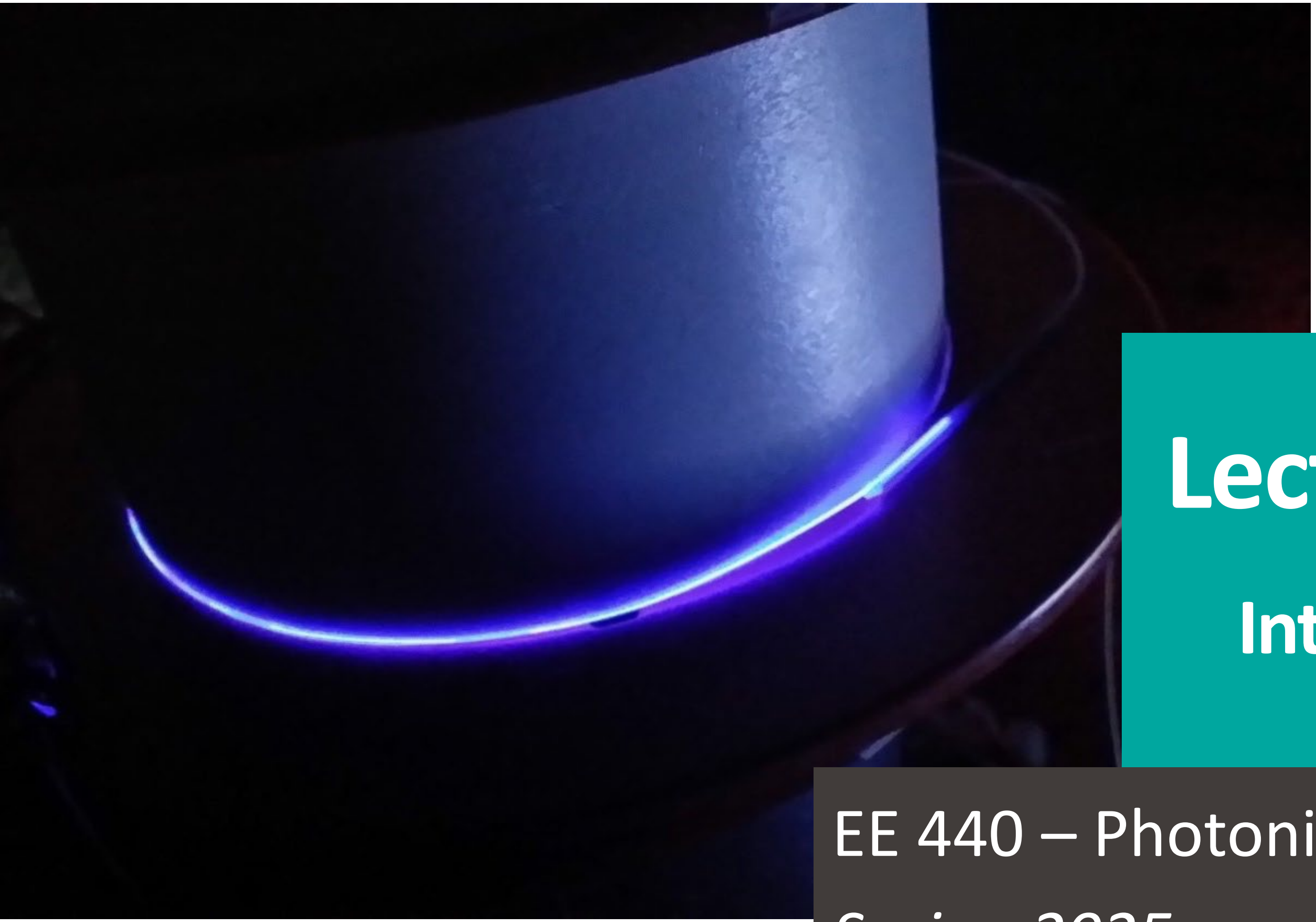


Lecture 1

Introduction and basic concepts

EE 440 – Photonic systems and technology

Spring 2025

Ecole
Polytechnique
Fédérale de
Lausanne

Prof. Camille Brès - camille.bres@epfl.ch

Lecture 1: outline

Course information

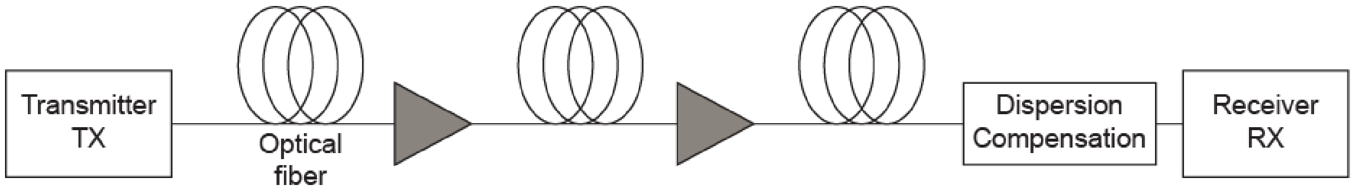
Introduction to photonics and fiber optics

Fundamentals of light sources

Course objectives

By the end of this course, you should:

- Understand how *fiber-optics communication systems* work.



- *Understand how key devices* work.

Optical amplifier

Transmitter

Receiver

Dispersion compensation

Optical fiber

- Be able to *analyze the operation* of those sub-systems.

		Topic of the week	Reading	Computer labs/Exercises
Basics	Week 1: 18/02	Introduction and basics concepts	Agrawal 'Fiber optic communication systems'- § 1	CL: Intro to VPI
Optical transmitter	Week 2: 25/02	Light sources	Saleh & Teich - § 11, 13, 15 Agrawal 'Fiber optic communication systems'- § 3	Exercises 1: sources
	Week 3: 04/03	Optical modulators	Saleh & Teich - § 20	CL: sources
	Week 4: 11/03	Ring resonators		
Optical waveguide, the optical fiber	Week 5: 18/03	Loss and dispersion	Saleh & Teich - § 9 Agrawal 'Fiber optic communication systems'- § 2, 8	CL: modulation
	Week 6: 25/03	Propagation equation		Exercises 2: modulator, propagation
	Week 7: 01/04	Nonlinear effects	Agrawal 'Fiber optic communication systems'- § 2, 6	CL: Propagation
Receivers	Week 8: 09/04	Photodetectors	Agrawal 'Fiber optic communication systems'- § 4 Saleh & Teich - § 18	CL: Nonlinear effects
	Week 9 : 15/04	Bit error rate		Exercises 3: nonlinear effects, detectors
Optical amplification	Week 10: 29/04	Basic of optical amplification	Saleh & Teich - § 14 Agrawal 'Fiber optic communication systems'- § 7	CL: Receivers and BER
	Week 11: 06/05	Optical amplifiers		Exercises 4: BER, amplifiers
Other components	Week 12: 13/05	Bragg gratings, couplers etc		CL: Amplifiers
	Week 13: 20/05	No course		
Conclusions	Week 14; 27/05	Performance limits and trends	Agrawal 'Fiber optic communication systems'- § 5 Saleh & Teich - § 24	Exercises 5: revision

A few words of introduction

Some photonic applications (1)

Telecommunication
- Lasers, fibers, modulators detectors etc…
- Free-space optical links

Information and communication technologies
- CCD and CMOS sensors for imaging
- Data storage and retrieval (CD, DVD etc.)
- Optical interconnects (high performance computing)

Sensors and spectroscopy
- Many applications including sensors for:
  - Position, distance, pressure etc.
  - Angular rate (fiber gyroscopes)
  - Gas concentration (absorption spectroscopy)

Energy – Solar cells


Optical communication


Environmental monitoring


Solar cells

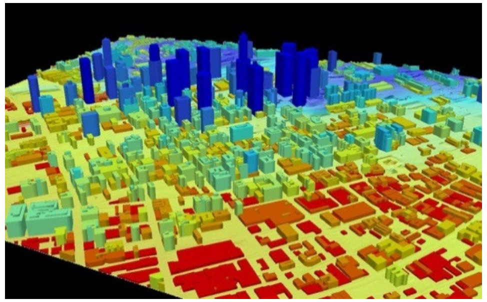
Some photonic applications (2)

Security
- Intrusion detection
- Light detection and ranging (LiDAR)

Lighting
- LEDs for indoor lighting
- Artistic lighting and displays

Biophotonics
- Optical tweezers
- Optical tomography
- Two photon imaging

Military
- Surveillance
- Weapon guidance


Detection and ranging

LED TV


LED lightbulbs

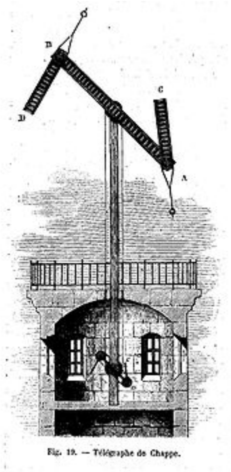

Range finders

History of fiber optics

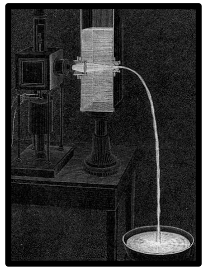
Earliest making of glass
~2000 BC

~30 BC
Romans glass decorations

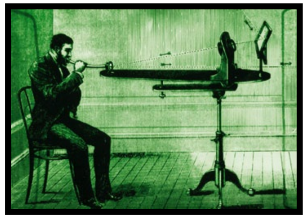
Chappe
Semaphore telegraph
1790



Colladon
‘light fountain’
1842

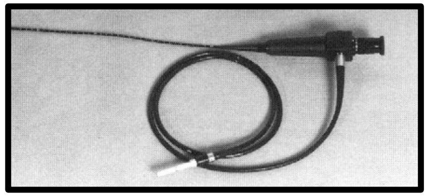


1880
Bell
Photophone
(optical telephone)



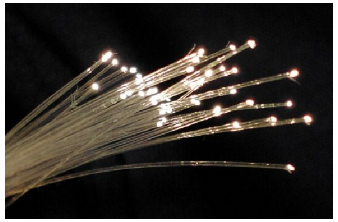
Baird, Hansell
Transparent rods to tansmit images
1930

1950
Van Heel,Hopkins
flexible fibroscope



Cao
Theory of low loss fibers
1964

First fabricated low loss fiber
(< 20dB/km)
1970

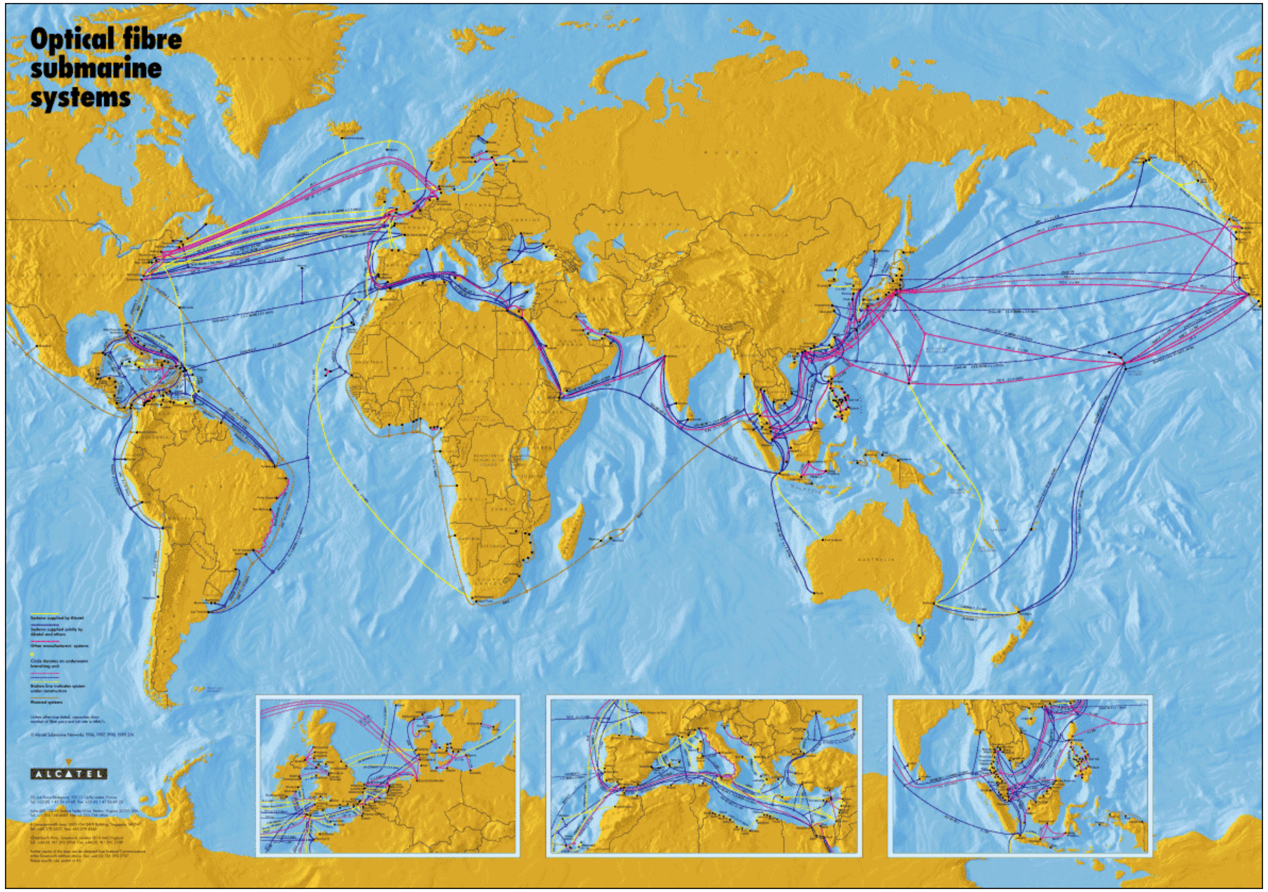


First fiber-based telephone system installed
1977

Cisco first commercial router
1986

100/400G technology
Billions of km of fiber installed
Nowadays

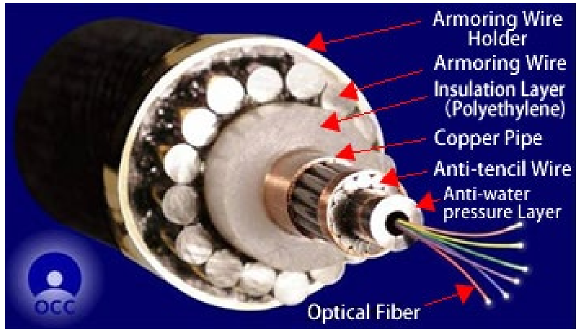
Optical fiber submarine systems



Continents are today connected by fiber optical communications links

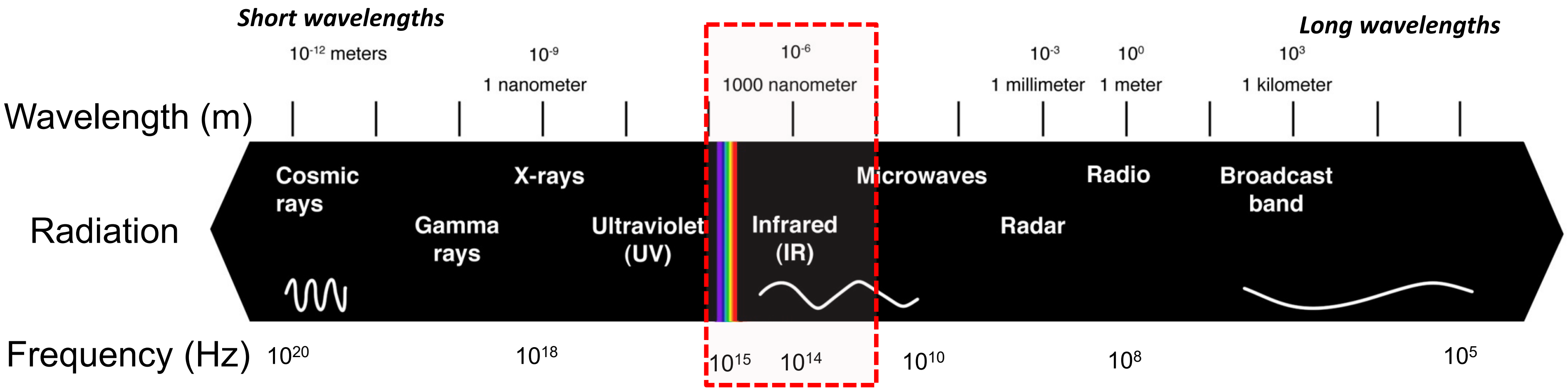
Fibers are also used for:

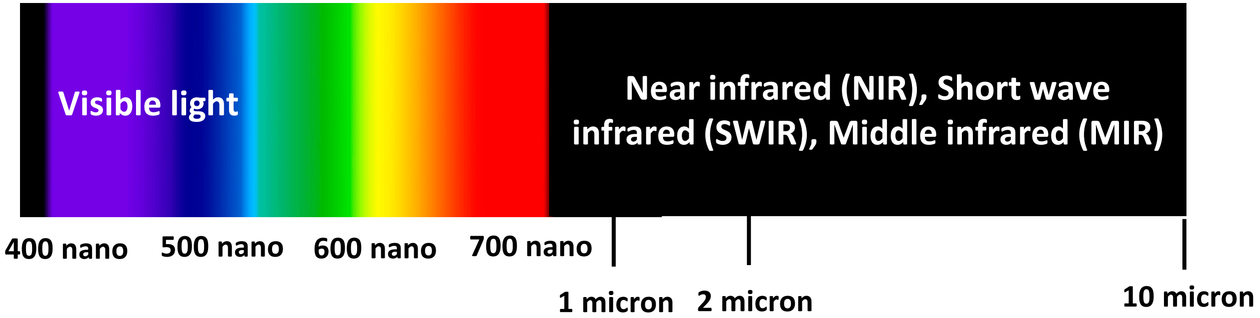
- Intercity connects and city networks
- Providing high speed connections to terminals providing wireless services
- High speed (100 Mb/s and above) services FTTx, where x = curb, home etc.



What is optical communication?

A system in which information is carried by an **electromagnetic wave** - *the carrier* - with a **frequency** $\nu \approx$ **200 THz**.





Motivation for lightwave communications

Before 1960 , communication technologies are dominated by wired and free space analog / digital transmission

- Cable bandwidth has been increased and reached its limit at <1GHz.
- Short (few km) repeater distances.
- Cable size is a problem in metropolitan overcrowded cable ducts.
- Microwave communication increased carrier frequencies but is still bandwidth-limited:

$$BW_{usable} \sim 0.1 \nu_{carrier}$$

As early as the 1960s, demand exceeds capabilities and drives new technology.
Cost become critical.

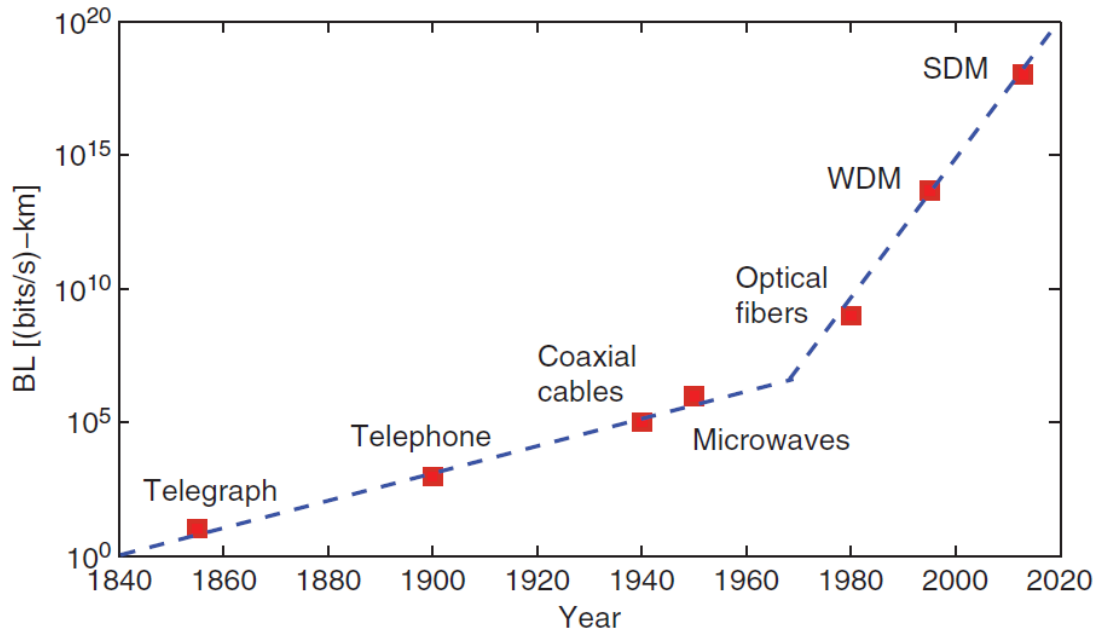
Figure of merit: bandwidth-distance product

Limits of wired communication Cable attenuation

- Cable dispersion
- Repeater-spacing (eg. < 1km at 256 Mb/s)
- Cable volume and deployment cost

Limits of Microwave- and Satellite-communication:

- Improved repeater-limitation for long distances
- But at the expense of the achievable data-rates
- Very high costs



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

Properties of optical fibers

Advantages:

- Extremely low attenuation
- Large bandwidth
- Low weight, compact, flexible
- Isolated from the environment
- Low sensitivity to environmental conditions
- Provides electrical isolation between terminals

Disadvantages

- Not wireless, installation is costly and slow
- Hardware is expensive compared to mass produced electronics

Fiber optics vs. wireless

Fiber systems:

- High data rates
- Long distances
- One ‘medium’ per system
- Static links
- Expensive installation

Wireless systems:

- Relatively low data rates
- Short distances
- Shared ‘medium’
  - Regulations
  - Cross-talk
- Mobility
- Easy and flexible installation

Fiber optics and wireless communications should not be seen as competing technologies but rather as complementary

Foundation of modern fiber optic communication

Two key developments

Laser (1958)

- Light amplification by the stimulated emission of radiation
- Principle developed by Townes, Basov and Prokhorov
- 1964 Novel prize

Optical fiber (1964)

- Charles Kao
- < 20 dB/km loss allowed > 1 km repeater spacing
- 2009 Nobel prize

A necessary advancement

The optical amplifier (1987)

- Sir David Payne (Southampton, UK)
- Emmanuel Desurvire (AT&T Bell)

Side note : recall on the decibel (dB)

Logarithmic unit used to express *the ratio* between two values of a physical quantity (often power)

$$\text{difference in dB} = 10 \cdot \log_{10}\left(\frac{P_2}{P_1}\right)$$

- Example: compare 1 W to 50 mW

dB	Power ratio
30	1000
20	100
10	10
3	1.995 (≈ 2)
0	1
-3	0.501 (≈ 1/2)
-10	0.1
-20	0.01
-30	0.001

The 'dBm' expressed the *absolute power* on a log scale relative to 1 mW

$$\mathrm{P}_{dBm} = 10 \cdot \log_{10}\left(\frac{P[W]}{1\ \mathrm{mW}}\right) = 10 \cdot \log_{10}\left(P[mW]\right)$$

Optical communication history – 4 main generations

First generation

- Gallium Arsenide (GaAs) lasers at 0.8 µm
- 45 Mb/s, 10 km multimode fibers (MMF)

Second generation

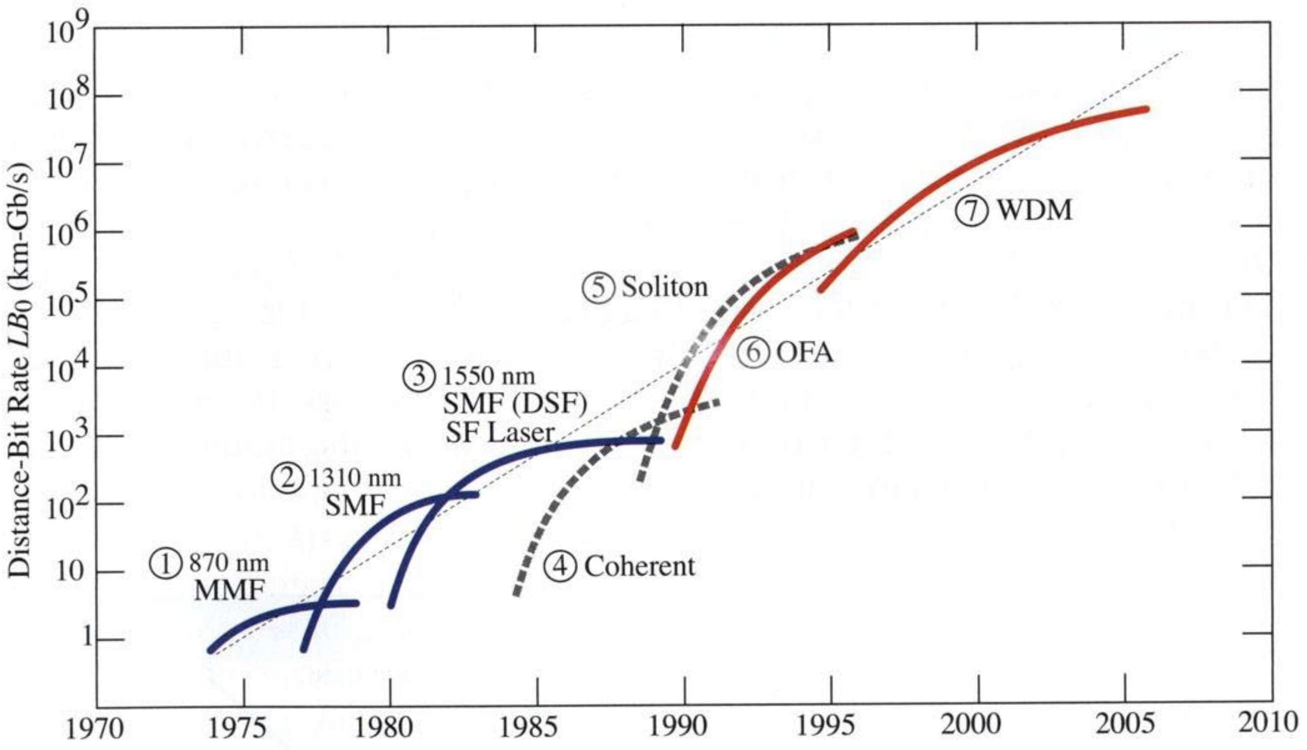
- InGaAsP lasers at 1.3 µm
- 1.7 Gb/s, 50 km single mode fiber (SMF)

Third generation

- Lasers at 1.55 µm, single mode
- 2.5 Gb/s, 100 km

Fourth generation

- Optical amplification
- Multiplexing (WDM)

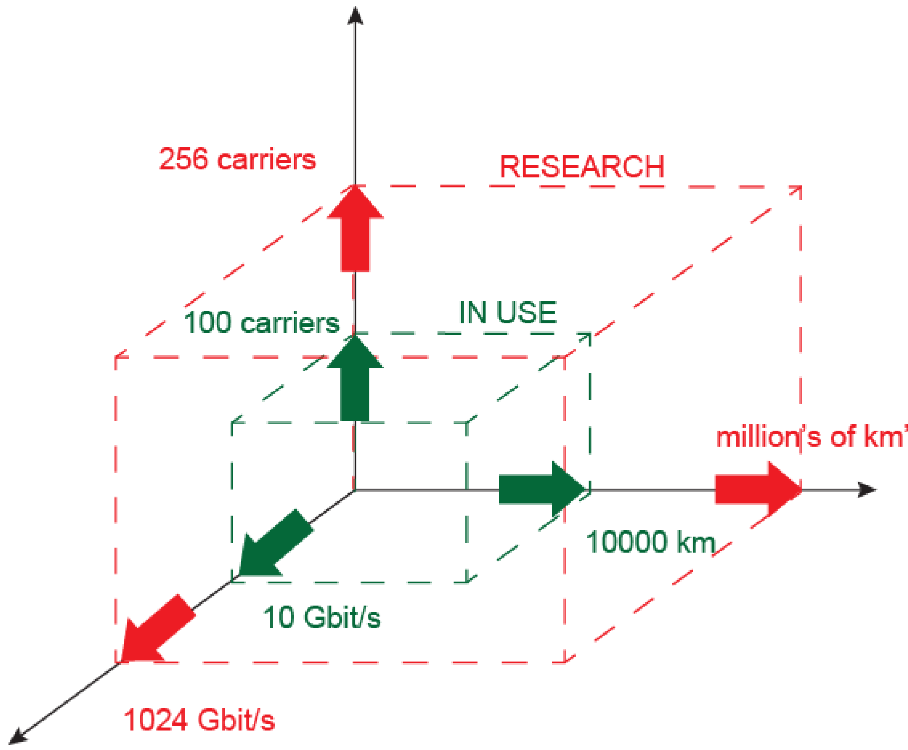


The bit-rate distance product has increased eight orders of magnitude

Progress in lightwave communications

Efforts have been made to:

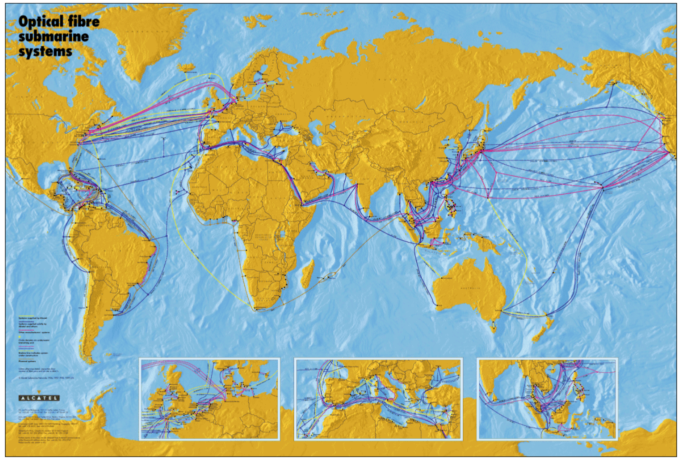
- Increase the data rate per channel
- Increase the number of channels
- ‘Increase’ the distance between repeaters



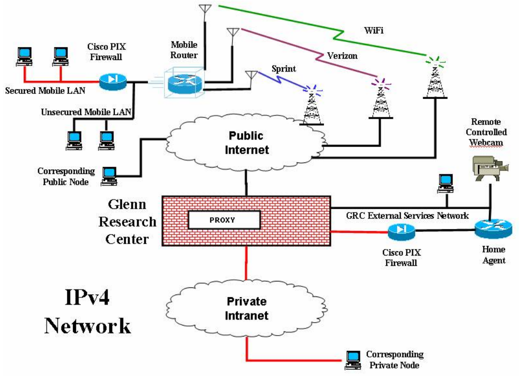
Progress has been extremely rapid. Laboratory systems are always pushing the way forward

Technology drivers

Long distance, large capacity networks

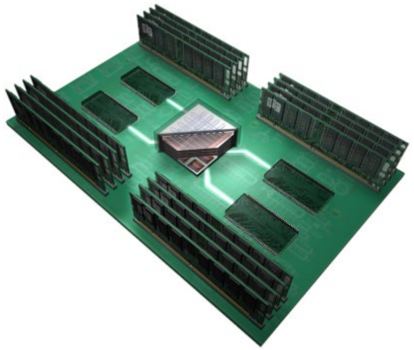


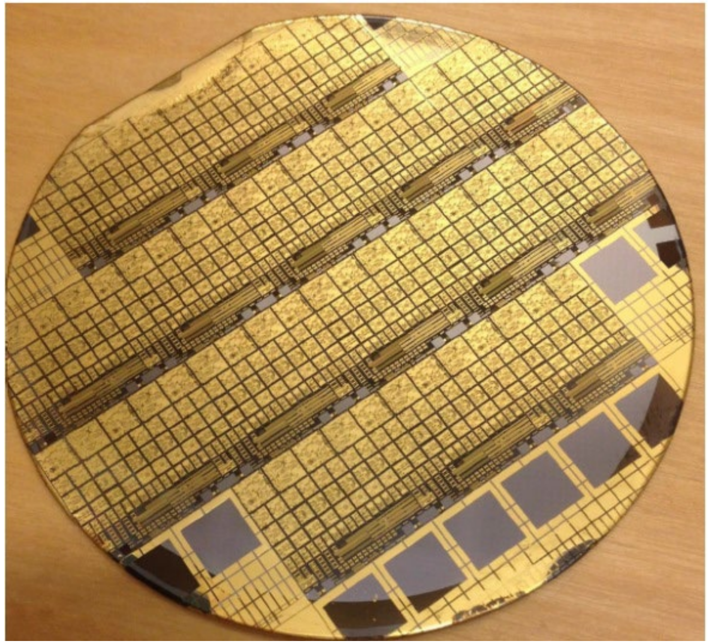
Satellite-Communication and Backbone-Networks for Mobile Communication:

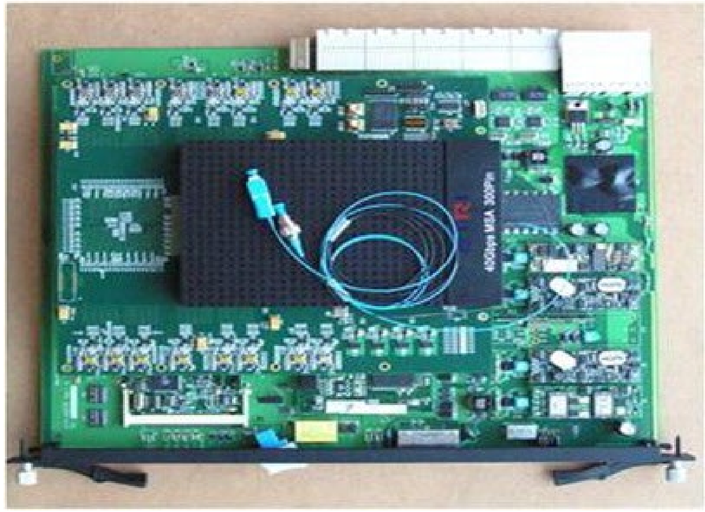


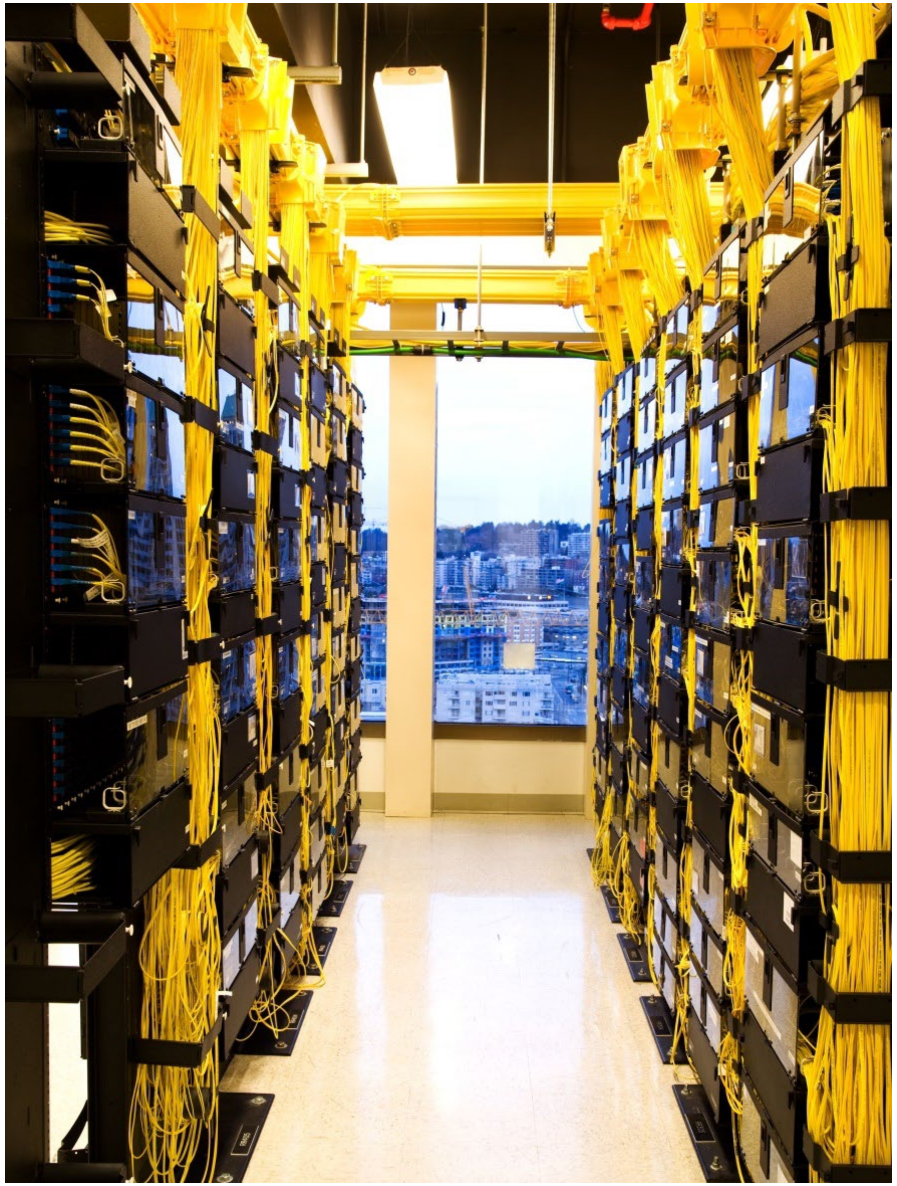
Future Consumer Applications:
Fiber to the home

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









Basic communication concepts

Some definitions for digital signals (1)

T_B (s): symbol period or time duration

f_s (Bd): symbol rate expressed in baud, the number of distinct symbol changes (signaling events) made to the transmission medium per second

$$f_s = \frac{1}{T_B}$$

Symbol rate (Bd)

- If m bits are conveyed per symbol, the bit rate B (bits/s) is

$$B = mf_s$$

Bit rate (bits/s)

- For binary signaling, the baud rate is equivalent to the bit rate

Δf (Hz): the bandwidth, range of frequencies of signal for which the signal amplitude is within a specified range of its maximum value (e.g. 3 dB)

Some definitions (2)

C: the channel capacity (bits/s) the highest rate of information that can be transmitted reliably (error-free) through a channel

- Shannon's channel coding theorem : for an information rate, B (bits/s) such that $B \leq C$, then there is a coding technique which enables transmission over a noisy channel with no errors.

In the presence of an additive white Gaussian noise (AWGN) the Shannon-Hartley theorem states:

$$C = (2\Delta f) \log_2 \left(1 + \frac{S}{N}\right)$$

Channel capacity for additive white gaussian noise of power N

- S is the average received signal power over the bandwidth in Watts
- N is the average power of the noise and interference over the bandwidth in Watts

Some definitions (3)

S: spectral efficiency (bits/s/Hz), the information rate that is transmitted over a given bandwidth in a specific communication system

- A way to assess the use of the available spectrum

$$S = \left(\frac{\text{Total throughput}}{\text{Bandwidth used}}\right)$$

Spectral efficiency (bits/s/Hz)

Some definitions (3)

Capacity of fiber is much greater than bit rate of an individual user

- $BW_{usable} \sim 0.1 \nu_{carrier} \sim \text{Tbits/s}$
- Individual rates limited by the electronics are in the Gbits/s
- Can interleave users to optimize the utilization of the optical fiber

Multiplexing: method by which multiple signals are combined over a shared medium

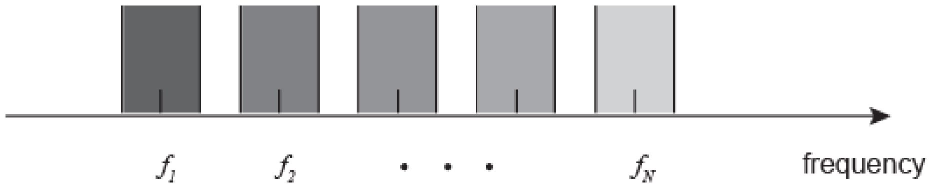
Transmit many channels simultaneously utilizing various dimensions

- *Polarization* multiplexing (PolMux)
- *Time* division multiplexing (TDM)
- *Frequency/Wavelength* division multiplexing (WDM/FDM)
- *Code* division multiplexing (CDMA)
- *Space* division multiplexing (SDM)

Multiplexing

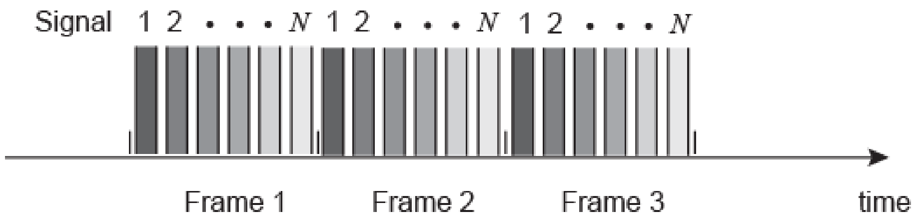
Frequency-division multiplexing (FDM):

- Carrier of distinct frequencies are modulated by the different signals.
- At the receiver, the signals are identified by the use of filters tuned to the carrier frequencies.



Time division multiplexing (TDM):

- Data is transmitted in a sequence of time frames, each with a set of time slots allocated to bits/bytes of the different signals,
- They must be synchronized to the same clock
- At the receiver, each signal is identified by its location with the frame.



Multiplexing

Multiplexing may be electronic or optical

In electronic:

- Signals are multiplexed to generate a composite electrical signal that is then used to modulate the light source in any of the optical modulation schemes.
- For example, an FDM electronic signal may be generated by the use of subcarriers (sub-carrier multiplexing SCM).

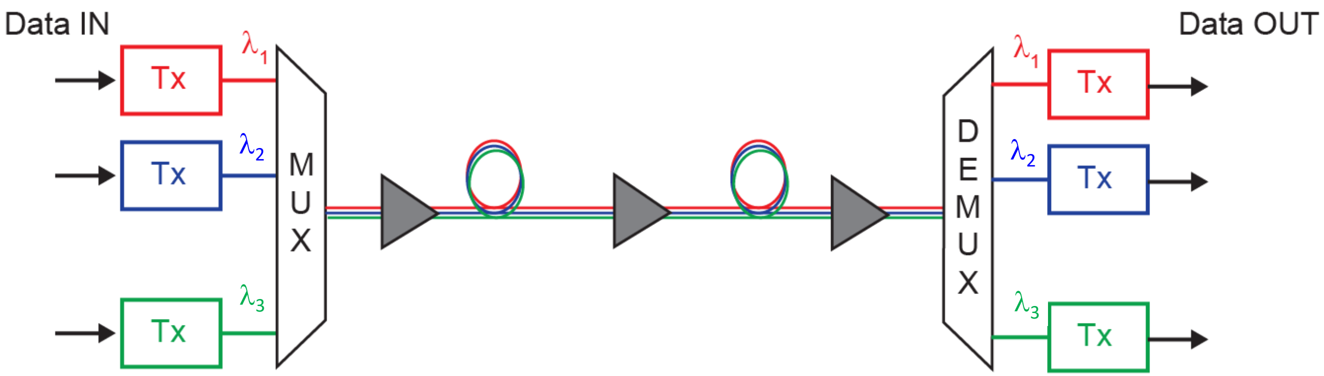
In optic:

- The labels distinguishing the multiplex signals are optical in nature
- For example, optical FDM uses different optical frequencies as the carriers of the various signals. These carriers are then separated by optical filters
- When the frequencies are widely spaced (greater than 20 GHz), this is called wavelength division multiplexing (WDM)

WDM systems

Wavelength division multiplexing

- Multiple optical carriers are independently modulated and transmitted over the same fiber.
- Optical signal at receiver is demultiplexed into separate λ channels using an optical technique.
- The users' wavelength are on a grid (ITU grid, e.g. 100 GHz).



System limitations include:

- amplifier gain uniformity and laser wavelength stability,
- residual dispersion,
- fiber nonlinearities and other interchannel crosstalk.

System capacity and spectral efficiency

The use of WDM can increase the systems capacity

- Transmits multiple bit streams over the same fiber simultaneously
- When N channels at bit rates B_1, B_2 …. B_N are transmitted, the total bit rate of the WDM link becomes

$$B_T = B_+ + B_2 + \cdots + B_N$$

- For channels equally spaced by $\Delta\nu_{ch}$, total bandwidth used by a WDM system is

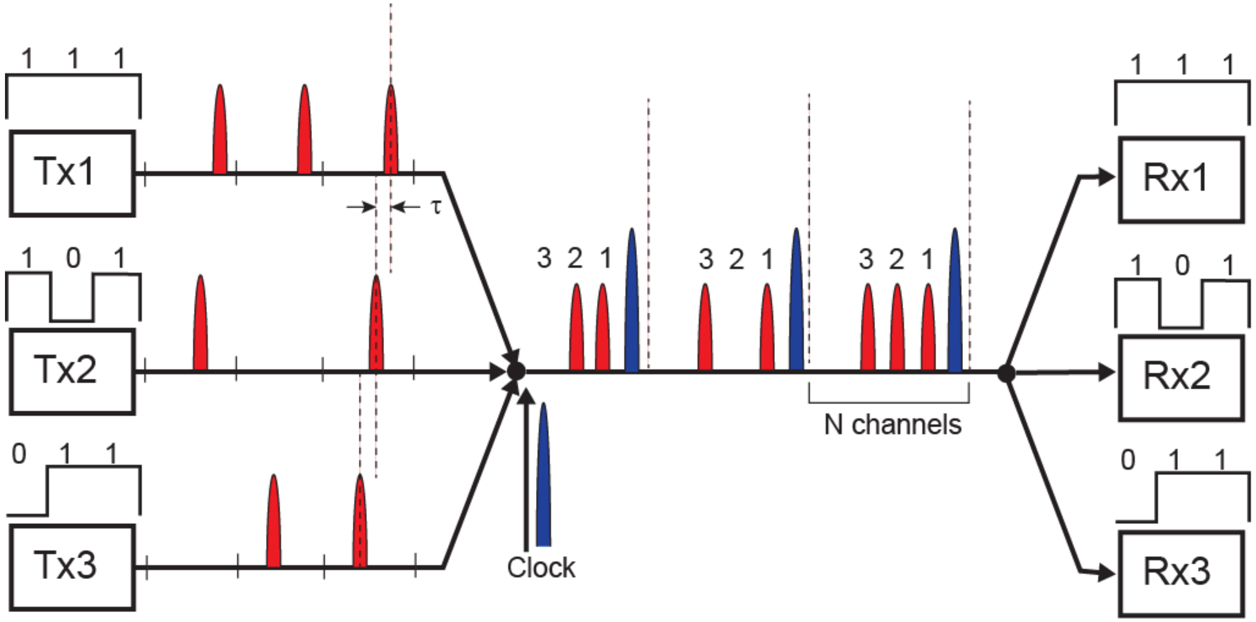
$$BW_T = N\Delta\nu_{ch}$$

- Spectral efficiency for WDM systems is: $$S = \frac{B_T}{N\Delta\nu_{ch}}$$

OTDM

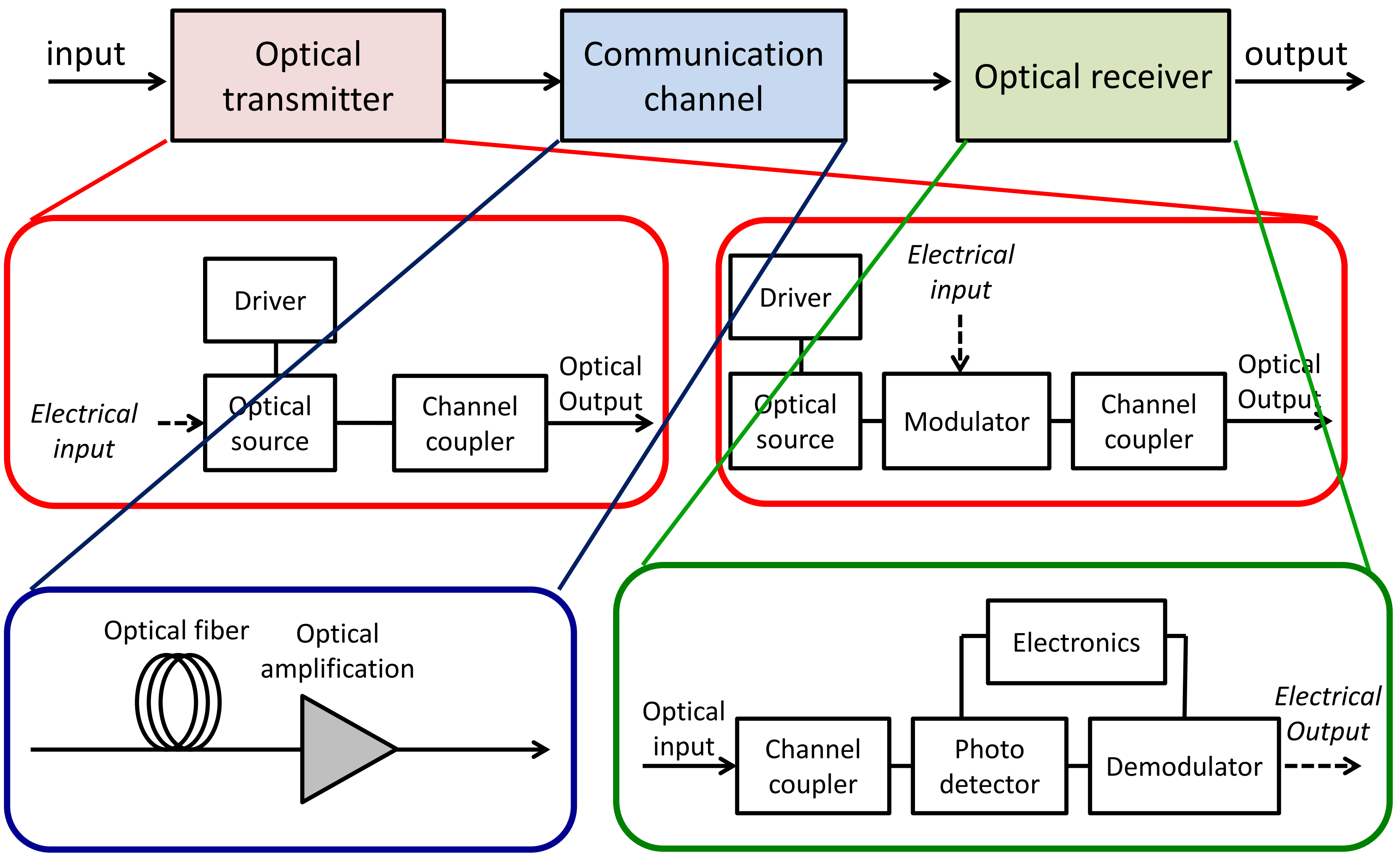
Optical time domain multiplexing

- TDM is commonly performed in the electrical domain
- N signals modulated at the rate B on the same optical carrier are multiplexed in time to form a composite signal with a rate NB



An optical communication system

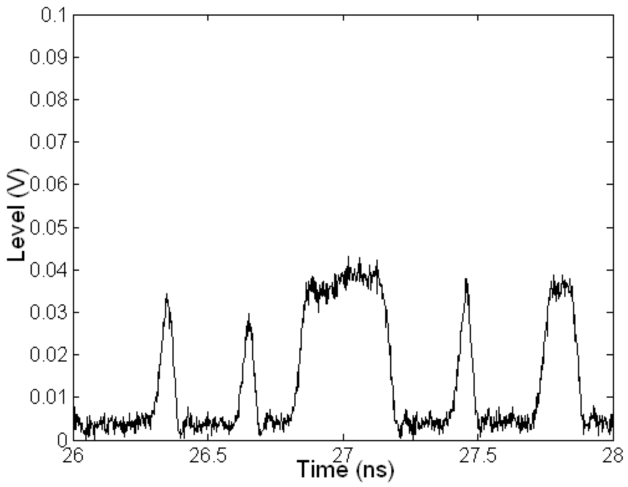
Components of an optical communication system

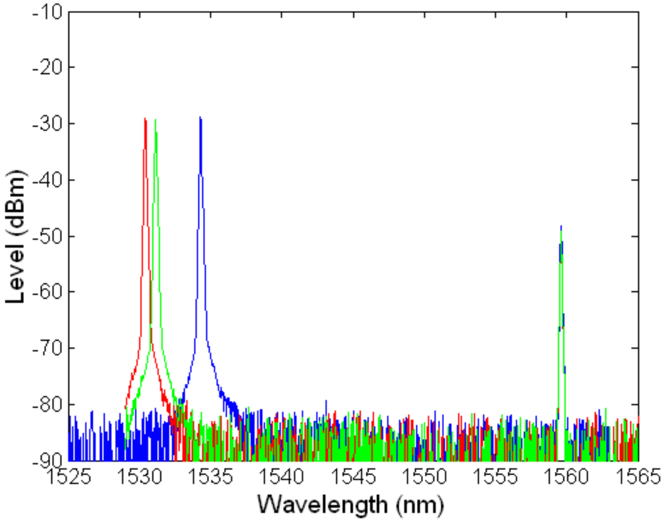


Evaluating system performance

The signal waveform in the time domain

- Oscilloscope: 100 ps resolution
- Sampling oscilloscope: 20 ps resolution
- Streak camera: 2 ps resolution
- Auto-correlator: 10 -100 fs resolution





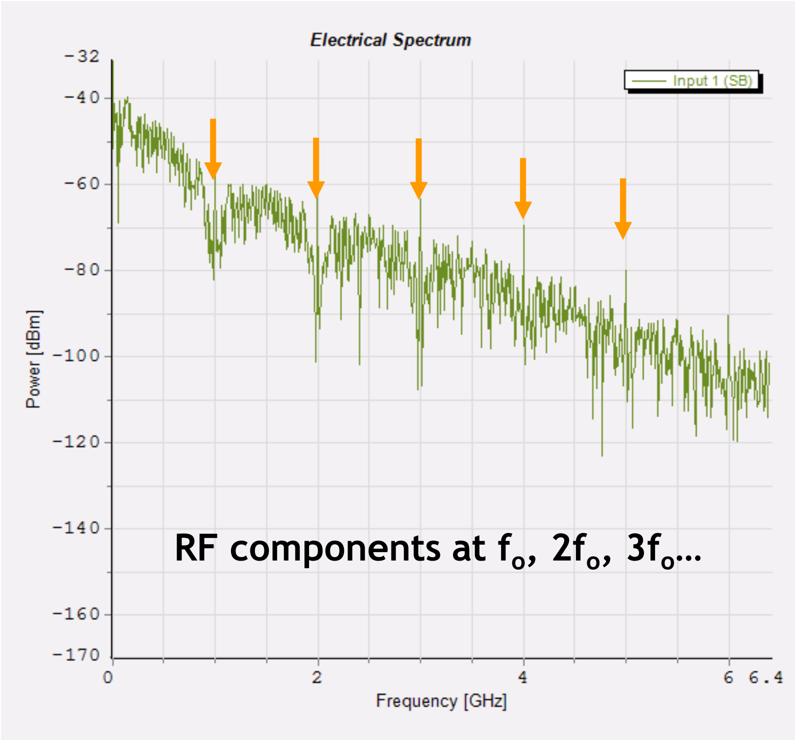
The optical spectrum

- Contains information on how the optical energy/power is distributed over different wavelengths/frequencies
- Gives information on: wavelength, linewidth, noise, power levels …

Evaluating system performance

The radio frequency (RF) spectrum

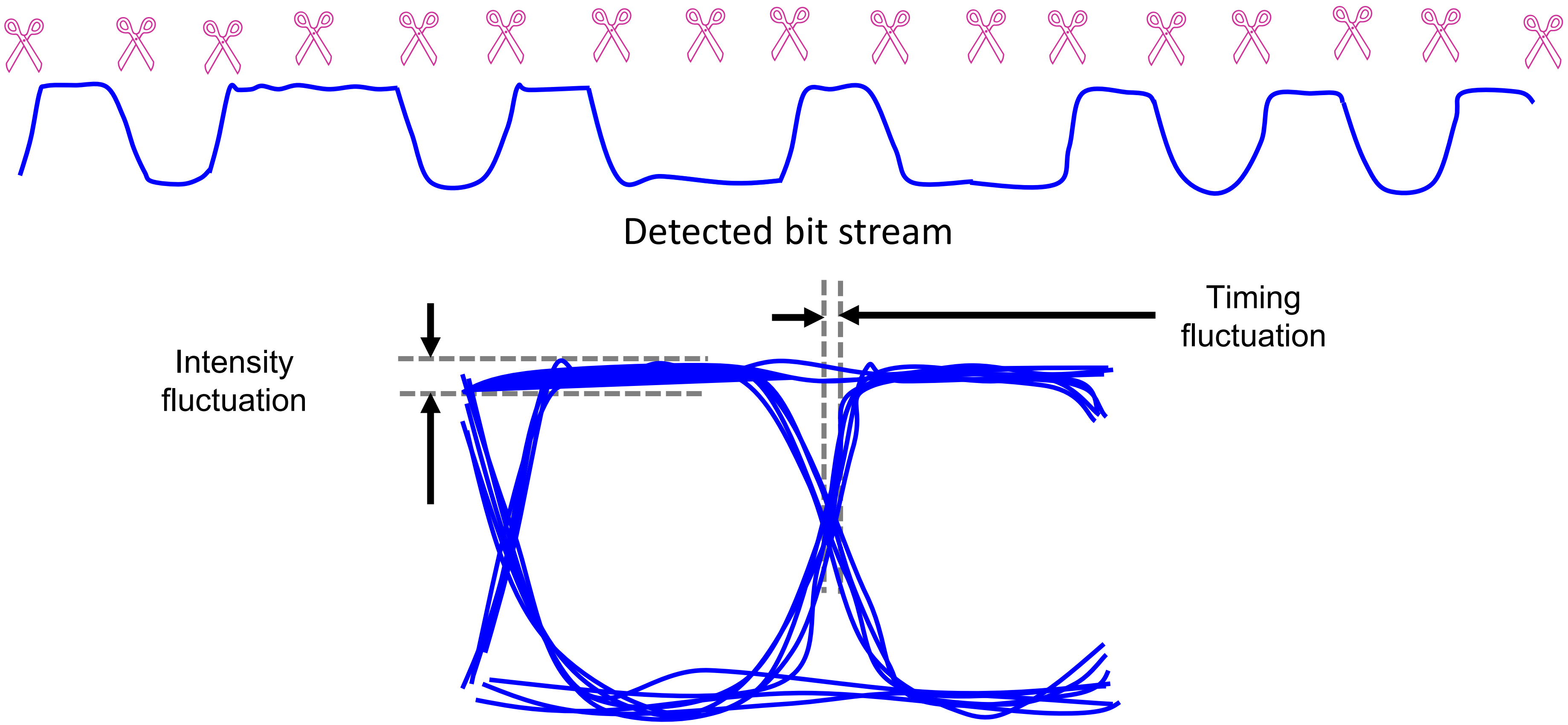
- Shows power versus frequency data.
- Gives information about a source: repetition rate, phase noise, relative intensity noise etc…



Evaluating system performance

The eye diagram (eye pattern)

- An oscilloscope display in which a received digital signal is repetitively sampled and applied to the vertical input, while the data rate triggers the horizontal sweep.



Evaluating system performance

The bit error rate (bit error ratio) – BER

- Definition

$$BER = \frac{\text{Number of bits detected incorrectly}}{\text{Total number of bits transmitted}}$$

- How is BER obtained ?
  - Directly detecting the bits and comparing them against the original

Transmitted:	…0 0 1 0 0 1 1 0 0 1 0 1 1 1 0 1 0 0 1 1 0 0 0 1 0 1 0 1 0 …
Detected:	…0 0 1 0 0 **0** 1 0 0 1 0 1 1 **0** 0 1 0 0 1 1 0 **1** 0 1 0 1 0 1 **1** …

  - Estimated from the eye diagram (statistical)
  - Other methods (to be covered in more details later)

Electromagnetic waves – properties of light

Wave vs. Electromagnetic optics

Light propagates in the form of waves

- In free space, light waves travel with speed c_0 (2.997 924 10^8 m/s)
- In a medium characterized by a refractive index n ($\geq$ 1), light travels at a reduced speed

$$c = \frac{c_0}{n}$$

Speed of light in a medium

- Frequency (ν) and wavelength (λ) are related by $\nu = \frac{c}{\lambda}$

However wave optics (scalar approach) is unable to explain some simple experiments:

- Such as the division of light at a beam splitter
- Such phenomena depends on the polarization of light …

Light must be treated in the context of a vector rather than scalar theory
$\Rightarrow$ Electromagnetic optics

Maxwell's equation in free space

An electromagnetic field is described by two related vector fields that are function of position **r** = (x, y, z), and time t,

- The electric field $\boldsymbol{\mathcal{E}}(\mathbf{r}, t)$
- The magnetic field $\boldsymbol{\mathcal{H}}(\mathbf{r}, t)$

They must satisfy Maxwell's equations

$$\nabla \times \boldsymbol{\mathcal{E}} = -\mu_0 \frac{\partial \boldsymbol{\mathcal{H}}}{\partial t} \qquad \nabla \cdot \boldsymbol{\mathcal{E}} = 0$$

$$\nabla \times \boldsymbol{\mathcal{H}} = \epsilon_0 \frac{\partial \boldsymbol{\mathcal{E}}}{\partial t} \qquad \nabla \cdot \boldsymbol{\mathcal{H}} = 0$$

Maxwell's equations (free space)

- ϵ_0 the electrical permittivity of free space ($1/36\pi\ 10^{-9}$ F/m)
- μ_0 the magnetic permeability of free space ($4\pi\ 10^{-7}$ H/m)

The wave equation

A necessary condition for $\boldsymbol{\mathcal{E}}(\mathbf{r},t)$ and $\boldsymbol{\mathcal{H}}(\mathbf{r},t)$ to satisfy Maxwell's equation is that each components satisfy the wave equation:

$$\nabla^2 u - \frac{1}{c_0^2}\frac{\partial^2 u}{\partial t^2} = 0$$

The wave equation in free space

with $$c_0 = \frac{1}{\sqrt{\epsilon_0 \mu_0}}$$

The wave equation (basis of wave optics) is embedded in the structure of electromagnetic theory

Maxwell's equation in medium (without free charges or current)

Two additional vector fields are required:

- Electric flux density (or displacement) $\boldsymbol{\mathcal{D}}(\mathbf{r},t)$
- Magnetic flux density $\boldsymbol{\mathcal{B}}(\mathbf{r},t)$

$$\nabla \times \boldsymbol{\mathcal{E}} = -\frac{\partial \boldsymbol{\mathcal{B}}}{\partial t} \qquad \nabla \cdot \boldsymbol{\mathcal{B}} = 0$$

$$\nabla \times \boldsymbol{\mathcal{H}} = \frac{\partial \boldsymbol{\mathcal{D}}}{\partial t} \qquad \nabla \cdot \boldsymbol{\mathcal{D}} = 0$$

Maxwell's equations (source free medium)

$$\boldsymbol{\mathcal{D}} = \epsilon_0 \boldsymbol{\mathcal{E}} + \boldsymbol{\mathcal{P}}$$

- The polarization density $\boldsymbol{\mathcal{P}}$ is the macroscopic sum of the electric dipoles moments induced by the electric field $\boldsymbol{\mathcal{E}}$.

$$\boldsymbol{\mathcal{B}} = \mu_0 \boldsymbol{\mathcal{H}} + \mu_0 \boldsymbol{\mathcal{M}}$$

- The magnetization density $\boldsymbol{\mathcal{M}}$ is the macroscopic sum of the magnetic quadrupole induced by the magnetic field $\boldsymbol{\mathcal{H}}$.

Linear, nondispersive, homogeneous, isotropic medium

$\boldsymbol{\mathcal{P}} = \epsilon_0 \, \chi \, \boldsymbol{\mathcal{E}} \implies \boldsymbol{\mathcal{D}} = \epsilon_0 (1 + \chi) \boldsymbol{\mathcal{E}} = \epsilon \boldsymbol{\mathcal{E}}$

- Electric susceptibility χ
- Let $\epsilon_r = 1 + \chi$, the relative permittivity also called dielectric constant

Can also write $\boldsymbol{\mathcal{B}} = \mu \boldsymbol{\mathcal{H}}$

It can be shown that each components of $\boldsymbol{\mathcal{E}}(\mathbf{r}, t)$ and $\boldsymbol{\mathcal{H}}(\mathbf{r}, t)$ must now satisfy:

$$\nabla^2 u - \frac{1}{c^2} \frac{\partial^2 u}{\partial t^2} = 0$$

The wave equation in source free medium

With $c = \frac{1}{\sqrt{\epsilon \mu}}$

We also find that : $n = \frac{c_0}{c} = \sqrt{\frac{\epsilon \mu}{\epsilon_0 \mu_0}}$ and $n = \sqrt{1 + \chi}$

Linear refractive index for Nonmagnetic medium

Monochromatic electromagnetic waves

All components of the electric and magnetic fields are harmonic functions of time with the same frequency ν (angular frequency $\omega = 2\pi\nu$)

- $\boldsymbol{\mathcal{E}}(\mathbf{r},t) = \mathcal{E}(\mathbf{r})\cos[\omega t + \phi(\mathbf{r})]$ ($\mathcal{E}(\mathbf{r})$: amplitude and $\phi(\mathbf{r})$: phase)

Can adopt complex representation $\mathbf{E}(\mathbf{r},t) = \mathbf{E}(\mathbf{r})e^{i\omega t}$:

- $\boldsymbol{\mathcal{E}}(\mathbf{r},t) = \mathrm{Re}\{\mathbf{E}(\mathbf{r},t)\}$
- $\mathbf{E}(\mathbf{r}) = \mathcal{E}(\mathbf{r})e^{i\phi(\mathbf{r})}$ is the complex amplitude vector

We can show that the complex amplitude of any of the 3 components of $\mathbf{E}$ and $\mathbf{H}$ must satisfy:

$$\nabla^2 U + k^2 U = 0$$

$$k = \frac{\omega}{c} = n\frac{\omega}{c_0}$$

Helmholtz equation

Some important parameters

Free space wavenumber k_0 :

- For a traveling plane wave, the wavenumber is the spatial equivalent of frequency.

$$k_0 = \frac{\omega}{c_0} = \frac{2\pi}{\lambda_0}$$

Propagation constant β :

- Determines how the phase of light varies along the propagation direction
- Note that we are neglecting the losses upon propagation… will be covered later

$$k \equiv \beta = n(\omega)k_0 = n(\omega)\frac{2\pi}{\lambda_0}$$

From Maxwell to quantum

Particle (photon) properties of light

- Interaction with the quantized electronic states of matter are due to energy-exchange between discrete energy quanta E (photon):

$$E = h\nu$$

Energy of photon with frequency ν

- h: Planck's constant, 6.626 10^{34} Js
- Annihilation/creation of photons leads to attenuation/amplification of the optical wave

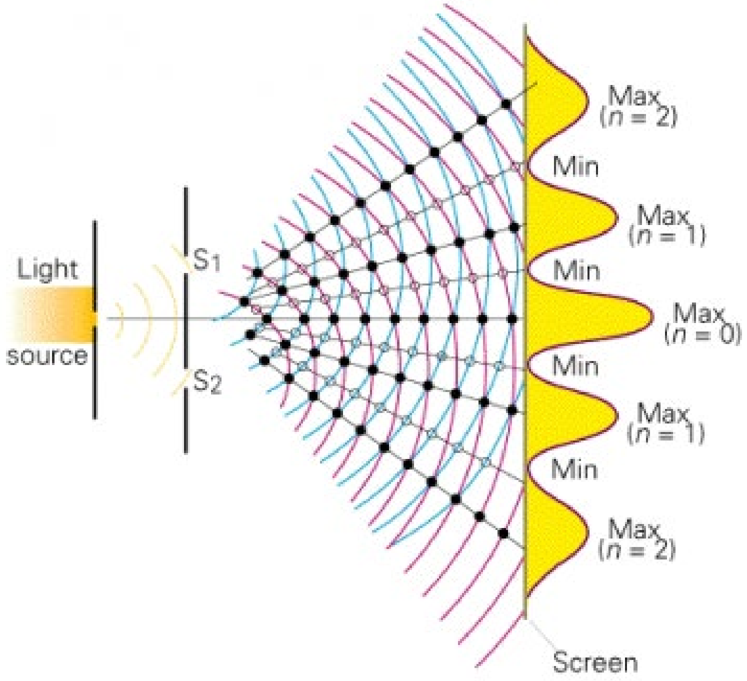
Energy quantization of the light field:

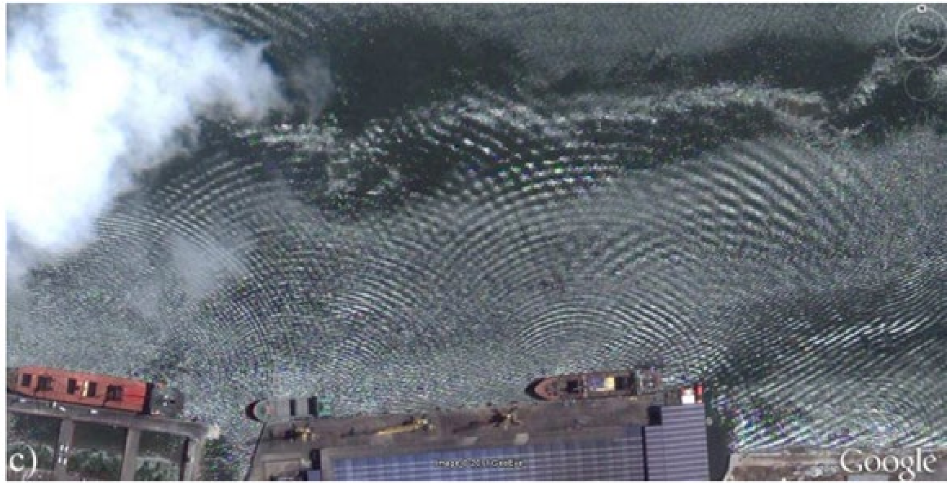
- The field energy is described by the number of photons making up the field.

The double slit experiment

Using a monochromatic light

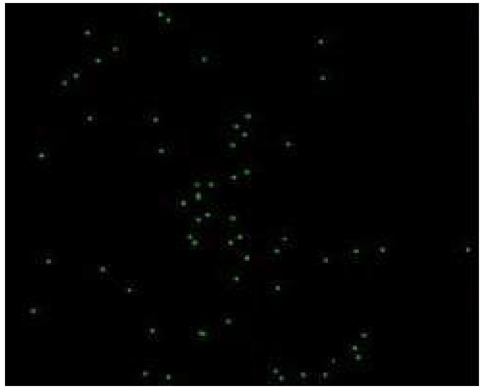
- Both slits create circular light waves which overlap
- Highest light intensity on the screen is behind the middle section of the double slit
- Some screen areas which a direct view of the source have no light hits
- There are more intensity maxima than there are slits.





The double slit experiment

Using a single photon source



Statistical properties of random light

An arbitrary optical wave is described by the wavefunction

$$u(\mathbf{r}, t) = \mathrm{Re}[U(\mathbf{r}, t)]$$

With $U(\mathbf{r}, t)$ the complex wavefunction

- For monochromatic light it may take the form $U(\mathbf{r})e^{i\omega t}$
- For polychromatic light, may comprise the sum of many similar functions (ω_i)

For random light, both $u(\mathbf{r}, t)$ and $U(\mathbf{r}, t)$ are random and characterized by a number of statistical averages

Temporal coherence

Stationary light at fixed location ***r*** typically fluctuates as a function of time:

- The random function $U(t)$ has a constant intensity: $I = \langle |U(t)|^2 \rangle$
- The random fluctuations of the complex wave function $U(t)$ are characterized by a time scale representing the “memory” of the random function
- Function appears smooth during over this scale but erratic when examined over longer time scales

A quantitative measure of this temporal behavior is given by the temporal coherence function $G(\tau)$:

$$G(\tau) = \langle U^*(t)U(t+\tau) \rangle$$

Temporal coherence function

$$G(\tau) = \lim_{\tau \to \infty} \frac{1}{T} \int_{t_0}^{t_0+T} U^*(t)U(t+\tau)dt$$

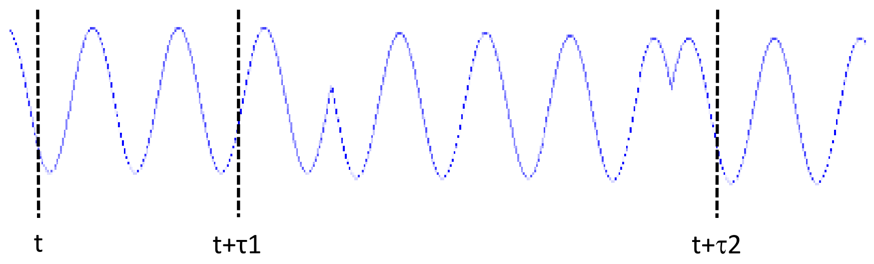
Degree of temporal coherence

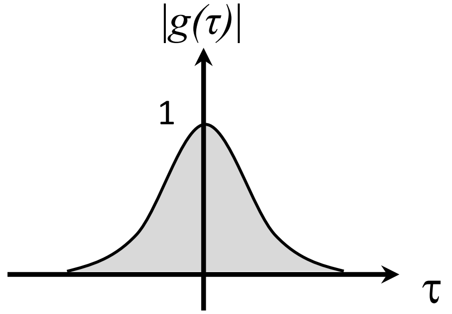
$$g(\tau) = \frac{G(\tau)}{G(0)} = \frac{\langle U^*(t)U(t+\tau)\rangle}{\langle U^*(t)U(t)\rangle}$$

Complex degree of temporal coherence

Properties of $g(\tau)$:

- $0 \leq |g(\tau)| \leq 1$
- For $|g(\tau)| = 1$ the wave is totally coherent (example $|g(0)| = 1$, the field is always coherent with itself)
- For most sources $|g(\tau)|$ decreases from its maximum value $|g(0)| = 1$
- The fluctuations become uncorrelated for sufficiently large τ.

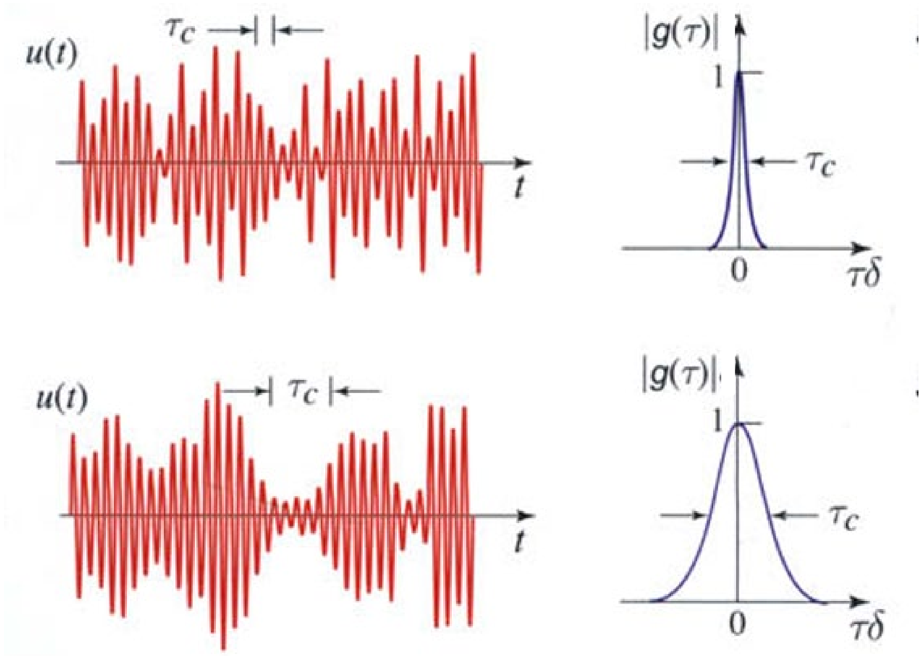




Coherence time τ_c and length l_c

If $|g(\tau)|$ decreases monotonically with τ, the value τ_c at which it drops to a prescribed value (for eg. 1/2) serves as a measure of the memory time

τ_c is called the *coherence time*



- If $\tau < \tau_c$ fluctuations are strongly correlated
- If $\tau > \tau_c$ fluctuations are weakly correlated
- We define the coherence length:

$$l_c = c\tau_c$$

Coherence length

Power spectral density

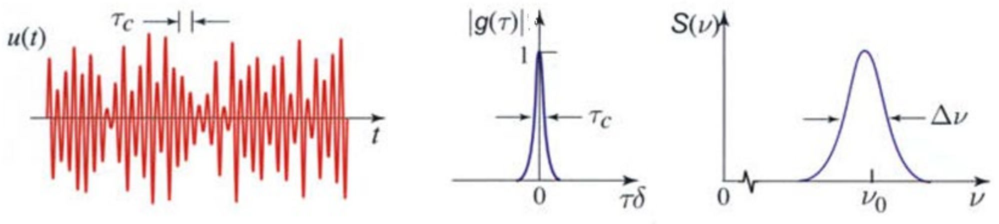
The power spectral density $S(\nu)$ is the frequency response of a random or periodic signal.

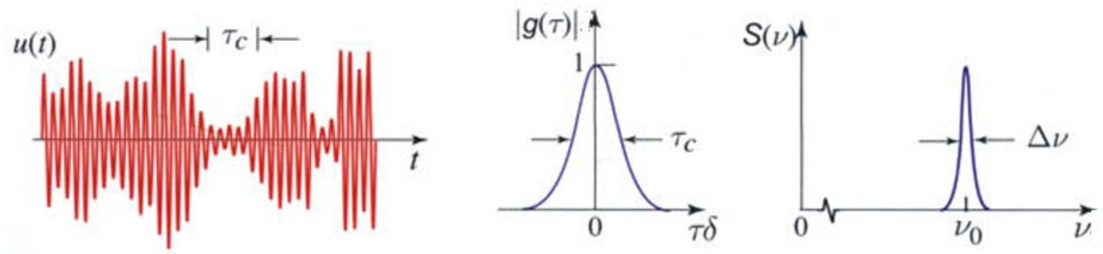
- It describes how the average power is distributed over frequency
- It actually represents the intensity spectral density (W/cm^2-Hz)
- Often simply referred to as the spectral density or the spectrum
- It is often confined to a band centered about a central frequency ν_0 with a spectral width $\Delta\nu$

Power spectral density

The temporal coherence function $G(\tau)$ and $S(\nu)$ form a Fourier transform pair:

$$S(\nu) = \int_{-\infty}^{\infty} G(\tau)\exp(-2\pi\nu\tau)d\tau$$





- There are several definitions for spectral width. One of the most common is the *full width at half maximum (FWHM)*
- The relation between spectral width and coherence time depends on the spectral profile. For sufficiently smooth function:

$\Delta\nu \cdot \tau_c \approx 1$	$\Delta\nu \cdot \tau_c \approx 0.32$	$\Delta\nu \cdot \tau_c \approx 0.66$
rectangular	*Lorentzian*	*Gaussian*

Light sources for photonic systems

Different types of light sources have different degree of coherence and thus power spectral densities.

Incoherent light is characterized by low degree of coherence (large spectral width):

- the nature of the emitted light is entirely chaotic, with a signal comparable to noise
- For example: light emitting diodes (LEDs)

Coherent light has high degree of coherence and well defined optical wave function

- For example: laser light

Depending on the applications, not all sources are created equal

- Performance of a photonic system will strongly depend on the properties/quality of the source