FIBER LASERS AND AMPLIFIERS
Bright light from glass threads

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OUTLINE

- Lasers - basic terms
- Fabrication of RE-doped fibers
- Continual and pulse lasers
- Soliton lasers
- Lasers based on double-clad fibers
- Fiber amplifiers

WHAT IS LASER?

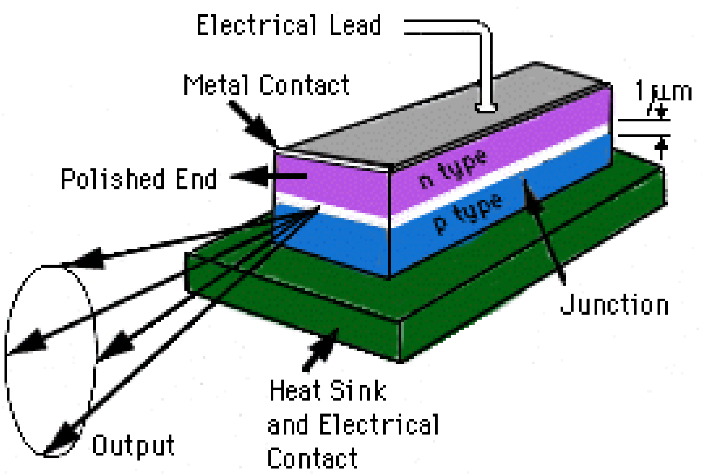
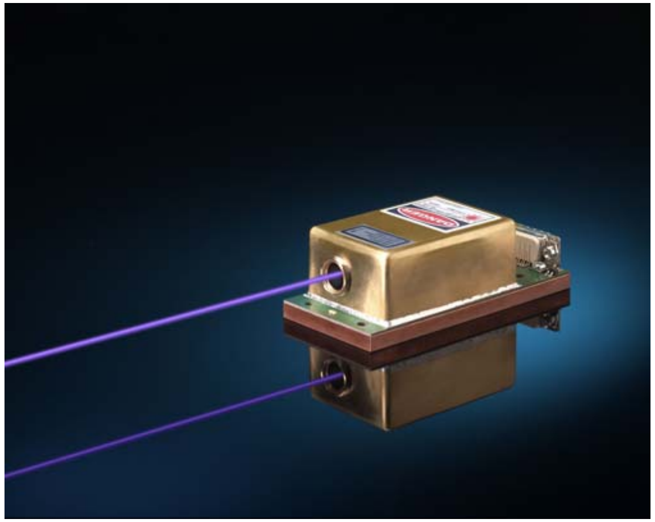
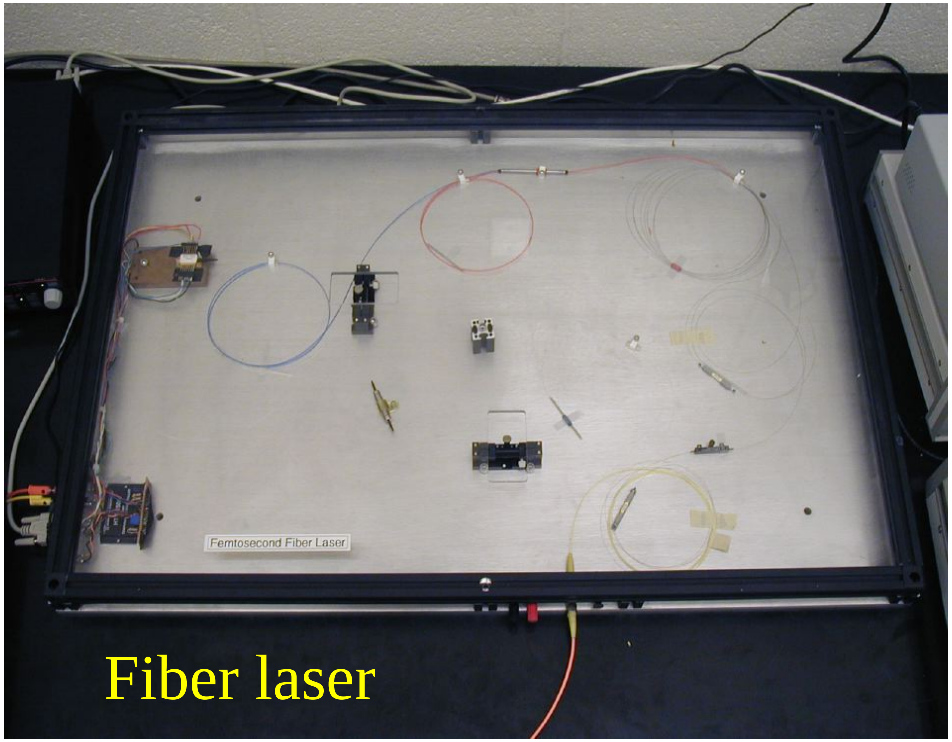


Diagram of Semiconductor Laser



Solid state laser



Fiber laser

WHAT IS LASER?

Optical oscillator employing stimulated light emission

Light **O**scillator by **S**timulated **E**mission of **R**adiation

~~**LOSER**~~

LASER

Light **A**mplification by **S**timulated **E**mission of **R**adiation

Rubby laser 16. 5.1960, **Maiman' s paper in Nature, August 6, 1960, Vol. 187, No. 4736, pp. 493-494**

Sun:

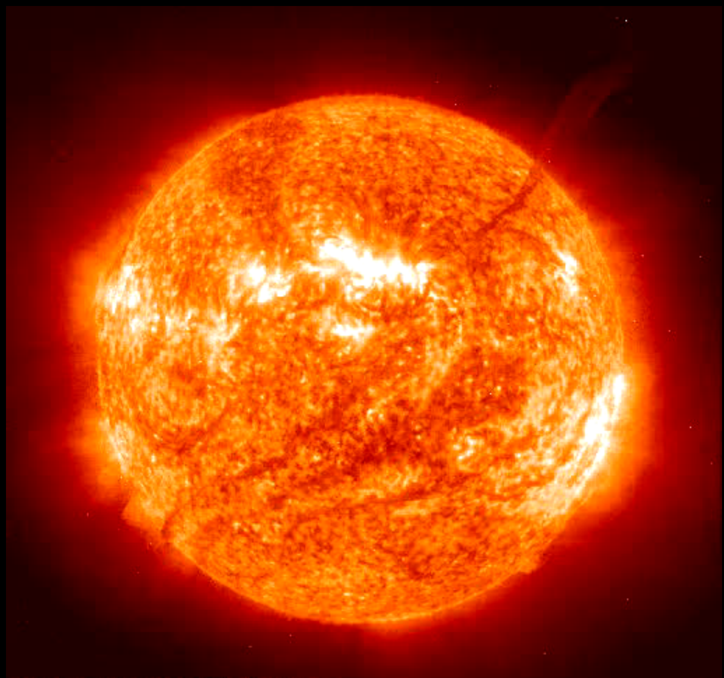
temperature of the surface: 5780 K
Stefan-Boltzmannův law:
$I=\sigma T^4$ [W/m²] $\rightarrow$

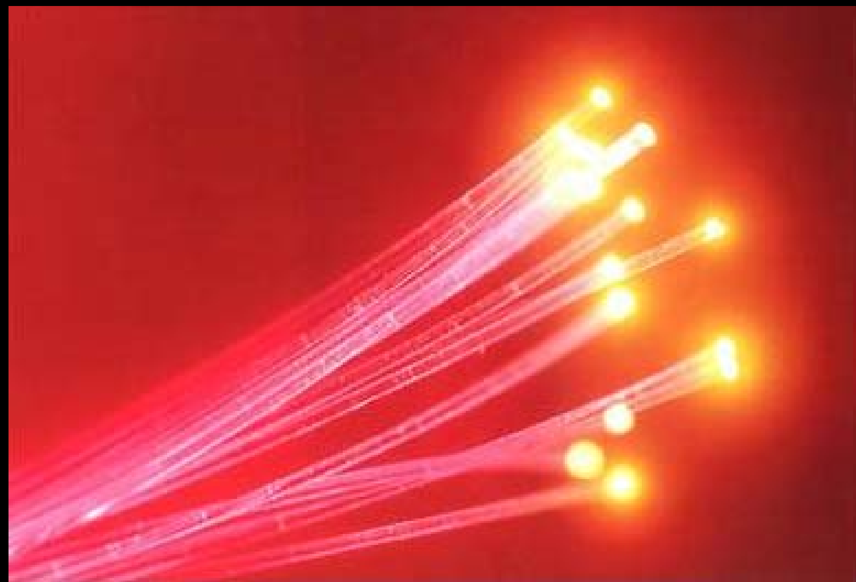
Intenzity of light on the surface of Sun:
I= 63 MW/m^2

Optical fiber:

at optical power of 1W in optical fiber $\rightarrow$

Light intensity in the fiber core is :
12.7 GW/m^2
approx. **200 x** more than on Sun





LASER CHARACTERISATION

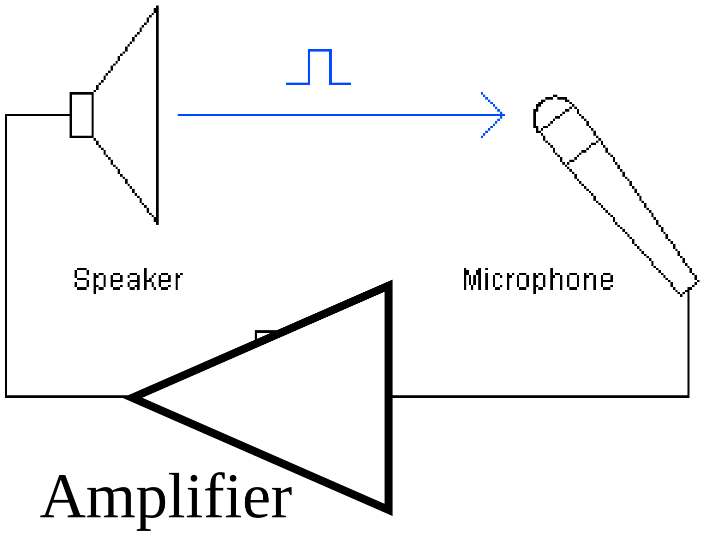
- Laser emits light due to Amplified Stimulated Emission (ASE)
- Light beam from laser has spatial coherence that allow us to focuse it into a small spot
- Light beam has temporal coherence that makes possible to emit only one frequency

  Laser radiation can bring high powers (cold nuclear fusion induced by Nd:YAG laser

LASER – LIGHT OSCILLATOR

What requires any oscillator?

Acoustic oscillator



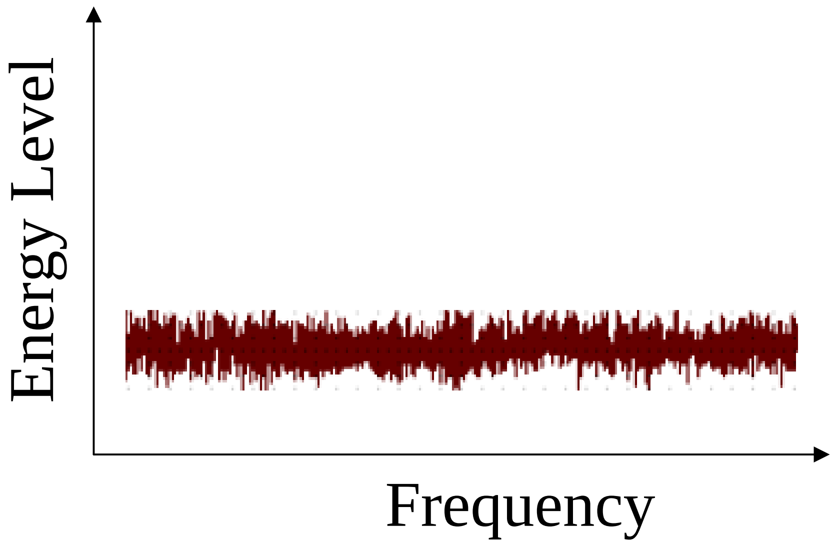
It requires gain and feedback!

OSCILLATOR FREQUENCY

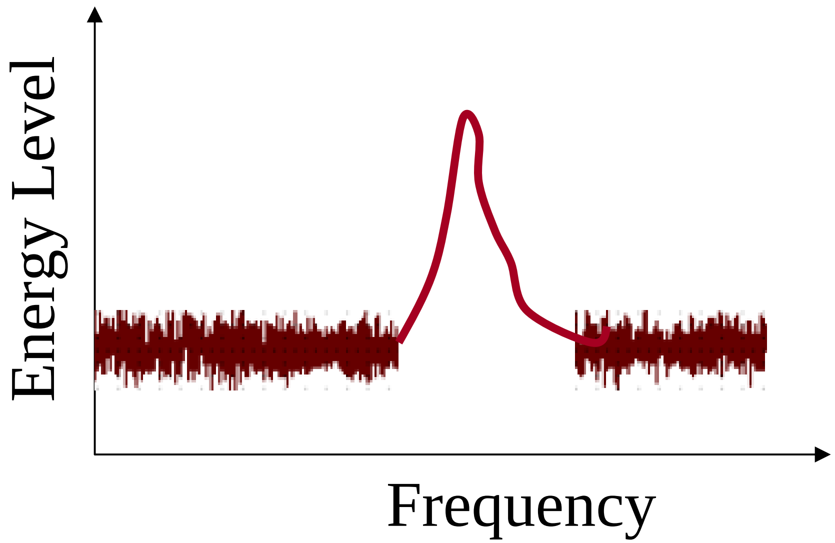
What determines the frequency of the oscillation?

Resonance!

gain<loss



gain≥loss

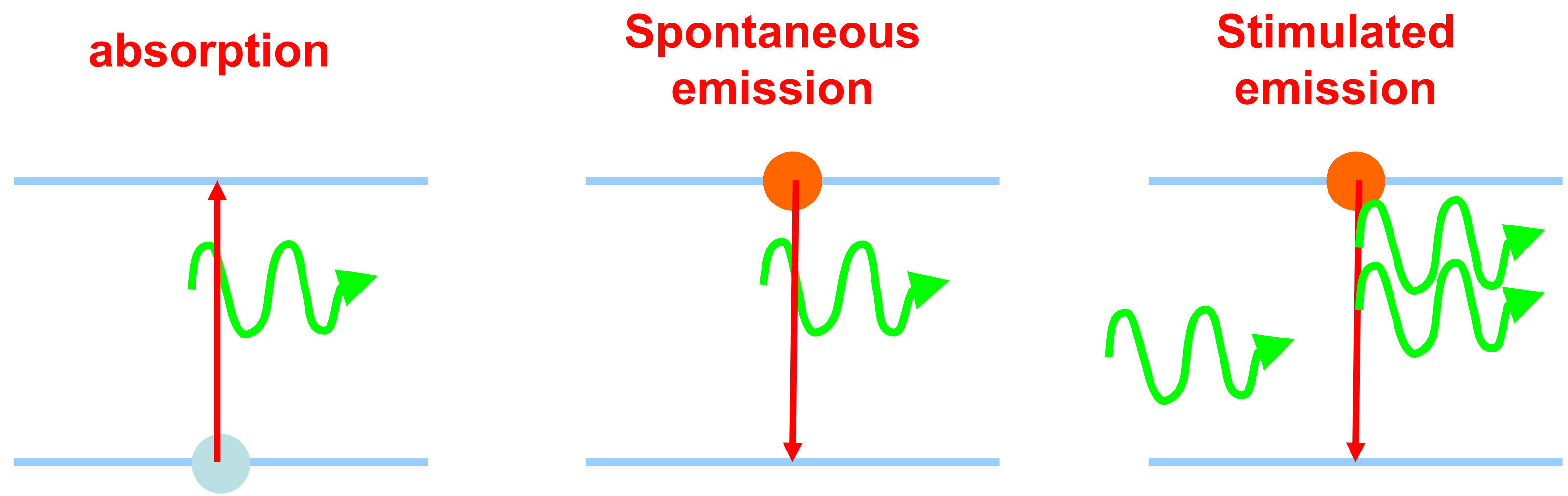


LASER GAIN

GAIN is obtained in gain medium (ruby crystal, glasses doped with rare-earth elements, etc) via

Amplified Stimulated Emission (ASE)

SPONTANEOUS AND STIMULATED EMISSION



Stimulated emission is <u>an emission</u> of light **induced by the interaction of photon** with excited atoms ⇒
<u>Two photons</u> with the same wavelength, phase and polarisation (coherent light) are obtained (amplification - ASE)

CONDITION FOR ASE

- Strong pumping $\Rightarrow$ Inversion population
- Signal photons for interaction with excited atoms

? How to provide these photons

Lasers:

Result of spontaneous emission and feedback
(provided by laser resonator)

Amplifiers

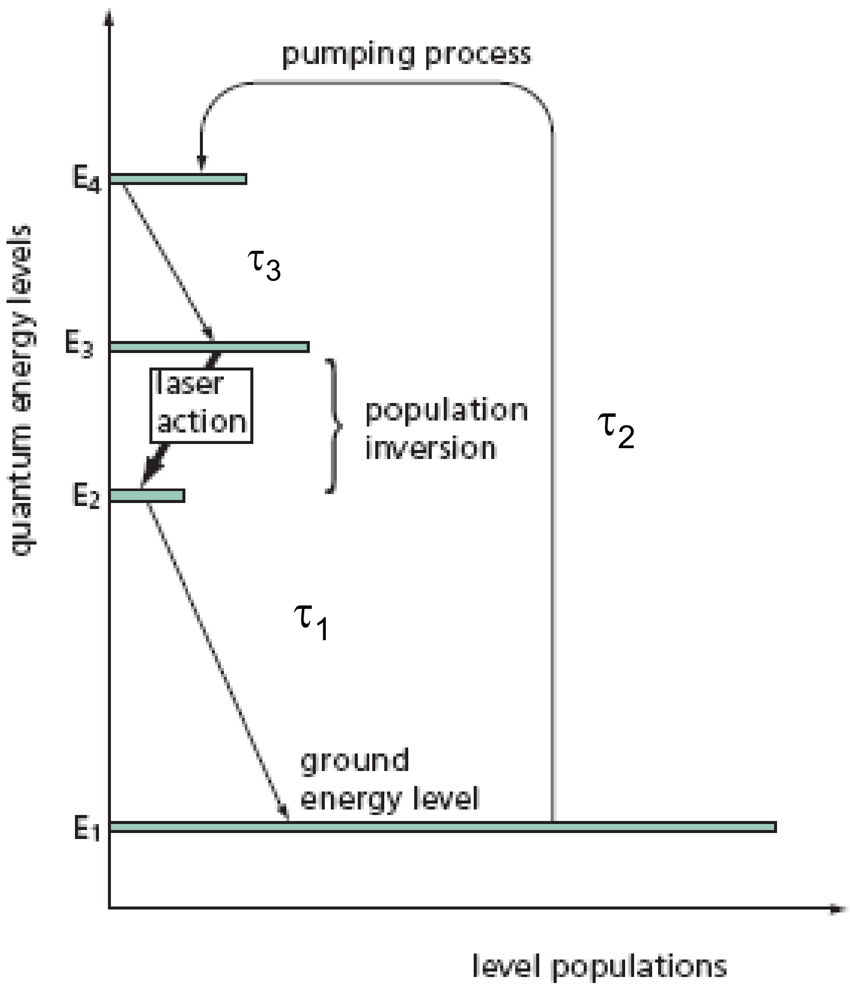
From amplified signal

RESTRICTIONS TO ASE

- Interactions between closely spaced RE atoms – decay of ASE. *Caused by the vibration of glass matrices (phonons)* They can be controlled by matrix composition
- Interaction of excited atoms with –OH ions – decay of ASE ⇒ Requirements for dry glasses
- Spontaneous emission that contributes to noise
- Optical losses of the fiber materials (scattering) decrease a number of signal photons

HOW TO PROVIDE MORE PHOTONS FOR ASE?

POPULATION INVERSION



$$N_2 = N_1 \exp\left(-\frac{E_2 - E_1}{kT}\right)$$

Boltzmann law $N_2 < N_1$

$\tau_2 >> \tau_1$ + strong pumping → $N_3 > N_2$

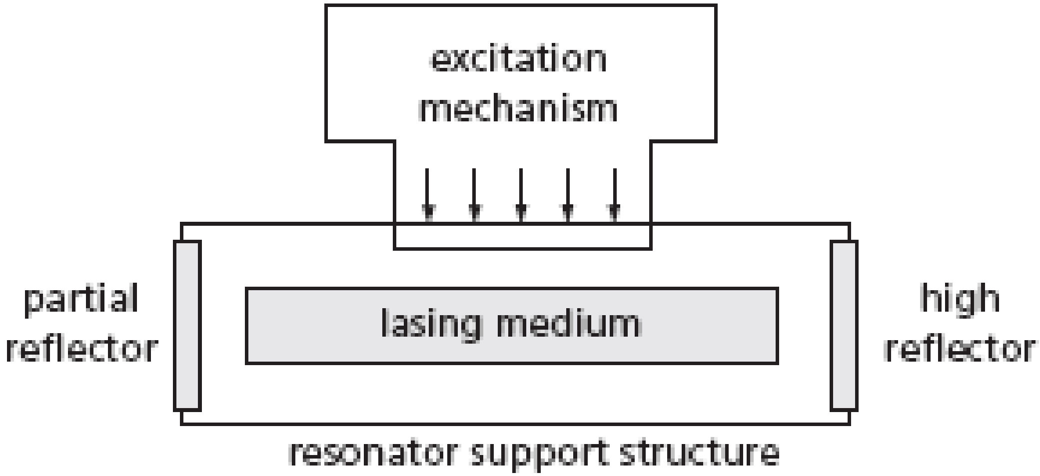
Electrons on 3rd level create population inversion and light with frequency

$\nu = (E_3 - E_2)/h$

can be amplified

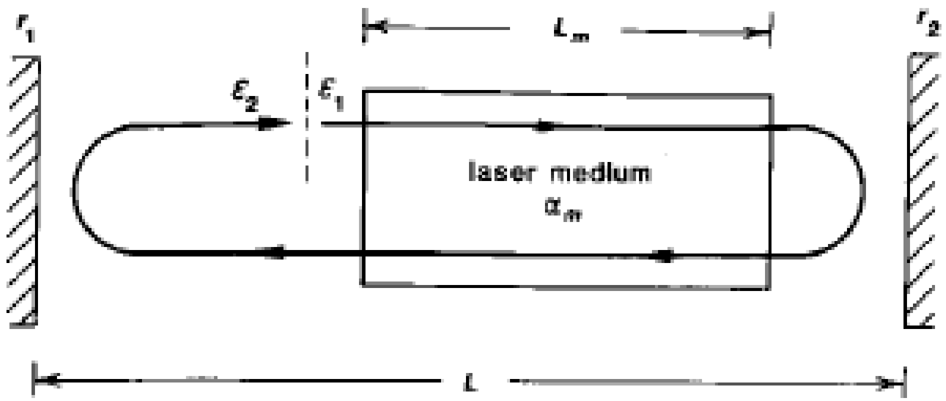
HOW TO PROVIDE MORE PHOTONS FOR ASE?

OPTICAL RESONATOR - Feedback



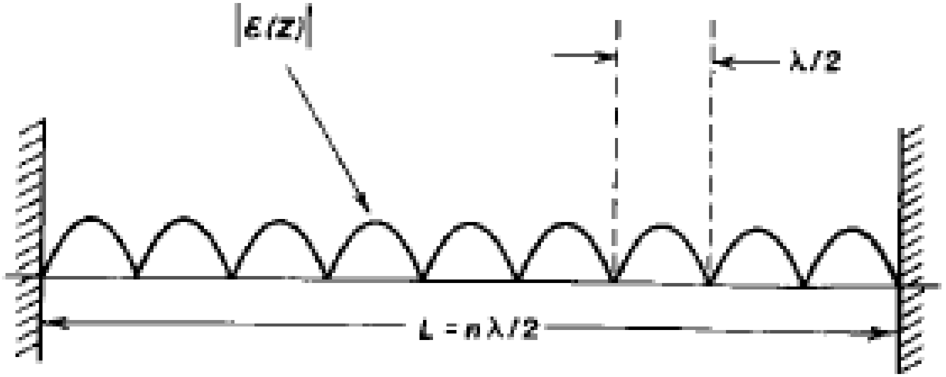
Reflects axially propagating photons back to gain medium
a part of photons pass through partial reflector out of the resonator

AXIAL RESONANT MODES



$$\frac{2\omega L}{c} = N2\pi$$

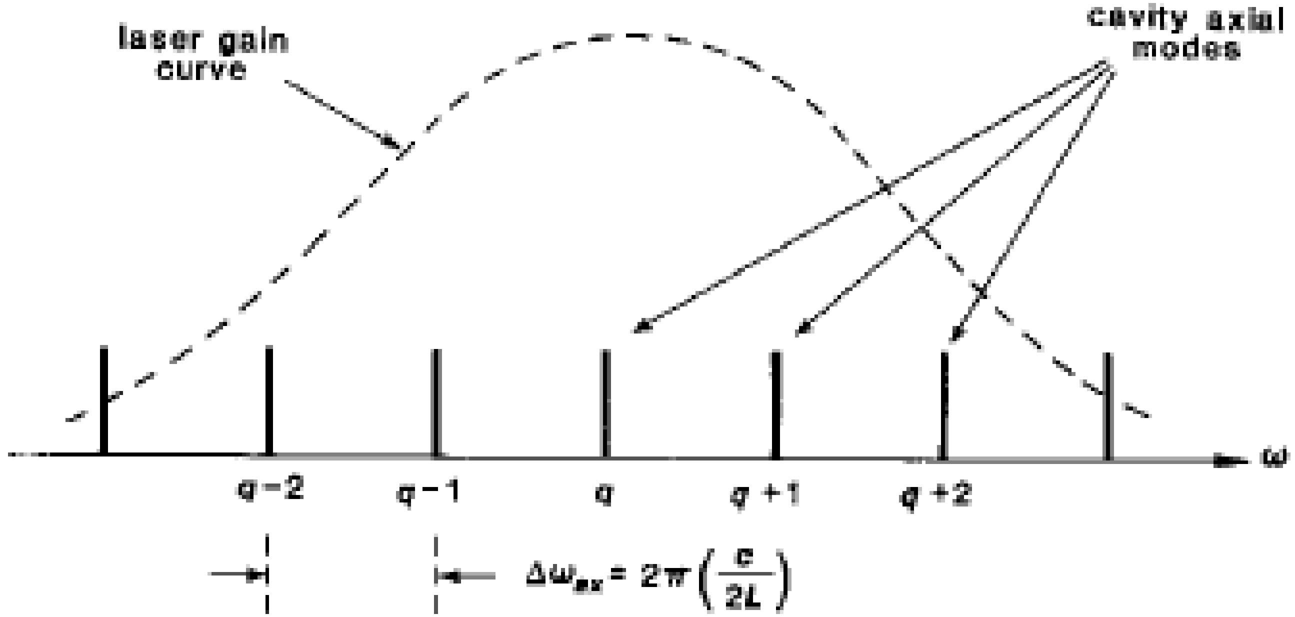
N : integer



$$L = N\frac{\lambda}{2}$$

Only modes with the same phase strengthen the field

GAIN AND AXIAL RESONANT MODES



Multiple resonant modes propagate in resonator and bring energy obtained from gain

Gain curve have multiple resonant modes

LASER – OPTICAL OSCILLATOR

Conditions for laser oscillations:

1. Enough strong active medium
   Gain of the active medium > optical losses in the resonator
2. Phase synchronisation $\Delta\varphi=2\beta L=2\pi N$
   The phase of the feedback signal is synchronised with the phase of the input signal

FIBER LASERS

1. Employ glass fiber cores doped with rare-earth elements (Er, Yb, Nd, Tm)
2. Optical core itself is used as the resonator

MOTIVATION FOR FIBER LASERS AND AMPLIFIERS

As optical fibers can transmit high light intensities in the fiber cores they could be used for

*rapid and broad band light sources for telecommunications – **fiber lasers***

*Long telecommunication lines – **amplifiers***

IPE research in the field

Er-doped fibers for C band (1530-1595 nm)

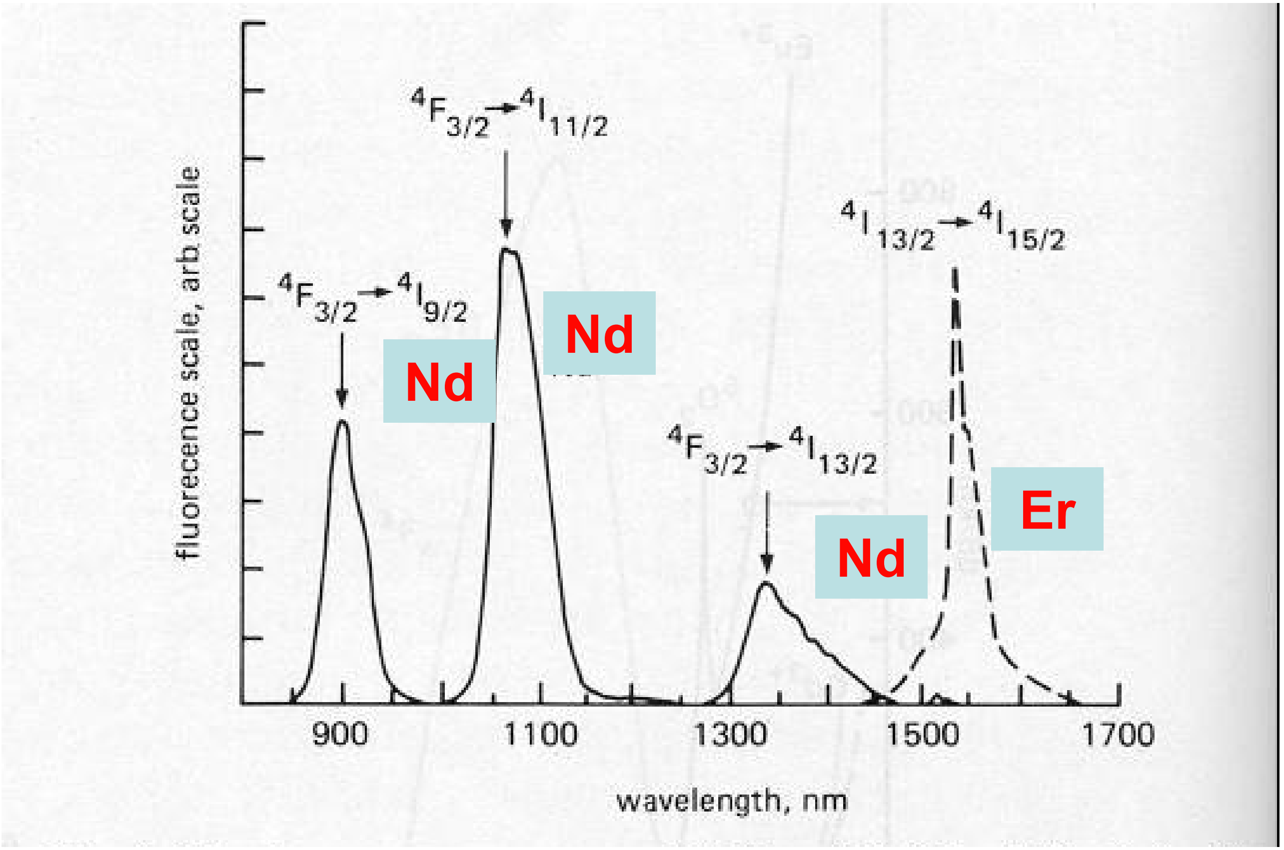
Er/Yb fibers for C band, Yb as sensitiser

Tm-doped fibers for S band (1460-1530 nm)

RE IONS IN TELECOMMUNICATIONS

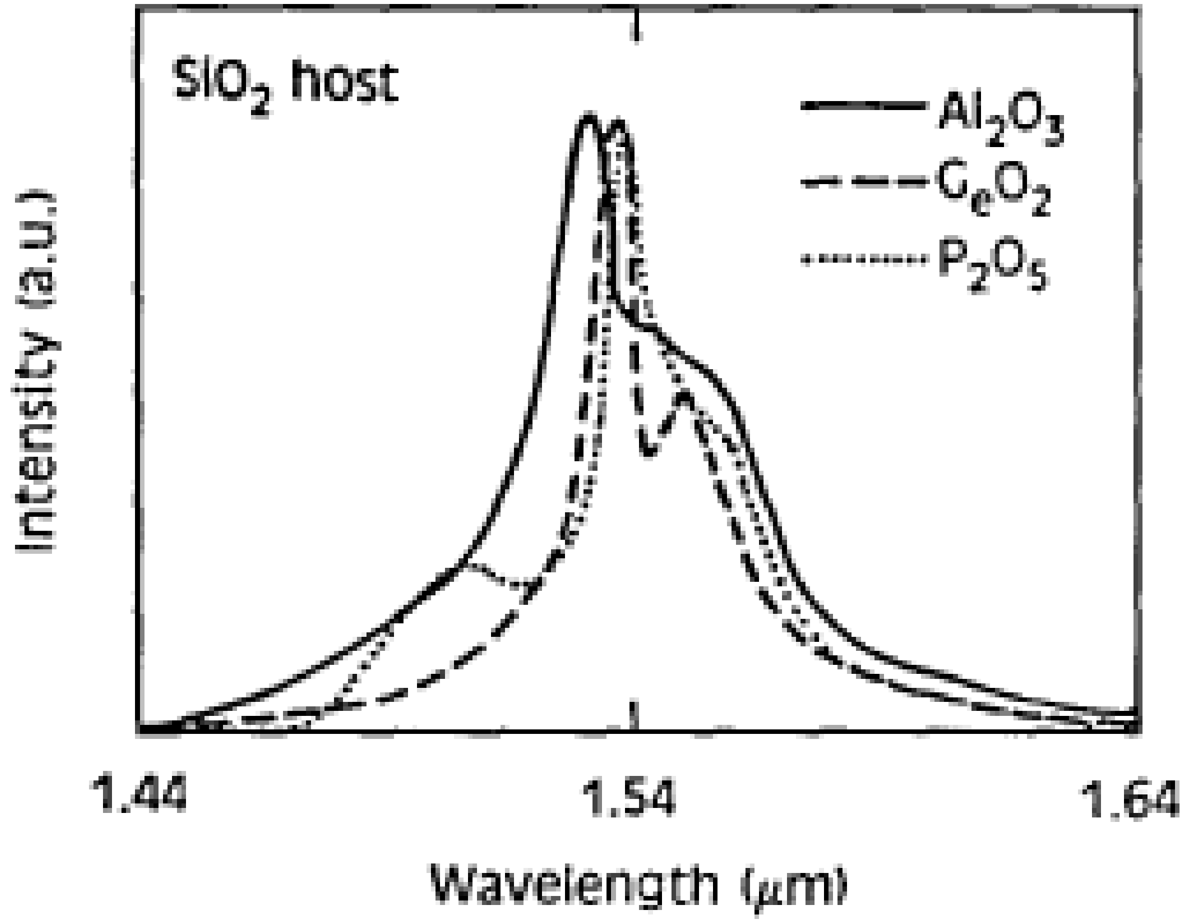
- Nd ions – 1300 nm – (strong ASE only in fluoride glasses)
- Er ions – 1550 nm (strong ASE in silica glasses)
- Yb ions – 1060 nm (silica glasses) used for pump lasers
- Tm ions – 1470 nm (silica glasses) -
  S band or 810 nm (strong ASE in silica glasses)

EMISSION SPECTRA OF RE IONS



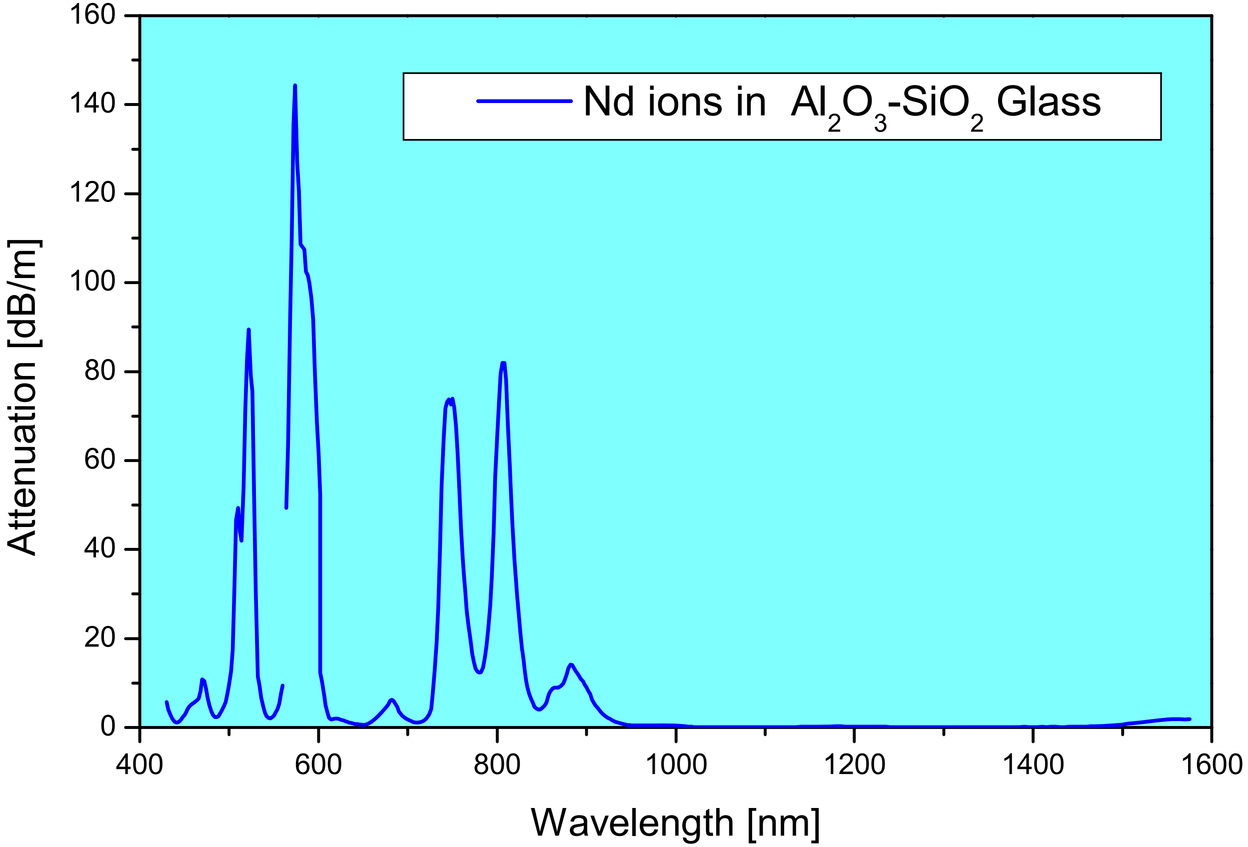
The emission spectra of Er and Nd ions in $GeO_2/P_2O_5/SiO_2$ glass

EFECT OF GLASS COMPOSITION ON Er EMISSION



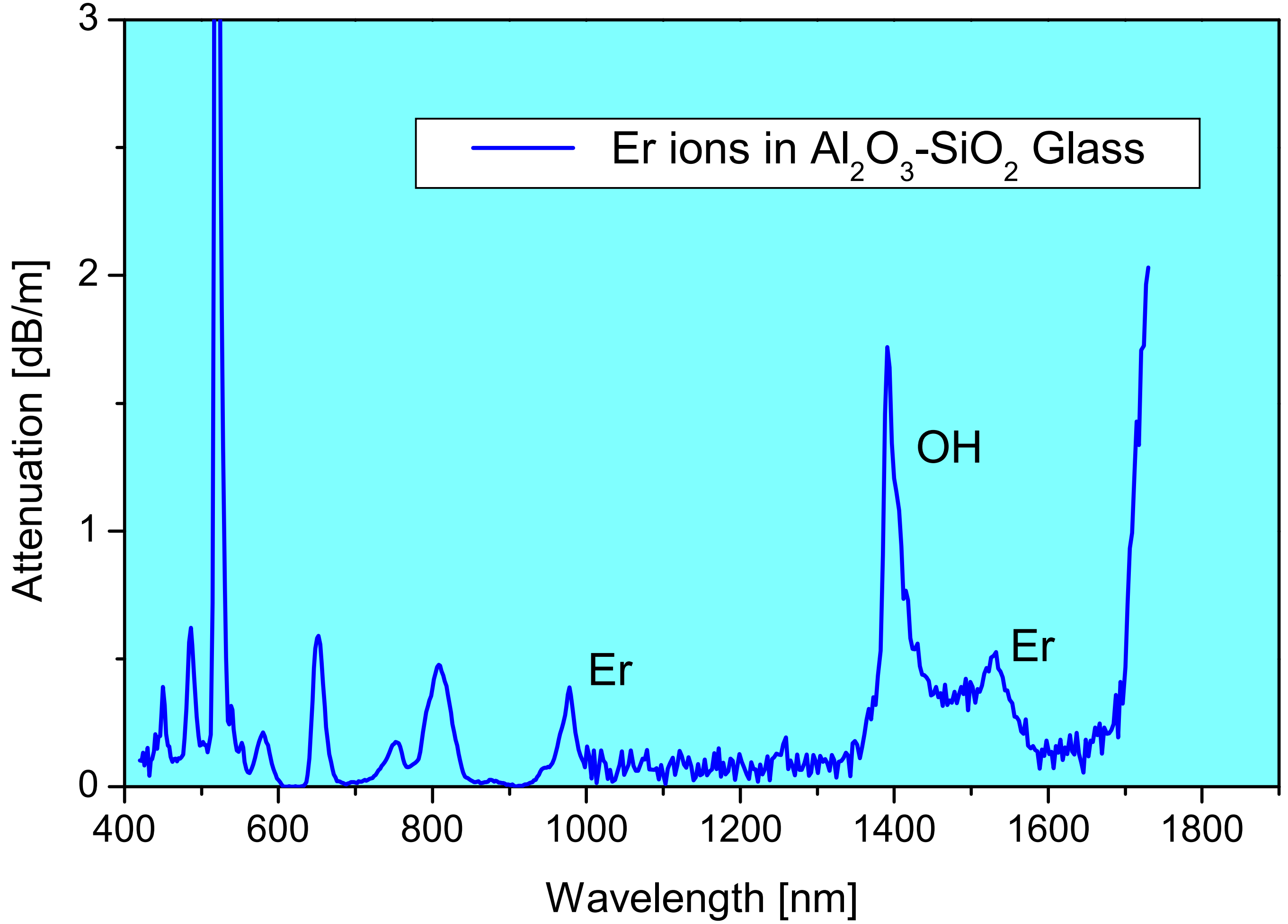
Emission bands depends on material composition

ABSORPTION SPECTRA OF Nd IONS

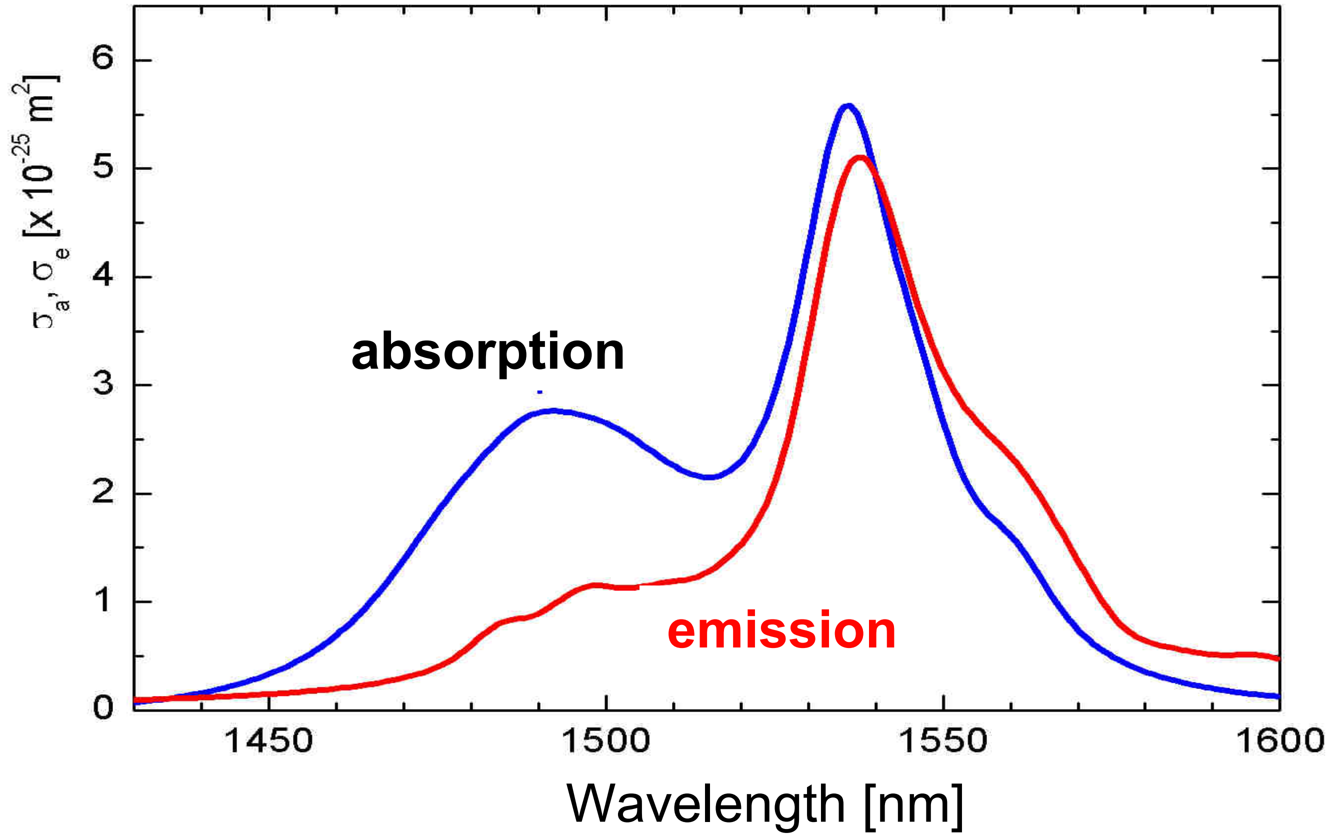


Absorption bands of RE ions are used for pumping

ABSORPTION SPECTRA OF Er IONS



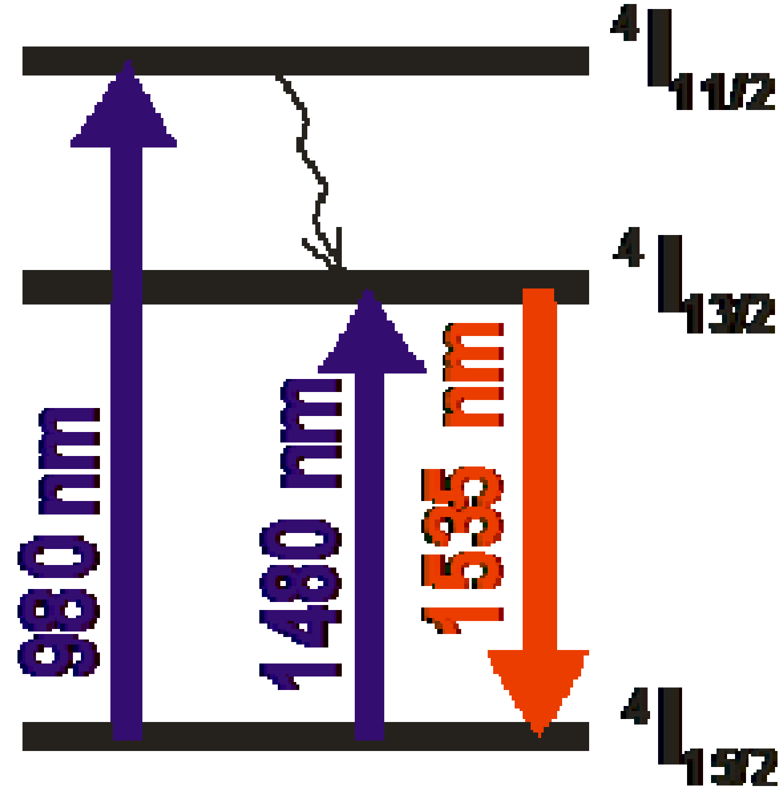
ABSORPTION AND ASE of Er/Yb-DOPED FIBER



σ- transition cross-section (a – absorption, e-emission)

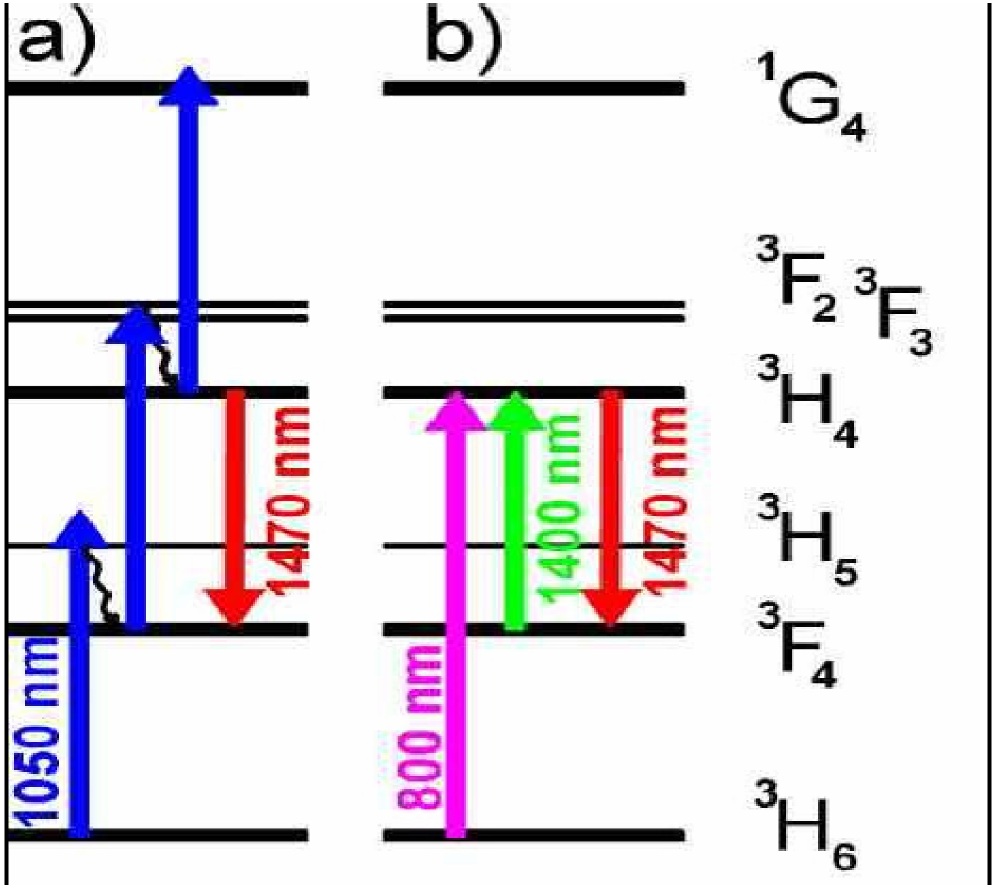
Linear resonator without mirrors

ENERGY DIAGRAM OF Er-BASED LASERS



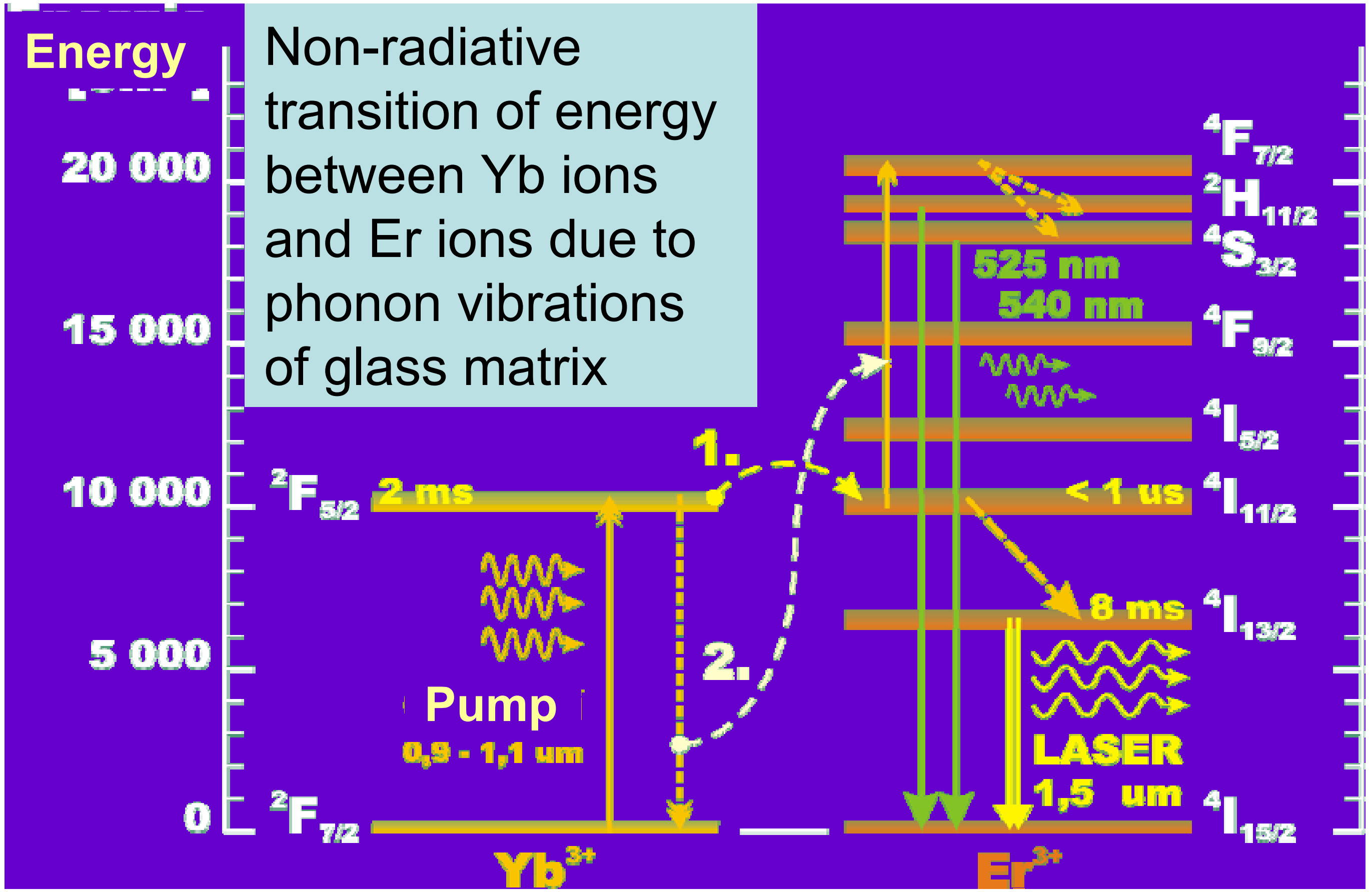
For C band

ENERGY DIAGRAM OF Tm-BASED LASERS



For S band

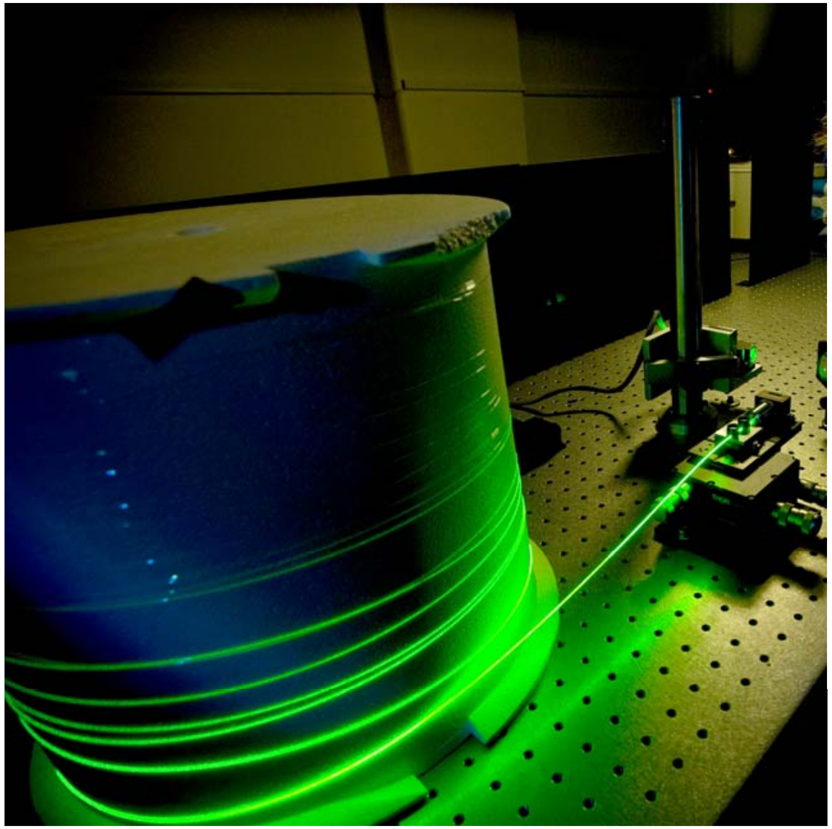
ENERGY DIAGRAM OF Er/Yb-BASED LASERS



Er/Yb FIBER LASERS

- 1064 nm - optical pump of Yb
- Transfer of energy from excited Yb to Er ions due to phonon vibrations ⇒ Non-radiative excitation of Er ions
- Non-radiative transition of Er ions to a levels with a lower energy (1550 nm)
- Emission of photons at 1550 nm
- Non-radiative transition of Er ions to a levels with a higher energy (green up/conversion)

Er/Yb FIBER LASER



Fiber pumped at 1060 nm, ASE 1550 nm + green up-conversion

TECHNOLOGICAL ISSUES

Issues

- Methods and raw materials for controlled doping RE ions in silica-based glasses suitable for optical fibers drawing
- Materials limiting the factors restricting erbium ASE (decay processes) $\Rightarrow$ Controlled matrix composition
- Materials controlling non-radiative energy transfers (phosphorous oxide)

TECHNOLOGICAL ISSUES

Glass matrix compositions

Silica glasses doped with

Aluminium oxide (Al_2O_3) limits interactions between closely-spaced RE ions

Phosphorous oxide (P_2O_5) controls matrix vibrations (phonons)

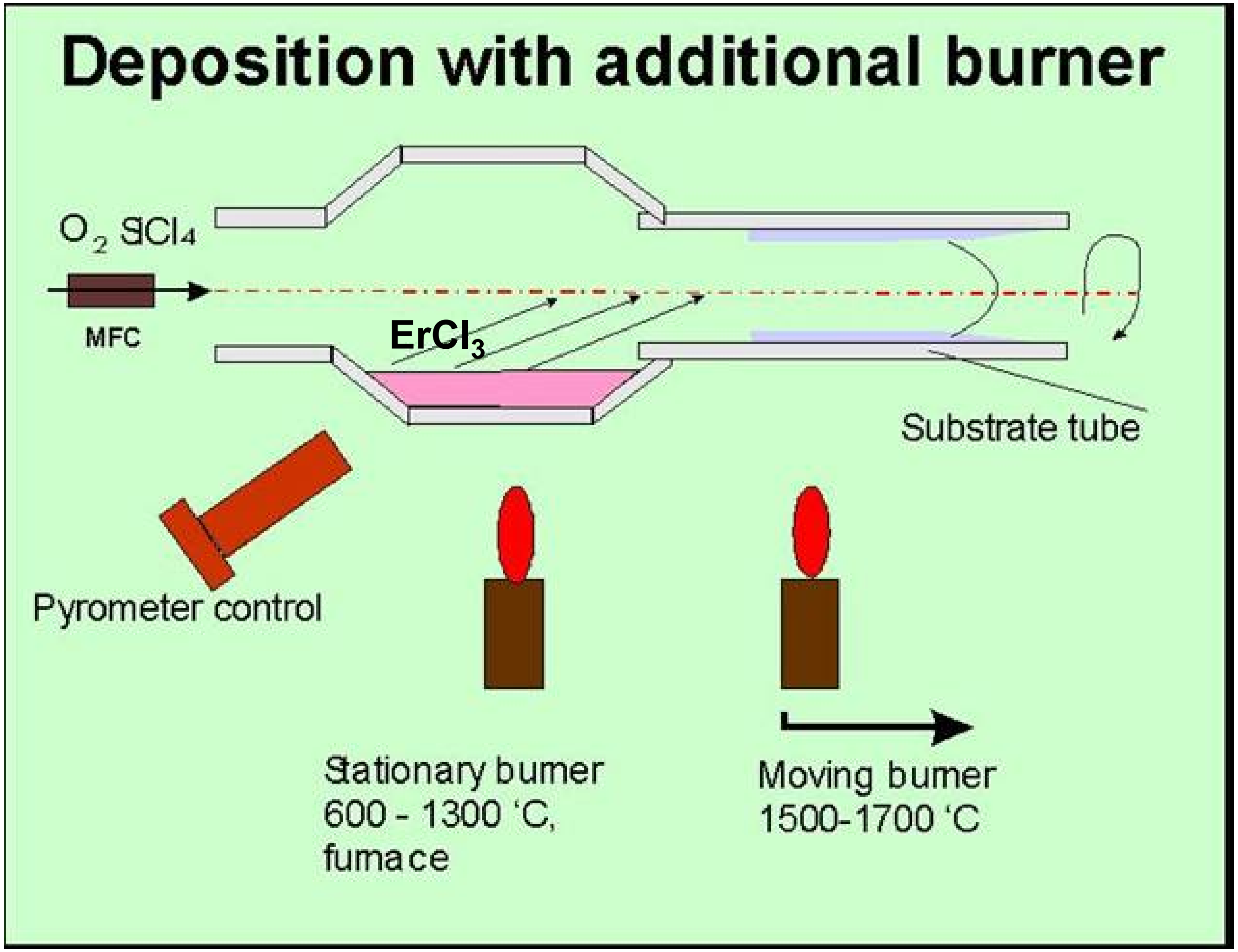
Raw materials

Solid chemical substances with high boiling points (RE chlorides, Al chloride, RE chelates) $\Rightarrow$ Special techniques are necessary.

TECHNOLOGIES FOR RE-DOPED FIBERS

- MCVD method for doping RE from gaseous phase (organometallic raw materials)
- Solution-doping method
- Sol-gel method

MCVD DOPING FROM GASEOUS PHASE



Modification: RE dopants are avaporated outside the tube

PERFORMANCE OF DOPING FROM GASEOUS PHASE

Advantages

Raw materials with boiling points 600-1000°C ($AlCl_3$, $ErCl_3$, $NdCl_3$, organometallic compounds of RE

Dopant content controlled by heating temperature (the stationary burner, furnace)

Large cores can be prepared using dopants evaporated outside the tube – similarity with the standard MCVD

Disadvantages

Technically complicated – it is necessary to prevent dopant condensation

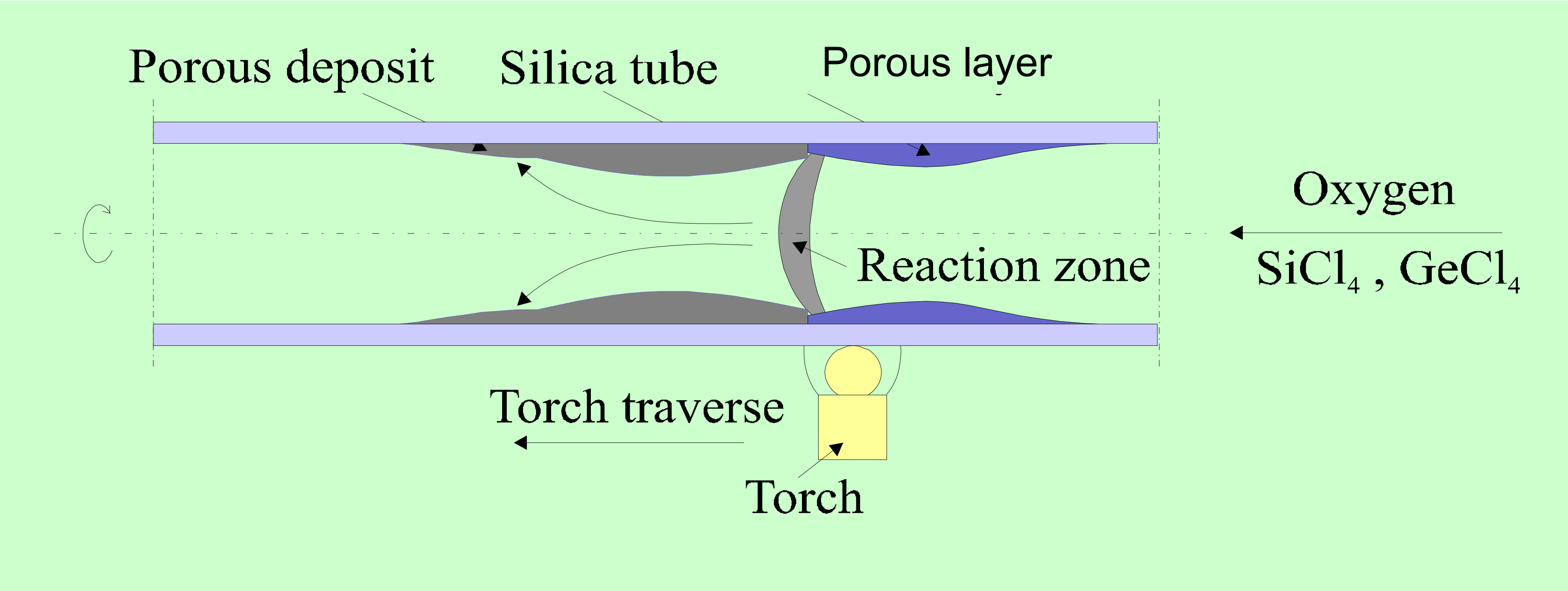
Dopant availability

SOLUTION-DOPING METHOD

- MCVD preparation of a porous layer
- Soaking the layer with solutions of dopants (Al, RE chlorides, nitrates)
- Drying and sintering soaked layer into a glass layer
- Collapse of the tube with the glass layer into a preform

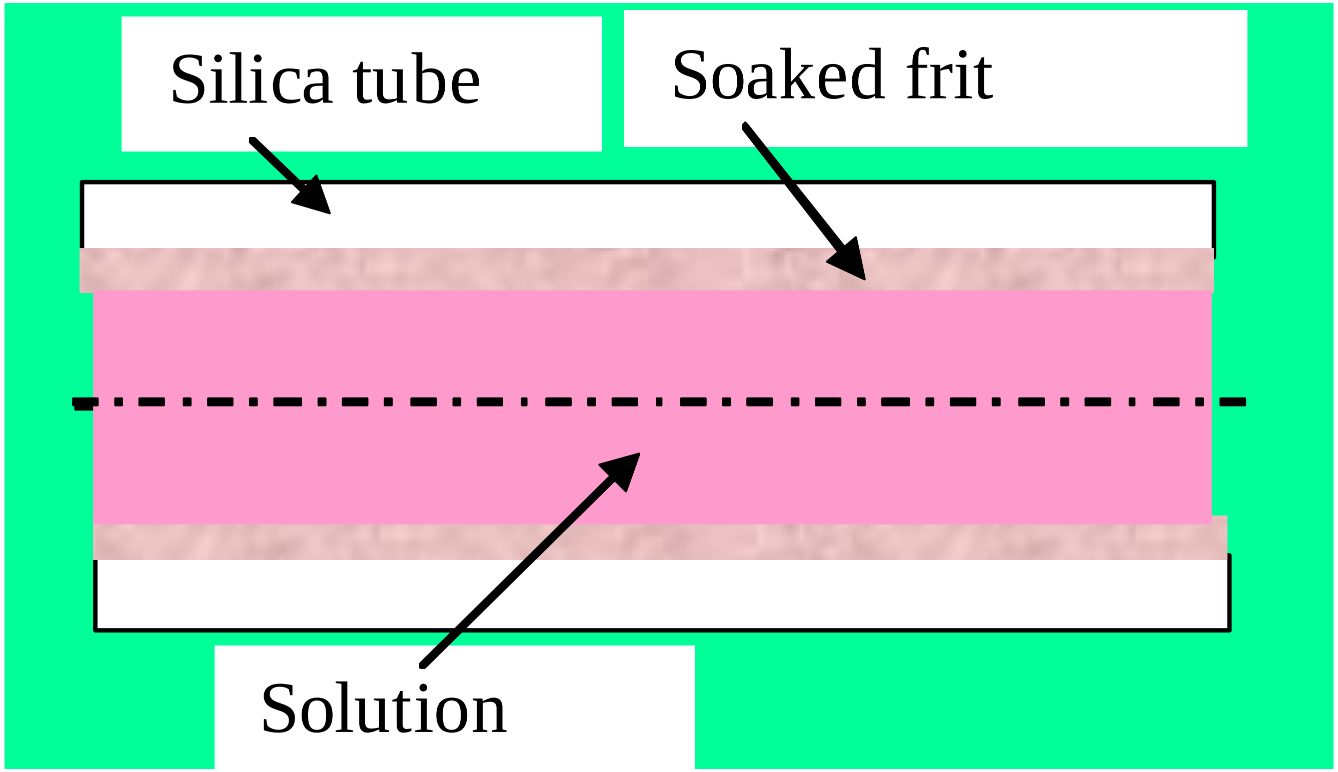
MCVD DEPOSITION OF POROUS LAYER (FRIT)

t = 1000 - 1200 °C



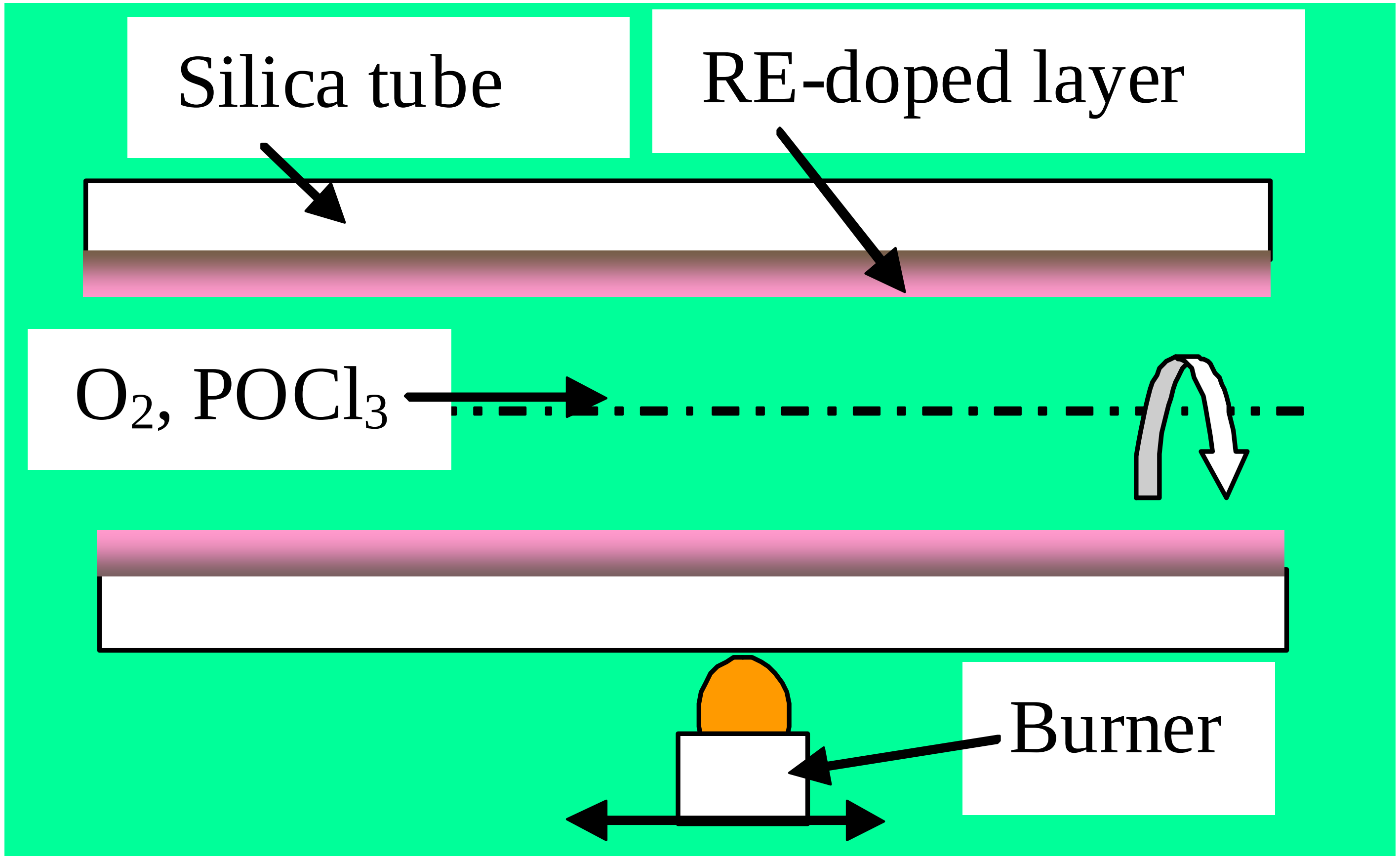
2. SOAKING THE FRIT (t = 25 °C)

Aqueous solutions Re, Al chlorides



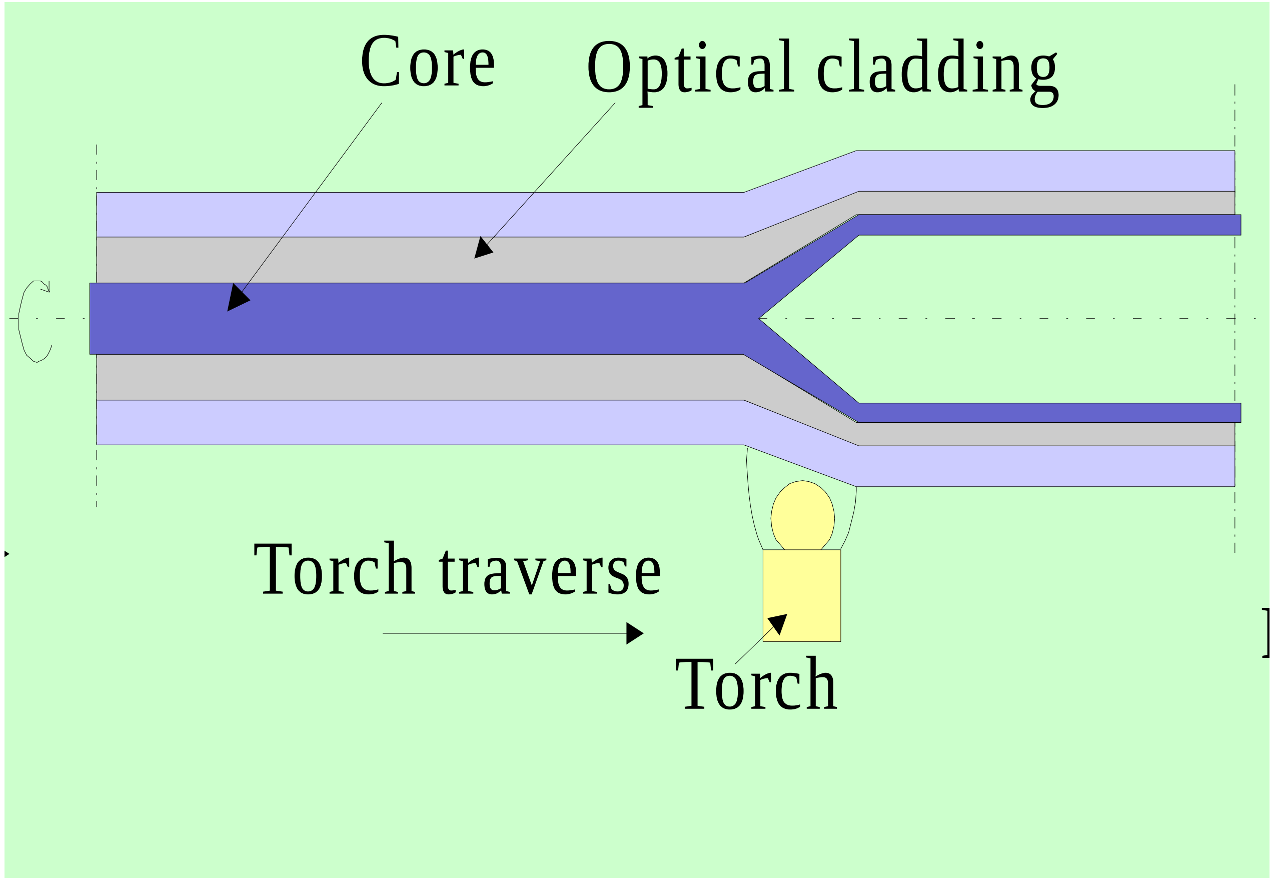
3. DRYING AND SINTERING THE SOAKED FRIT

t = 25-1700 °C



SOLUTION DOPING – TUBE COLLAPSE

- **Temperatures 1900-2000 °C**

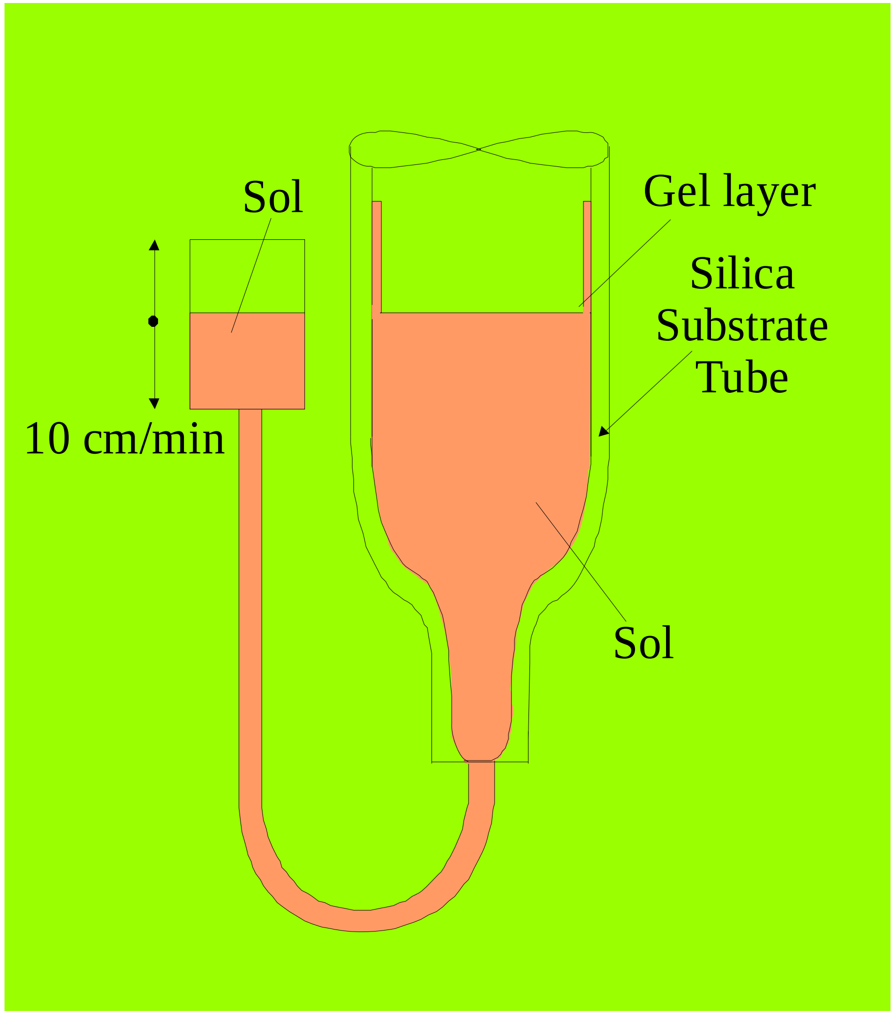


SOL-GEL METHOD IPE

- Mixing starting sols from silicon alkoxide – tetraethoxysilane, $POCl_3$ and Er, Yb and Al chlorides
- Application of a thin gel layer onto the inner wall of the substrate silica tube
- Drying, sintering of the gel layer
- Collapse of the tube with layers into a preform

1. PREPARATION OF GEL LAYER (t = 25 °C)

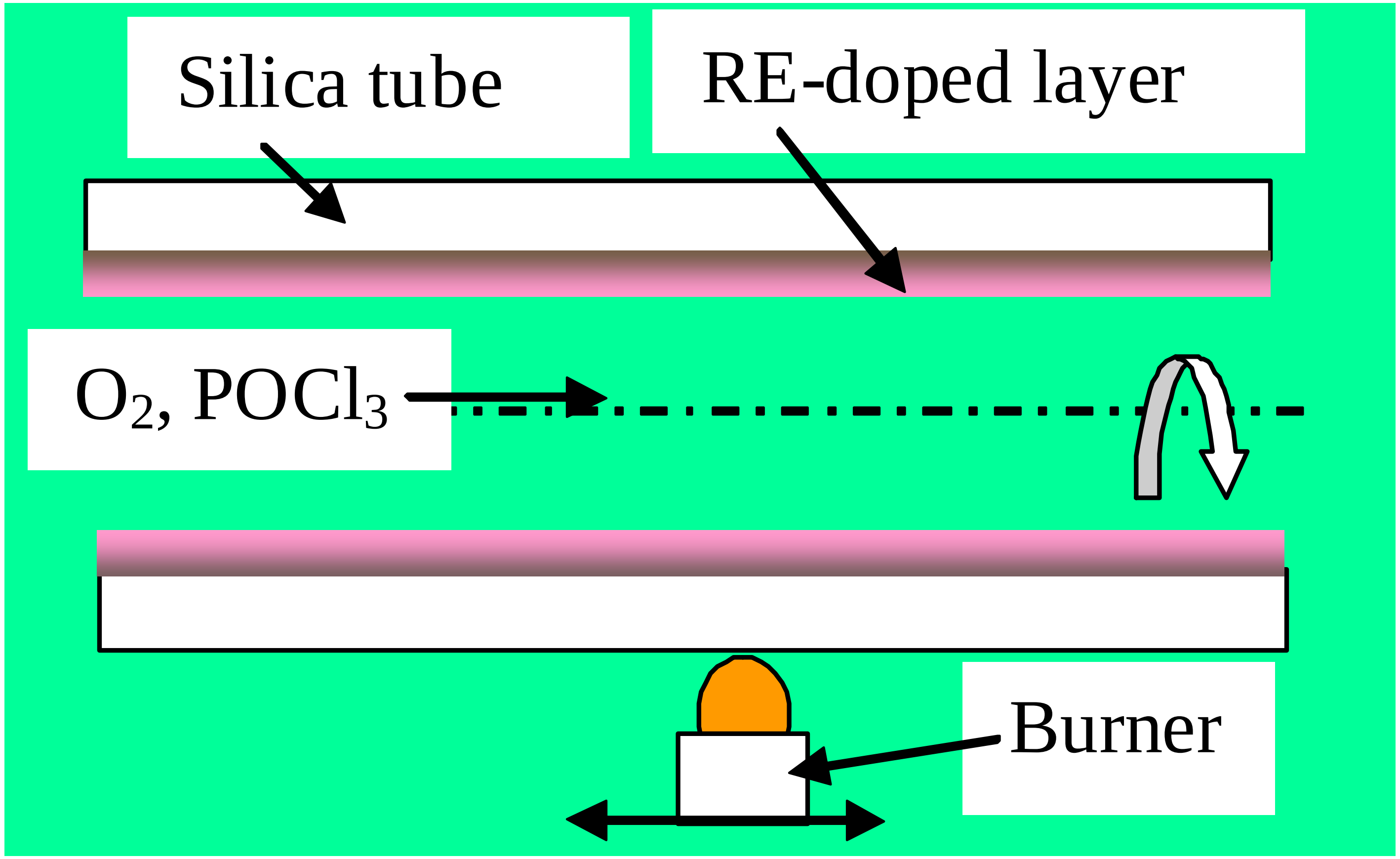
Approach IPE



SOL-GEL METHOD – TREATMENT OF GEL LAYERS

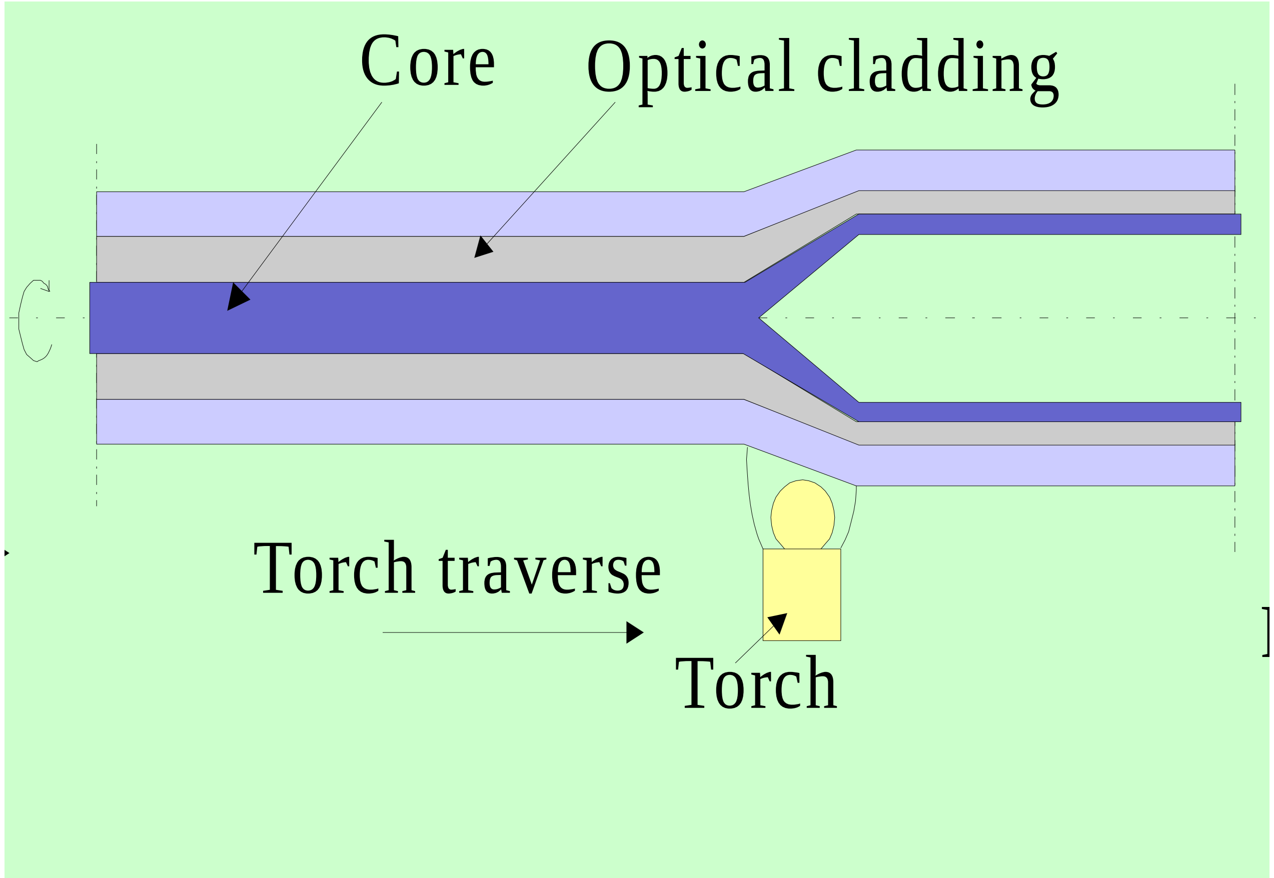
2. DRYING AND SINTERING THE GEL LAYER

t = 25-1700 °C



TUBE COLLAPSE

- **Temperatures 1900-2000 °C**



CRITICAL ISSUES

- **Solution doping**

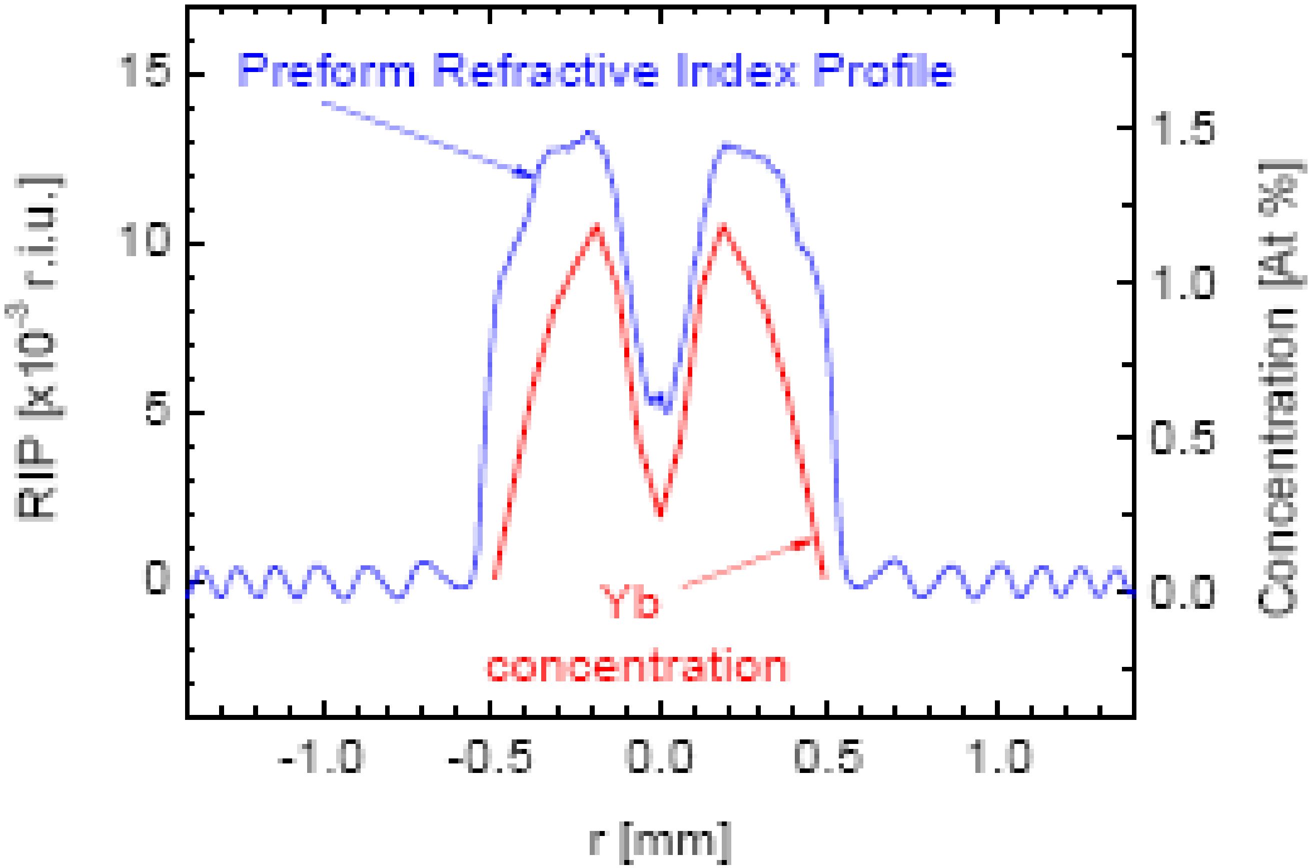
  Preparation of porous frits (homogeneity, pore dimensions)

  Sintering the dried soaked frits (completeness)

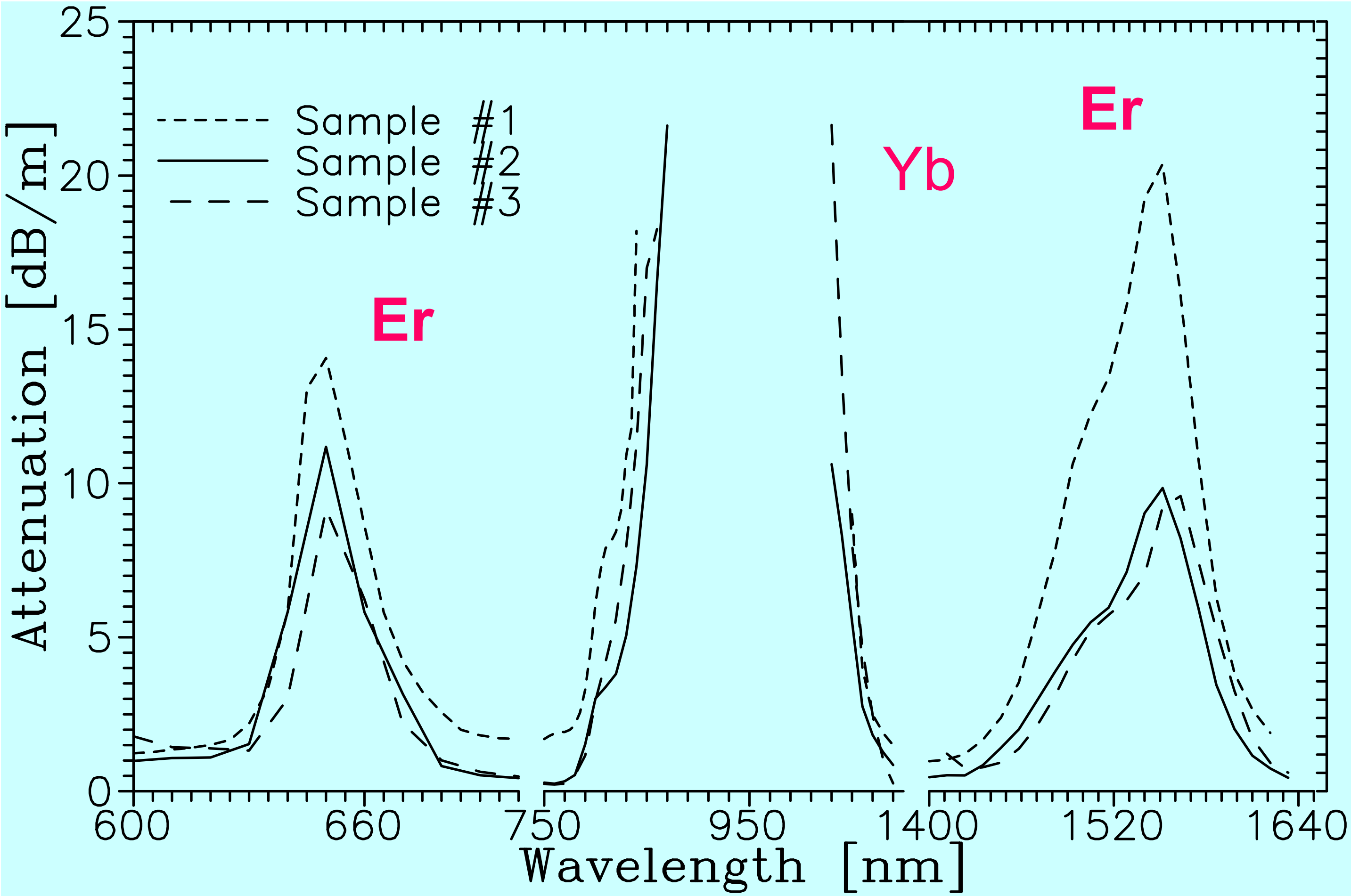
- **Sol-gel**

  Drying the gel layer (cracks, defects)

CONCENTRATION AND RI PROFILES



ABSORPTION SPECTRA OF Yb and Er IONS



Solution Doping and Sol-Gel methods

PERFORMANCE

The developed techniques have enabled us to prepare fibers with concentrations

Er_2O_3 (0.01-0.1 mol.%)

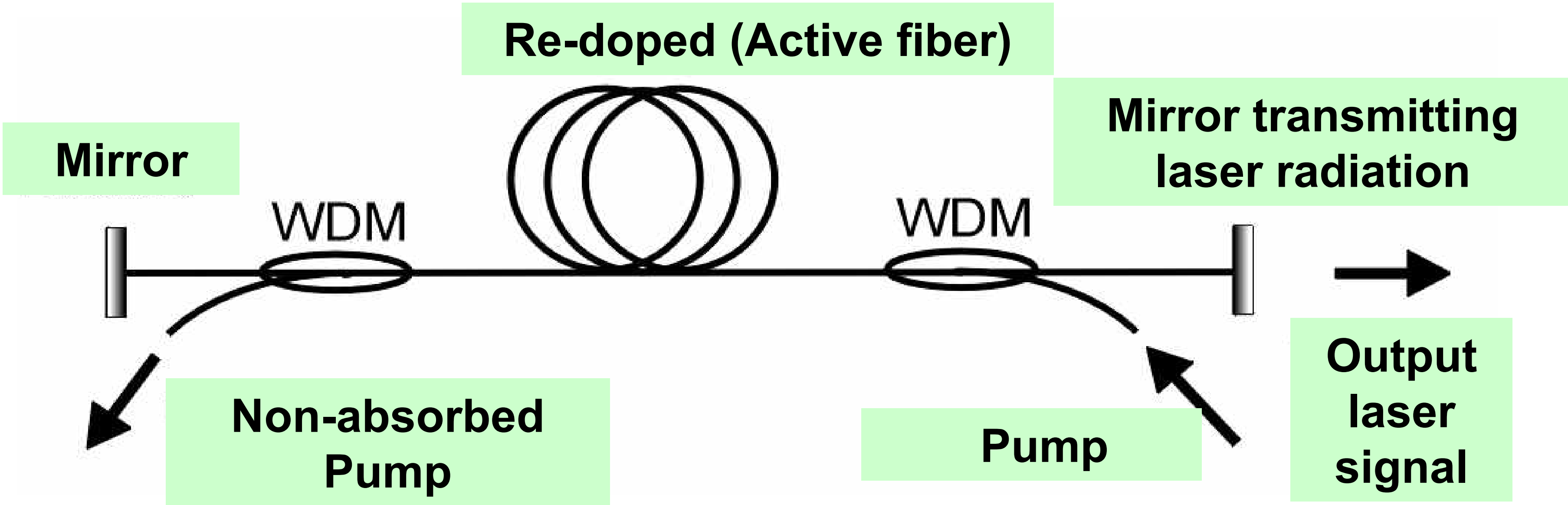
Yb_2O_3 (0.5-10 mol.%)

Al_2O_3 (1-8 mol.%)

$POCl_3$ (1-18 mol.%)

CONTINUAL FIBER LASER (CW)

1. Linear (Fabry-Perot resonator)



WDM transmits only pump not laser signal (ASE)

Fiber gratings can be used instead of the mirrors

RESONATOR MODES

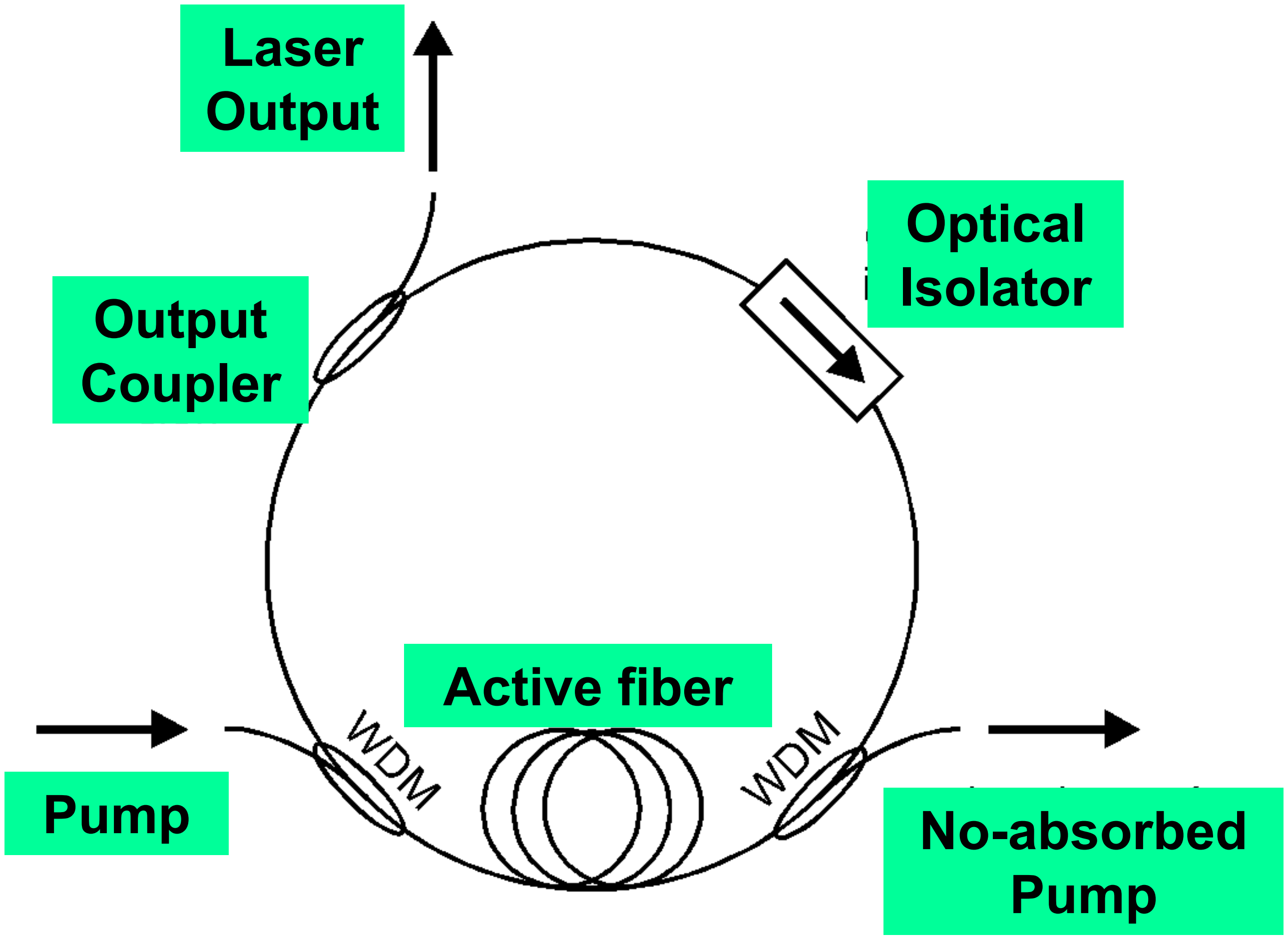
- Light is transmitted in laser resonators in longitudinal resonator modes
- Frequency difference of the modes in a linear resonator (a length L of 10 m, n~1.5) is $\Delta\nu = c/(2nL) \sim 10$ MHz ($\Delta\lambda$ = 0,000008 nm.)

  Compare with InGaAsP laser L= 300 mm where $\Delta\nu$=142 GHz ($\Delta\lambda$= 0,8 nm.)

  Very narrow spacing of resonator modes in continuous fiber lasers

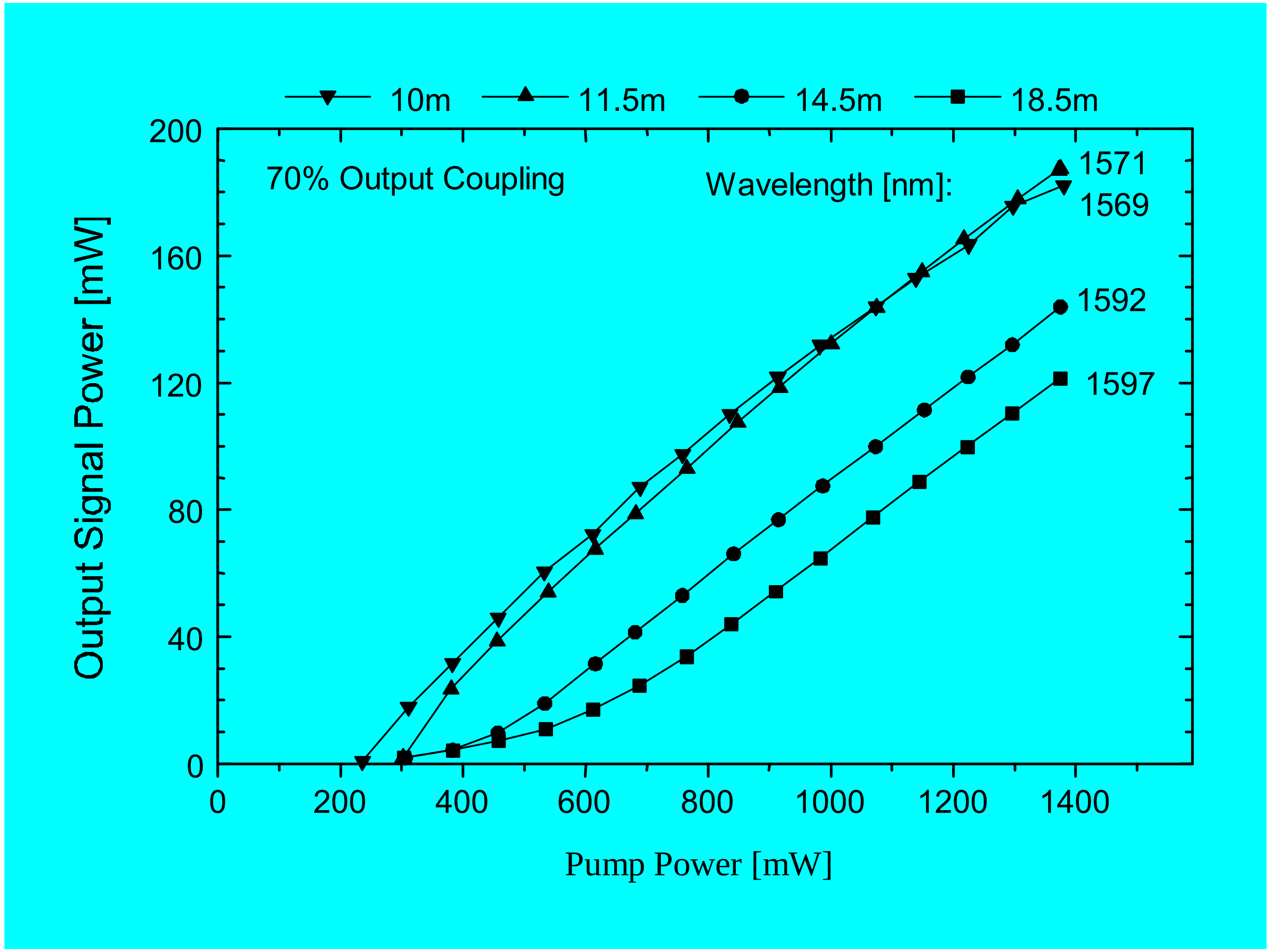
CW FIBER LASER

2. Ring resonator



$\Delta \nu$ = 10 MHz pro L=20 m.

IPE-CONTINUAL Er/Yb RING LASER



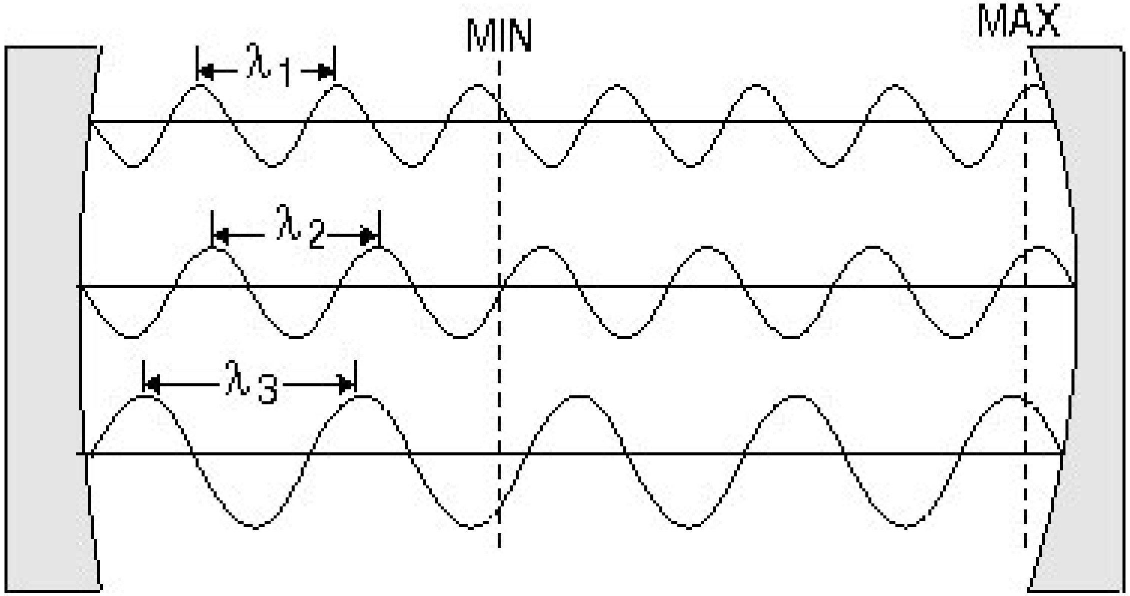
Pump at 1060 nm (NdYAG or Yb laser)

PULSE LASERS

In a fiber ring Er laser (L=20 m) $\Delta\nu$ = 10 MHz $\Rightarrow$ N **~10^5 resonator modes** (free oscillating modes)

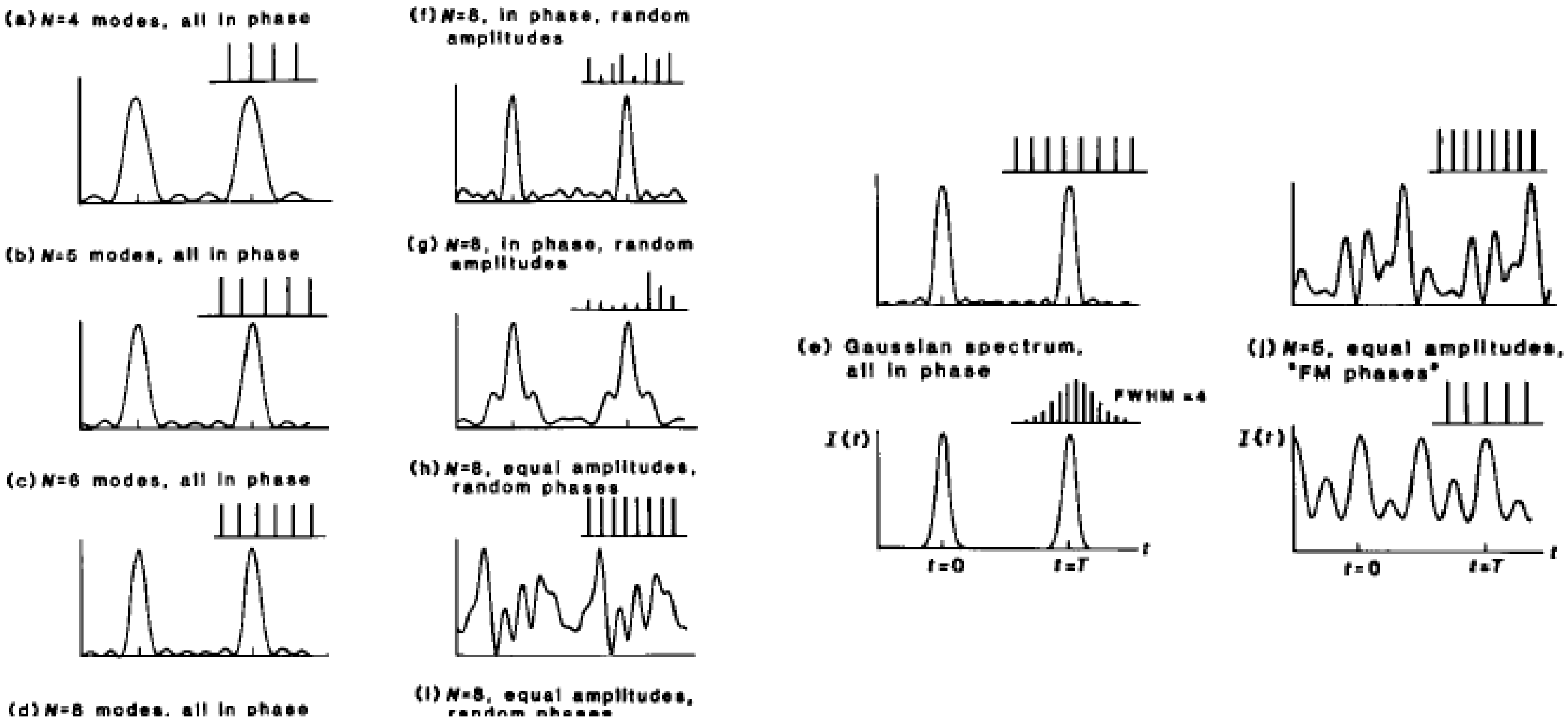
It is necessary to synchronise resonator modes e.g. by inserting optical switch into resonator that opens and closes with a period T_F
$\Rightarrow$ formation of pulse train with a period $T_F = L/c$

MODE LOCKING – INERFERENCE IN TIME



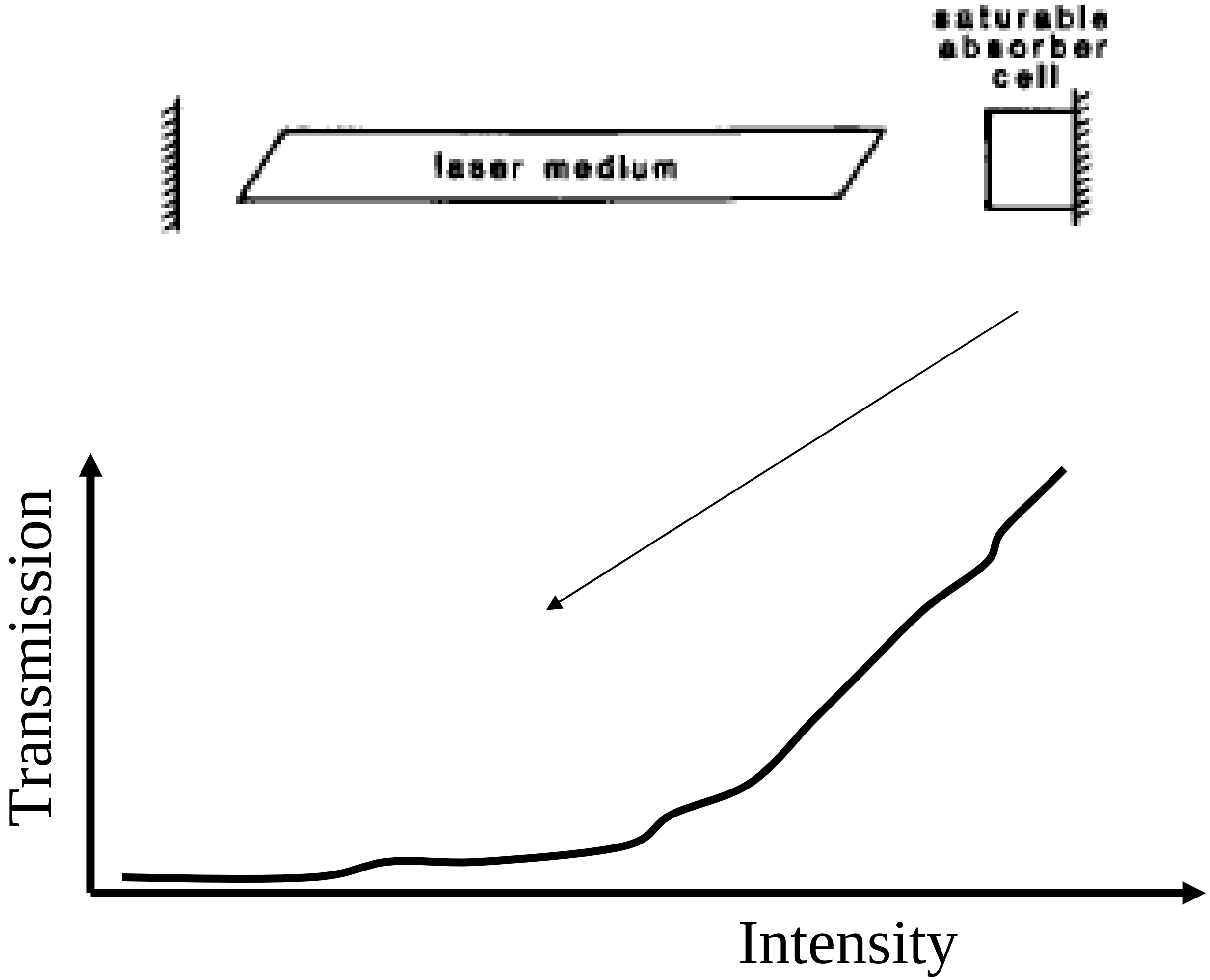
Result of mode interference

MODES IN PHASE AND OUT OF PHASE

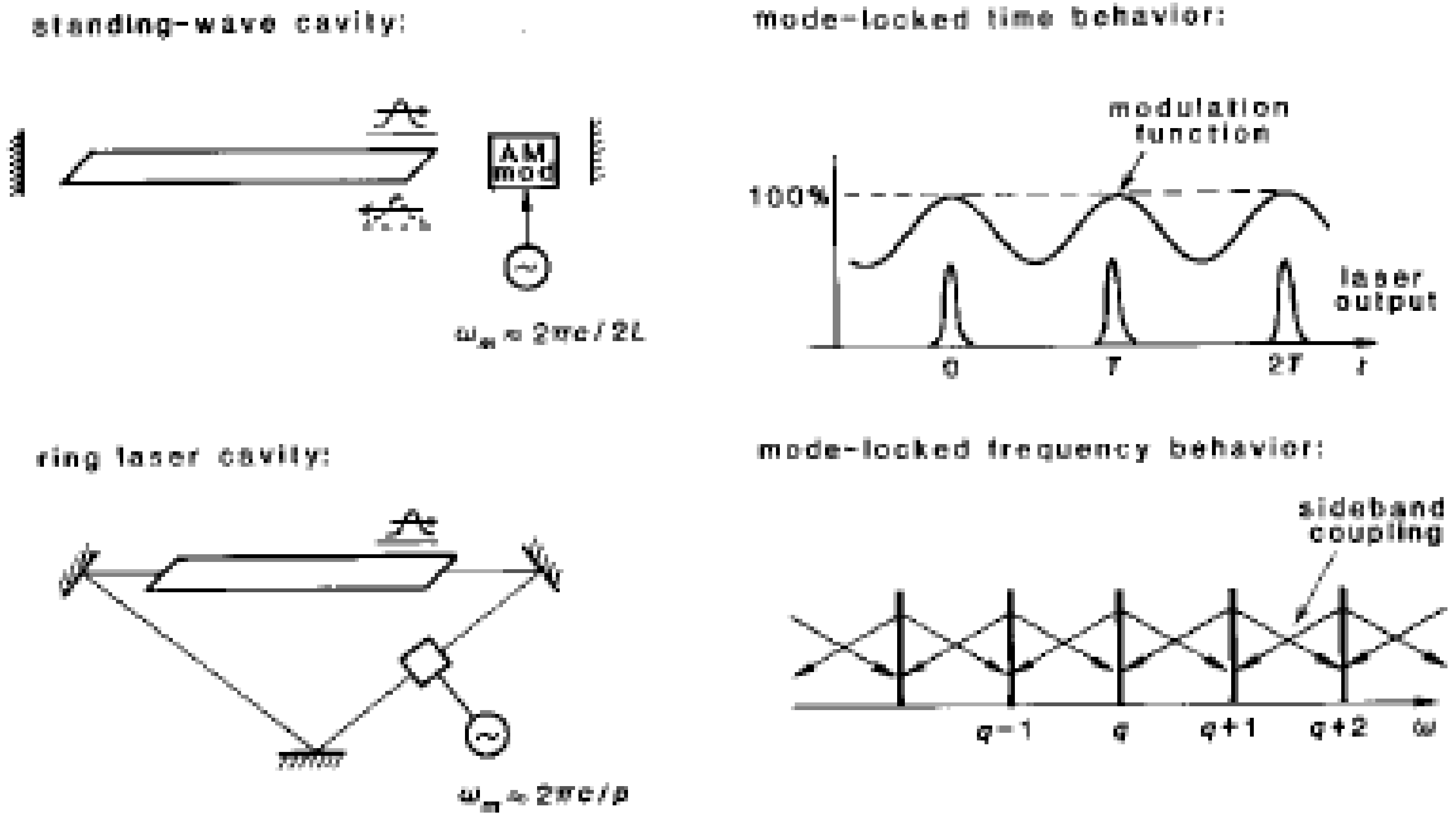


How to use this interference effect in pulse lasers? Insert loss element in the resonator

PASSIVE MODE-LOCKING



ACTIVE MODE-LOCKING



MODE-LOCKED LASERS

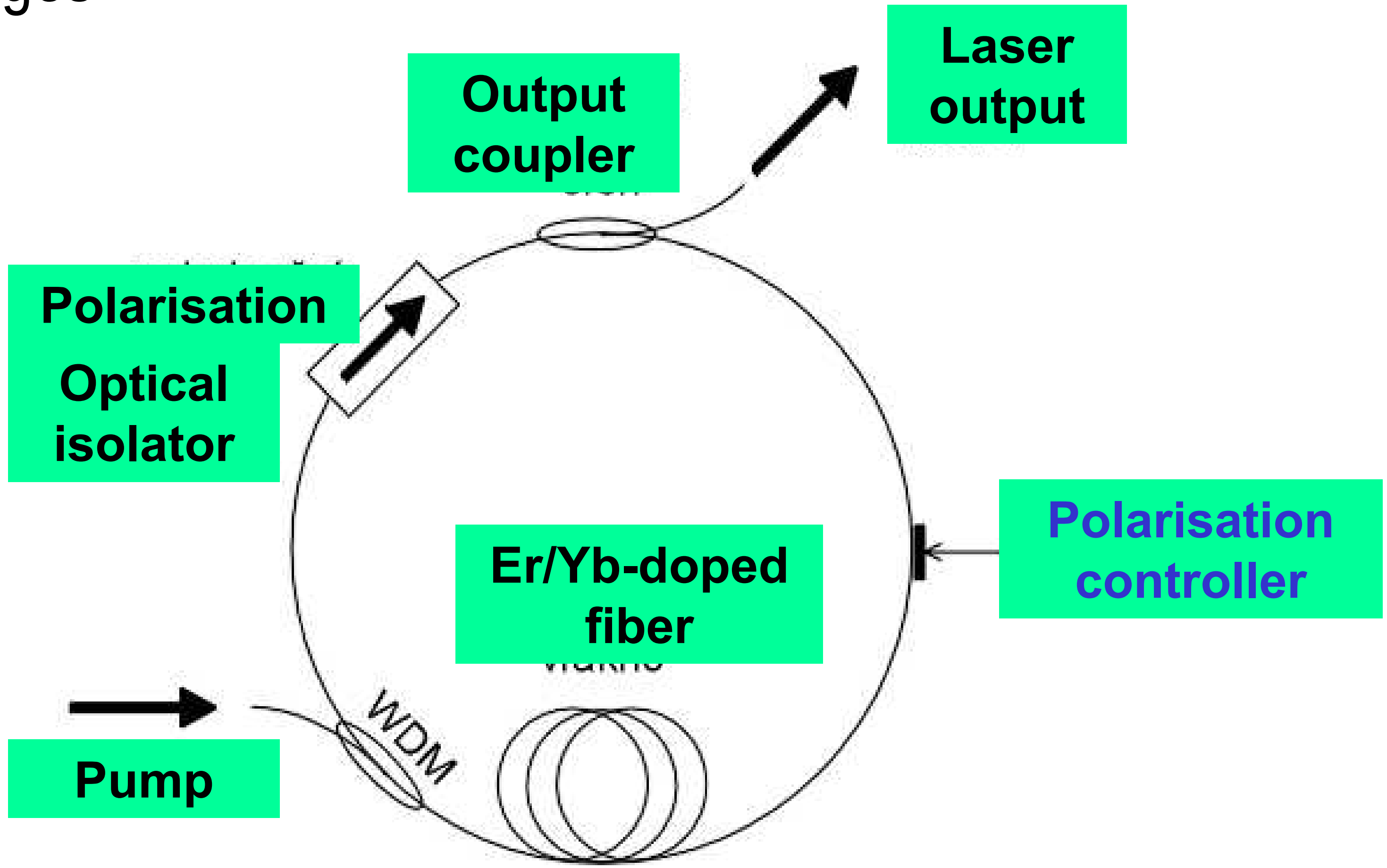
Mode locking can be achieved by:

Passive mode locking - by means of polarisation optical isolator in the ring

Active mode locking - by means of Mach-Zehnder amplitude modulator (lithium niobate) in the ring

IPE PULSE LASER

Pulse laser with passive mode locking due to nonlinear polarisation changes



OPTICAL SOLITONS

Due to high light intensities in core of high-power lasers nonlinear Kerr effect takes place

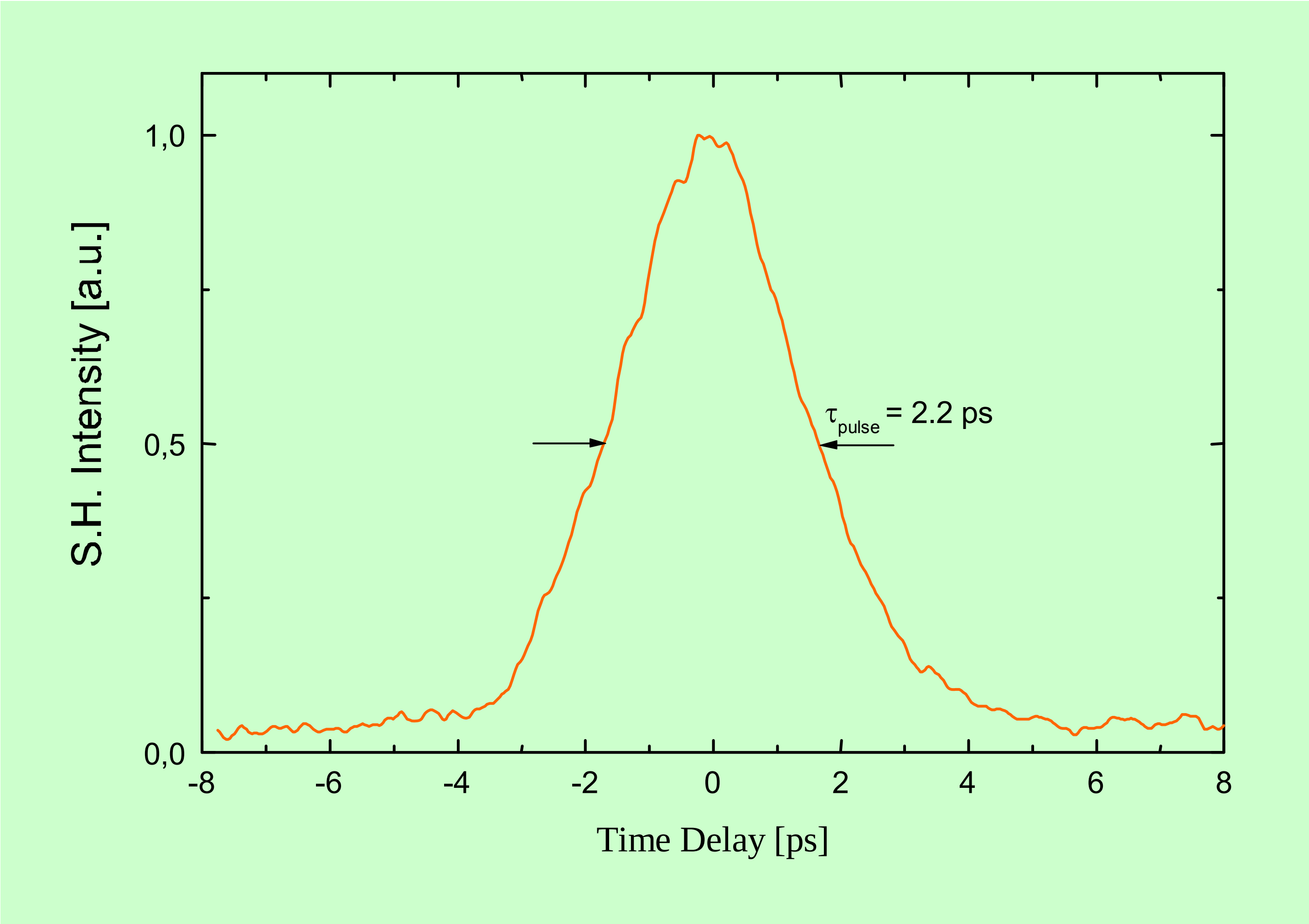
$\Delta n \sim$ Light intensity

Different parts of an pulse carry different energy ⇒ different refractive index and different dispersion ⇒ Narrow high-energy pulses can be transmitted in telecommunication lines without dispersion – **optical solitons**

Optical soliton lines offer long lengths (~1000 km) without amplification

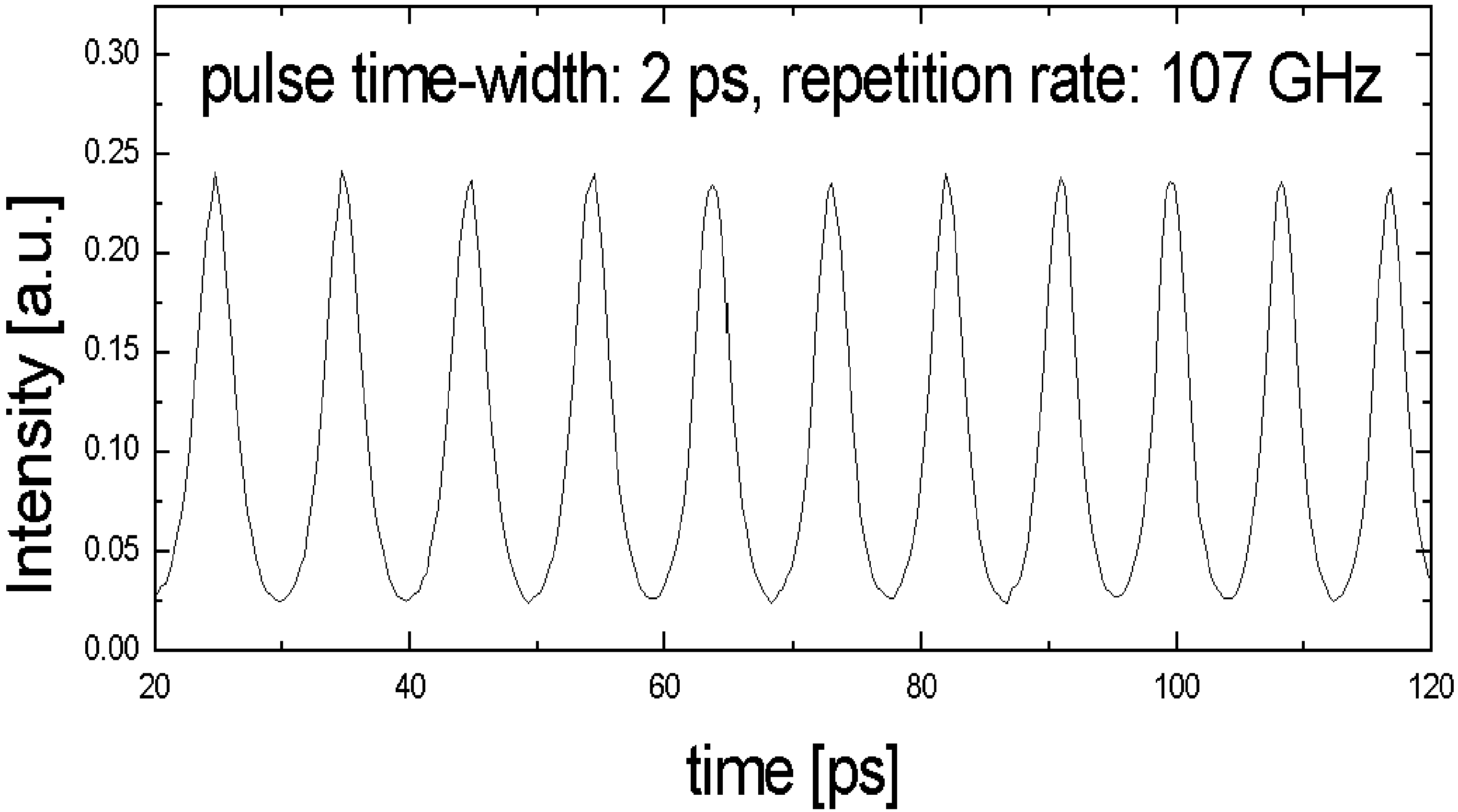
Problems – sensitivity of solitons to fiber irregularities ⇒several pulses are formed

Er/Yb FIBER LASER- SOLITON PULSE



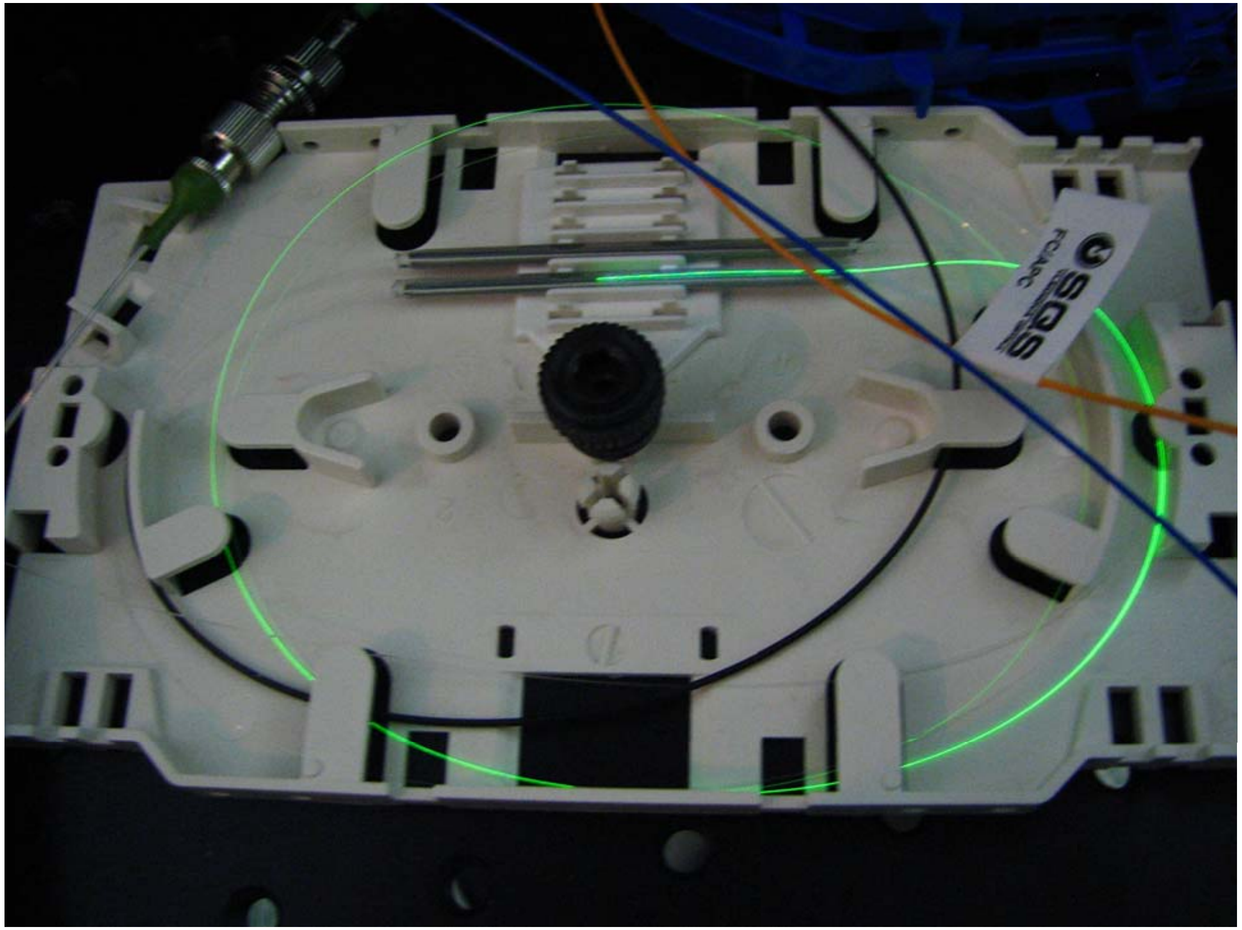
SOLITON TRAIN GENERATION

optical solitons ⇒novel laser sources



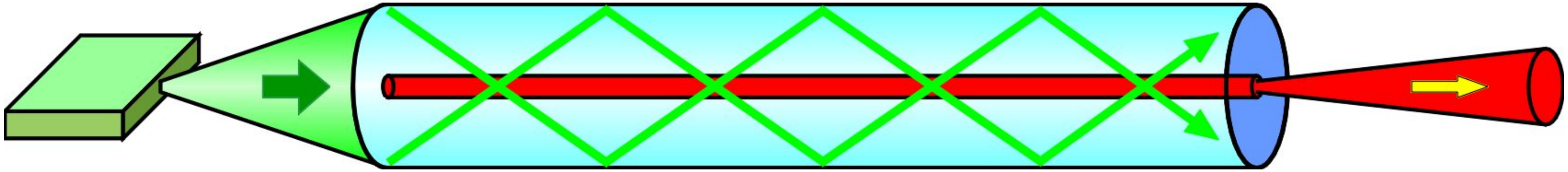
Er/Yb fiber, pump Yb laser at 1060 nm

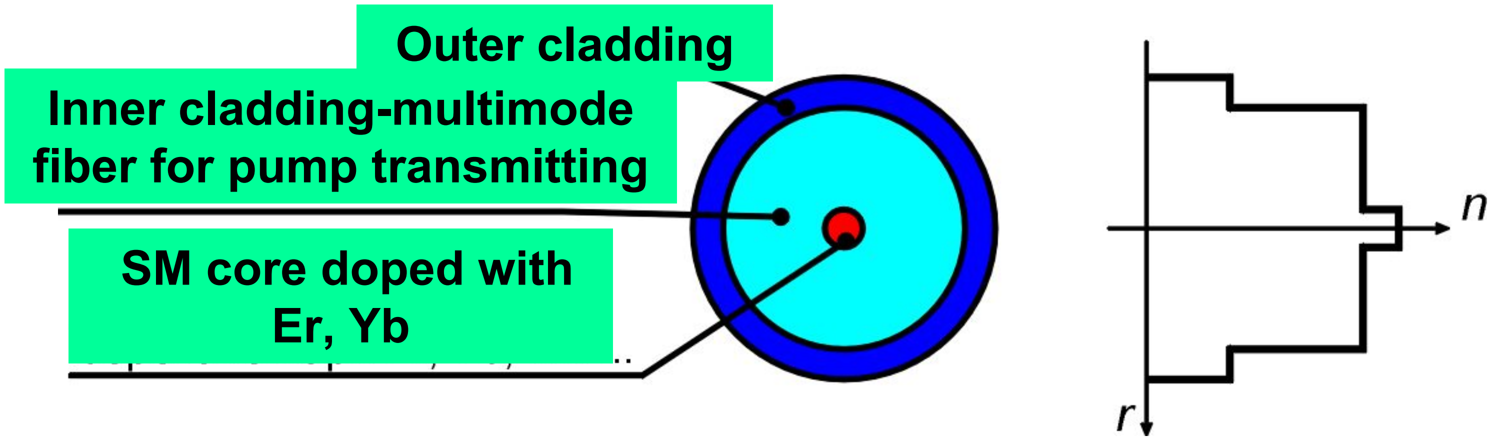
SOLITON LASER IPE



Green up-conversion accompanies strong ASE
of Er at 1550 nm

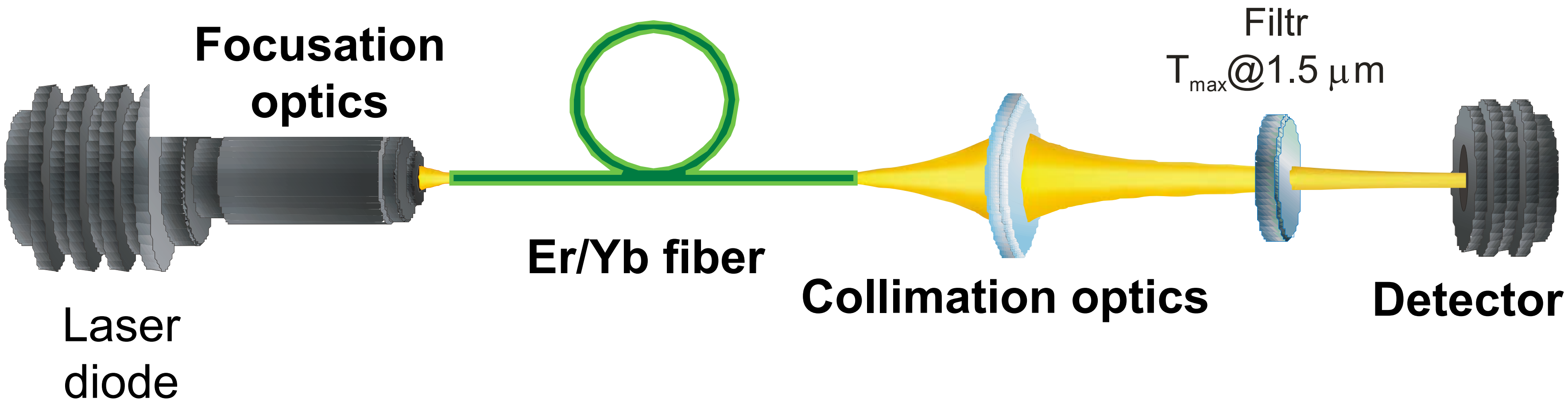
Double-clad (DC) fibers





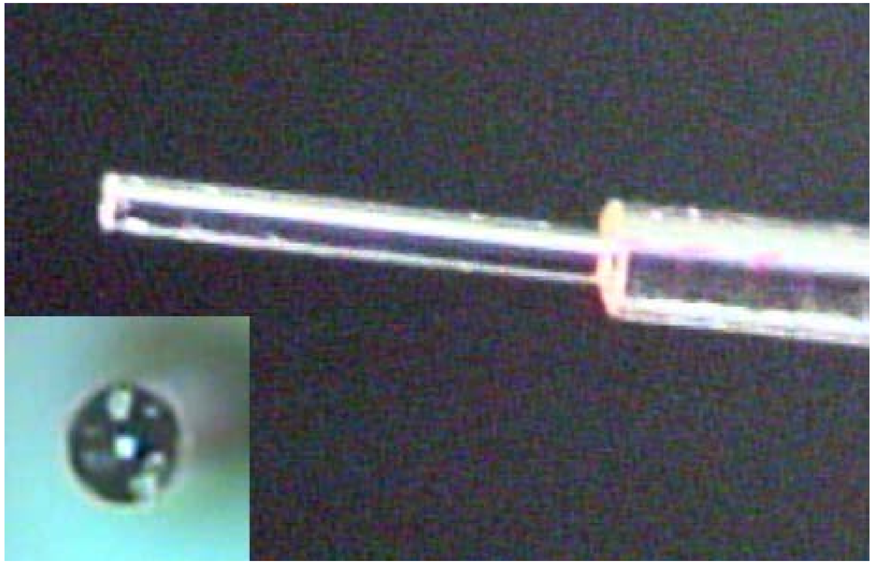
DC fibers transform a divergent beam from a high-power laser diode into a high quality laser beam of a DC-based laser

Launching of light into a circular DC fiber by bulk optics (IPE)

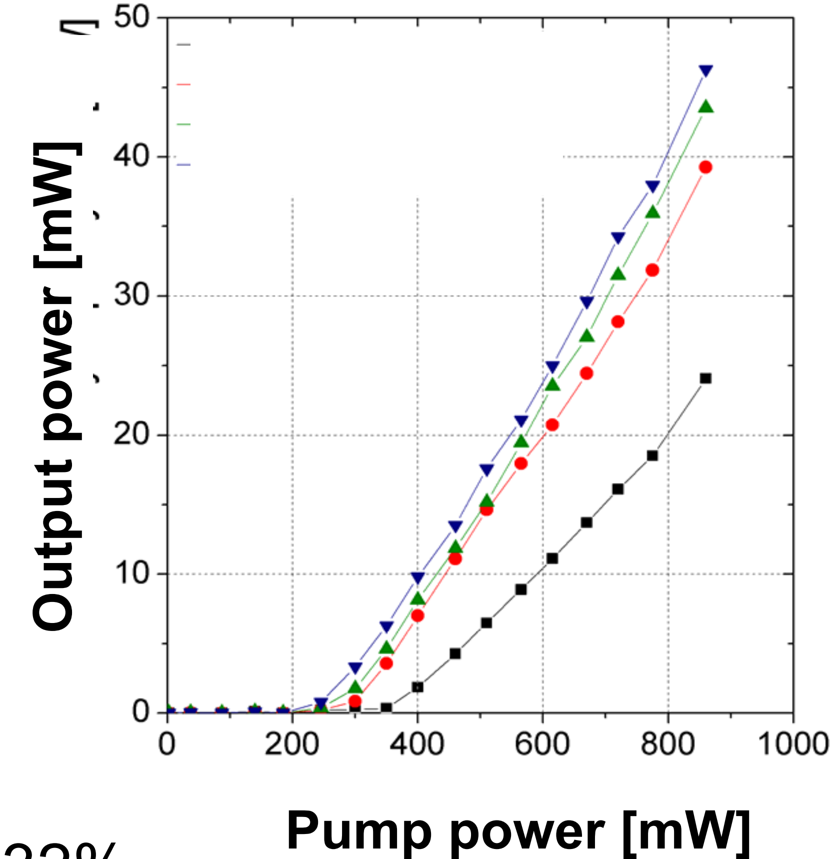


LASER BASED ON CIRCULAR DC FIBERS

Excitation by bulk optics

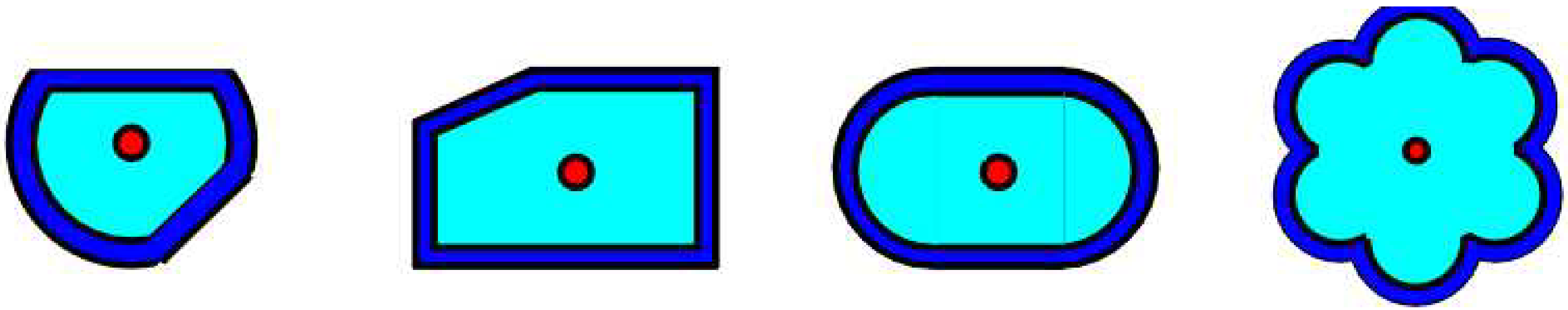


Detail of the fiber end



Er/Yb – doped fiber, laser efficiency 32%
(pump 750 mW @ 969 nm)

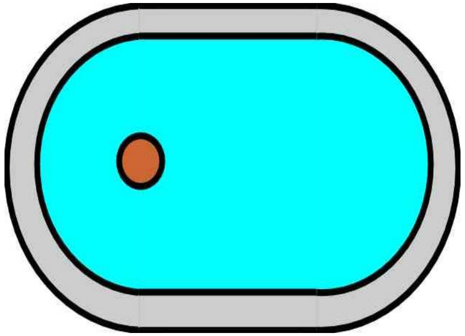
OPTIMUM CROSS-SECTIONS OF DC FIBERS

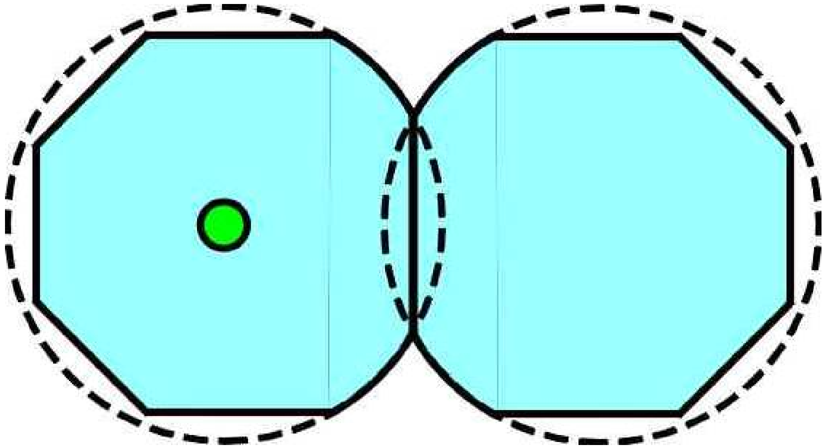


The best pumping efficiency for these cross-sections

DC FIBER TYPE STADIUM - IPE

Theoretical shape

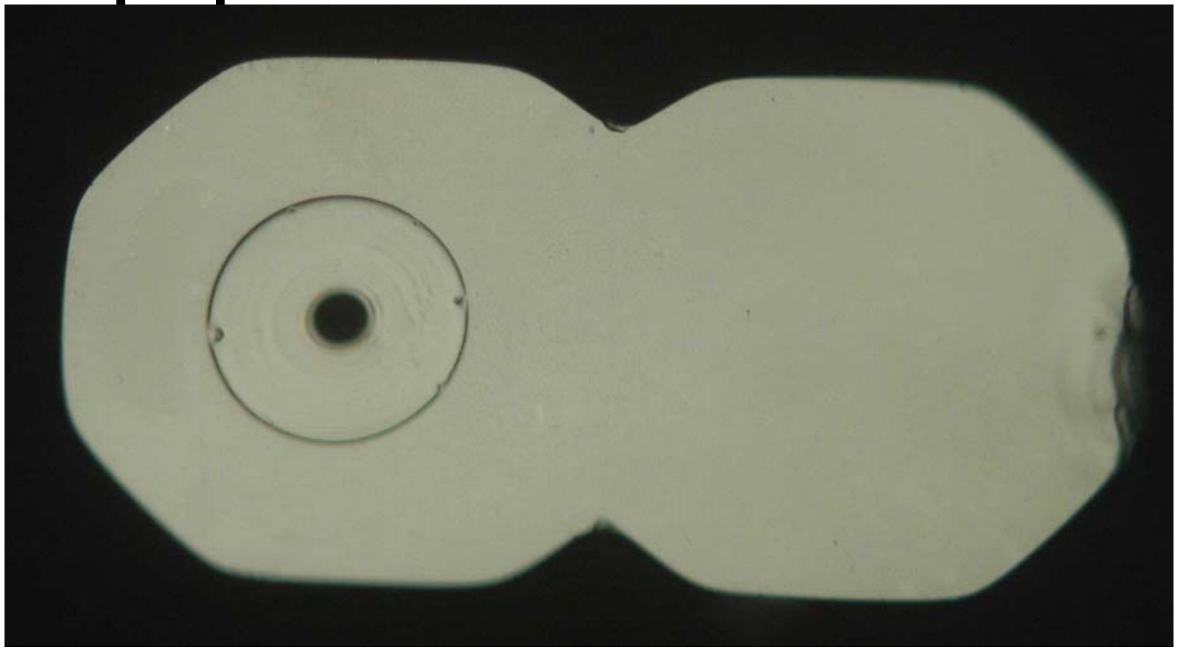




Practical realisation
Combining two side-polished preforms

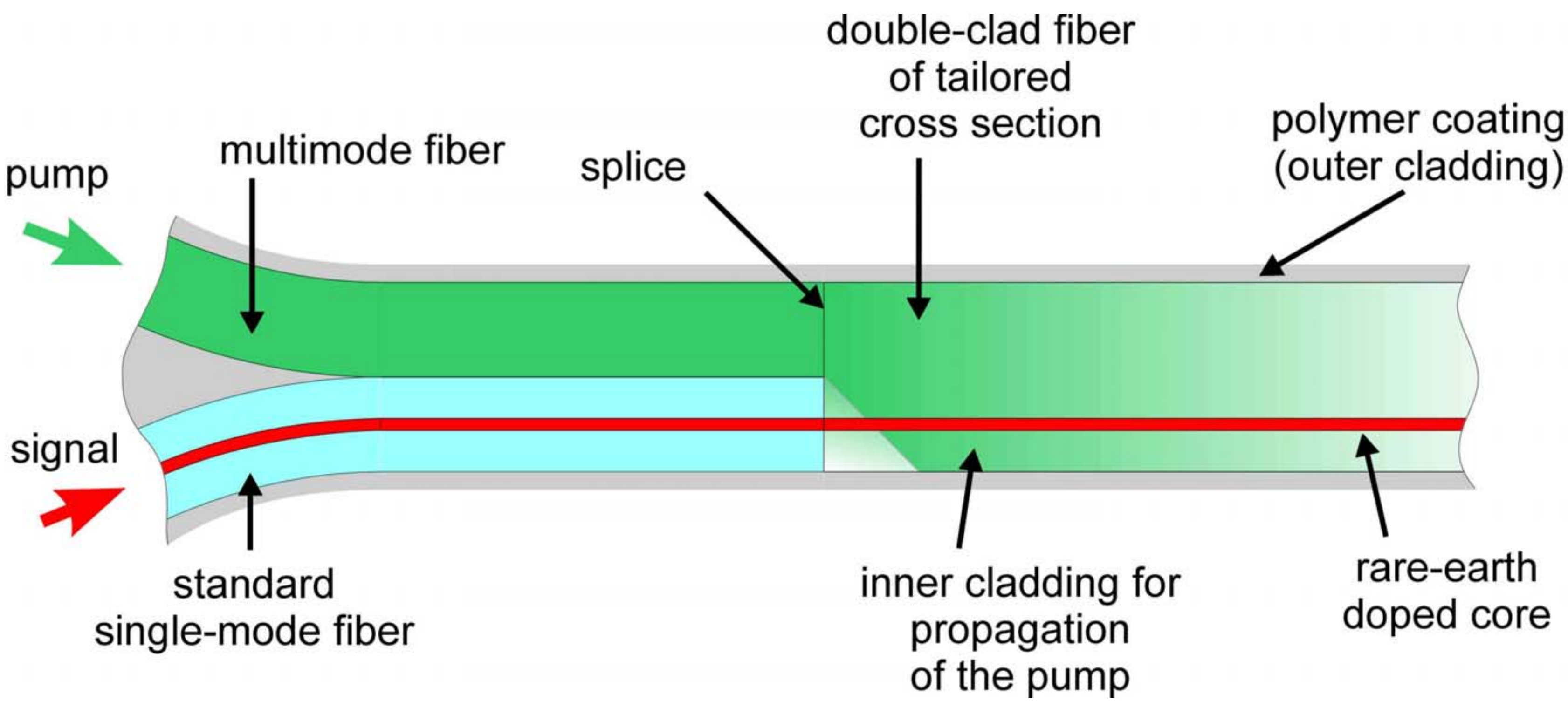
DC FIBER TYPE STADIUM - IPE

Microscope photo of the DC fiber prepared in IPE



Dimensions 125x250 μm

SPLICING OF PUMP AND SIGNAL FIBERS

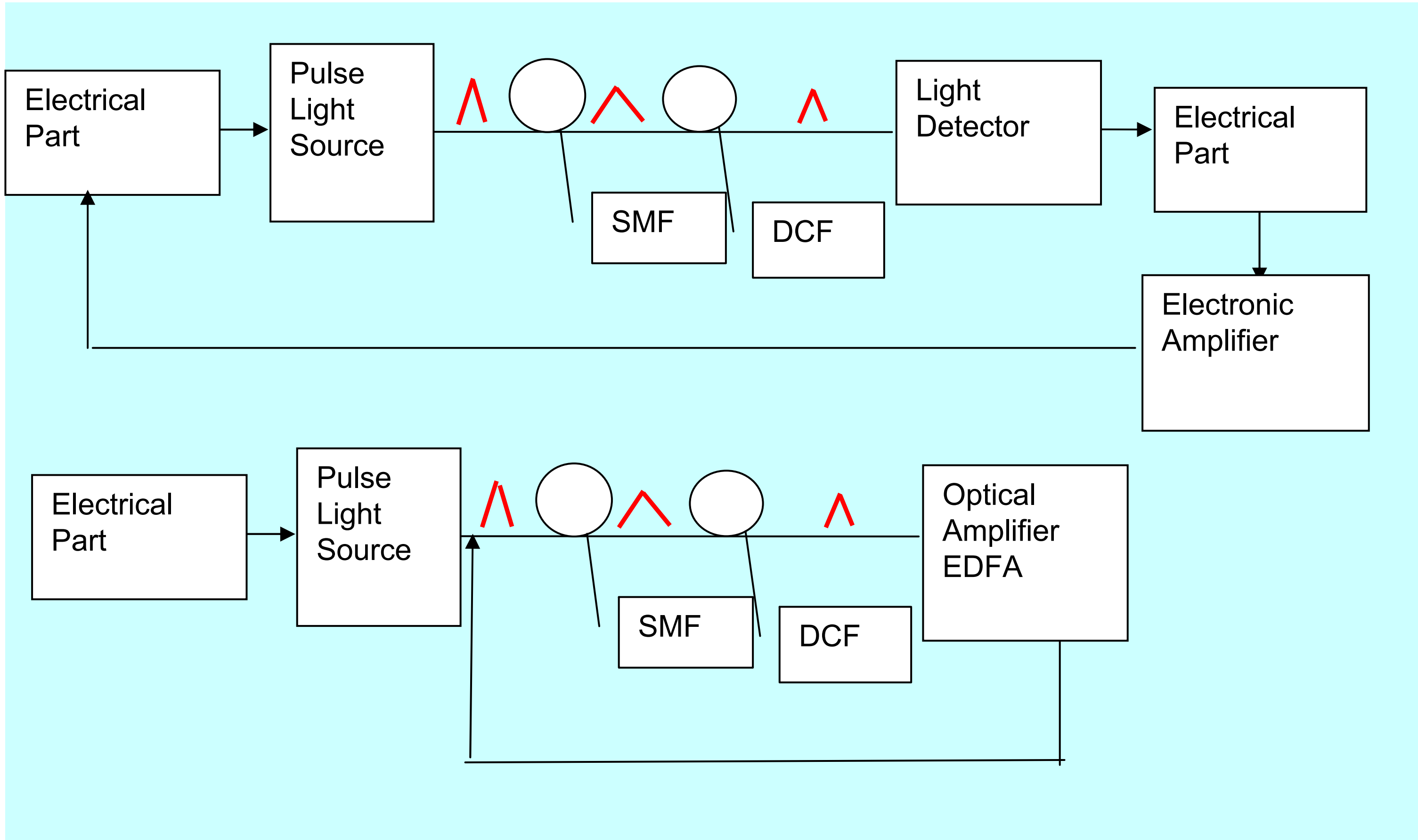


Video

OPTICAL AMPLIFICATION

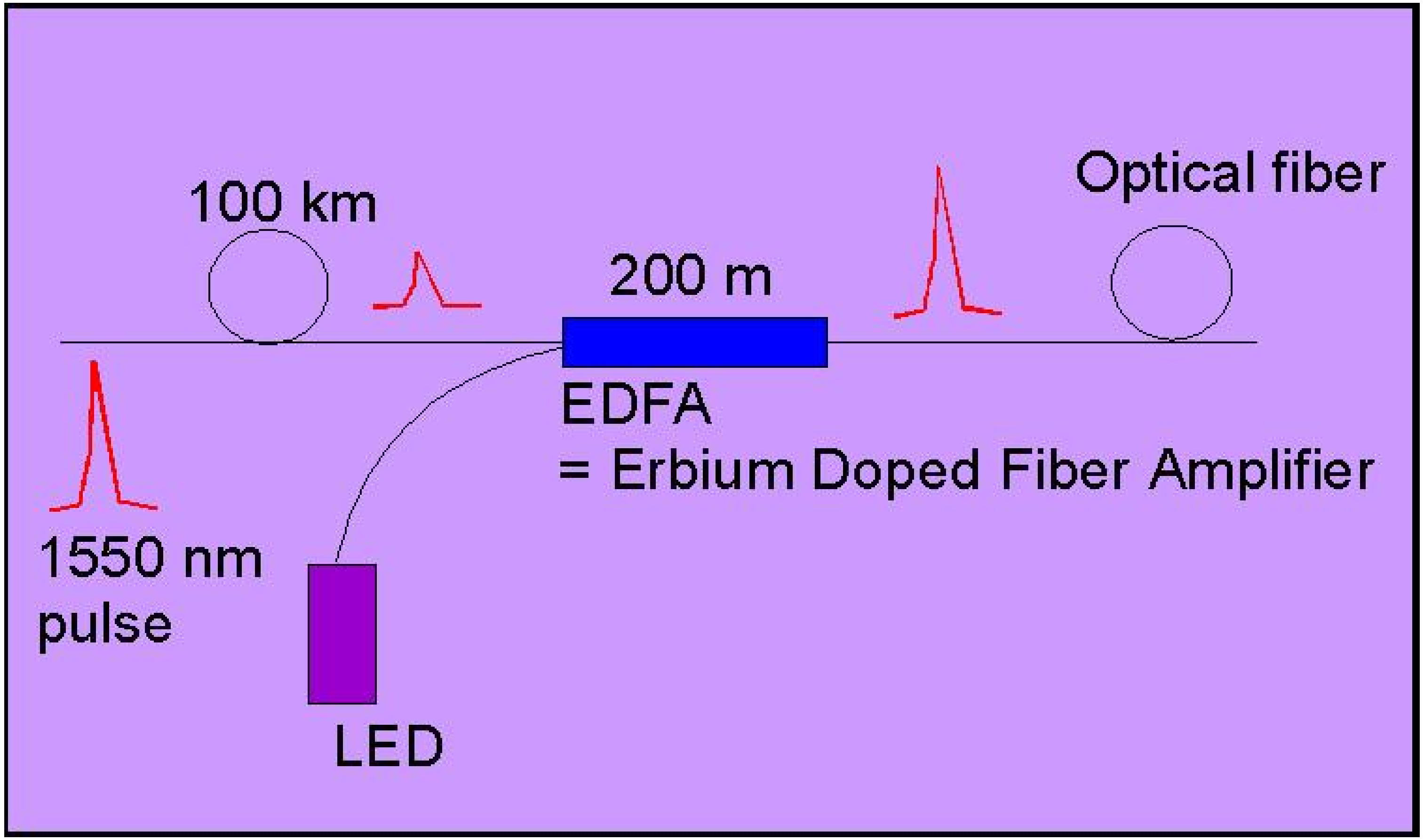
→~1970

1970 →



AMPLIFIERS

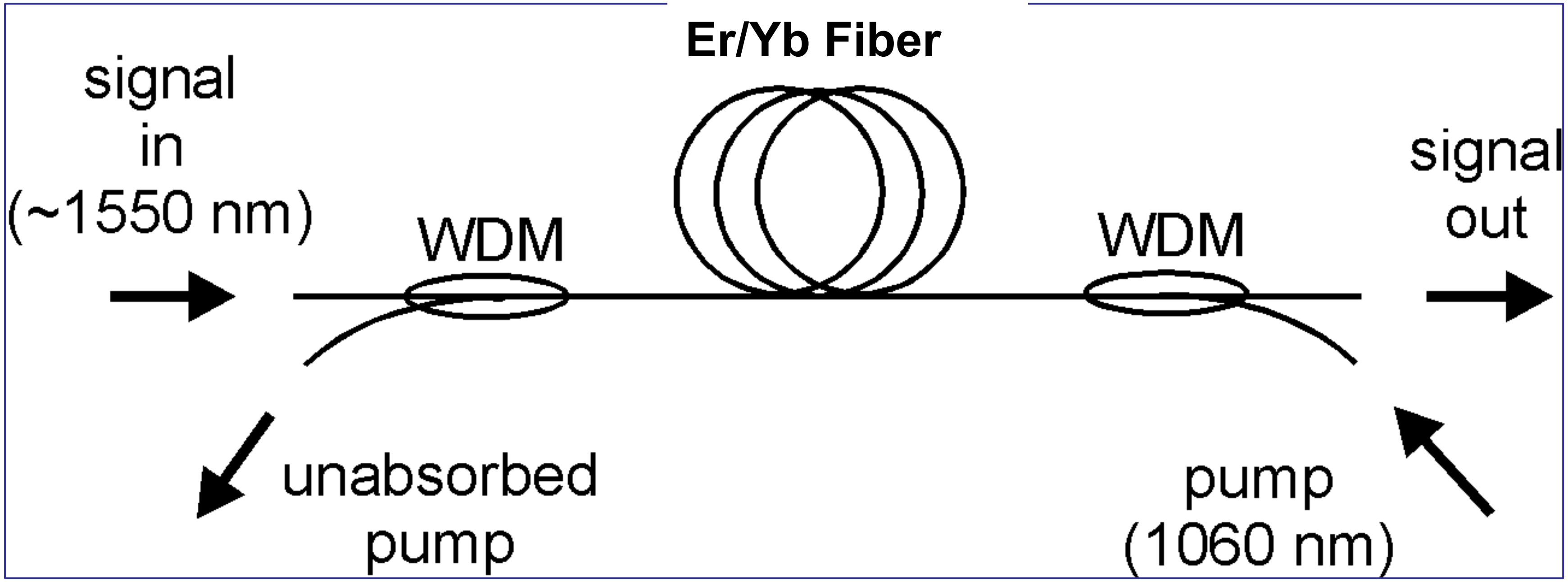
A source of signal photons is amplified signal



Can be used in WDM systems, it is tunable

Er/Yb AMPLIFIER

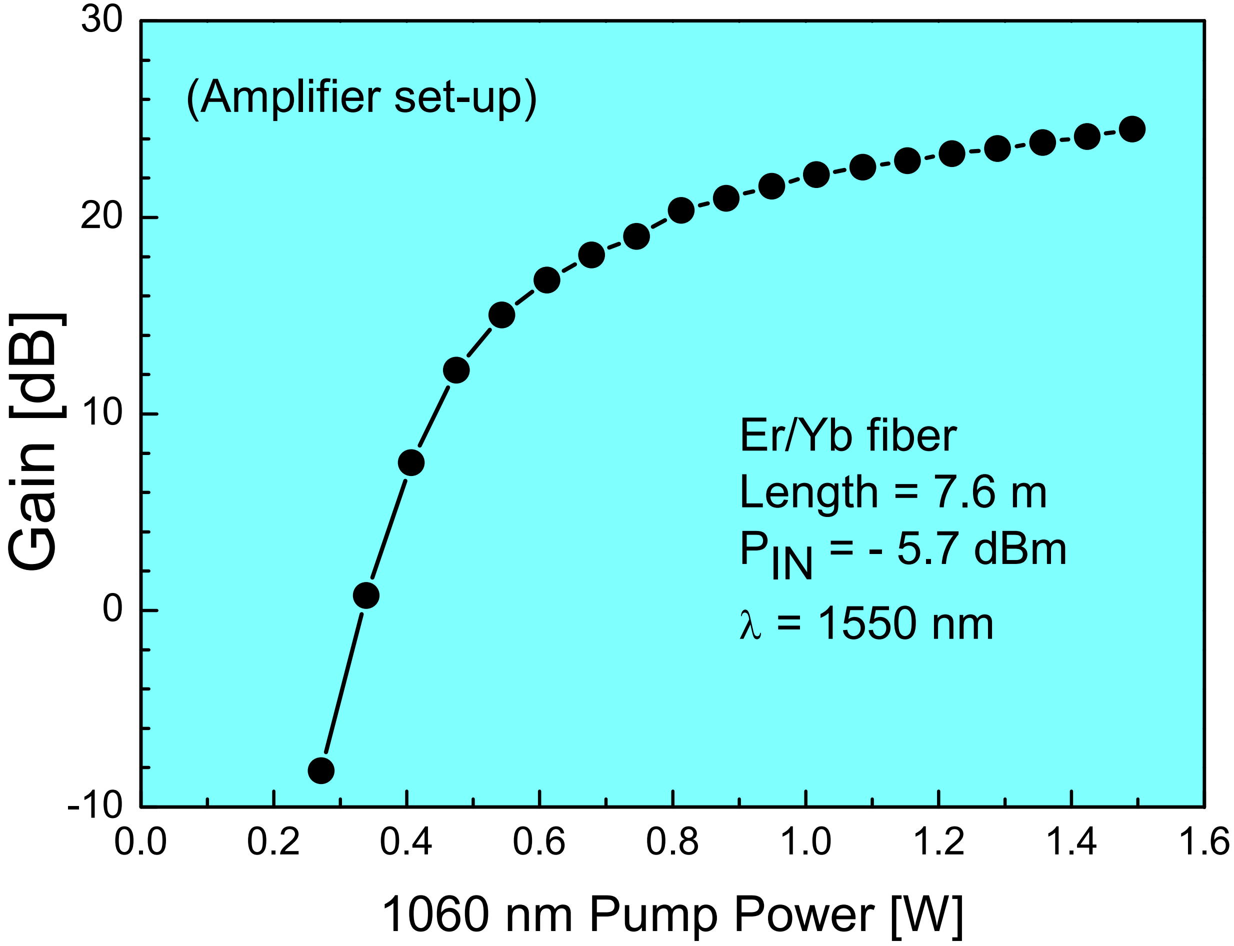
Booster configuration



Pump: 1060 nm - Yb fiber laser – IRE Polus YLD-5000

Signal: External cavity tunable laser – E-TEK Dynamics MLTS 1550

GAIN OF AMPLIFIER



CONCLUSIONS

- RE-doped fibers (Er, Yb,Tm) are powerful means for development of fiber lasers and amplifiers – <u>gain sources</u>
- EDFA (Erbium-Doped Fiber Amplifiers) are broadly used in telecommunication lines (incl. submarine ones)
- Fiber lasers pumped via high-power laser diodes represent novel direction for the investigation of high-power lasers

NOVEL DIRECTIONS

- Fiber lasers based on RE nanoparticles – better suppressing (decreasing) effects of ASE decay processes.
- Raman amplifiers which offer distributed amplification over telecommunication lines