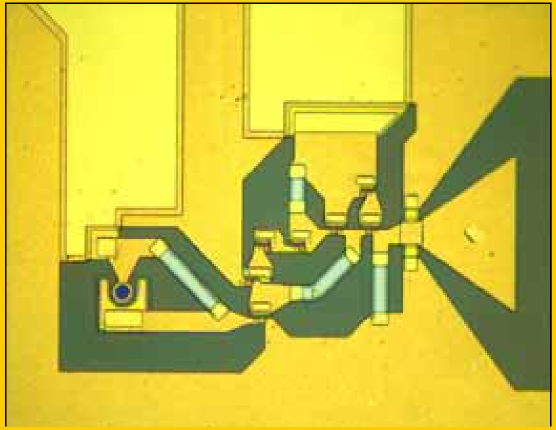
Optoelectronics
and
Optical Communications



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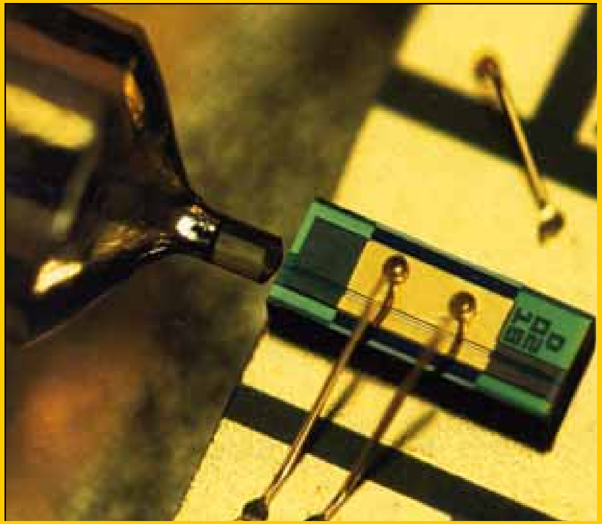
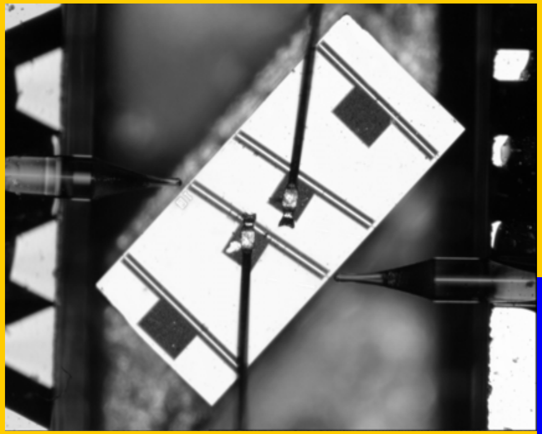
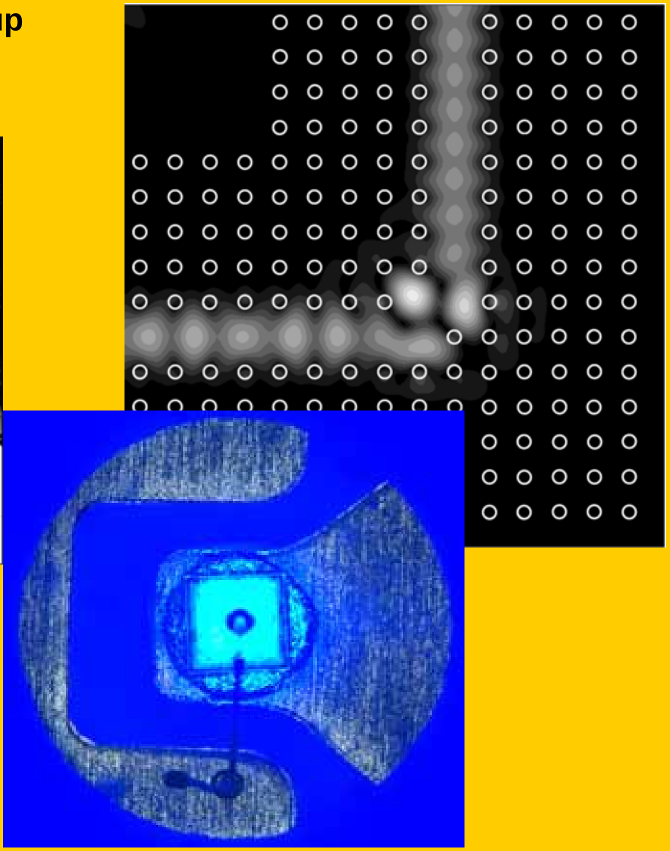
Version 18.02.2010

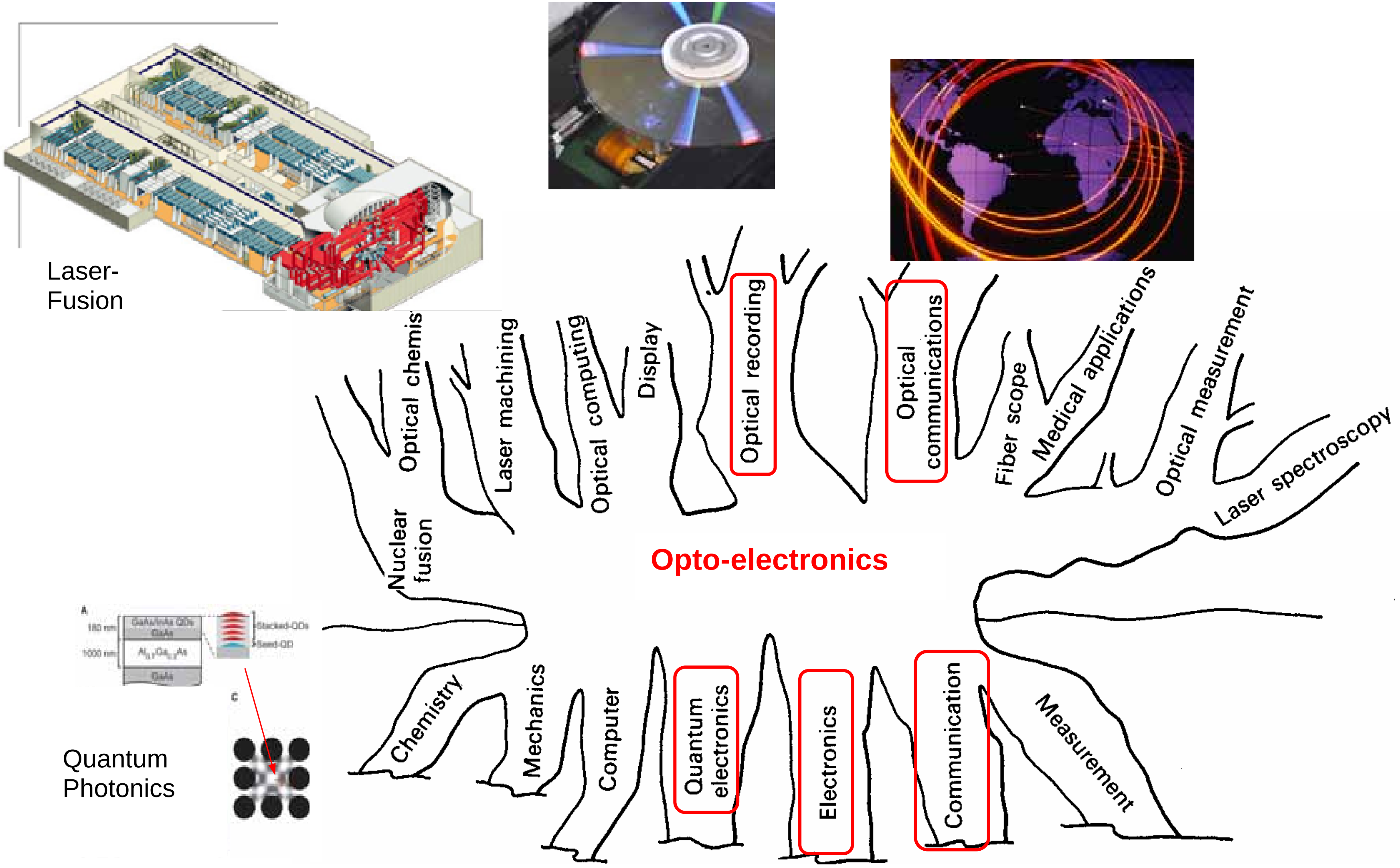






Why is Photonics an enabling Science and Technology ?

What else does Optoelectronic and Photonic advance ?



Photonics provides Base or enabling Function / Technology in many Applications

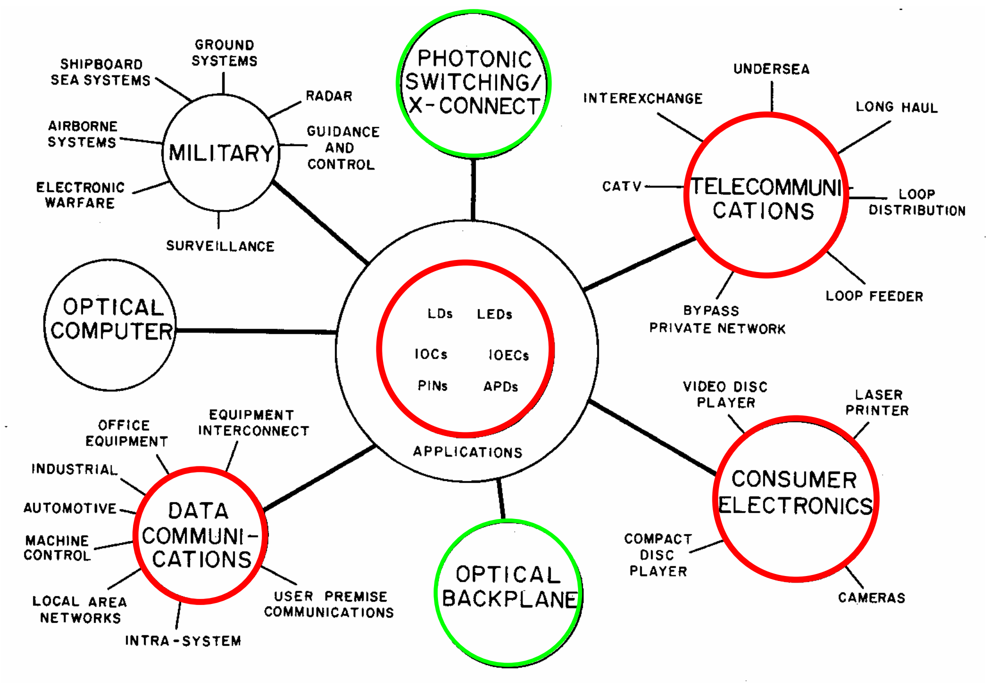
Photonics for Fiberoptic Communication

Breakthrough and future Driver of high economic and social impact are:

- Tele and Data Com
- Wireless Com
- Internet, e-commerce, on-demand-services, etc.

Key for the success of the optical communication was the parallel evolution of

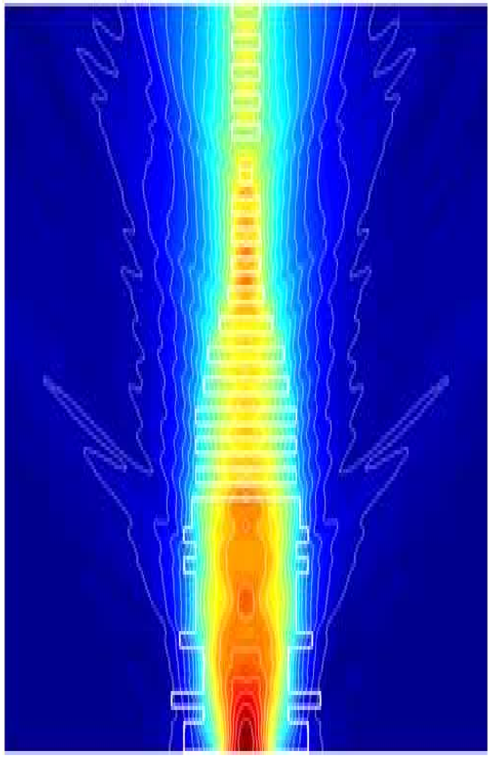
1) **semiconductor technology,**
2) **computer technology,**
3) **high speed electronics and**
4) **the successful establishment of powerful new services and applications:**



○ Near future

Photonics = Molding the Flow of Light

(by optoelectronic devices)



computer optimized waveguide taper

Generation

Transportation

Detection

Processing and Manipulation

of Ligthwaves

➡ **Required new theoretical Background:**

- **Propagation of Photon Fields**
- **Interaction between Photon Fields and Electron Systems in Insulators, Semiconductors and Metals**
- **Quantum Electronic Device Concepts**
- **Heterojunction Devices**

What is needed for mastering the field of Photonics ?

The course builds on your previous and refreshed knowledge of

- Electro-magnetic fields and waves, Maxwells-Equation, Polarization (Dr. Leuchtmann, Prof. Vahldieck, 4.sem)
- Semiconductors, Bandstructure, pn-junctions (Prof. Fichtner, Dr. Schenk, 4.sem)
- Physics of Optics and Quantum Mechanics, Schrödinger-equation (D-Phys., 3. sem)

and **extends** the teaching contents to:

- **Material Models for Dipoles and dipole interaction in atoms and crystals**
- **Light Propagation in dispersive, active and passive media**
- **Dielectric optical waveguides**
- **Semi-classical Interaction between EM-field and bound or quasi-free electrons**
  ➡ optical gain and absorption in active optical materials
- **Semiconductor based Devices mainly for Optical Communication**
  - **Light Emitting Diodes**
  - **Optical Amplifiers**
  - **LASERs**
  - **Photodetectors**
  - **Modulaors**
- **Concepts of simple Fiberoptic Data-transmission and Links**

What remains to be done ?

Unsolved and emerging Challenges and Topics in Photonics:

- **Large Scale monolithic/hybrid Optoelectronic Integration**
- **“transparent” Routers and Central Stations for fully transparent networks**
- **Quantum and Optical Data-processing and Computing ?**
- **3D Optical Storage**
- **Low Cost Optical Packaging**

- **Nano-scaled Quantum Optics**
- **Highly parallel Tb/s Links for Computers**
- **Tb/s single fiber links**
- **Advancing electronics to 200-300 Gb/s**

Goals of the Course:

Conceptual teaching goals:

- provide solid base and methodology of fiberoptics and optoelectronics

- emphasis on generic concepts and techniques

- enable you to study yourself and work independently with advanced literature

Self-Studies

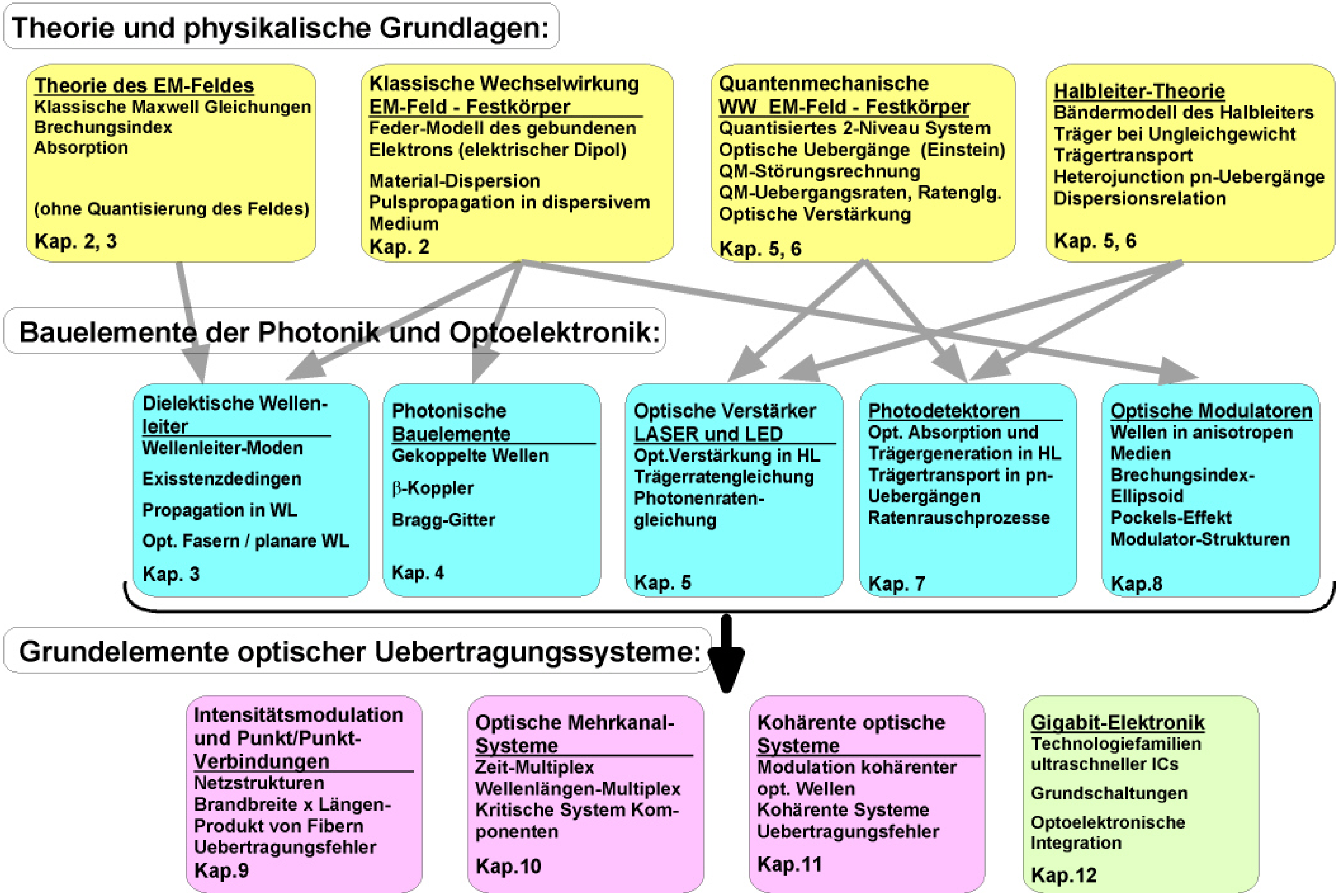
Pages marked on the right side are intended for self-studies, either because they contain

- repetitions of previously known material
- straight forward extension of previous content
- lengthy but simple proofs

➔ Lengthy mathematical proofs are discussed in terms of the solution method, the assumptions and the final results, which is elaborated in detail.
Proofs are mostly detailed in the corresponding appendix.

It is recommended to study and derive these proofs as a formal and methodological training and exercise.

Struktur der Vorlesung: OPTOELEKTRONIK und OPTISCHE KOMMUNIKATION



Theorie und physikalische Grundlagen:

Theorie des EM-Feldes
Klassische Maxwell Gleichungen
Brechungsindex
Absorption

(ohne Quantisierung des Feldes)

Kap. 2, 3

Klassische Wechselwirkung EM-Feld - Festkörper
Feder-Modell des gebundenen Elektrons (elektrischer Dipol)

Material-Dispersion
Pulspropagation in dispersivem Medium
Kap. 2

Quantenmechanische WW EM-Feld - Festkörper
Quantisiertes 2-Niveau System
Optische Uebergänge (Einstein)
QM-Störungsrechnung
QM-Uebergangsraten, Ratenglg.
Optische Verstärkung

Kap. 5, 6

Halbleiter-Theorie
Bändermodell des Halbleiters
Träger bei Ungleichgewicht
Trägertransport
Heterojunction pn-Uebergänge
Dispersionsrelation

Kap. 5, 6

Bauelemente der Photonik und Optoelektronik:

Dielektische Wellenleiter
Wellenleiter-Moden

Exisstenzdedingen

Propagation in WL

Opt. Fasern / planare WL

Kap. 3

Photonische Bauelemente
Gekoppelte Wellen

β-Koppler

Bragg-Gitter

Kap. 4

Optische Verstärker LASER und LED
Opt.Verstärkung in HL
Trägerratengleichung
Photonenratengleichung

Kap. 5

Photodetektoren
Opt. Absorption und Trägergeneration in HL
Trägertransport in pn-Uebergängen
Ratenrauschprozesse

Kap. 7

Optische Modulatoren
Wellen in anisotropen Medien
Brechungsindex-Ellipsoid
Pockels-Effekt
Modulator-Strukturen

Kap.8

Grundelemente optischer Uebertragungssysteme:

Intensitätsmodulation und Punkt/Punkt-Verbindungen
Netzstrukturen
Brandbreite x Längen-Produkt von Fibern
Uebertragungsfehler
Kap.9

Optische Mehrkanal-Systeme
Zeit-Multiplex
Wellenlängen-Multiplex
Kritische System Komponenten

Kap.10

Kohärente optische Systeme
Modulation kohärenter opt. Wellen
Kohärente Systeme
Uebertragungsfehler

Kap.11

Gigabit-Elektronik
Technologiefamilien ultraschneller ICs

Grundschaltungen

Optoelektronische Integration

Kap.12

Recommended Literature:

Primary references:

The course uses drawings and figures from the following books:

Ebeling, Yariv, Ming, Sargent, Suematsu, Casey/Panish, Gowar, Agrawal, Senior, Loudon, Coldren

[1] G. Agrawal, Fiber-optic Communication Systems, Wiley, 1992

Good overview, comprehensive, but short on formal proofes.

G. Agrawal, Nonlinear Fiber Optics, Academic Press, 1989

Specialized book on wave propagation in optical fibers (good chapter on linear pulse broadening)

[2] L. Coldren, S. Corzine, Diode Lasers and Photonic Integrated Circuits, Wiley, 1995

Excellent and detailed treatment on diode laser theory and devices

[3] B.E.A Saleh, M.C. Teich, Fundamental of Photonics, Wiley, 1991

Good overview, comprehensive, but short on formal proofes. Interesting didactic “soft” approach

Secondary references:

[4] M. Ming, K. Liu, Principles and Applications of Optical Communications, Irwin, 1996

Good overview, comprehensive, but short on formal proofes and theory

[5] K.J. Ebeling, Integrated Optoelectronics, Springer, 1993

Very similar to the course, covers most of the course material – currently out of print, new edition has been announced for 2005! Highly recommended if available !

[6] R. Loudon,The Quantum Theory of Light, Oxford, 1972

[7] A. Yariv, Quantum Electronics, Wiley, 1975

[8] G.P. Agrawal, N.K. Dutta, Semiconductor Lasers, Kluwer, 1993

[9] J. Gowar, Optical Communication Systems, Prentice-Hall, 1984

[10] H.C. Casey, M.B. Panish, Heterostructure Lasers, Academic Press, 1978

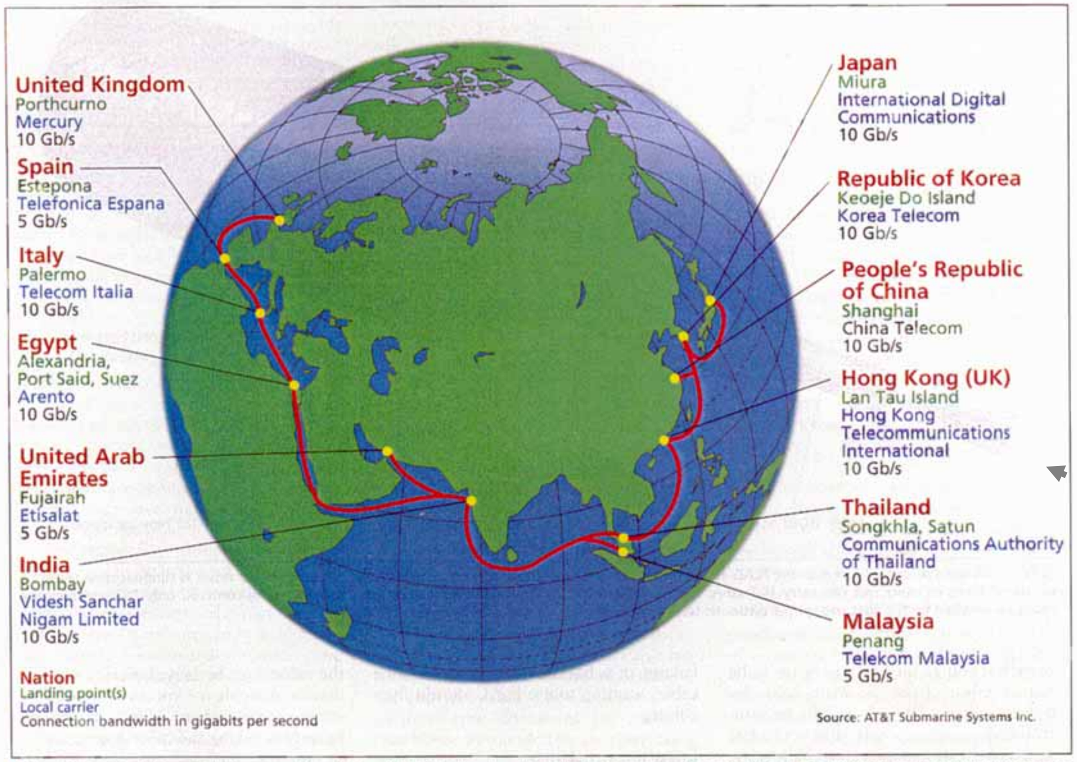
[11] Y. Suematsu, A.R. Adams, Handbook of Semiconductor Lasers and Photonic Integrated Circuits, Chapman & Hall, 1994

[12] A. Yariv, An Introduction to Theory and Applications of Quantum Mechanics, Wiley, 1982

[13] M. Sargent, M.O. Scully, W.E. Lamb, Laser Physics, Addison Wesley, 1974

[14] J. M. Senior, Optical Fiber Communications, Prentice Hall, 1992

1 Perspectives of Optical Communication



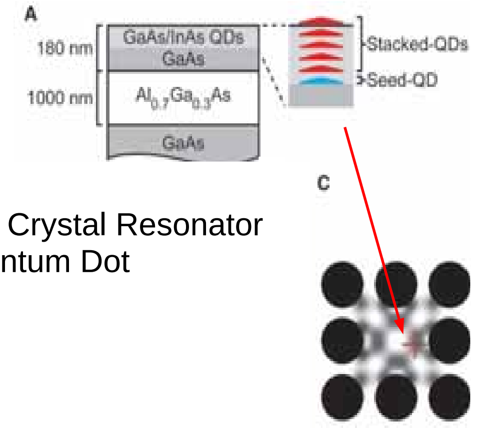
Source: AT&T Submarine Systems Inc.

▲ The 27 300-km fiber-optic link around the globe—FLAG, for short—will snake its way around the world from Cornwall in the United Kingdom to a site near Tokyo Bay. Preventing shark bites to the cable when laid and making deals for landing points were among the challenges faced by the FLAG Ltd. consortium and its contractors in building the system. All-optical-technology amplifiers are embedded every 45 to 85 km in the cable. Electro-optical repeaters at the landings regenerate the signal at higher power levels for the next series of undersea amplifiers.

Tomorrow's key issues:

Down-scaling photonics, Tb/s interconnects

- What are the challenges for the future. What are the conditions for continued progress ?
- What is the potential for the future evolution of Lightwave Technology ?



Photonic Crystal Resonator with Quantum Dot

Past and today's key issues: Past / Today - Large Scale and high capacity

- What are the reasons for the dominant position of modern Lightwave Communication.

  What key (disruptive) inventions have been necessary in the past ?
- What are the technical and also economic advantages of Lightwave technology?
- What is the role of Optoelectronics in areas like Optical Storage, Optical Sensing, Display Technology ?

1 Perspectives of Optical Communication

1.1 Historical overview of optical communication

Light was attractive as a **carrier of information** in combination with a **source**, a **suitable low loss transmission medium** (eg. air, glass, lens systems) and **detector** since **historic human technology**.

Optical Morse-Codes, Signaling Flags, Optical Beacons for ships, etc.

Light described as a electromagnetic (EM) wave with µm-wavelength, resp. 200THz carrier frequency provides:

+ Small signal attenuation

+ High directionality, efficient and small antennas by lenses and mirror systems

+ Availability of a very **sensitive, but slow receivers** , the human eye and early photoconductors

+ High propagation velocity and low dispersion

+ Availability of simple but slow mechanical modulators

But historic lightwave technology had severe shortcomings (until begin 20th century):

- Lack of a **light source that could be modulated at high data rates,** of **a fast electrical photodetector**
- Only **line-of-sight connections (free space) and scattering** in dust, rain, fog, trees, etc.
- Lack of a **compact, controlled transmission media (optical waveguides)**

The emerging Quantum Electronics of the 20th century paved the way to Photonics

Theoretical Advancements:
From Maxwell to Quantum Mechanics

The **classical physics of the 18th and 19th century** developed the wave theory of light based on **Maxwell's equation** describing most **wave propagation effects** in free space and dielectrics.

The duality of light as **propagating waves and energy quanta (photons), used to describe the atomic interaction for light generation/detection,** remained an unsolved problem of classical physics.

This discrepancy in the description of light triggered the revolution of modern physics and quantum mechanics.
Only modern **Quantum Electrodynamics** provided a self-consistent description at the begin of the 20th century and paved the way to Lightwave technology 50 years (!) later.

Wave properties of Near Infrared Light:

Propagation effects of light waves (Interference, Diffraction, Dispersion, Reflection, Refraction, etc.) are described by Maxwell's theory successfully.

Light with a wavelength λ (~0.8 - 1.6μm) is represented by an **EM-wave** with an oscillation frequency ω ~200 THz

The vector wave is defined by the amplitude and polarization state of the field vectors $\vec{E}(\vec{r},t), \vec{D}(\vec{r},t), \vec{H}(\vec{r},t), \vec{B}(\vec{r},t)$

➡Light waves can not interact directly with each other.

➡The state of a light wave can only be changed by interaction with the **microscopic electronic system** of matter:
- **dielectric or magnetic polarization**
- **absorption losses**

➡ **an atomistic** (quantum mechanical) **model for the interaction of lightwave and materials is needed !**

Particle (photon) properties of Light:

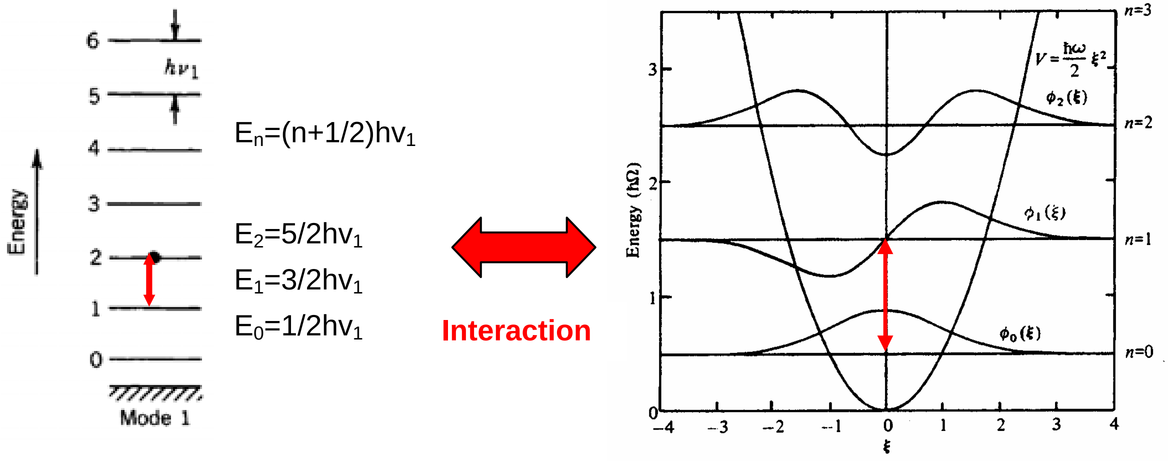
Interaction with the quantized electronic states of matter (photoeffect, light generation, etc.) take place by **energy-exchange** (anihilation or generation of a photon) of discrete **energy quanta E** (photon):

$E = h\nu = \hbar\omega$ h = Plank's constant (h=6.626 10^{-34} Js, $\hbar =$=1.055 10^{-34} Js)

The annihilation or creation of photons by interaction with matter leads to an attenuation α, resp. amplification g=$-\alpha$ of the light intensity I of the optical wave:

➡ **energy quantization of the light field**, then the field variables E, H are no longer continuous, but are also quantized (field quantization).

The field energy is described by the number of photons making up the field.



$E_n=(n+1/2)h\nu_1$

$E_2=5/2h\nu_1$

$E_1=3/2h\nu_1$

$E_0=1/2h\nu_1$

Interaction

Quantization of Electron Motion in atoms an solids:

Energy exchange of a photon field with matter can only be understood if the energy of electron motion is also quantized. For strong interaction the photon energy must be equal to the energy difference of the electronic states.

➡ **atomic motion of electrons in matter is quantized** and classical oscillator matter-models break down

Only **Quantum Mechanics**, developed at the begin of the 20th century, allows to resolve the apparent contradiction and to describe both aspects of light and matter satisfactorily.

Concepts of Quantum Electronic Devices

Optical fields behave very similar to RF- or Microwave fields, however oscillating at much higher THz-frequencies (~10^{15}Hz) beyond the reach of transistor electronics (~10^{11}Hz).

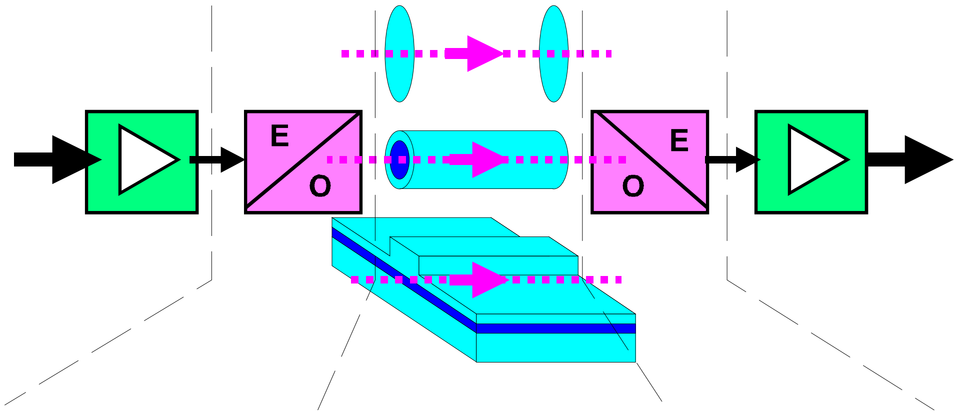
Dipole-oscillations in atoms and crystal lattices have oscillation frequencies similar to optical fields and can interact

➡ use of **atomic oscillators as quantum electronic device for light waves**

Manipulation of optical waves (modulation, generation, detection or propagation) **requires control of the refractive index n,** resp. ε **and/or of the attenuation α of the transmission medium.**

The development of **Molecular Amplifiers** and **Quantum Electronics** in the second half of the 20th century enabled the generation and manipulation of highly coherent and monochromatic optical fields.

Generic functional blocks of an optical communication system



DATA ELECTRONICS E/O-Converter OPTICAL TRANSMISSION O/E- Converter ELECTRONICS DATA

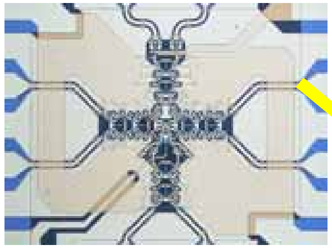
LASER, LED
MODULATORS

FIBERS, WAVEGUIDES
LENSES, Integrated Optics
Optical Amplifiers

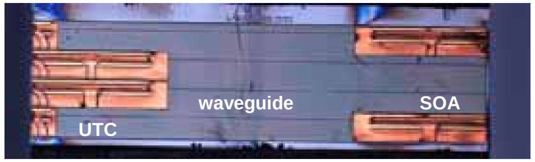
PIN-, AVALANCHE-
PHOTODIODES

Signal processing **Light Generation** **Light Detection** **Signal processing**

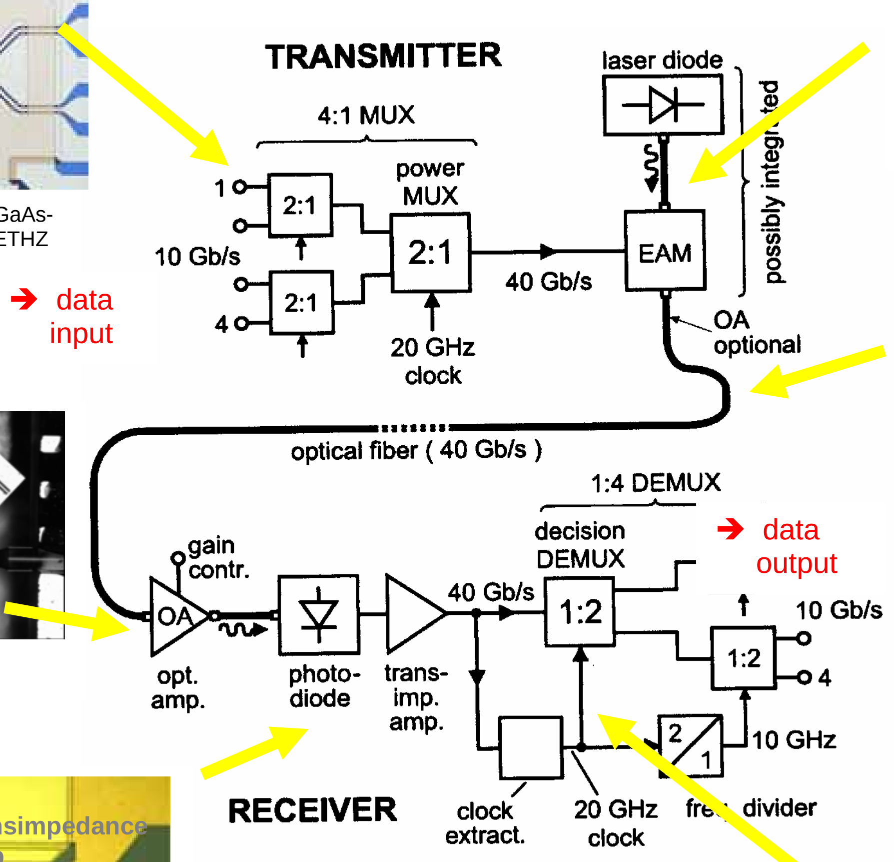
Functional blocks of
40Gb/s (4x10Gb/s)-Point-to-Point fiberoptic ETDM Links:

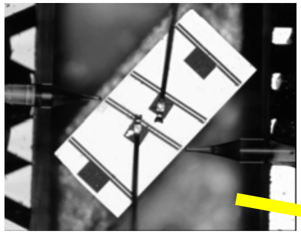


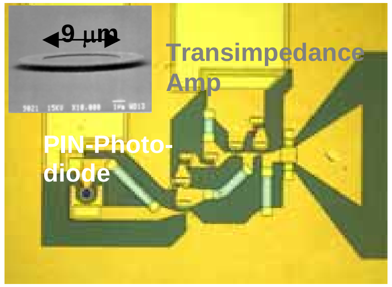
80Gb/s MUX with InP/InGaAs-DHBT, I. Schnyder, IfE, ETHZ

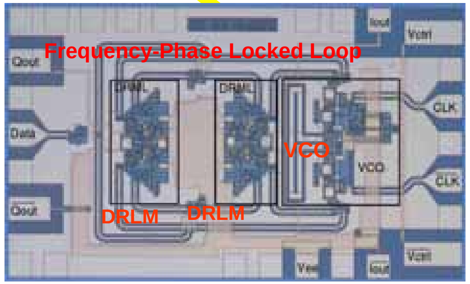


2ps-pulse generating InGaAsP-diode laser, H-J., Lohe, R. Scoillo, H.J. Lohe IfE, ETHZ









- **40 Gb/s fiber-optics is commercial and is deployed**
- **80-160 Gb/s TDM-systems are demonstrated for feasibility but the electronics is not yet commercial. No fundamental bottle-neck.**

1.2 Motivation for Light wave Com: Limitations of Electrical Communication

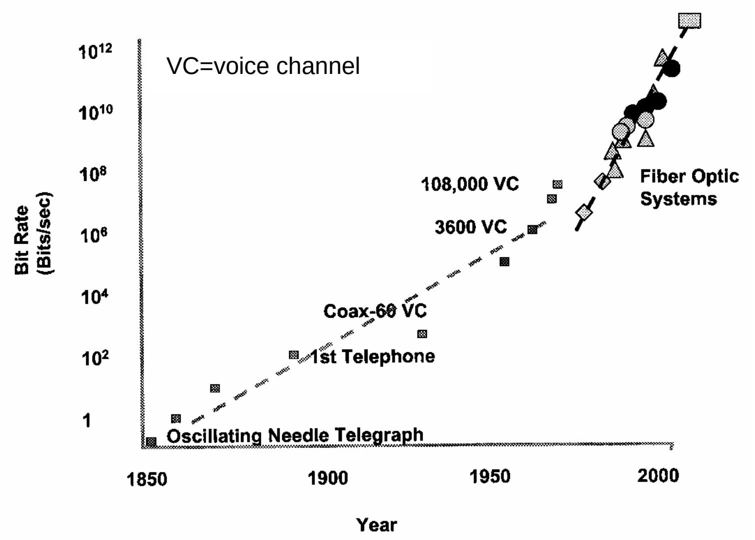
Before (1860-) 1960:

Wired and the **free space analog / digital transmission (RF- and µm-wave)** dominates communication technology.

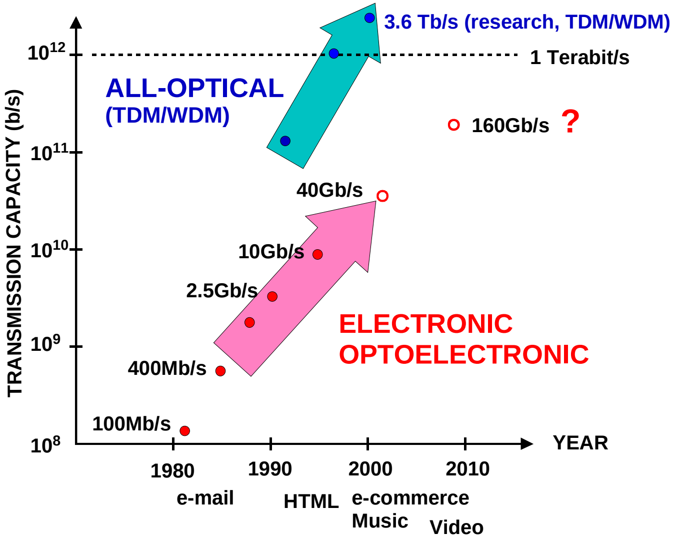
- Cable bandwidth has been increased and reached its limit at <1GHz (→ short (few km) repeater distances).
- Cable size is a problem in metropolitan overcrowded cable ducts.
- Microwave communication increased carrier frequencies but is bandwidth-limited (~0.1 $f_{carrier}$)

Since ~1960 the demand exceeds the capability of the systems, and drives the technology. Cost become critical.

Historical development of Communication technology:



Future development trends of fiberoptic and wireless communication technology



New Demand Drivers appear calling for a new technology:

Wireless Com, e-mail , Internet, e-commerce, on-demand services, etc.

Limits of wired communication in 1960: (twisted pairs and coaxial cables , dominated by voice communication)

- **Cable attenuation** (typ. 1dB/m at 1GHz for best coaxial cables)
- **Cable dispersion**
- **Repeater-spacing in communication systems** (eg. < 1km at 256 Mb/s)
- **Cable volume and deployment cost**

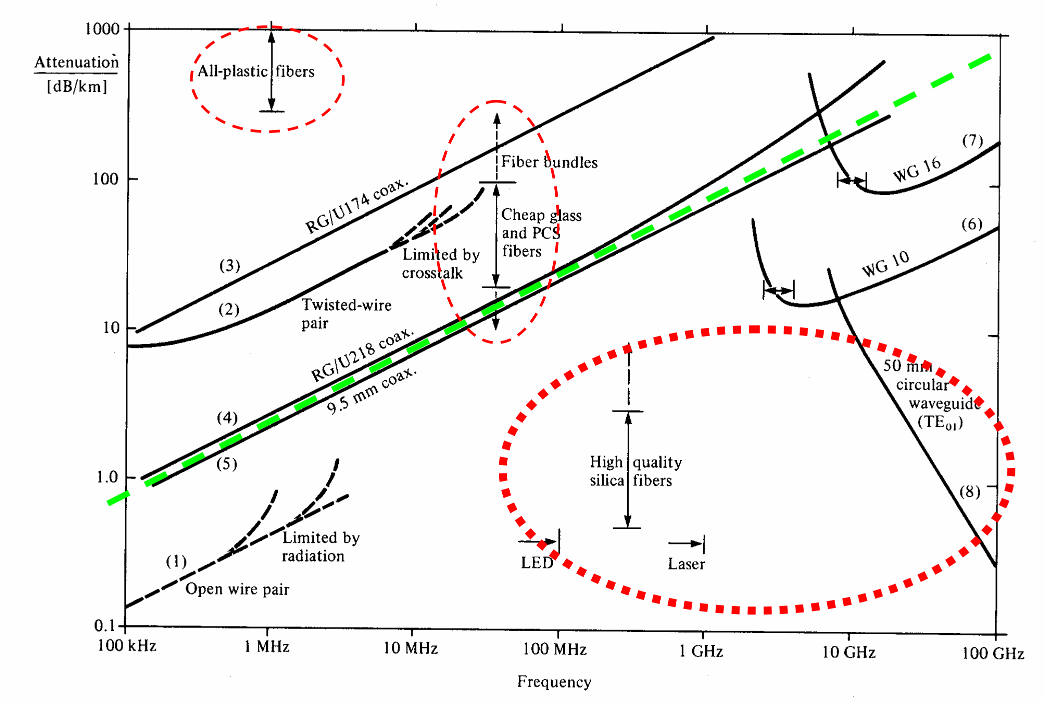
Limits of Microwave- and Satellite-communication:

improved the repeater-limitation for long distances but at the expense of the achievable data-rates and very high costs.

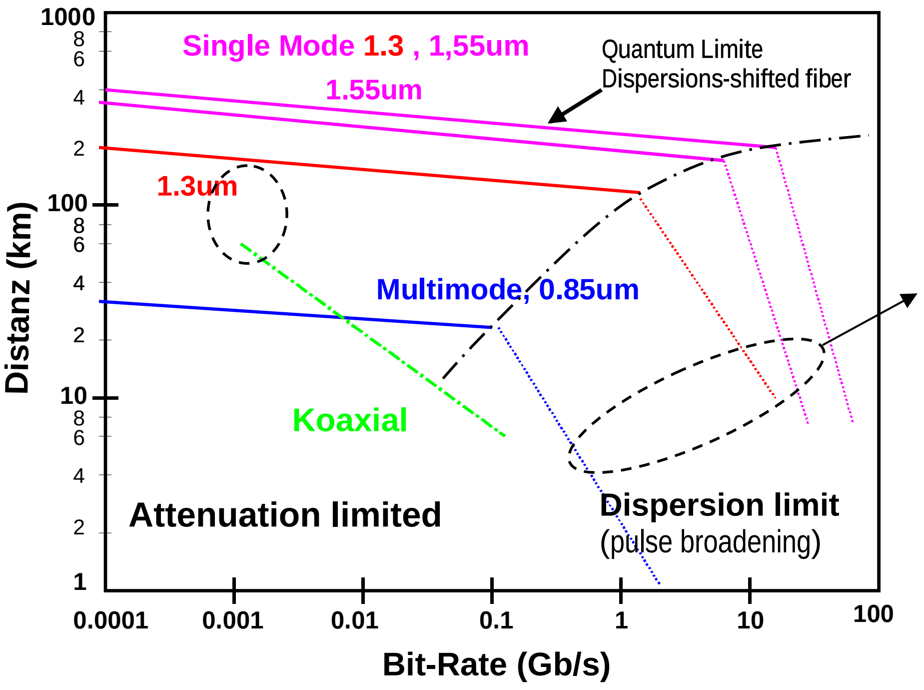
After 1970 the world was ready for a new communication technology:

➡ fiberoptics with a near ideal transmission medium is the only choice

Attenuation of different transmission media:



Dispersion and Bandwidth:



1.3 Fiberoptic and Optoelectronics:

Revolution of the communication technology

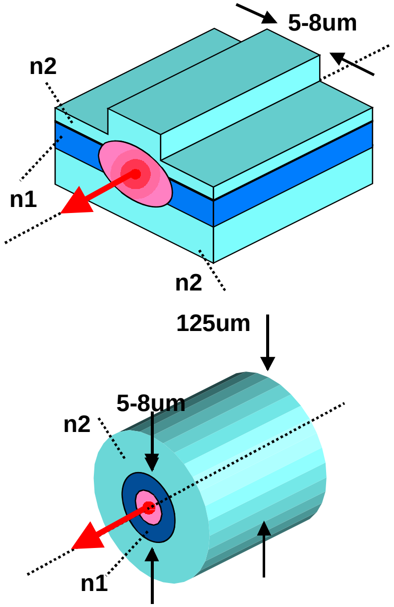
Two key inventions revolutionized the electrical communication technology in 1960:

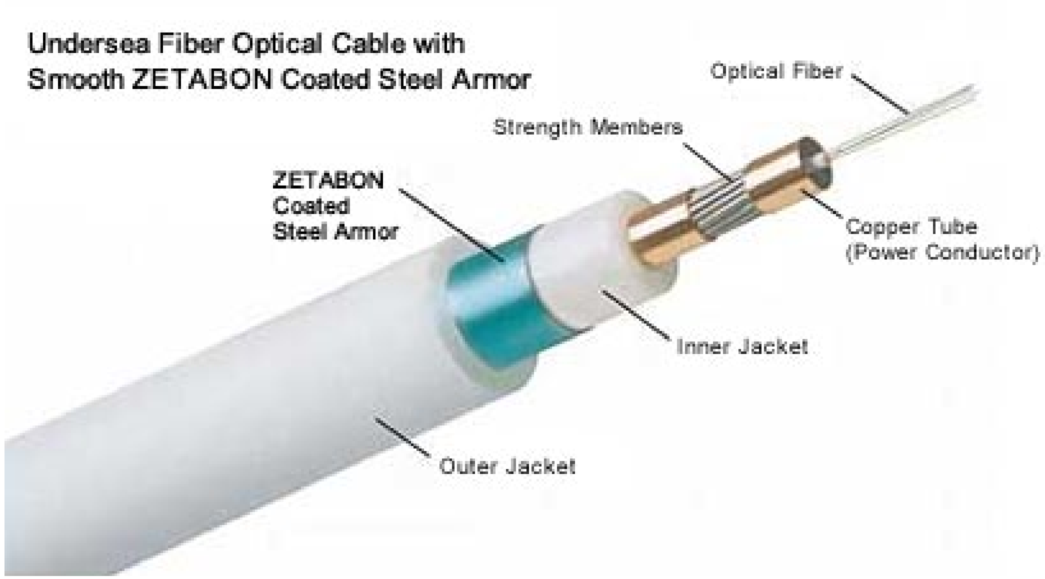
1. **LASERs** (1962 Ruby-solid state-LASER dby Maiman, 1960 Gas-LASERs) and mainly by the Semiconductor-LASERs 1962 by N.Nathan, W.Dumke, G.Burns, M.Quist, R. Rediker, R. Keyes, R. Haus, G. Fenner, J. Kingsley, N. Holonyak et. al.), allowed the **Efficient, compact generation and fast current modulation of coherent optical radiation**

2. **Low loss and compact optical glass fiber** as a transmission medium (1000x smaller attenuation) with low dispersion (100x smaller) and low volume (ϕ: cm → 0.1mm) (Kapany et al. 1958, Kao 1966, Keck, Kapron, Maurer, 1970)

Optical glass fiber improves the transmission capacity by 2-3 orders of magnitude with respect to attenuation, bandwidth, dispersion and volume.

Until to date 150 million fiber-km have been installed word-wide !





1.4 Evolution of Optical Communication 1970 - today

Since 1970 the performance of fiberoptic communication increased through four system-generations by improving on:

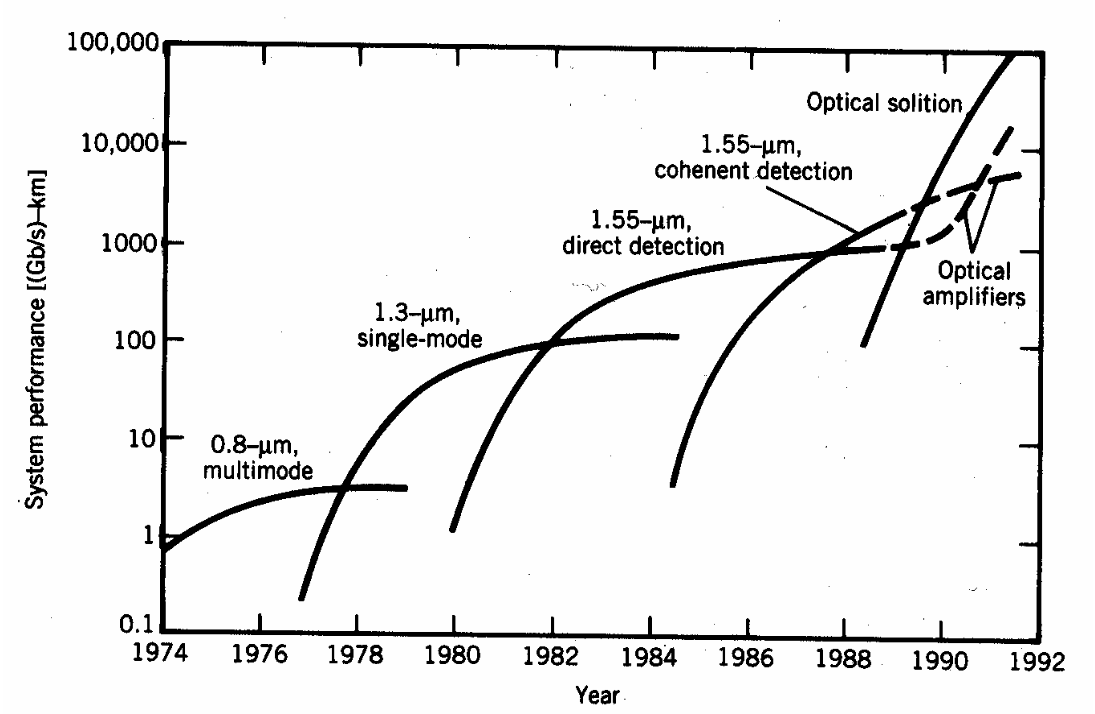
a) the transmission wavelength λ (0.8 – 1.6μm) and spectral width Δω ,

b) the fiber type (multi-mode → single mode fibers),

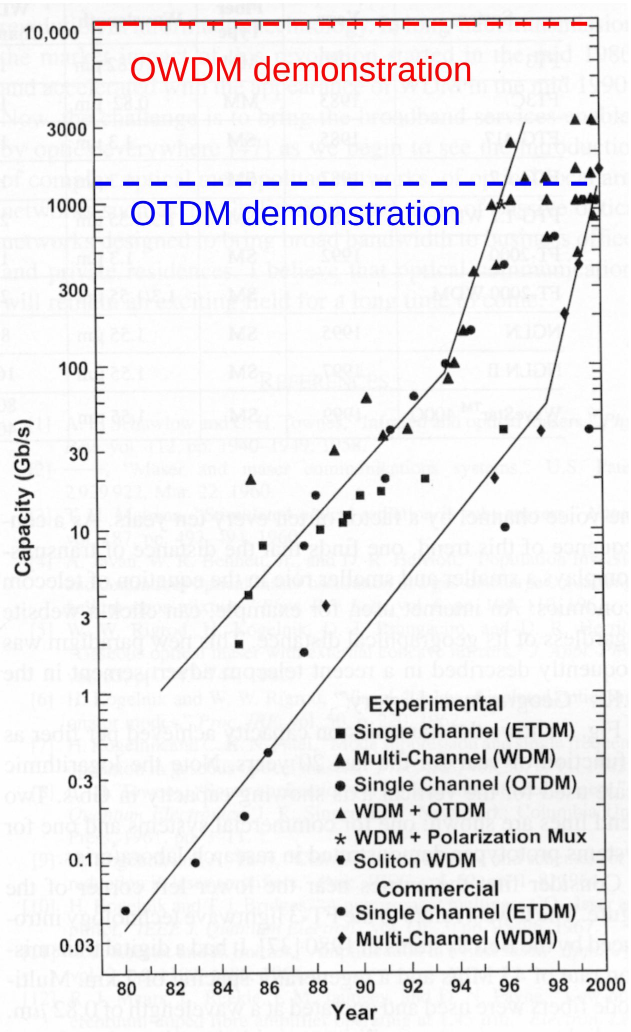
c) optical amplification and

d) the dispersion-free nonlinear optical soliton pulse propagation

Fiberoptic System Generations: 256 Mb/s ➡ 40 Gb/s :



Steps and Milestones towards 10Tb/s data rates:



1.4.1 Optical Fibers as an almost ideal Transmission Medium

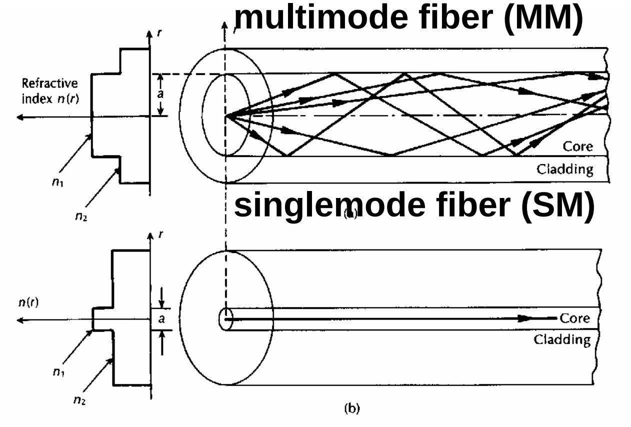
Concept of dielectric waveguides:

Low loss dielectric waveguides consisting of a dielectric **core** of high index of refraction n_1 and a **cladding** with lower index n_2, $n_1 > n_2$, guide optical waves very efficiently in the vicinity of the core by **total reflection**.

To decrease the fiber losses down to less than a 1dB/km,

1) doped ultra high purity glasses or quartz (SiO_2) are used as dielectrics material
2) avoid sub-micron sized interface roughness

Fiber types:



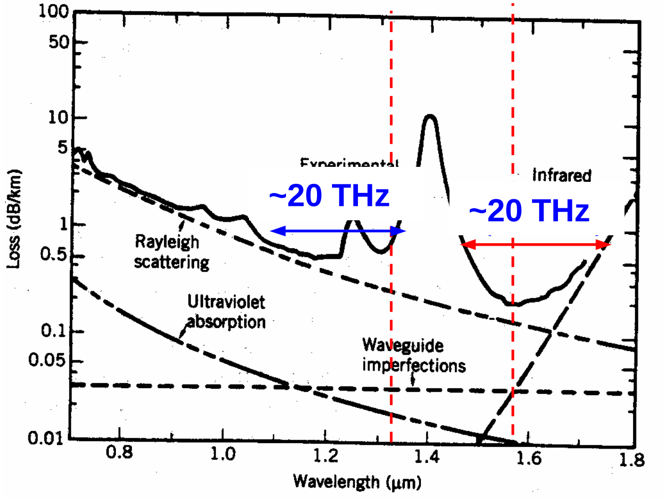
multimode fiber (MM)

core ∅~50µm

singlemode fiber (SM)

core ∅~7µm

Fiber Losses vers. Wavelength:



Short fiber history:

1966 K. Kao proposed the concept of **low loss dielectric optical fibers**

1970 successful establishment of a fiber fabrication process for optical **multi-mode** (MM) **fiber** (~50µm core diameter) with an attenuation <20dB/km

1979 first fabrication of a **single-mode** (SM) **fiber** (~5-10µm core diameter) with low dispersion (~10 ps/nm/km) and reduced losses toward 0.2dB/km (Miya et. al.) ➡ 10 Gb/s data rates and ~100km repeater distances become possible

1.4.2 Semiconductor Lasers: Efficient Light Generation and Modulation

Research succeeded in the period 1960 - 1970 in translating the concept of the **Microwave MASER and LASER** (Light Amplification by Stimulated Emission of Radiation) to ultra compact semiconductor lasers.

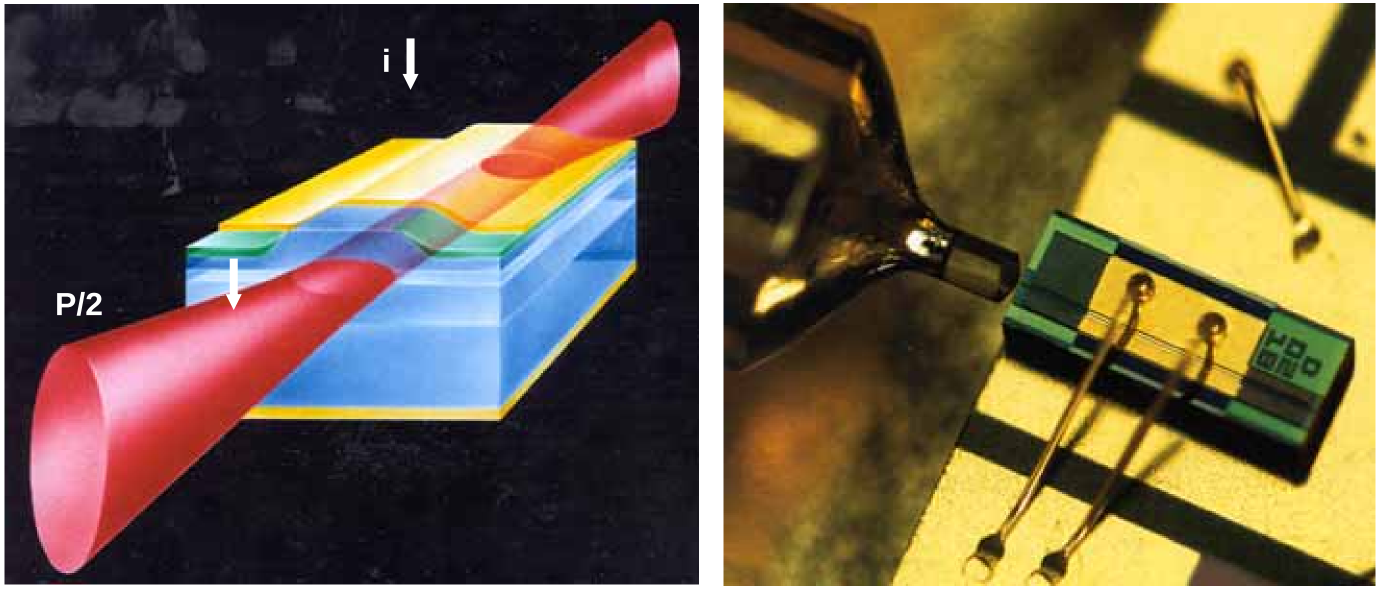
➡ molecular or atomic feedback amplifiers for light oscillators in the 100 THz-region

(equivalent to the electronic transmission transistor oscillator)

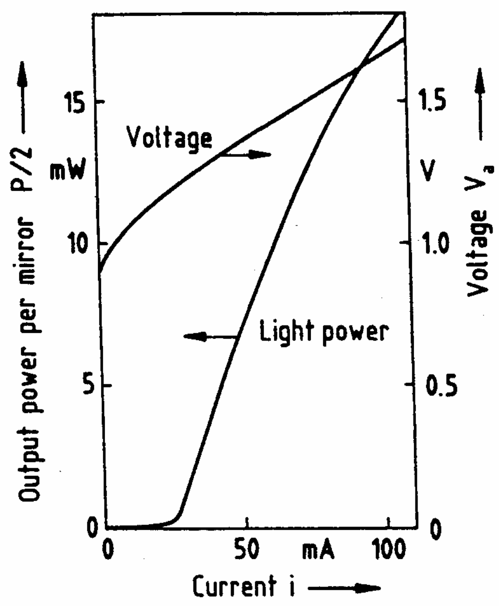
Semiconductor-Lasers were realized as compact and simple current pumped pn-diodes from the III-V-compound semiconductor GaAlAs or InP for efficient generation of highly **monochromatic and coherent optical fields** (at λ=0.8 – 1.6μm ~ bandgap energy E_g).

The optical **output power P_{opt} is proportional to the electrical current I** through the forward-biased pn-diode and can be **current-modulated** up to high (<~60GHz) frequencies.

Schematic construction of an AlGaAs-Diode Laser (with fiber):



Light–Current Characteristic:



Short diode laser history:

1962 first demonstration of a homojunction GaAs-pn-diode lasers at a wavelength λ~0.85μm and pulsed mode operation at a low temperature T of –200K (IBM, Bell Labs, RCA, …..)

1970 Room temperature, Continuous Wave (CW) Double Heterojunction-GaAs/AlGaAs/GaAs-Laser Diode at λ~0.85μm (Hayashi, Panish, Alferov)

1970-75 Dynamic single-frequency Laser @λ~850nm (Kogelnik, Nakamura, Reinhard, Casey,…)

1976 Roomtemperature, CW-DH-InP/InGaAsP Laser at λ~1.30μm (Hsieh et al.)

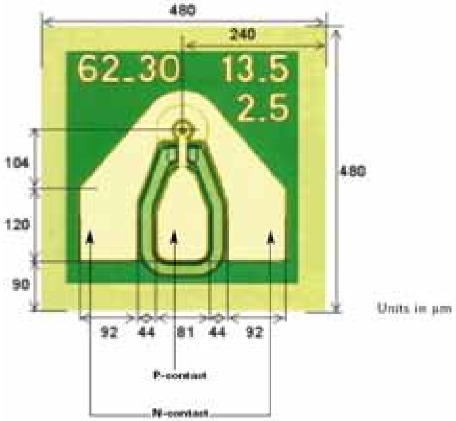
1978 Roomtemperature, CW-DH-InP/InGaAsP Laser at λ~1.55μm (Akiba et al.)

1988 VCSELs, DFBs (Distributed Feedback Laser diode) (Iga, Suematsu, ….)

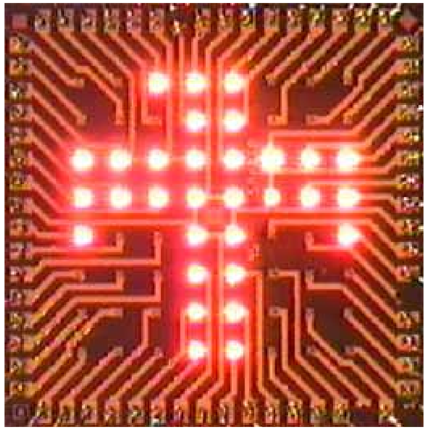
Longterm goal of laser diode development:

- lower operation currents in the mA- to μA-range (thresholdless lasers)
- longer wavelength operation in the range of λ~2-2.5μm (fiber losses → 0.01dB/km)
- 40 – 80GHz bandwidth for short distance links
- monolithic integration with photodetectors, external modulators, optical amplifiers, electronics, ….

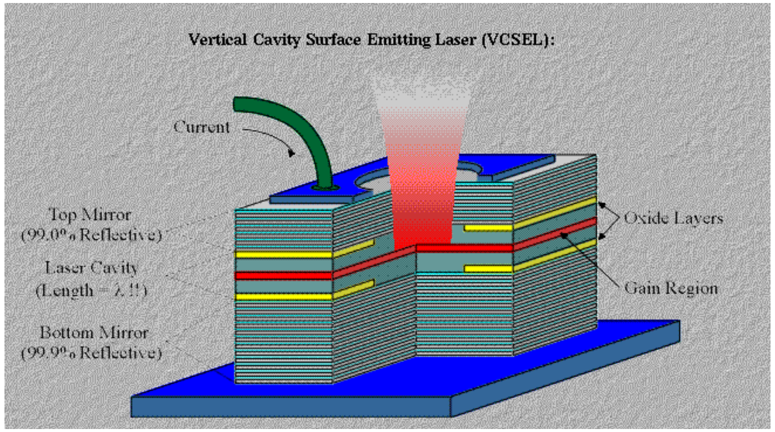
Example of a compact modern Vertical Cavity Surface Emitting Laser VCSEL for mA-operation:



Top view of a 10μm ∅ VCSEL



VCSEL 2D-array



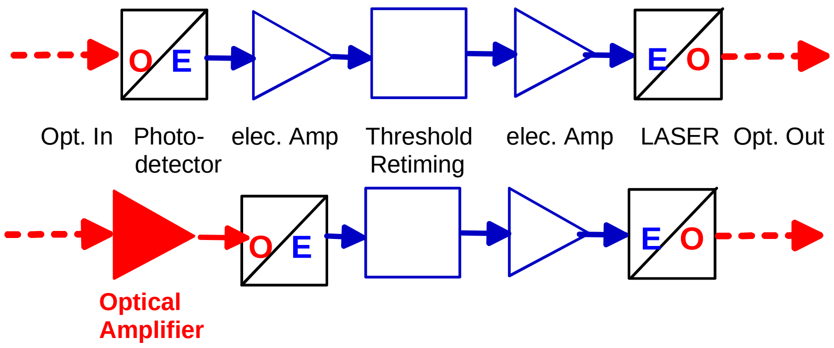
Schematic VCSEL structure

1.4.3 Optical Amplifiers for Optical Amplification with THz-Bandwidth

Before the 4th generation of fiberoptic systems optical signals had to be **converted back into electrical signals in 3R-repeaters** for **1) amplification** and **2) regeneration** and **3) retransmission** (after a repeater distance ~20-70km).

3R-electronic repeaters for re-amplified, regenerated and retimed are limited by transistor technology (40 Gb/s today)

Optical low noise signal amplification by an optical amplifier provides inherent **THz- system bandwidth**
Electronic ⇦⇨ Optical Amplifiers: 100 GHz ⇦⇨ 10 THz



Conventional electronic 3R-repeater

Optical amplifier with 2R-repeater

Solutions for optical amplifiers (OA):

- **Erbium-fiber-amplifiers, EDFA (optical pumping)**

  active Erbium-atoms are used as dopand of the fiber core. Optical pumping of the Er-atoms at 980nm by a laser diode. Pumped Er provides light amplification (30-40dB, NF~4dB)@1550nm.

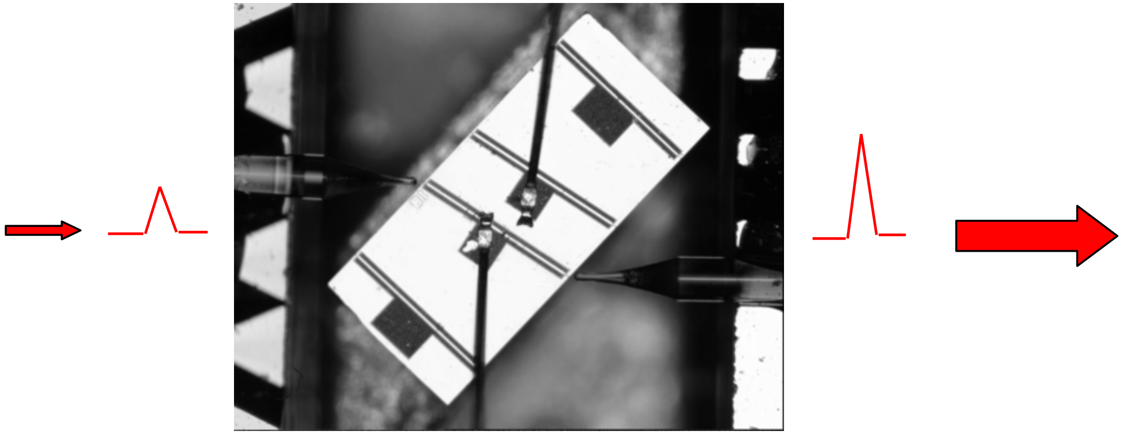
- **Semiconductor Optical Amplifier, SOA (current pumping)**

  use a DC-current pumped pn-diode for optical gain (~20-30dB). SOAs provide multi-THz-bandwidth and a compact and efficient construction (mm-size).

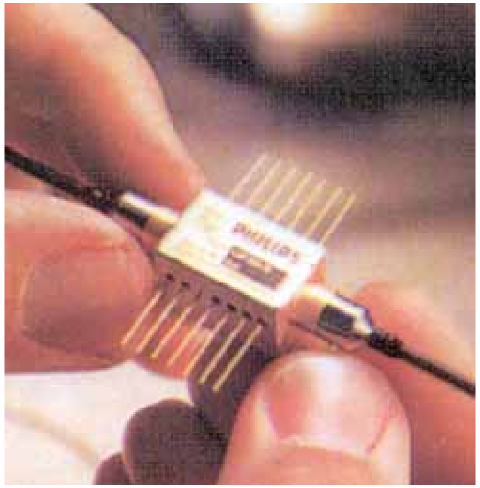
➡ The optical amplifier was a milestone towards Tb/s-communication.

SOA-Realization (courtesy OptoSpeed):

SOA with angled anti-reflection coated mirrors:



Pig-tailed and packaged SOA:



Properties:

G(I_D,λ) ~30dB

NF ~6-7dB

Optical bandwidth typ. 50nm (~10 THz)

Brief history of OAs:

1987 first fiber amplifier using Er-doped fibers **EDFA** (Erbium Doped Fiber Amplifier) at λ=1550nm

1989 first SC-diode amplifier **SOA** (Semiconductor Optical Amplifier) bei λ= 1300 nm

1990 first fiber amplifier at λ=1300nm

In contrast to electronic 3R-regeneration optical amplifiers do not restore the signal shape or the timing position. Regeneration and retiming is still done by electronics.

1.5 Electronics for Signal Processing

Highspeed digital and analog electronic signal processing before and after the fiber is required in repeaters or switches.

In terms of bandwidth electronic IC become an **electronic bottle-neck** - therefore fiberoptics has become a major technology driver for high speed analog and digital IC-technologies.

Analog Circuits:

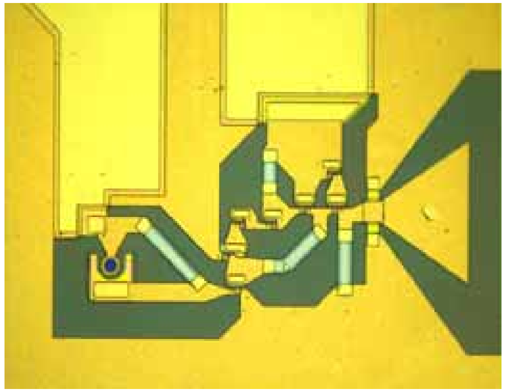
- Low noise pre-amplifiers (for photodetection with photodiodes)
- Gain-controlled broadband main-amplifiers
- Driver circuits and power amplifiers for LEDs, Lasers and modulators

Digital Circuits:

- MUX , DEMUX
- Threshold-Switches, Data-FlipFlops, Frequency Deviders
- Clock-Data-Recovery CDR, PLL

Examples of State-of-the-art High Speed Electronics:

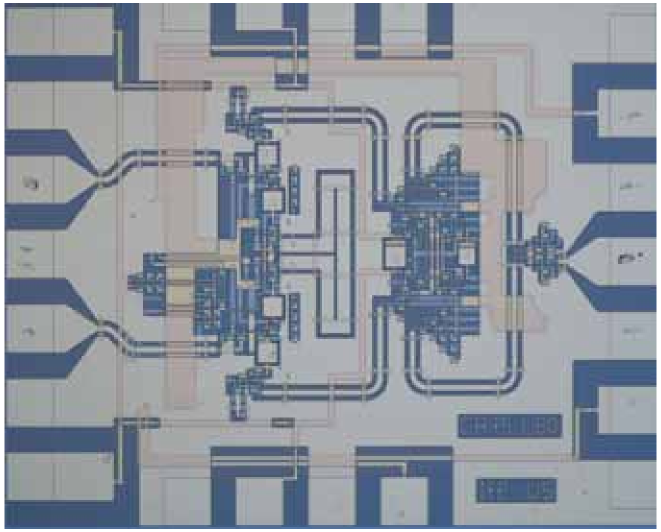
70 and 40 Gb/s Photoreceiver with integrated PD:



InP/InGaAs-HBT, D. Huber et al., IfE, ETHZ

The InGaAs photodiode is monolithically integrated for minimal parasitic elements.

56 GHz Phase Locked Loop:



InP/InGaAs-HBT, V. Schwarz, IfE, ETHZ

150 Gb/s-Frequency Divider with InP HBTs:

Fastest realized IC-circuit worldwide ! (NTT, 2005)

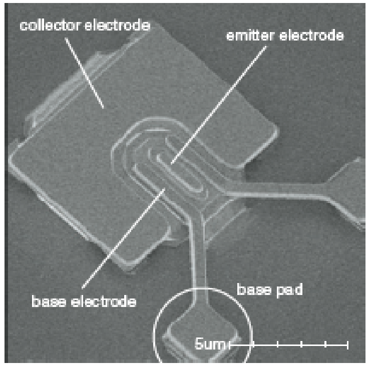


Fig.1 SEM photograph of the InP HBT

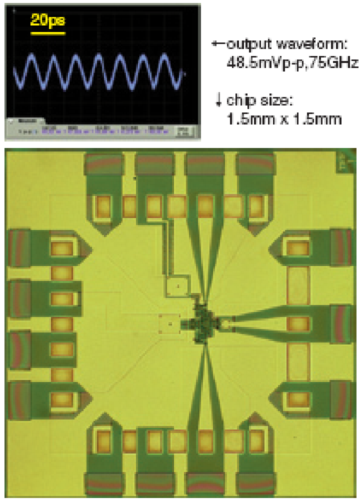
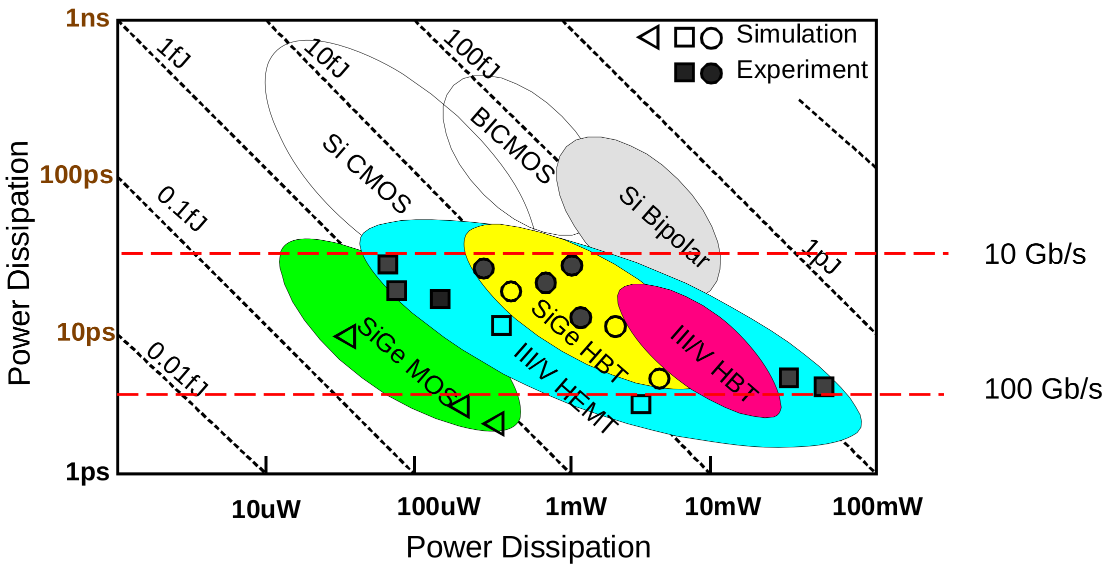


Fig.2 1/2 dynamic frequency divider IC and its output waveform for 150-GHz input

State-of-the-Art of competing High Speed Electronics: Trade-off between switching speed and power consumption



Key requirements:

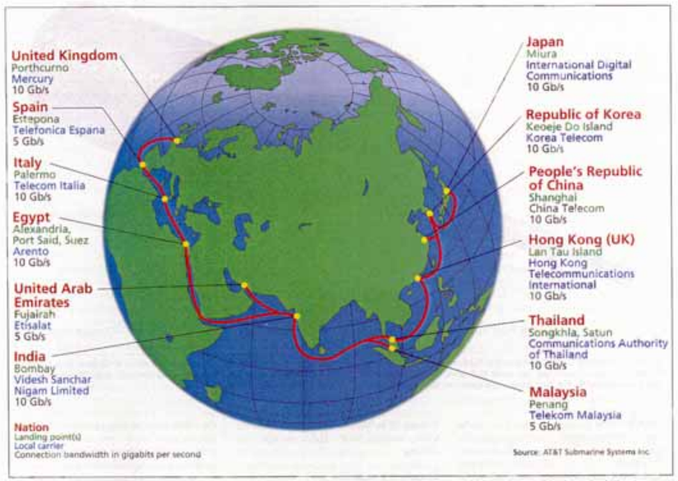
- High analog bandwidth
  40 Gb/s (~30 GHz, t_d~10ps) f_T~150 GHz
  80 Gb/s (~ 60 GHz, t_d~5ps) f_T~250-300 GHz
  160 Gb/s (~100 GHz, t_d~2.5ps) f_T~400-600 GHz
- MSI-level Integration (500-2000 transistors)
- Breakdown voltages > 3V
- Low power operation
- High Speed on-chip-wiring and package

Technology candidates:

III/V-HBTs, HEMTs, SiGe-HBTs,
Sub-100nm CMOS

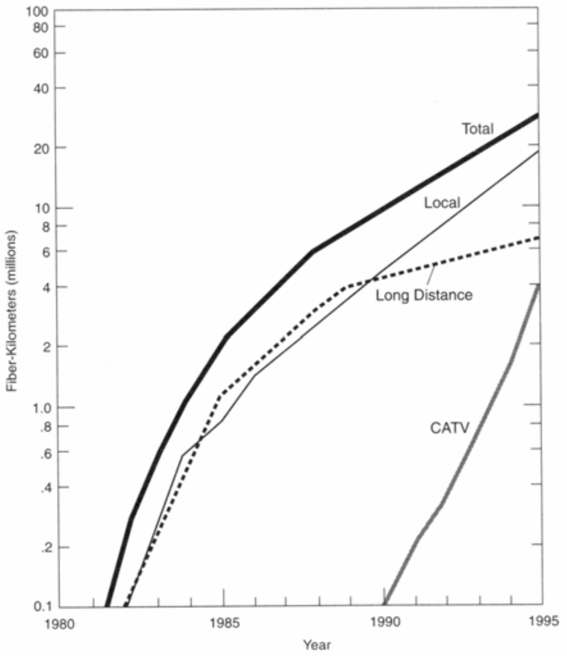
1.6 Technology-Drivers for Optical Communication

Long Distance, Large Capacity Networks:



Source: AT&T Submarine Systems Inc.

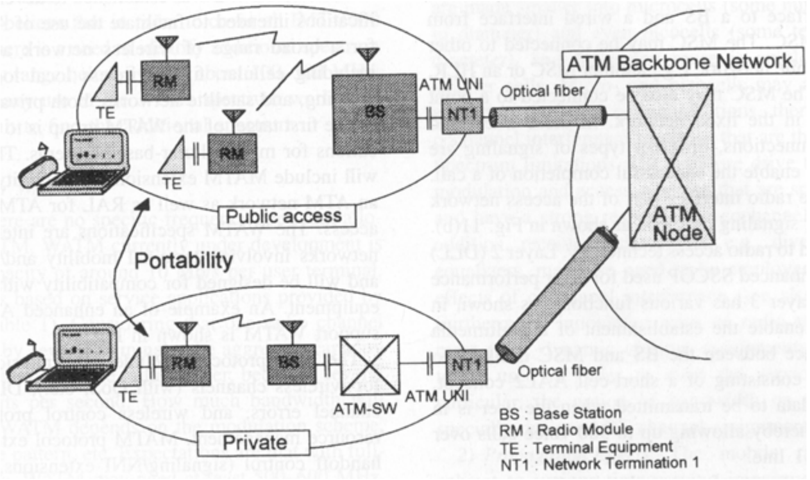
▲ The 27 300-km fiber-optic link around the globe—FLAG, for short—will snake its way around the world from Cornwall in the United Kingdom to a site near Tokyo Bay. Preventing shark bites to the cable when laid and making deals for landing points were among the challenges faced by the FLAG Ltd. consortium and its contractors in building the system. All-optical-technology amplifiers are embedded every 45 to 85 km in the cable. Electro-optical repeaters at the landings regenerate the signal at higher power levels for the next series of undersea amplifiers.



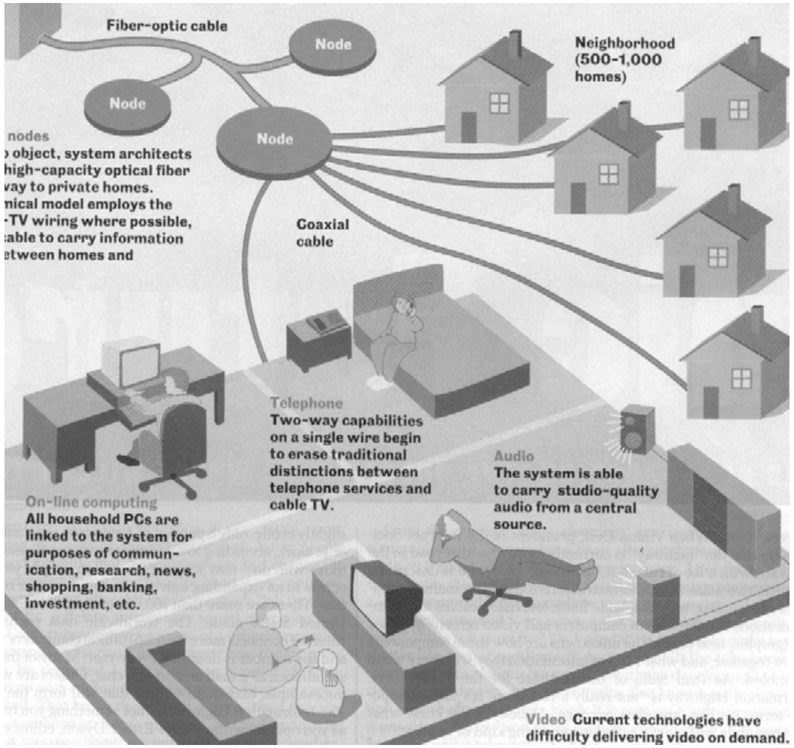
Today:
150 Mio.km of fibers
in ground !!!

Satellite-Communication and Backbone-Networks for Mobile Communication:

Mobile Communication-Networks need an optical Back-Bone-Network for the aggregated high capacitiy data streams.

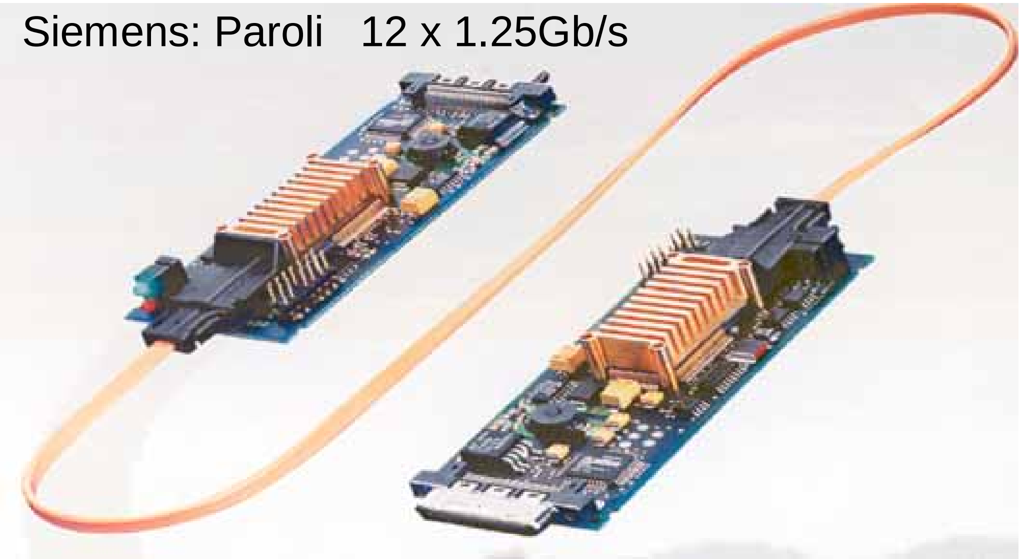


Future Consumer Applications: Fiber to the home



Emerging Application: Tb/s Highly Parallel Links for Inter-Chip- and Inter-board-Com:

Parallel Fiber-Ribbon communication (z.B. Siemens, Paroli)



Siemens: Paroli 12 x 1.25Gb/s

Goals for short distance inter-chip parallel interconnection:
eg. 200x40Gb/s = 8Tb/s aggregated

1.7 Future Challenges of optical Communication

Even after 40 years of research and commercial success the evolution of optical communication is far from an end – on the contrary the quest for **Tb/s communication** and **dense optical integration** has just begun with a promise for an other **1000-fold performance improvement**.

From Giga- to Terabit-Communication Technology: Requirements

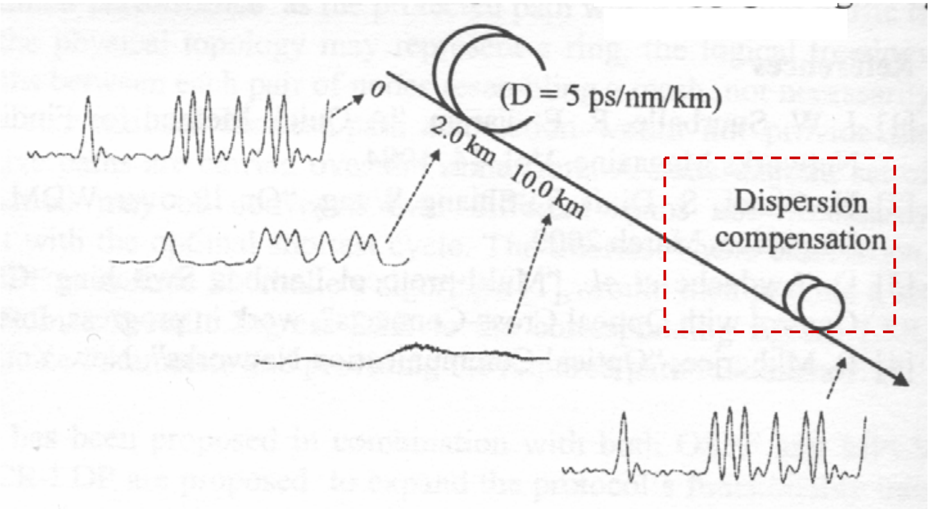
the following challenges have to be overcome:

1) Compensation of fiber dispersion at ultra high data rates for OTDM:

THz-band width allows the transmission of ps- and sub-ps pulses, however at these data rates fiber dispersion becomes strong and has to be compensated precisely after just a few km of transmission.

For fixed / known transmission distances an adaptive compensation is possible but becomes challenging for applications with variable distances eg. LAN (Local Area Networks).

Optical pulse at the fiber-in- and output and after dispersion compensation:



Transmitter bit-pattern

Receiver bit-pattern
(after 12km)

Compensated bit-pattern

2) Ultra-broadband optical amplifiers:

The bandwidth of high gain SOAs and EDFAs is only a few nm wide (resp. a few THz), therefore in future **broadband optical amplifiers**, eg. Raman-amplifiers with high pumping requirements are needed.

3) All-optical ps-Switches and Logic Elements:

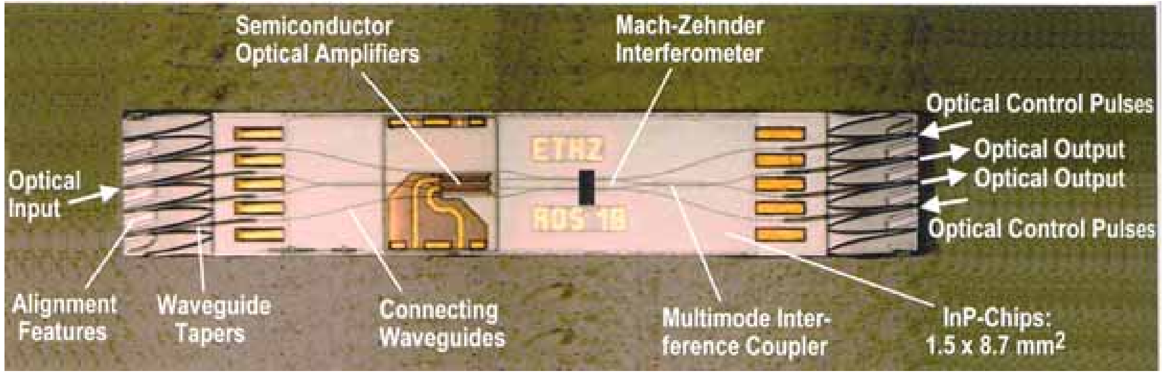
Because it is unlikely that electronic circuits will be able to process signals in the ps- or even sub-ps range (eg. DEMUX, header recognition, etc.) **all-optical processing completely in the optical domain** is an alternative, because **optical processes are inherently fast** (THz-bandwidth). Unfortunately nonlinearities are weak requiring high pulse energies.

Devices with optical in- and outputs without a conversion in the electrical domain are called **all-optical**.

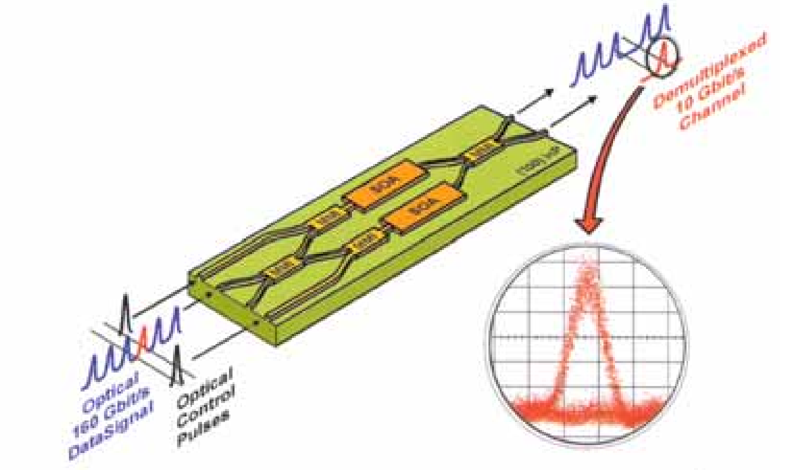
Example:

All-optical Switch (DEMUX) based on InP-SOAs for data rates up to 300 Gb/s (500fs switching times):

1:16 Demultiplexing-Experiment at 160 Gb/s:

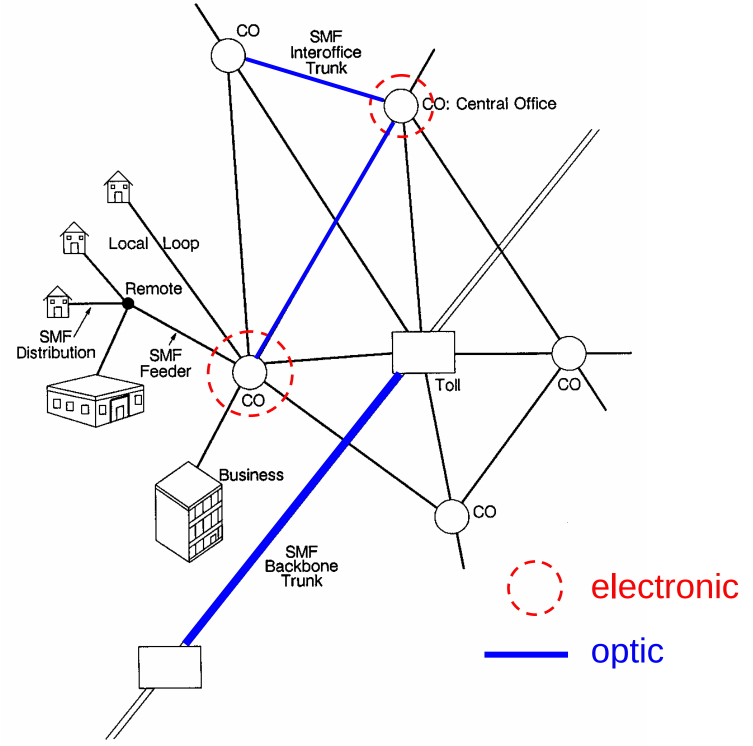


(IQE, Prof. Melchior, ETHZ)



This type of all-optical can process data rates of 500 – 1000 Gb/s – however the technology is still in its infancy.

4) Optical Switching and Routing:



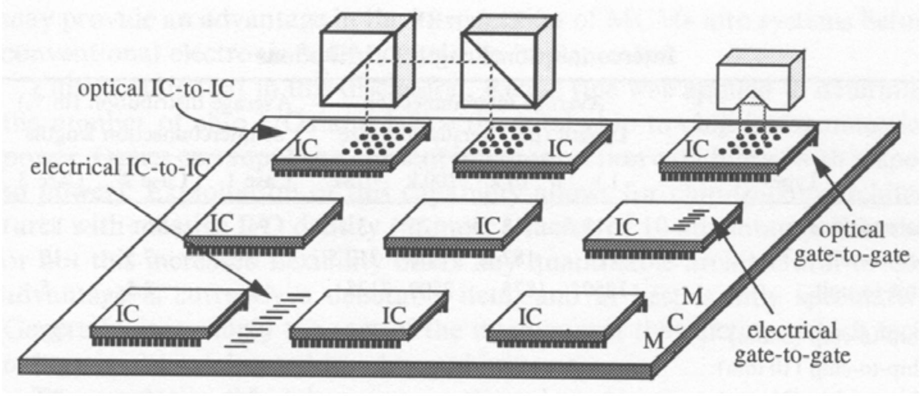
Distribution and switching of optical signals is the task of so called central offices and is carried out to a large extent in the electrical format.

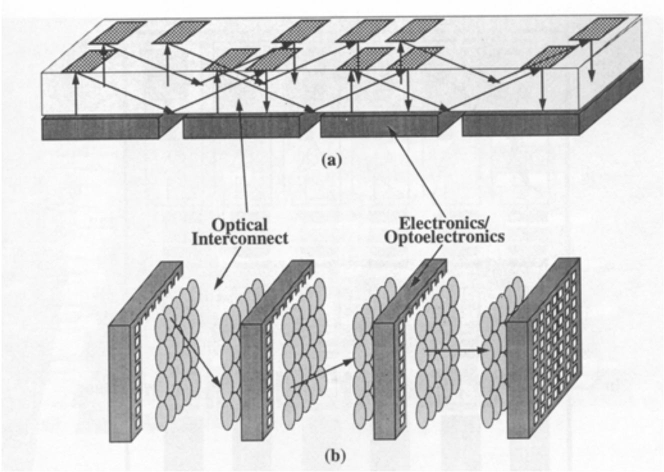
The necessary functions and complexity is not yet available in the optical format.

As a result switching is currently not yet optically transparent and creates an **electronic bottle-neck**.

Optical transparent switching is still in research, because optical solutions are so far too expensive and complex in comparison to electronic signal distribution/processing.

5) Tb/s Optical Back-Planes, Chip-to-Chip and Board-to-Board-Links:

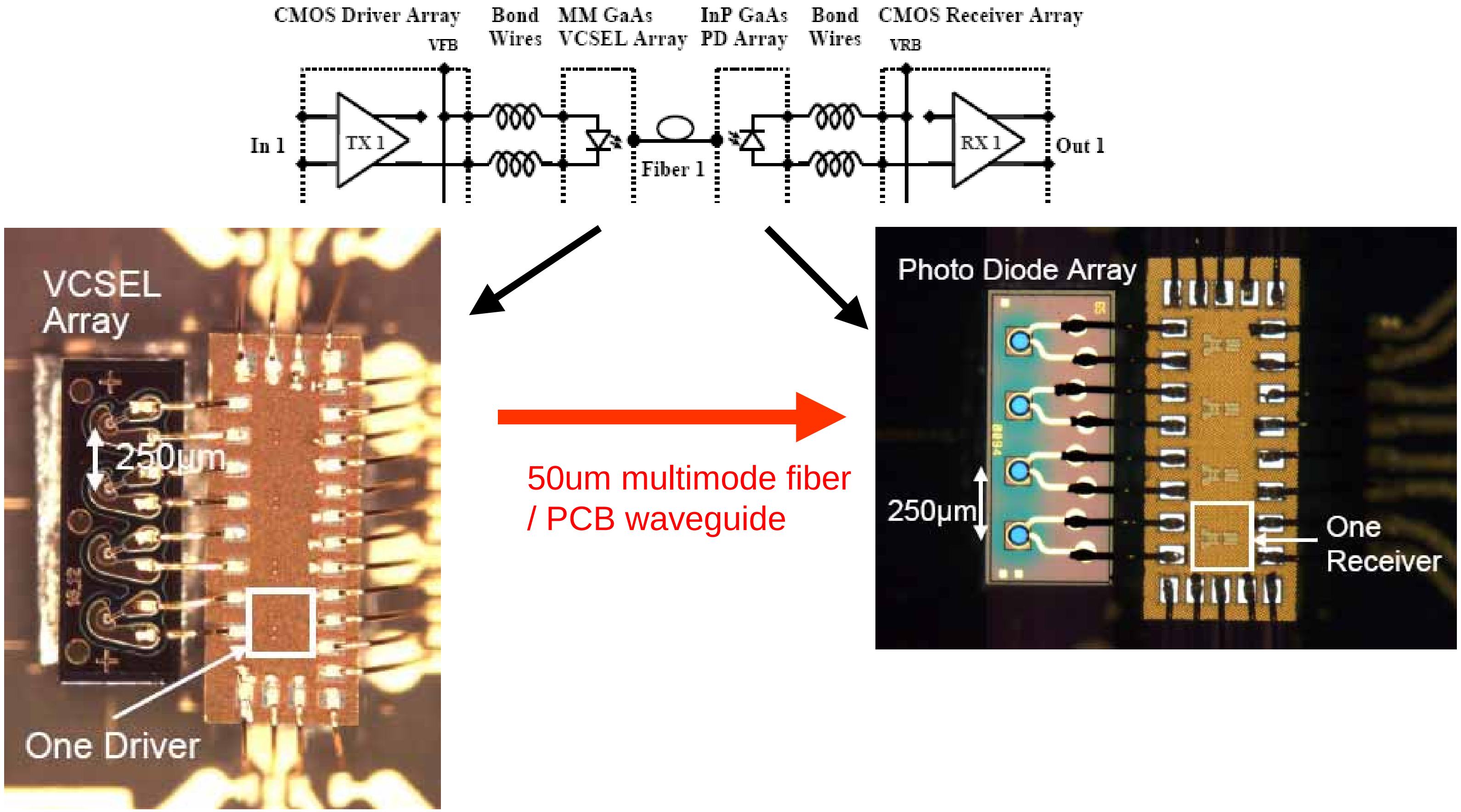




Modern Processor-IC will have Tb/s-throughput and **parallel In- and Output aggregated data rates of several Tb/s** (eg. 100x40Gb/s=4Tb/s) calling for optical solutions for

- bandwidth even over cm -m
- spatial channel density (eg. 250µm/ch), 1D or 2D-parallelism
- low cross-talk

Example: 4x10 Gb/s Parallel Fiberoptic Link with 2mW/Gb/s based on 90nm CMOS and VCSELs:

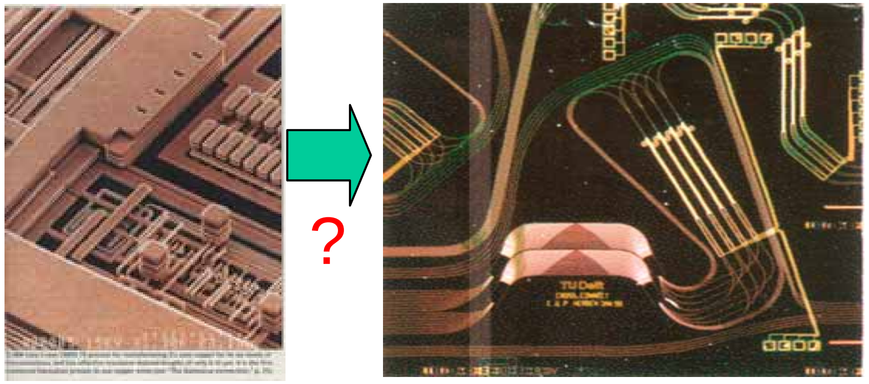


50um multimode fiber / PCB waveguide

6) Towards High Density Optoelectronic and Photonic Integration:

Optoelectronic Integration is difficult and limited by:

1) a technology incompatibility of the device
2) low wiring density by low contrast optical waveguides with mm-bend radii



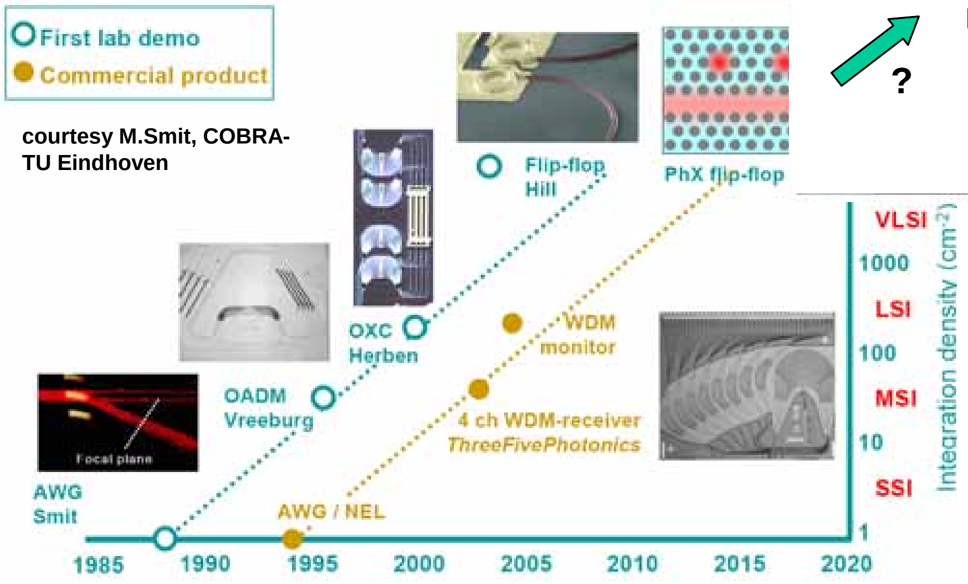
IBM ~70um

M.Smit, COBRA-Tu Eindhoven ~700um

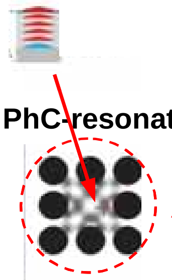
Progress in Monolithic Photonic Integration:

Quantum-Photonic Devices

Status and Projections



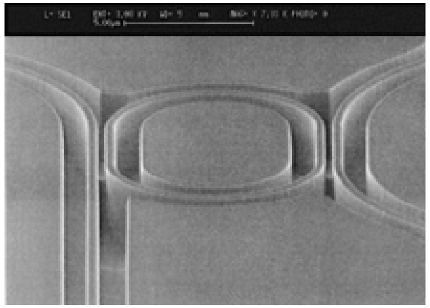
courtesy M.Smit, COBRA-TU Eindhoven



- **Nano-Photonics**
- **Photonic Crystals** (bandgap WG)
- **Photon Wire Circuits** (high contrast WG)
- Micro-Photonics (low contrast WG)

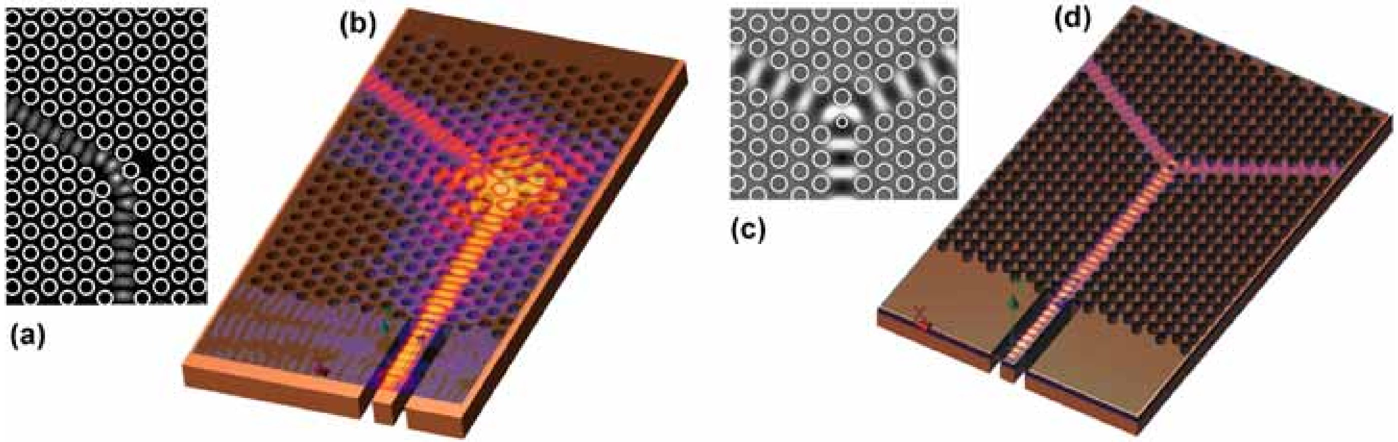
- (Hybrid Integration)

Photon Wires: **high contrast WG with strong guiding**



High Density due to small bend radius of ~ 5µm

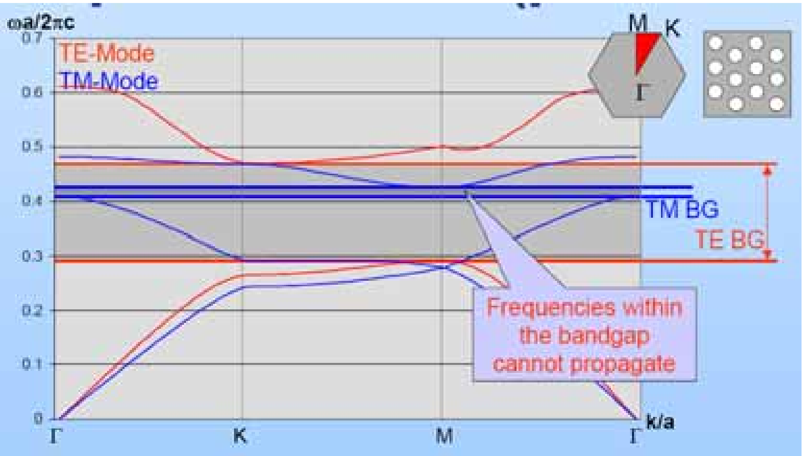
Photonic Crystal: air-holes in planar WG



High Density:

Device Area Reduction to the wavelength scale λ^2

Dispersion characteristic of triangular PhC:



Frequencies within the bandgap cannot propagate

PhC-Power Splitter in InP: