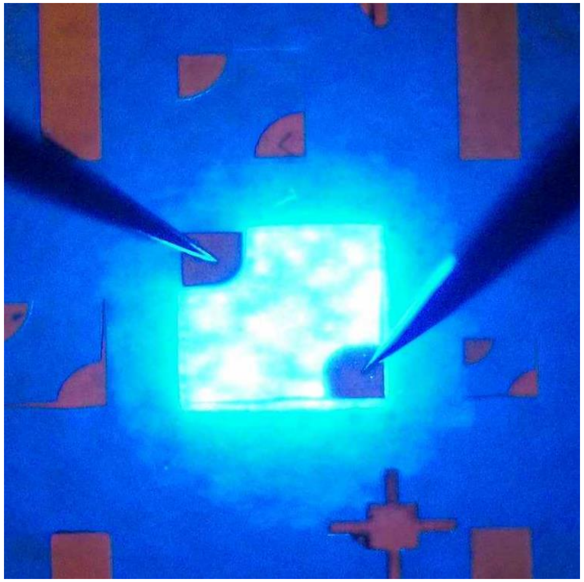
Optoelectronics
ELEC-E3210



Lecture 6

Aalto University
School of Electrical
Engineering

Outline

- Semiconductor Optical Amplifier
- Optical modulation
- Electroabsorption modulators

P. Bhattacharya: chapter 11
J. Singh: chapter 12

Optical amplification

- ***Optical signal attenuates in optic/optoelectronic systems => amplification needed***
- *Alternatives*
  - *Laser amplifier*
    - *Any kind of laser (solid-state, gas, dye, etc.) can be used*
    - *Most solutions use optical pumping*
  - *DFA = doped fiber amplifier*
    - *Optical pumping of rare-earth dopants in an active fiber*
  - ***SOA = semiconductor optical amplifier***
    - ***Offers optoelectronic solution, pumping by electric current***
  - *Raman amplifier*
    - *Amplification by stimulated Raman scattering in fibers*
    - *Optical pump at anti-Stokes wavelength, amplification at Stokes*
  - *OPA = optical parametric amplifier (optical pumping)*
    - *Interaction of several optical beams in nonlinear crystal*

Amplifier performance

Large gain bandwidth

- Allows WDM
- Short pulse (<ps) amplification

Gain saturation

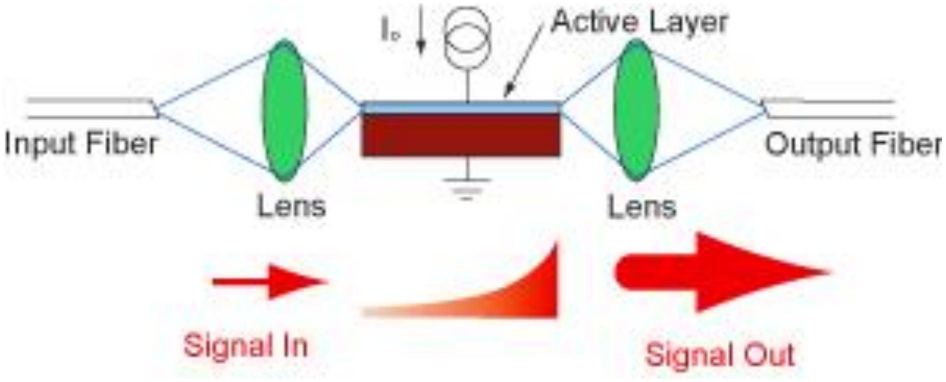
- Limits performance in WDM
- Pulse shape distortion

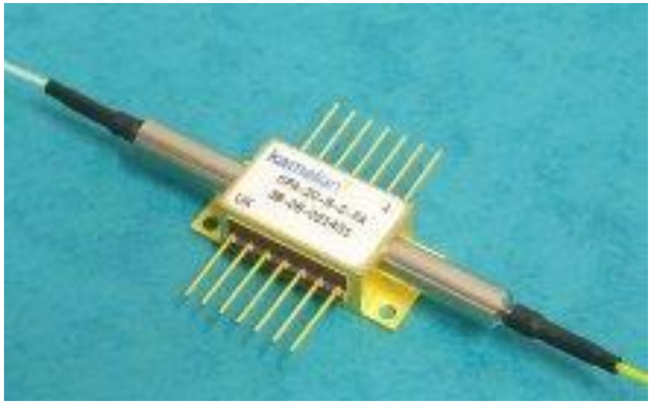
Noise and amplifier induced chirp

- Spontaneous emission noise adds to the signal noise
- Induced chirp (=frequency shift) can be exploited for pulse compression

Principle of SOA operation

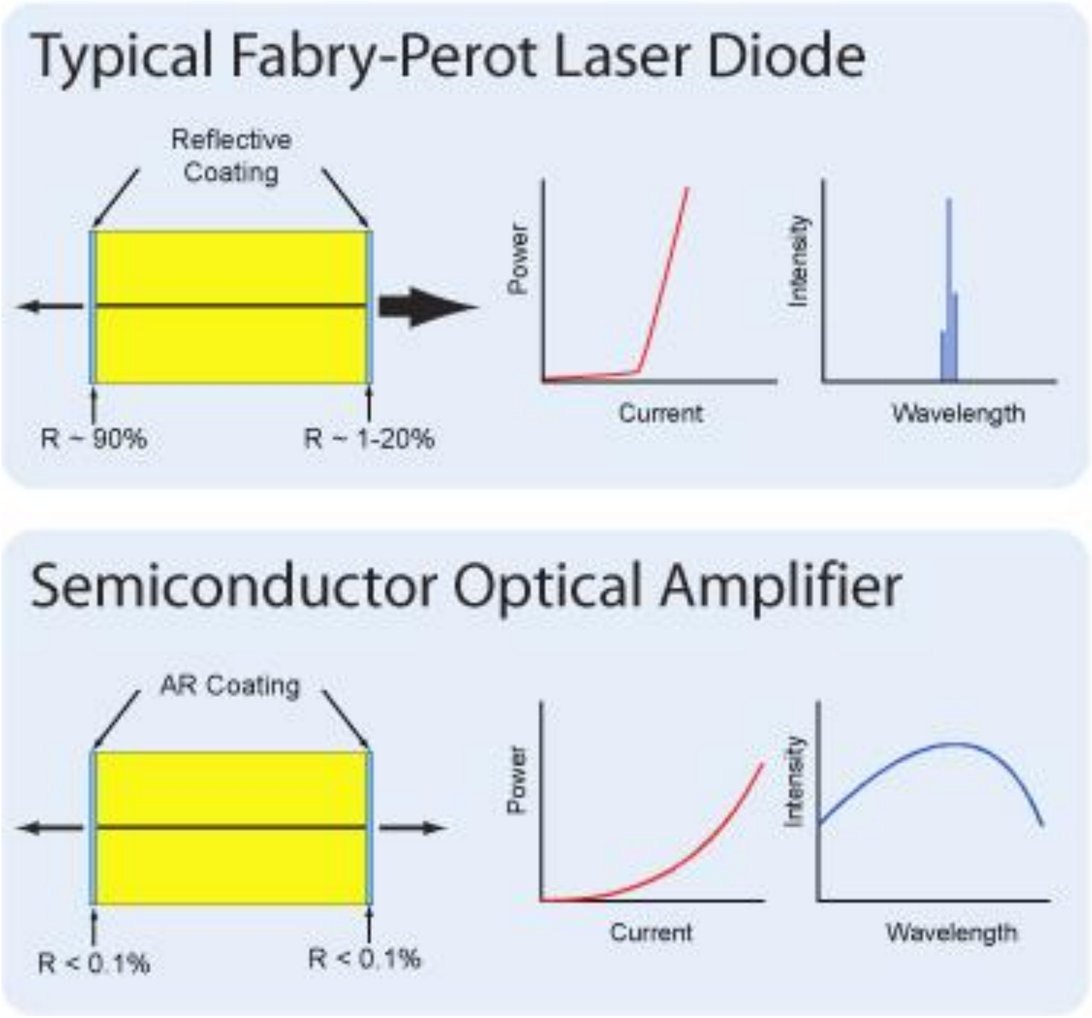
SOA = semiconductor optical amplifier





- *Amplification through stimulated emission in semiconductors*
- *Amplification can be changed with injected current*
- *Self-lasing must be suppressed*

Principle of SOA operation



SOA properties

- *High optical nonlinearity makes SOAs attractive for*
  - *all-optical signal processing like all-optical switching and wavelength conversion*
  - *clock recovery, signal demultiplexing and pattern recognition*
- *Comparison with EDFA (erbium-doped fiber amplifier)*
  - *SOA has*
    - *higher noise*
    - *lower gain*
    - *moderate polarization dependence*
    - *high nonlinearity*
    - *fast changes of gain cause phase changes which can distort the signal*
    - *can have gain in different wavelength regions from the EDFA*
    - *can be integrated with other elements*
  - *EDFA generally better for optical communications*

SOA Analysis

- *RATE equation for the carriers in the active area*

$$\frac{dn}{dt} = \frac{J}{ed} - \frac{n}{\tau} - \Omega\left(n - n_{nom}\right) N_p \qquad \text{where} \quad \Omega = \frac{\Gamma c\, \partial g / \partial n}{n_r}$$

d is the thickness of the active layer, N_p *is the photon density*

- *Optical power is*

$$P = A_m v N_p \hbar\omega = A_m N_p \hbar\omega c / n_r \qquad \Rightarrow \qquad \frac{P}{A_m \hbar\omega} = N_p\, c / n_r$$

A_m *is the area of the optical mode*

SOA Analysis

- *RATE equation with optical power as a variable*

$$\frac{dn}{dt} = \frac{J}{ed} - \frac{n}{\tau} - \frac{\partial g}{\partial n}\left(n - n_{nom}\right)\frac{P}{A_m \hbar\omega}$$

with the optical confinement factor Γ included in differential gain

$$\Gamma \frac{\partial g}{\partial n} \rightarrow \frac{\partial g}{\partial n}$$

Steady state:

$$\frac{dn}{dt} = \frac{J}{ed} - \frac{n}{\tau} - \frac{\partial g}{\partial n}\left(n - n_{nom}\right)\frac{P}{A_m \hbar\omega} = 0$$

SOA Analysis

- *Solve n:*

$$\Rightarrow \quad n\left(\frac{1}{\tau}+\frac{\partial g}{\partial n}\frac{P}{A_m\hbar\omega}\right)=\frac{J}{ed}+\frac{\partial g}{\partial n}\frac{n_{nom}P}{A_m\hbar\omega}$$

$$\Rightarrow \quad n=\frac{\dfrac{\tau J}{ed}+\dfrac{\partial g}{\partial n}\dfrac{n_{nom}\tau P}{A_m\hbar\omega}}{1+\dfrac{\partial g}{\partial n}\dfrac{\tau P}{A_m\hbar\omega}}=\frac{\dfrac{\tau J}{ed}+n_{nom}\,P/P_s}{1+P/P_s}$$

where $\quad P_s=\dfrac{A_m\hbar\omega}{\tau\partial g/\partial n}\quad$ is saturation power

SOA Analysis

- *Solve g:*

$$g = \frac{\partial g}{\partial n}\left(n - n_{nom}\right) = \frac{\partial g}{\partial n}\left(\frac{\tau J/(ed) + n_{nom} P/P_s}{1 + P/P_s} - \frac{n_{nom} + n_{nom} P/P_s}{1 + P/P_s}\right)$$

$$= \frac{\partial g}{\partial n}\left(\frac{\tau J/(ed) - n_{nom}}{1 + P/P_s}\right) = \frac{g_0}{1 + P/P_s}$$

where $g_0 = \frac{\partial g}{\partial n}\left(\frac{\tau J}{ed} - n_{nom}\right)$ is the cavity gain at small photon densities

SOA Analysis

- *Optical power change in the cavity*

$$\frac{dP}{dz} = gP = \frac{g_0 P}{1 + P/P_s}$$

constant g would lead to exponential increase in power

- *Separation of variables*

$$\Rightarrow \quad \frac{dP}{\dfrac{g_0 P}{1 + P/P_s}} = dz \qquad \Rightarrow \quad \frac{P_s + P}{g_0 P P_s} dP = dz$$

SOA Analysis

- *Total gain of the device by integration over the amplifier length L*

$$\int_{P_{in}}^{P_{out}} \frac{P_s + P}{g_0 P P_s} dP = \int_0^L dz \quad \Rightarrow \quad \int_{P_{in}}^{P_{out}} \left(\frac{1}{g_0 P} + \frac{1}{g_0 P_s} \right) dP = \int_0^L dz$$

$$\Rightarrow \quad \frac{1}{g_0} \ln\left(\frac{P_{out}}{P_{in}} \right) + \frac{1}{g_0 P_s} \left(P_{out} - P_{in} \right) = L$$

$$G = \frac{P_{out}}{P_{in}} = G_0 \exp\left(-\frac{G-1}{G} \cdot \frac{P_{out}}{P_s} \right), \quad G_0 = \exp\left(g_0 L \right)$$

SOA Analysis

- *Total gain of the device*

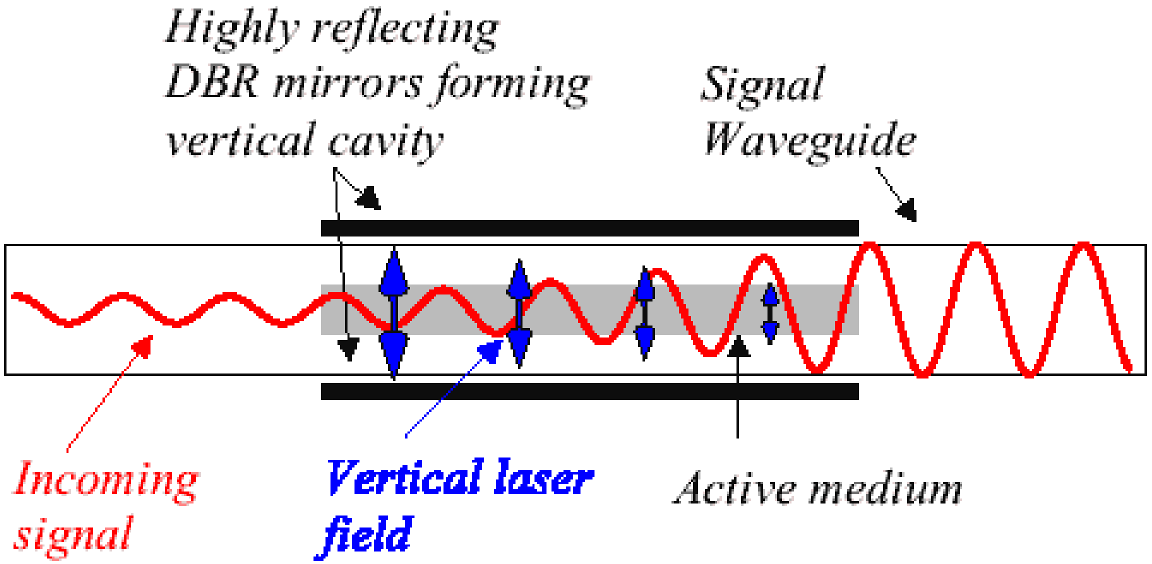
$$G = \frac{P_{out}}{P_{in}} = G_0 \exp\left(-\frac{G-1}{G} \cdot \frac{P_{out}}{P_s} \right), \quad G_0 = \exp(g_0 L)$$

Gain saturates at high optical powers!

G falls by ~ 4dB when $P_{out} = P_s$

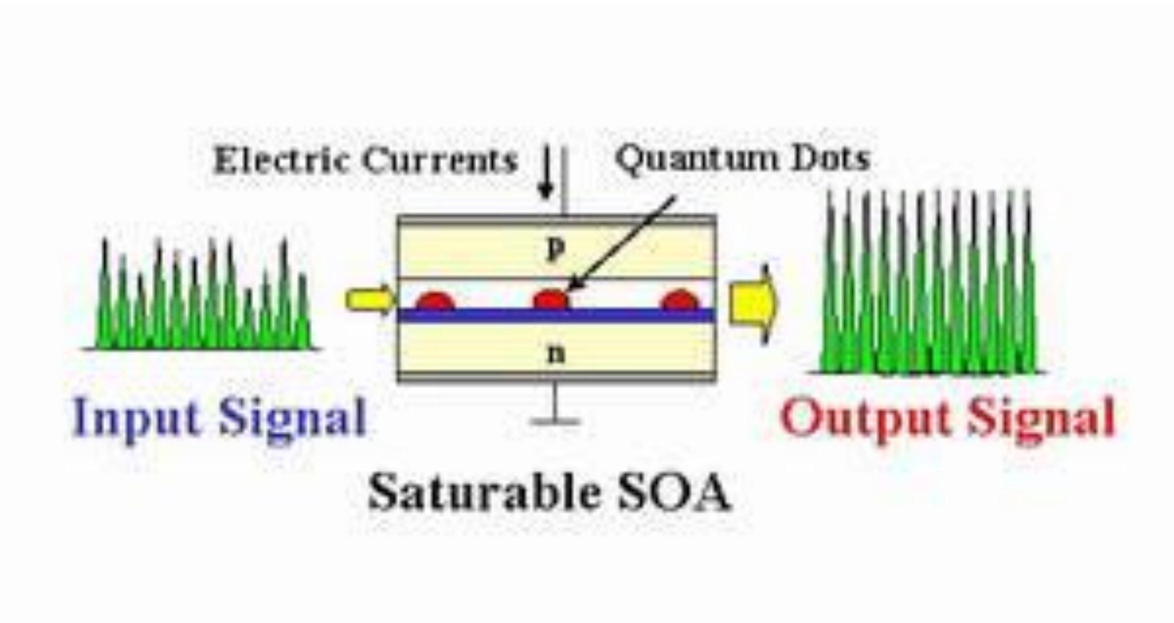
Gain saturation causes pulse distortion and can affect the chirp of the pulse via self-phase modulation

Linear optical amplifier (example)



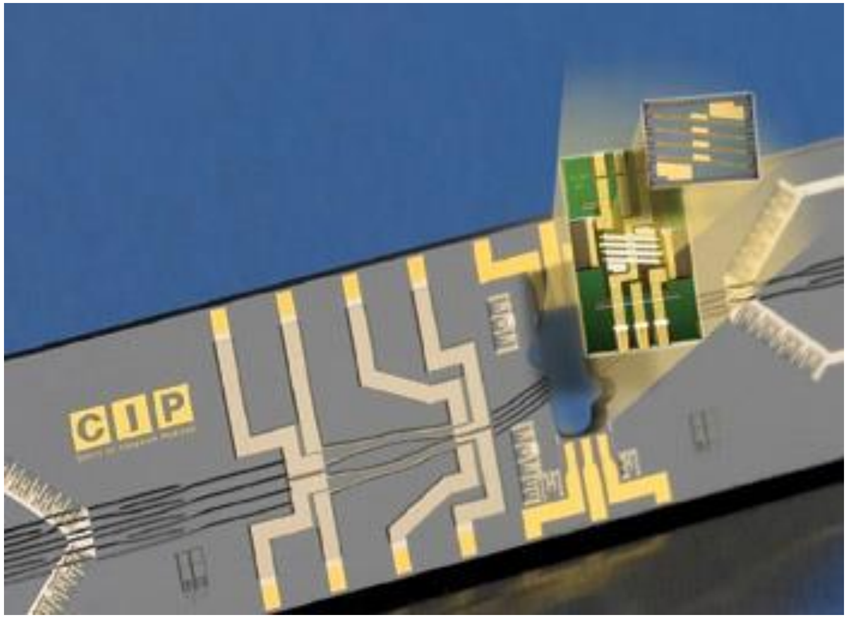
- VCSEL structure in vertical direction
- Amplification for lateral direction
- Carrier concentration saturated when lasing in vertical direction
  => constant gain

Advanced SOA (example)



"Tokyo, March 4, 2005 — Fujitsu Limited and Fujitsu Laboratories Limited today announced the development of the world's first semiconductor optical amplifier (SOA) enabling waveform re-shaping of high-speed optical signals at 40Gbps by using quantum dots".

Integrated SOA (example)



"*Figure 4. This photomontage shows the hybrid integration assembly of SOAs into a planar lightwave circuit (PLC). The SOA array (top right) solders onto a silicon carrier (middle) that is used to place the SOAs into a machined hole in the PLC (background). The silica waveguides forming the Mach-Zehnder interferometers are the thin black lines running horizontally across the PLC.*"

http://www.photonics.com/Content/ReadArticle.aspx?ArticleID=30460

Outline

- Semiconductor Optical Amplifier
- Optical modulation
- Electroabsorption modulators

P. Bhattacharya: chapter 11
J. Singh: chapter 12

Optical modulation

What is an optical modulator ?

A device used to turn off and on an optical signal.

What are they used for?

Lasers, communications, lab use etc.

How do they work?

Via absorption, interference or refraction

Non communications (low speed)

Mechanical, Liquid Crystals, Acousto-optic

Communications (high speed)

Electro-optic, Franz Keldysh, and Quantum Confined Stark Effects

Optical modulation

- **Direct modulation** on semiconductor lasers:
  - Electronic circuit modulates the injection current and thus the light output
  - Output frequency shifts with drive signal
  - Limited extinction ratio → because we don't want to turn off laser at 0-bits
  - Impact on distance*bit-rate product

- **External modulation**
  - Light passes through a material whose optical properties can be modified by external means
  - Electro-optical modulation
  - Electroabsorption modulation
  - Always incur 6-7 dB insertion loss

Direct vs external modulation

Direct modulation

- Simple, cost-effective and compact
- Device speed controlled by processes internal to the laser
- Emission frequency can alter with drive current. Only the output intensity is altered with ease.

External modulation

- Additional component and loss
- Higher speed (controlled by the modulator)
- Emission frequency unaltered (low chirp) but phase content can be altered

Direct vs external modulation

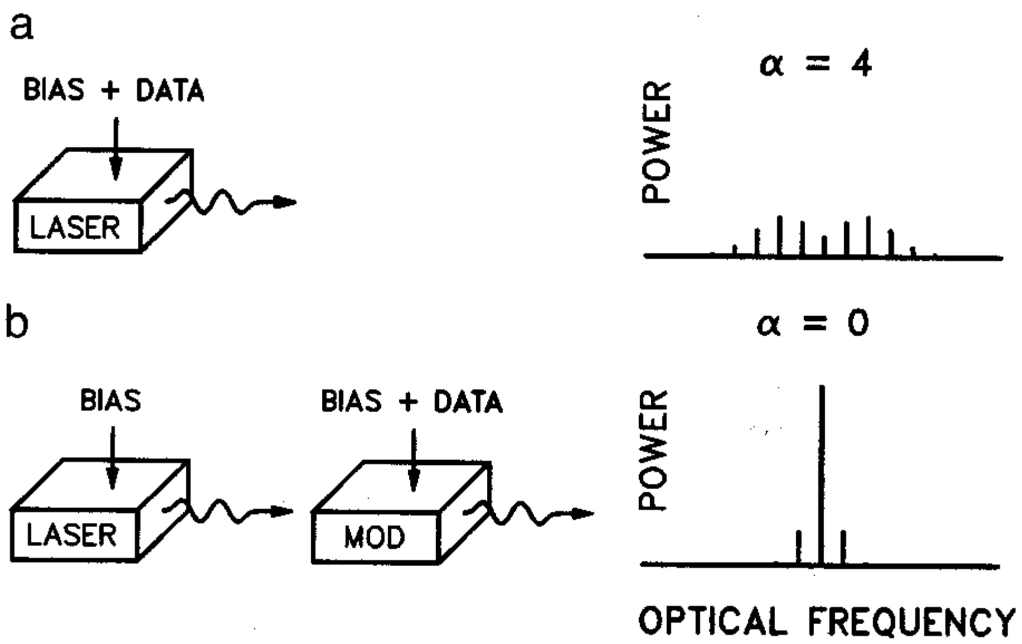
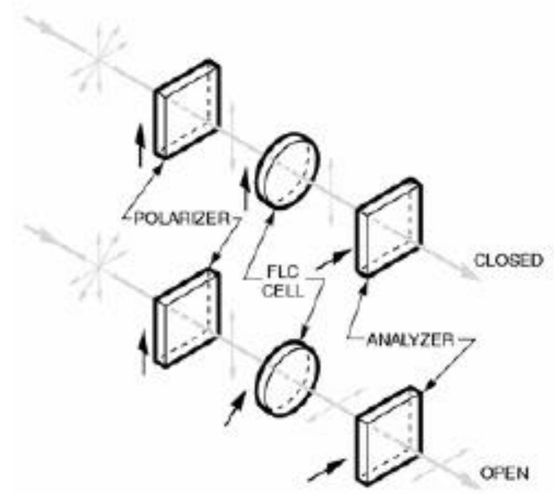


Fig. 9.2 Comparison of transmitted spectra for (a) direct and (b) external modulation.

Mechanical shutters and liquid crystals

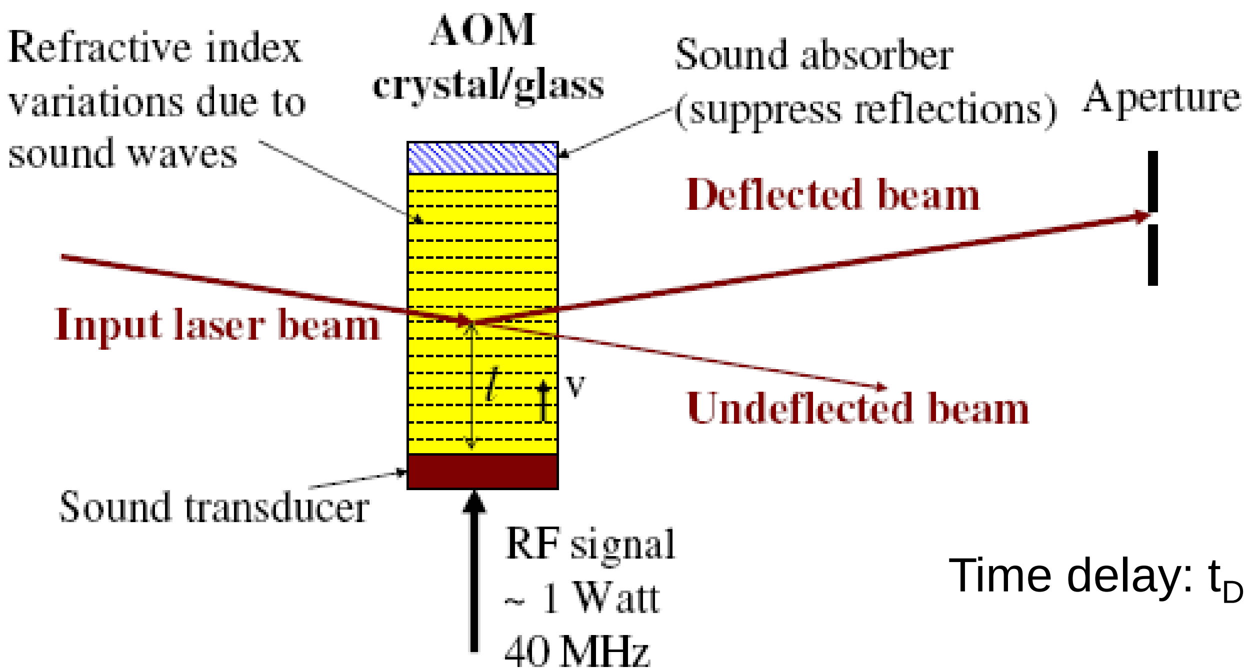
Shutter

Ferroelectric liquid crystal



- rod-like molecules are free to twist in the crystal around a certain axis
- tilts towards applied field and modulates index of refraction for polarized light

Acousto-optic modulator



Time delay: $t_D = l / v$

- RF signal is converted to sound waves in crystal using a piezo-electric transducer
- Sound waves are collimated to form grating
- Bragg scattering from grating gives deflected beam
- Capabilities: 100 MHz, broad-band UV-IR

Outline

- Semiconductor Optical Amplifier
- Optical modulation
- Electroabsorption modulators

P. Bhattacharya: chapter 11
J. Singh: chapter 12

Electroabsorption (EA) Modulator

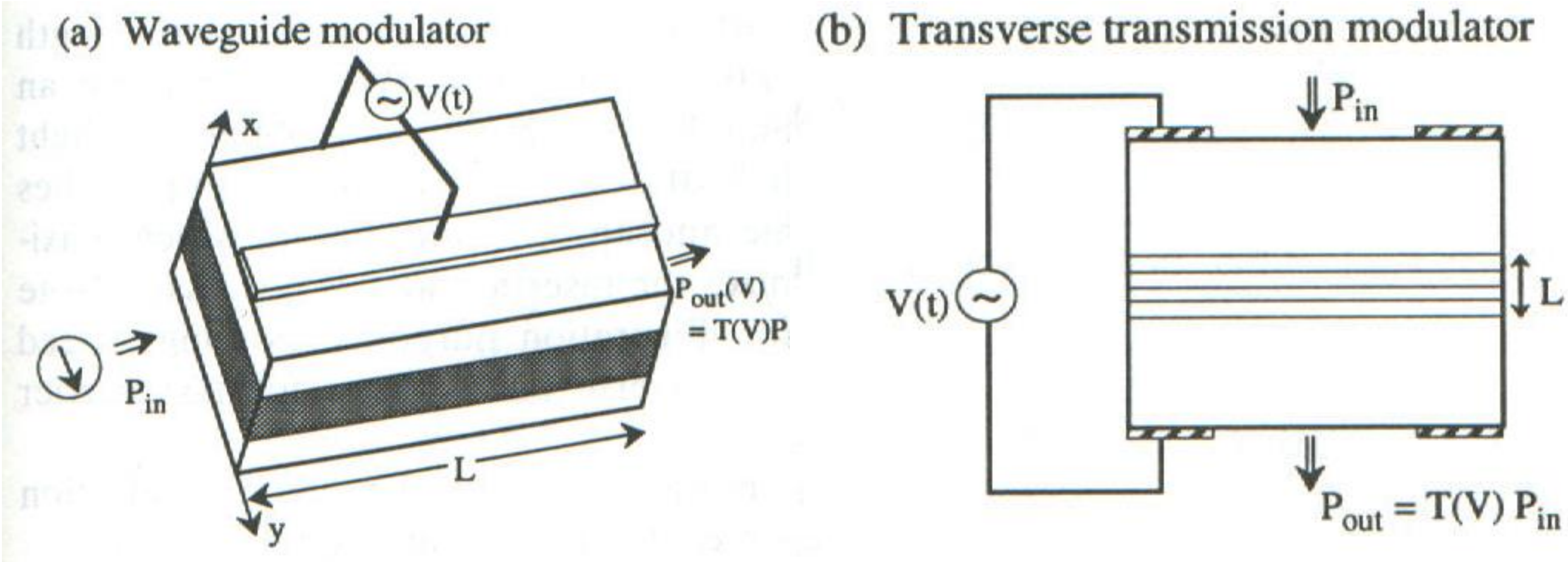
- **Franz-Keldysh and Stark effect modulators**
  - Change of the absorption spectrum with bias is weak for practical modulation devices (either very large field or several millimeter long devices needed)

- **Quantum confined Start effect (QCSE)**
  - By applying electric field parallel to the quantum well growth direction, the absorption can be changed dramatically at the desired wavelength

Electroabsorption (EA) Modulator

- EA modulator is a semiconductor device
  - Typically has the same structure as the laser diode.
  - Used for controlling the output intensity of a laser
- Use an applied electric field (reverse bias) to change the absorption spectrum.
- Typically no carriers are injected into the active region. However, carriers are generated due to absorption of light.
- Advantages
  - Zero biasing voltage
  - Low driving voltage (a few volts)
  - Low/negative chirp
  - High speed (modulation bandwith up to tens of GHz)
  - Can be integrated with DFB laser! → data transmitter, photonic integrated circuit

Schematics of an EA modulator



- Waveguide type is more commonly used.
- Transmission type does not lead to high enough extinction ratio.
- Electric field is applied in a perpendicular direction with respect to the modulated light beam
- Quantum well structures can be used for high extinction ratio

Franz-Keldysh Effect

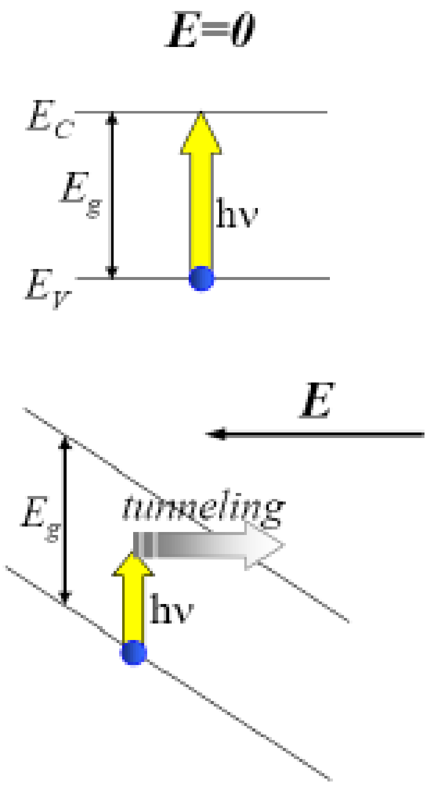
The electric field bends the bands.
This results in a energy barrier.

Can write Schrödinger's equation:

$$\left(-\frac{\hbar}{2m_r}\frac{\partial^2}{\partial z^2}+eFz\right)\phi(z)=E_z\phi(z)$$

This problem has been solved:
Solutions are Airy Functions:

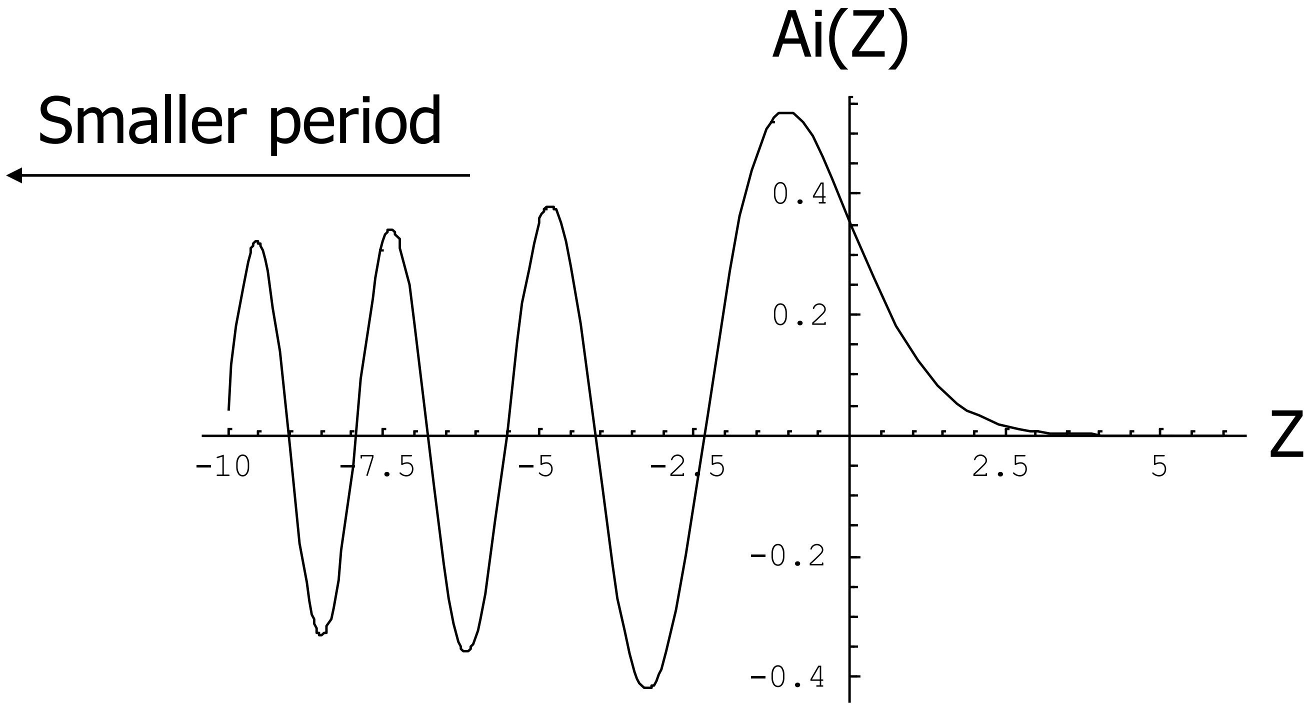
$$\phi\left(E_g-\hbar\omega\right)\propto Ai\left(E_g-\hbar\omega\right)$$



Franz-Keldysh Effect

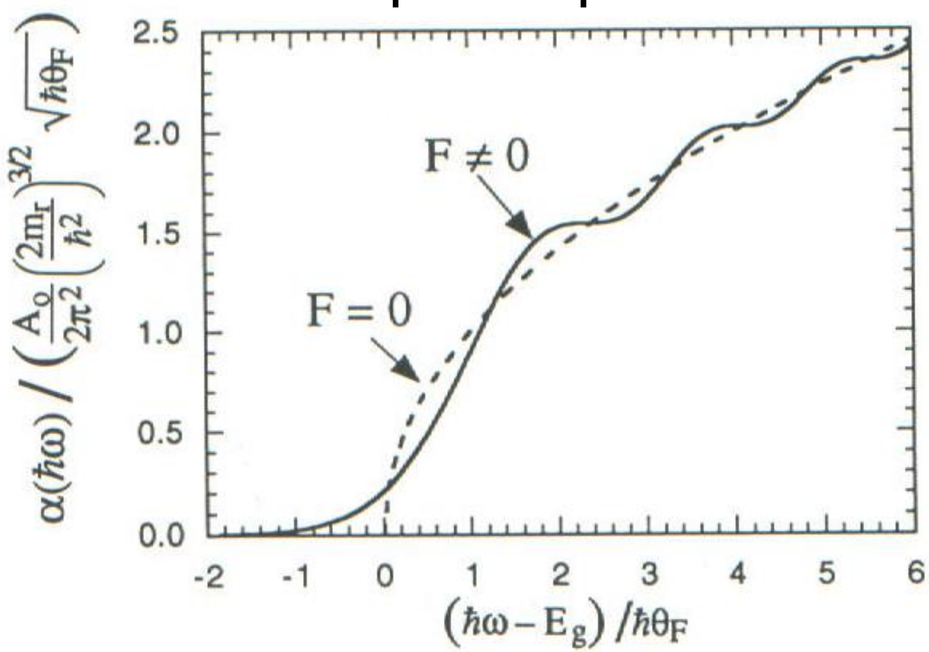
Airy Function *Ai* (Z)

- Z>0: electron-hole energy+E_g < electric field potential
- Z<0: electron-hole energy+E_g > electric field potential, i.e. above bandgap → oscillation wavefunction



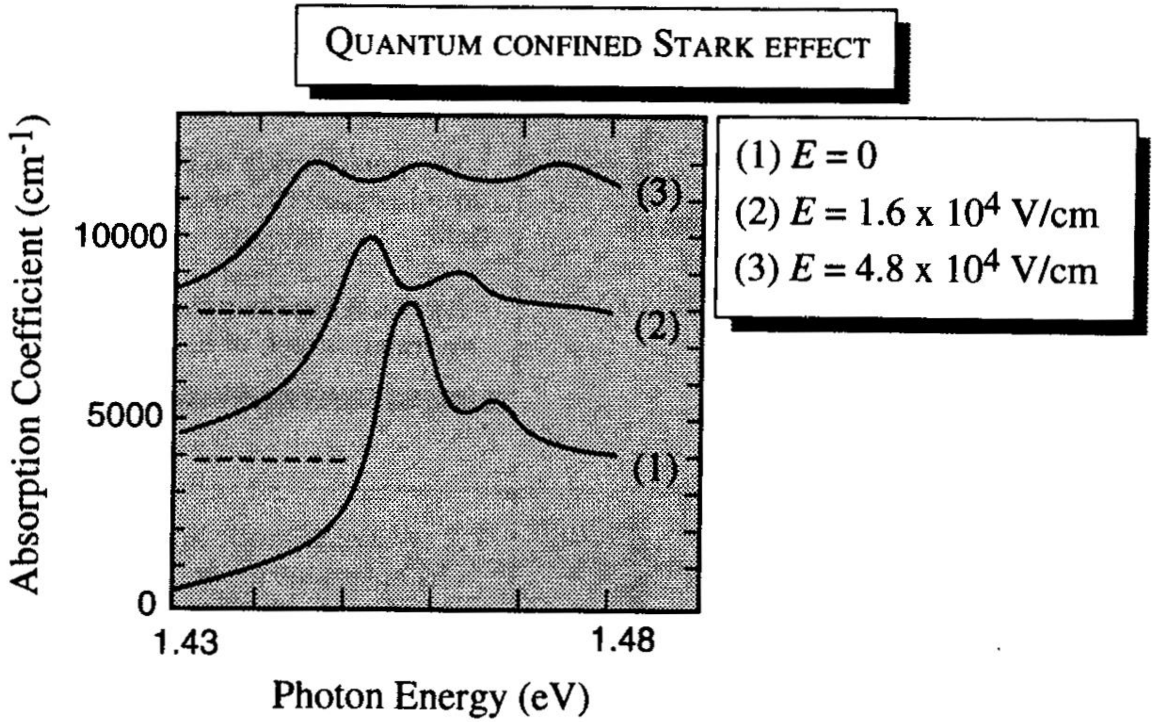
Franz-Keldysh Effect

Absorption spectrum



- Absorption spectrum reduces to the familiar square root dependence of energy when $F \to 0$.
- The exponential tail means that the electron and hole wavefunctions overlap for energies less than the bandgap

Quantum Confined Stark Effect



- Exciton absorption peak red-shifts with increasing electric field strength.
- Works well for modulation!

Quantum Confined Stark Effect

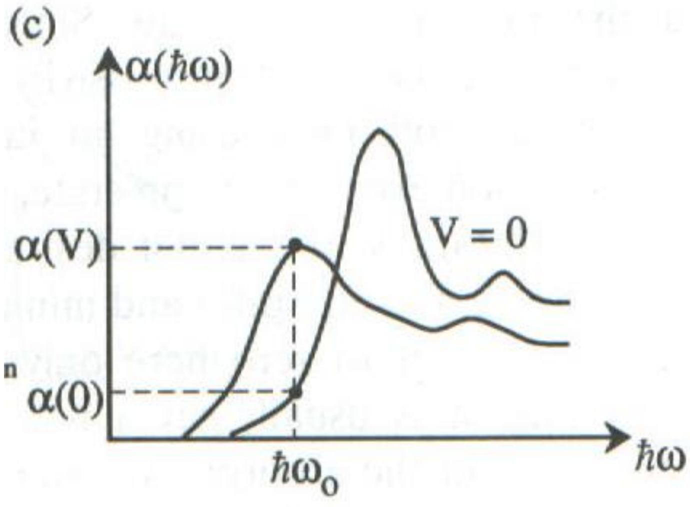
- The red-shift of the exciton resonances in the QCSE is primarily due to a change in the ground state intersubband energy separation
- Absorption coefficient due to excitonic absorption in a quantum well and the energy shift are given by

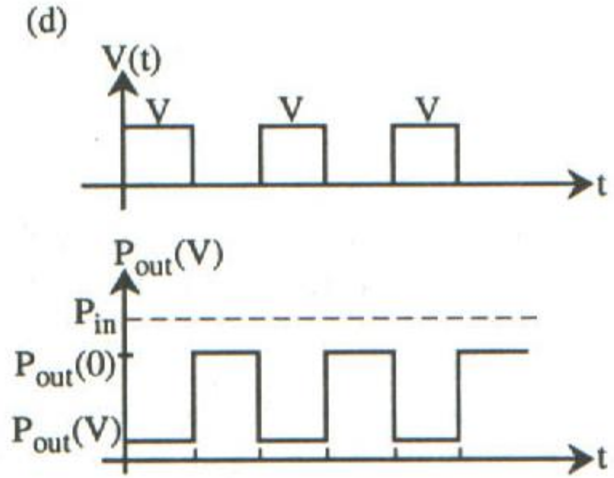
$$\alpha^{ex}(\hbar\omega) = \frac{2.9 \times 10^3}{\Delta E_{FWHM} L_z} \exp\left[\frac{-(E^{ex} - \hbar\omega)^2}{1.44\, \Delta E_{FWHM}^2}\right]$$

$$\Delta E = \frac{1}{24\pi^2}\left(\frac{15}{\pi^2} - 1\right)\frac{m_{eff}^* e^2 F^2 L_z^4}{\hbar^2}$$

- For a field of (1-10) x 10^4 V/cm the shift in the absorption edge and exciton resonances in a 10nm GaAs/AlGaAs MQW is ~ 10 – 50 meV
- QCSE depends strongly on the well width (thicker well requires smaller field for the same shift)

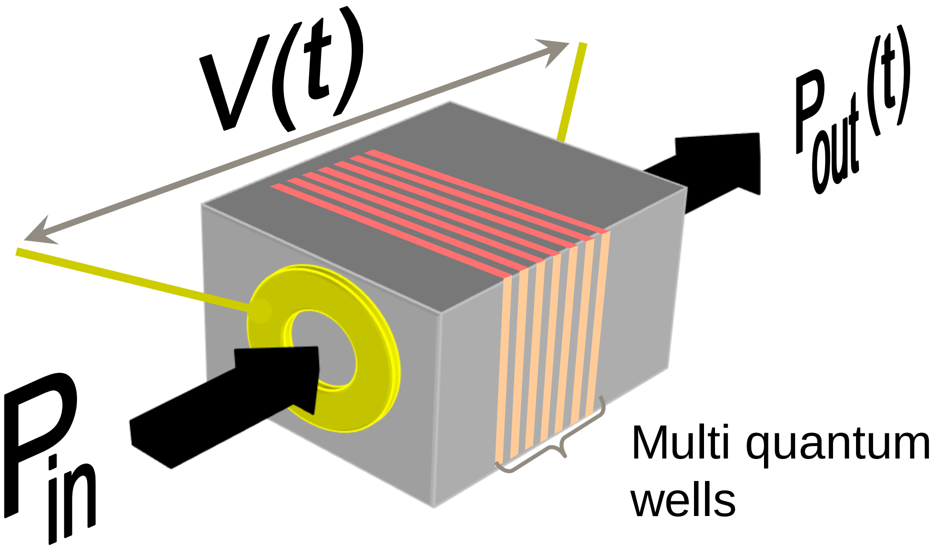
Quantum Confined Stark Effect

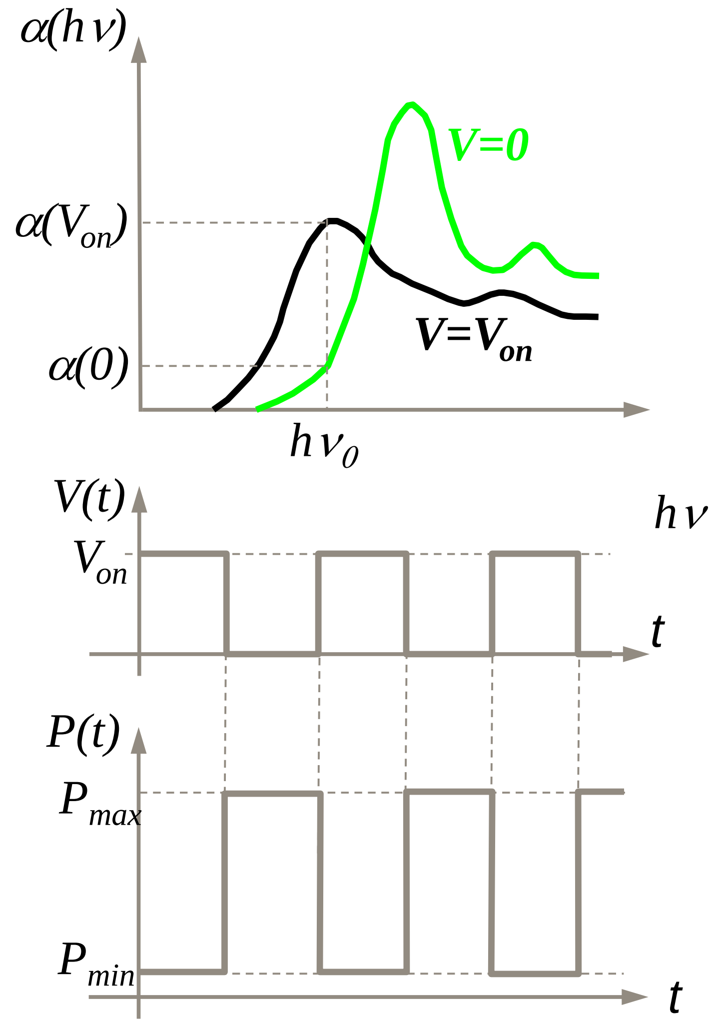




- By applying electric field parallel to the quantum well growth direction, the absorption can be changed dramatically at the desired wavelength.
- QCSE changes the absorption only in a very narrow band

QCSE modulator

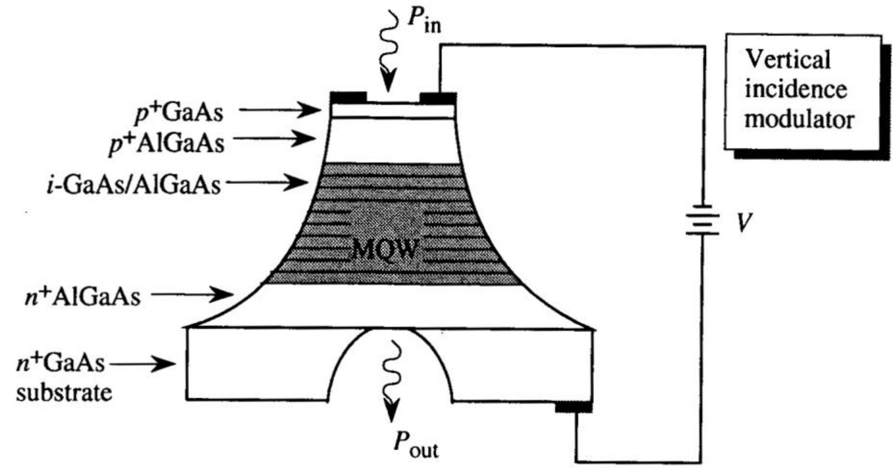


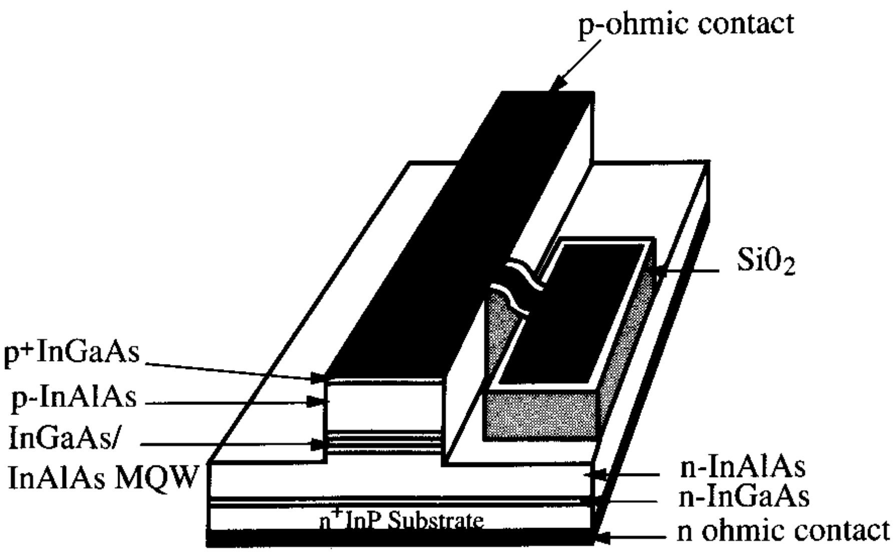


→ EA modulators based on QCSE operate efficiently only near the exciton absorption peak

Schematics of an EA modulator

- Mesa-etched modulator
  - Total thickness of MQW region ~ 1μm
  - Mesa diameter 50 – 100 μm

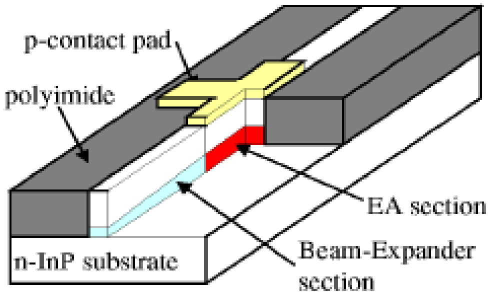


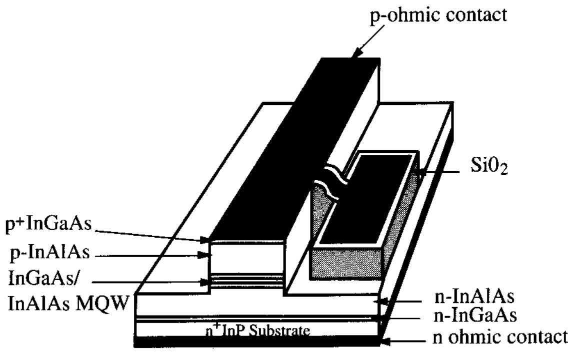


- InP-based guided wave MQW electroabsorption modulator
  - Light is incident on one of the waveguide facets
  - Couple of hundred microns in length

Design considerations for EA modulators

- Operation principle
- Contrast ratio
- Insertion loss
- Modulation efficiency
- Chirp considerations and optimization
- Packaging and Integration





Extinction Ratio (Contrast Ratio)

$$R_{on/off} = \frac{P_{out}(V_{on} = 0)}{P_{out}(V_{off} = V)} = \frac{e^{-\alpha(0)L}}{e^{-\alpha(V)L}}$$

$$R_{on/off}(dB) = 10\log(R_{on/off}) = 4.343 \cdot \left[\alpha(V) - \alpha(0)\right]L$$

- BER directly effected by extinction ratio
- Contrast ratio can be made as large as possible by increasing the length of the modulator. But propagation loss then becomes an issue.

Insertion Loss

- Absorptive loss
  - The longer the modulator is, the larger the insertion loss.
  - Trade-off with Extinction Ratio

$$\text{Loss} = \frac{P_{in} - P_{out}(V=0)}{P_{in}} = 1 - e^{-\alpha(0)L}$$

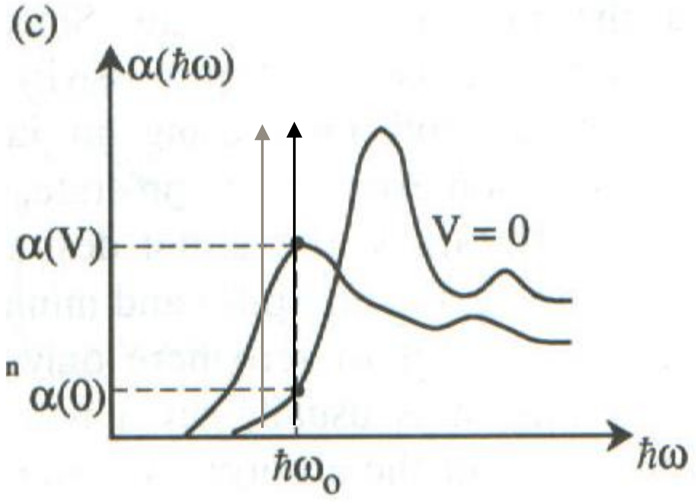
- Single mode fiber coupling loss
  - Waveguide coupler can be used to reduce coupling loss
  - Can be as good as 1 dB
  - Typical numbers are 5-6 dB

Modulation Efficiency

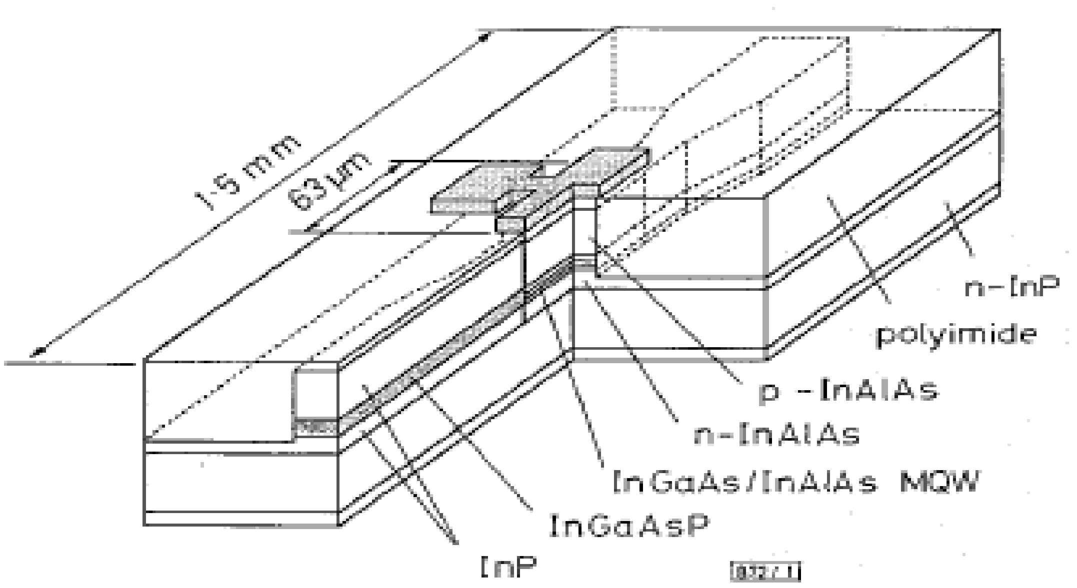
- Modulation efficiency quantifies how much voltage do we need to modulate the optical signal.

$$\frac{R_{on/off}}{\Delta V} = 4.343\frac{[\alpha(V)-\alpha(0)]L}{\Delta V} = 4.343\frac{\Delta\alpha}{\Delta F}$$

- Smaller detuning will increase the modulation efficiency. However, it also results in a larger insertion loss.

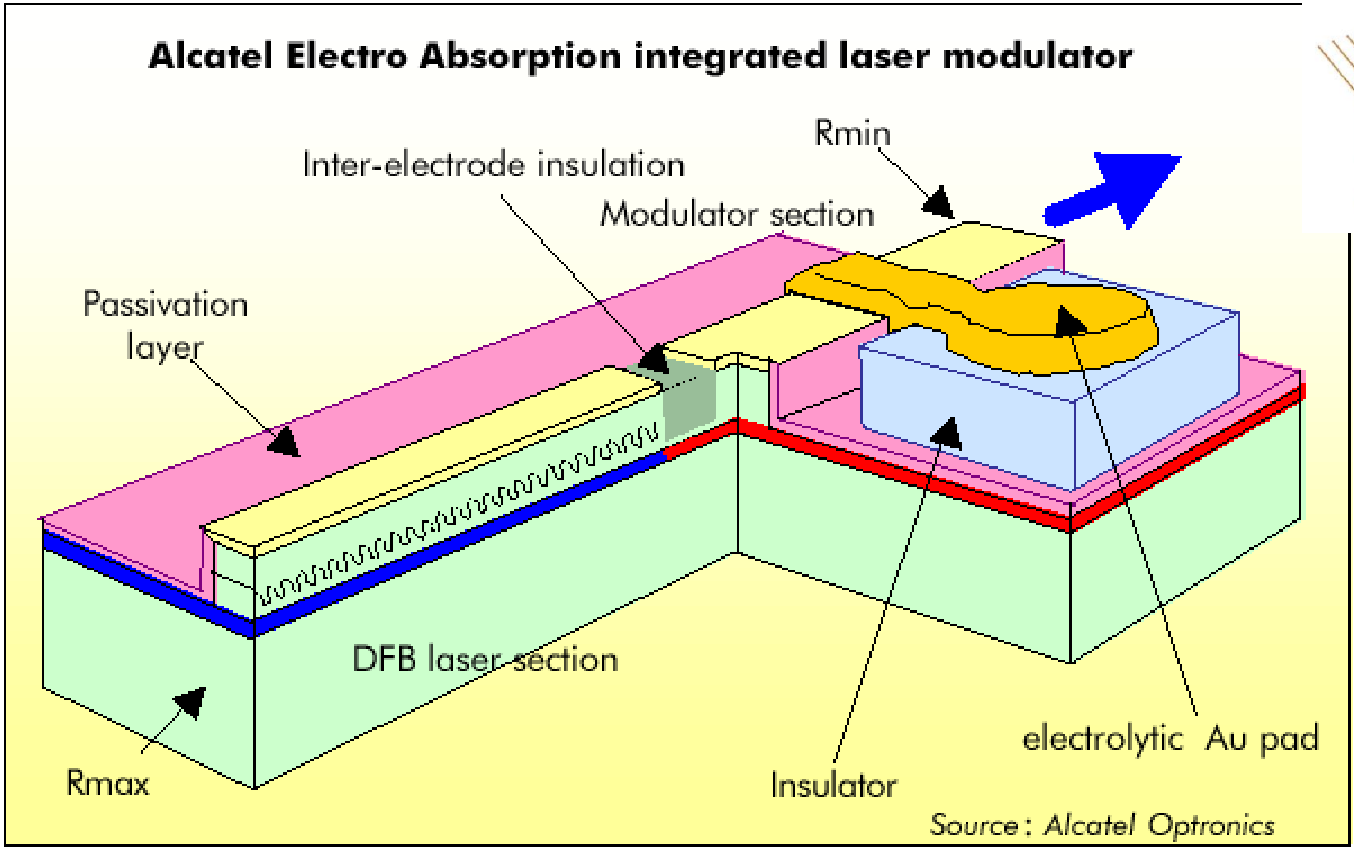


40GHz Modulator



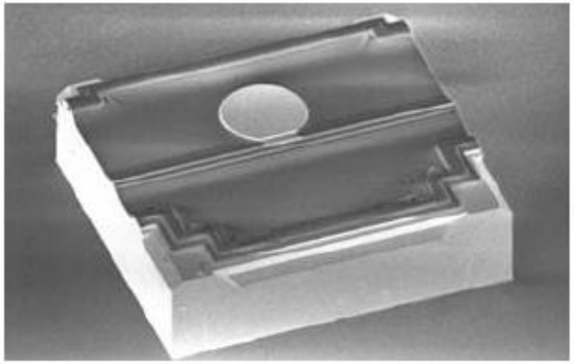
Long device length for easy packaging
short modulator section to reduce capacitance
low driving voltage of 2.8V
low insertion loss of 8dB

Integrated DFB-EA Transmitter



- 10Gb/s module, Ith = 20mA, Pmax = 4mW @80mA , extinction ratio = 15dB for -2.5V.

40G-SR-EAM-1550 - 1.55μm 40Gbit/s Electro Absorption Modulator (EAM)



Features

- 1.55μm C-band operation
- High optical output power
- Available as packaged device or chip-on-carrier
- Customer defined specifications available
- Buried heterostructure InP structure
- Low insertion loss
- Low polarisation sensitivity
- Low drive voltage
- Low chirp
- High speed K connector electrical interface

Applications

- Short reach data links
- High speed optical interconnects
- RF on fibre

The 40G-SR-EAM-1550 electro absorption modulator provides high speed external optical modulation at speeds of 40Gbit/s. The device operates across the 1550nm C-Band with low dispersion penalty. It relies on the electro absorption effect and is intended for use with a continuous wave laser diode source.