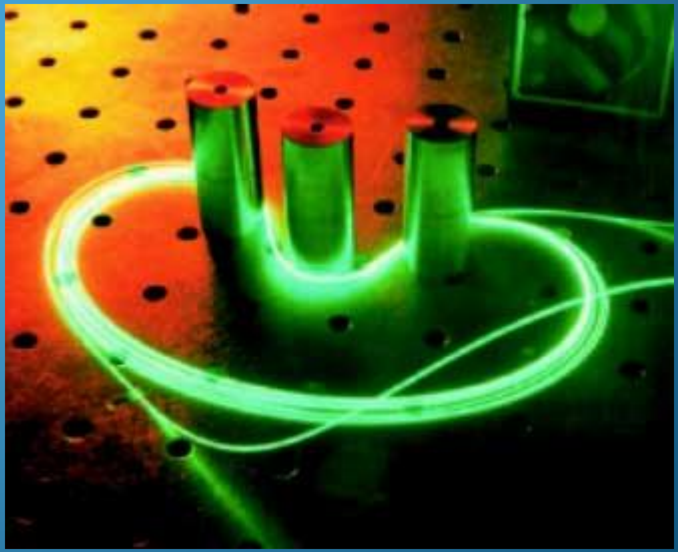
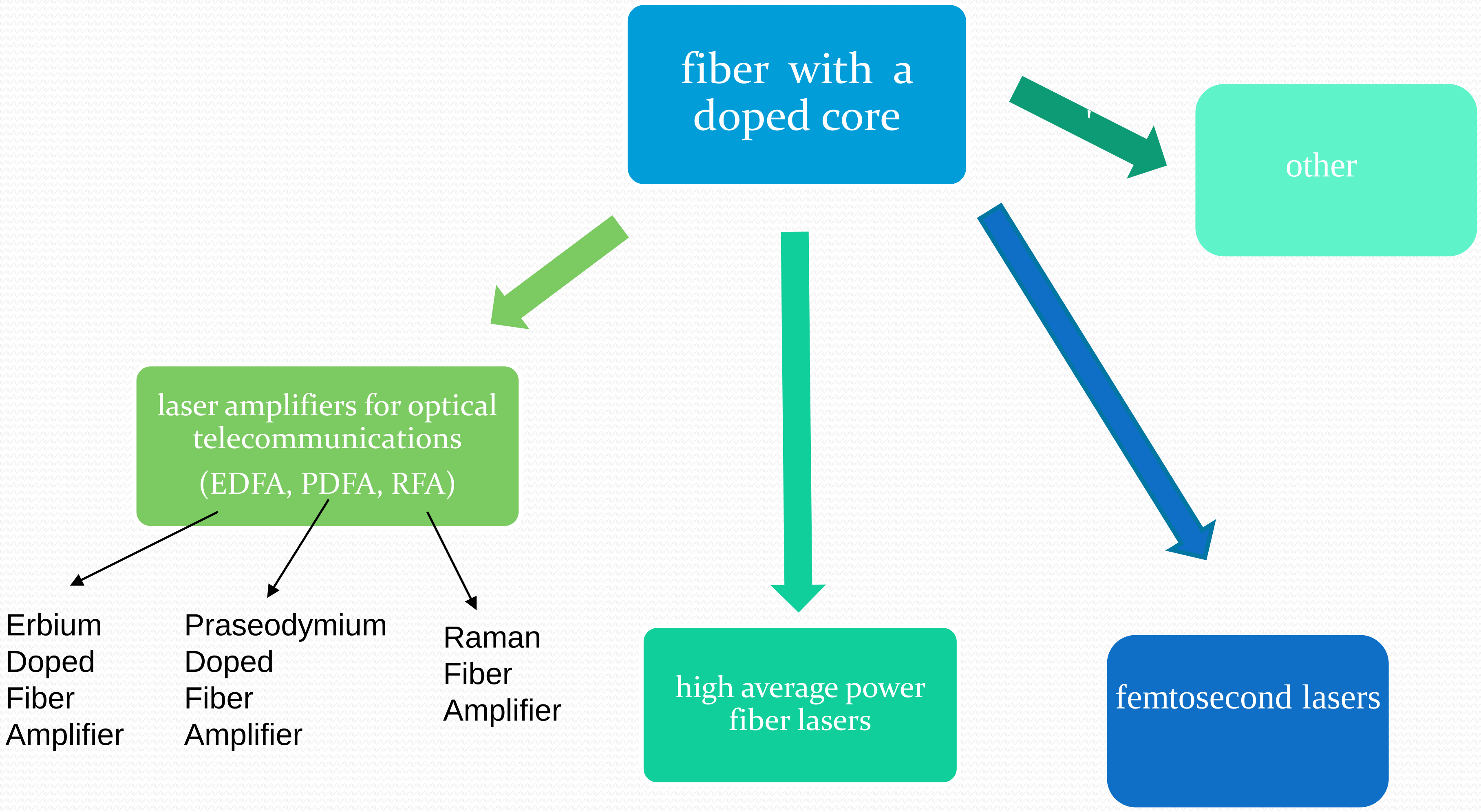
Lasers
lecture 12

Czesław Radzewicz

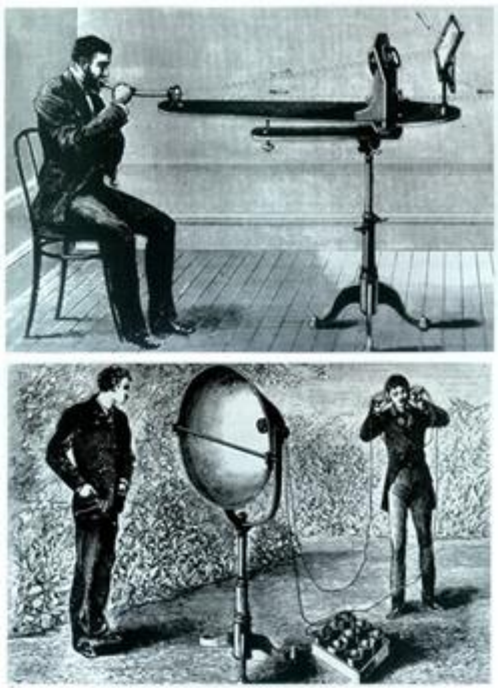


general classification of fiber lases



optical telecommunications

Graham Bell - **lightphone**



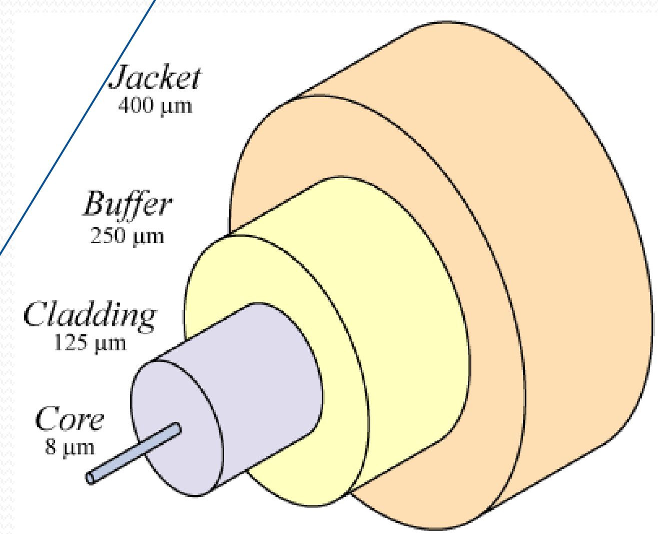
voice transmission by use of sun rays travelling in free space

<u>idea</u>:

- light propagation direction is modulated with an oscillating membrane driven by voice
- The beam is collected with a parabolic mirror
- Selenium crystal works a detector driving headphones

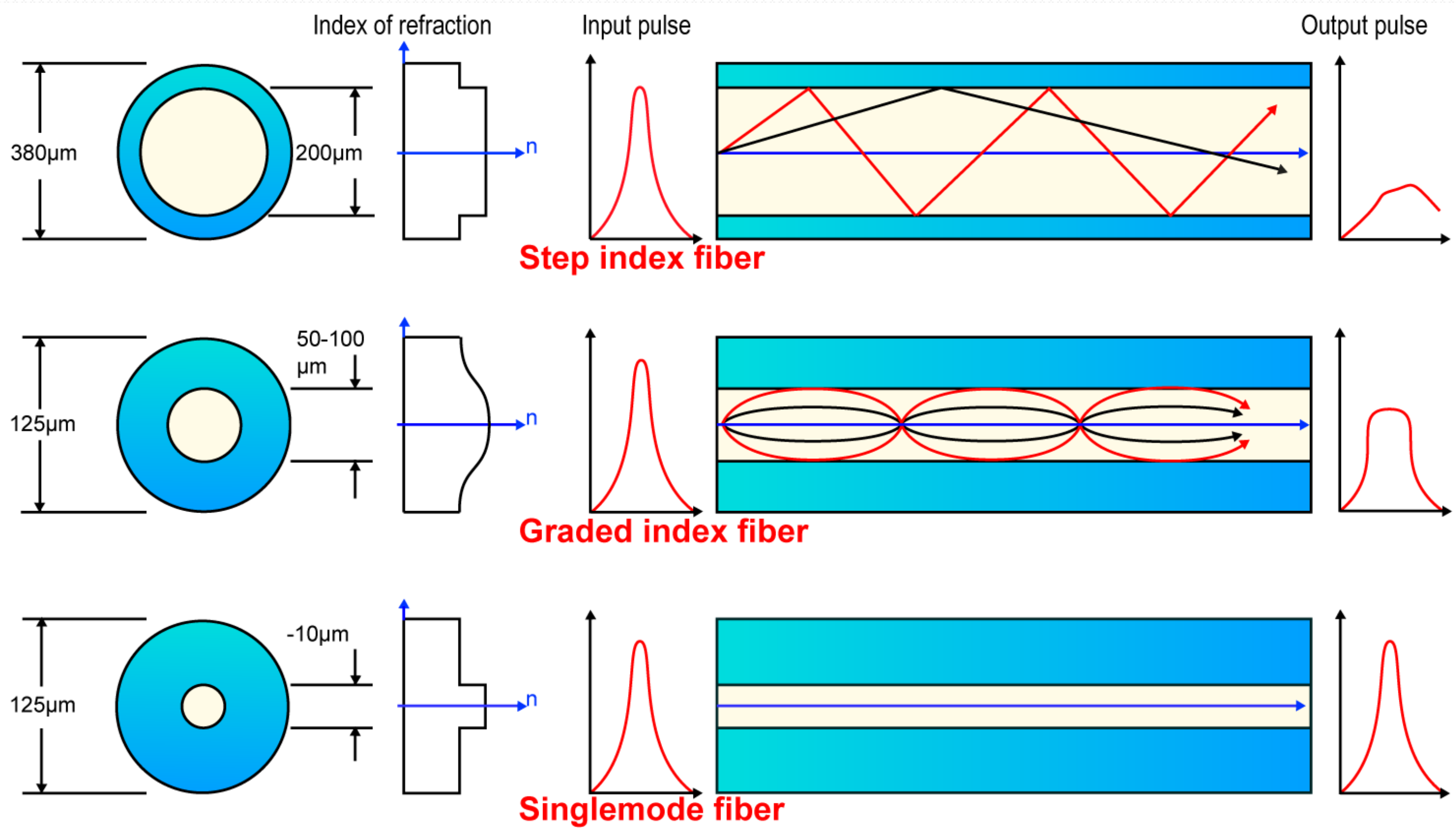
3.06.1880 – transmission successful over 213 meters

modern single-mode fiber



today – transoceanic optical cables

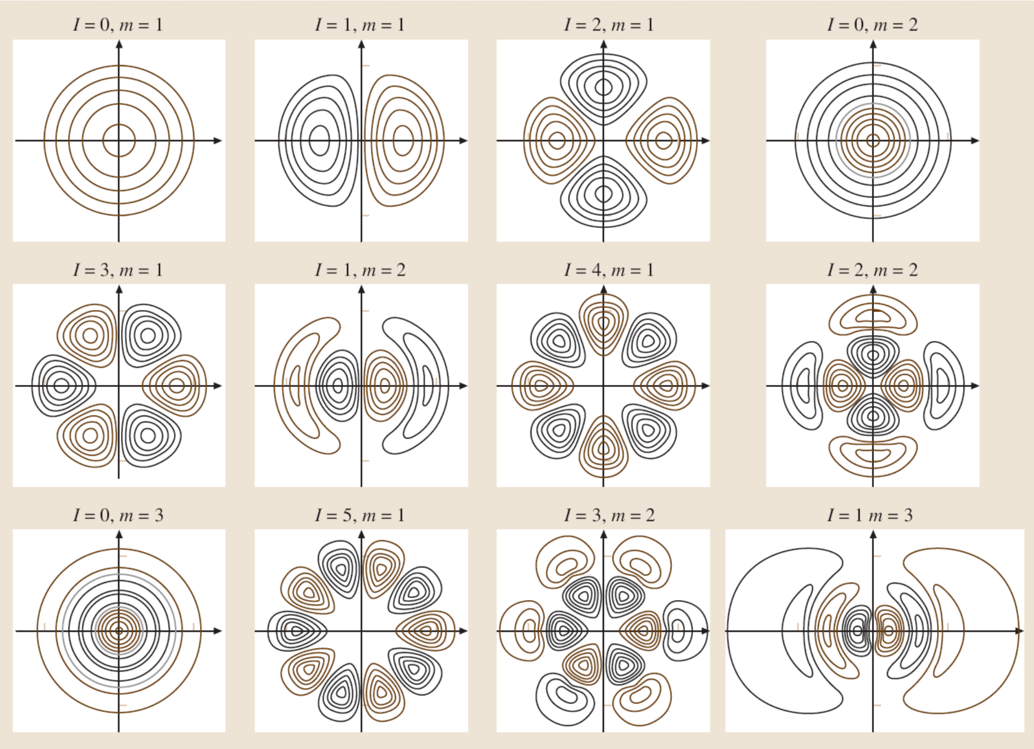
single-mode vs multimode fibers

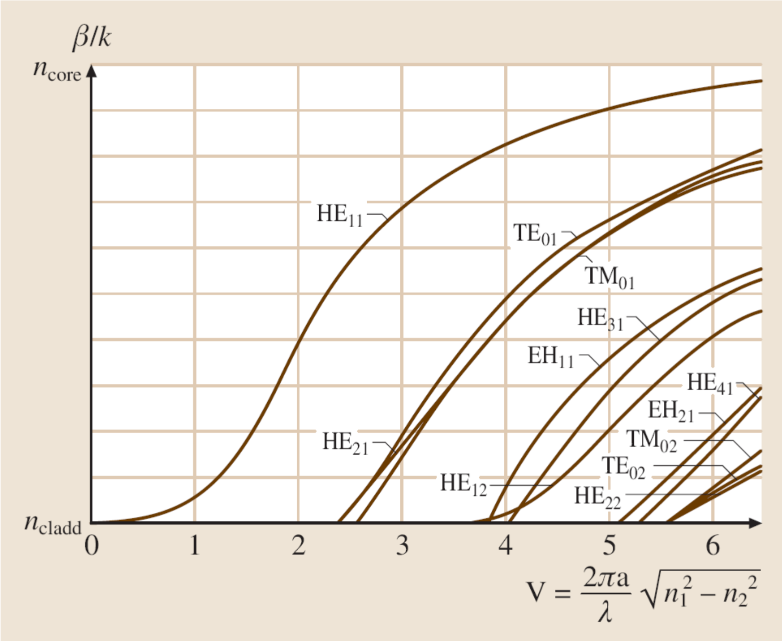


fiber modes

$$\frac{\partial^2 \psi}{\partial r^2} + \frac{1}{r}\frac{\partial \psi}{\partial r} + \frac{1}{r^2}\frac{\partial^2 \psi}{\partial \phi^2} + \left[k_0^2 n^2(r) - \beta^2\right]\psi = 0$$

2a – diameter of the core





a cylindrical fiber is single-mode if :

$$V < 2.405$$

laser (doped) fibers

- rare earth dopants

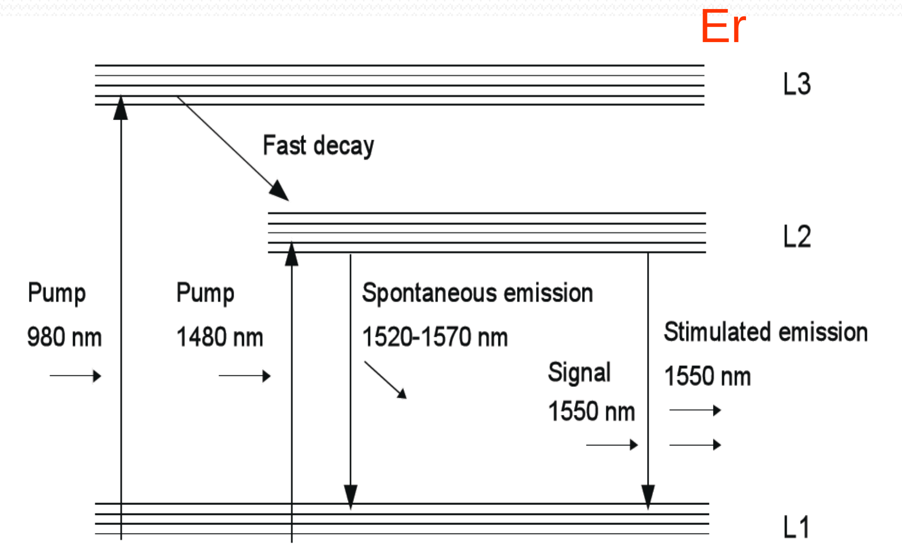
  - **element** (pump waveleght -> laser wavelength)
  - **neodymium** (808 nm → 1.06 μm)
  - **ytterbium** (976 nm → 1.04 μm)
  - **erbium** (980 nm → 1.50 μm)
  - **praseodymium** 1.3 μm
  - **thulium** 1.9 μm
  - **holmium** 2.1 μm
  - mixtures of the above

- Materials for laser fibers

  - quartz glass (most popular although the dopants concentration is limited, transparent up to 2.2 μm)
  - fluoride glasses (transparency window from 0.2 up to 7 μm)

  e.g.. ZBLAN (zirconium, barium, lanthanum, aluminum and sodium fluorides, high dopant concentration is possible)

Erbium Doped Fiber Amplifiers (EDFA)



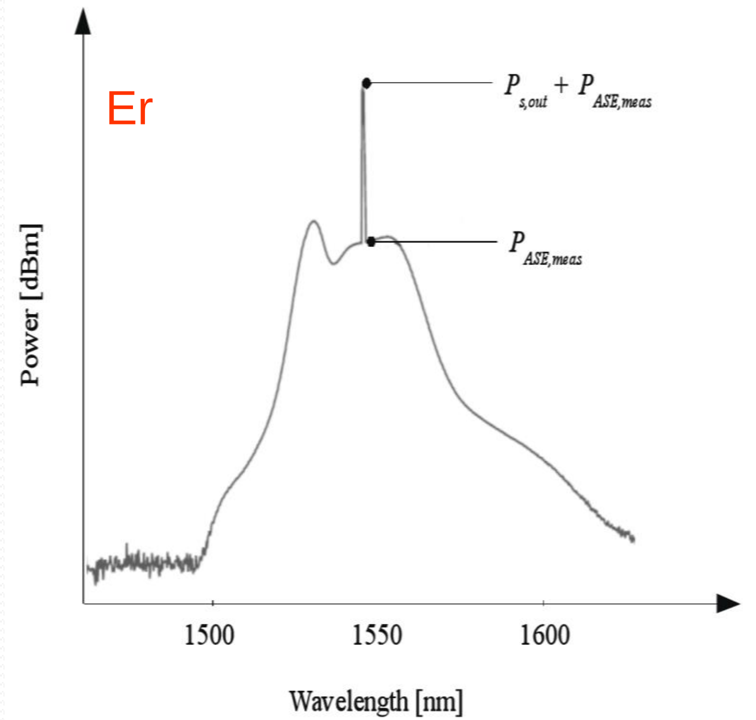
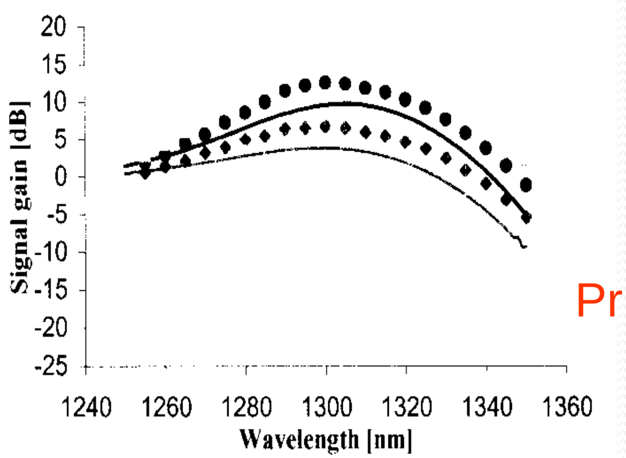


Fig. 3: Typical output power spectrum of an EDFA. A broad pedestal due to ASE noise covers the entire gain bandwidth. The signal peak is at 1550 nm. Two power levels are indicated: measured noise power $P_{ASE,meas}$ below the signal peak, and measured total power $P_{s,out} + P_{ASE,meas}$ at the signal peak.



Laser amplifiers in optical telecommunications

- Amplification of light signals in optical fibers
- High bandwidth and therefore expensive electronic repeaters are not required
- Simultaneous amplification of many channels possible. EDFA are not sensitive to the format and bit rate of the data being transmitted.

Disadvantages:

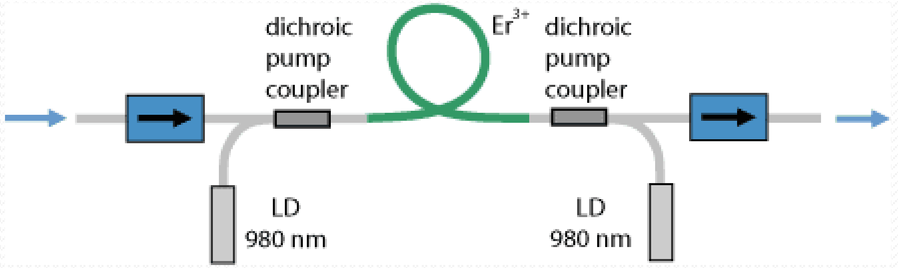
EDFA do not cancel dispersion leading to pulse broadening

Excess noise – remember the no cloning theorem holds!

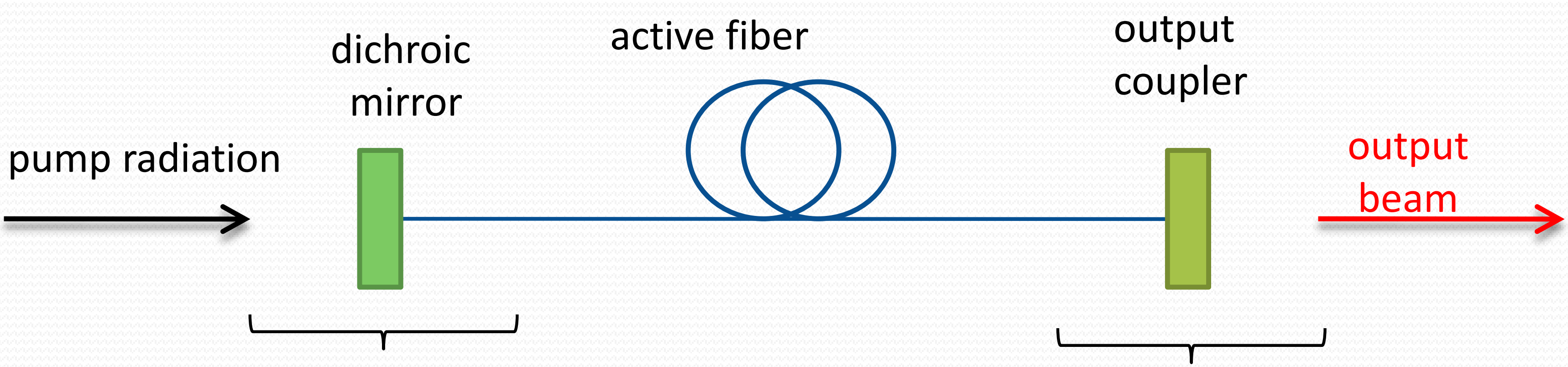
Optical amplifiers used in optical telecommunications:

- EDFA (Erbium Doped Fiber Amplifier) – bands C and L of 1,55μm window
- PDFA (Praseodymium Doped Fiber Amplifier) – band O (1,3 μm window)
- RFA (Raman Fiber Amplifier, universal wavelength coverage)
- SOA (Semiconductor optical amplifier)

typical EDFA design



the simplest fiber laser cavity



Dichroic mirror – technical realization:

- multilayer dielectric mirror applied directly on the fiber face
- fiber Bragg mirror
- fiber coupler followed by a mirror
- free space dichroic mirror

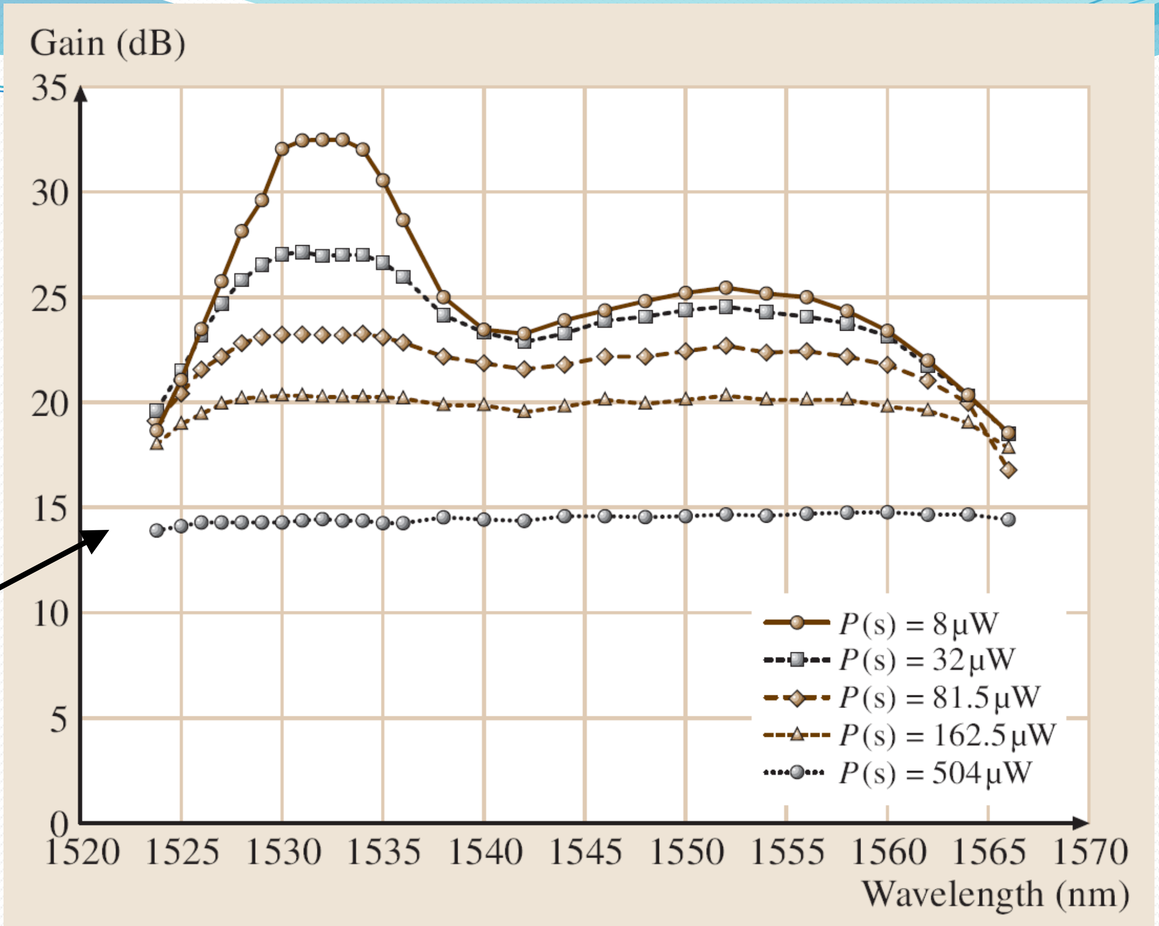
Output coupler – technical realization:

- fiber face (4%)
- fiber Bragg mirror
- free space OC

EDFA

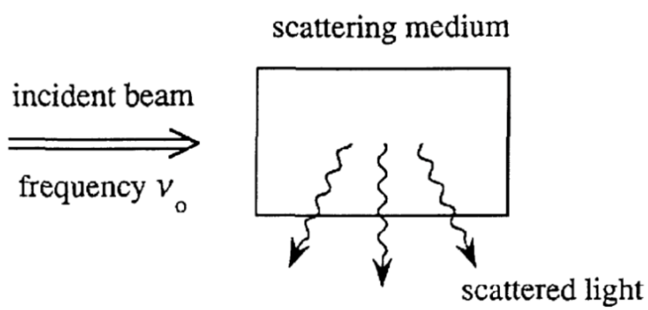
- pump – diode laser @ 980 nm
- gain > 20dB
- bandwidth > 40 nm
  (approx. 160 channels)

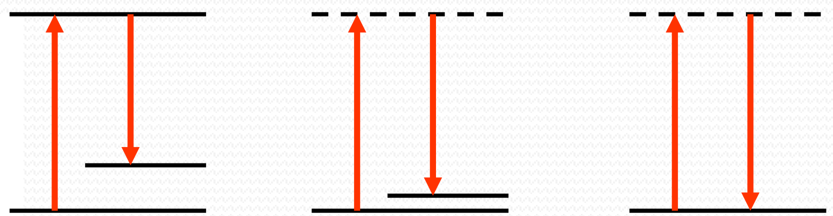
In a chain of EDFA non-uniform Er^{3+} amplification is a source of problems. Modern EDFA are equipped with modules that compensate this non-uniformity.

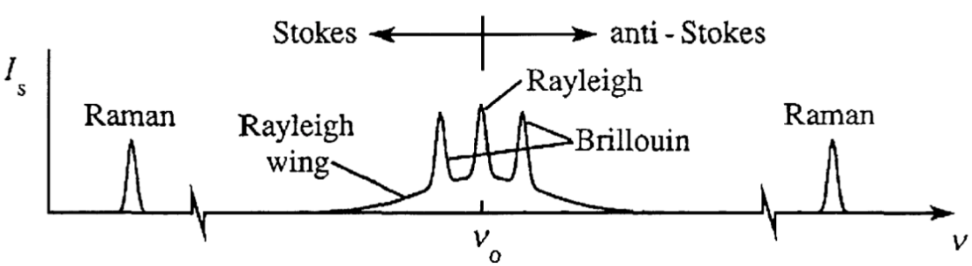


Band	Description	Wavelength Range
O band	original	1260 to 1360 nm
E band	extended	1360 to 1460 nm
S band	short wavelengths	1460 to 1530 nm
C band	conventional ("erbium window")	1530 to 1565 nm
L band	long wavelengths	1565 to 1625 nm
U band	ultralong wavelengths	1625 to 1675 nm

reminder: light scattering in condensed media







typical numbers for spontaneous processes

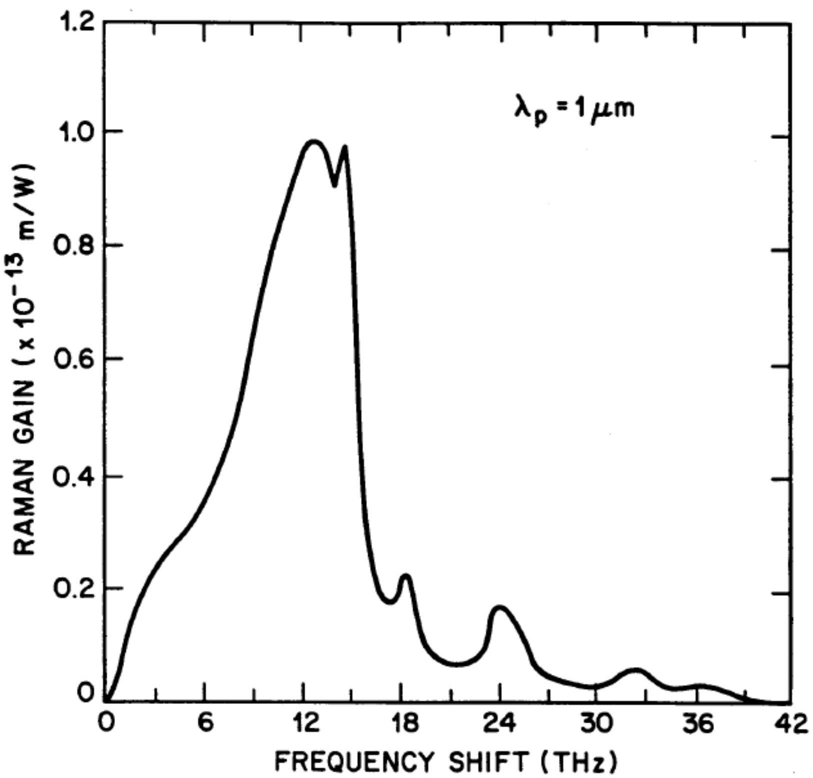
Process	Shift (cm^{-1})	Linewidth (cm^{-1})	Relaxation time (sec)	Gain[a] (cm/MW)
Raman	1000	5	10^{-12}	5×10^{-3}
Brillouin	0.1	5×10^{-3}	10^{-9}	10^{-2}
Rayleigh	0	5×10^{-4}	10^{-8}	10^{-4}
Rayleigh-wing	0	5	10^{-12}	10^{-3}

[a] Gain of the stimulated version of the process.

- Stimulated Raman Scattering (SRS)
- Stimulated Brillouin Scattering (SBS)

When besides the main field (ω_0) there are fields with frequencies resonant with Raman and/or Brillouin shifted fields we observe stimulated scattering which depletes the main field and amplifies Raman/Brillouin fields.

Raman gain in fused silica (SiO_2)



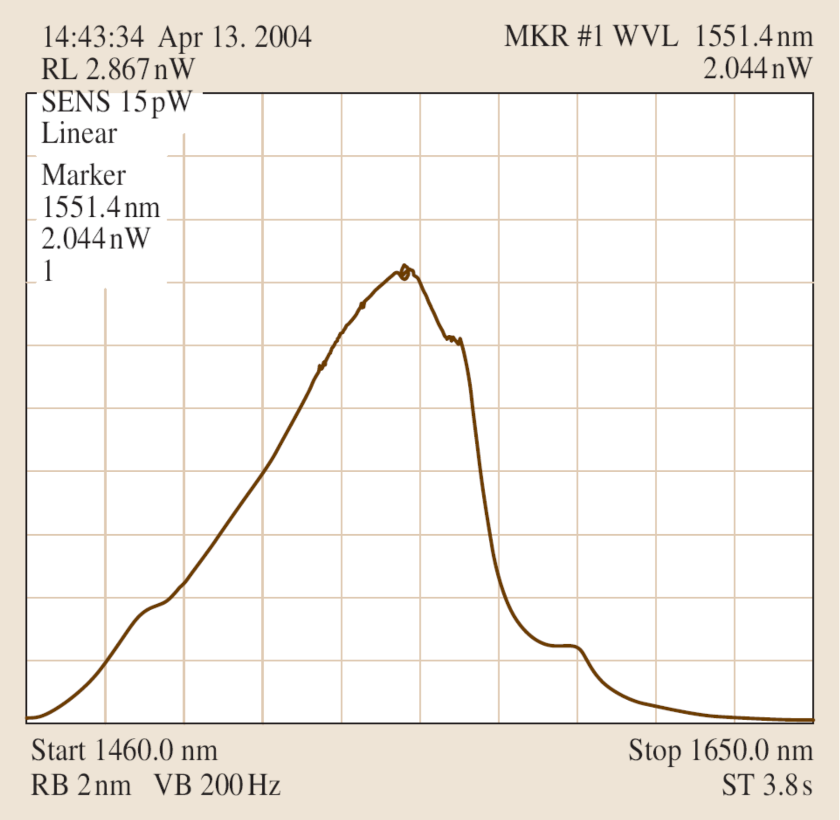


Fig. 8.81 Spontaneous Raman scattering from 25 km of a standard single-mode fiber

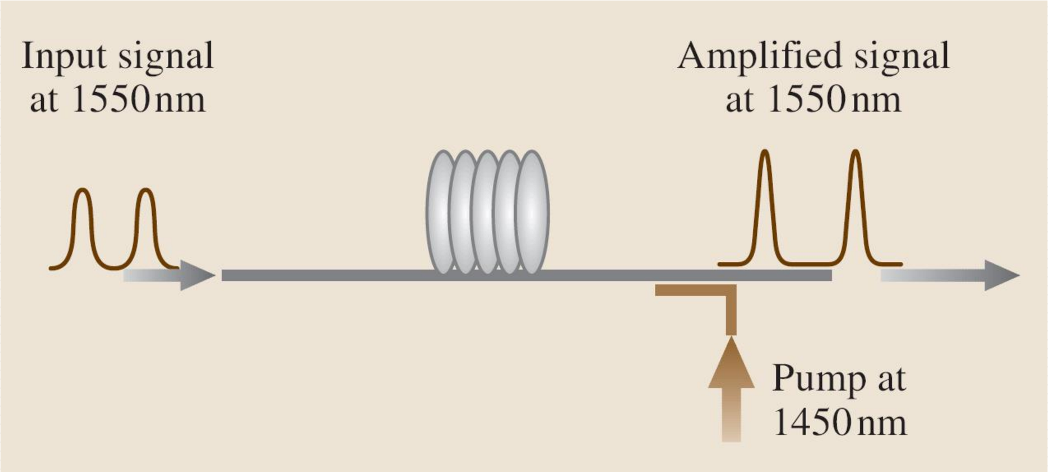
Raman Fiber Amplifier (for telecom applications)

- Principle of operation: Stimulated Raman gain
- For fused silica fibers the Stokes shift is around 13-14 THz (approx. 100 nm @ 1550 nm)
- advantages:

✓ universality – the Raman gain exists for any pump wavelength so signal with any wavelength can be amplified.

✓ by using several pumps with different wavelengths one can create a flat Raman gain band

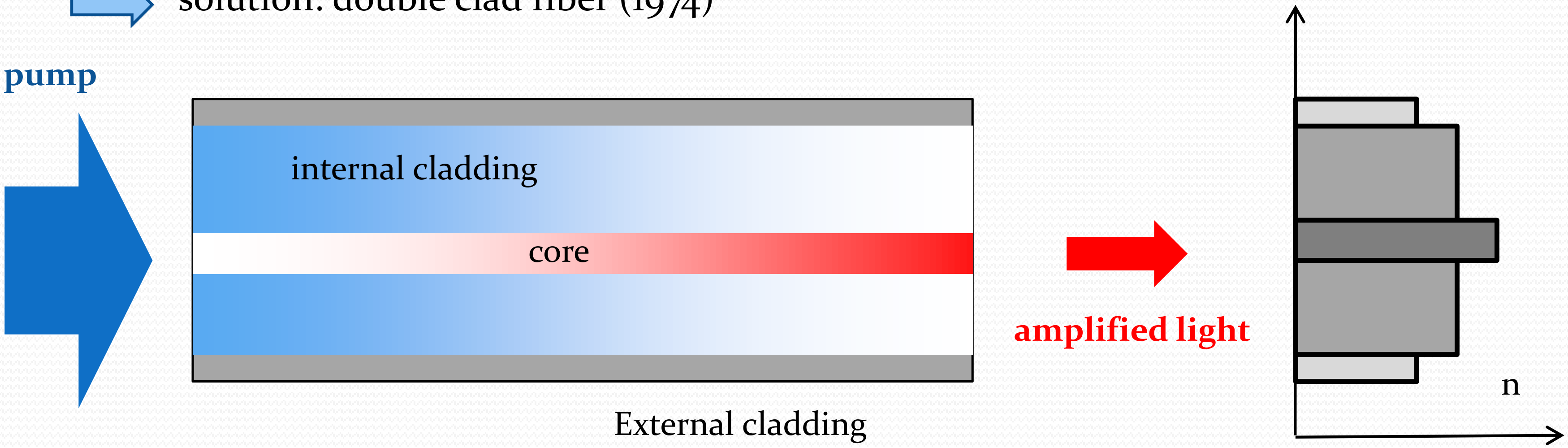
✓ can be used in the existing fiber systems without major investment



fiber amplifiers with high average power

- dopants: Er^{3+}, Nd^{3+}, Yb^{3+}
- Fiber core is too small to accommodate low quality pump beams (diode lasers or diode laser stacks)

  ⇒ solution: double clad fiber (1974)



- Thermal effects are limited due to:
  - geometry
  - high quantum efficiency (> 90% for Yb)
- Use of high power, high efficiency diode lasers with poor beam quality
- No limitations on the amplifier length due to light diffraction

limitations of fiber laser technology

- Large interaction length + small mode area → nonlinear effects:
  - Self-phase modulation (spectra broadening, pulses which cannot be compressed to their initial duration

$$B = \frac{2\pi}{\lambda}\int_0^L n_2\,(z)I(z)dz$$

  - Stimulated Raman scattering

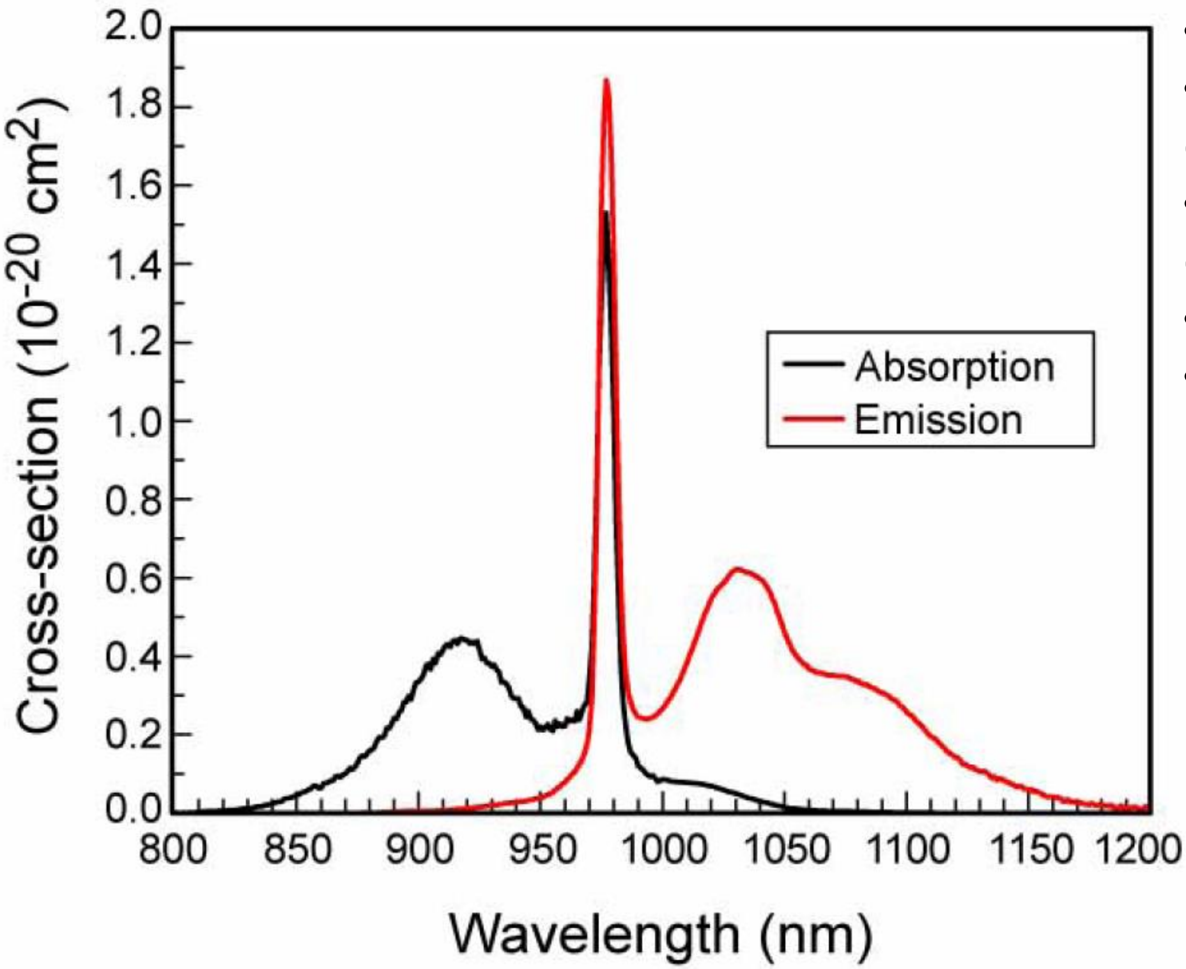
$$P_{th}^{SRS} \cong \frac{16A_{eff}}{g_R L_{eff}}, \quad g_R \cong 10^{-13}\text{m/W for fused silica}$$

  - Stimulated Brillouin scattering

$$P_{th}^{SBS} \cong \frac{21A_{eff}}{g_B L_{eff}}, \quad g_B \cong 5 \times 10^{-11}\text{m/W}$$

energy transferred to another wavelength

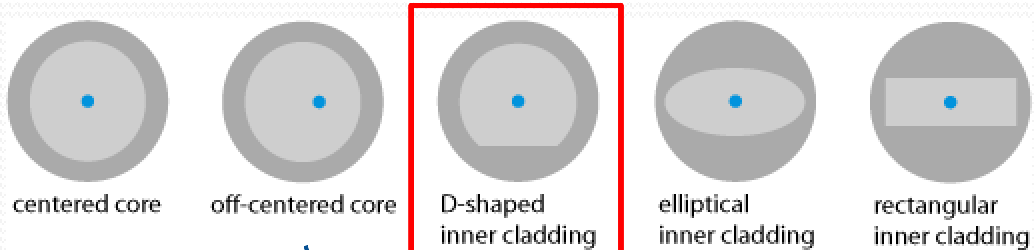
properties of Yb3+:fused silica

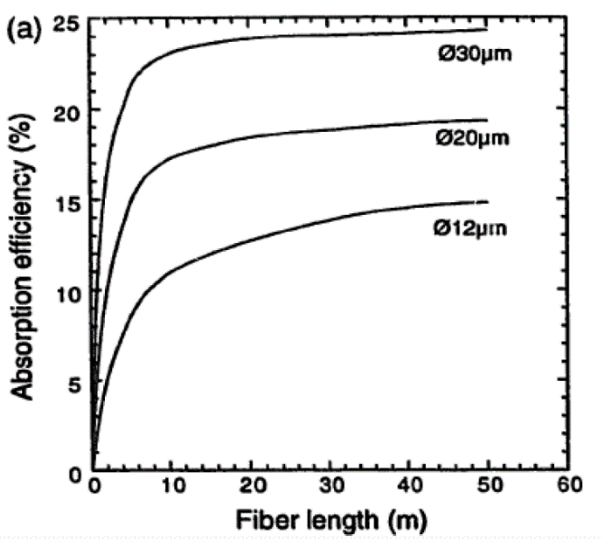


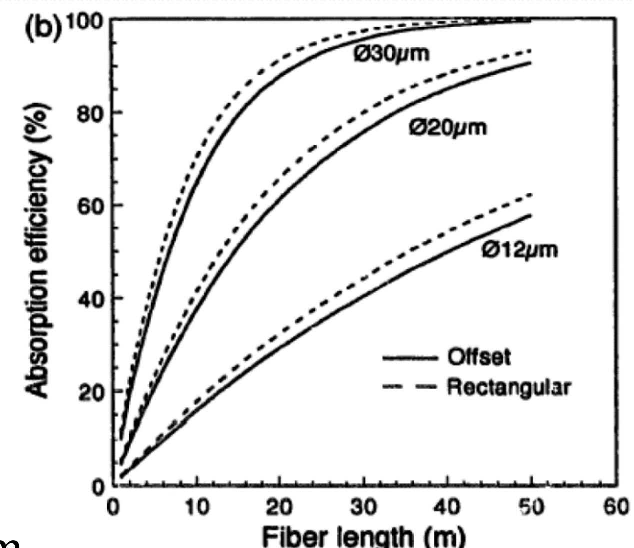
- quasi 3-level systems
- long lifetime of the upper level (2 ms)
- bandwidth > 100 nm (theoretical pulse duration: 16 fs)
- U_{sat} = 40-80 J/cm²
- quantum defect 3.5% - 9.5%

double-clad fiber

- core-clad coupling







cladding diameter 400 μm

single-mode operation required

- V < 2.405
- $V = \frac{2\pi}{\lambda} a_{eff} NA = \frac{2\pi}{\lambda} \underline{a_{eff}} \underline{\sqrt{n_{core}^2 - n_{clad}^2}}$
- we need low NA !
- the lowest available in MOCVD technology $NA \approx 0.06$

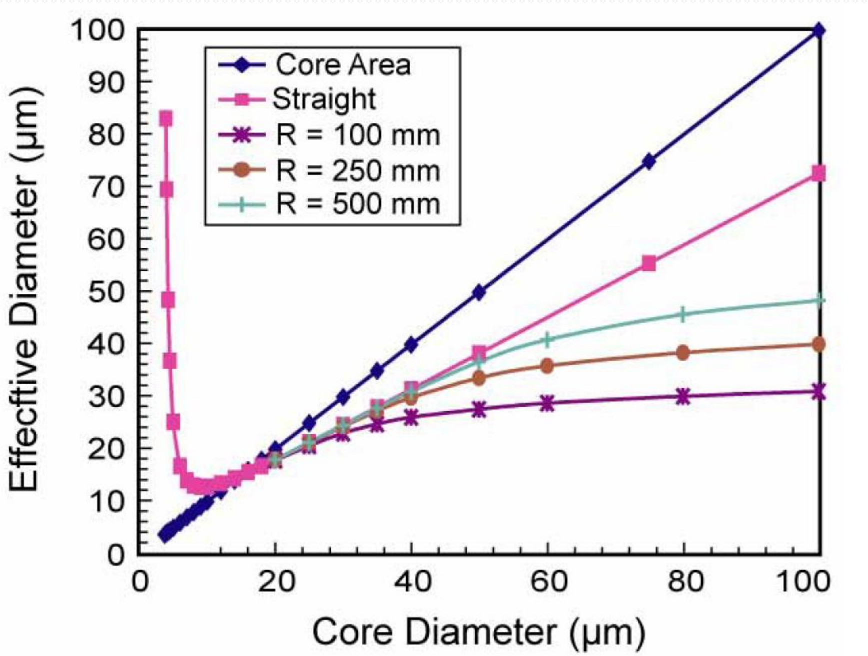
➡ available core ~ 15 μm @ 1μm

➡ larger cores favor higher order modes

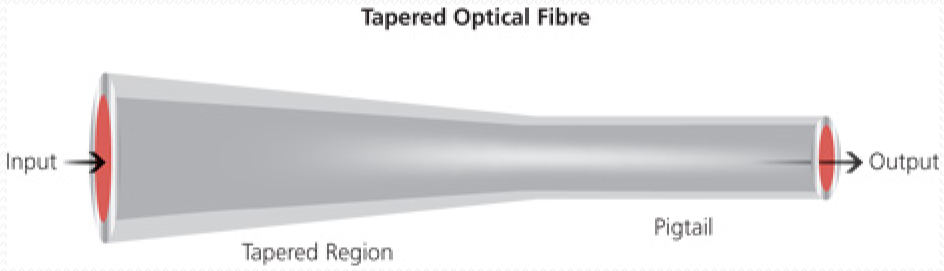
single-mode operation required, 2

- LMA – Large Mode Area (up to 65 μm diameter)
- single mode selection:

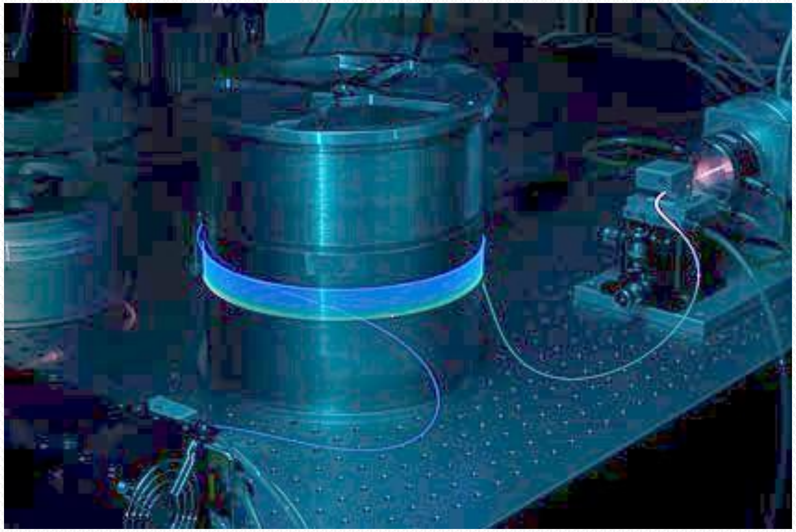
coiling

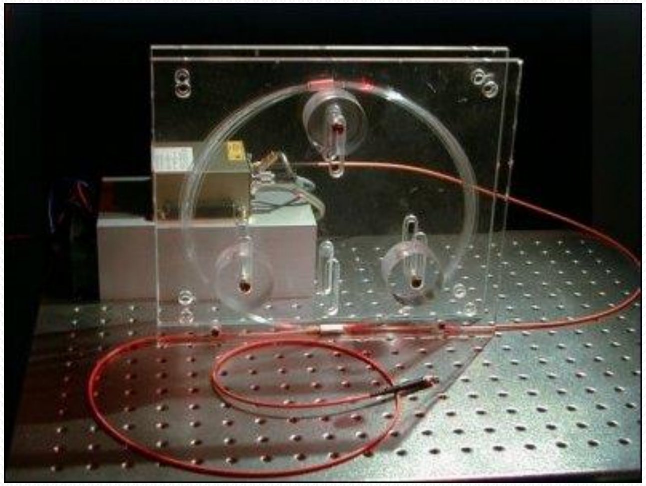


tapering



coiling

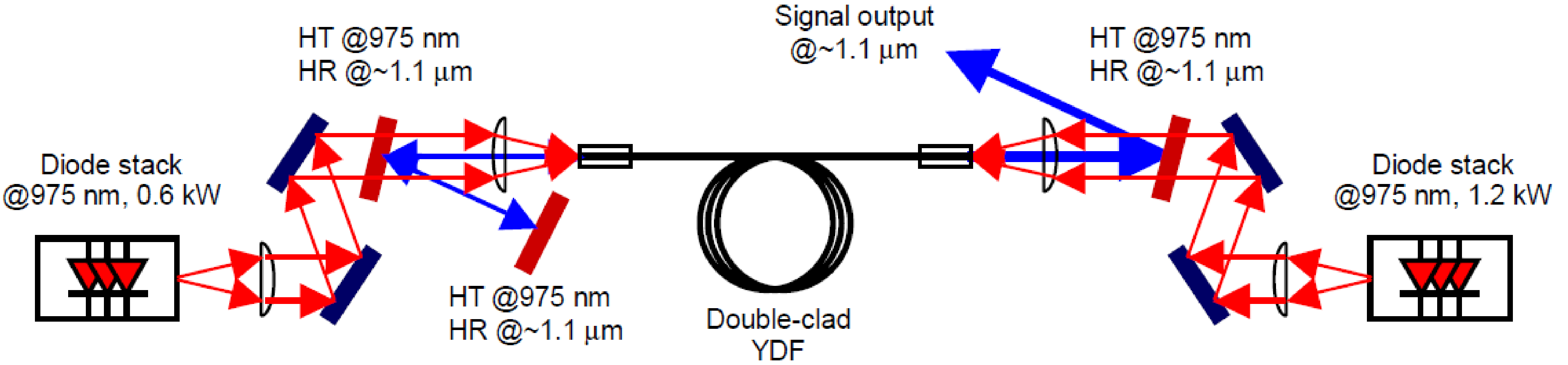




2004, 1.34 kW in cw operation

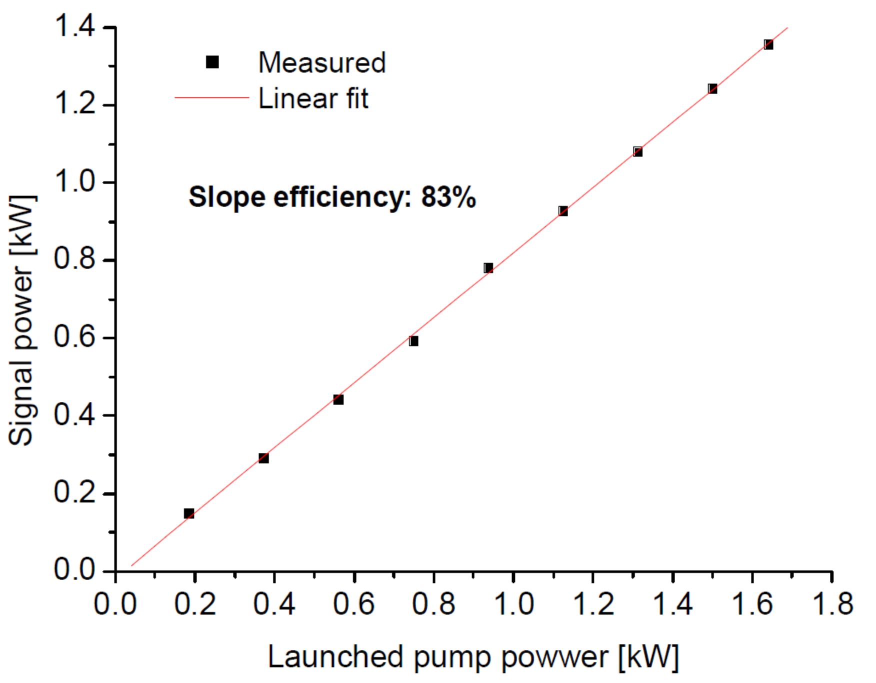
- core: 40 μm, NA<0.05, V = 5.7
- cladding: 650/600 μm, D-shaped, NA = 0.48
- fiber length 12 m
- losses LP_{01} < 0.04dB/m @ R > 10 cm
- losses LP_{11} ~ 1dB/m @R = 12 cm

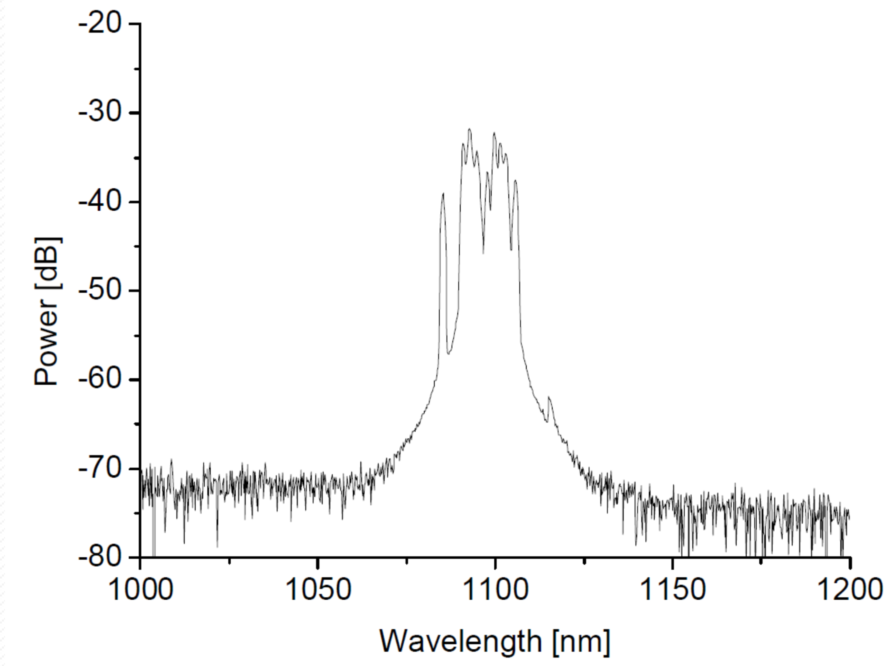
-uncoated fiber ends (OC)
- pump coupling eff. ~ 90%



Y. Jeong, J. K. Sahu, D. N. Payne, and J. Nilsson, *Ytterbium-doped large-core fiber laser with 1.36 kW continuous-wave output power,* Opt.Express, vol. 12, pp. 6088–6092, 2004

2004, 1.34 kW in cw operation, 2



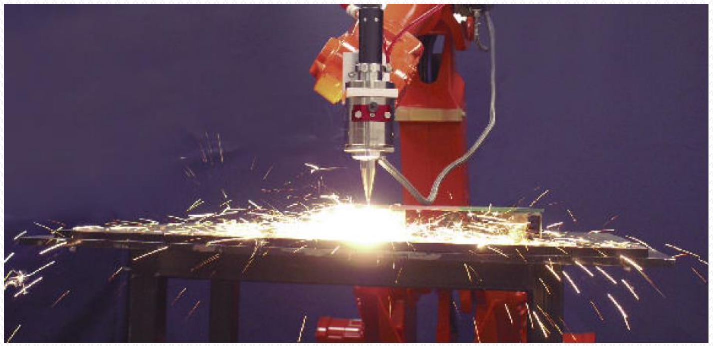


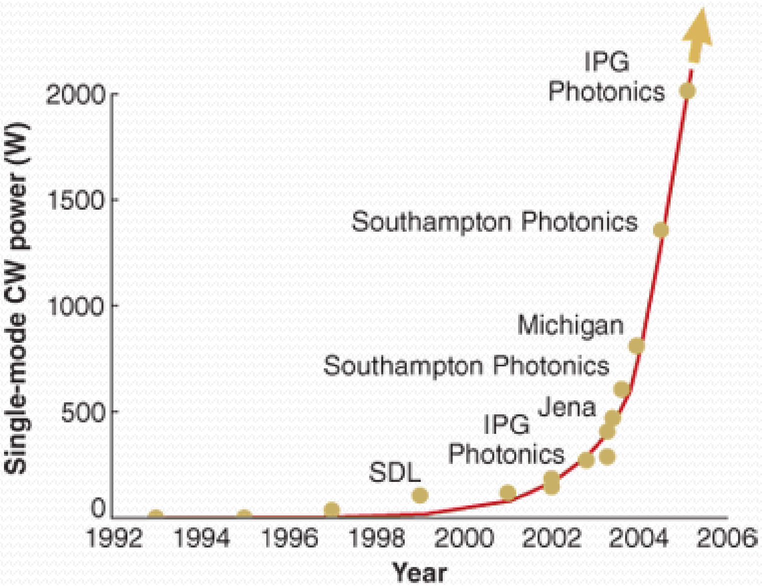
- quantum efficiency 95%!
- M^2: 1.4 (without optimization)

- intensity: 1.5 W/µm² (threshold: > 6 W/µm²)

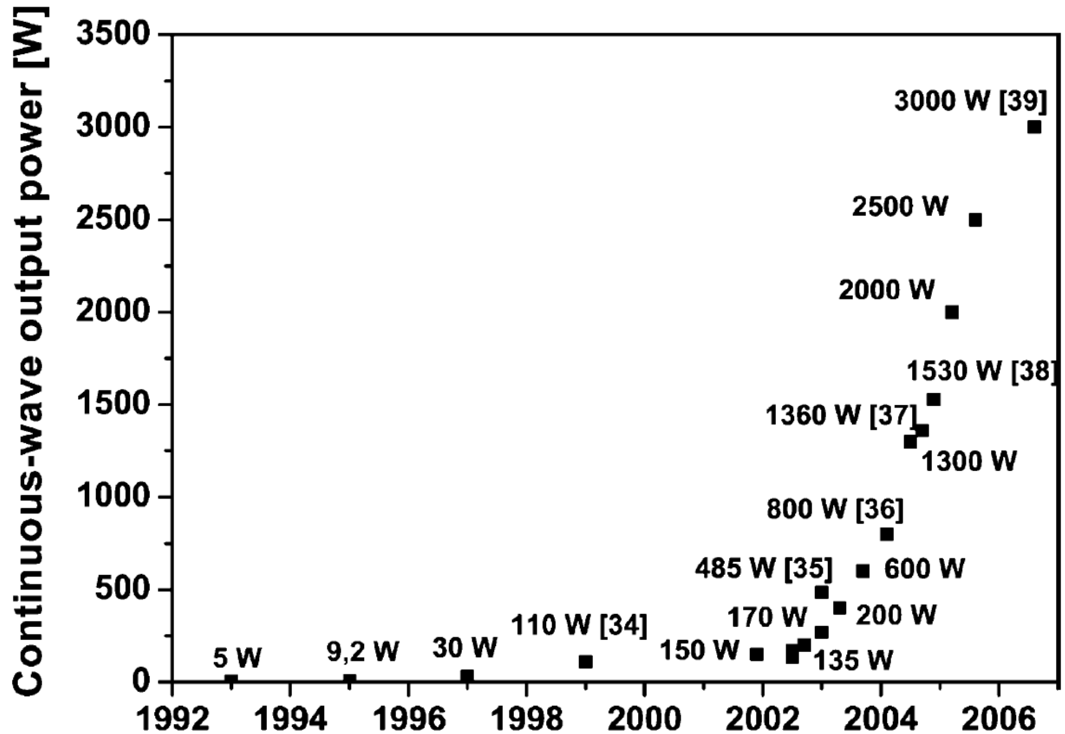
Y. Jeong, J. K. Sahu, D. N. Payne, and J. Nilsson, *Ytterbium-doped large-core fiber laser with 1.36 kW continuous-wave output power*, Opt.Express, vol. 12, pp. 6088–6092, 2004

high power cw fiber lasers





Source: A. Galvanauskas, U. of Michigan



high power cw fiber lasers, 2

power supply
10-40 kW

single mode modules with a few hundred Watt powers

outputs of the modules are combined in a multimode fiber to form the output beam

5kW optical power

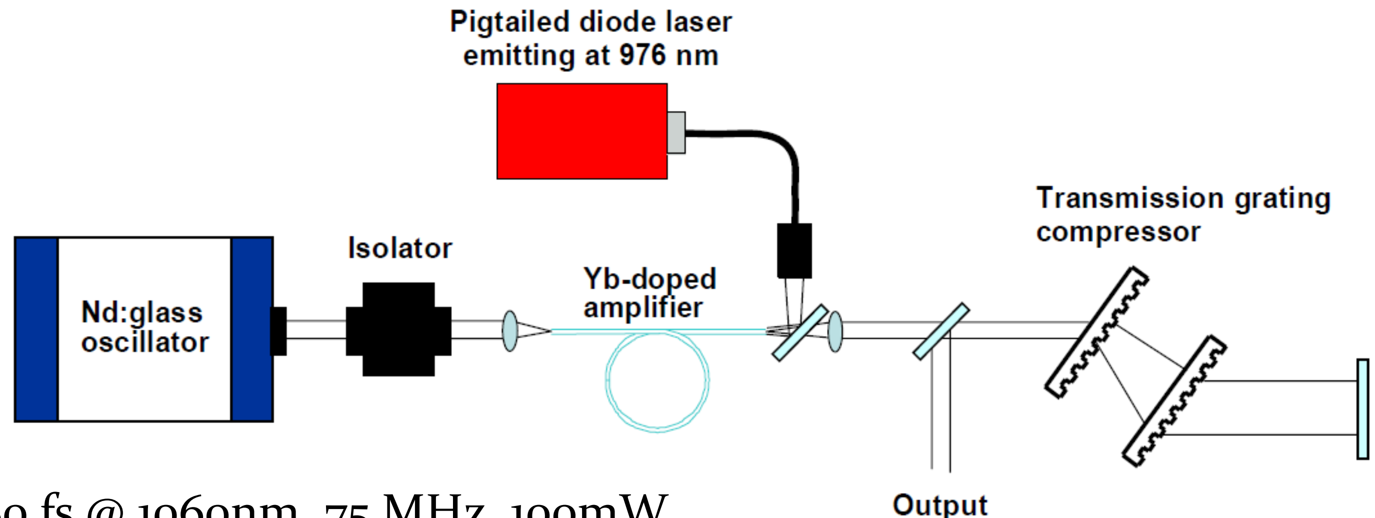
high power cw fiber lasers, 3

At 1 µm, the company's single-mode YLS-SM ytterbium-doped fiber lasers span a power range from 1 to 10 kW, says Markevitch. These single-mode systems are used in advanced materials-processing applications requiring extremely high power and brightness, such as fine cutting and surface structuring, cutting high-reflectivity metals, microwelding, sintering, and engraving, as well as remote processing and directed-energy applications.

"[IPG's] multimode YLS ytterbium-doped CW fiber lasers span a power range from 1 to 100 kW and can be manufactured up to several hundreds of kilowatts upon customer request," says Markevitch. "Their many uses include cutting, drilling, brazing, welding, annealing, heat treating, and cladding. With continuous improvement in their design, wall-plug efficiencies of standard industrial YLS system have now reached over 40%, and the industry record YLS-ECO series has a WPE exceeding 50%.

John Wallace, „Photonics Products: High-power Fiber Lasers: Kilowatt-level fiber

2002 – nonlinearity under control



- seed: 180 fs @ 1060nm, 75 MHz, 100mW
- fiber length: 9 m
- core: 30 μm, NA = 0.06
- cladding: 400 μm, D-shaped, NA = 0.38
- V ≈ 5 (4 modes)
- coiled down to R < 10cm

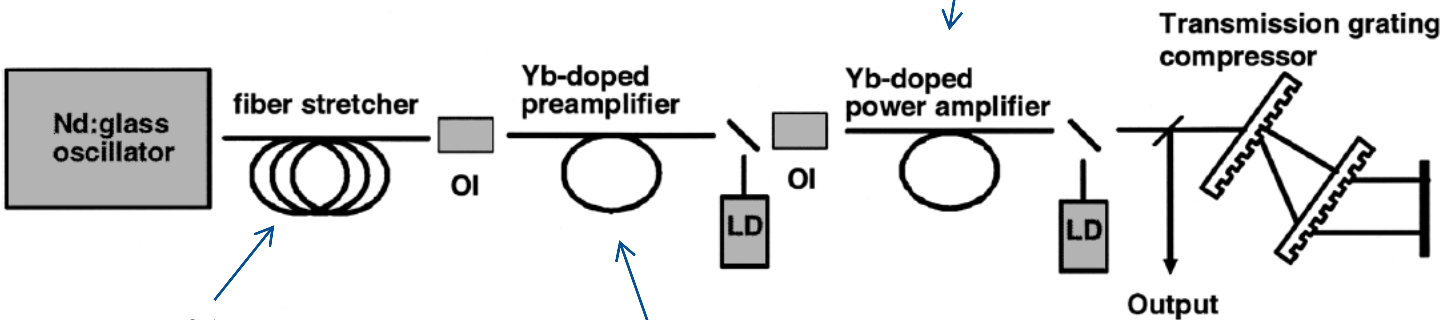
- transmission gratings >94%

duty cycle 0.45

Jens Limpert, T. Schreiber, T. Clausnitzer, K. Zöllner, H. Fuchs, E. Kley, H. Zellmer, and A. Tünnermann ,*High-power femtosecond Yb-doped fiber amplifier,* Optics Express, Vol. 10, Issue 14, pp. 628-638

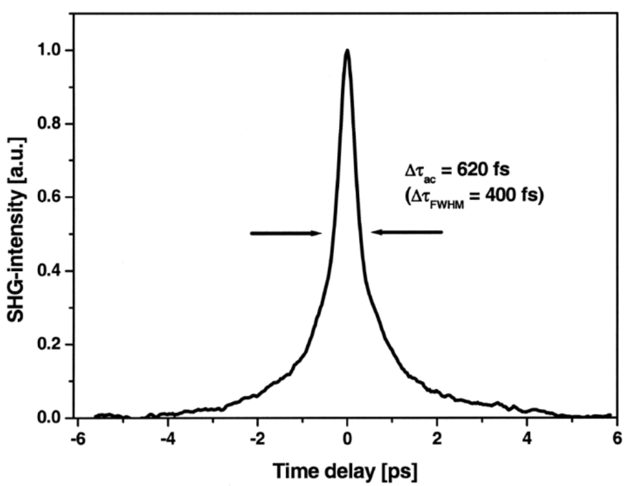
2003 – CPA fiber amplifier

L = 13.5 m, core: 28.5 μm, NA = 0.06
140W, M^2 = 1.1



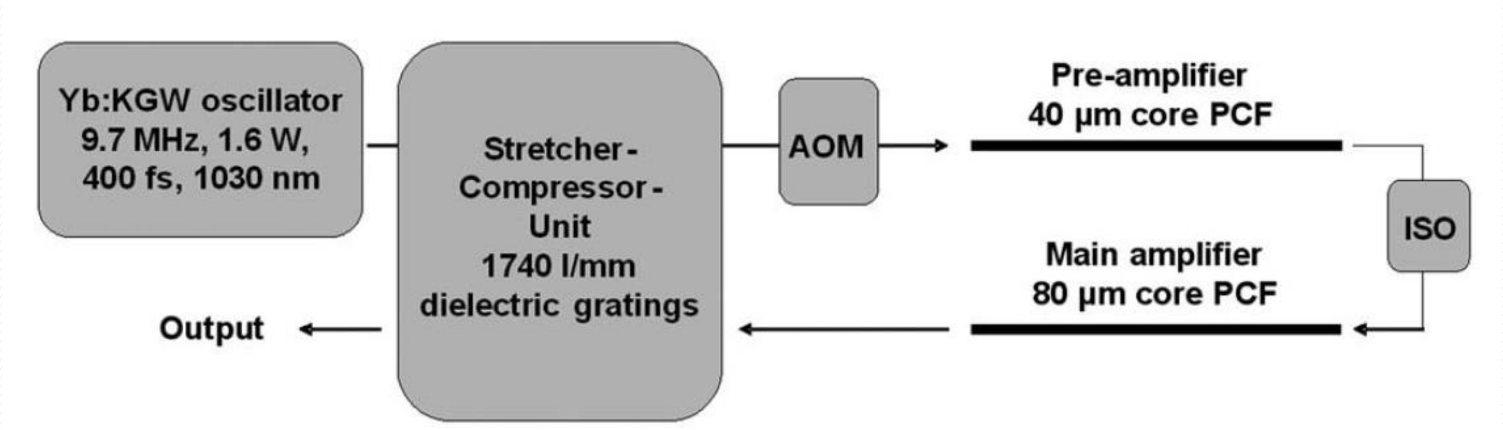
300 m fiber
w(P=15mW) = 22.7 nm

compressor efficiency 54%
polarization purity 50%



L = 15 m, core: 10 μm,
NA = 0.08
2W

2007 – 0.7 mJ @ 100 kHz



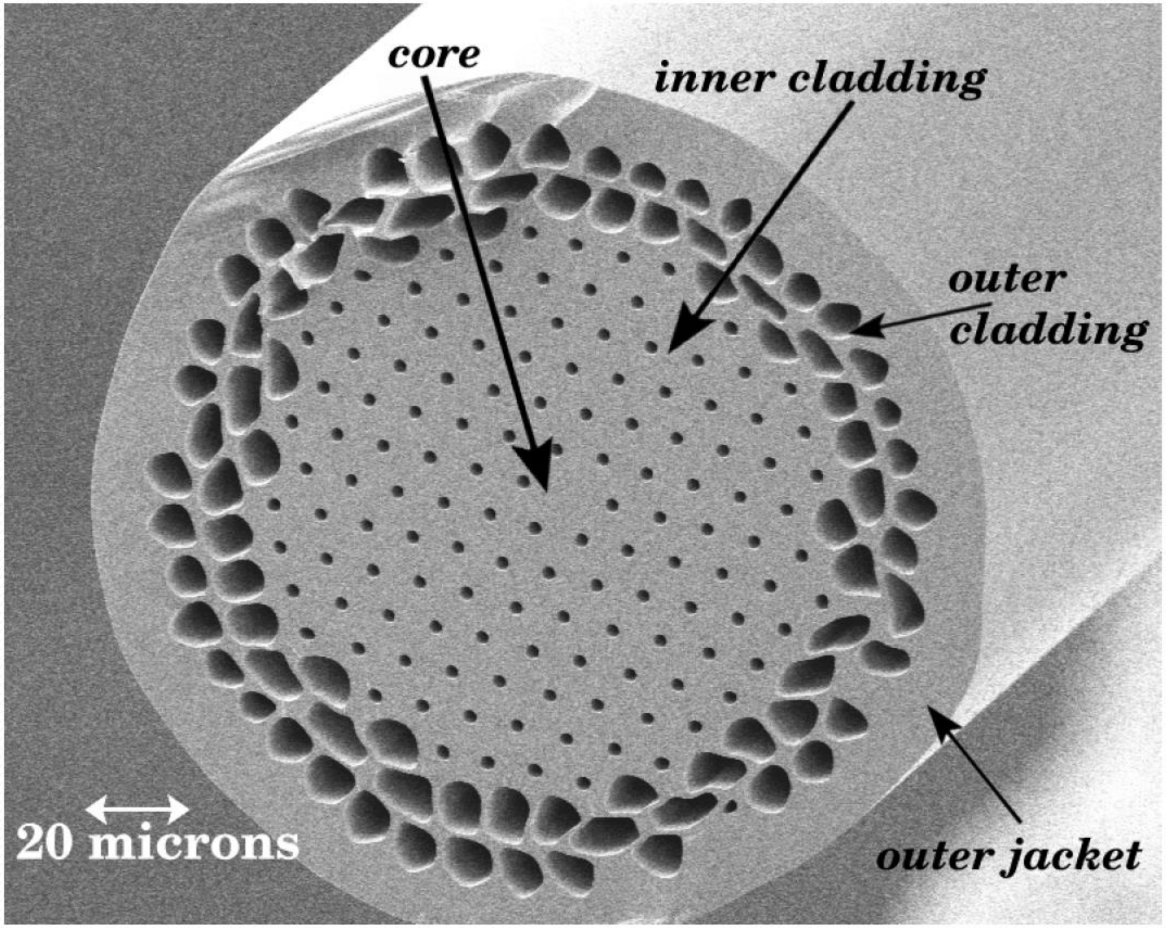
-Pulse stretching to 2 ns with 3.3 nm spectrum
- modulator loss: 75%
- fibers 1.2 m
- the first fiber PM
- the second fiber immersed in water

- efficiency: 66%, 50%....
- 0.5mJ, 780 fs, 200 kHz, B = 4.7
- 0.7mJ, 800 fs, 100 kHz, B = ??
- 1.45mJ, 800 fs, 50 kHz, B = 7
- $M^2 < 1.2$
- polarization purity 98%

Authors' conclusion: **Fiber CPA will be able to generate mJ pulses @ MHz rep. rates**

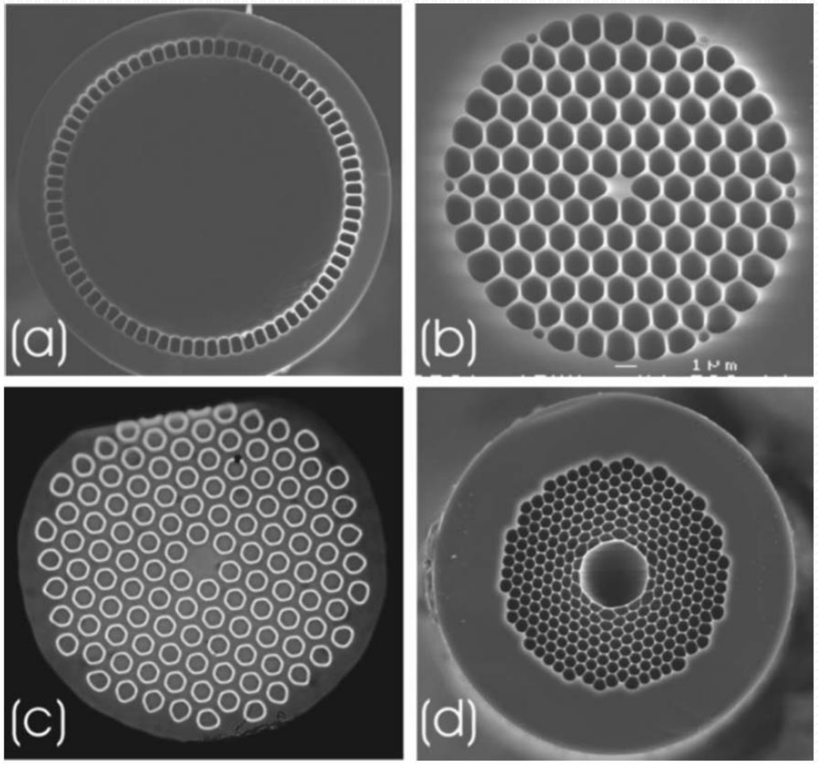
F. Röser, D. Schimpf, O. Schmidt, B. Ortaç, K. Rademaker, J. Limpert, and A. Tünnermannı, *Millijoule pulse energy high repetition rate femtosecond fiber chirped-pulse amplification system,* Opt. Letters, vol. 32, pp. 3495, 2007

photonics fibers – towards larger core size



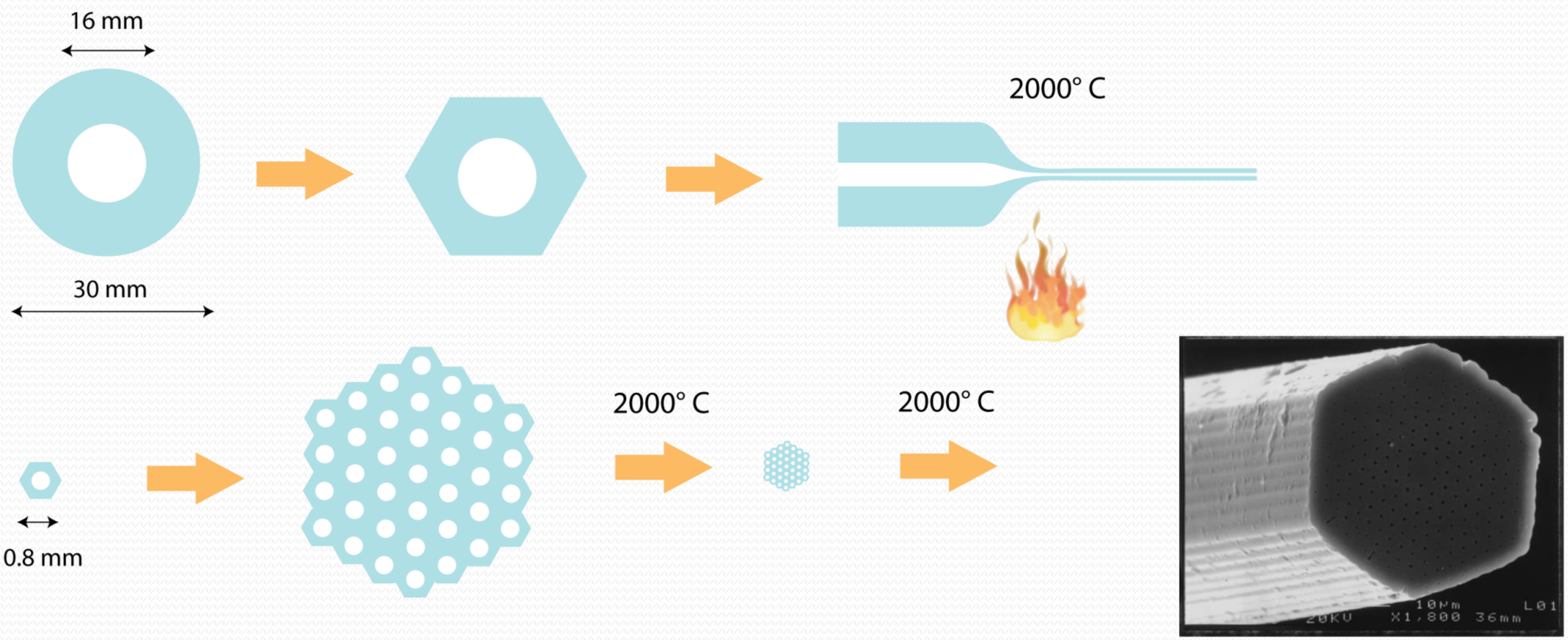
photonics fibers – new functionalities

- Single mode in a wide wavelength range
- Geometrical factors allow for a very precise control of NA, fibers with mode diameters up 85 μm are commercially available.
- External cladding: $n \approx 1$ (air- clad), provides high NA for pump beam.
- Small inner cladding improves core-cladding coupling

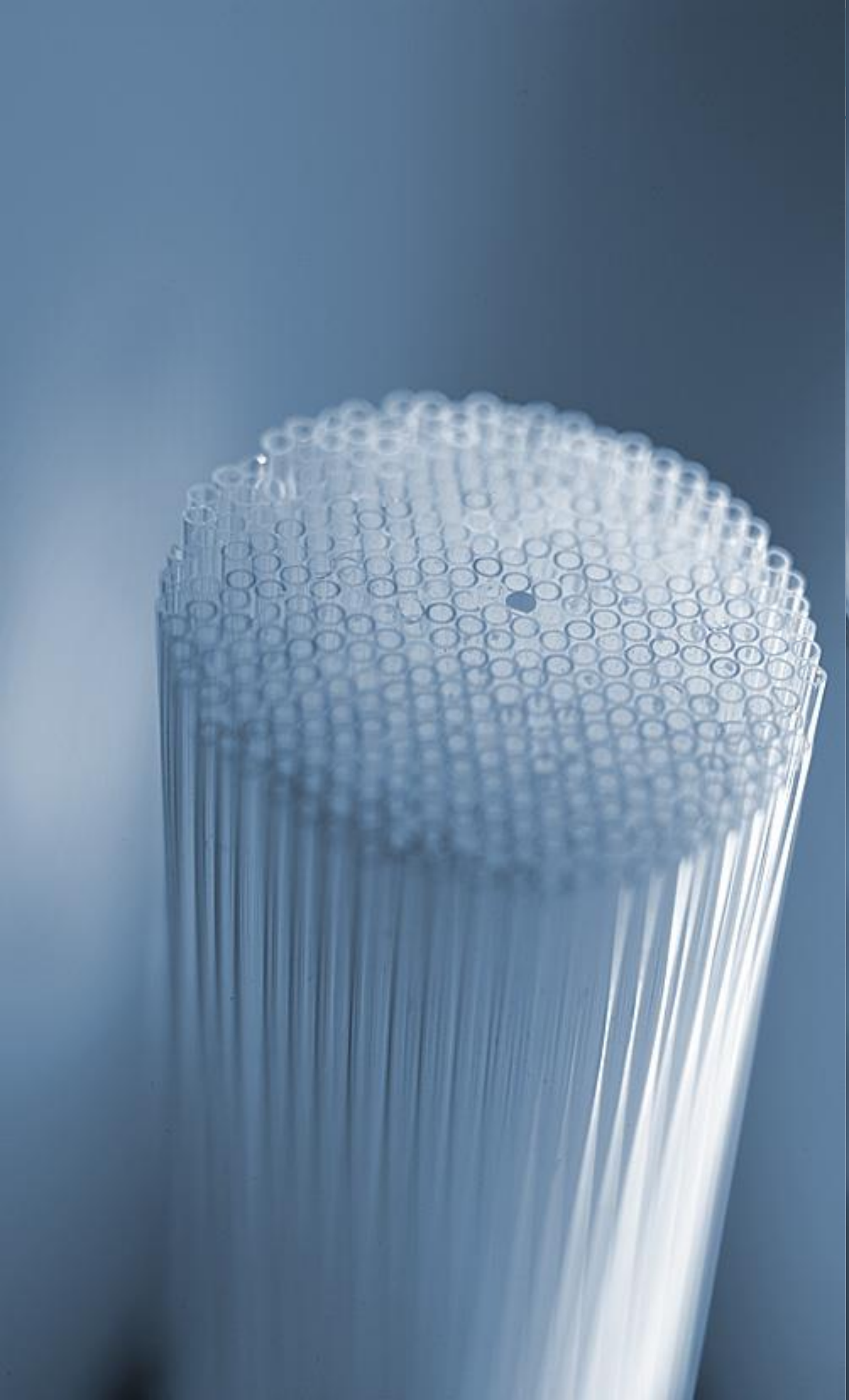


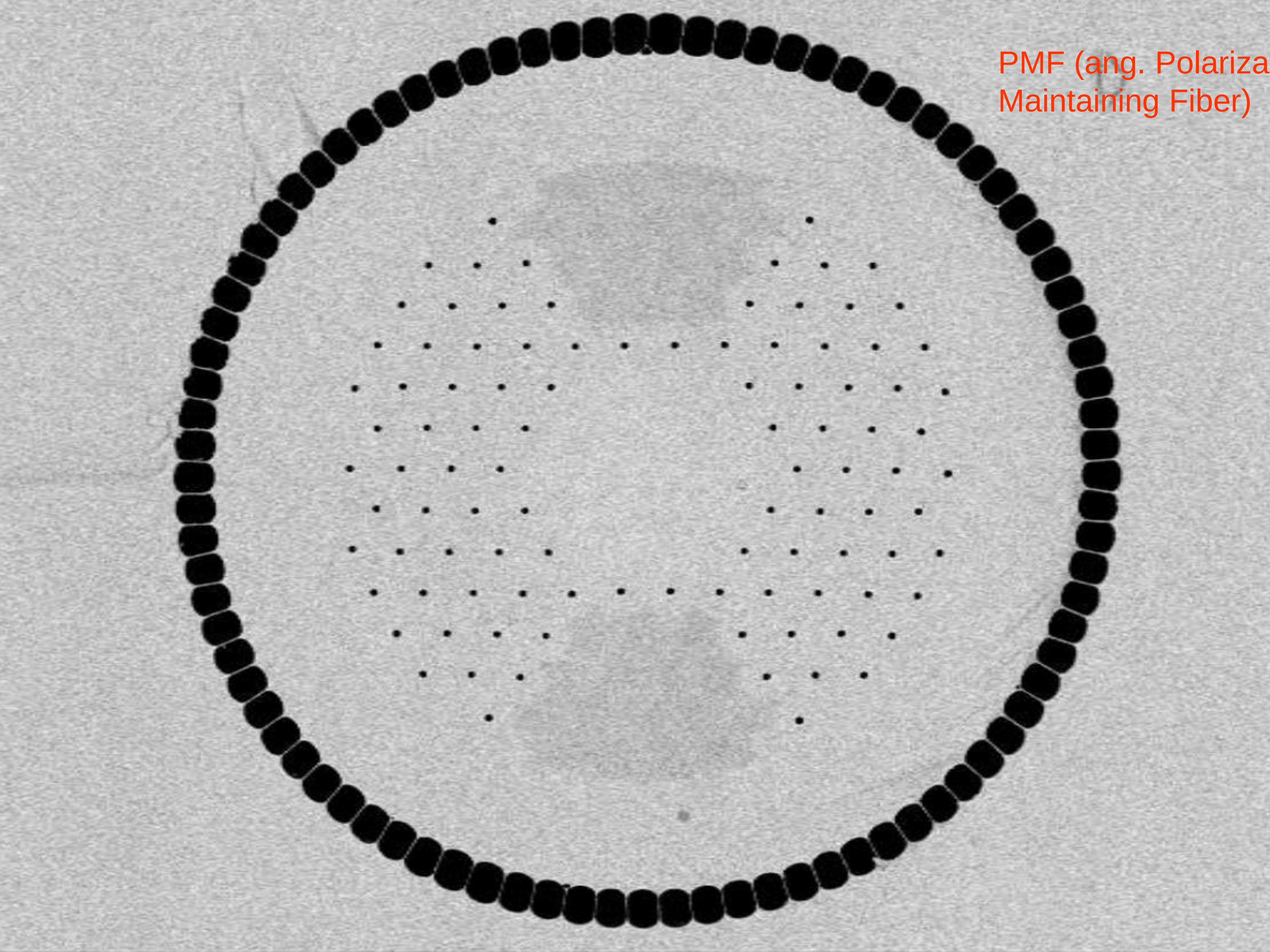
photonics fibers – technology

- Stacking and drawing



J. Knight,T.Briks, P.Russell, andD.Atkin, "All-silica single-mode optical fiber with photonic crystal cladding," Opt. Lett., vol. 21, pp. 1547–1549, 1996



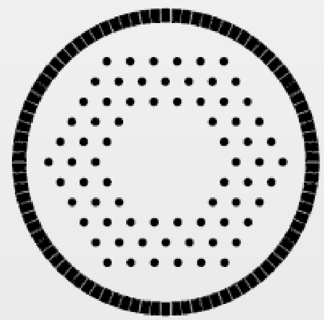



PMF (ang. Polariza
Maintaining Fiber)

Larger core to maximize absorption and minimize length

Increased fiber diameter to remove bending loss

ROD TYPE FIBER



TYPICAL SPECS:

Core size: 50-100 μm
Pump cladding: 200 μm
Outer diameter: 1-2 mm

NORMAL AIRCLAD FIBER