambda_0$

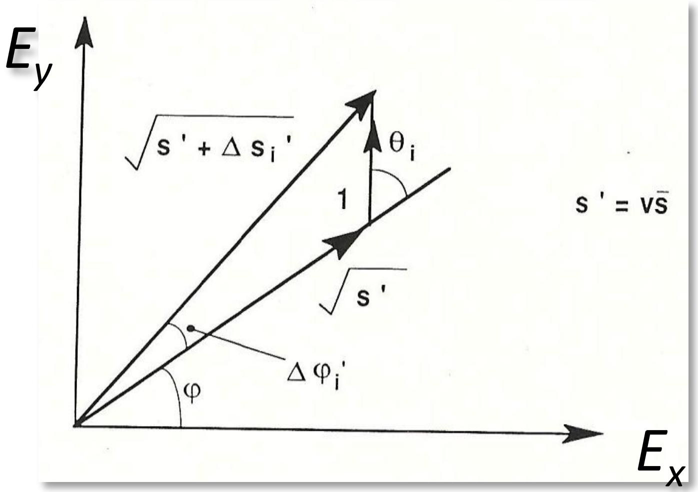
Slowly varying complex amplitude

Semiconductor laser linewidth

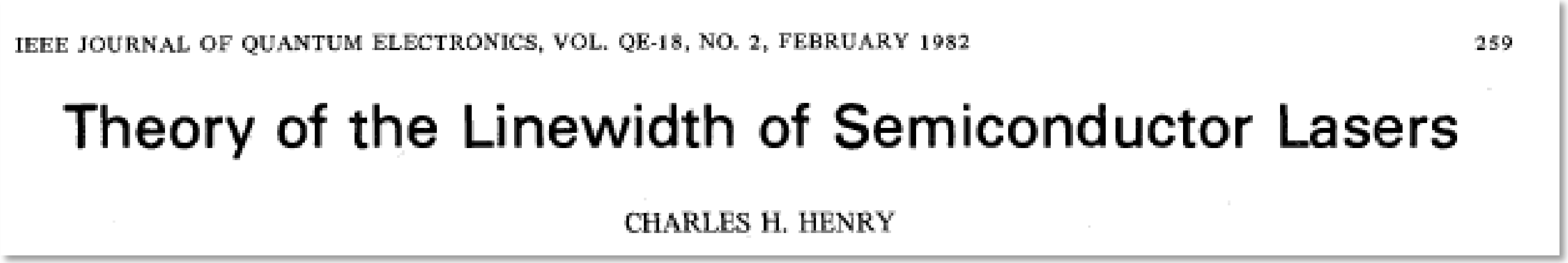
Schematic representation of the change of **magnitude and phase** of the lasing field E due to the spontaneous emission of one photon.

$$S = |E|^2$$

$$E = E_x + iE_y$$



- The linewidth of gas and solid-state lasers well described by the conventional laser theory (Lorentzian shape with Δf~1/P)
- But the linewidth of semiconductor lasers is significantly higher.



IEEE JOURNAL OF QUANTUM ELECTRONICS, VOL. QE-18, NO. 2, FEBRUARY 1982 259

Theory of the Linewidth of Semiconductor Lasers

CHARLES H. HENRY

- The enhanced linewidth is because $\Delta S \rightarrow \Delta N \rightarrow \Delta n \rightarrow \Delta \phi$

- Henry introduced a **phenomenological** factor (α) to account for amplitude–phase coupling.

- The **linewidth enhancement factor α** is a very important parameter of semiconductor lasers. Typically **α=3-6**

Rate equation for the optical field (E)

$$S = \left|E\right|^2$$

Photon density (intensity)

$$\frac{dS}{dt} = \frac{1}{\tau_p}\left(N-1\right)S + \frac{\beta_{sp}N}{\tau_N}$$

$$\Rightarrow$$

Complex field $E = E_x + iE_y$

$$\frac{dE}{dt} = \frac{1}{2\tau_p}(1+i\alpha)(N-1)E + \sqrt{\frac{\beta_{sp}N}{\tau_N}}\,\xi$$

α factor

Langevin stochastic term: complex, uncorrelated, Gaussian white noise

$$\xi = \xi_x + i\xi_y$$

$$k = \frac{1}{2\tau_p}, \quad D = \frac{\beta_{sp}N_0}{\tau_N}$$

$$\frac{dE_x}{dt} = k(N-1)(E_x - \alpha E_y) + \sqrt{D}\,\xi_x$$

$$\frac{dE_y}{dt} = k(N-1)(\alpha E_x + E_y) + \sqrt{D}\,\xi_y$$

Diode lasers are class B lasers

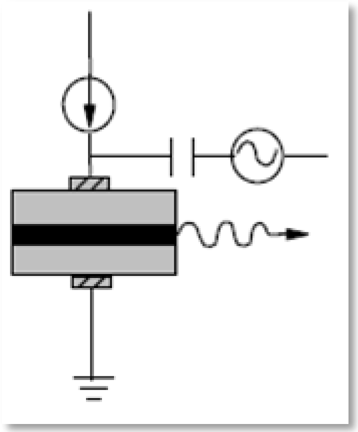
- Class A lasers: governed by only one rate equation, no oscillations.

- Class C lasers: governed by three rate equations (N, S, P=macroscopic atomic polarization), can display a chaotic output.

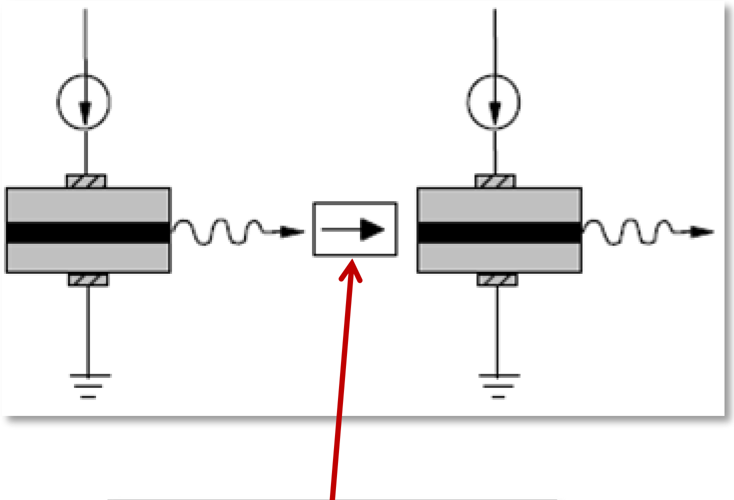
- Class B lasers: governed by two rate equations, transient relaxation oscillations.

But: a diode laser with an external perturbation can display a chaotic output

Current modulation

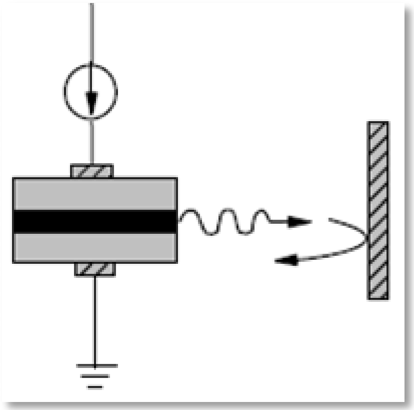


Optical injection



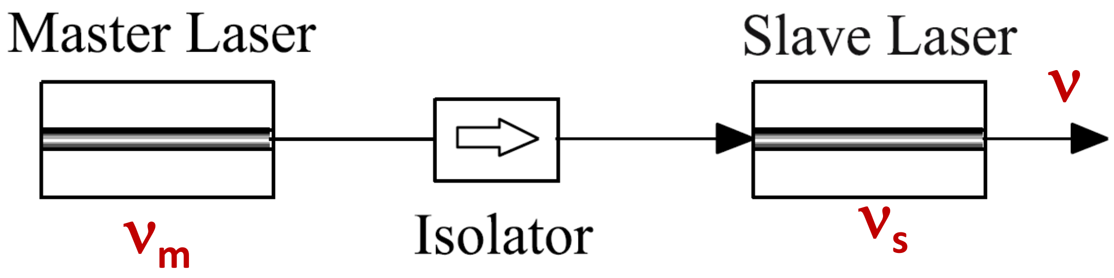
Optical isolator

Optical feedback



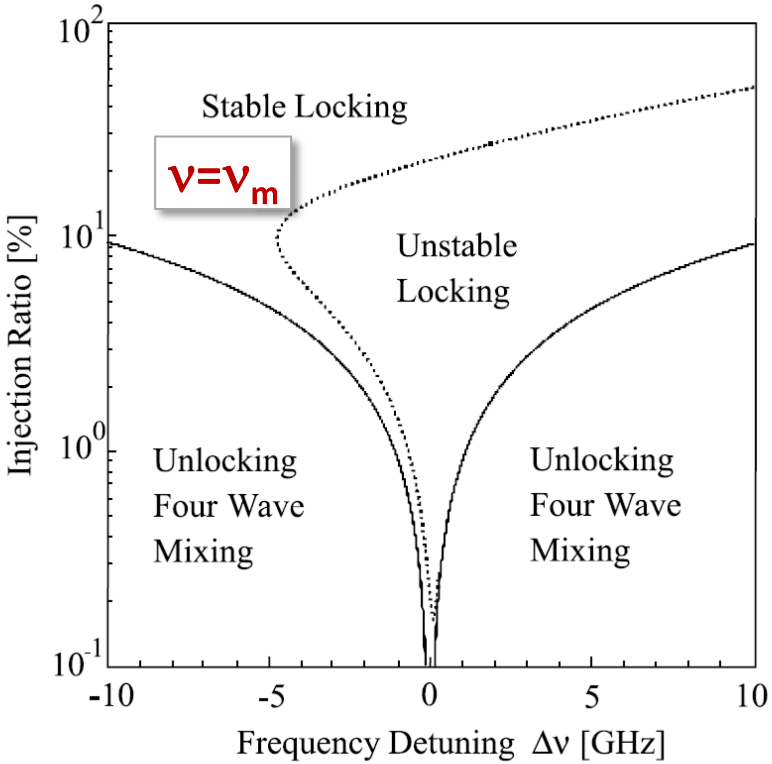
Adapted from M. Sciamanna PhD thesis (2004)

Optical Injection



Detection system
(photo detector,
oscilloscope,
spectrum
analyzer)

- Two Parameters:
  - Injection ratio
  - Frequency detuning $\Delta\nu = \nu_s - \nu_m$
- Dynamical regimes:
  - Injection locking (cw output)
  - Period-one oscillation
  - Period-two oscillation
  - Chaos



Adapted from J. Ohtsubo

Optical Injection Model

$$\frac{dE}{dt} = \frac{1}{2\tau_p}(1+i\alpha)(N-1)E \quad + \underbrace{i\Delta\omega + \sqrt{P_{\text{inj}}}}_{\text{optical injection}} + \underbrace{\sqrt{D}\xi(t)}_{\text{spontaneous emission noise}}$$

$$\underbrace{\frac{dN}{dt} = \frac{1}{\tau_N}\left(\mu\text{-}N\text{-}N|E|^2\right)}_{\text{Solitary laser}}$$

optical injection

P_{inj}: injection strength

$\Delta\omega$: frequency detuning

spontaneous
emission
noise

$$D = \frac{\beta_{sp} N_0}{\tau_N}$$

Solitary laser

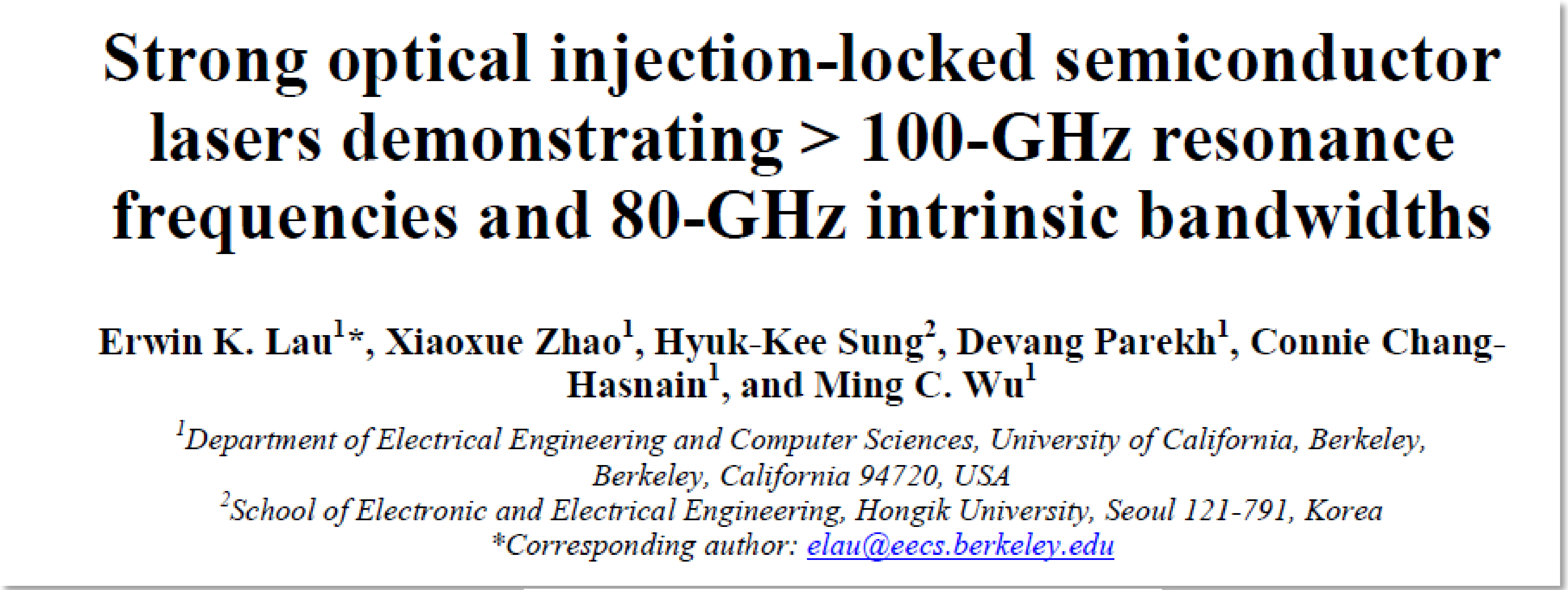
5 parameters: **α τ_p τ_N μ D**

μ: pump current parameter

Typical parameters:

α= 3, τ_p = 1 ps,

τ_N = 1 ns, D=10^{-4} ns^{-1}

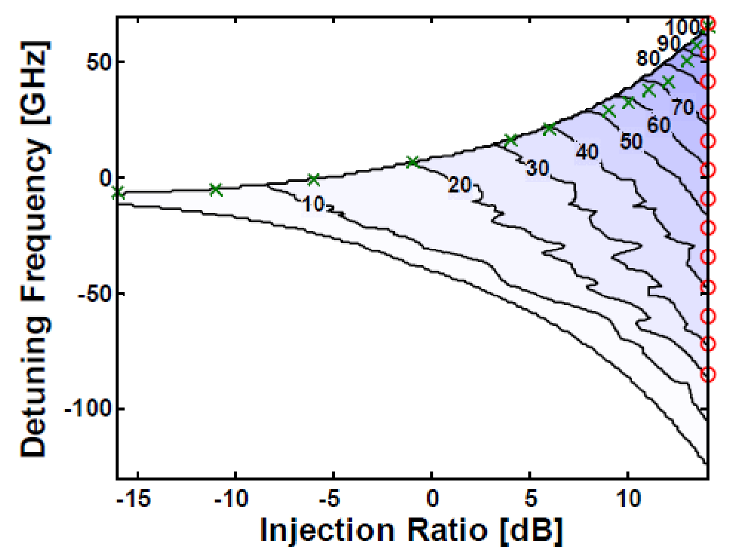


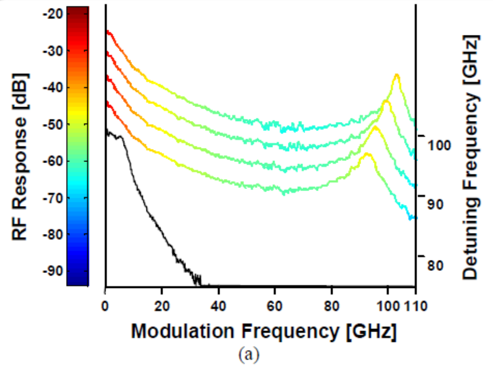
Strong optical injection-locked semiconductor lasers demonstrating > 100-GHz resonance frequencies and 80-GHz intrinsic bandwidths

Erwin K. Lau[1]*, Xiaoxue Zhao[1], Hyuk-Kee Sung[2], Devang Parekh[1], Connie Chang-Hasnain[1], and Ming C. Wu[1]

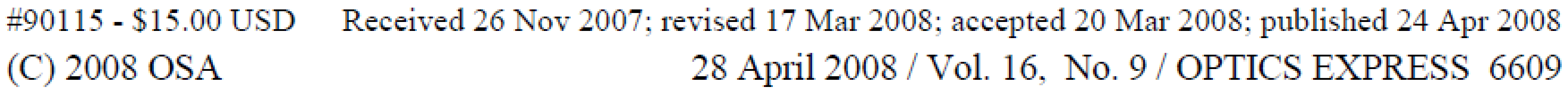
[1]*Department of Electrical Engineering and Computer Sciences, University of California, Berkeley,*
Berkeley, California 94720, USA
[2]*School of Electronic and Electrical Engineering, Hongik University, Seoul 121-791, Korea*
**Corresponding author: elau@eecs.berkeley.edu*

Injection locking increases the resonance frequency and the modulation bandwidth





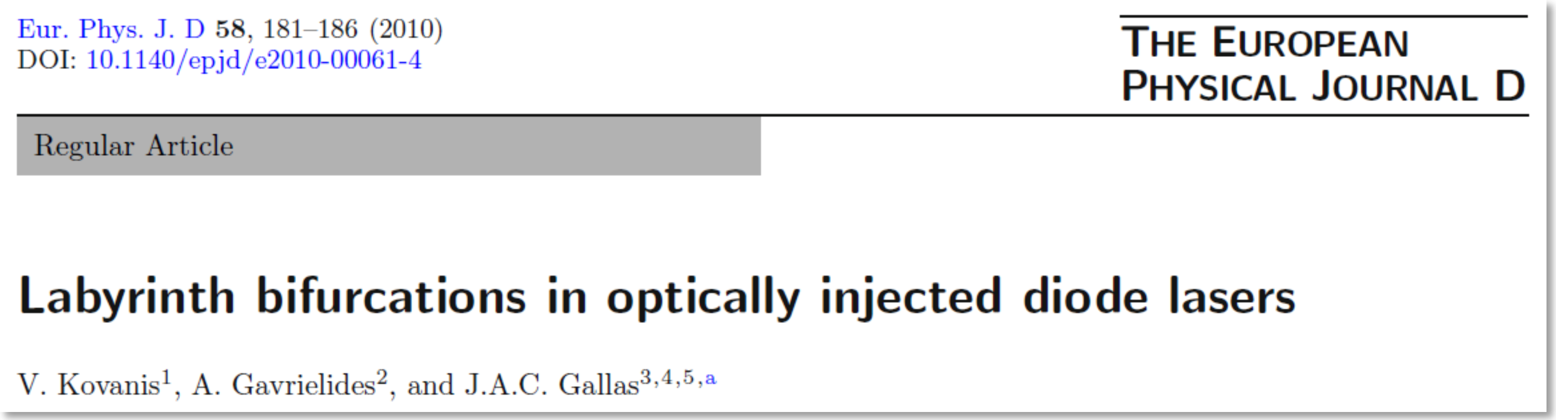
(a)



#90115 - $15.00 USD Received 26 Nov 2007; revised 17 Mar 2008; accepted 20 Mar 2008; published 24 Apr 2008

28 April 2008 / Vol. 16, No. 9 / OPTICS EXPRESS 6609

Outside the injection locking region: nonlinear dynamics



Eur. Phys. J. D **58**, 181–186 (2010)
DOI: 10.1140/epjd/e2010-00061-4

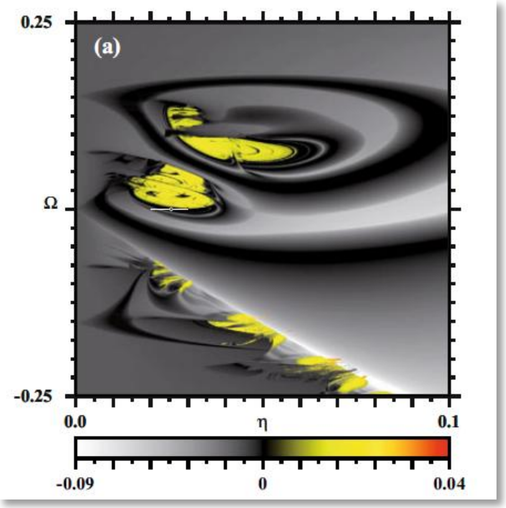
THE EUROPEAN
PHYSICAL JOURNAL D

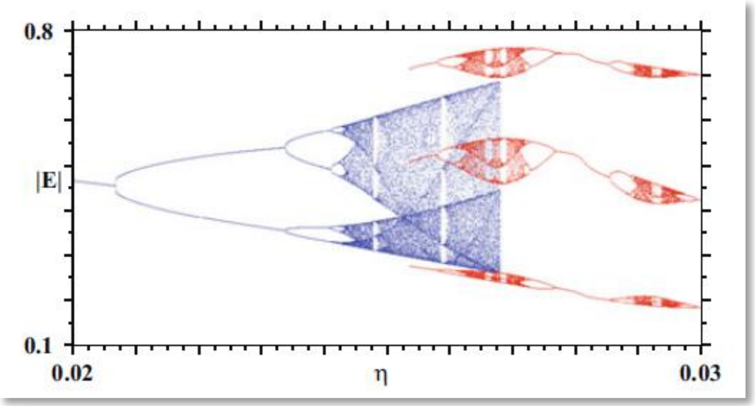
Regular Article

Labyrinth bifurcations in optically injected diode lasers

V. Kovanis[1], A. Gavrielides[2], and J.A.C. Gallas[3,4,5,a]

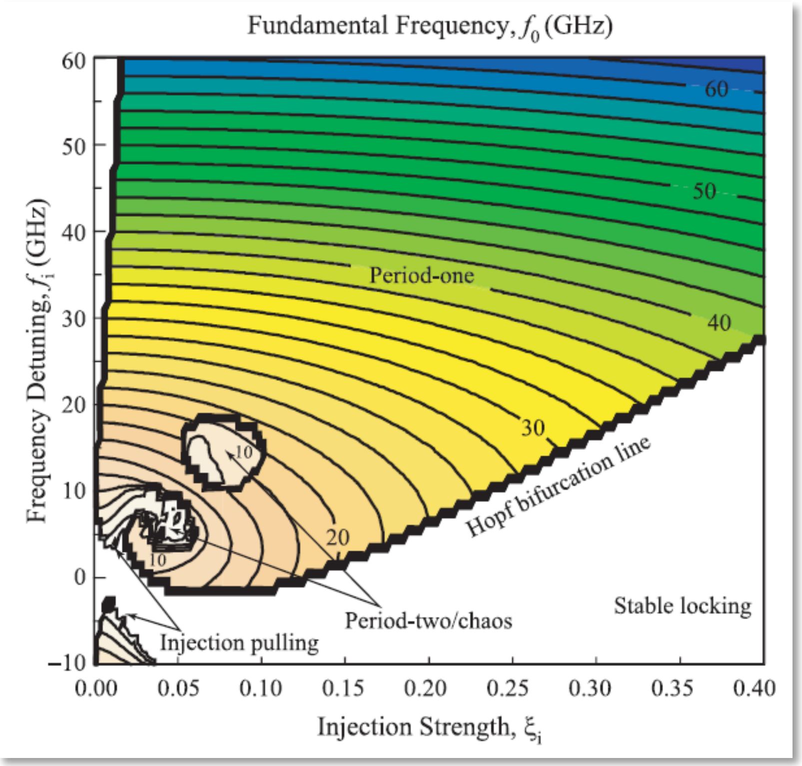
Lyapunov diagram





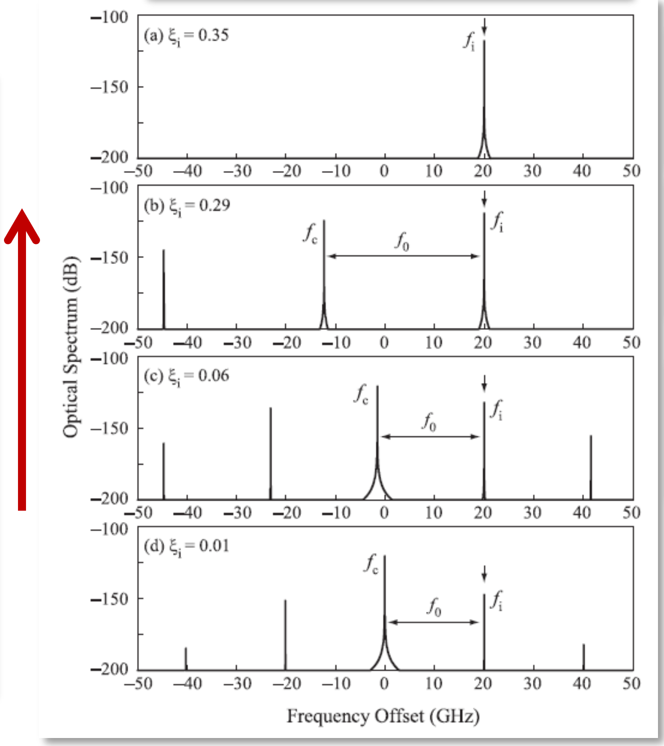
Bifurcation diagram increasing the injection strength

Nonlinear dynamics can be useful



Increasing injection

Optical spectra



Injection locking

Single sideband

Double sideband

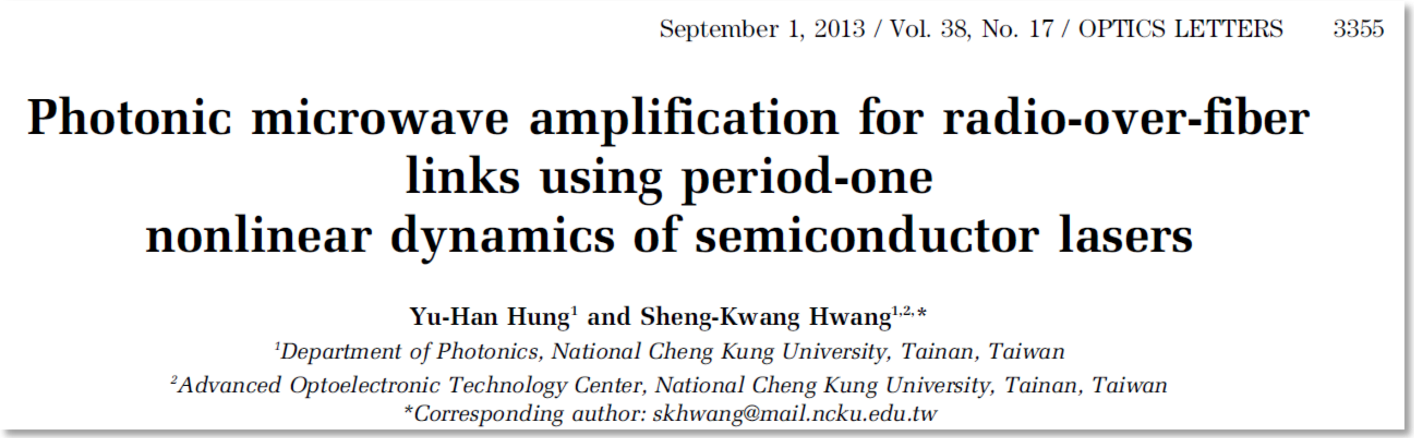
FWM

f_0 depends on the competition of two effects:

- The red-shift of the cavity resonance with increasing injection strength
- Frequency pulling: the injected field pulls the lasing frequency away from the cavity resonance towards the injected frequency

S-C Chan, S-K Hwang, and Jia-Ming Liu, Optics Express 15, 14921 (2007)

The P1 oscillation can generate a laser output that contains a microwave modulation on the optical carrier



September 1, 2013 / Vol. 38, No. 17 / OPTICS LETTERS 3355

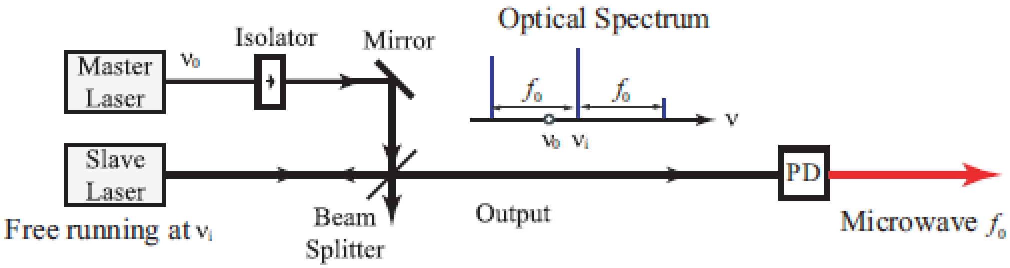
Photonic microwave amplification for radio-over-fiber links using period-one nonlinear dynamics of semiconductor lasers

Yu-Han Hung[1] **and Sheng-Kwang Hwang**[1,2,*]

[1] *Department of Photonics, National Cheng Kung University, Tainan, Taiwan*

[2] *Advanced Optoelectronic Technology Center, National Cheng Kung University, Tainan, Taiwan*

**Corresponding author: skhwang@mail.ncku.edu.tw*



The optical spectrum is highly asymmetric: the low-frequency sideband is much stronger than the high-frequency one.

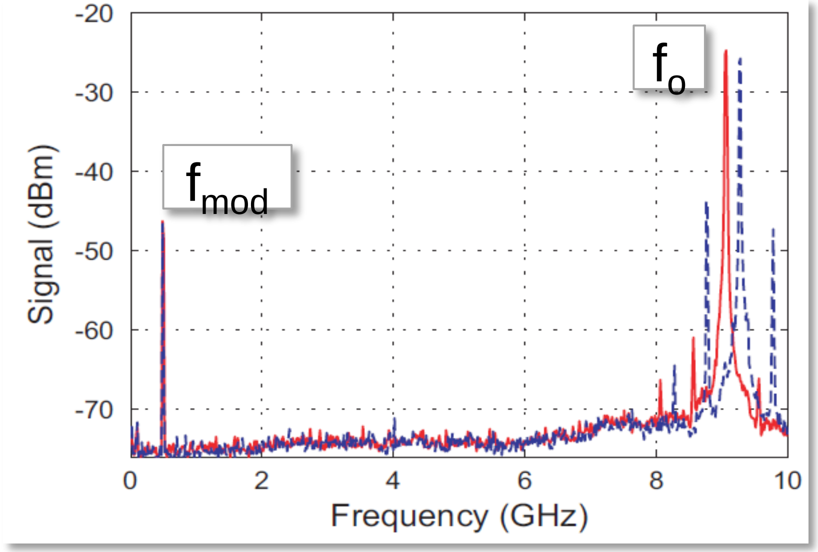
This can be useful for distributing microwaves to remote antennas through long distance optical fibers.

Limit-Cycle Dynamics with Reduced Sensitivity to Perturbations

Thomas B. Simpson,[1,*] Jia-Ming Liu,[2] Mohammad AlMulla,[2] Nicholas G. Usechak,[3] and Vassilios Kovanis[3]

To appear in PRL (2013)

Power spectra



P1 oscillation + a weak modulation of the current of the slave laser.

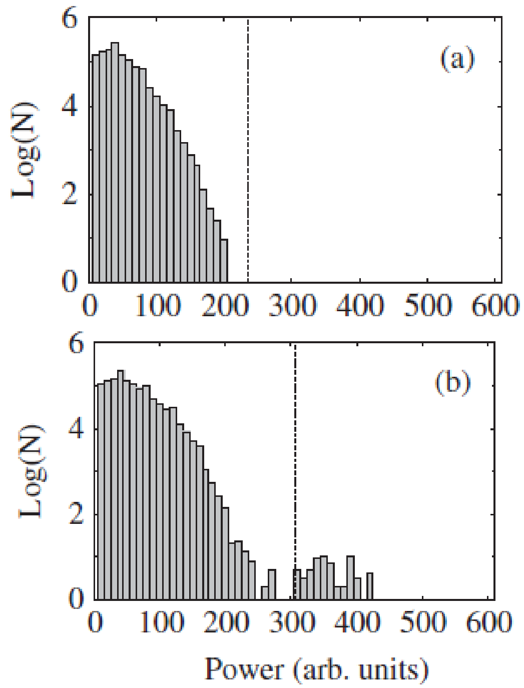
The sidebands are minimized when $\Delta\omega$=-2.1 GHz (**red**), and are strong when $\Delta\omega$=-1.2 GHz (**blue**).

There are special operation conditions where f_0 is insensitive to perturbations and depends only on the injection strength.

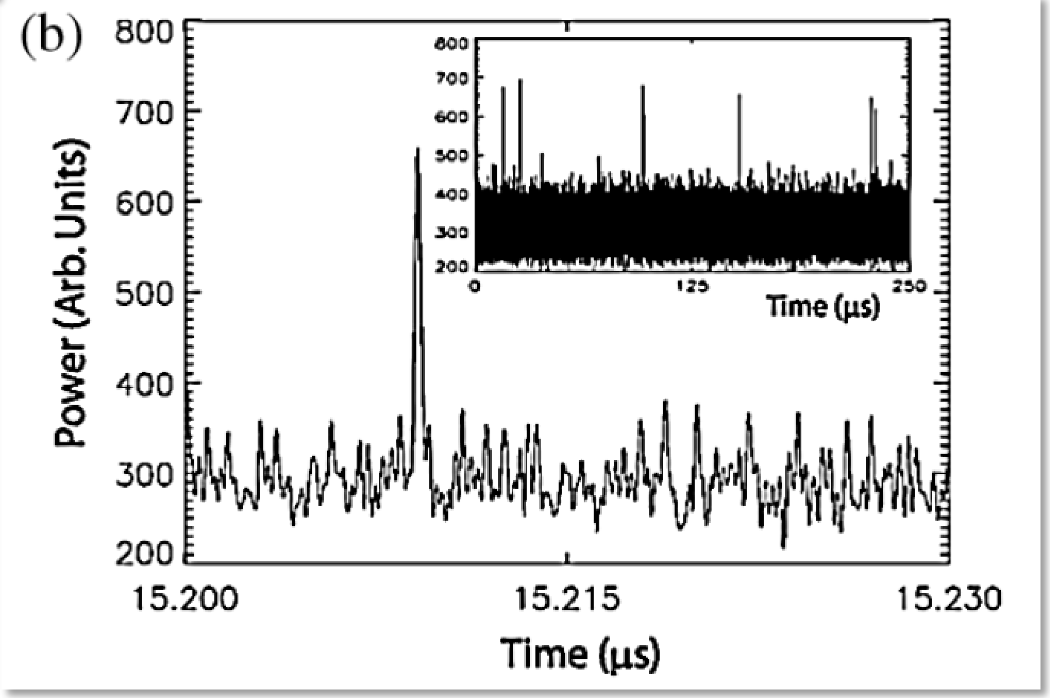
Potential for narrow-linewidth, frequency-tunable photonic microwave oscillators.

But nonlinear dynamics can also be dangerous: ultra-high intensity pulses

Distribution of pulse amplitudes for different injection conditions



Time series of the laser intensity



C. Bonatto et al, PRL 107, 053901 (2011),
Optics & Photonics News February 2012,
Research Highlight in *Nature Photonics* DOI:10.1038/nphoton.2011.240

Outline

Part 1

1. Introduction to semiconductor lasers (SCLs)
2. Simplest model and dynamics with time-varying current parameter

Part 2

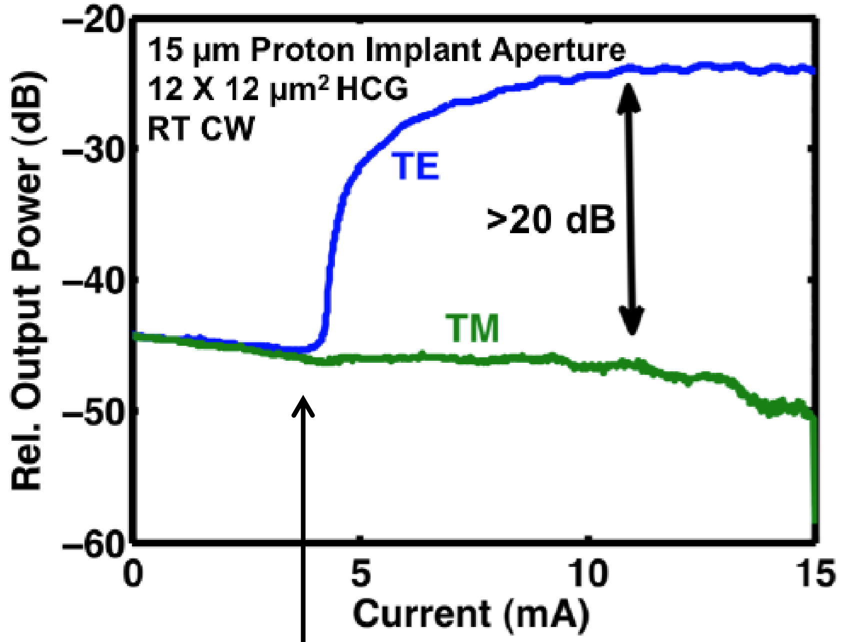
1. Applications of SCLs
2. More complicated models, dynamics with optical injection, polarization properties

UNIVERSITAT POLITÈCNICA
DE CATALUNYA
BARCELONATECH

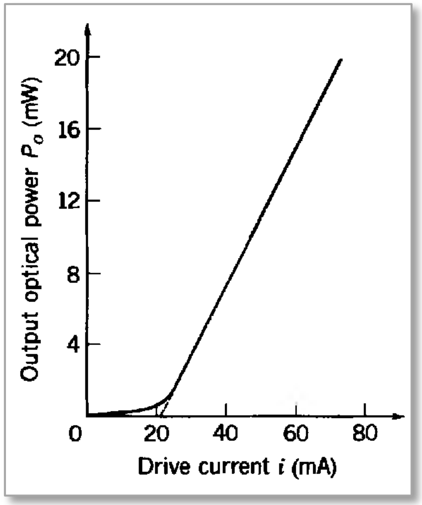
Diode lasers emit linearly polarized light

In edge-emitting lasers (EELs): fixed polarization

Log scale

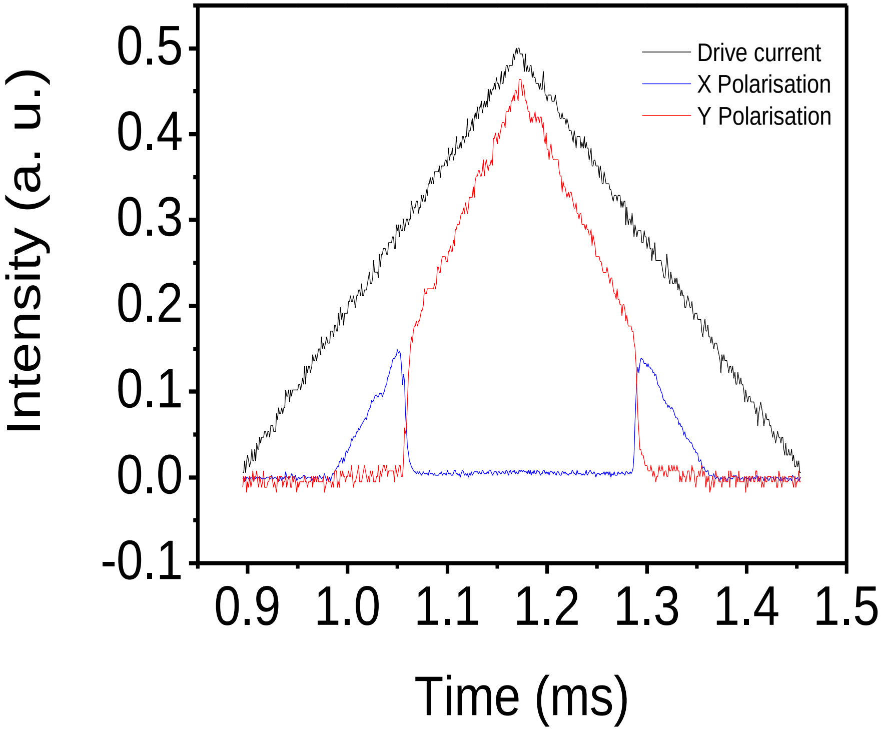


threshold current



But in VCSELs: polarization switching (PS)

- Circular cavity geometry: two linear orthogonal modes (x, y).
- Often there is a **polarization switching** when the pump current is increased.
- Also **hysteresis**: two PS points (for increasing and for decreasing current).

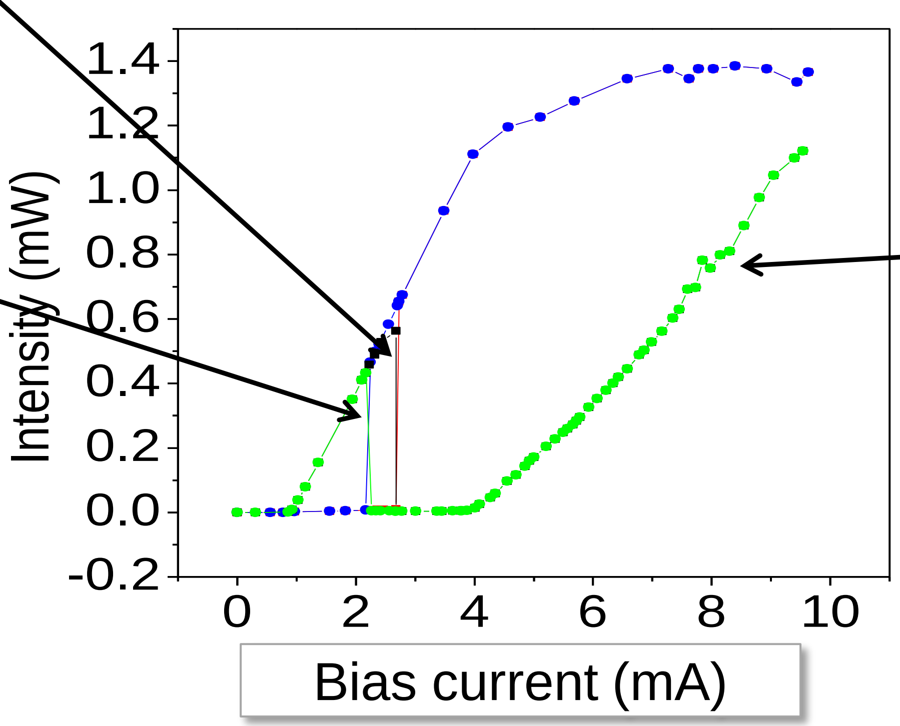


Adapted from Hong and Shore, Bangor University, Wales, UK

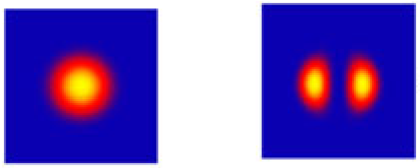
Polarization-resolved LI curve: biestability and hysteresis

PS1: current increases

PS2: current decreases



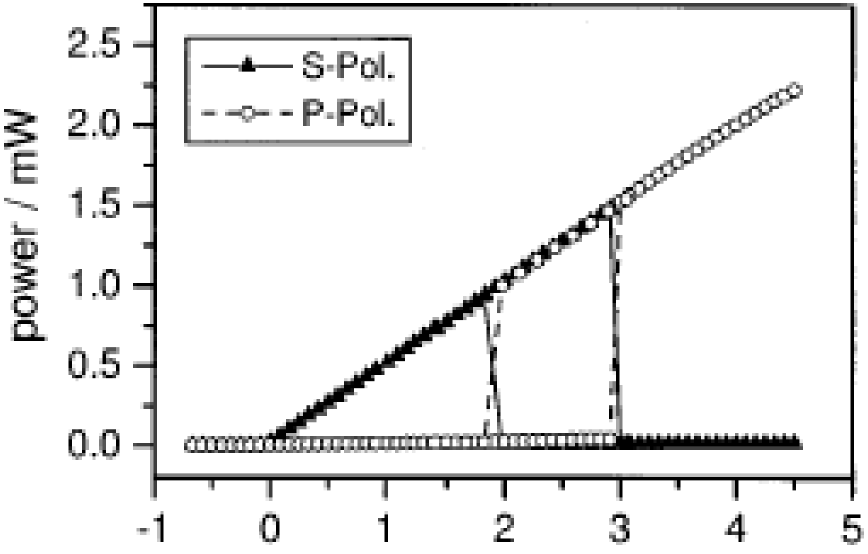
Two transverse modes with orthogonal polarization



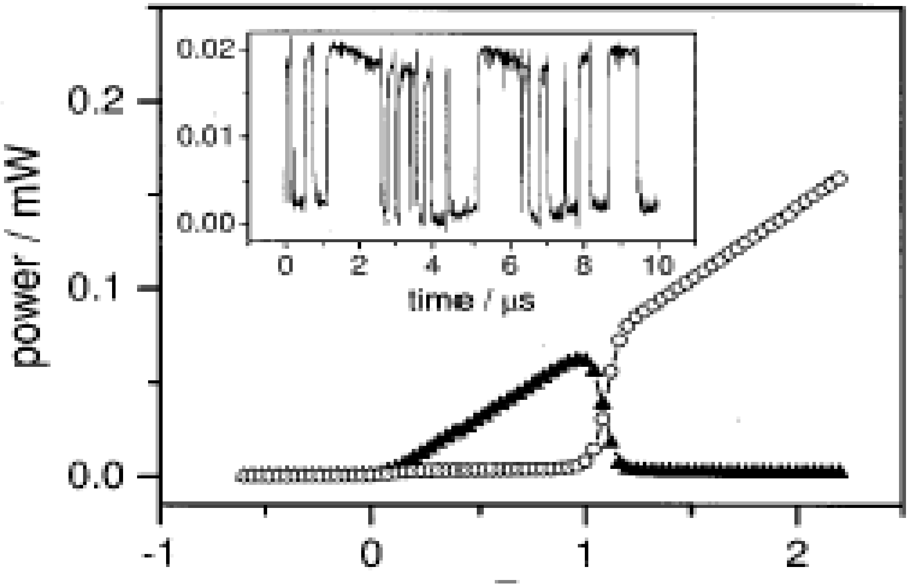
Source: Hong and Shore, Bangor University, Wales, UK

Two types of polarization switching

Current-driven

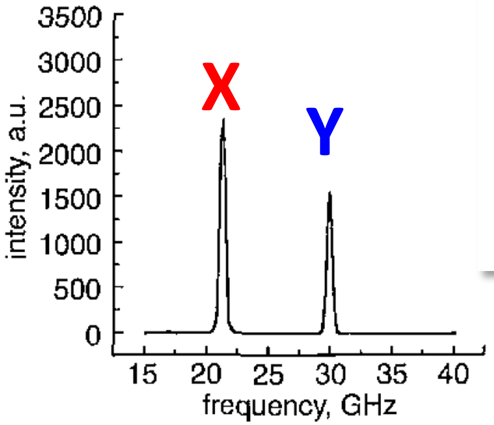


Stochastic

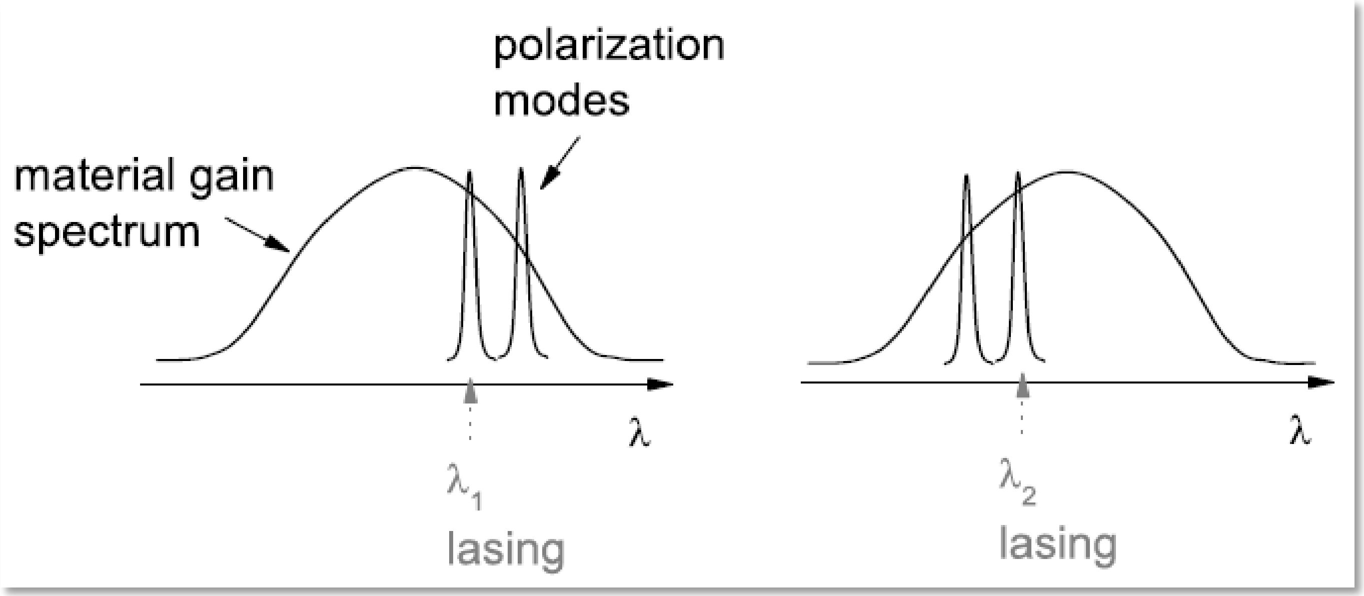


Adapted from J. Kaiser et al, JOSAB 19, 672 (2002)

Current driven PS: why?



Y. Hong et al, Elec. Lett. (2000)



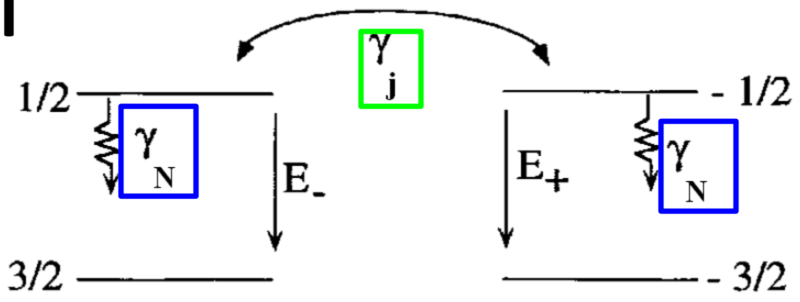
When the pump current increases ⇒ Joule heating ⇒ **different thermal shift** of the **gain** curve and of the **cavity modes**

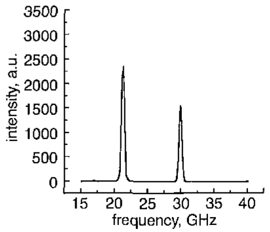
Explains Y → X PS only

Adapted from M. Sciamanna PhD Thesis (2004)

VCSEL spin-flip model

Assumes a four-level system in which e/h with **spin down (up)** recombine to **right (left) circularly polarized** photons:





$$\boxed{\frac{dE_\pm}{dt} = \kappa(1+i\alpha)(N_\pm - 1)E_\pm - (\gamma_a + i\gamma_p)E_\mp + D\xi_\pm}$$

dichroism

birefringence

$$E_x = (E_+ + E_-)/\sqrt{2}$$

$$E_y = -i(E_+ - E_-)/\sqrt{2}$$

$$\boxed{\frac{dN_\pm}{dt} = -\boxed{\gamma_N}(N_\pm - \mu) - \boxed{\gamma_j}(N_\pm - N_\mp) - 2\gamma_N\ N_\pm\,|E_\pm|^2}$$

Carrier recombination

Pump: carrier injection

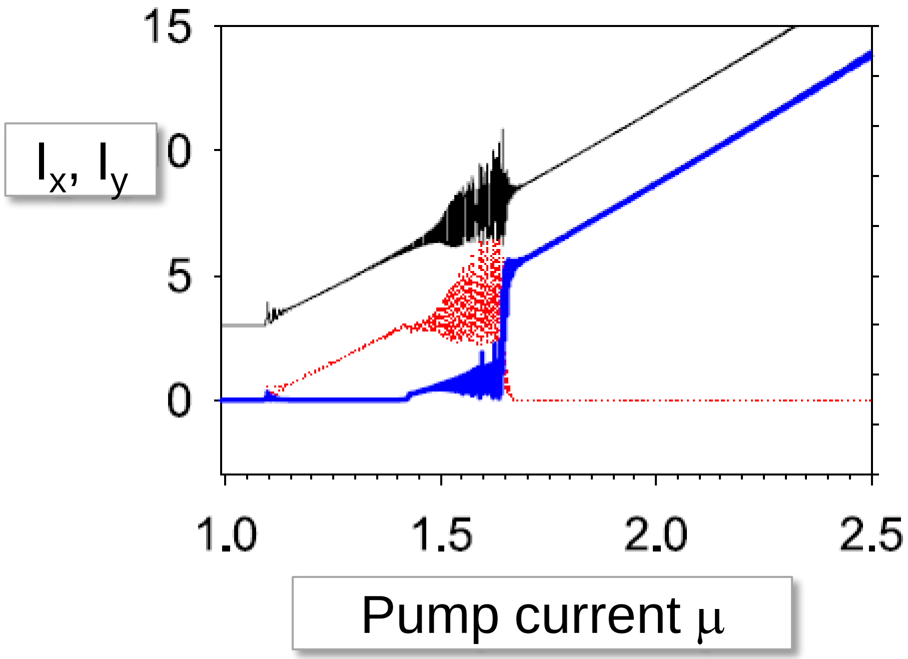
spin-flip rate

Stimulated recombination

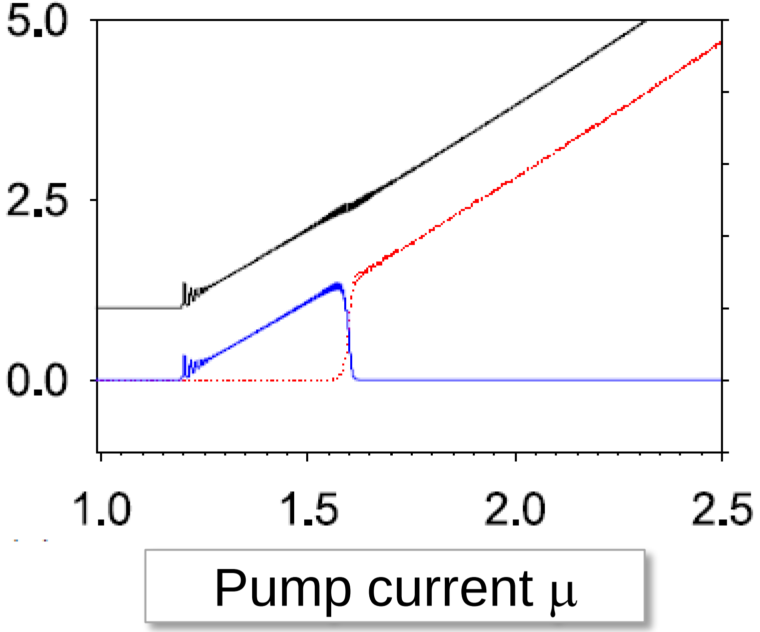
San Miguel et al, PRA 54, 1728 (1995),
Martin Regalado et al, JQE 33, 765 (1997).

The SFM model can explain both: $Y \rightarrow X$ and $X \rightarrow Y$ PSs

γ_a <0 and small birefringence: $X \rightarrow Y$



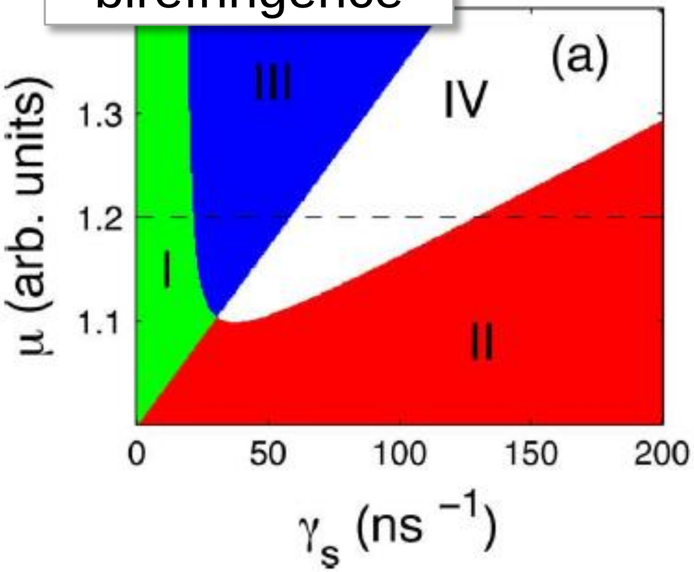
γ_a >0 and large birefringence: $Y \rightarrow X$



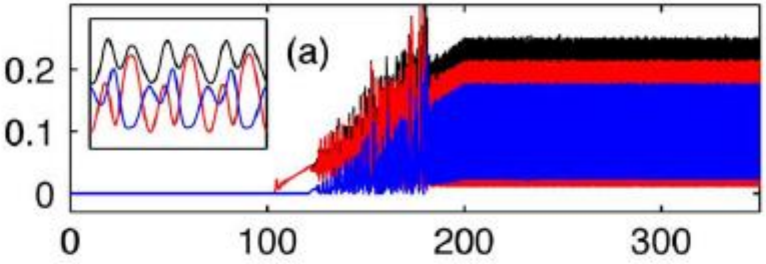
M. S. Torre, C. Masoller and P. Mandel, PRA 74, 043808 (2006)

The stability of the X & Y polarizations depends on the spin-flip rate

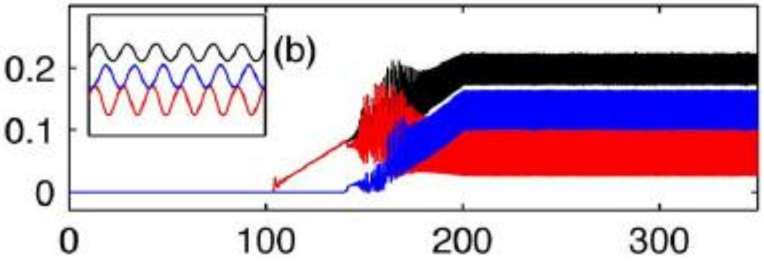
γ_a <0 and small birefringence



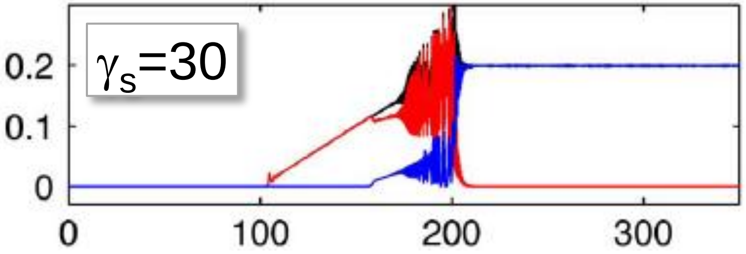
γ_s=10



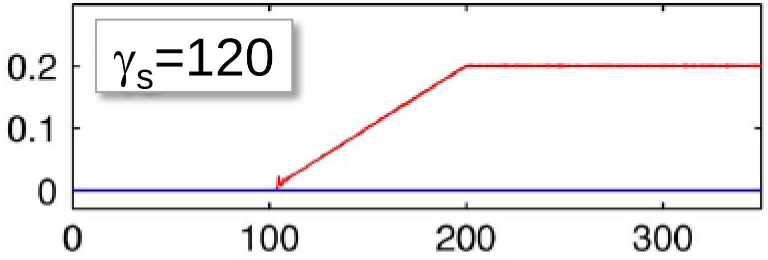
γ_s=20



γ_s=30

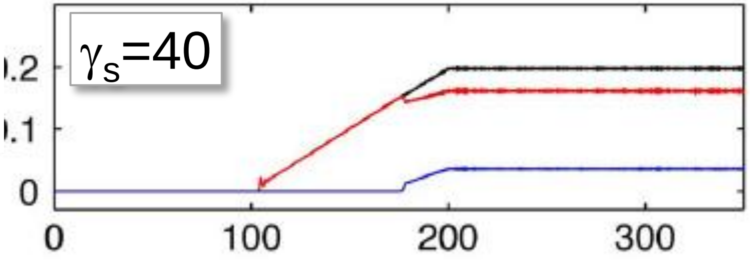


γ_s=120

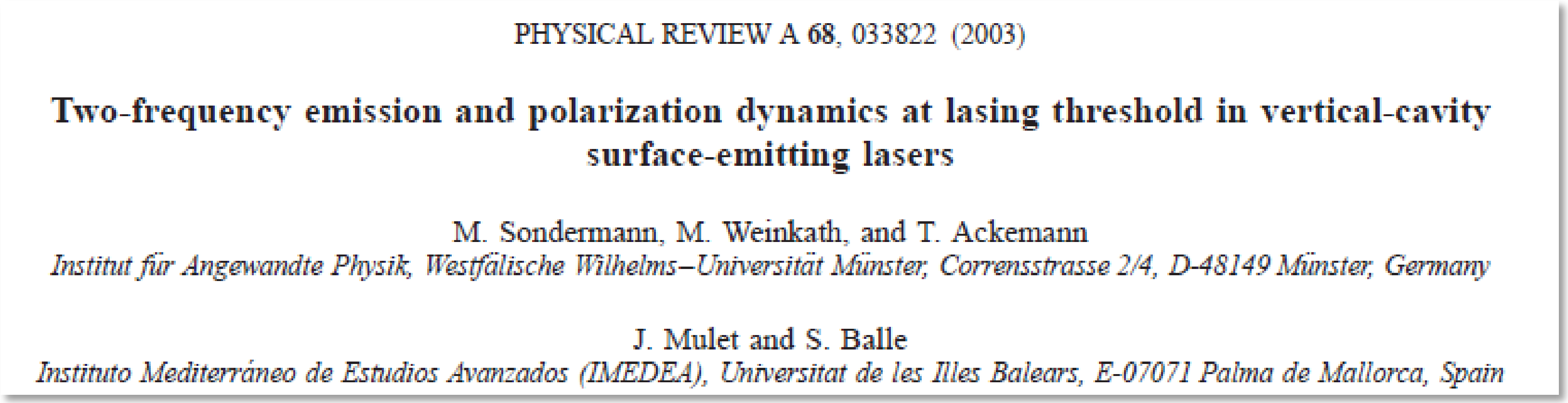


Time (ns)

γ_s=40



M. S. Torre and C. Masoller, JQE 45, 206 (2009)



PHYSICAL REVIEW A 68, 033822 (2003)

Two-frequency emission and polarization dynamics at lasing threshold in vertical-cavity surface-emitting lasers

M. Sondermann, M. Weinkath, and T. Ackemann
Institut für Angewandte Physik, Westfälische Wilhelms–Universität Münster, Corrensstrasse 2/4, D-48149 Münster, Germany

J. Mulet and S. Balle
Instituto Mediterráneo de Estudios Avanzados (IMEDEA), Universitat de les Illes Balears, E-07071 Palma de Mallorca, Spain

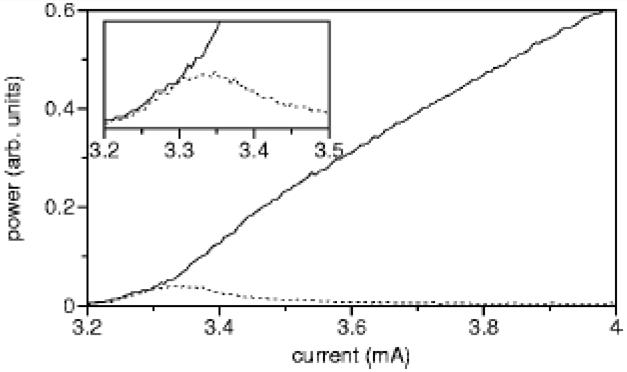


FIG. 2. Polarization resolved, time-averaged power at a substrate temperature of 61 °C. Solid (dashed) lines denote the power of the polarization mode with lower (higher) optical frequency. The inset shows a magnification of the current interval around threshold.

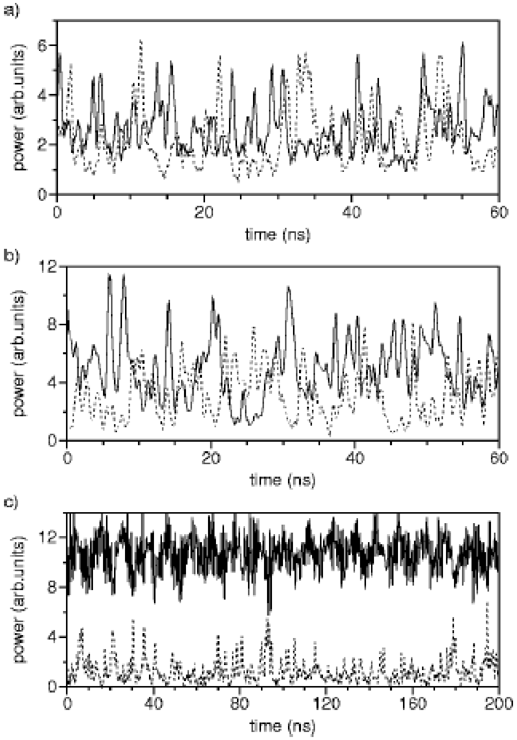


FIG. 3. Polarization resolved time traces in the regime of two-frequency emission: 1% above the lasing threshold (a), at the point of maximum power of the mode with higher optical frequency (4% above the threshold) (b), and 8% above the threshold (c). Solid (dashed) lines denote the power of the polarization mode with lower (higher) optical frequency (bandwidth 1 GHz).

Anti-correlated oscillations experimentally observed and well modeled with the SFM model and a small spin-flip rate

Thermal effects

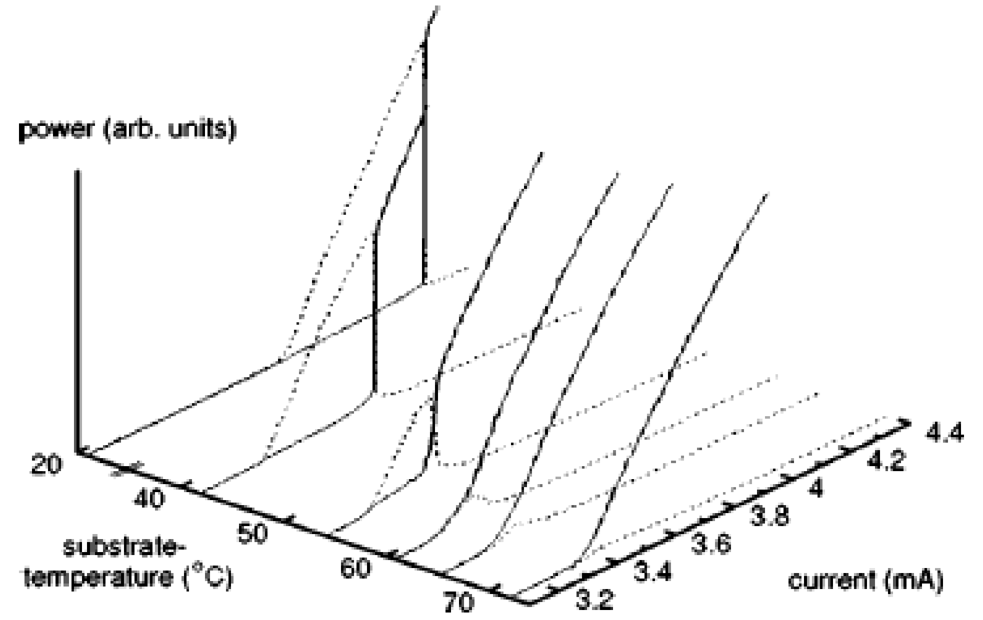
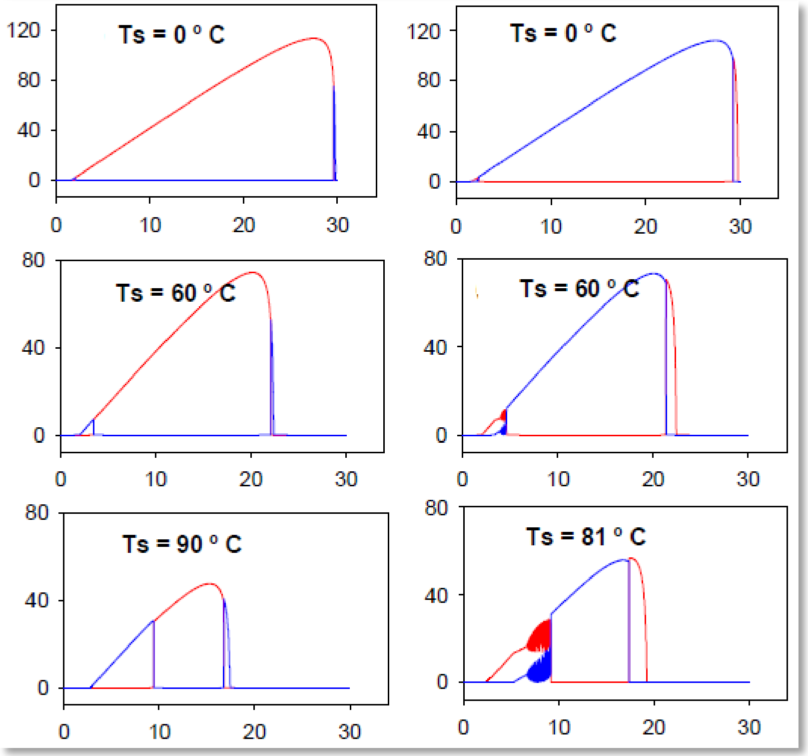


FIG. 1. Polarization resolved power against current (*LI* curve) in dependence of the substrate temperature. Solid (dashed) lines denote the power of the mode with lower (higher) optical frequency.

M. Sondermann et al, PRA 68, 033822 (2003)

Assuming a linear increase of the spin-flip rate with Ts:

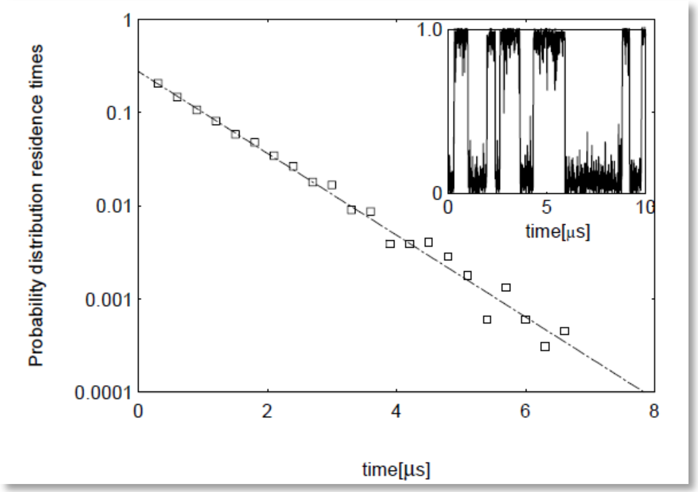


M. S. Torre and C. Masoller, Optics Express 16, 21282 (2008)

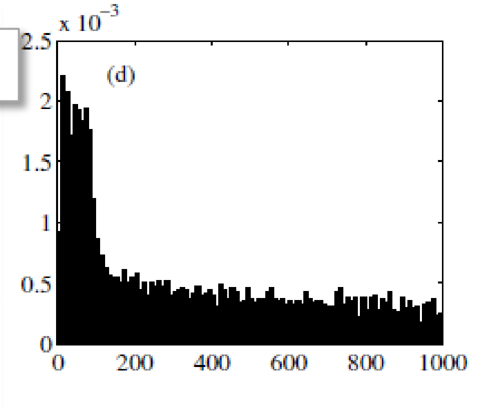
Stochastic polarization switching

- Krammer’s theory: switching among two potential wells

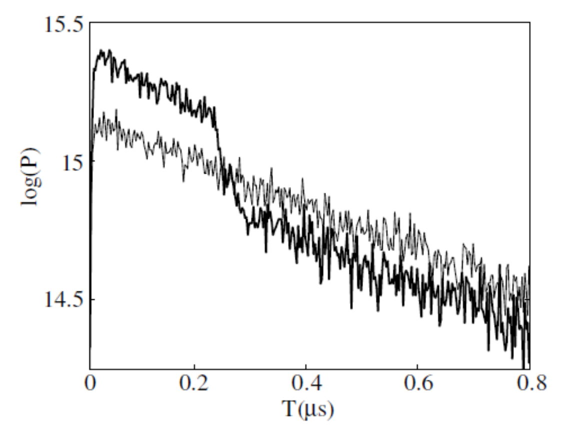
Histogram of residence times



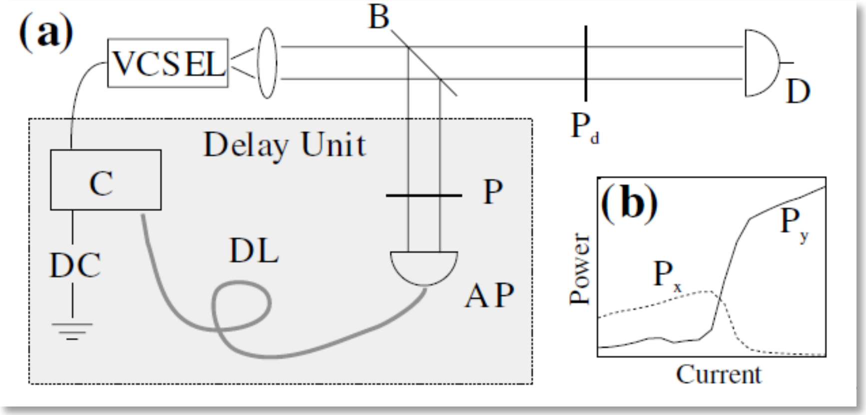
Willemsen, PRL 82, 4819 (1999)



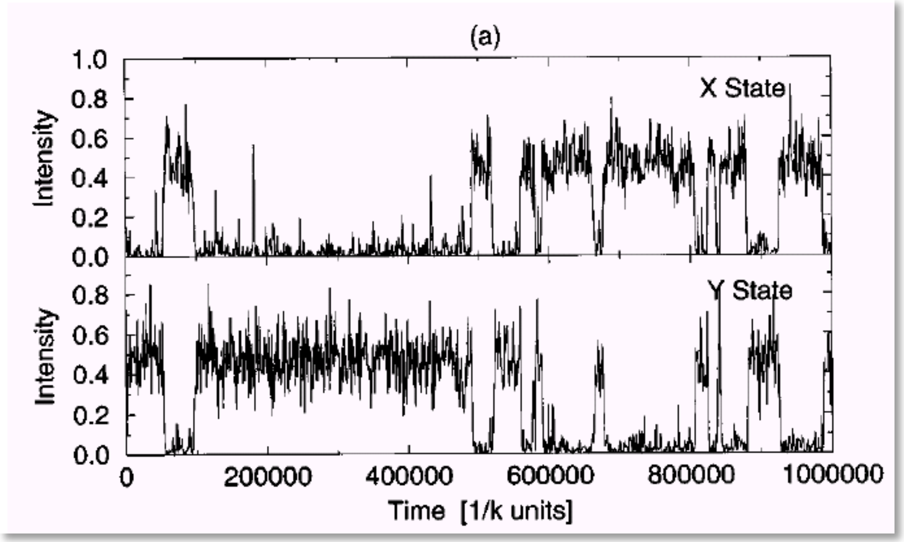
C. Masoller PRL 90 020601 (2003)

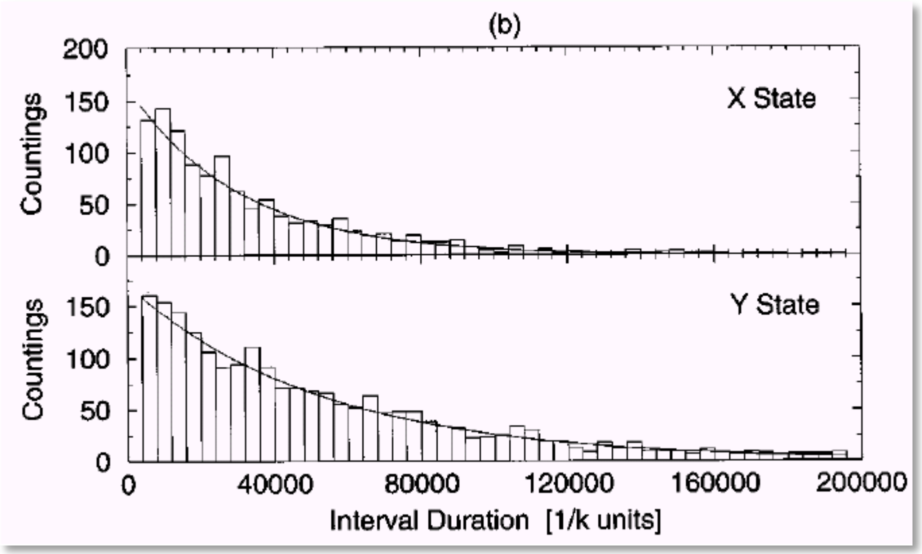


J. Houlihan et al, PRL 92, 050601 (2004)



SFM model is in good agreement with the observations





Travagnin, van Exter, and Woerdman, PRA **56**, 1497 (1997)

Stochastic or chaotic polarization switching?

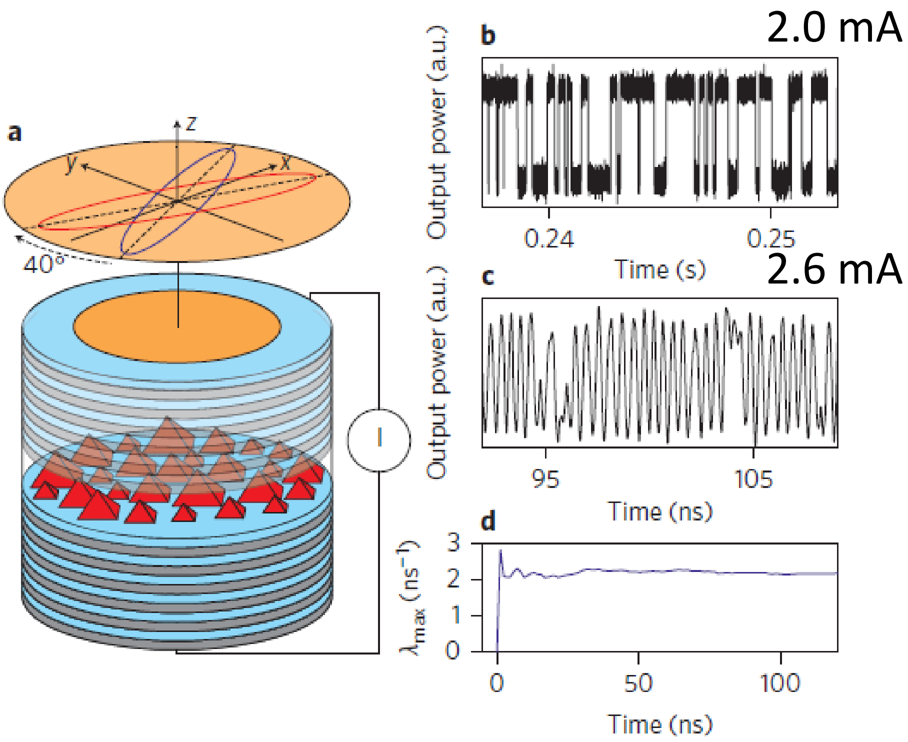
nature photonics

ARTICLES

PUBLISHED ONLINE: 18 NOVEMBER 2012 | DOI: 10.1038/NPHOTON.2012.286

Deterministic polarization chaos from a laser diode

Martin Virte[1,2], Krassimir Panajotov[2,3], Hugo Thienpont[2] and Marc Sciamanna[1]*



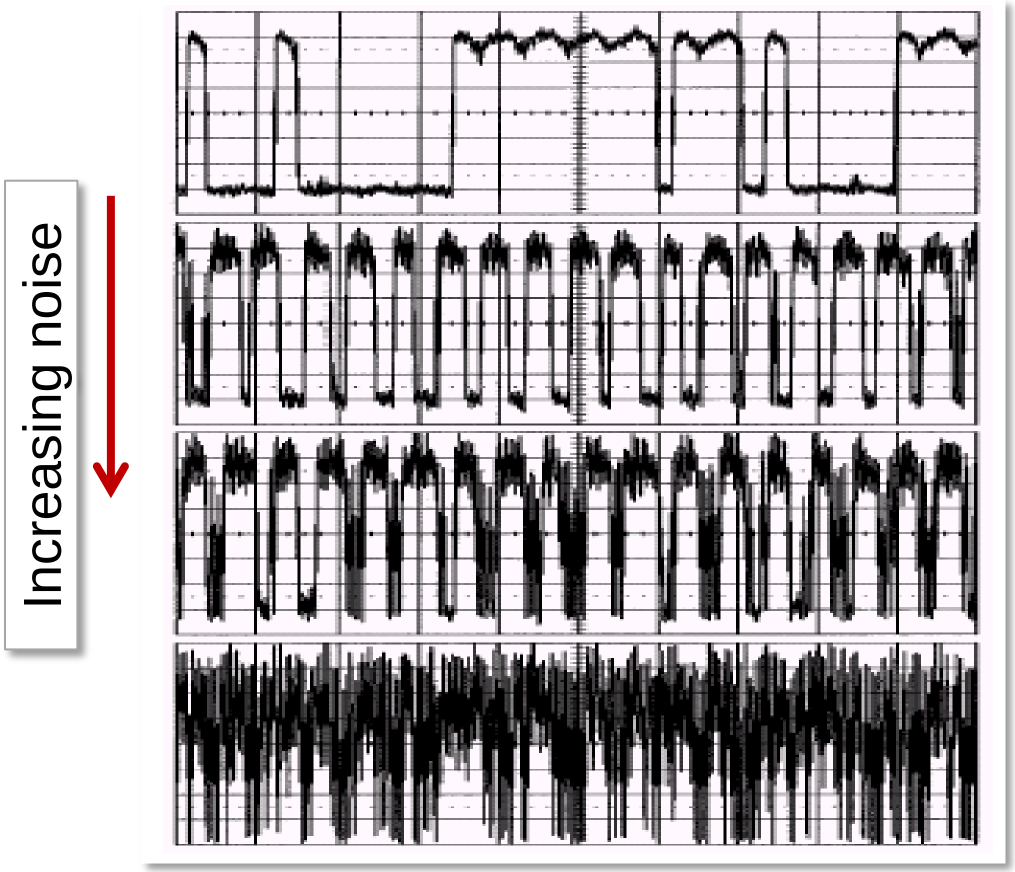
2.0 mA

2.6 mA

- The first example of a free-running diode laser (QD VCSEL) generating chaos.
- The underlying physics comprises a nonlinear coupling between two elliptically polarized modes.

Stochastic Resonance

- Temporal evolution of the intensity of one polarization mode, when the bias current has superimposed a **weak** sinusoidal modulation and noise.

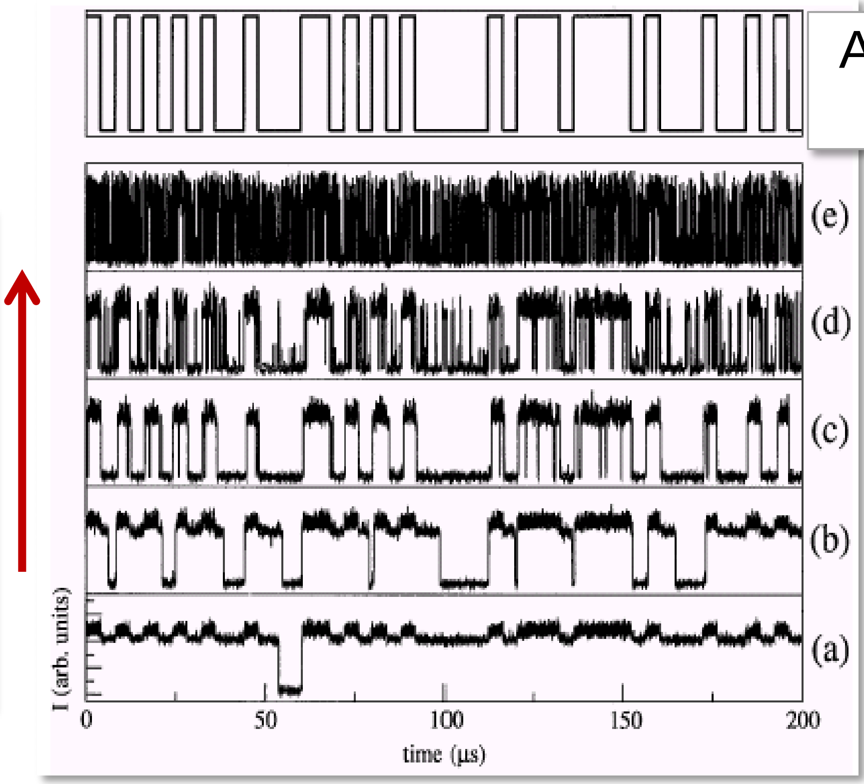


Giacomelli et al, PRL **82**, 675 (1999)

Interplay of stochastic switching and aperiodic modulation

Time evolution of the intensity of one polarization mode, when the dc bias current has superimposed an aperiodical **weak** signal + noise.

Increasing noise



A-periodic signal

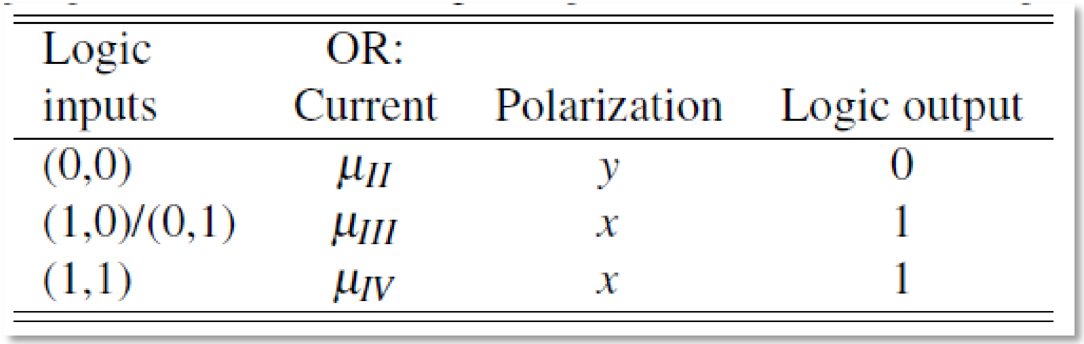
Optimal response for an intermediate noise level: stochastic resonance

Barbay et al PRL **85**, 4652 (2000)

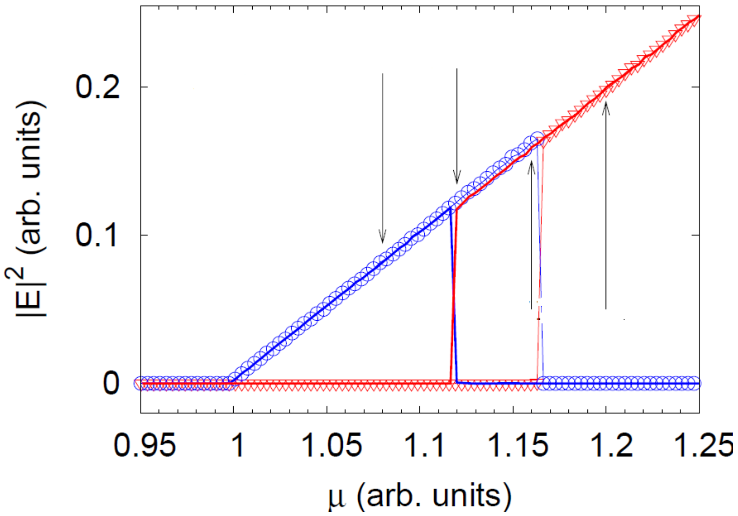
Can this be useful?

MAYBE YES

For implementing a VCSEL-based logic gate



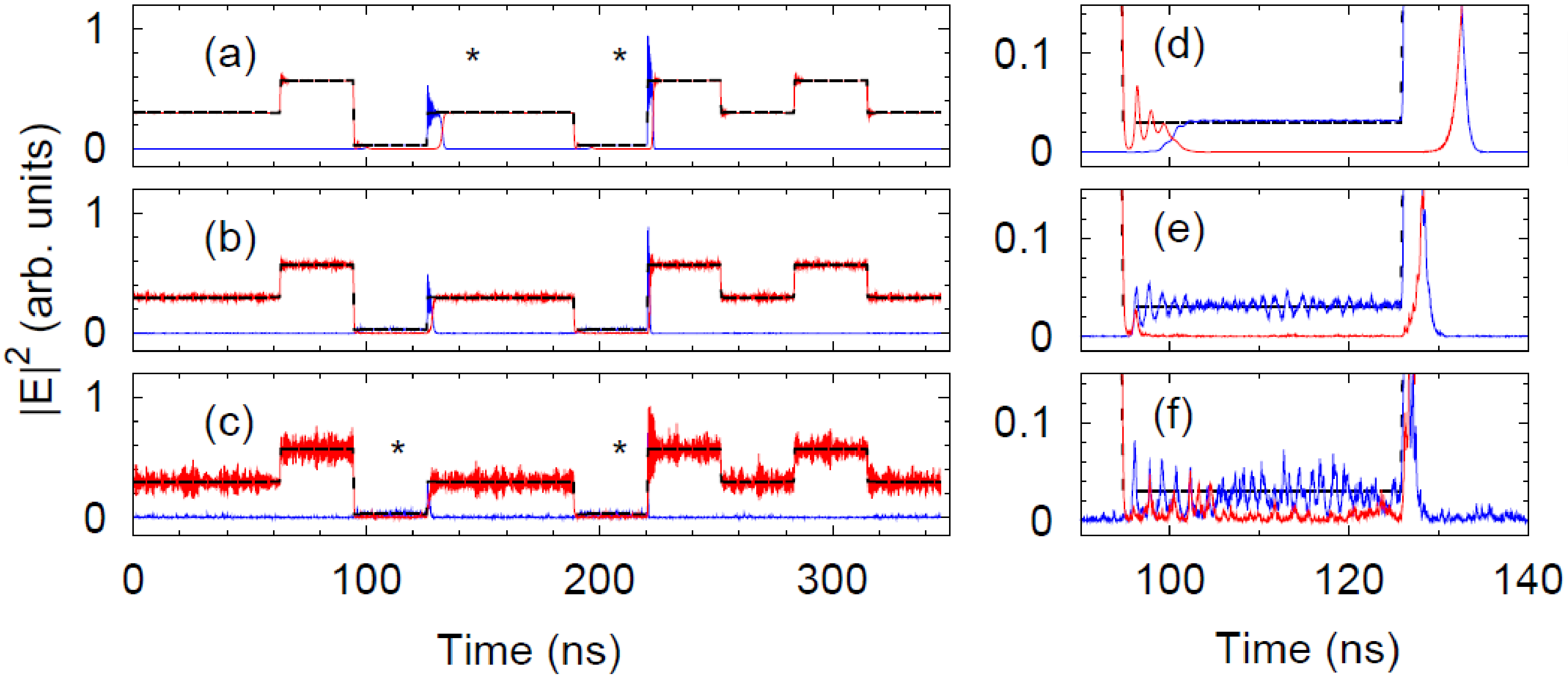
Logic inputs	OR: Current	Polarization	Logic output
(0,0)	μ_{II}	y	0
(1,0)/(0,1)	μ_{III}	x	1
(1,1)	μ_{IV}	x	1



- **Input**: a three-level signal (that encode the two logic inputs) modulates the laser current.
- **Output**: the polarization of the emitted light

- The three levels are such that the laser emits the correct polarization only with the help of optical noise (internal: spontaneous emission or external: incoherent injected light).

Logic Stochastic Resonance



Weak noise

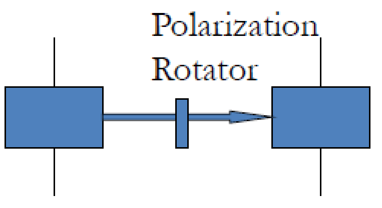
Strong noise

- With **weak** noise: **long delay** in the turn-on of the correct polarization
- With **strong** noise: X and Y are emitted **simultaneously**
- With optimal noise: correct output (**Y** in level I, **X** in II and III)

J. Zamora-Munt and C. Masoller, Opt. Express **18**, 16418 (2010)

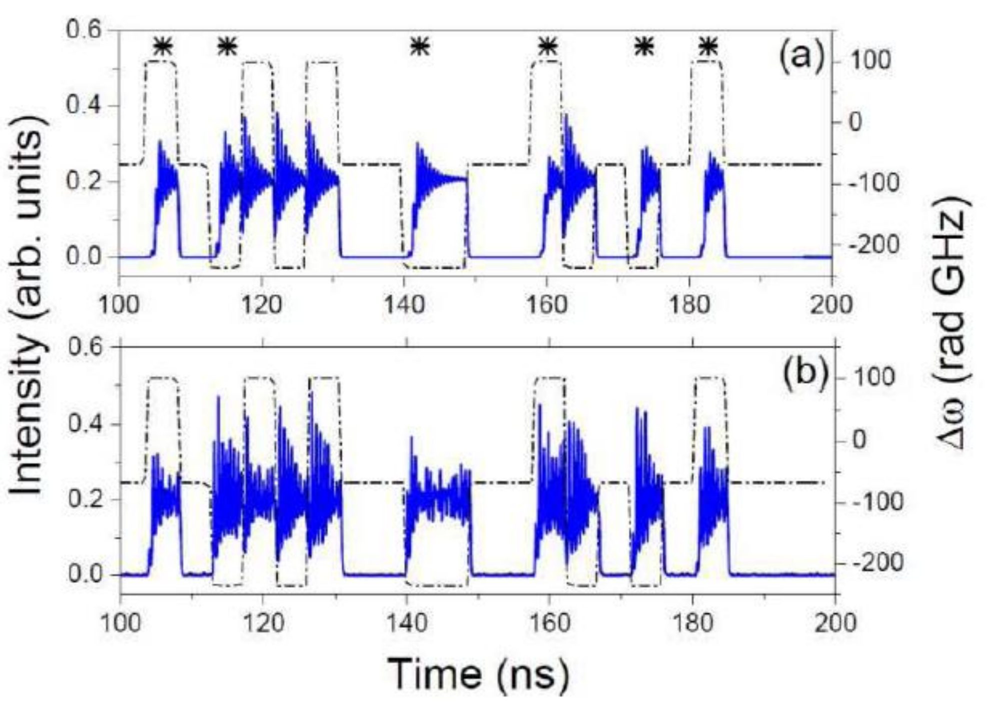
Also demonstrated numerically all-optically

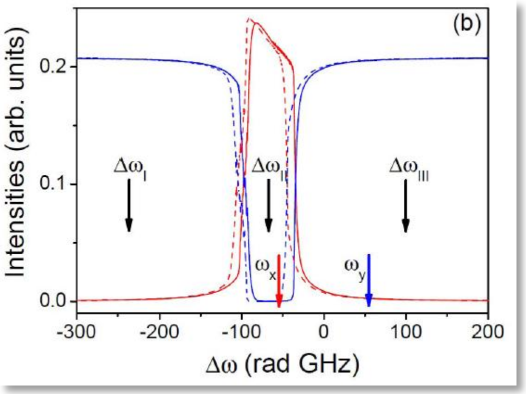
- By using **orthogonal** optical injection
- The logic inputs are encoded in the **wavelength** of the injected light.



Weak noise

Stronger noise

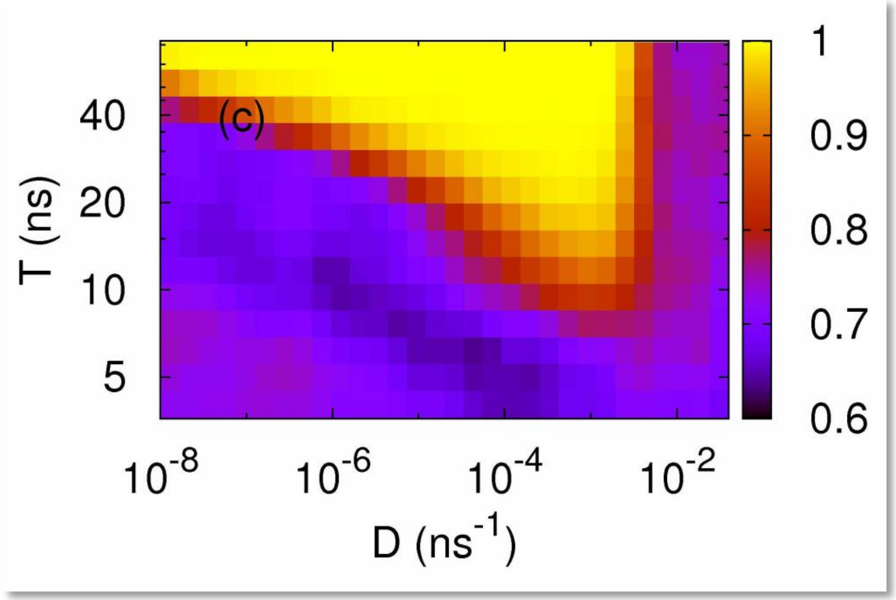




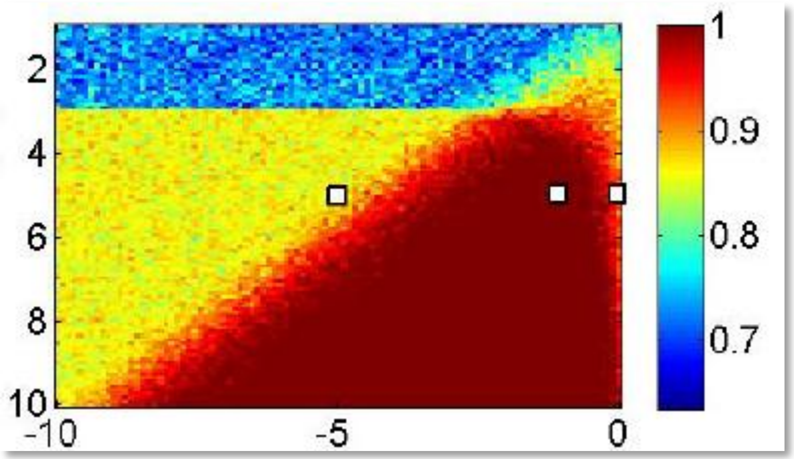
M. Salvide, C. Masoller and M. S. Torre, JQE **49**, 886 (2013)

Probability of correct logic output

Opto-electronic implementation

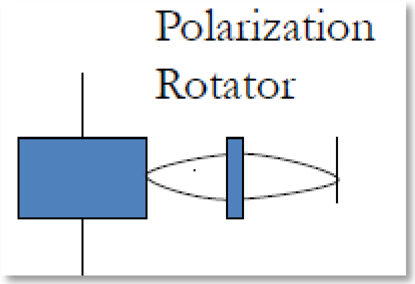


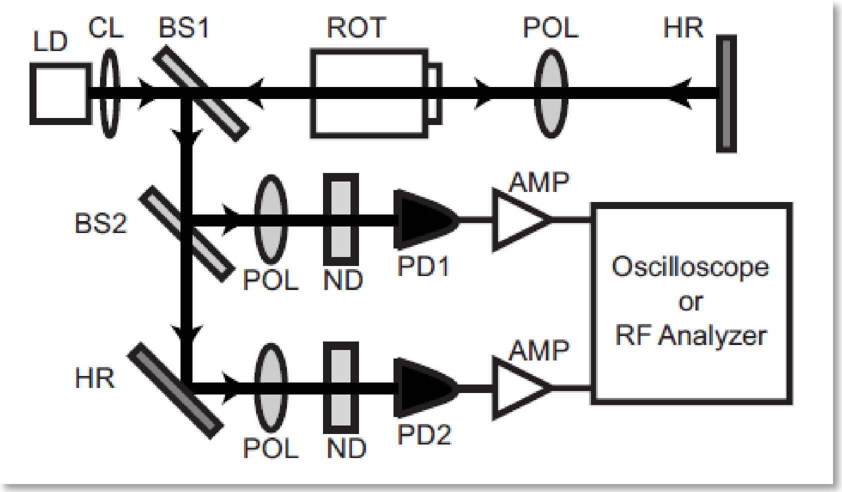
All-optical implementation



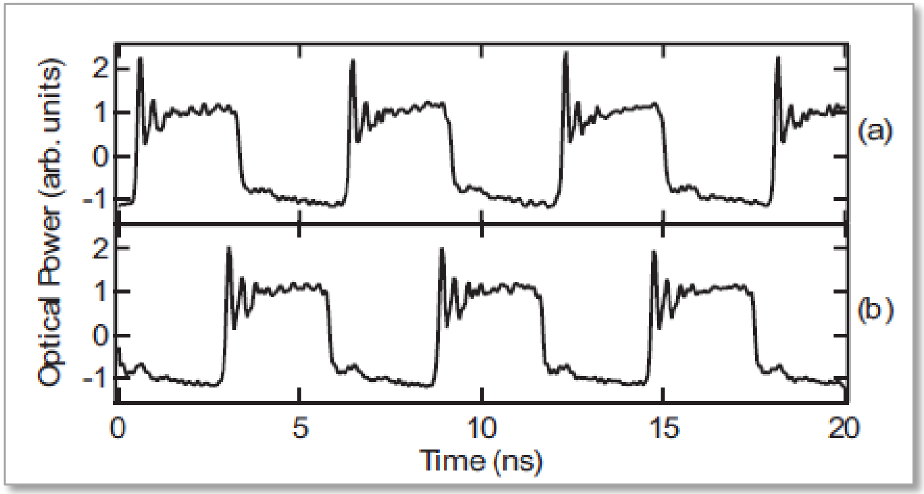
Log (D)

In EELs: PS can be induced with polarization-rotated (PR) feedback





All-optical regular square-wave switching



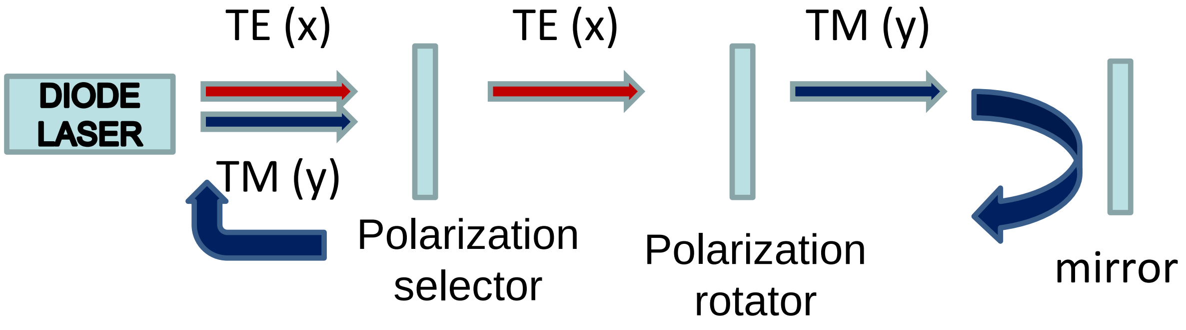
The repetition rate is controlled by the feedback delay time

A. Gavrielides et al, PRE 81, 056209 2010

Why square-wave switching?

PR feedback: only one polarization is selected, is rotated and then is re-injected into the laser.

TE (x) is the natural lasing polarization of the "solitary" laser.



DIODE LASER

TE (x)

TM (y)

Polarization selector

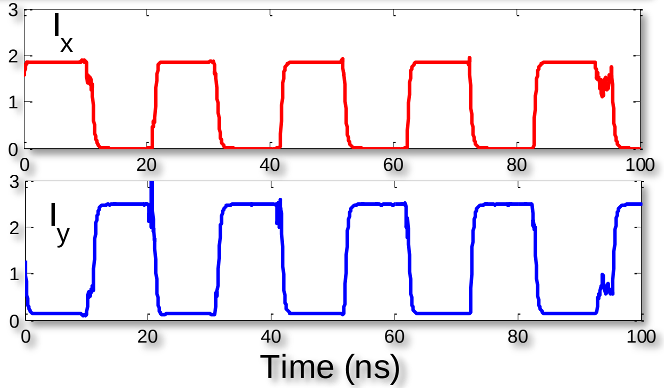
TE (x)

Polarization rotator

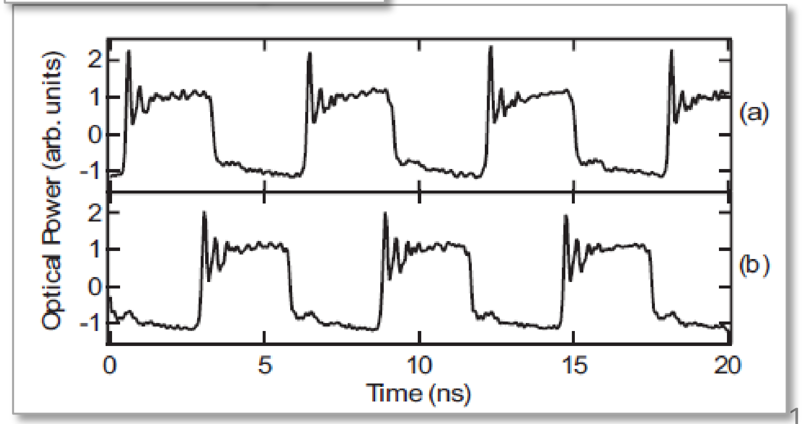
TM (y)

mirror

Sharp rising and falling edges



Periodicity: 2τ

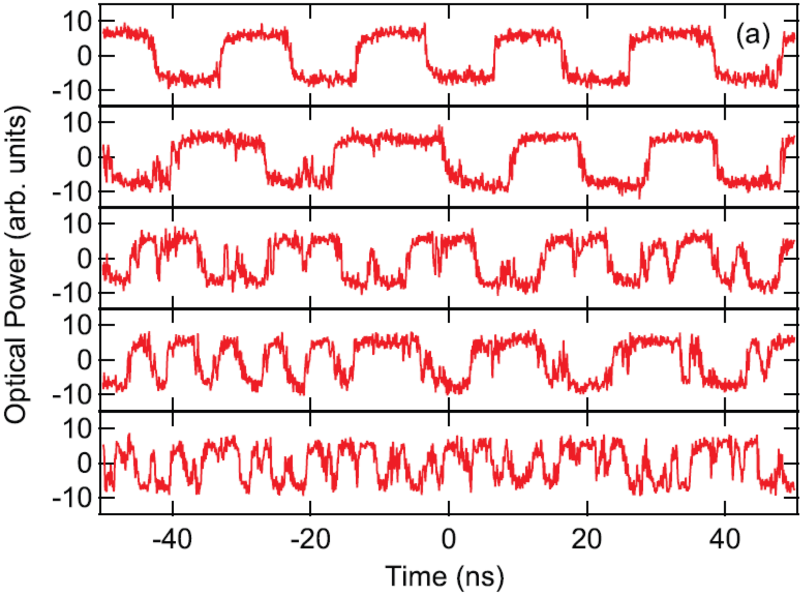


TE (x)

TM (y)

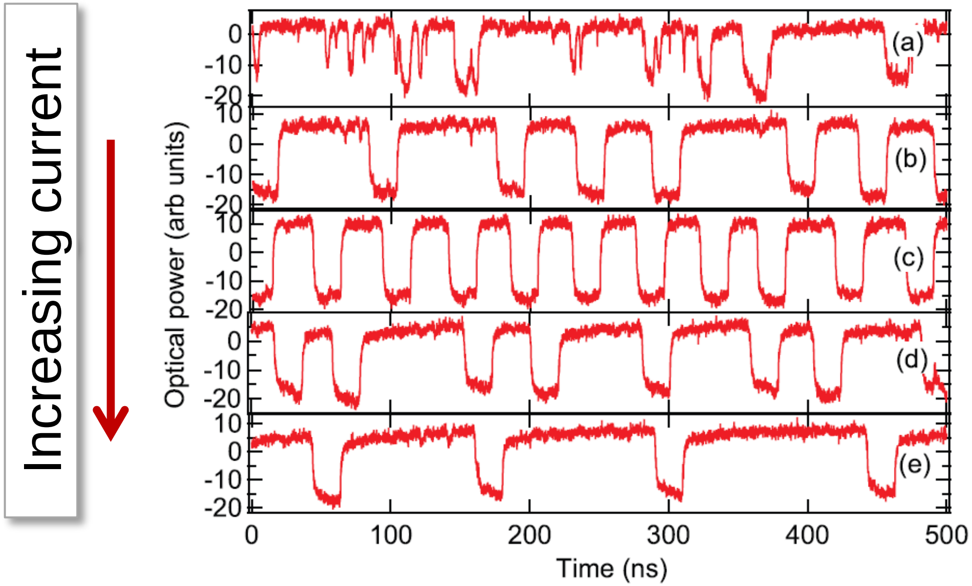
VCSELs with PR feedback

Noisy and unstable SWs:



Time traces taken under identical conditions

Influence of the laser current:

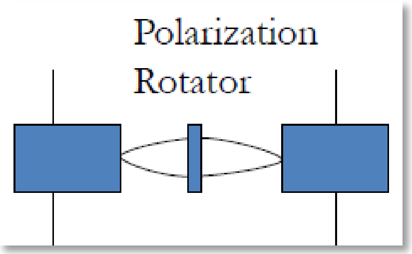


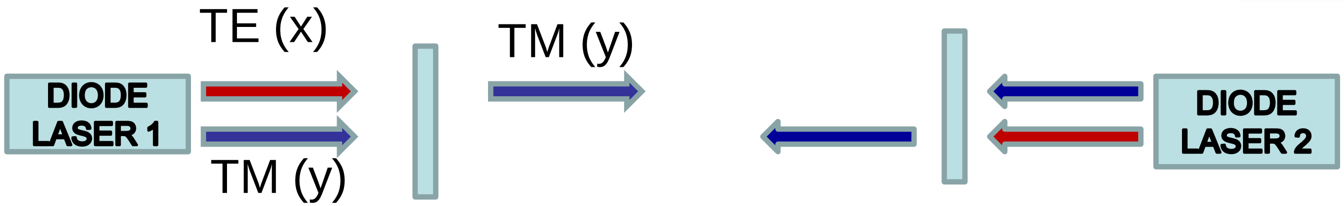
Regular for a certain current value

D. W. Sukow, T. Gilfillan, B. Pope, M. S. Torre, A. Gavrielides, and CM, Phys. Rev. A **86**, 033818 (2012)

SWs in coupled lasers?

Polarization-rotated optical coupling

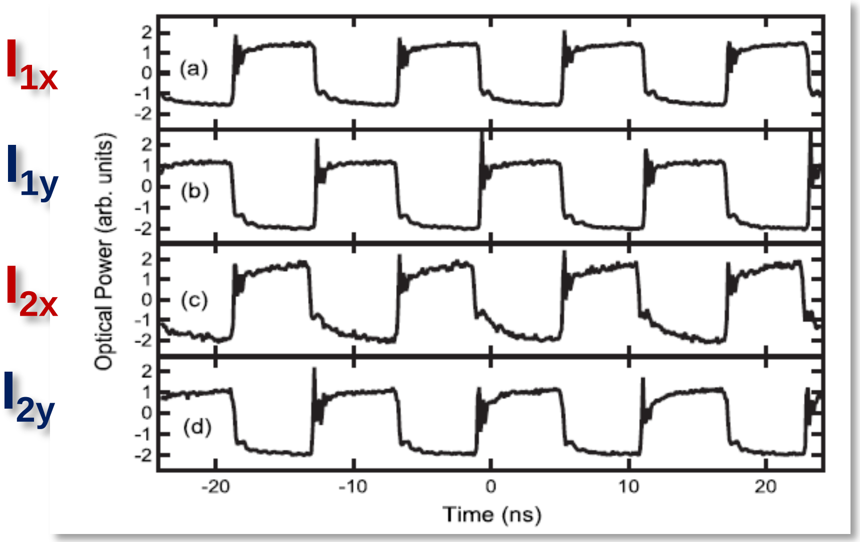




Polarization selector & rotator

Polarization selector & rotator

TE (x) is the natural lasing polarization without coupling

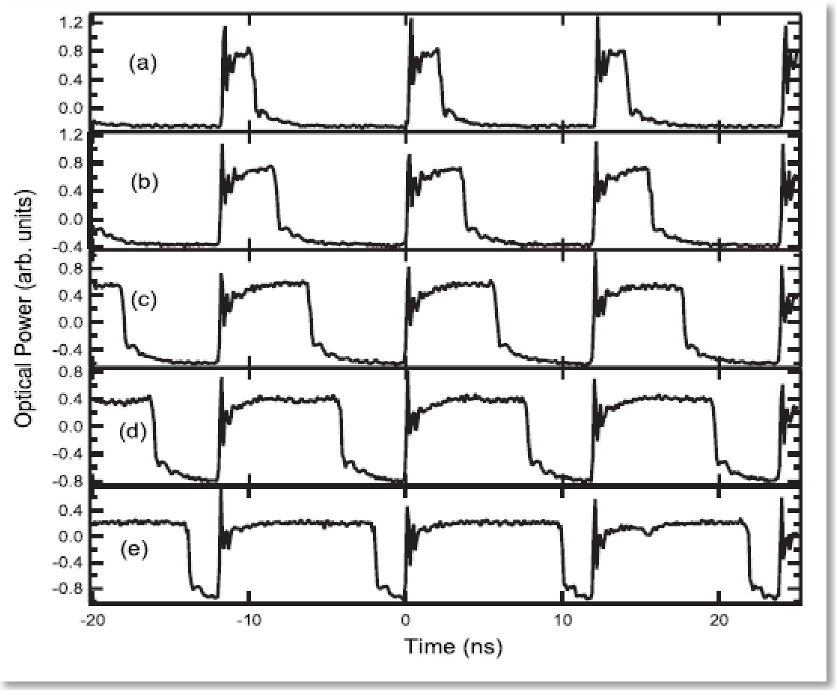


The two lasers switch simultaneously

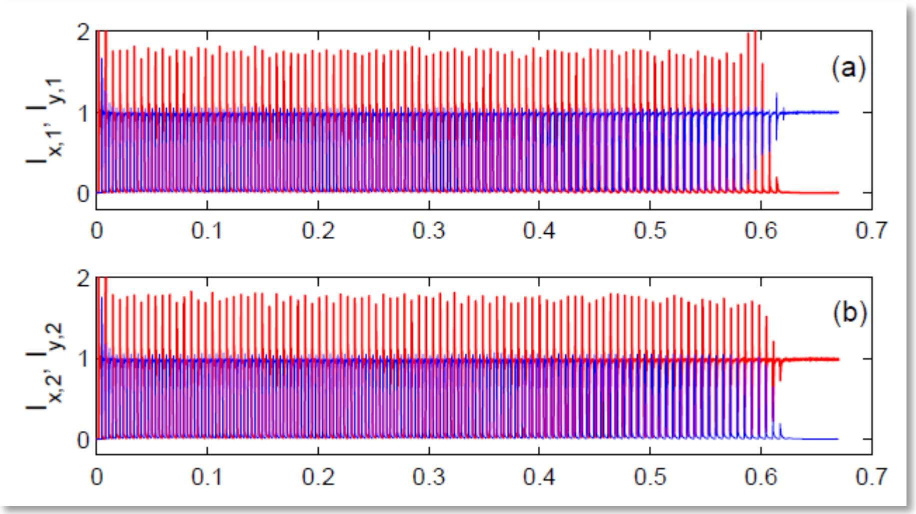
D. Sukow et al, PRE 81, 025206R (2010)

But: the SWs are a transient dynamics

Experiments :
(intensity of one mode of one laser)

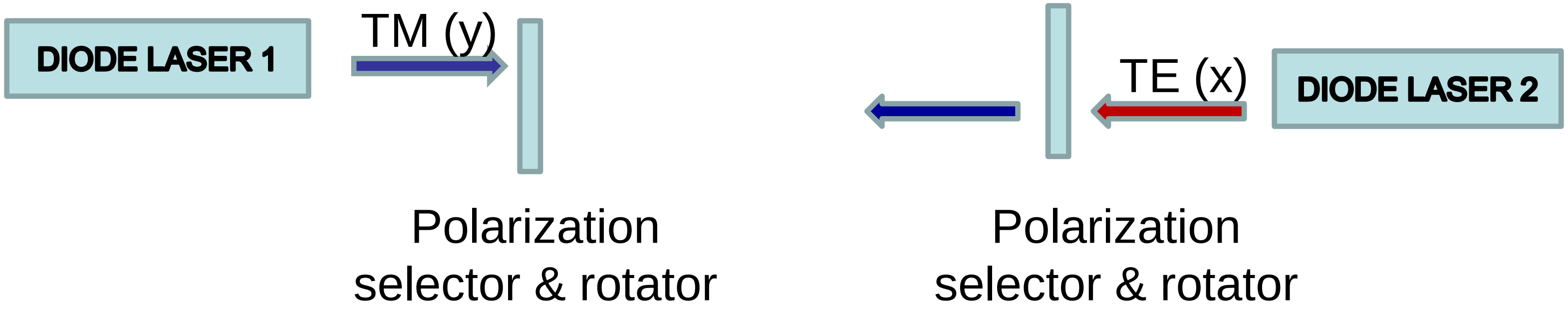


Simulations: after a transient the lasers emit cw orthogonal modes



L2 emits solitary mode (**x**),
L1 emits orthogonal mode (**y**)

Why?



DIODE LASER 1

TM (y)

Polarization
selector & rotator

Polarization
selector & rotator

TE (x)

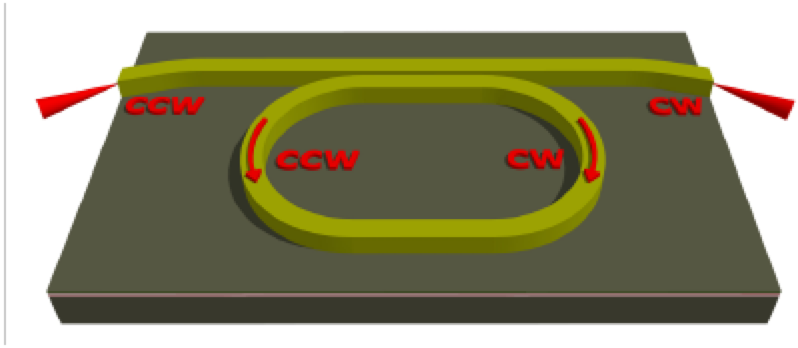
DIODE LASER 2

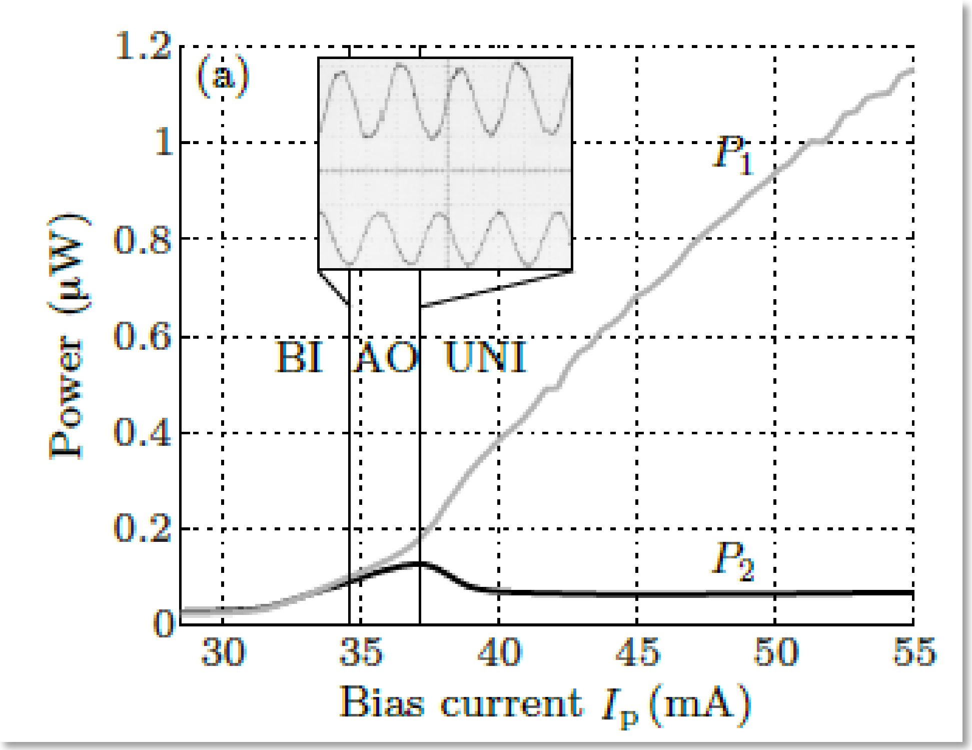
In the stationary state the lasers are coupled unidirectionally: Laser 2 → Laser 1

But in certain parameter regions, deterministic SWs are stable. Because these regions are very narrow, the SWs observed experimentally are likely to be sustained by noise.

C. Masoller, D. Sukow, A. Gavrielides & M. Sciamanna, PRA 84, 023838 (2011)
C. Masoller, M. Sciamanna and A. Gavrielides, Phil. Trans. R. Soc. A 371, 20120471 (2013)

In ring lasers: also two-mode switching



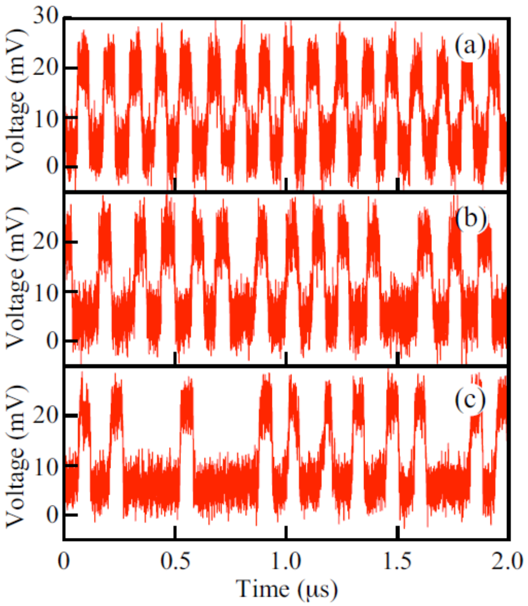


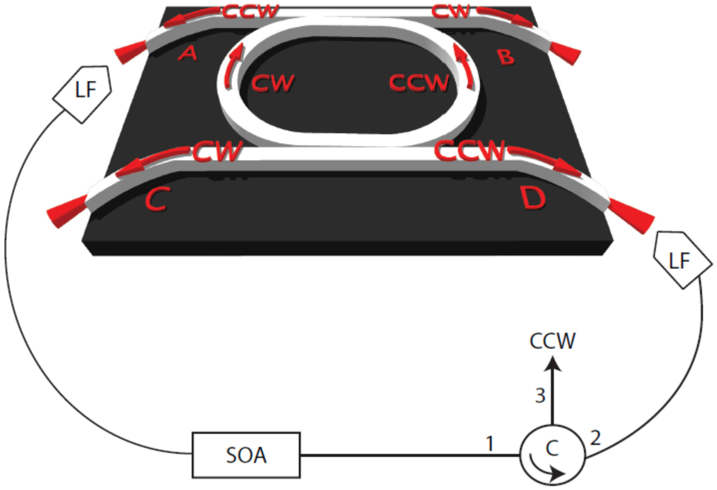
Experimental LI curve of a SRL

Adapted from W. Coomans PhD thesis; M. Sorel et al, Opt. Lett. 27 1992 (2002)

And also SWs when feeding one directional mode into the other

Increasing the injection current





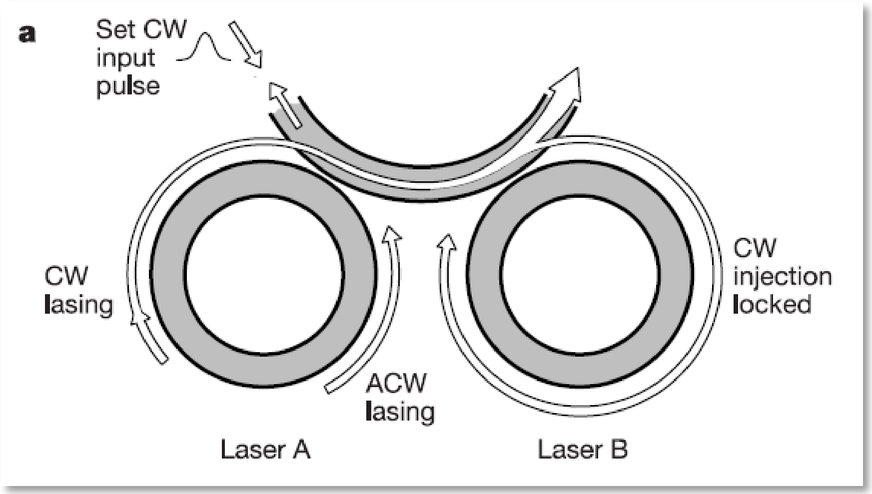
$$\dot{E}_{ccw} = \kappa(1+i\alpha)\left(G_{ccw}N-1\right)E_{ccw} - k(1+\delta k)e^{i\phi_k}E_{cw} + \tilde{F}_{ccw},$$

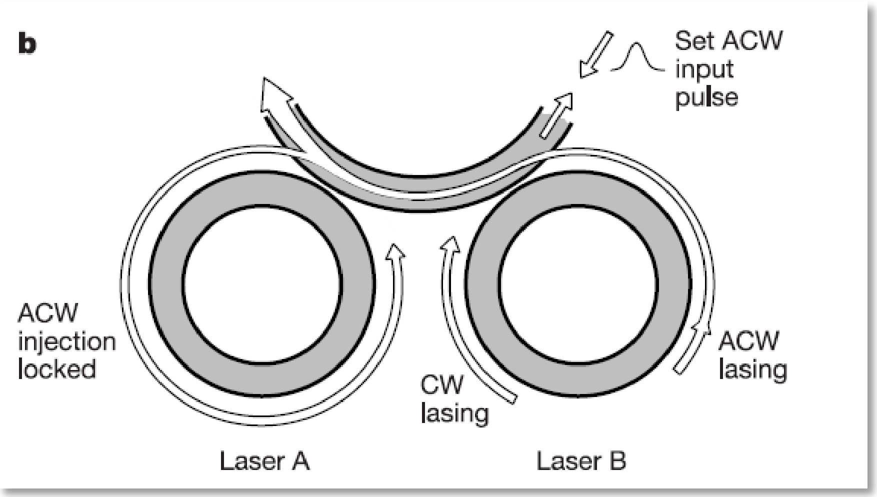
$$\dot{E}_{cw} = \kappa(1+i\alpha)\left(G_{cw}N-1\right)E_{cw} - k(1-\delta k)e^{i\phi_k}E_{ccw} - \eta e^{i\theta}E_{ccw}(t-\tau) + \tilde{F}_{cw},$$

$$\dot{N} = \gamma\left(\mu - N - NG_{cw}|E_{cw}|^2 - NG_{ccw}|E_{ccw}|^2\right).$$

L. Mashal et al, Optics Express 20, 22503 (2012)

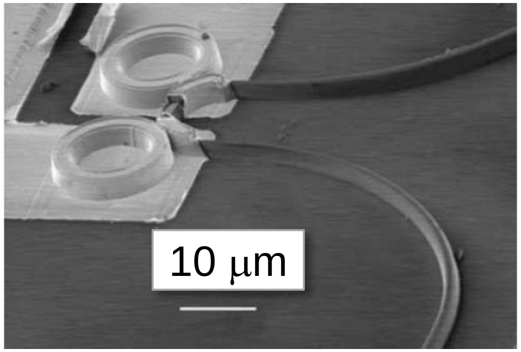
Coupled SRLs: optical memory





Light from laser A injection-locks laser B, forcing it to lase only in the CW direction

Light from laser B injection-locks laser A, forcing it to lase only in the ACW direction



M. T. Hill et al, Nature 432, 206 (2004)

Take home message

- The nonlinear dynamics of semiconductor lasers induced via an external perturbation (modulation, injection, feedback) can be useful for certain applications.

- The nontrivial interplay of noise and nonlinearity can also be useful for applications.

Suggested literature for further reading:

- A. Larsson, Advances in VCSELs for Communication and Sensing, IEEE J. Sel. Top. Quantum Electron. Vol 17, pp 1552, 2011.
- Remembering the Million-Hour laser, Optics & Photonics News (OPN) May 2012
- Multidimensional optical data storage, OPN July/August 2010
- Lasers in communications, OPN March 2010
- Integrated Silicon Photonics: Harnessing the Data Explosion, OPN March 2011

THANK YOU FOR YOUR ATTENTION !

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http://www.fisica.edu.uy/~cris/