Photonic Devices Based on III-V Multiple Quantum Wells

Claudio Coriasso

Turin Technology Centre

AVAGO TECHNOLOGIES

Outline

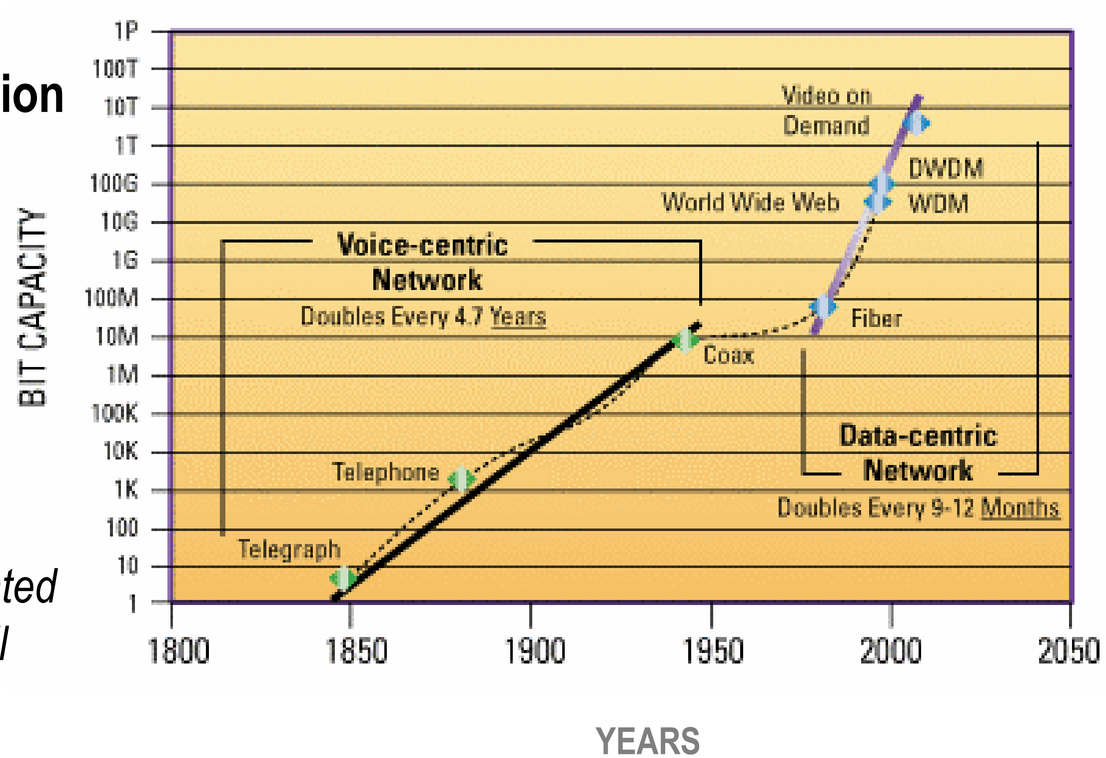
1) III-V Multiple Quantum Wells

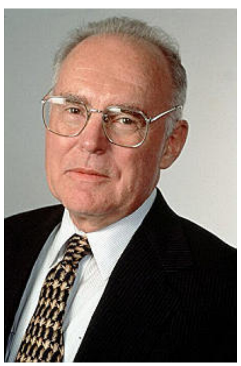
2) Photonic integration

3) Photonic devices

4) New trends in photonic integration

5) Avago's snapshot

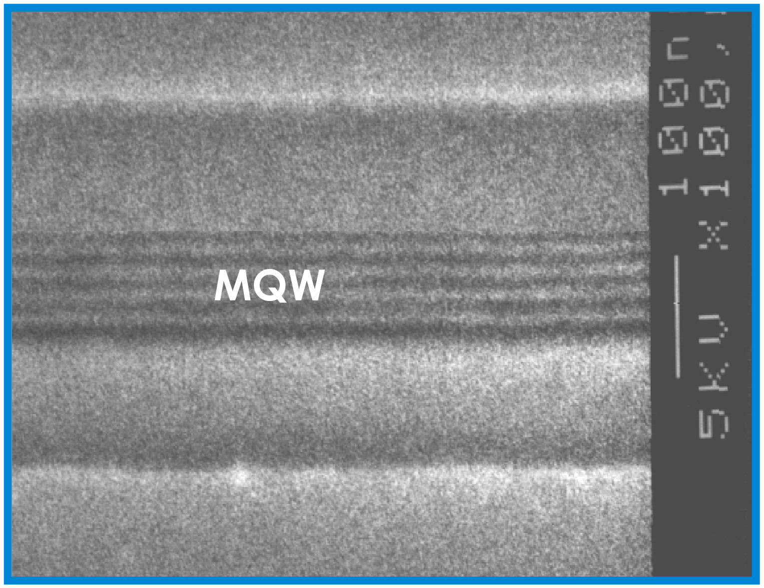




"In 1975 there will be 65000 components in every integrated circuit. Integrated circuits will allow home computers and mobile communication."
G. Moore 1965

1) III-V Multiple Quantum Wells (MQW)

Atomic-scale controlled artificial structures



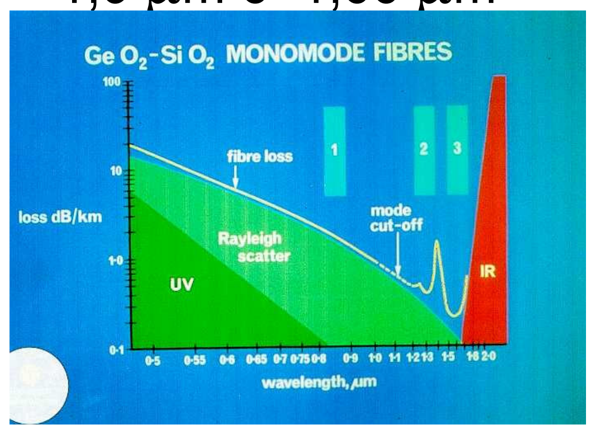
Semiconductor material requirements for photonic devices

•Optical gain, light emission ...

→ Active + passive devices

•... at wavelength of interest: λ = 1,3 μm e 1,55 μm

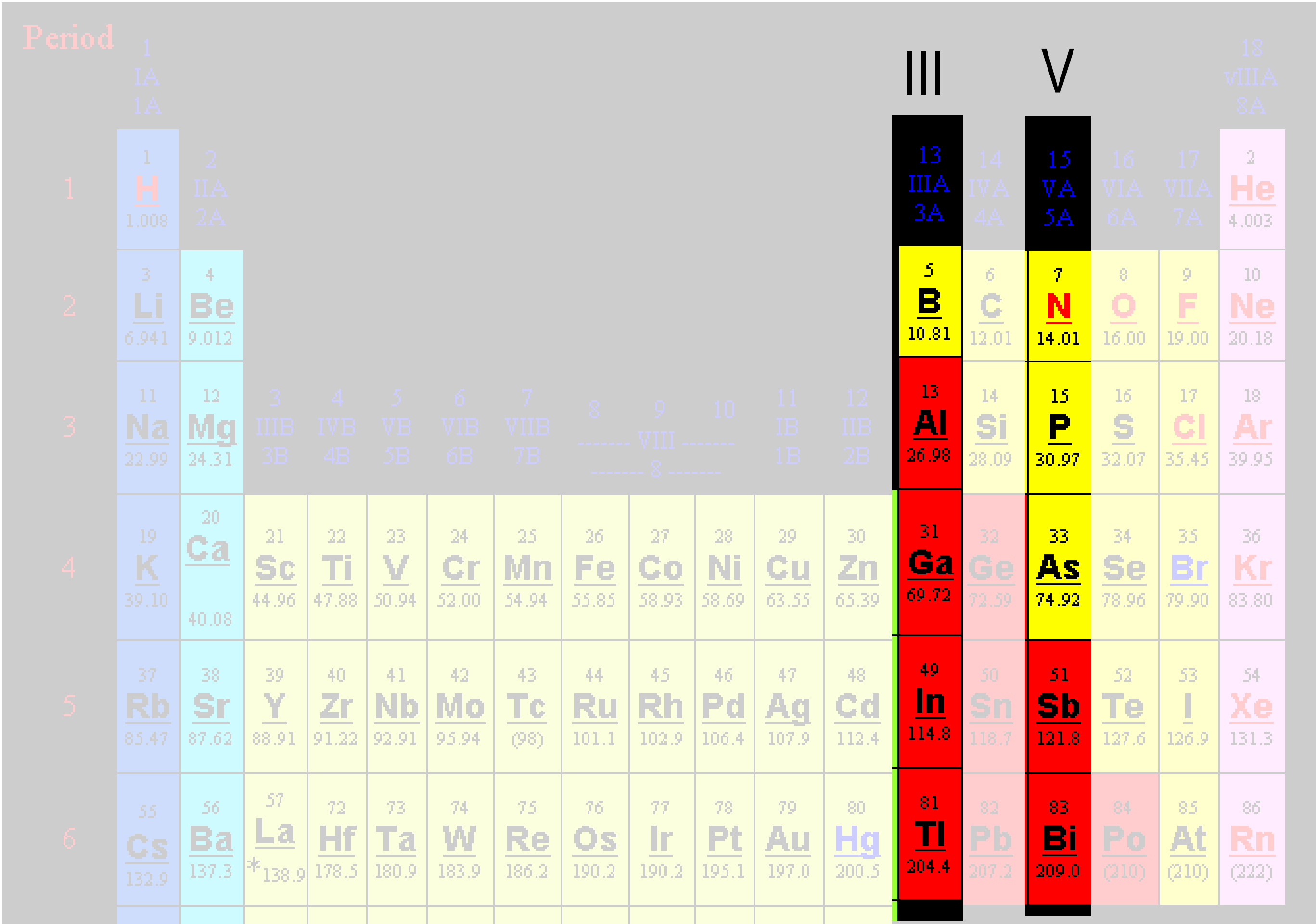
→



•The material has to be compatible with commercial substrates:

→ Si, GaAs, InP (IV, III-V, III-V)

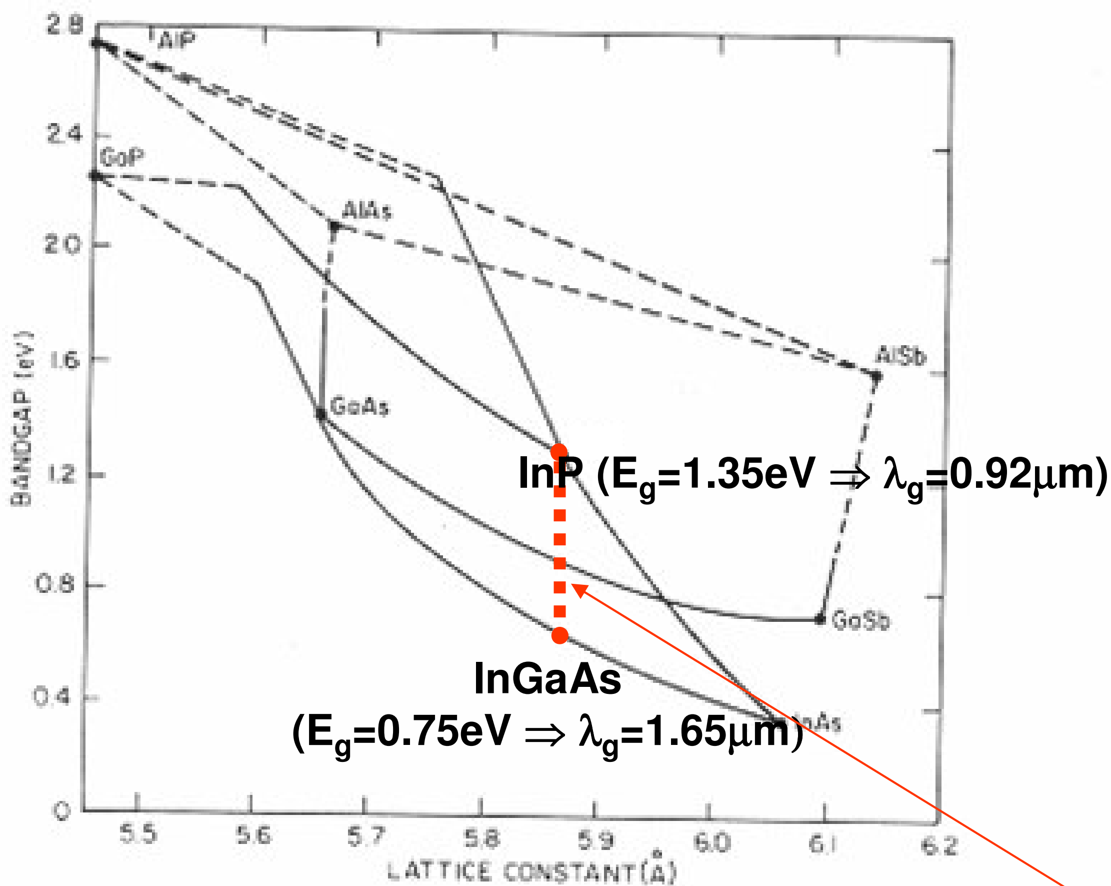
III-V semiconductor materials



There are no single elements or binary compounds compatible with commercial substrates and emitting light at 1.3 µm e 1.55 µm.
Semiconductor alloys of III-V elements are the best materials for photonic devices.

Quaternary alloy InGaAsP

T. P. Pearsall, GaInAsP Alloy Semiconductors, Wiley (1982)



Variation of the bandgap as a function of lattice constant for III–V binary and alloy semiconductors

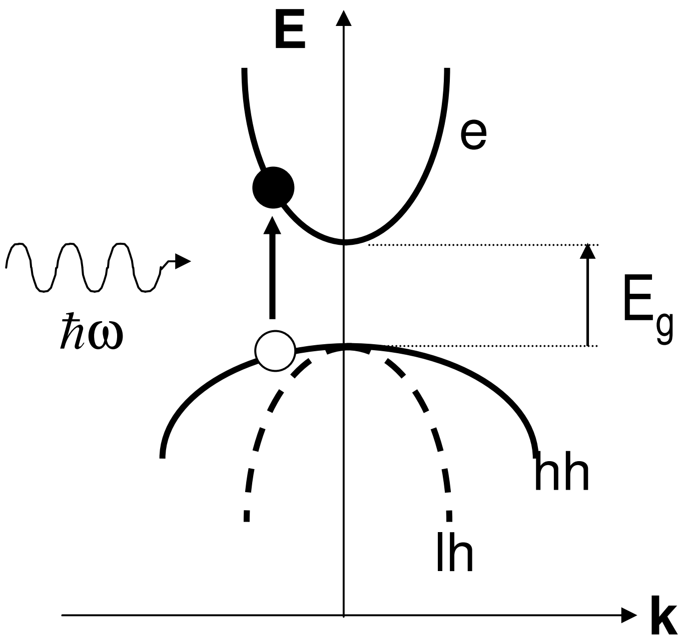
$In_{1-x}Ga_xAs_yP_{1-y}$
alloys cover all the spectral range required for optical telecom

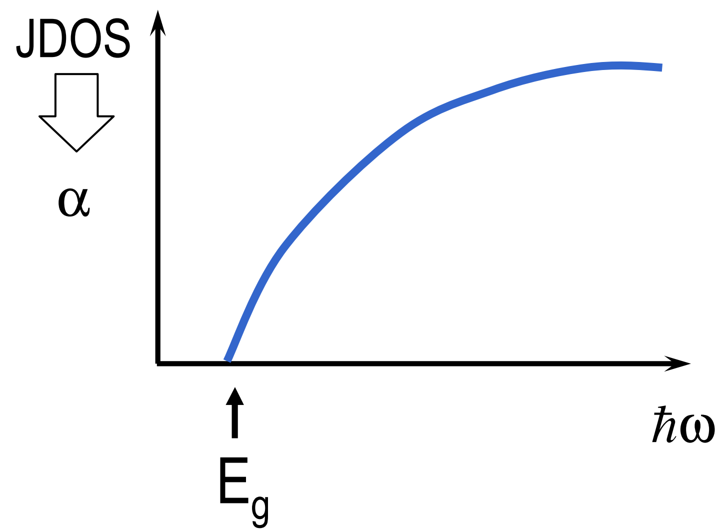
- High quality material
- Established growth techniques and material processing
- Suited for active devices (lasers, amplifiers, modulators, ...) and passive structures (waveguides, couplers, ...)

$In_{1-x}Ga_xAs_yP_{1-y}$
lattice matched to InP
(λ_g=0.92 - 1.65µm)

AVAGO TECHNOLOGIES

Optical properties of semiconductors



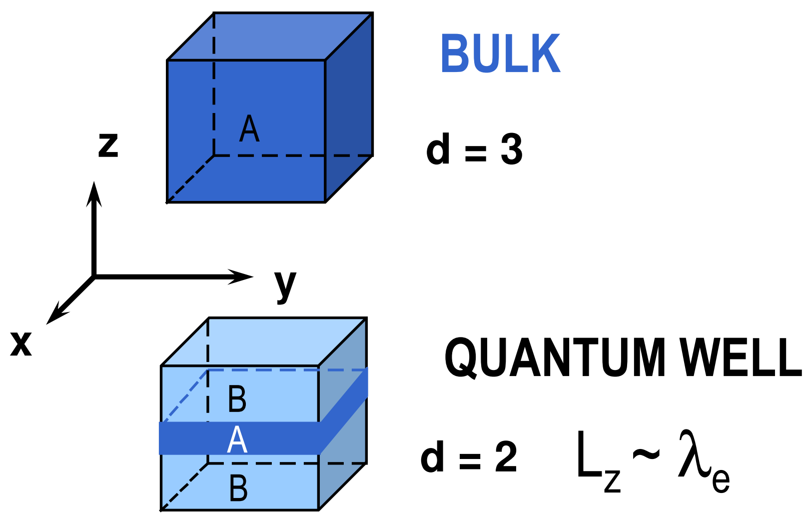


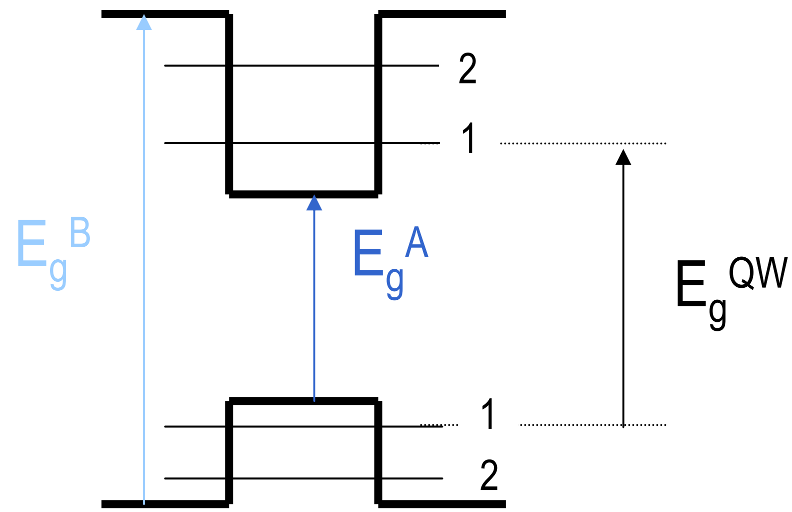
$$m_{hh}^{*} > 9\, m_e^{*}$$

$$m_{lh}^{*} \cong m_e^{*}$$

$$JDOS \propto \sqrt{\hbar\omega - E_g}$$

Quantum Wells





QW is a planar waveguide for electrons

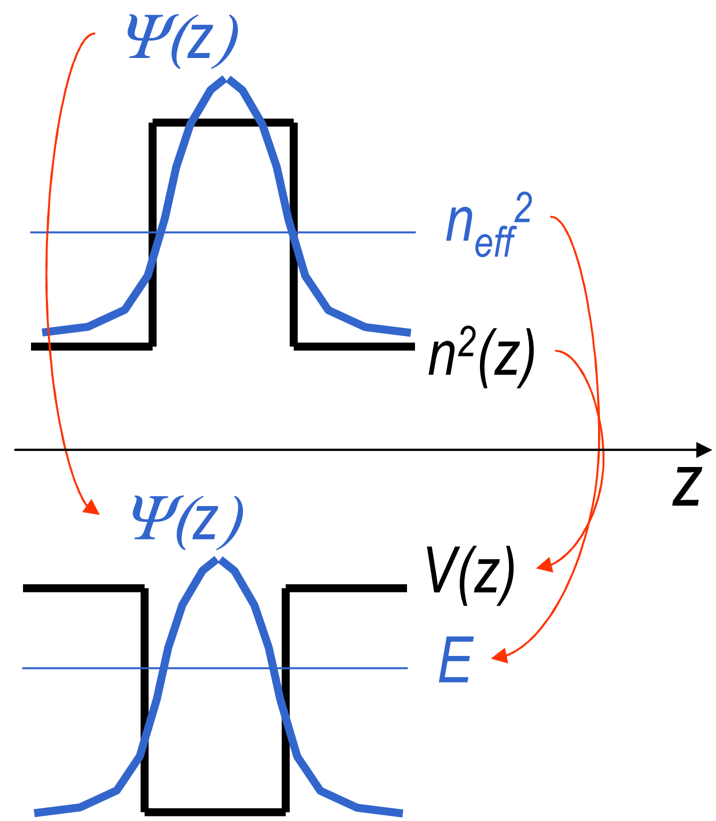
Photon wave eqn. vs. Electron wave eqn.

Helmholtz equation (*photon*)

$$\left[\frac{d}{dz^2}^2 + k_0^{\ 2} n^2(z)\right]\psi(z) = n_{eff}^{\ \ 2}\psi(z)$$

Schroedinger equation (*electron*)

$$\left[-\frac{\hbar^2}{2m}\frac{d^2}{dz^2} + V(z)\right]\psi(z) = E\psi(z)$$



$n^2(z) \Rightarrow -V(z)$

cladding $\Rightarrow$ barrier

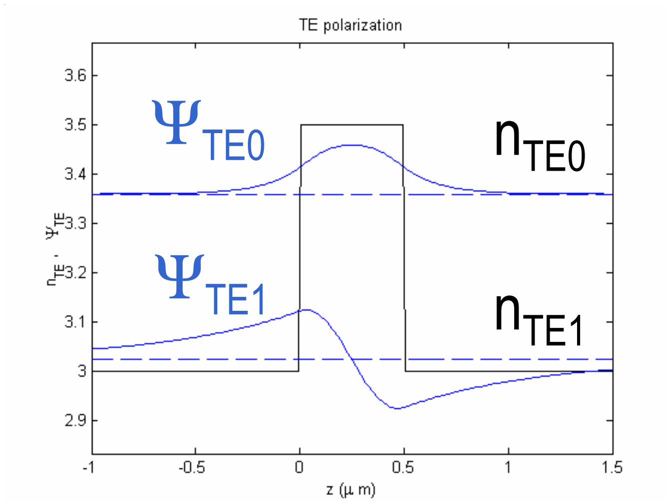
core $\Rightarrow$ well

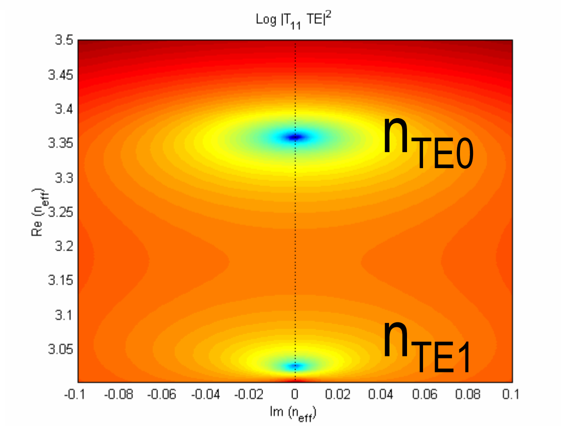
potential wells confine electrons (quantum wells)

refractive index ridges confine photons (optical waveguides)

Eigenfunction/Eigenvalues Calculation

Waveguide

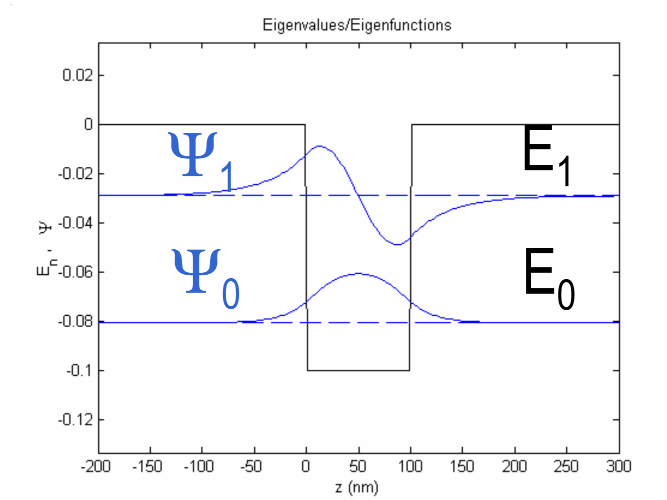


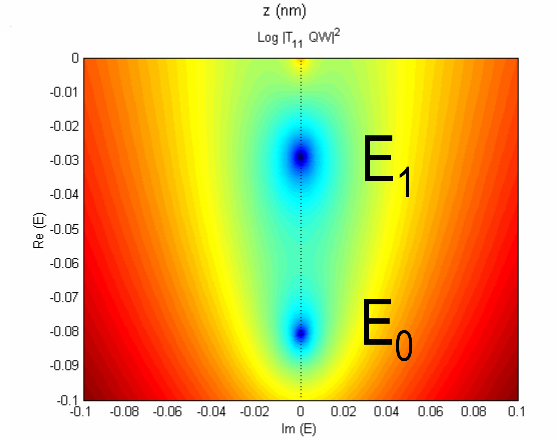


$$\Psi_{TE}(z^-) = \Psi_{TE}(z^+)$$

$$\frac{\partial}{\partial z}\Psi_{TE}(z^-) = \frac{\partial}{\partial z}\Psi_{TE}(z^+)$$

Quantum Well

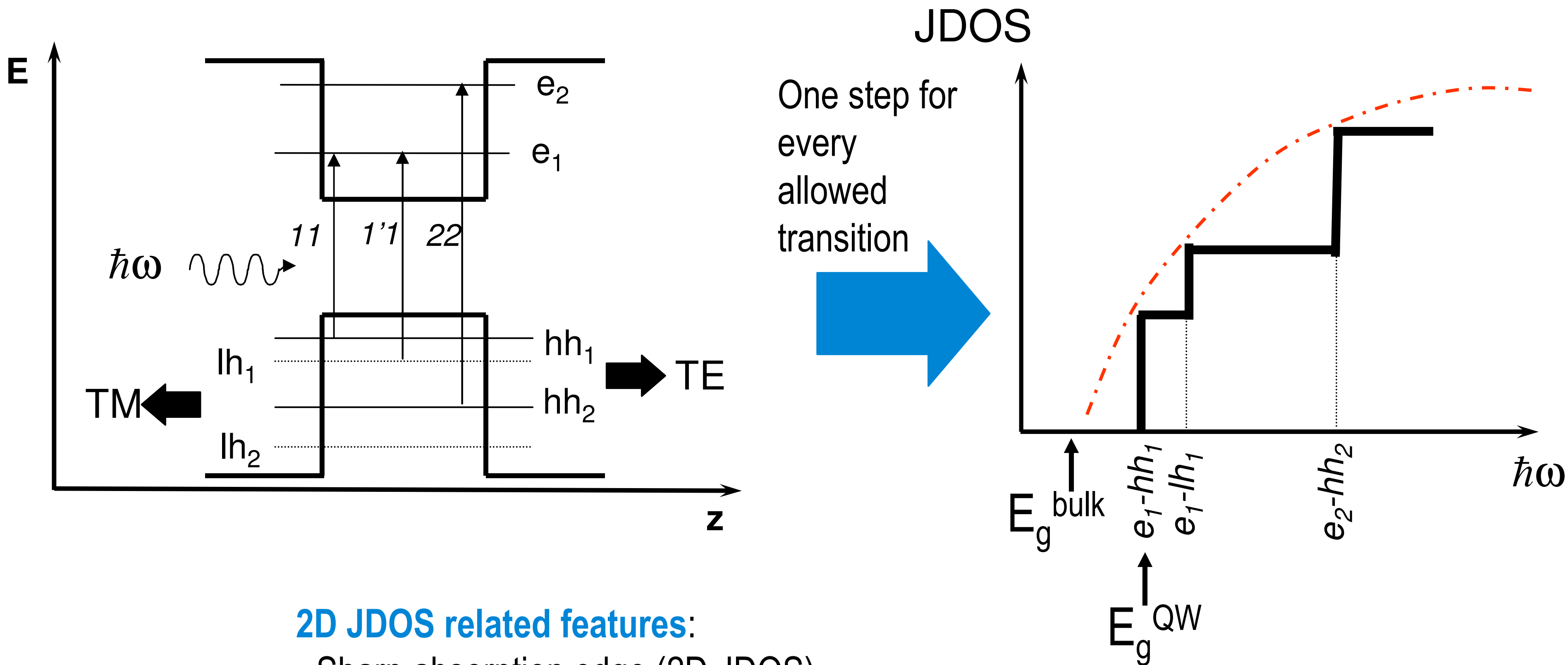




$$\Psi(z^-) = \Psi(z^+)$$

$$\frac{1}{m(z^-)}\frac{\partial}{\partial z}\Psi(z^-) = \frac{1}{m(z^+)}\frac{\partial}{\partial z}\Psi(z^+)$$

QW band structure

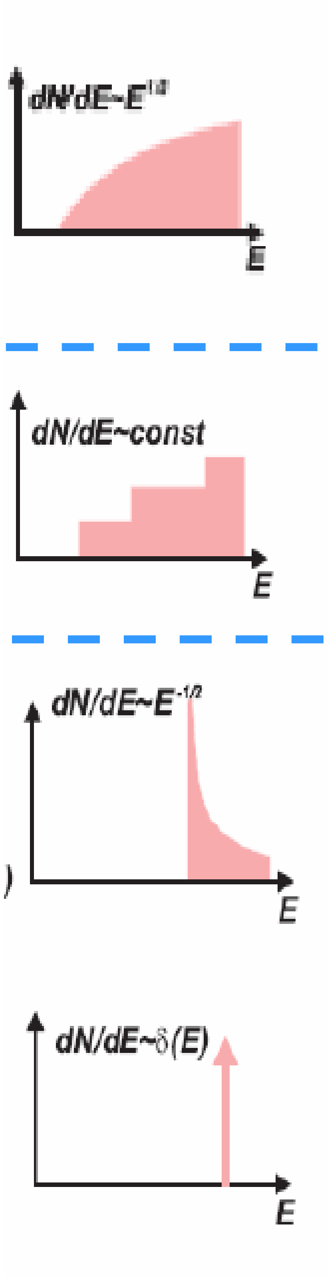


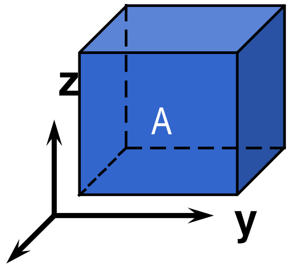
2D JDOS related features:

- Sharp absorption edge (2D JDOS)
- High differential gain
- Wide gain bandwith
- High electroabsorption efficiency (QCSE)
- Strong optical nonlinearities
- . . .

$$JDOS = \sum_{i\,j} \frac{\mu_{i\,j}}{\pi\,\hbar^2}\,\Theta\left(\hbar\omega - E_{i\,j}\right)$$

Reduced dimensionality structures

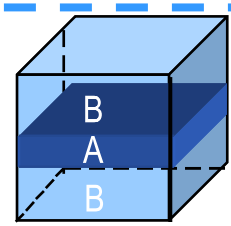




BULK

d = 3

Q.M. **E.M.**

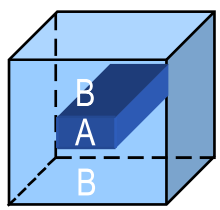


QUANTUM WELL ⟷ **PLANAR WAVEGUIDE**

d = 2

$L_z \sim \lambda_e$

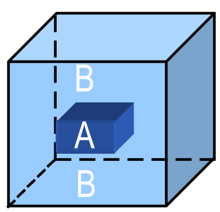
1975: R.Dingle and C.Henry
USA Patent Application



QUANTUM WIRE ⟷ **CHANNEL WAVEGUIDE**

d = 1

$L_z, L_y \sim \lambda_e$

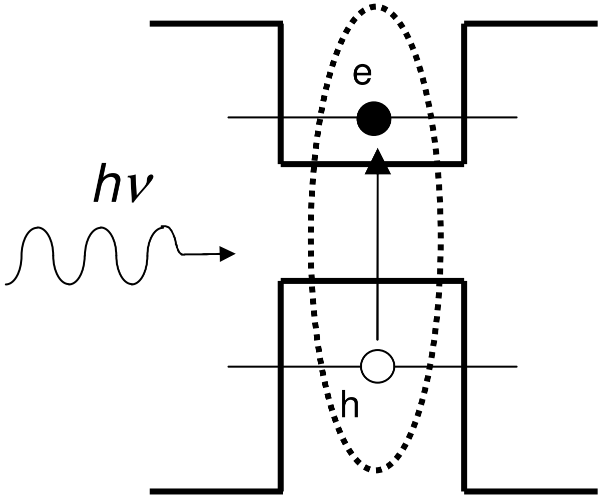


QUANTUM DOT ⟷ **OPTICAL RESONATOR**

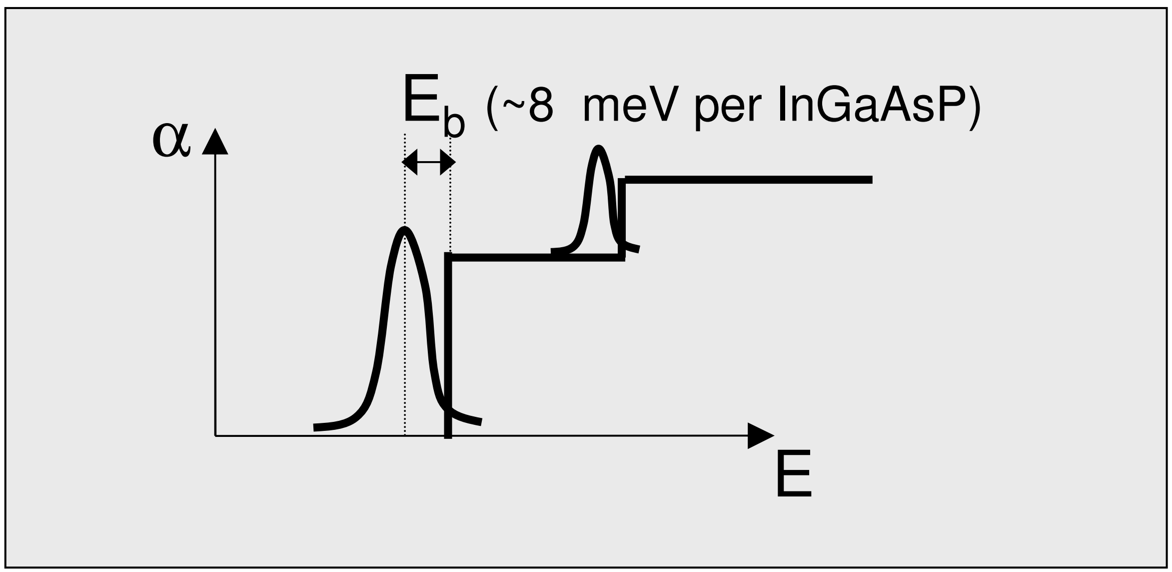
d = 0

$L_z, L_y, L_x \sim \lambda_e$

Excitons

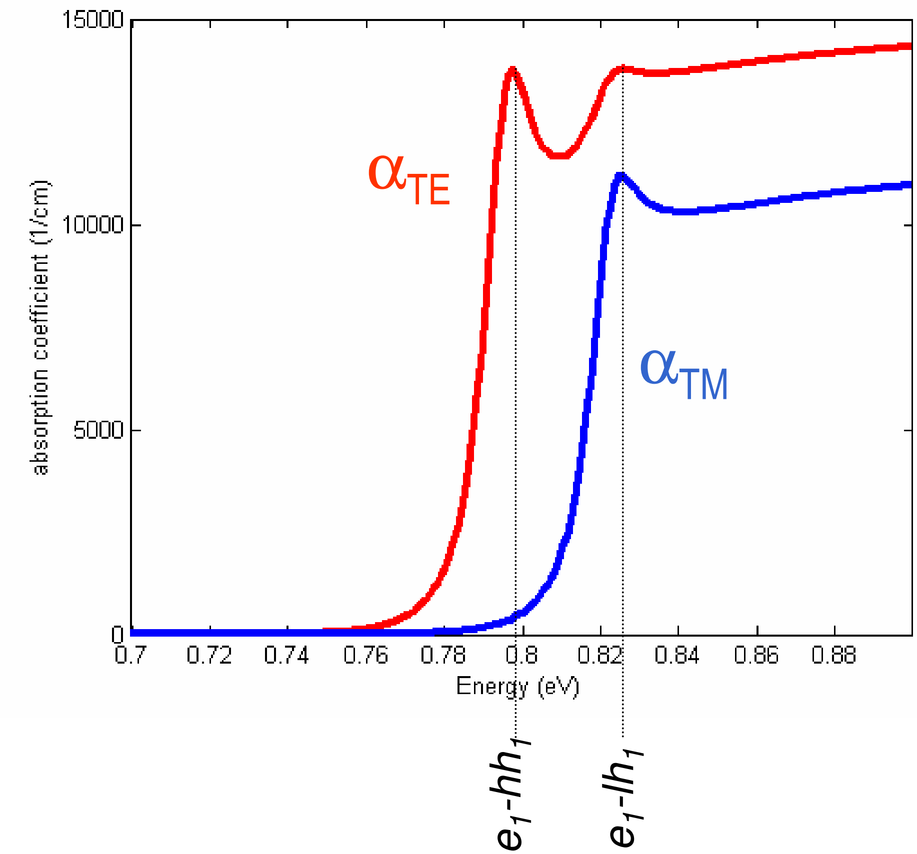


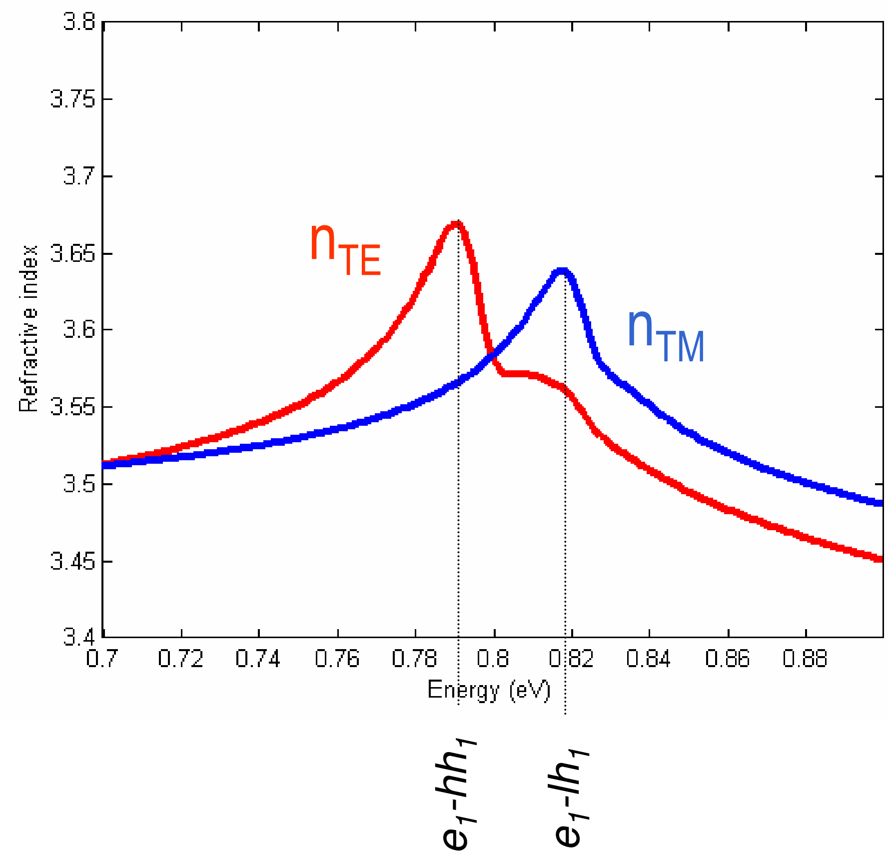
e - h semi-bound states ($\tau \sim 100$ fs) which produce sharp absorption peaks detuned from the transition energies (absorption steps) by their binding energy



QW optical properties

$$n(\lambda) + i\,k(\lambda) = n(\lambda) + i\,\frac{\alpha(\lambda)\cdot\lambda}{4\pi} \;\Rightarrow\; \alpha(\lambda) \propto JDOS + exciton\ peaks$$





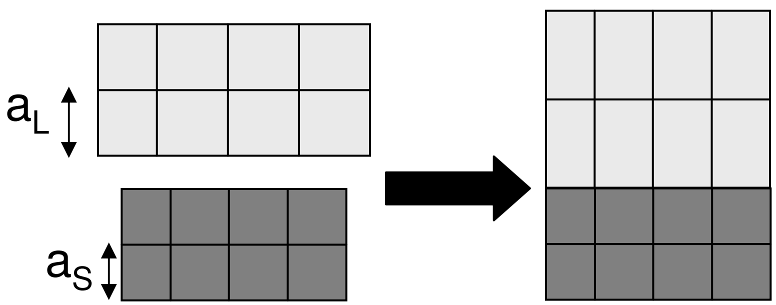
Strong dichroism ⇒

Polarisation selection rules:
TE: 3/4 hh, 1/4 lh
TM: 0 hh, 1 lh

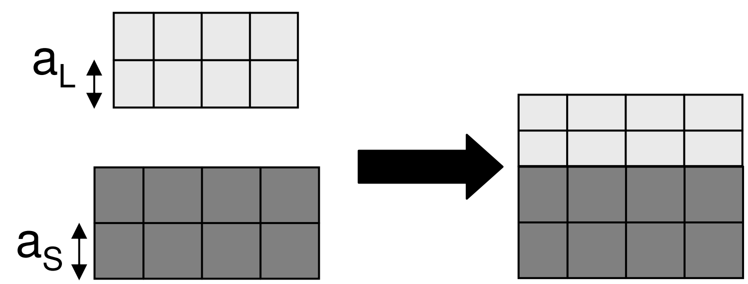
Strain(1)

The epitaxial layer can be grown with a lattice parameter slightly different from the substrate lattice parameter (lattice mismatch).

$$m = \frac{a_L - a_S}{a_S} \quad , \; a_L = \textit{lattice parameter of the epitaxial layer}$$
$$a_S = \textit{lattice parameter of the substrate}$$



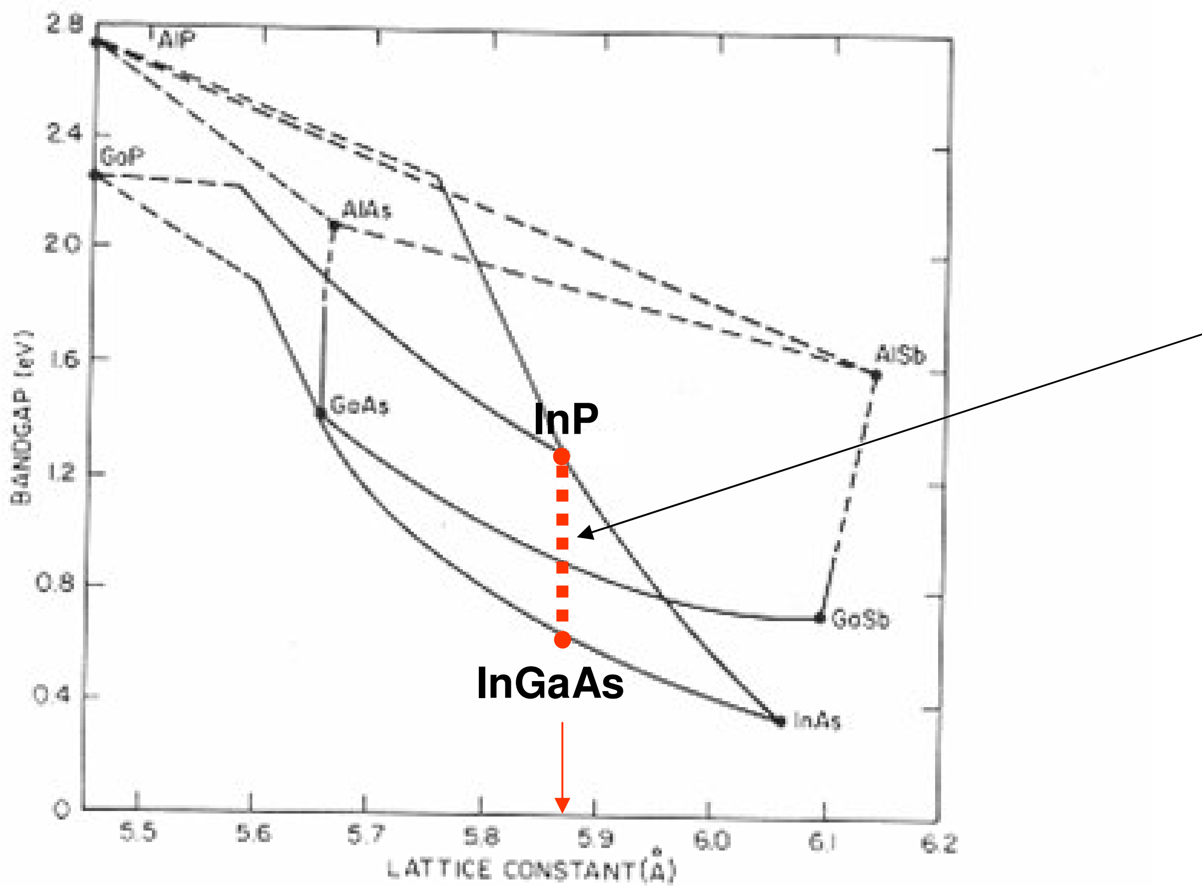
compressive strain
m>0



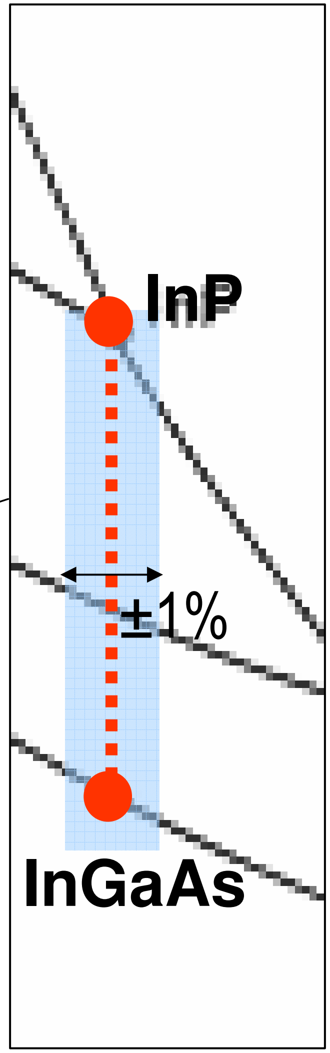
tensile strain
m<0

Strain(2)

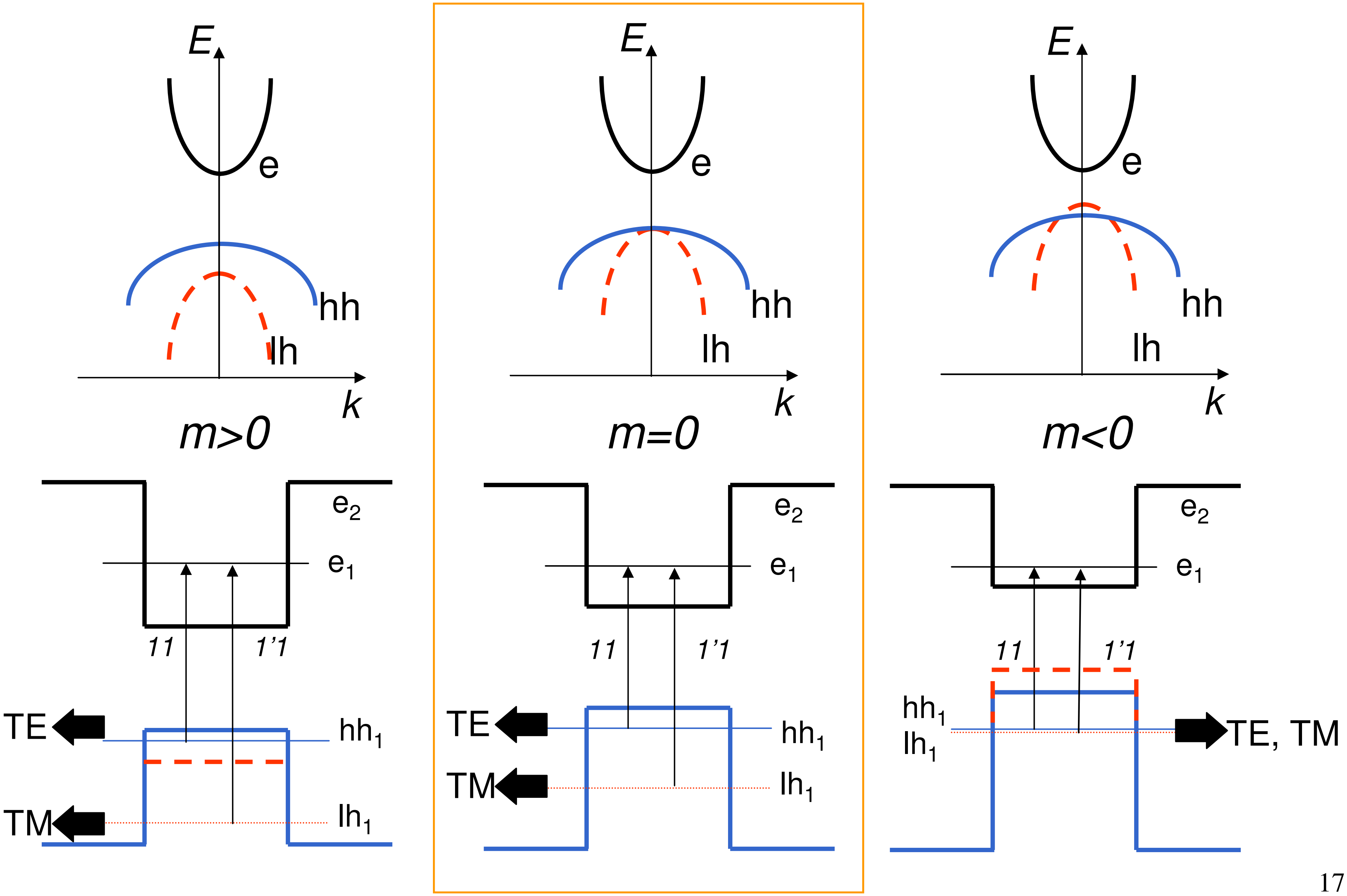
T. P. Pearsall, GaInAsP Alloy Semiconductors, Wiley (1982)



Variation of the bandgap as a function of lattice constant for III–V binary and alloy semiconductors



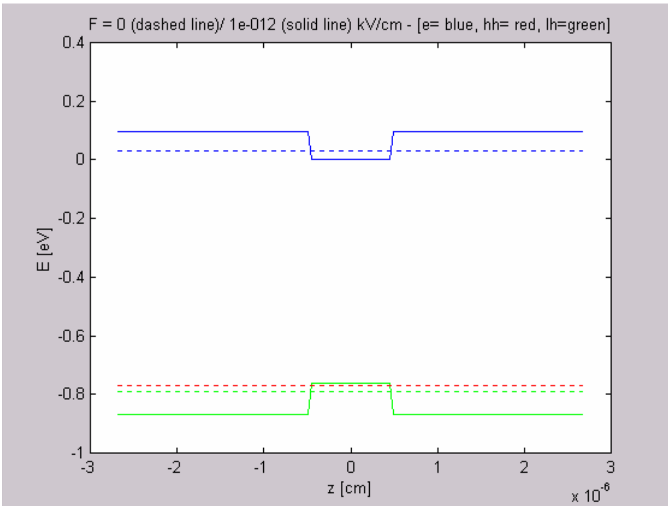
Strain effect on band structure:



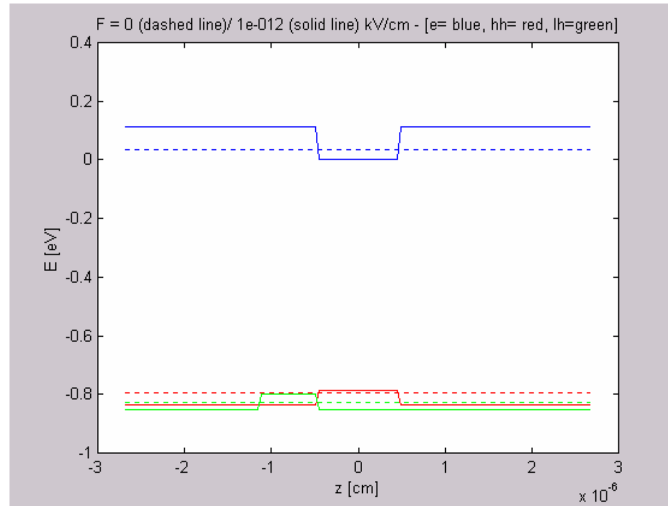
AVAGO TECHNOLOGIES

Effect of band discontinuities on escape times

Unstrained InGaAsP/InP MQW:



Strained InGaAsP/InP MQW:



Band discontinuities:

Unstrained:

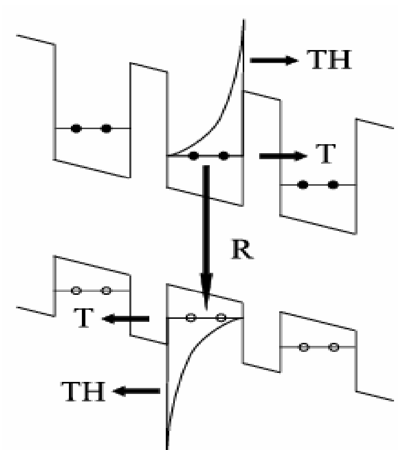
ΔV_e = 94 meV

ΔV_{hh} = 107 meV

Strained:

ΔV_e = 111 meV

ΔV_{hh} = 47 meV



hh escape times (F=70kV/cm):

Unstrained:

τ_{hh}^{T} = 3.9 ps

τ_{hh}^{TU} = 13.2 ns

Strained:

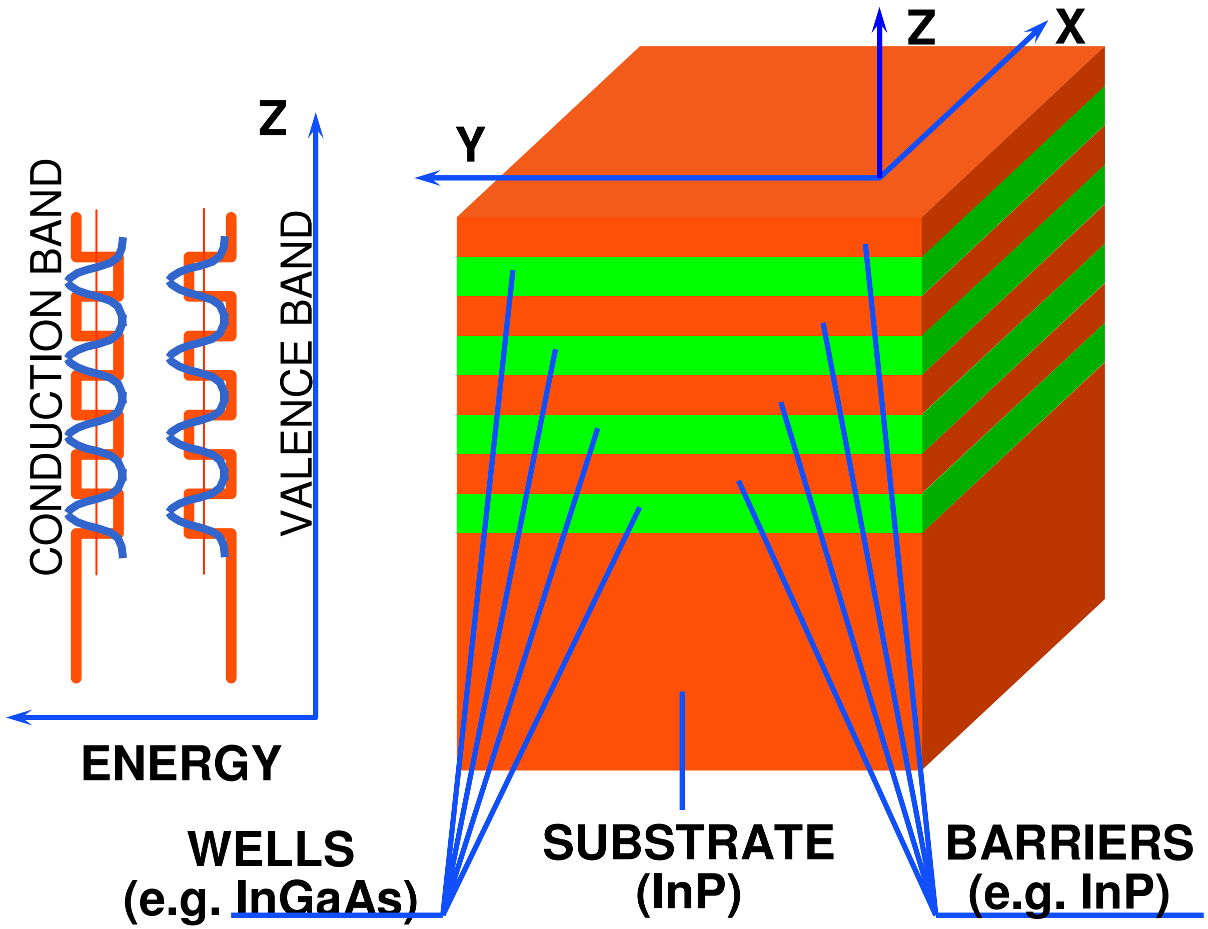
τ_{hh}^{T} < 0.1 ps

τ_{hh}^{TH} = 0.5 ps

Compatible with 10Gb/s modulation

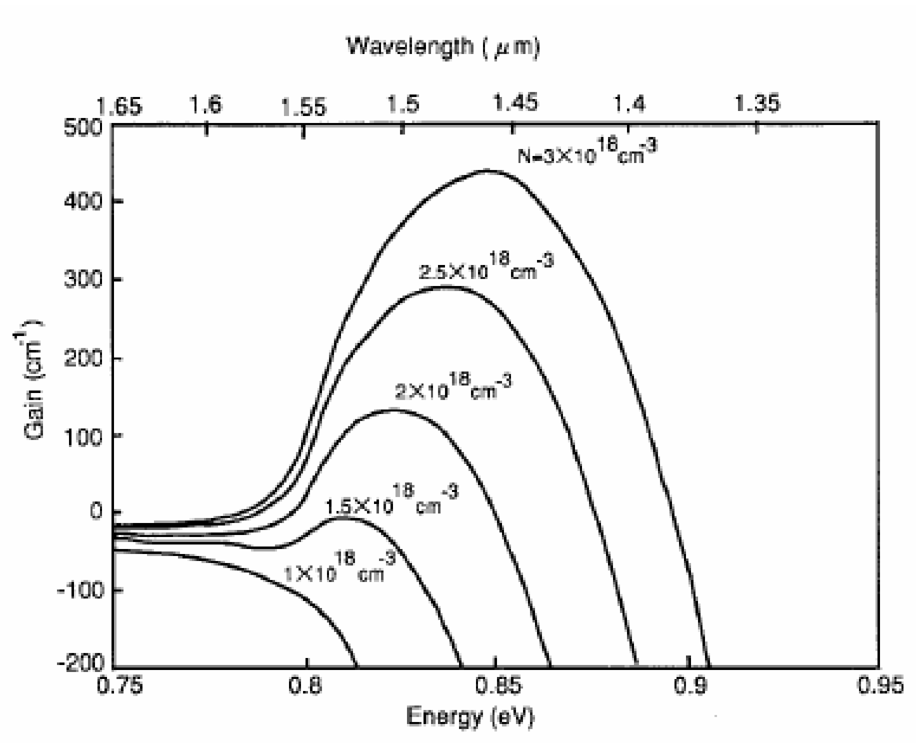
MQW heterostructures

Multi Quantum Wells are stacks of decoupled QWs
(with sufficiently thick barriers): **enhancement of single QW effects**

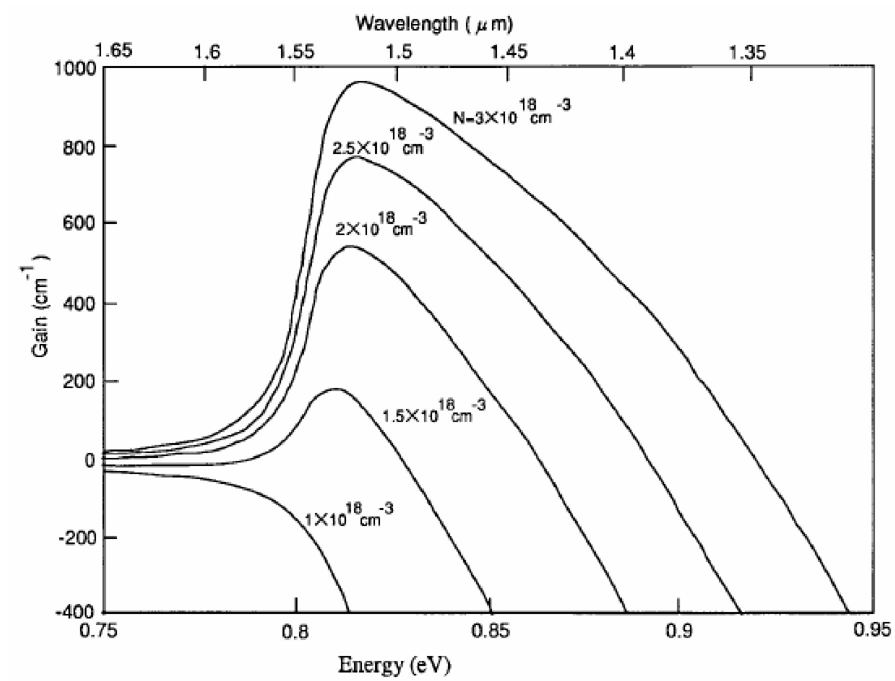


Optical gain in MQW vs. bulk

Bulk



MQW

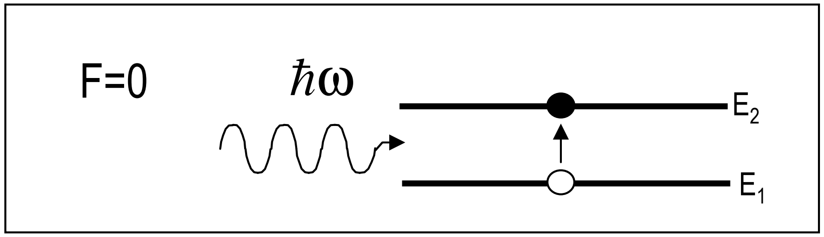


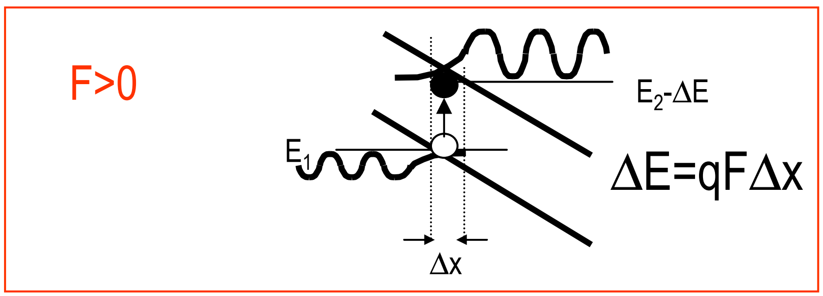
- higher differential gain
- wider spectral bandwidth

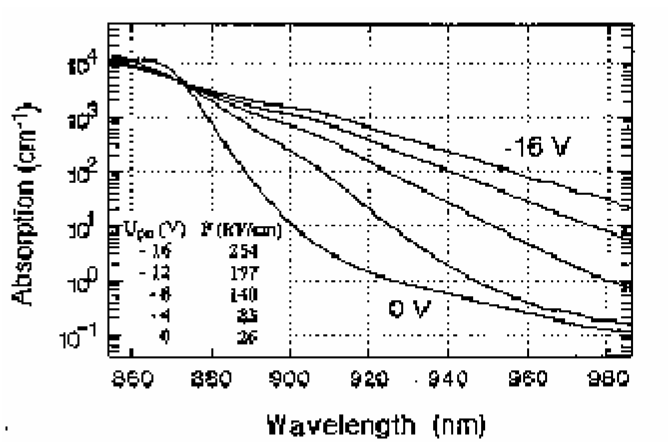
Electroabsorption in MQW vs. bulk

Bulk

Franz-Keldysh Effect:



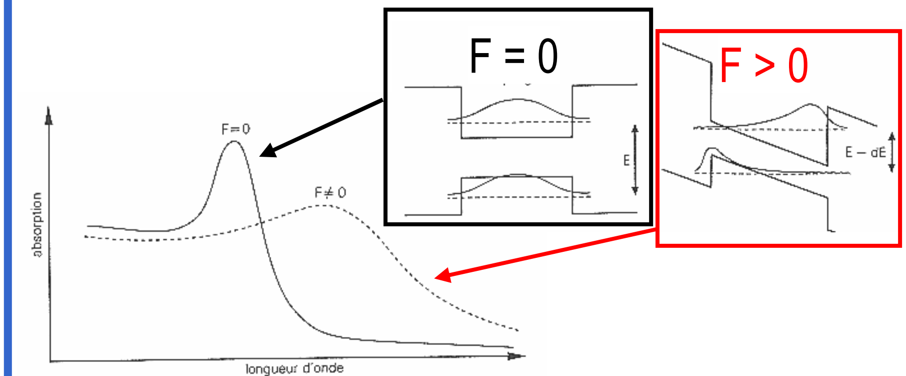


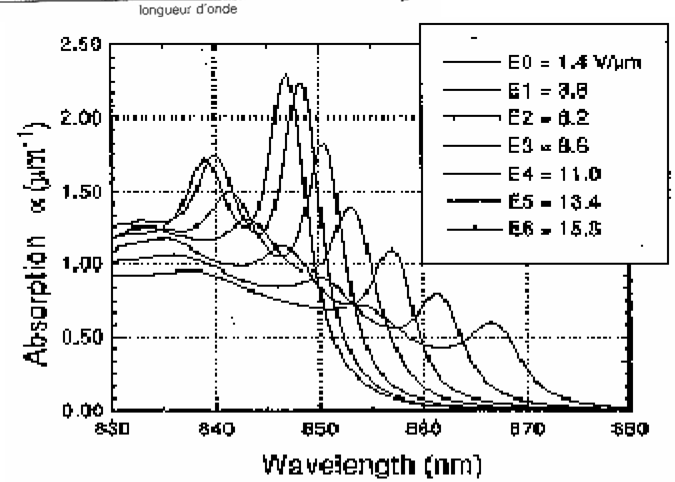


MQW

Quantum Confined Stark Effect:

D.A.B.Miller, Phys.Rev. Lett. 53 (1984)

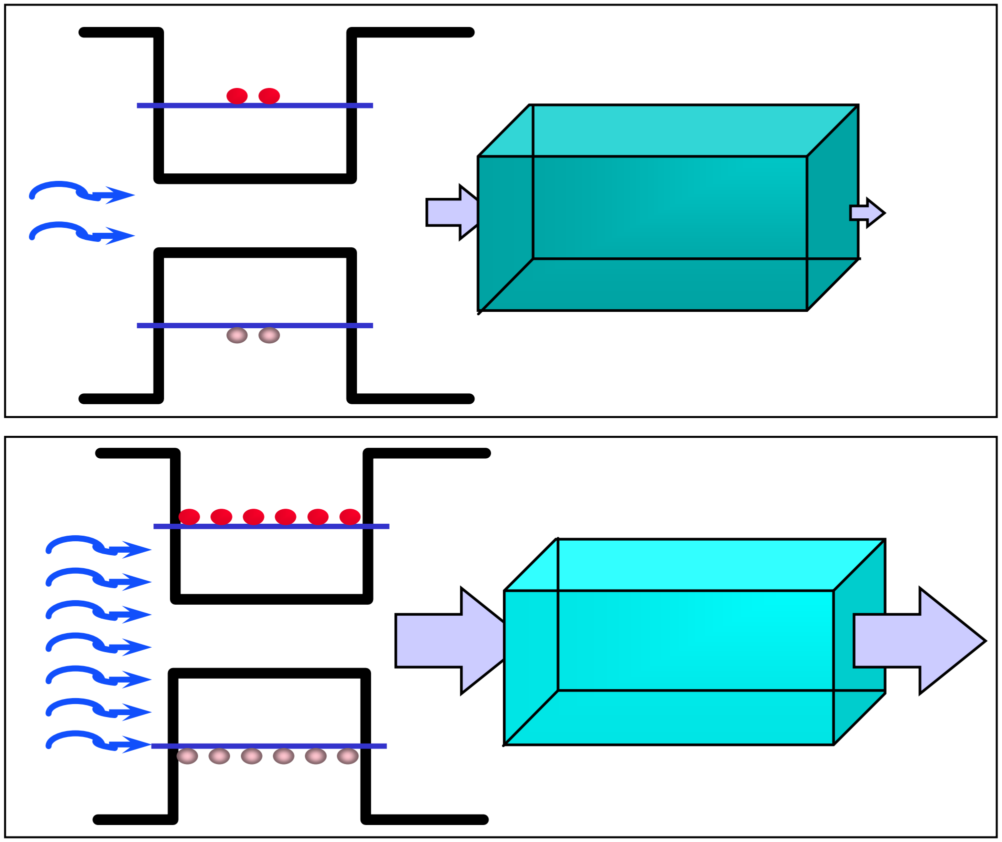


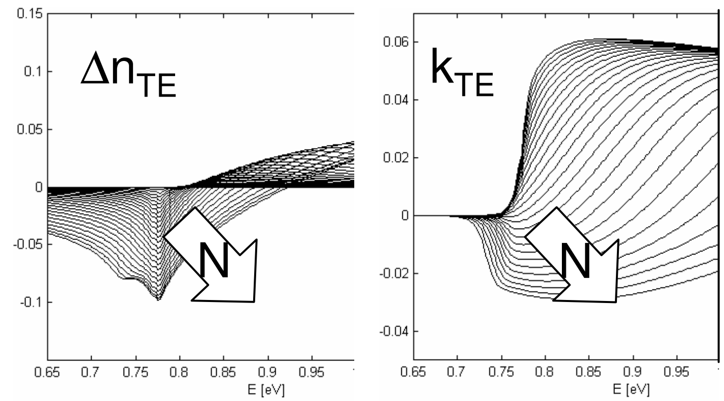


- higher contrast (E_g shift instead of tail appearence)
- narrower spectral bandwidth

Optical nonlinearities in MQW

At high optical power the MQW material becomes more transparent and also the (real part of) refractive index changes

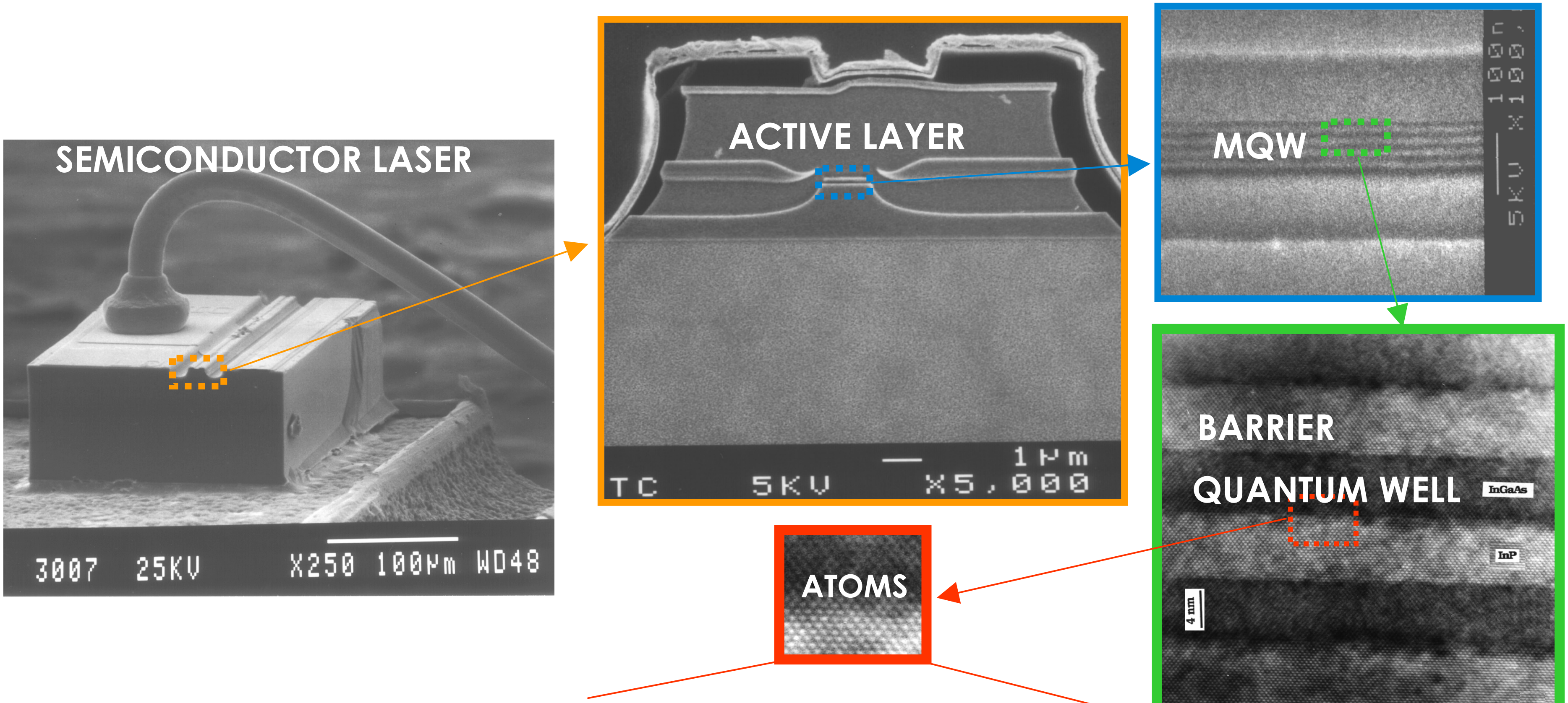




D.Campi, C.Coriasso Phys.Rev B51 (1995)

- Real (n) and imaginary (k) parts of refractive index strongly depend on the carrier density N.
- N can be increased through current injection or optical pumping.
- Optical properties (n, k) changes due to optical pumping are at the basis of the optical processing of optical signals *(optically controlled or all-optical devices).*

Quantum Wells:
Atomic-Controlled Artificial Structures



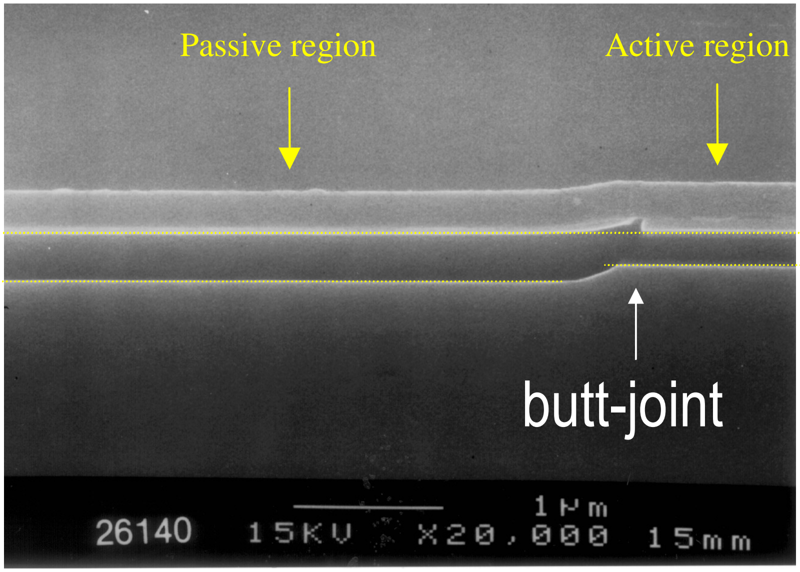
$$n(\lambda, N, F) + i\,k(\lambda, N, F) \Leftarrow \left[-\frac{\hbar^2}{2m}\frac{d^2}{dz^2} + V(z)\right]\psi(z) = E\psi(z)$$

Control of Optical Properties through atomic-scale technology

AVAGO TECHNOLOGIES

2) Photonic Integration

More functions on a single chip



AVAGO TECHNOLOGIES

Why Photonic Integration ?

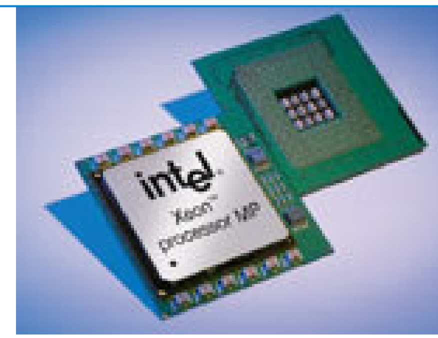
Monolithic integration provides **enhanced functionality**, like in Electronic Integrated Circuits (EICs)

Discrete component: Transistor

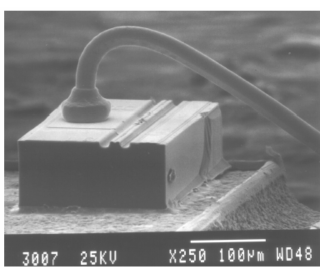
Electronics

monolithic integration

Electronic Integrated Circuit (EIC): Microprocessor



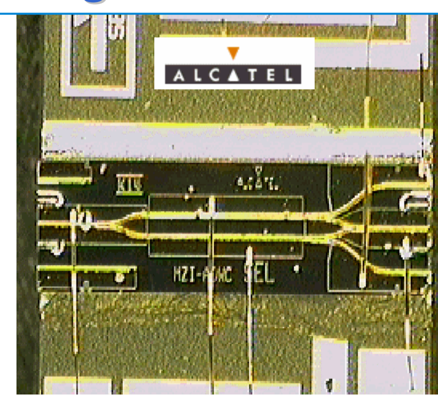
Discrete component: DFB laser



Photonics

monolithic integration

Photonic Integrated Circuit (PIC): Wavelength converter



PIC vs. EIC

EIC:

- mature technology
- high automation
- large scale integration: $>10^6$ components/chip
- low cost/surface: Si ~ 0.1 Euro/cm^2 *(10 Euro/4”wafer)*
  GaAs ~ 4 Euro/cm^2 *(80 Euro/2”wafer)*

PIC:

- novel technology
- low automation
- low scale integration: ~ 10 components/chip
- high cost/surface: InP ~ 12 Euro/cm^2 *(~240 Euro/2”wafer)*

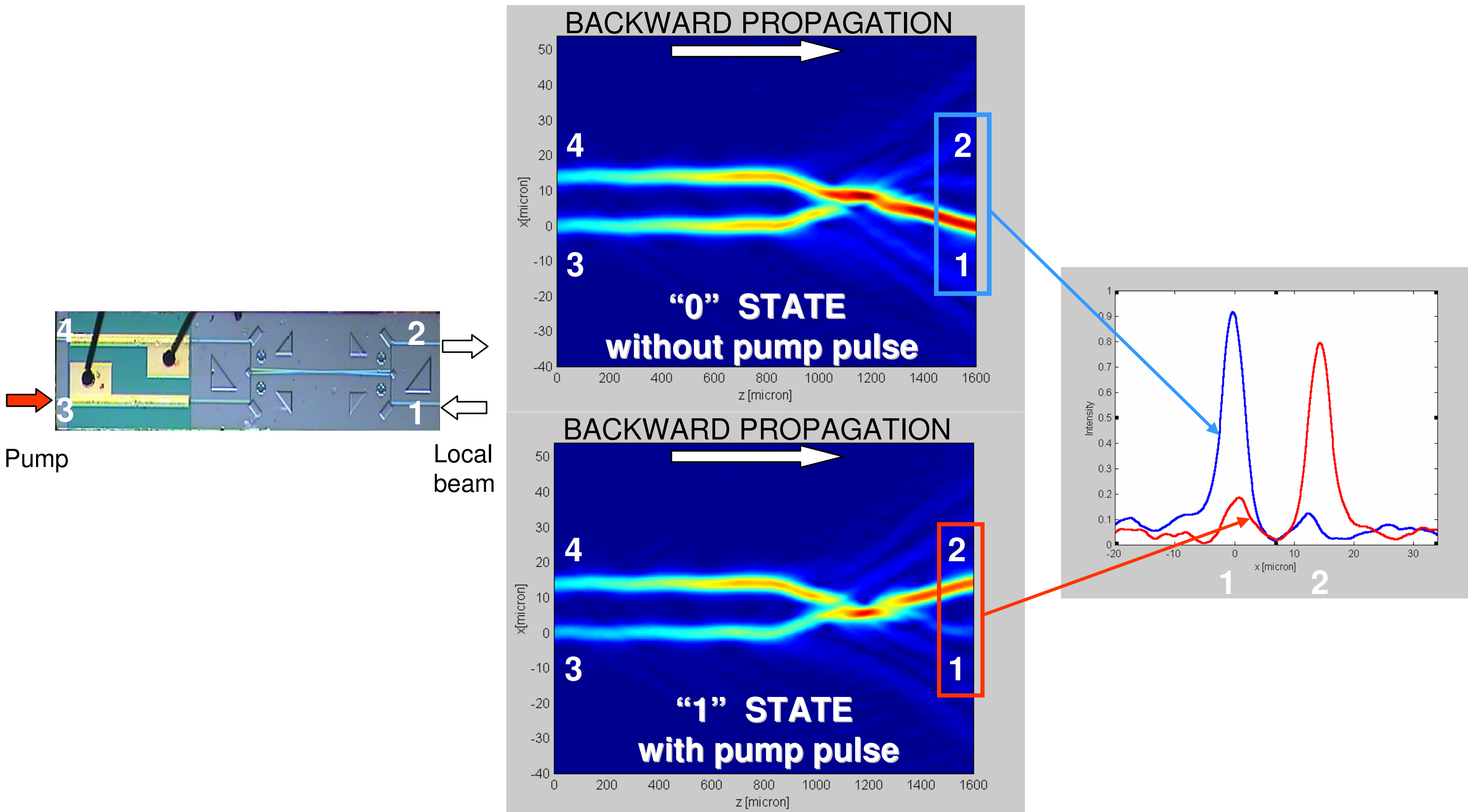
more on PIC vs. EIC

$\Delta x \approx \lambda_{photon} \approx 1\mu m$ $\Rightarrow$ PIC stripes are waveguides:
the phase plays a critic role $\Rightarrow$ interference

$\Delta x >> \lambda_{electron} \approx 10nm$ $\Rightarrow$ EIC stripes are like wires:
the phase doesn't play a significant role

<u>PICs are like **coherent EICs**</u>
(coherent or mesoscopic electronics)

Example of interference effects in PICs



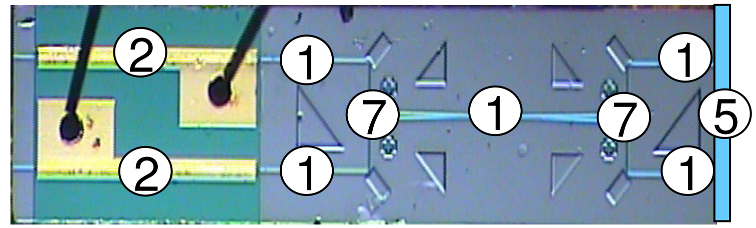
Photon beam appearance/disappearance without switching

AVAGO TECHNOLOGIES

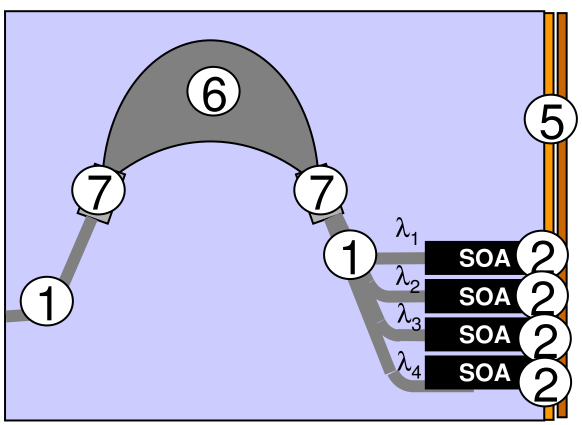
PIC components:

1. Waveguides
2. Gain sections (SOA)
3. Modulator section (EAM)
4. Gratings
5. AR / HR Coatings
6. Array Waveguide Gratings (AWG)
7. Couplers

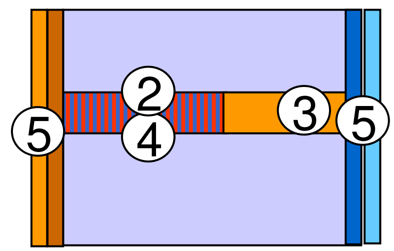
. . . .



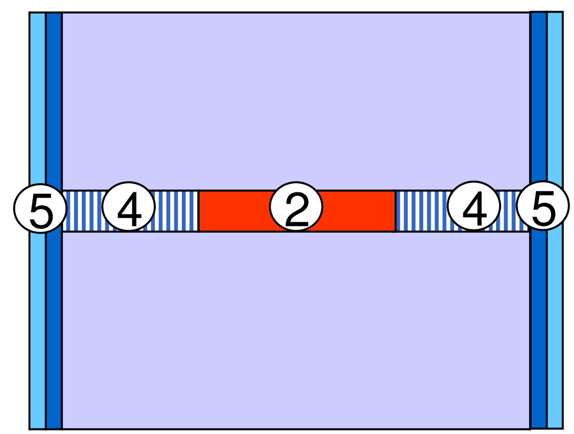
λ converter



λ selectable laser



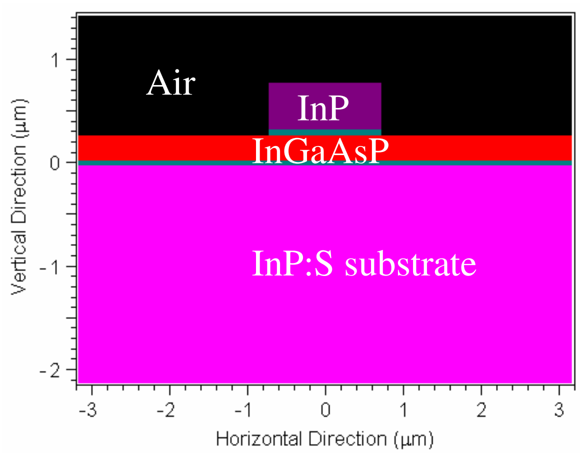
EML



optical gate

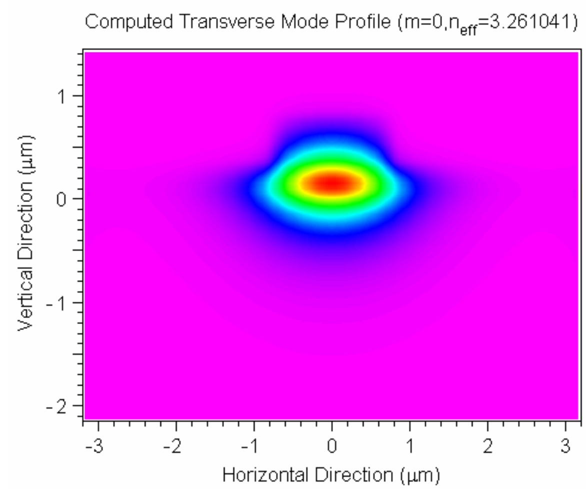
AVAGO TECHNOLOGIES

PIC modelling (1)

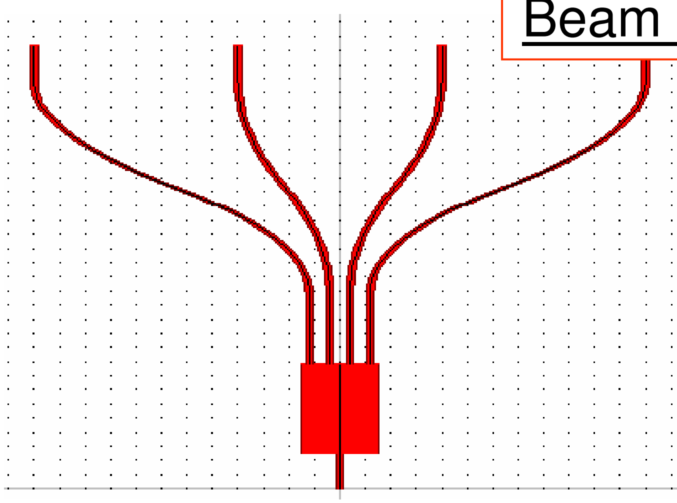


ridge waveguide

Mode Solver

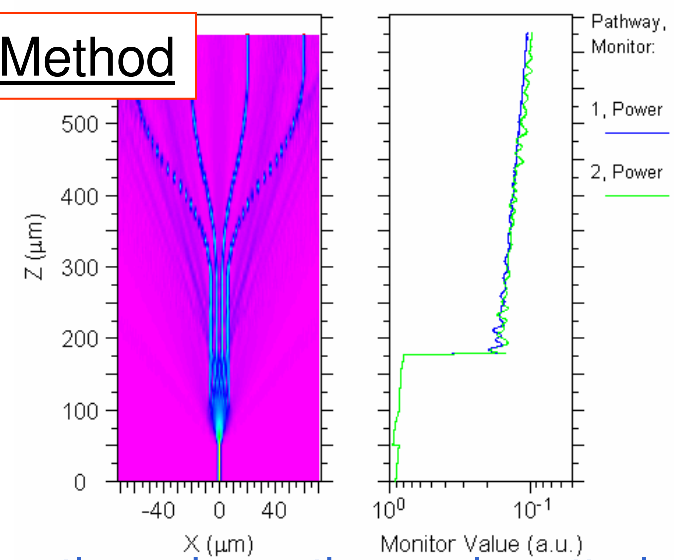


effective index, mode profile



MMI splitter

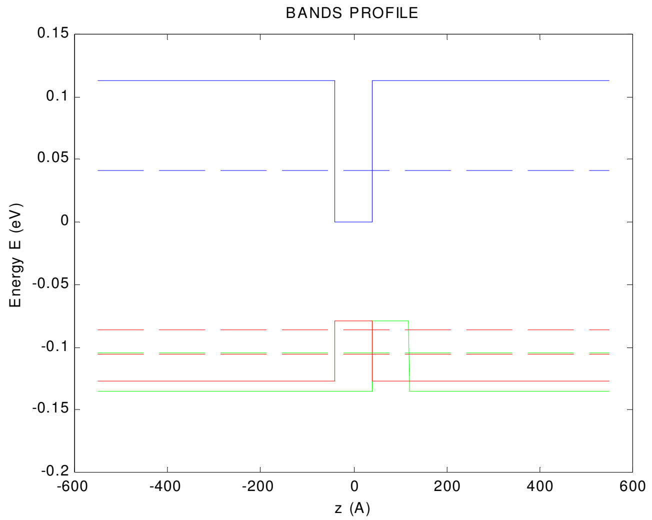
Beam Propagation Method



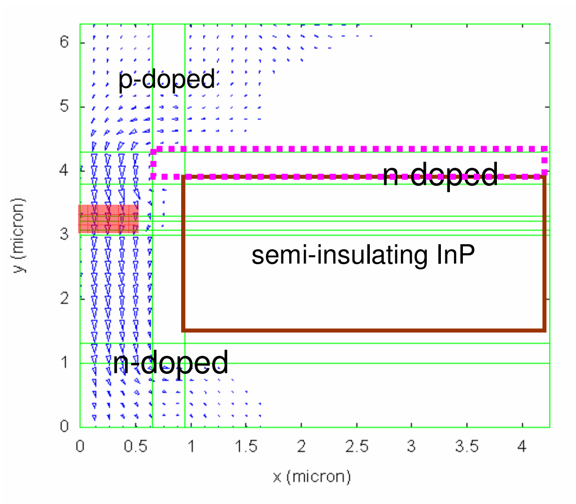
field propagation, absorption and scattering loss

PIC modelling (2)

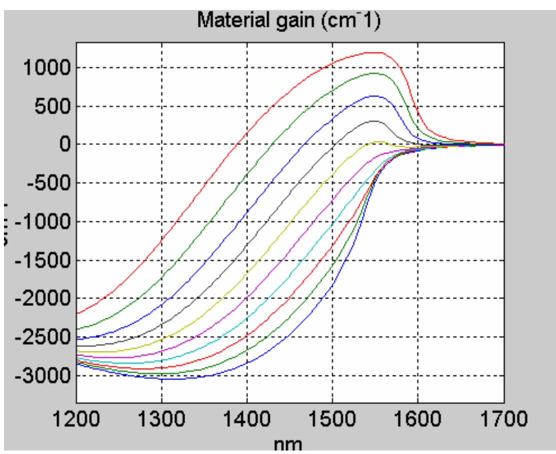
MQW band profile and levels



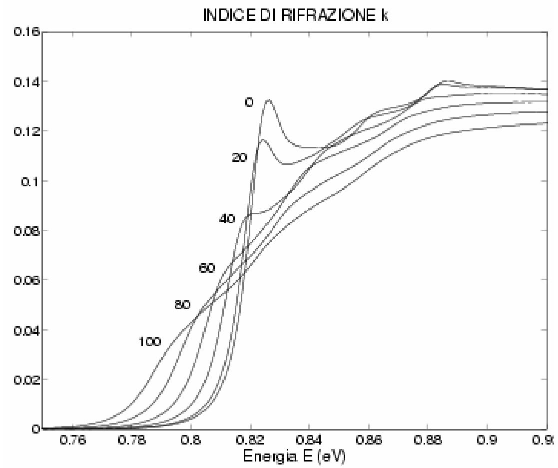
Carrier concentration and electric field



Gain



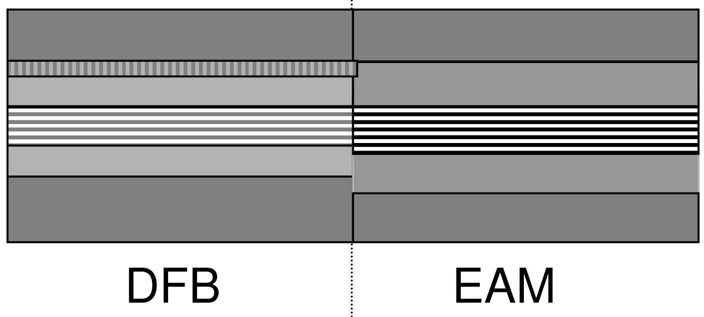
Optical properties: n+ik (λ, F, T)



AVAGO TECHNOLOGIES

Monolithic Integration Technologies

BUTT-COUPLING OR BUTT JOINT

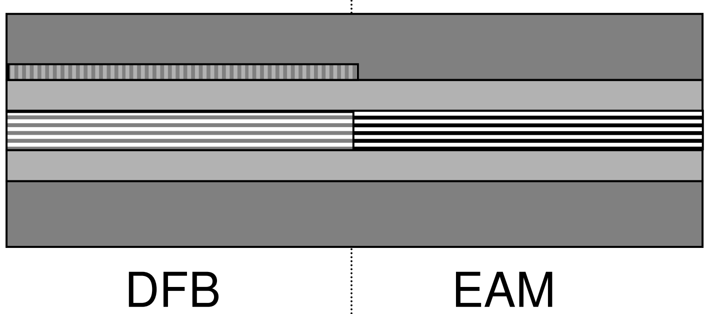


- DFB growth
- Complete etching in EAM region
- EAM re-growth

☺ Independently optimized structures

☹ Interface morphology

SELECTIVE AREA GROWTH (SAG)

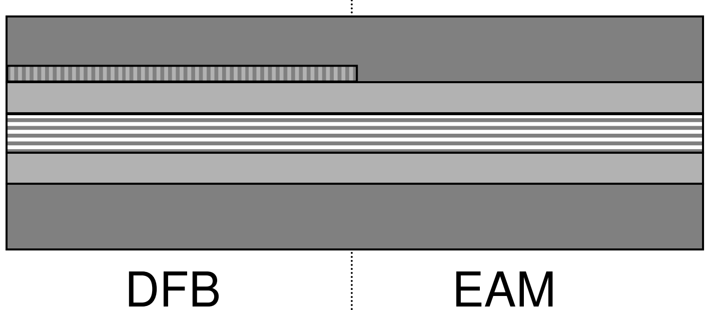


- Common growth DFB and EAM with SiO_2 mask (different Eg)

☺ One growth

☹ Complex calibration
Trade-off between structures

IDENTICAL LAYER



- One common MQW acting as DFB active layer and EAM core

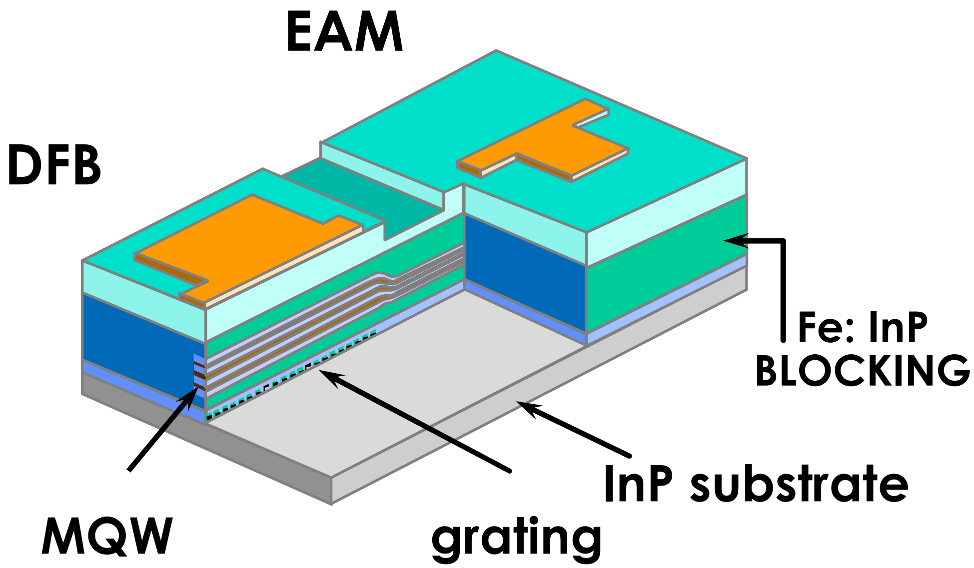
☺ Easy growth

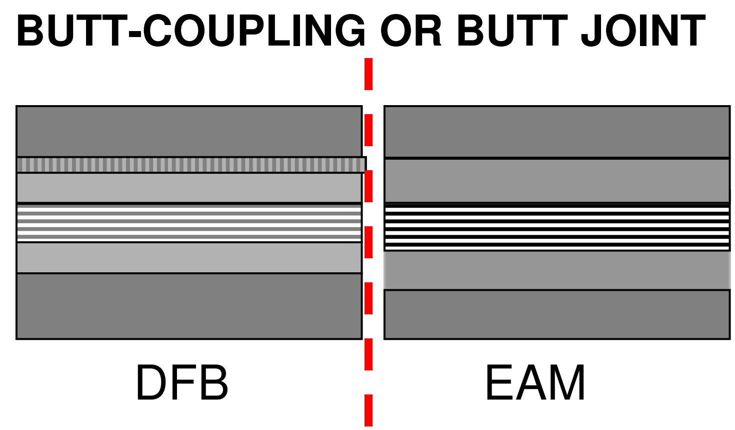
☹ Strong compromise between DFB and EAM

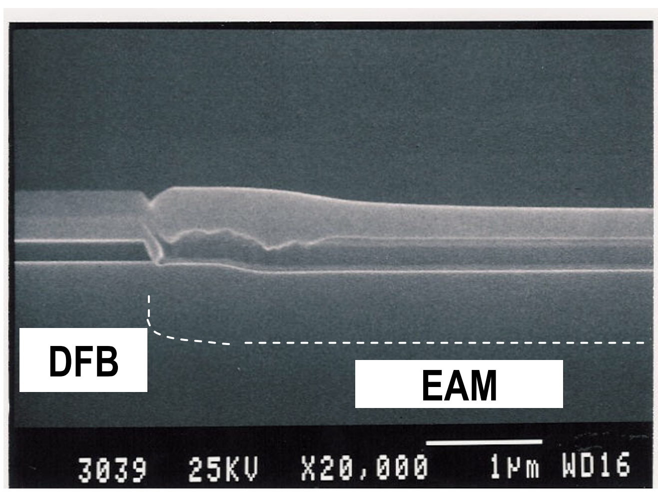
+ QW intermixing, …

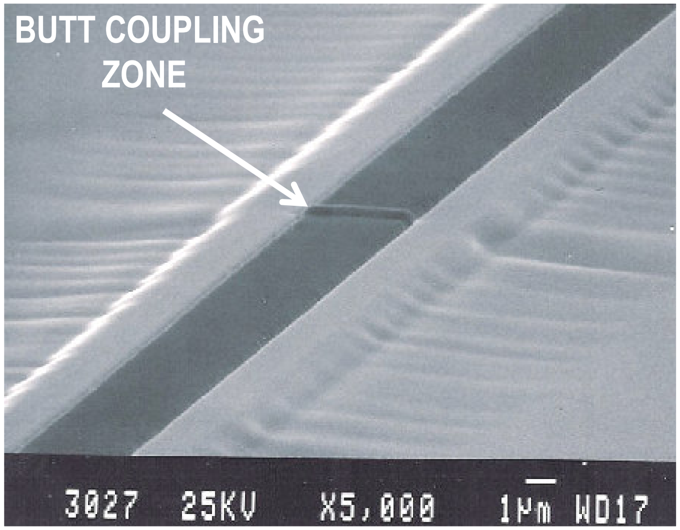
AVAGO TECHNOLOGIES

Butt coupling

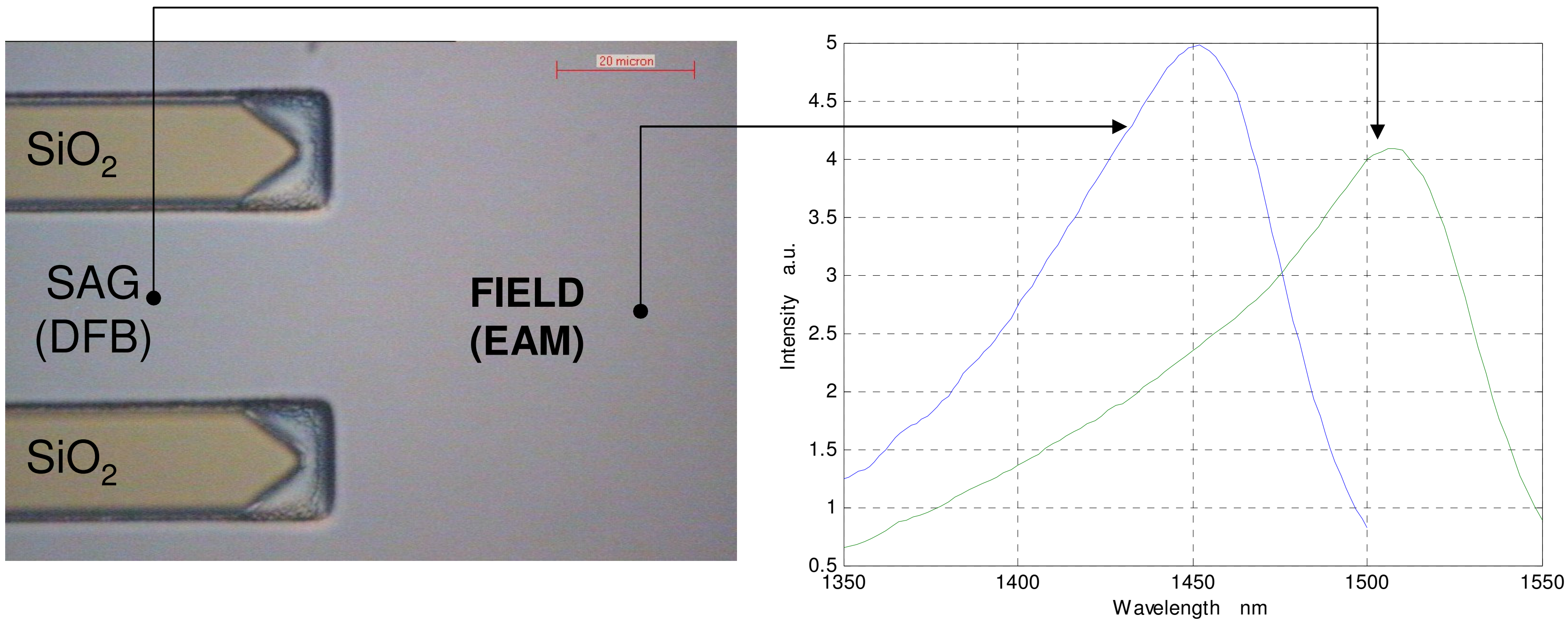








SAG as monolithic integration technique

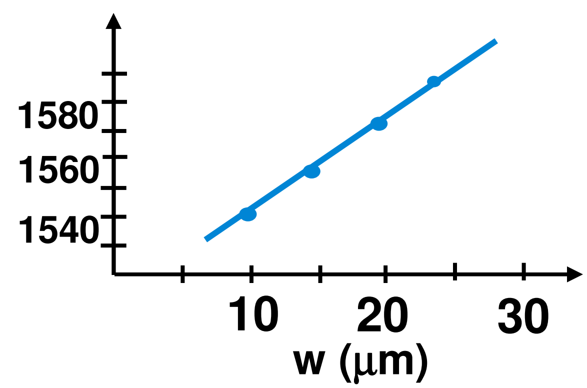


In enrichment in SAG region

⇒ thickness enhancement on SAG;

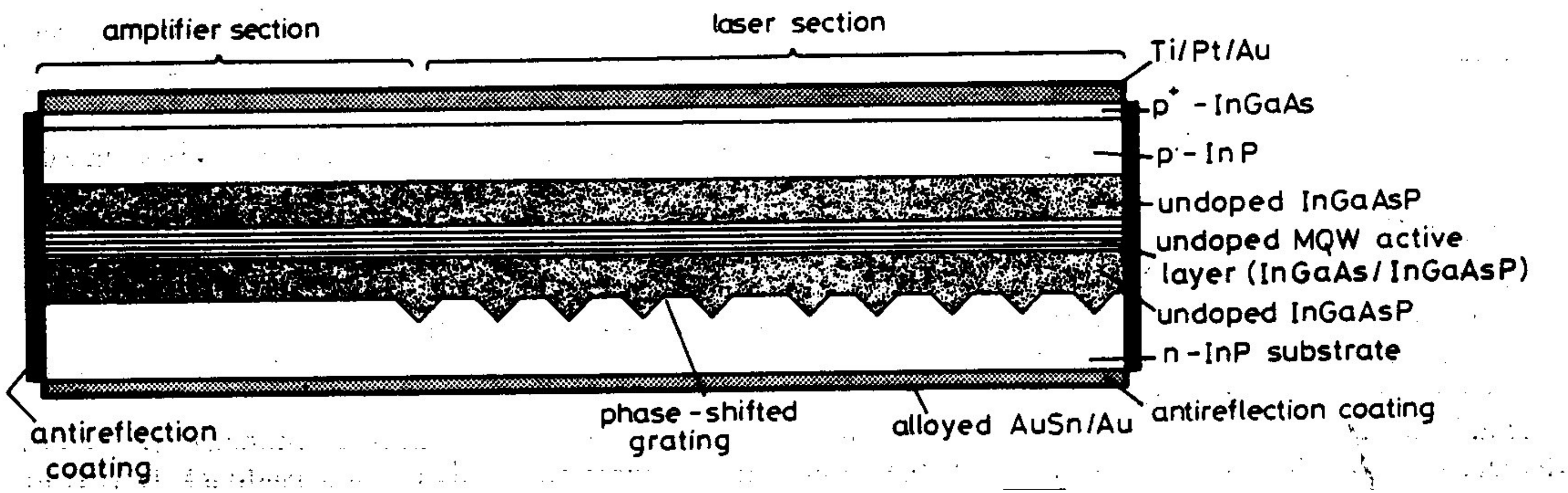
⇒ Eg FIELD > Eg SAG;

⇒ λ PL FIELD < λ PL SAG



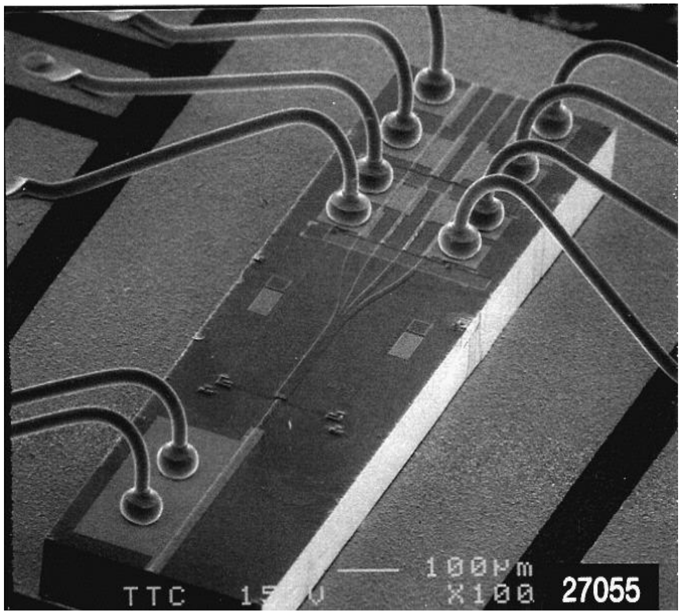
Monolithic integration between DFB (SAG region) and EAM (FIELD)

Identical Layer



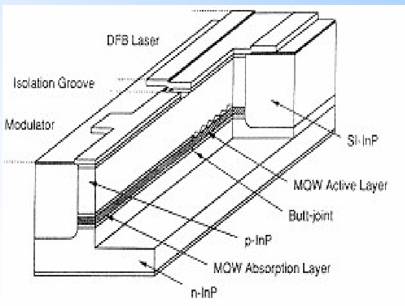
3) Photonic Devices

Some examples of MQW photonics (hopefully useful) devices

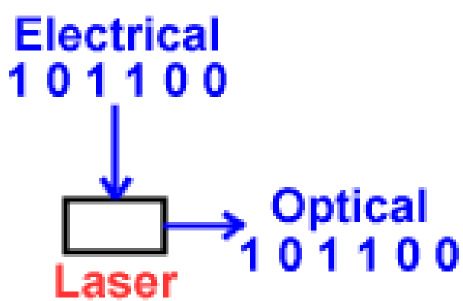


Integrated EAM-DFB (EML)

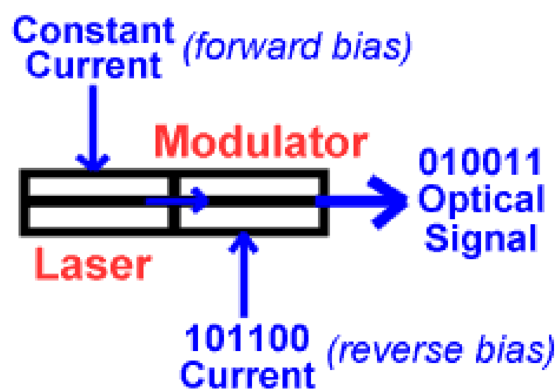
External modulation of a DFB laser (EML)



• Device based on the monolithic integration between a DFB laser and an Electro-Absorption Modulator (EAM).
• The DFB is biased at a constant current (CW).
• The EAM switch from transparency to opacity by applying a modulated voltage (HF signal).



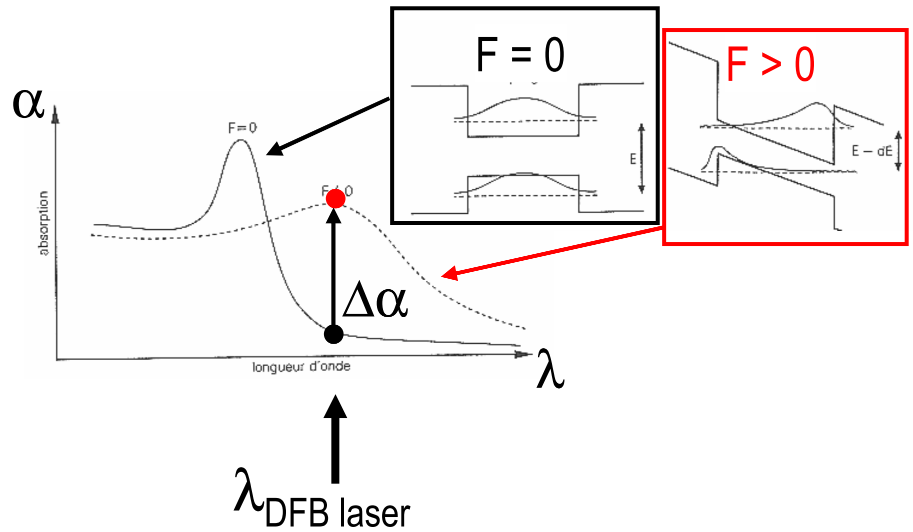
DM-DFB

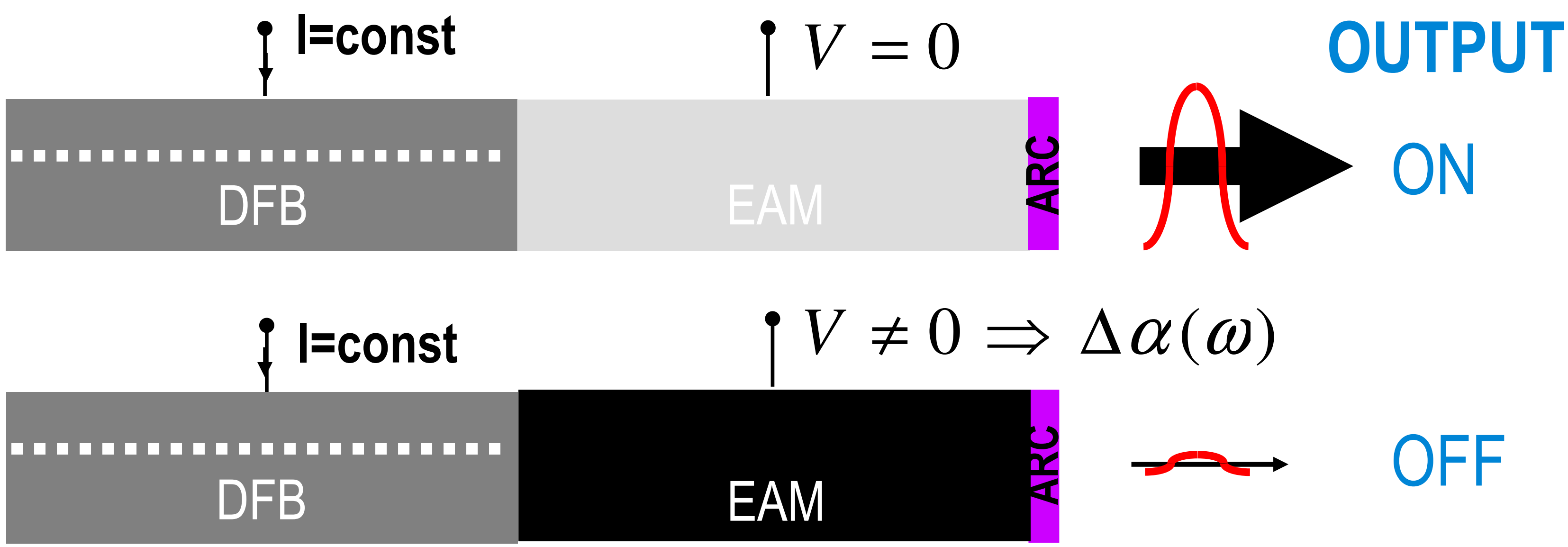


EML

EML's operating principle

QCSE:

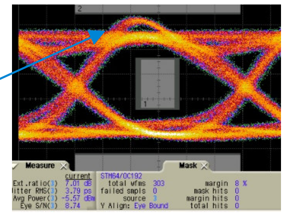




Key advantages of EML

Dynamics: The high frequency response is directly related to the fast dynamics of the modulator and not to the dynamic of the DFB laser, perturbed by carrier-relaxation effects

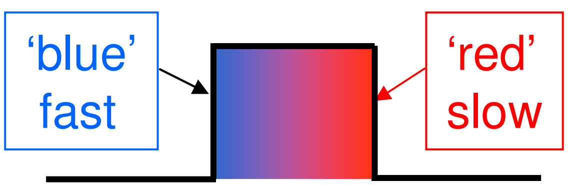
Carrier relaxation in DFB laser



Chirp: Frequency chirp in EAM is much smaller (~ 10 times) than in DM-DFB and can be either positive or negative. In DM-DFB the chirp is always positive (α_H>0)

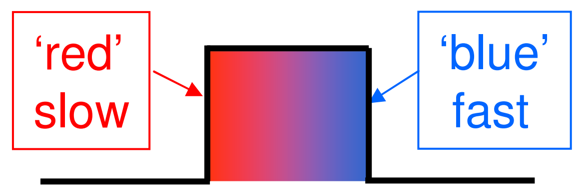
$$\Delta\alpha(\omega) \Rightarrow \Delta n(\omega) = \frac{c}{\pi} \mathrm{P}\int_0^\infty \frac{\Delta\alpha(\omega')d\omega'}{\omega'^2 - \omega^2} \Rightarrow \alpha_H = \frac{4\pi}{\lambda}\frac{\Delta n}{\Delta\alpha} \Rightarrow \Delta\nu(t) = \frac{\alpha_H}{4\pi}\frac{1}{P}\frac{dP}{dt}$$

$$1)\ \alpha_H > 0$$



Pulse broadening in propagation DM-DFB case (max 10km @10Gb/s)

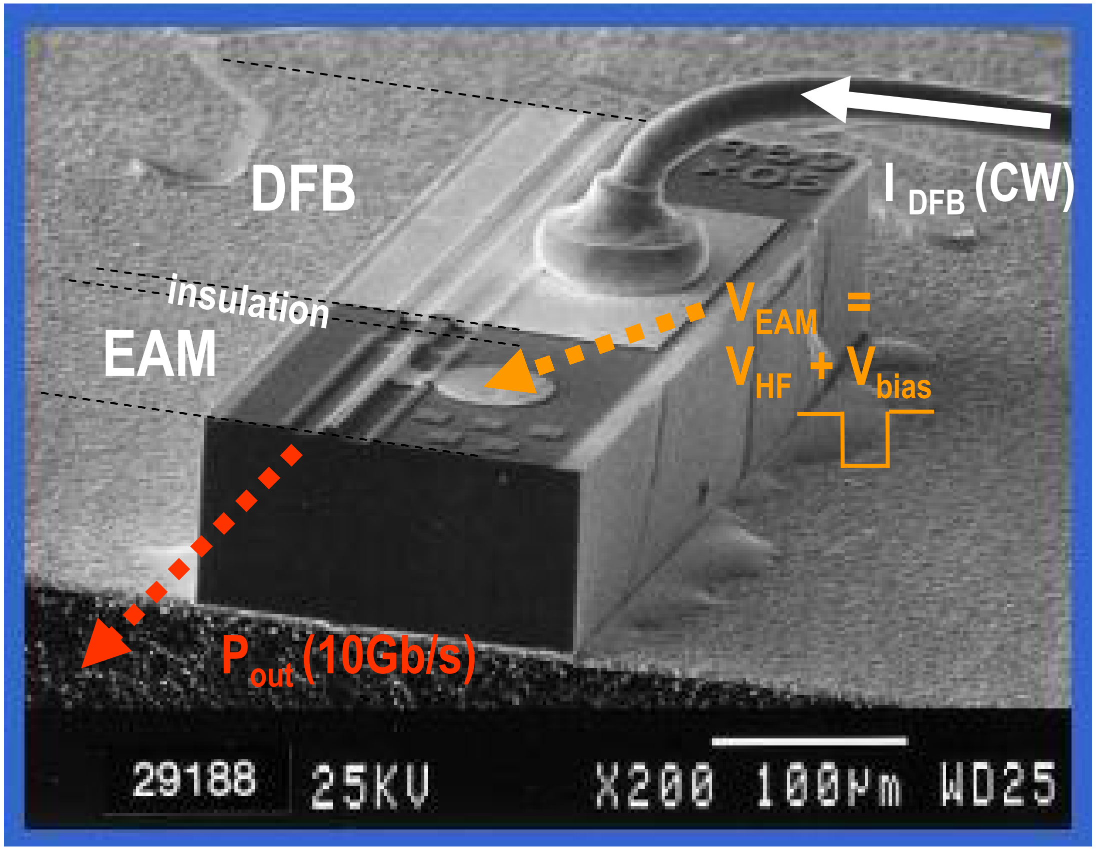
$$2)\ \alpha_H < 0$$

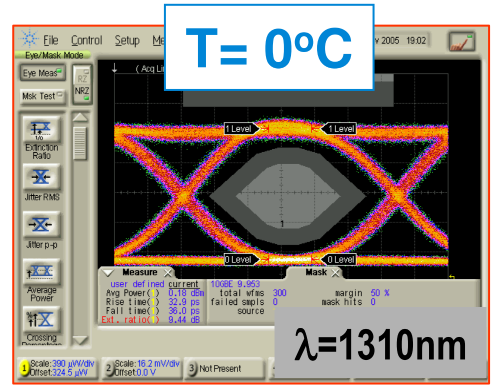


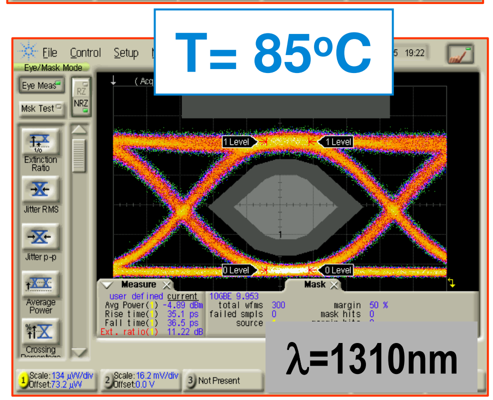
Pulse propagation beyond limit of spectrally-pure pulses (~75km@10Gb/s)

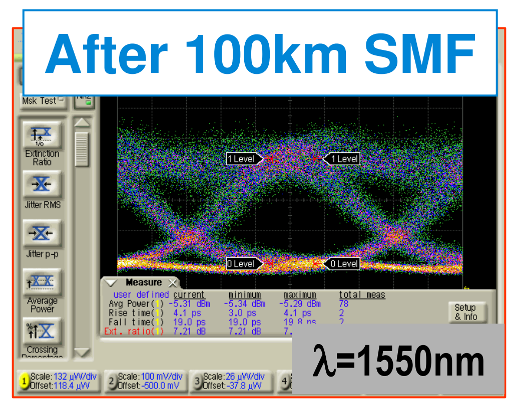
Uncooled 10Gb/s EML chip

Ref: C. Coriasso, ECOC '06









Ref: M. Meliga, APOC '05

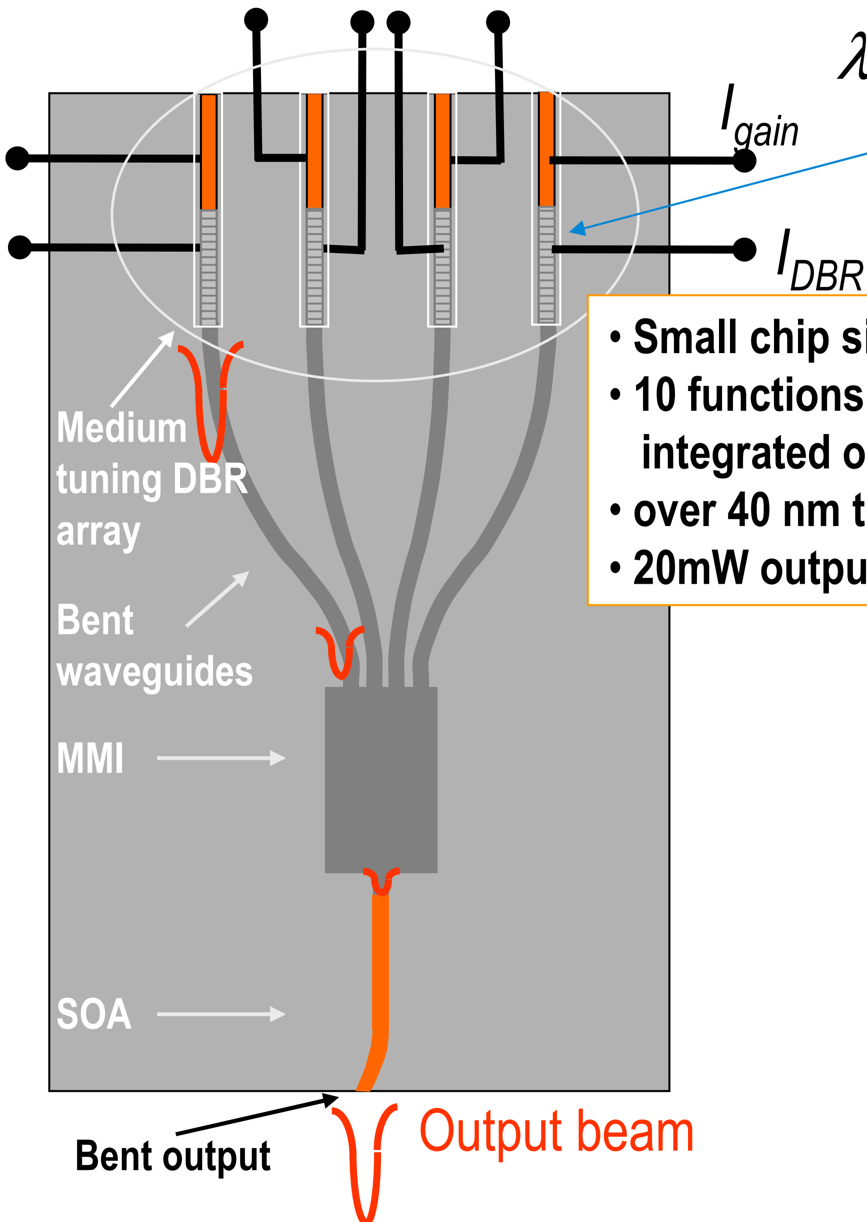
High quality dynamics (10Gb/s eye diagram):
- from 0°C to 85°C (1310nm)
- after 100km fiber span (1550nm)

AVAGO TECHNOLOGIES

Wide tunable WDM laser

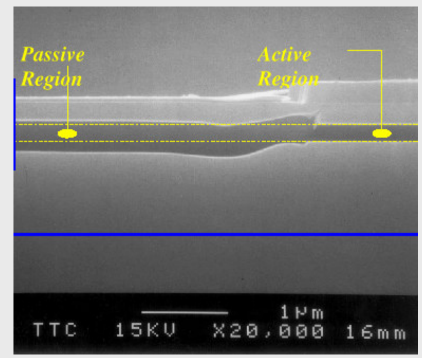
Ref: R. Paoletti, ECOC ‘03

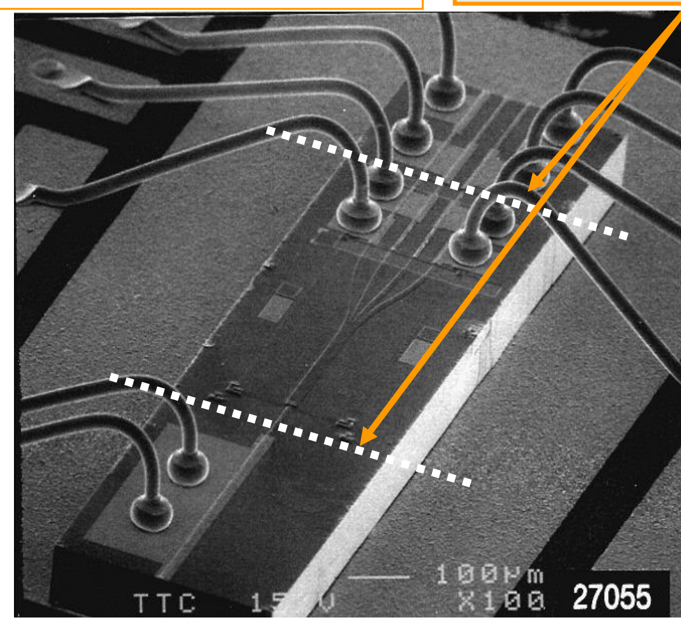
$$\lambda_B = 2\Lambda n(I_{DBR})$$



- Small chip size (0.67 mm^2)
- 10 functions monolithically integrated on a single chip
- over 40 nm tuning range
- 20mW output power

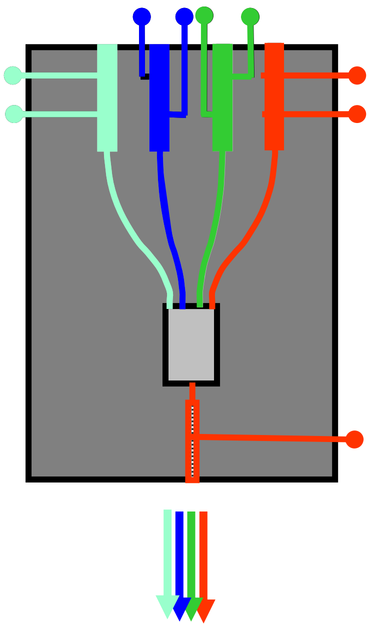
Active MQW - Passive bulk Butt coupling integration

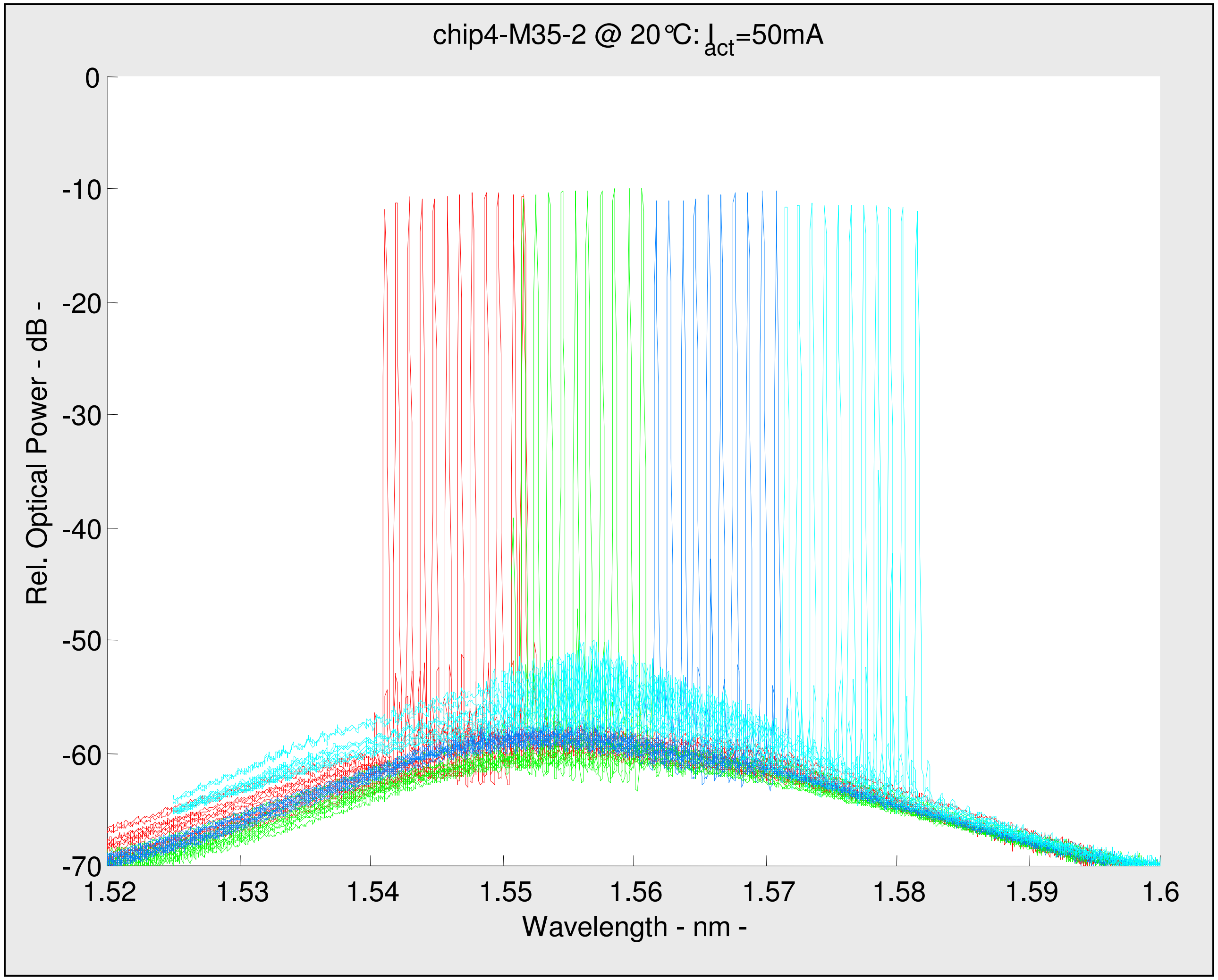




AVAGO TECHNOLOGIES

Device results: >40nm tuning range

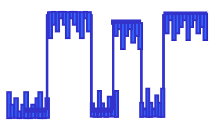


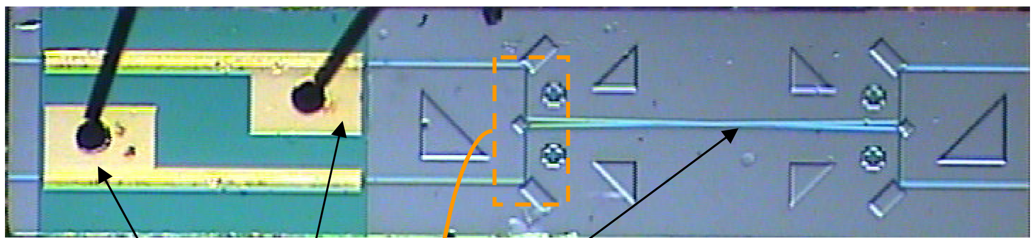


All-optical 10Gb/s wavelength converter

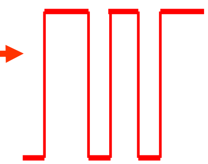
Monolithically integrated
Michelson's interferometer
(chip size: 0.5 x 2.0mm = 1mm^2)

10Gb/s optical data in





10Gb/s optical data out

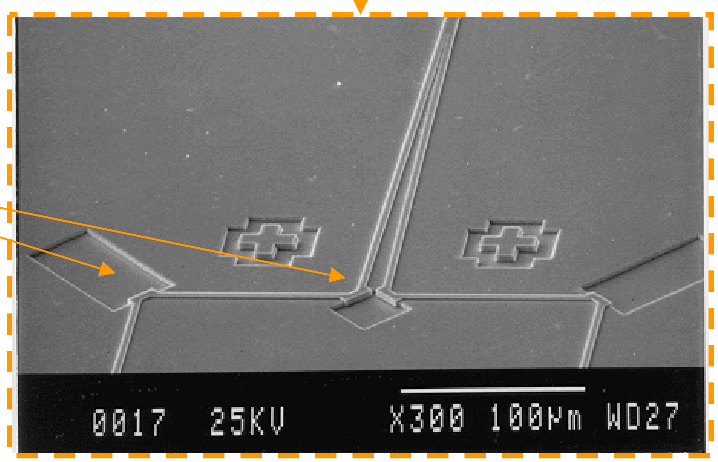


SOA

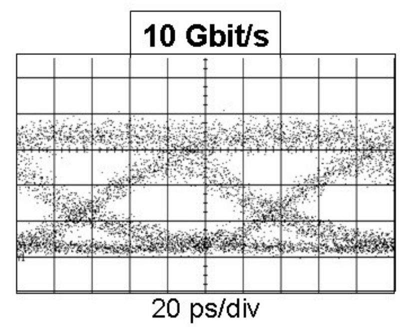
X coupler

Ref: C. Coriasso, OSA '99

Waveguide µ-mirrors



λ_1=1553nm ⇒ λ_2=1559nm

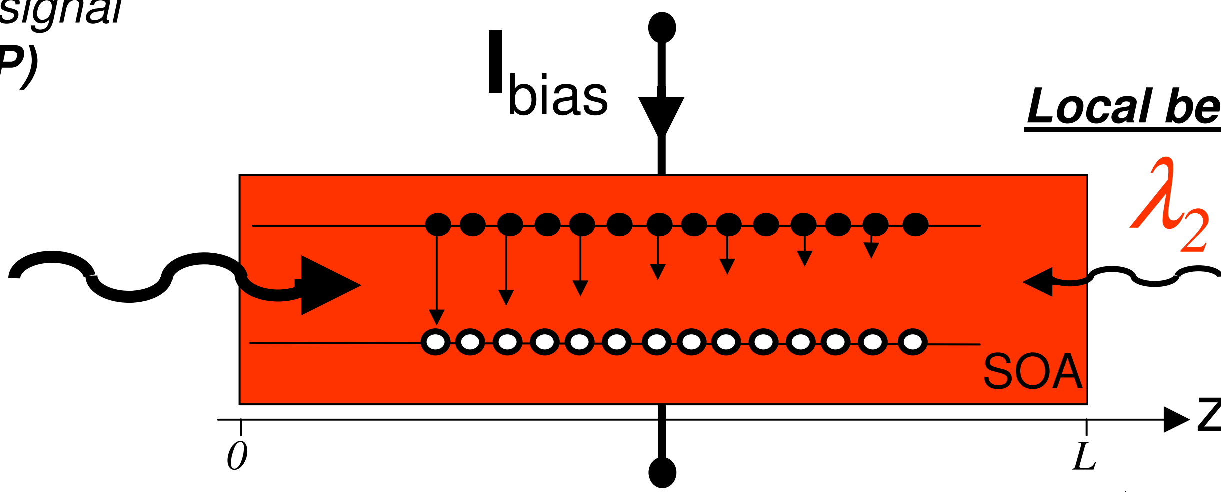


Cross Phase Modulation (XPM)

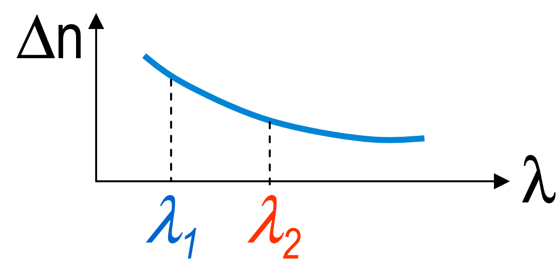
$$\Delta n\,(\lambda_2, z)$$

Optical signal
(PUMP)
λ_1

Local beam CW
λ_2



Stimulated recombination: $\Delta N(\lambda_1, z)$ ⇨ Refractive index change:

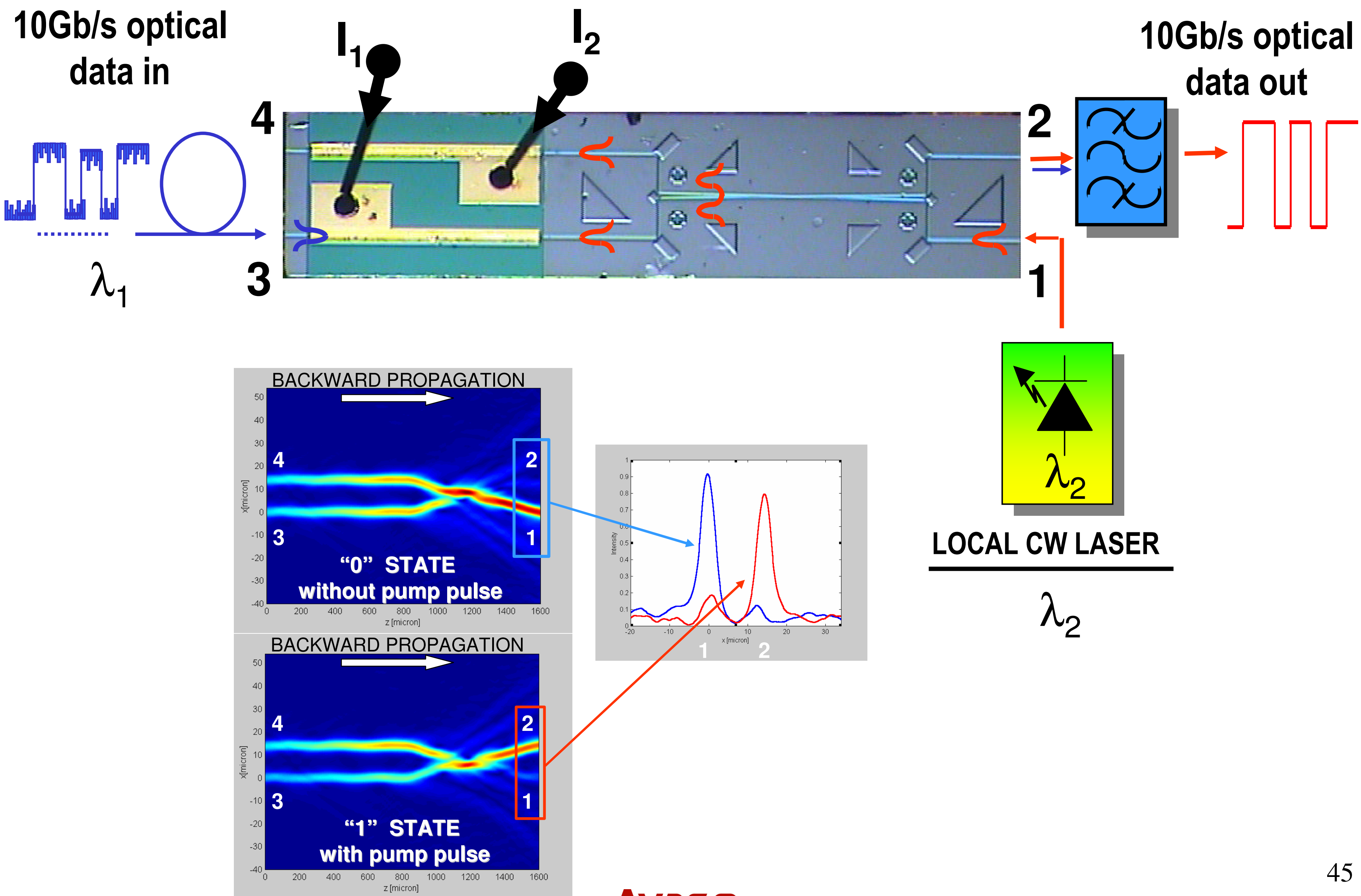


PHASE Change: ⇩

INTENSITY Change ← *Interferometer*

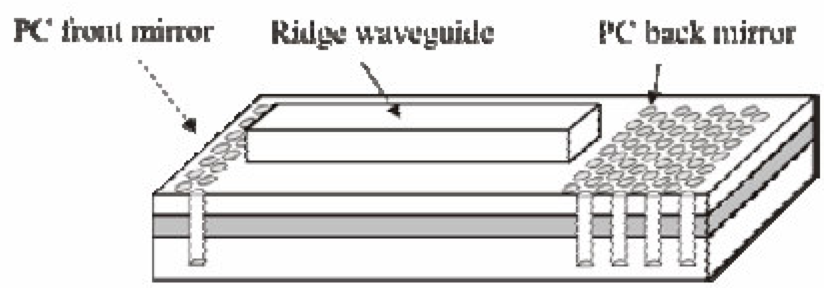
$$\Delta\phi(\lambda_2) = \frac{2\pi}{\lambda_2}\int_0^L \Delta n(\lambda_2, z)\,dz$$

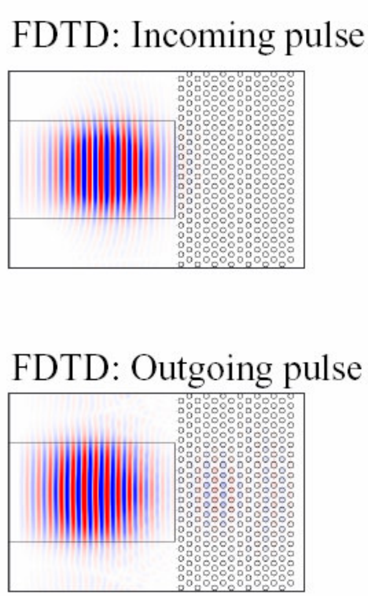
Principle of operationo of λ-converter



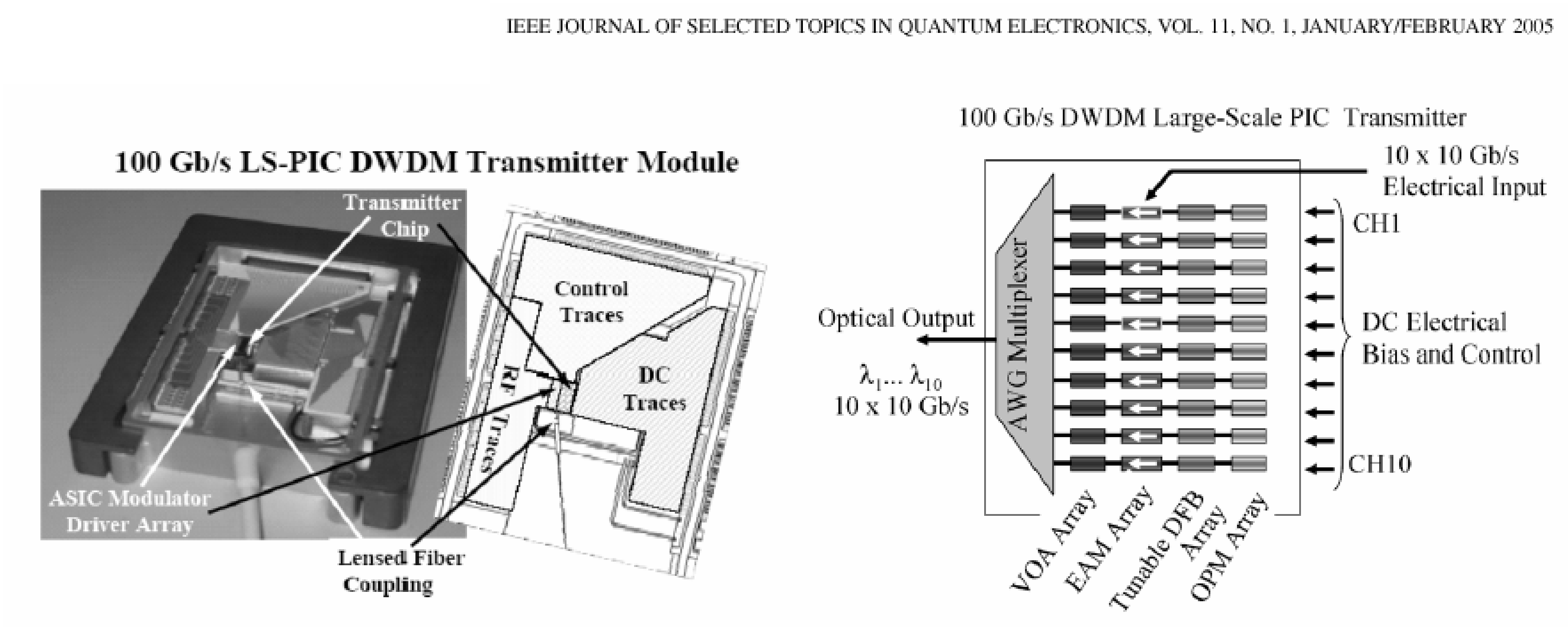
AVAGO TECHNOLOGIES

4) New trends in photonic integration





Large scale InP monolithic integration



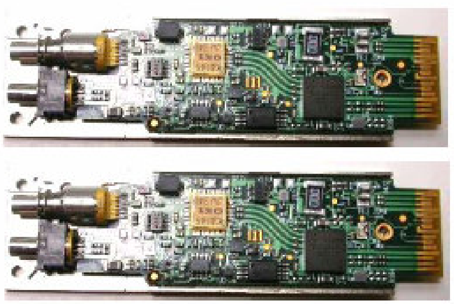
10x10Gb/s transmitter chip incorporation over 50 functions monolithically integrated on a single chip

Ref: www.infinera.com

Silicon Photonics

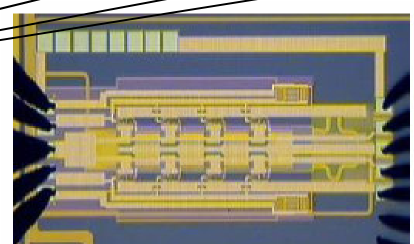
Electronics and Optics in a single monolithic Si-chip:

Ref: www.luxtera.com

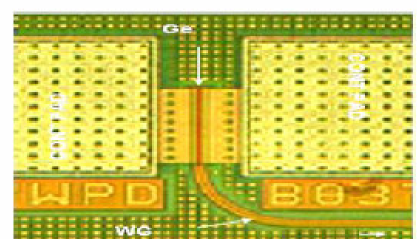


Standard hybrid solution

InP-based
bonded
laser chips
(Future Si lasers?)



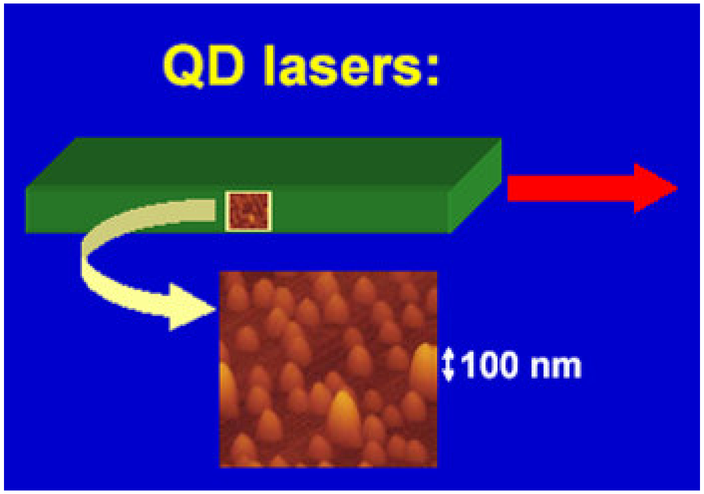
10G MZ Modulators

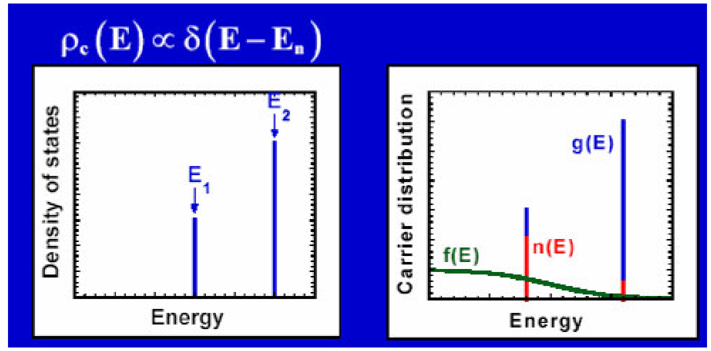


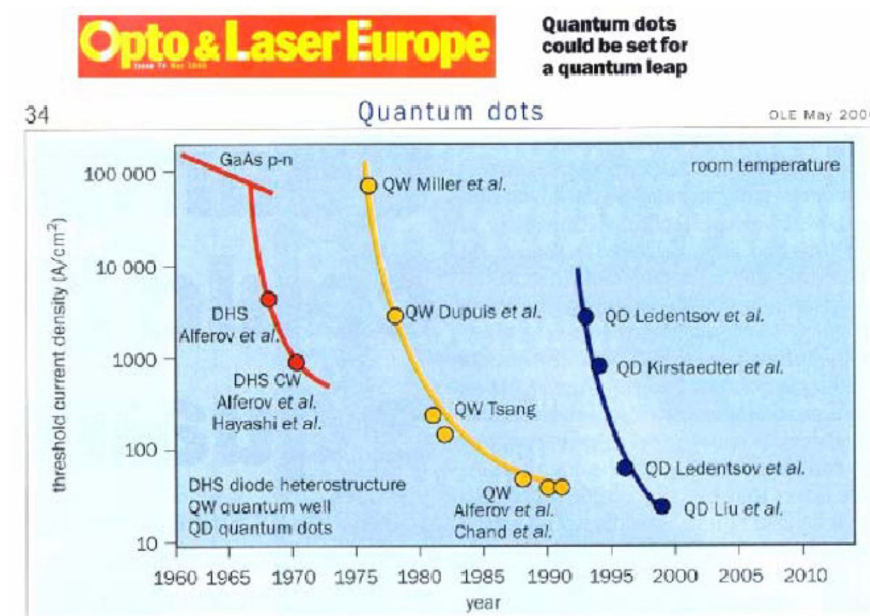
Integrated Photodiodes

AVAGO TECHNOLOGIES

Quantum dots

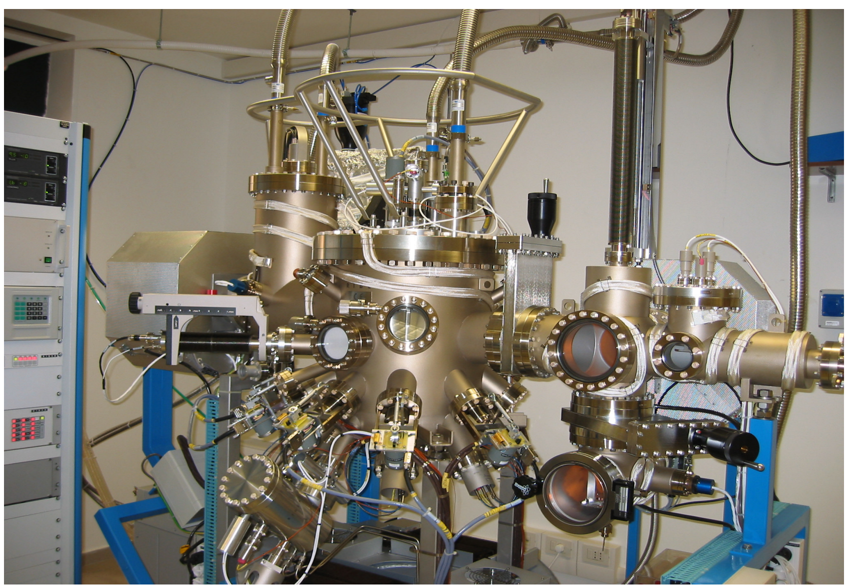






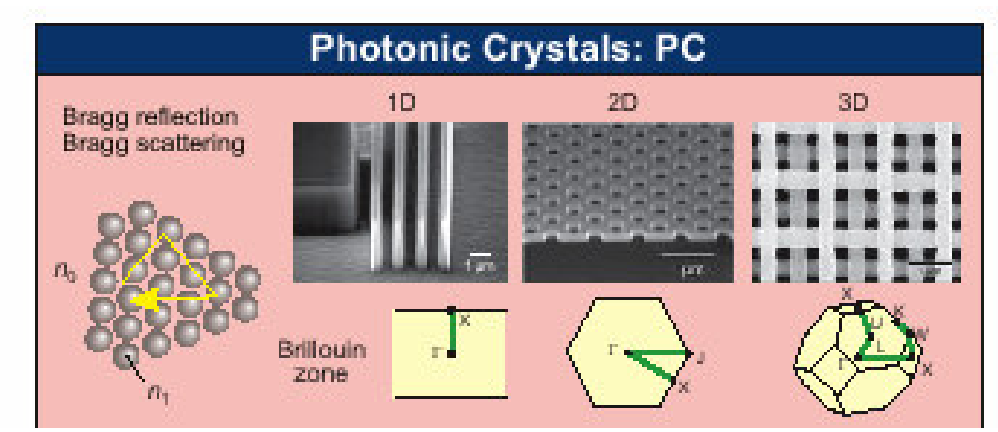
Diode laser progress: the superior gain in quantum-dot devices results in a lower threshold current.

MBE



+ high-T_o laser, SOA, …

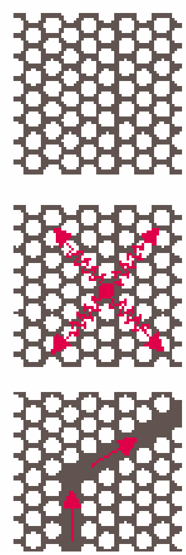
Photonic Crystals

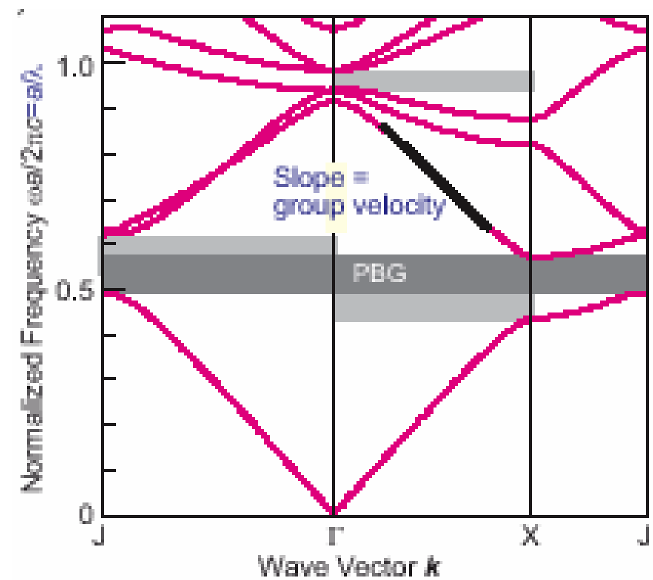


- Artificial multidimensional periodic structure
  Optical analog to solid state crystals
  e.g. Photonic band (Ohtaka,'79)
- Photonic bandgap (PBG) (Yablonovitch,'87):
  Frequency range with no optical modes
- Doping of impurity atoms and defects
  → Light resonance and localization

↓

Thresholdless laser (Yablonovitch,'87)
Waveguides with sharp bend (Joannopoulos,'96)
etc.



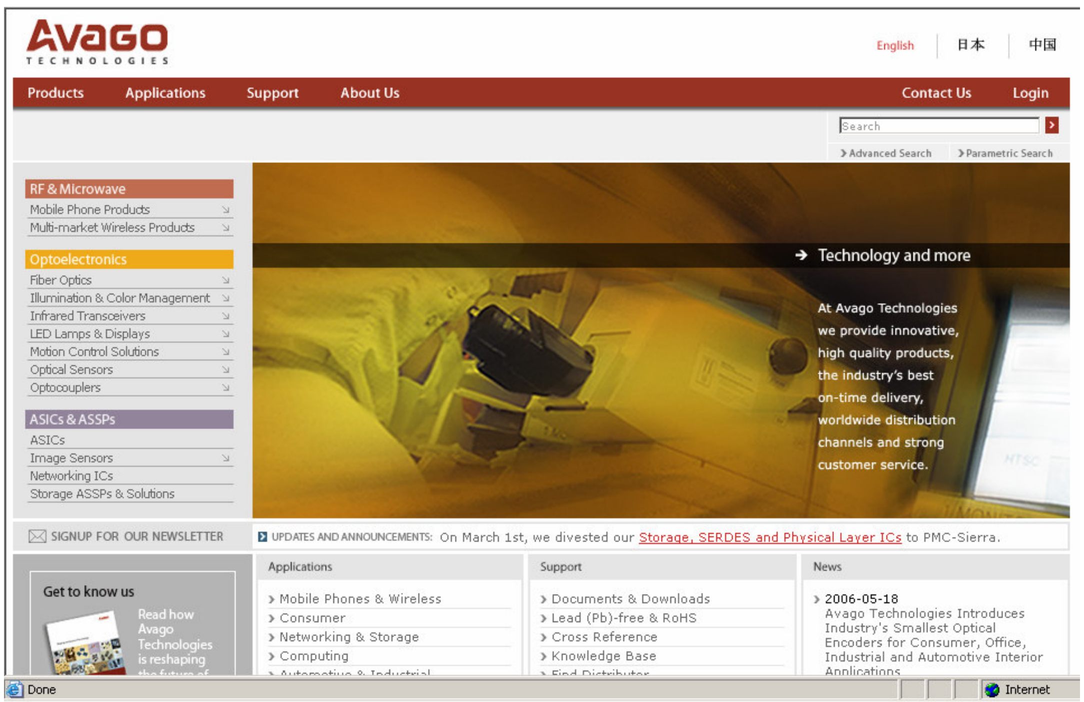


Applications:

- Nanophotonic devices
- Slow light
- *negative refraction*

5) Avago Technologies snapshot

www.avagotech.com



- **Headquarters:**
  San Jose, CA
  Singapore

- **6500 employees worldwide**

- **Over 2000 patents and patent applications**

- **Over 5000 products**
  (optoelectronics, fiber optics, RF, ASICs)

- **Former HP's Components Division (1961-)**

HP roots

- Stanford University classmates Bill Hewlett and Dave Packard founded HP, a test and measurement company, in 1939.
- The company's first product, built in a Palo Alto garage, was an audio oscillator—an electronic test instrument used by sound engineers. One of HP's first customers was Walt Disney Studios, which purchased eight oscillators to develop and test an innovative sound system for the movie Fantasia.
- Several technological companies were founded in the valley around that garage (now national monument) which was then called Silicon Valley.

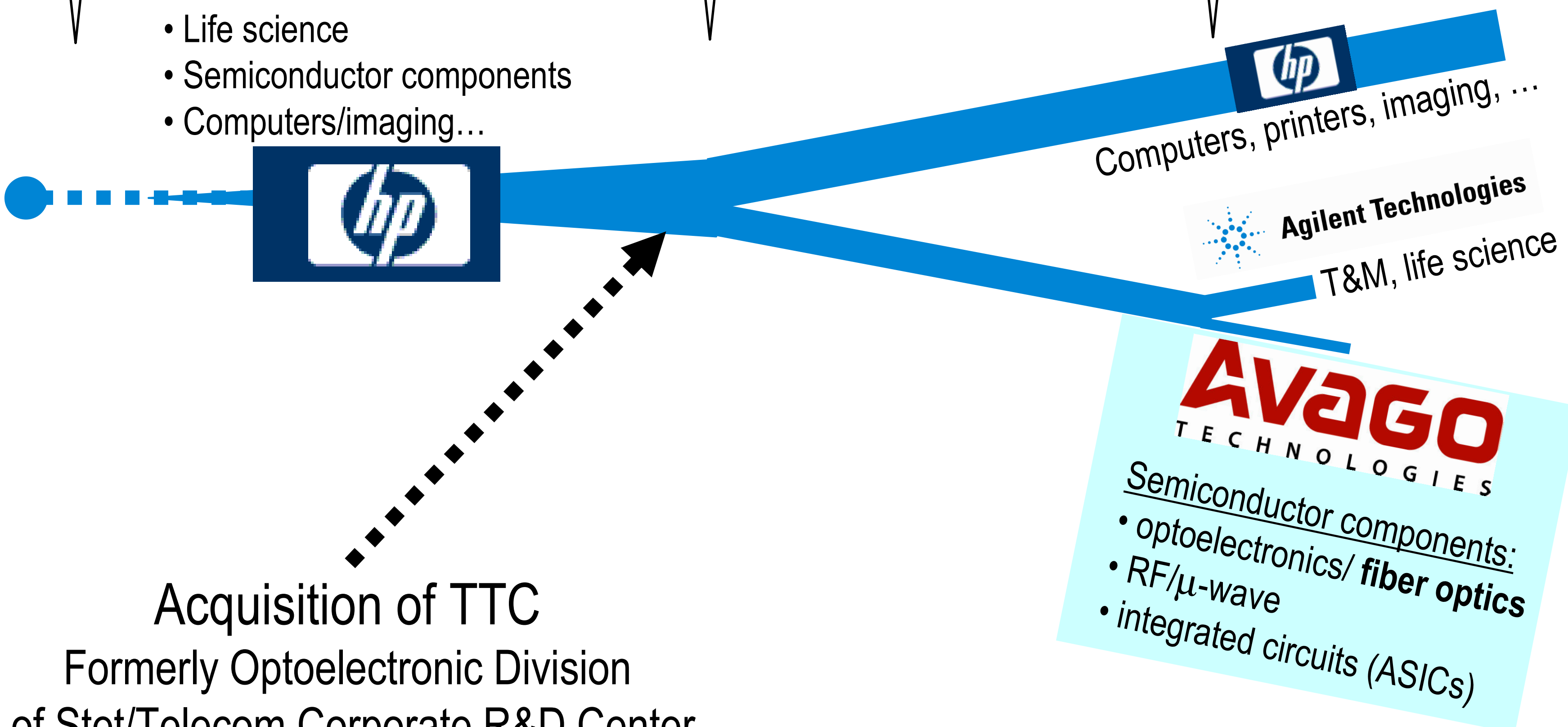
Avago's Road to Independence

1939
Hewlett Packard Foundation (T&M)

- Test & Measurement
- Life science
- Semiconductor components
- Computers/imaging…

November 1, 1999
Agilent spin-off
~40000 employees

December 1, 2005
Avago spin off
~ 6500 employees



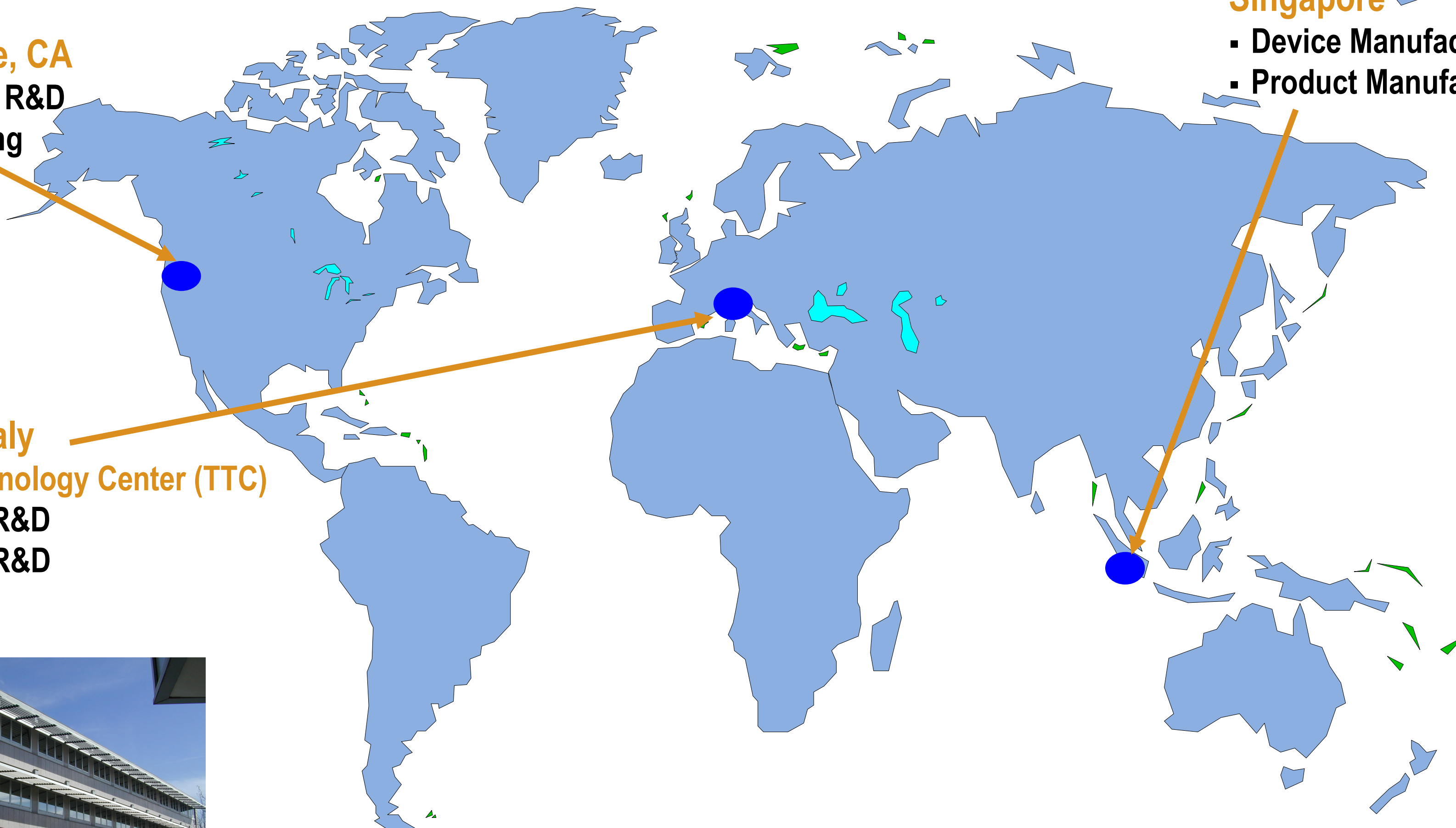
Acquisition of TTC
Formerly Optoelectronic Division
of Stet/Telecom Corporate R&D Center

Fiber Optic Business

Worldwide Operations

Singapore
- Device Manufacturing
- Product Manufacturing

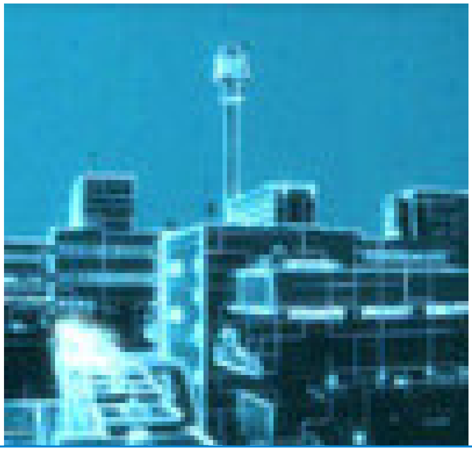
San Jose, CA
- Product R&D
- Marketing



Torino, Italy
Turin Technology Center (TTC)
- Devices R&D
- Product R&D

The Turin Technology Center (TTC)

Via G. Schiaparelli, 12
10148 Torino
Italy



R&D on photonic devices since late 70's

Activity: **R&D**

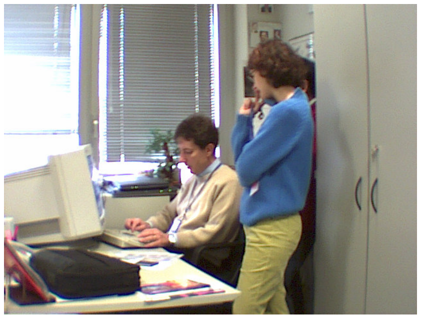
- **Fiber Optics Transceivers**
- **Semiconductor lasers**

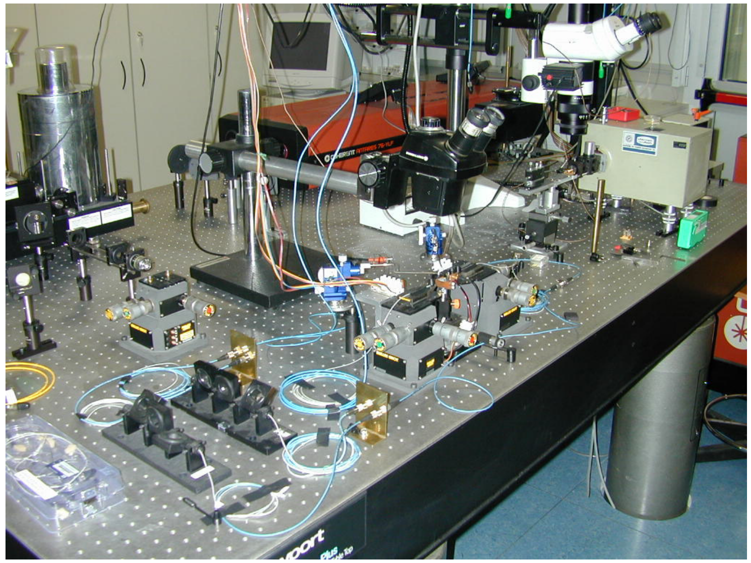
People: **70 (Mainly R&D Engineers)**

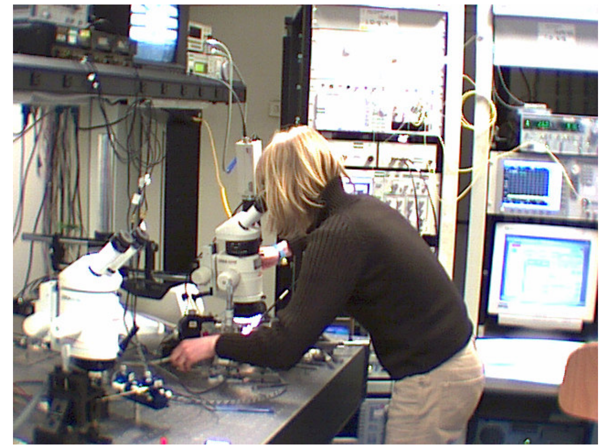
Expertise: **Optoelectronic and photonic technologies**

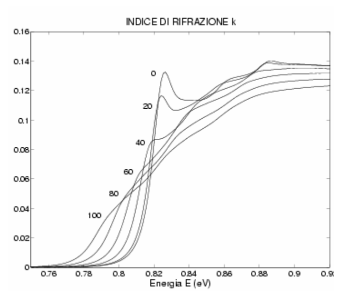
- **New devices and components conception and design**
- **Semiconductors**
- **Device design, prototyping and characterisation**
- **Components packaging and characterisation**

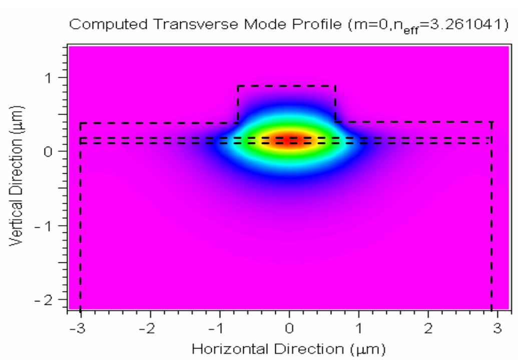
R&D Design/Characterization

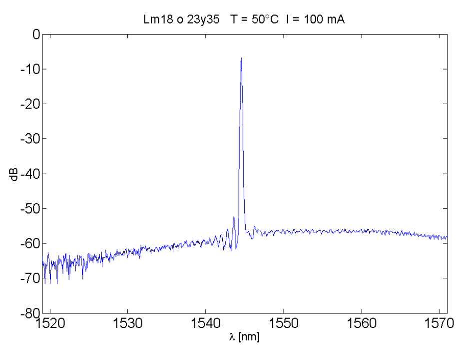


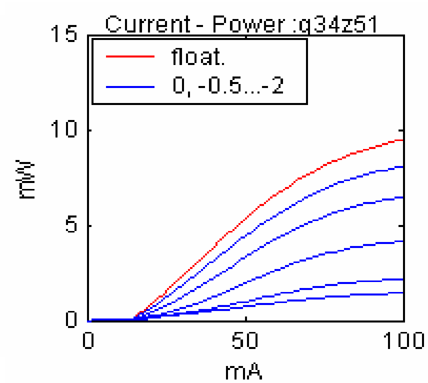


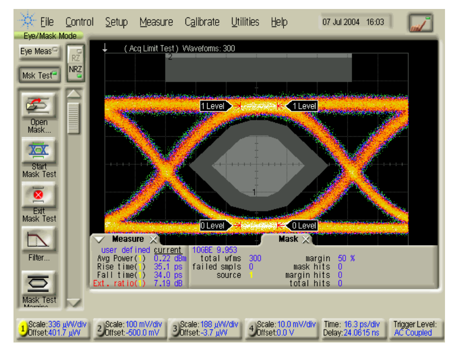




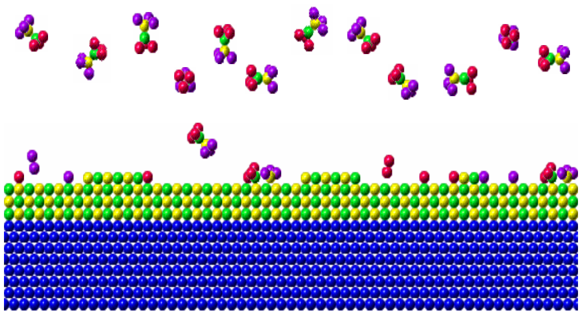


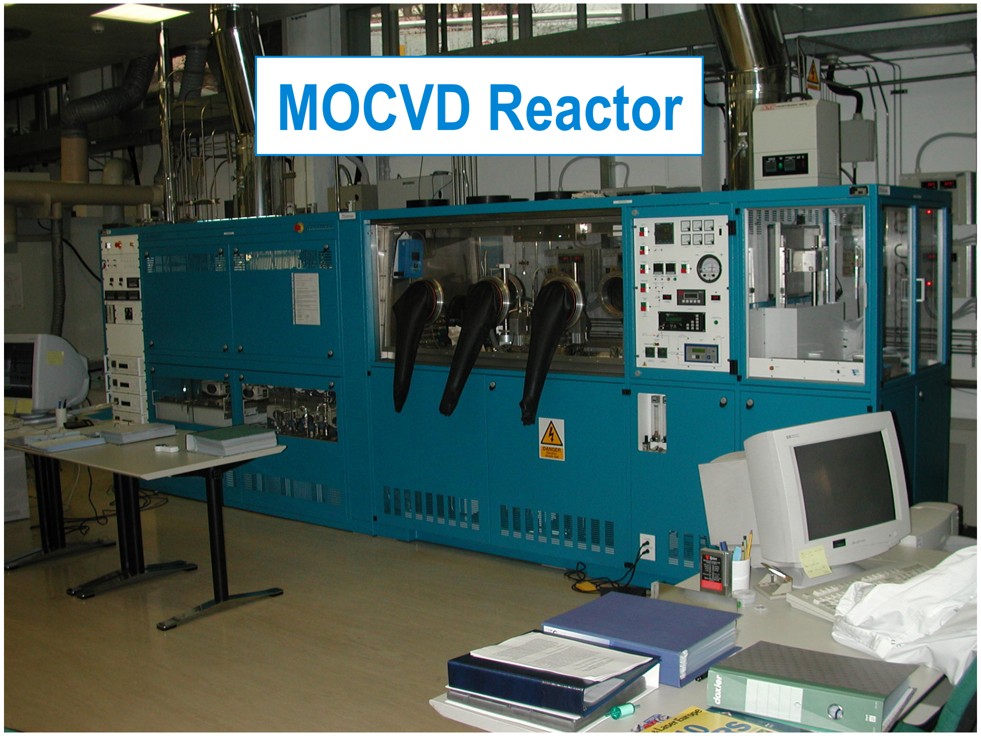


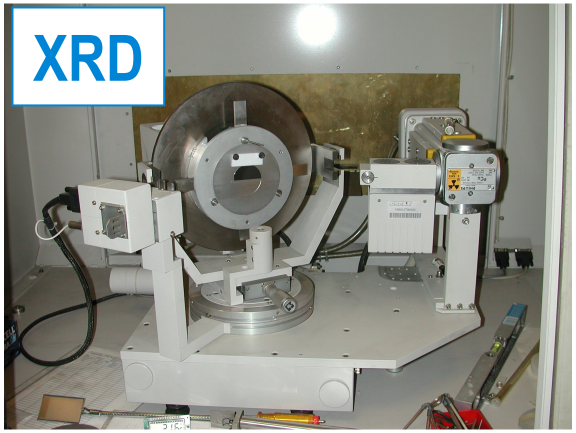




MQW Epitaxy and material characterization



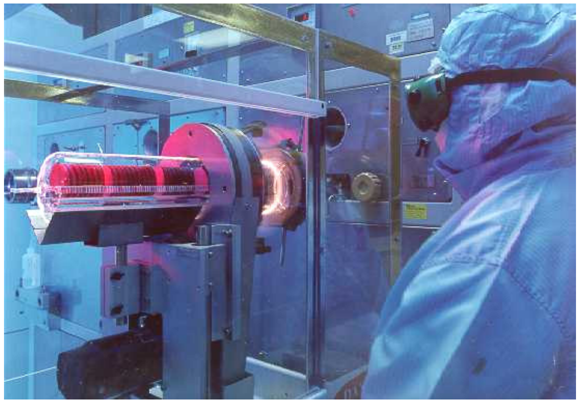




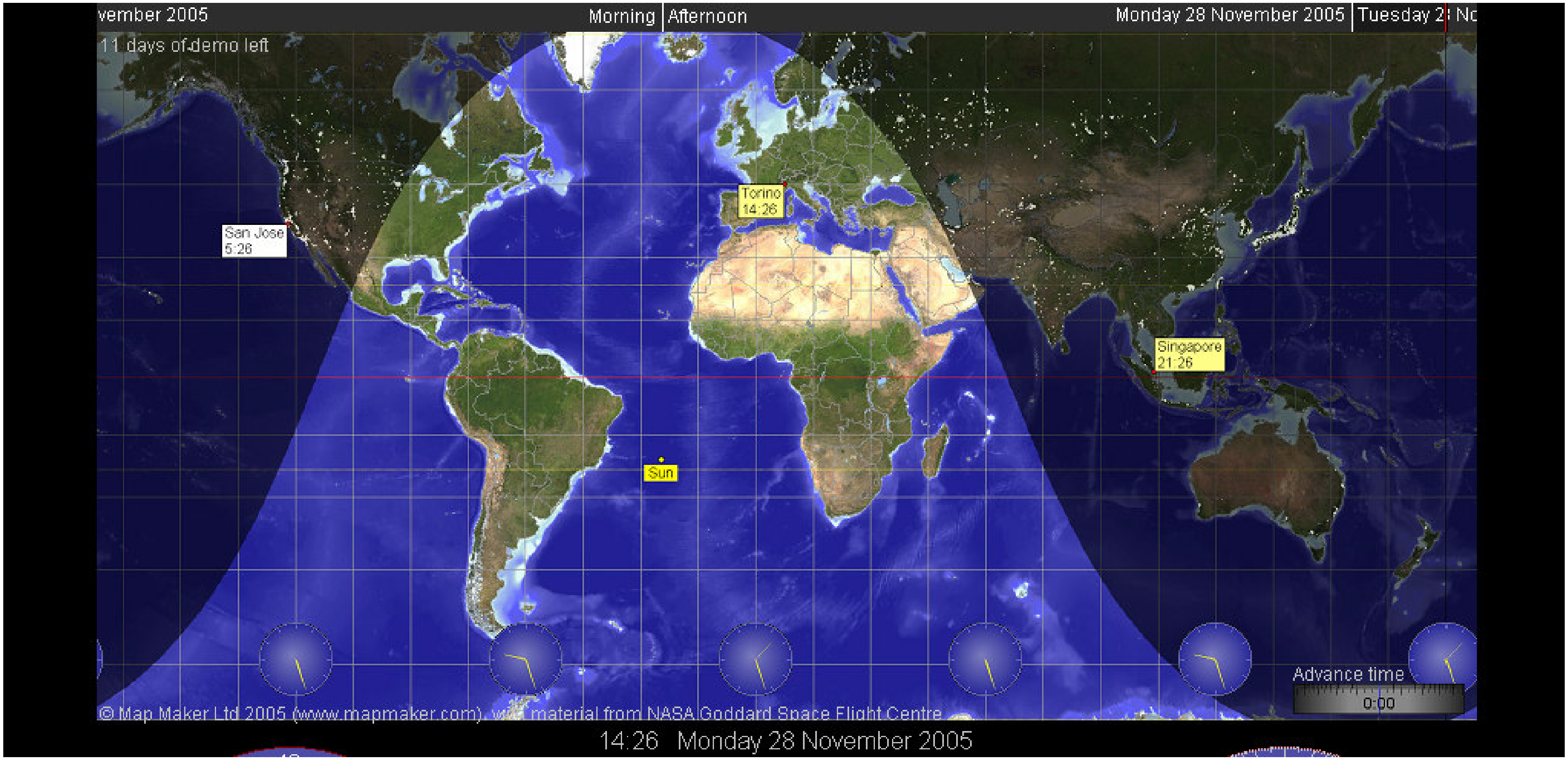
AVAGO TECHNOLOGIES

Technology processing

Manufacturing



Chip development requires team work across the globe: not an easy task!

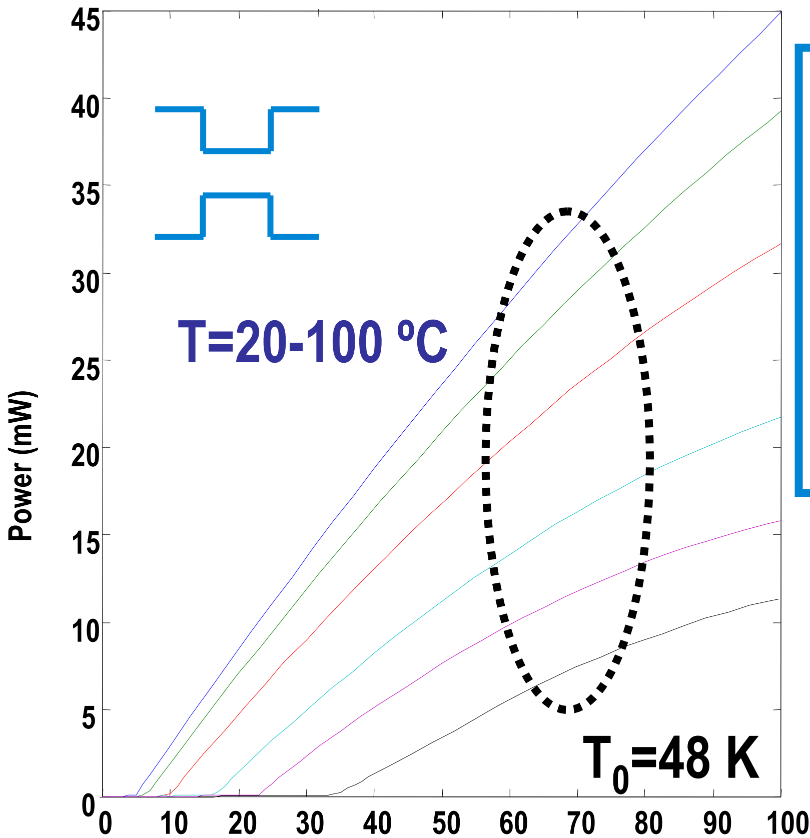


[www avagotech.com](www.avagotech.com)

www.torinoscienza.it/lab-vr/agilent

(visita virtuale ai laboratori TTC)

Effect of band discontinuities on I_{th} (T)



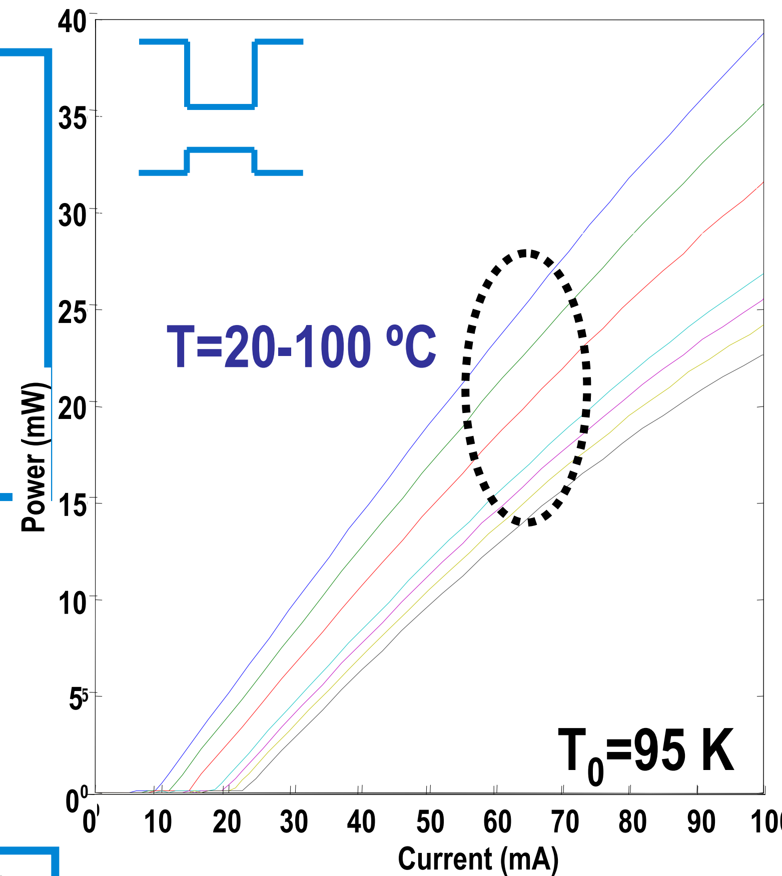
InGaAsP/InP MQW

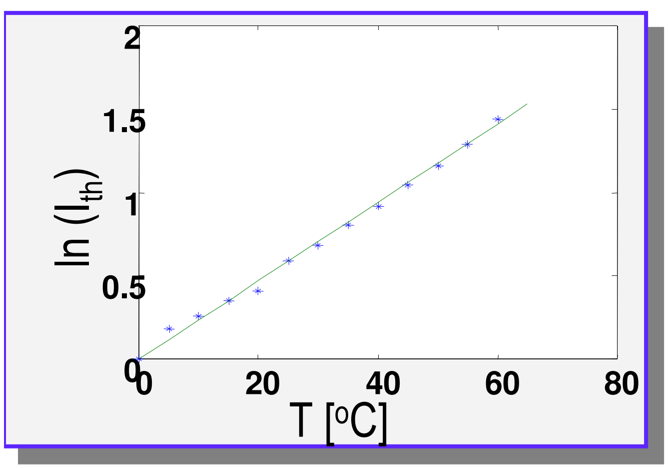
Unstrained:

$\Delta E_c:\Delta E_v$ = 40:60

Optimized strain

$\Delta E_c:\Delta E_v$ = 50:50 or better



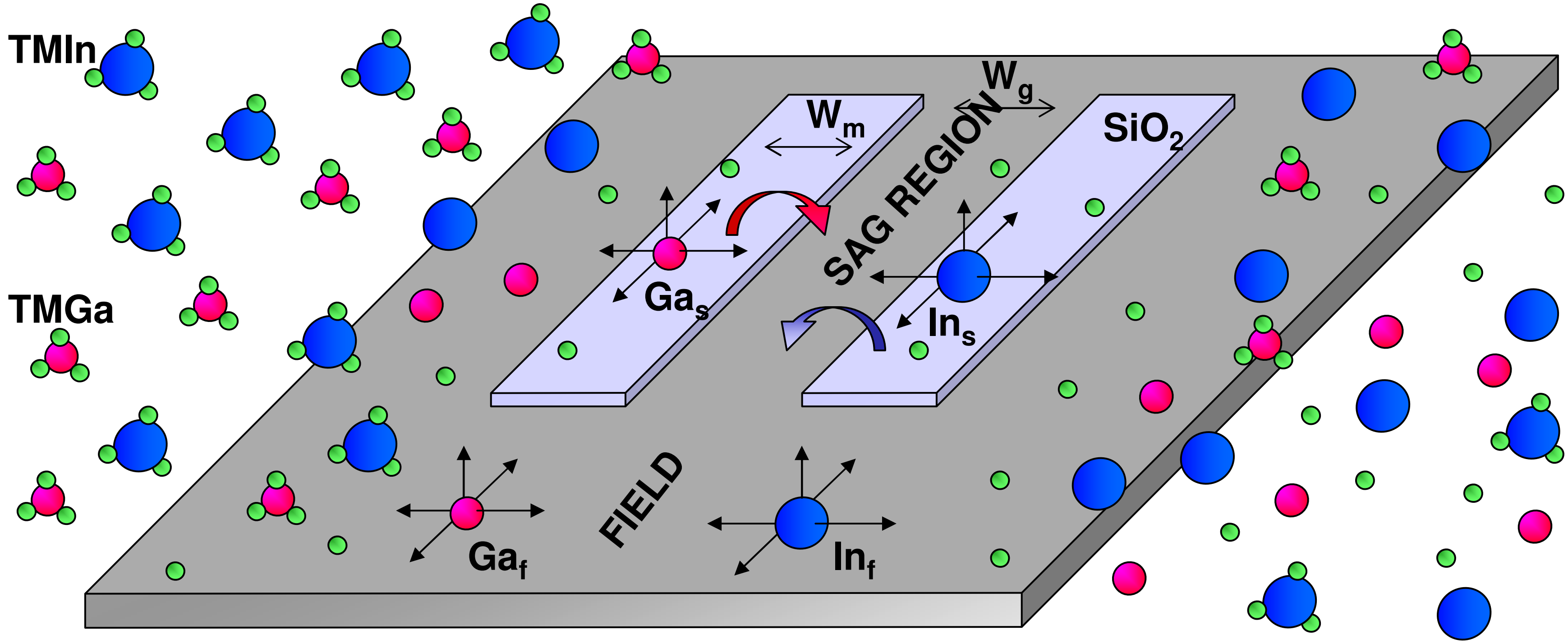


InGaAlAs/InP MQW

$\Delta E_c:\Delta E_v$ = 70:30

$$I_{TH}(T+\Delta T) = I_{TH}(T)\cdot \exp\left(\frac{\Delta T}{T_0}\right)$$

Selective Area Growth (SAG)



Ga_f = Ga atom on field ; In_f = In atom on field ; Ga_s = Ga atom on SiO_2 ; In_s = In atom on SiO_2 ;
L_d Ga = Ga diffusion length ; L_d In = In diffusion length ;

- The growth rate on SiO_2 is ZERO $\Rightarrow L_d\,Ga_f$ & $L_d\,In_f < L_d\,Ga_s$ & $L_d\,In_s$
- $L_d\,Ga_s < L_d\,In_s \Rightarrow$ **In enrichment on SAG region**