Basics of Optical Telecommunications

Szilvia Nagy

Department of Telecommunications

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Outline – General Properties

- Modeling of light
  - photons
  - electromagnetic waves
  - geometrical optics
  - field theory
- Optical networks
  - use
  - topologies
  - elements
- Standards

Outline – Fibers

- Properties of optical fibers
  - geometry
  - modes
  - attenuation
  - dispersion
  - fabrication
- Nonlinear effects
  - Brillouin scattering
  - self-phase modulation
  - cross-phase modulation
  - four-wave mixing
  - Raman scattering

Outline – Lasers

- Operation of lasers
    - Properties
    - applications
- Atomic energy levels
- Population inversion
- Energy bands in solid states
- Heterojunctions in semiconductors
- Quantum well lasers
- Vertical cavity surface emitting lasers
- Lasers as sources in optical telecommunications

Outline – Amplifiers, regenerators, detectors

- Amplifiers
  - Erbium doped fibers
  - Raman amplifiers
  - Semiconductor optical amplifiers
- Dispersion compensation
  - Dispersion shifted fibers
  - Dispersion compensating fiber
  - Compact dispersion compensation
- Detectors
  - PIN
  - APD

Outline – Modulators, switches

- Physical basics
  - electrooptic effect
  - magnetooptic effect
  - acoustooptic effect
  - elastooptic effect
  - thermooptic effect
  - Bragg grating, Bragg mirrors
  - interferometers
- Modulation
- Switching

Outline – Splitters, multiplexers

- Splitting
  - photolithography channels
  - fused fibers
  - interferometers
- Filtering, multiplexing, demultiplexing
  - prism
  - grating
  - Bragg layers
- WDM

Outline – Soliton communication

- Nonlinear effects in fibers
- History of solitons
- Korteweg—deVries equations
- Envelop solitons
- Solitons in optical fibers
- Amplification of solitons – optical soliton transmission systems

Modeling of light

Photon model

- particles with energy $h\nu$,
- bosons
- useful in
  - quantum mechanics
  - particle physics
  - telecommunications
    electron excitations: lasers, detectors

Modeling of light

Electromagnetic wave model

- the Maxwell equations describe the behavior
- $c = (\mu_0\varepsilon_0)^{-1/2}$ velocity of light in vacuum
- $v = (\mu\varepsilon)^{-1/2}$ velocity of propagation in materials
- refraction index: $n = (\mu_r\varepsilon_r)^{-1/2}$
- used in optical telecommunication
  - modeling the fiber as waveguide

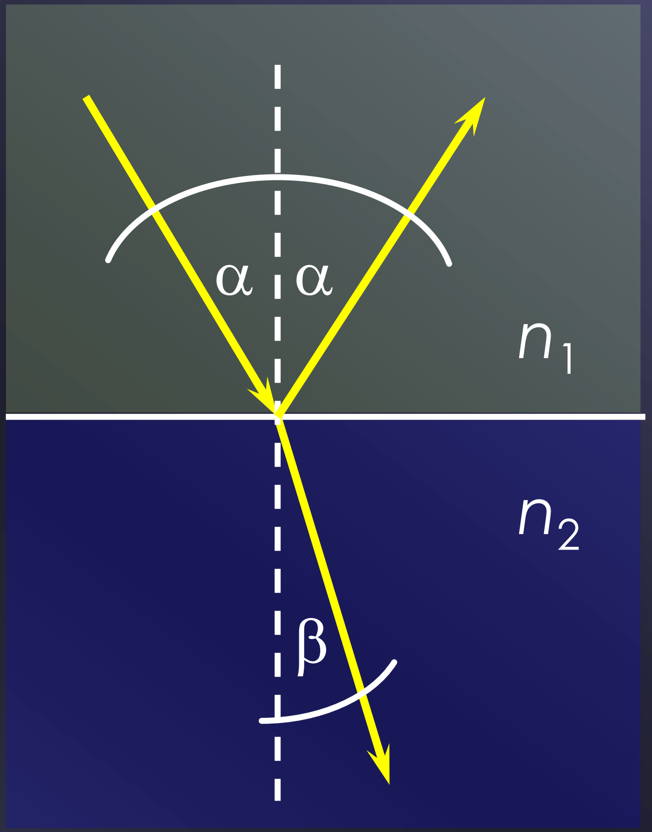
Modeling of light

Geometrical optics

- rays
- Snelius—Descartes law

$$n_1 \sin\alpha = n_2 \sin\beta$$

- reflection and transmission

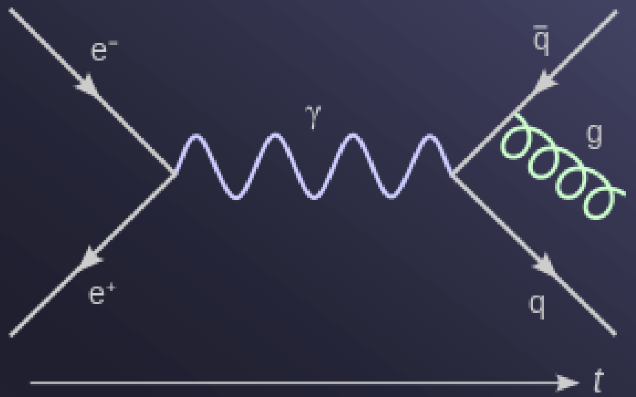


$n_1 < n_2$

Modeling of light

Field theory

- force carrier particle in electromagnetic interaction
- particle-like excitation – some say, it is a spread out field unit that generates and collapses
- similar to gluons, W, Z bosons, and the Higgs bosons – they are generated due to spontaneous symmetry breaking
- useful in
  - particle physics
  - telecommunications – not yet



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Networks

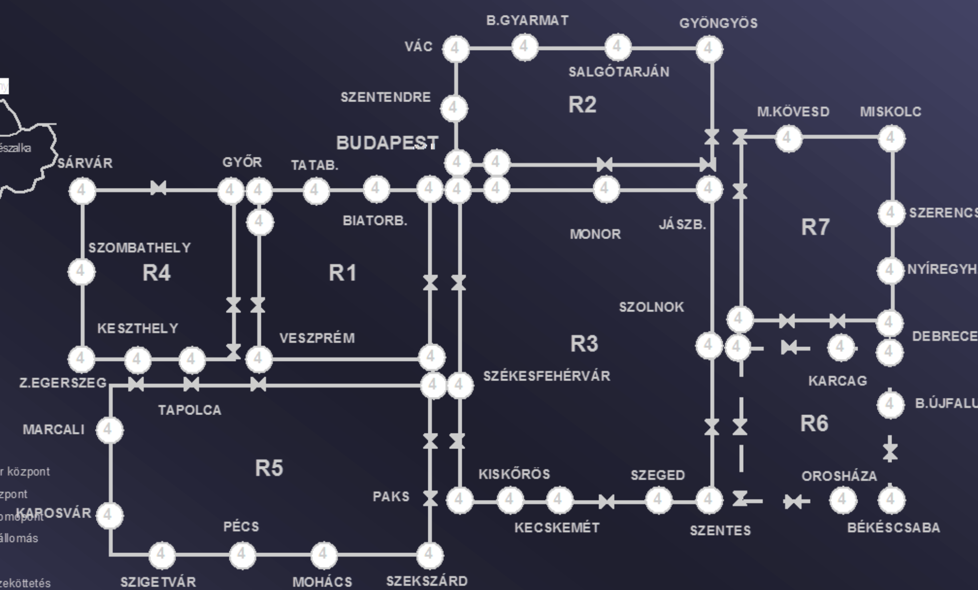
Levels

- Intercontinental – exclusive, silica cables
- long haul continental – almost exclusive, silica
- national backbones – almost exclusive, silica
- regional backbones – mostly optical, silica
- local – still lot of copper, but FTTX increasing, silica or plastic
- indoors – rare, mostly plastic optical cables
- intra vehicle – rare, plastic (glass is not suitable)

Networks

Topologies

- Intercontinental to regional backbones – reserved doule ring, mesh



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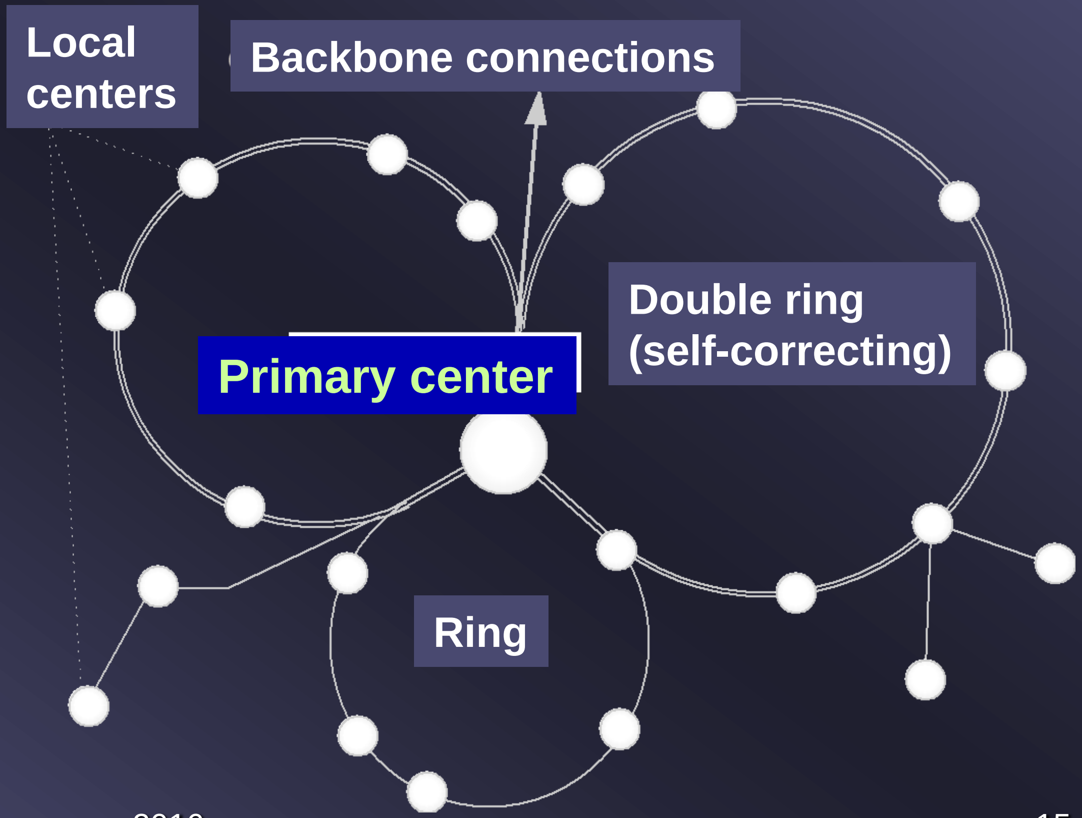
Networks

Topologies

- Intercontinental to regional backbones – reserved doule ring, mesh
- local – mostly tree



Networks

Topologies

- Intercontinental to regional backbones –doule ring (reserved), mesh
- local – mostly tree (PON)
- indoors – mostly star
- intra vehicle – tree or bus

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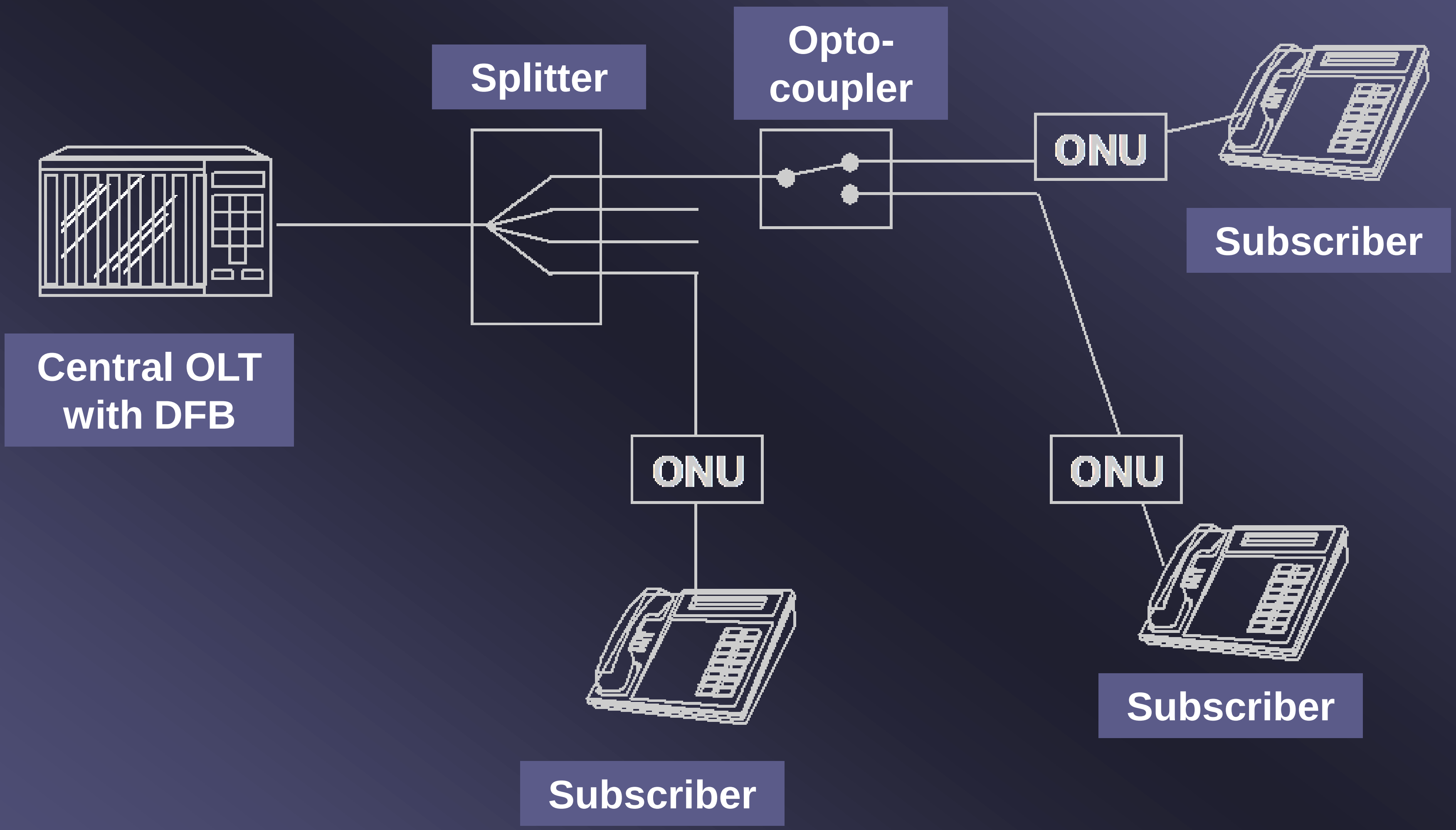
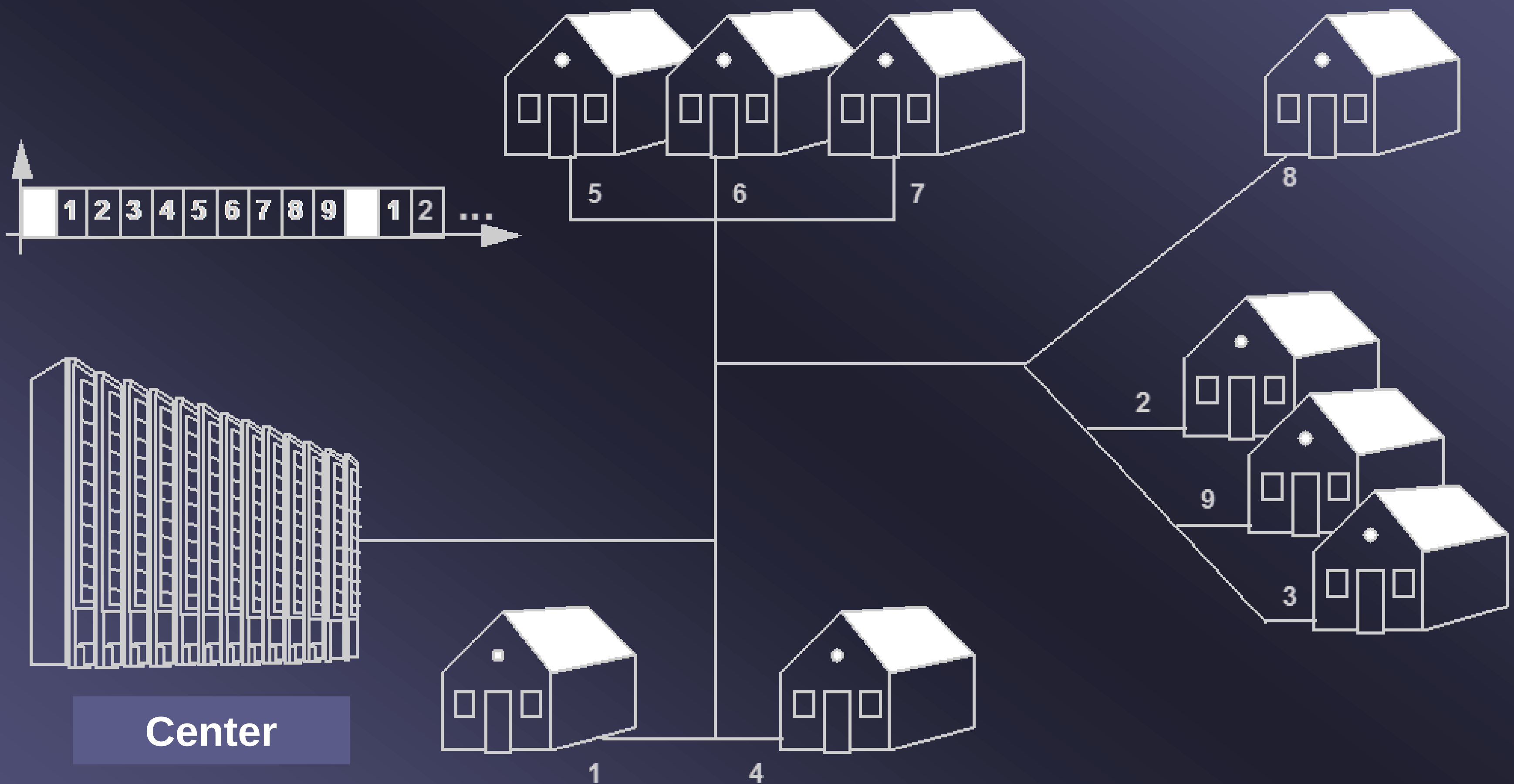
Passive optical networks (PON)



TDMA in PON



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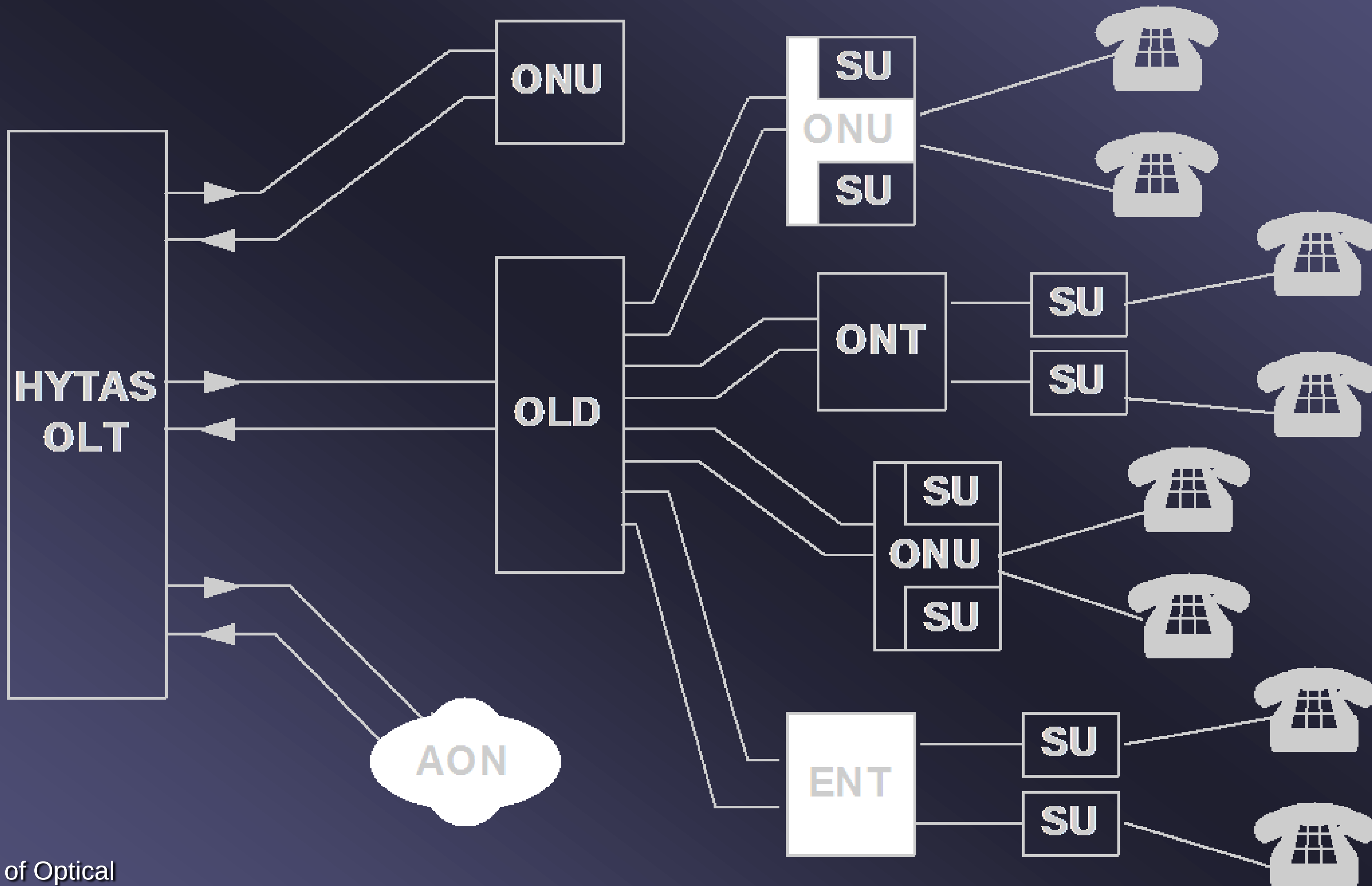
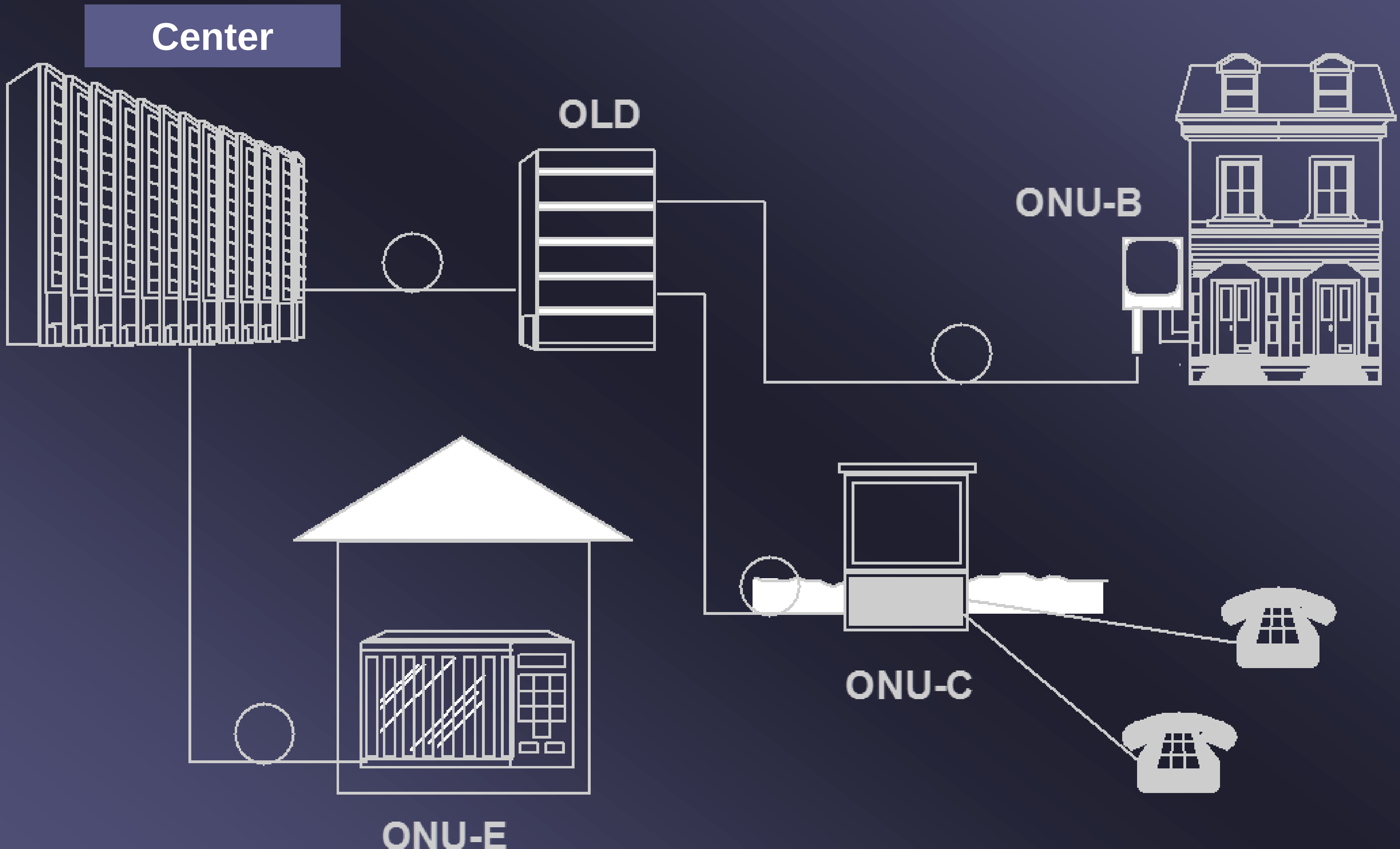
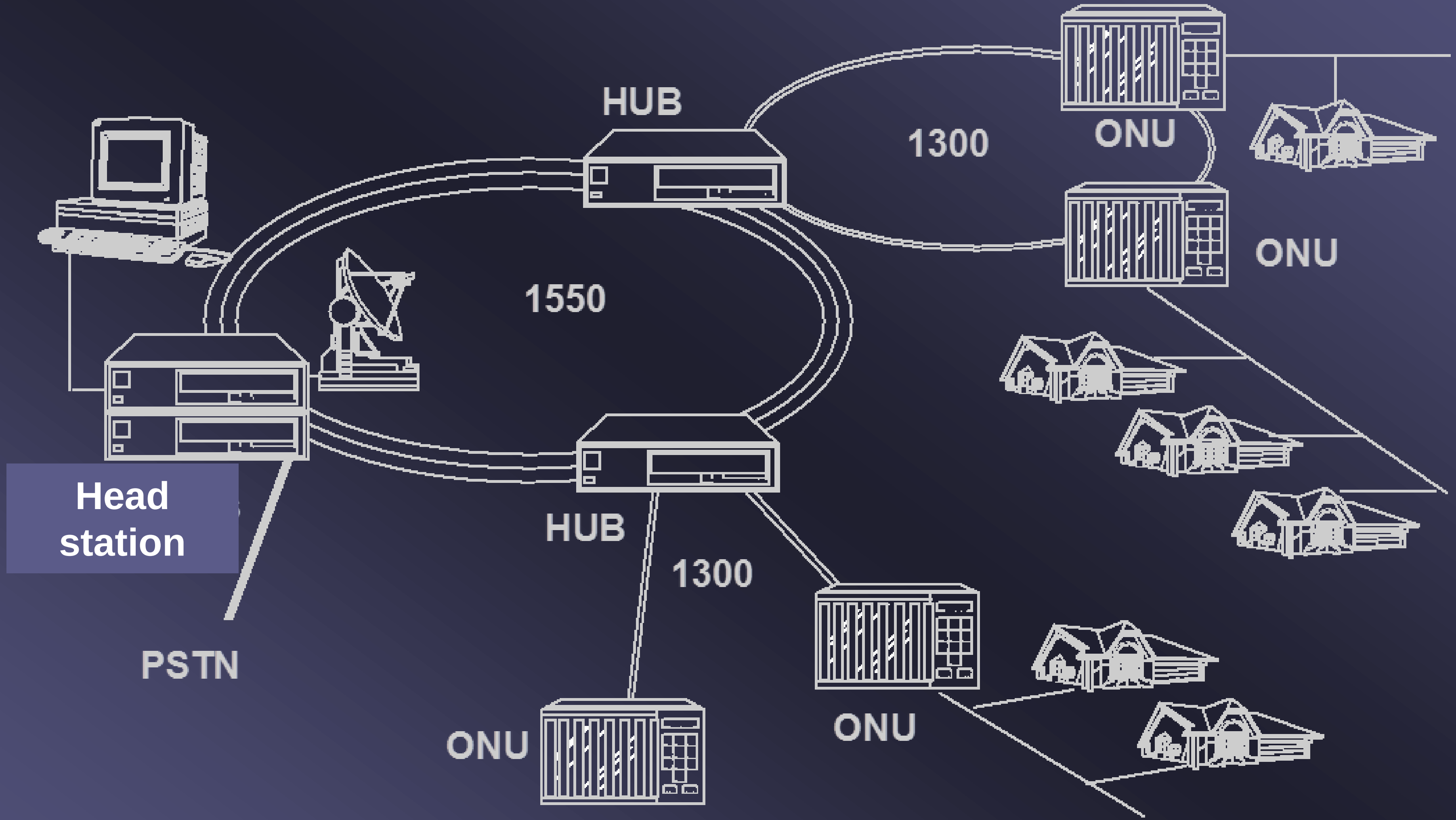
Hytas



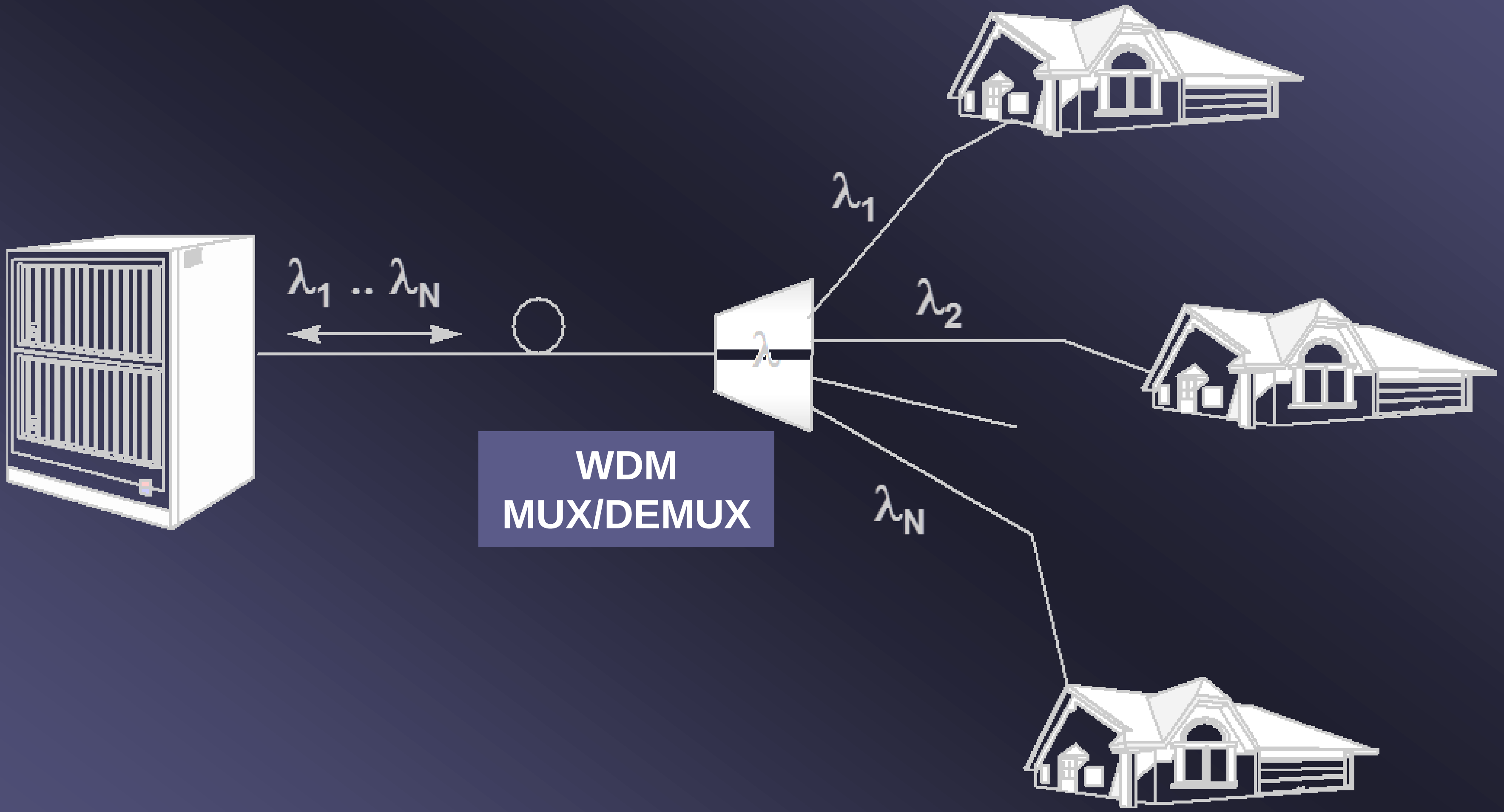
Subscriber units



Cable TV networks



WDM in PON access networks



Networks

Elements

- Passive
  - fiber
  - splitter
  - multiplexer/demultiplexer
  - dispersion compensator
  - switch
- Active
  - source, detector
  - amplifier
  - modulator

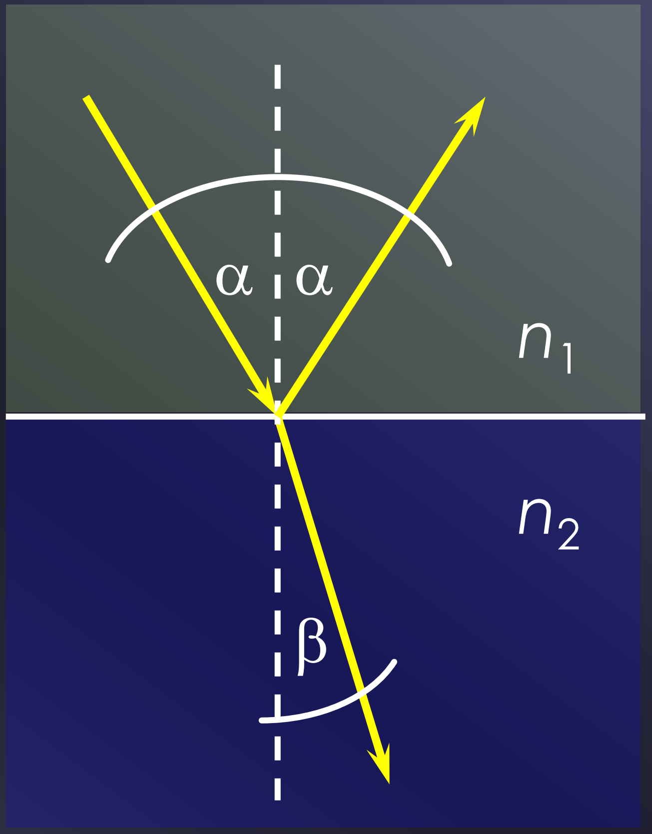
Fibers

Geometrical optics

- rays
- Snelius—Descartes law

$$n_1 \sin\alpha = n_2 \sin\beta$$

- reflection and transmission

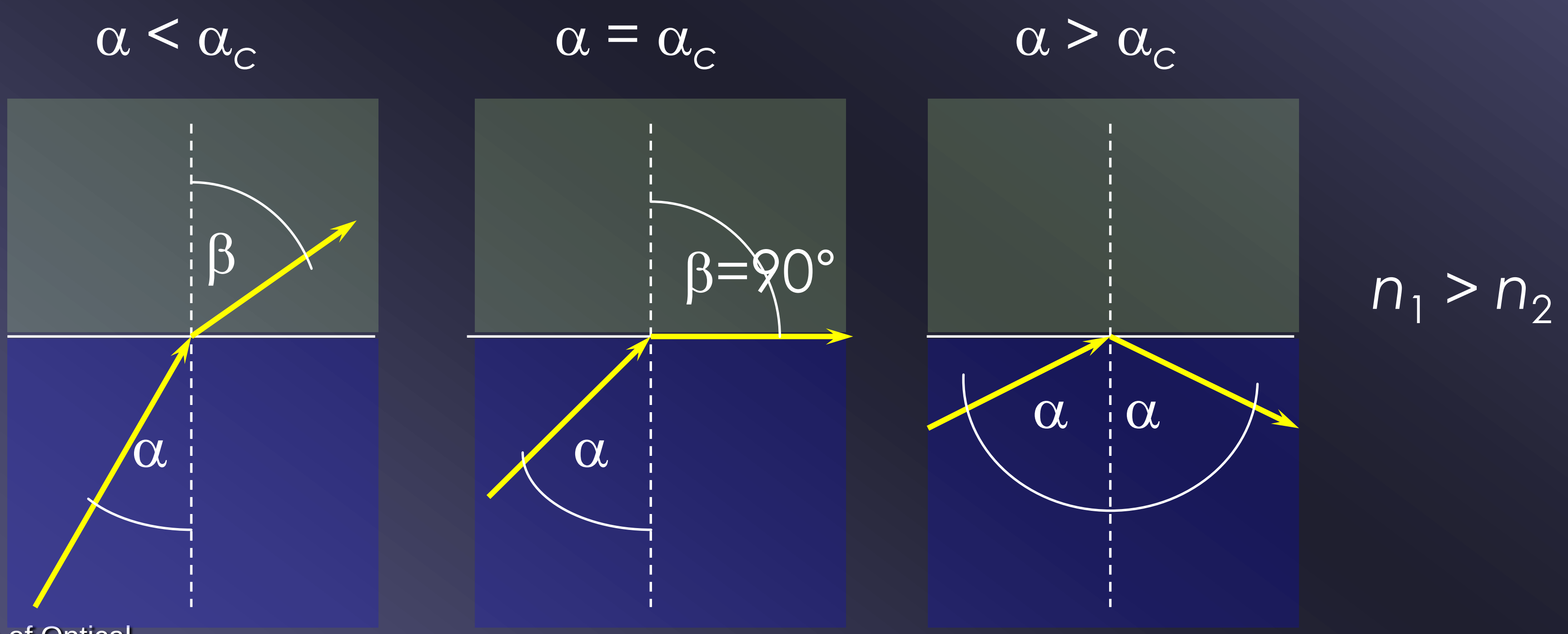


$n_1 < n_2$

Fibers

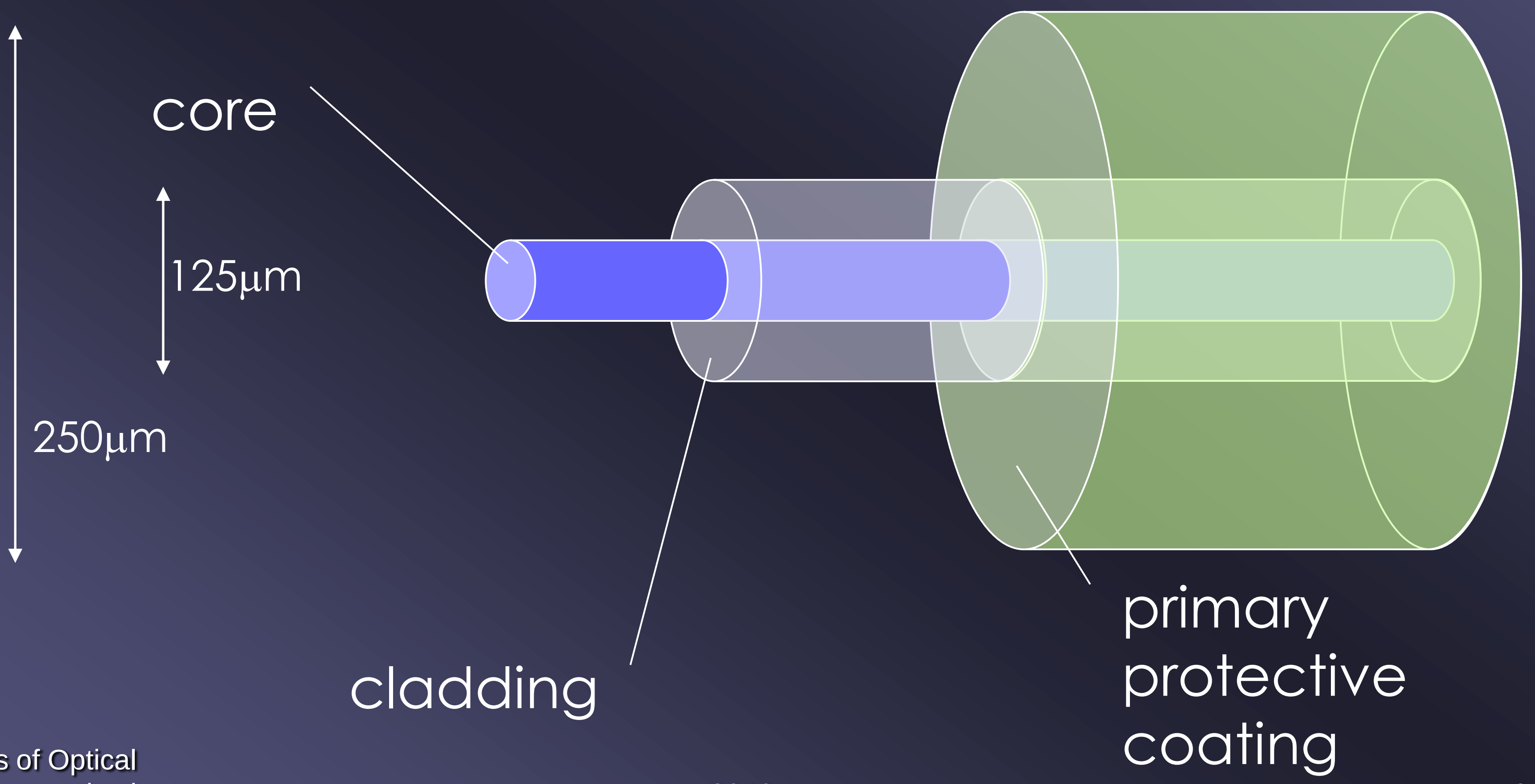
Geometrical optics

- total internal reflection – no transmitted light



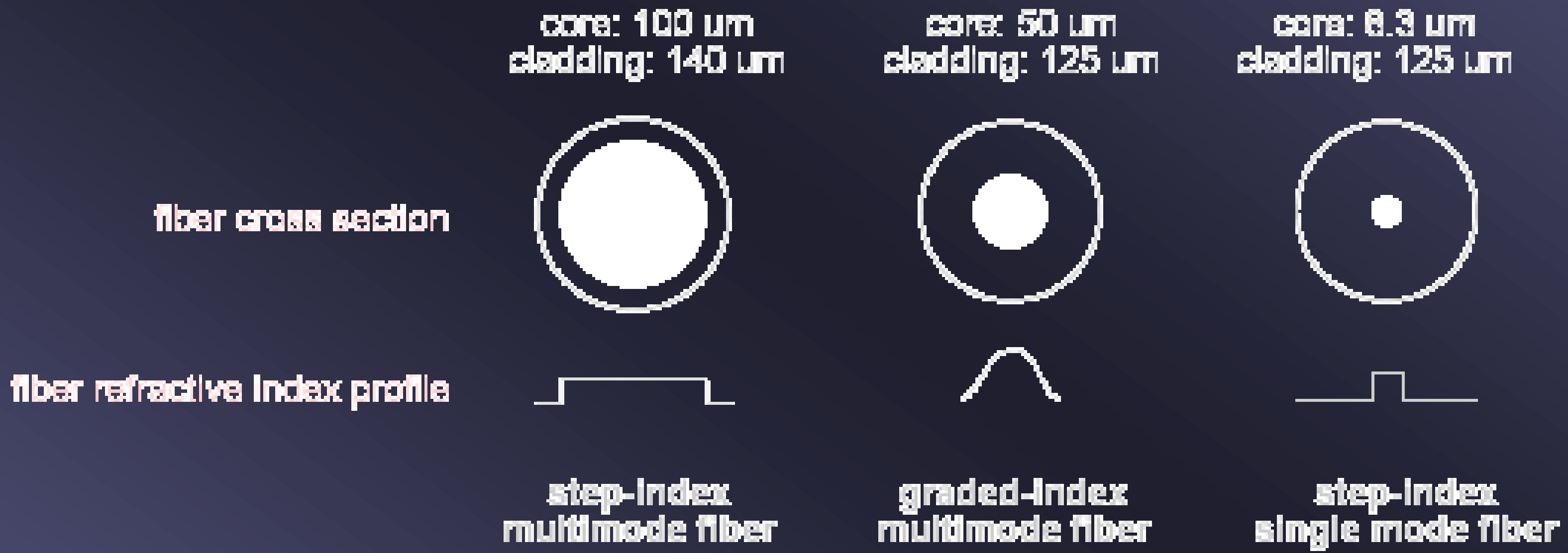
Modeling of the fiber

The fiber



Modeling of the fiber

Index profiles



Modeling of the fiber

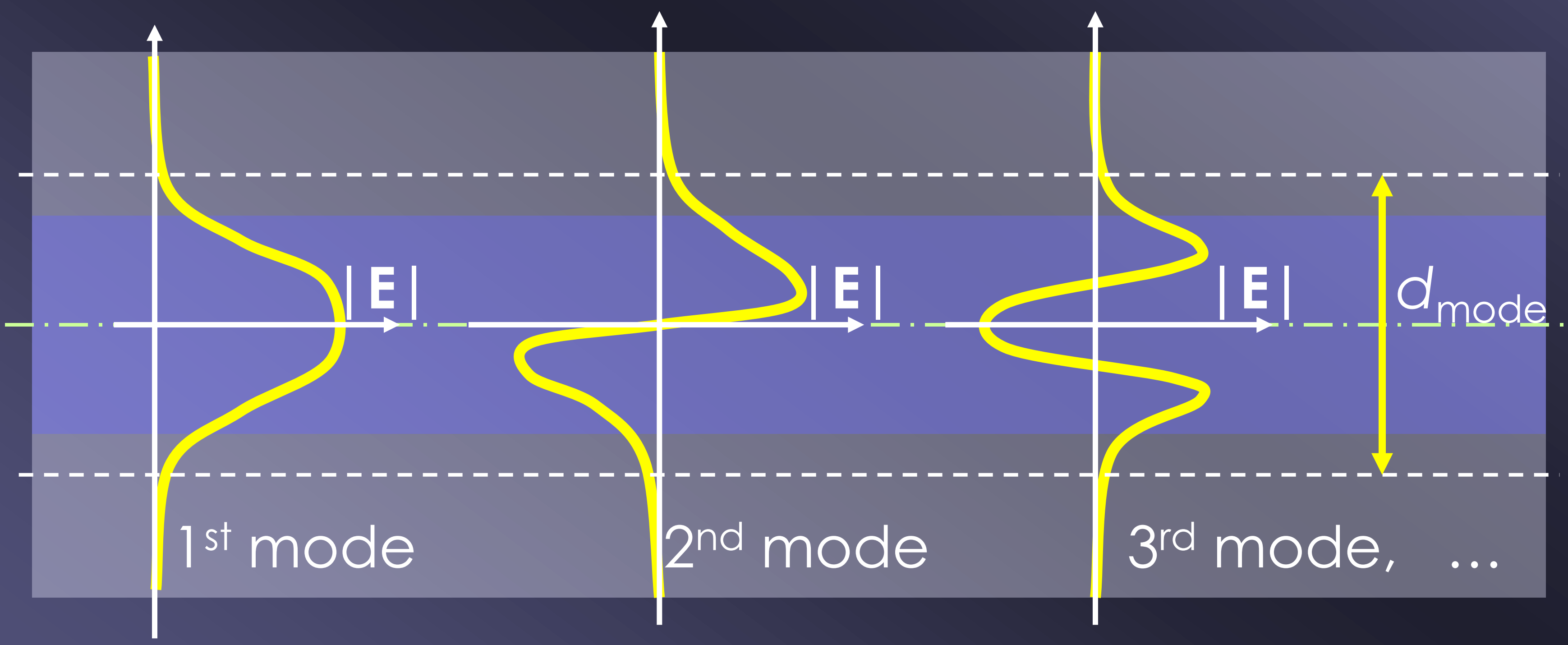
Waveguide (cylindrical) with possible propagating modes

- solution of the electromagnetic wave equation with cylindrical boundary conditions
  - Bessel (and Hankel) functions along the radius
  - propagating waves along the axis

Modeling of the fiber

Mode field diameter

- ligth slightly „penetrates” to the cladding



Modeling of the fiber

Geometrical optics point of view

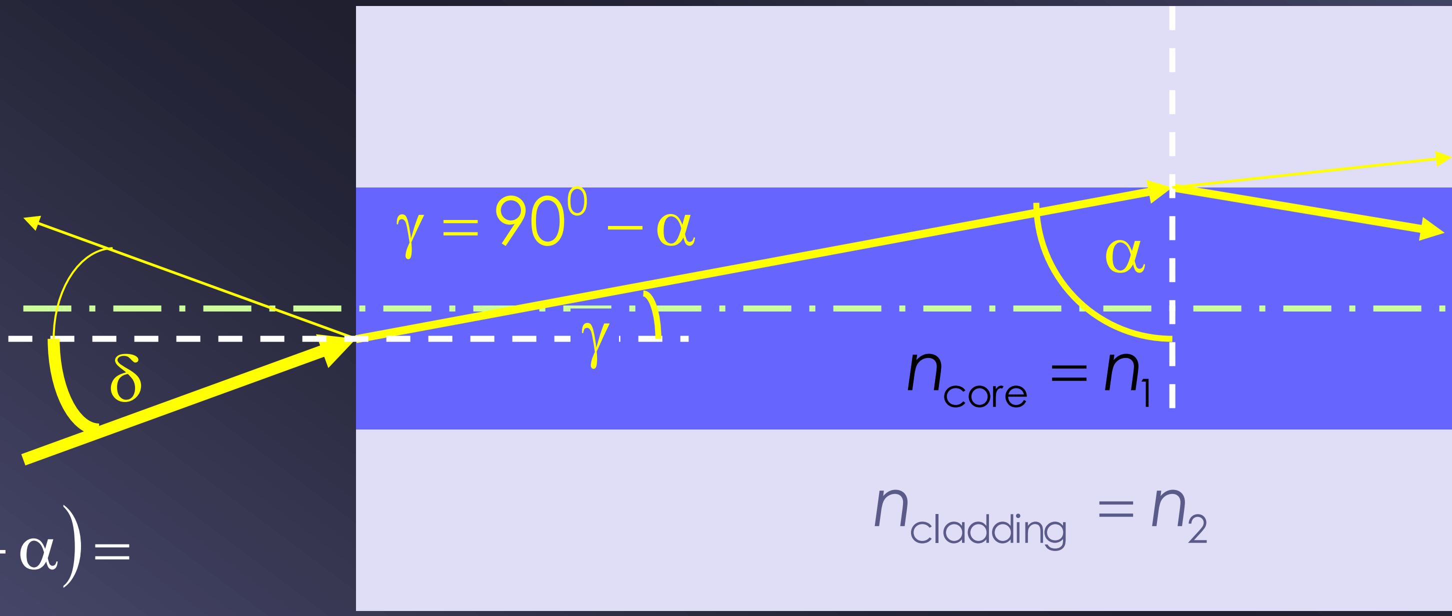
- ray bouncing in the cylinder, reflecting (or bending) at the boundaries

$$\frac{\sin\delta}{\sin\gamma} = \frac{n_{core}}{n_{air}}$$

$$\sin\delta = n_1 \cdot \sin\gamma$$

$$\sin\gamma = \sin(90° - \alpha) =$$

$$= \cos\alpha$$



$n_{air} \approx 1$

Modeling of the fiber

Geometrical optics point of view

- ray bouncing in the cylinder, reflecting (or bending) at the boundaries

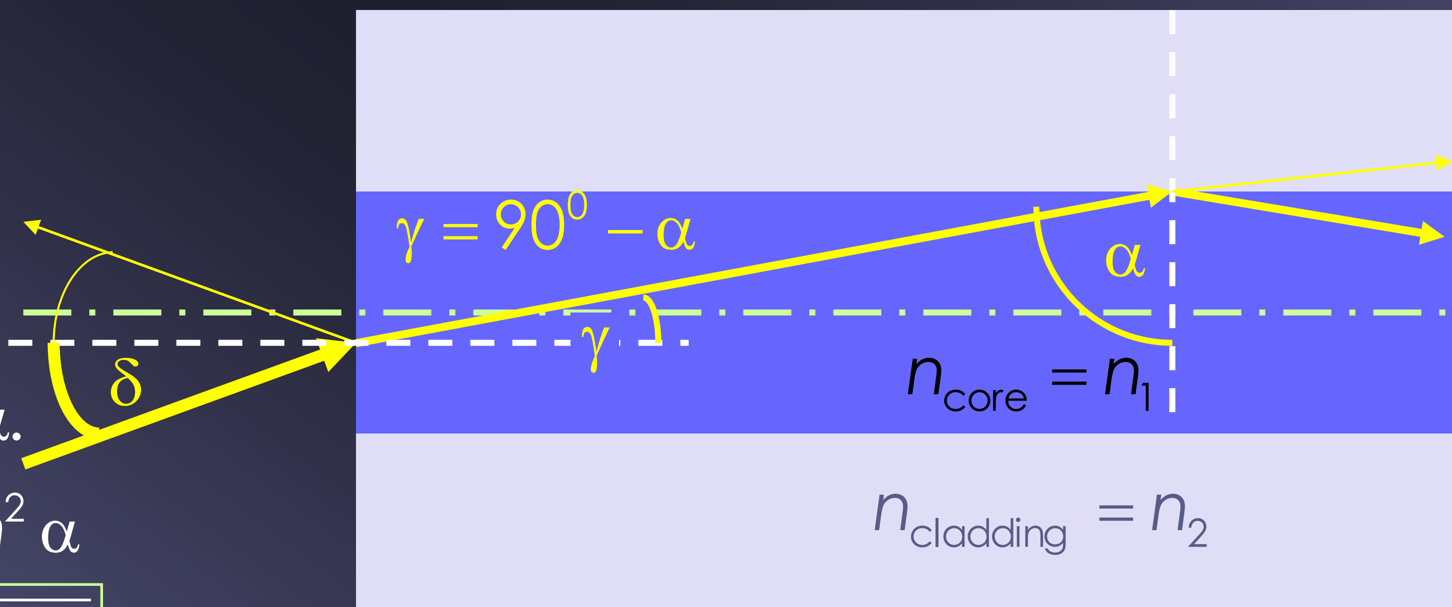
$$\frac{\sin\delta}{\sin\gamma} = \frac{n_{core}}{n_{air}}$$

$$\sin\delta = n_1 \cdot \sin\gamma$$

$$\sin\delta = n_1 \cdot \cos\alpha.$$

$$\cos^2\alpha = 1 - \sin^2\alpha$$

$$\boxed{\sin\delta = n_1\sqrt{1-\sin^2\alpha}}$$



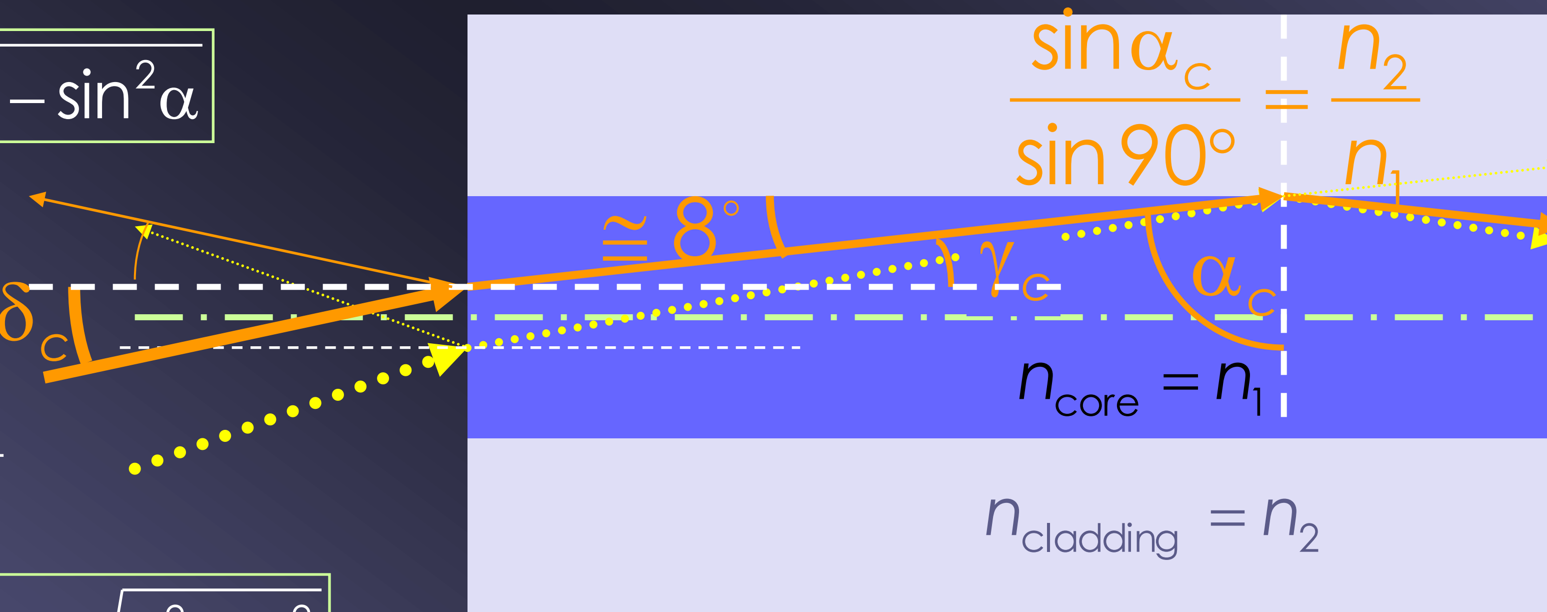
$n_{air} \approx 1$

Modeling of the fiber

Geometrical optics point of view

- ray bouncing in the cylinder, reflecting (or bending) at the boundaries

$$\sin\delta = n_1\sqrt{1-\sin^2\alpha}$$



$$\sin\alpha_c = \frac{n_2}{n_1}$$

$$\sin\delta_c = NA = \sqrt{n_1^2 - n_2^2}$$

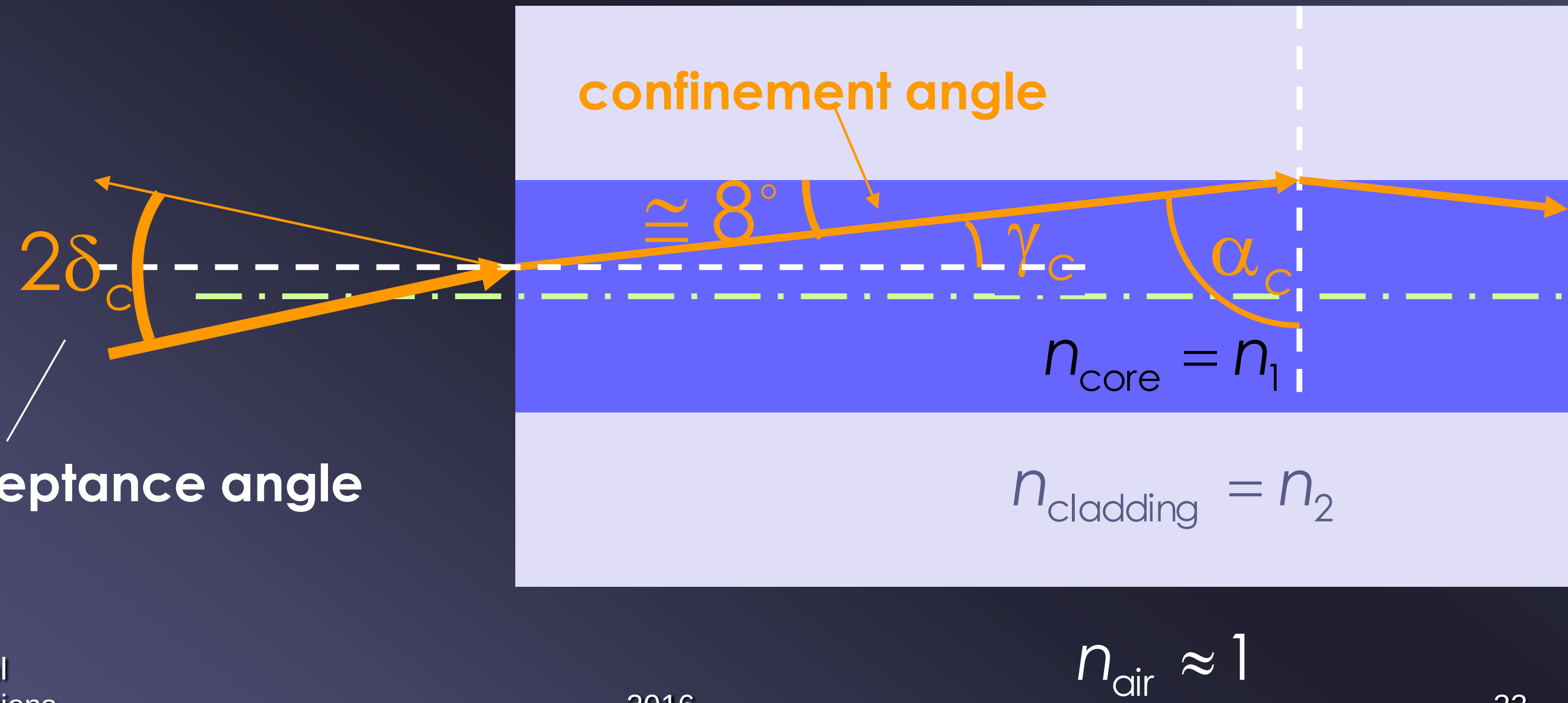
$n_{air} \approx 1$

Modeling of the fiber

Geometrical optics point of view

- numerical aperture

$$\sin\delta_c = NA = \sqrt{n_1^2 - n_2^2}$$

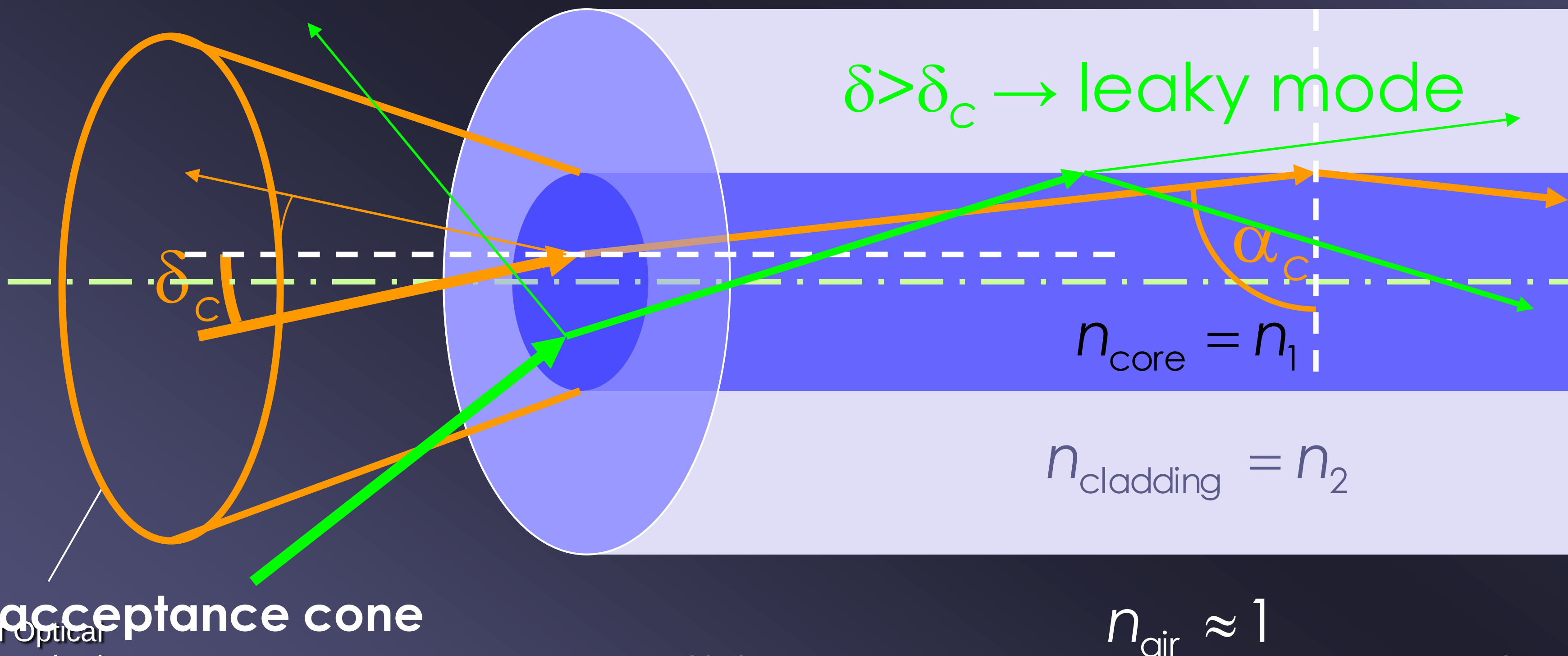


Modeling of the fiber

Geometrical optics point of view

- numerical aperture

$$\sin\delta_c = NA = \sqrt{n_1^2 - n_2^2}$$

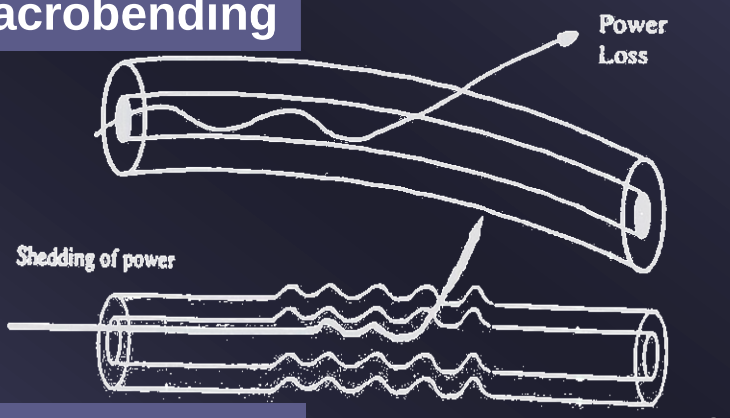


Properties of the fiber

Fiber attenuation

- absorption – cumulative
  - $(1 - \alpha)^L$
  - depeds on the composition
- scattering – cumulative
  - Rayleigh scattering
  - $(1 - S)^L$
  - $A\lambda^{-4}$
- coupling losses – at the ends
- bendings

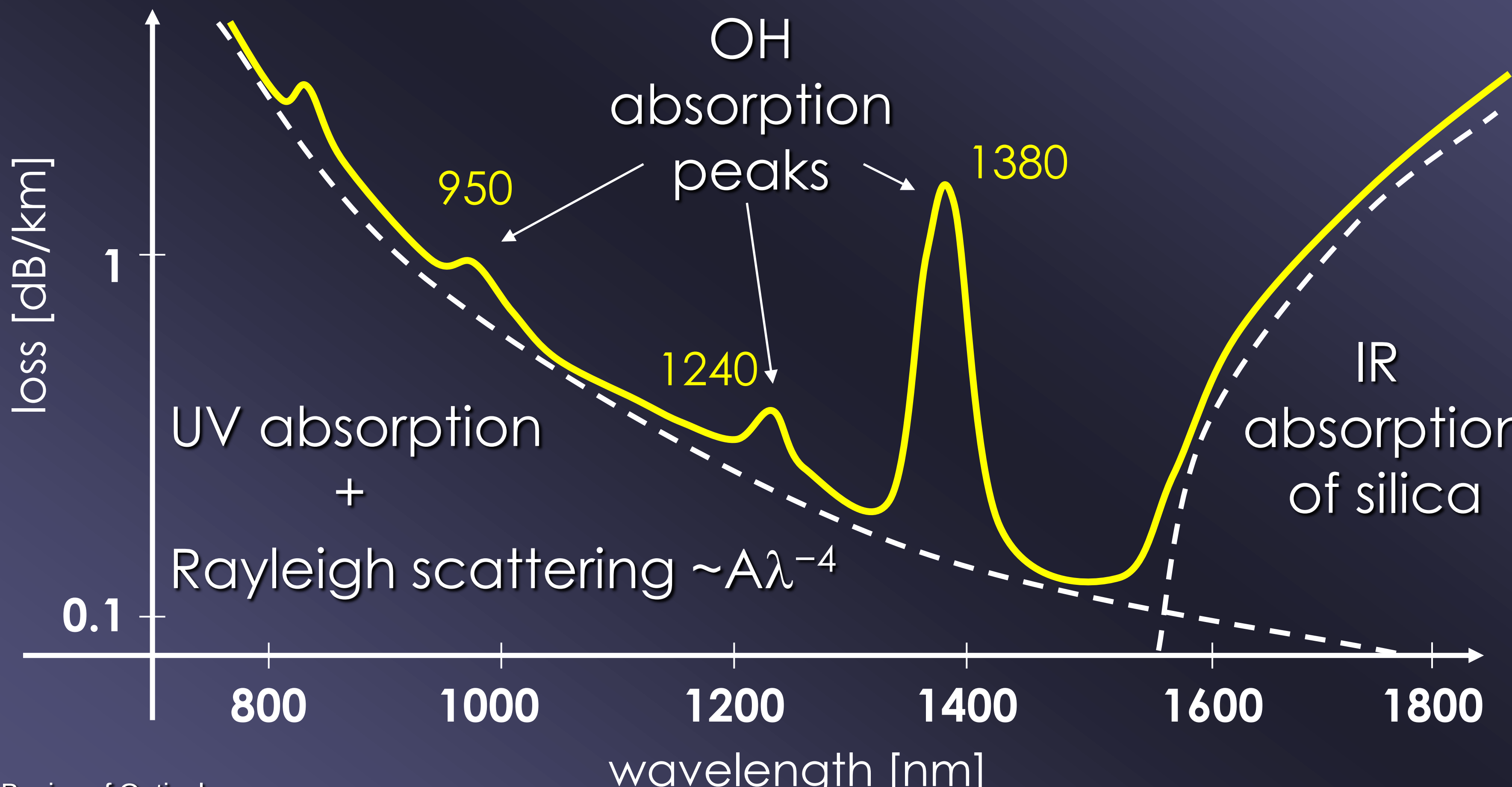
macrobending



microbending

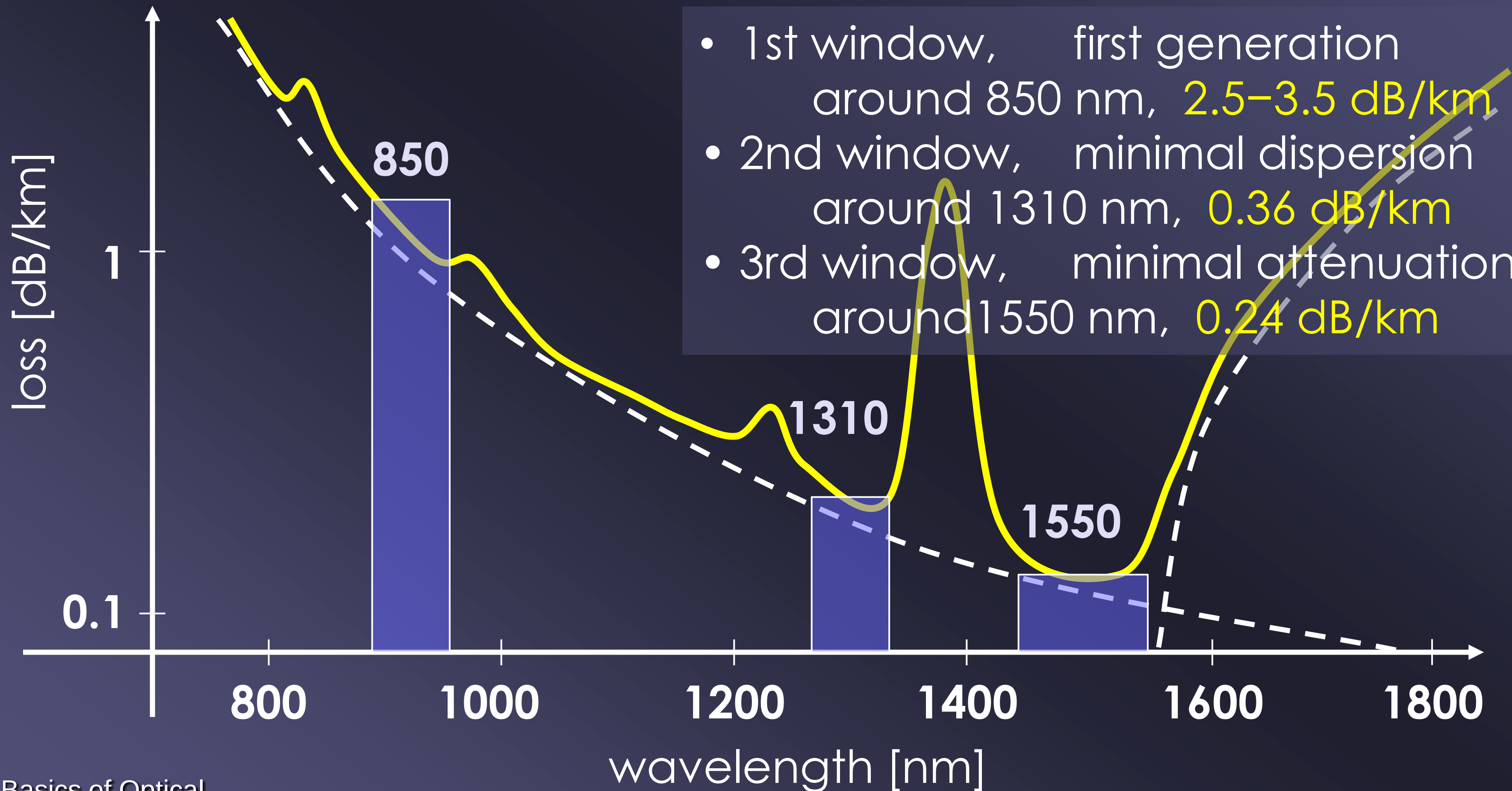
Properties of the fiber

Total attenuation of silica – attenuation peaks



Properties of the fiber

Total attenuation of silica – optical windows



- 1st window, first generation around 850 nm, 2.5–3.5 dB/km
- 2nd window, minimal dispersion around 1310 nm, 0.36 dB/km
- 3rd window, minimal attenuation around 1550 nm, 0.24 dB/km

Properties of the fiber

Fiber dispersion

The spreading out of the light pulses as they propagate in the fiber. (ps/km)

- modal dispersion
- chromatic dispersion
  - material dispersion
  - waveguide dispersion
- polarization mode dispersion

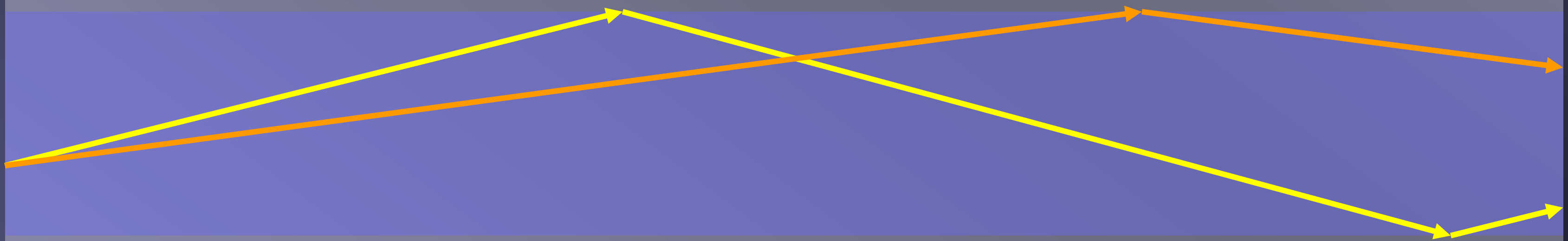
$$\Delta t_{chr} = \Delta t_{mat} + \Delta t_{wg}$$

$$\Delta t_{total} = \sqrt{\Delta t_{mod}^{2} + \Delta t_{chr}^{2} + \Delta t_{pol}^{2}}$$

Properties of the fiber

Modal dispersion

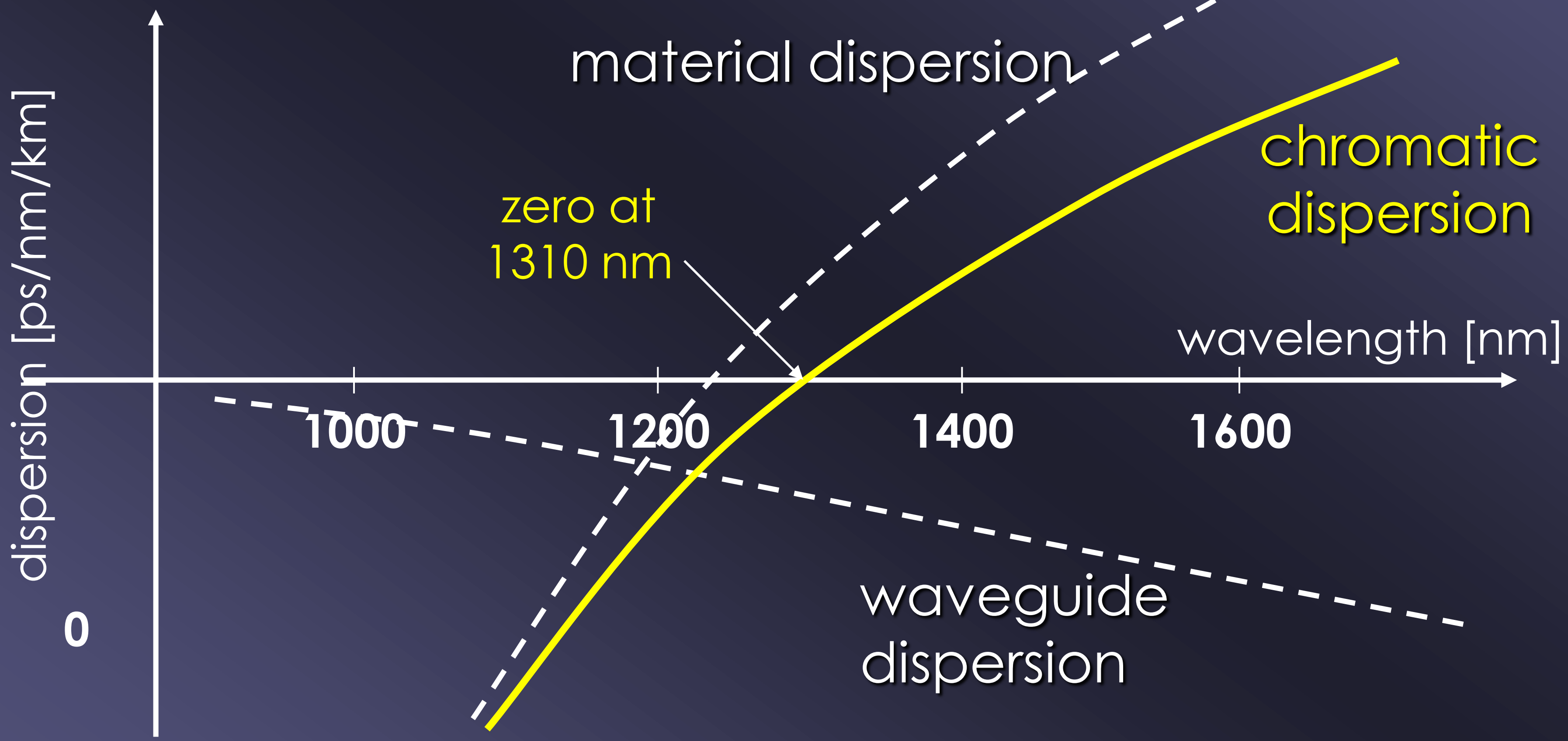
- multimode fibers
- different characteristic velocity for different propagating modes



the lenght of the way is different
(geometrical optics point of view)

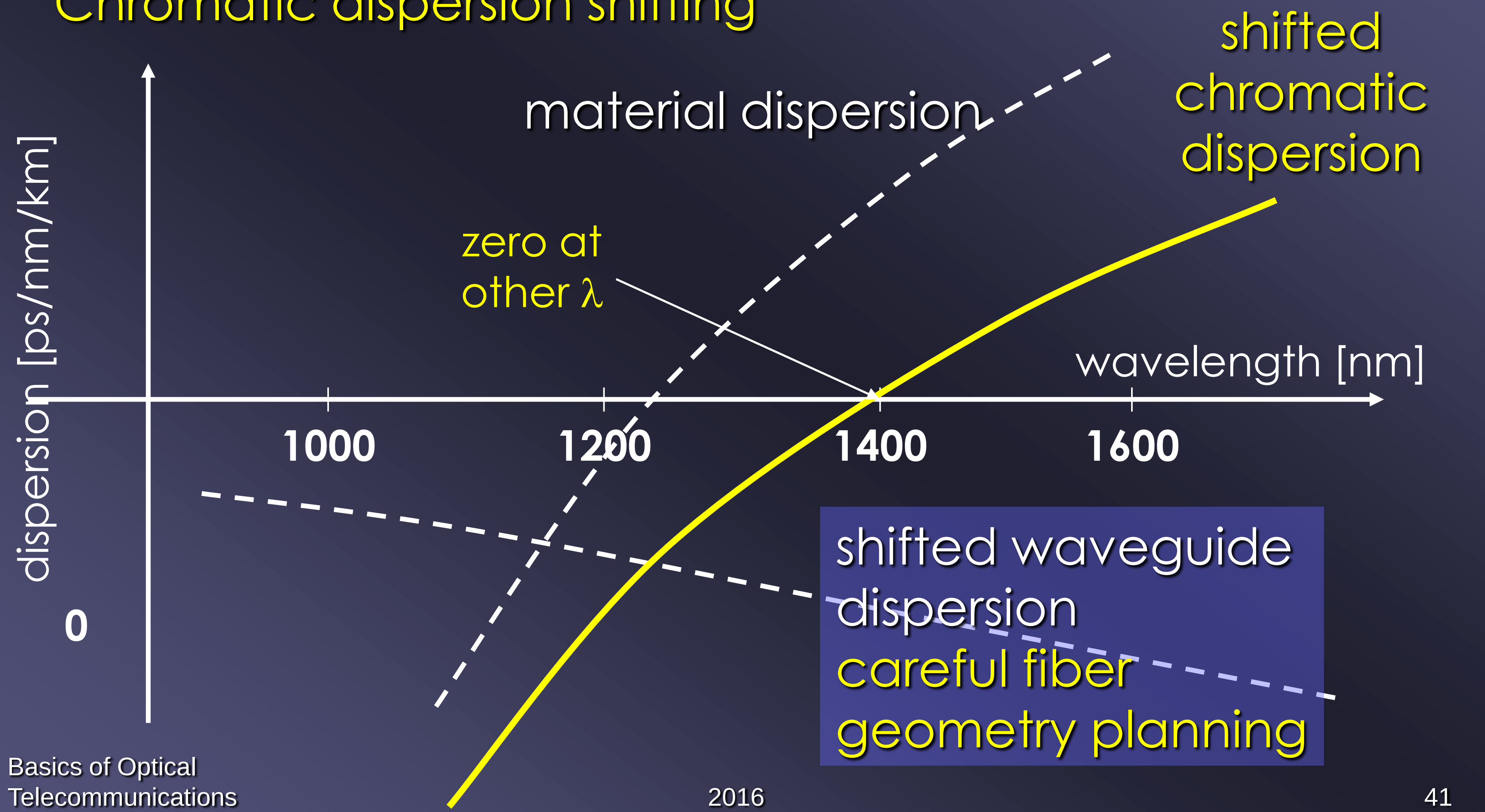
Properties of the fiber

Chromatic dispersion



Properties of the fiber

Chromatic dispersion shifting



Nonlinear effects

Nonlinear effects

- Brillouin scattering
- self-phase modulation
- cross-phase modulation
- four-wave mixing
- Raman scattering

Nonlinear effects in fibers

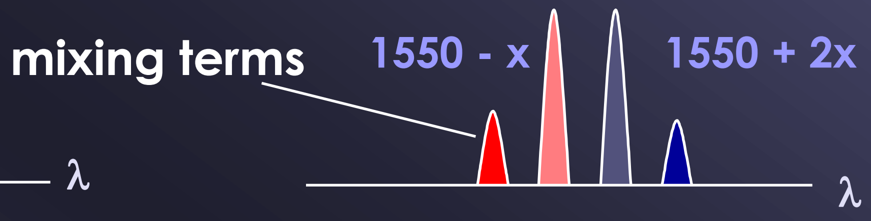
- Brillouin scattering:
  - acoustic vibrations caused by electro-magnetic field
    (e.g. the light itself, if *P*>3mW)
  - acoustic waves generate refractive index fluctuations
  - scattering on the refraction index waves
  - the frequency of the light is shifted slightly direction dependently (~11 GHz backw.)
  - longer pulses – stronger effect

Nonlinear effects in fibers

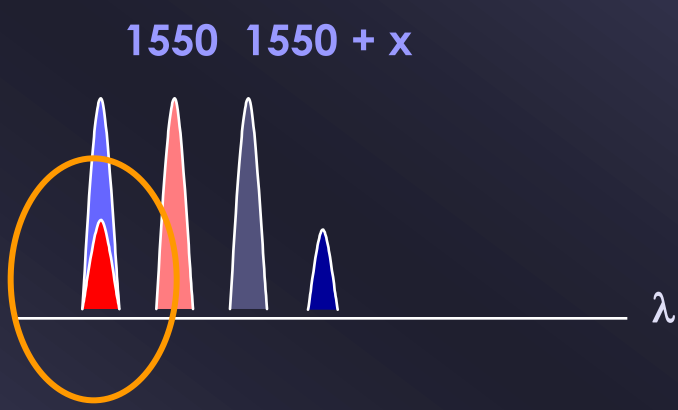
- Raman scattering:
  - optical phonons (vibrations) caused by electromagnetic field and the light can exchange energy (similar to Brillouin but not acoustical phonons)
- Stimulated Raman and Brillouin scattering can be used for amplification
- Self-phase and cross-phase modulation
- Four-wave mixing

Nonlinear effects in fibers

- Four-wave mixing



P_{crit}>10 mW



Nonlinear effects in fibers

- (Pockels effect:
  - refractive index change due to external electronic field
  - $\Delta n \sim |\mathbf{E}|$ - a linear effect)

Nonlinear effects in fibers

- Kerr effect:
  - the refractive index changes in response to an electromagnetic field
  - $\Delta n = K \lambda |\mathbf{E}|^2$
  - light modulators up to 10 GHz
  - can cause self-phase modulation, self-induced phase and frequency shift, self-focusing, mode locking
  - can produce solitons with the dispersion

Nonlinear effects in fibers

- Kerr effect:
  - the polarization vector

$$P_i = \varepsilon_0 \sum_{j=1}^{3} \chi_{ij}^{(1)} E_j + \varepsilon_0 \sum_{j=1}^{3} \sum_{k=1}^{3} \chi_{ijk}^{(2)} E_j E_k + \varepsilon_0 \sum_{j=1}^{3} \sum_{k=1}^{3} \sum_{\ell=1}^{3} \chi_{ijk\ell}^{(1)} E_j E_k E_\ell + \ldots$$

Pockels

Kerr

  - if $\mathbf{E}=\mathbf{E}_\omega \cos(\omega t)$, the polarization in first order is

$$\mathbf{P} \cong \varepsilon_0 \left(\chi^{(1)} + \chi^{(3)} \left| \mathbf{E}_\omega \right|^2 \right) \cdot \mathbf{E}_\omega \cos(\omega t)$$

Nonlinear effects in fibers

- Kerr effect:

$$\mathbf{P} \cong \varepsilon_0 \left(\chi^{(1)} + \chi^{(3)} \left|\mathbf{E}_\omega\right|^2\right) \cdot \mathbf{E}_\omega \cos(\omega t)$$

  - the susceptibility

$$\chi = \chi^{(1)} + \frac{3}{4} \chi^{(3)} \left|\mathbf{E}_\omega\right|^2$$

  - the refractive index

$$n = n_0 + \frac{3}{8n_0} \chi^{(3)} \left|\mathbf{E}_\omega\right|^2 = n_0 + n_2 I$$

  - n_2 is mostly small, large intensity is needed (silica: $n_2 \approx 10^{-20}$ m^2/W, $I \approx 10^9$ W/cm^2)

Nonlinear effects in fibers

- Gordon-Haus jitter:
  - a timing jitter originating from fluctuations of the center frequency of the (soliton) pulse
  - noise in fiber optic links caused by periodically spaced amplifiers
  - the amplifiers introduce quantum noise, this shifts the center frequency of the pulse
  - the behavior of the center frequency modeled as random walk

Nonlinear effects in fibers

- Gordon-Haus jitter:
  - dominant in long-haul data transmission
  - $\sim L^3$,
  - can be suppressed by
    - regularly applied optical filters
    - amplifiers with limited gain bandwidth
  - can also take place in mode-locked lasers

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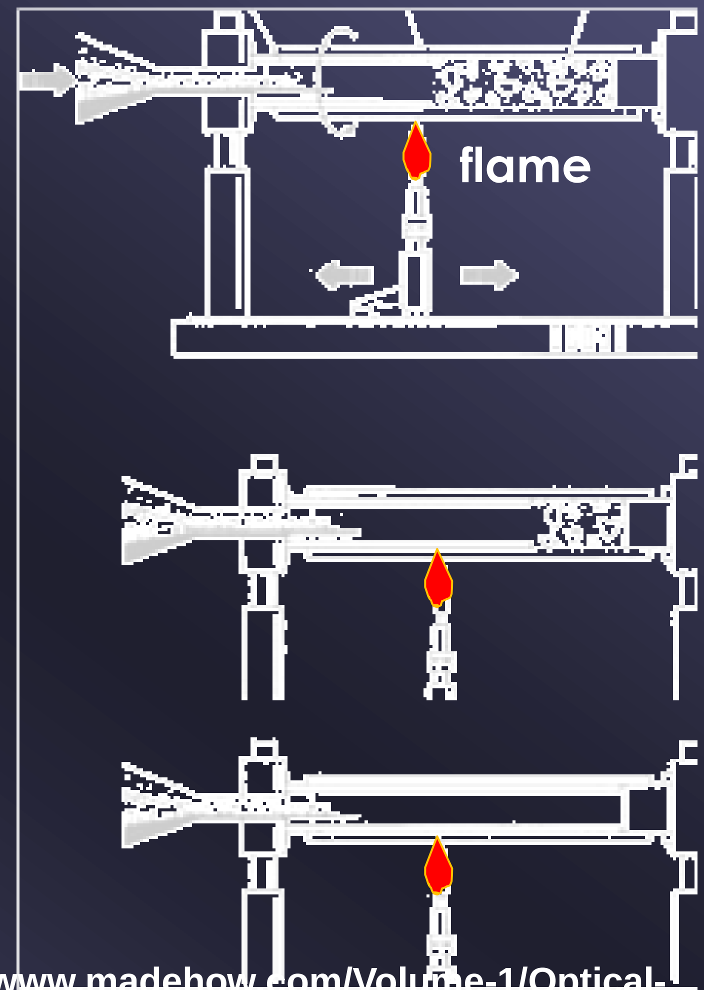
Fabrication of fibers

- Vapor deposition, ususally starting from the cladding
  - cleaning
  - burning $SiCl_4$ + dopants in oxigen inside the cladding
  - preform collapsing – slow heating of the cladding and the glassy soot ⟶ they melt together and collapse into solid rod

see: https://www.youtube.com/watch?v=uSnjo5tOGQA



http://www.madehow.com/Volume-1/Optical-Fiber.html

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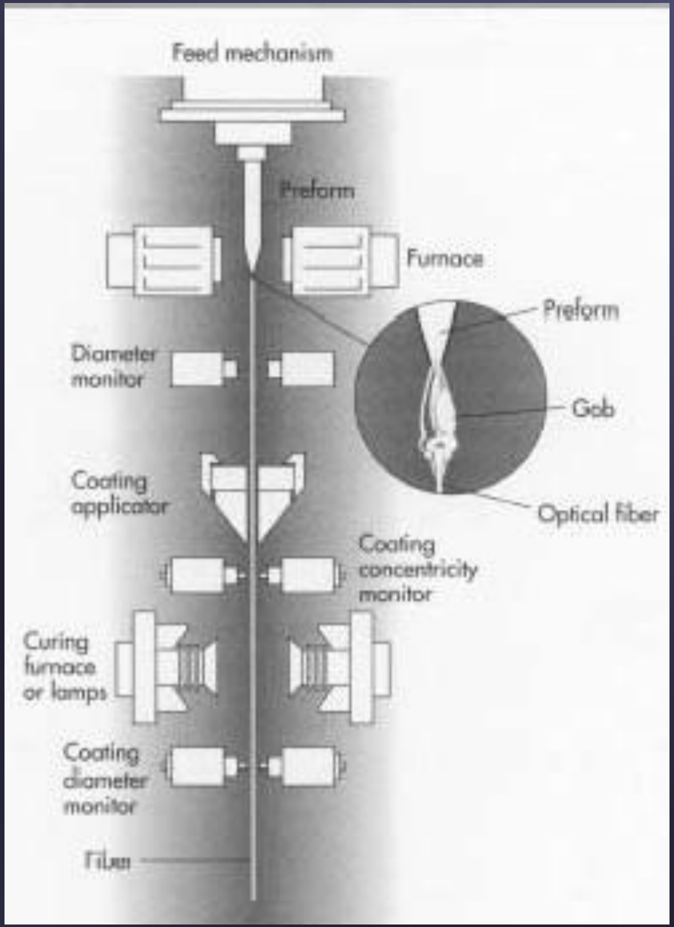
Fabrication of fibers

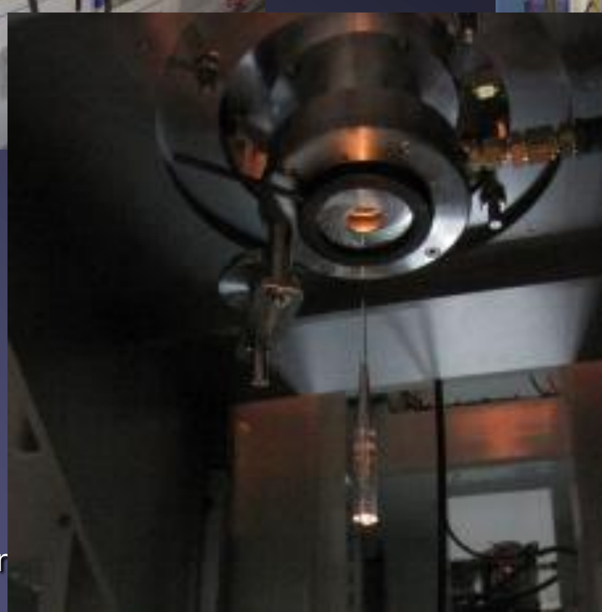
- Fiber pulling from preform
  - quartz furnace at the top of the pulling tower
  - forming of a droplet
  - droplet pulls the fiber
  - after achieving the sufficient diameter/length the gob is cut
  - reel pulls the fiber

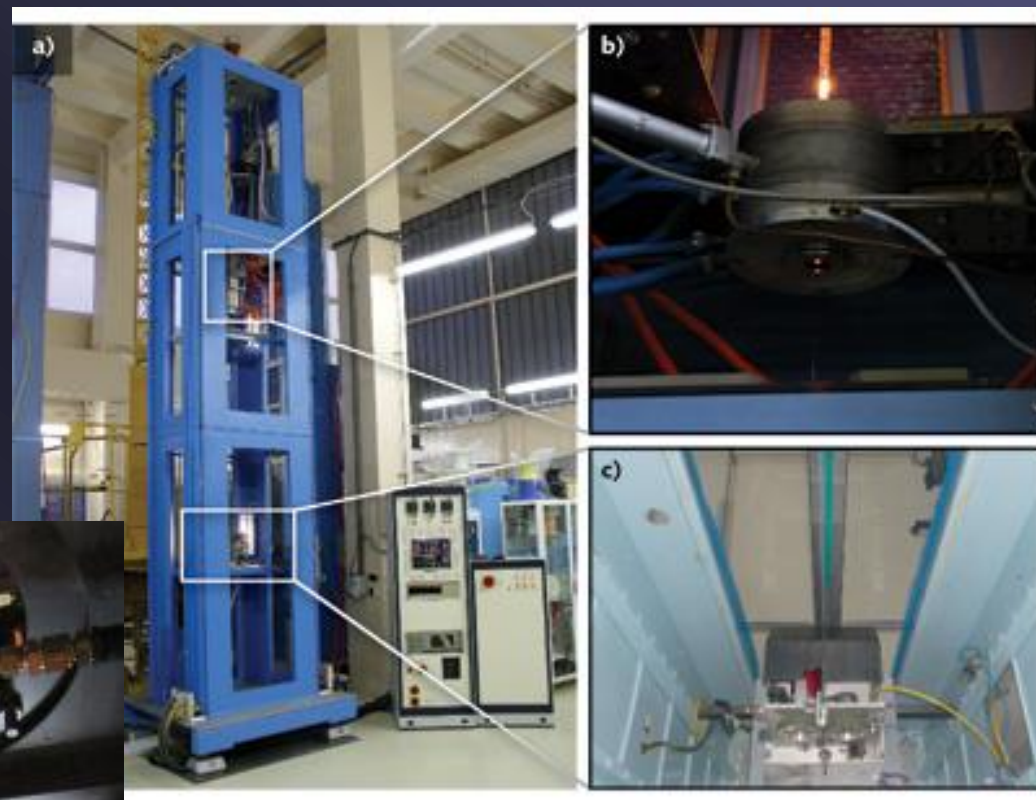


http://www.madehow.com/Volume-1/Optical-Fiber.html

Fabrication of fibers

http://www.orc.soton.ac.uk/silicafibrefacilities.html

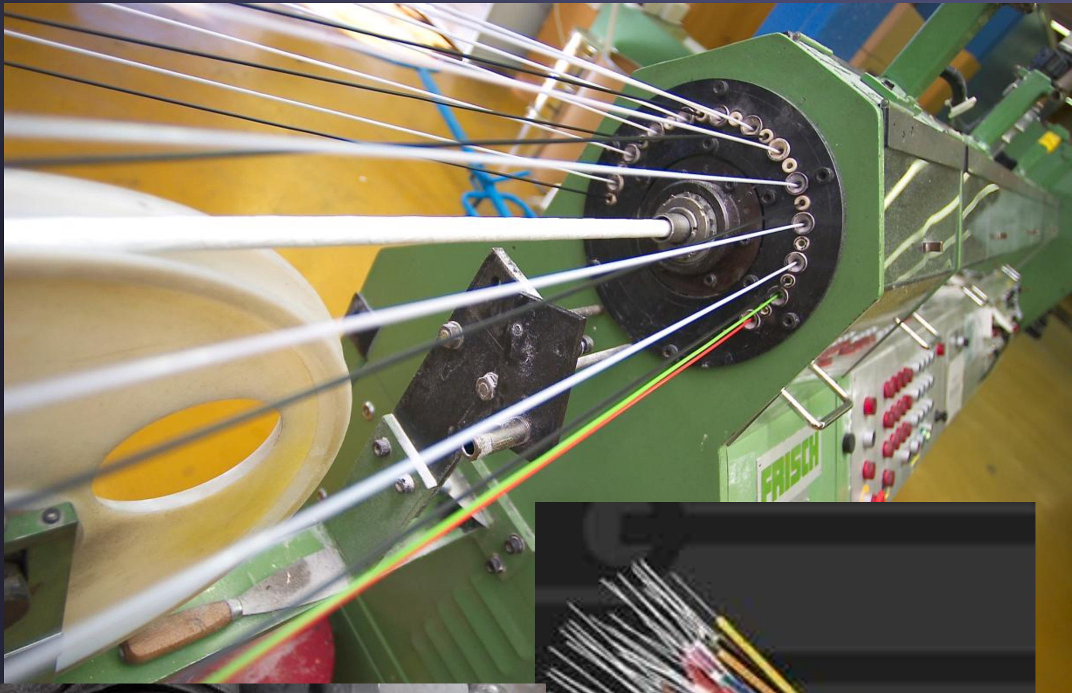


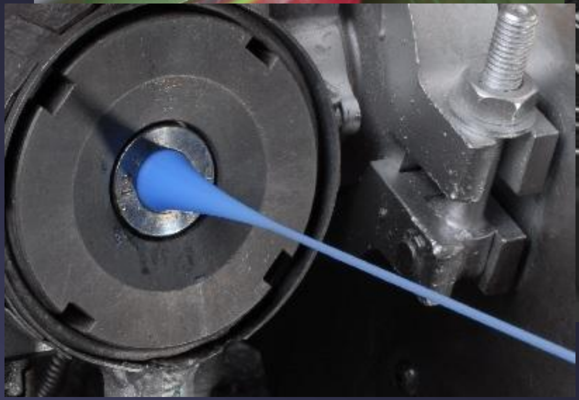


http://www.laserfocusworld.com/articles/print/volume-49/issue-12/features/optical-fiber-manufacturing-stack-and-draw-technique-creates-ultrasmall-diameter-endoscopes.html

Cable production

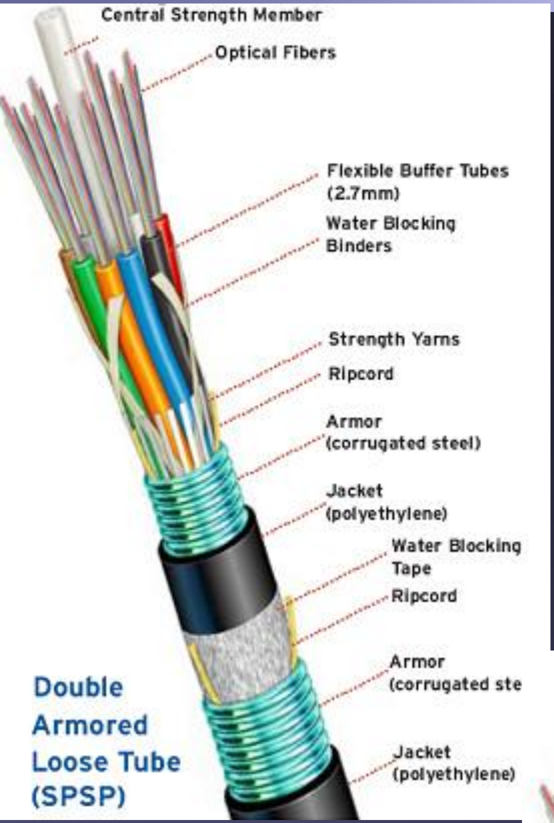
- From reels of fiber with primary coating
- SZ twist
- sheath extrusion
- various fillings
- various protective layers: armors, jackets, sheaths
- various strength members
- ribbon or cylindrical





www.indbolanews.com, www.spiktelintl.com, www.cables-cgp.com

Cable production



www.conductix.com, http://surplus-fiber.com/new-draka-fiber-cable/, www.hydro-cable-systems.com

Cable types

- Indoor
  - Patch, Switch, Pigtail
  - FTTH loose cables
- Outdoor
    - loose or tight
    - ribbon or cylindrical
  - air
    - self sustaining or not
  - undreground, or underwater
    - armored or not

Connectors

- PC or APC
- ferrule
- cylindrical or rectangular housing

Outline – Lasers

- Operation of lasers
    - Properties
    - applications
- Atomic energy levels
- Population inversion
- Energy bands in solid states
- Heterojunctions in semiconductors
- Quantum well lasers
- Vertical cavity surface emitting lasers

Properties of lasers

- Monochromatic light – small bandwidth
- Small divergence – narrow and directed beam
- Coherent beam – all photons have nearly the same phase

- Usually not too high power, but
- High power density
- Not an effective energy transformer

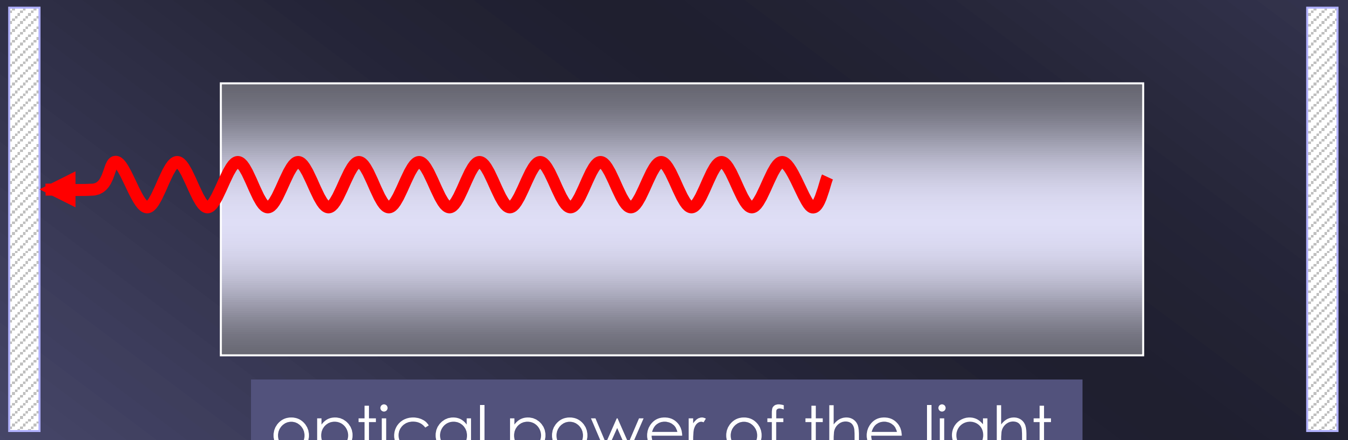
Application of the lasers

- Materials processing – cutting, drilling, welding, heat treating, …
- Reading optical signs – CD, barcode, …
- Graphics – printers, color separators, printing plate makers, …
- Laboratory, measurements
- Medicine – bloodless scalpel, tumor destroying, …
- Military – target designators, finders, …
- Telecommunications

Operation of lasers

What is needed for laser operation

- Laser gain – an optical amplifier
- Optical resonator – positive feedback



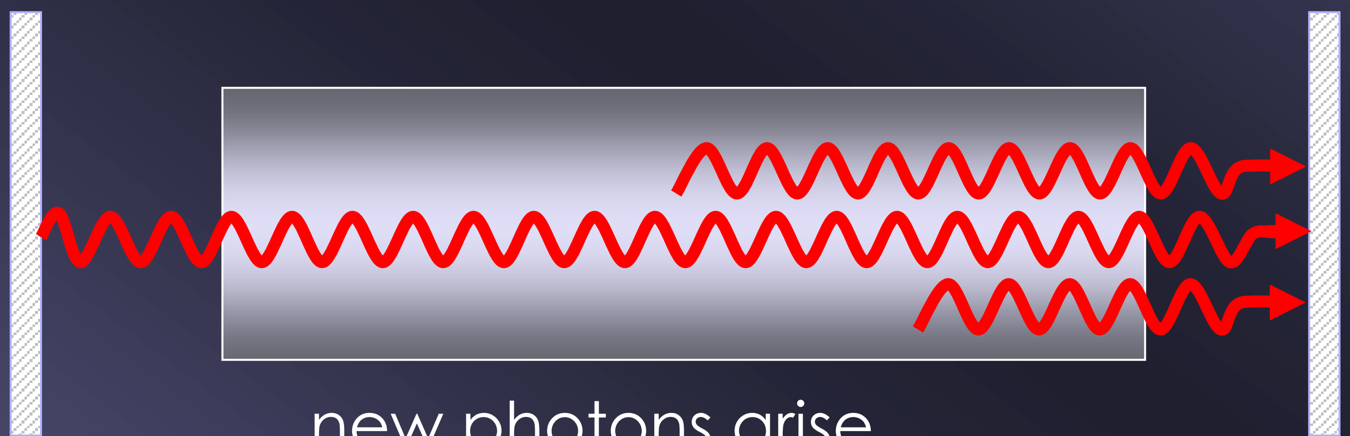
reflection

optical power of the light
before reflection: $\mathcal{P}$
after reflection: $(1-\tau_1)\mathcal{P}$

Operation of lasers

What is needed for laser operation

- Laser gain – an optical amplifier
- Optical resonator – positive feedback



new photons arise

reflection

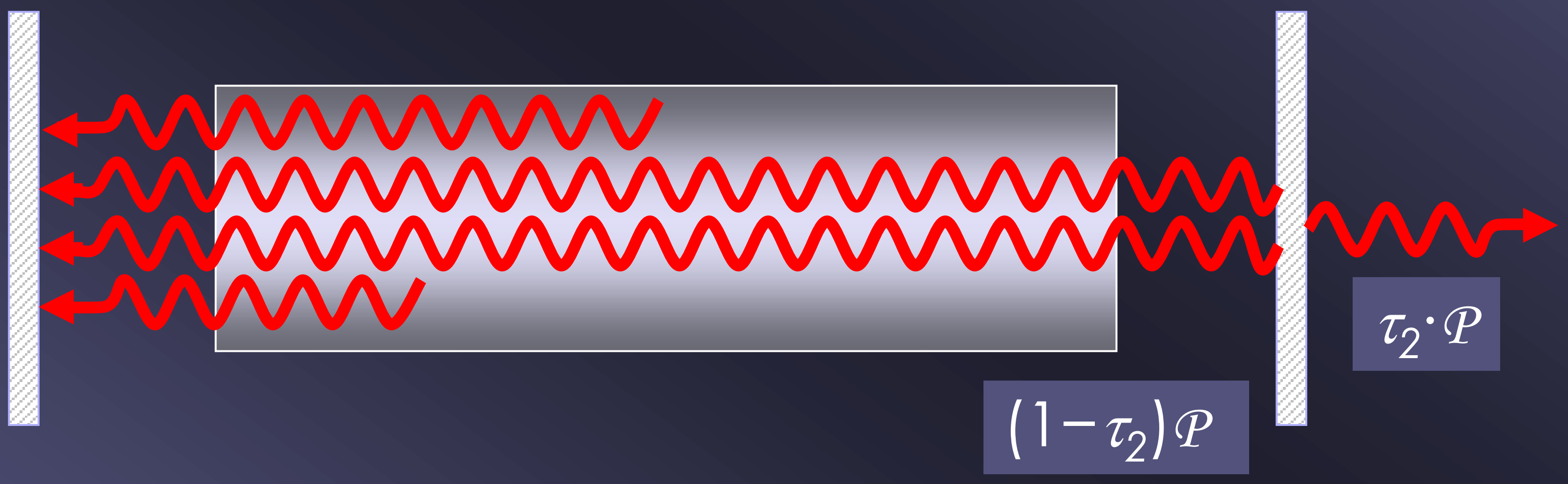
optical gain in the amplifier:

$$\mathcal{P} \longrightarrow g\cdot\ell\cdot\mathcal{P}$$

Operation of lasers

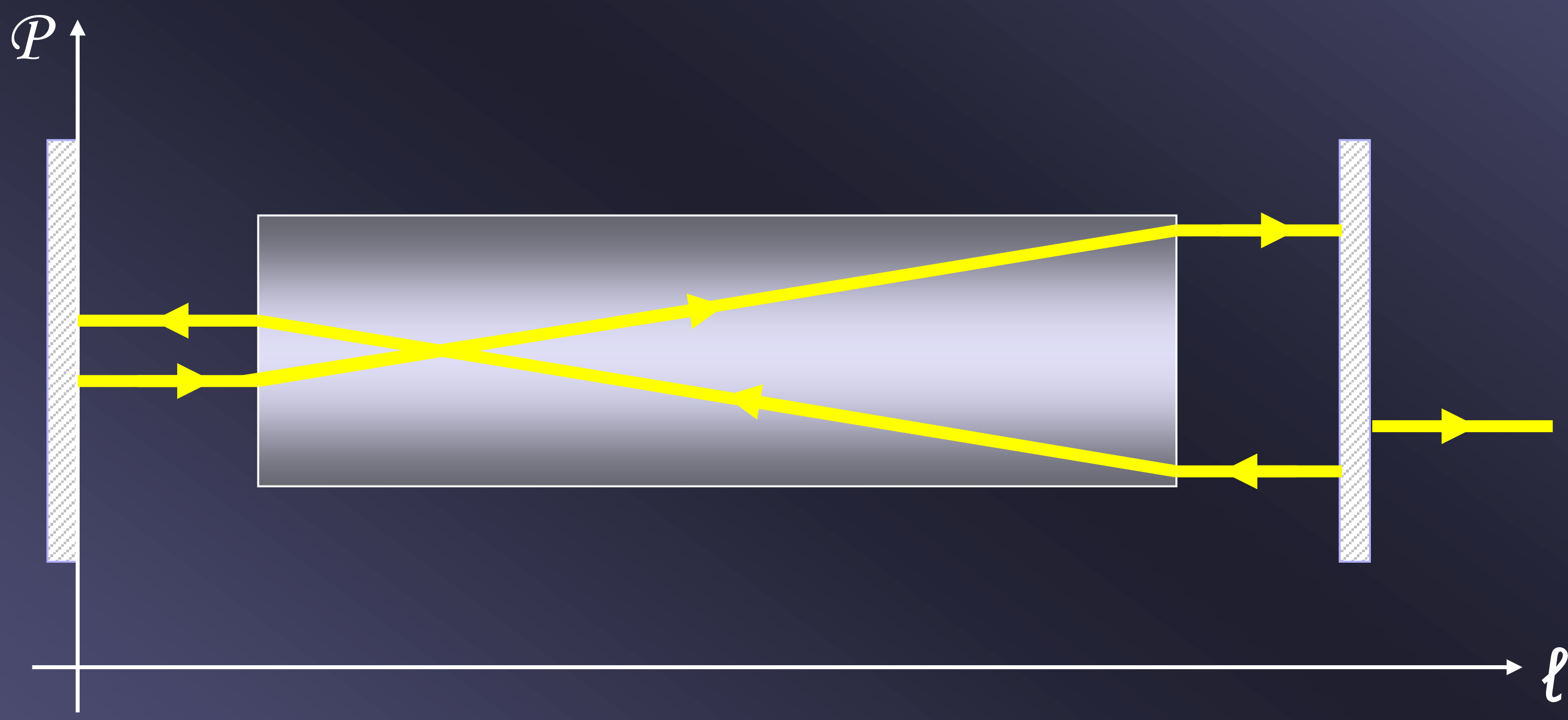
What is needed for laser operation

- Laser gain – an optical amplifier
- Optical resonator – positive feedback



Operation of lasers

In equilibrium the gain and the losses have to be the same: the power of the light varies as

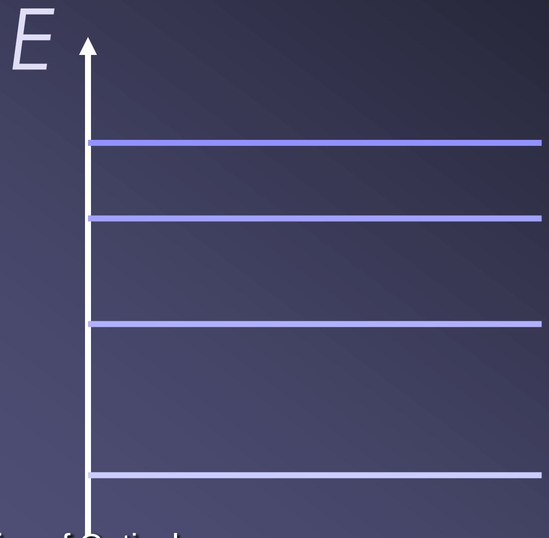


Atomic energy levels

The solution of the Schrödinger equation

$$\hat{H}\Psi = E\Psi$$

results in - quantized eigenenergies
- corresponding wave functions



⋮

2^{nd} excited state

1^{st} excited state

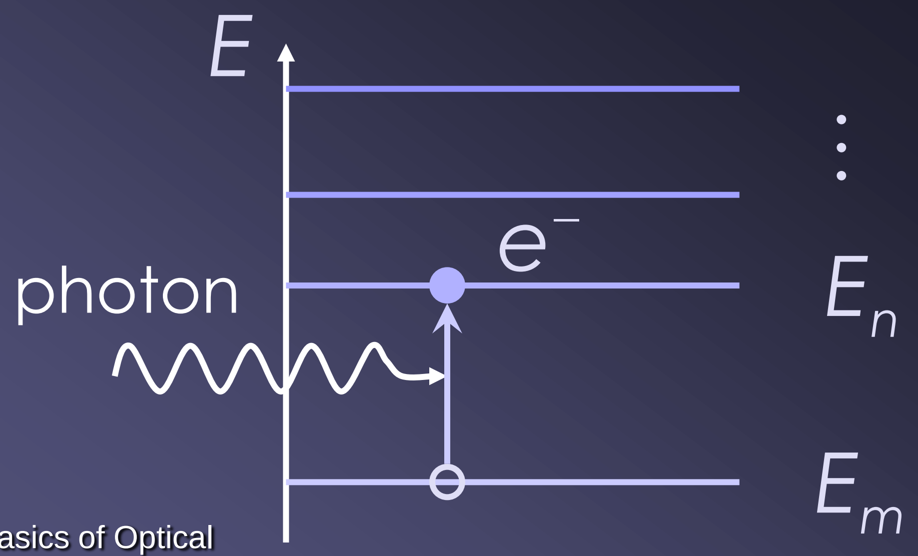
ground state

Atomic energy levels

If a photon of energy

$$h\nu = E_n - E_m$$

interacts with an atom, an electron can be excited from energy level E_m to level E_n



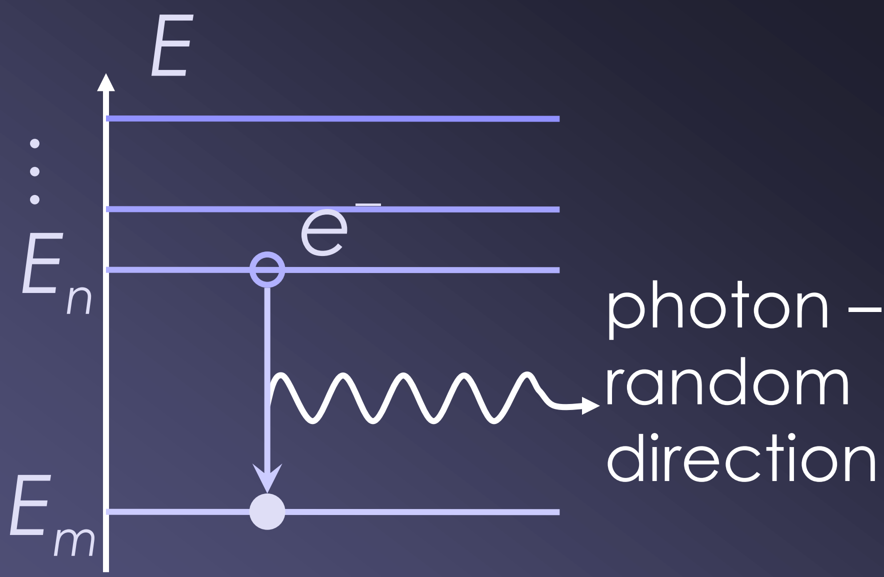
photon absorption – relative rate:

$$r_{mn} = B_{mn} \cdot f_m (1 - f_n) \cdot \rho(h\nu)$$

Atomic energy levels

An excited electron from energy level E_m can relax to a lower from energy level E_n, releasing a photon of energy

$$h\nu = E_n - E_m$$



spontaneous emission – relative rate:

$$r_{nm} = A_{nm} \cdot f_n (1 - f_m)$$

spontaneous lifetime

Atomic energy levels

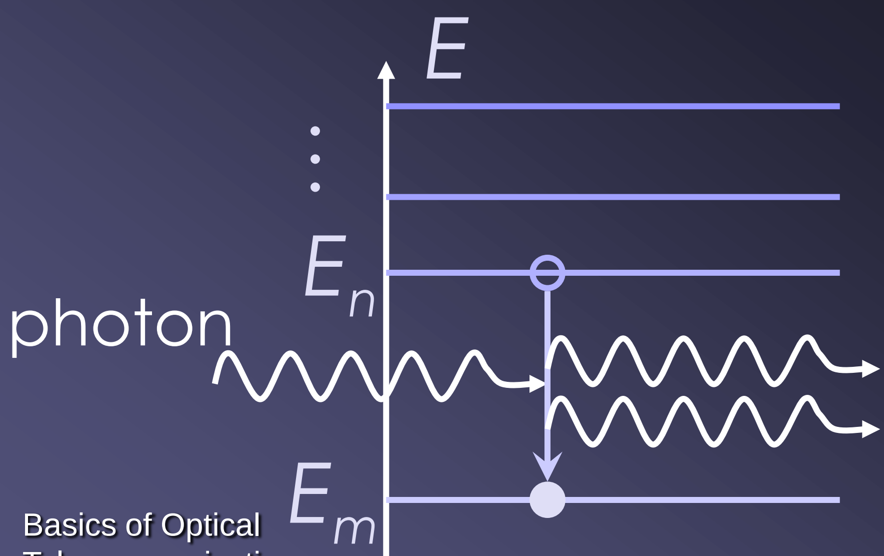
If a photon corresponding to the energy

$$h\nu = E_n - E_m$$

interacts with an atom which has an excited electron at energy level E_n, it can stimulate the electron to relax to level E_n

stimulated emission

$$r_{mn}^{stim} = B_{mn} f_m \left(1 - f_n\right) \rho\left(h\nu\right)$$



2 photons – same direction, same phase

Atomic energy levels

Stimulated emission can take place long before the spontaneous lifetime.

Stimulated emission:

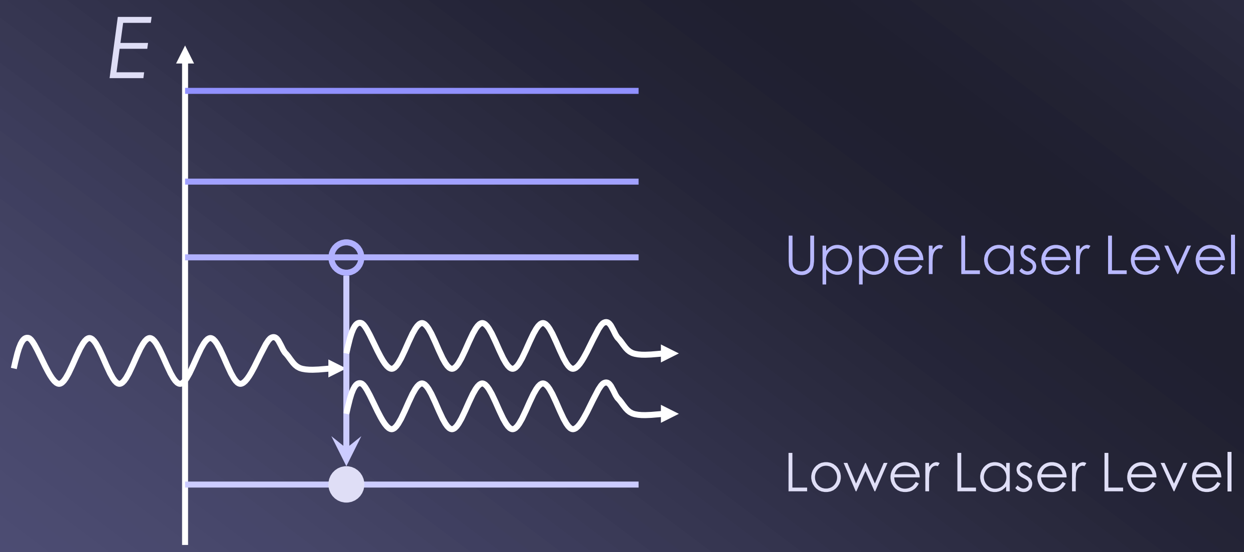
one photon in ⟶ two photons out

The optical amplifier can be a collection of atoms with lots of electrons excited to the same state (with long spontaneous lifetime).

Atomic energy levels

Light Amplification by Stimulated Emission of Radiation

The resonator is usually much longer than the wavelength.



Atomic energy levels

In equilibrium, the relative rates

$$r_{mn} = r_{nm} + r_{nm}^{\text{stim}}$$

Thus the photon density at energy $h\nu$

$$\rho(h\nu) = \frac{A_{nm}}{B_{mn}\dfrac{f_m(1-f_n)}{f_n(1-f_m)} - B_{nm}}$$

relative occupation probability

Population inversion

In thermodynamical equilibrium, the population of the states follow Boltzmann's law

$$N_i = N_0 \cdot e^{-\frac{E_i}{k_B T}}$$

⟶ the relative occupation probability is

$$\exp\left(\frac{E_n - E_m}{k_B T}\right)$$

thus

$$\rho(h\nu) = \frac{A_{nm}}{B_{mn} \cdot \exp\frac{E_n - E_m}{k_B T} - B_{nm}}$$

Population inversion

Comparing the resulting photon density with the black body radiation

$$\rho(h\nu) = \frac{4h\nu^3}{c^2 \cdot \left(\exp\frac{h\nu}{k_B T} - 1 \right)}$$

$$\rho(h\nu) = \frac{A_{nm}}{B_{mn} \cdot \exp\frac{E_n - E_m}{k_B T} - B_{nm}}$$

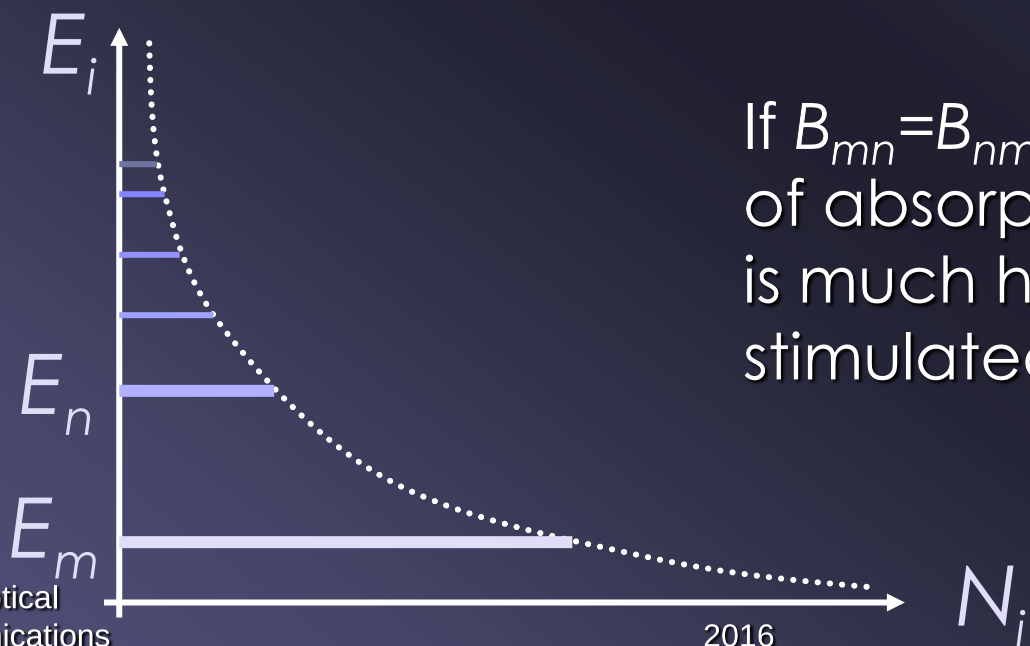
$$B_{mn} = B_{nm}$$

$$\frac{A_{nm}}{B_{nm}} = \frac{4h\nu^3}{c^2}$$

Population inversion

In thermodynamical equilibrium, the population of the states follow Boltzmann's law

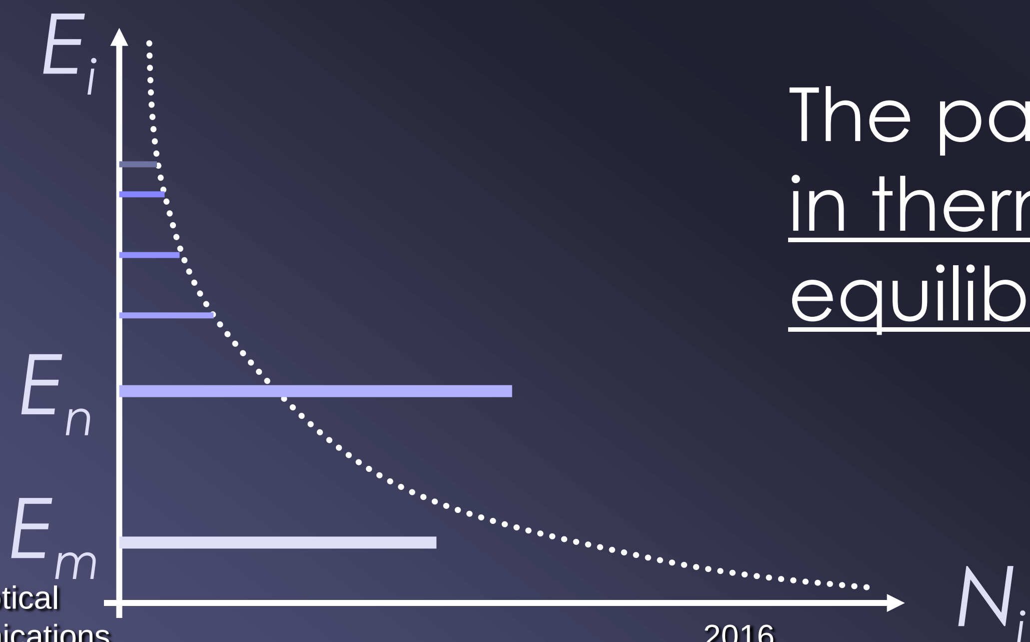
$$N_i = N_0 \cdot e^{-\frac{E_i}{k_B T}}$$



If $B_{mn}=B_{nm}$, the relative rate of absorption in equilibrium is much higher than that of stimulated emission

Population inversion

Somehow the number of electrons in the upper laser level is increased → population inversion occurs.

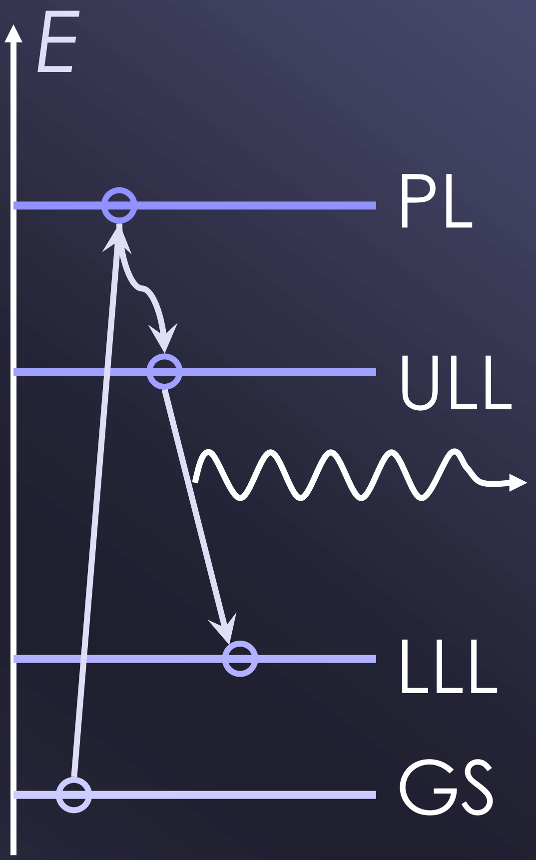


The particles are not in thermodynamical equilibrium

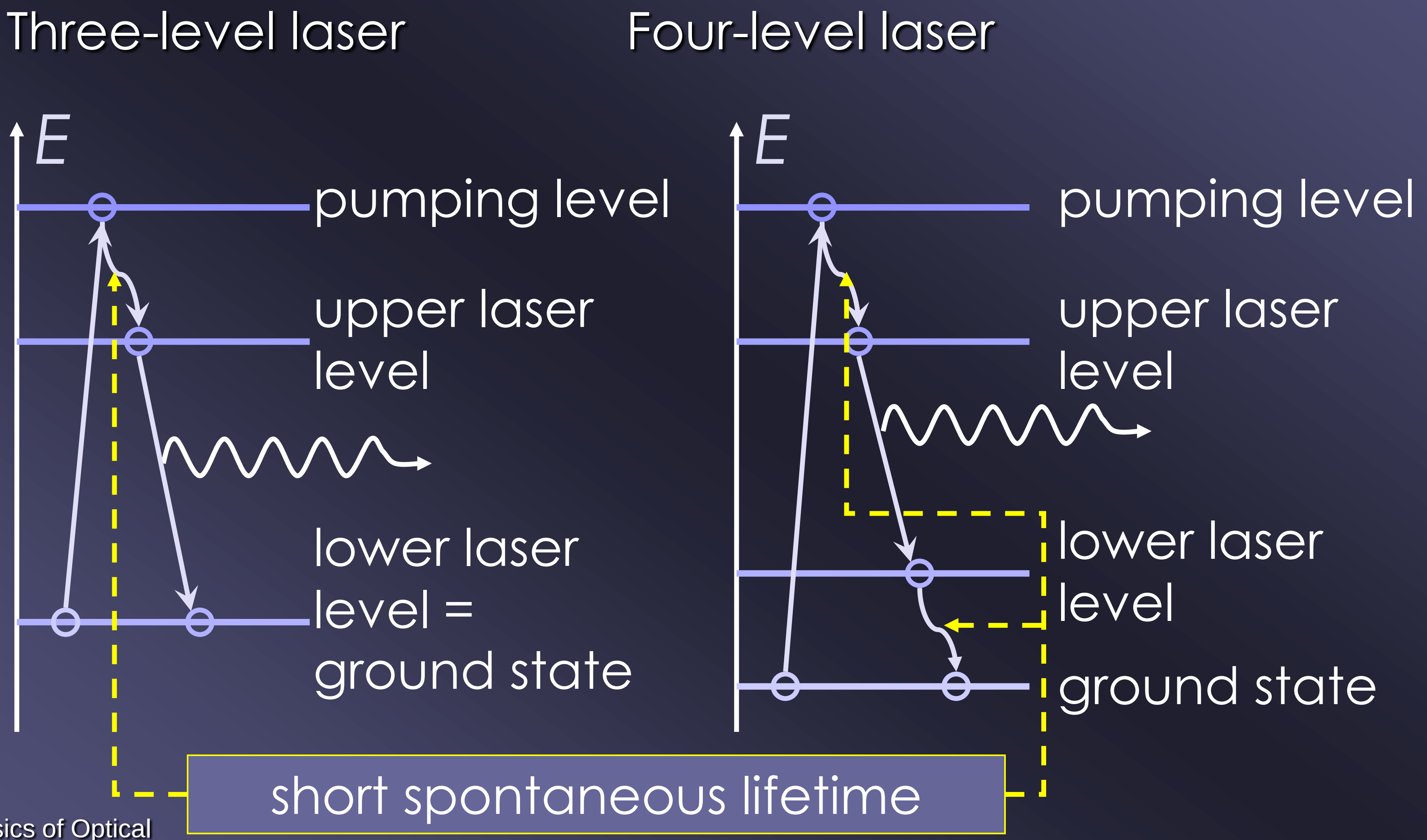
Population inversion

Population inversion is generated by

- exciting the electrons to a level with short spontaneous lifetime above the upper laser level: pumping
- from the pumping level the electrons relax to the upper laser level, which has longer spontaneous lifetime
- electrons accumulate at the upper laser level



Population inversion



Population inversion

Inverse population can be generated by

- special filters
- electrical pumping
  - direct electrical discharge
  - radio frequency field
  - electron beam
  - p-n heterostructure
- optical pumping
- chemical pumping
- nuclear pumping

Energy bands in solid states

In solids the atomic niveaus broaden → energy bands are formed

- vibrations (and rotations) in the crystal
- momentum dependence of energy levels
- splitting of degenerate states, …

⋮

conduction band

bandgap – no electrons are allowed

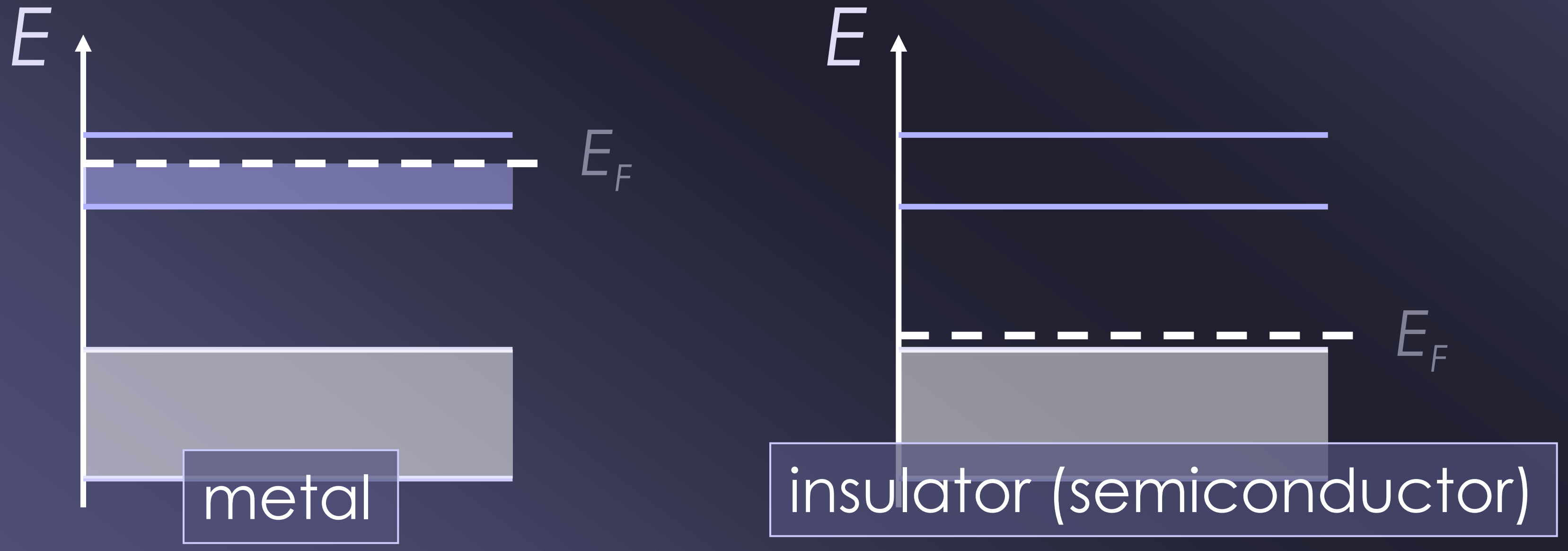
valance band

⋮

Energy bands in solid states

The Fermi level is the highest energy level occupied by electrons:

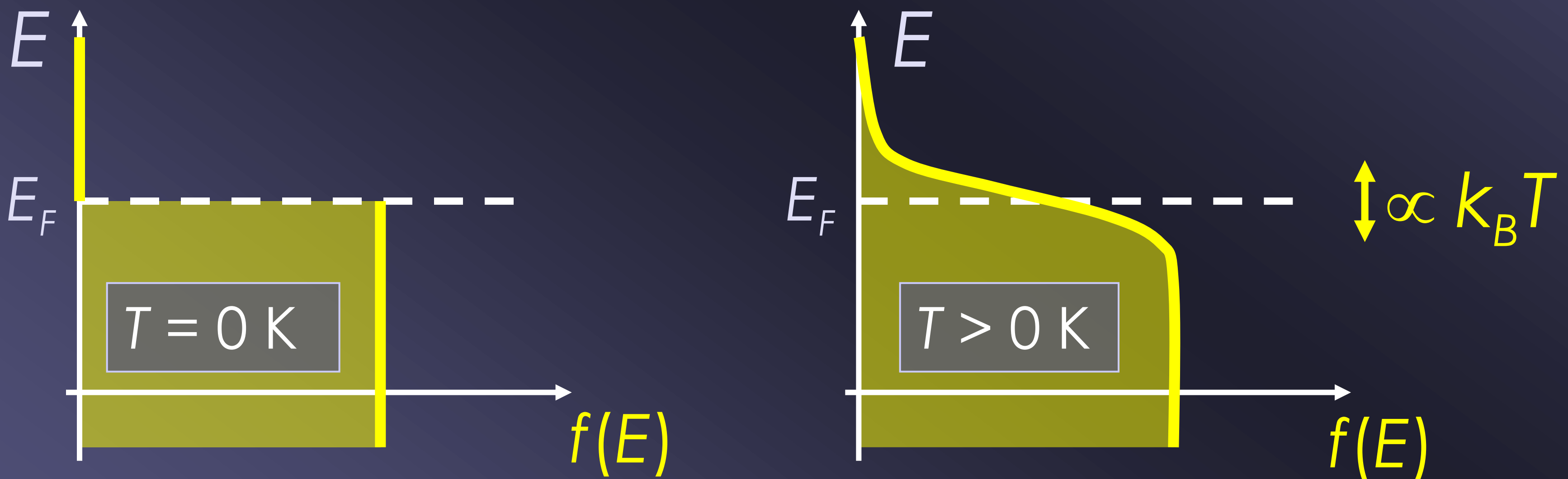
- Fermi level in the conduction band ⟶ metal
- Fermi level in the gap ⟶ insulator



Energy bands in solid states

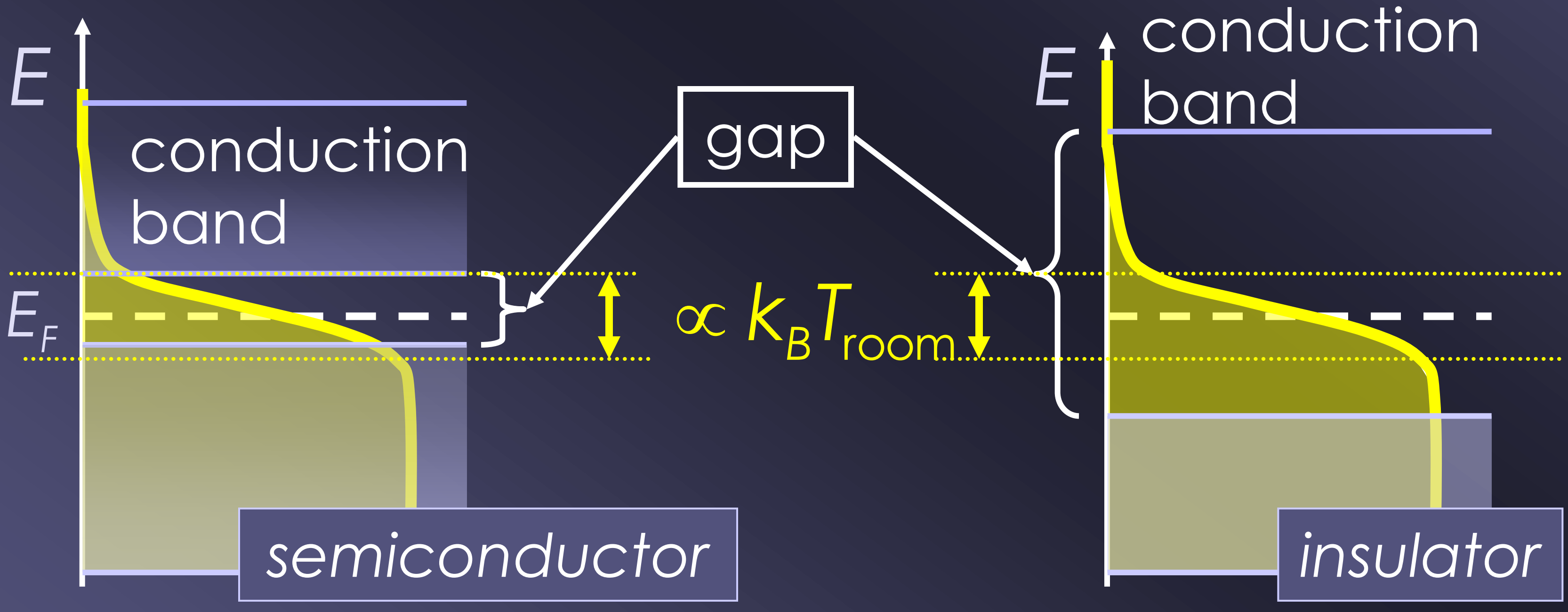
- At non-zero temperature, the Fermi level is not strict, the occupation probability will follow Fermi-Dirac statistics

$$f(E) = \frac{1}{1 + \exp\frac{E - E_f}{k_B T}}$$



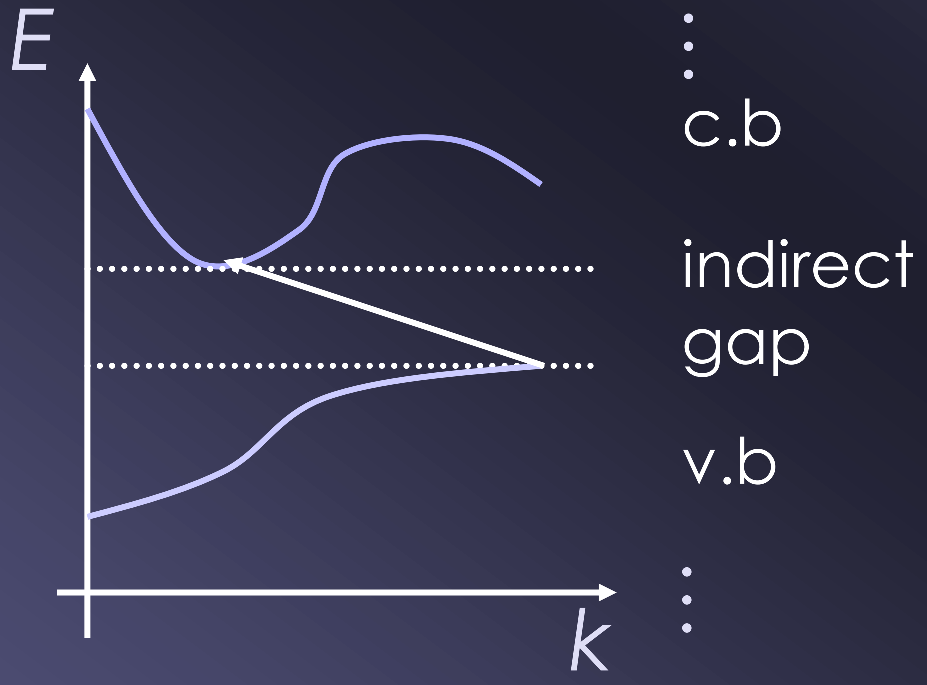
Energy bands in solid states

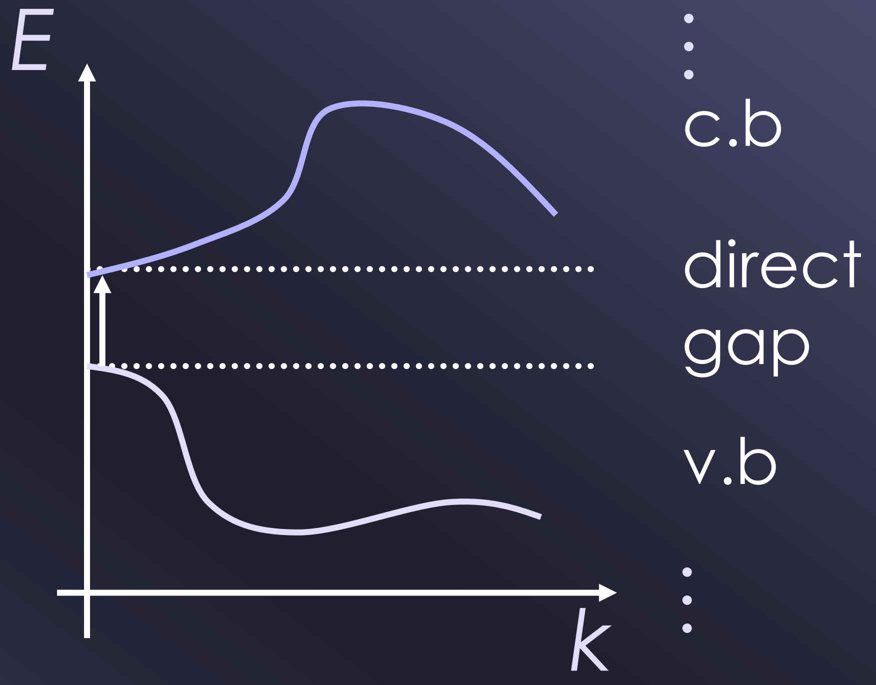
So if an insulator has a bandgap $\propto k_B T_{room}$, considerable amount of electrons can be present in the conduction band:



Energy bands in solid states

In a crystal the energy levels depend on the electron’s wave number *k* (quasi momentum):





momentum conservation → no photon emission

no momentum to be taken → photon emission

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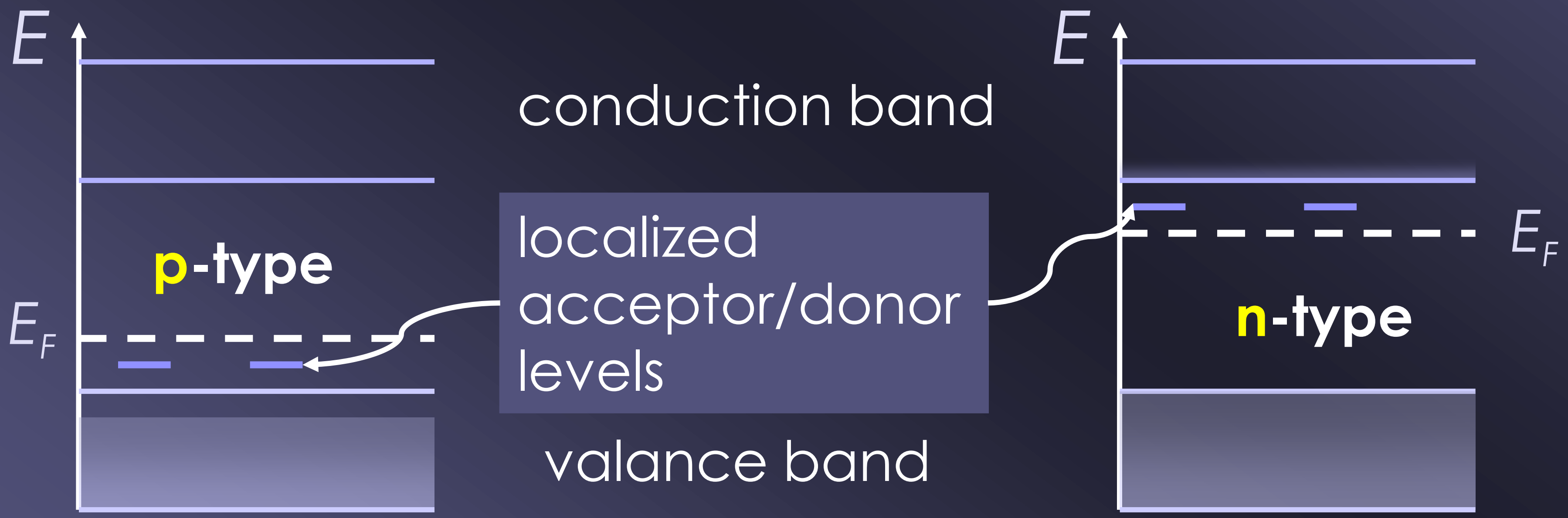
Heterojunctions in semiconductors

Charge carriers can be injected to semiconductors by doping:

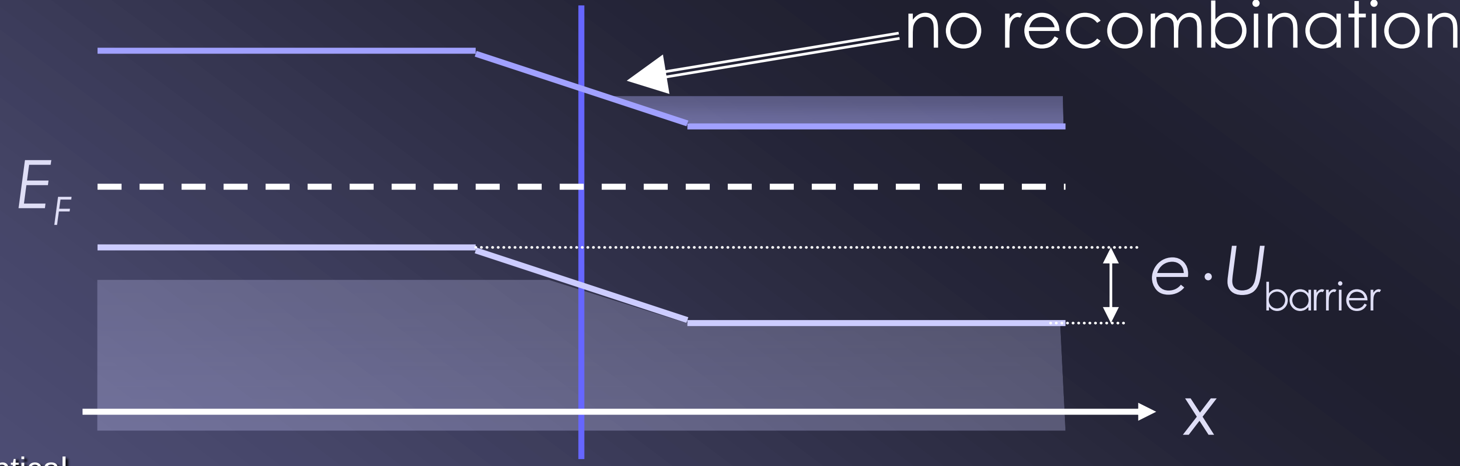
- group V atoms: electrons n-type
- group III atoms: holes p-type



Heterojunctions in semiconductors

If n-type and p-type doped semiconductor layers are brought in contact,

- the positive and negative charge carriers near the junction can recombine
- photons can be emitted
- potential barrier builds

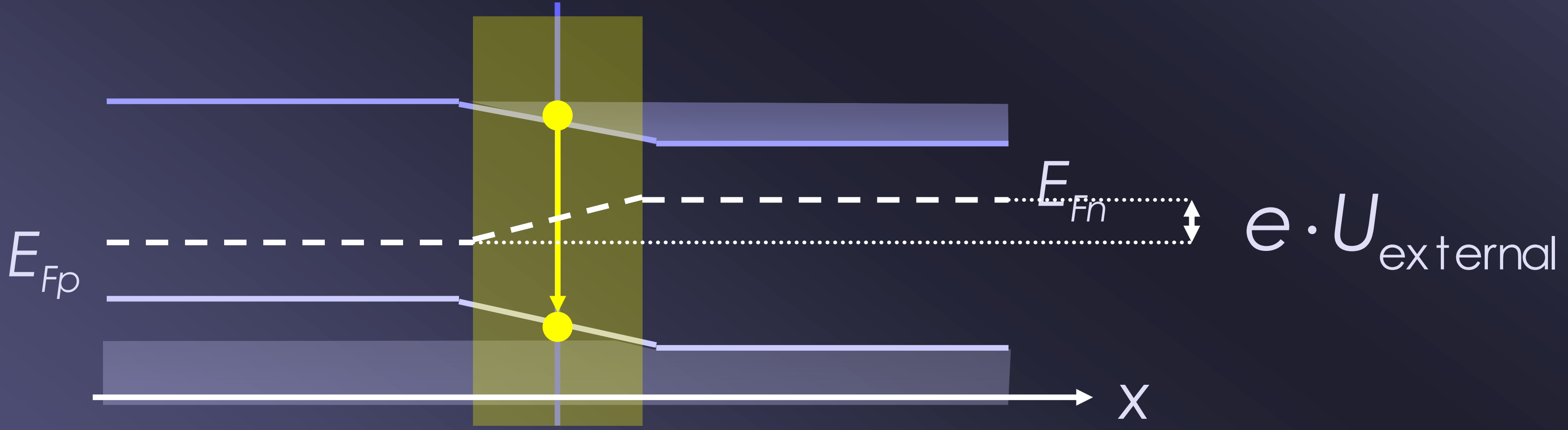


Heterojunctions in semiconductors

If n-type and p-type doped semiconductor layers are brought in contact,

- the recombination stops, unless external bias is applied ⟶ LEDs

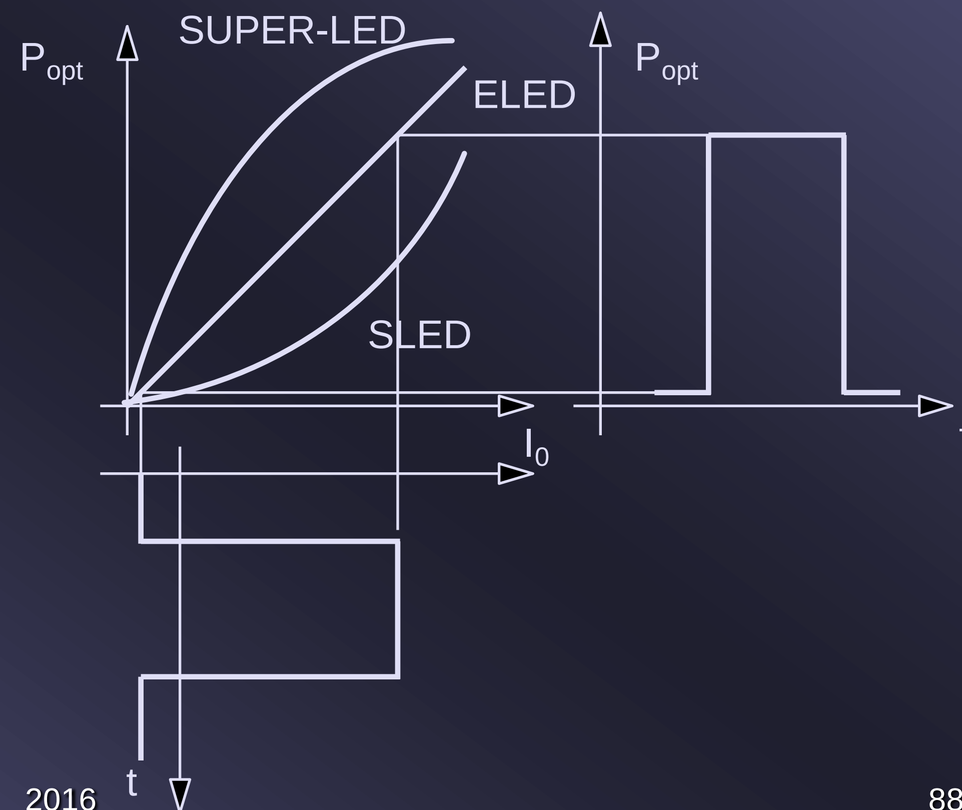
recombination possible
active region



Heterojunctions in semiconductors

If n-type and p-type doped semiconductor layers are brought in contact,

- the recombination stops, unless external bias is applied
  LEDs
- 1 ns –100 ns



Heterojunctions in semiconductors

The simple heterojunctions have some disadvantages

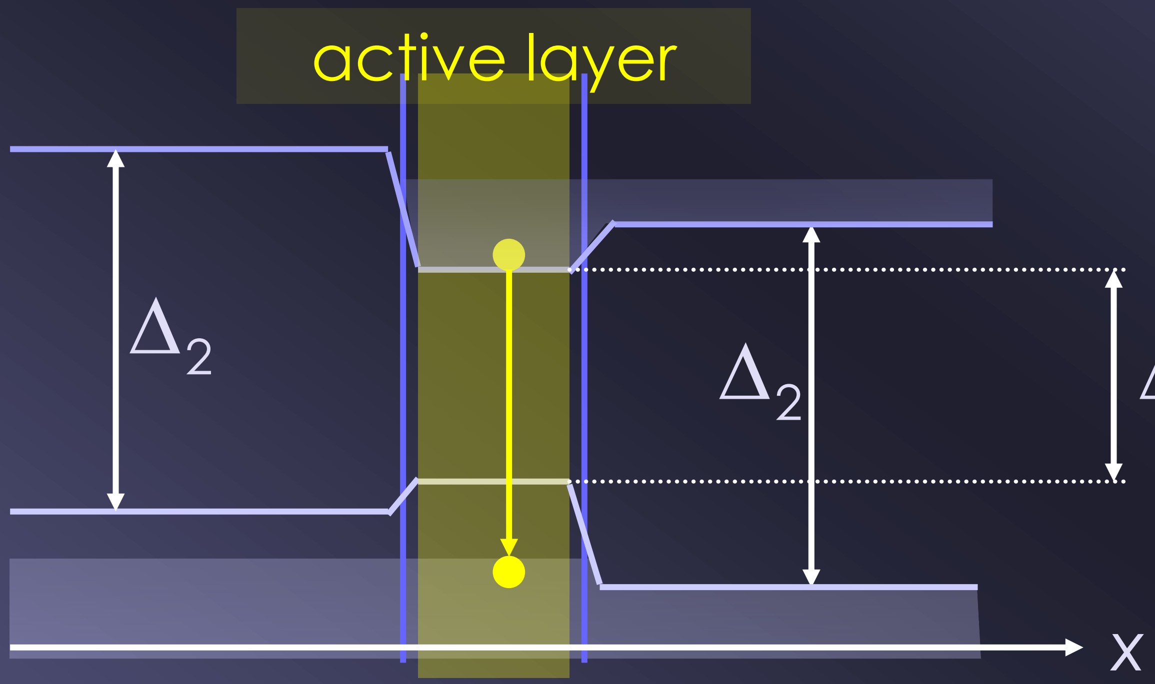
- due to the relative large spatial dimension, high current is needed for creating sufficient population inversion
- the heat generated by the current is very high, destroys the device

Solution:

restrict the high current density region into small region ⟶ double heterojunction

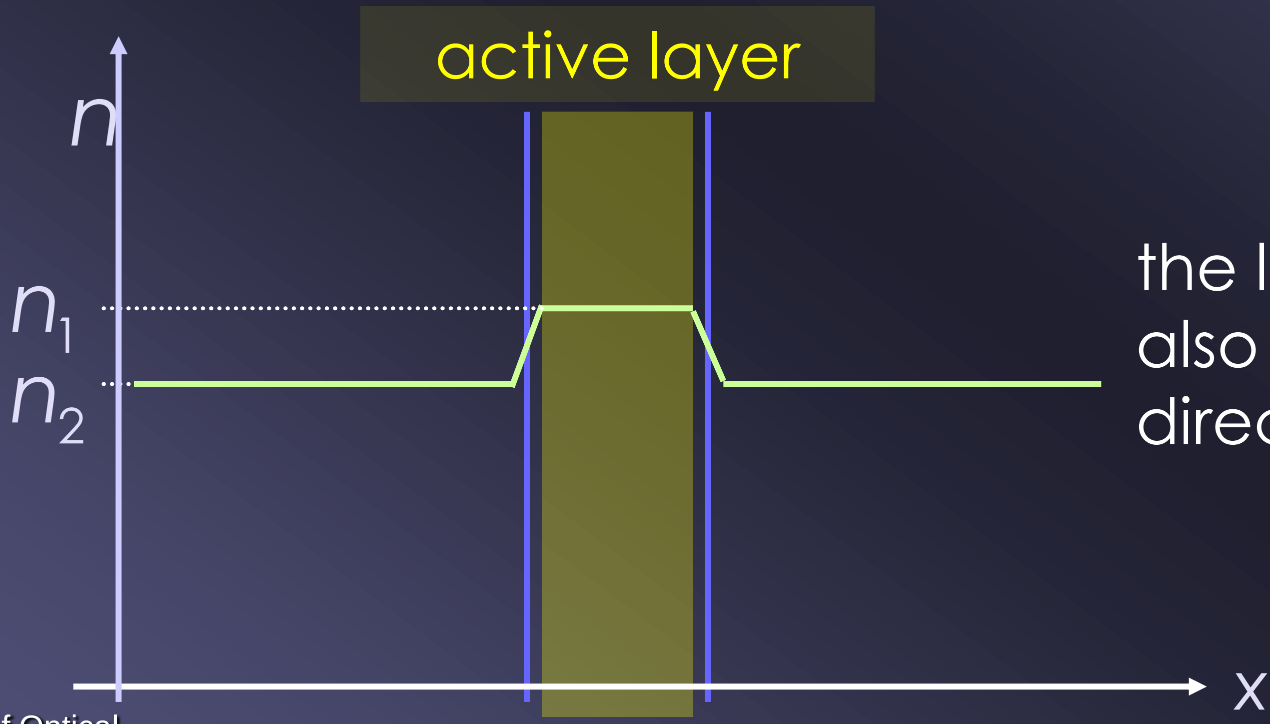
Heterojunctions in semiconductors

The double heterojunction localizes the population inversion into a small region of space applying two different materials with different bandgaps Δ_1 and Δ_2



Heterojunctions in semiconductors

The semiconductors of the double hetero-junction have different refractive indices n_1 and n_2 (not just different bandgaps Δ_1, Δ_2)



the laser beam is also localized in direction x

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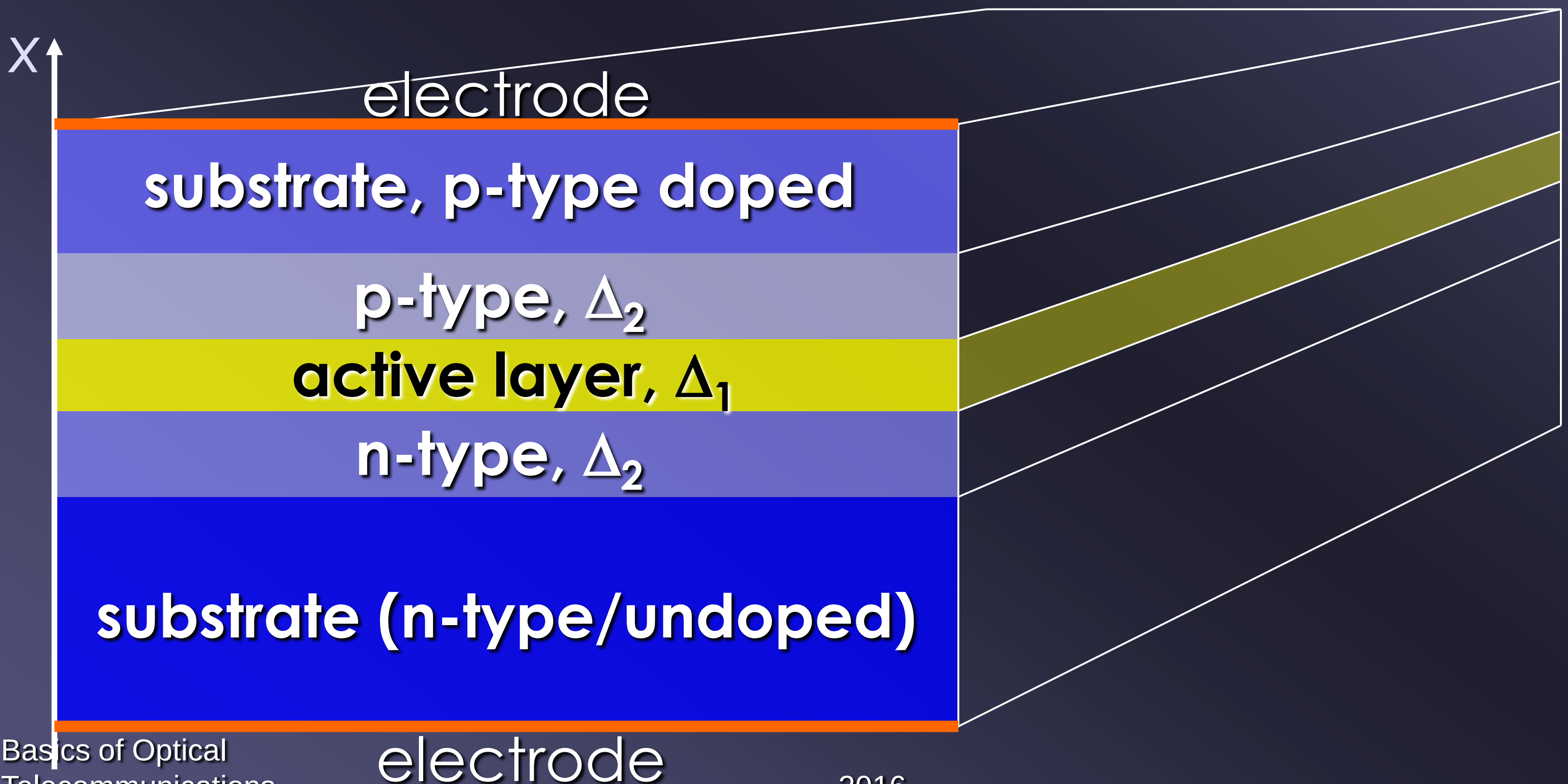
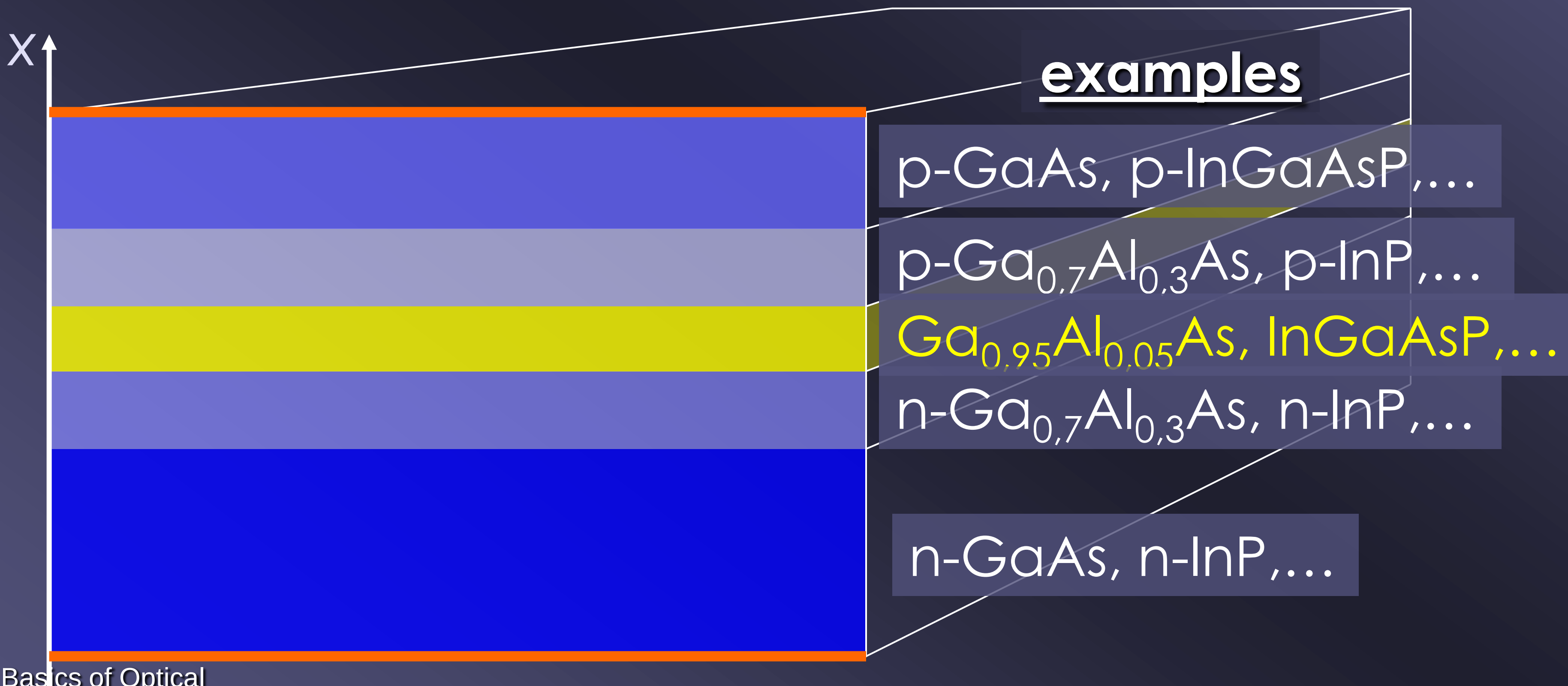
Heterojunctions in semiconductors

The double heterojunction localizes the population inversion and the laser beam into a small region of space ⟹ less heat



Heterojunctions in semiconductors

Materials grown upon each other should have similar grid distance in order not to produce strain or dislocations in the crystal.



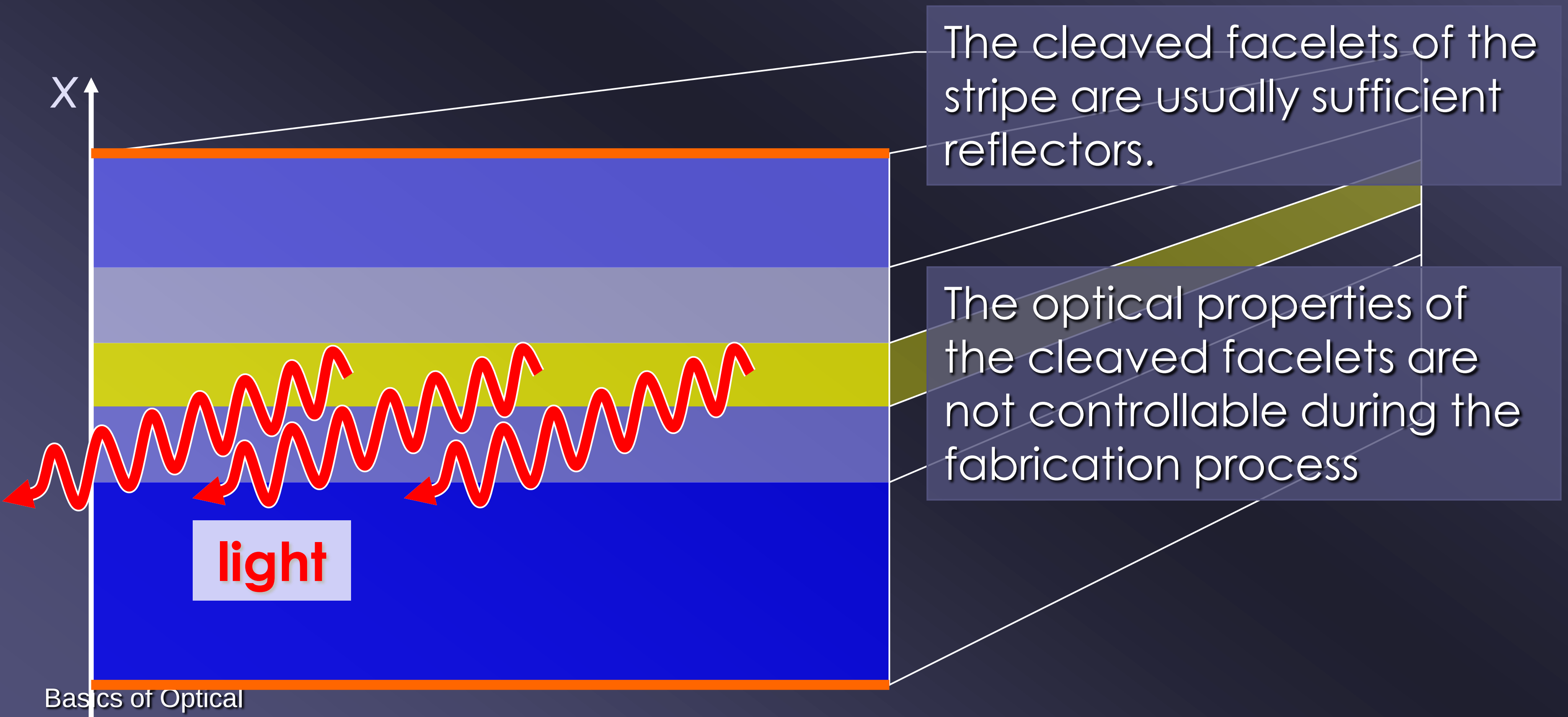
Heterojunctions in semiconductors

Thin layers of semiconductors have to be grown on each other with very accurate layer thickness:

- metal-organic chemical vapor deposition
- molecular beam epitaxy

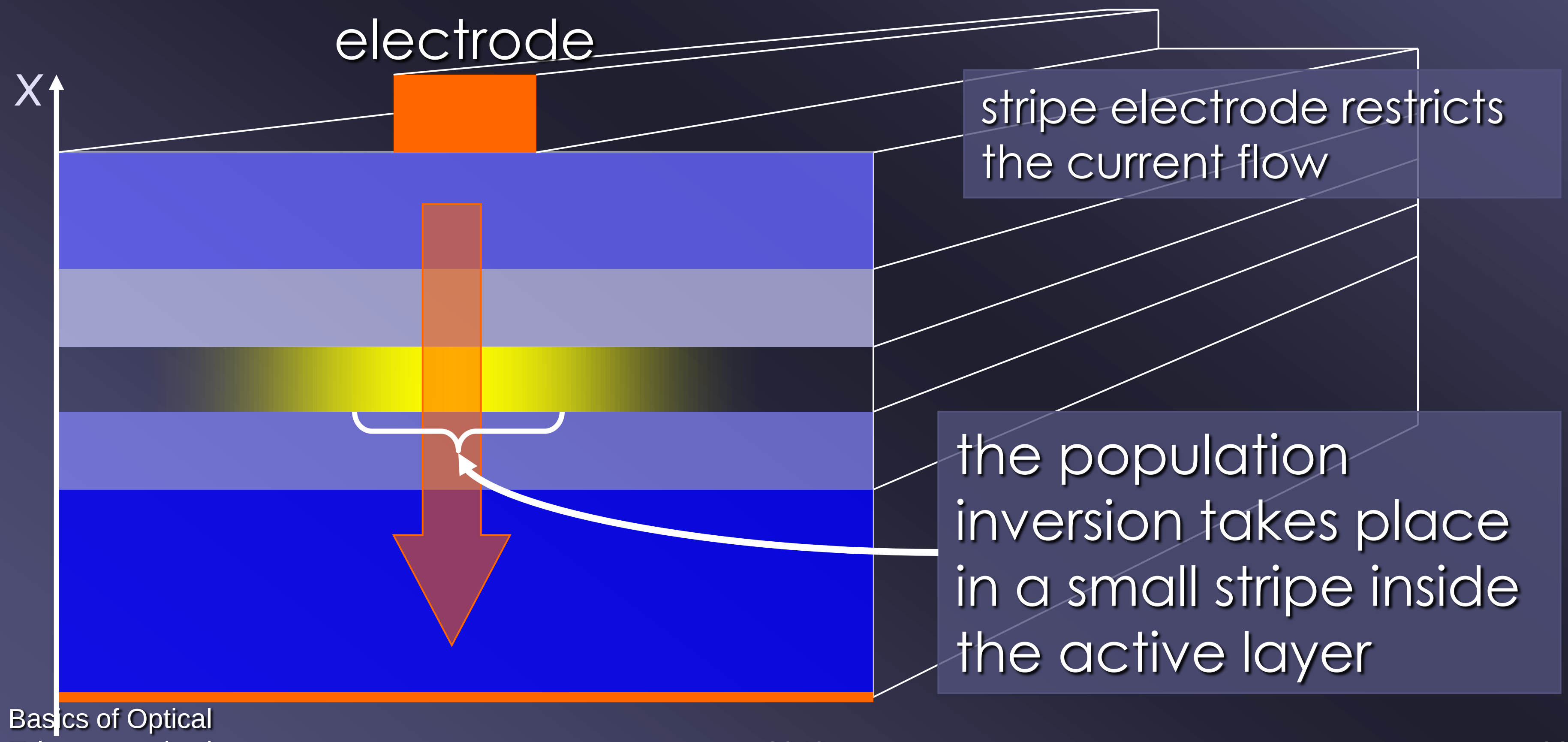
Heterojunctions in semiconductors

The mirrors placed parallel to the plane plotted the light propagates parallel to the layer



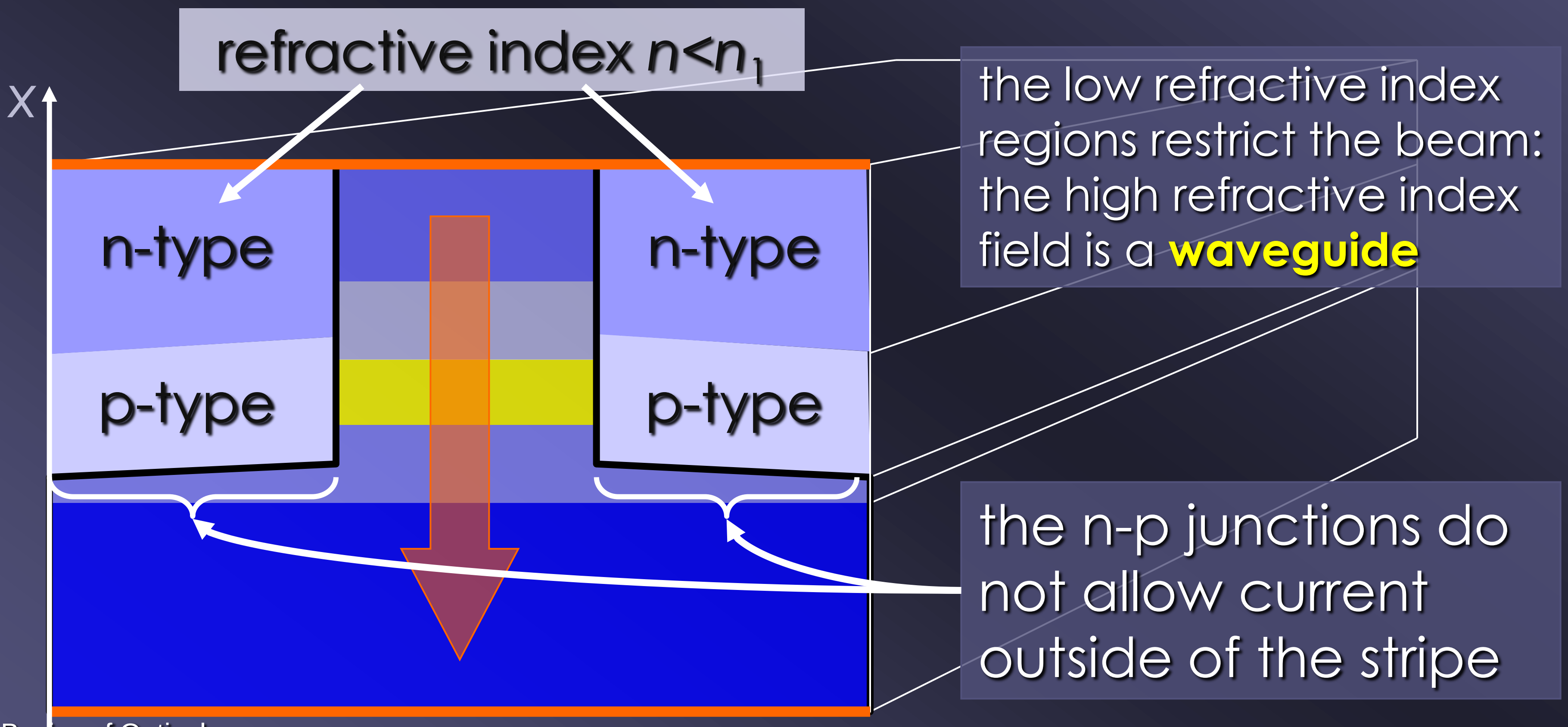
Heterojunctions in semiconductors

The population inversion can be restricted in the other dimension, too:



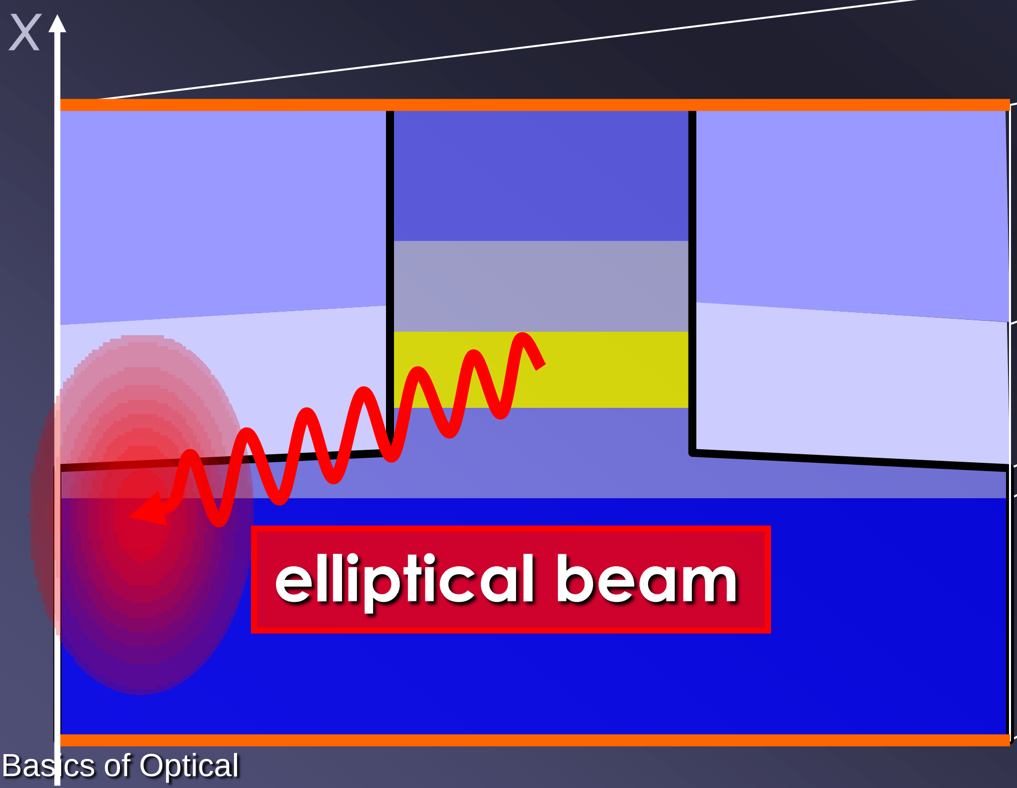
Heterojunctions in semiconductors

With special geometry the laser beam can be localized, as well as the population inversion



Heterojunctions in semiconductors

With special geometry the laser beam can be localized, as well as the population inversion



the thinner the layer, the **less modes** can propagate

+

the thinner the layer, the **less current** is needed for sufficient amount of inverse-population charge carriers

Heterojunctions in semiconductors

- For proper optical confinement single waveguide mode is needed $\longrightarrow$ the higher order modes have to be cut off.
- This requires thickness

$$d \propto \frac{\lambda}{2\sqrt{n_g^{\,2} - n_c^{\,2}}}$$

or less. For λ= the1.3 μm, d<0.56 μm.

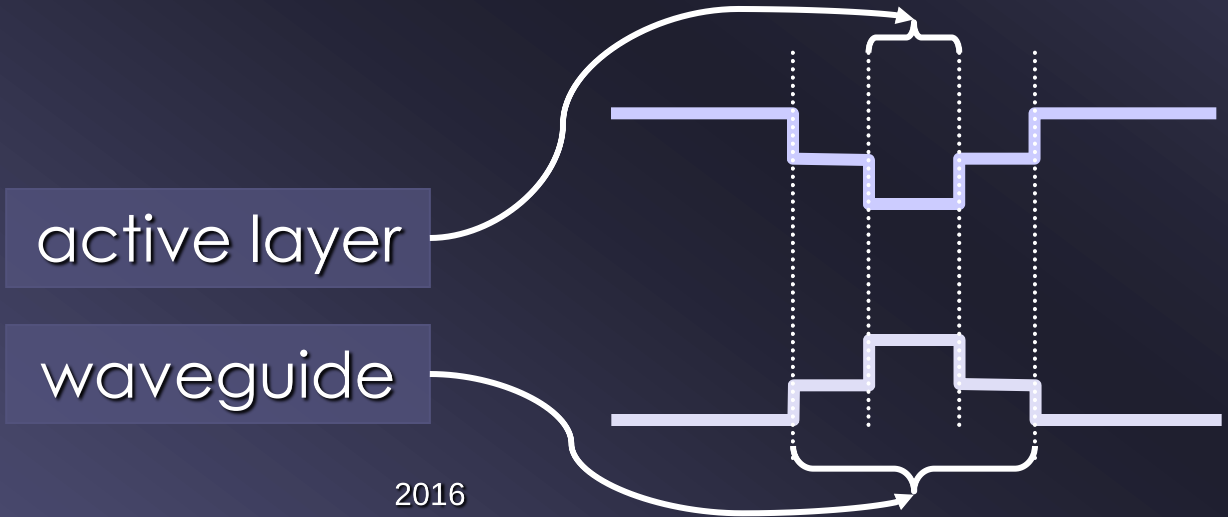
(n_g and n_c are reflective indices of waveguide and the cladding)

Heterojunctions in semiconductors

If the waveguide is too thin, the light spreads out of it → the loss increases.

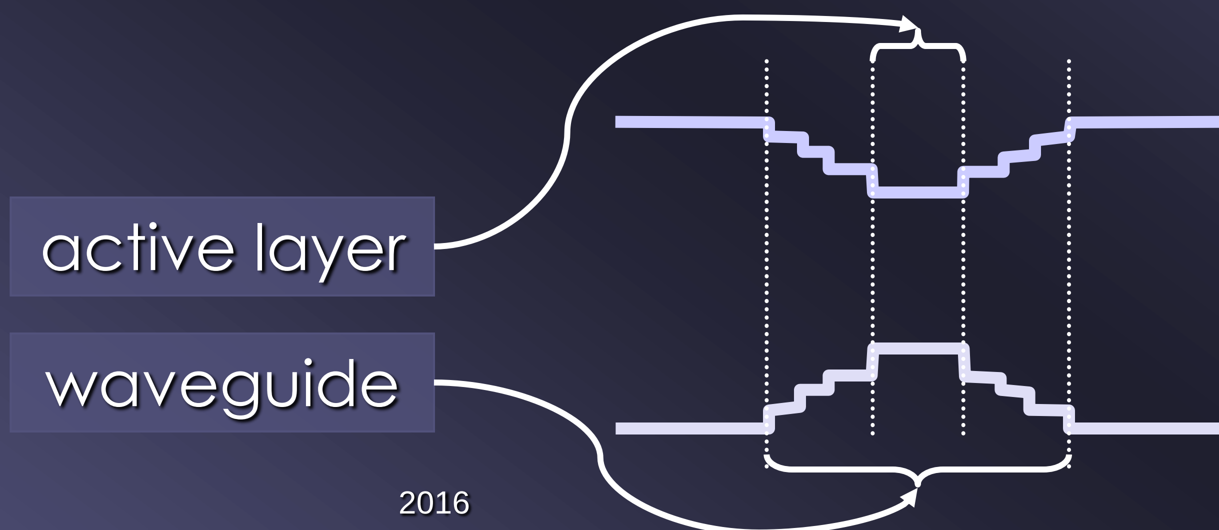
For confining the population inversion thinner layers would be needed.

Solution: the waveguide and the active layer are not the same – **S**eparate **C**onfinement **H**eterostructure (SCH)



Heterojunctions in semiconductors

- If the waveguide is too thin, the light spreads out of it ⟶ the loss increases.
- For confining the population inversion thinner layers would be needed.
- Solution: the waveguide and the active layer are not the same – **GR**aded **IN**dex SCH (GRINSCH)



Quantum well lasers

If the active region is thin enough, ~10 nm

- only few layers of atoms in the active region
- **quantum well** is formed

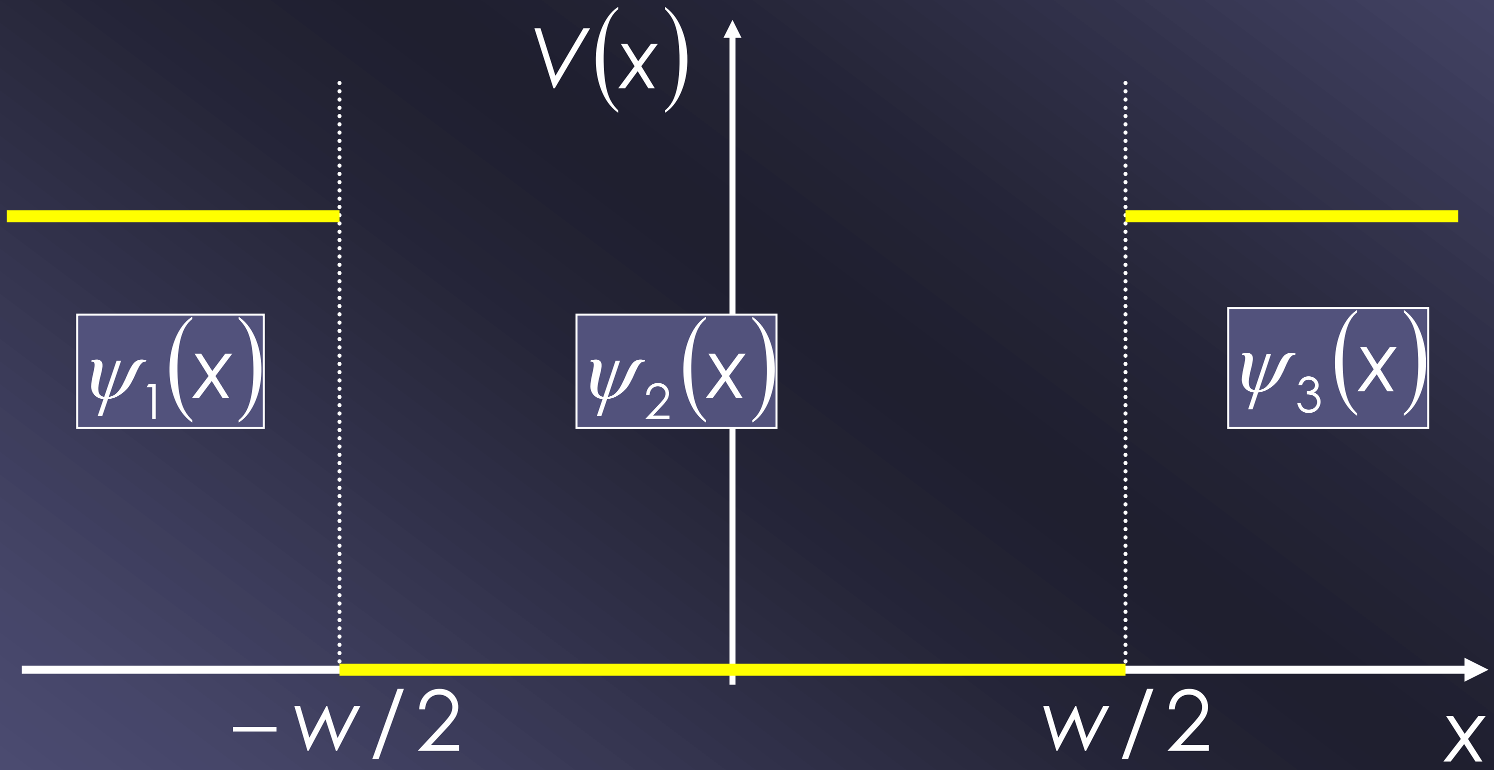
The solution of the Schrödinger equation of quantum wells:

I. electron in a potential well in the x direction
II. free electron gas solution in the *yz* plane

$$E(\mathbf{k}) = \frac{\hbar^2\left(k_y^{\ 2} + k_z^{\ 2}\right)}{2m}$$

Quantum well lasers

The solution of the 1D potential well problem:



Quantum well lasers

The solution of the 1D potential well problem:

- the Schrödinger equation

$$\frac{\hbar}{2m}\frac{\partial^2}{\partial x^2}\psi_1(x)+V_0\psi_1(x)=E\psi_1(x) \qquad x<-\frac{w}{2}$$

$$\frac{\hbar}{2m}\frac{\partial^2}{\partial x^2}\psi_2(x)=E\psi_2(x) \qquad -\frac{w}{2}<x<\frac{w}{2}$$

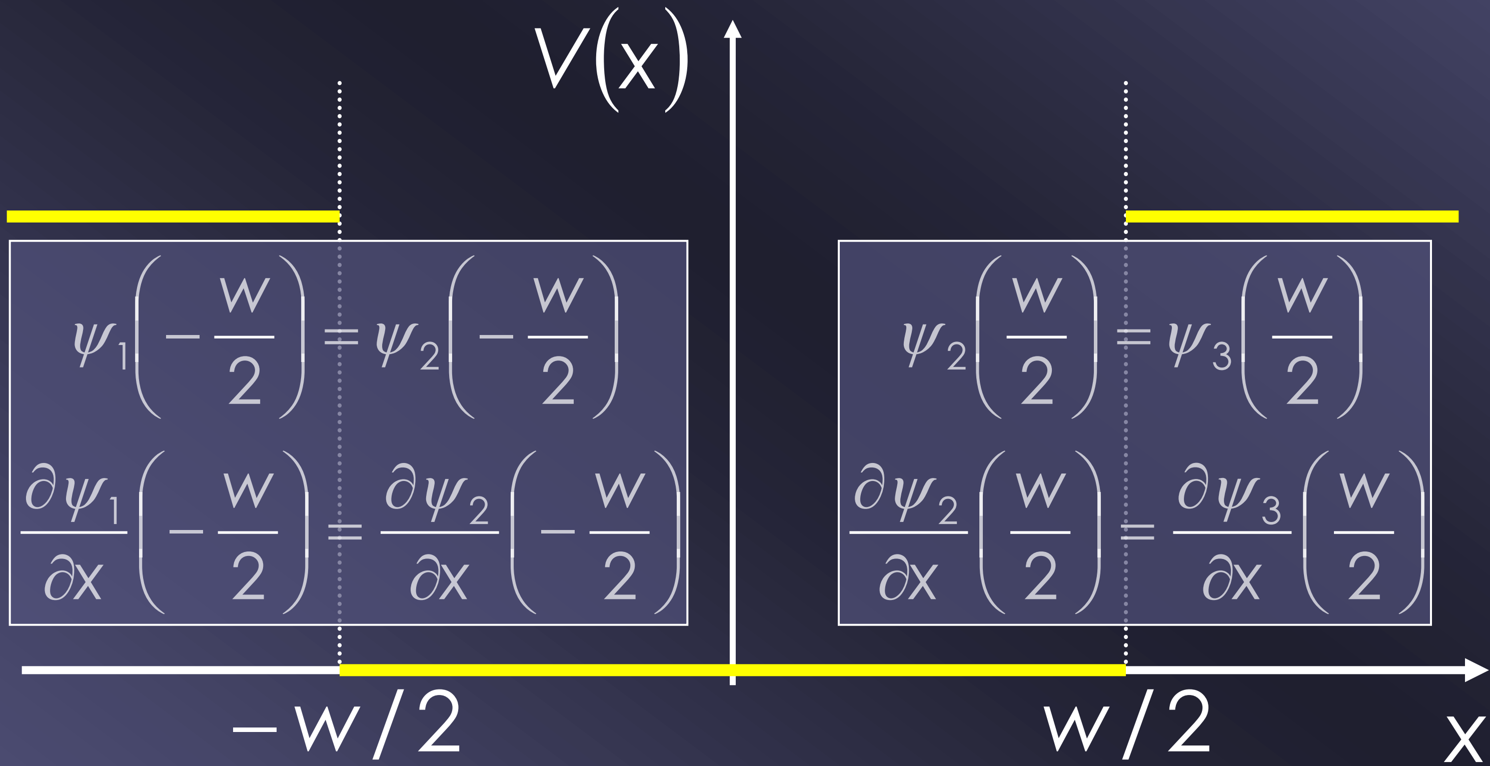
$$\frac{\hbar}{2m}\frac{\partial^2}{\partial x^2}\psi_3(x)+V_0\psi_3(x)=E\psi_3(x) \qquad x>\frac{w}{2}$$

Quantum well lasers

- the boundary conditions:

$$\psi_1\left(-\frac{w}{2}\right)=\psi_2\left(-\frac{w}{2}\right)\qquad \frac{\partial\psi_1}{\partial x}\left(-\frac{w}{2}\right)=\frac{\partial\psi_2}{\partial x}\left(-\frac{w}{2}\right)$$

$$\psi_2\left(\frac{w}{2}\right)=\psi_3\left(\frac{w}{2}\right)\qquad \frac{\partial\psi_2}{\partial x}\left(\frac{w}{2}\right)=\frac{\partial\psi_3}{\partial x}\left(\frac{w}{2}\right)$$



Quantum well lasers

- The solution of the differential equation system:

$$\psi_1(x) = A_1 \exp(\kappa \cdot x)$$

$$\psi_2(x) = a_2 \sin(k \cdot x) + b_2 \cos(k \cdot x)$$

$$\psi_3(x) = A_3 \exp(-\kappa \cdot x)$$

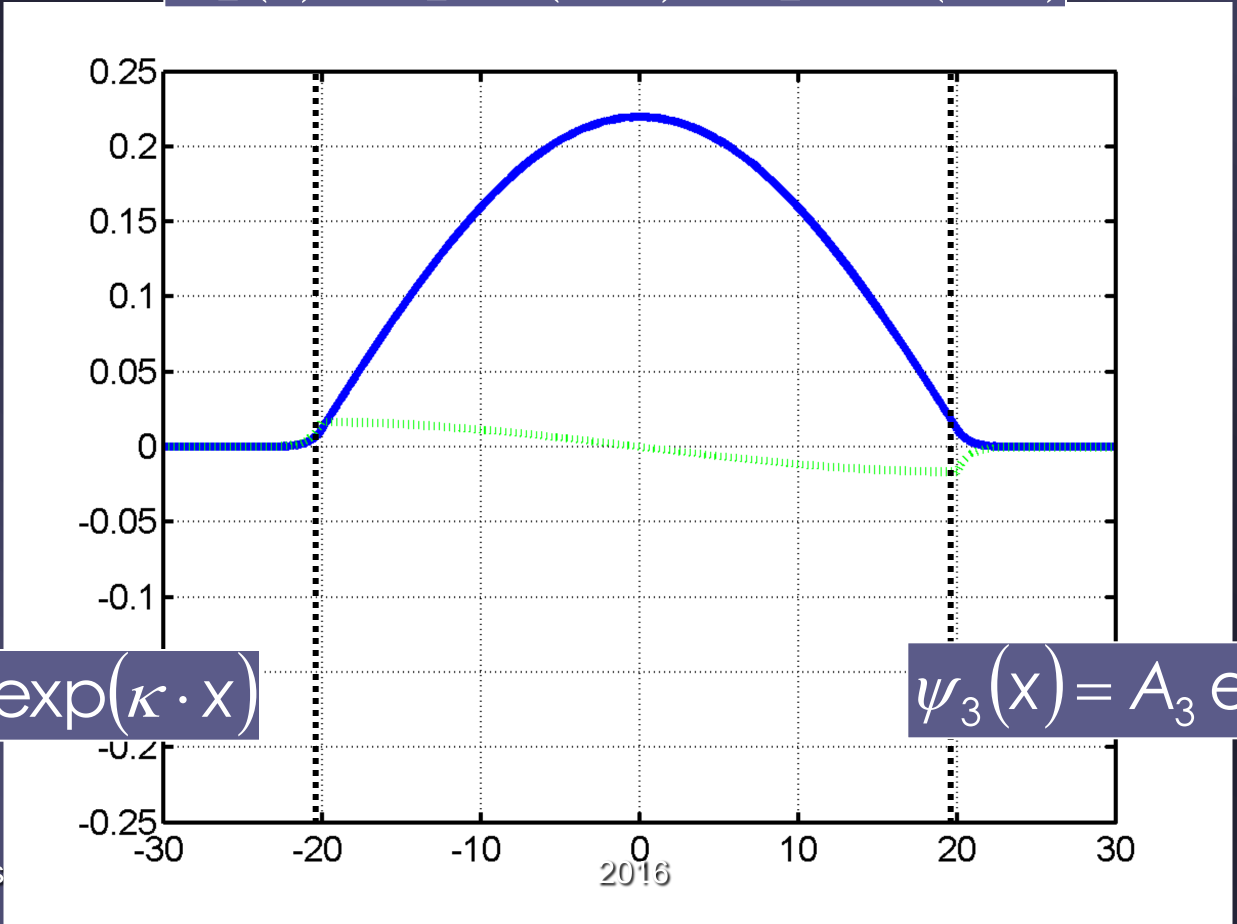
with

$$\kappa = \frac{\sqrt{2m(V_0 - E)}}{\hbar} \quad \text{and} \quad k = \frac{\sqrt{2mE}}{\hbar}$$

Quantum well lasers

- For V0=1 a.u., w=40 a.u., E=0.0029 a.u.:

$$\psi_2(x) = a_2 \sin(k \cdot x) + b_2 \cos(k \cdot x)$$



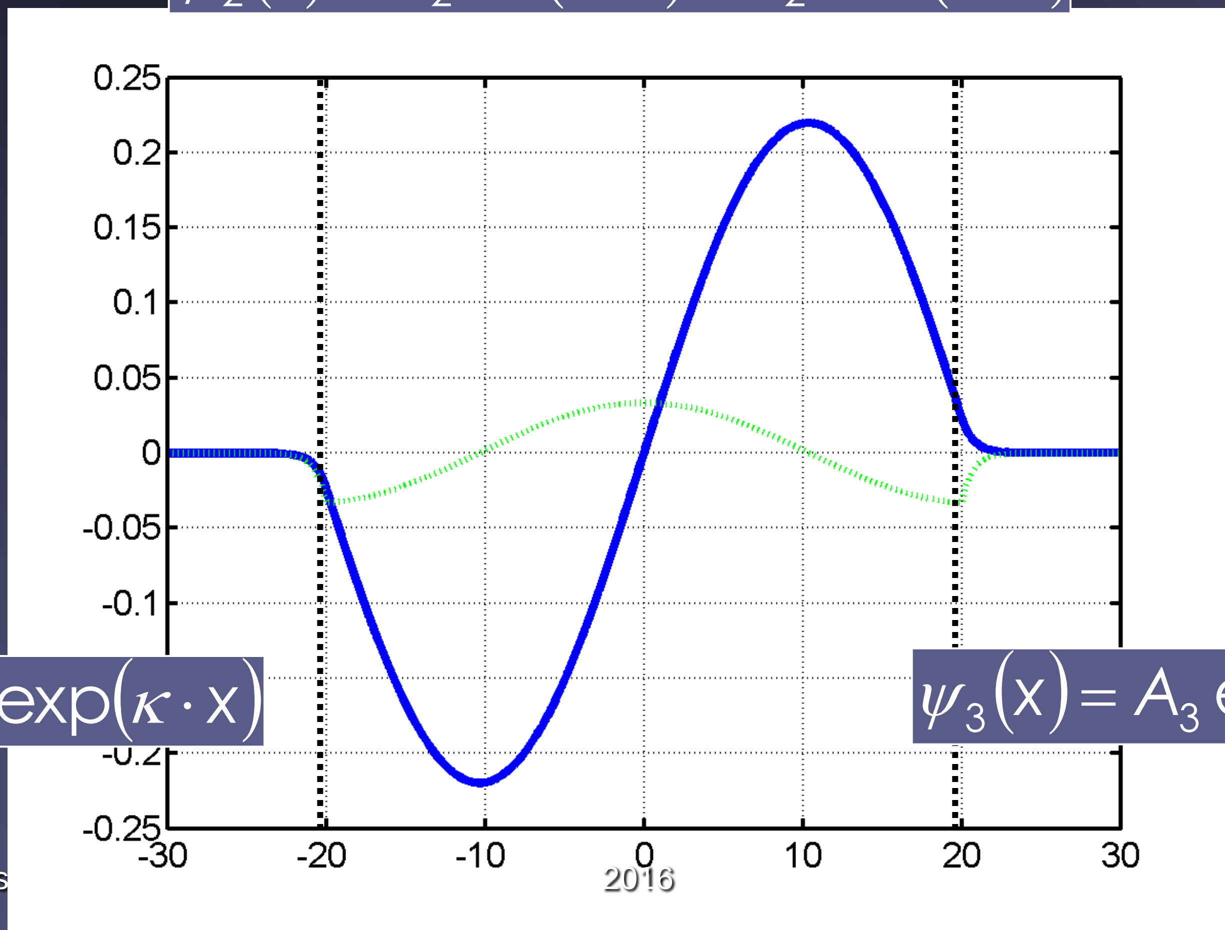
$$\psi_1(x) = A_1 \exp(\kappa \cdot x)$$

$$\psi_3(x) = A_3 \exp(-\kappa \cdot x)$$

Quantum well lasers

- For V0=1 a.u., w=40 a.u., E=0.0115 a.u.:

$$\psi_2(x) = a_2 \sin(k \cdot x) + b_2 \cos(k \cdot x)$$



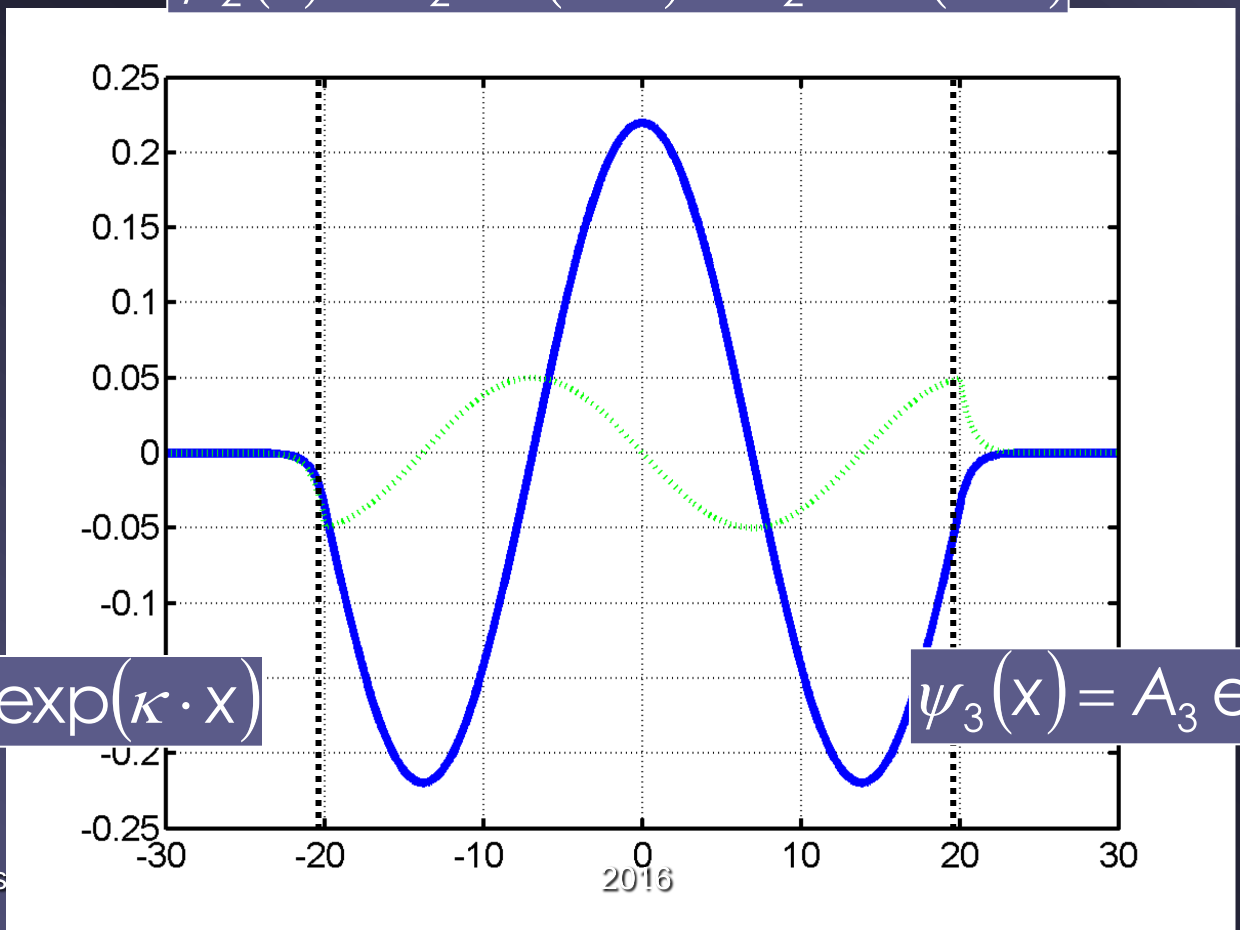
$$\psi_1(x) = A_1 \exp(\kappa \cdot x)$$

$$\psi_3(x) = A_3 \exp(-\kappa \cdot x)$$

Quantum well lasers

- For V0=1 a.u., w=40 a.u., E=0.0259 a.u.:

$$\psi_2(x) = a_2 \sin(k \cdot x) + b_2 \cos(k \cdot x)$$



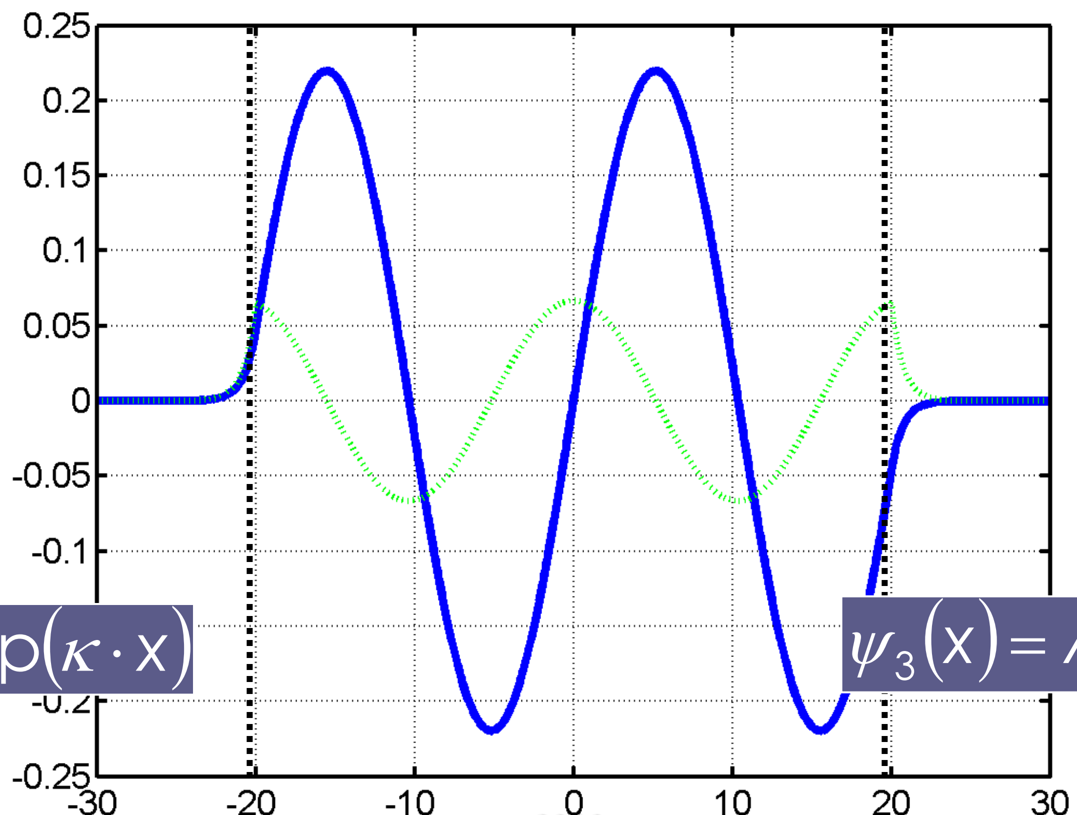
$$\psi_1(x) = A_1 \exp(\kappa \cdot x)$$

$$\psi_3(x) = A_3 \exp(-\kappa \cdot x)$$

Quantum well lasers

- For V0=1 a.u., w=40 a.u., E=0.0460 a.u.:

$$\psi_2(x) = a_2 \sin(k \cdot x) + b_2 \cos(k \cdot x)$$



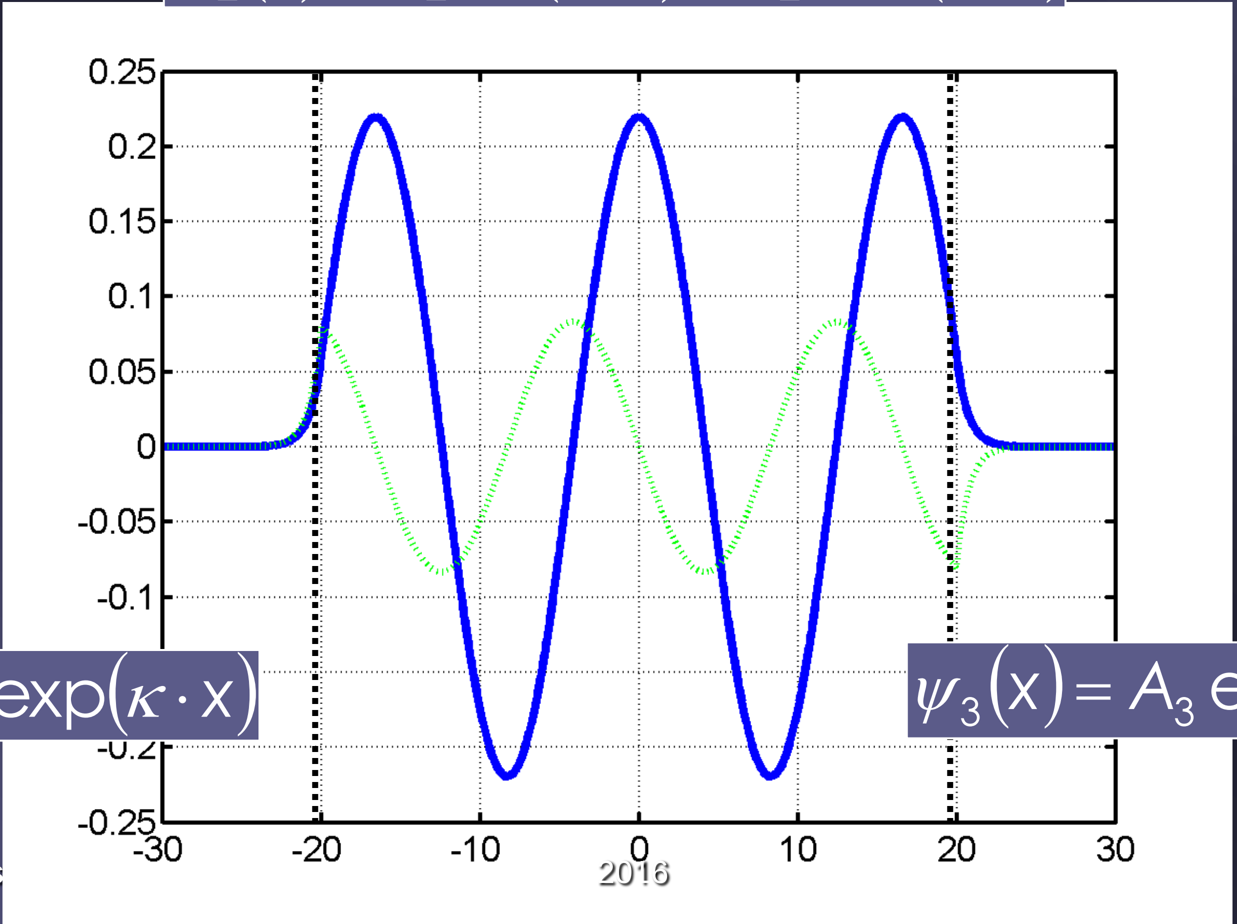
$$\psi_1(x) = A_1 \exp(\kappa \cdot x)$$

$$\psi_3(x) = A_3 \exp(-\kappa \cdot x)$$

Quantum well lasers

- For V0=1 a.u., w=40 a.u., E=0.0718 a.u.:

$$\psi_2(x) = a_2 \sin(k \cdot x) + b_2 \cos(k \cdot x)$$



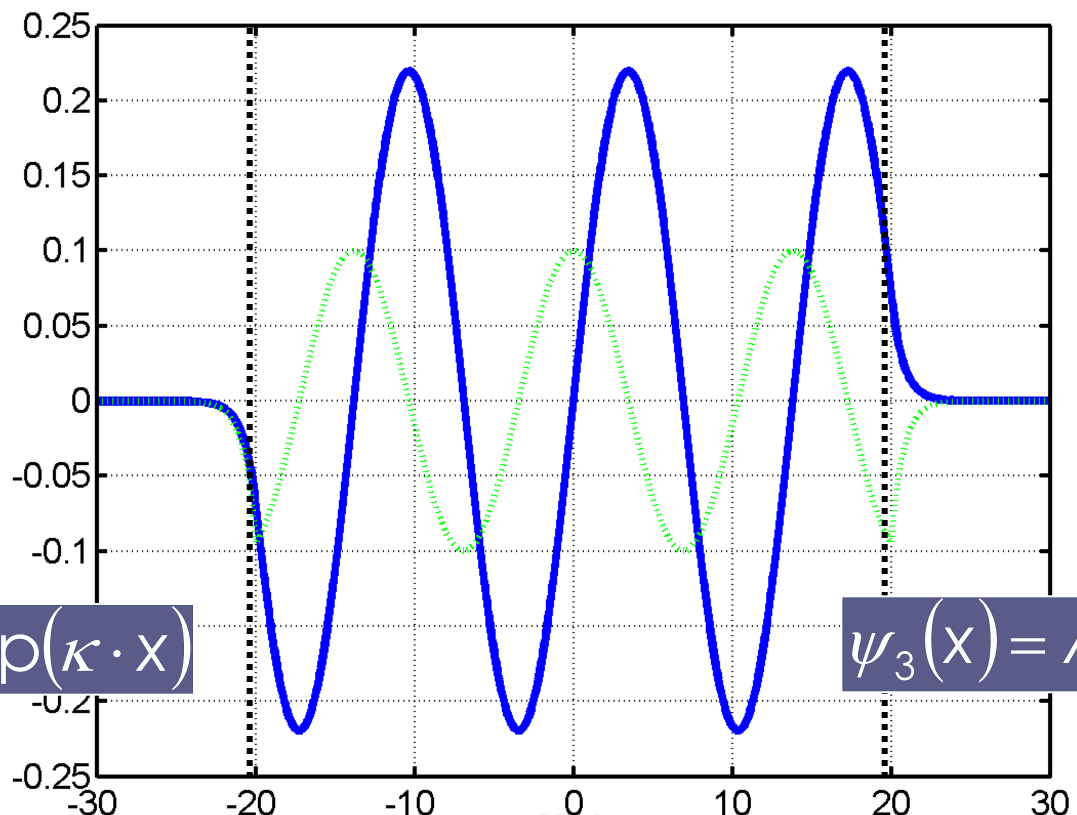
$$\psi_1(x) = A_1 \exp(\kappa \cdot x)$$

$$\psi_3(x) = A_3 \exp(-\kappa \cdot x)$$

Quantum well lasers

- For V0=1 a.u., w=40 a.u., E=0.1035 a.u.:

$$\psi_2(x) = a_2 \sin(k \cdot x) + b_2 \cos(k \cdot x)$$

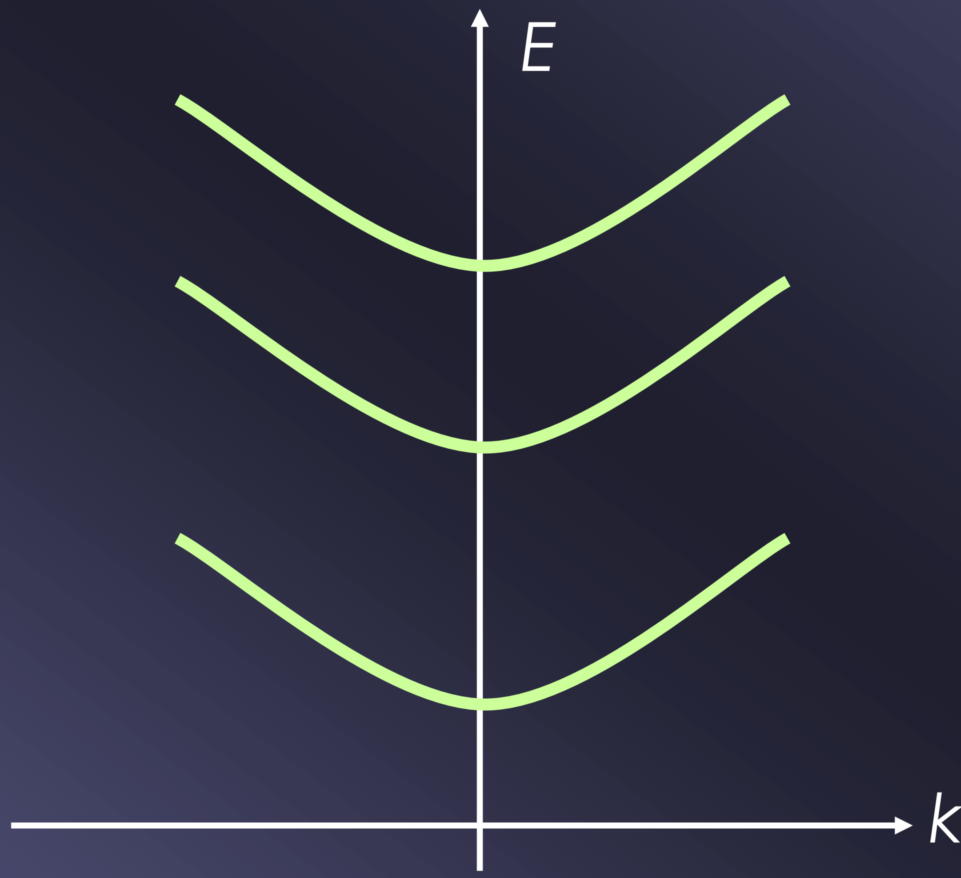


$$\psi_1(x) = A_1 \exp(\kappa \cdot x)$$

$$\psi_3(x) = A_3 \exp(-\kappa \cdot x)$$

Quantum well lasers

The energy versus quasi momentum function:

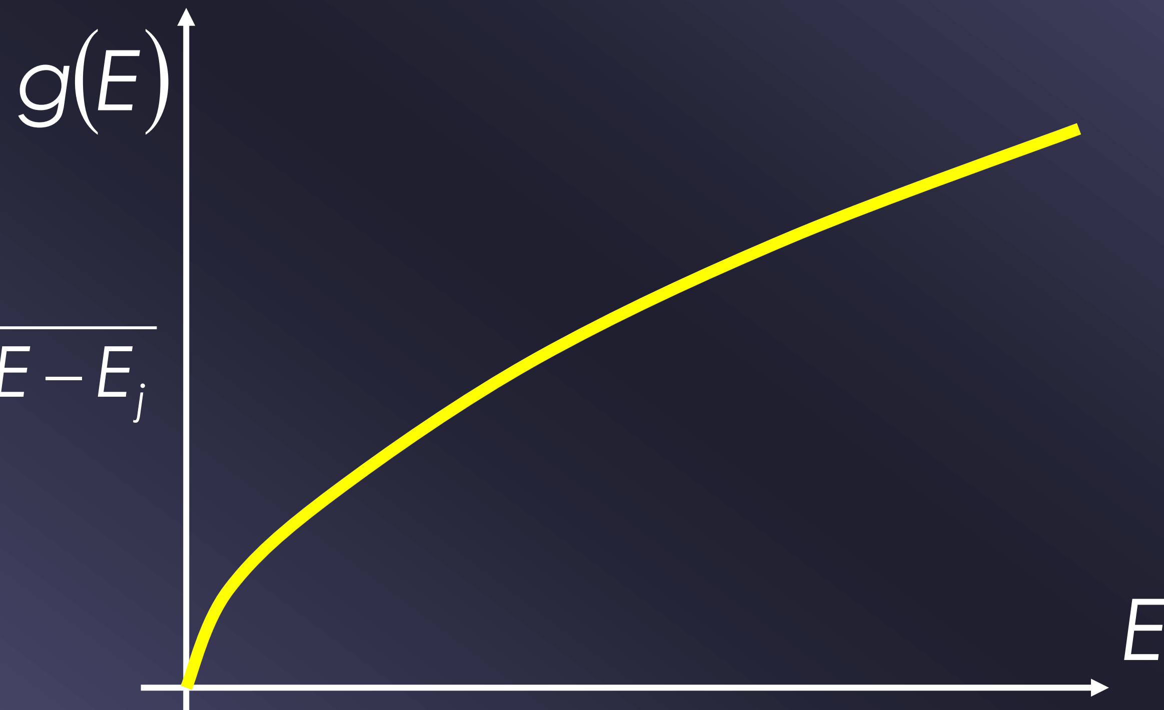


Quantum well lasers

If the free electron gas is restricted to two or less dimensions, the density of states behaves different from the 3D case

- 3D

$$g(E)=\frac{dN}{dE}\propto\sqrt{E-E_j}$$

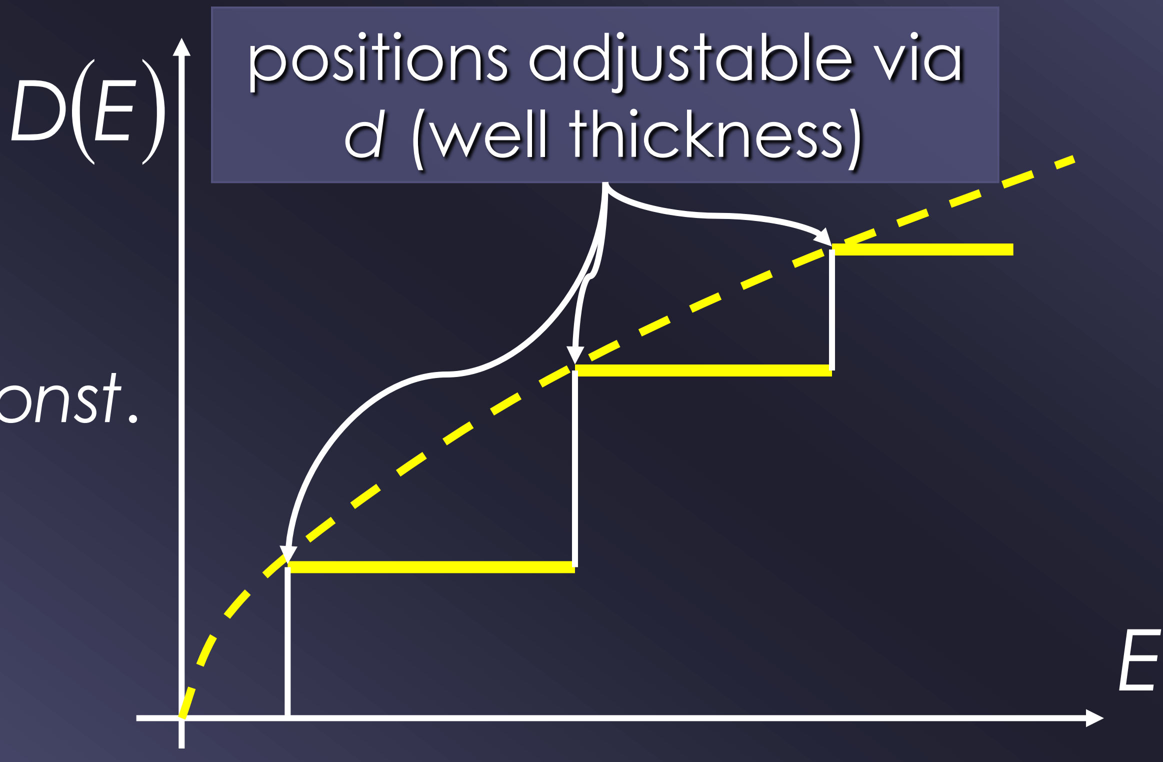


Quantum well lasers

If the free electron gas is restricted to two or less dimensions, the density of states behaves different from the 3D case

- 2D

$$D(E) = \frac{dN}{dE} = const.$$

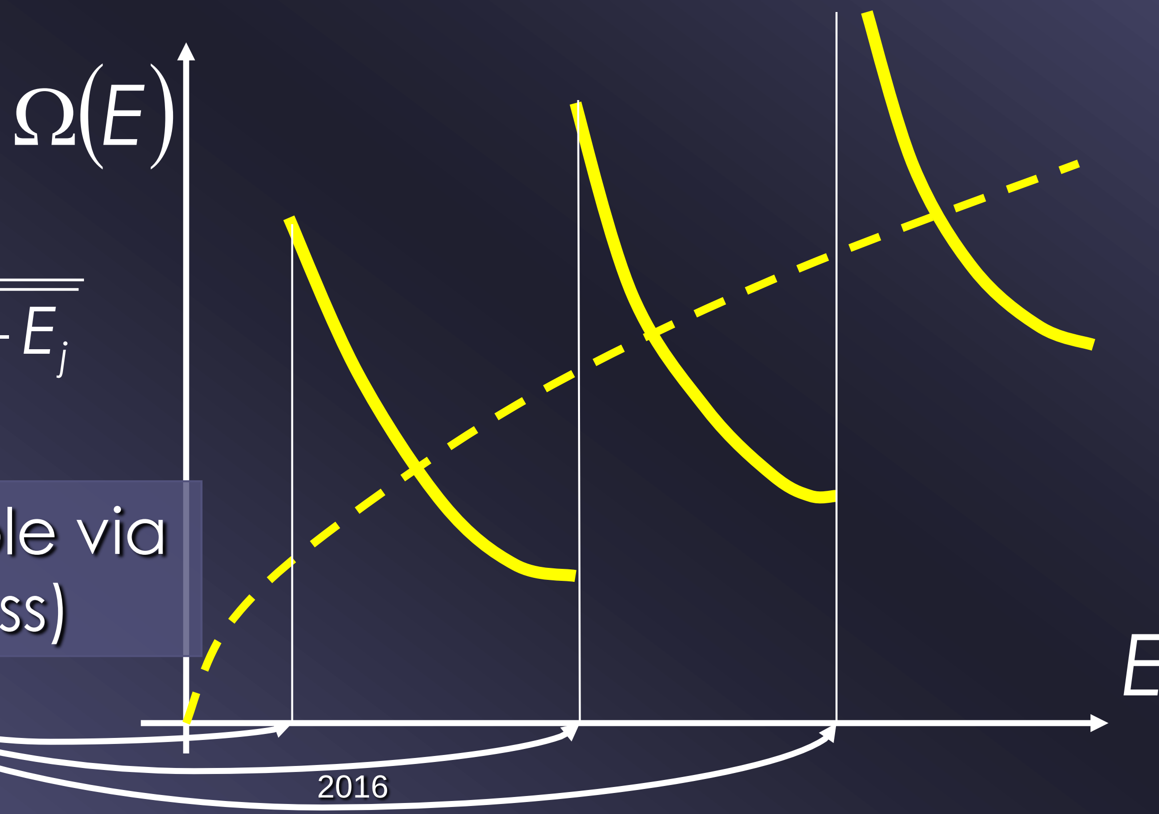


Quantum well lasers

If the free electron gas is restricted to two or less dimensions, the density of states behaves different from the 3D case

- 1D

$$\Omega(E)=\frac{dN}{dE}=\frac{1}{\sqrt{E-E_j}}$$



positions adjustable via *d* (well thickness)

Quantum well lasers

The absorption spectrum is also different for 2D electron systems from the bulk case:

- 3D:

$$\alpha \propto \sqrt{h\nu - \Delta}$$

- 2D:
  the absorption spectrum is steplike with resonances at the frequencies corresponding to the energy differences

  better absorption spectrum, transparency.

Quantum well lasers

- Usually a single quantum well (SQW) is too thin for confining the light
- multiple quantum wells (MQW) with barrier layers can be applied:

Quantum well lasers

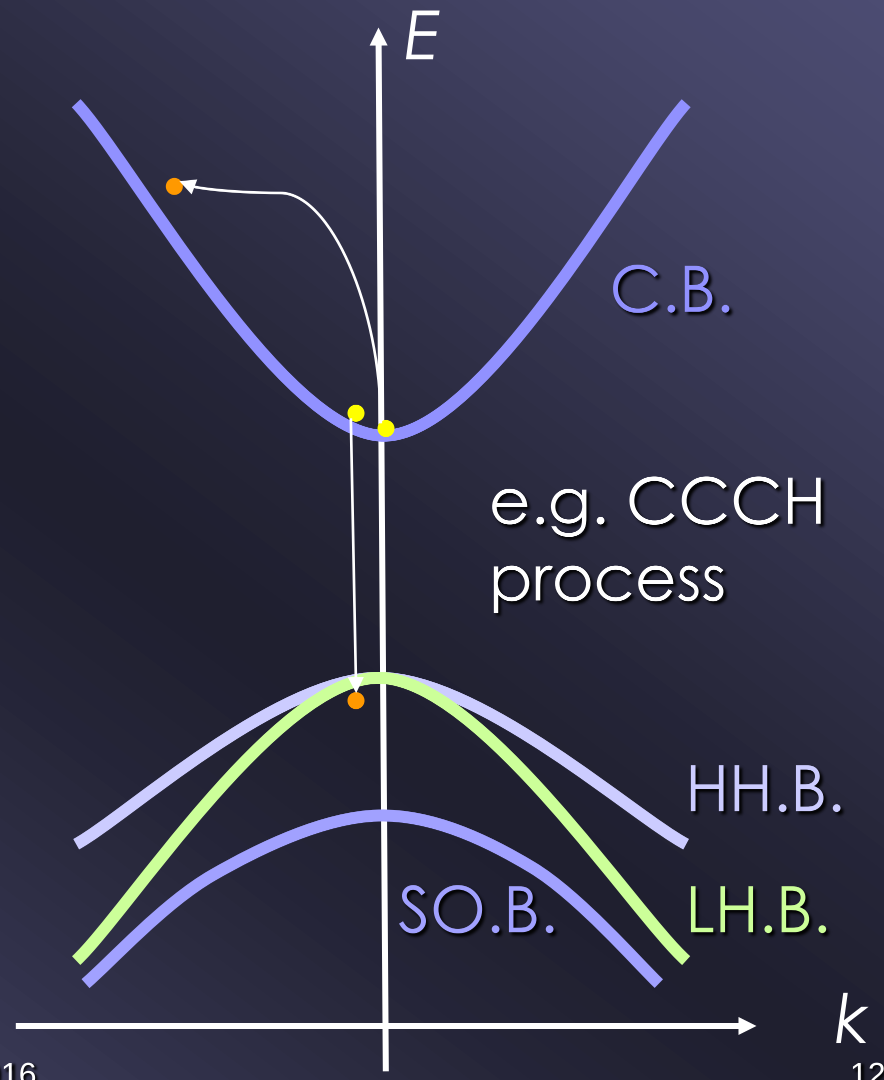
The quantum well lasers have higher threshold than the bulk lasers, but they also have higher gain, better transparency.

Quantum wells based on GaAs perform well, low loss, high gain

Quantum wells based on InP have higher loss (Auger recombination,…)
a **strain** in the QW layers improves the performance of QW InGaAsP lasers

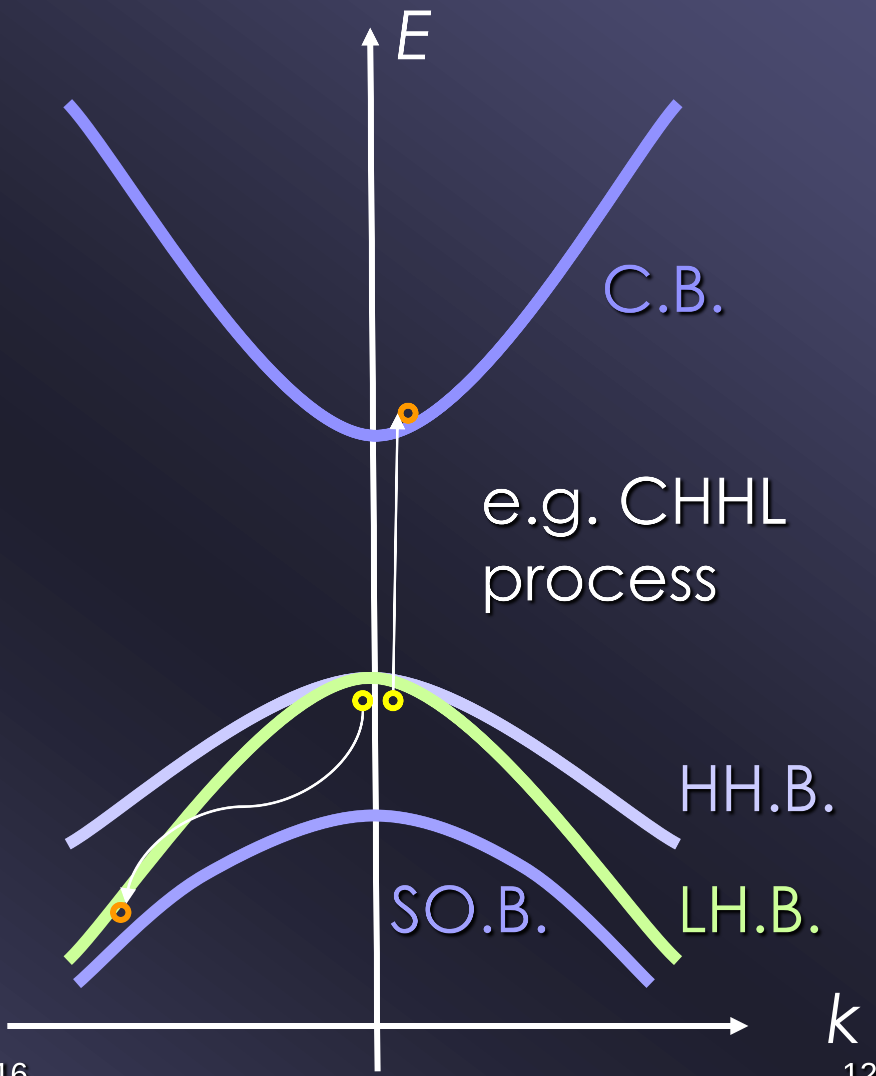
Quantum well lasers

In the Auger recombination the energy which is released via an electron-hole recombination is absorbed by an other electron, which dissipates the energy by generating lattice oscillations (phonons)



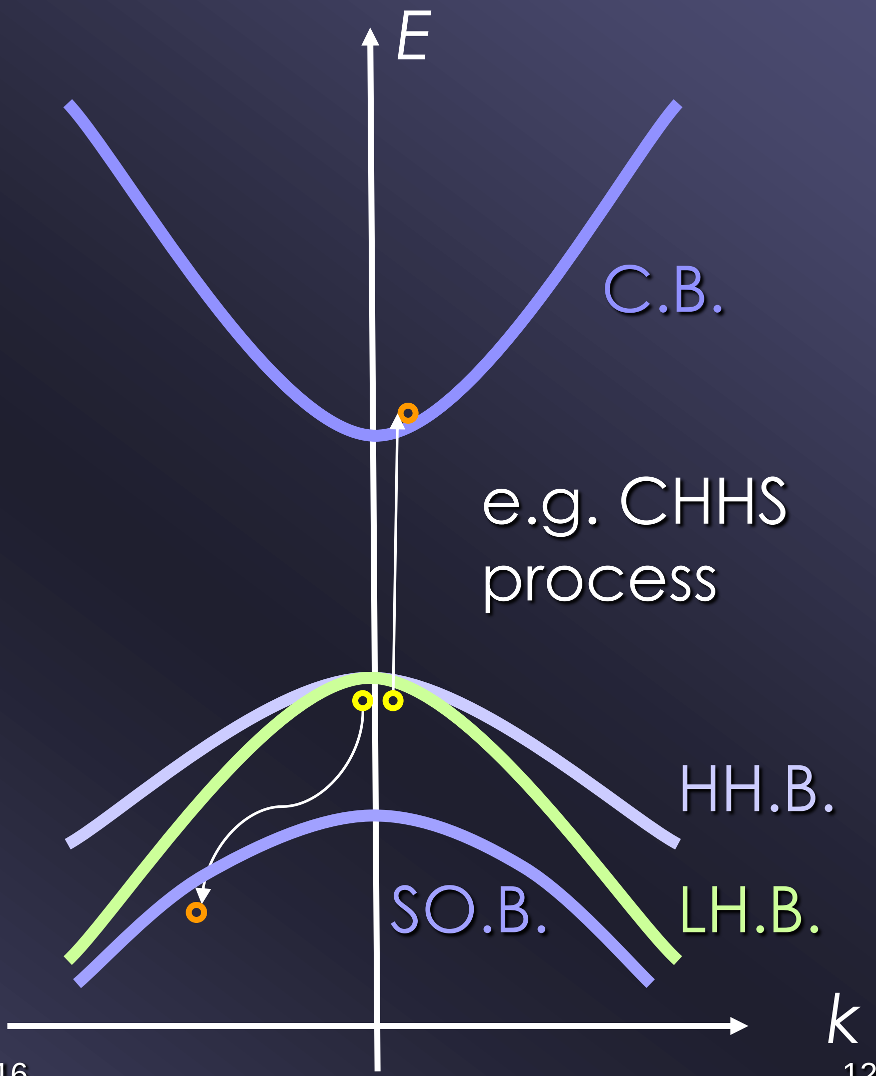
Quantum well lasers

In the Auger recombination the energy which is released via an electron-hole recombination is absorbed by an other hole, which dissipates the energy by generating lattice oscillations (phonons)



Quantum well lasers

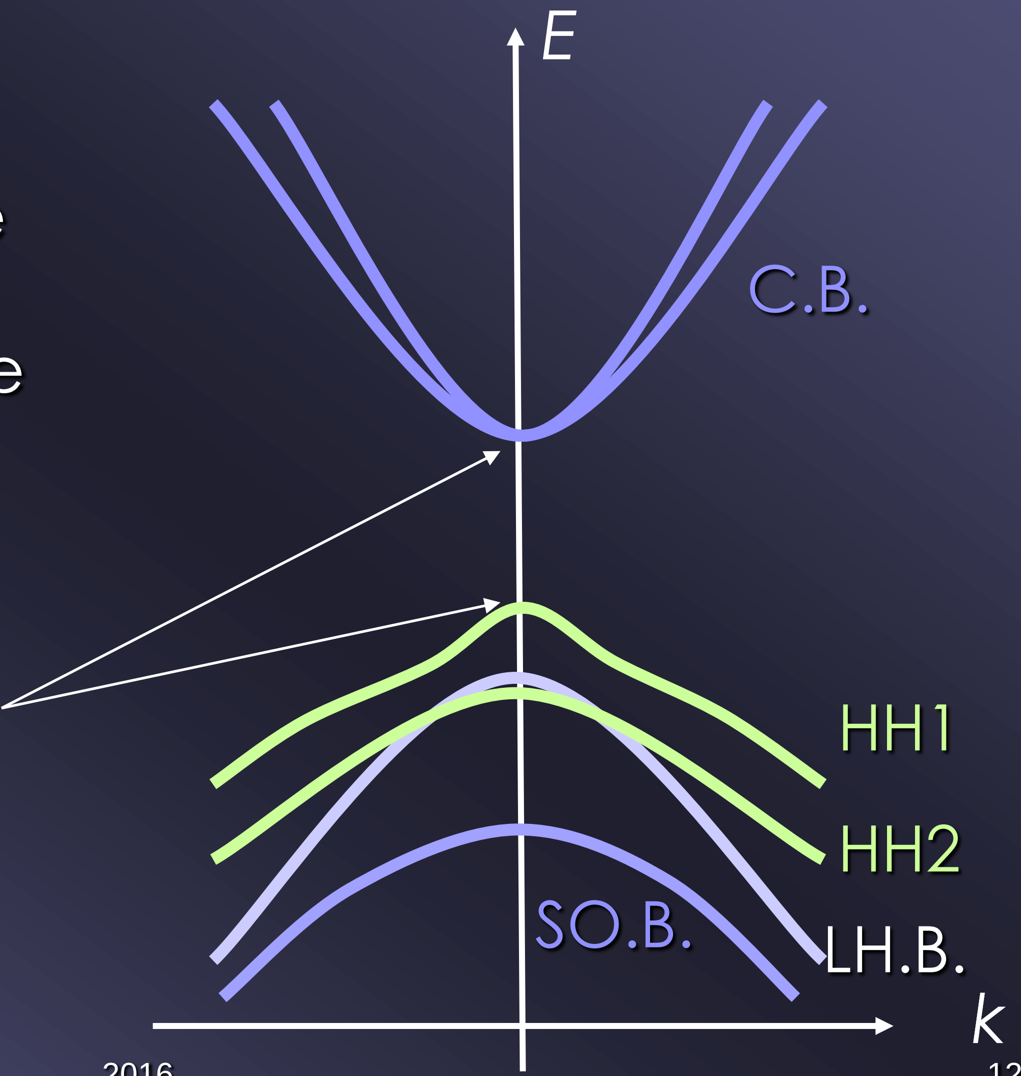
In the Auger recombination the energy which is released via an electron-hole recombination is absorbed by an other hole, which dissipates the energy by generating lattice oscillations (phonons)



Quantum well lasers

Quantum wells cause splitting in the conduction band, lift the degeneracy of the heavy hole and light hole bands, and distort the shape

⟶ Similar effective mass (curvature) means more effective population inversion (smaller threshold)



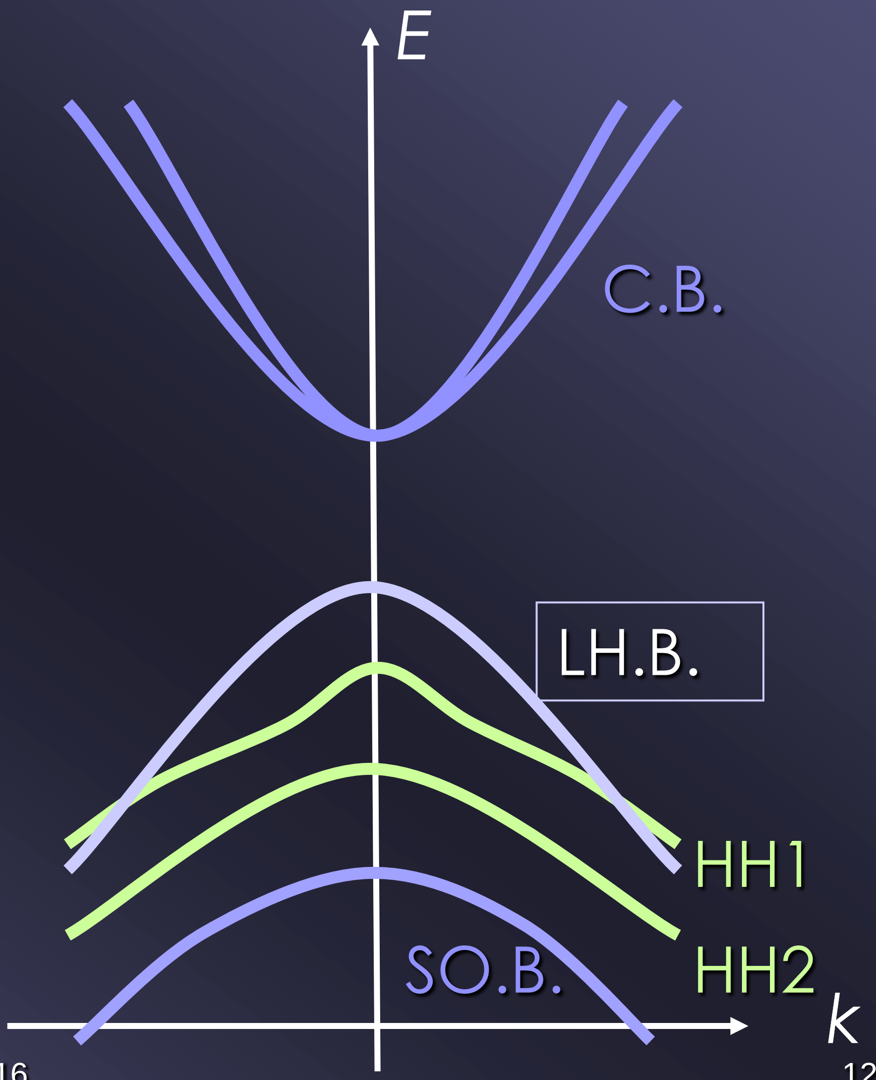
Quantum well lasers

Quantum wells + <u>tensile strain</u> lifts the light hole bands

⟶ TM mode

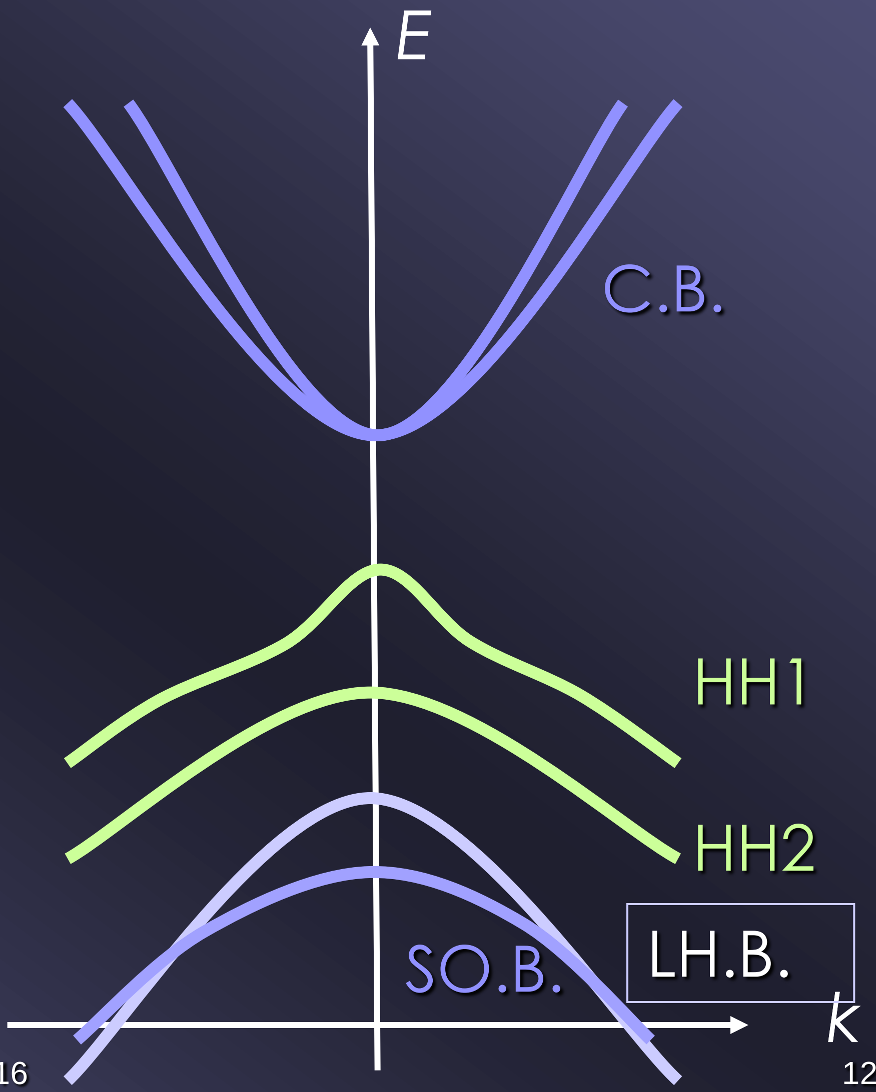
The split off band is also depressed

⟶ less Auger recombination, higher carrier density is possible



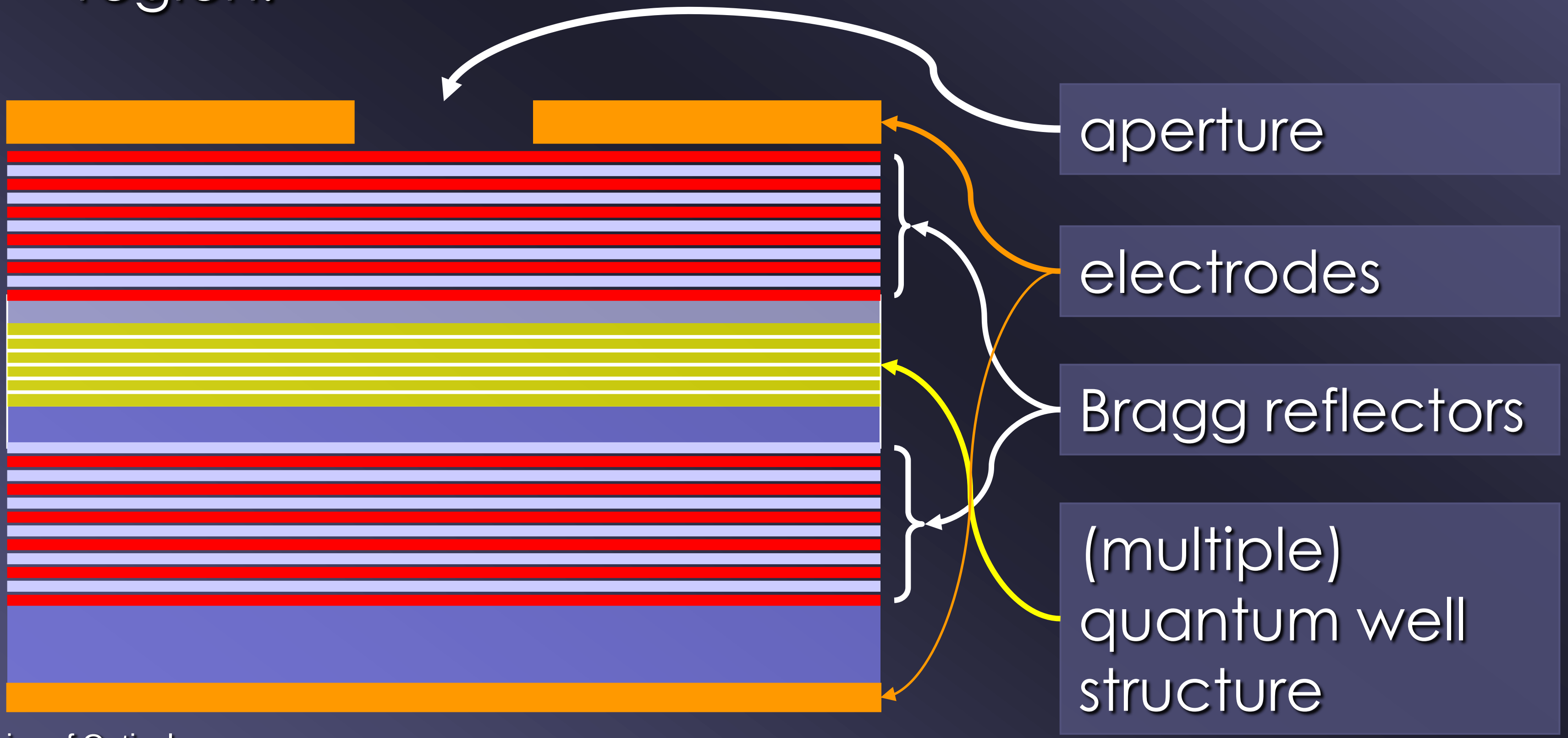
Quantum well lasers

Quantum wells + <u>compressive strain</u> depresses the light hole bands, and further reduce the heavy hole band's curvature ⟶ TE modulation and further decrease in threshold level



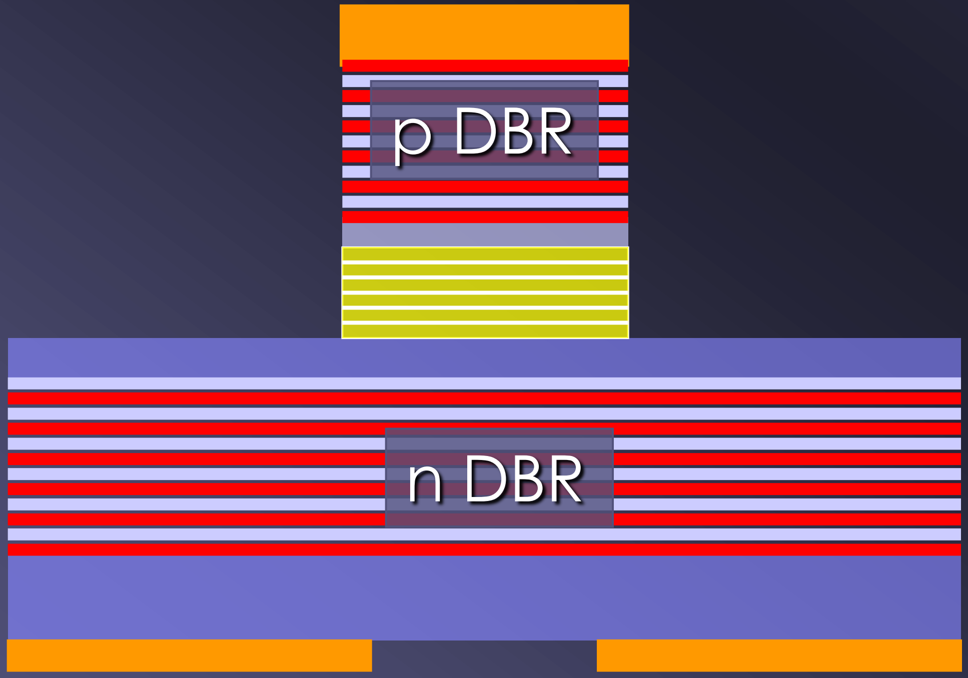
VCSELs

The high gain of quantum wells make possible to place the resonator above and under the active region:



VCSELs

The confinement of population inversion in the *y* and *z* dimensions is necessary

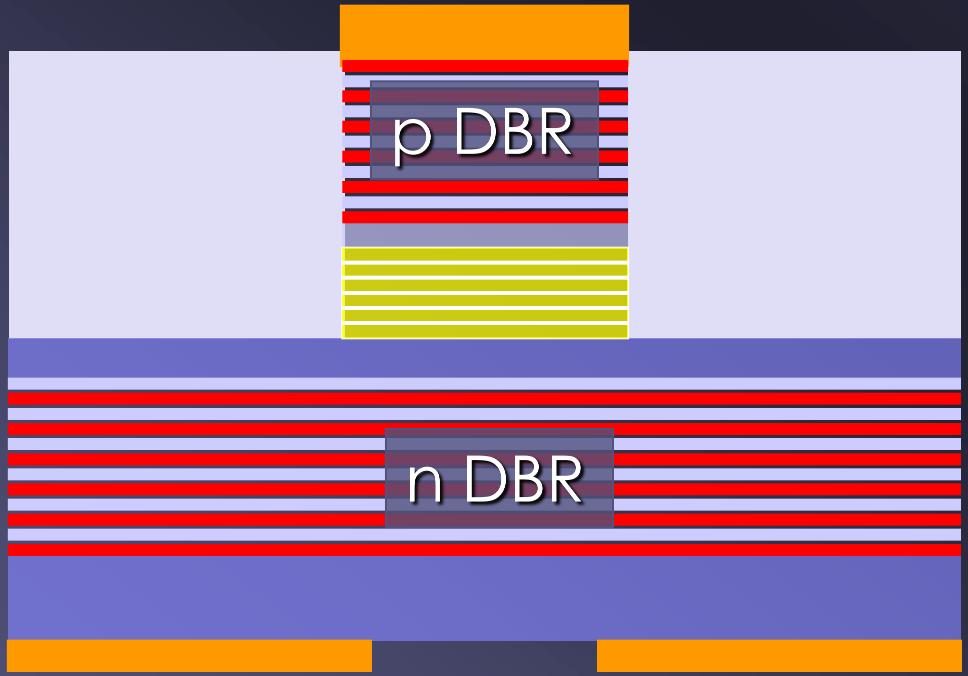


etched mesa/air post VCSEL

aperture usually at the bottom

VCSELs

The confinement of population inversion in the *y* and *z* dimensions is necessary



the etched regions are regrown epitaxially

(e.g., high index nipi layers – passive antiguide region)

buried regrowth VCSELs

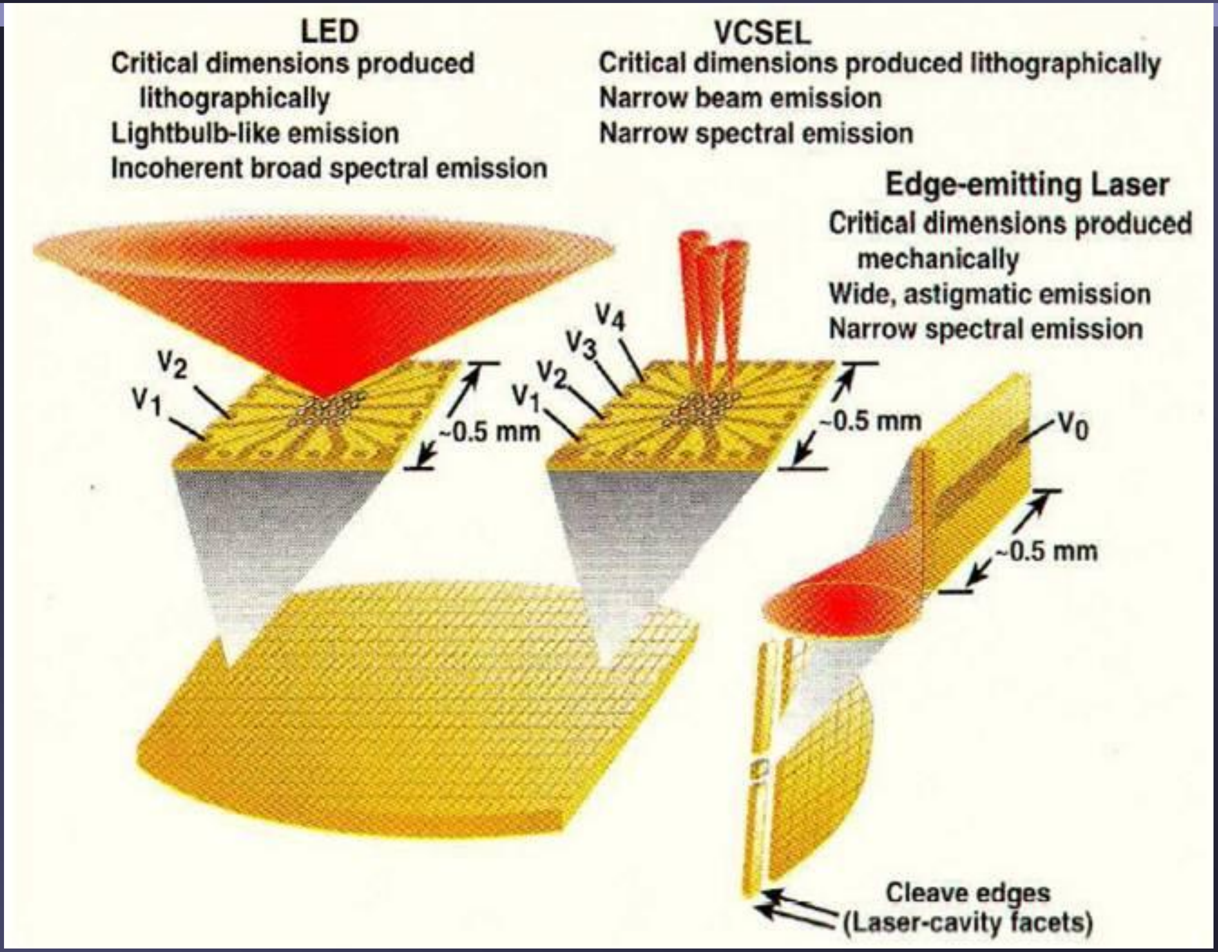
VCSELs

Since the reflectors are grown upon the diode structure

- the resonator length is much shorter than the edge emitting lasers' cavity (less modes)
- the properties of the reflectors can be monitored during the growth

  ⟹ very good reflectance can be produced
- it is easier to couple the VCSEL's light into an optical fiber
- laser arrays can be produced

LEDs, EELs, VCSELs



Soda, Iga, Kitahara and Suematsu 1979;
Axel Scherer and Jack Jewell, 1988

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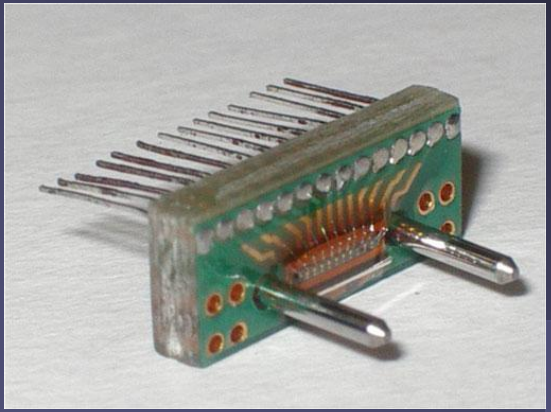
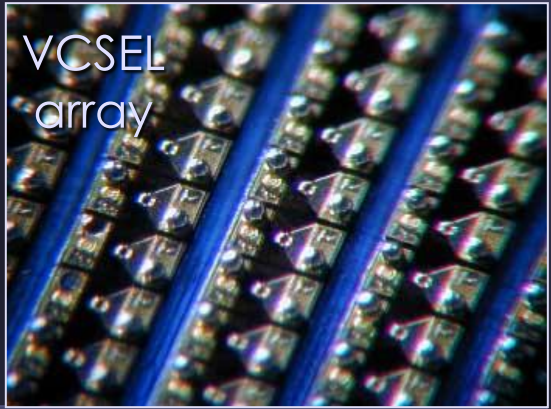
VCSELs

- low electric power consumption
- capability of on-wafer testing
- simplified fiber coupling and packaging
- longitudinal single-mode emission spectrum
- suitability for 2D-array integration, multi-fiber compatibility

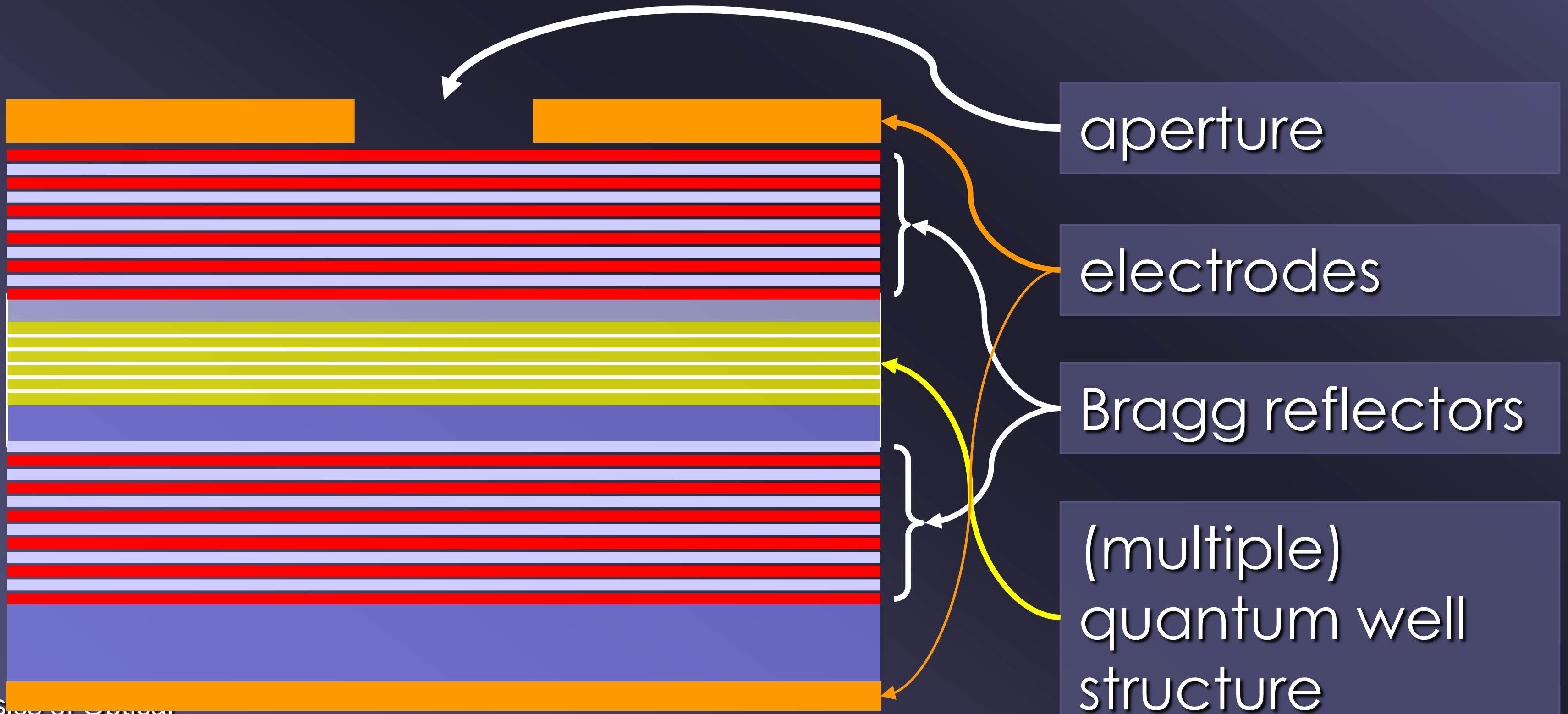




http://www.wsi.tum.de/Research/AmanngroupE26/AreasofResearch/SurfaceEmittingLasers/tabid/110/Default.aspx, http://www.photonics.com/Product.aspx?PRID=21251, http://atlas-service-enews.web.cern.ch/atlas-service-enews/2009/news_09/news_vcsel.php, www.thorlabs.de,

VCSELs

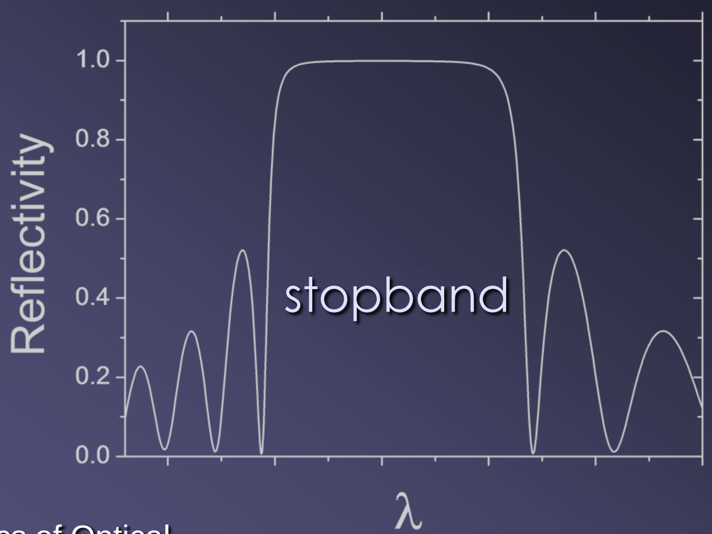
The high gain of quantum wells make possible to place the resonator above and under the active region:



VCSELs

Distributed Bragg reflector is a structure formed from multiple layers of alternating materials with varying refractive index. Each layer boundary causes a partial reflection of an optical wave. For waves whose wavelength is close to

4×the optical thickness of the layers,

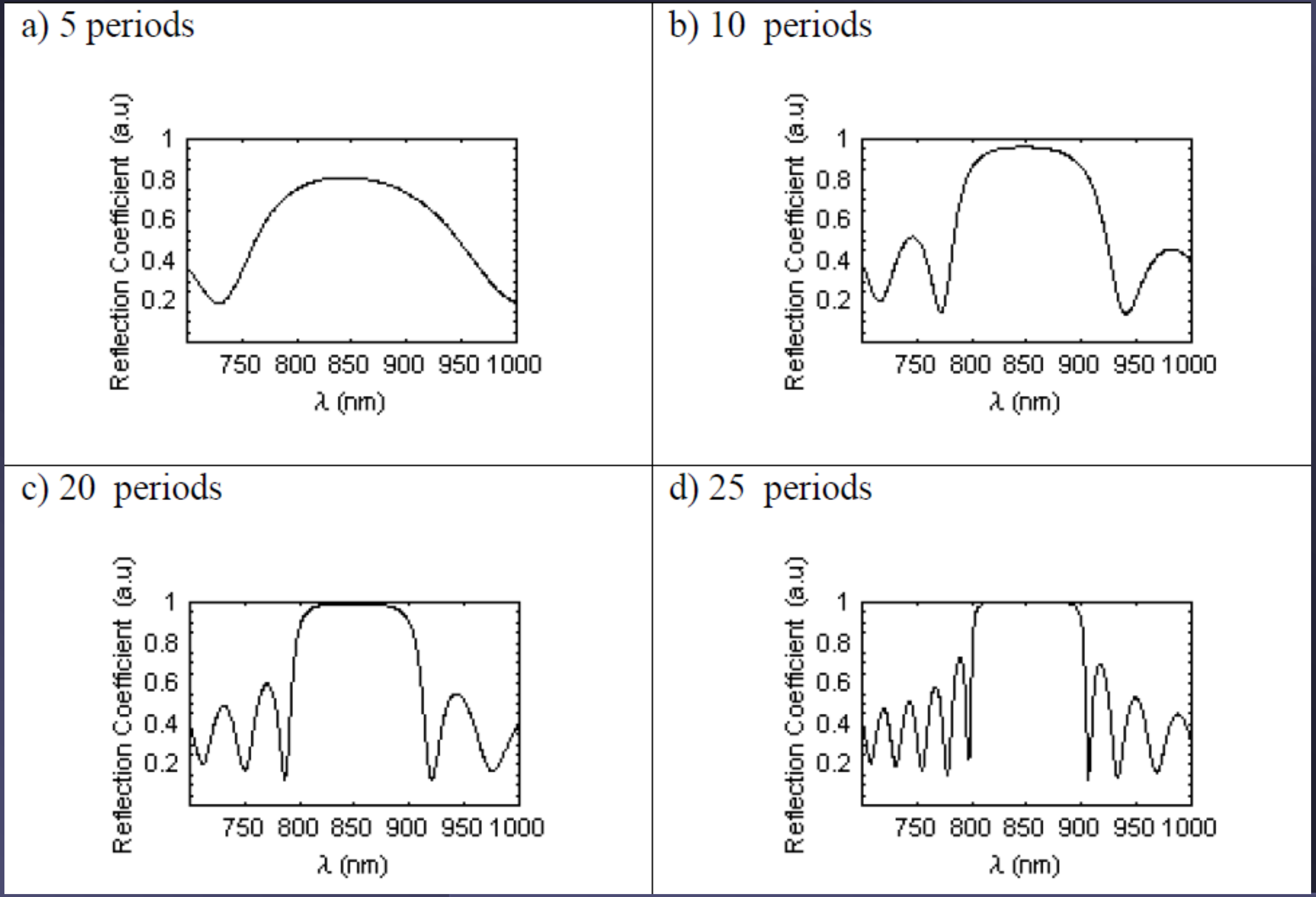


the many reflections combine with constructive interference, and the layers act as a high-quality reflector.

http://en.wikipedia.org/wiki/Distributed_Bragg_reflector

VCSELs

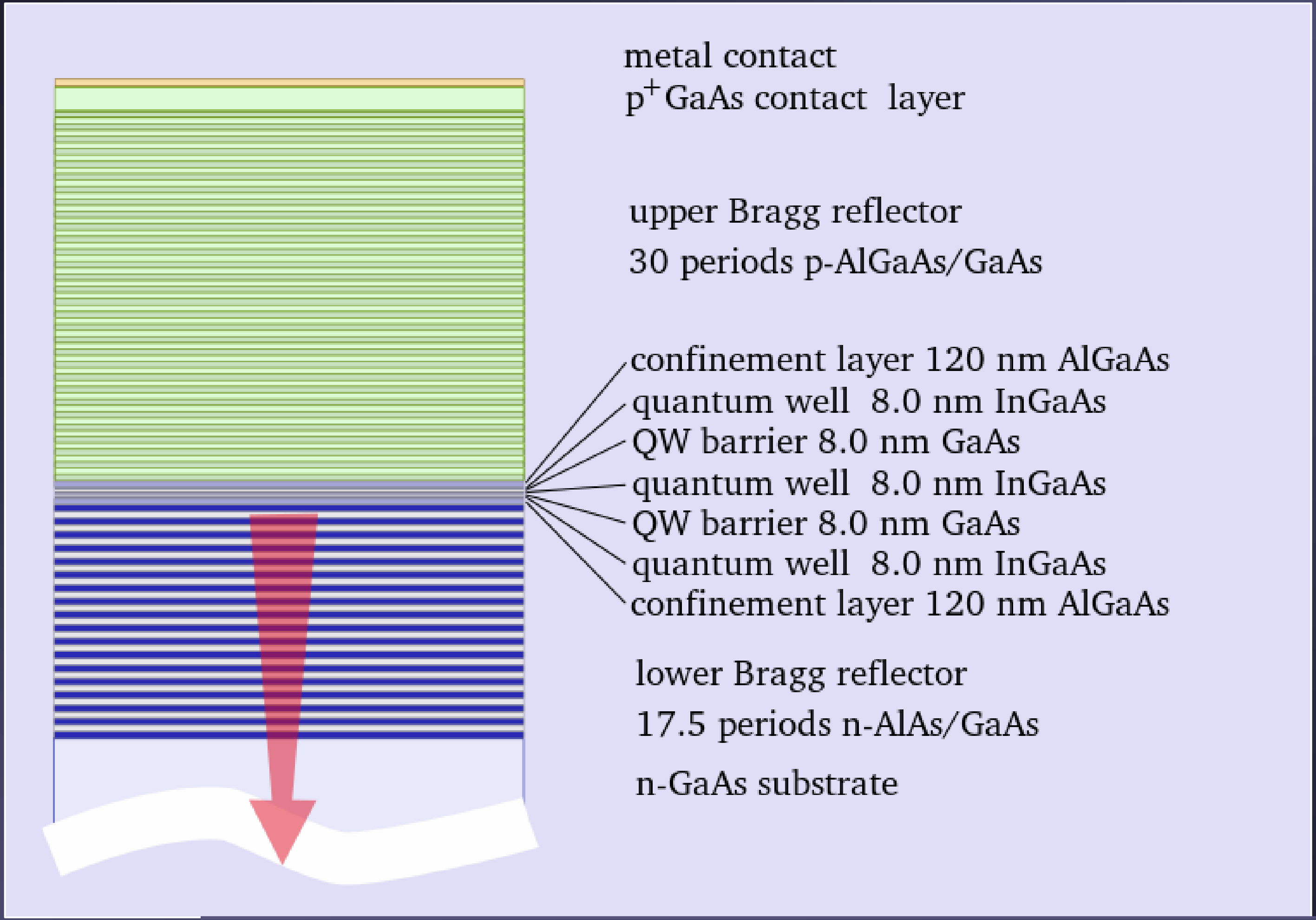
Distributed Bragg reflector



C. J. Hepburn : Temperature Dependent Operation of Vertical Cavity Surface Emitting Lasers (VCSELs) – PhD diss.

VCSELs

Layers

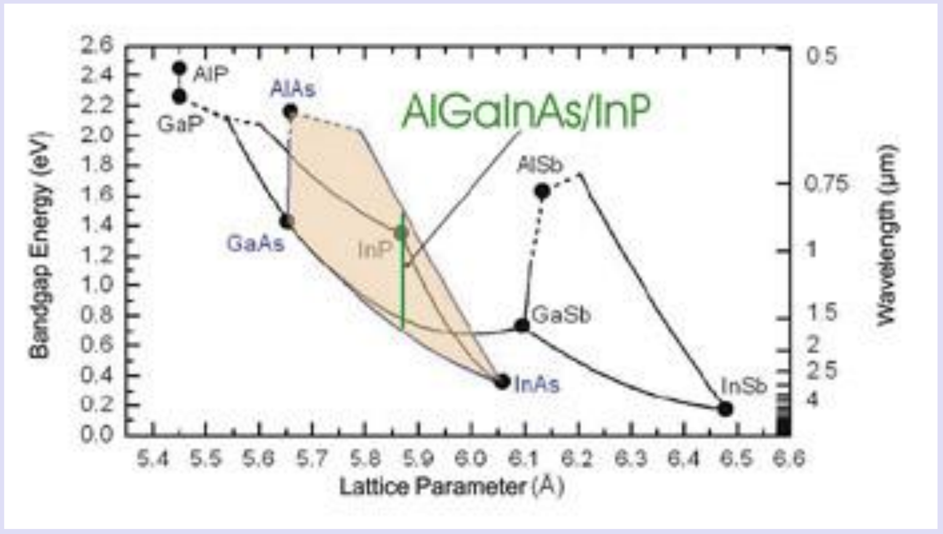


http://en.wikipedia.org/wiki/Vertical-cavity_surface-emitting_laser

VCSELs

Material composition:

- (GaIn)(NAs) on GaAs substrate 1.31µm,
- (InGaAl)As, (InGa)(AsP), and (AlGa)(AsSb) on InP 1.31µm and 1.55µm



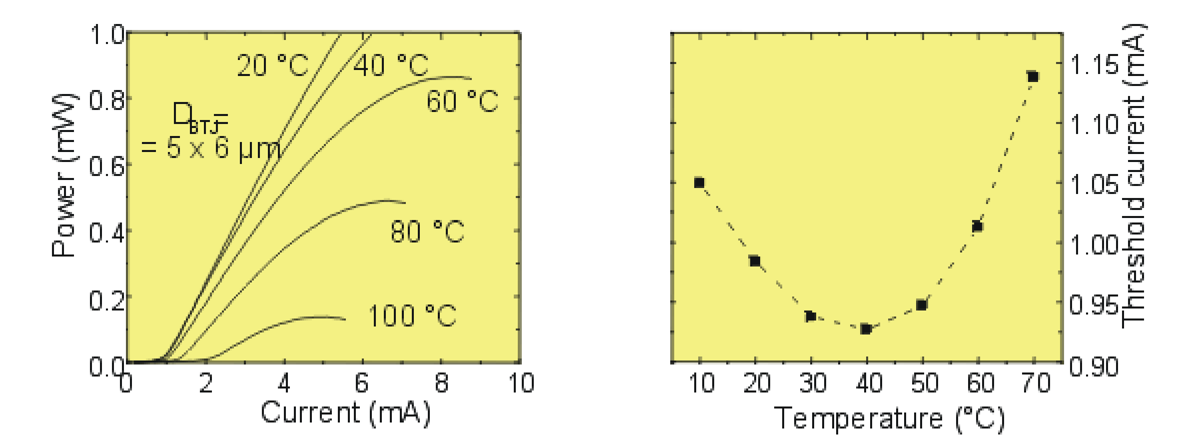
http://www.wsi.tum.de/Research/AmanngroupE26/AreasofResearch/SurfaceEmittingLasers/tabid/110/Default.aspx

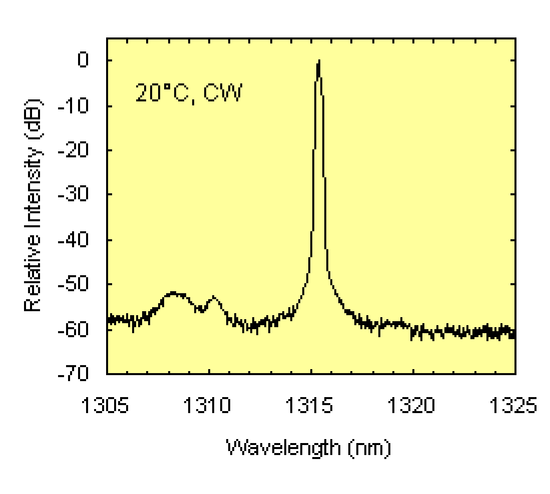
GaAs–AlGaAs system:

- Similar lattice constant
- Strong variation of the refractive index on Al concentration
- Selective oxidation of Al

VCSELs

Power characteristics



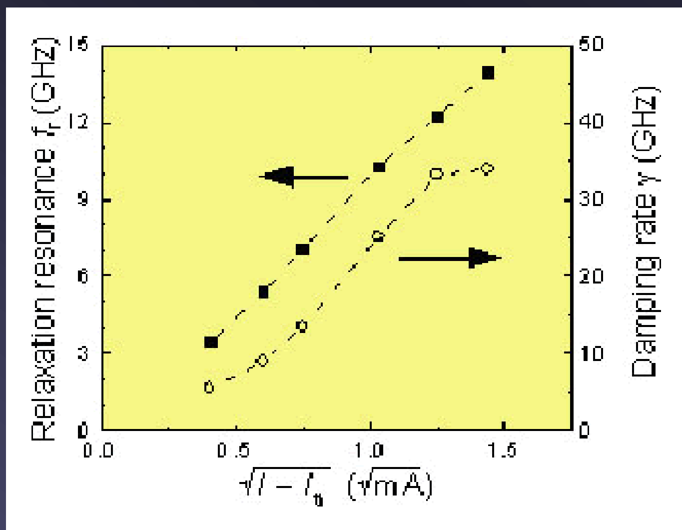


BTJ-VCSELs at 1.55µm

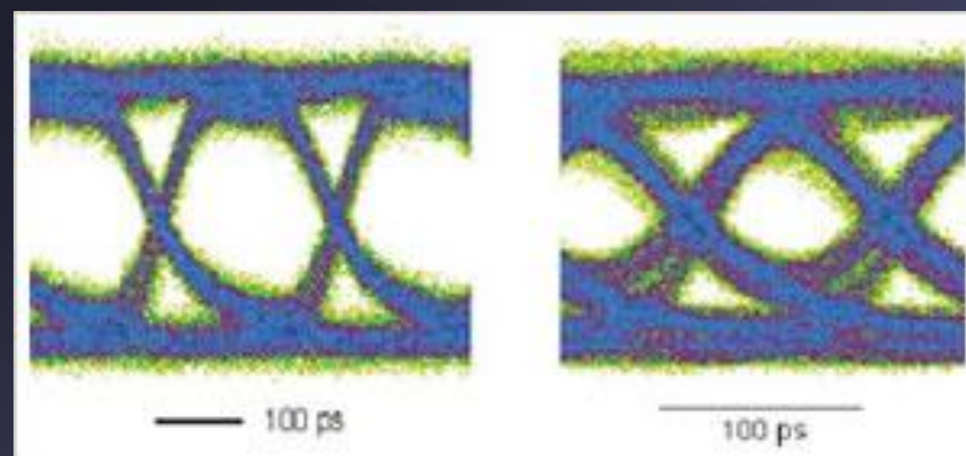
http://www.wsi.tum.de/Research/AmanngroupE26/AreasofResearch/SurfaceEmittingLasers/tabid/110/Default.aspx

VCSELs

Modulation characteristics



http://www.wsi.tum.de/Research/AmanngroupE26/AreasofResearch/SurfaceEmittingLasers/tabid/110/Default.aspx

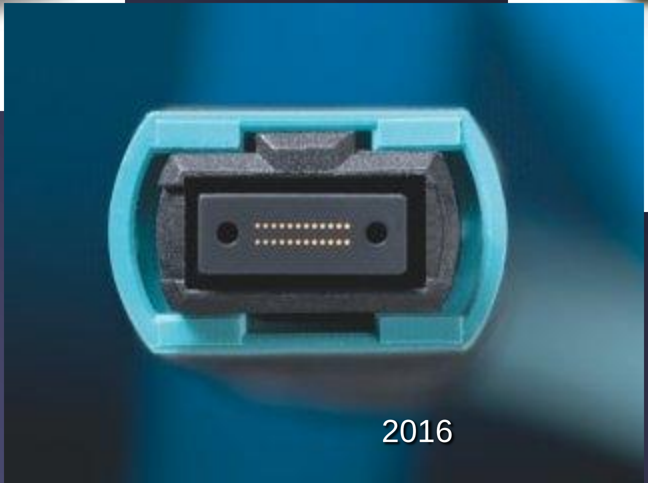


back-to-back measurement at 5 and 10Gbit/s

MPO compatibility

The multimode MPO and other multifiber systems' sources are usually VCSEL arrays

40 or 100 Gb/s data rate



www.elpeus.com,
www.connections.rdm.com

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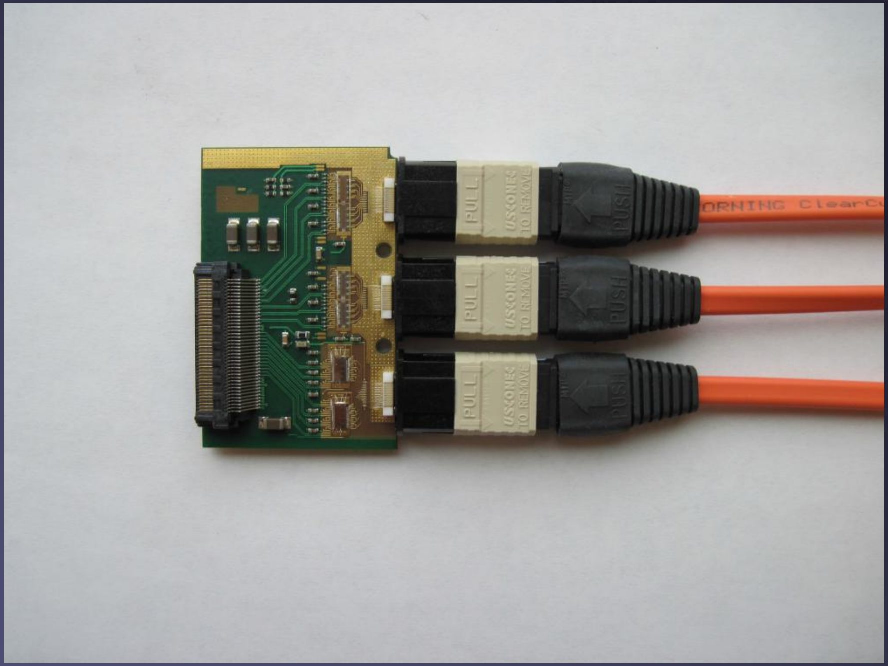
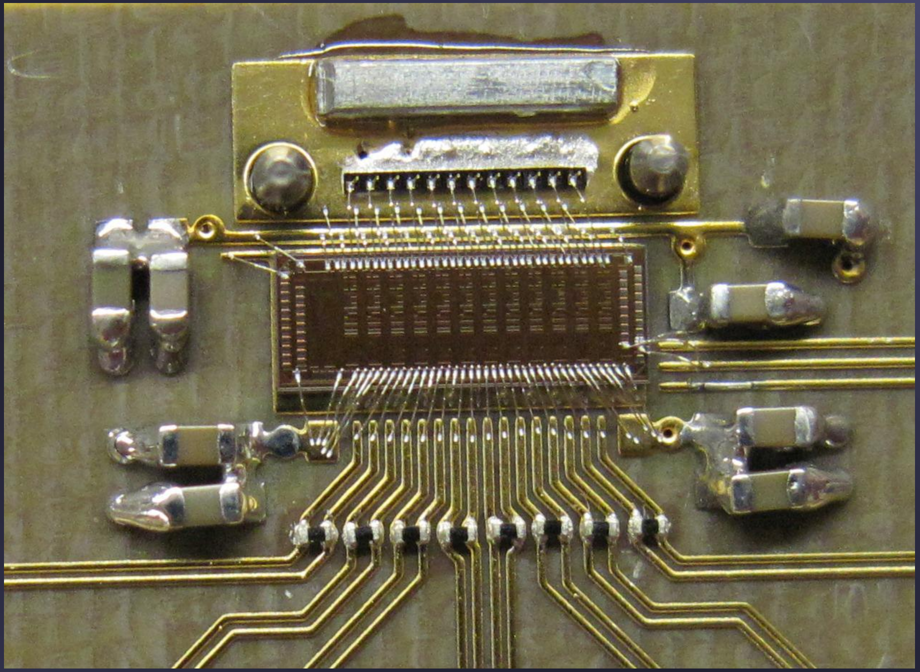
MPO compatibility

The multimode MPO and other multifiber systems' sources are usually VCSEL arrays

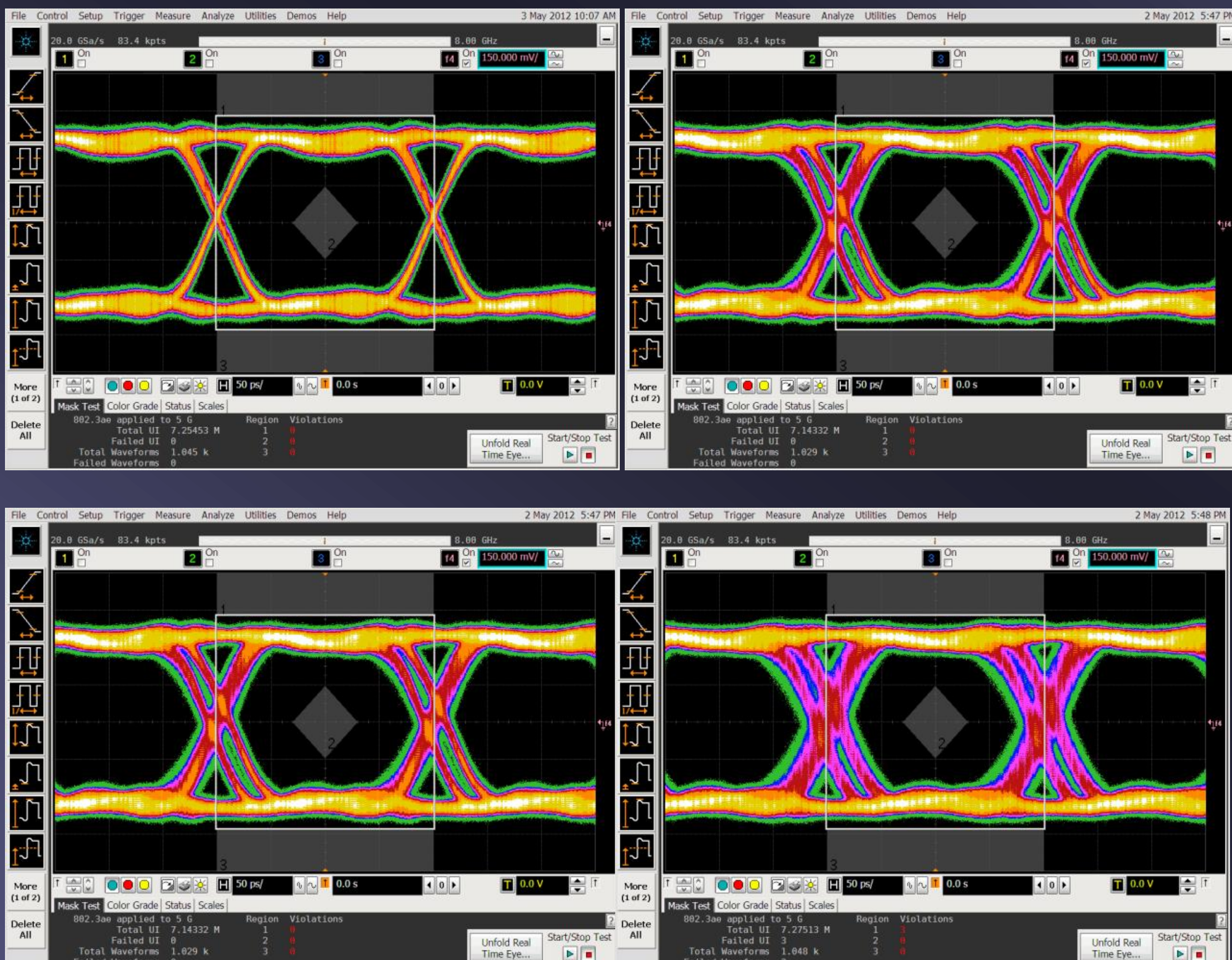




Gan et al. Radiation-Hard/High-Speed VCSEL Array Driver

MPO compatibility

Eye diagrams



10 Gb/s small form-factor pluggable SFP+ transceiver @ 5 Gb/s with optical loopback / VCSEL driver @ 5 Gb/s after 10 Gb/s SFP+ receiver

One channel active/ all channels active

Gan et al. Radiation-Hard/High-Speed VCSEL Array Driver

VCSELs

The confinement of population inversion in the y and z dimensions is necessary, it can be achieved by

- Ion implantation
- Selective oxidation
- Etched mesa – with or without regrowth
- Buried Tunnel Junction

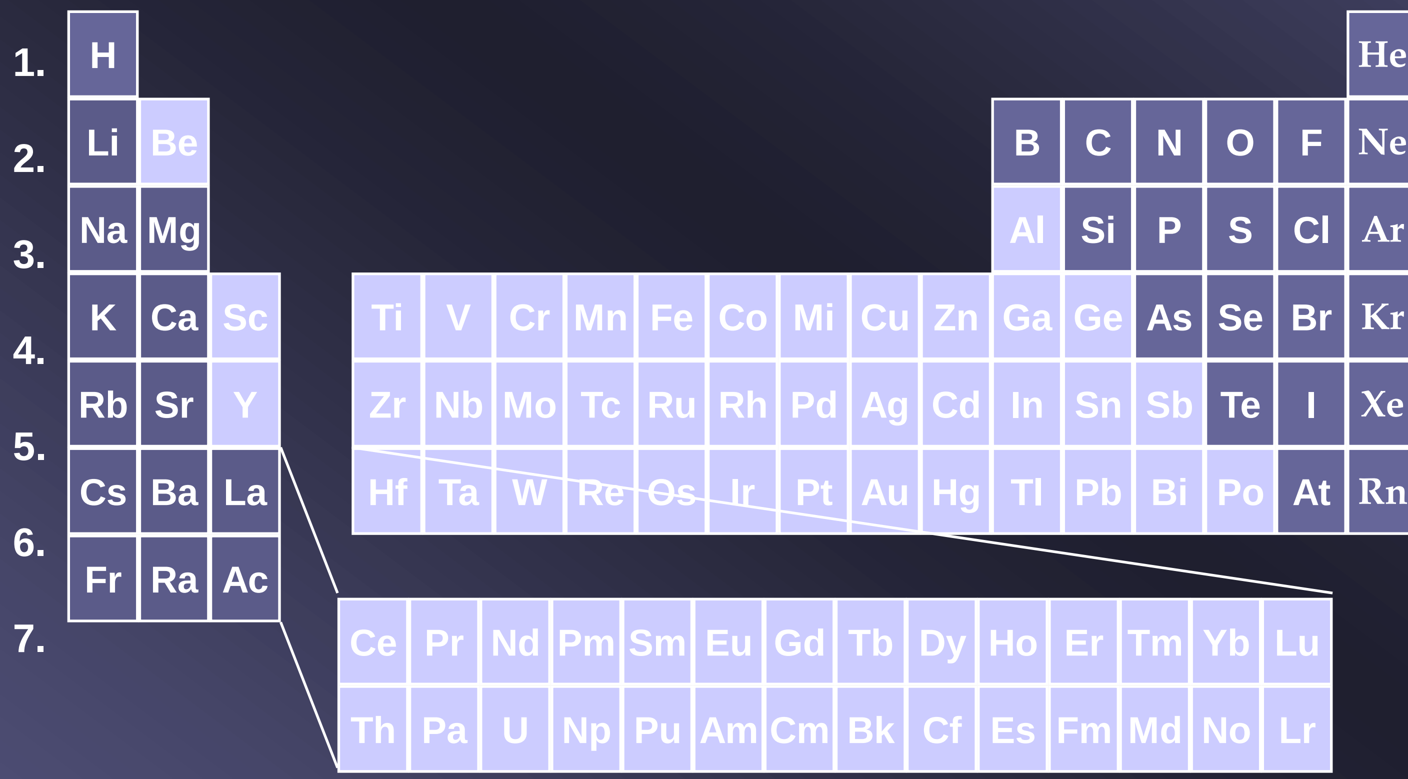
Outline – Amplifiers, regenerators, detectors

- Amplifiers
  - Erbium doped fibers
  - Raman amplifiers
  - Semiconductor optical amplifiers
- Dispersion compensation
  - Dispersion shifted fibers
  - Dispersion compensating fiber
  - Compact dispersion compensation
- Detectors
  - PIN
  - APD

Erbium doped fibers

The 4f (5f) orbitals of the rare earth metals are special:

- the electronic structure is $[Xe]4f^{N-1}5d^{1}6s^{2}$ or $[Xe]4f^{N}6s^{2}$



Erbium doped fibers

The 4f (5f) orbitals of the rare earth metals are special:

- the electronic structure is $[Xe]4f^{N-1}5d^{1}6s^{2}$ or $[Xe]4f^{N}6s^{2}$
- they are usually 3+ ions
- $5s^{2}5p^{6}$ orbitals have larger radius, than the 4f ⟹ isolating "sphere" ⟹ atom-like behavior
- energy spectrum of very narrow bands if the insulator is doped by lantanoids

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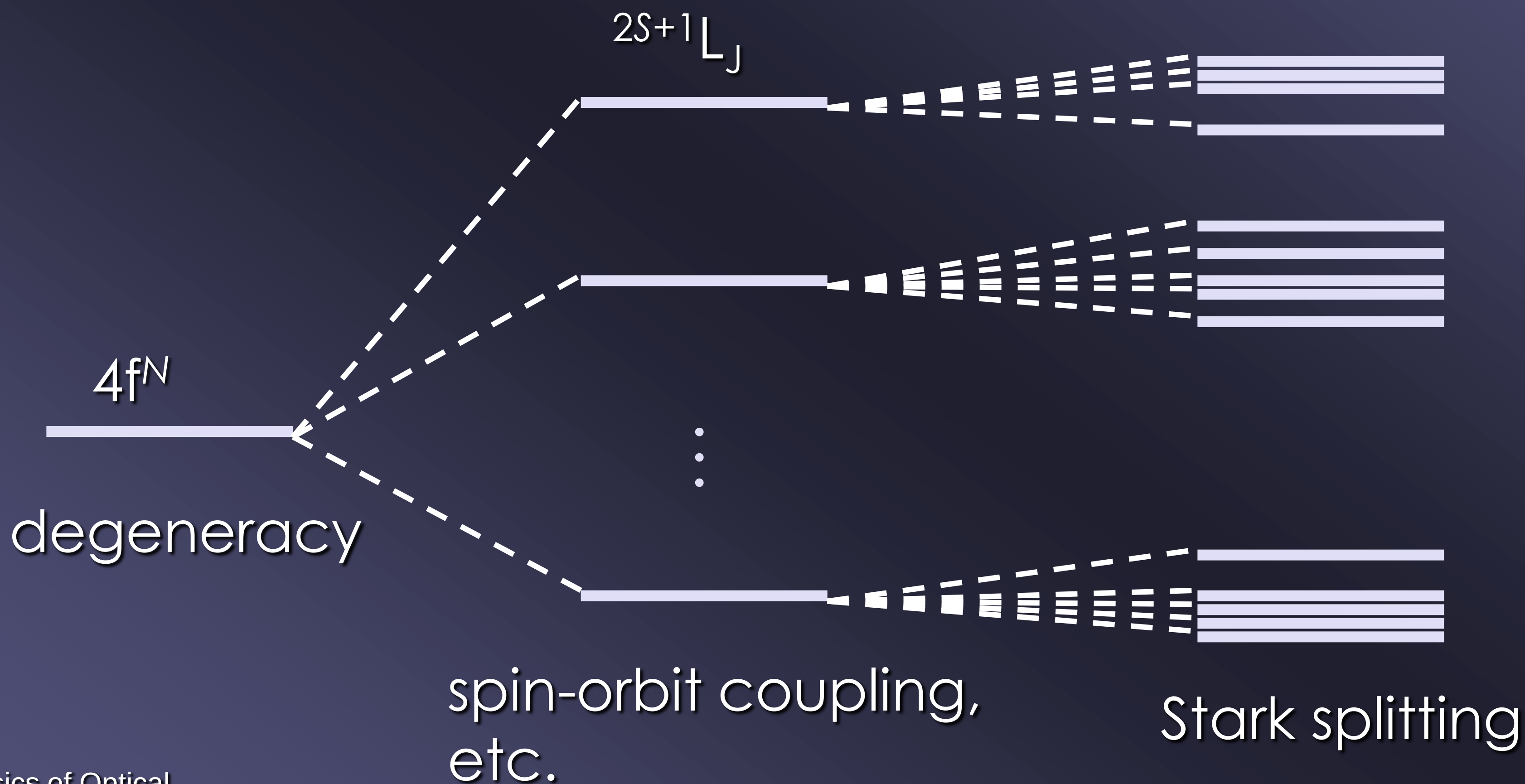
Erbium doped fibers

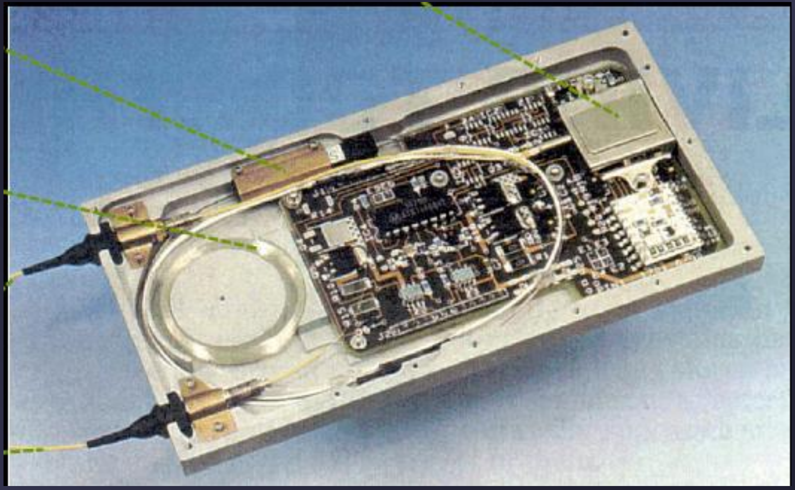
The 4f orbitals of the rare earth metals is split by atomic forces and the crystalline field



Erbium doped fibers

The $^4I_{13/2} \leftrightarrow {}^4I_{15/2}$(GS) transition in Er^{3+} ions belong to photons of wavelength ~1.5 μm

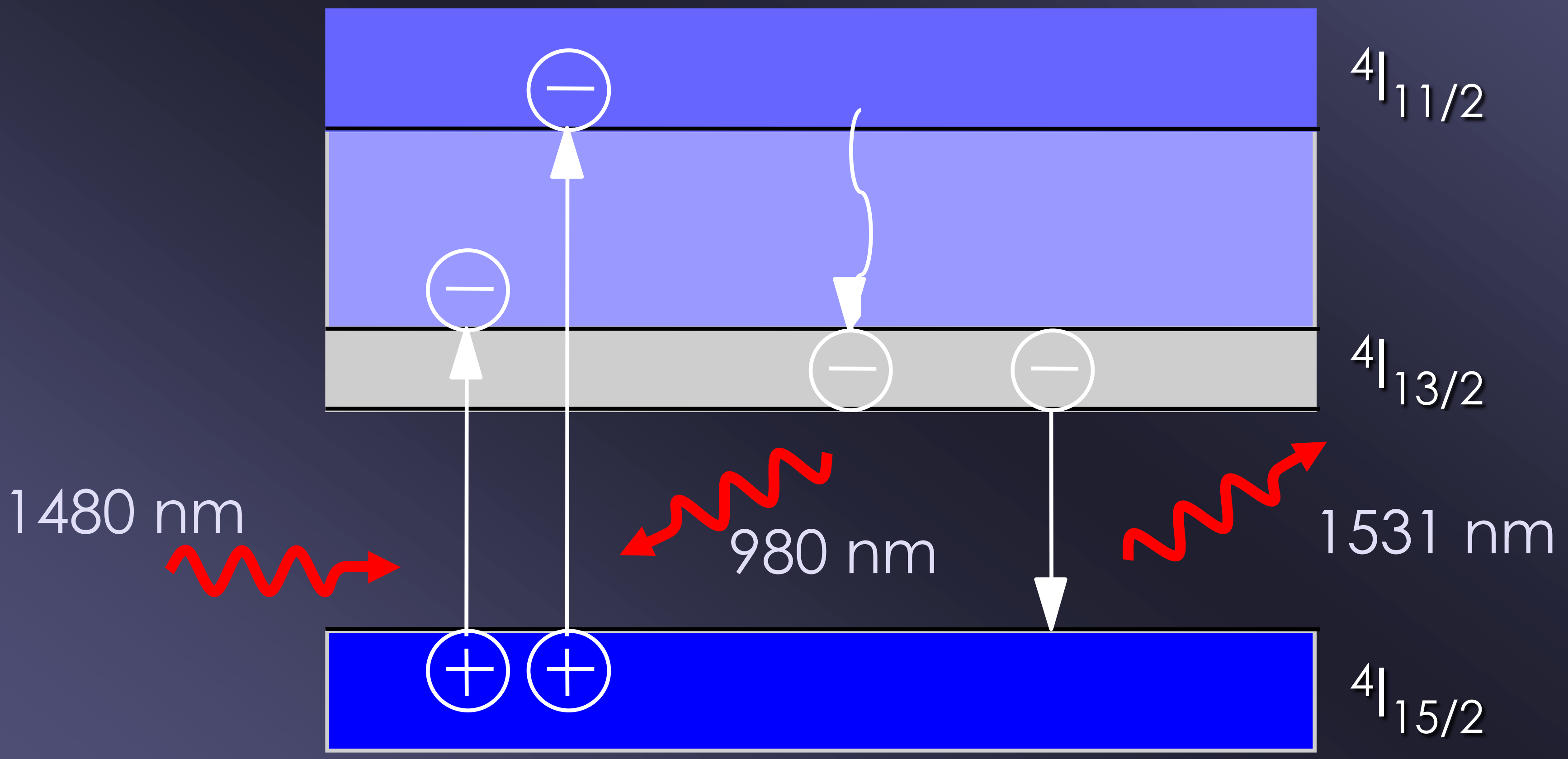
- two main pump regions: 1480 nm and 980 nm with significant absorption
- large gap between the two lowest level $^4I_{13/2}$ and $^4I_{11/2}$ ⟹ large lifetime of the $^4I_{13/2}$ (~10 ms, depending on hosts), mostly radiative transition
- three-level system
- concentration quenching
  ⟹ shorter lifetime



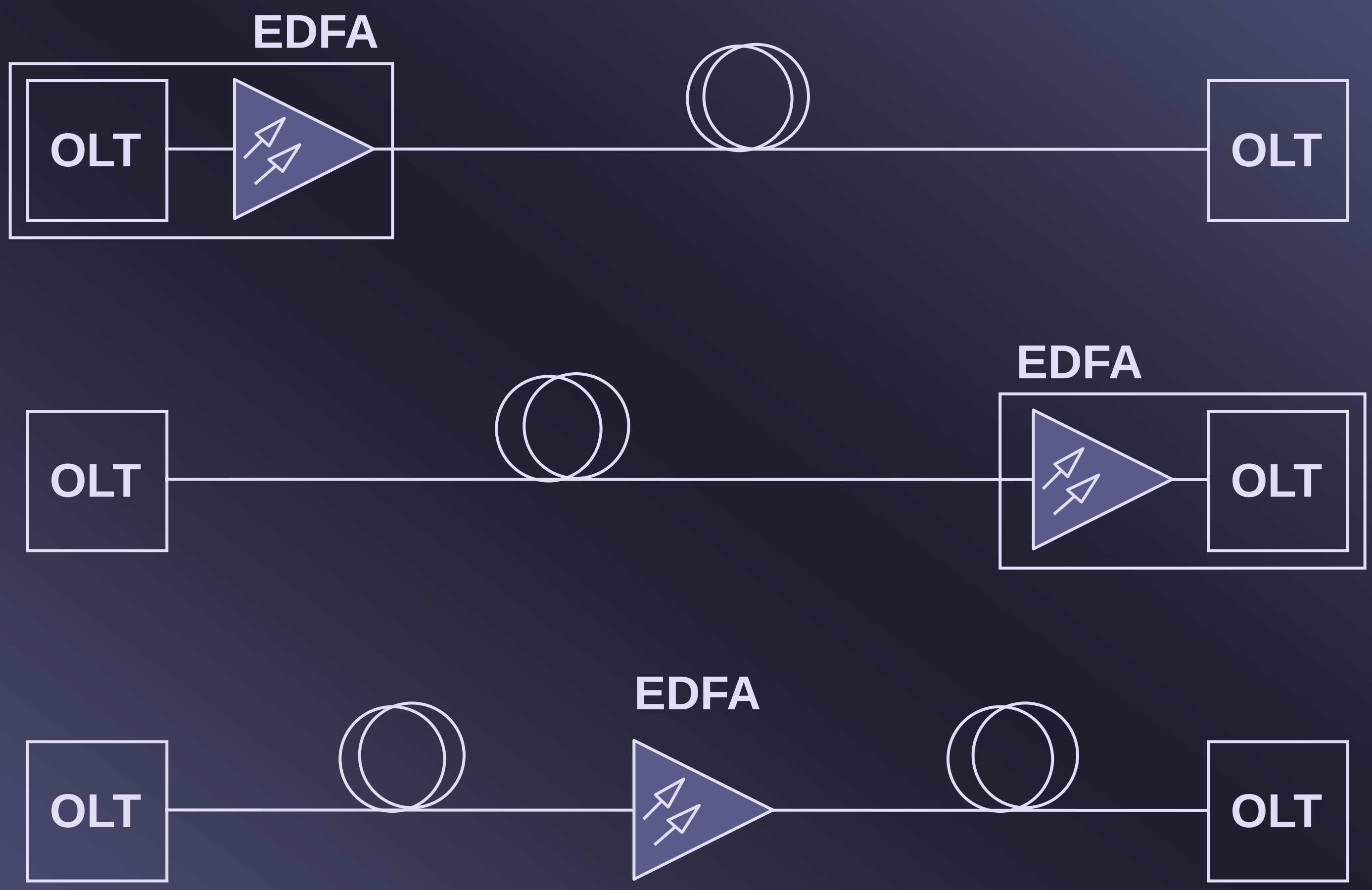
Venkataranaman: Optical Amplifiers

Erbium doped fibers

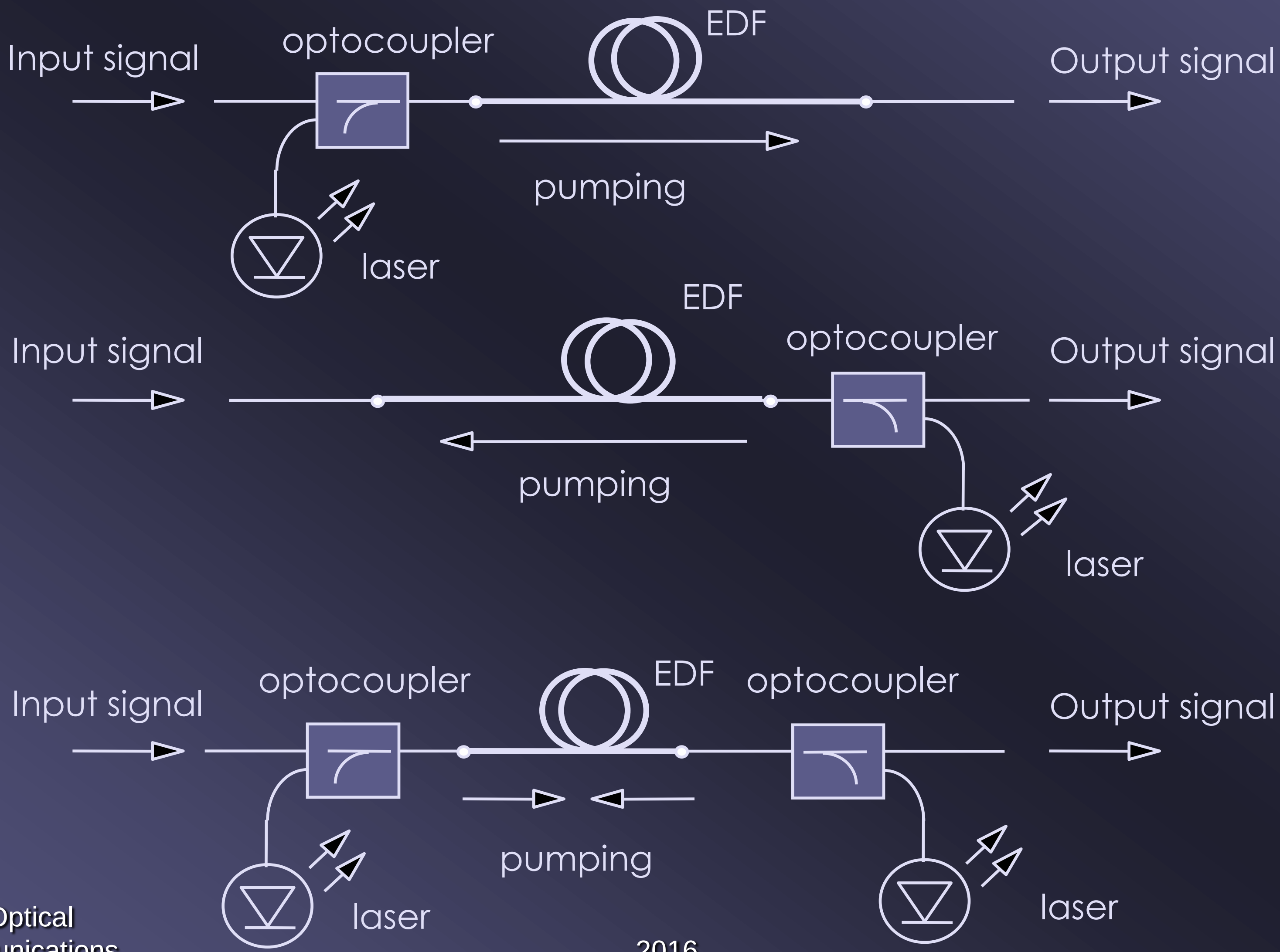
- The $^4I_{13/2} \leftrightarrow {}^4I_{15/2}$(GS) transition in Er^{3+} ions belong to photons of wavelength ~1.5 μm



Application of EDFAs



Pumping of EDFAs



Raman amplifiers

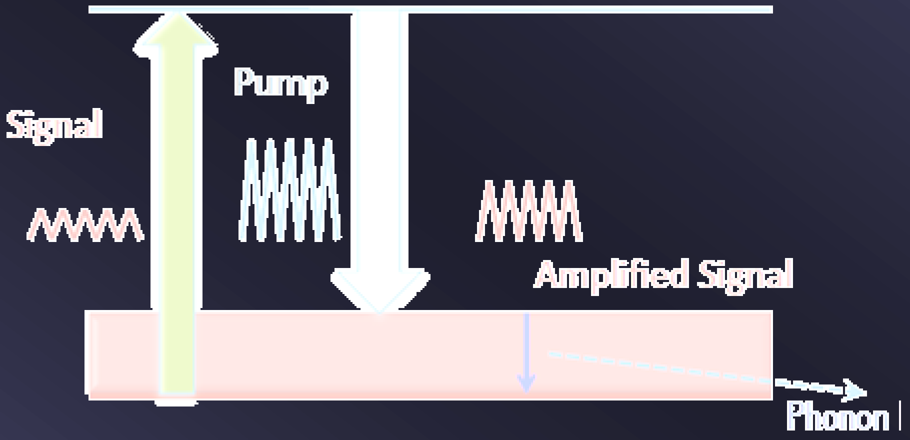
Based on stimulated Raman scattering

-the pumping photon gives part of its energy to the fiber

-energy relaxes as phonon

-better for end amplifier

backward pumping is usual



Venkataranaman: Optical Amplifiers

Semiconductor optical amplifiers

Based on semiconductor heterojunctions, but not in laser mode

- preventing laesr mode by antireflection coating and carefully chosen cleave angle
- electrically pumped
- best for in-line amplifier, compact
- strong nonlinearity
- larger noise
- smaller amplification
- smaller bandwidth

Venkataranaman: Optical Amplifiers

Regenerators

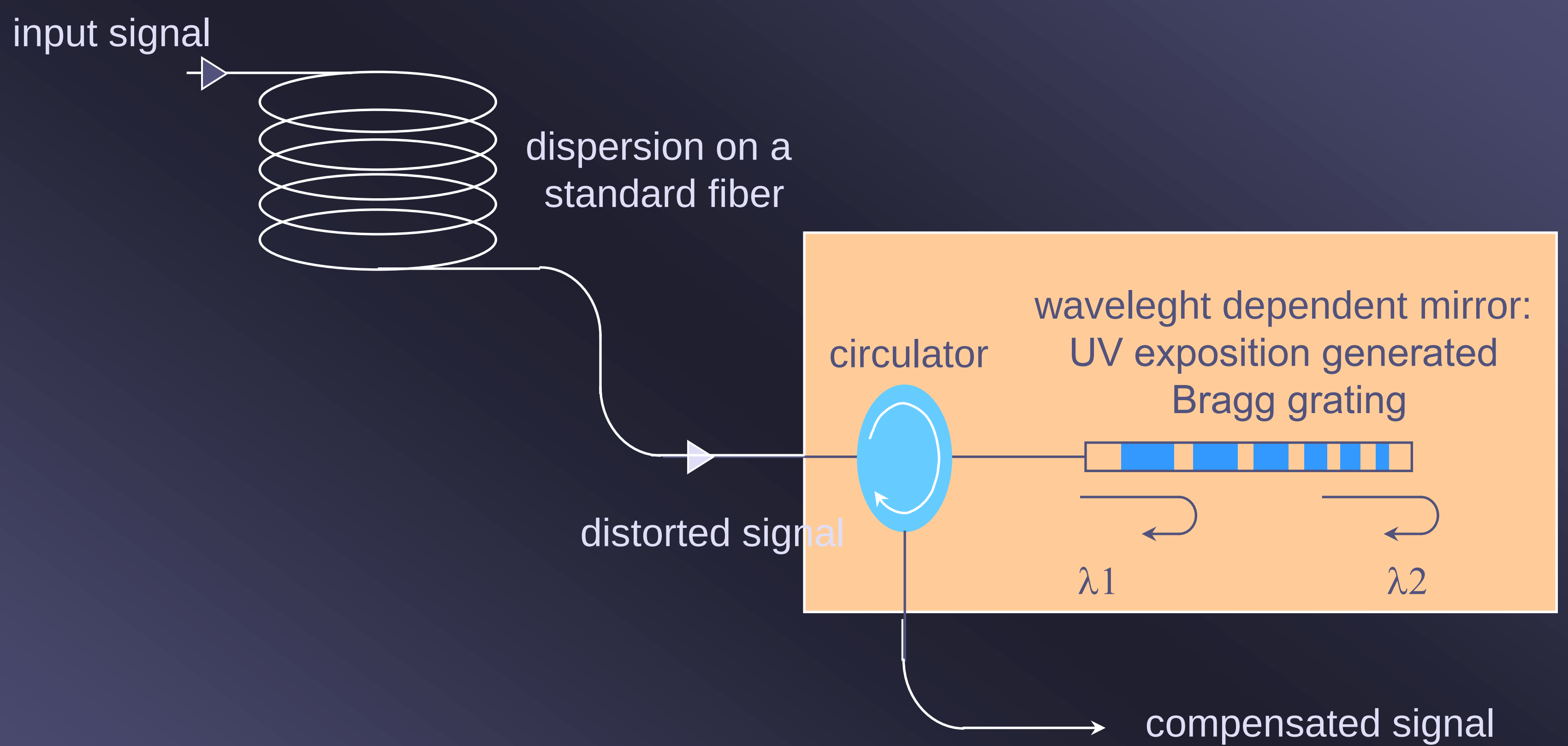
An optical regenerator consists of

- amplifier
- dispersion compensator

Dispersion compensators can be

- dispersion shifted fibers – no need for dispersion compensators
- regular fibers
  - dispersion compensating fibers
  - Bragg grated fiber and circulator

Dispersion compensation



Receivers

Receivers produce electrons or other charge carriers from photons.

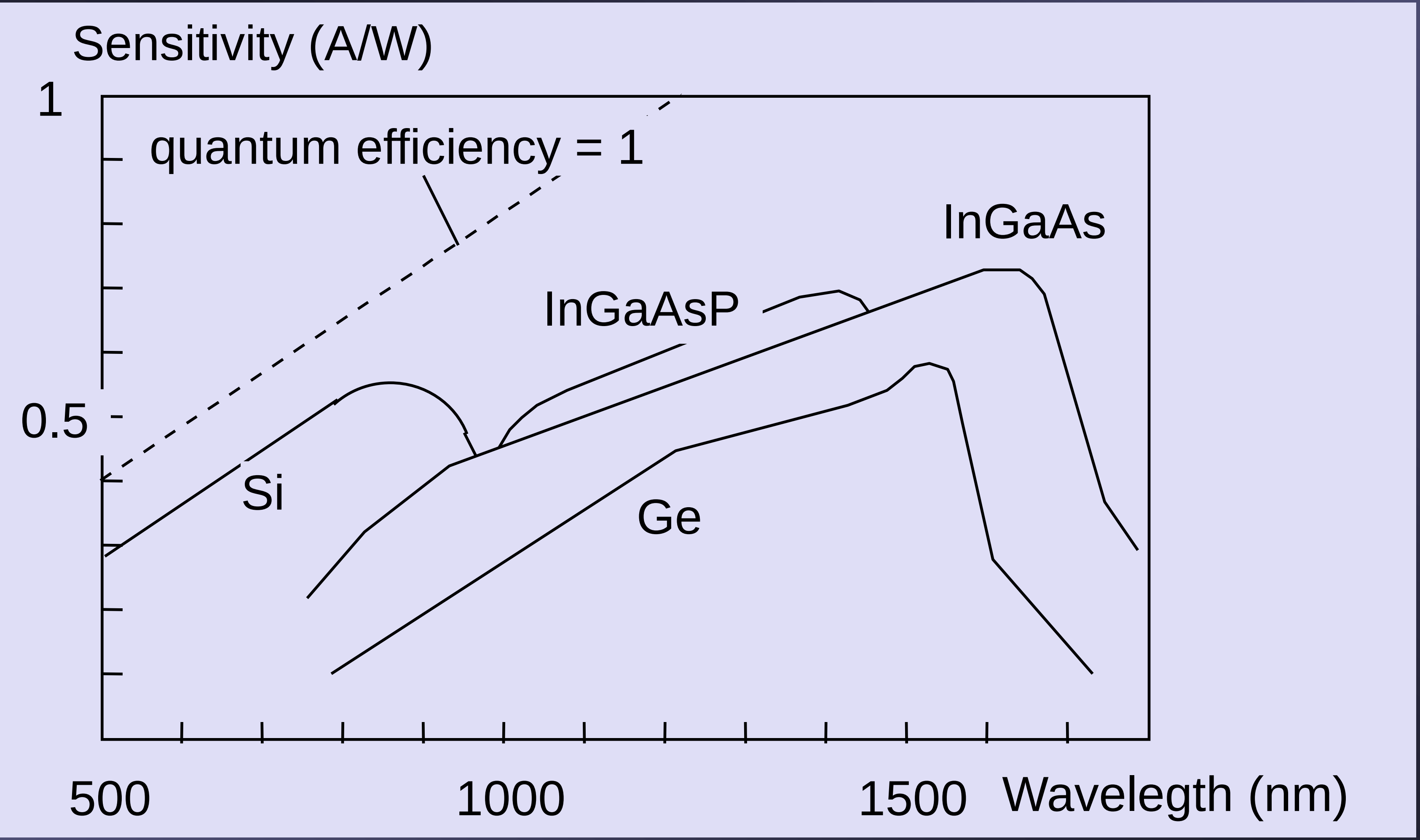
Requirements:

- Large efficiency
  - decreasing reflection – connection
  - increasing detecting area – PIN
  - decreasing the recombination of the generated charge carriers – APD
- Low noise
- Compatibility
- Quick response
- Wavelength selectivity (not necessarily)

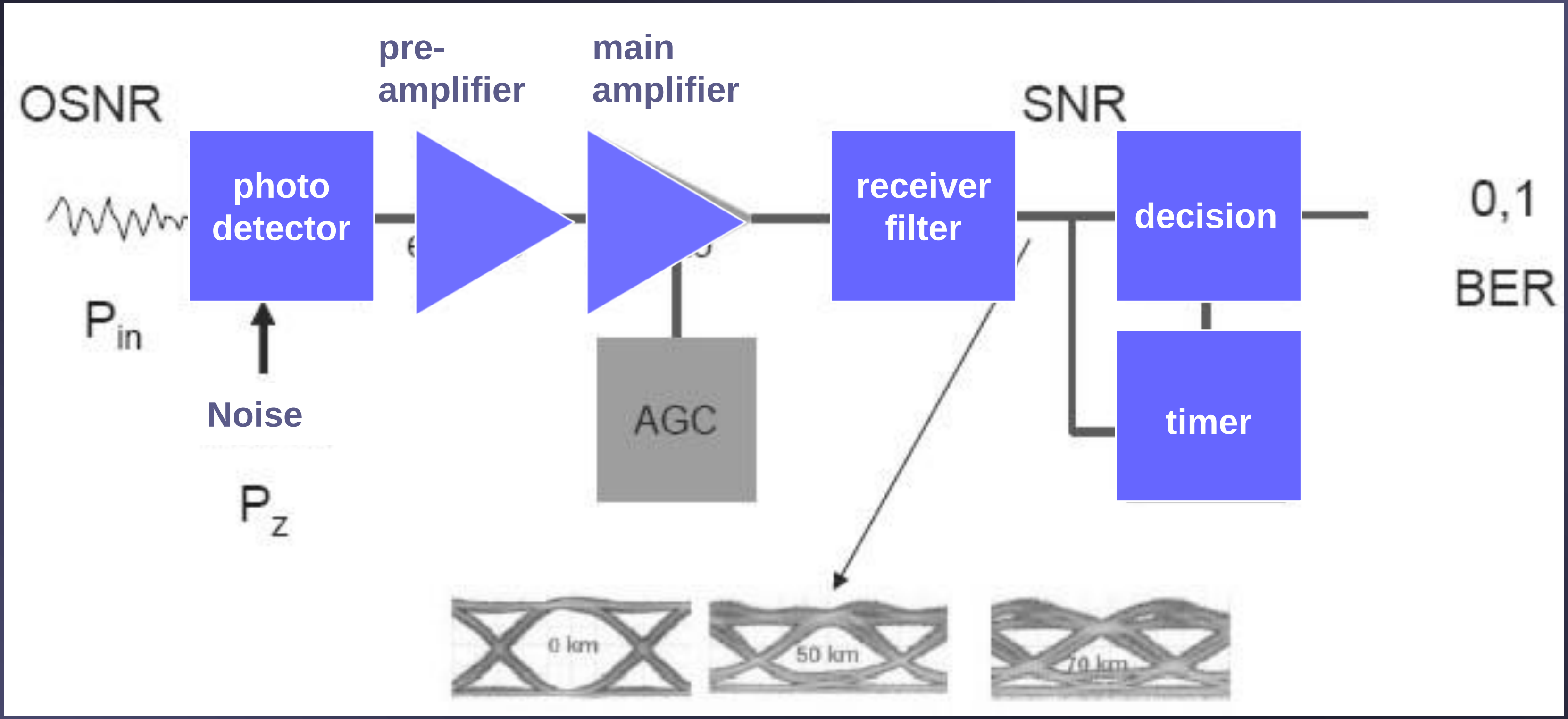
Parametrs of detectors

- Quantum efficiency: $\eta = J_f / e\Phi$: the rate of the photons and the arising charge carriers
- Sensitivity: $R = e\eta / h\nu$: current arising from the incoming power in the detector
- Bandwidth: depends on the charge carriers' crossing time in the empty
- Noise:
  - dark current
  - shotnoise

Receivers


Sensitivity (A/W)
1
quantum efficiency = 1
InGaAs
InGaAsP
0.5
Si
Ge
500
1000
1500
Wavelegth (nm)

Receivers

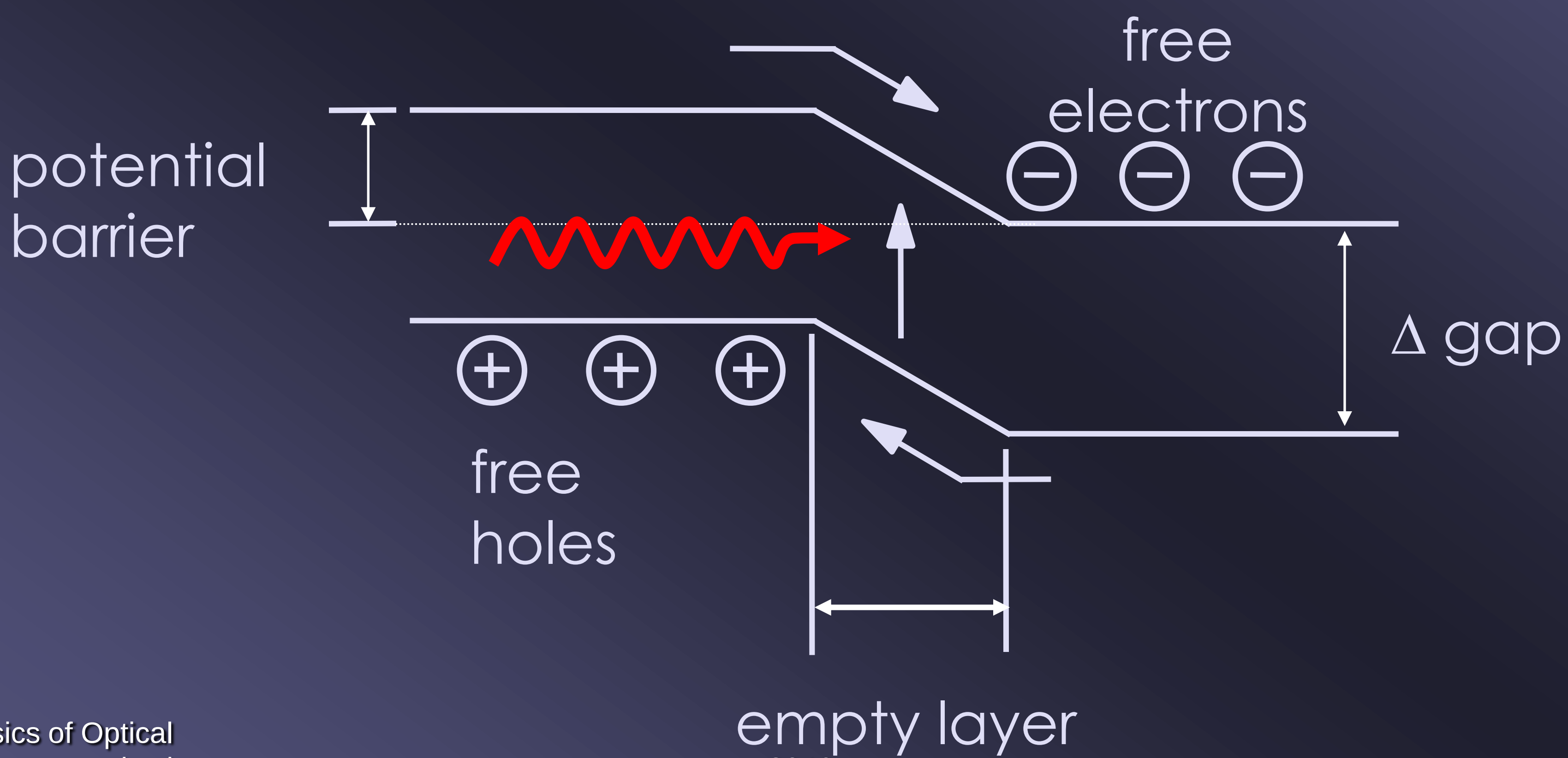


Receiver sensitivity: received optical power necessary for 10^{-9} BER
Quantum limit: 36 photons/bit, practically ~1000 photons/bit

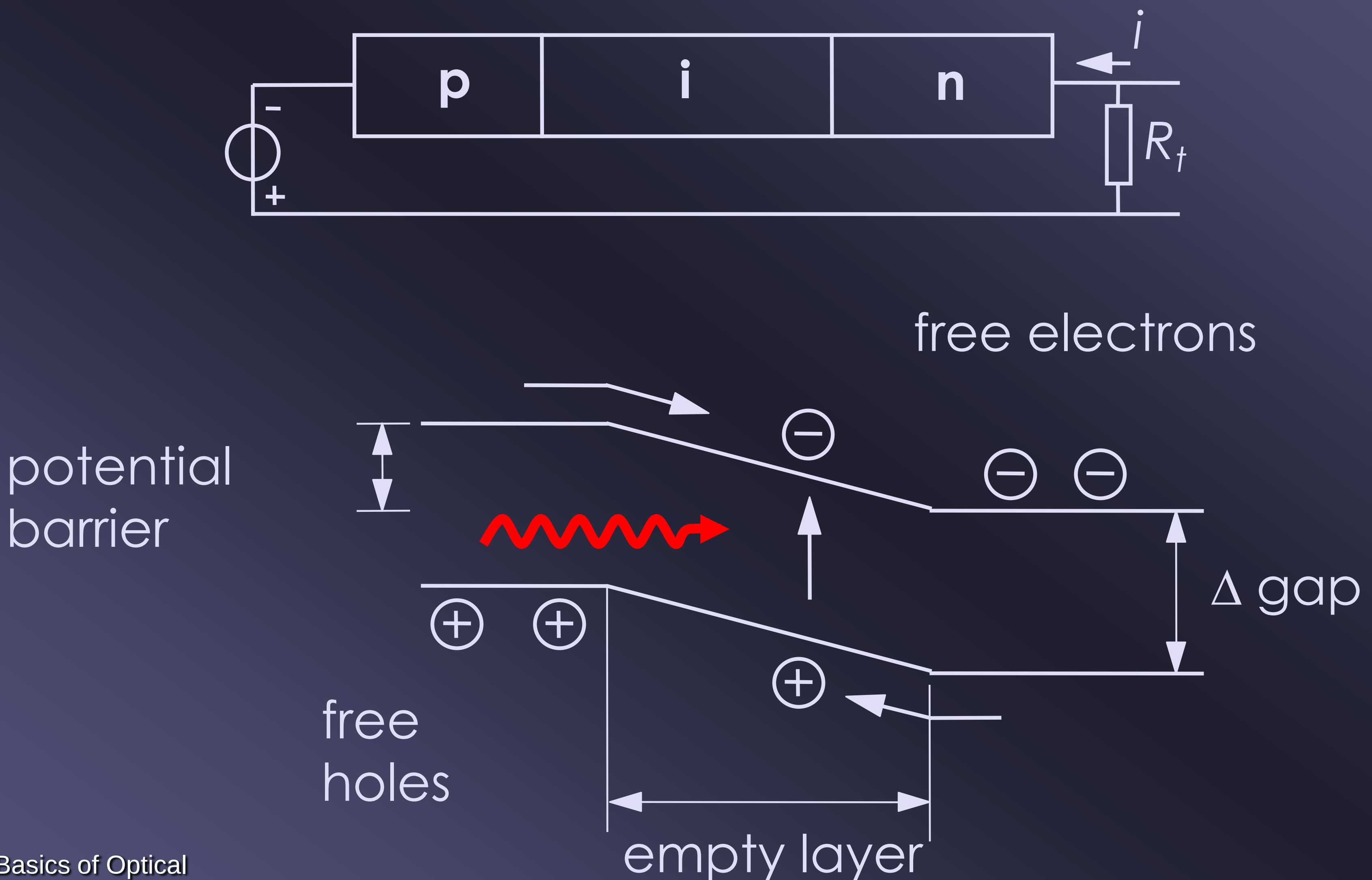
p-n hetrerojuction photodiode

Reverse bias empty layer between p and n

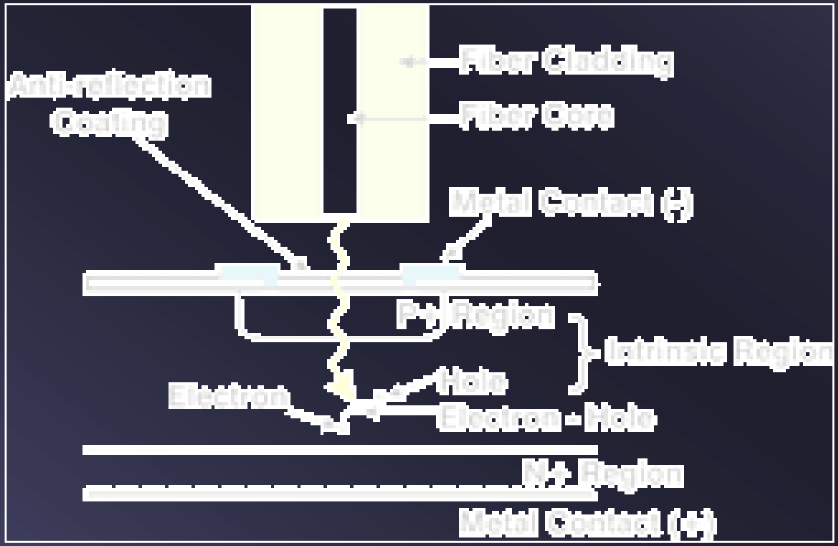
Electron-hole pairs arise due to photon excitations

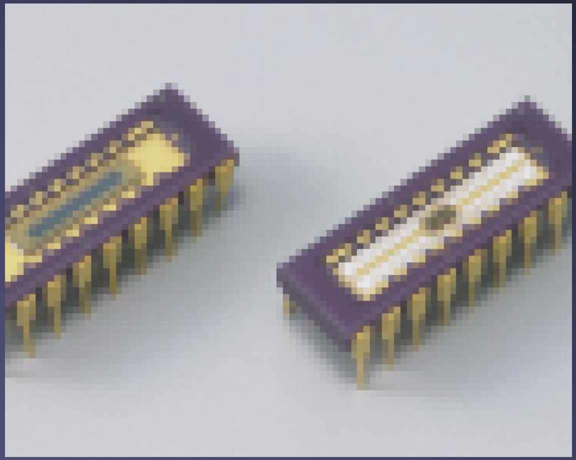


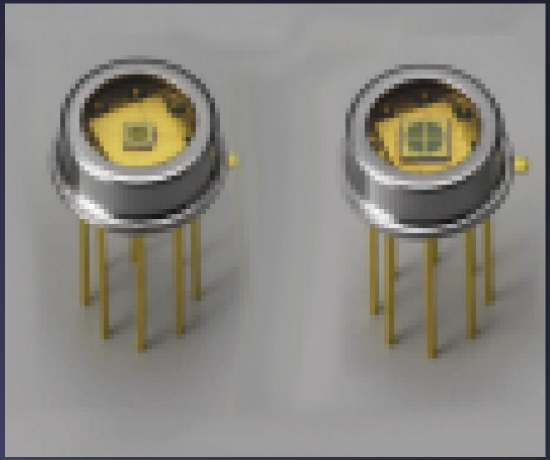
PIN fotodióda

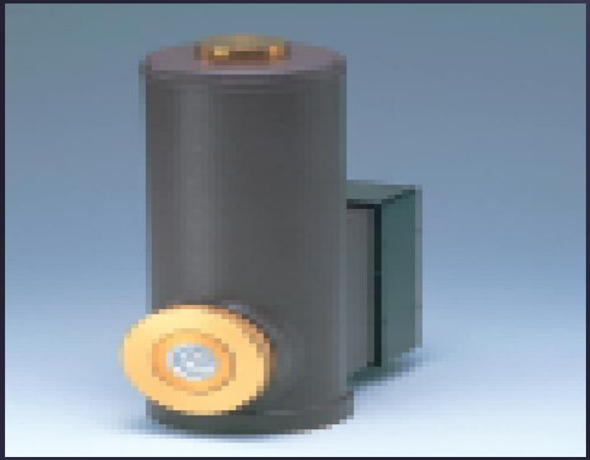


PIN photodiode

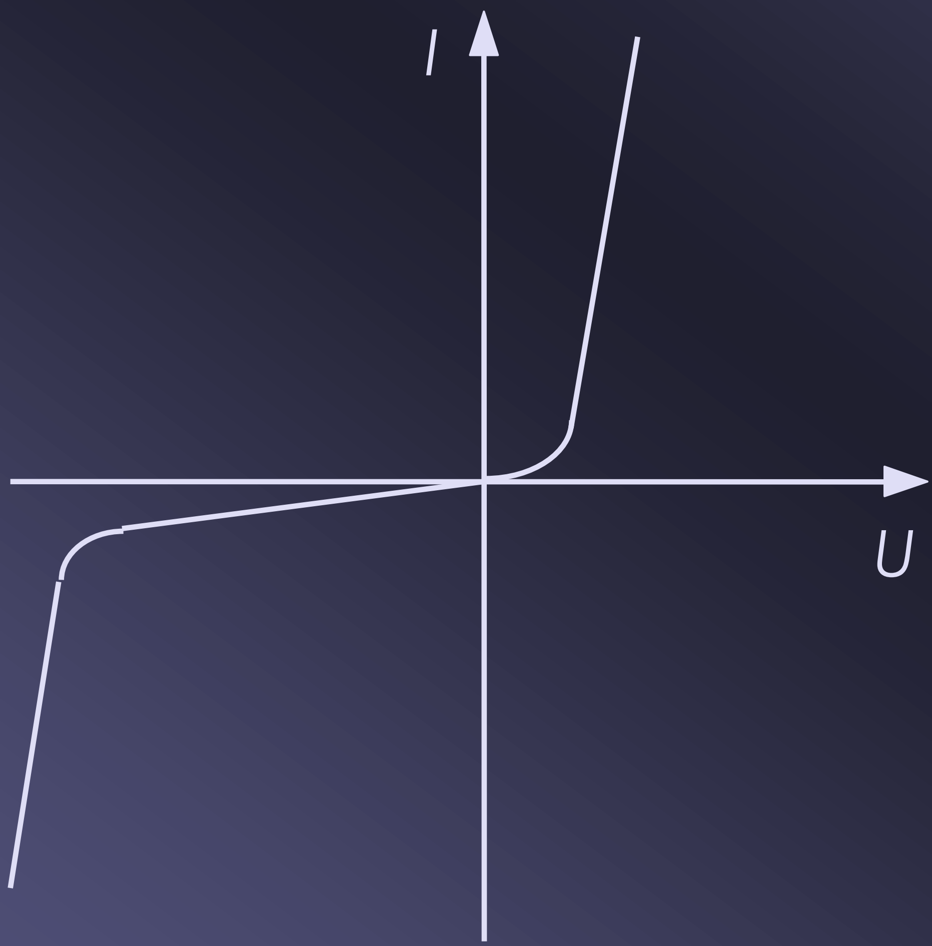






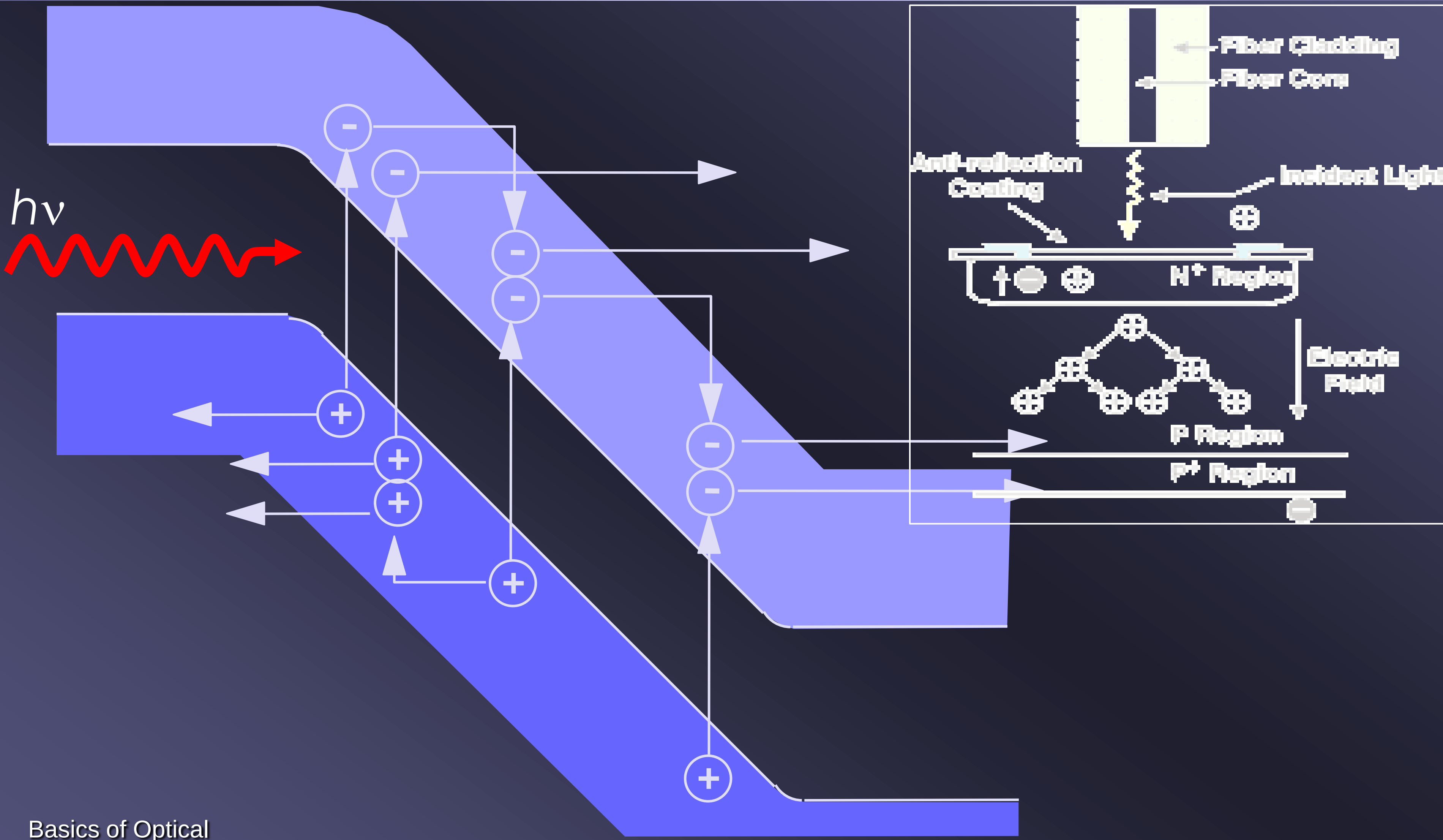


Avalanche photodiodes



Avalanche:
due to the large voltag, large electronic field
one electron can be accelerated so that its kinetic energy can generate more electron-hole pairs

Avalanche photodiodes



Outline – Modulators, switches

- Physical basics
  - electrooptic effect
  - magnetooptic effect
  - acoustooptic effect
  - elastooptic effect
  - thermooptic effect
  - Bragg grating, Bragg mirrors
  - interferometers
- Modulation
- Switching

Modulators

Modulation methods

External

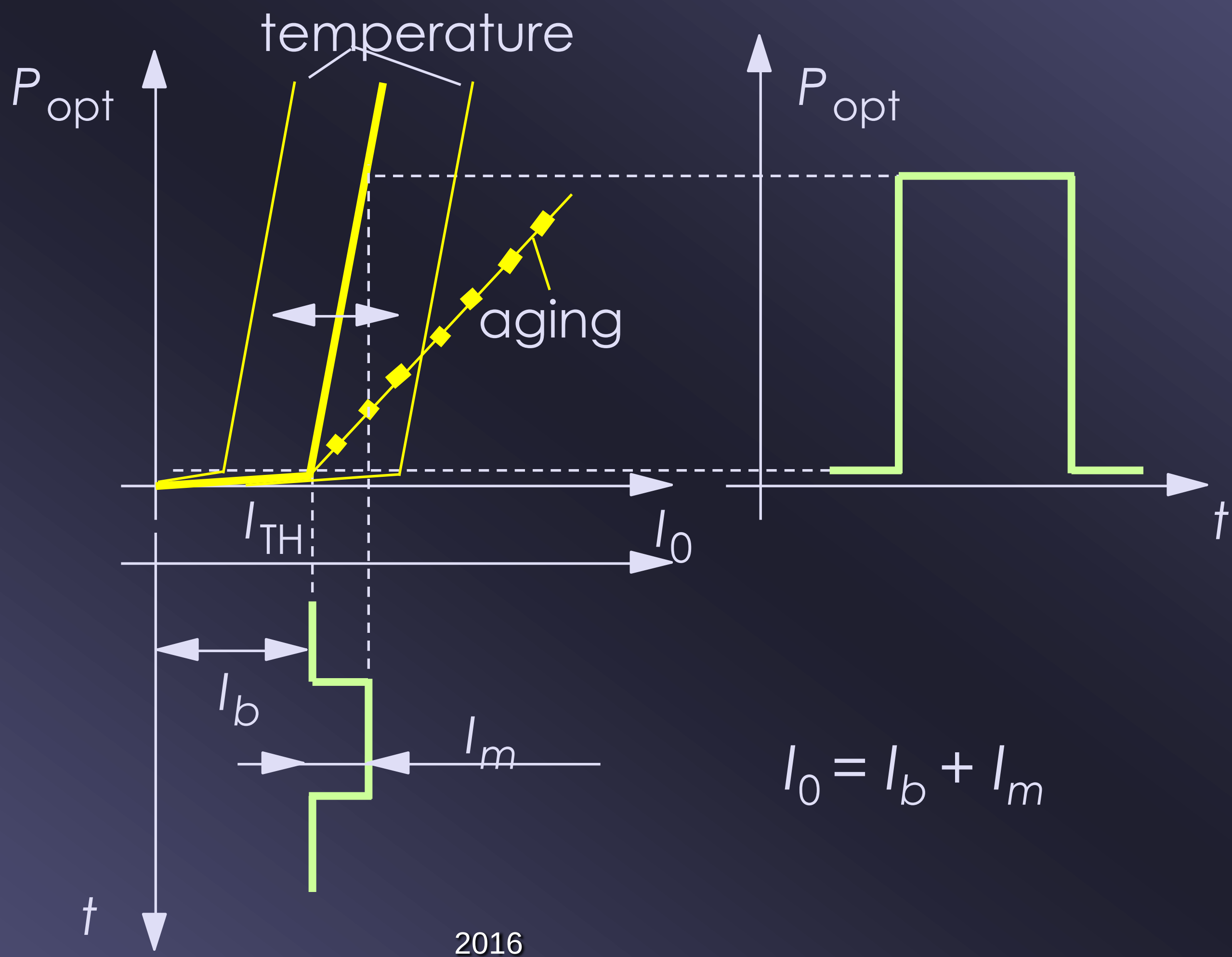
- interferometer
- absorption
- reflection

Direct

- internal modulation of the laser current

Direct modulation

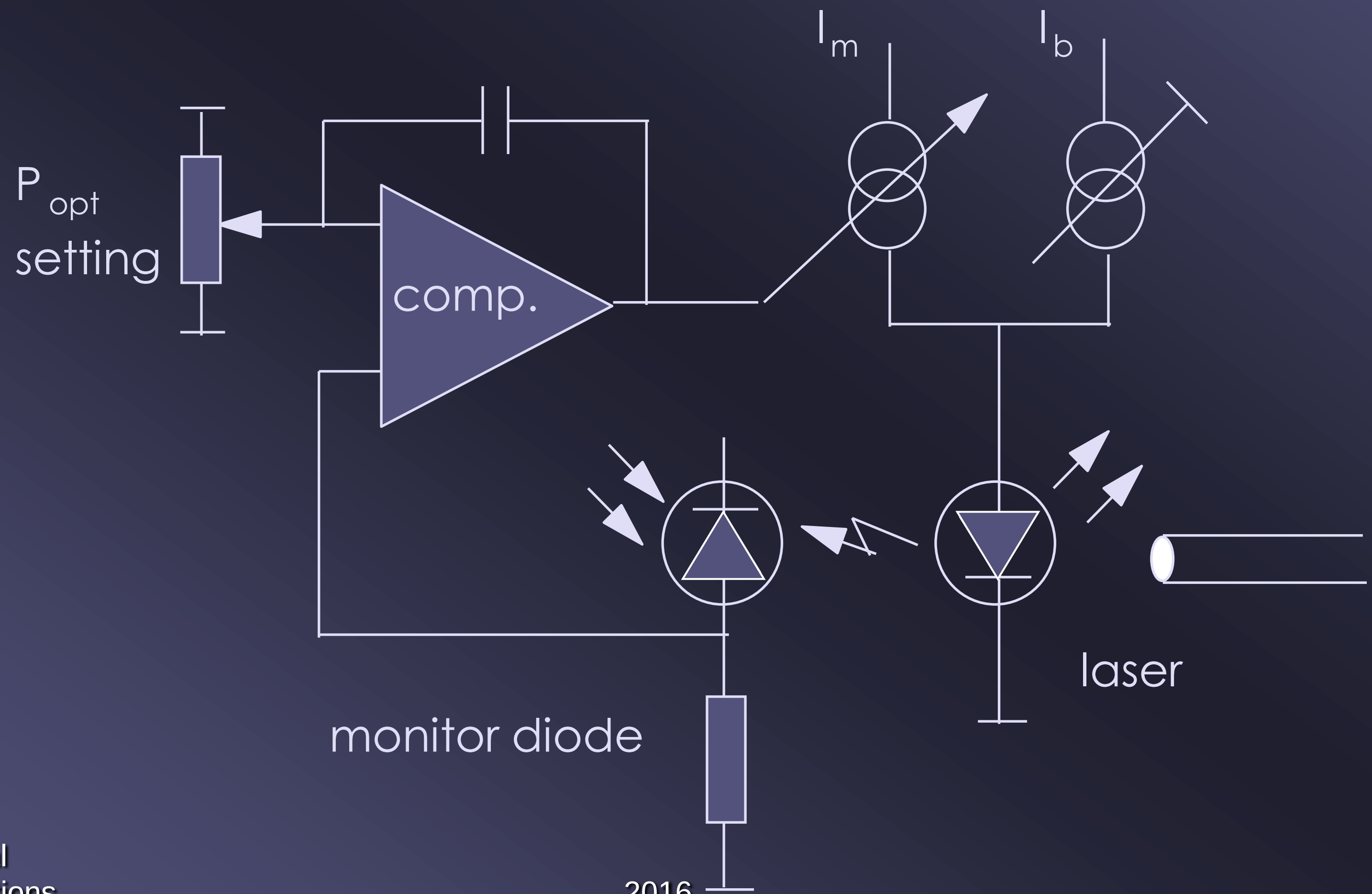
- Driving current is modulated



$$I_0 = I_b + I_m$$

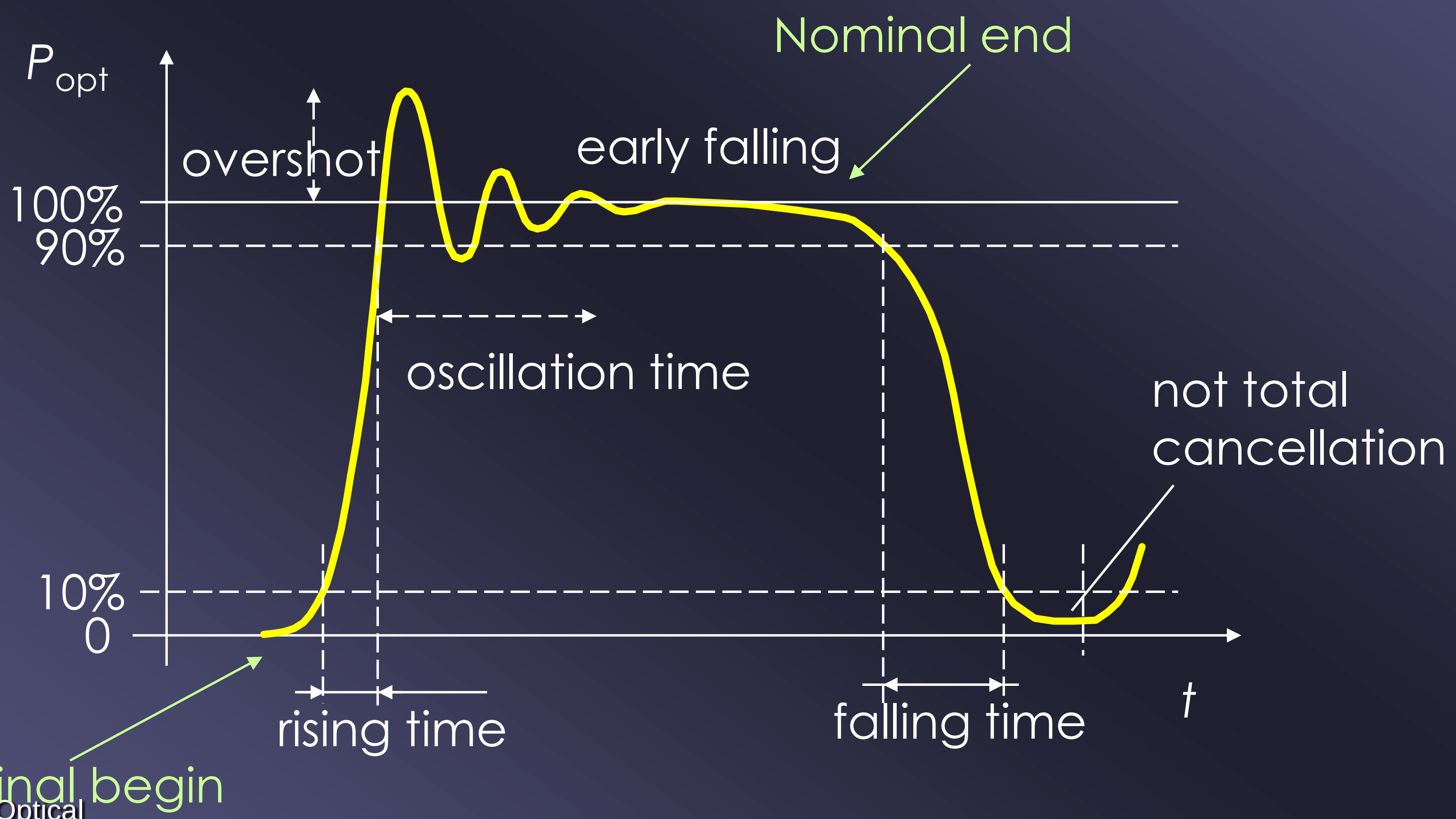
Direct modulation

- Laser driver

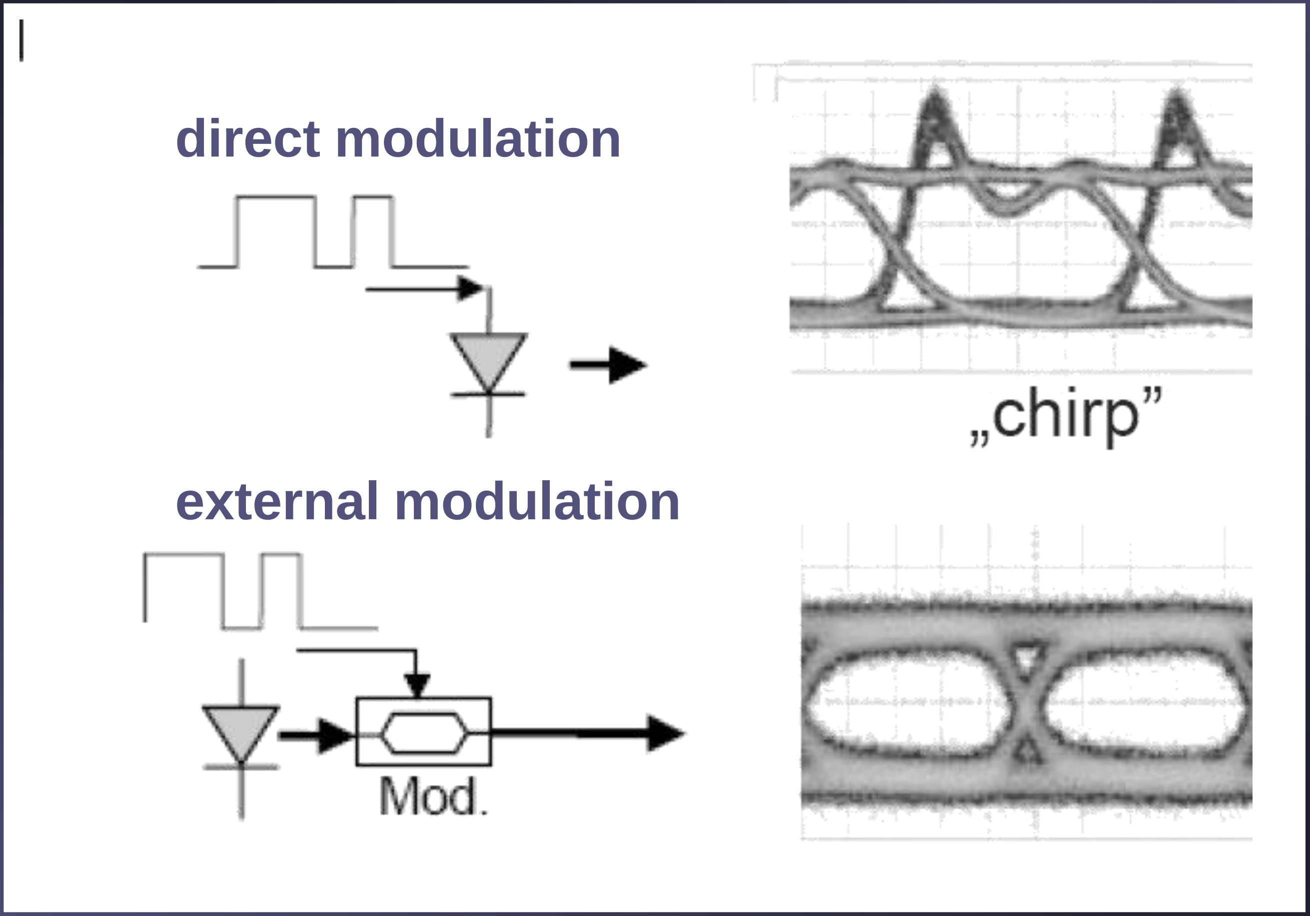


Direct modulation

- Distortion of the pulse



Direct vs. external modulation



Physics – electrooptic effects

Optical property changes due to electronical field changes

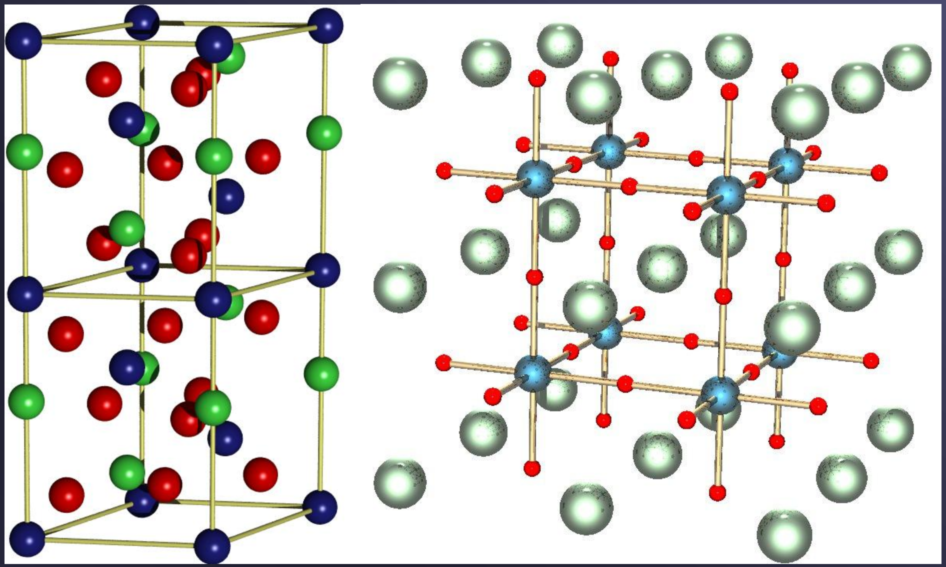
Types

- index change
  - linear – Pockels
  - quadratic – Kerr
- activity change – electrogyration
- absorption change – electroabsorption
- gap change – Frank-Keldysh (bulk semiconductors)
  – quantum confined Stark (q-wells)
- liquid crystals

Physics – electrooptic effects

Electrooptical materials

- $LiNbO_3$
- $BaTiO_3$



By Cadmium at English Wikipedia - Transferred from en.wikipedia to Commons., Public Domain, https://commons.wikimedia.org/w/index.php?curid=2527511, By Ahellwig - created with Povray 3.6, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=163749

Physics – magnetooptic effects

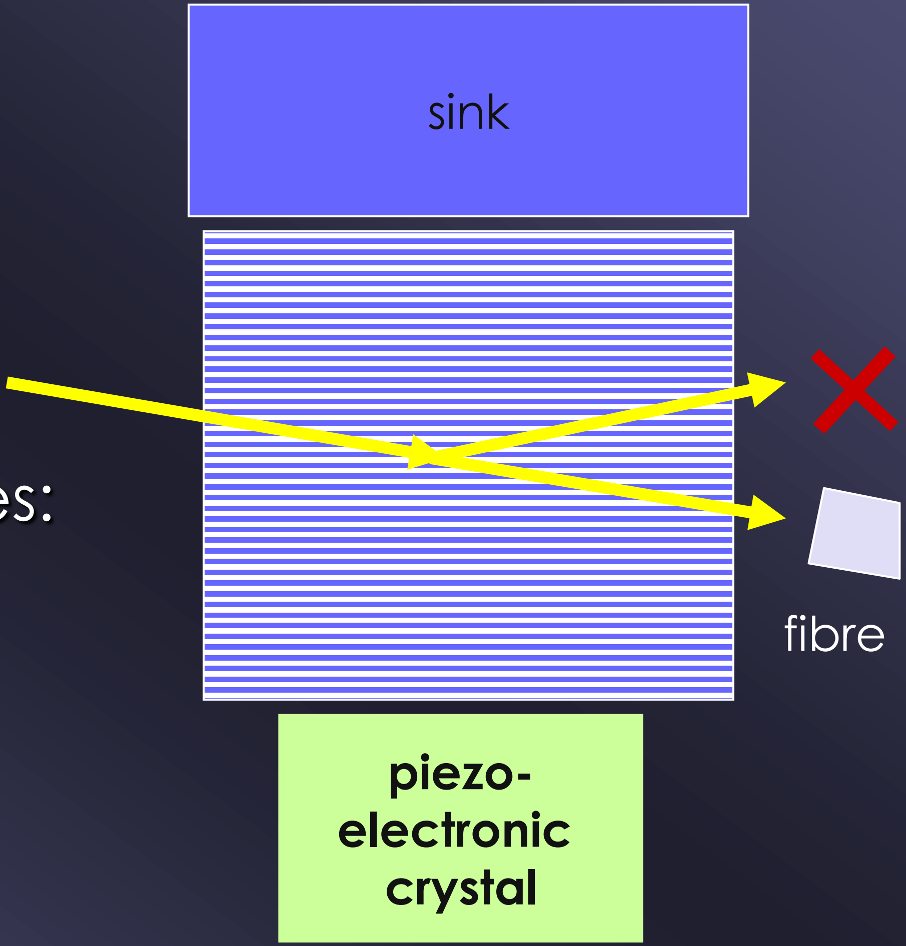
Optical property changes due to magnetic field changes

- index change
- Faraday rotator
- CdMnTe, CdMnHgTe, TdGdG, …

Physics – acousto- and elastoptic effects

Optical property changes due to density or strain changes

- index change
  - a piezoelectronic signal tranciever generates acoustic waves in the crystal,
  - due to the density waves: optical grating
  - light is reflected on the grating
- material, e.g.



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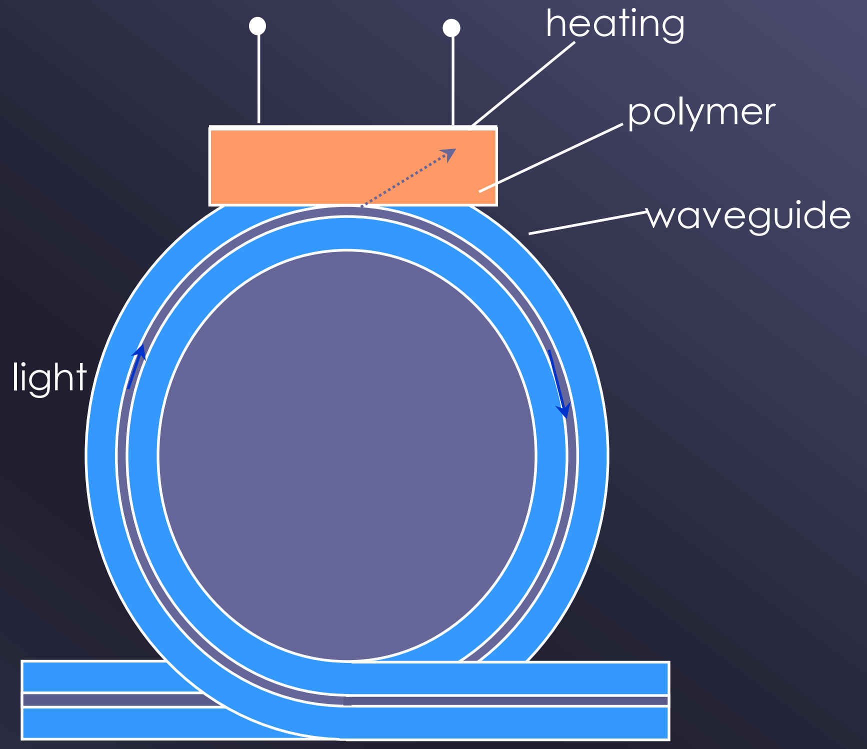
Physics – thermoooptic effects

Optical property changes due to temperature changes

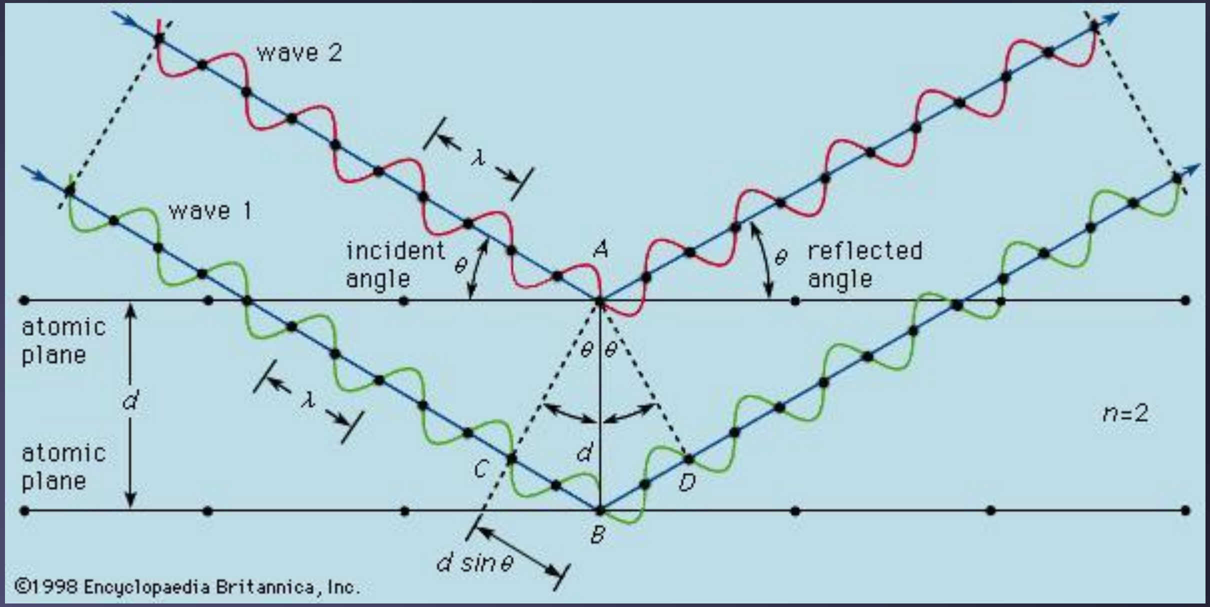
- index change



Physics – Bragg gratings

Periodically changing optical properties can induce constructive or destructive interference

- gratings
- multilayers



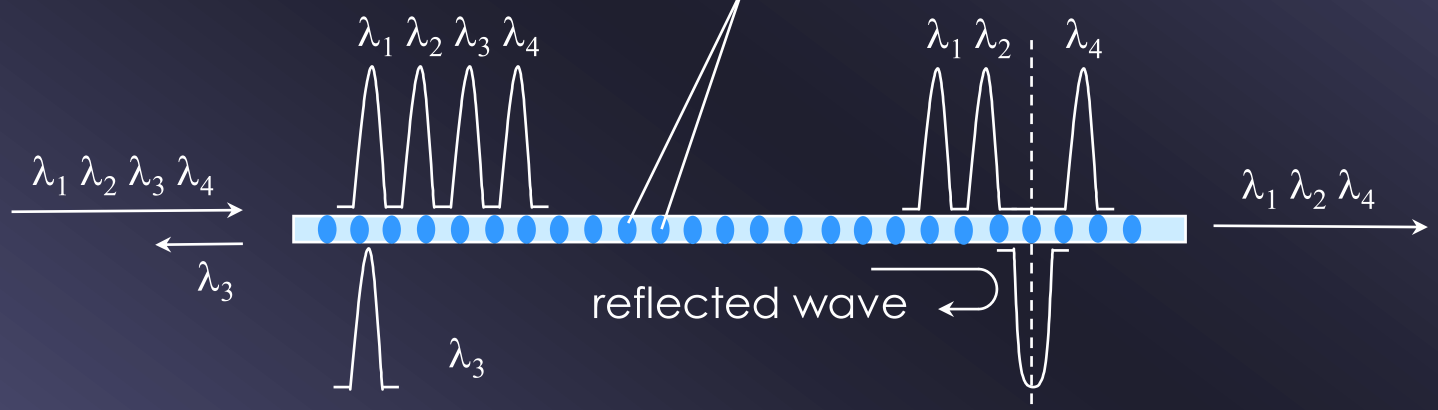
www.britannica.com

Physics – Bragg gratings

Periodically changing optical properties can induce constructive or destructive interference

- gratings
- multilayers

Ge doping+UV exposition
periodic index variation in the fiber

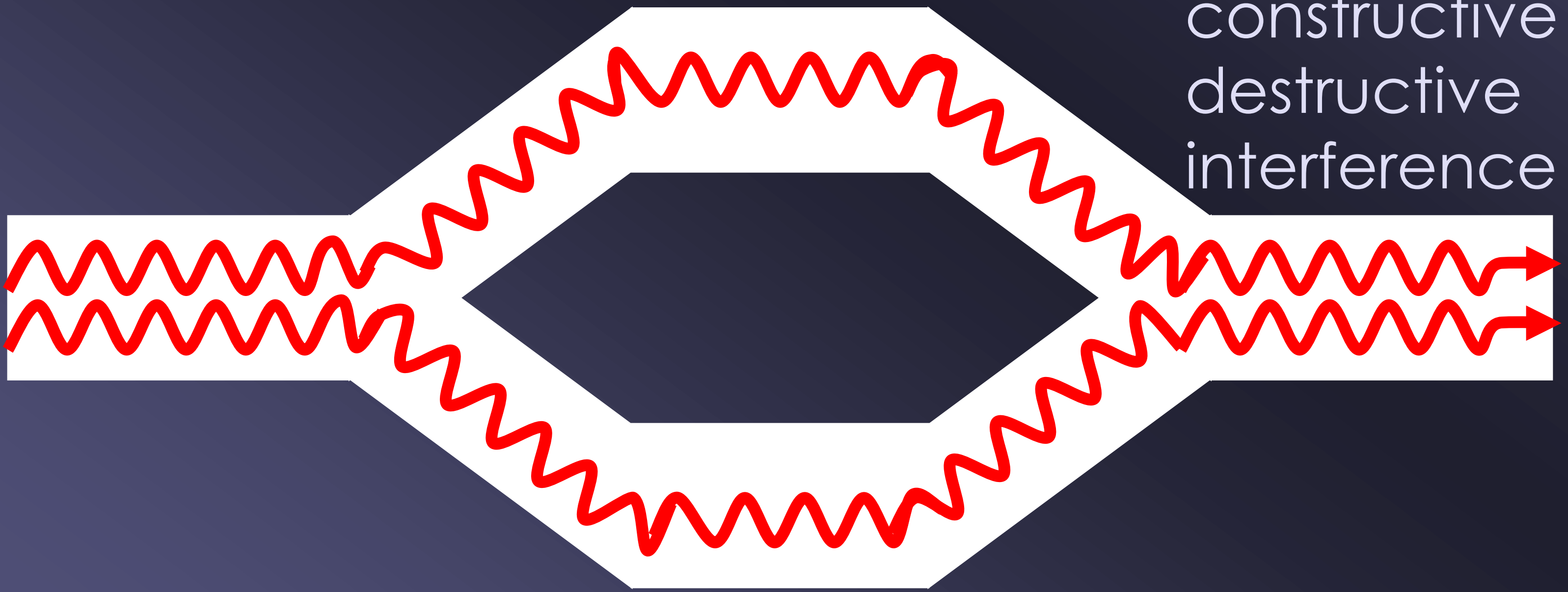


Bragg grating in fibers – add and drop MUX

sensors

Modulators

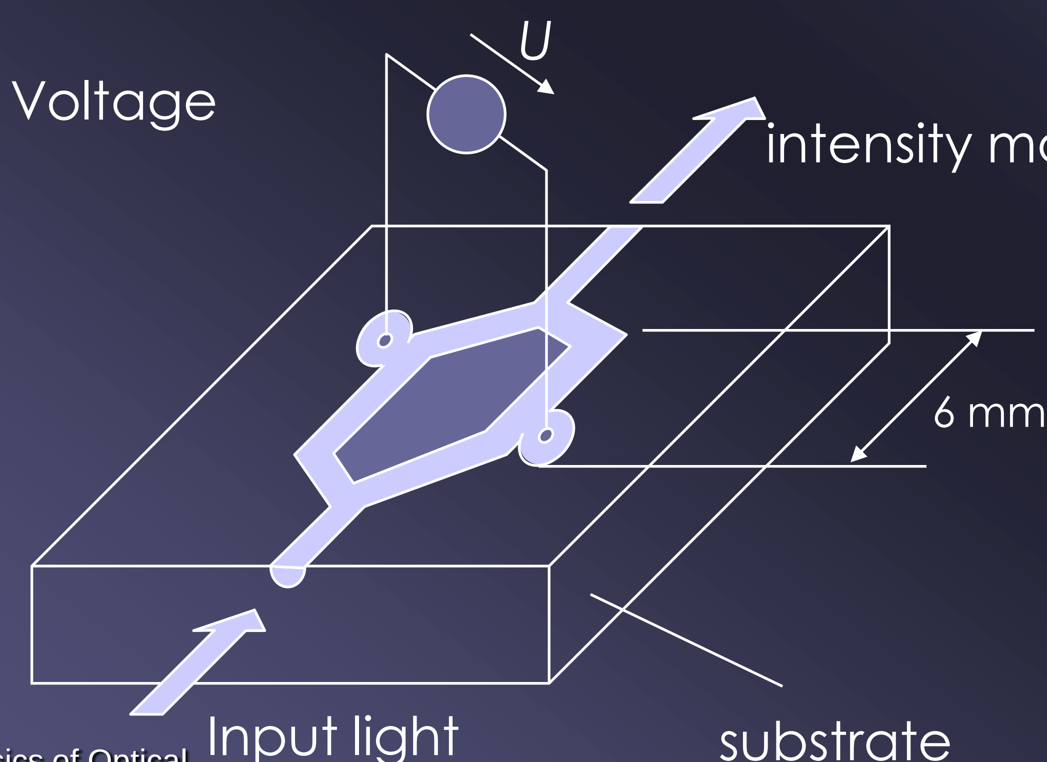
- External modulation
  with Mach—Zehnder interferometer



Difference in optical paths→ constructive or destructive interference

Modulators

- External modulation
  with Mach—Zehnder interferometer

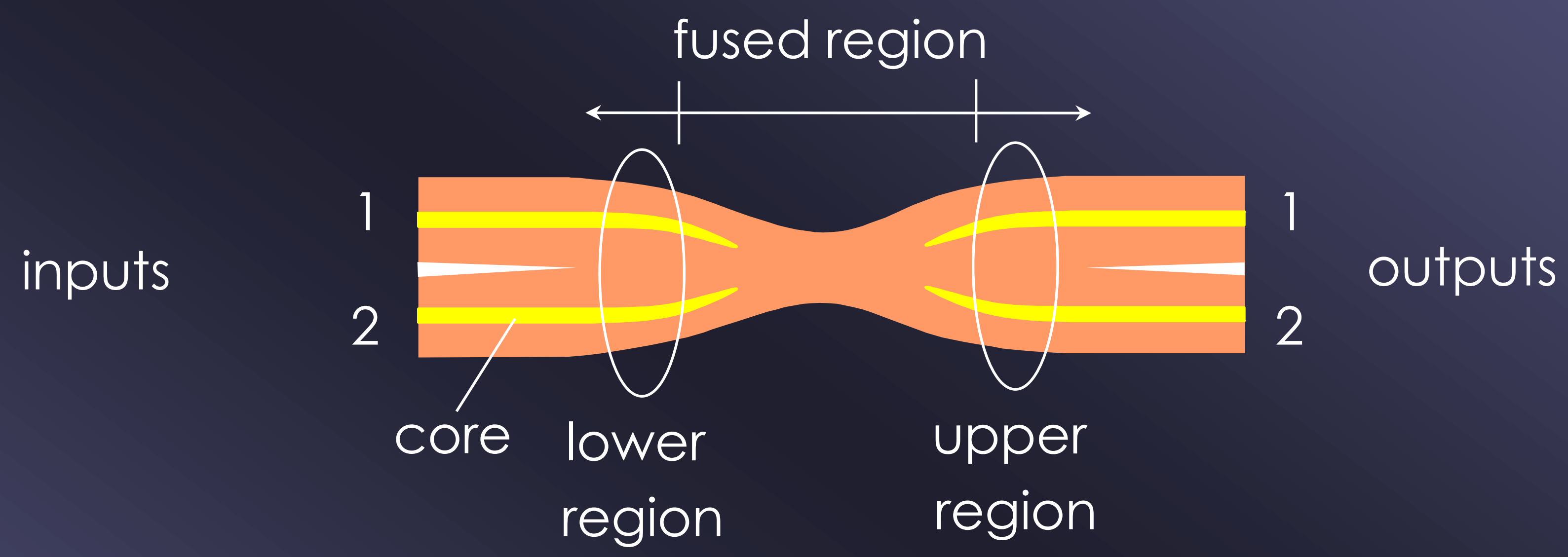


Modulating voltage changes the refractive index of the material

Outline – Splitters, filters

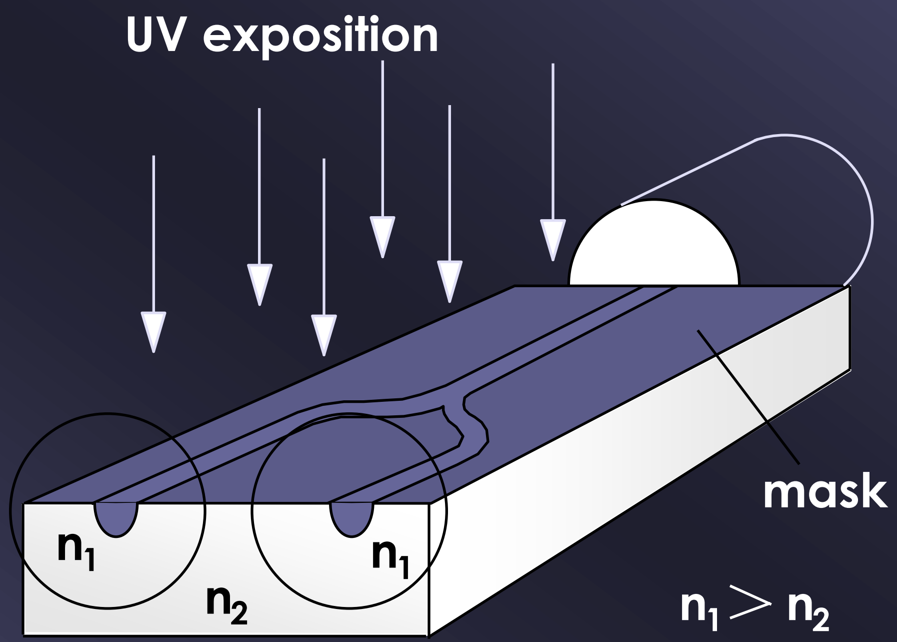
- Splitting
  - polymerized channels
  - fused fibers
  - interferometers
- Filtering, multiplexing, demultiplexing
  - prism
  - grating
  - Bragg layers

Fused fiber couplers



- splitting rate can be influenced by the fabrication process,
- coupling length can influence the wavelenght selectivity

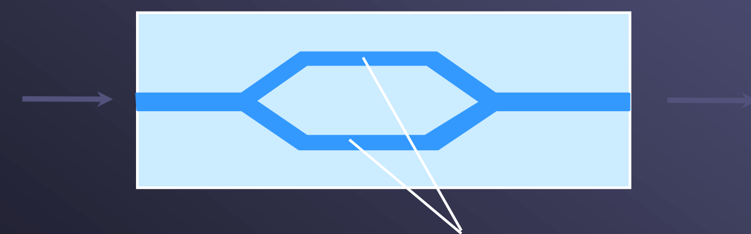
Polymerized optocoupler



Optical slicing

(Optical slicing/interleaving)

Mach-Zender inteferometer



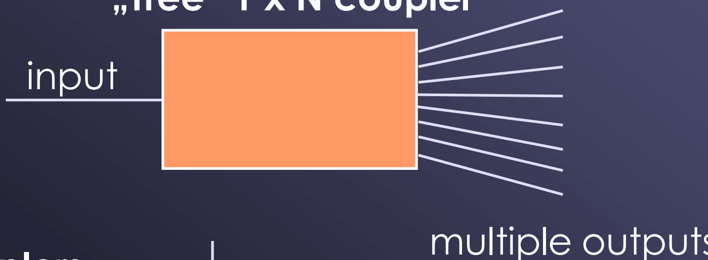
(Fused Biconic Tapered)

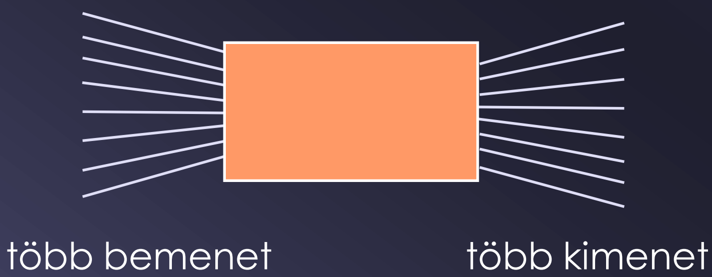
Temperature dependence: 1 pm/°C (-5 °C …+70 °C)

Optocoupler geometries

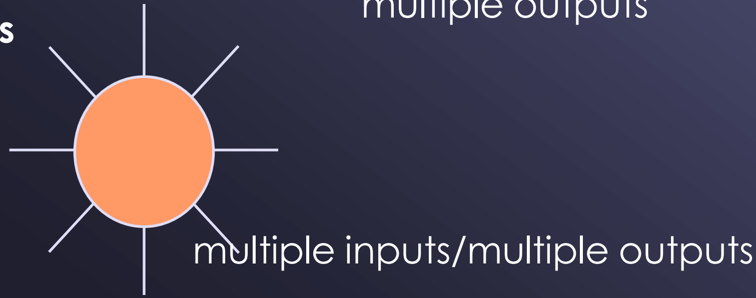
„T" coupler

„Tree" 1 x N coupler

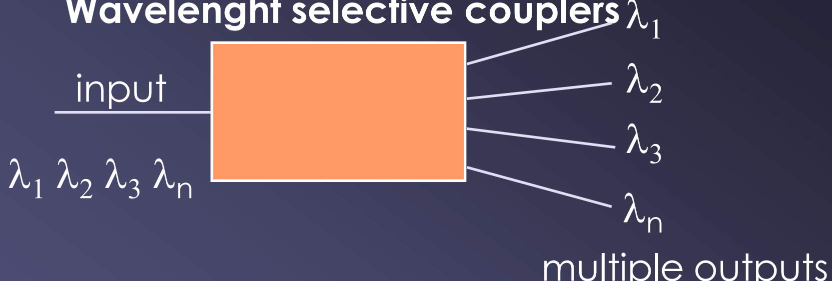




Star couplers



Wavelenght selective couplers



$$\text{Loss (dB)} = -10 \log\left[\frac{P_1 + P_2 + \ldots P_n}{P_{be}}\right]$$

$$\text{Directivity (dB)} = -10 \log\left[\frac{P_n}{P_m}\right]$$

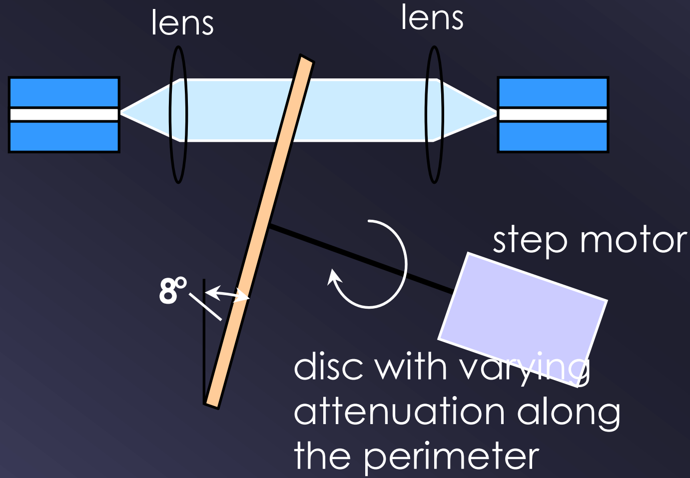
Attenuators

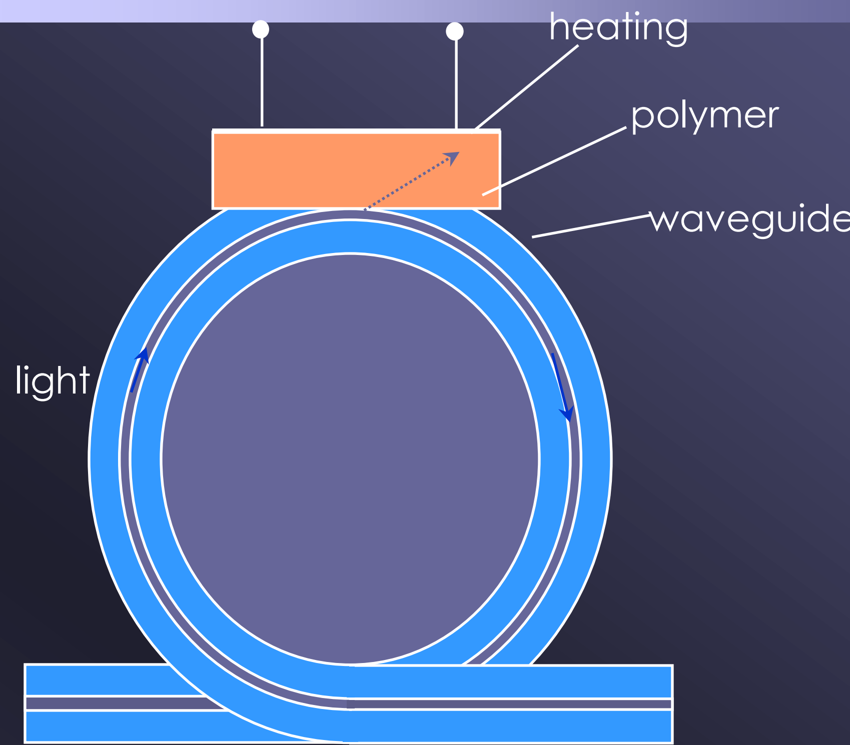
Types:

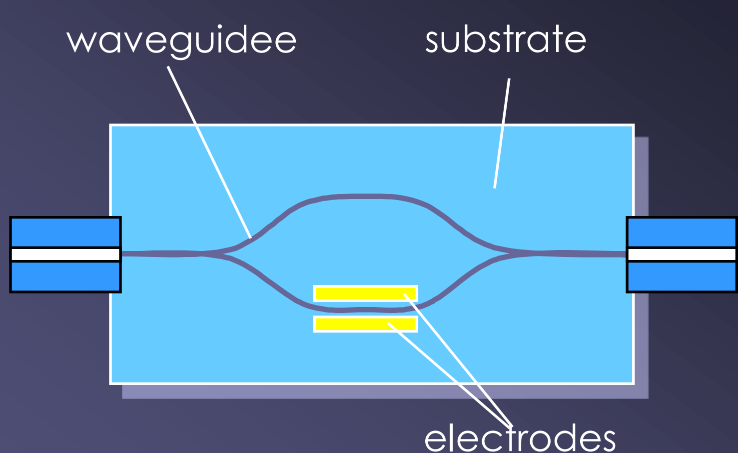
- active
- passzív
  - fix
  - variable
    - calibrated
    - not calibrated

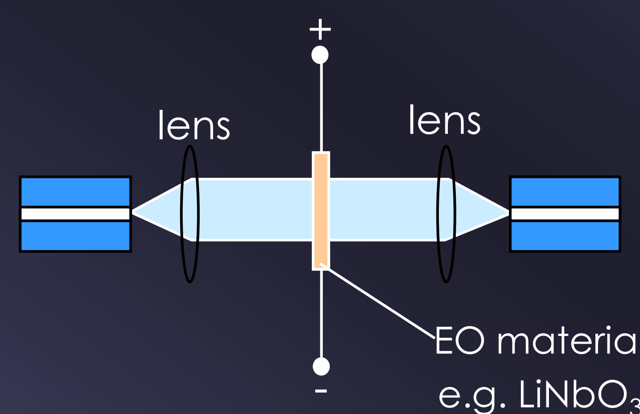
Use: meaurements, signal power control in PONs

Különböző kivitelű csillapítók









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Optical switches

For changing the optical path at the network nodes

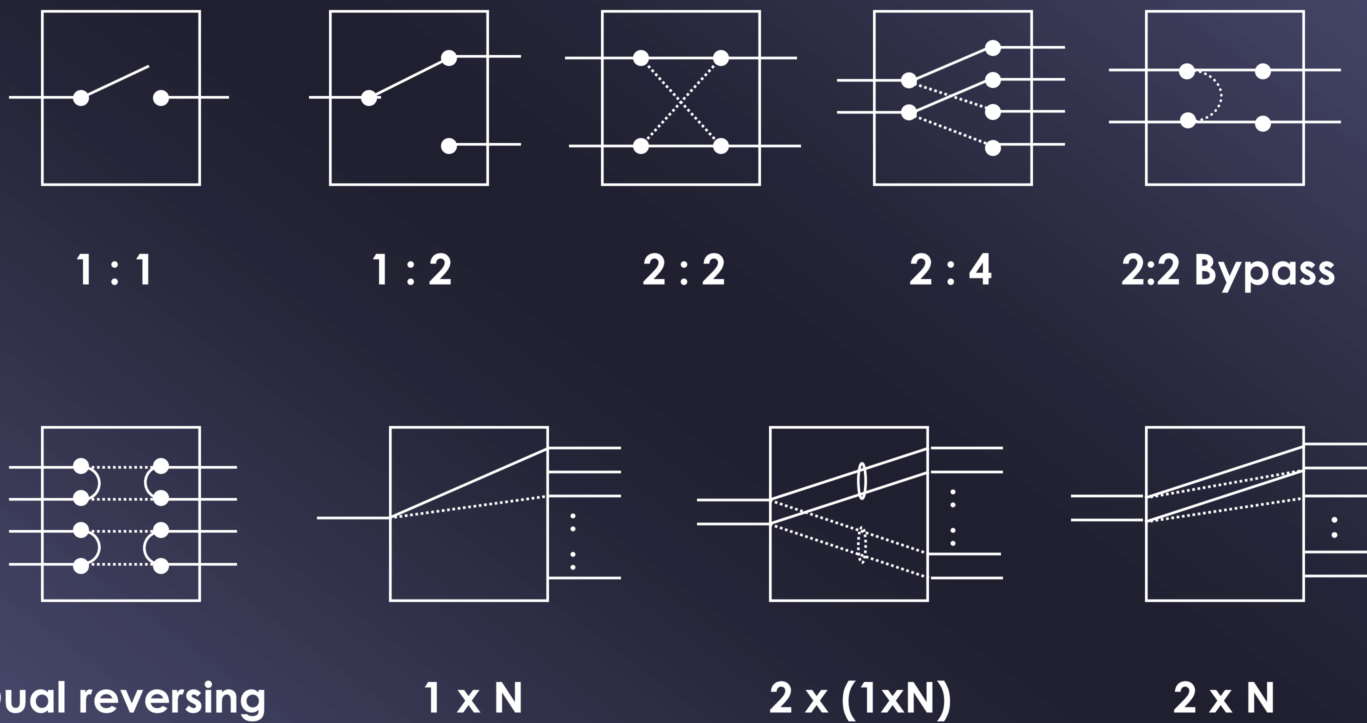
Applications:

- switching the signal path
- backward signal supression
- multiplexeling
- reserving optical paths
- measurements

Types:

- electromechanical,
- electrooptical

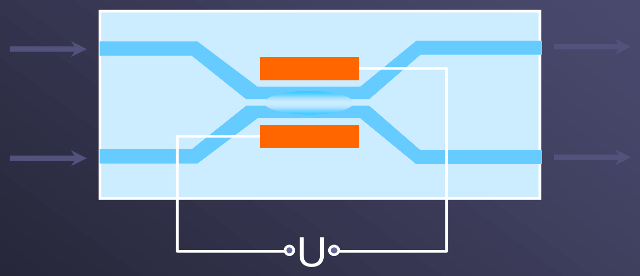
Otical switch topologies



Requirements for optical switches

Insertion loss	0.5 dB
Loss incremet for repetition	0.01 dB
Switching time	< 15 ms
Voltage, current	5 V, 50 mA
Reflection attenuation	- 65 dB
Operation domain	1300, 1550, (1650) nm

Elektrooptical switches



Advantages:

- ns switching times,
- stable

Disadvantages

- large insertion loss,
- large PDL, crosstalk
- no favoured state

substrate: lithium-niobate
barium-titanate
elektrodes: Si-Mg oxide

MEMS

Movable elements: miniature mirrors or prisms

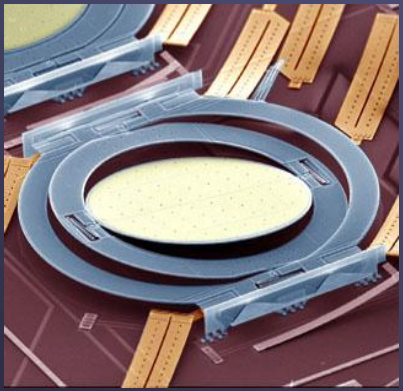
Moving elements: solenoids, piezos

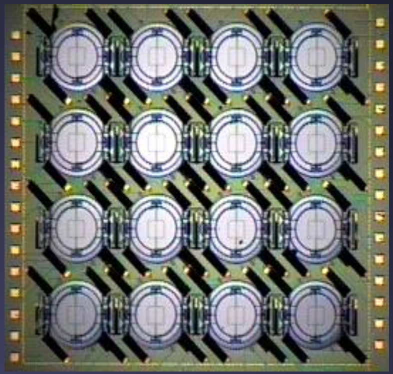
Advantages:

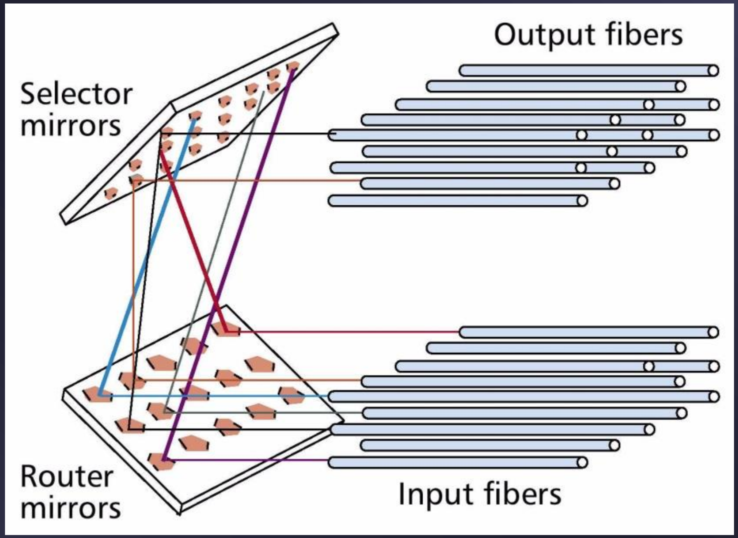
- low polarization and wavelength dependence,
- insensitive for environmental effects,
- low power control signals,
- cheap manufacturing

Disadvantages:

- complicated control for larger switch matrices,
- ms switching times



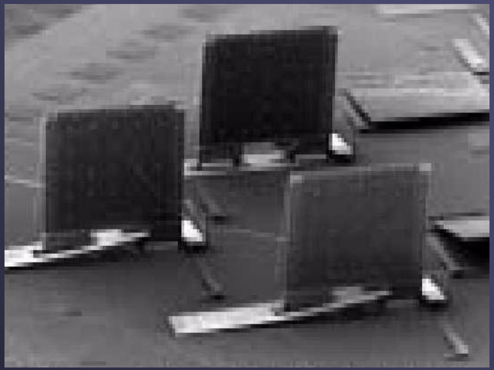




MEMS

Movable elements: miniature mirrors or prisms

Moving elements: solenoids, piezos

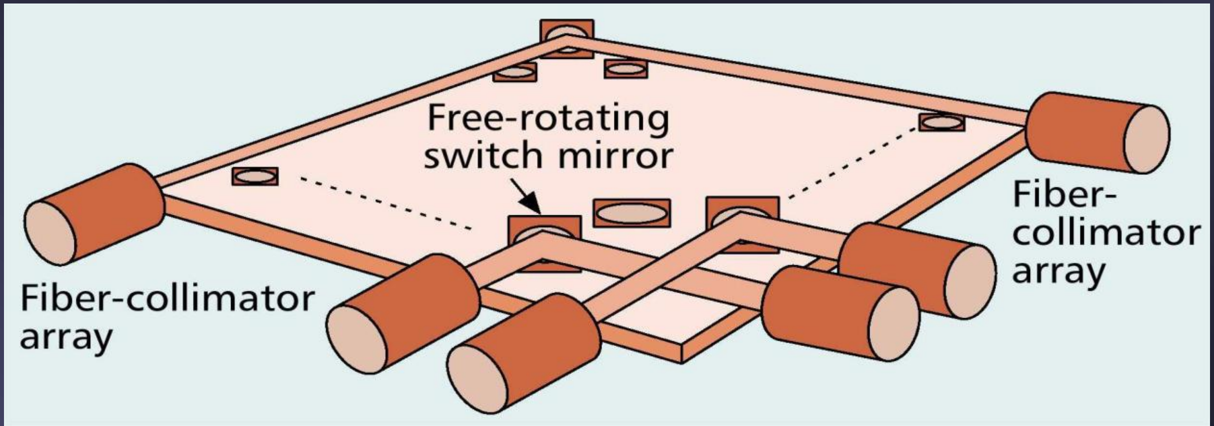


Advantages:

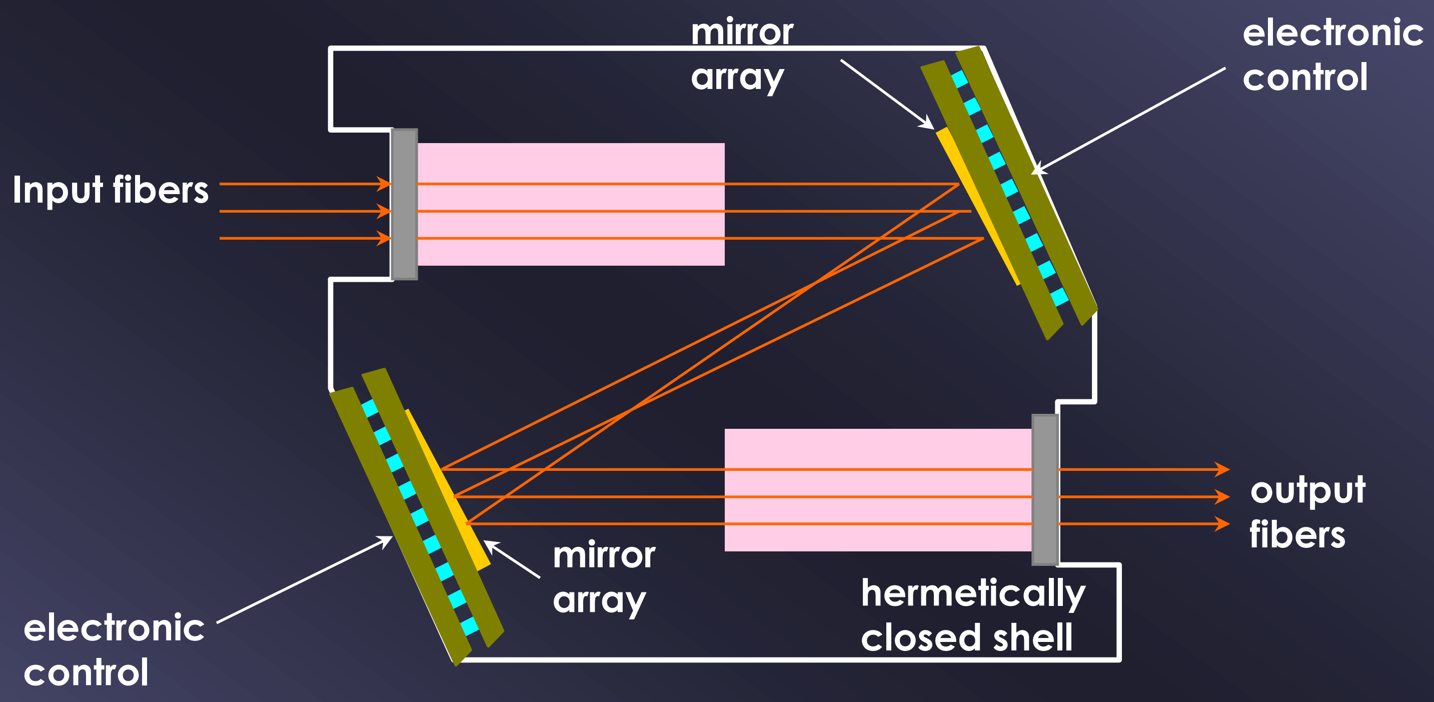
- low polarization and wavelength dependence,
- insensitive for environmental effects,
- low power control signals,
- cheap manufacturing

Disadvantages:

- complicated control for larger switch matrices,
- ms switching times



OXC switching cell



Thermooptical switch

Thermically tunable polymer waveguides

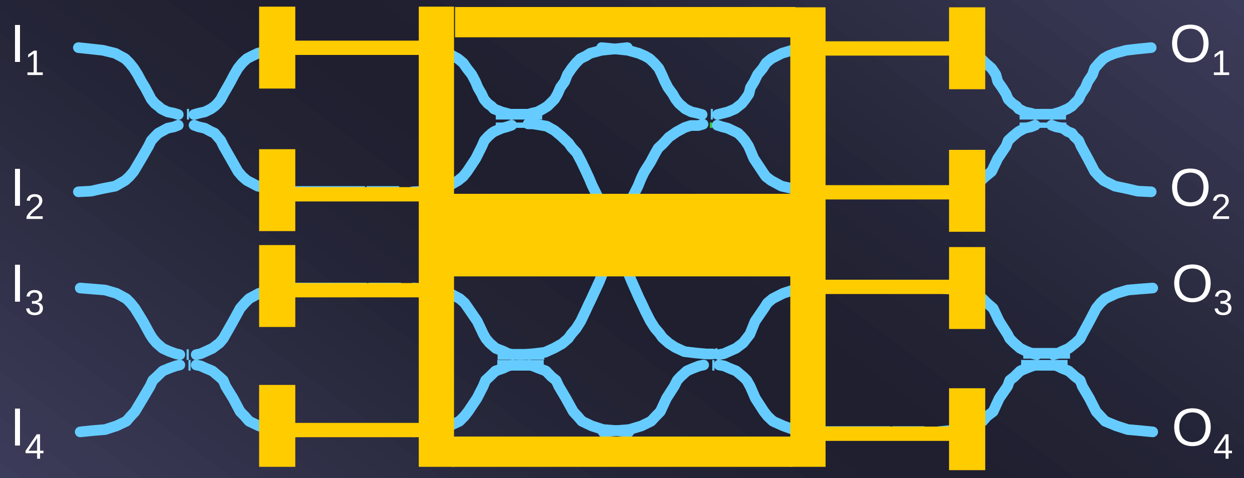
- temperature dependent index,
- silitium substrate
- heating: thin film electrode on the polymer stack

Properties:

- acceptable attenuation,
- medium polarization dependence,
- large crosstalk,
- high power consumption,
- switching times: 1…10 ms

Thermooptical switch

2x2 thermooptical switch array



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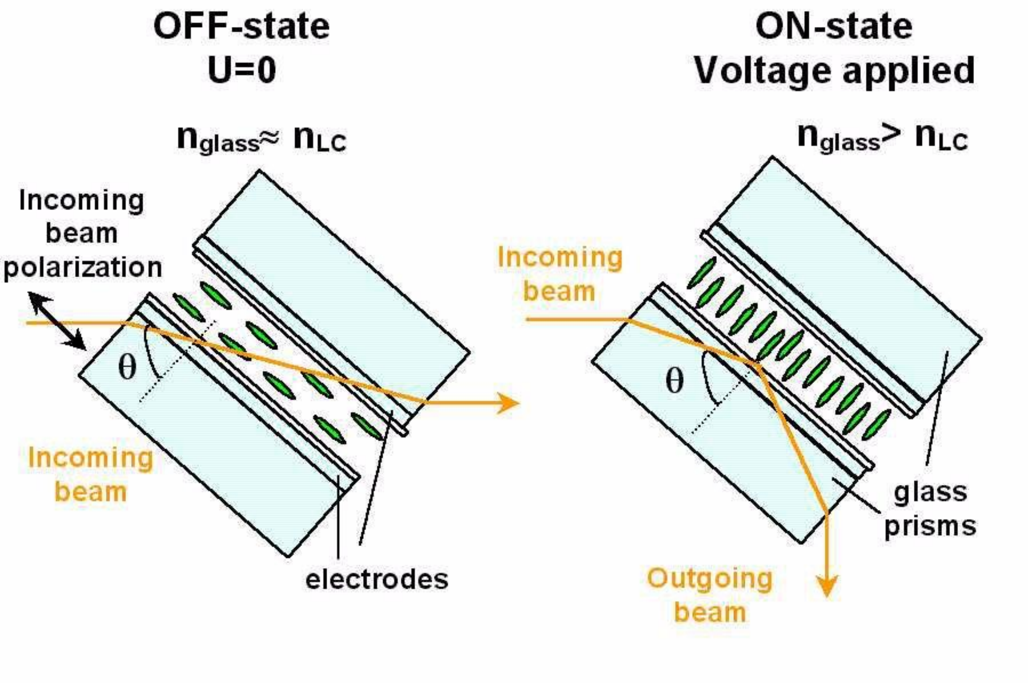
Liquid crystal switches

Liquid crystal cells

- polarization splitters
- voltage controlled polarization
- polarization sensitive or insensitive switch arrays

Properties

- large attenuation,
- higher crosstalk,
- complicated control,
- switching time:
  - 100 ms nematic liquids,
  - 10 ms ferroelecric liquids



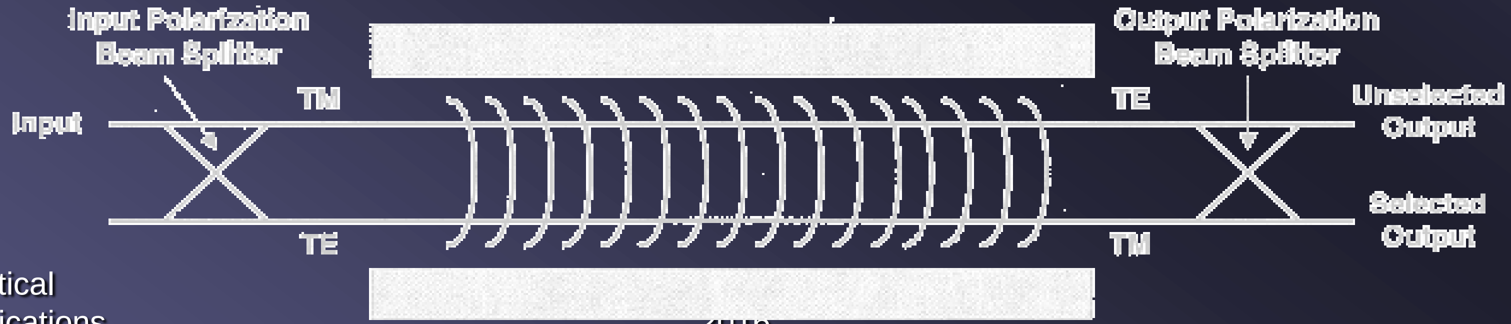
Acoustooptical switches

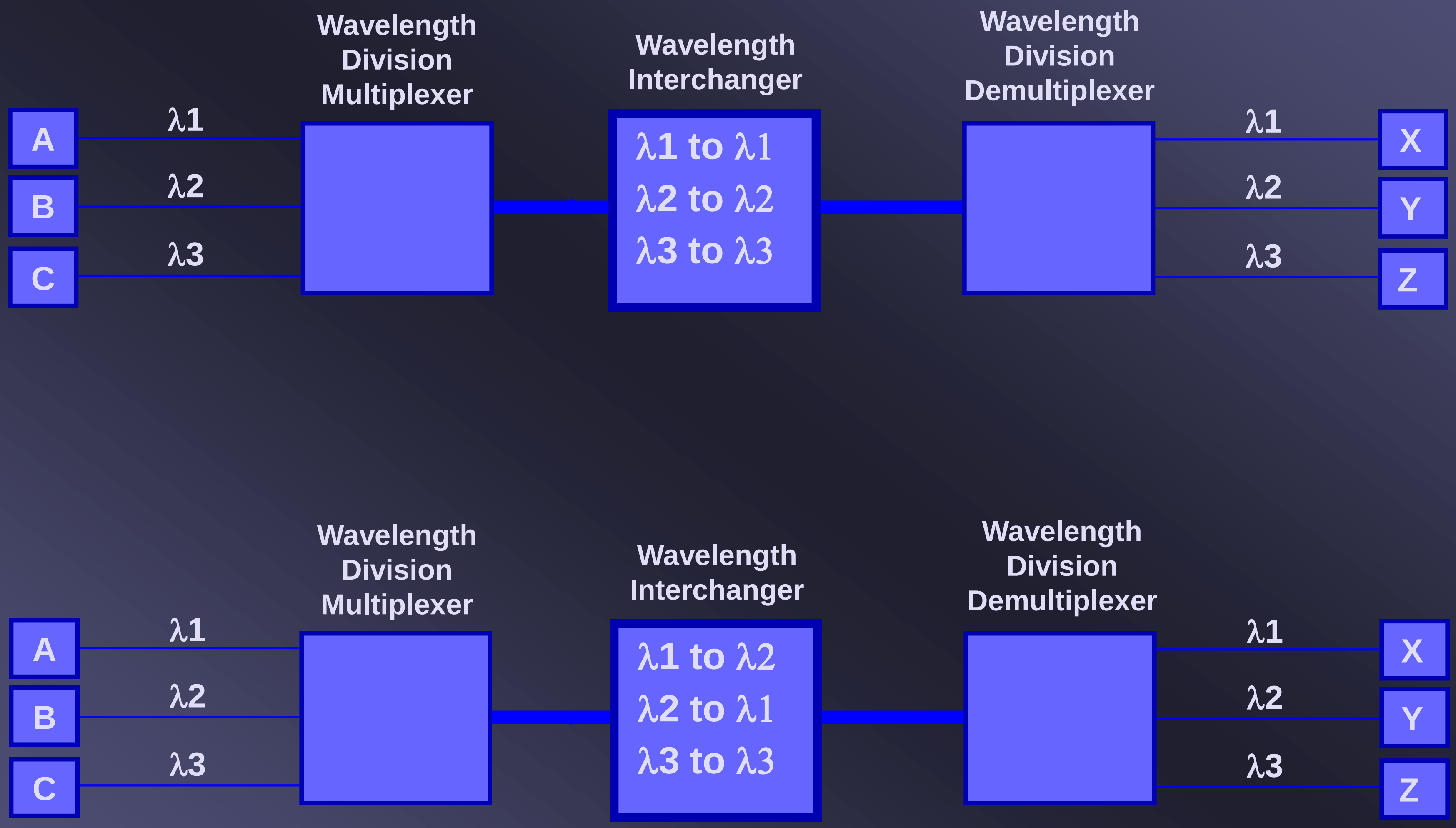
Directed acoustical waves influece the optical medium

- material e.g., TeO_2,
- index changes due to transversal acoustic waves,
- tunable by frequency

Properties:

- wavelength dependent attenuation,
- costly control circuits,
- switchin time: ~10 ms,
- low density

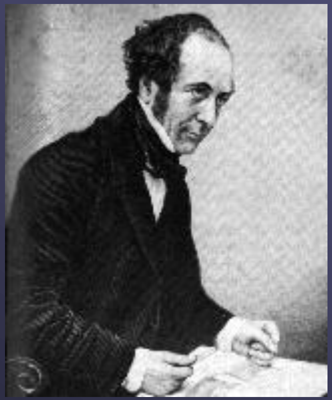



Wavelength Division Multiplexer
Wavelength Interchanger
Wavelength Division Demultiplexer
A
B
C
λ1
λ2
λ3
λ1 to λ1
λ2 to λ2
λ3 to λ3
λ1
λ2
λ3
X
Y
Z
Wavelength Division Multiplexer
Wavelength Interchanger
Wavelength Division Demultiplexer
A
B
C
λ1
λ2
λ3
λ1 to λ2
λ2 to λ1
λ3 to λ3
λ1
λ2
λ3
X
Y
Z

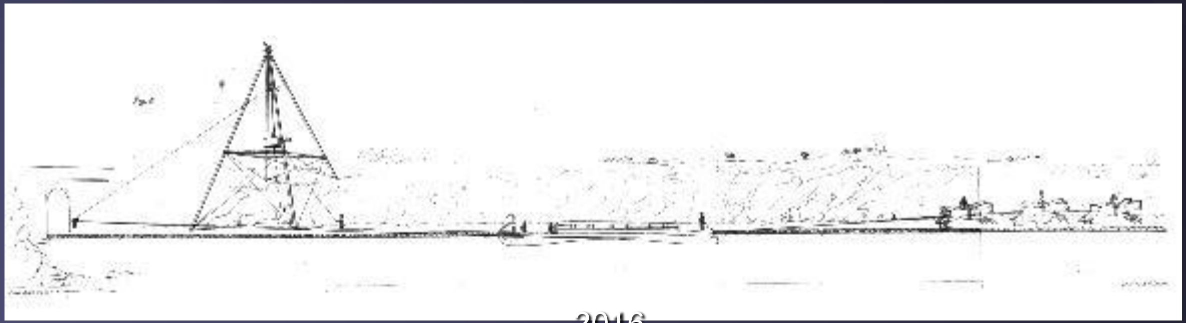
Outline – Soliton communication

- Nonlinear effects in fibers
- History of solitons
- Korteweg—deVries equations
- Envelop solitons
- Solitons in optical fibers
- Amplification of solitons – optical soliton transmission systems

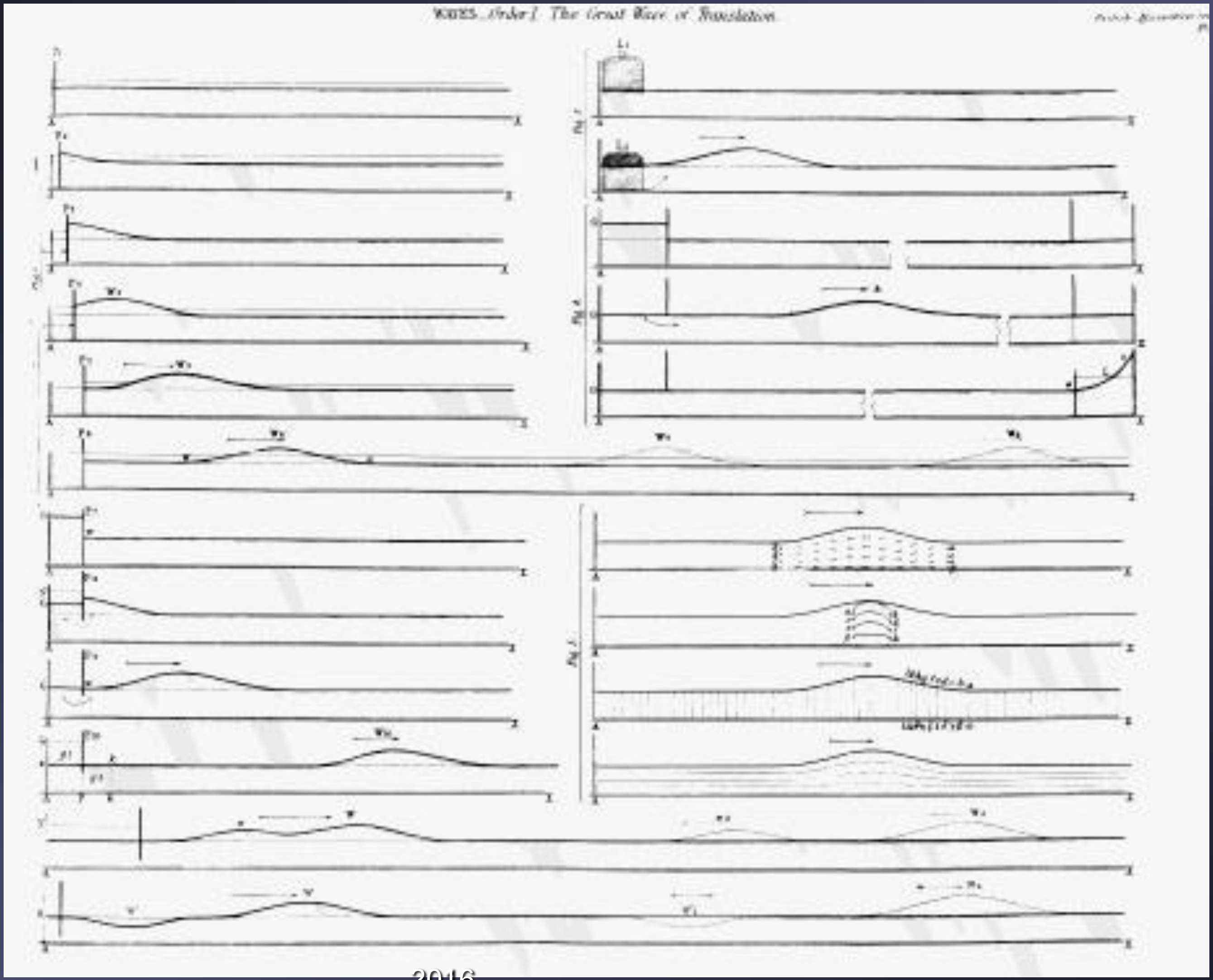
History of solitons



- John Scott Russel (1808-1882)
- 1834, Union Canal, Hermiston near Edinbourgh, a boat was pulled
- after the stop of the boat a „wave of translation” arised
- 8-9miles/hour wave velocity
- traveled 1-2 miles long



History of solitons



J. S. Russel, Report on Waves, 1844

History of solitons

Snibston Discovery Park

History of solitons

Scott Russel Aqueduct, 1995

Heriot-Watt University Edinbourgh

History of solitons

- 1870s J. Boussinesq, Rayleigh both deduced the secret of Russel's waves: the dispersion and the nonlinearity cancels each other
- 1964 Zabusky and Kruskal solves the KdV equation numerically, solitary wave solutions: **soliton**
- 1960s: nonlinear wave propagation studied with computers: many fields were found where solitons appear

History of solitons

- 1970s A. Hasegawa proposed solitons in optical fibers
- 1980 Mollenauer demonstrated soliton transmission in optical fiber (10 ps, 1.5 μm, 700 m fiber)
- 1988 Mollenauer and Smith sent soliton light pulses in fiber for 6000 km without electronic amplifier

Korteweg—deVries equations

- In 1895 Korteweg and deVries modeled the wave motion on the surface of shallow water by the equation

$$\frac{\partial h}{\partial \tau} + h\frac{\partial h}{\partial \xi} + \frac{\partial^3 h}{\partial \xi^3} = 0$$

where

	h	wave height
	τ	time in coordinates
	ξ	space coordinate

} moving with the wave

Korteweg—deVries equations

Derivation of the KdV equation

- a wave h propagating in x direction can be described in the coordinate system (ξ,τ) traveling with the wave as

$$\frac{\partial h}{\partial \tau} = 0$$

- Using the original (x,t) coordinates:

$$\frac{\partial h}{\partial \tau} = 0 \quad \xrightarrow[t = \tau]{x = \xi + v\tau,} \quad \frac{\partial h}{\partial t} + v\frac{\partial h}{\partial x} = 0$$

Korteweg—deVries equations

Stationary solution of the KdV equation

- Dispersive and nonlinear effects can balance to make a stationary solution

$$\frac{\partial h}{\partial \tau} + h\frac{\partial h}{\partial \xi} + \frac{\partial^3 h}{\partial \xi^3} = 0$$

$$v(h) = v_0 + \mathrm{const}\cdot h$$

$$\omega = kv = \omega_0 + \mathrm{const}\cdot k^2\omega_0$$
$$= \omega_0 + \mathrm{const}\cdot k^3 v_0$$

Korteweg—deVries equations

Stationary solution of the KdV equation

- Dispersive and nonlinear effects can balance to make a stationary solution

$$\frac{\partial h}{\partial \tau} + h\frac{\partial h}{\partial \xi} + \frac{\partial^3 h}{\partial \xi^3} = 0$$

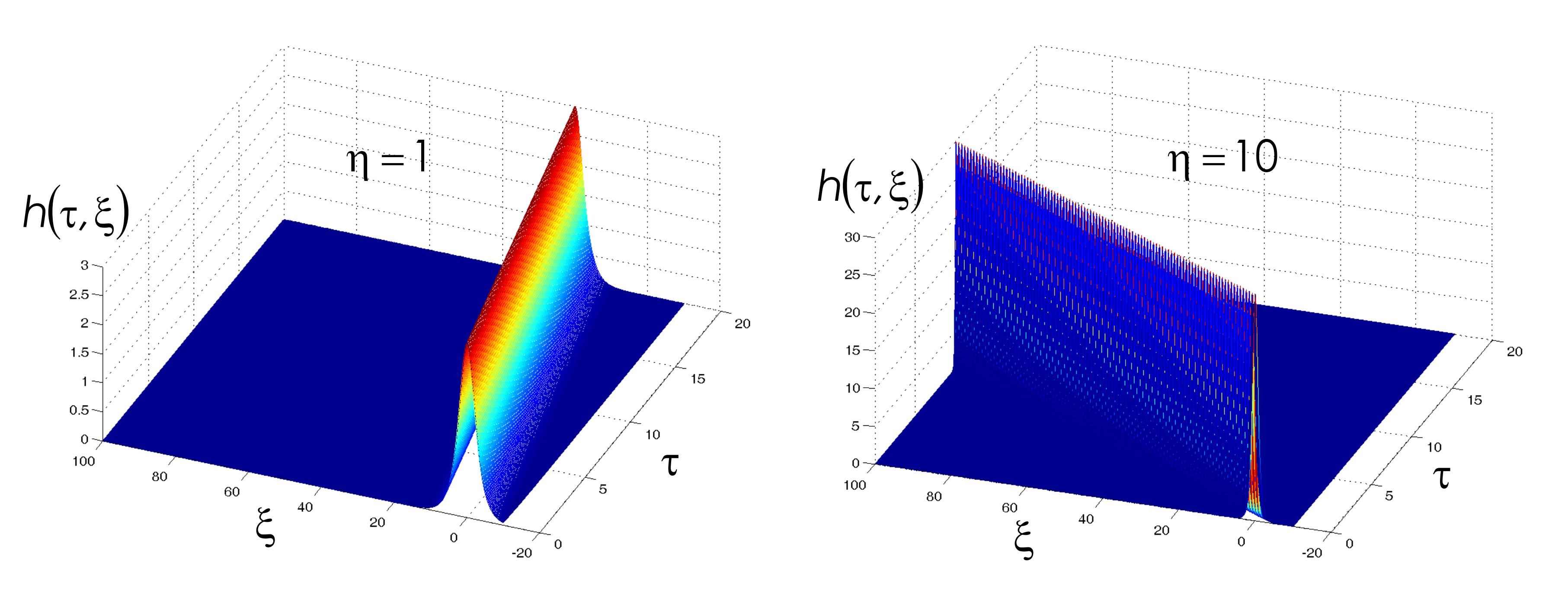
$$h(\tau,\xi) = 3\eta\,\mathrm{sech}^2\frac{\sqrt{\eta}}{2}(\xi - \eta\tau)$$

where η is the velocity of the solitary wave in the (ξ,τ) space

Korteweg—deVries equations

Stationary solution of the KdV equation

$$h(\tau,\xi)=3\eta\,\mathrm{sech}^2\frac{\sqrt{\eta}}{2}(\xi-\eta\tau)$$



Korteweg—deVries equations

The KdV equation and the inverse scattering problems

- the Schrödinger equation:

$$\frac{\partial^2 \Phi}{\partial x^2} + (\lambda - u(x,t))\Phi = 0$$

- if „potential" $u(x,t)$ satisfies a KdV equation,
  - λ is independent of time
  - $u(x,0) \rightarrow 0$ as $|x| \rightarrow \infty$
  - the Schrödinger equation can be solved for $t=0$ for a given initial $u(x,0)$

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Korteweg—deVries equations

The KdV equation and the inverse scattering problems

- $t=0$ scattering data can be derived from the $t=0$ solution
- the time evolution of Φ and thus the scattering data is known

$$\frac{\partial\Phi}{\partial t} = A\frac{\partial^3\Phi}{\partial x^3} + B\frac{\partial u}{\partial x}\Phi + Cu\frac{\partial\Phi}{\partial x}$$

- $u(x,t)$ can be found for each $\Phi(x,t)$ by inverse scattering methods.

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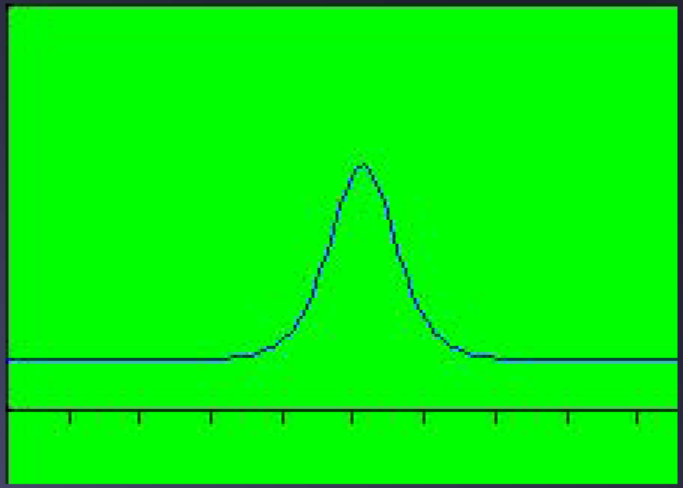
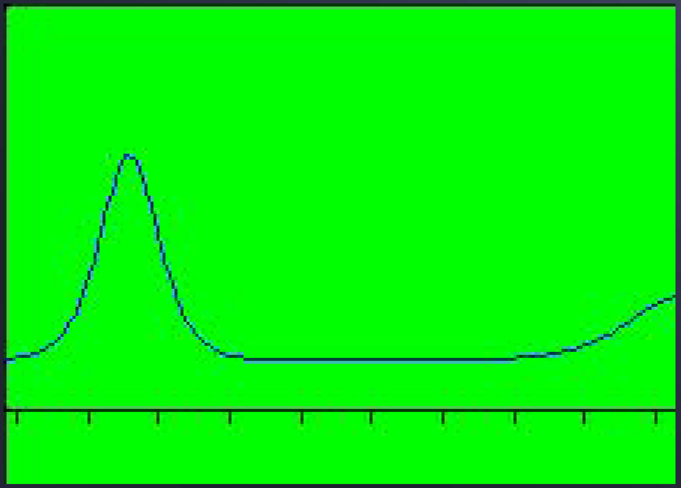
Korteweg—deVries equations

Solutions of KdV equations with various boundary conditions in various dimensions





soliton propagating and scattering

Korteweg—deVries equations

Solutions of KdV equations with various boundary conditions in various dimensions

soliton wave in the sea (Molokai)

Korteweg—deVries equations

- Solutions of KdV equations with various boundary conditions in various dimensions

soliton wave in the sky

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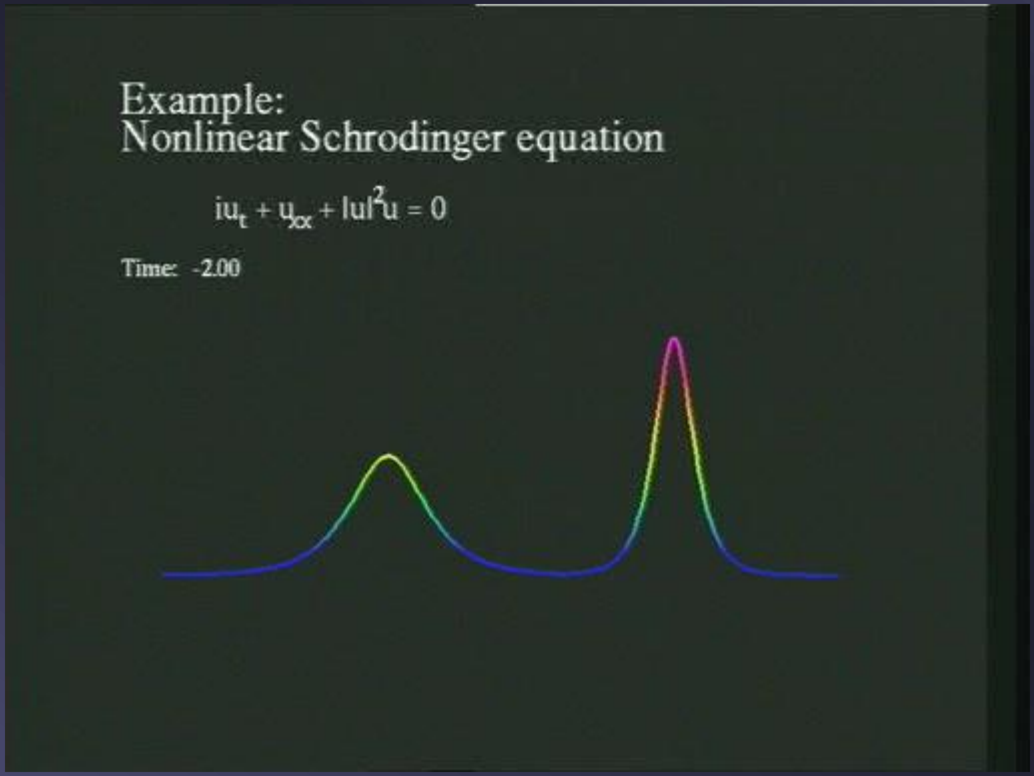
Korteweg—deVries equations

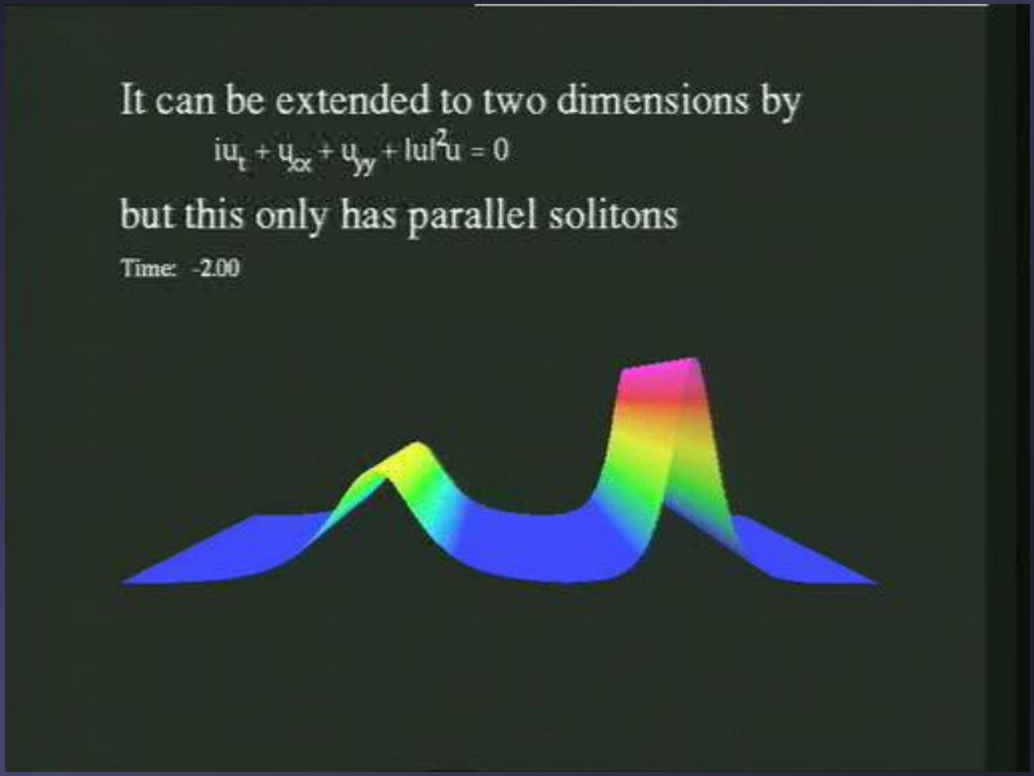
Solutions of KdV equations with various boundary conditions in various dimensions



two solitons 1D

Korteweg—deVries equations

Solutions of KdV equations with various boundary conditions in various dimensions



two solitons 2D

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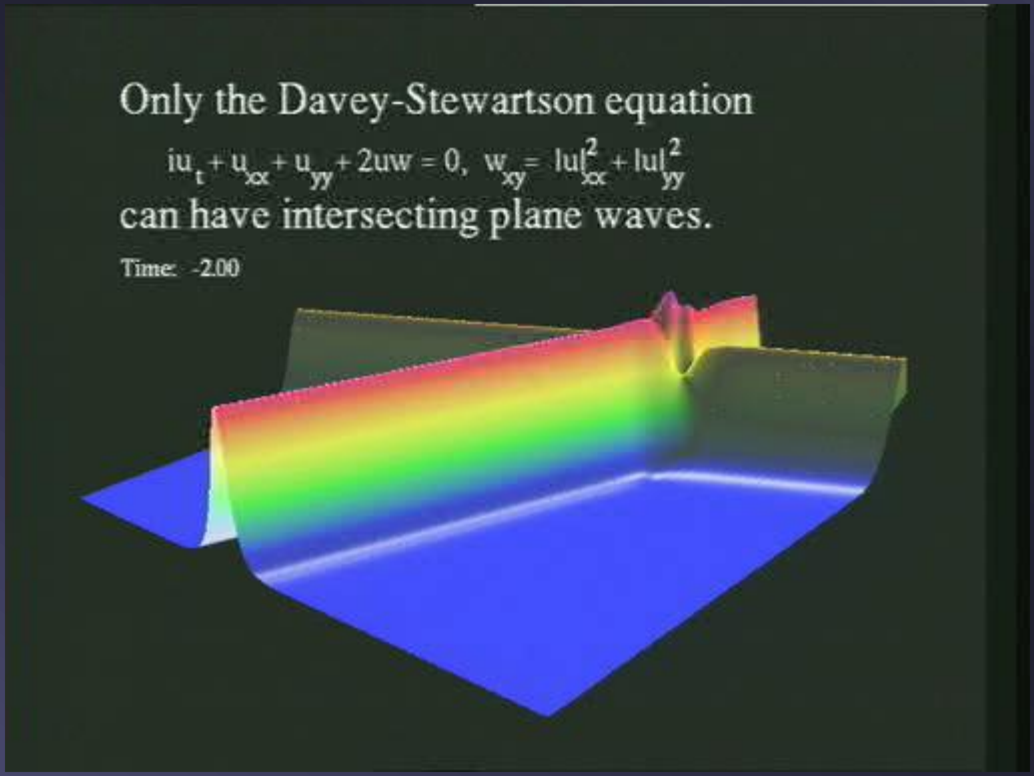
Korteweg—deVries equations

Solutions of KdV equations with various boundary conditions in various dimensions



crossing solitons

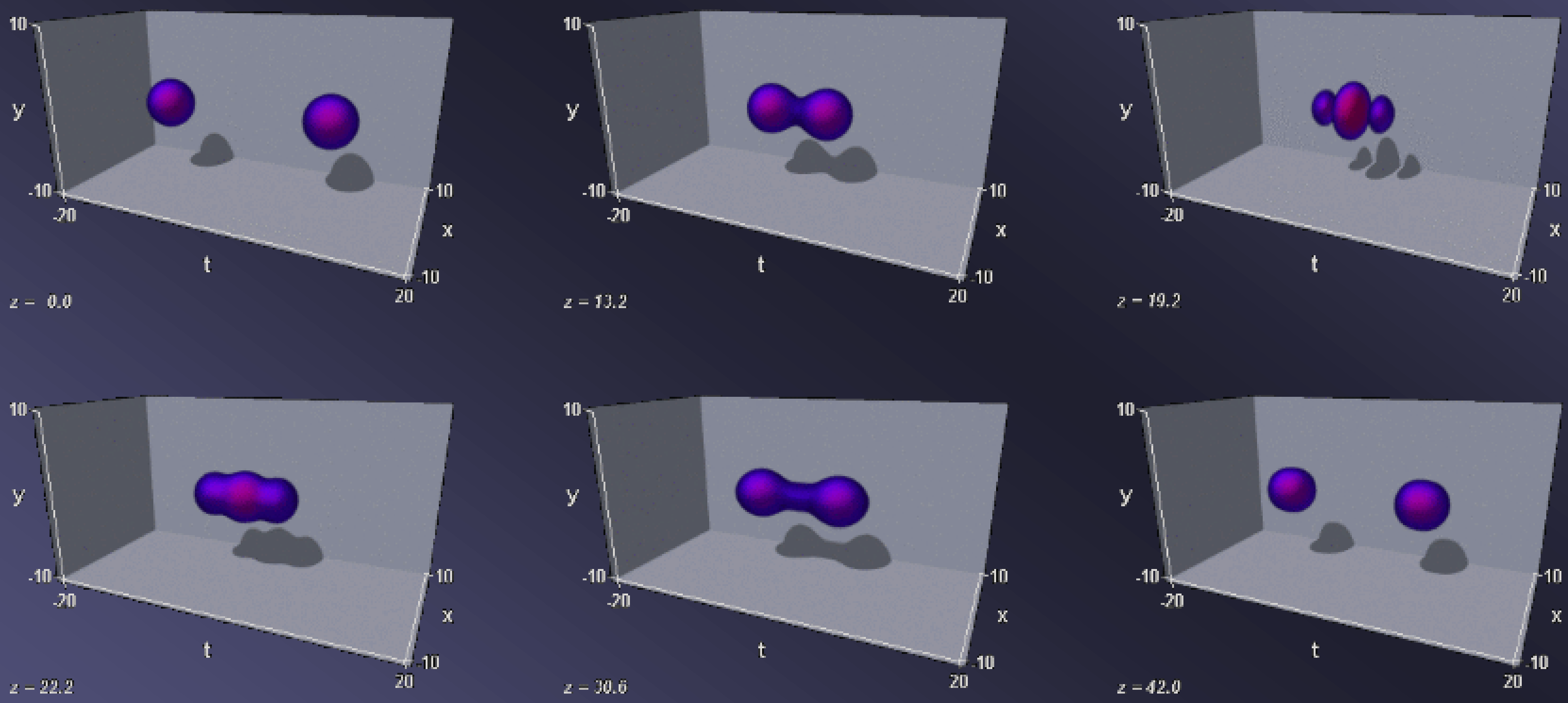
Korteweg—deVries equations

Solutions of KdV equations with various boundary conditions in various dimensions

crossing solitons

Korteweg—deVries equations

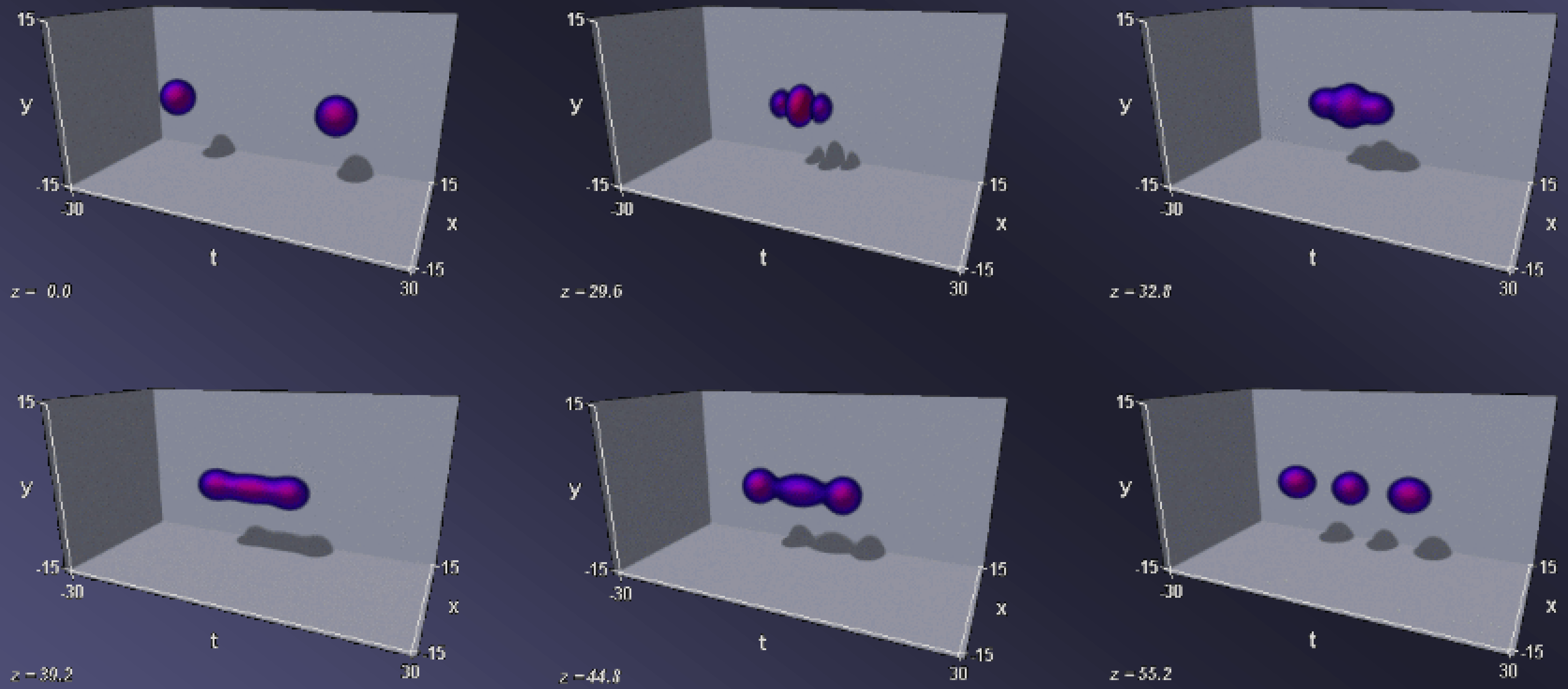
Solutions of KdV equations with various boundary conditions in various dimensions



airball soliton scattering

Korteweg—deVries equations

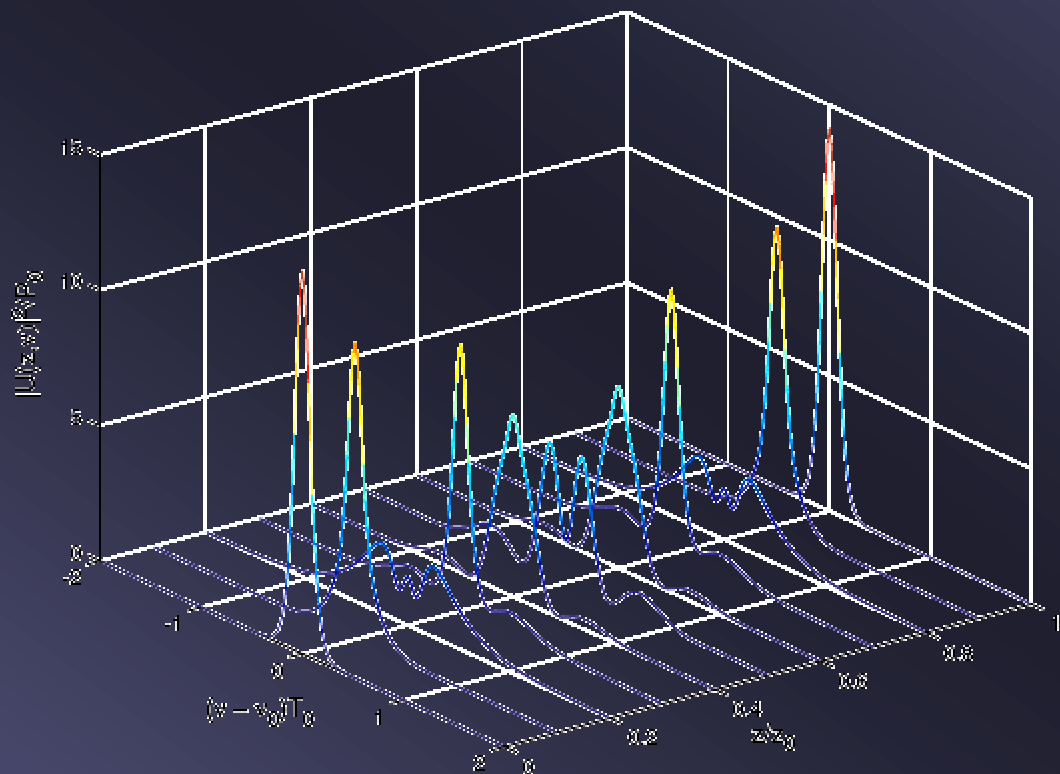
Solutions of KdV equations with various boundary conditions in various dimensions



airball soliton scattering – a pinch

Korteweg—deVries equations

Solutions of KdV equations with various boundary conditions in various dimensions

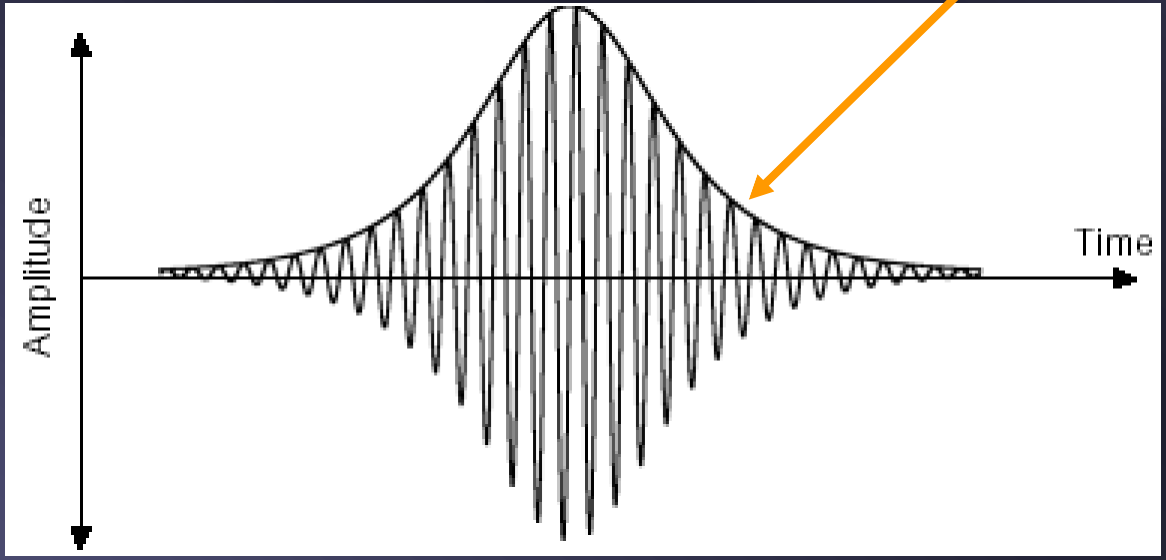


higher order soliton

Envelop solitons

Envelop of a wave

- if the amplitude of a wave varies (slowly)



envelop of the wave

$$h(t,x)$$

complex amplitude

Envelop solitons

- If the wave can be described by

$$E(x,t) = \mathrm{Re}\left(\hat{E}(x,t)\cdot e^{i(k_0 x - \omega_0 t)}\right)$$

the wave equation for the envelop $\hat{E}(x,t)$

$$i\frac{\partial \hat{E}}{\partial \xi} - \frac{k''}{2}\frac{\partial^2 \hat{E}}{\partial \tau^2} + g\frac{\left|\hat{E}\right|^2 \hat{E}}{\delta^2} = 0$$

reduction factor, ~1/2

with $k'' = \left.\frac{\partial^2 k}{\partial \omega^2}\right|_{\omega=\omega_0} = D\frac{\lambda}{\omega}$, $\delta = \frac{\Delta\omega_0}{\omega_0}$ and $g = \frac{2\pi n_2 \alpha}{\lambda}$.

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Envelop solitons

- Normalization

$$i\frac{\partial\hat{E}}{\partial\xi}-\frac{k''}{2}\frac{\partial^2\hat{E}}{\partial\tau^2}+g\frac{\left|\hat{E}\right|^2\hat{E}}{\delta^2}=0$$

$$q=\frac{\sqrt{g\lambda}}{\delta}\hat{E},\quad T=\frac{\tau}{\sqrt{\lambda k''}},\quad X=\frac{\xi}{\lambda}$$

$$i\frac{\partial q}{\partial X}-\frac{1}{2}\frac{\partial^2 q}{\partial T^2}+\left|q\right|^2 q=0$$

Envelop solitons

- Solving the non-linear Schrödinger equation

$$i\frac{\partial q}{\partial X}-\frac{1}{2}\frac{\partial^2 q}{\partial T^2}+|q|^2 q=0$$

  - test function

$$q(T,X)=\sqrt{\rho(T,X)}e^{i\sigma(T,X)}$$

  - the new equation

$$i\frac{\partial \rho}{\partial X}+\frac{\partial}{\partial T}\left(\rho\frac{\partial \sigma}{\partial T}\right)=0$$

Envelop solitons

- looking for solitary wave solution of the new equation

$$i\frac{\partial \rho}{\partial X}+\frac{\partial}{\partial T}\left(\rho\frac{\partial \sigma}{\partial T}\right)=0$$

- if $|q|^2=\rho$ is a stationary solution

$$\frac{\partial \rho}{\partial X}=0 \longrightarrow \rho\frac{\partial \sigma}{\partial T}=C(X)$$

it can be shown, that C is independent of X

Envelop solitons

- the solutions

$$\rho = \rho_0 \mathrm{sech}^2 \sqrt{\rho_0} T$$

$$\sigma = \frac{\rho_0}{2}$$

- which give

$$q(T,X) = \eta\,\mathrm{sech}\left(\eta\left(T + \kappa X - \vartheta_0\right)\right) e^{-i\left(\kappa T - \frac{\eta^2+\kappa^2}{2} X + \sigma_0\right)}$$

ϑ_0 and σ_0 are phase constants

$\eta = \rho^{1/2}$: amplitude and pulse width

κ: transmission speed

Solitons in optical fibers

- envelop equation of a light wave in a fiber

$$i\frac{\partial\hat{E}}{\partial\xi}-\frac{k''}{2}\frac{\partial^2\hat{E}}{\partial\tau^2}+g\frac{\left|\hat{E}\right|^2\hat{E}}{\delta^2}=0$$

- fiber loss rate per unit length: γ

$$i\frac{\partial\hat{E}}{\partial\xi}-\frac{k''}{2}\frac{\partial^2\hat{E}}{\partial\tau^2}+g\frac{\left|\hat{E}\right|^2\hat{E}}{\delta^2}=-\frac{i\gamma\hat{E}}{\delta^2}$$

with

$$k''=\left.\frac{\partial^2 k}{\partial\omega^2}\right|_{\omega=\omega_0},\quad \delta=\frac{\Delta\omega_0}{\omega_0},\quad g=\frac{2\pi n_2\alpha}{\lambda}.$$

Solitons in optical fibers

- Solitons can arise as solution of

$$i\frac{\partial \hat{E}}{\partial \xi} - \frac{k''}{2}\frac{\partial^2 \hat{E}}{\partial \tau^2} + g\frac{\left|\hat{E}\right|^2 \hat{E}}{\delta^2} = -\frac{i\gamma \hat{E}}{\delta^2}$$

if the real part of the nonlinear term is dominant,

$$g\frac{\left|\hat{E}\right|^2 \hat{E}}{\delta^2} > \frac{\gamma \hat{E}}{\delta^2} \quad \xrightarrow{\; g = \frac{2\pi n_2 \alpha}{\lambda} \approx \frac{\pi n_2}{\lambda} \;} \quad \frac{\pi n_2 \left|\hat{E}\right|^2}{\lambda} > \gamma$$

Solitons in optical fibers

- the condition for existence of a soliton:

$$\frac{\pi n_2 \left|\hat{E}\right|^2}{\lambda} > \gamma$$

- example:

$$\lambda \approx 1500 \text{ nm}$$

$$|\hat{E}| \approx 10^6 \text{ V/m}$$

$$n_2 \approx 1.2\times10^{-22} \text{ m}^2/\text{V}^2$$

$$\Bigg\} \quad \gamma < 2\times10^{-4} \text{ m}^{-1}$$

$$\downarrow$$

1.7 dB/km

Solitons in optical fibers

- the normalized equation, with $\Gamma = \frac{\gamma\lambda}{\delta^2}$

$$i\frac{\partial q}{\partial X} - \frac{1}{2}\frac{\partial^2 q}{\partial T^2} + |q|^2 q = -i\Gamma q$$

- if Γ is small enough, **perturbation techniques** can be used

$$q(T,X) = \eta(X)\ \operatorname{sech}(\eta(X)T)e^{-i\sigma(X)} + O(\Gamma)$$

$$\eta(X) = q_0 e^{-2\Gamma X}$$

$$\sigma(X) = \frac{q_0^{\ 2}}{8\Gamma}\left(1 - e^{-4\Gamma X}\right)$$

Solitons in optical fibers

- The solution of the normalized soliton equation in fibers with loss predicts
  - the amplitude η of the soliton decreases as it propagates:

$$\eta(X) = q_0 e^{-2\Gamma X}$$

  - the width σ of the soliton increases

$$\sigma(X) = \frac{q_0^2}{8\Gamma}\left(1 - e^{-4\Gamma X}\right)$$

  - **their product remains constant**

Solitons in optical fibers

- Effects of the waveguide manifest as

$$i\left(\frac{\partial q}{\partial X}+\Gamma q\right)-\frac{1}{2}\frac{\partial^2 q}{\partial T^2}+|q|^2 q$$

$$+i\delta\left(\beta_1\frac{\partial^3 q}{\partial T^3}+\beta_2\frac{\partial}{\partial T}\left(|q|^2 q\right)+\beta_3 q\frac{\partial}{\partial T}|q|^2\right)=0$$

higher order linear dispersion

nonlinear dispersion of the Kerr coefficient

nonlinear dissipation due to Raman processes (imaginary!!!)

Solitons in optical fibers

- Necessary condition for existence of a soliton

$$\tau_0\sqrt{P_0} = 9.3\times10^{-2}\ \lambda^{3/2}\sqrt{|D|S}$$

- τ_0 : pulse length [ps]
- P_0: required pulse power [W]
- λ : wavelength [μm]
- D : dispersion [ps/(nm km)]
- S : cross-sectional area [μm^2]

e.g., S=60 μm^2, λ=1.5 μm, $|D|$=10 ps/(nm km)

τ_0=10 ps, P_0=180 mW

Solitons in optical fibers

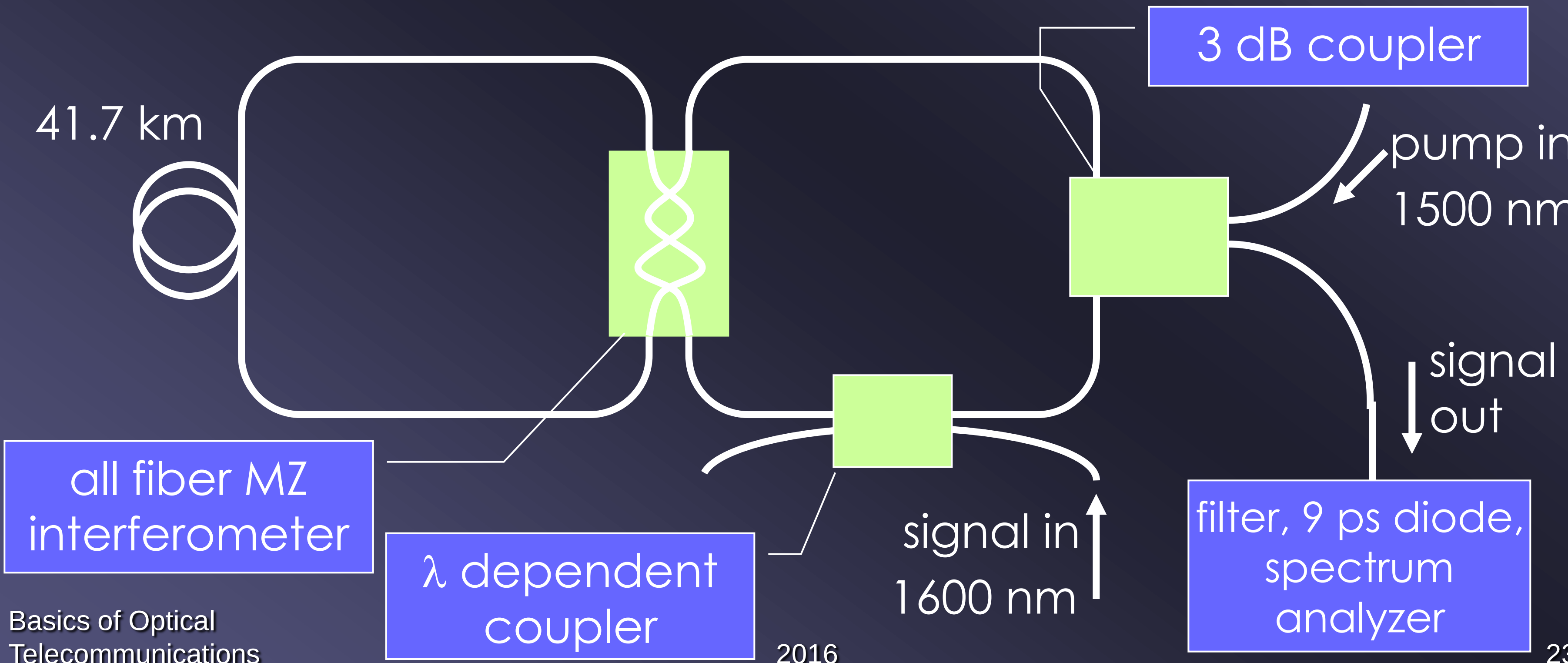
- Soliton generation needs
  - low loss fiber (<1 dB/km)
  - spectral width of the laser pulse be narrower than the inverse of the pulse length
  - Mollenauer & al. 1980, AT&T Bell Lab.
    - 700 m fiber, 10^{-6} cm^2 cross section
    - 7 ps pulse,
    - F^{2+} color center laser with Nd:YAG pump
    - 1.2 W soliton threshold

Amplification of solitons

- For small loss the soliton propagates with the product of its pulse length and height being constant
- reshaping is needed for long-distance communication application
- reshaping methods:
  - induced Raman amplification – the loss compensated along the fiber
  - repeated Raman Amplifiers
  - Er doped amplifiers

Amplification of solitons

- Experiment on the long distance transmission of a soliton by repeated Raman Amplification (Mollenauer & Smith, 1988)



Amplification of solitons

- Erbium doped fiber amplifiers, periodically placed in the transmission line
  - distance of the amplifiers should be less then the soliton dispersion length
  - dispersion shifted fibers or filters for reshaping
- quantum noise arise
  - spontaneous emission noise
  - Gordon—House jitter

Optical soliton transmission systems

The soliton based communication systems mostly use on/off or DPSK keying

- In soliton communication systems the timing jitters which originate from frequency fluctuation are held under control by narrow band optical filters
  - frequency guiding filter
  - e.g., a shallow Fabry-Perot etalon filter

(in non-soliton systems, these guiding filters destroy the signal, they are not used)

Optical soliton transmission systems

- It is possible to make the soliton “slide” in frequency
  - sliding frequency guiding filters
  - each consecutive narrow-band filter has slightly different center frequency
  - center frequency sliding rate: $f' = df/dz$
  - the solitons can follow the frequency shift
  - the noise can not follow the frequency sliding, it drops out

Optical soliton transmission systems

- Wavelength division multiplexing in soliton communication systems
  - solitons with different center frequency propagate with different group velocity
  - in collision of two solitons, they propagate together for a while
  - collision length:

$$L_{coll} = \frac{2\tau}{D\Delta\lambda}$$

Optical soliton transmission systems

- during the collision both solitons shifts in frequency (same magnitude, opposite sign)
- first part of the collision: the fast soliton's velocity increases, while the slow one becomes slower
- at the second part of the collision, the opposite effect takes place, symmetrically

Optical soliton transmission systems

- if during the collision the solitons reach an amplifier or a reshaper, the symmetry brakes
- the result is non-zero residual frequency shift can arise, unless

$$L_{coll} > 2L_{amp}$$

Optical soliton transmission systems

- if a collision of two solitons take place at the input of the transmission
- half collision
- it can be avoided by staggering the pulse positions of the WDM channels at the input.

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