Optoelectronic devices

Prof. Dr. H. Hillmer

1 very important

2 important

3 for specialists

Lehrveranstaltungen der „Technischen Elektronik“ --- „Lectures offered by Technological Electronics"

real title / translation

Masterthesis

- **WS** | **3 SWS** | Nr.5266
  Semiconductor Lasers
  Halbleiterlaser
- **WS / SS** | **2 SWS** | Nr.2281
  Praktikum Optoelektronik I
  (Mikrosystemtechnik, Fabry Pérot arrays, Messung und Simulation)
  Practical training in Optoelectronics I
  (Microsystem technology, Fabry Pérot arrays, measurement and simulation)
- **WS / SS** | **2 SWS** | Nr.2282
  Praktikum Optoelektronik II
  (Messungen an Halbleiterlasern)
  Practical training in Optoelectronics II
  (Measurement of semiconductor Lasers)
- **SS** | **2 SWS**
  Microsystem Technology
  Mikrosystemtechnik in der Optoelektronik
  Nr.5267
- **SS** | **2 SWS**
  Technology of Electronic and Optoelectronic Devices
  Technologie der elektronischen und optoelektronischen Bauelemente
  Nr.8500
- **WS / SS** | **2 SWS** | Nr. 2215
  Mikrosystemtechnik Praktikum
  Microsystem Technology practical training
- **WS** | **2 SWS** | Nr.2211
  Semiconductor memories
  Halbleiter Speicher
- **WS** | **2 SWS** | Nr.2285
  Nanosensorics
  Nanosensorik
- **WS** | **2 SWS** | Nr.5272
  Nanosensorics Lab training
  Nanosensorik Lab Training
- **WS / SS** | **2 SWS** | Nr. 5273
  Studentenseminar Elektronik und Photonik
  Seminar in Electronics and Photonics
- **SS / WS** | **2 SWS** | Nr. 3180
  Seminar Optoelectronics I + II
  Studentenseminar Optoelektronik
- **SS** | **4 SWS** | Nr.2213
  Photonische Komponenten und Systeme
  Photonic components and Systems
  (Hillmer, Witzigmann, Bangert)

Bachelorthesis

- **WS** | **4 SWS**
  Optoelectronic Devices
  Komponenten der Optoelektronik
  Nr. 5265
- **WS / SS** | **2 SWS**
  Seminar Elektronik und Optoelektronik
  Seminar in Electronics and Optoelectronics
  Nr.5269
- **WS / SS** | **2 SWS**
  Studentenseminar Mikrosystemtechnik und Nanotechnologie
  Seminar Microsystem Technology and Nanotechnology
  Nr. 2218
- **WS** | **3 SWS**
  Elektronische Bauelemente
  Electronic components
  Nr. 2209
- **WS** | **2 SWS**
  Werkstoffe der Elektrotechnik
  Materials of electrical Engineering
  (ET und Mechatronik)
  Nr. 5605
- **SS** | **2 SWS**
  Grundlagen der technischen Optik
  Basics of technical Optics
  Nr. 2272
- **WS** | **2 SWS**
  Grundwissen der Elektronik
  Basic knowledge of Electronics
  (Informatik und WiIng)
  Nr.2206

Content of the lecture

1. Introduction

in the lecture: emphasis on methodology
motivation: frequency multiplexing in optical communication systems, colours of some exotic butterflies and trogons by photonic crystals: looking into the successful solutions of nature, a promising approach for an advanced working engineer

2. General requirements on information transmission

3. Fundamental principles in optics

- Differentiation: ray optics ↔ wave optics ↔ quantum optics
- refractive optics ↔ diffractive optics
- Refractive index, polarisation, interference, diffraction, coherence
- material properties of glass; dispersion, absorption

4. Optical waveguiding

- waveguides
- fibres
- special emphasis on
  - intermode dispersion: modal dispersion
  - intramode dispersion: material dispersion and waveguide dispersion

5. Interferometers (Michelson, Fabry-Pérot, Mach-Zehnder)

6. Multilayer mirrors and interference filters

7. Introduction to lasers

- material properties of semiconductors: electrons, holes, band structure
- pn-homojunction, pn-heterojunction
- optical and electrical confinement
- absorption of radiation, emission of light
- different cavity and resonator structures (e.g. edge and surface emitters)
- in-plane FP, in-plane DFB, in-plane DBR, VC arrays

8. Introduction to LEDs

- principles, materials, sensitivity of the human eye, applications

9. Light detecting/absorbing devices:

- photodiodes
- solar cells

10. Microoptics

Recommended literature / *Literaturempfehlung*

1) <u>Optoelectronic devices + semiconductor lasers / *Komponenten der Optoelektronik + Halbleiterlaser*</u>

S. Kasap, H. Ruda and Y. Boucher:
: Illustrated Handbook of Optoelectronics and Photonics, Cambrigde University Press, 2009

S. O. Kasap:
: Optoelectronics and photonics, Prentice Hall, 2001

J. Gowar:
: Optical Communication Systems, 2nd Ed., Prentice Hall, 1993

H. Hillmer and S. Hansmann
: Semiconductor Lasers, from Handbook of Lasers and Optics Chapter 11.3, 1st Edition, Ed. F. Träger, Springer, ISBN-10:0-387-95579-8, pages 695-726 ; ISBN-13:978-0-387-95579-7
http://www.springerlink.com/content/v9r801/?sortorder=asc&p_o=0

H. Hillmer and T. Kusserow
: Semiconductor Lasers, from Handbook of Lasers and Optics Chapter 11.3, 2nd Edition, Ed. F. Träger, Springer, ISBN-978-3-642-19408-5, pages 757-792

J. Singh:
: Semiconductor Devices – an Introduction, McGraw-Hill

J. Singh:
: Semiconductor Devices - Basic Principles, John Wiley & Sons, New York 2001

J. Jahns, S. Helfert:
: Introduction to Micro- and Nanooptics, Wiley-VCH, Weinheim, 2012

K. J. Ebeling:
: Integrierte Optoelektronik, 2. Aufl., Springer Verlag, 1992

H. Fouckhardt:
: Photonik, Teubner Verlag, Stuttgart 1994

H. Fouckhardt:
: Halbleiterlaser – unter Verwendung Fourier-optischer Methoden, Vieweg + Teubner Verlag, 2011

H. Hultzsch (Herausgeber):
: Optische Telekommunikationssysteme, Damm Verlag, 1996

W. Bludau:
: Halbleiter-Optoelektronik, Hanser Verlag, 1995

T.E. Sale:
: Vertical Cavity Surface Emitting Lasers, RSP, John Wiley & Sons, Chichester, UK, 1995

C. Breck Hitz:
: Understanding Laser Technology, PennWell Books, Tulsa, Oklahoma, 1985

L. A. Coldren and S. W. Corzine:
: Diode Lasers and Photonic Integrated Circuits, John Wiley & Sons, New York 1995

S. L. Chuang:
: Physics of Optoelectronic Devices, John Wiley & Sons, New York 1995

W. Harth and H. Grothe:
: Sende- und Empfangsdioden für die optische Nachrichtentechnik, Teubner Verlag, Stuttgart 1994

M. Young:
: Optik, Laser, Wellenleiter, Springer-Verlag, Heidelberg, 1997

M. Young:
: Optics and lasers, Springer-Verlag, Heidelberg, 1993

P. Bhattacharya:
: Semiconductor Optoelectronic Devices, 2nd edition, Prentice Hall, London 1997

F. K. Kneubühl und M. W. Sigrist:
: Laser, Teubner Verlag, 1995

O. Svelto and D. C. Hanna:
: Principles of Lasers, 4th edition, Plenum Press, New York 1998

G.P. Agrawal and N.K. Dutta:
: Long-Wavelength Semiconductor Lasers, Van Nostrand Reinhold, New York, 1986

H. Ghafouri-Shiraz und B.S.K. Lo:
: Distributed Feedback Laser Diodes: Principles and Physical Modelling, John Wiley & Sons, Chichester, UK, 1996

S. M. Sze:
: Physics of semiconductor devices , John Wiley & Sons, New York

V. Brückner:
: Optische Nachrichtentechnik: Grundlagen und Anwendungen, Teubner Verlag, Stuttgart, 2003

H.Hillmer und J. Salbeck:
Kap. 8, “Materialien der Optoelektronik – Grundlagen und Anwendungen”, in Bergmann Schäfer, Band 6, Festkörper, Auflage 2005, Walter de Gruyter Verlag, Berlin, New York.

J.G. Proakis und M. Salehi:
Grundlagen der Kommunikationstechnik, 2. Auflage, Pearson Studium, München, 2004

B.E.A. Saleh and M.C. Teich:
Fundamentals of Photonics, John Wiley & Sons, Inc., 1991

O. Solgaard:
Photonic Microsystems – Micro and Nanotechnology Applied to Optical Devices and Systems, Springer Science+Business Media, 2009

Ulrich Hahn:
Physik für Ingenieure Band 1: Mechanik, Thermodynamik, Schwingungen und Wellen, 2015
Physik für Ingenieure Band 2: Elektrizität und Magnetismus, Optik, Messungen und ihre Auswertung, 2015

2) Optical communications / *Optische Nachrichtentechnik*

J. H. Franz, V. K. Jain:
Optical Communication, Narosa, New Dehli

J. Gowar:
Optical Communication Systems, 2nd Ed., Prentice Hall, 1993

G. Grau und W. Freude:
Optische Nachrichtentechnik, Springer Verlag, 1991

H. G. Unger:
Optische Nachrichtentechnik, Band 1 und 2, Hüthig Verlag

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J. M. Senior:
Optical Fiber Communications, 2nd Ed., Prentice Hall, 1993

G. Winstel und C. Weyrich:
Optoelektronik I, Serie Halbleiter-Elektronik, Band 10, Springer Verlag

G. Winstel und C. Weyrich:
Optoelektronik II, Serie Halbleiter-Elektronik, Band 11, Springer Verlag

Y. Suematsu, K. I. Iga:
Introduction to optical fibre communications

V. Brückner:
Optische Nachrichtentechnik: Grundlagen und Anwendungen, Teubner Verlag, Stuttgart, 2003

3) Technology of electronic and optoelectronic devices - *Technologie der elektronischen und optoelektronischen Bauelemente*

S. Büttgenbach:
Mikromechanik - Einführung in Technologie und Anwendungen, 2. Auflage, Teubner Verlag, Stuttgart 1994

H. I. Smith:
Submicron- and nanometer-structures technology, 2nd edition, NanoStructures Press, 437 Peakham Road, Sudbury, MA 01776, USA, 1994

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H. Beneking:
Halbleiter-Technologie - Eine Einführung in die Prozeßtechnik von Silizium und III-V-Verbindungen Teubner Verlag, Stuttgart 1991

I. Ruge und H. Mader:
Halbleitertechnologie, Serie Halbleiter-Elektronik, Band 4, Springer Verlag, 1991

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Introduction to Micro- and Nanooptics, Wiley-VCH, Weinheim, 2012

L. F. Thompson, C. G. Willson, and M. J. Bowden:
Introduction to Microlithography, 2nd edition, ACS Professional Reference Book, American Chemical Society, 1994

D. V. Morgan and K. Board:
An introduction to semiconductor microtechnology, 2nd edition, John Wiley & Sons, Chichester 1994

S. M. Sze:
Semiconductor devices - Physics and technology, John Wiley & Sons, New York 1985

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Modern Semiconductor Device Physics , John Wiley & Sons, New York 1998

W. M. Moreau

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U. Hilleringmann
Silizium-Halbleitertechnologie, 3. Auflage, Teubner Verlag, Stuttgart, 2002
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N. Schwesinger, Carolin Dehne, Frederic Adler:
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O. Solgaard:
Photonic Microsystems – Micro and Nanotechnology Applied to Optical Devices and Systems, Springer Science+Business Media, 2009

4) <u>Microsystem technology - *Mikromechanik und Mikrosystemtechnik*</u>

W. Menz, J. Mohr und O. Paul:
Microsystem Technology, VCH Verlag, 2001
W. Menz und J. Mohr:
Mikrosystemtechnik für Ingenieure, 2. Aufl., VCH Verlag, 1997
S. Fatikov, U. Remold,
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Lehrbuch Mikrosystemtechnik: Anwendungen, Grundlagen, Materialien und Herstellung von Mikrosystemen; Oldenbourg Verlag München, 2009
O. Solgaard:
Photonic Microsystems – Micro and Nanotechnology Applied to Optical Devices and Systems, Springer Science+Business Media, 2009

as well as papers from current journals (ask the lecturer!)

5) For refreshing the basics in optics - *zur Wiederholung der Grundlagen in Optik*

F. and L. Pedrotti:
Introduction to optics, Prentice Hall, 1993
F. Pedrotti, L. Pedrotti, W. Bausch und H.
Schmidt: Optik - eine Einführung,
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M. Born and E. Wolff:
Principles of optics, sixth edition, 1997, Cambridge University Press

6) For refreshing the basics in semiconductor electronics - *zur Wiederholung der Grundlagen in Halbleiter-Elektronik*

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R. Müller:
Bauelemente der Halbleiter-Elektronik, Serie Halbleiter-Elektronik, Band 2, Springer
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P. Horowitz, W. Hill:
The art of electronics, Cambridge University Press, 1989
E. Böhmer:
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K. Hoffmann:
Systemintegration: Vom Transistor zur großintegrierten Schaltung, Oldenbourg Wissenschaftsverlag,
2003 H.- G. Wagemann, T. Schönauer:
Silizium- Planartechnologie: Grundprozesse, Physik und Bauelemente, Teubner Verlag, 2003
R. Sauer:
Halbleiterphysik – Lehrbuch für Physiker und Ingenieure, Oldenbourg Verlag, München 2009

7) Foundations in mathematics – *Grundlagen der Mathematik*

Erwin Kreyszig:
Advanced engineering mathematics, John Wiley & Sons, New York

Motivation
of the lectures

optoelectronic devices
and
semiconductor lasers

Chapter 1

Introduction

Optoelectronics (Photonics)

Optical communication

tele- data-
communication

long-haul e.g. long distance calls

- IR lasers
- silica fibres
- modern topics:

  WDM

  TDM

local e.g. inside a computer

- LEDs
- blue lasers
- polymer- and silica fibres

Optical data processing

- storage (CD, DVD, Blu- ray Disc)
- printing
- barcode readers

Illumination

+ luminescent signs LEDs (all colours and white)

Display and projection technology

- liquid crystal (LCD)
- micromirror arrays
- laser TV
- LED displays
- micro field emitters

Microsystems (micromachining) including optics

- sensors
- photonic crystals

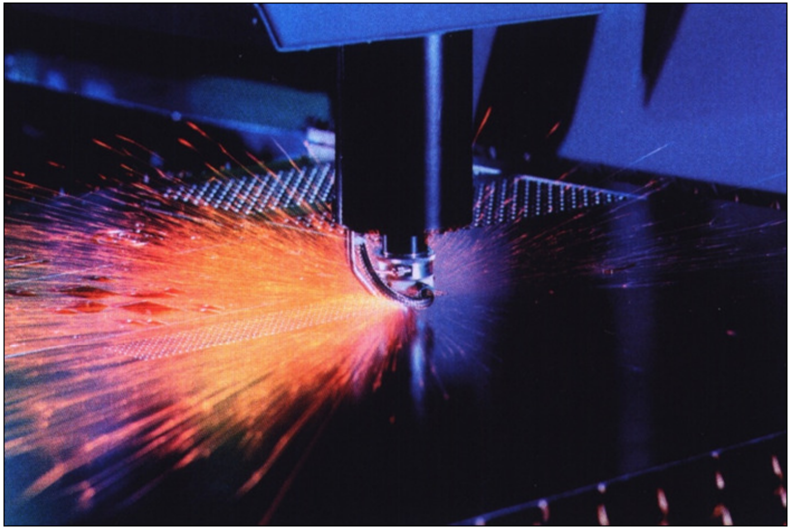
Material processing

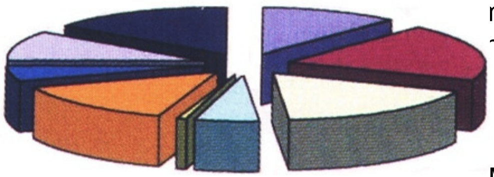
- welding
- soldering
- cutting
- drilling
- medical

Photovoltaic

- solar cells

Market segments of optical technologies



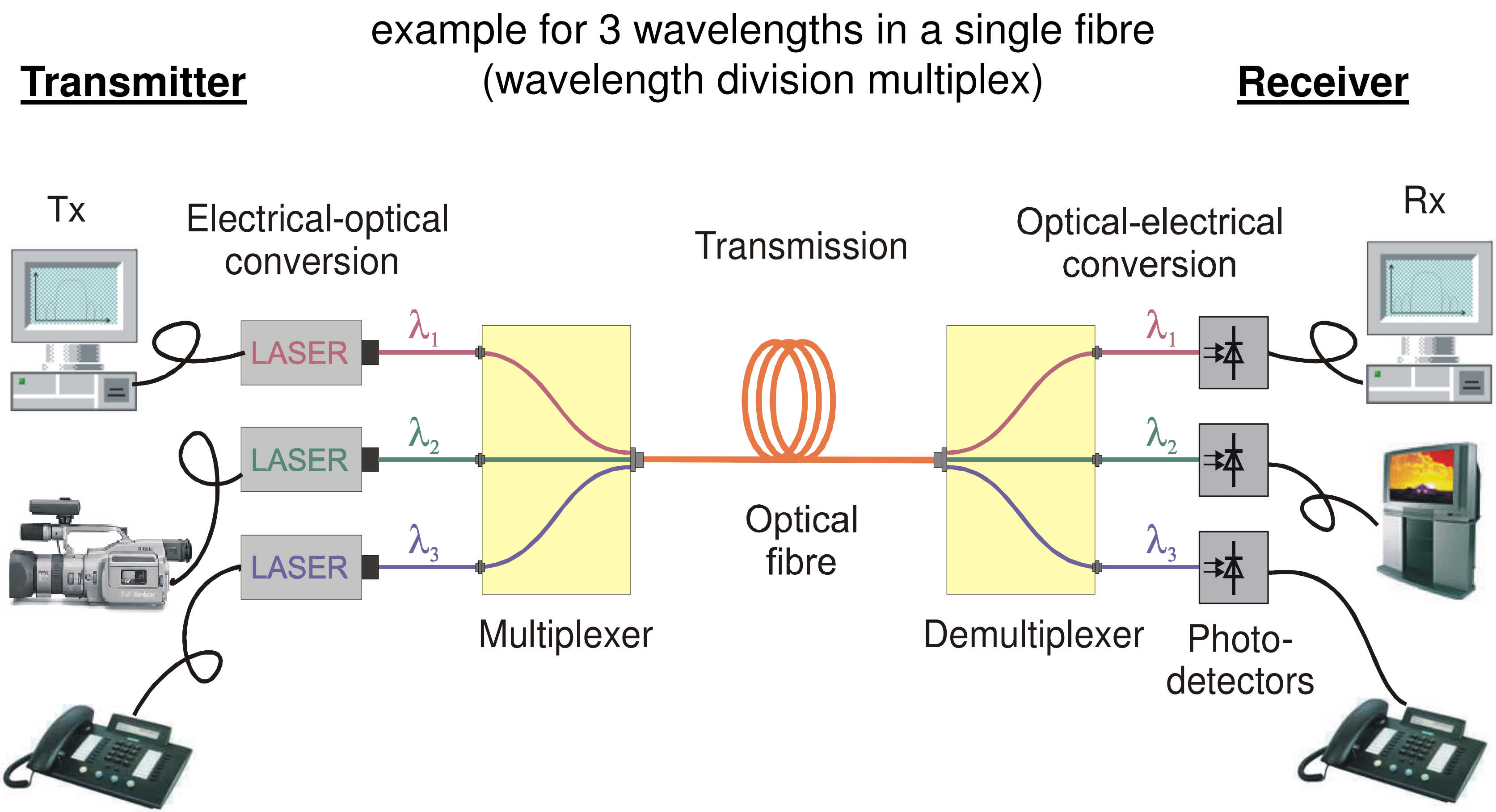


Direct application of lasers : in production technology this laser drills highly precise holes (500 holes / min)

The optical technologies contain nine fields. The biggest fraction in Germany in 2005 was image processing and measurement field.

All direct applications: cutting, drilling, soldering, welding

Motivation I
Optical communication, ultra-high optical data rates



2001: first transatlantic operation

Real-time transmission of video, control data, voice over 7000 km

- **surgery on a human patient**
- **7000 km between**

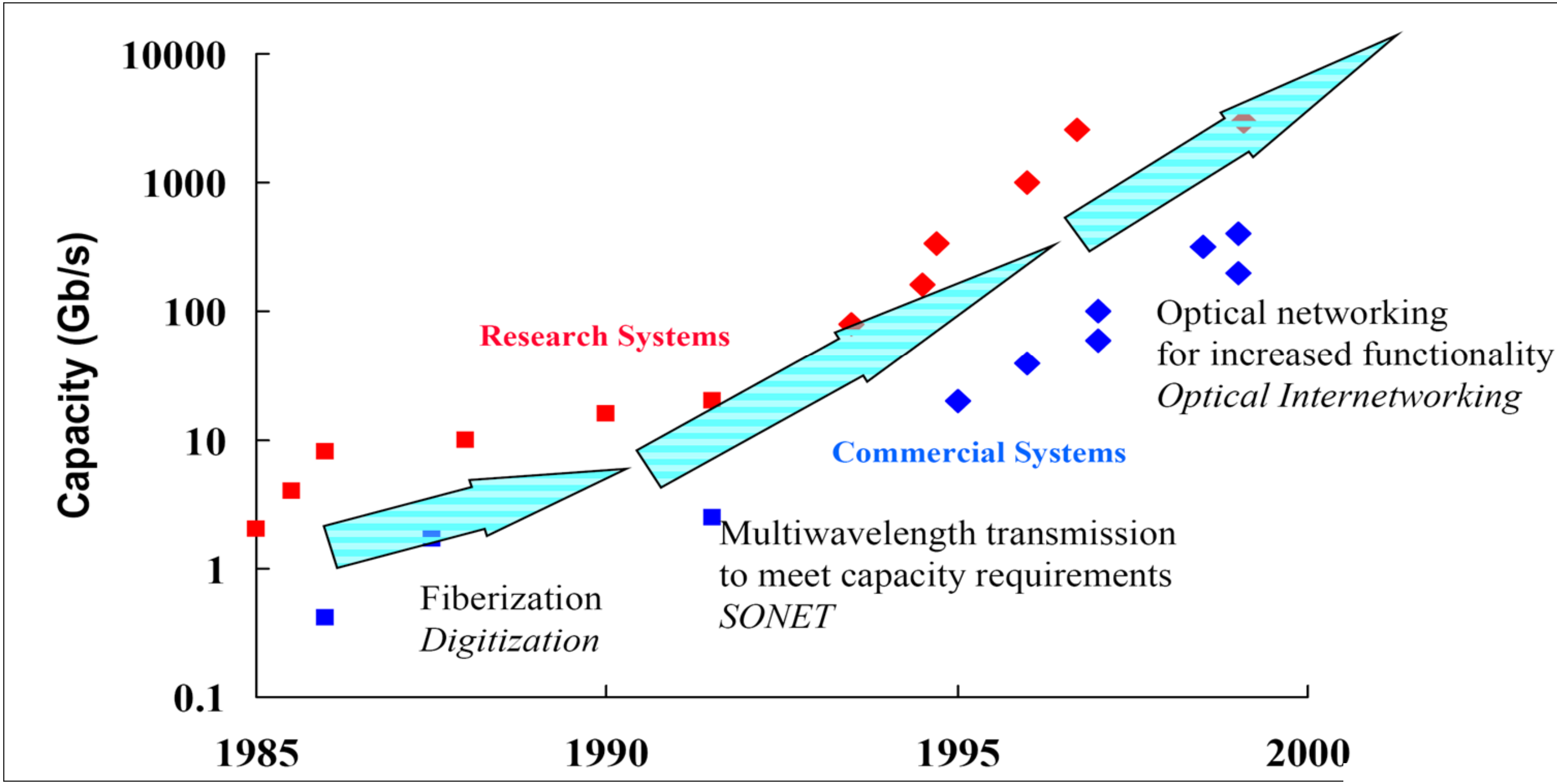
  Strasbourg, France (patient)

  New York, USA (surgeon)
- **time delay 155 ms**

  (for surgery to be feasible,

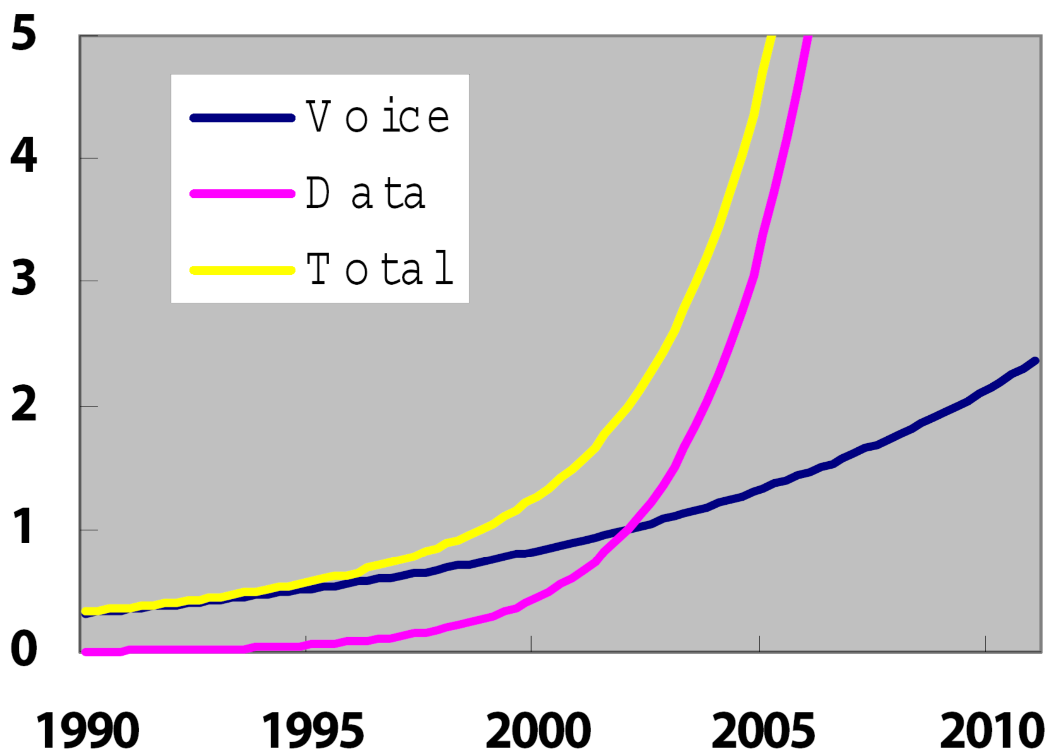
  acceptable time delay < 330 ms)
- **operation performed in 54 min.**
- **high – speed 10 Gbit/s fibre optic link**
  - video
  - data for robotic system
  - telephone

Motivation II
Lightwave technology eras



AT&T

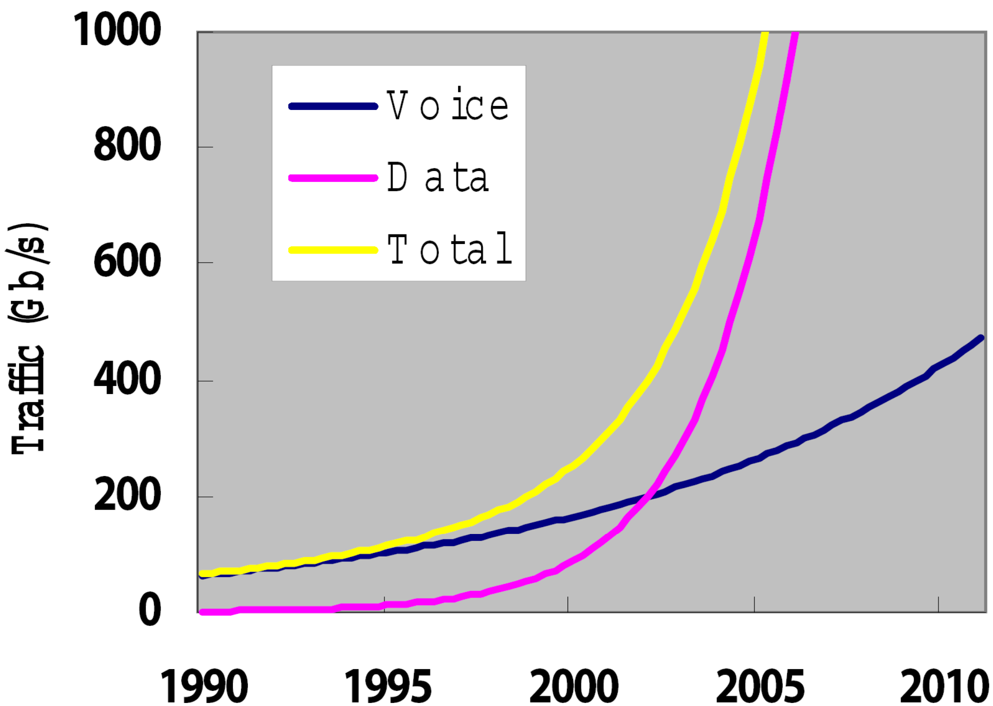
Network traffic: the shift to data I



- Yearend 1997
- Voice growth assumed 10%
- Data growth assumed 50%
- Voice/Data crossover at 2002

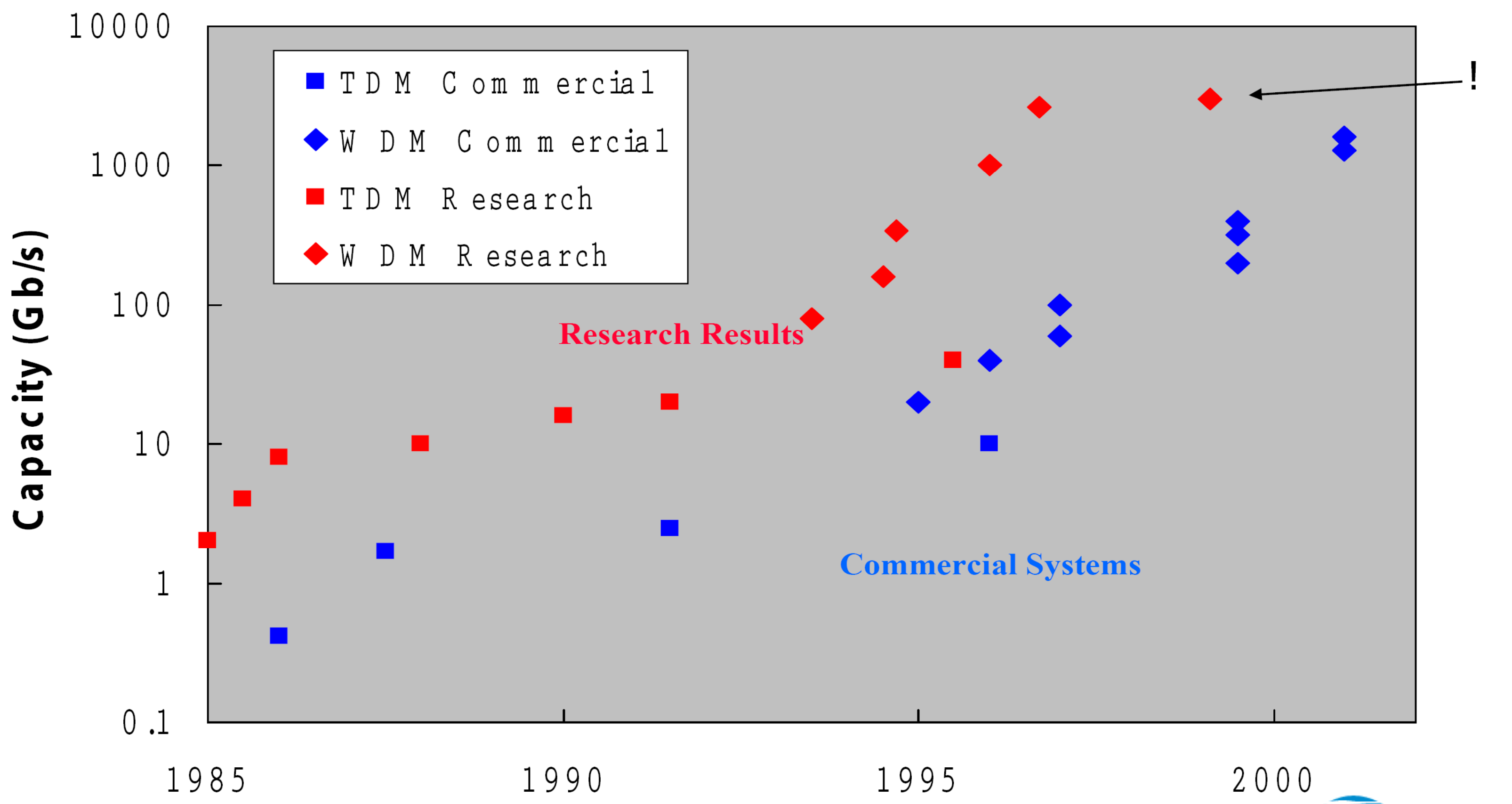
K. G. Coffman and A. Odlyzko
AT&T Labs

Network traffic: the shift to data II



- Total backbone traffic is comparable to the capacity of new single-fiber systems
- Between the availability of new systems and the ubiquitous deployment of their capacity lies billions of dollars and tremendous effort
- Next generation systems have the potential to outstrip demand - maybe

Single fibre capacity



Bionics

(a thrilling combination of

technics / engineering and biology)

... looks into the

principles of success in nature

... looking for possible applications in engineering

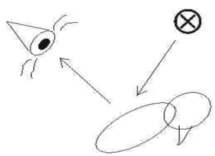
... a philosophy for advanced working engineers

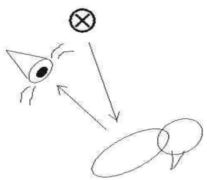
Lives in ...

... rain forests of
central America

Flag bird of the state of
Guatemala

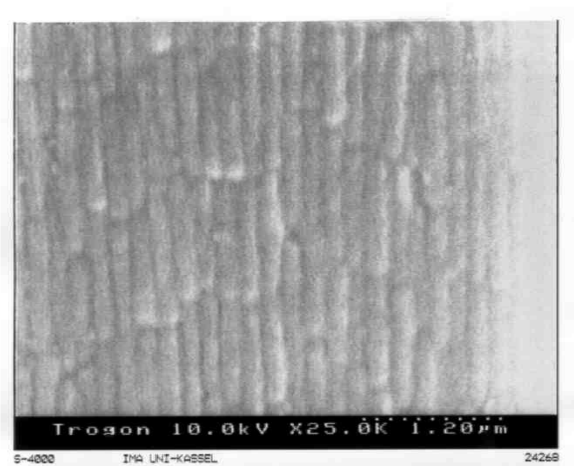
Colour tuning by moving light source



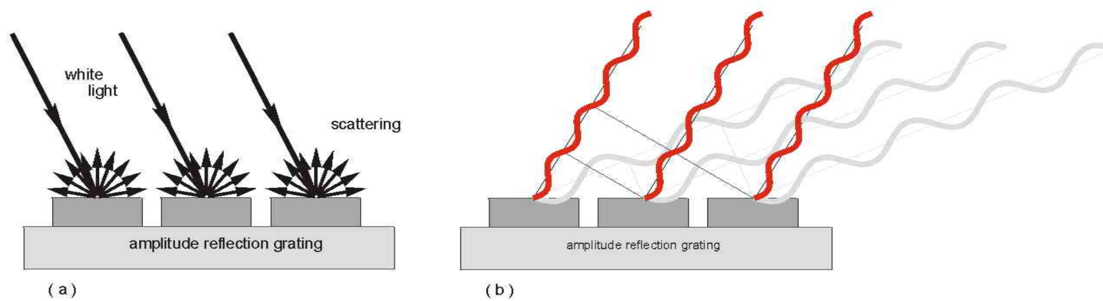


Generation of opalescent colours in nature
Bionics

Periodic gratings on wingfeathers of a violet trogon



Colour filters based on constructive interference

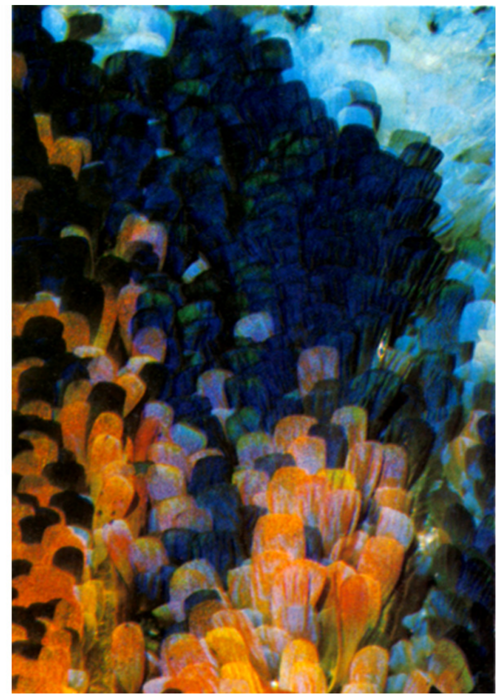


1D
photonic crystal

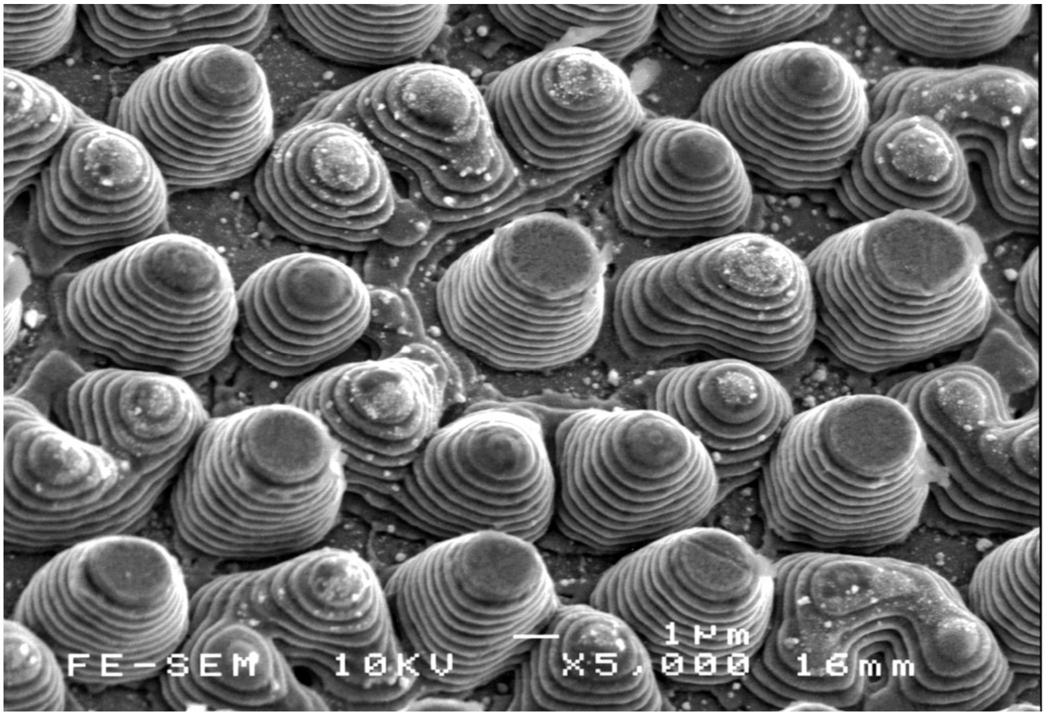
Colour tuning by tilting or rotation

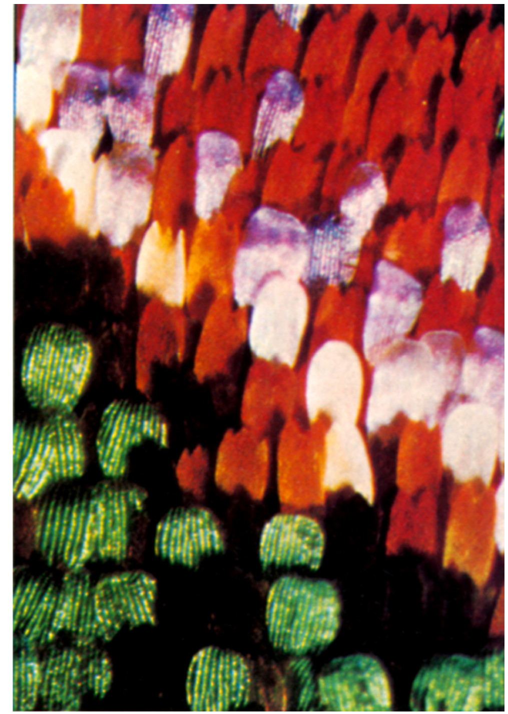
colour appearance:

a) pigments provide the colours
b) periodic alignment of scales/layers



Example for a) south American castnia





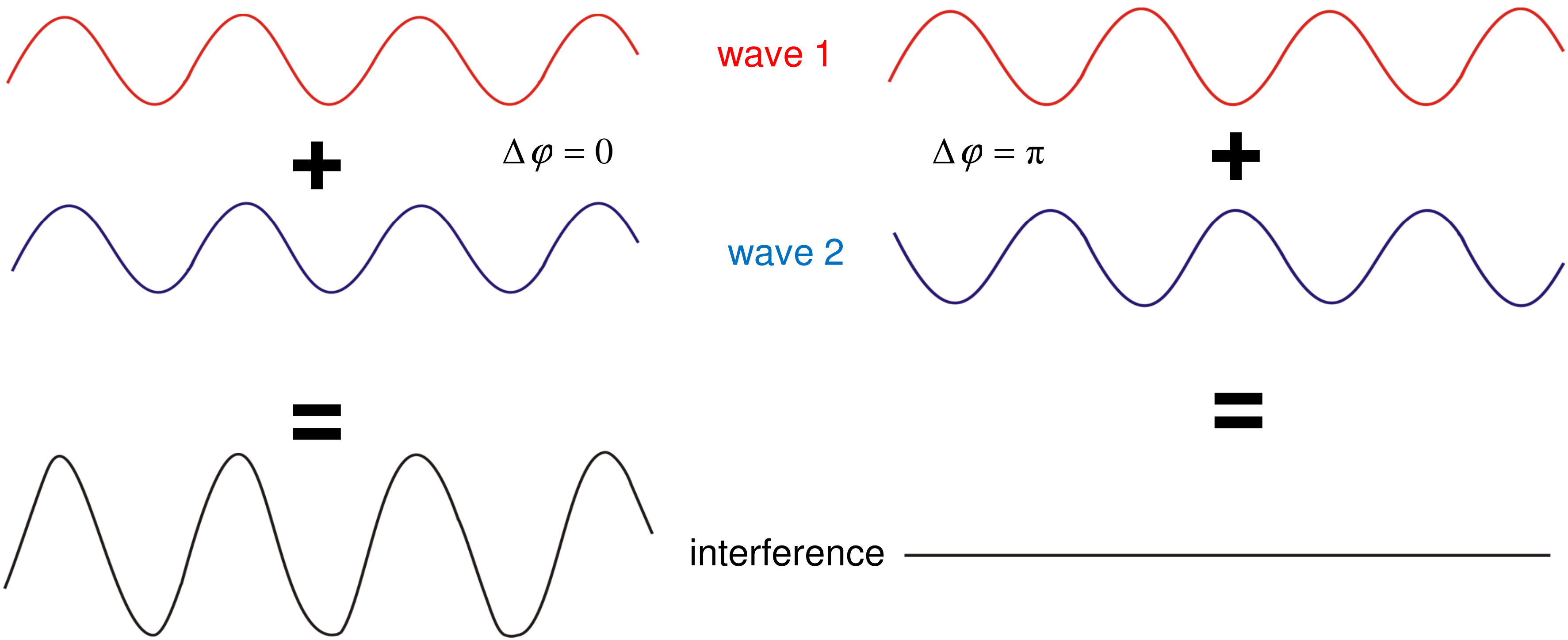
varying colour impression due to different observation angles
example for b)

Asian swallowtail
(papilio machaon)

Interference of two waves of identical wavelength

constructive Interference

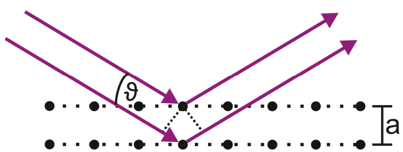
destructive Interference



Micro- and Nanostructures
Light Wavelength Selection

optoelectronic devices

X-ray diffraction at
lattice planes of
solid state crystals



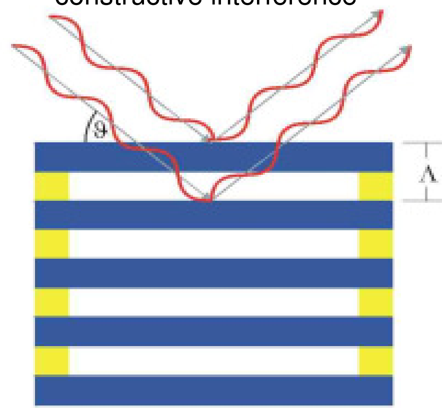
Bragg-condition:

$2a \sin\vartheta = m\lambda$

lattice constant: $a \approx 0.3$ nm
X-ray wavelength λ
m=1, 2, 3...

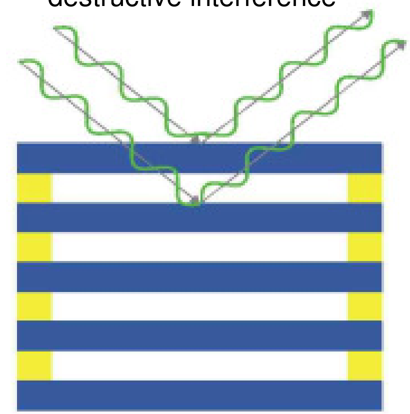
diffraction of light (IR) at periodically
aligned semiconductor layers

constructive interference



reflected lightwaves
with matching phase

destructive interference



reflected lightwaves
with opposite phase

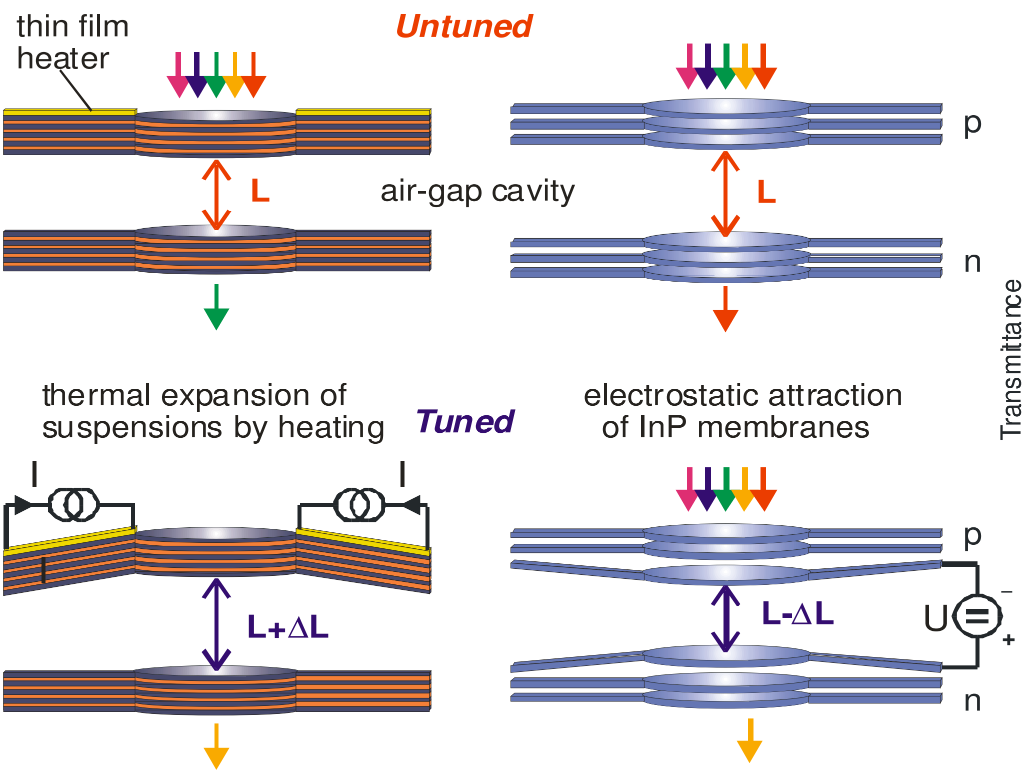
$$\Lambda = \frac{m\,\lambda_B}{2\,\bar{n}_{eff}\,\sin\vartheta}$$

grating period Λ= 90 ... 250 nm
Light wavelength λ_B=0.6 ... 1.5 µm (in air)

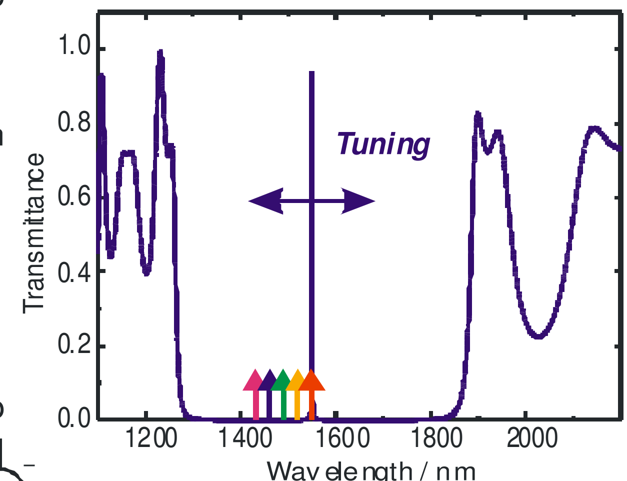
Application:
Micromechanical Tunable filters, principles

Thermal tuning for dielectric mirros

Electrostatic tuning for semiconductor mirrors

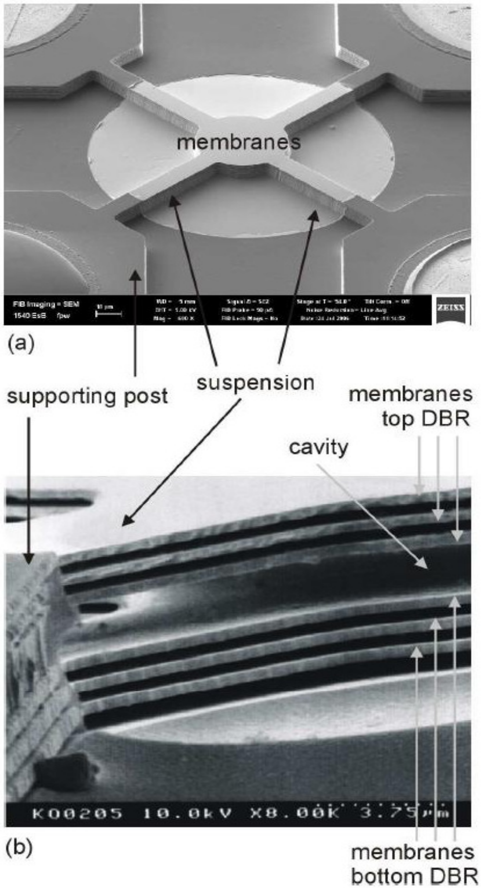


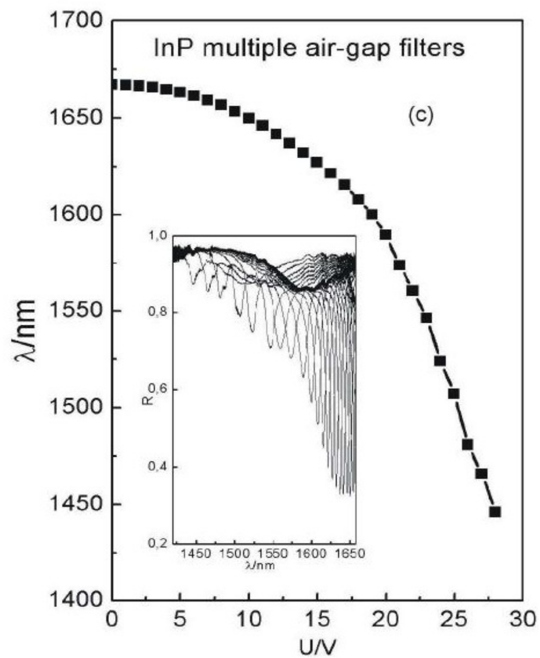
Wavelength tuning achieved by change of cavity length L



Application of photonic crystals in micromachined tunable filters

optoelectronic devices





electrostatic actuation

ultra-wide tuning range : 221nm

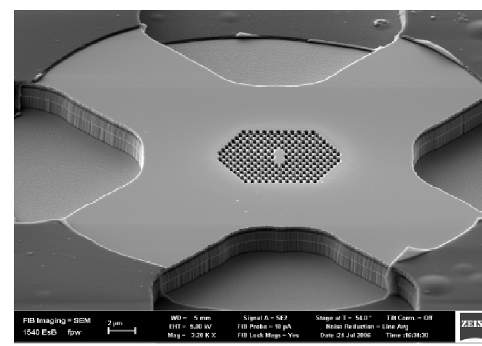
actuation voltage : 0 … 28V

continuous tuning

single tuning parameter

ultra-low power consumption

1µA in reverse current



Application of micromachined tunable Fabry Pérot filters

I. Datacommunication in-house fibre optical networks

II. Computers, Industrial networks

III. Sensorics and analytics

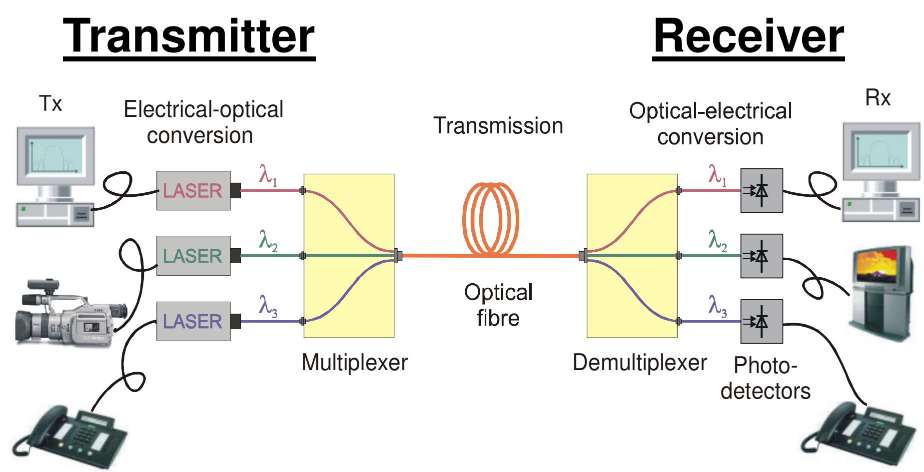
IV. Measurement technology

V. Confocal microscopy

VI. Medical applications

VII. Telecommunication, in dense wavelength division muliplexed systems

example for 3 wavelengths in a single fibre
(wavelength division multiplex)



Institute of **N**anostructure technology and **A**nalytics (INA)

optoelectronic devices

Synergies

Electrical engineering ⟷ Physics

NanoNetzwerk Hessen

NANONETZWERKHESSEN

NanoImprintKonsortium Hessen

NIH NANOIMPRINT-HESSEN

CCA
Competence Center Aerospace
Kassel Calden

Netzwerk
Hessen-China
德国黑森州中国合作促进中心

UniKasselTransfer

CINSaT

Center for **I**nterdisciplinary **N**anostructure **S**cience **a**nd **T**echnology

Institute of Nanostructure technology and Analytics (INA)

optoelectronic devices

- Deposition:
  IBD, MBE, PECVD, evaporation, FIB
- Plasma and Ion beam supported etching:
  RIE, CAIBE, barrel etching, FIB
- critical point drying
- Lithography: nanoimprint, ion beam, optical, e-beam
- analytics and measurement technology:
  FIB, REM, AFM, STM, XRD, PL, REFL
  faseroptical characterization (OSA,..)
  white light interferometry, ellipsometry

Nanostructuretechnology

Nanophotonics

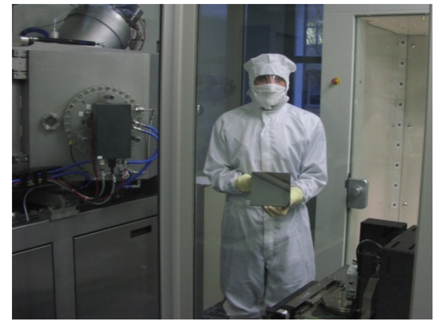
Nanoelectronics

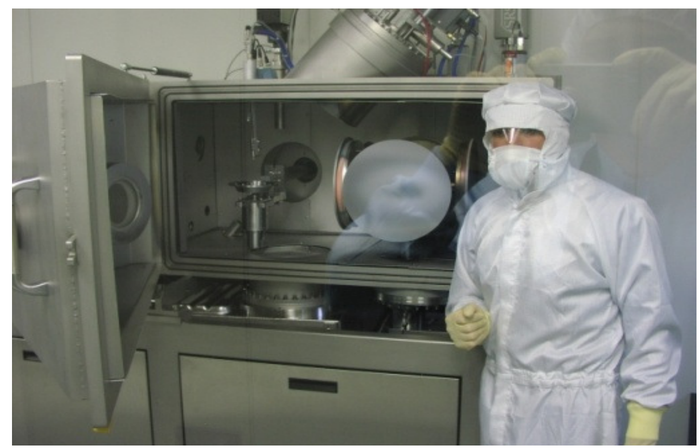
Nanomechanics

Optoelectronics

Nanosystemtechnology

Ion beam deposition technology at INA in Kassel





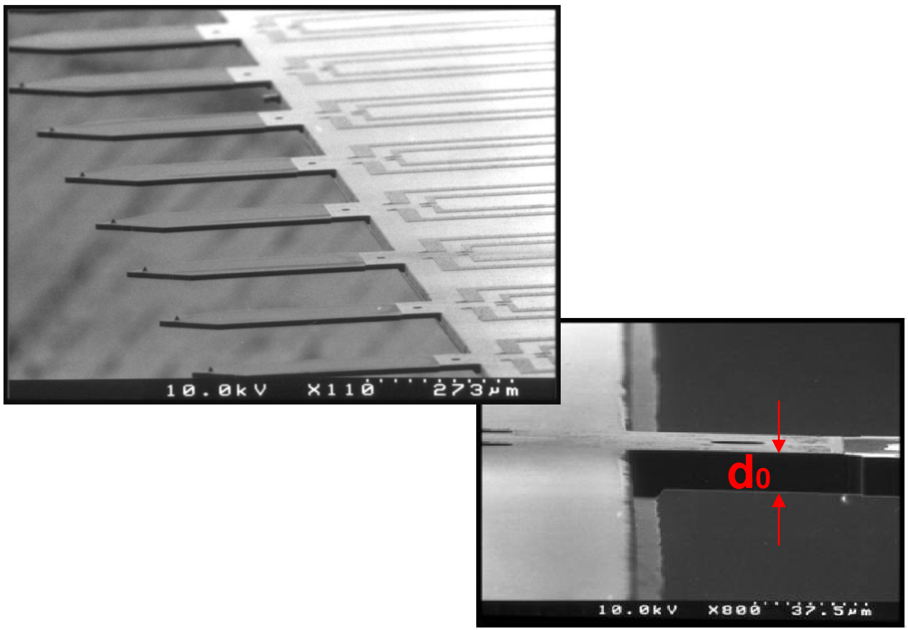
Deposition of multilayer structures:
TiO_2, ZrO_2, SiO_2, Y_3O_4, a-Si, Mo, Ta_2O_5, BC_3, C, ITO, AL_2O_3 …

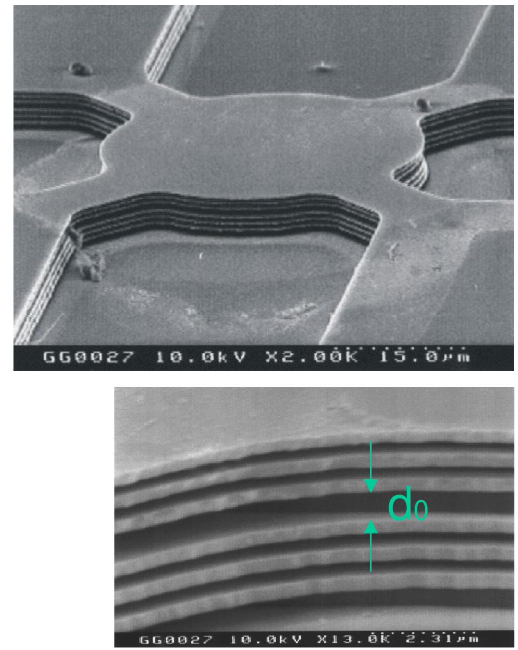
Motivation IV Atomic force microscopy (AFM) cantilever arrays and air gap filters

optoelectronic devices

AFM cantilever array

all air gap filter



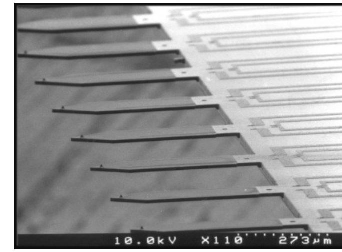


resonant frequency ~ d_0

selected wavelength ~ $2d_0$

AFM cantilever on Rosetta space

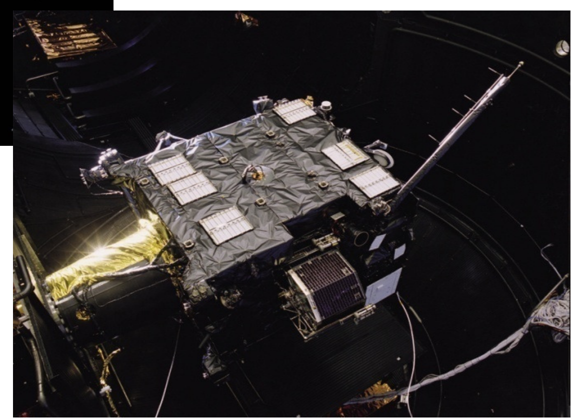
use of AFM cantilever arrays for precise particle and gas sensing, via changes in resonant frequency



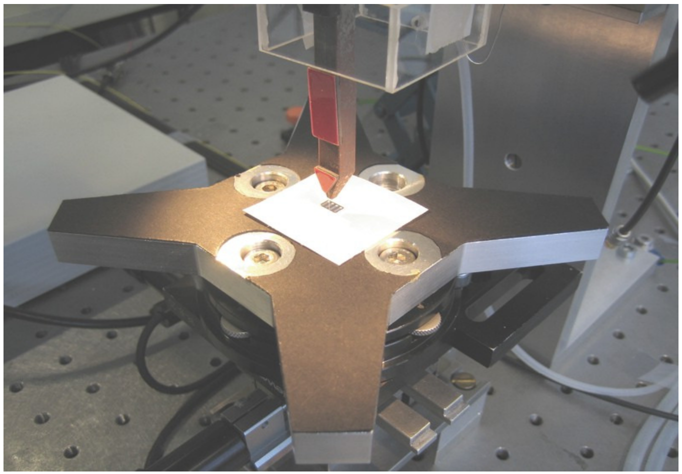
Launch date: March 2004

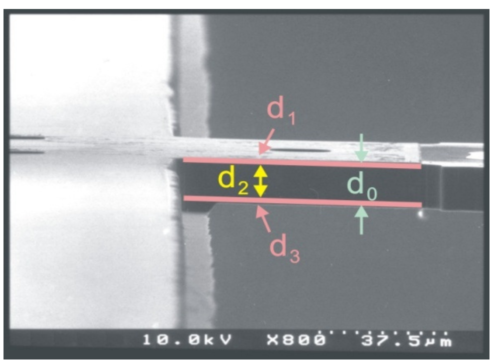
Goal: rendez-vous with comet „Churyumov-Gerasimenko „

ETA: Mai 2014



images taken from http://www.dlr.de/DLR-Rosetta/





+ measurement of reflectance and transmission spectra as well as mode profiles

+ theoretical model calculations (1D, up to quasi 3D)

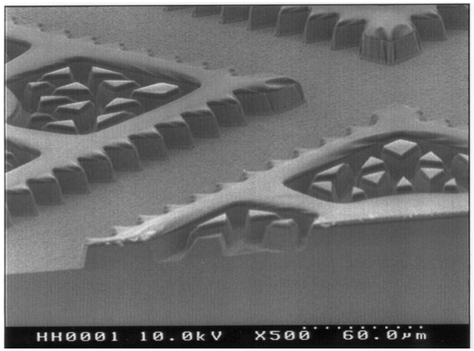
+ line-shape fitting and parameter extraction

e.g.

variation of parameters d_1, d_2, d_3 to achieve optimum agreement

Motivation VI
Ultra-bright LEDs

optoelectronic devices

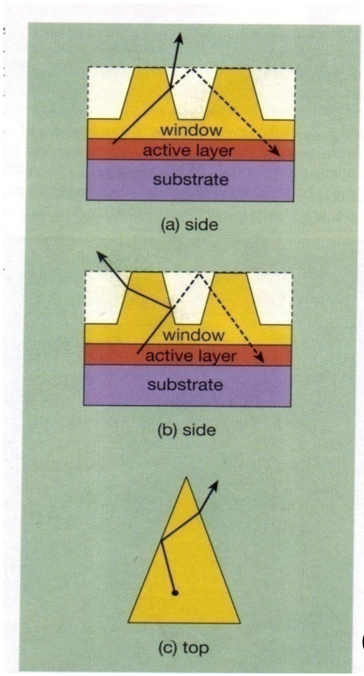


Technological Implementation:

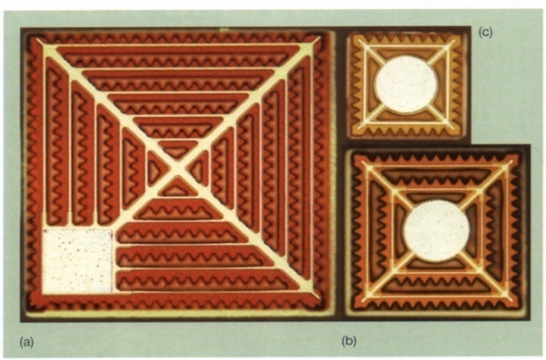
Reactive Ion-Etching (RIE)

(INA Kassel for OSRAM)

improved
light - extraction



OSRAM



Different models

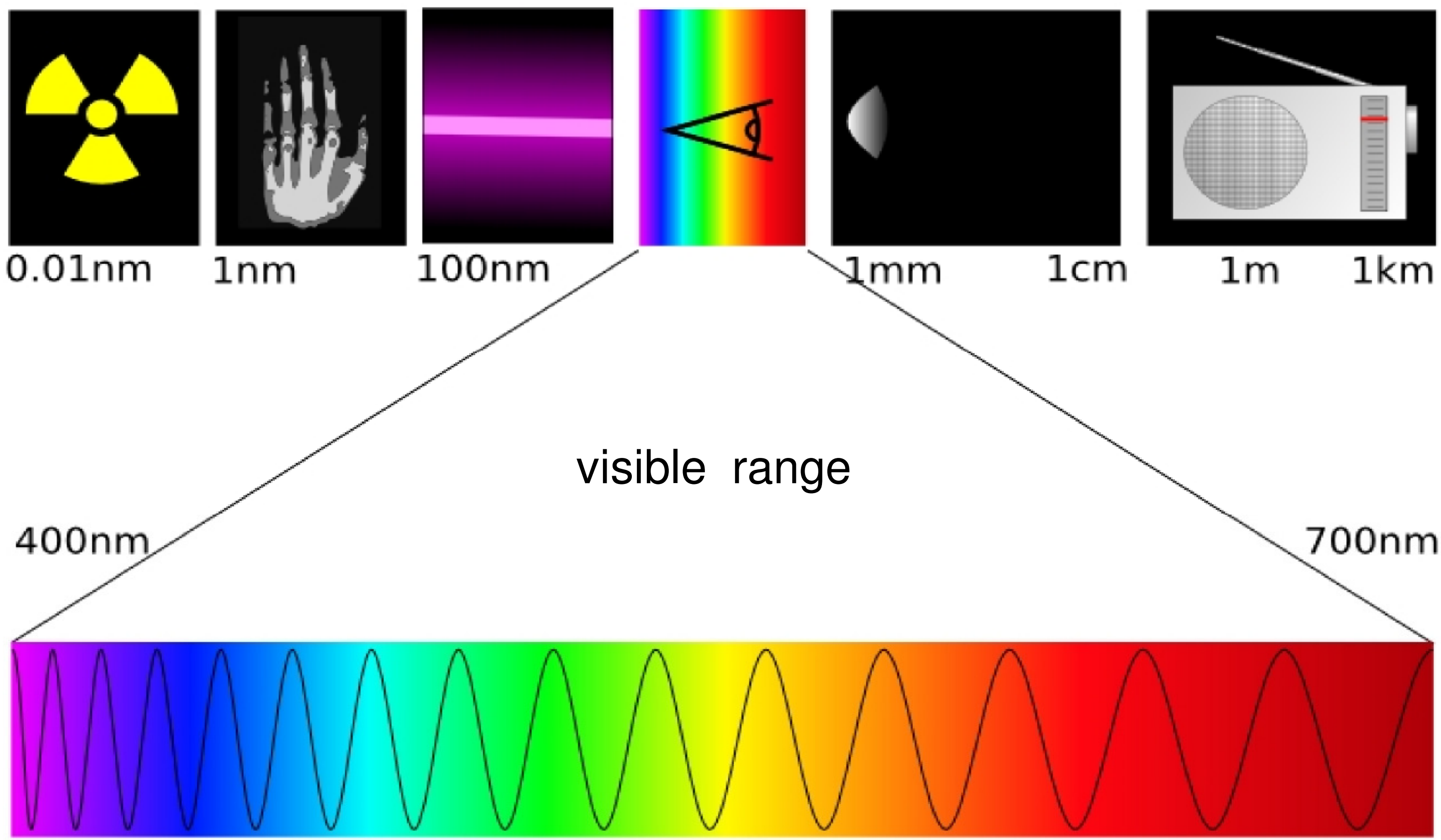
(top-view)

OSRAM

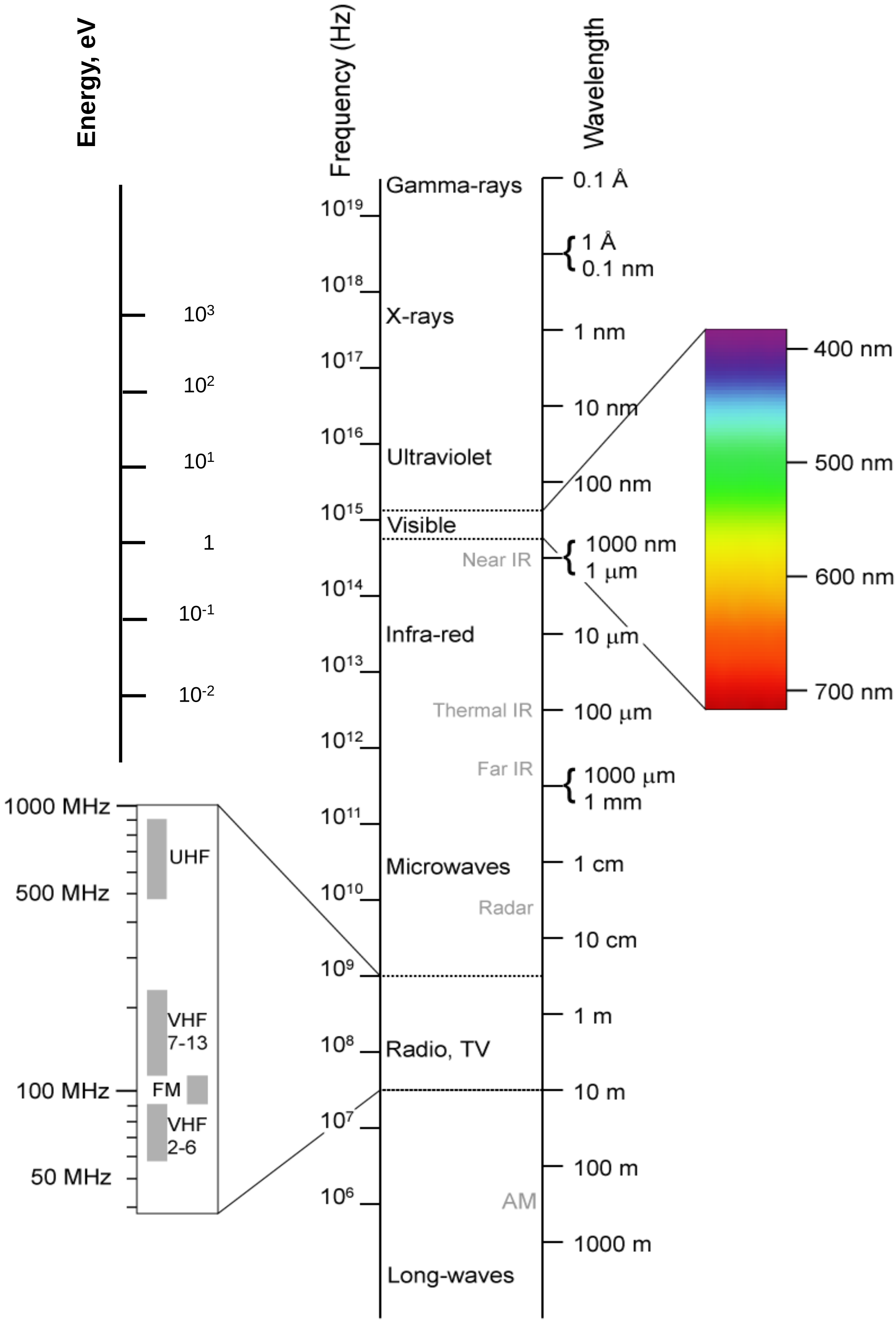
Chapter 2

General requirements on information transmission

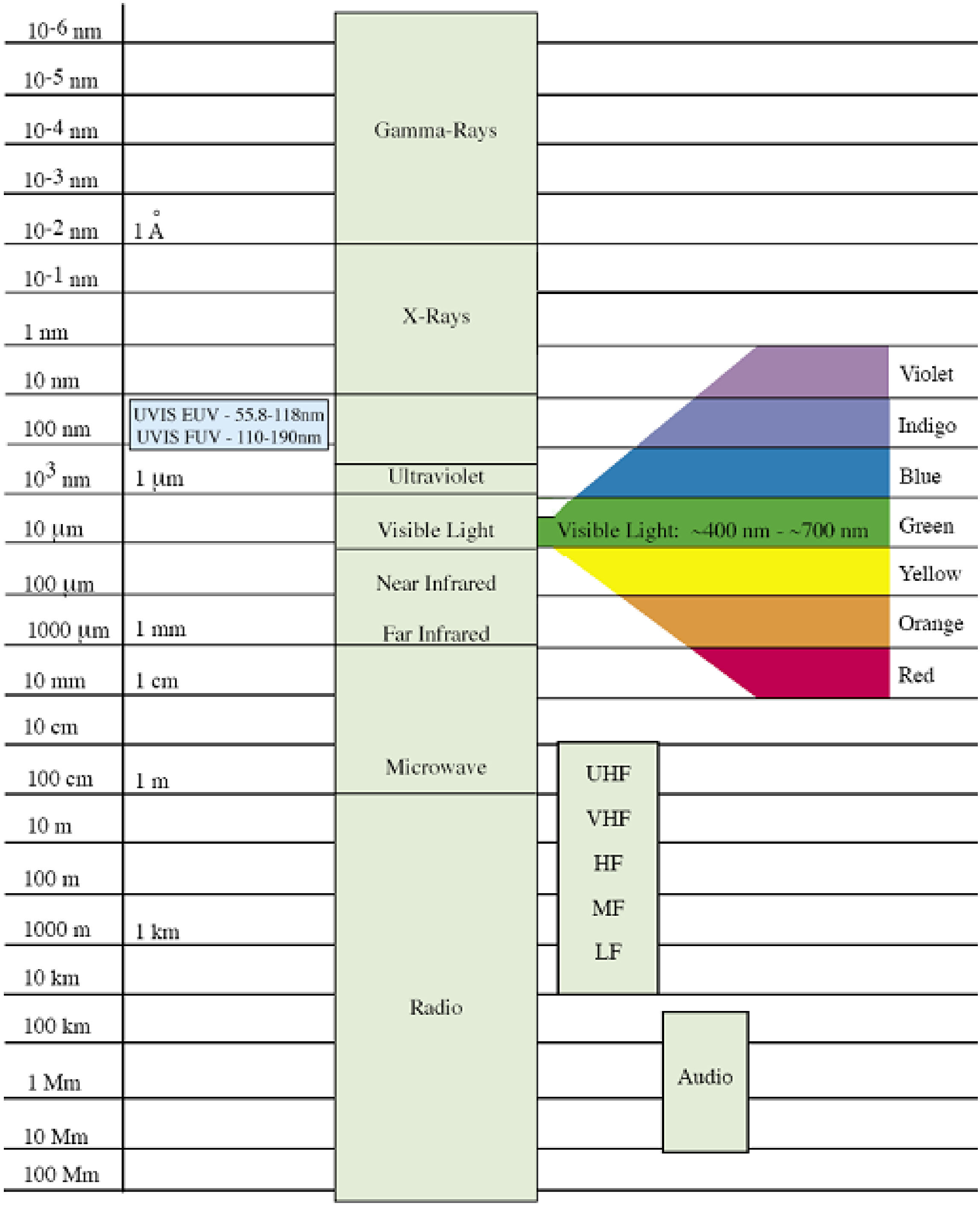
The electromagnetic spectrum



The electromagnetic spectrum

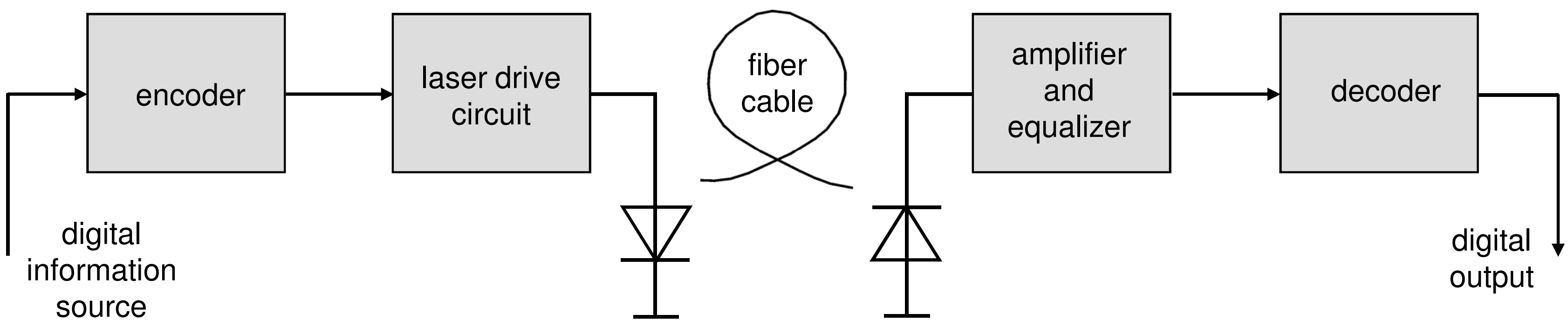


The electromagnetic spectrum

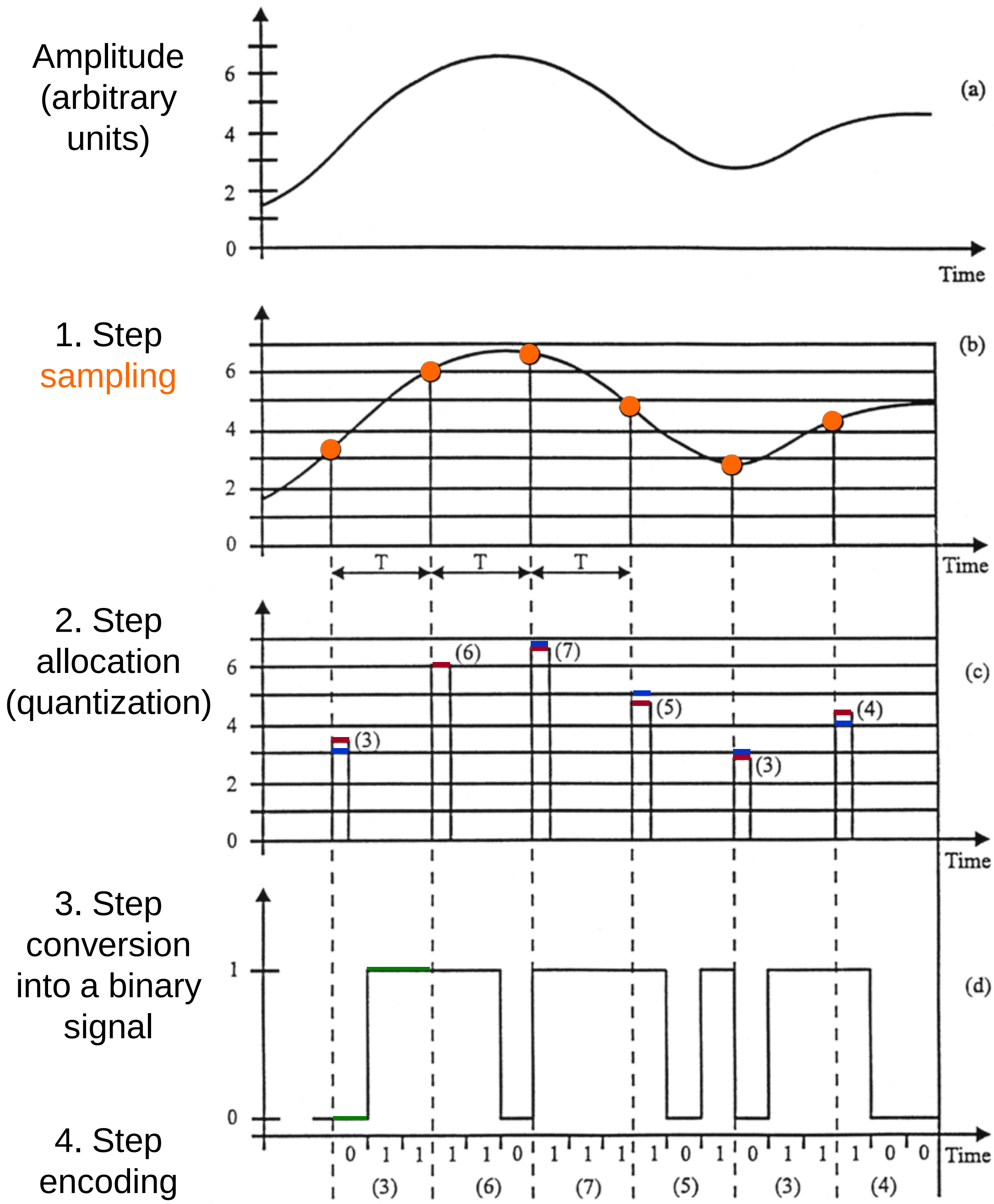


nm=nanometer, Å=angstrom, µm=micrometer, mm=millimeter,
cm=centimeter, m=meter, km=kilometer, Mm=Megameter

Schematic set-up of an optical fibre communication system



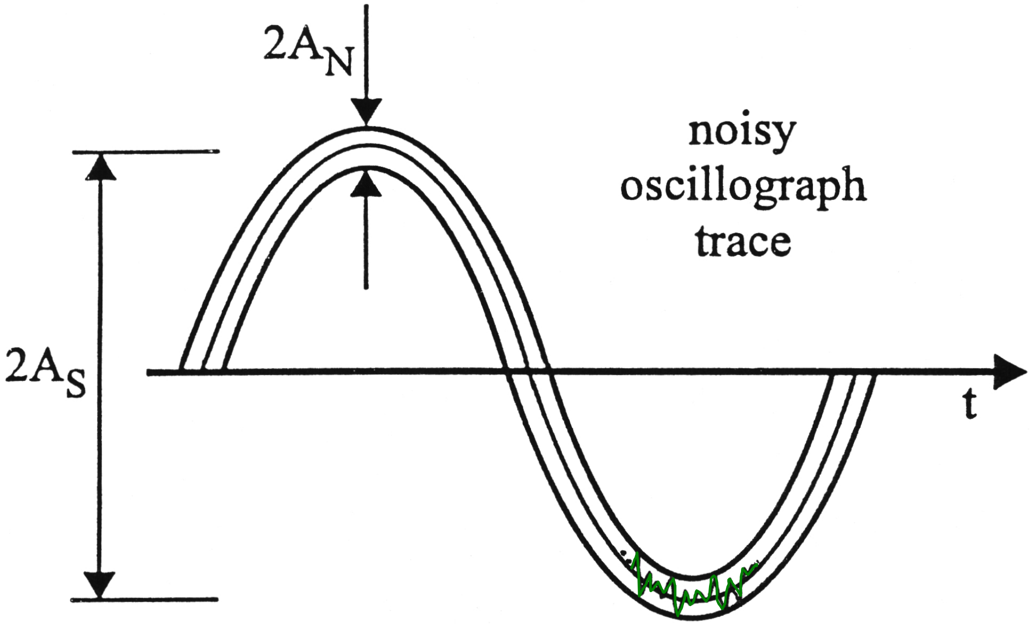
Conversion of an analog signal into a binary digital signal



Steps in the conversion of an analog waveform into a binary digital signal:

1. Part of an analog waveform
2. Analog waveform sampled at time intervals of T
3. The sampled waveform showing allocation of amplitude to one of $2^3 = 8$ levels
4. Sampled information converted to binary digital form with 3 bits / sample

Noisy waveform



Signal-to-noise ratio (dynamic range) $= \dfrac{A_S}{A_N}$

Required number of quantized levels
→ smallest integer larger or equal to

$$m = \left\lceil \frac{A_S}{A_N} \right\rceil$$

Required number of binary digits to encode the signal

$$M = \log_2 m$$

To guarantee that quantization noise ≤ original noise of the waveform:

$$\boxed{B = f_{\max} \cdot \log_2\left(1 + \frac{A_S^2}{A_N^2}\right)} = \text{minimum number of bits/s required}$$

is called shannon criterion.

describes
- minimum bit rate to digitally transmit an analog
  waveform without excessive quantization noise
- channel capacity

Requirements on information transmission

Sampling Theorem

$f_{Sampling} = 2\, f_{max}$

Shannon criterion

$$B = f_{\max} \cdot \log_2\left(1 + \frac{A_S^2}{A_N^2}\right) = \text{minimum number of bits/s required}$$

Examples

Examples for the information contents of written text, voice, video signals

Example 1. **Printed book 250 pages ≈ 10^5 words, in average 5 letters per word**

ASCII code (each letter is represented by 7 binary digits)

7 x 10^5 x 5 = 3.5 Mbits

Example 2. **Telephone (speach channel)**

Our speech includes frequencies from 300 Hz ... 3.4 kHz

→ normal tel. channel is specified with a bandwith of 3 kHz

S/N = 30 dB (A_S / A_N = 31.6) is required

Nyquist and shannon criteria require:

a. information rate B = 0.332 x 30 x 3000 = 30 kbit /s

b. encoding of e.g. 5 bits per sample

c. minimum sampling frequency = 6 kHz

However in practice: 64 kbit /s, analog waveform is sampled at f_{Sample} = 8 kHz, each sample is encoded into an 8 bit word.

Example 3. **Fabricating an ADD compact disc from a historic recording**

50 min music, signal bandwidth = 20 kHz (what a human ear can detect)

dynamic range 80 dB (e.g. a symphony by L.v. Beethoven)

Encoding: 14 bits per sample, f_{Sample} = 44.33 kHz

→ B = 620 kbit / s

→ total information content = 60 x 50s x 620 kbit/s = 1.86 Gbit

Today more bits per sample are used.

Example 4. **Video film (movie), (625 line PAL color TV signal)**

required f_{Max} 5.5 MHz, S/N = 50 dB for good quality

→ min. information rate B = 0.332 x 50 x 5.5 x 10^6 = 91 Mbit /s

100 min movie : → total information content 550 Gbit

Encoding is satisfactory using 8 bits per sample

$f_{Sampling}$ = n x 4.43 MHz = e.g. 17.7 MHz (n an integer)

→ B = 8 x 17.7 = 142 Mbit /s

However in most movies only a small fraction of the picture changes from frame to frame.

→ considerably reduction in the encoding

→ not too fast changing sceneries can be satisfactorily transmitted at 2 ... 10 Mbit/s

Example 5. **Movie on DVD,**

100 min movie : → total information content 4.7 GB (4482 Mbyte)

for video and audio; audio standard date rate 256 Kbit/s :

256 Kbit/s * 60 s/min * 100min =1536000 Kbit (= 187,5 Mbyte)

residual content for video : 4482 Mbyte - 187,5 Mbyte – 100Mbyte (safety margin) = 4194,5 Mbyte

4194,5 * 8 * 1024 / 6000 = 5715 Kbit/s date rate for video

→ B = 5,9 Mbit/s medial bit rate

Example 6. **Movie on blue ray discs**

100 min movie : → total information content 25 GB (23841 Mbyte)

for video and audio; audio standard date rate 256 Kbit/s :

256 Kbit/s * 60 s/min * 100min =1536000 Kbit (= 187,5 Mbyte)

residual content for video : 23841 Mbyte - 187,5 Mbyte – 100Mbyte (safety margin) = 23553,5 Mbyte

23553,5 Mbyte * 8 * 1024 / 6000 = 32158 Kbit/s date rate for video

→ B = 32 Mbit/s medial bit rate

Multiplexing techniques

= simultaneous transmission of a number of independent signals

increase of information transmission capacity

TDM

time division multiplex

Certain time slots are allocated to a certain signal

e.g. 30 telephone signals (64 kbit/s) can be transmitted over a channel of 2.048 Mbit/s capacity

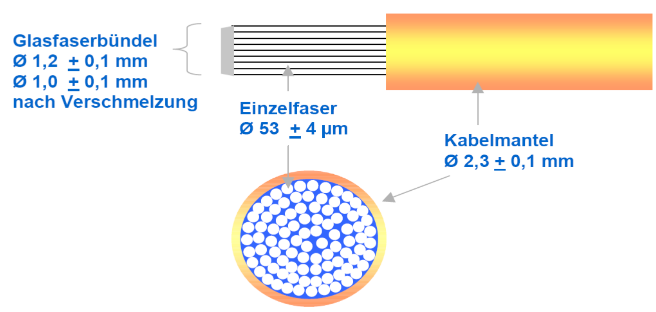
WDM

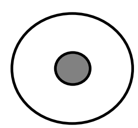
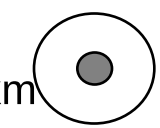
wavelength division multiplex

(unique for optical communication) various signals are transmitted at diff. wavelength (colours) across the same fibre

SDM

space division multiplex



Advantages of optical systems	Compared to electrical systems
1. larger bandwidth optical frequency ~ 10^{14} Hz (NIR) theoretical limit ~ 50 THz today : 10 Gbit/s (practice), 20 - 60 Gbit/s (research) attenuation in optical fibres much less → considerably larger distances between repeaters	Limit ~ 1 GHz (attenuation ↑ with f ↑) than in coaxial cables
2. material : glass or polymers → small size and weight interesting for mobiles (cars and aircrafts)	Material : copper
3. no potential problems (since insulators)	Serious potential problems
4. no interference or crosstalk between neighbor fibres (no shielding required)	Interference or crosstalk
5. Nearly perfect signal security	Weak signal security
6. low transmission loss 0,18 dB/km (1,55 µm) independent of modulation frequency  For single mode fibre	20 dB/km  at 100MHz For core diameter 3,3 µm; cladding diameter 18,5 µm

Chapter 3

Fundamental principles in optics

Four key phenomena

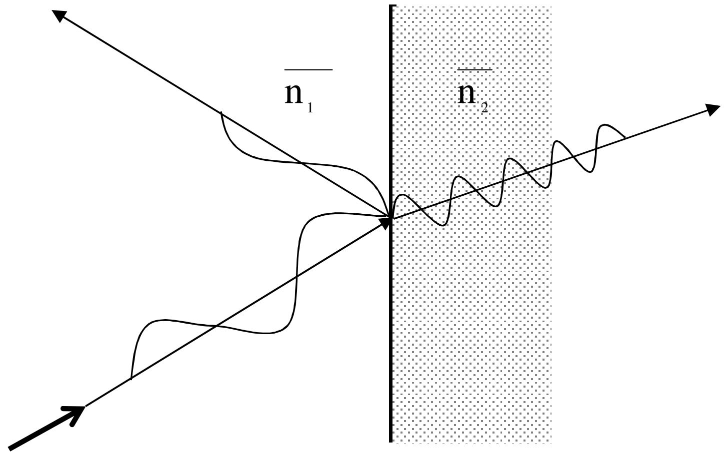
which are important
if electromagnetic waves are superimposed :

- Polarization
- Interference
- Diffraction
- Coherence

Example : let us consider a semiconductor crystal

a) $\lambda >> a$ lattice constant of the crystal ($a \approx 0.3$ nm)

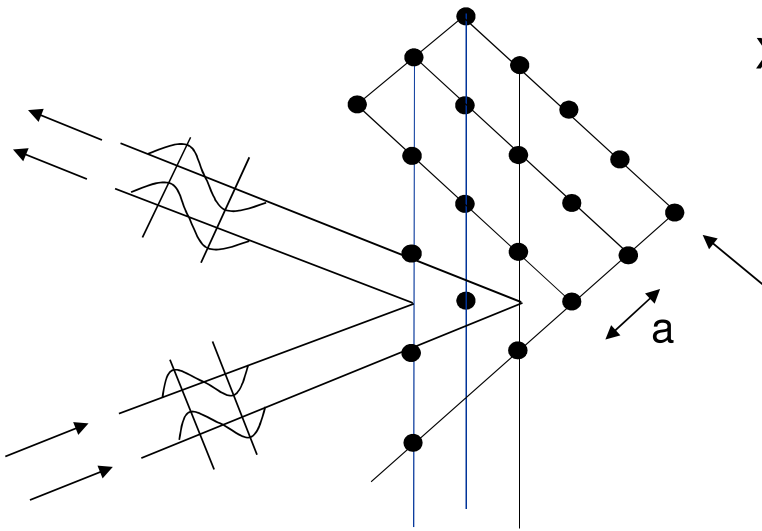
Light wave experiences (feels) a continuum $\longrightarrow$ the optical density of the medium is described by an averaging refractive index $\overline{n}$



$$\overline{n}_1 < \overline{n}_2$$

Phase velocity is different

b) λ (X – rays) $\lesssim$ a lattice constant of the crystal

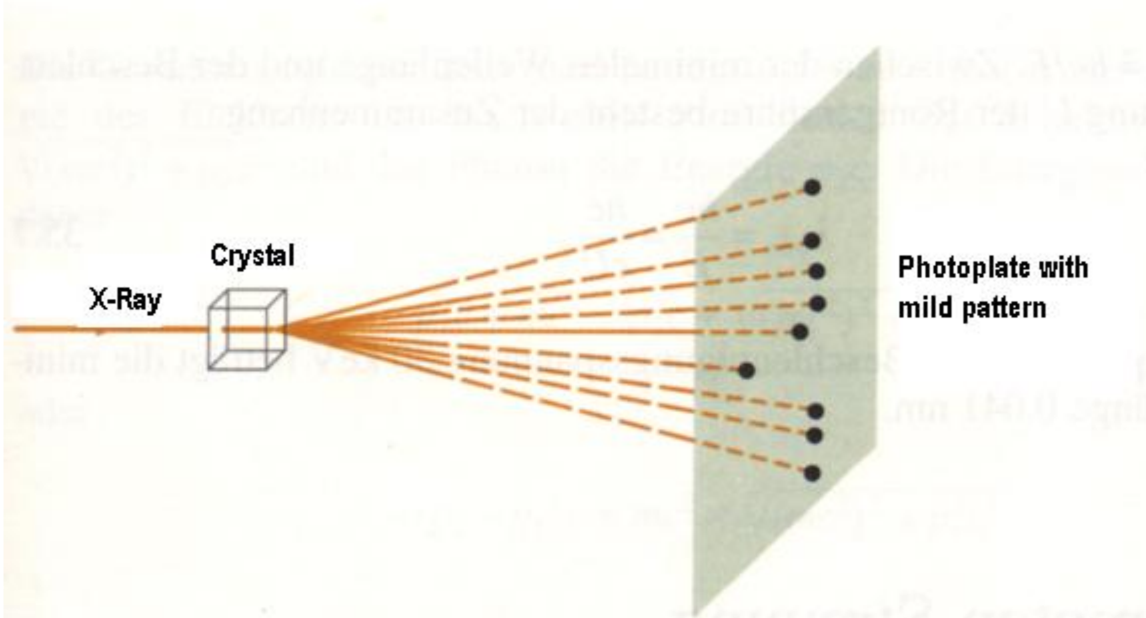


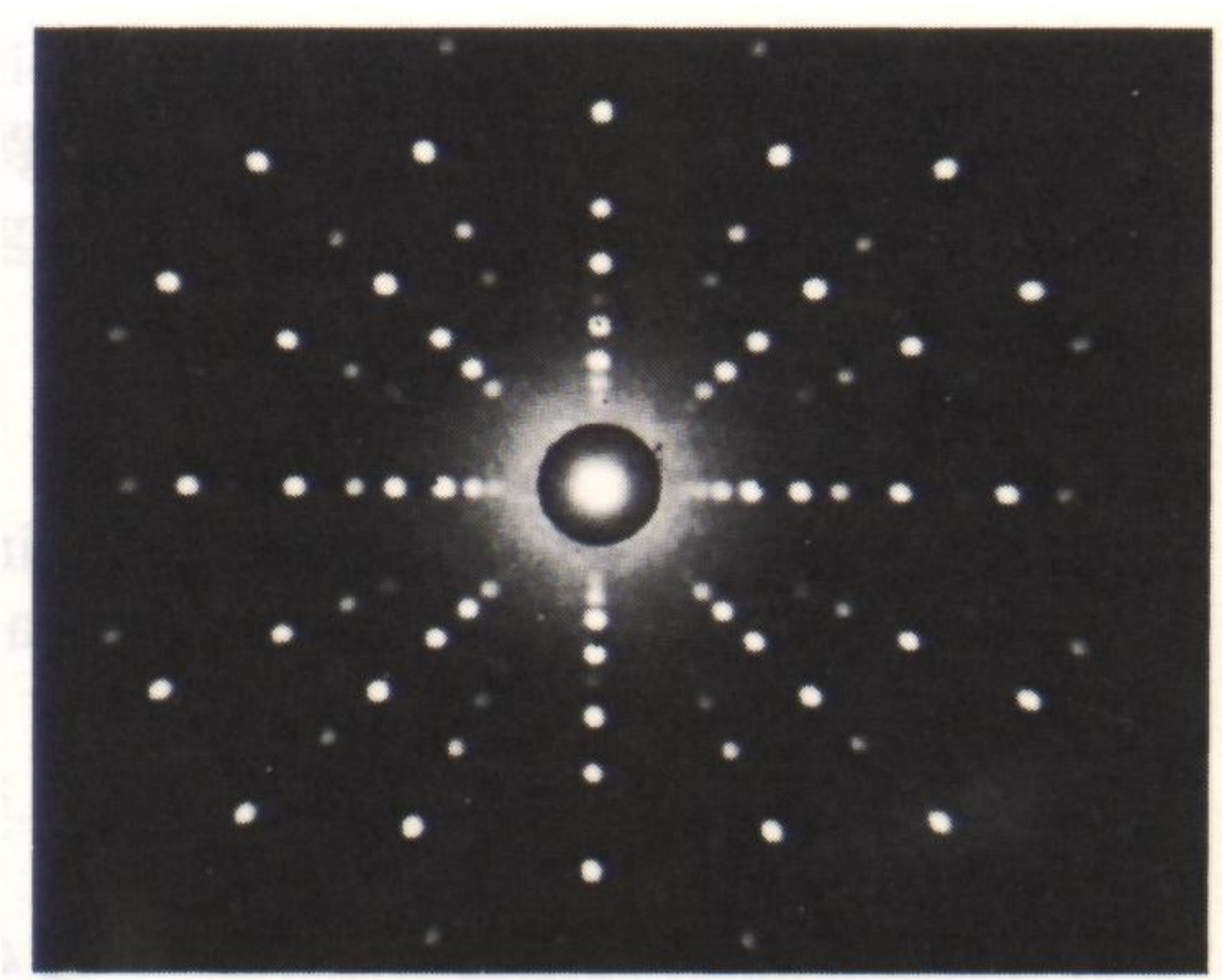
X –ray diffraction

surface of the crystal

phase velocity not different

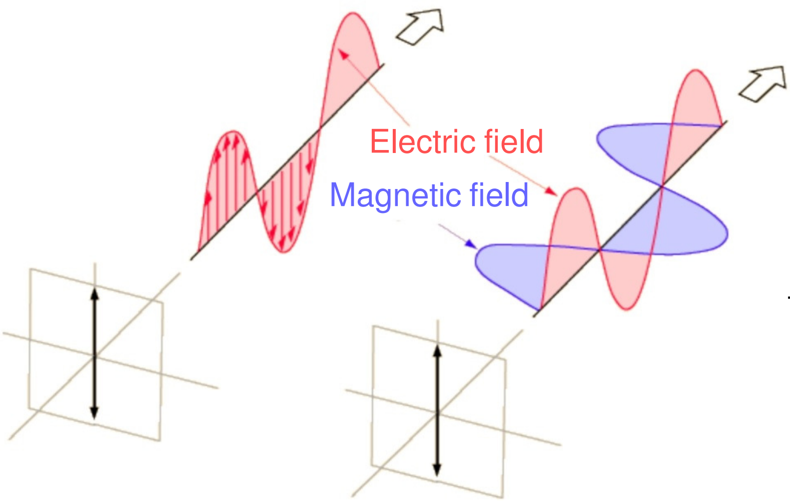
Diffraction pattern



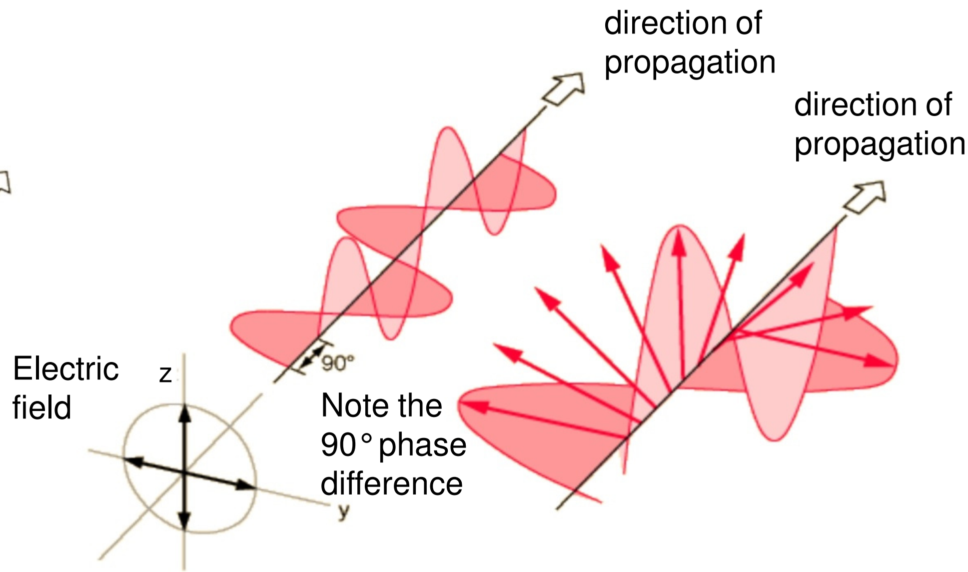


Classification of Polarisation

linear

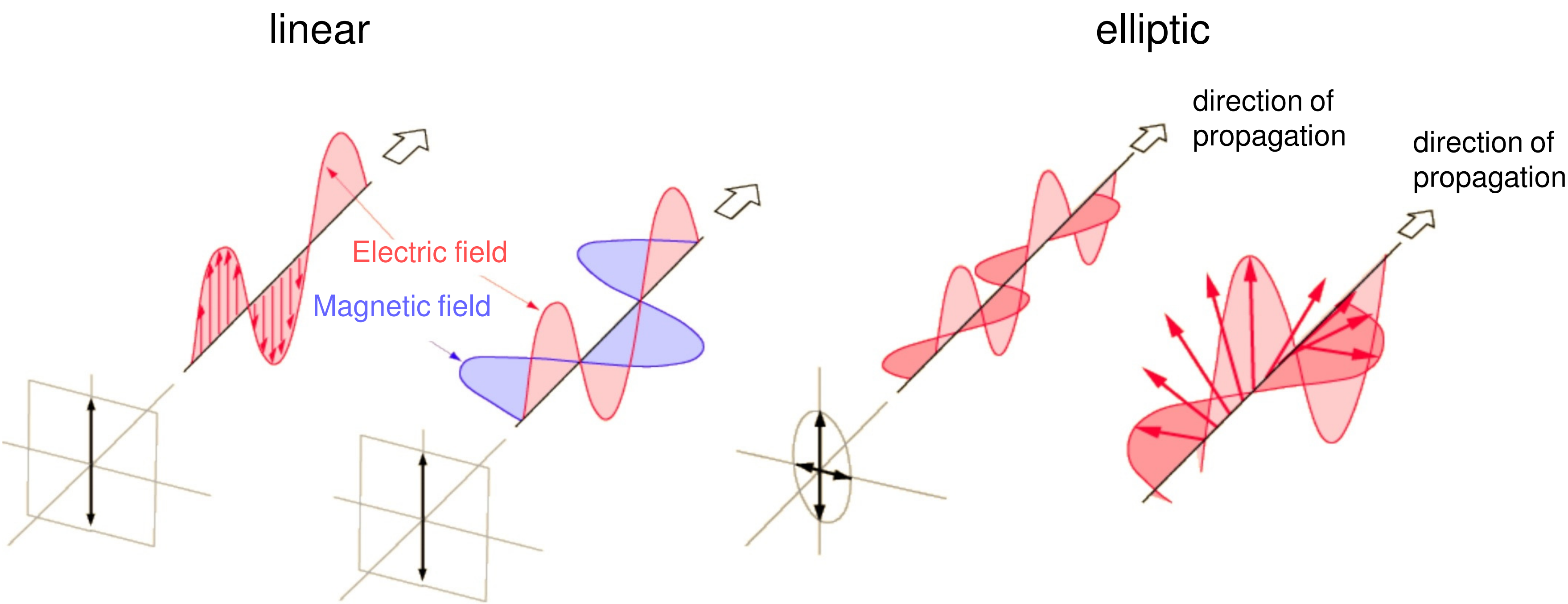


circular



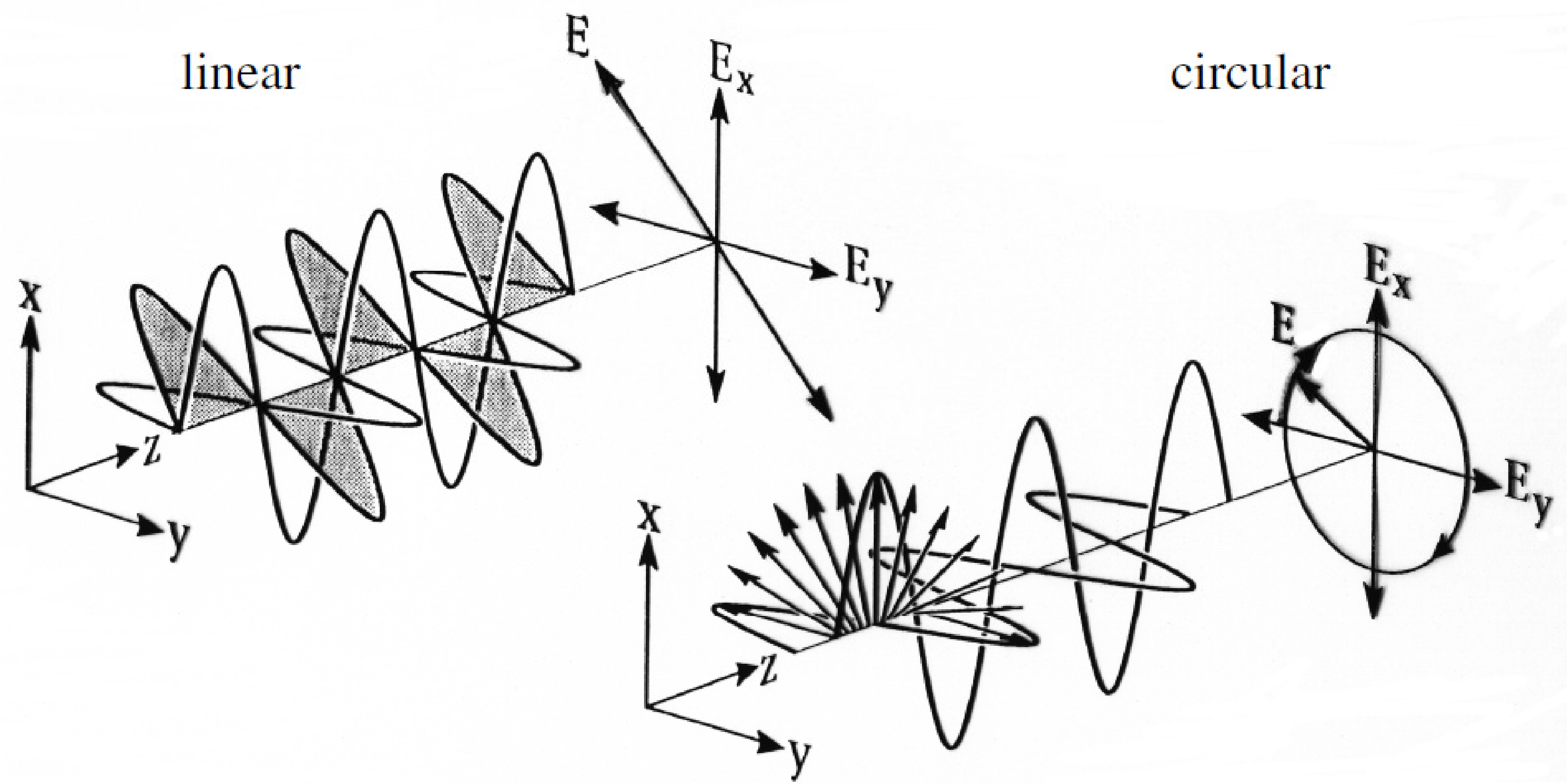
If this wave is approaching an observer, its electric vector would appear to be rotating counter clockwise. This is called right – circular polarisation.

Classification of Polarisation



If this wave is approaching an observer, its electric vector would appear to be rotating counter clockwise. This is called right – elliptic polarisation.

Polarisation III



0 ← phase difference → Π/2 , 3Π/2 (elliptical polarisation: if the 2 wave have different amplitude)

Implementation of polarisation : by polarizers

Rotation of polarisation : e.g. quarter-wave plate

Interference of two waves

electric fields $E_1 = E_1(t)$, $E_2 = E_2(t)$, both complex,

since $\bar{E}_1 \,//\, \bar{E}_2$ scalar properties can be considered.

< >, indicates a time average

* = conjugate complex

$$
\begin{aligned}
E_{\text{total}} &= E_1 + E_2 \\
I_{\text{total}} &\sim <|E_{tot}|^2> = <E_{tot.} E^*_{tot.}> \\
&= <(E_1+E_2)(E_1+E_2)^*> \\
&= <(E_1+E_2)(E_1^*+E_2^*)> \\
&= <E_1E_1^*> + <E_1E_2^*> + <E_2E_1^*> + <E_2E_2^*> \\
&= <|E_1|^2> + <2\,Re\{E_1E_2^*\}> + <|E_2|^2> \\
&= I_1 + <2\,Re(E_1E_2^*)> + I_2
\end{aligned}
$$

$I_1 = I_2$, $\bar{E}_1$ indicates the amplitude

Often a superposition of a wave with itself after a retardation τ occurs :

$$
\begin{aligned}
E_1(t) &= \hat{E}_1 \exp(-j\omega t), \\
E_2(t) &= E_1(t+\tau) = \hat{E}_1 \exp(-j\omega(t+\tau)),
\end{aligned}
$$

$$
\begin{aligned}
I_{\text{total}} &\sim <|E_1+E_2|^2> \\
&= <|E_1|^2> + <|E_2|^2> + 2\cdot <Re\{E_1E_2^*\}> \\
&= <|E_1|^2> + <|E_1|^2> + 2\cdot <|E_1|^2> \cdot \\
&\cdot <Re\{\exp(-j\omega t)\cdot\exp(j\omega t)\cdot\exp(j\omega\tau)\}> \\
&= 2I_1 + 2I_1\,Re\{\exp(j\omega\tau)\} \\
&= 2I_1 + 2I_1\cos(\omega\tau) \\
&= 4I_1\cos^2\frac{\omega\tau}{2}
\end{aligned}
$$

The resulting interference pattern is $\cos^2$ – like

Maximum intensity = $4\,I_1$

Minimum intensity = 0

Average intensity = $2\,I_1 = I_1 + I_2$ according to energy conservation

Coherence I

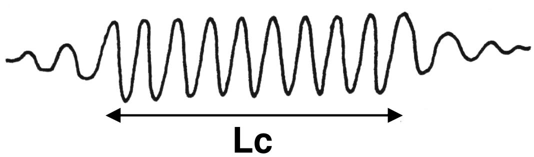
for a good efficiency of diffractive elements: coherence length of the light very important

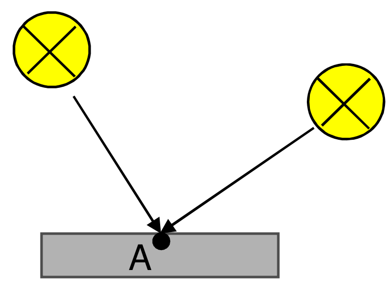
L_C = length of wave packet in which a fixed phase relation exists (no phase jumps within the coherence length).

→ the more monochromatic the longer L_C

light interferes if
- temporal coherence
- spatial coherence

is fulfilled



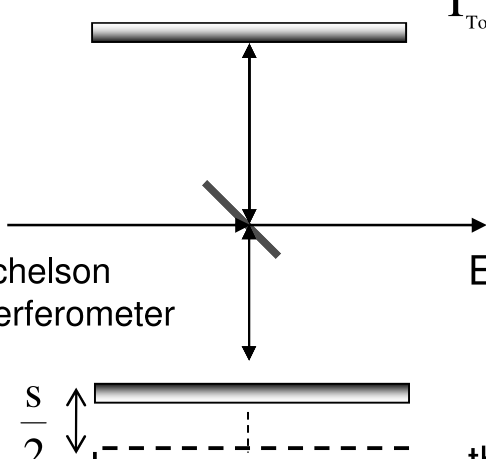


Characteristic for incoherence

if $I_{total} = I_1 + I_2$ in point A

Characteristic for coherence

$$I_{Total} = I_1 + I_2 + \underbrace{2 \cdot \sqrt{I_1 \cdot I_2} \cdot \cos\left(\frac{2\pi \cdot s}{\lambda} + \Delta\varphi \right)}_{\text{interference term}}$$



Michelson Interferometer

Enables to measure coherence length L_C

maximum possible path difference so that interference still occurs $\frac{L_C}{2}$

Coherence II

Wave propagates with the light velocity c

→ L_C corresponds to a coherence time $\tau_c = L_C / c$

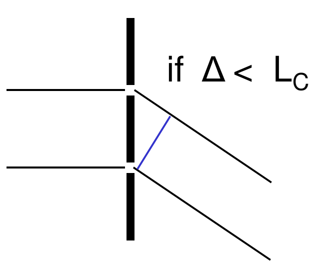
Coherence time τ_c is connected to linewidth (bandwidth) Δf via Fourier Theorem

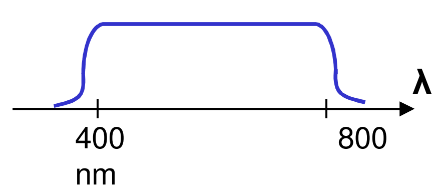
$$\Delta f = \frac{1}{2\pi \cdot \tau_C} = \frac{c}{2\pi \cdot L_C}$$

→ temporal coherence is a measure for spectral purity

Example	L_C	τ_C	**Δf / f**
Low pressure spectral lamp, Ne	3 cm	0.1 ns	$3.4 \cdot 10^{-6}$
Low pressure spectral lamp, Kr	100 m	300 ns	$1.1 \cdot 10^{-9}$
Laser, HeNe, 633 nm	500 km	1.6 ms	$2.1 \cdot 10^{-11}$
Laser, InGaAlAs / InP, 1.55 µm	60 m	200 ns	$5 \cdot 10^{-9}$

Interference with „**white light**“ ?





A) Quasi white light (finite bandwidth)

→ interference occurs since Δ < L_C (spectrometer work due to this fact)

B) Ideally white light (infinite bandwidth) → no interference Δ > L_C !

The different orders overlap completely and homogeneously

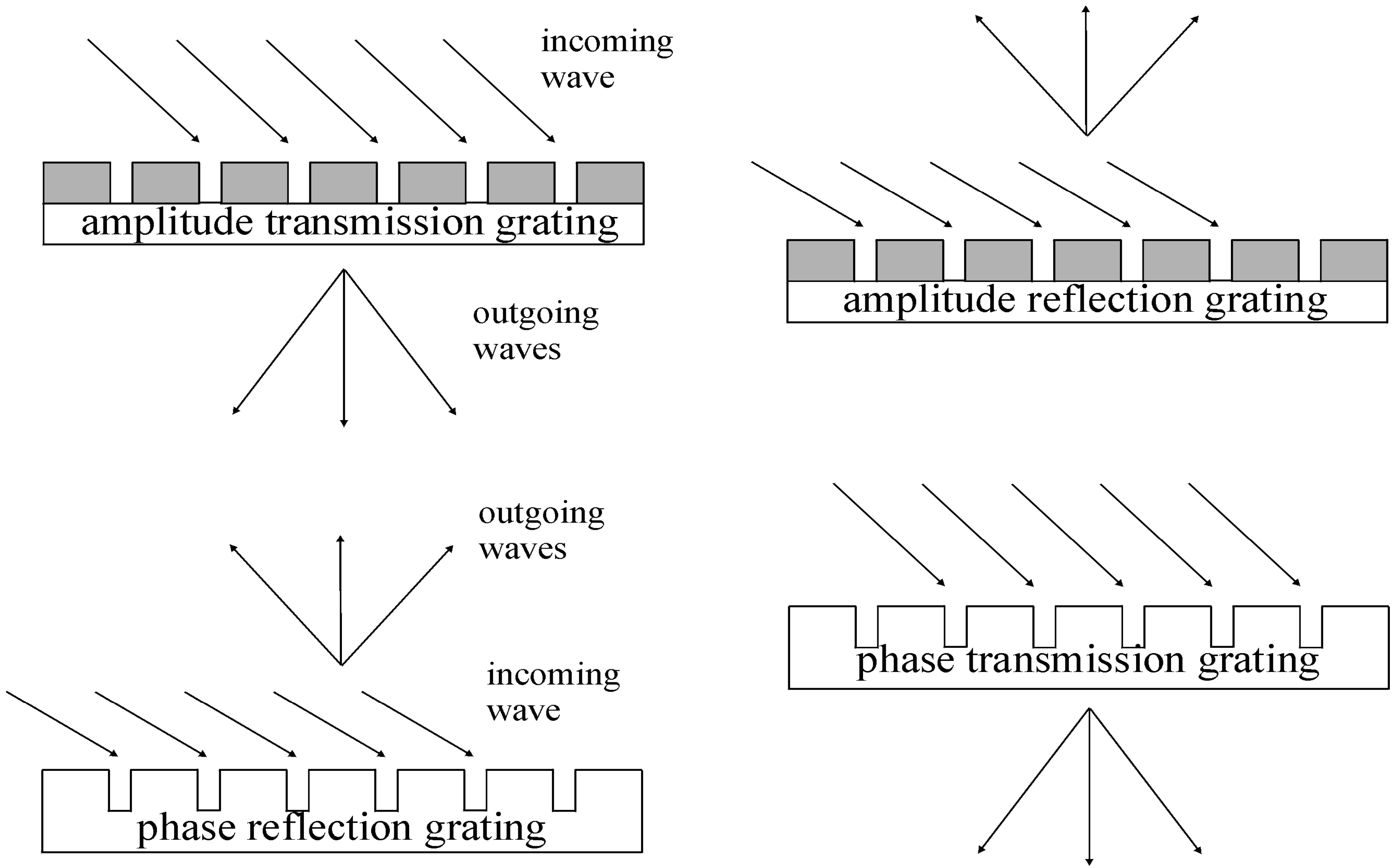
Laser type	Coherence length
Fibre laser stabilized/ unstabilized	100km / 50µm
HeNe stabilized/ unstabilized	1km / 20cm
Semiconductor Diode laser with external Resonator	0,1- 1km / < 1mm
Dye laser	5- 250m
Ar or Kr with Etalon	1m
flash- lamp pumped Nd: YAG	1cm

For temporal coherence

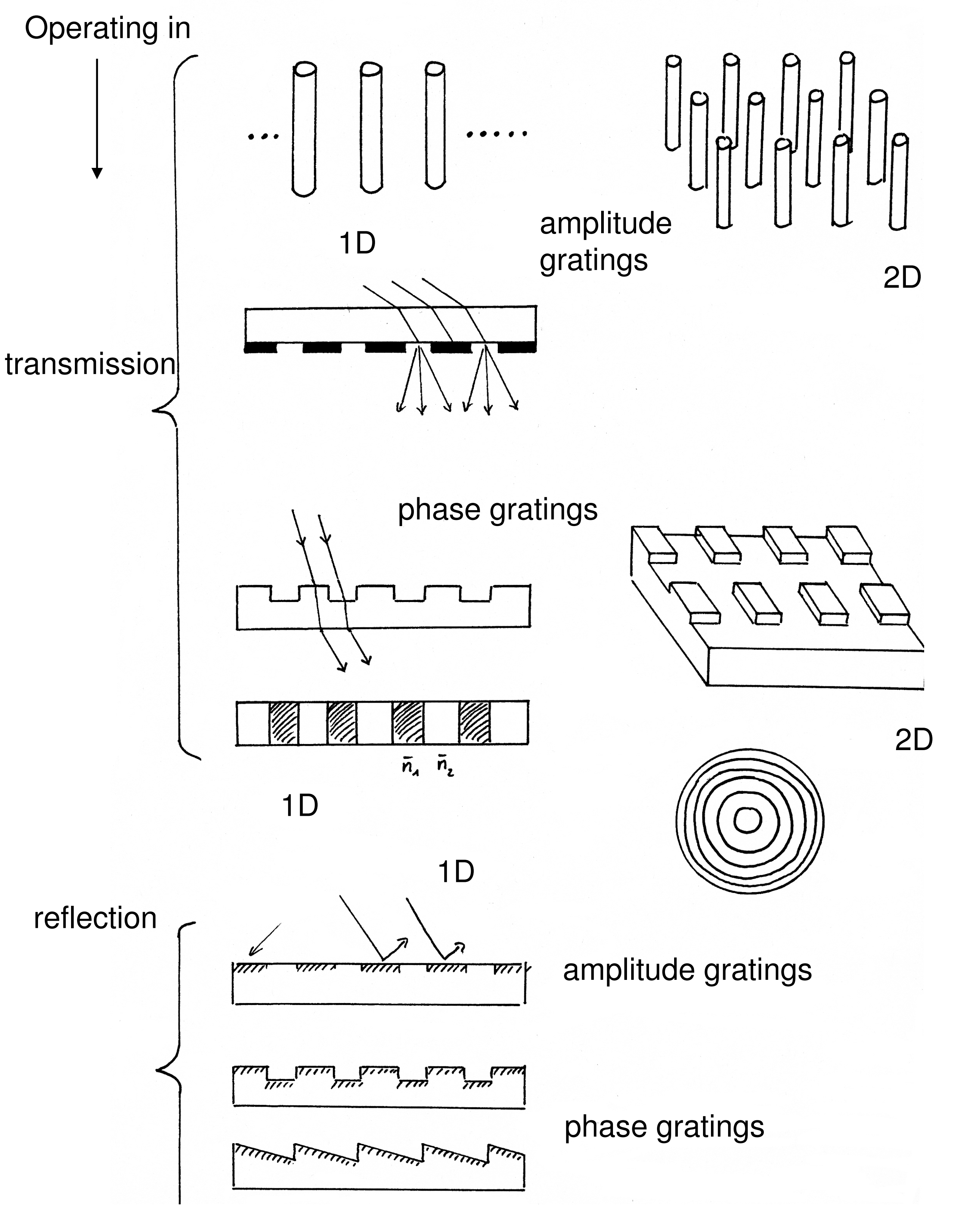
$$L_c \approx \frac{132\text{m}}{\Delta f}$$

for a Gaussian beam profile

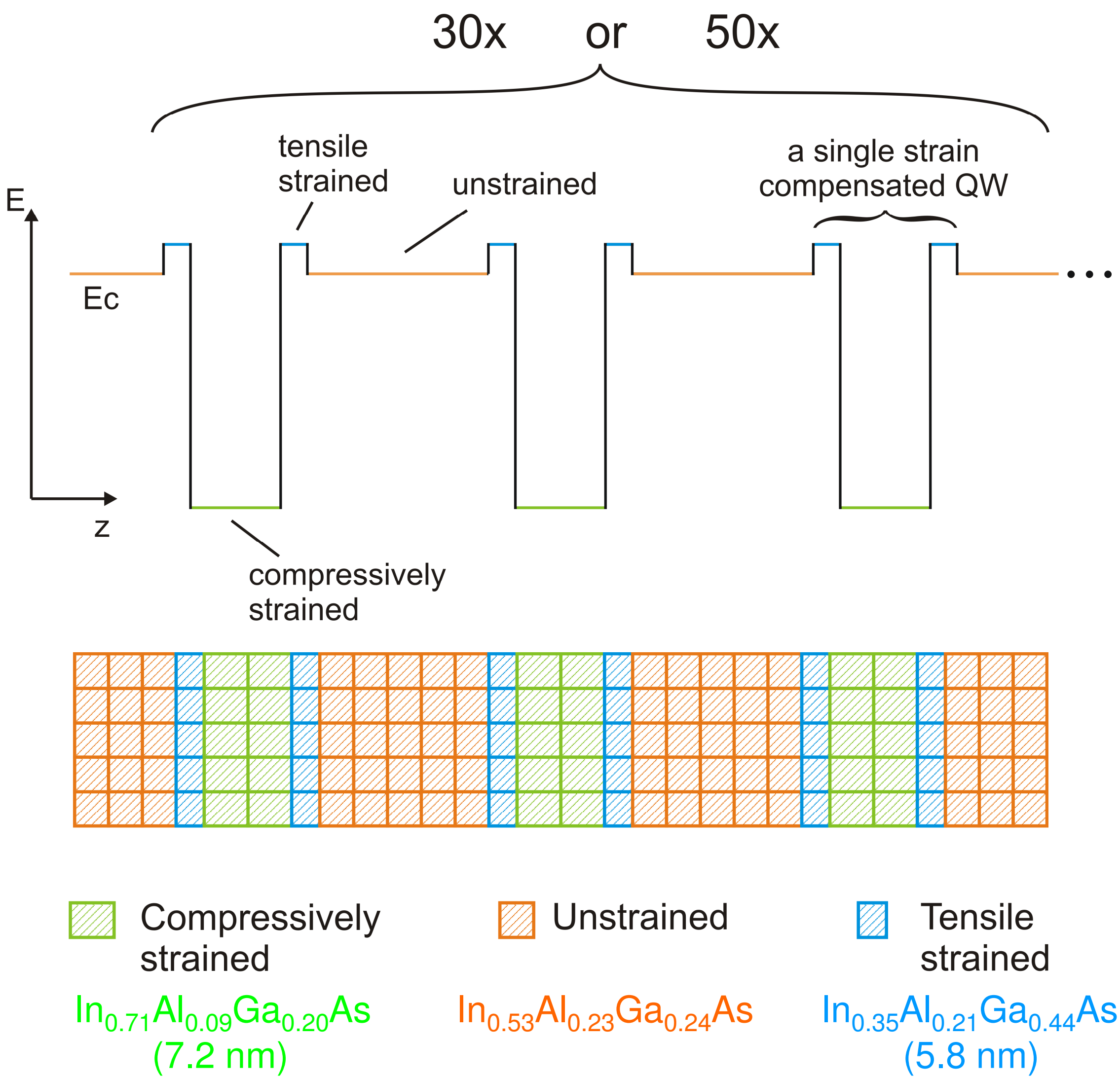
Examples of different types of gratings



Examples of gratings



X-ray diffraction (XRD) at a strain compensated multiple quantum well structure



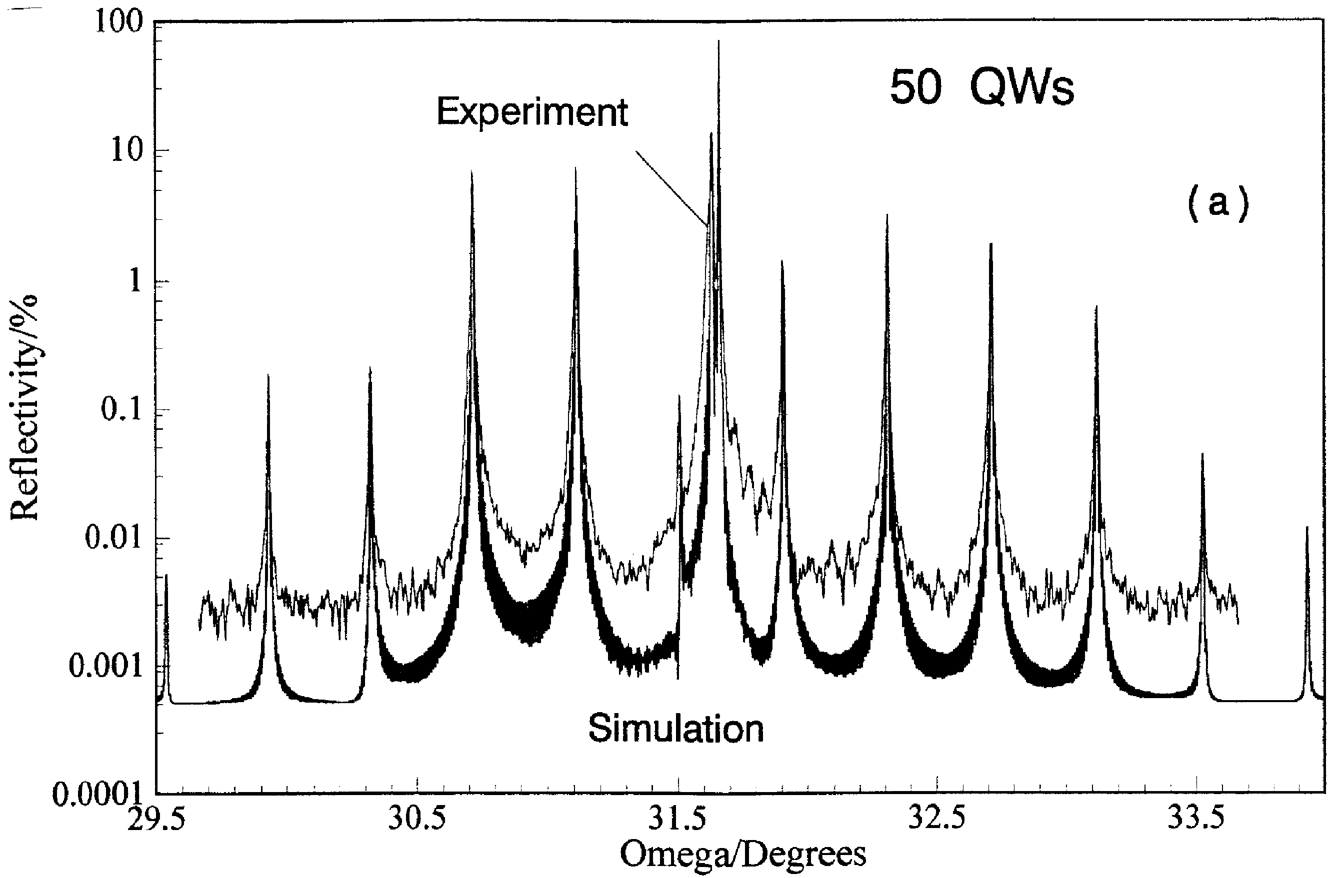
10x is used for the active layer of ultrafast semiconductor lasers

a single square represents a qubic uni cell here

For the lecture a smaller number of unit cells is displayed as in reality

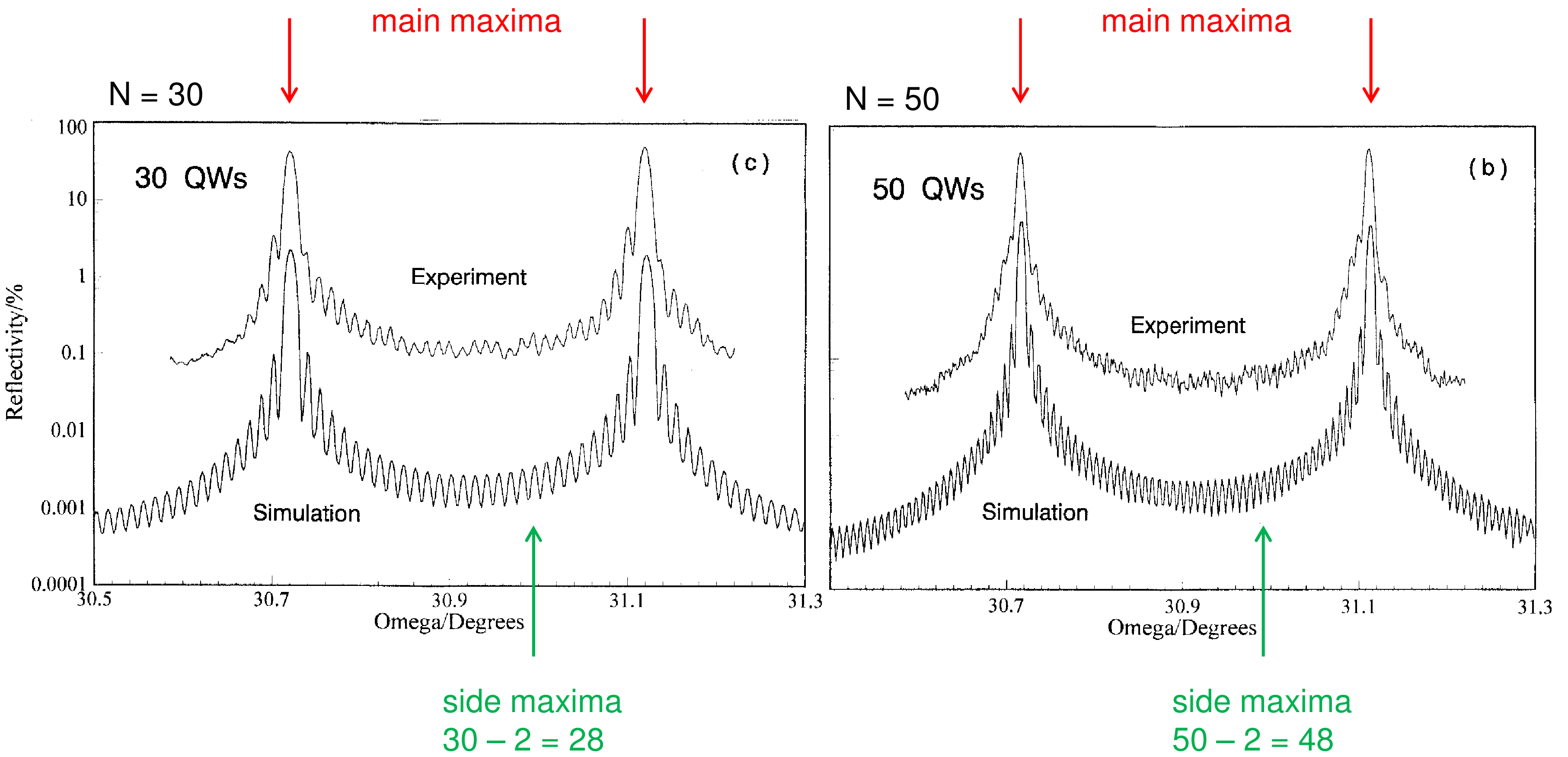
X-ray diffraction (XRD) at a strain compensated multiple quantum well structure

Rocking curve (XRD) $\hat{=}$ diffraction pattern (optics)



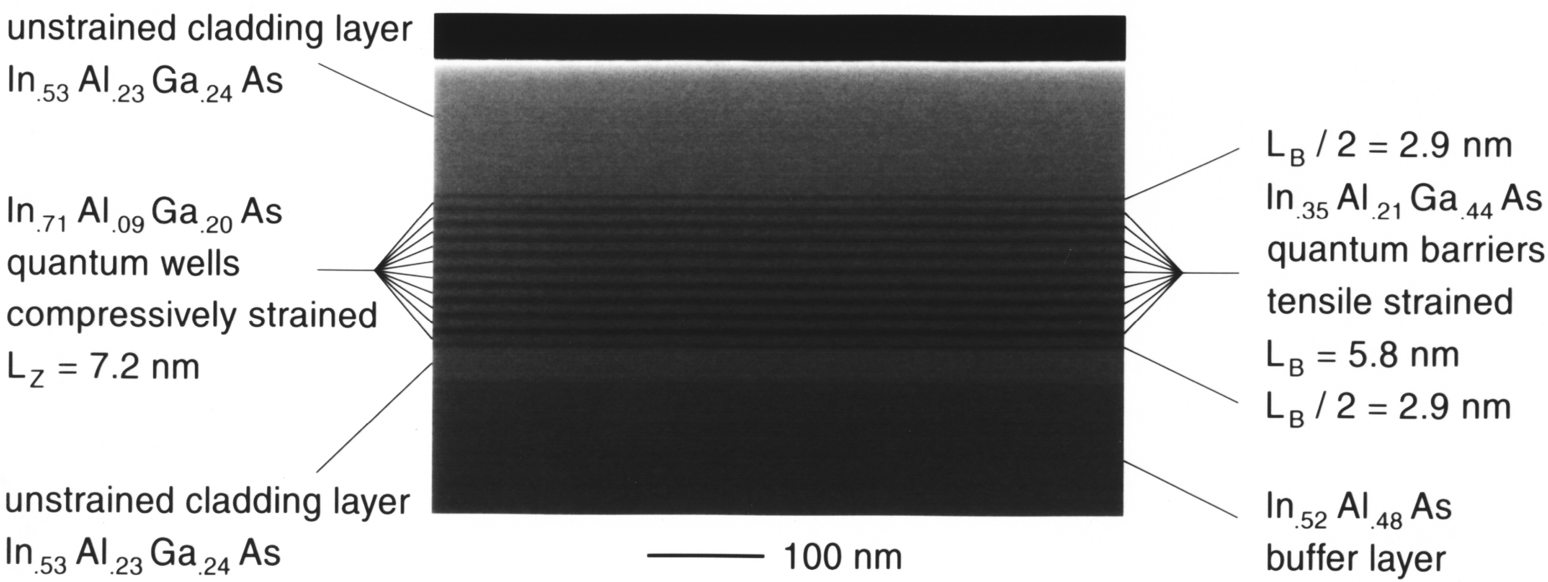
H.Hillmer
J. Crys. Growth 175/176 (1997) 1120-1125

X-ray diffraction (XRD) at a strain compensated multiple quantum well structure



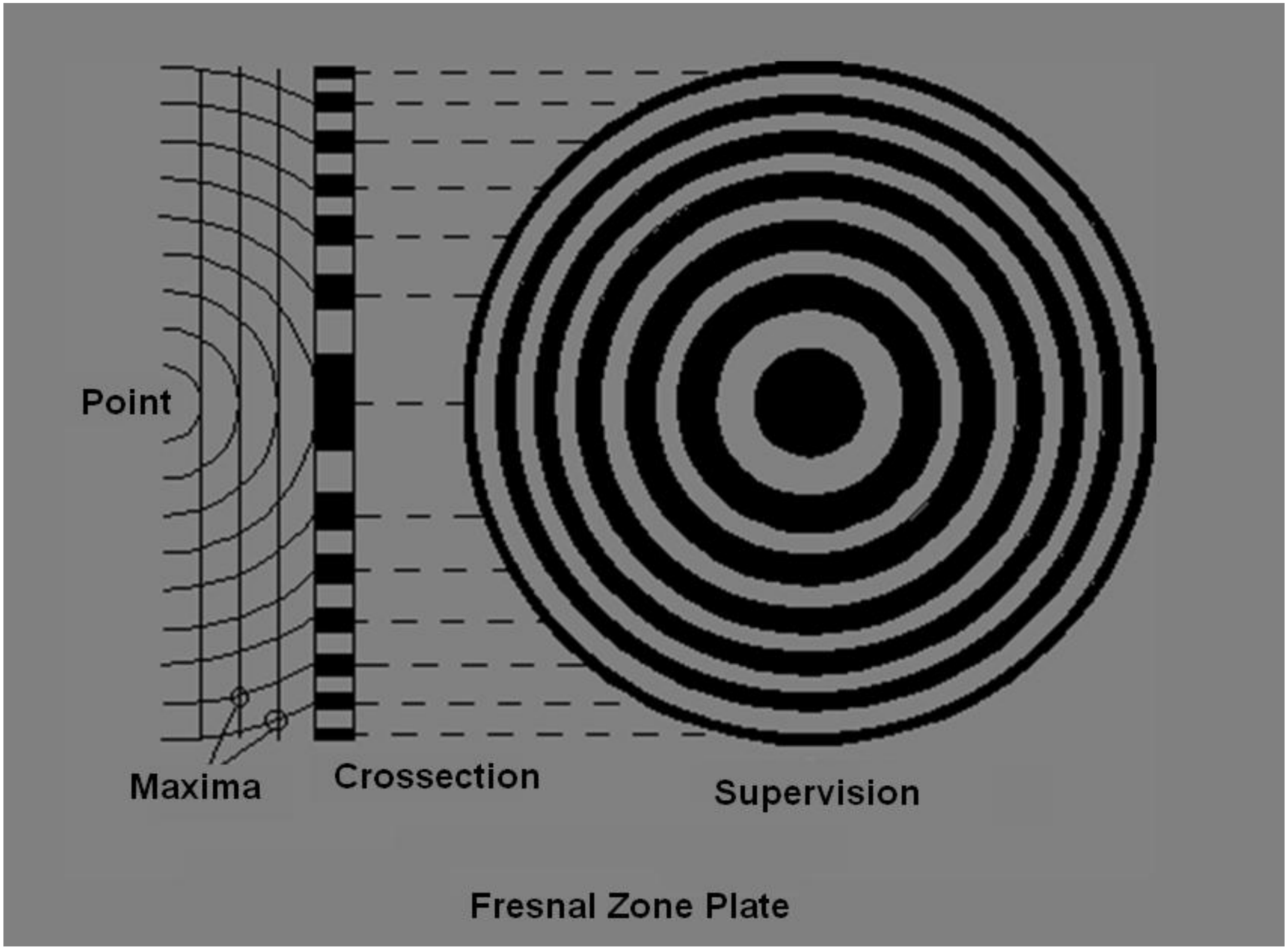
X-ray diffraction (XRD) at a strain compensated multiple quantum well structure

MBE grown strain - compensated multiple quantum well heterostructure for high - speed 1.55 µm laser diodes

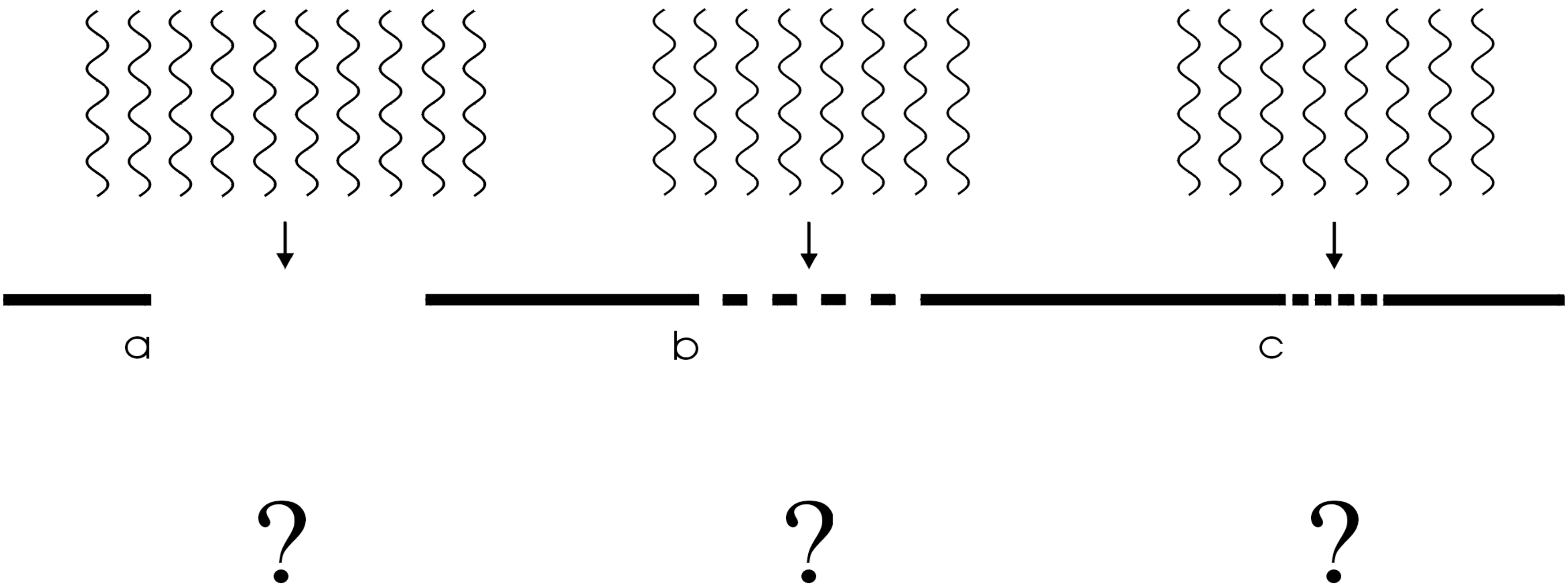


10 QWs

Fresnel Zone plate



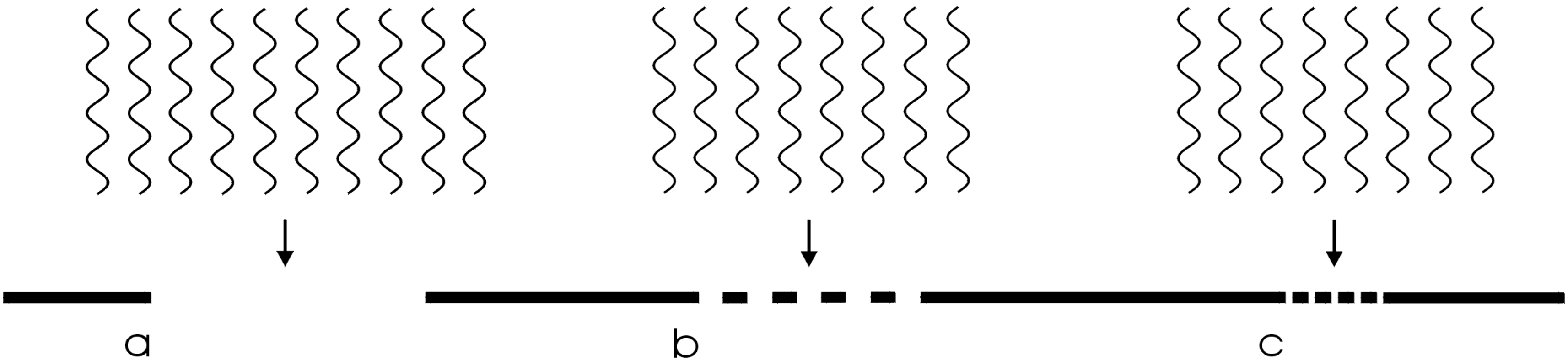
Interaction of light with objects of different size



Interaction of light with objects of different size

optoelectronic devices

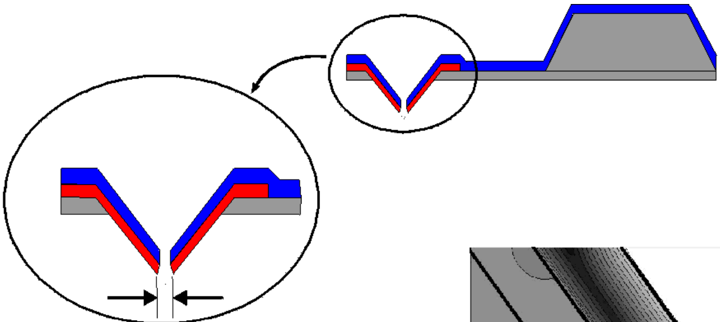
Size of structure > λ	Size of structure ~ λ	Size of structure << λ



shadows	diffraction	
Daily life	Opalescent colors in nature	Under distinct circumstances we are able to observe something
fabrication of integrated circuits (ideal case)	electron diffraction, x-ray diffraction, micro lasers, micro filters	fabrication off new synthetic materials, optical near field microscopy

Near field microscopy

Resolution << wavelength



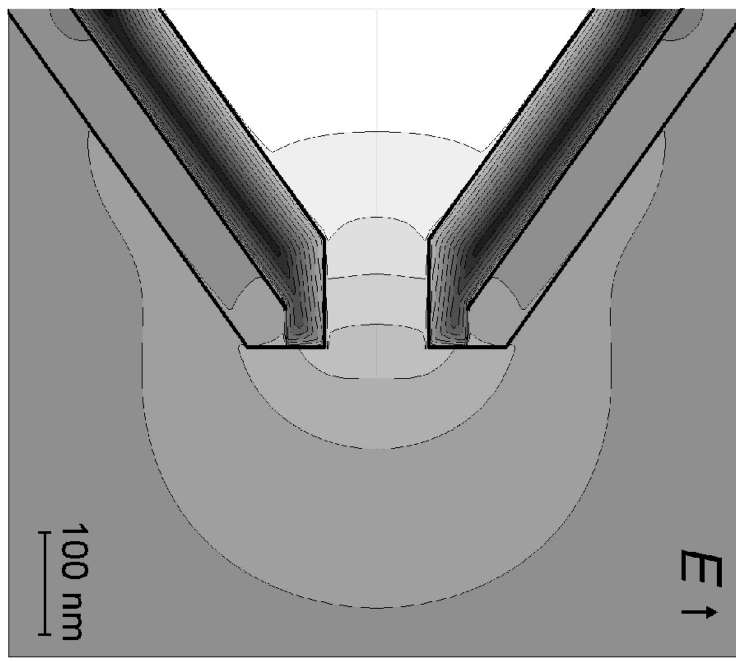
50-100nm

~~resolution~~

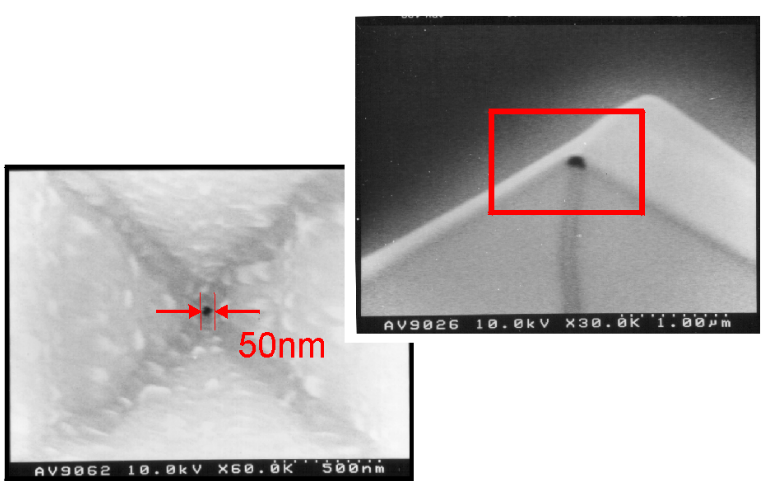
~~conventional microscope~~

$$\cancel{\Delta x_{min} = 0,61 \frac{\lambda}{NA}}$$

~~(Rayleigh-criterium)~~



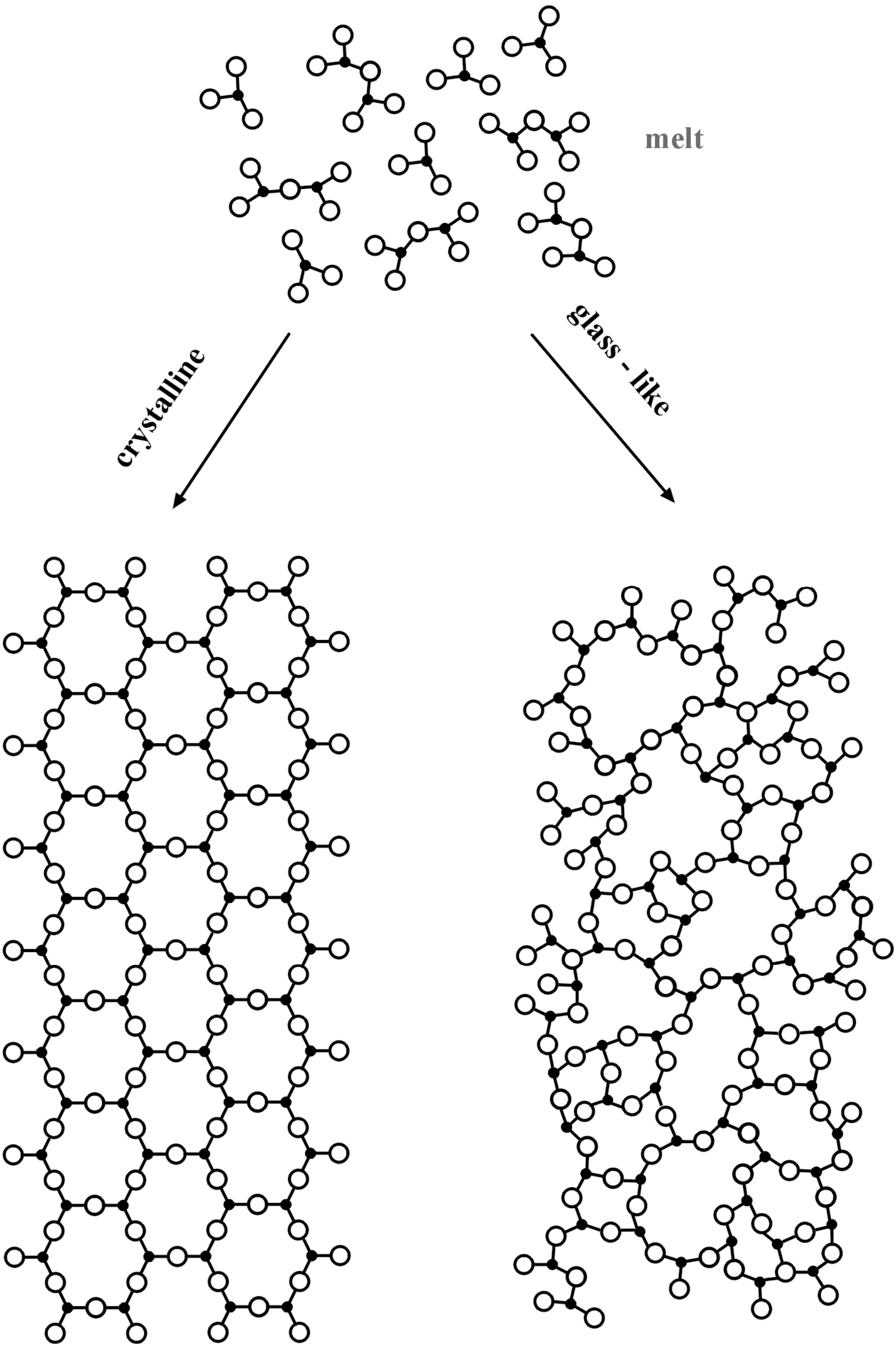
logarithmic intensity distribution (factor 10 between grey levels, respectively)



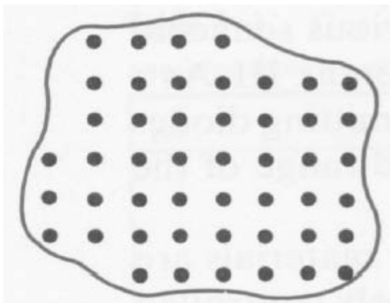
Chapter 4

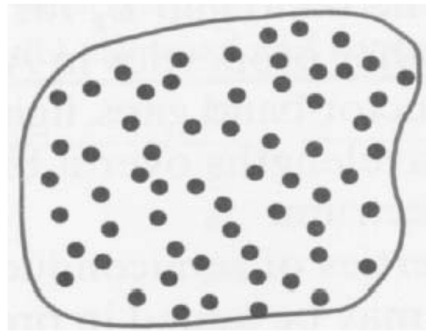
Optical Waveguiding

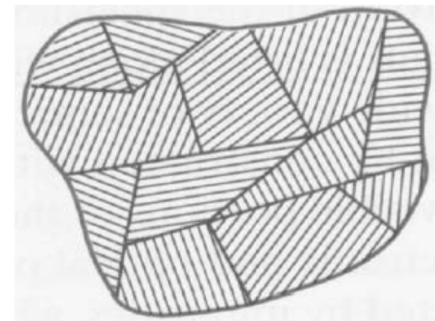
Fused silica vs. glass

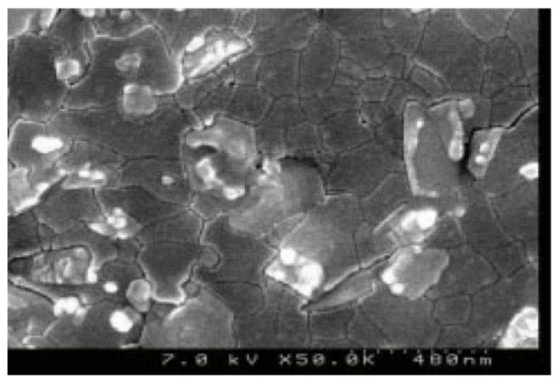


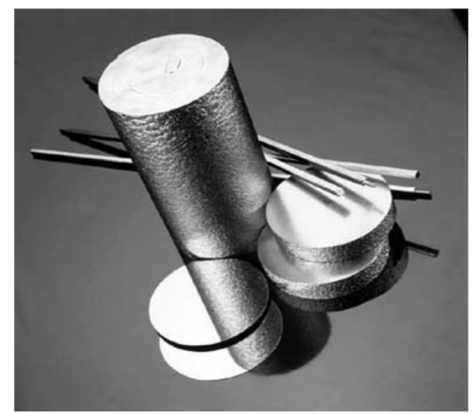
Classification of solids











crystalline

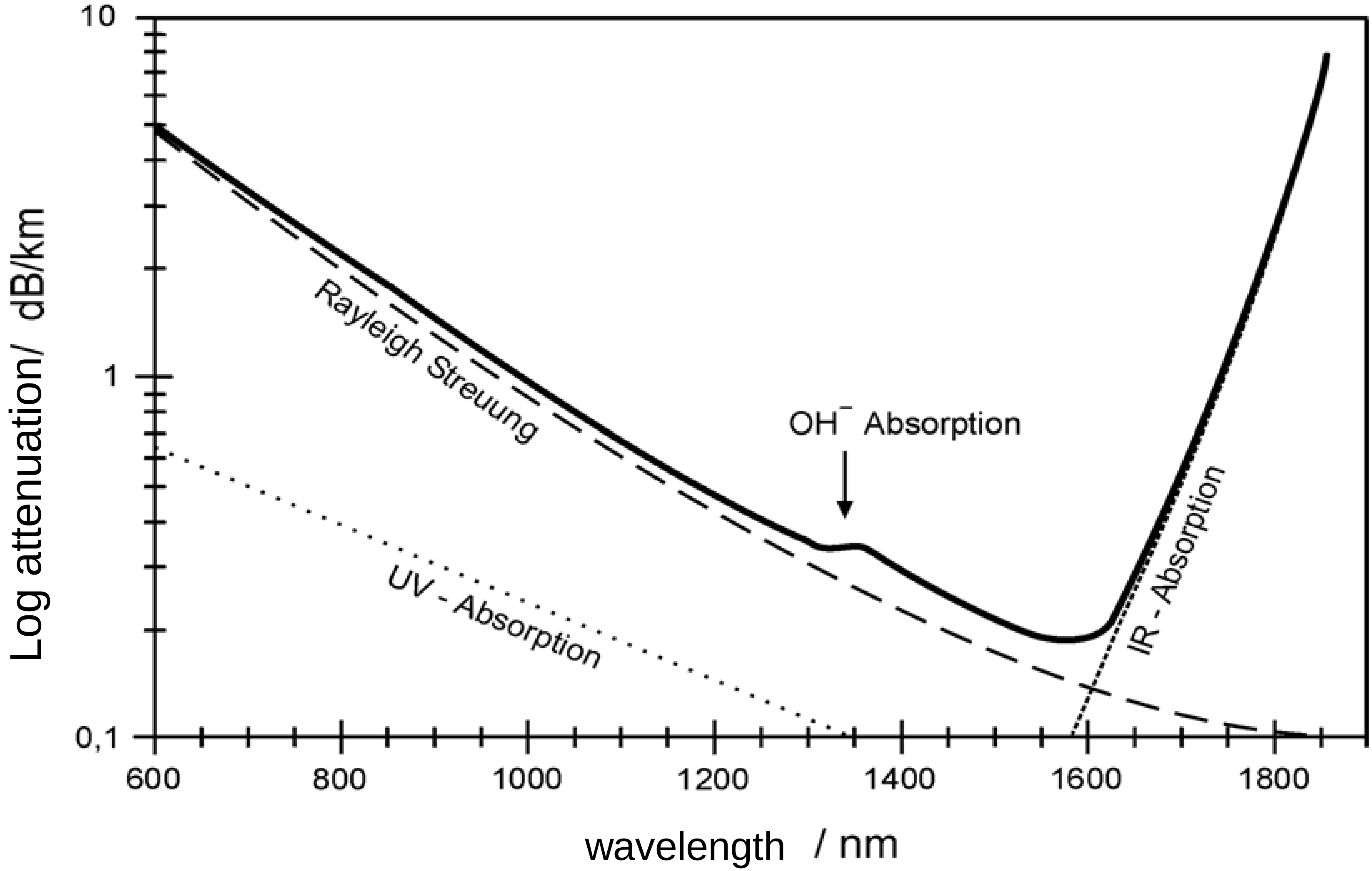
amorphous or glass-like

(within this lecture the minor differences between both classes are not focussed)

polycrystalline

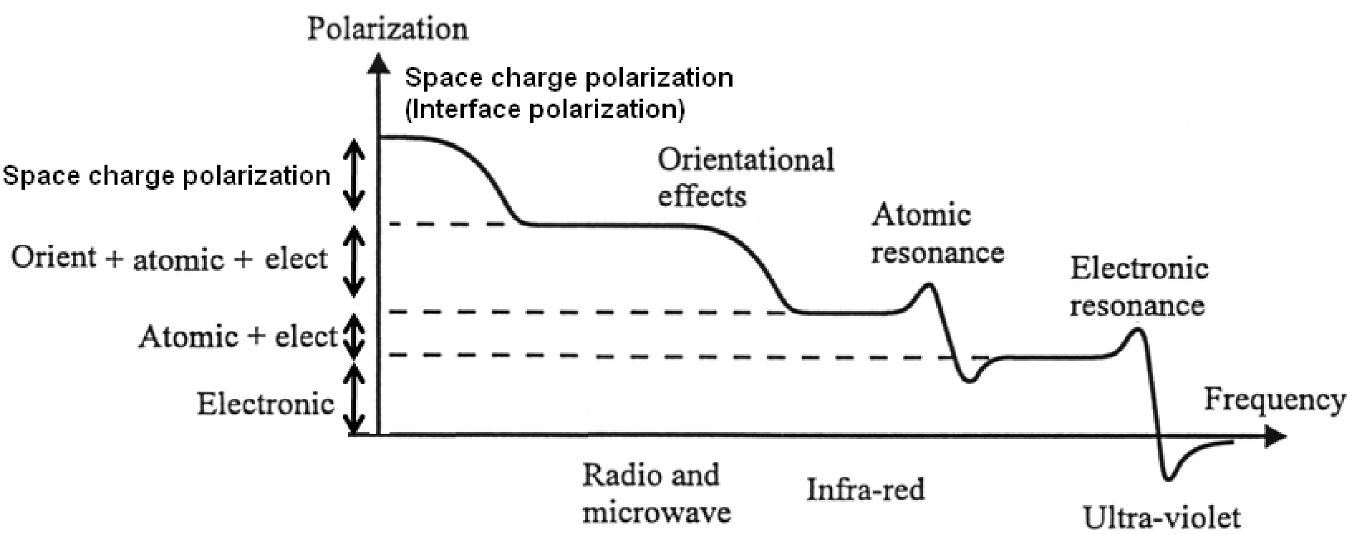
Spectral attenuation of a silica fibre

Absorption of silica as a function of wavelength



Refractive index of silica glass

A propagating electromagnetic wave excites atomic groups (molecules), atoms and electrons to forced, damped oscillations. At low frequencies f : each of these oscillators follows the forced oscillations; if f is further increased they come into resonance (power is absorbed from the wave field and reemitted in different directions); at very high f the oscillator is unable to follow the forced oscillations. The resonance f for vibrations is located at lower f than for electrons. The polarisation P „describes“ the amplitude of the forced oscillations.

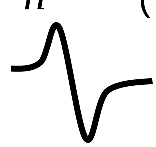


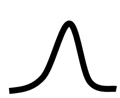
Dispersion means : $\bar{n} = \bar{n}(\lambda)$ or $\omega = \omega(\mathrm{k})$

or f is not simply proportional to 1 / λ : $f = \dfrac{c_0}{\bar{n}(\lambda)} \cdot \dfrac{1}{\lambda}$

Since the relative permittivity $\varepsilon = 1 + \dfrac{P}{\varepsilon_0 E}$

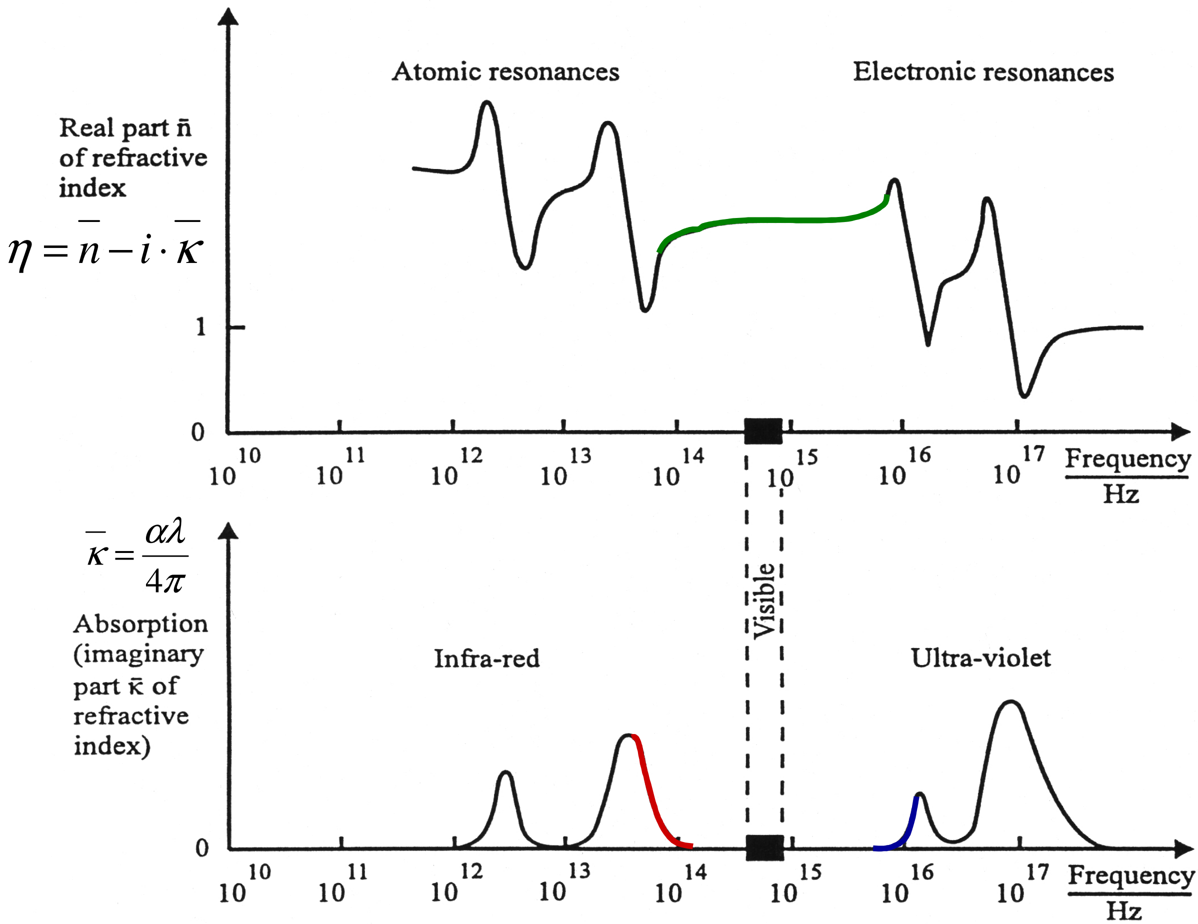
a quality similar picture can be drawn for $\bar{n}$ (= dispersion curve)

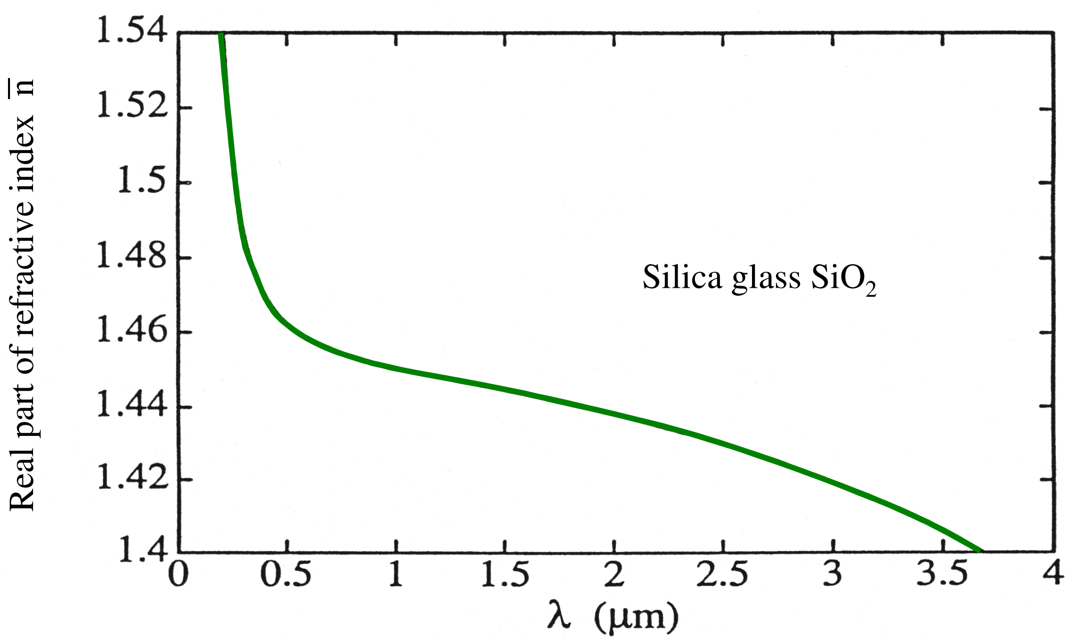
Each resonance in the dispersion curve  is accompanied by a resonance

in the absorption curve 

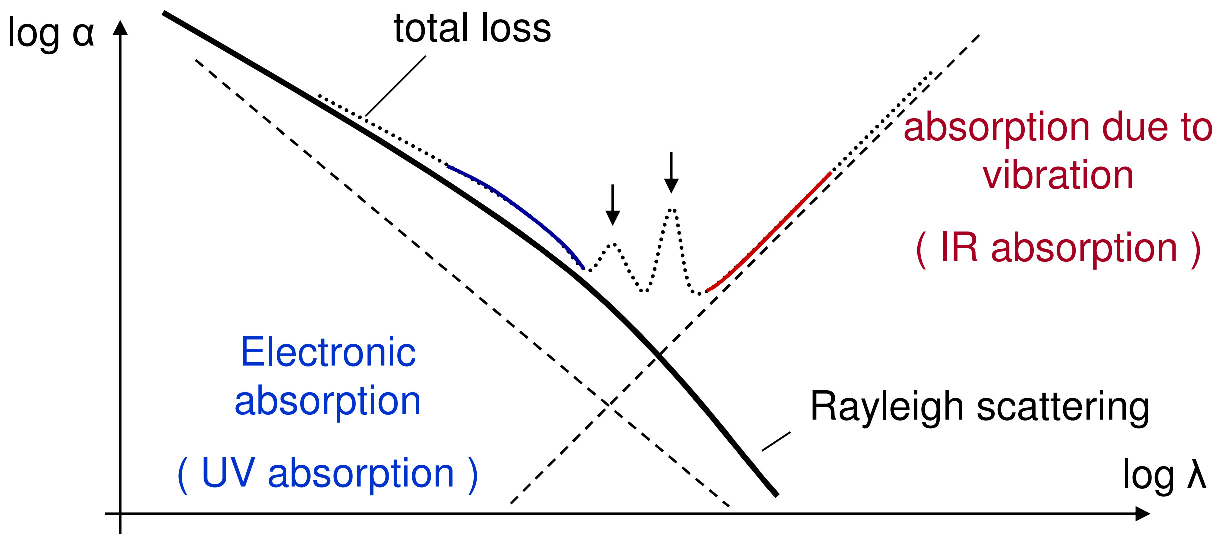
→ this relates $\bar{n}$ and α (Kramers – Kronig relation, causality).

The complex refractive index $\eta = \bar{n} - i \cdot \bar{\kappa}$



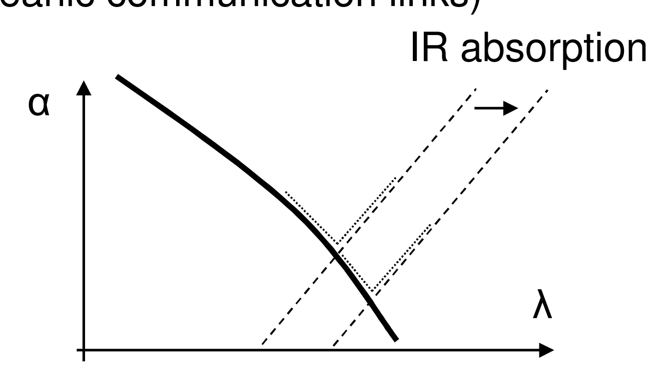


a) These phenomena already explain important parts of the absorption curve of a silica fibre:



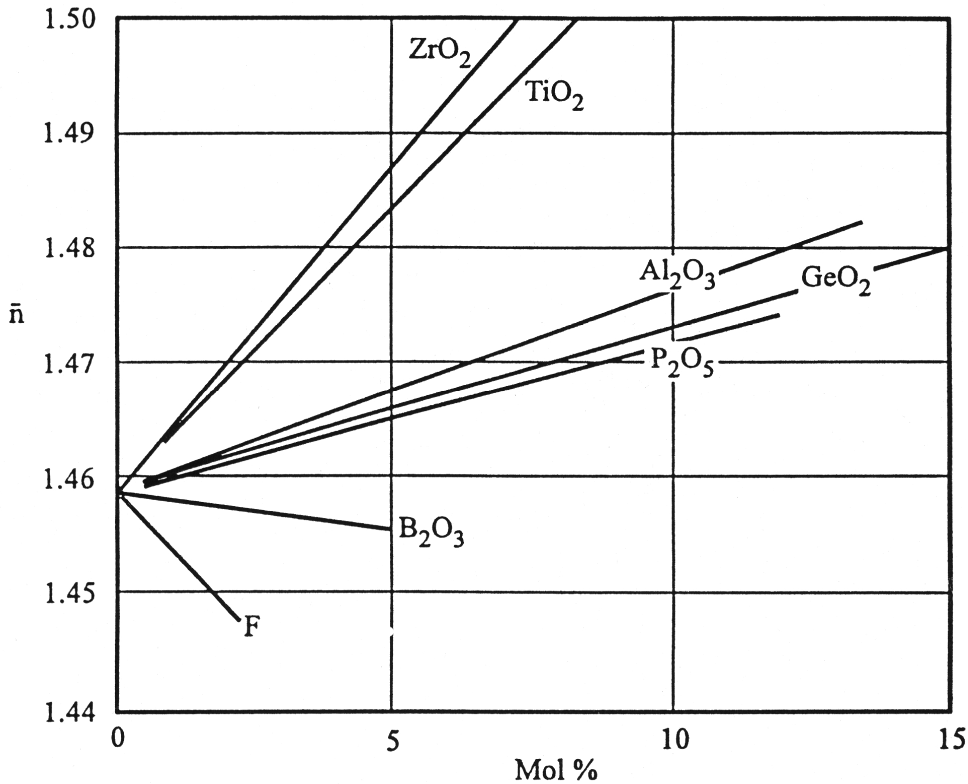
↓ ↓ Due to impurities (OH – absorption)

b) If silica is replaced by heavy metal fluorine glasses the absorption in the fibre in the IR (vibrations) is shifted to higher λ (due to the larger masses of the atoms). This is studied in current research: → absorption minimum is shifted to larger λ
(application : long-haul oceanic communication links)

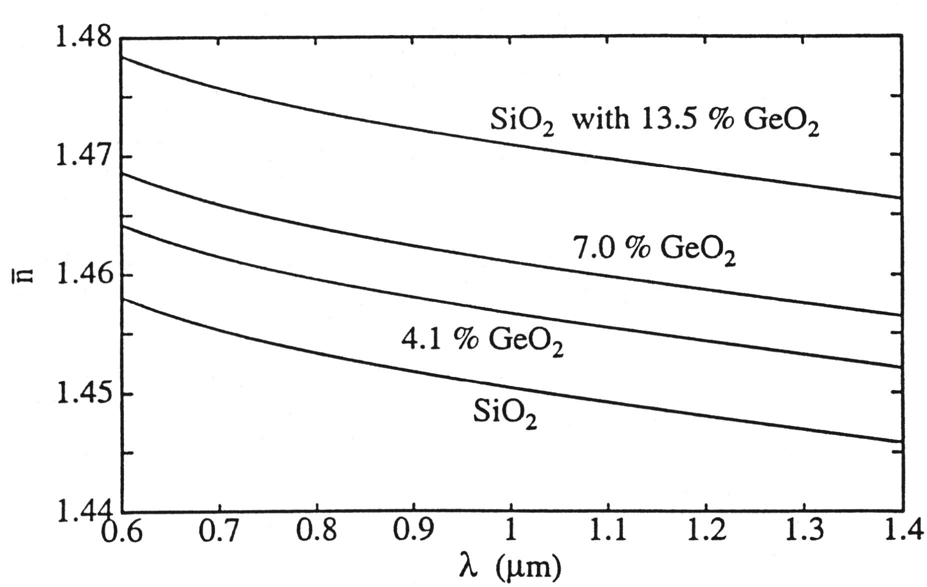


c) At shorter λ, cheap polymer fibres can be used over short distances

Adding oxide impurities to SiO_2 → variation of $\bar{n}$ (application : index profiles in fibres)



Silica fibre doped with various impurities



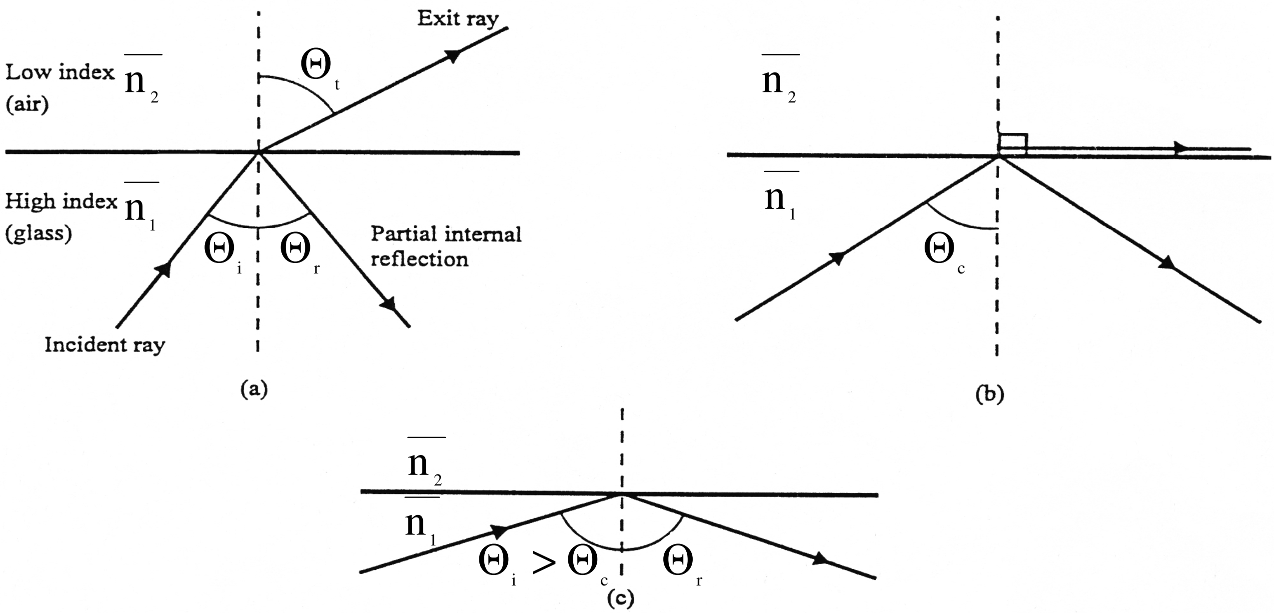
Ray model in optical fibres

Law of reflection $\theta_i = \theta_r$ $(i = \text{incident}; r = \text{reflected})$

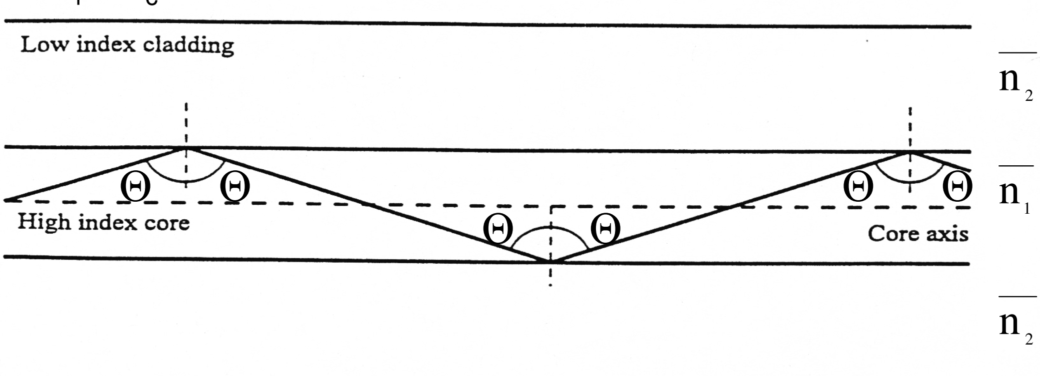
Snell`s law $\bar{n}_1 \sin\theta_i = \bar{n}_2 \sin\theta_t$ (deutsch : Brechungsgesetz)

for $\theta_i > \theta_c$ critical angle $\rightarrow$ only a reflected beam

Snell`s law can no longer be fulfilled with real angles θ_t.

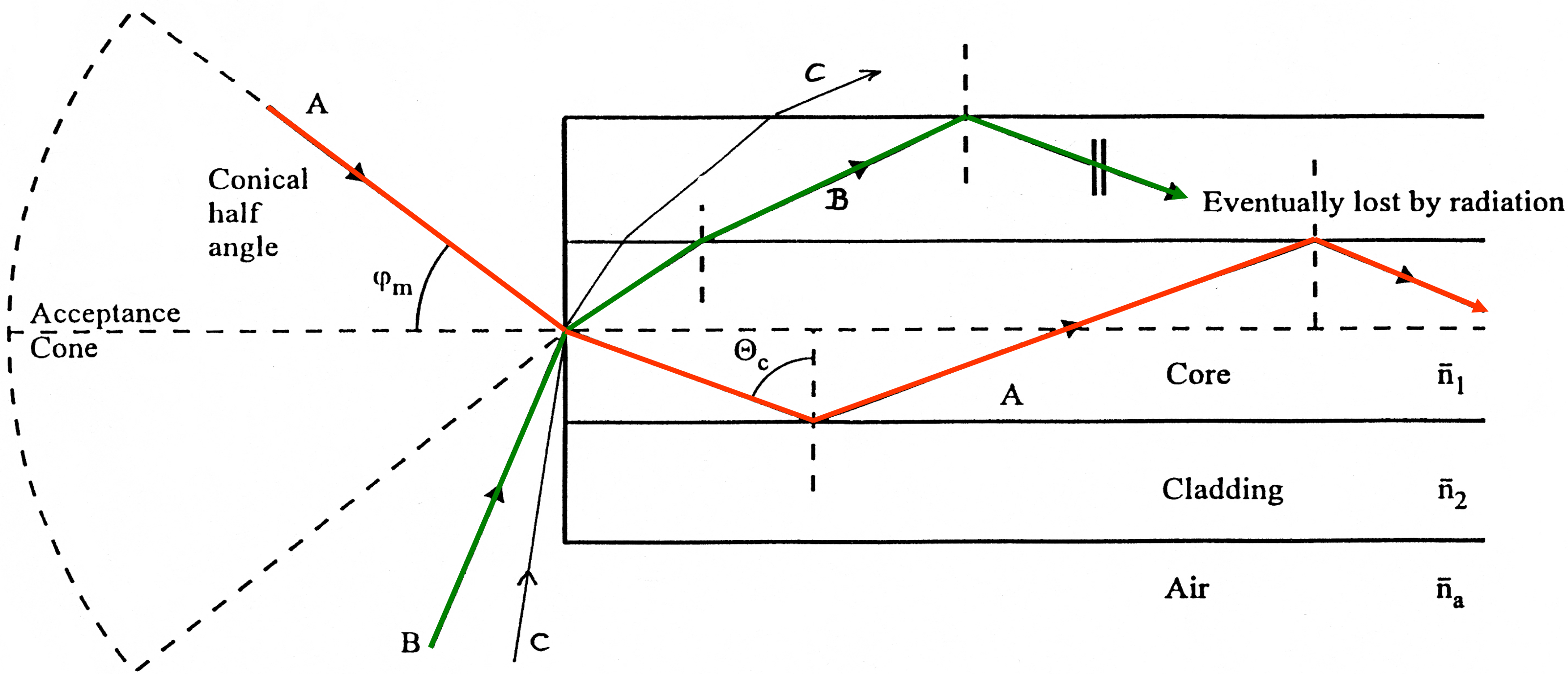


Light rays incidence on high to low refractive index interface. (a) Refraction and partial reflection. (b) Limiting case of $\theta_i \geq \theta_c$ where the transmitted beam travels under an angle of 90° with respect to the normal. (c) Total internal reflection for $\theta_i > \theta_c$.



Guiding of a light ray by total internal reflection in a high index medium $\bar{n}_1$ surrounded by a low index medium $\bar{n}_2$ ($\bar{n}_2 < \bar{n}_1$) as in a perfect optical fibre.

Acceptance angle of fibre waveguides



Rays A and B are launched into the fibre. An incident ray is refracted at the core-air interface. For sufficiently small angles φ : total internal reflection at the core-cladding interface (zig – zag path).

A - core mode or guided mode

B - cladding mode ($\varphi > \varphi_m$) , high losses, due to interface roughness

C - radiation mode

Maximum acceptance angle φ_m, numerical aperture optoelectronic devices

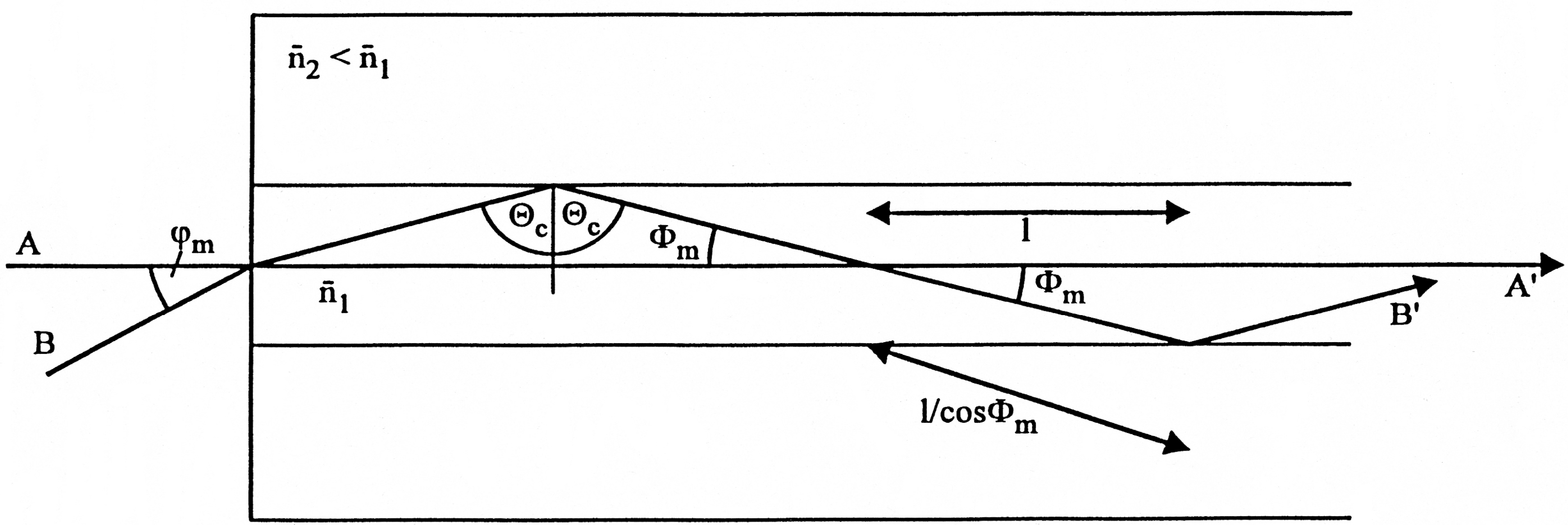
using $\theta = \theta_C$ and Snell`s law

refractive index difference $\Delta \bar{n} = \bar{n}_1 - \bar{n}_2$

mean refractive index $\bar{n} = (\bar{n}_1 + \bar{n}_2)/2$

$$\varphi_m = \arcsin \sqrt{2 \cdot \bar{n} \cdot \Delta \bar{n}}$$

numerical aperture $NA = \sin \varphi_m$



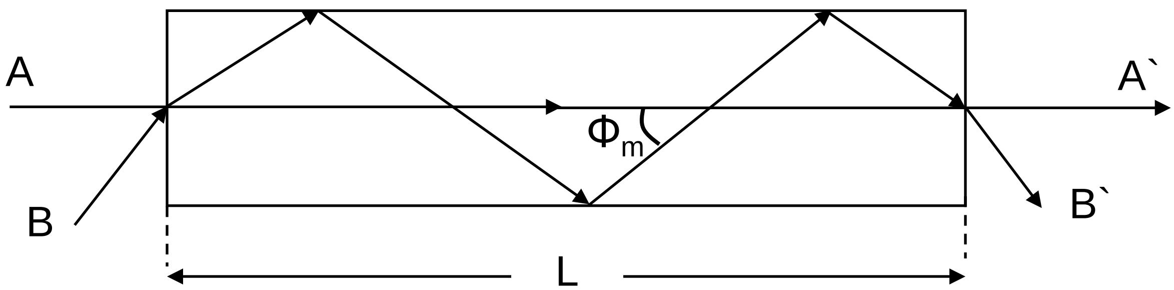
AA` : axial ray

BB` : critical core mode (total internal reflection at the core-cladding interface)

due to symmetry reasons the max. acceptance angle and the radiation angle at the end of the fibre are identical

Modal dispersion in a step-index fibre

Different guided modes propagate on zig-zag paths under different angles.



AA`is approximated. Since $\Phi_m$ is very small, AA`is called the axial path.

propagation of a δ – pulse:

AA` : travelling time $t_a = L\dfrac{\bar{n}_1}{c}$ $\Phi_m = 90^o - \Theta_c$

BB` : $t_b = \dfrac{L}{\cos\Phi_m} \cdot \dfrac{\bar{n}_1}{c} = \dfrac{L}{\sin\Theta c} \cdot \dfrac{\bar{n}_1}{c} = \dfrac{\bar{n}_1^{\,2} L}{\bar{n}_2 \cdot c}$

time difference (pulse spreading)

$$\Delta t = t_b - t_a = \frac{\bar{n}_1 L}{\bar{n}_2 \cdot c}\Delta\bar{n}$$

modal dispersion (= multipath time dispersion)

$$\frac{\Delta t}{L} = \frac{\bar{n}_1 \Delta\bar{n}}{\bar{n}_2 \cdot c}$$

(this model provides the correct result but is too simple and will be corrected later.)

(length related to pulse spreading)

to avoid intersymbol interference of „1“ and „0“

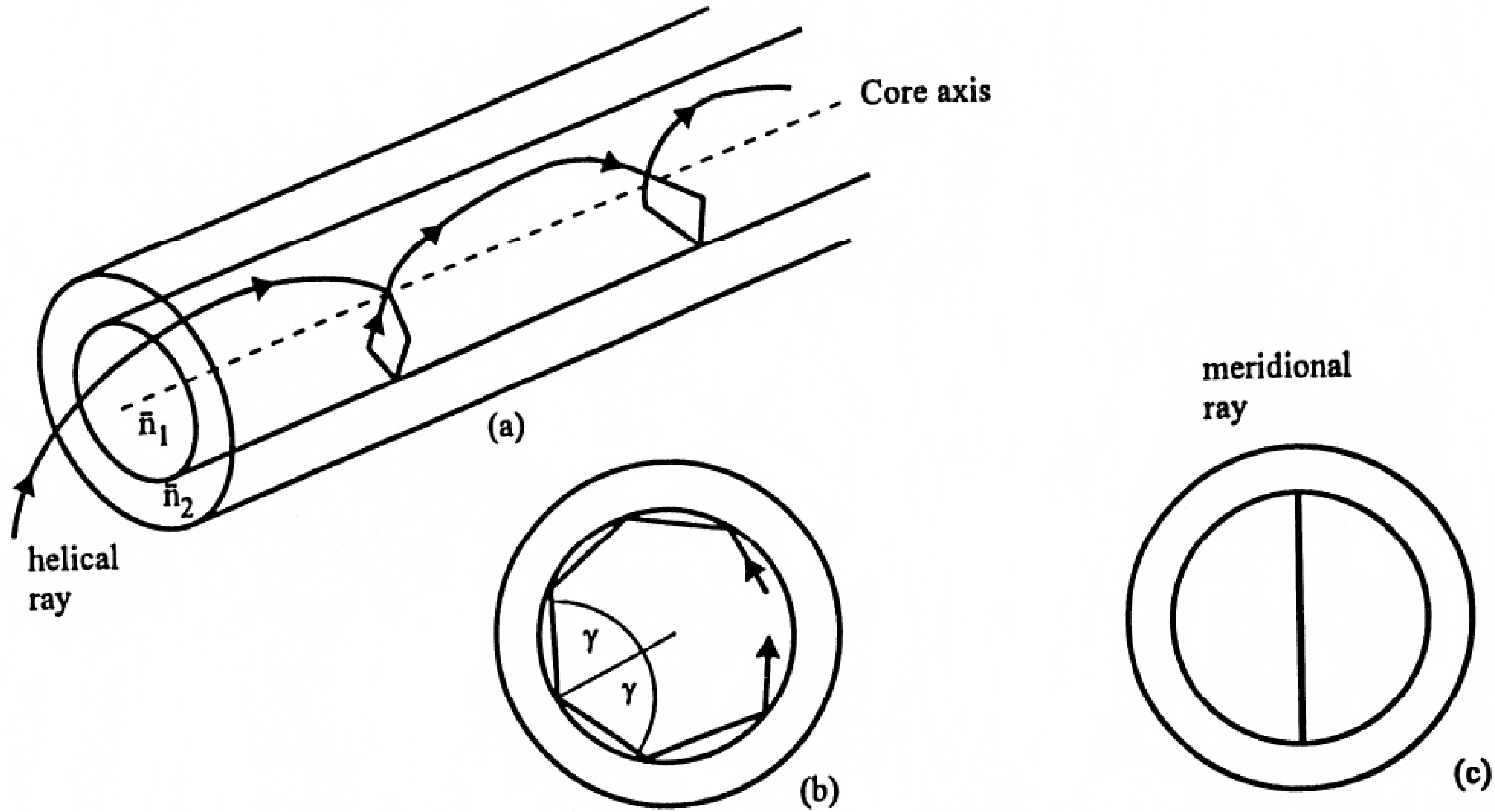
max. bit rate: $B = \dfrac{1}{\Delta t} = 2 f_{\max}$

bandwidth – length product: $f_{\max} \cdot L = \dfrac{c \cdot \bar{n}_2}{2\Delta\bar{n} \cdot \bar{n}_1}$

bit – rate – length product: $BL = c \cdot \bar{n}_2 / \left(\Delta\bar{n} \cdot \bar{n}_1\right)$

Helix modes

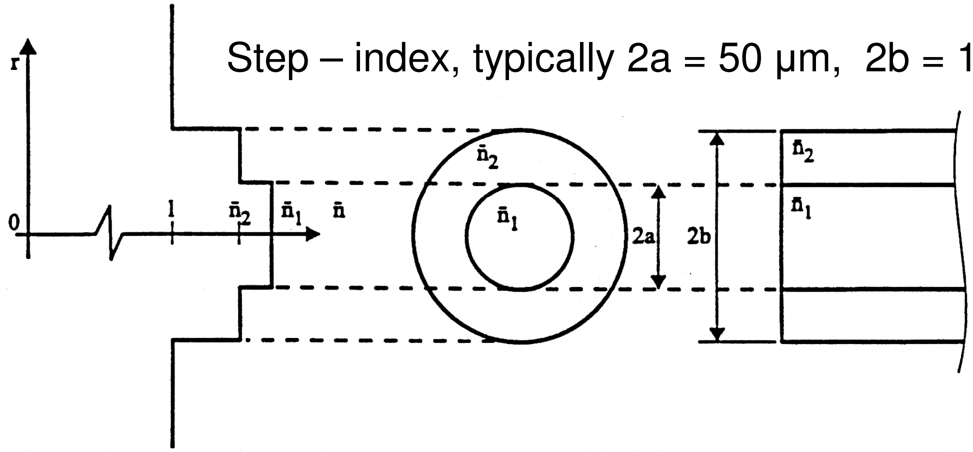
Up to now meridional rays, traveling through the fibre axis were considered.



However, a larger number follows helical paths, undergoing a much larger number of reflections at the core-cladding interface → higher losses and higher modal dispersion but less important as meridional modes.

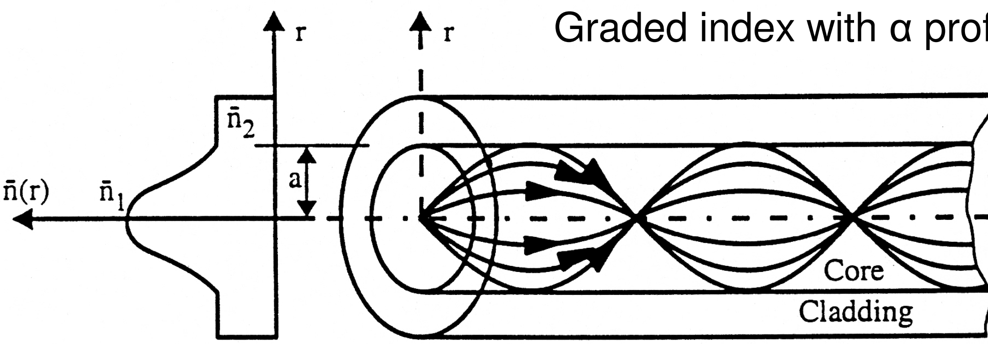
Step-index fibres and graded-index fibres

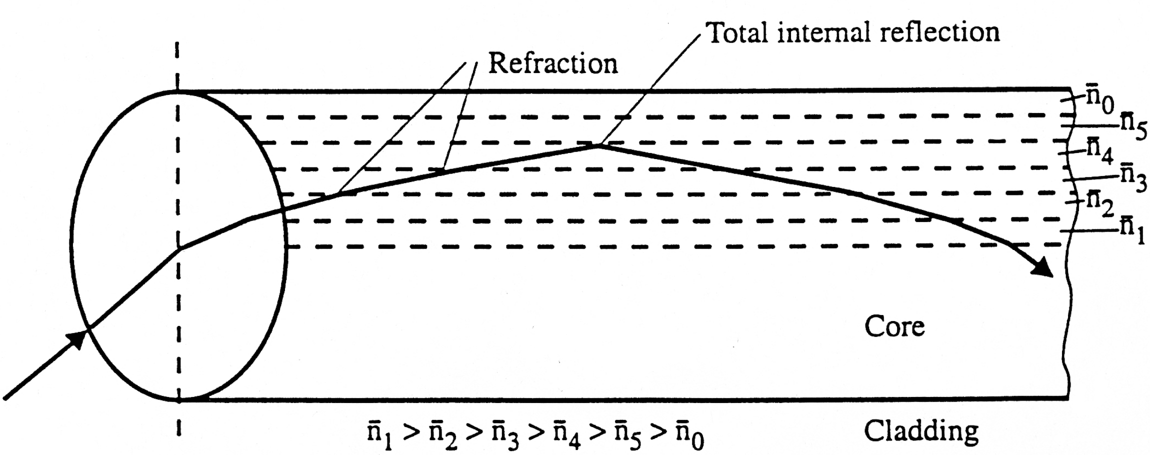
Step – index, typically 2a = 50 μm, 2b = 125 μm.



The relatively small bit – rate – length product of step – index fibres initiated the development of graded – index fibres.

Graded index with α profile.

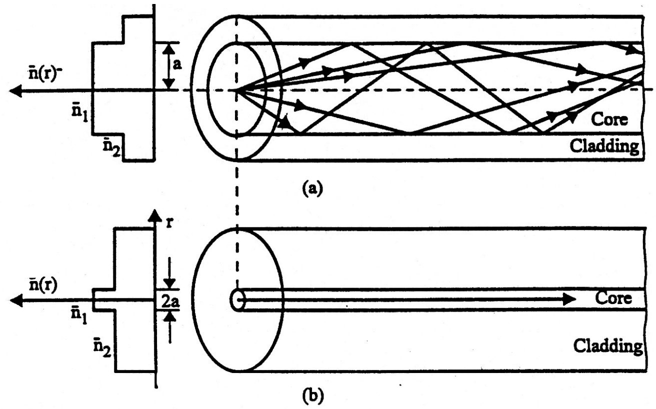




multi –mode fibre

here: step – index

single – mode fibre



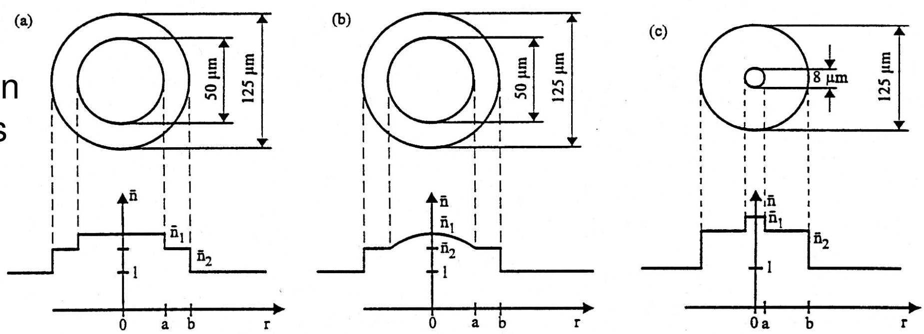
Graded index fibres are also multimode

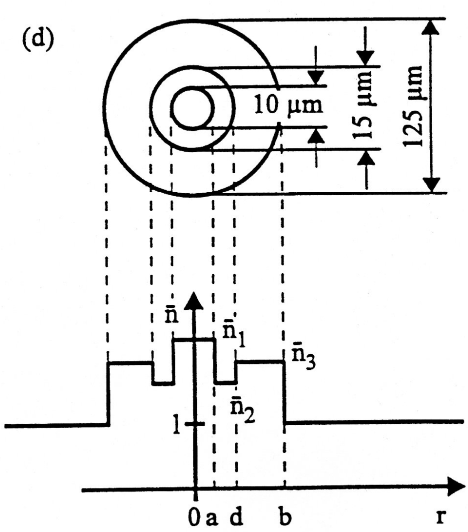
The path in (b) is approximated Ø very small

The importance of graded index fibres has somewhat declined due to the development of single – mode fibres ($\Delta n = 0.01$, narrow core : $2a = 8$ µm).

Single – mode fibres : only a single zig-zag path under a well defined angle. Description requires a wave – theoretical model .

In comparison again 4 types of fibres :





a) Step – index multimode fibre

b) Graded index multimode fibre

c) Step – index single-mode fibre

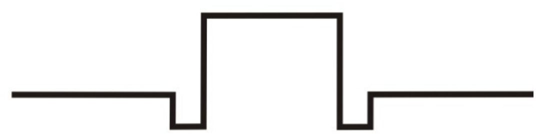
d) Single-mode fibre

Multiple cladding profile fibre

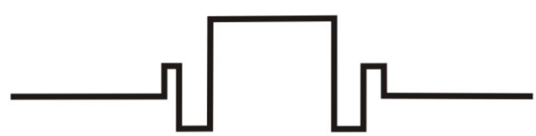
Modern and future single mode fibre types

Single-clad fibre

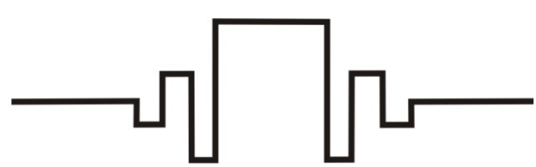
Double-clad fibre



Triple-clad fibre



Quadruple-clad fibre



Refractive index profile of an α-type graded index fibre

$$\bar{n}(r) = \begin{cases} \bar{n}_1 \left(1 - 2\Delta \left(\frac{r}{a}\right)^{\alpha}\right)^{1/2} & \text{for } r > a \text{ in the core} \\ \bar{n}_1 (1 - 2\Delta)^{1/2} = \bar{n}_2 & \text{for } r > a \text{ in the cladding} \end{cases}$$

$$\Delta = \frac{\bar{n}_1^2 - \bar{n}_2^2}{2\bar{n}_1^2} \approx \frac{\bar{n}_1 - \bar{n}_2}{\bar{n}_1}$$

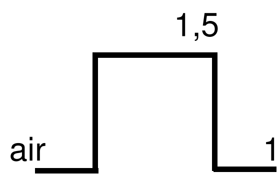
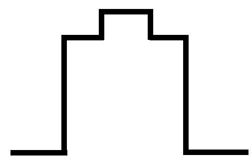
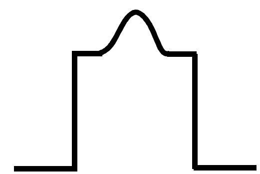
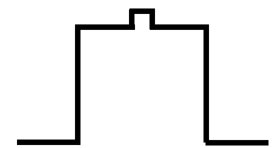
Refractive index profile of a graded index fibre with α – profile. Δ is the mean relative refractive index difference between core and cladding (the approximation holds for $n_1 \approx n_2$). → $\Delta << 1$.

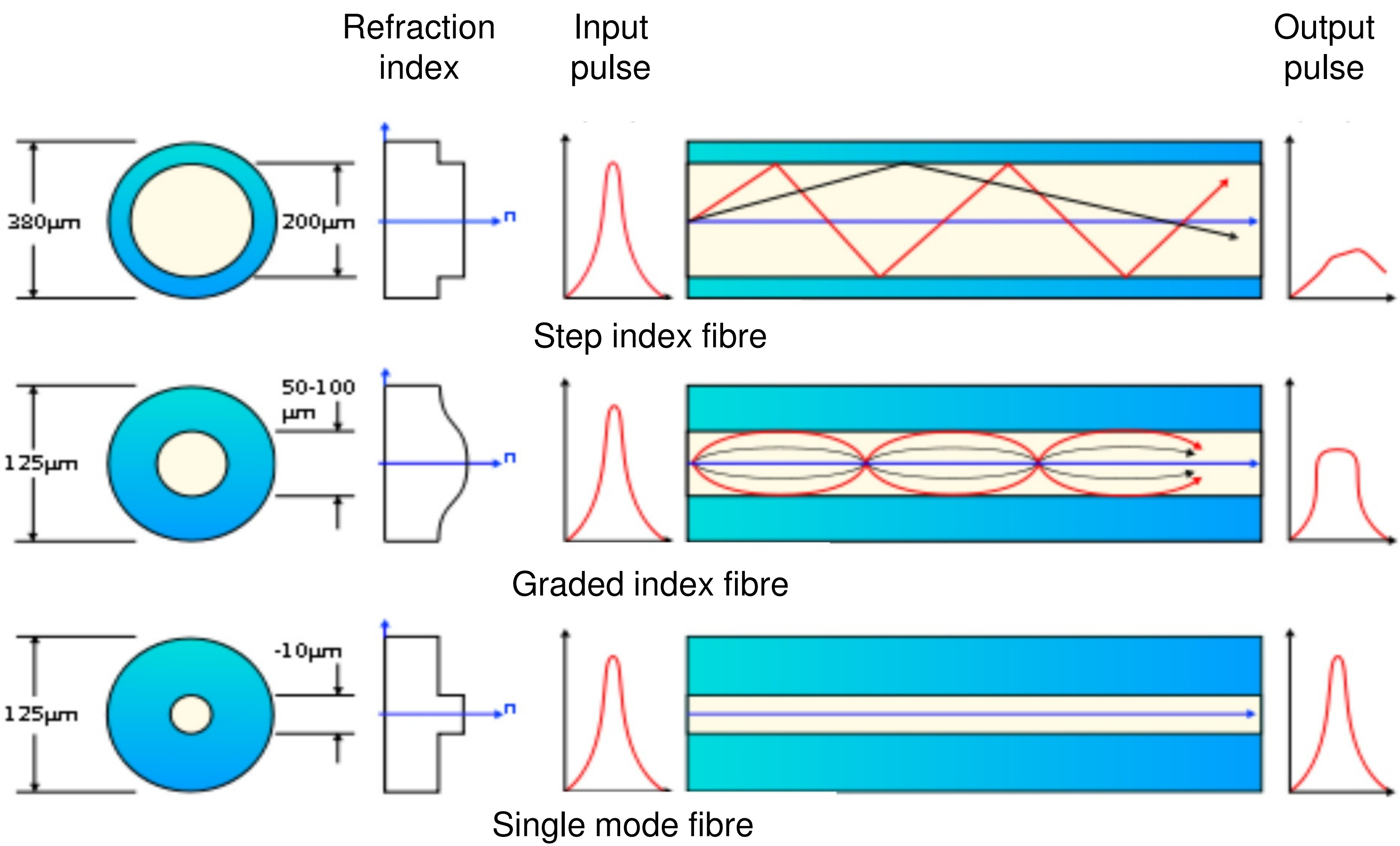
The profile parameter α =0 ... ∞. The optimum is usually close to the parabolic profile (α = 2). In practice α has to be carefully controlled during the technological process.

Sinusoidal trajectories for the ray propagation in the core.

- Rays close to the axis : shorter paths but with higher $\bar{n}$ → lower propagation velocity
- Rays in the outer regions : longer paths but also lower $\bar{n}$ regions → higher propagation velocity.

The difference in propagation velocity path compensates for the path difference → multiple path dispersion reduced to

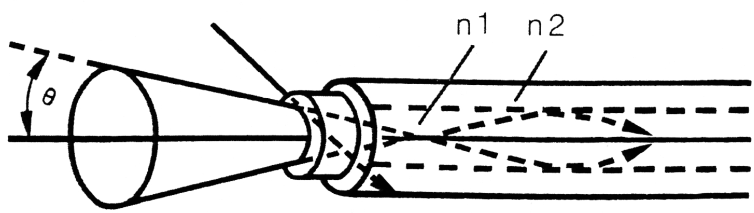
Fibre type				
Modal dispersion $\Delta t / L$	2500 ns / km	30 ns / km	0,1 ns / km	This is no longer a problem for single mode fibres. The limits are there dominated by the remaining spectral dispersion (which, however, is much smaller than modal dispersion)
Bit-rate length product $B \cdot L$	500 $\frac{\text{kbit}}{\text{s}} \cdot \text{km}$	30 $\frac{\text{Mbit}}{\text{s}} \cdot \text{km}$	10 $\frac{\text{Gbit}}{\text{s}} \cdot \text{km}$	


Refraction
index
Input
pulse
Output
pulse
380µm
200µm
n
Step index fibre
50-100
µm
125µm
n
Graded index fibre
-10µm
125µm
n
Single mode fibre

Conclusion: fibre

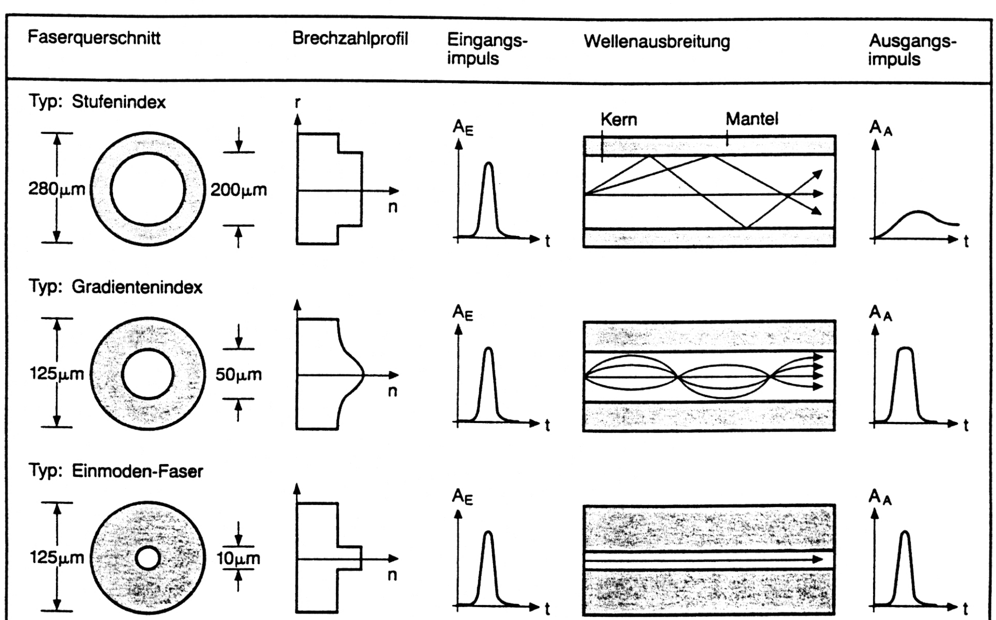
Optical fibre consists of a transparent core and a cladding material with low attenuation. Used to transmit informations by light waves.

Basic principle for optical transmission is the total internal reflection based on the law of refraction. All light is reflected when a ray of light strikes a medium boundary at an angle larger than a particular critical angle with respect to the normal to the surface and the refractive index is lower on the other side of the boundary.



3 types of optical fibres can be differentiate with regard to the geometrical dimensions and the optical transmission characteristics:

a) multimode fibre with step-index profile
b) multimode fibre with graded-index profile
c) single mode fibre with step-index profile



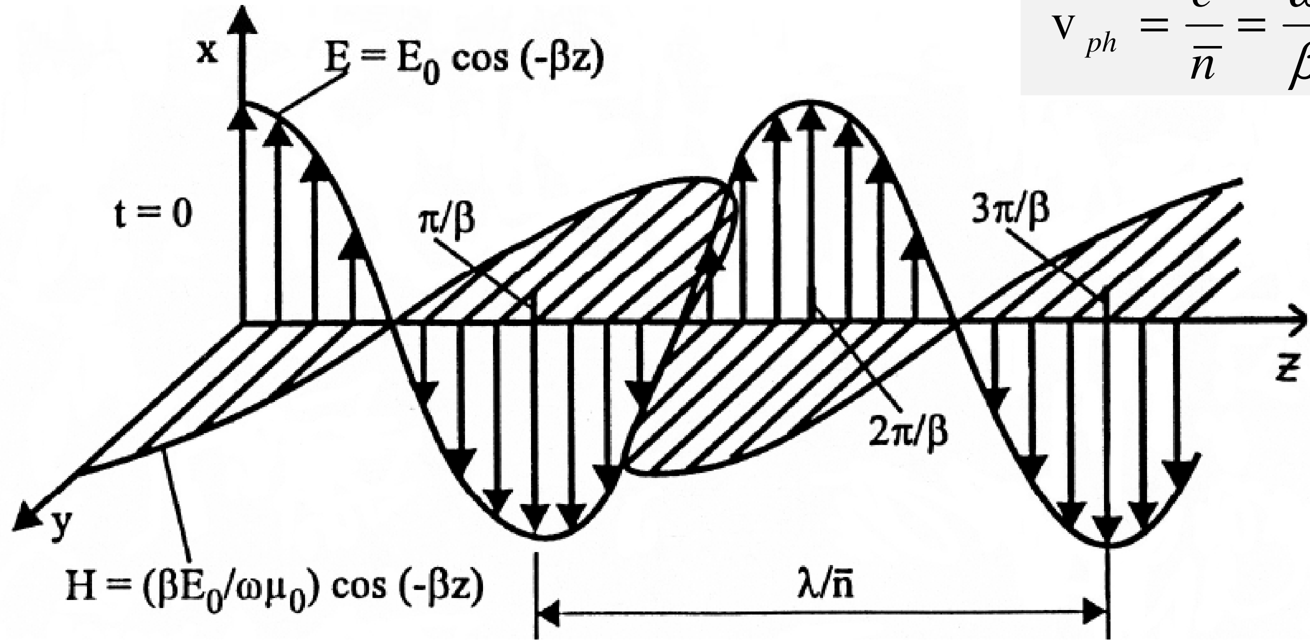
Plane electromagnetic wave

Linear polarized wave of angular frequency ω propagating in z – direction :

$$E(x, y, z, t) = E_0 \exp(i\omega t - i\beta z), \qquad E_0 = \text{complex amplitude}$$

a) lossless media: propagation constant is real: $\beta = \dfrac{2\pi}{\lambda/\overline{n}} = \dfrac{\omega \cdot \overline{n}}{c}$

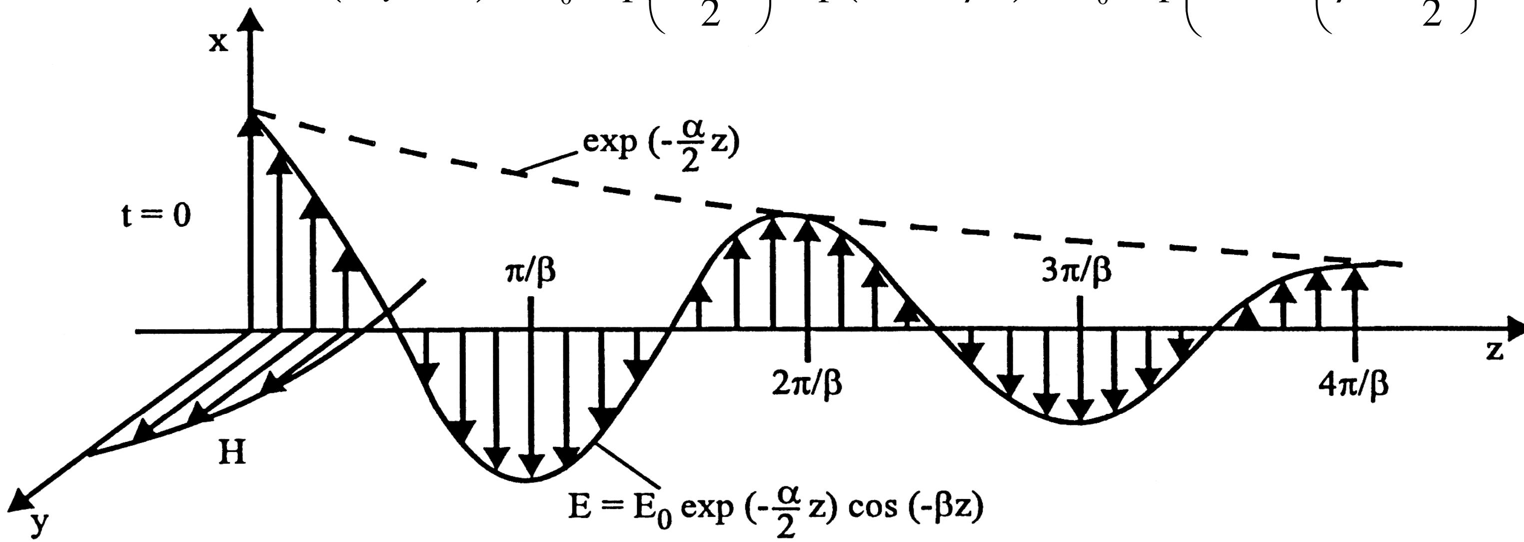
$$v_{ph} = \frac{c}{\overline{n}} = \frac{\omega}{\beta} = \frac{\omega\lambda}{2\pi \cdot \overline{n}}$$



Plane electromagnetic waves II

b) lossy media: $I(z) = I_0 \exp(-\alpha z) \quad \sim \quad |\mathrm{E}_0|^2 \exp(-\alpha z)$

$$E(x,y,z,t) = E_0 \exp\left(\frac{-\alpha z}{2}\right) \exp(i\omega t - i\beta z) = E_0 \exp\left(i\omega t - i\left(\beta - \frac{i\alpha}{2}\right)\cdot z\right)$$



propagation constant is complex

$$\gamma = \beta - i\cdot\frac{\alpha}{2} = \frac{\omega}{c}\left(\bar{n} - i\kappa\right)$$

refractive index is complex

$$\bar{\eta} = \bar{n} - i\kappa$$

extinction coefficient

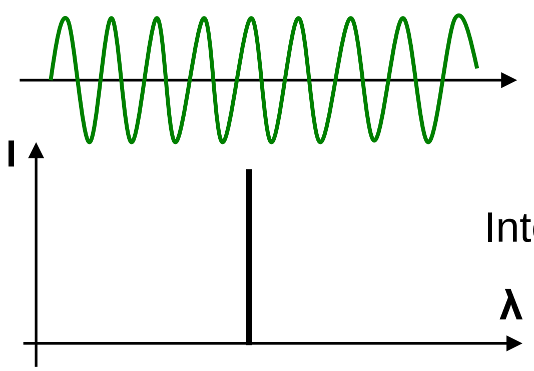
$$\kappa = \frac{c\alpha}{2\omega} = \frac{\alpha\lambda}{4\pi}$$

Propagation of light in media

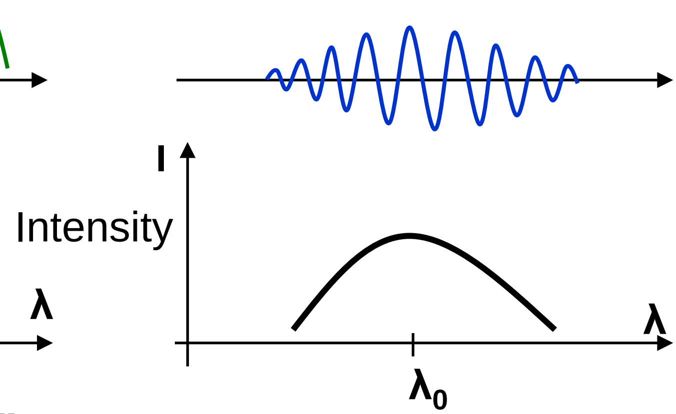
Often the same problems in understanding occur → first a short overview

Overview:

Monochromatic wave



wave packet (pulse in time domain)



$$\frac{\lambda}{\bar{n}} \cdot f = \frac{c}{\bar{n}}$$

$$\beta = \frac{2\pi}{\lambda / \bar{n}}$$

$$\omega = 2\pi \cdot \mathrm{f}$$

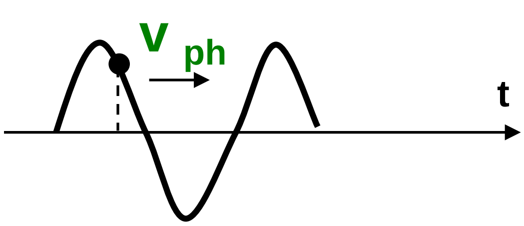
f - frequency

c - vacuum light velocity

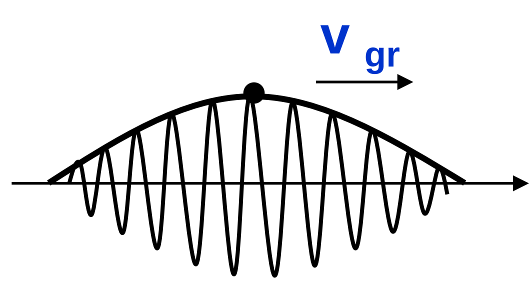
λ - vacuum wavelength

ω - angular frequency

β - propagation constant (wave vector)



propagation velocity of a point of fixed phase



Propagation velocity of the envelope of the packet (group velocity of the wave packet = phase velocity of the envelope)

$$\mathrm{v}_{ph} = \frac{\omega}{\beta} = \frac{c}{\bar{n}(\lambda)}$$

v_{ph} – phase velocity

$\bar{\mathrm{n}}$ - phase refractive index

$$\mathrm{v}_{\mathrm{gr}} = \left. \frac{d\omega}{d\beta} \right/_{\beta=\beta_0} = \frac{c}{\bar{n}_{gr}(\lambda)}$$

v_{gr} – group velocity

$\bar{\mathrm{n}}_{\mathrm{gr}}$ - group refractive index

$$\bar{\mathrm{n}}_{\mathrm{gr}} = \bar{\mathrm{n}}(\mathrm{f}_0) + \mathrm{f}_0 \left. \frac{\partial \bar{\mathrm{n}}}{\partial f} \right/_{\mathrm{f}_0}$$

Time function (time domain) and spectrum (frequency domain)

f(t) and F(f) connected by Fourier transformation:

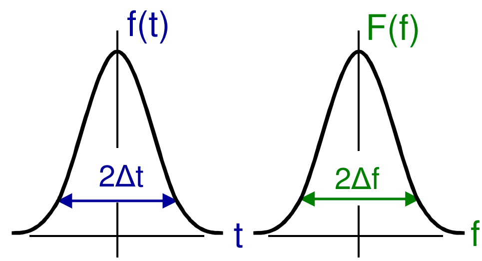
$$f(t) = \int_{-\infty}^{\infty} F(f) \cdot e^{i2\pi \cdot f \cdot t} df \qquad\qquad F(f) = \int_{-\infty}^{\infty} f(t) \cdot e^{-i2\pi \cdot f \cdot t} dt$$

i.e. f (t) is composed of elementary sinusoidal oscillations

1. Bell-shaped pulse (Gaussian pulse)

$$f(t) = \frac{1}{\Delta t} \cdot \exp\left(-\pi \frac{t^2}{\Delta t^2} \right)$$

$$F(f) = \exp\left(-\pi \cdot \Delta t^2 \cdot f^2 \right) = \exp\left(-\pi \frac{f^2}{\Delta f^2} \right)$$



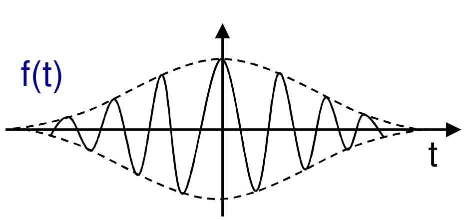
Δt, Δf – characteristic widths in time and spectral domains are inversely related **$\Delta f = (\Delta t)^{-1}$** $\rightarrow$ broad pulses in time produce narrow pulses in spectrum and vice versa.

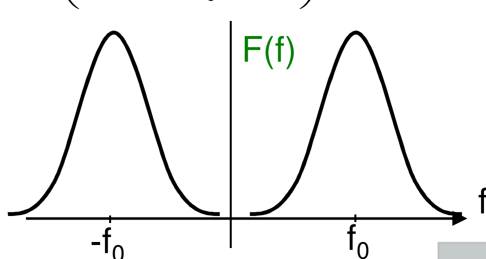
2. Gaussian pulse with high frequency carrier $\omega_0 = 2\Pi f_0$

$$f(t) = \frac{1}{\Delta t} \cdot \exp\left(-\pi \frac{t^2}{\Delta t^2} \right) \cos \omega_0 t = \frac{1}{2\Delta t} \exp\left(-\pi \frac{t^2}{\Delta t^2} \right) \left[e^{i\omega_0 t} + e^{-i\omega_0 t} \right]$$

envelope again gaussian

$$2F(f) = \exp\left(-\pi \frac{(f - f_0)^2}{\Delta f^2} \right) + \exp\left(-\pi \frac{(f + f_0)^2}{\Delta f^2} \right)$$

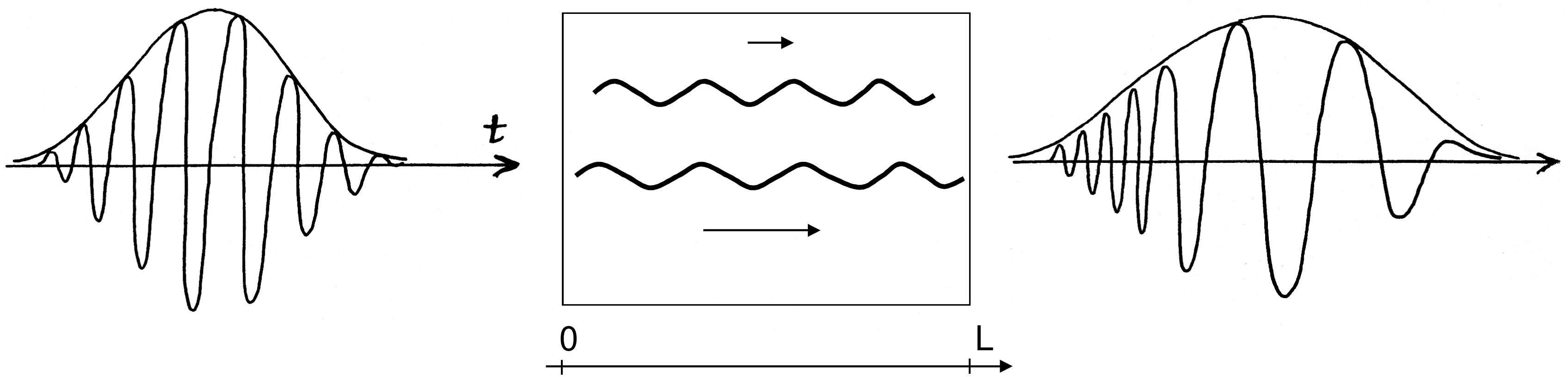




Note: Gaussian pulse with complex carrier $\exp(i\omega_0 t)$ has the spectrum $\exp\left(-\pi \frac{(f - f_0)^2}{\Delta f^2} \right)$

Pulse propagation in a dispersive medium $\bar{n} = \bar{n}(\omega)$ — optoelectronic devices

medium $\bar{n}(\omega)$



Superposition of sinusoidal spectral components

$$F(t, z=0) = \int_{-\infty}^{\infty} F(f) e^{i2\pi \cdot f \cdot t} df$$

Each component reveals an individual time delay $t'(f) = L / V_{ph}(f)$

$$V_{ph}(f) = \frac{2\pi f}{\beta(f)} = \frac{c}{\bar{n}(f)}$$

Time delays t' lead to phase shift of the components at the output z = L

$$F(t, z=L) = \int_{-\infty}^{\infty} F(f) e^{i2\pi \cdot f (t - t'(f))} df$$

The contribution of dispersion to pulse broadening is $\Delta t_D = \frac{2\pi L}{\Delta t} \cdot \frac{d^2\beta}{d\omega^2}$ $\qquad \frac{d\beta}{d\omega} = \frac{1}{V_{gr}(\omega)}$ $\qquad \beta(\omega) = \frac{\omega}{c}\bar{n}(\omega)$

→ pulse broadening ↑ with Δt ↓ , with chromatic dispersion ↑ $\left(\frac{d^2\beta}{d\omega^2}\uparrow\right)$.

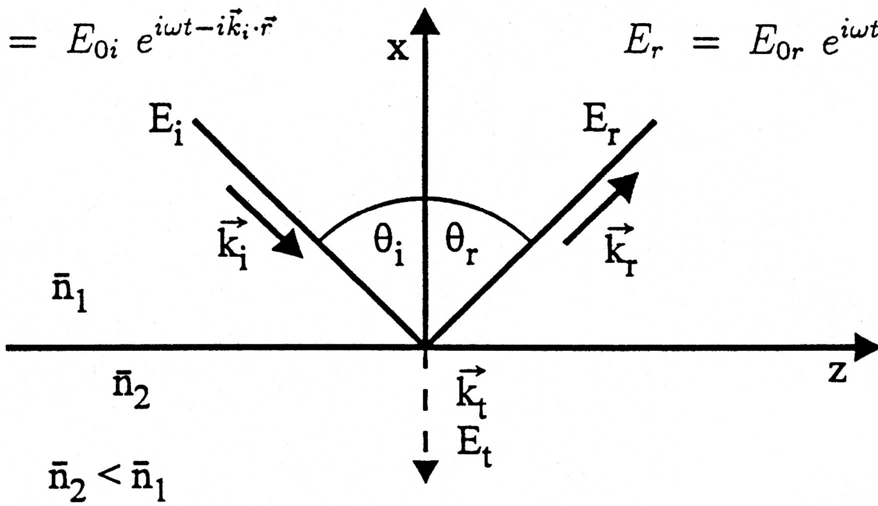
Short pulses have broad spectra; spectral components with a large frequency spacing travel at noticeably different speeds → noticeably different arrival times at the output → noticeably phase shifts → broad pulses.

Internal reflection of monochromatic plane waves

Helmholtz equation : $$\Delta E + \frac{\omega^2 \eta^2}{c^2} E = 0$$ here lossless media

el. field E (r,t) = E (x,y,z,t) here y = 0

$$E_i = E_{0i}\, e^{i\omega t - i\vec{k}_i \cdot \vec{r}} \qquad E_r = E_{0r}\, e^{i\omega t - i\vec{k}_r \cdot \vec{r}}$$



$$|E_{0r}| = |E_{0i}|$$

$$E_t = E_{0t}\, e^{i\omega t - ik_{tz} z + k_{tx} x}$$

Incident and reflected waves have to fulfill the dispersion relation: (according to Helmholtz equation)

$$k_{ix}^2 + k_{iz}^2 = \frac{\omega^2 \bar{n}_1^2}{c^2} = \bar{n}_1^2 k^2$$

For medium $\bar{n}_2$ internal reflection requires a plane wave solution propagating in z-direction but exponentially decaying in – x direction (see figure above).

Therefore : x-component of $\underline{k}_t$ is complex: $\underline{k}_t = (ik_{tx}, 0, k_{tz}) = (ik_{tx}, 0, k_{iz})$

$k_{tz} = k_{iz}$ is a consequence of the required continuity of tangential electric and magnetic field components.

According to Helmholtz equation the dispersion relation requires :

$$k_{tz}^2 - k_{tx}^2 = \frac{\omega^2 \bar{n}_2^2}{c^2} = \bar{n}_2^2 k^2$$

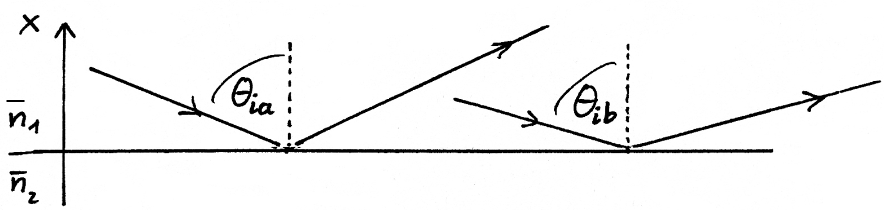
Interference of incident and reflected waves

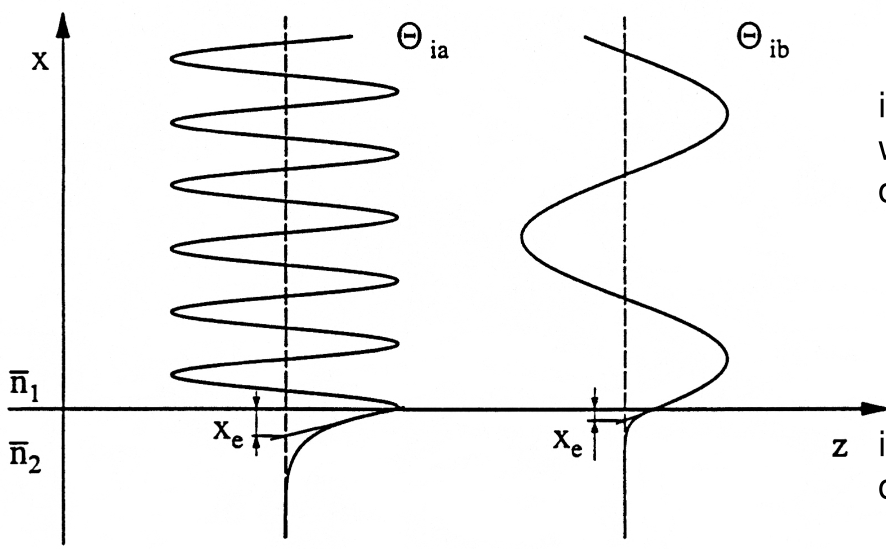
→ different field profiles in x – direction (this sheet)

→ different V_{ph} in z – direction

Illustration for 2 angles above θ_c : $\theta_c < \theta_{ia} < \theta_{ib}$

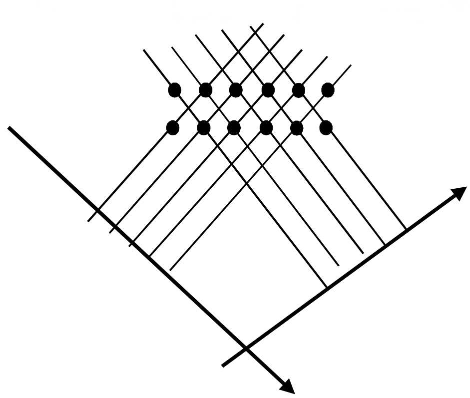
θ_{ia}	θ_{ib}
case	case
a	b



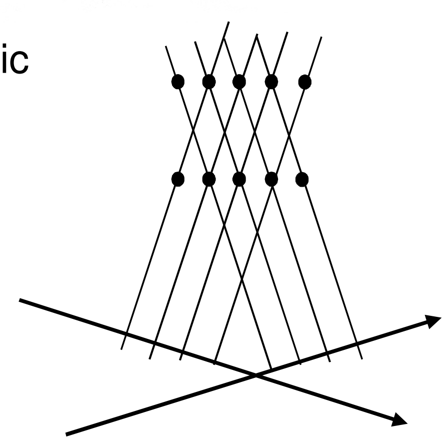


in $\bar{n}_1$ standing waves in x – direction

in $\bar{n}_2$ exponential decay



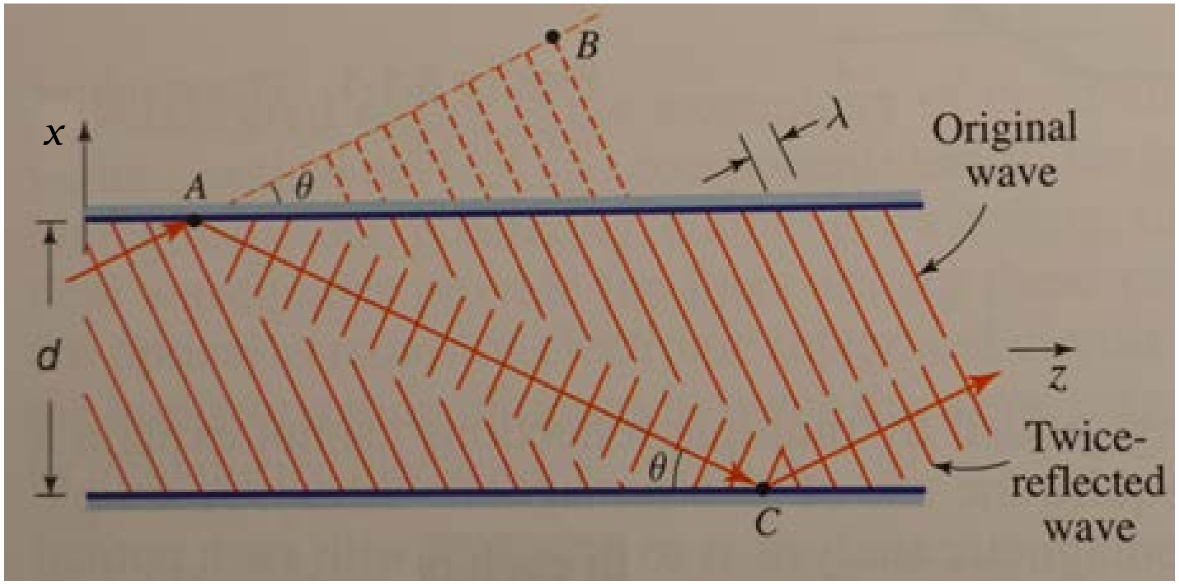
schematic



Constructive interference for light waves

The original wave undergoes interference with the wave reflected twice at the two interfaces

1. We consider the ray model with a plane wave neglecting the penetration into the cladding (ideally reflecting mirrors at the interfaces).



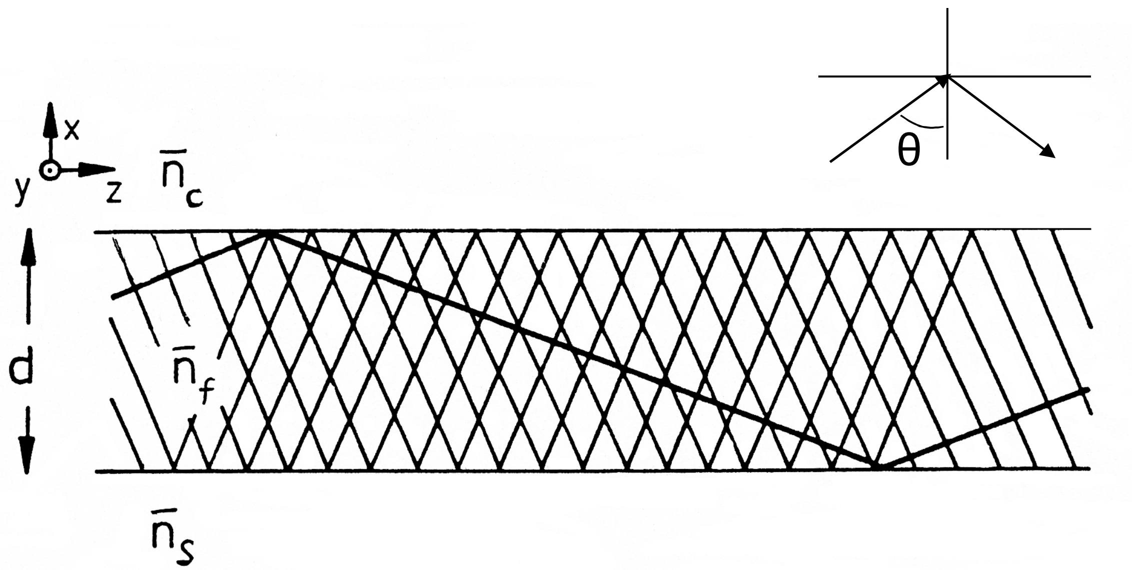
When construtive interference condition is satisfied, the phases of the two upward oriented plane waves reveal a phase shift of an integer multiples of λ .

2. Ray model with a plane wave but including the phase-shifts at the interfaces (see below).
3. Complete wave model, Solution of Helmholtz equation (see below).

Origin of modes in an optical waveguide

A simple illustration: modes correspond to an distinct angle θ.

A uniform total field in which all sub waves interfere constructively (although multiple reflections, zig-zag paths) corresponds to a mode.



→ only destinct θ provide this constructive interference and thus a uniform total field.

In reality : more complicated due to the phase – shifts (2φ) occurring during each internal reflection at the interfaces. Phase – shifts depend on all involved refractive indices and θ; described by Fresnel equations.

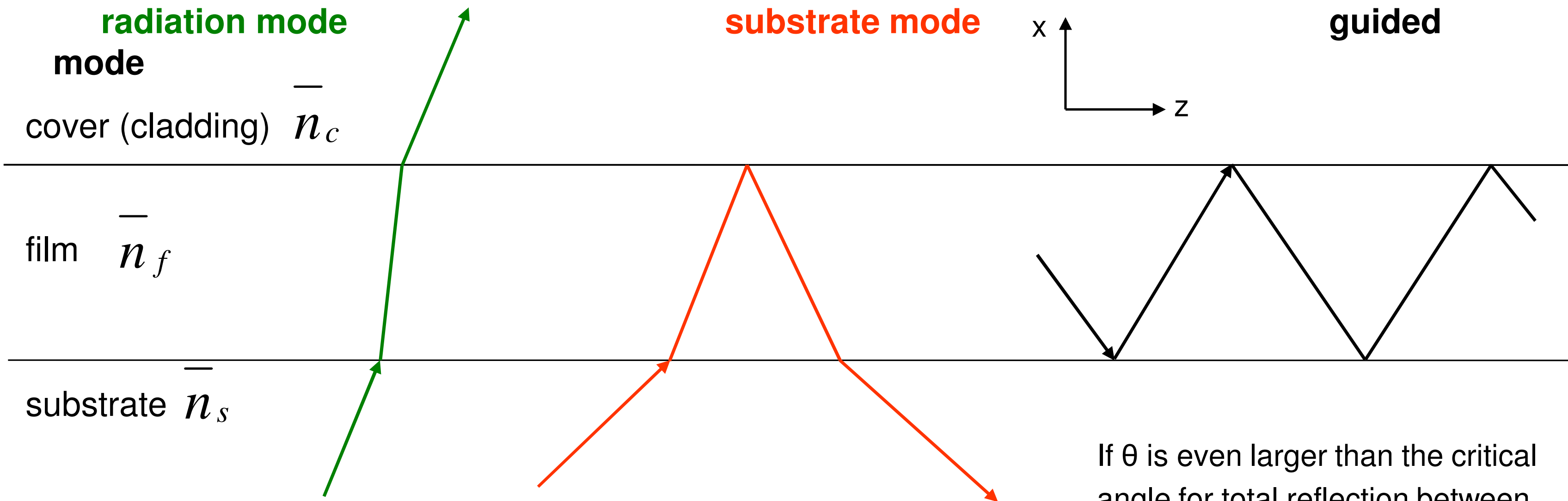
Result :

for TE fields

$$\tan\varphi = \frac{\sqrt{\bar{n}_f^2 \cdot \sin^2\theta_i - \bar{n}_C^2}}{\bar{n}_f \cdot \cos\theta_i}$$

$$\text{for the lower interface: replace } \bar{n}_C \text{ by } \bar{n}_S$$

Two - dimensional planparallel films



for small θ : the wave is refracted at the 2 interfaces

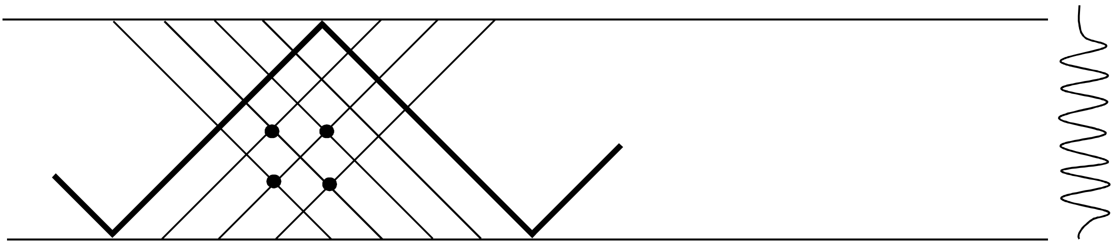
with increasing θ : the critical angle for total reflection at the cover material is reached and the wave is totally reflected. In the cover the wave decays exponentially in x – direction.

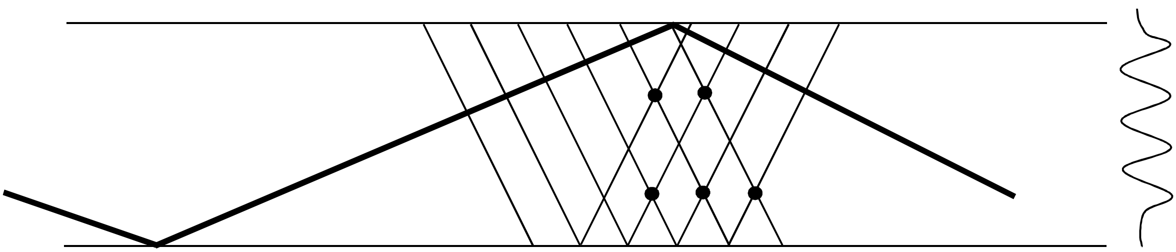
If θ is even larger than the critical angle for total reflection between film and substrate → total reflection occurs at both interfaces.

In the absence of absorption in the film material and absence of scattering at the interfaces : loss-free guiding → no energy escapes from the film.

$$\bar{n}_f > \bar{n}_s > \bar{n}_c$$

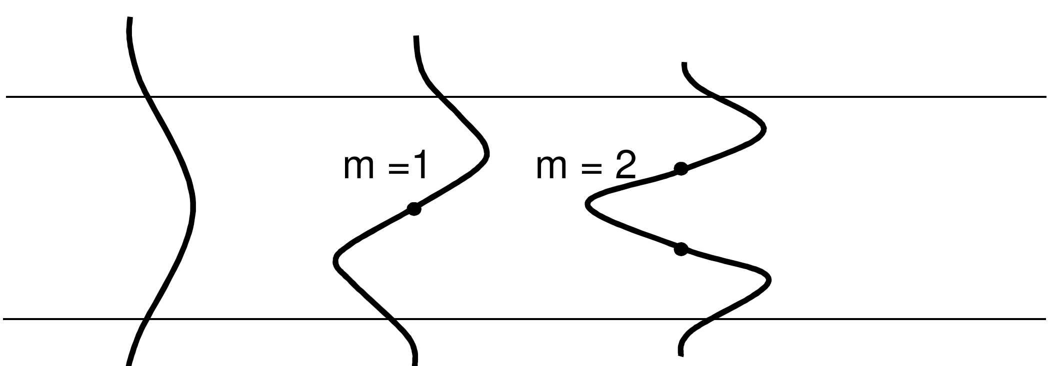
Schematic illustration of the interference of incident and reflected waves



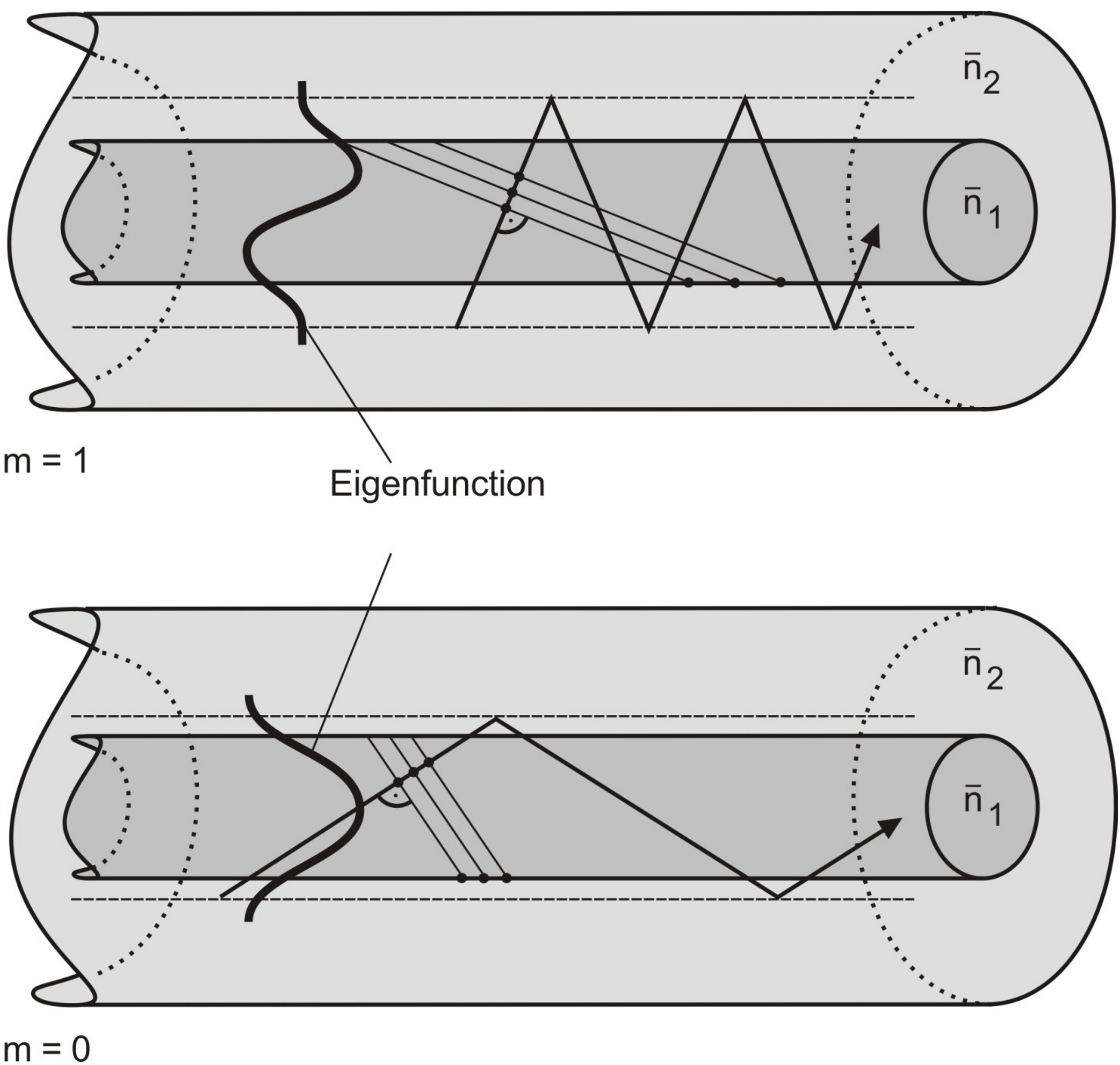


The order of the mode is given by the number of nodes (Knoten).

m is the order of the mode



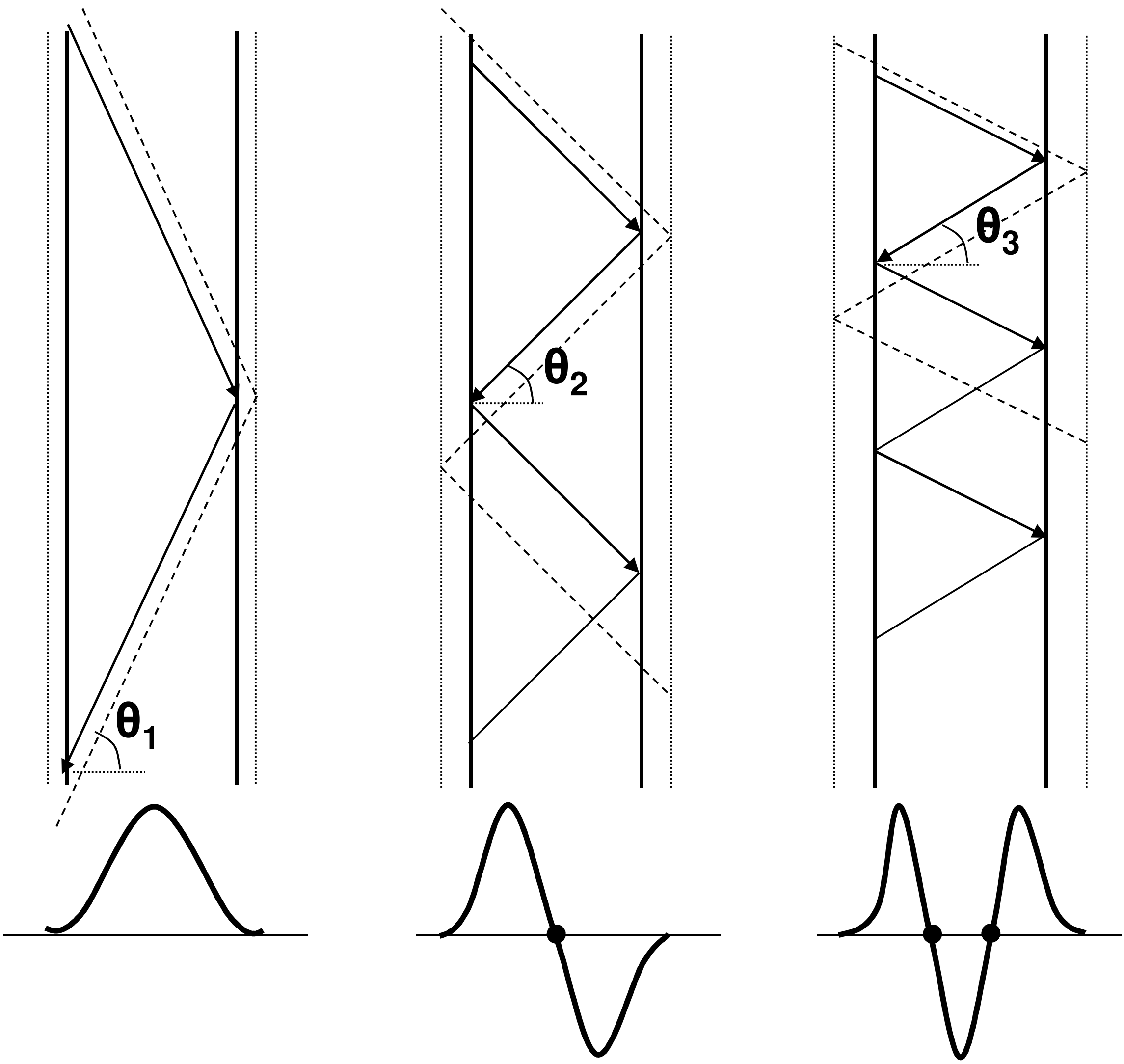
Light propagation in a multimode fibre



Summary of essential features

____ neglecting Goos-Hänchen shift

- - - - including Goos-Hänchen shift (virtual reflecting plane)



fundamental mode | 1. order mode | 2. order mode

$$\bar{n}_{eff\,1} > \bar{n}_{eff\,2} > \bar{n}_{eff\,3}$$

$$v_{ph1} < v_{ph2} < v_{ph3}$$

$$\bar{n}_{eff} = n_f \cdot \sin\theta \qquad \bar{n}_c \leq \bar{n}_s < \bar{n}_{effi} < \bar{n}_f$$

Single – mode waveguide

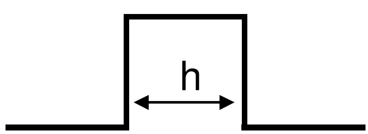
Only the fundamental mode can propagate → a single distinct θ ; all other θ do not provide a uniform constructive interference.

normalized frequency $= kh\sqrt{n_1^2 - n_2^2}$ symmetric case

3 possibilities to make a waveguide monomode :

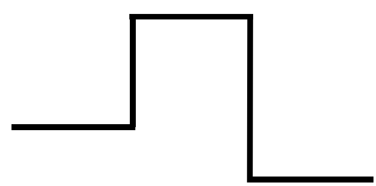
- to choose λ large enough
- to choose waveguide thickness h small enough
- to choose the difference $n_1^2 - n_2^2$ small enough

symmetric



always at least one solution (fundamental mode). The wider h, the more modes exist.

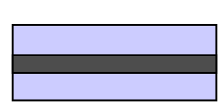
asymmetric

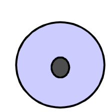


for small h it is possible that no solution exists.

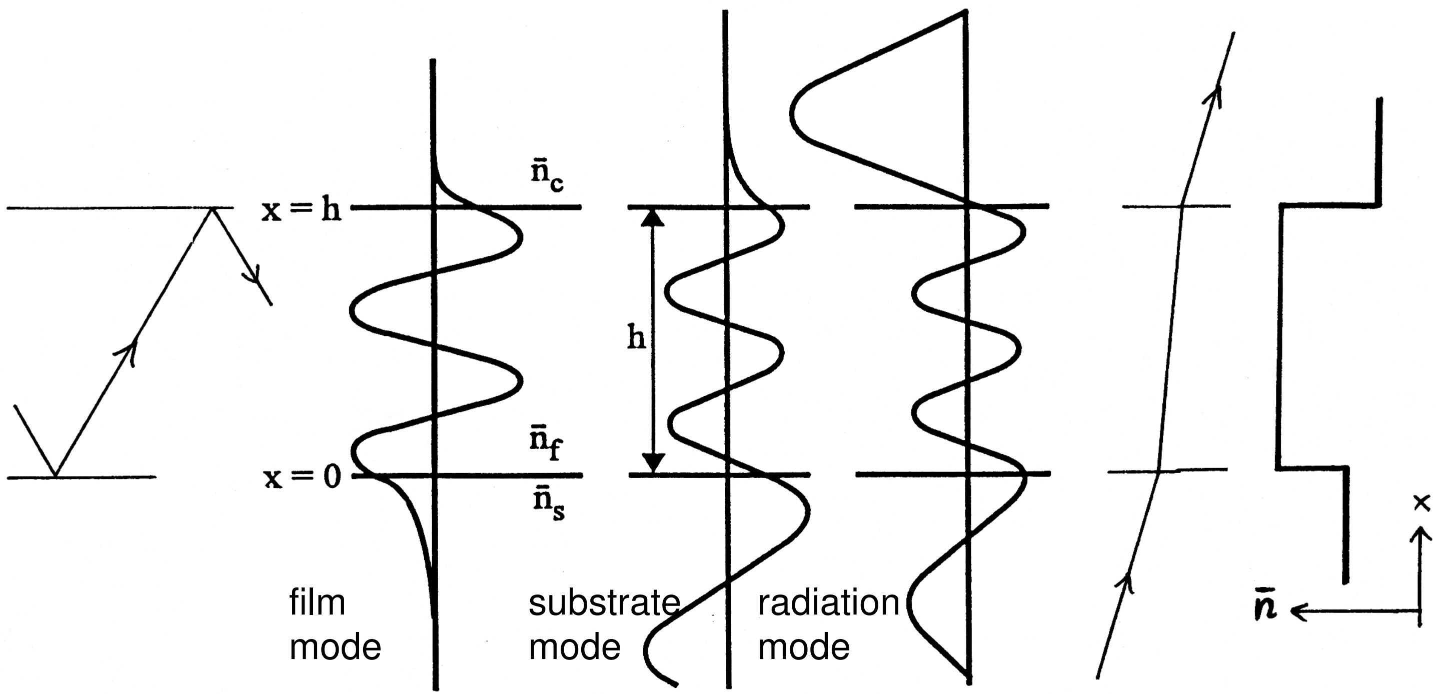
reversely : for a given h, wave guiding exists only below a cut-off frequency.

Note : a planar waveguide is involves 1D problem and a fibre involves a 2D problem. Look similar in a cross-sectional view, but have totally different mode structure !





Examples for field distributions – planar waveguide



$$\bar{n}_f - \bar{n}_c > \bar{n}_f - \bar{n}_s$$

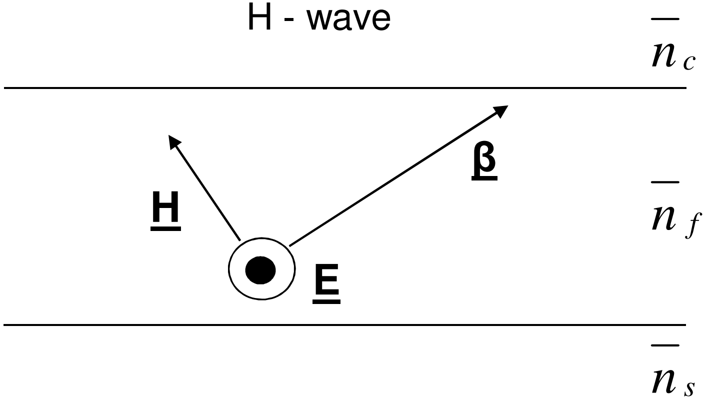
therefore, the field penetrates more into the substrate than in the cover layer for film modes.

Classification of waves and modes in optical waveguides **optoelectronic devices**

TE – Mode

TE – wave

H - wave



E no component in z - direction

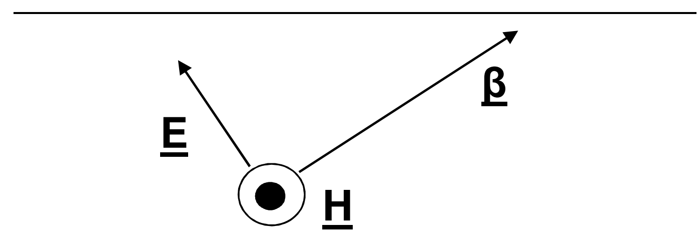
In propagation direction only a

H – component → H wave

TM – Mode

TM – wave

E - wave



H no component in z - direction

In propagation direction only an

E – component → E wave

During a reflection at an interface : phase shifts occur, described by Fresnel`s equations.

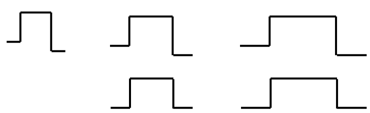
(phase shifts depend on all the involved indices and θ).

→ the TE and TM modes reveal different n_{eff} and different confinement factor.

Guided modes in planar waveguides

1. Inserting the Ansatz of propagating waves into Helmholtz equations provides a system of linear equations to be solved. The condition that a solution of this system of equations exists, provides a transcendent characteristic equation to be fulfilled.

providing → 0, 1 or more eigenvalues



$$\bar{n}_s \le \bar{n}_{eff,i} \le \bar{n}_f$$

$$\bar{n}_{eff} = \frac{\beta}{k} = \bar{n}_f \cdot \sin\theta$$

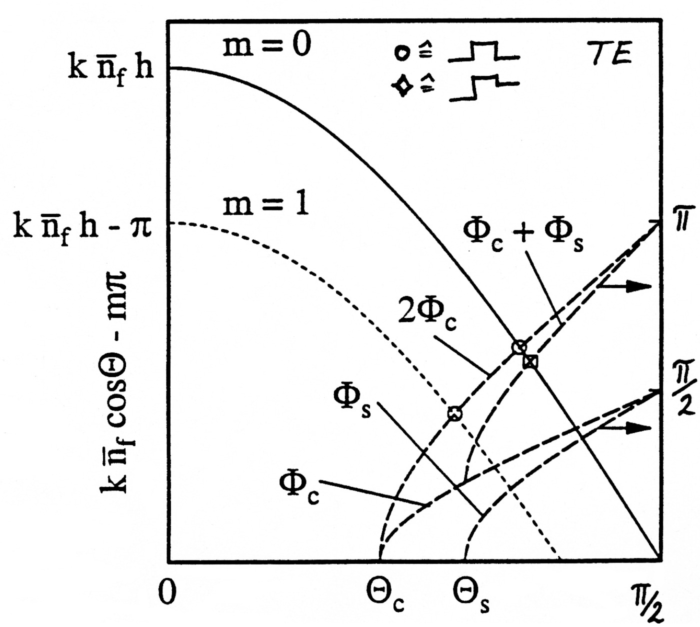
insertion of eigenvalues into the system of equations provides → corresponding eigenfunctions (electric field profiles, modes)

2. Following the intuitive approach : constructive interference providing a uniform total field only occurs for distinct angles θ. The total phase shift in a cycle must amount to an integer of 2π :

$$2k \cdot n_f h \cos\theta - 2\phi_c(\theta) - 2\phi_s(\theta) = m \cdot 2\pi$$

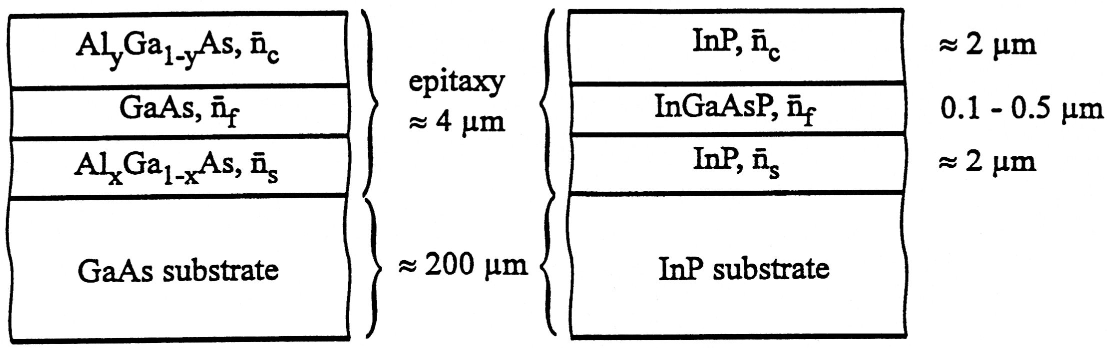
The phase shift after total internal reflection at the cover (substrate) interface is $2\Phi_c$ ($2\Phi_s$). This transcendent characteristic equation determines the permitted angles θ for constructive interference.

Solution → numerically or graphically → For TM – modes the equations are slightly modified. Intersection points (o,)indicate the modes, corresponding angle θ_m.



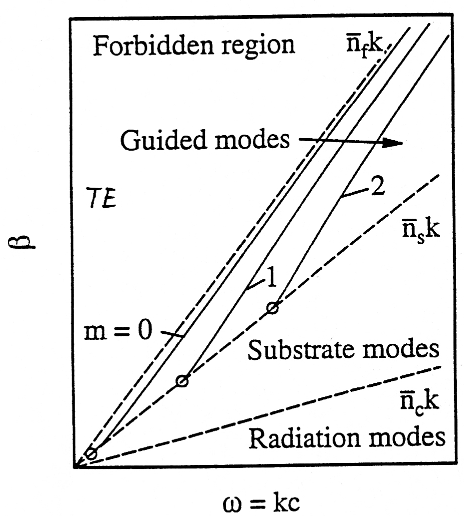
Examples:
Guided modes in planar waveguides

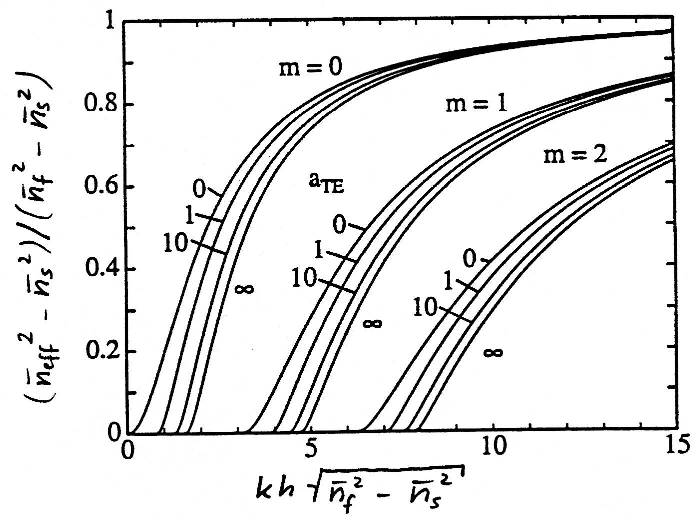
optoelectronic devices



asymmetric waveguide symmetric waveguide

Substrate and cover layers should be at least thick enough for the laterally decaying waves to be sufficiently attenuated before reaching further interfaces.





The dispersion relation ß = ß (ω) is obtained by numerically solving the characteristic equation. For TM – modes nearly identical. The lower cut-off frequency is marked by open circles.

$$a_{TE} = \left(n_s^2 - n_c^2\right)/\left(n_f^2 - n_s^2\right)$$

= asymmetry parameter

The vertical axis can be approximated by $\left(\beta - kn_s\right)/\left(kn_f - kn_s\right)$

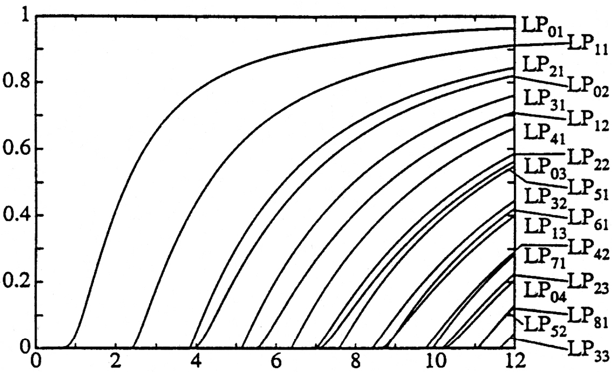
So that also in this figure a normalized dispersion relation ß = ß (k) is shown.

Continuation: wave propagation in step index fibres

$LP_{m\nu}$ = linear polarized modes

$m \geq 0$
$\nu \geq 1$ integers

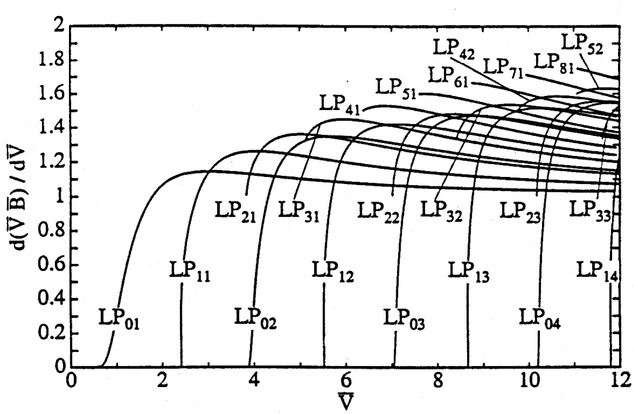
$$\frac{\beta - k\bar{n}_2}{k\bar{n}_1 - k\bar{n}_2}$$



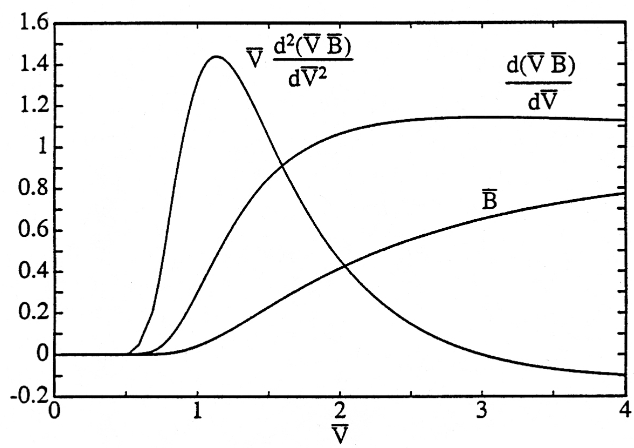
$$ka\sqrt{n_1^{\,2} - n_2^{\,2}}$$

Single mode fibre; weak waveguiding $\bar{n}_1 \approx \bar{n}_2$

Group delay coefficient



normalized propagation constant $\bar{B}$



Some examples: lowest order modes, electric field are shown

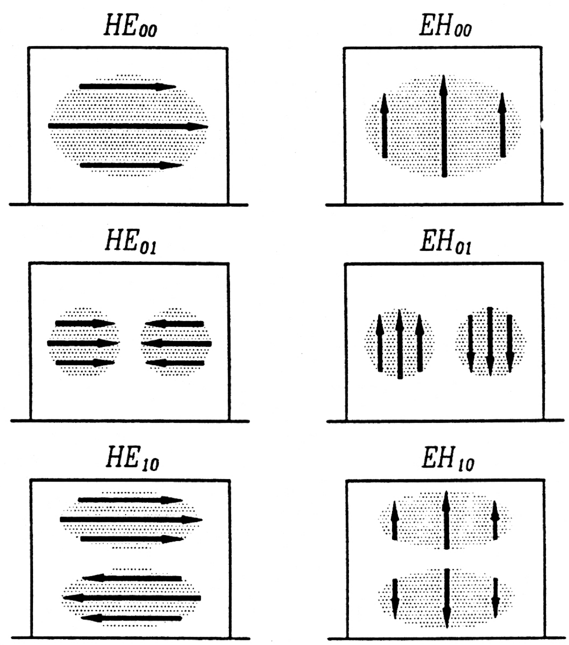
a) rectangular shaped waveguide

modes are not purely TM or TE like but mixtures: Hybrid – modes :

HE_{mn} originate from TE – modes
but E_y >> E_z , E_y

EH_{mn} originate from TM – modes
but E_x >> E_y , E_z

E^{y}_{00} E^{y}_{01} E^{y}_{10}



E^{x}_{00} fundamental mode

E^{x}_{01} 0 nodes in x - direction
1 nodes in y - direction

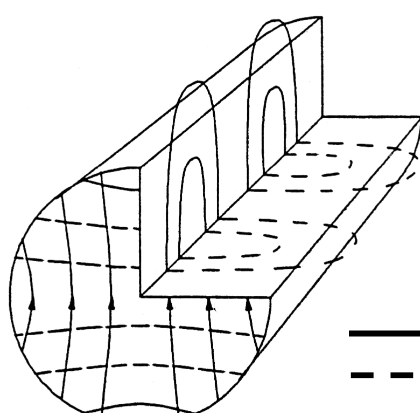
E^{x}_{10}

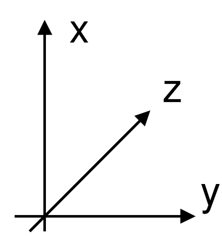
another classification scheme

b) fibre

also here : modes are hybrid modes $HE_{\nu\mu}$, $EH_{\nu\mu}$

HE_{11}

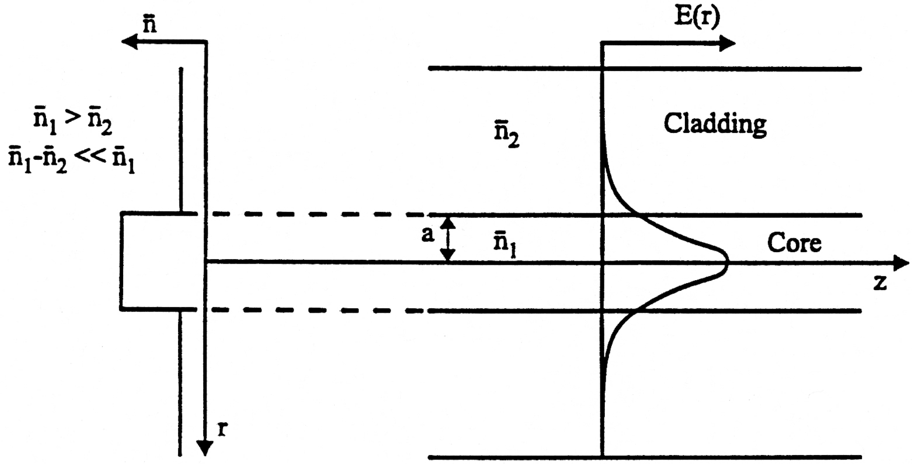




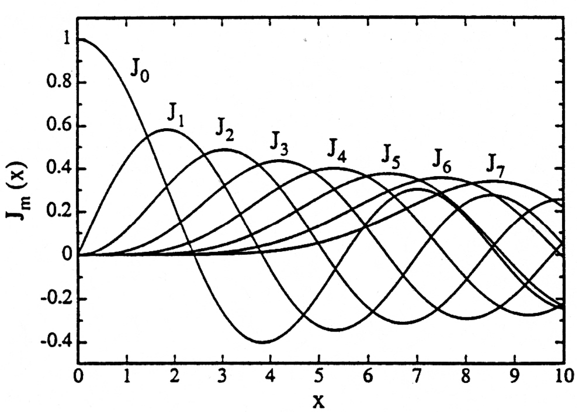
Electric field
Magnetic field

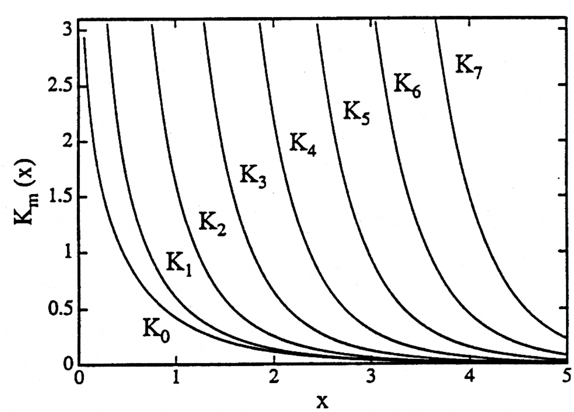
Wave propagation in step index fibres

Cylindrical symmetry. If $\overline{n}_1 \approx \overline{n}_2$ $\rightarrow$ linearly polarized propagating waves is a reasonable assumption.



Solution of Helmholtz´s equation in cylindrical coordinates (r, φ) involves Bessel functions I_m and modified Bessel functions K_m.



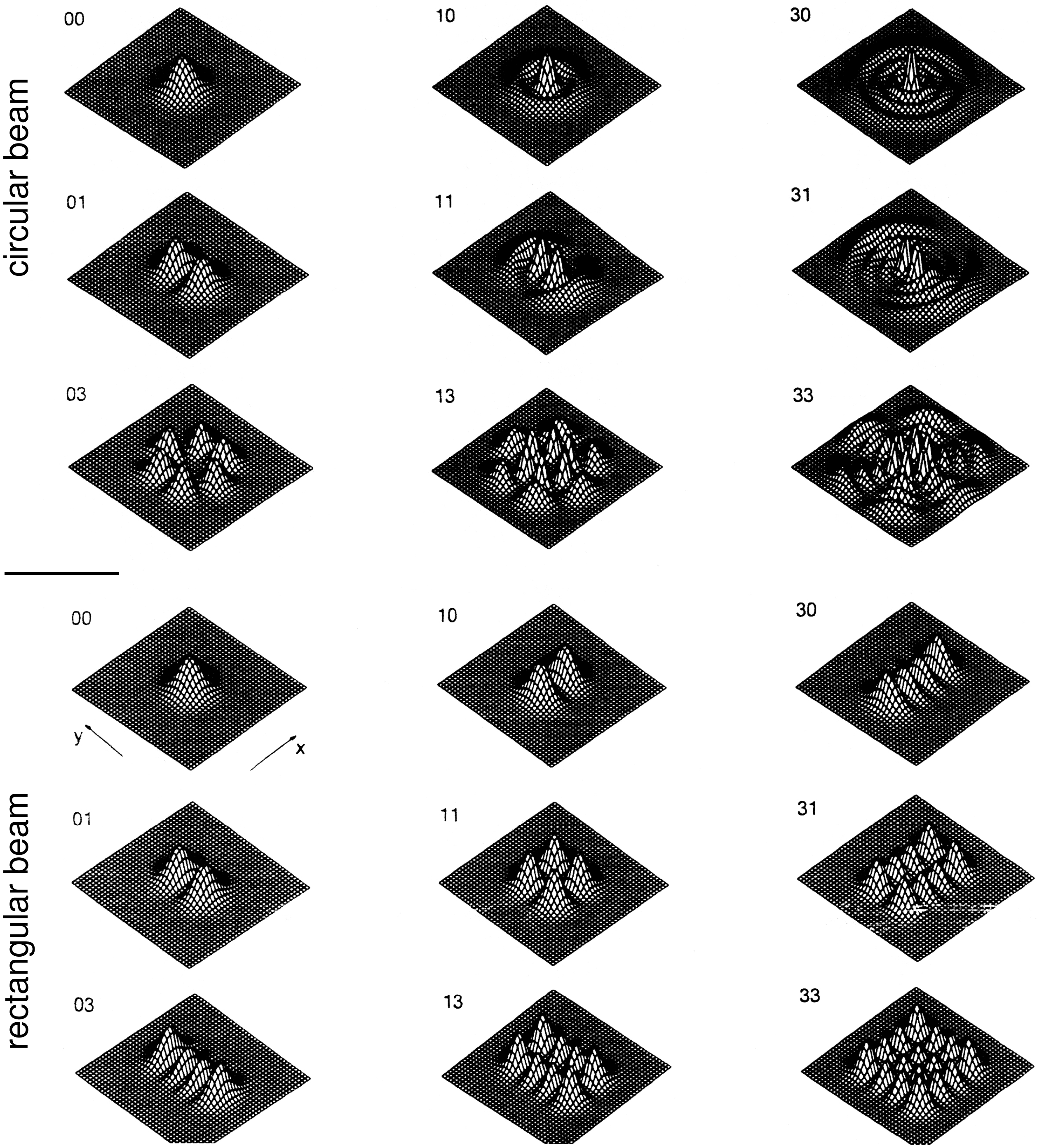


$$E(r,\varphi,z,t)=\begin{cases} C_1 I_m(ur/a)\cos(m\varphi+\varphi_0)\exp[i\omega t - i\beta z] & \text{for } r \le a \\ C_2 K_m(\omega r/a)\cos(m\varphi+\varphi_0)\exp[i\omega t - i\beta z] & \text{for } r \le a \end{cases}$$

$$U = a\sqrt{k^2 \overline{n}_1^2 - \beta^2} \quad \text{and} \quad w = \sqrt{\beta^2 - k^2 \overline{n}_2^2}$$

m integer, C_1, C_2 complex constants to be determined by the boundary conditions.

Circular and rectangular waveguide



Dispersion, overview

A. Modal dispersion (= intermodal dispersion) in multimode fibres Warning : the intuitive ray model does not provide all answers; Wavemodel (Helmholtz equation) → Dispersion relation → v_{gr} , n_{gr}; v_{gr} depends on λ via (different θ) different eigenfunctions, different cladding penetration.

B. Chromatic dispersion (= spectral dispersion) of the group velocity
   - Material dispersion $\bar{n}_i = \bar{n}_i(\lambda)$
     v_{gr} depends via the refractive index on λ.
   - Waveguide dispersion v_{gr} depends via the waveguide geometry on λ.

C. Polarization mode dispersion due to fibre bending, not axial inhomogeneties

D. Profile dispersion

Conclusion

Transmission in different spectral ranges

Optical transmission characteristics of optical fibres is determined by attenuation and bandwidth (dispersion)

Attenuation is affected by:

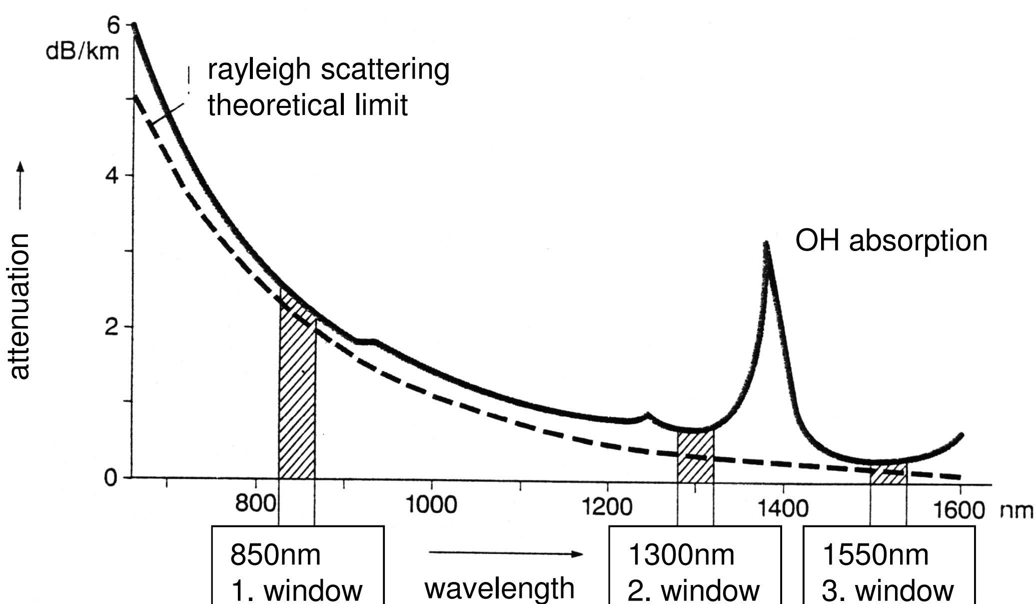
- rayleigh scattering
- absorption
- radiation losses

Bandwidth is limited by:

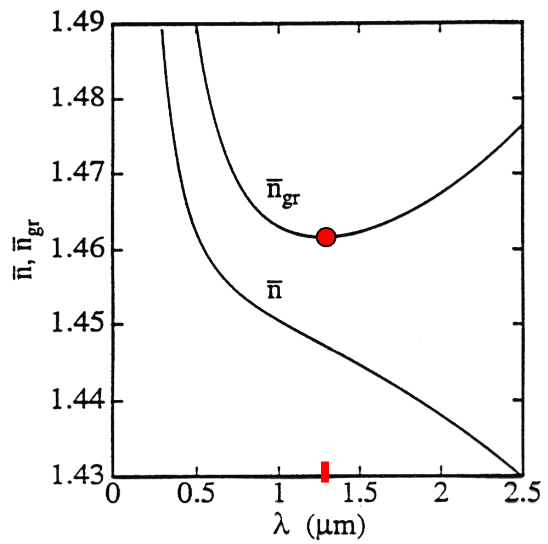
- modal dispersion
- material dispersion
- waveguide dispersion

Silica glass optical fibre (SiO_2) show three different „transmission windows" which show optimum attenuation and bandwidth.

- 1. window at λ= 850nm (cost-effective laser)
- 2. window at λ= 1300nm (minimal dispersion)
- 3. window at λ= 1550nm (minimal absorption)



Group index and group dispersion



minimum at λ_0 = 1.273 μm

$$\bar{n} = \frac{c}{v_{ph}} \qquad \text{analogous:}$$

$$\bar{n}_{gr} = \frac{c}{v_{gr}} = \frac{c}{d\omega/d\beta} = c\frac{d\beta}{d\omega} = c\frac{d}{d\omega}\left(\frac{\omega\bar{n}}{c}\right)$$

$$= \bar{n} + \omega\frac{d\bar{n}}{d\omega} \underset{\uparrow \text{exercise}}{=} \bar{n} - \lambda\frac{d\bar{n}}{d\lambda}$$

determined by

v_{ph}: propagation velocity of a monochromatic wave $\Big\}\ \bar{n}$

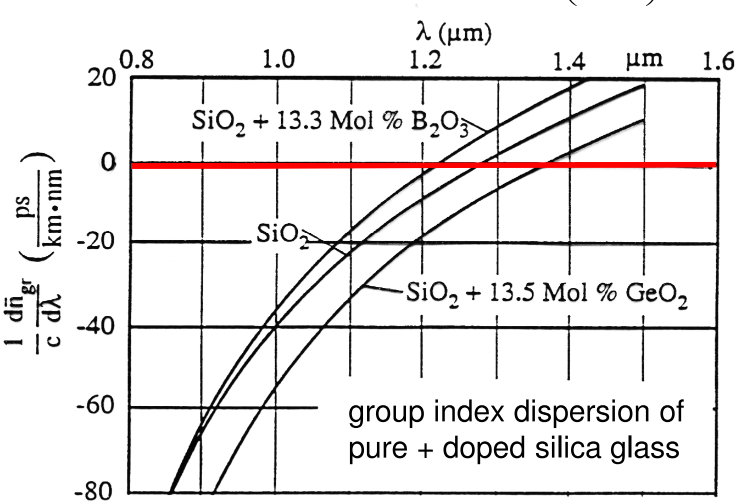
v_{gr}: propagation velocity of an optical pulse $\Big\}\ \bar{n}_{gr}$

Propagation of single elementary pulses of different carrier wavelength λ along L:

time delay $t = \frac{L}{v_{gr}} = \frac{L}{c}\bar{n}_{gr}$ of a single pulse

delay difference between 2 pulses with shifted carrier wavelength Δλ $\quad \Delta t \approx \frac{dt}{d\lambda}\Delta\lambda = \frac{L}{c}\cdot\frac{d\bar{n}_{gr}}{d\lambda}\Delta\lambda$

Delay difference per L: $\frac{\Delta t}{L} \approx \frac{\Delta\lambda}{c}\cdot\left(\frac{d\bar{n}_{gr}}{d\lambda}\right) = \frac{\Delta\lambda}{c}\cdot\left(\cancel{\frac{d\bar{n}}{d\lambda}} - \cancel{\frac{d\bar{n}}{d\lambda}} - \lambda\cdot\frac{d^2\bar{n}}{d\lambda^2}\right)$



remember:

time delay difference Δt in ps of 2 gaussian pulses with carrier frequency difference Δλ = 1 nm apart after travelling L = 1 km

Dispersion, overview

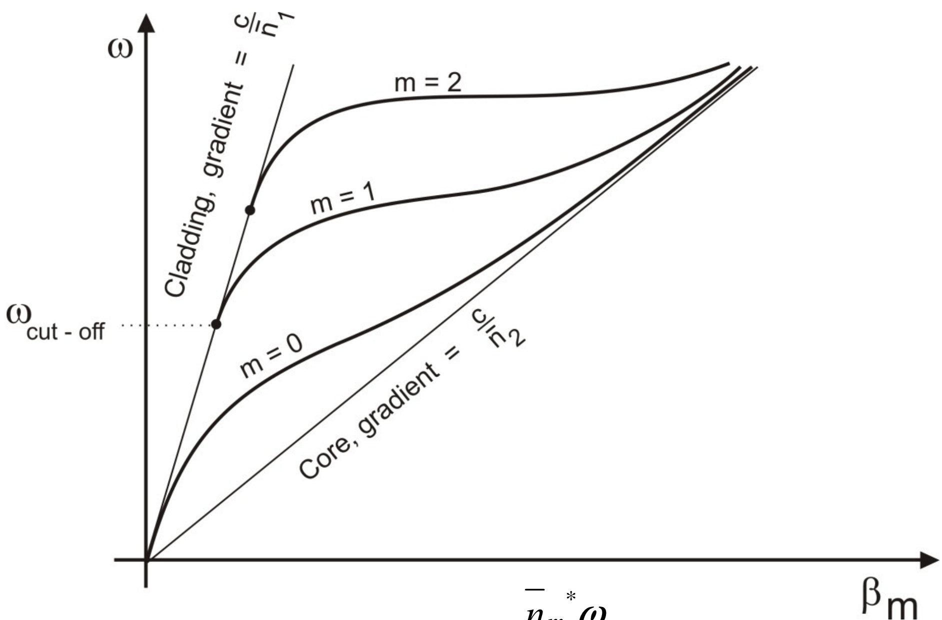
Dispersion relations Ω = Ω (k) Phonon waves in crystals,

Polariton waves in crystals

E = E (k) Electrons and holes in crystals

ω = ω (β_m) Photons in layered media

(waveguides, fibres)



$$\beta_m = k_1 \cdot \sin\theta_m = \frac{\bar{n}_m^{\,*}\omega}{c}$$

$\bar{n}_m^{\,*}$ - Eigenvalues

k - wave vektor

β_m - propagation constant in z - direction

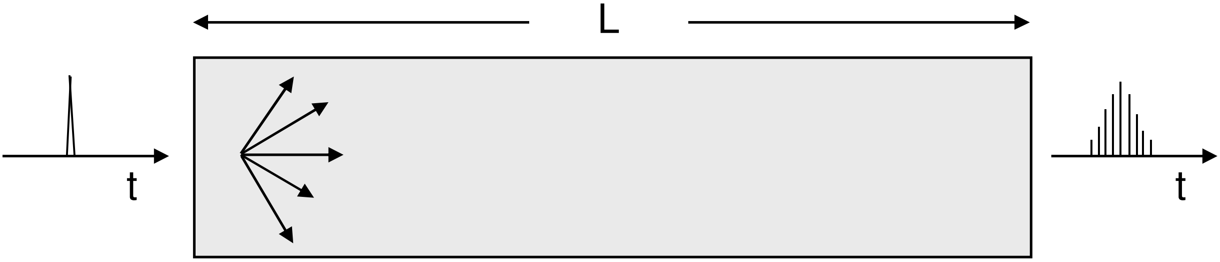
Note that: $\bar{n}_i = \bar{n}_i$ (λ) is not yet included. This material dispersion would modify the straight lines into slightly bent lines.

v_{gr} changes from mode to mode (intermodal dispersion and within a mode with λ (intramodal dispersion).

Modal dispersion

First, only modal dispersion considered:

Mode number : m = 0, 1, 2, ...



Light travels using different modes, propagating at different V_{gr}, respectively.

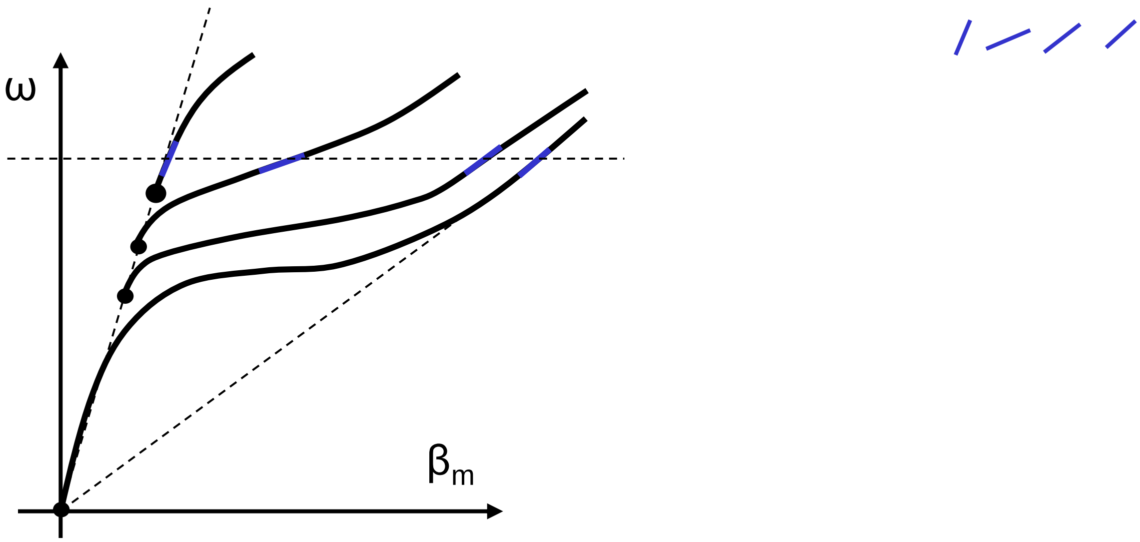
$$\Delta\tau = \frac{L}{v_{g,\min}} - \frac{L}{v_{g,\max}}$$

$$v_{g,\,\min} = \frac{c}{n_1} \qquad v_{g,\,\max} = \frac{c}{n_2}$$

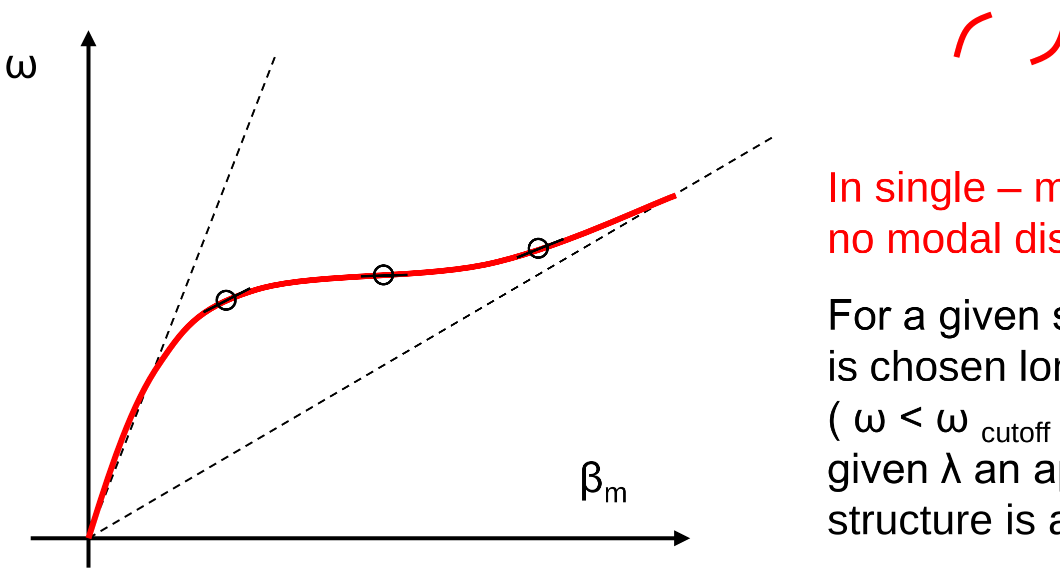
Neglecting that in between there may exist smaller slopes !
Intermodal dispersion related to the different slopes (waveguide dispersion as a part of intramodal dispersion is related to the evivatures.

Modal dispersion and Waveguide dispersion

a) Modal dispersion in a Multimode fibre; ω = const in this example. Intermodal dispersion related to the different slopes



b) Waveguide dispersion in a single mode fibre; small variation of ω (e.g.within the spectral laser line).Waveguide dispersion as a part of intramodal dispersion is related to the curvatures.



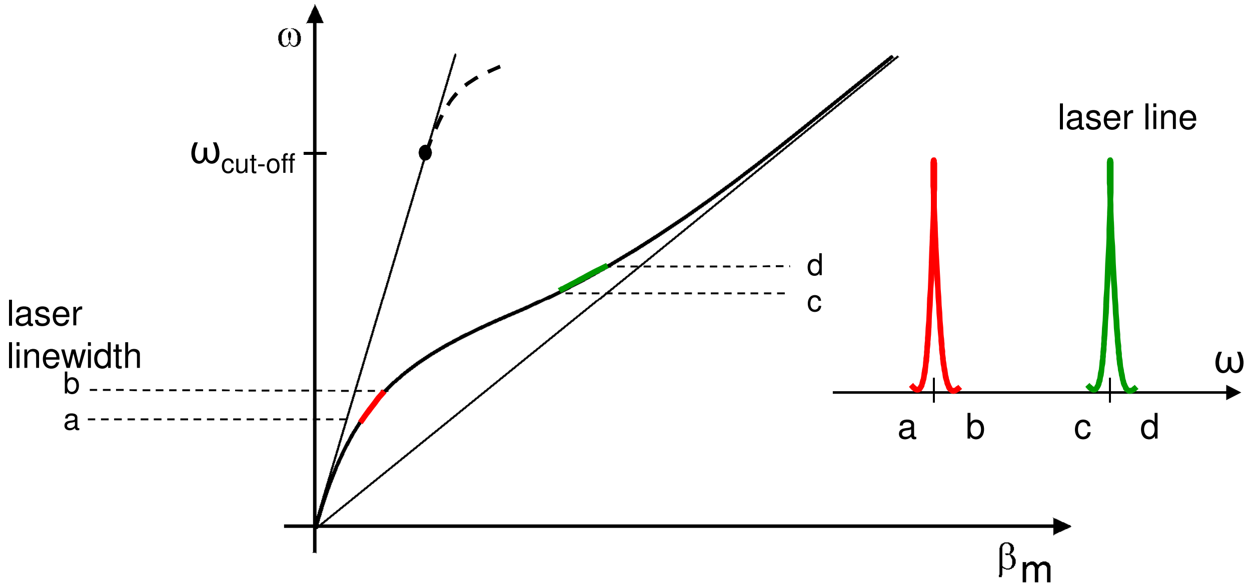
In single – mode fibres no modal dispersion;

For a given structure, λ is chosen long enough ($\omega < \omega_{cutoff}$) or for a given λ an appropriate structure is applied.

c) Waveguide dispersion also occurs in multimode fibres, e.g. in the lowest branch of the dispersion relation (a) and, thus, is similar to dispersion relation branch shown in red under b.

Waveguide dispersion

Now single-mode fibres considered (no modal dispersion) $\omega < \omega_{cut\text{-}off}$



v_{gr} depends on λ

Since : - mode profiles and eigenvalues depend on λ.

- in the ray model: for a constructive interference, slightly different λ require slightly different pathes (angles).

case 1: if $\omega_a < \omega_b < \omega_{cut\text{-}off}$

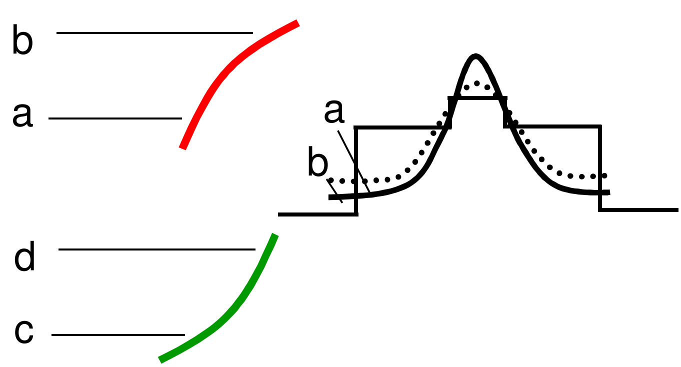
$\lambda_a > \lambda_b > \lambda_{cut\text{-}off}$

$v_{gr,a} > v_{gr,b}$

case 2: if $\omega_c < \omega_d < \omega_{cut\text{-}off}$

$\lambda_c < \lambda_d < \lambda_{cut\text{-}off}$

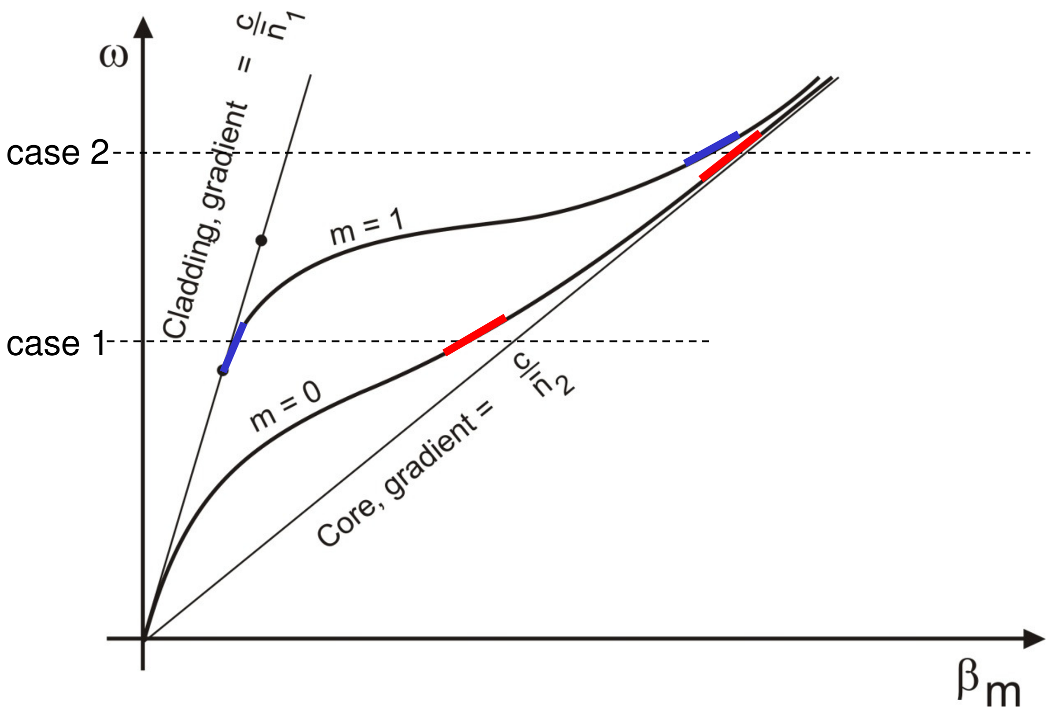
$v_{gr,c} < v_{gr,d}$



However :

a) in special situations the relation of the group velocities may be reverses according to the dispersion relation.

b) The cases v_{ph} ≤ and ≥ v_{gr} additionally exist.



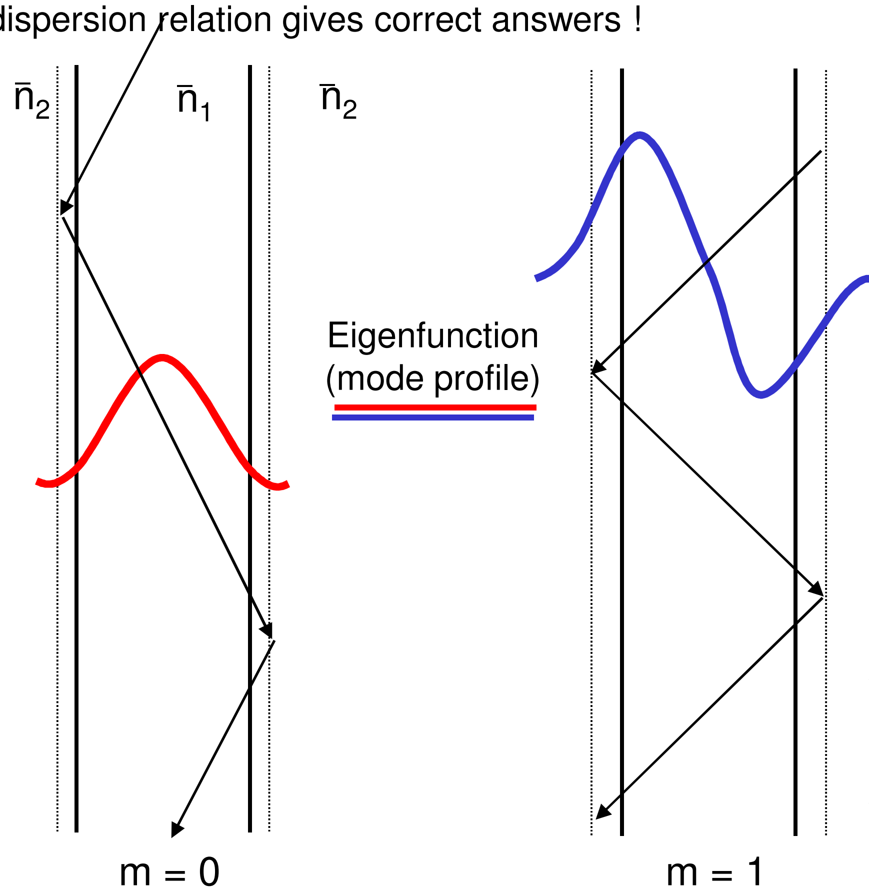
Modal dispersion

Warning: the simple view (ray model) : light traveling along the path of the fundament mode arrives more quickly than a higher „mode ray“ is wrong due to two reasons :

- v_g in z – direction is important
- Higher order modes penetrate more into the cladding where refractive index is low.

Only the dispersion relation gives correct answers !

However here also the ray model



$$v_{ph} = \frac{c}{\bar{n}_{eff}}$$

in z - direction but important is v_{gr}

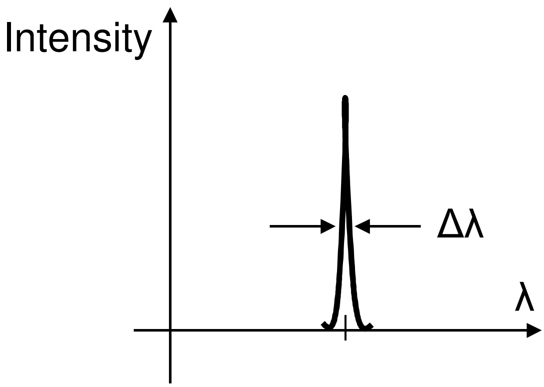
$\bar{n}_{eff}$ highest — Eigenvalue — $\bar{n}_{eff}$ lower

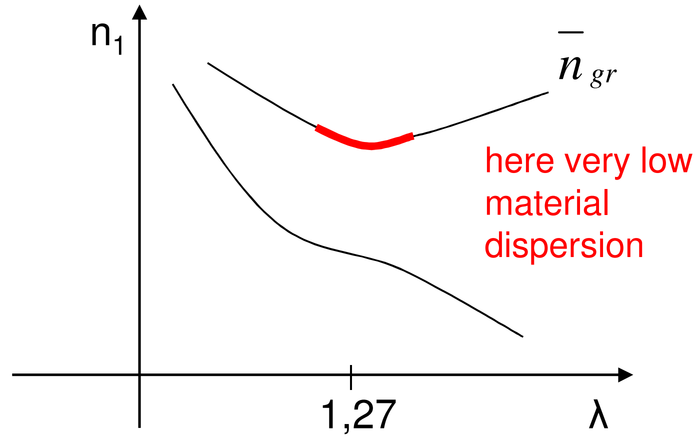
more in the core — more in the cladding

v_{ph} smaller ← always → v_{ph} larger

v_{gr} smaller ← in many cases → v_{gr} larger

Material Dispersion





$$\bar{n}_1 = \bar{n}_1(\lambda) \quad \rightarrow \quad \bar{n}_{gr} = \bar{n}_{gr}(\lambda) \qquad v_{gr} = \frac{d\omega}{dk} = \frac{c}{\bar{n}_{gr}}$$

$$v_{gr} = \frac{L}{t} = \frac{c}{\bar{n}_{gr}} \qquad dt = \frac{L}{c} d\bar{n}_{gr} \quad \text{Differentiation of the path - time law.}$$

$$\Delta\tau = \frac{L}{t} \cdot \frac{d\,\bar{n}_{gr}}{d\lambda} \Delta\lambda \qquad \bar{n}_{gr} = \bar{n} - \lambda \frac{d\bar{n}}{d\lambda} \qquad (\text{is a consequence of: } \bar{n}_{gr} = c\frac{d\beta}{d\omega} = c\frac{d}{d\omega}\left(\frac{\omega\bar{n}}{c}\right))$$

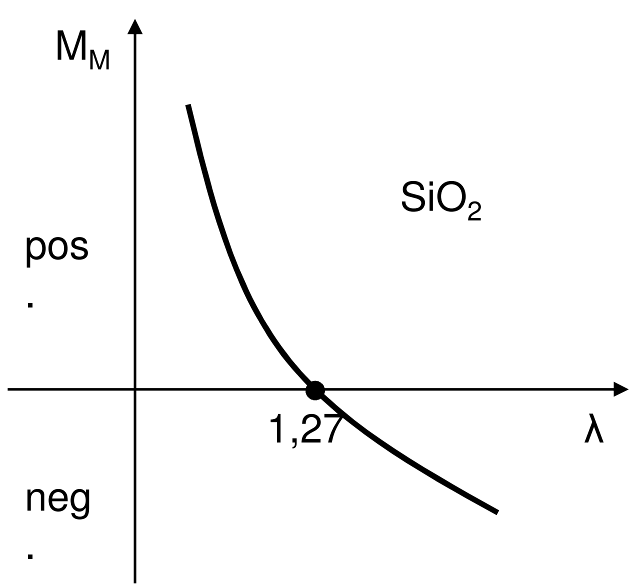
$$\rightarrow \quad \frac{\Delta\tau}{L} = \frac{\Delta\lambda}{c}\left(\frac{d\bar{n}}{d\lambda} - \frac{d\bar{n}}{d\lambda} - \lambda\frac{d^2\bar{n}}{d\lambda^2}\right) \qquad \frac{\Delta\tau}{L} = |M_M|\Delta\lambda$$

$$M_M = -\frac{\lambda}{c} \cdot \frac{d^2\bar{n}}{d\lambda^2}$$

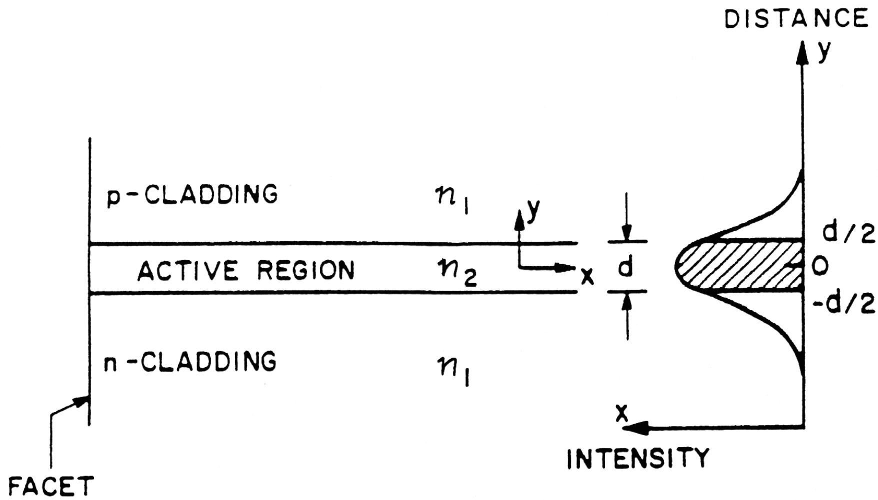
$v_{gr} = v_{ph}$ no dispersion

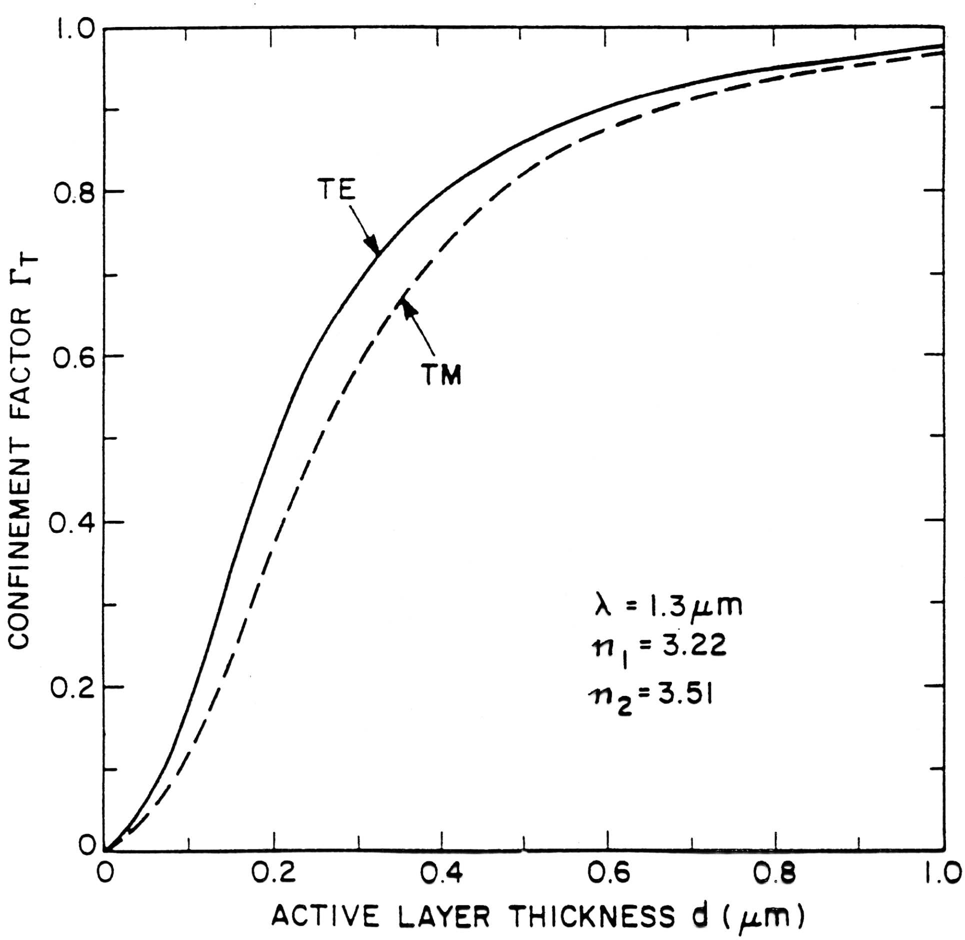
$v_{gr} < v_{ph}$ normal dispersion

$v_{gr} > v_{ph}$ abnormal dispersion



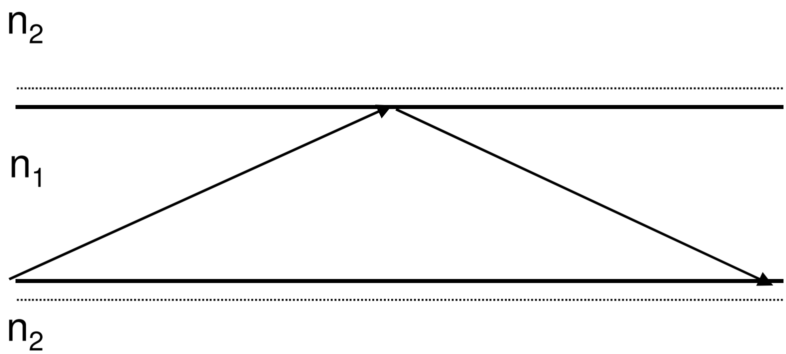
Confinement of the guided light field in the central layer





Dispersion

1. Mode dispersion



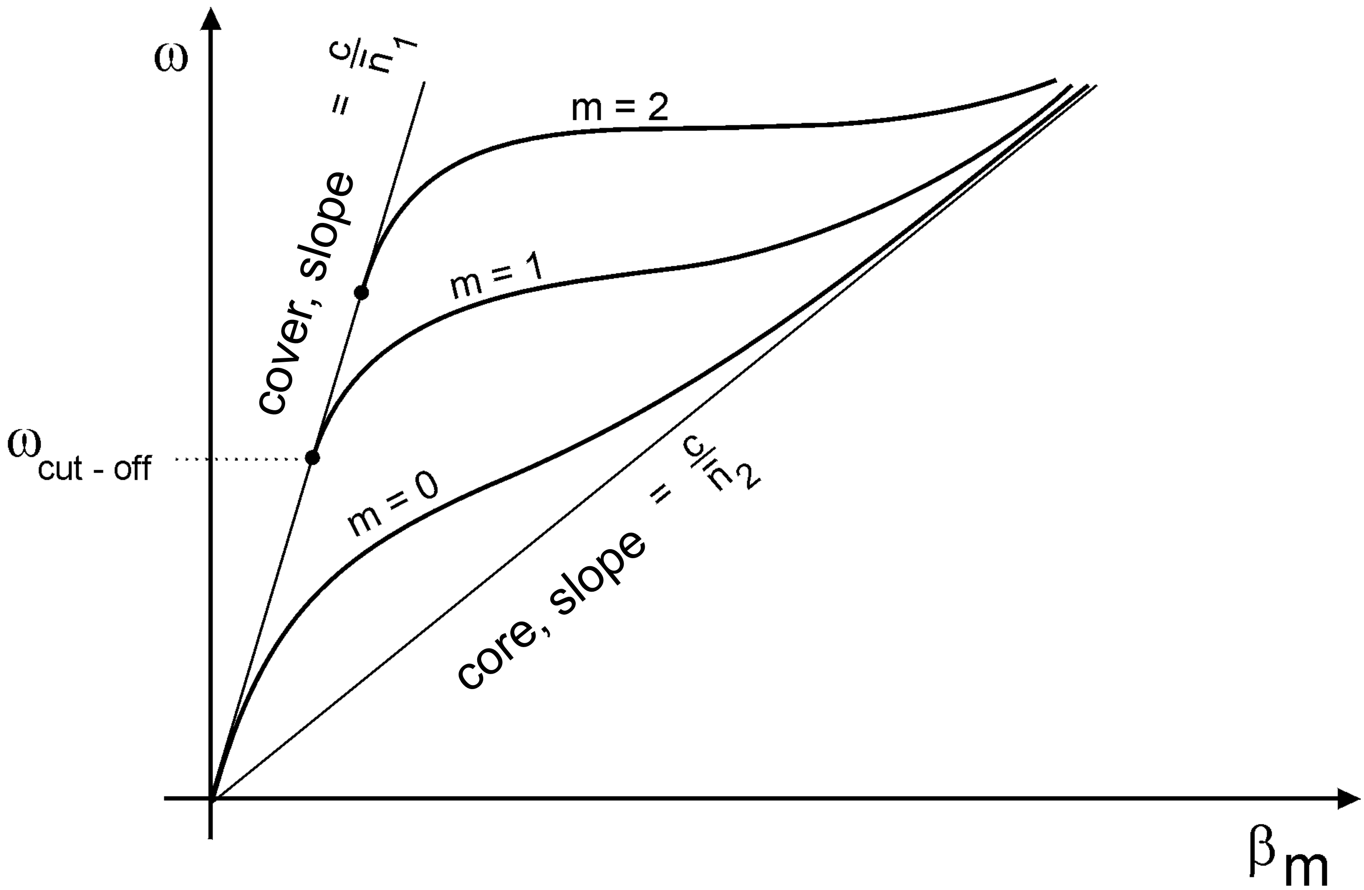
2. Chromatic dispersion = material dispersion + waveguide dispersion

   a) material dispersion $\bar{n}(\lambda)$

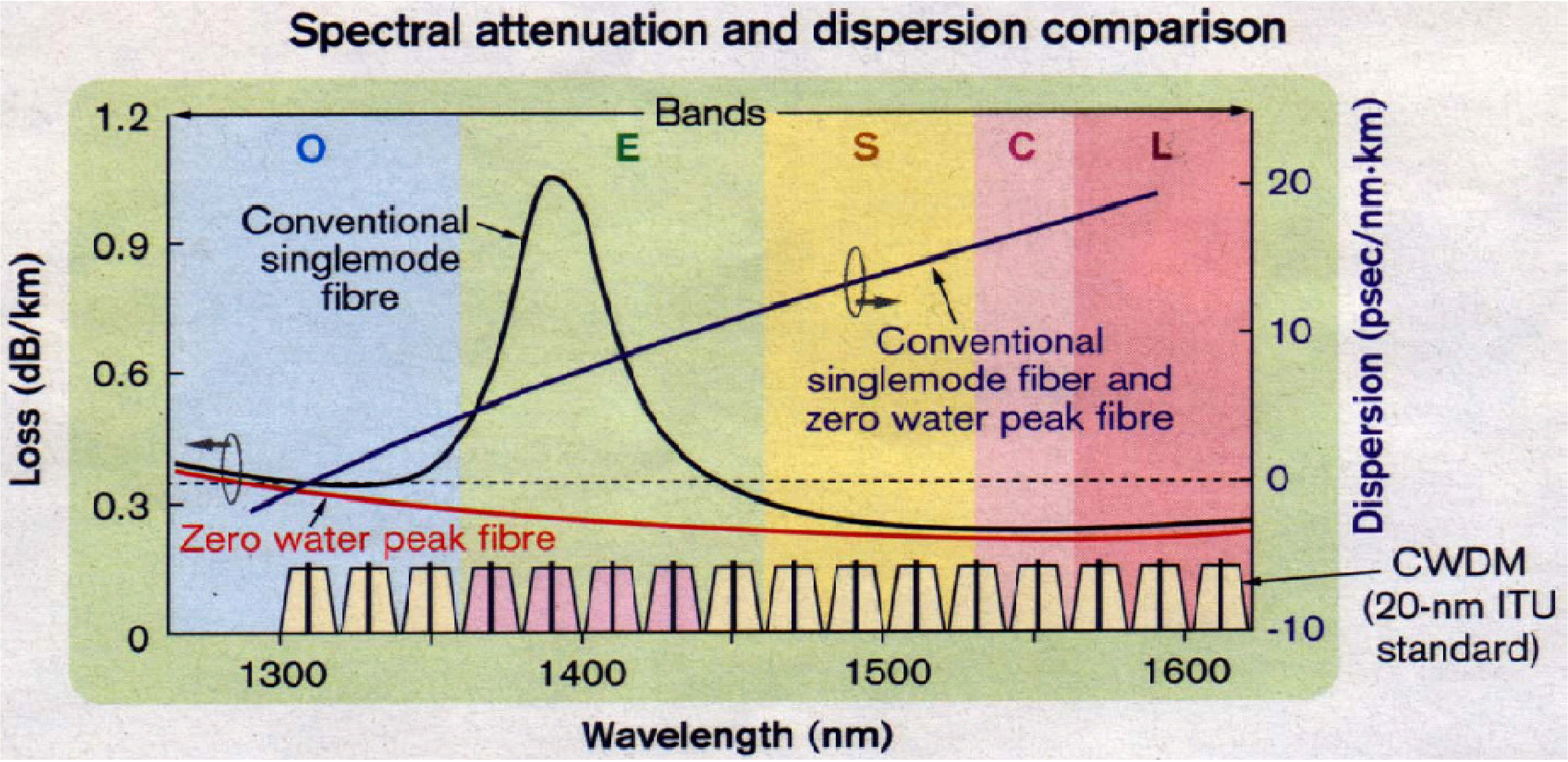
$$\frac{\Delta t}{l} = |M| \cdot \Delta\lambda = -\frac{\lambda}{c}\frac{d^2 n}{d\lambda^2}$$

   b) waveguide dispersion $\bar{n}(x)$

Dispersion relation of a multimode step-index fibre



schematic view of the dispersion relation of a quartz glass fibre, fundamental mode m=0, mode of first order m=1, mode of second order m=2

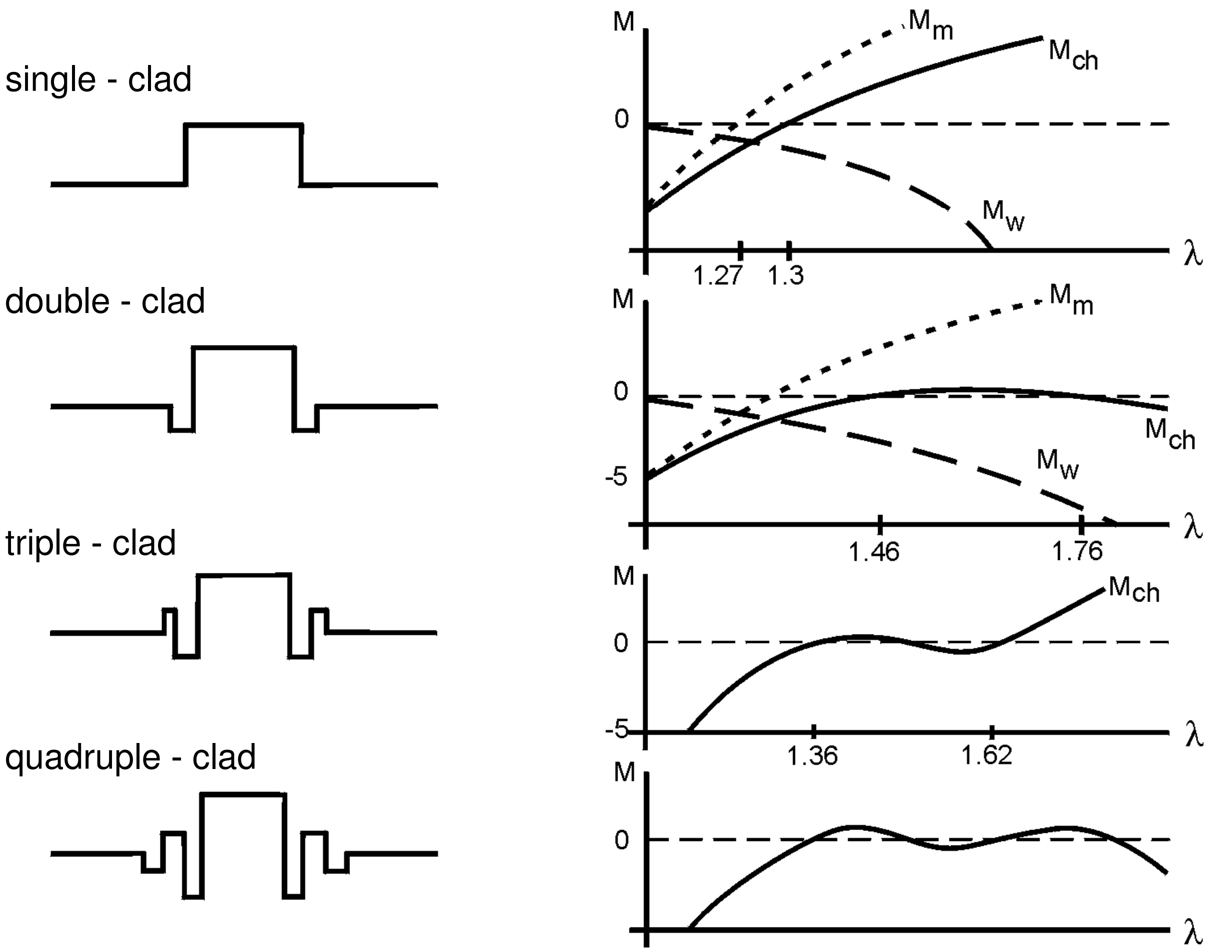

Spectral attenuation and dispersion comparison
Bands
O
E
S
C
L
1.2
0.9
0.6
0.3
0
Loss (dB/km)
20
10
0
-10
Dispersion (psec/nm·km)
Conventional singlemode fibre
Conventional singlemode fiber and zero water peak fibre
Zero water peak fibre
CWDM (20-nm ITU standard)
1300
1400
1500
1600
Wavelength (nm)

Multiple cladding profile fibre

Interplay of material and waveguide dispersion in different single – mode fibres

- the waveguide dispersion coefficient M_w (ps / (km*nm)) depends in a complicated way on geometry and refractive index profile of the fibre
- the material dispersion coefficient M_M (ps / (km*nm)) describes the wavelength dependence of the refractive index in a homogeneous bulk (3D) material.

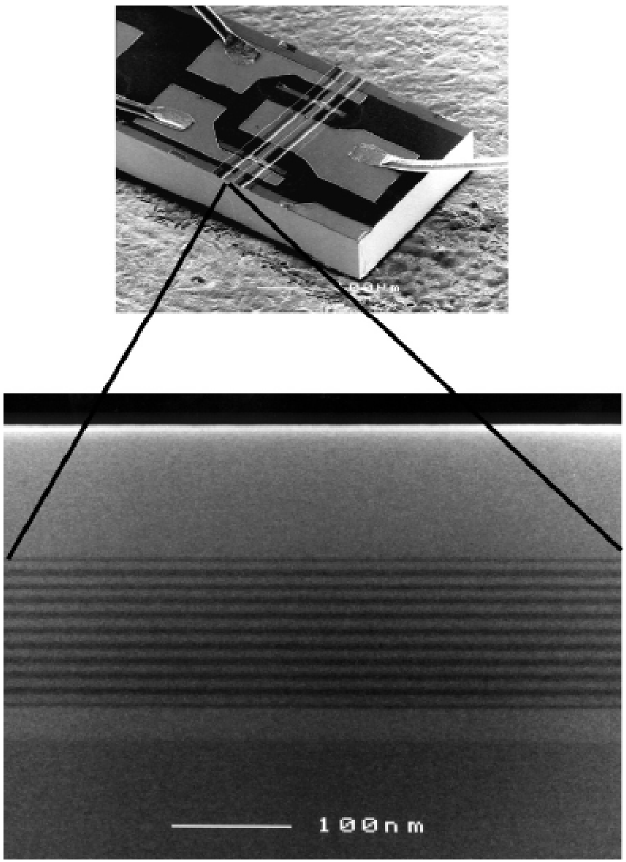
$$M_M = \frac{1}{c} \cdot \frac{d\bar{n}_{gr}}{d\lambda} = -\frac{\lambda}{c} \cdot \frac{d^2 \bar{n}_i}{d\lambda^2}$$



$$M_{Ch} = M_M + M_W$$

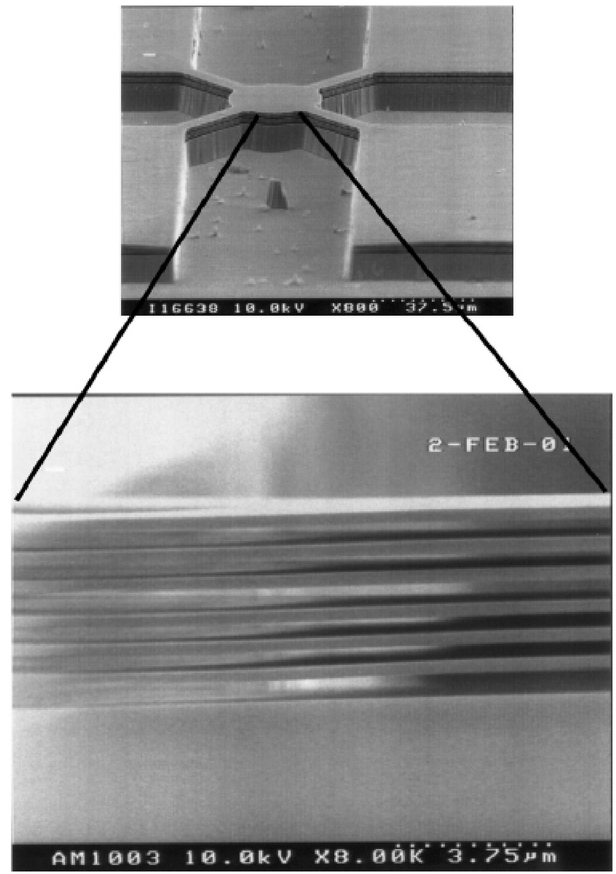
Micro optoelectronic devices

Tunable DFB laser



Multiple quantum well structure

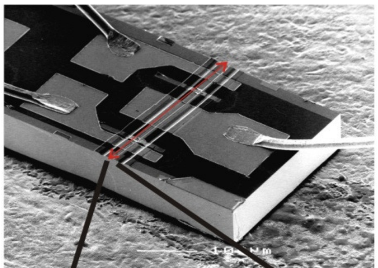
Semiconductor multiple air-gap filter structure



Optical multilayer resonator

Micro optoelectronic lasers

optical resonator

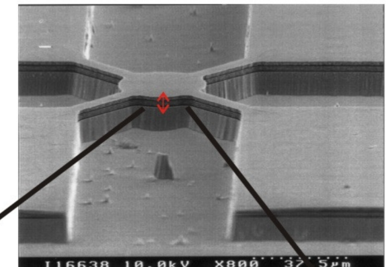


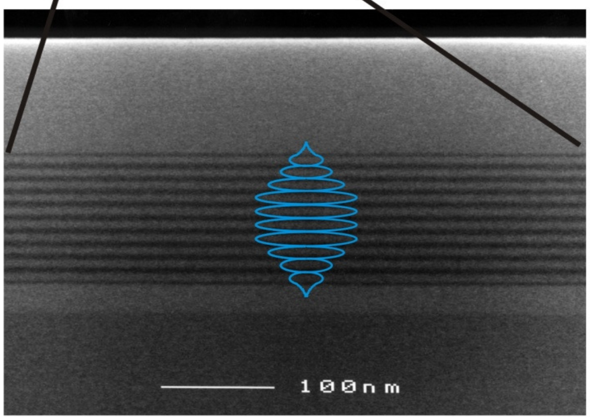
horizontal

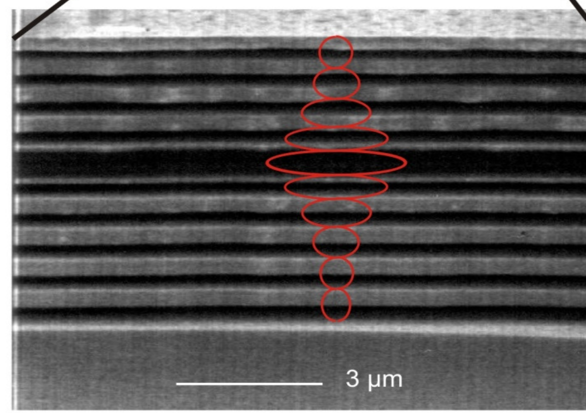
Edge emitter laser

vertical

VCSEL







AlGaInAs/AlGaInAs MQWs

electron wave resonator

Schrödinger-equation

GaInAsP/air-gap DBR

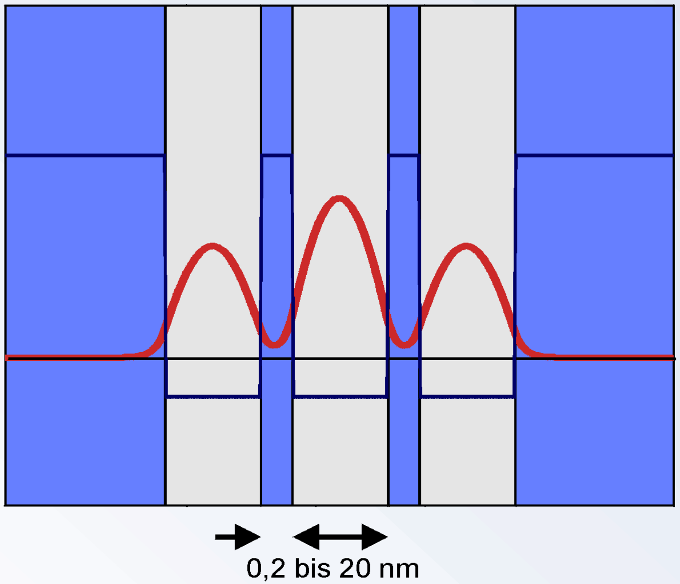
photon wave resonator

Helmholtz-equation

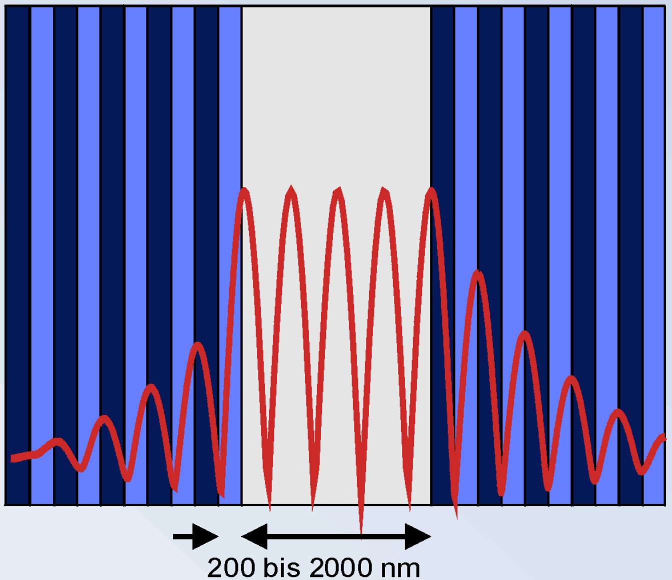
Multilayer structures

optoelectronic devices

Electron wave in a multiple quantum well



Photon wave in an optical resonator

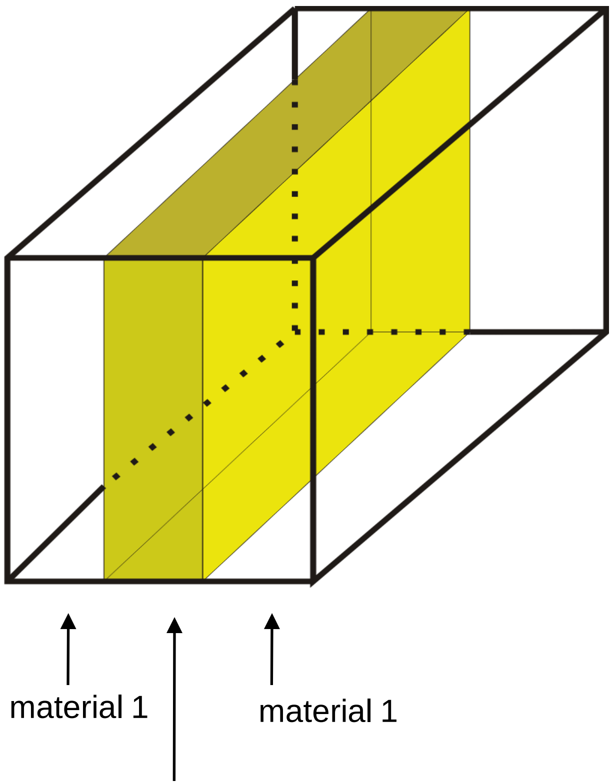


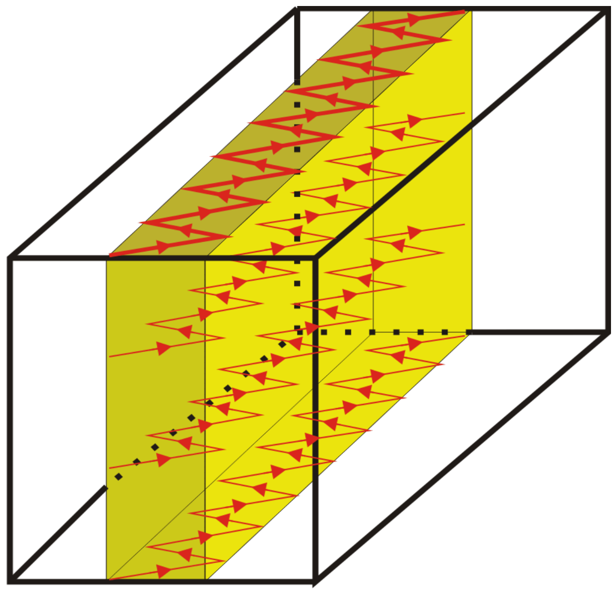
In the order of magnitude of the electron wave length CB Energy potential varies from layer to layer (due to the thin barriers, the wells are coupled)

In the order of magnitude of the light wavelength Refractive index varies from layer to layer

Photon wave in an optical resonator

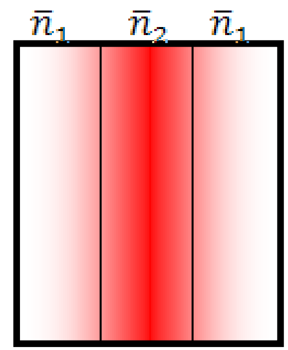
Solution of Helmholtz Equation





ray model

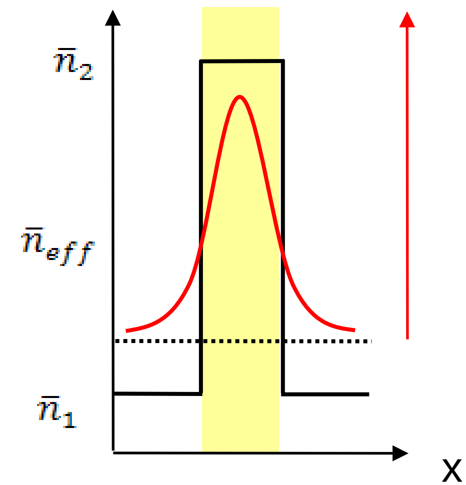
in x-direction
a light cage



wave model

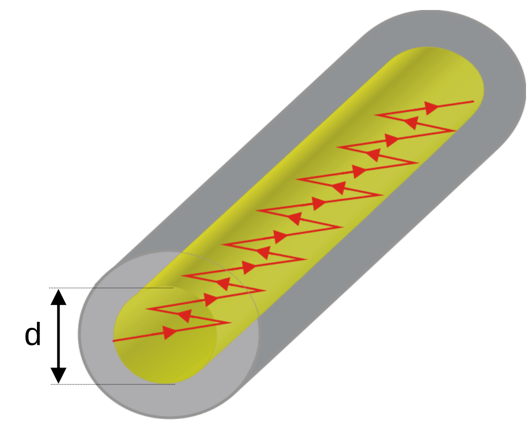
Refraction index

Light intensity



Applications :

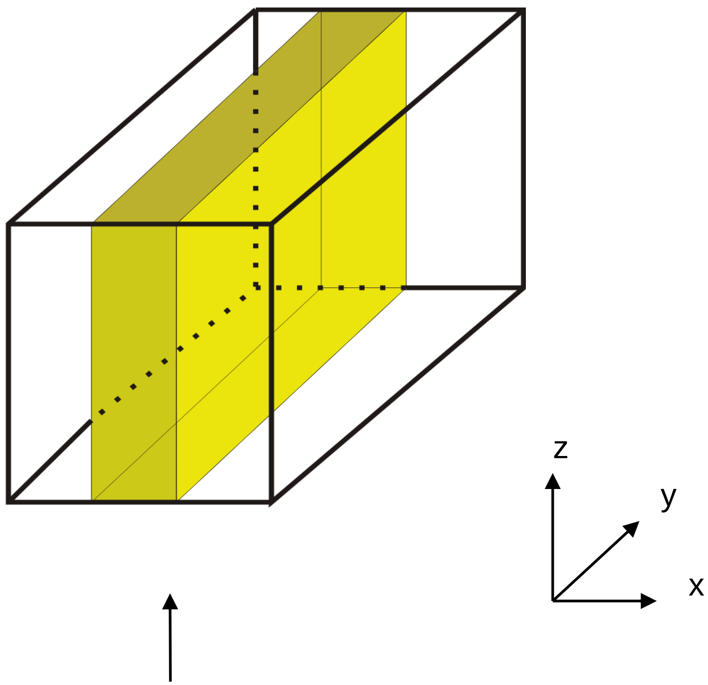
- fibres
- semiconductor laser resonator



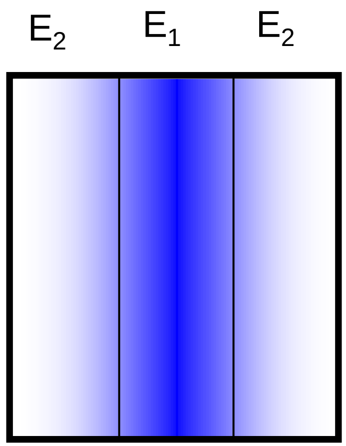
d ≥ Wavelength

Electron wave in a single quantum well

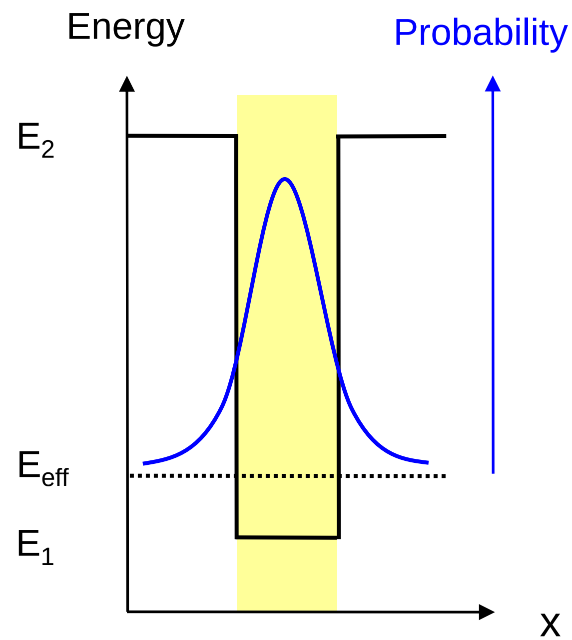
Solution of Schrödinger Equation



Low potential



Quantum mechanical model

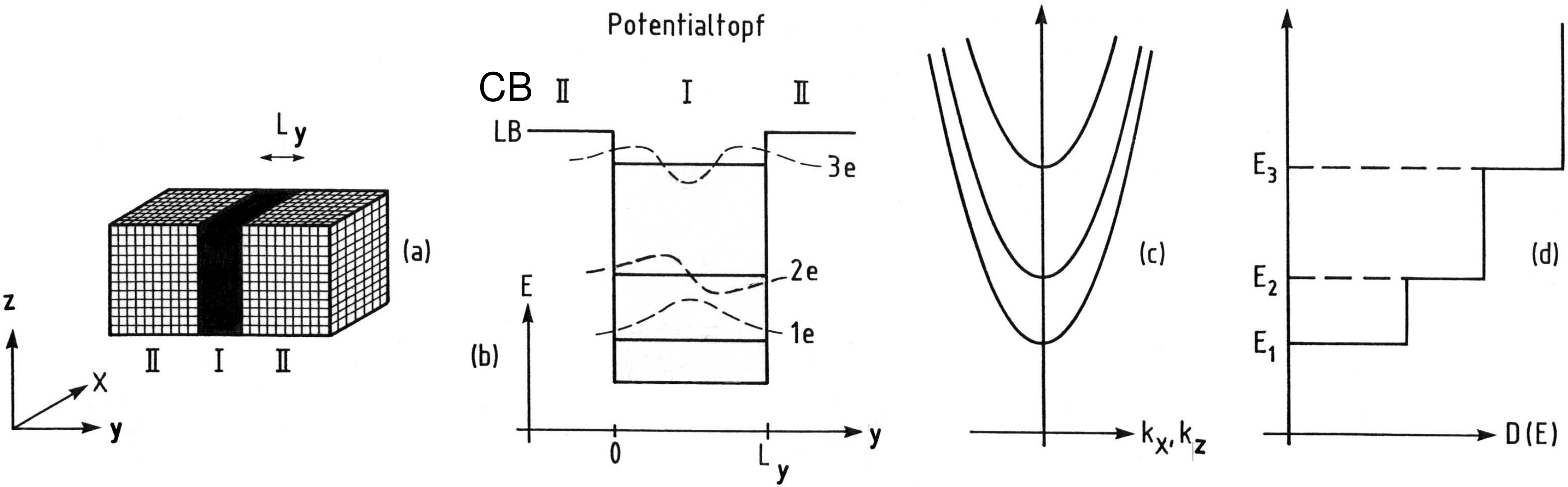


in x-direction a electron cage

Applications : - fast Transistors (HEMT, MODFET)
- modern opto electronic devices

Quasi 2D

potential well



schematic view in space

band structure in real space

band structure in k-space

density of states

Comparison of different wave types

	Classical waves		Quantum mechanical waves
	acoustic	**Electr. - magnetic**	**Material**
Example	Sound in air	light	Atoms, molecules
Wave equation	$\nabla(\rho \cdot c_S^2 \nabla p) - \rho \cdot \frac{\partial^2 p}{\partial t^2} = 0$	$\Delta \underline{E} + \frac{\omega^2 \cdot \overline{n}^2}{c^2} E - \frac{\varepsilon(\underline{r})}{c_0^2} \frac{\partial^2 \underline{E}}{\partial t^2} = 0$	$\frac{-\hbar^2}{2m^*} \Delta\Psi + V(\underline{r})\Psi - i \cdot \hbar \frac{\partial \Psi}{\partial t} = 0$
Property	Air pressure ρ	Electrical field **$\underline{E}$**	Probability $\lvert\psi\rvert^2$
Dispersion relation of free waves	$\omega = C_S \cdot k$	$\omega = C_0 / \sqrt{(\varepsilon\, k)}$	$\omega = \hbar k^2 / 2m^*$ $E = \hbar\omega$, $\underline{p} = \hbar \underline{k}$
Wavelength range	2 cm – 20 m	0.4 – 0.8 μm	$\lambda = h / p$ e (eV) : ≤ nm **C 60 : ≈ pm**