The Abdus Salam
International Centre
for Theoretical Physics

2443-25

Winter College on Optics: Trends in Laser Development and Multidisciplinary Applications to Science and Industry

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Fibre Laser

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FIBRE LASER

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Summary

Introduction

Fundamentals of light propagation

Fiber Lasers

- **Phenomena and limits in Fiber laser**

Next challenges (UV & Mid-infrared)

Conclusion

AIM:

Provide an Overview of Fiber Lasers

(high-power)

Swansea University

A bit about myself

1964 Born in Trieste

1989 Degree at Politecnico di Milano on laser resonator

1990 Optical Amplifiers (SIRTi & CSELT, Turin)

1991 Joined CRN & Politecnico di Milano (bulk and waveguide lasers).

- 1991-93 Collaboration with Italtel and IRE-Polus (now IPG) on optical amplifiers

1998 ORC Southampton, UK, on Fibre laser

1999 Lucent Bell Labs, NJ, USA, on supercontinuum sources

2007 Joined Swansea University: Head Laser group and responsible for Photonics Labs.

Collaborations with several companies, IXFibers, Perfos, Pirelli, Corning and Marconi/Ericsson on fibre devices

History

First laser was demonstrated in 1960 by T. Maiman

First fiber laser was demonstrated in 1963 E. Snitzer

Amplification in a Fiber Laser

Charles J. Koester and Elias Snitzer

Fiber lasers of neodymium-doped glass have been used on a pulsed basis to amplify 1.06-μ radiation. To prevent oscillation, the ends are polished at an angle such that reflected light is lost from the cavity. With the high inversion which can then be obtained, gains as large as 5×10^4 have been observed in a 1-m long fiber. The gain was measured as a function of pumping energy and as a function of time during the pumping pulse at which the amplification was determined.

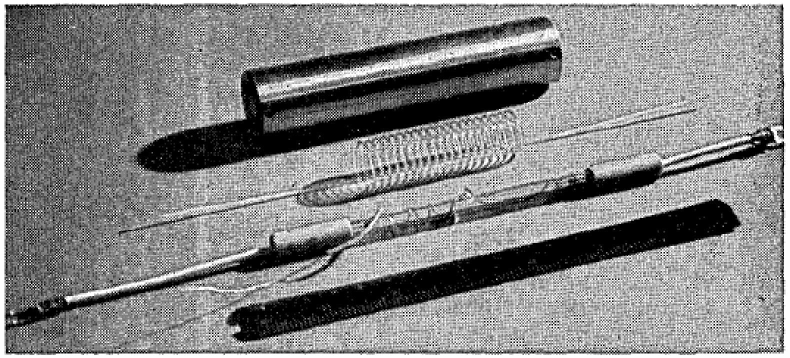
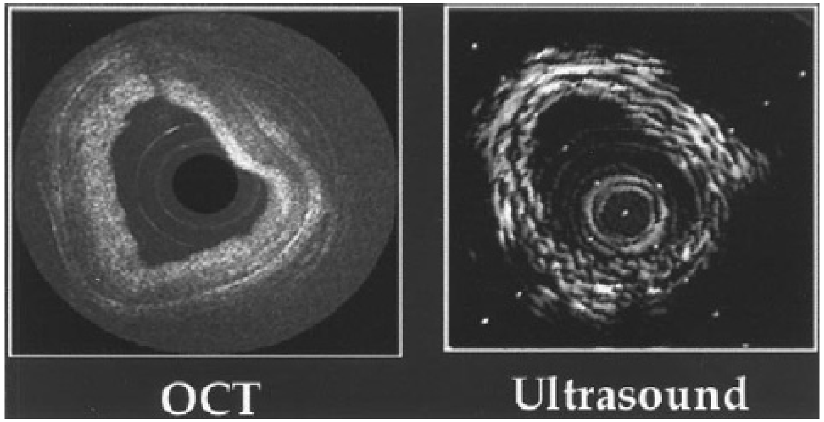


Fig. 1. Coiled fiber laser. From the top the components are: cavity, fiber laser, flashtube, and 18 cm scale

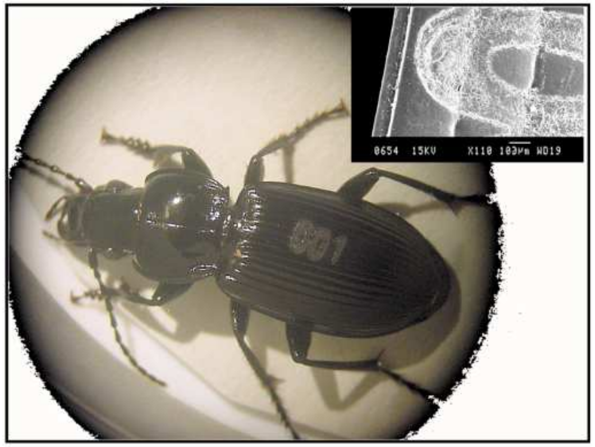
30 kW welding of steel.

several tens of mm



Blood vessel imaging

customized ear implant

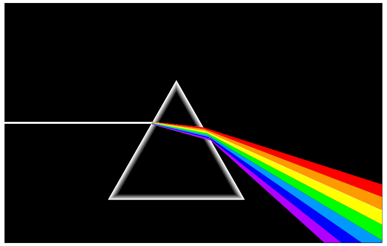


marking of beetles

Cleaning and restoration

Art Work

Property of laser light



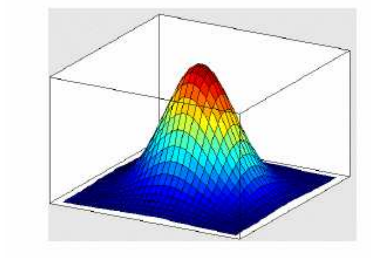
Monochromaticity

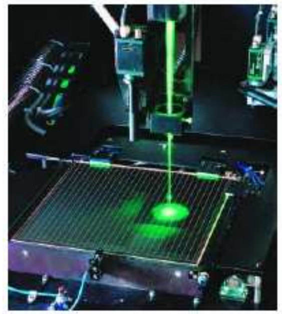
Directionality (Spatial Coherence)

Temporal Coherence

Brightness

Short Time duration





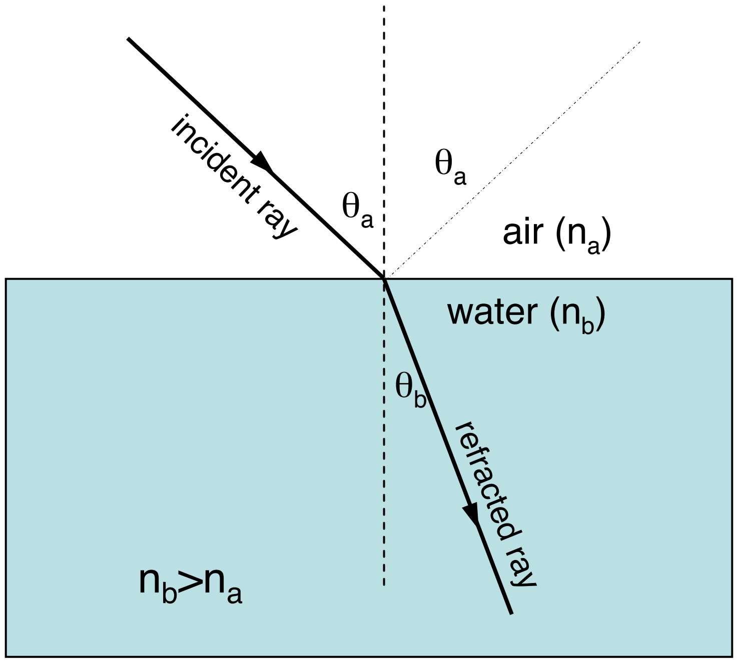
Can concentrate huge amount of energy

1) **on small areas (volumes) (μm^2 / μm^3)**
2) **During short time (10^{-15} s)**
3) **Transmit light over long distance (e.g. Earth-Moon distance control, power up satelites)**

Selectively interact with only specific materials/chemical specimens

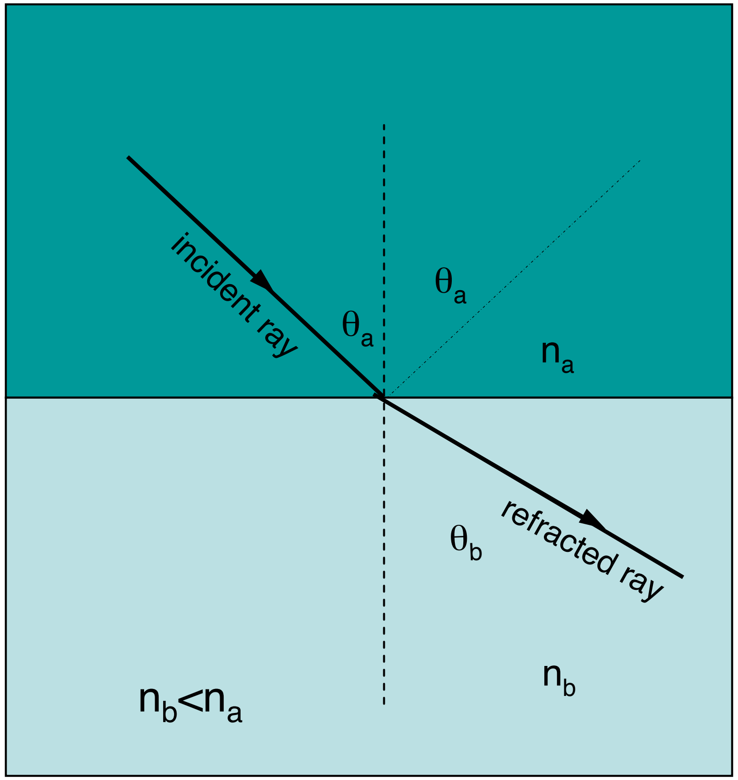
Fundamentals

Snell's law



$$n_a \sin(\theta_a) = n_b \sin(\theta_b)$$

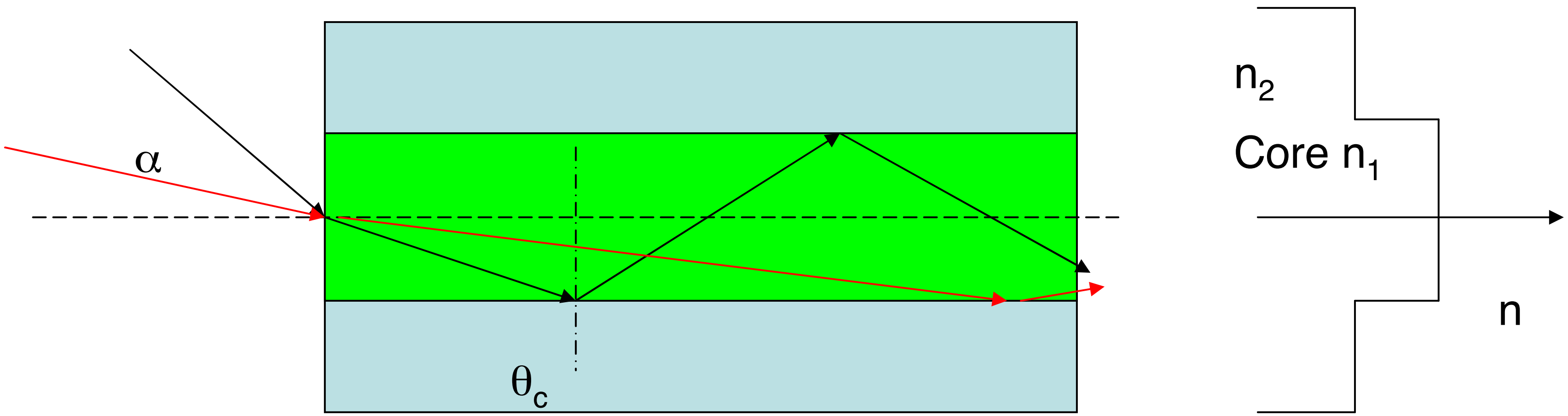
Total Reflection



$$n_a \sin(\theta_a) = n_b$$

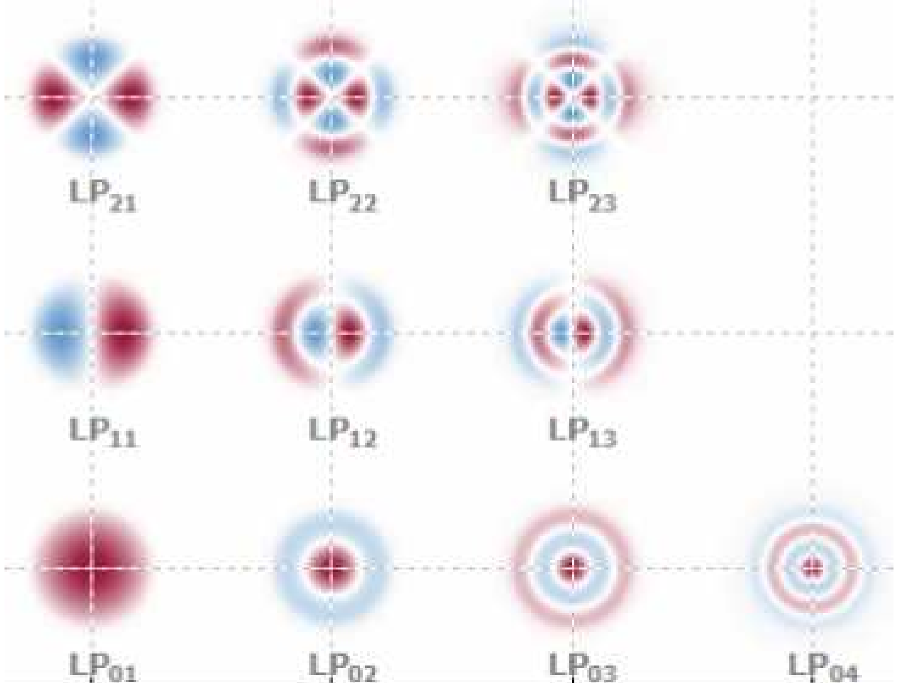
$$\theta_a = \arcsin\left(\frac{n_b}{n_a}\right)$$

Fiber Optic



$$NA = \sin(\alpha) = \sqrt{n_1^{\,2} - n_2^{\,2}}$$

Fiber Optic



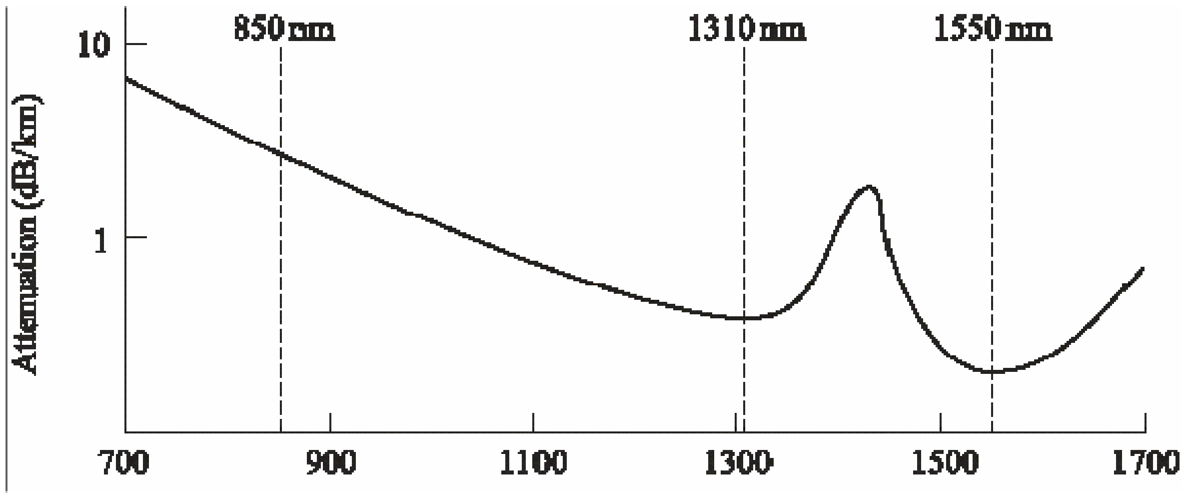
Single-mode operation
(step index profile)

$$\lambda_c = \frac{2\pi a}{2.405} \times NA$$

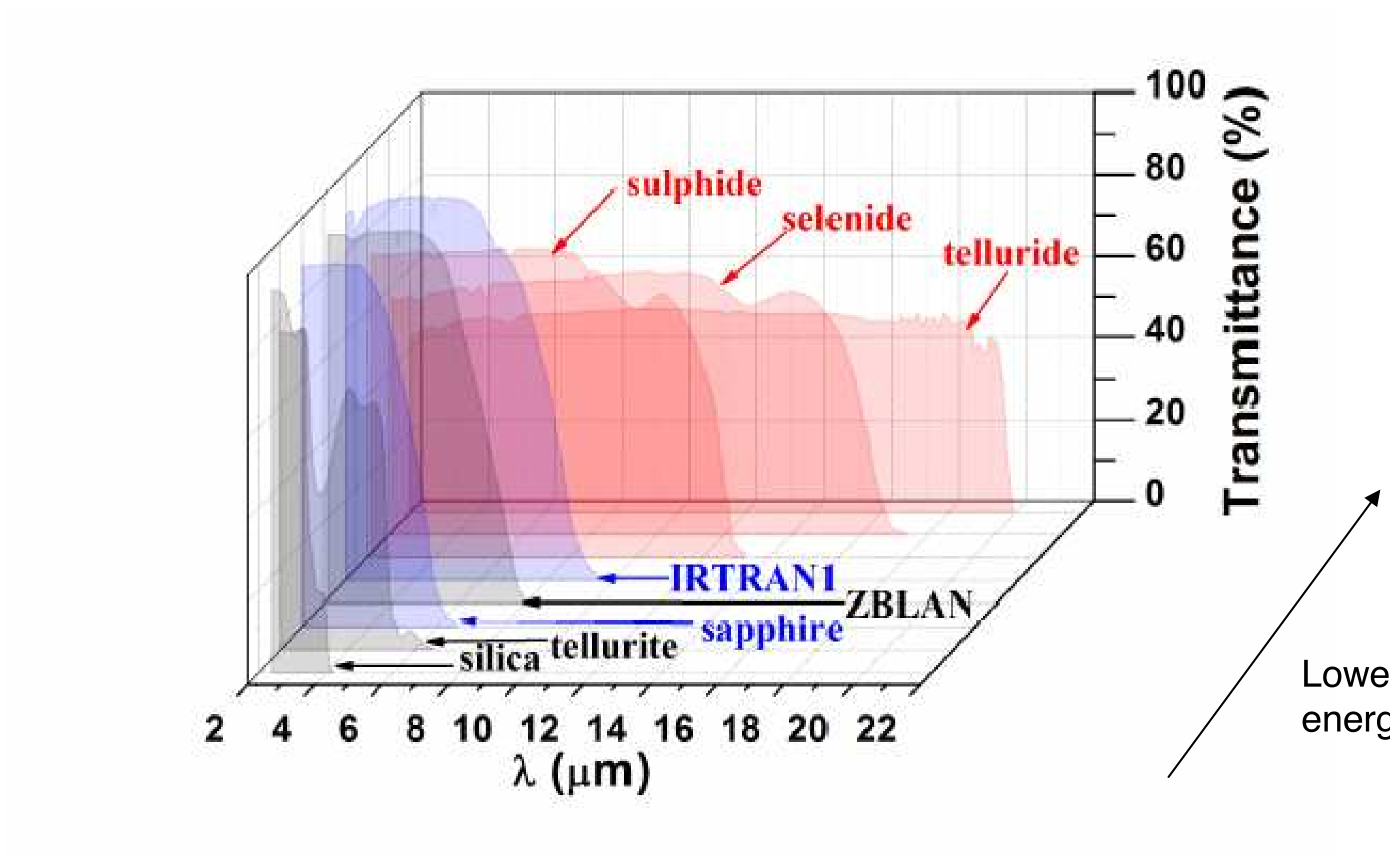
$$V = \frac{2\pi NA}{\lambda} < 2.405$$

Fiber Optic (silica)

Low Loss: 0.2 dB/km

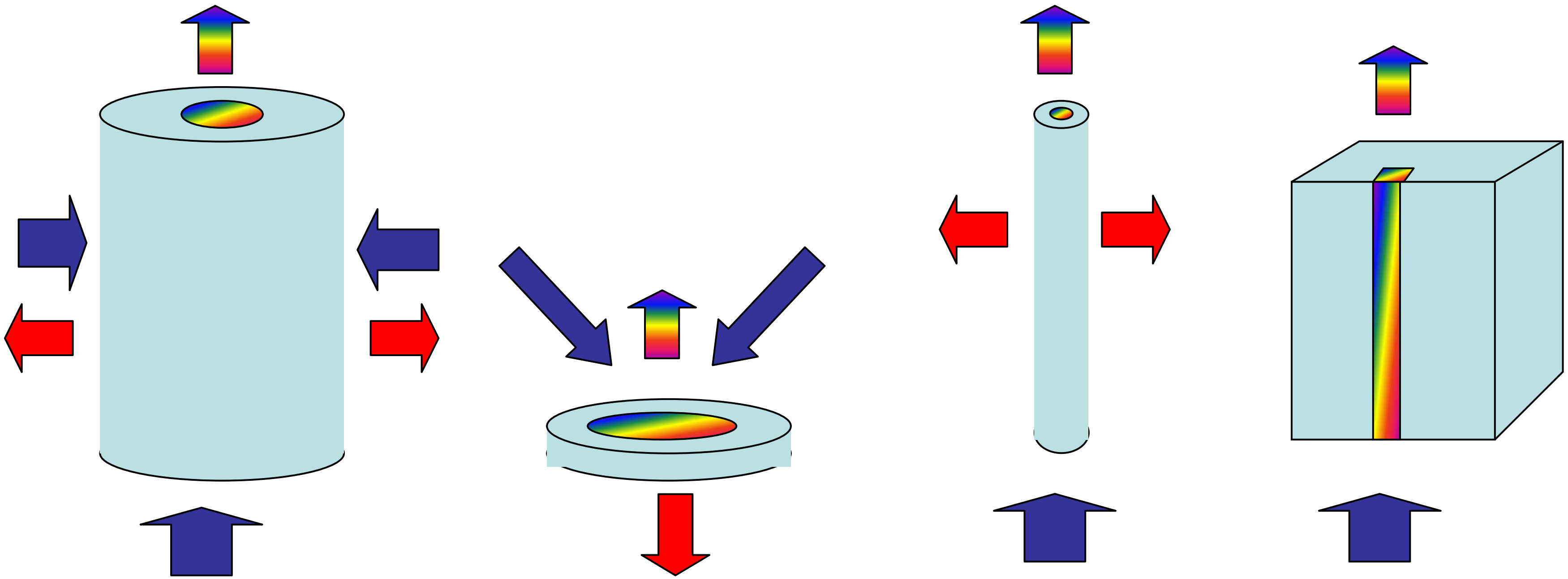


Fiber Optic (Other Glasses)

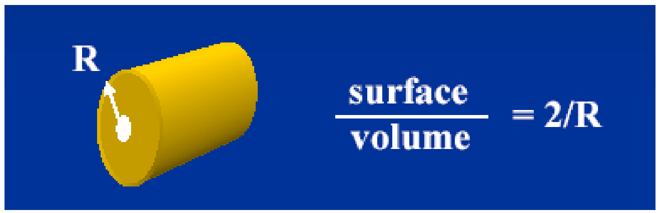


Jiri Orava, Tomas Kohoutek, A. Lindsay Greer, and Hiroshi Fudouzi, "Soft imprint lithography of a bulk chalcogenide glass," Opt. Mater. Express **1**, 796-802 (2011)

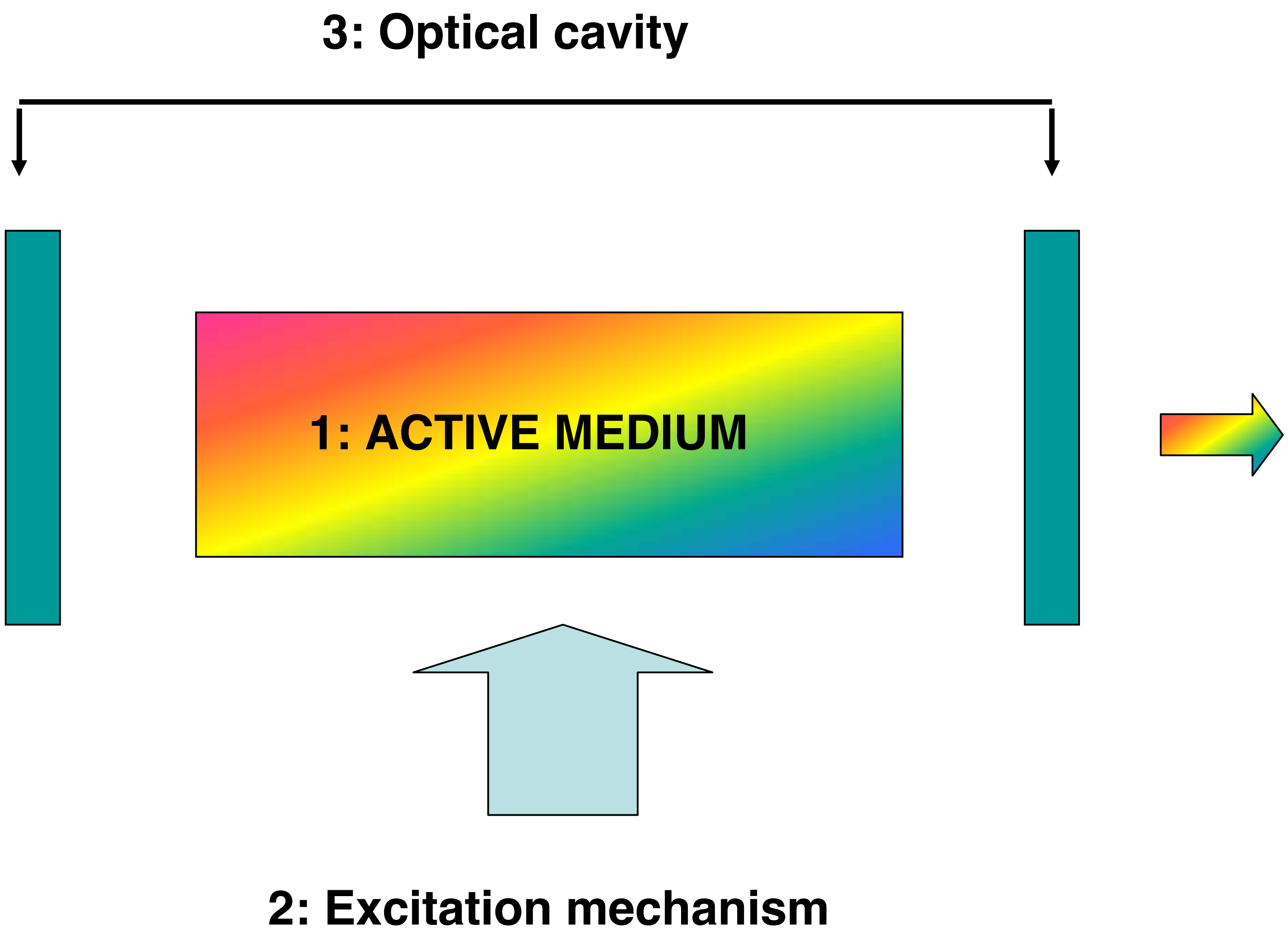
Type of lasers



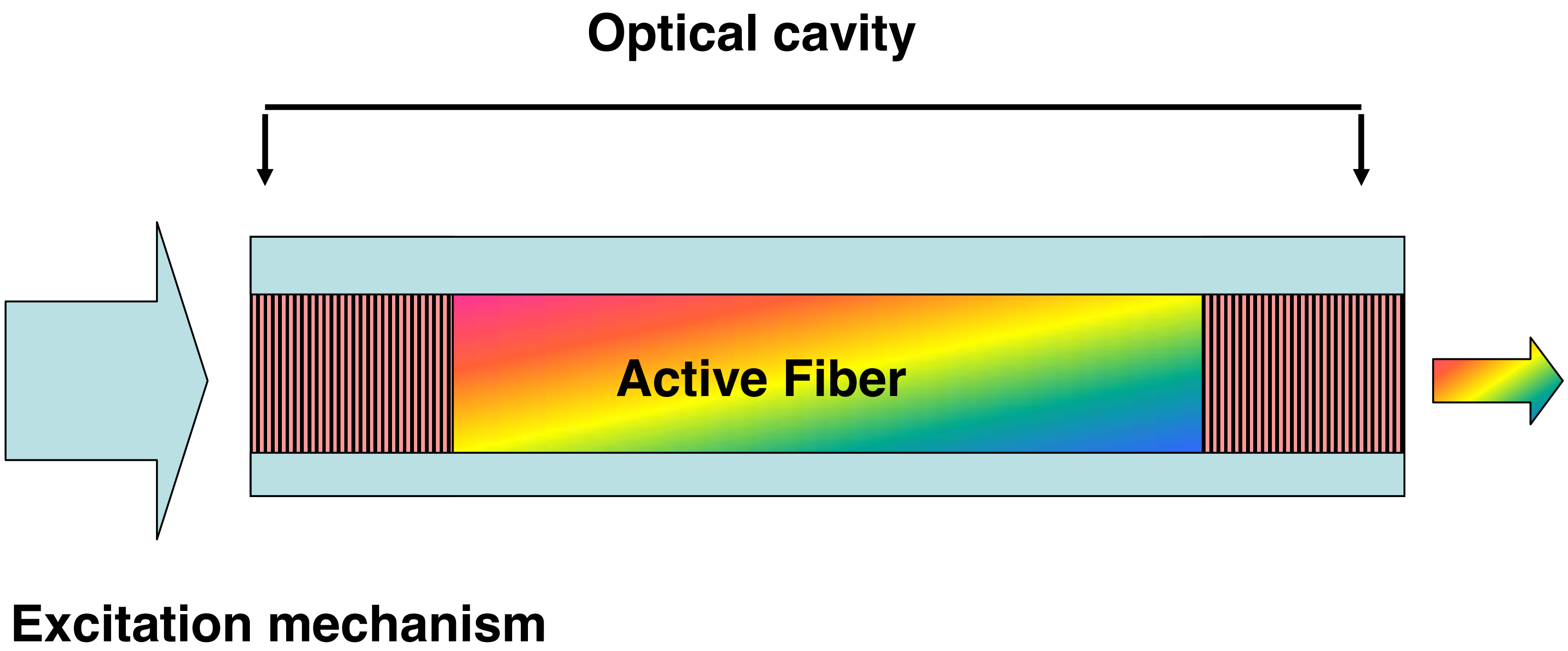
Rod laser | Disk laser | Fiber laser | Waveguide laser



Elements of a laser



Elements of a fiber laser



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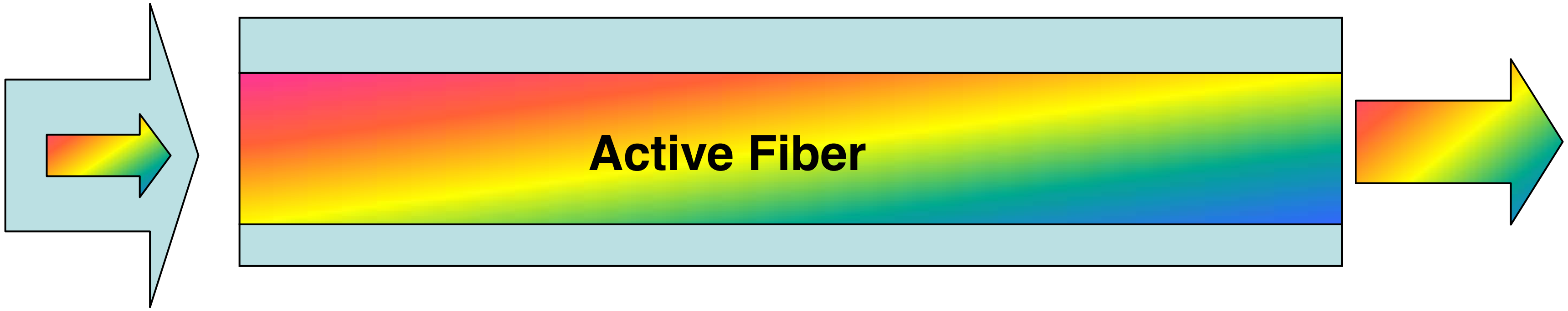
Elements of a fiber amplifier

Excitation mechanism



Why fiber devices?

Fiber lasers/devices:

Structural integration (fiber splicing)

High-gain (long interaction distance)

Compactness, robustness and reliability

Design flexibility and manufacturability

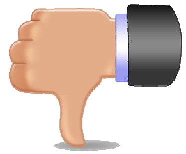
High efficiency (up to 40% electric-to to-optical))

High surface/volume ratio (good thermal management)

Diffraction-limited operation at multi-kW output powers

Photonic structures

Exploitation of non-linear effects



Fiber lasers/devices:

Need of glasses

Glasses are very different each other!

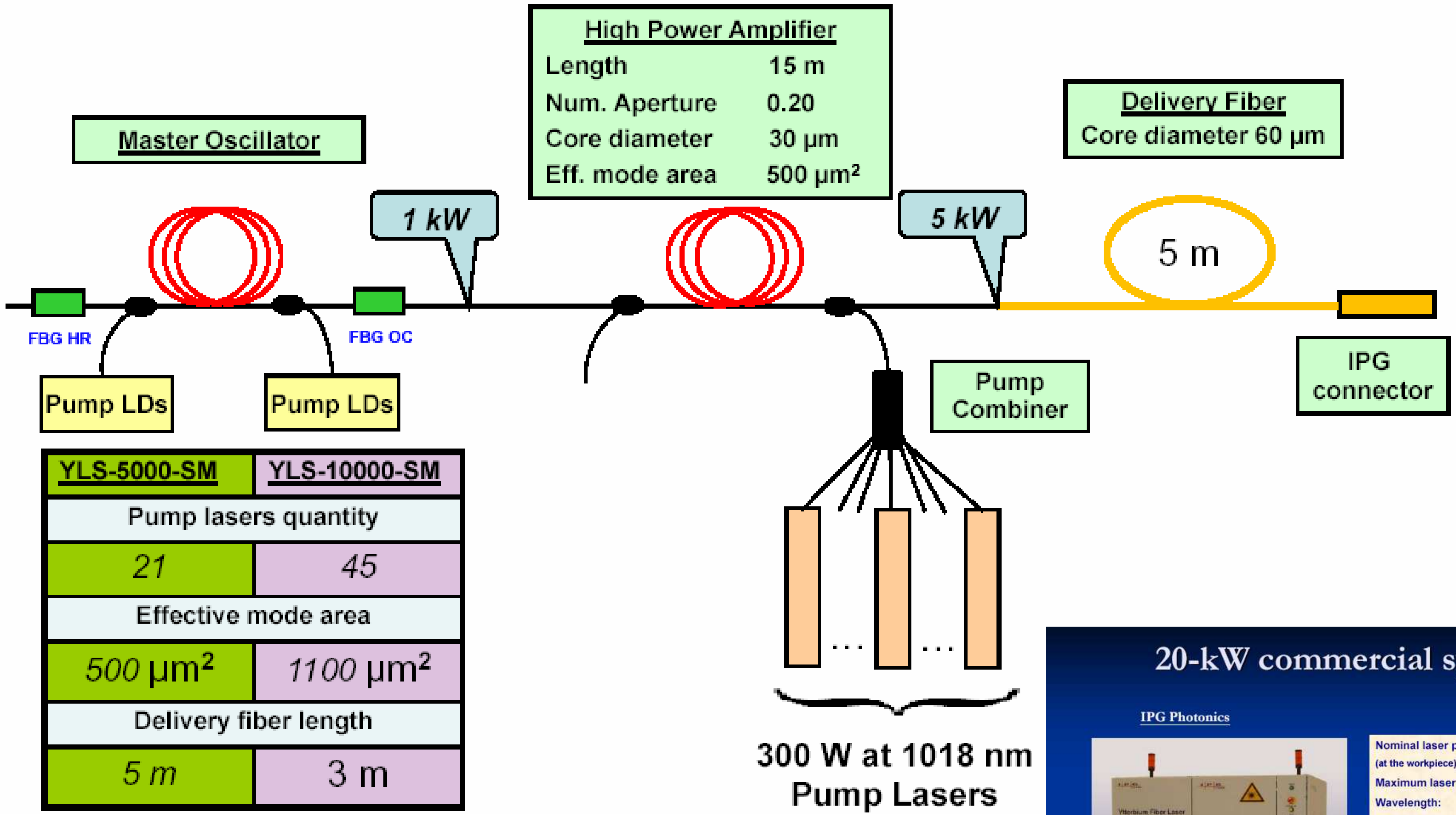
Small (relatively core size)

Constrain on power density (optical damage, non-linear effects (Raman, SBS, ASE))

Constrain on pulse energy (~mJ)

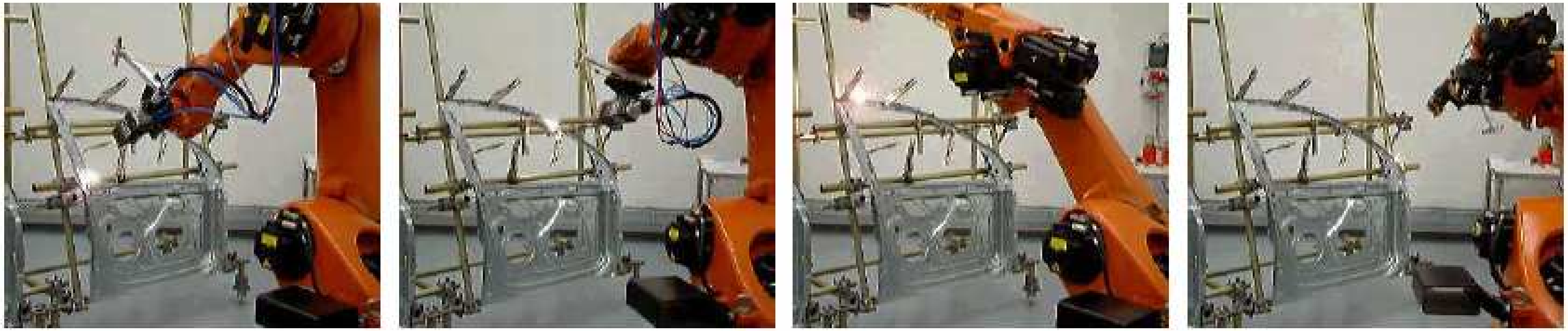
Limited amount of “all-fiber” components

Fiber devices (MOPA)



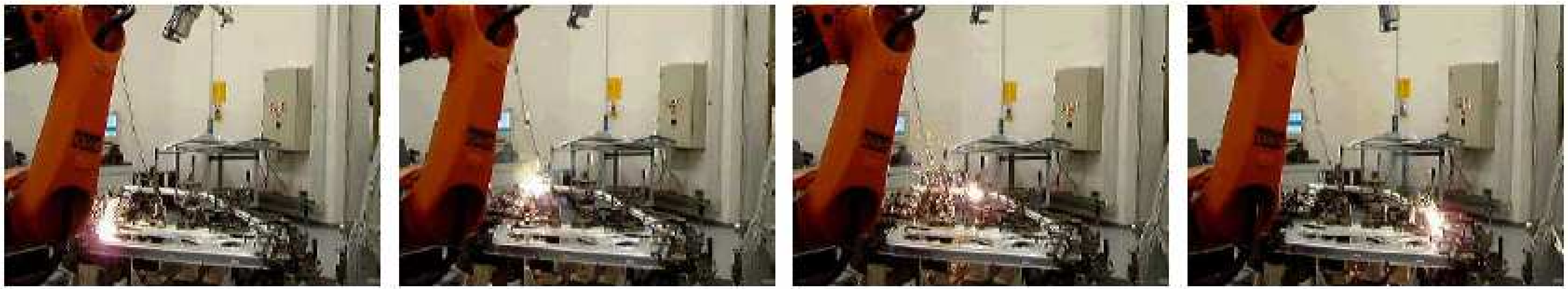
YLS-5000-SM	YLS-10000-SM
Pump lasers quantity	
21	45
Effective mode area	
500 µm²	1100 µm²
Delivery fiber length	
5 m	3 m

Industry



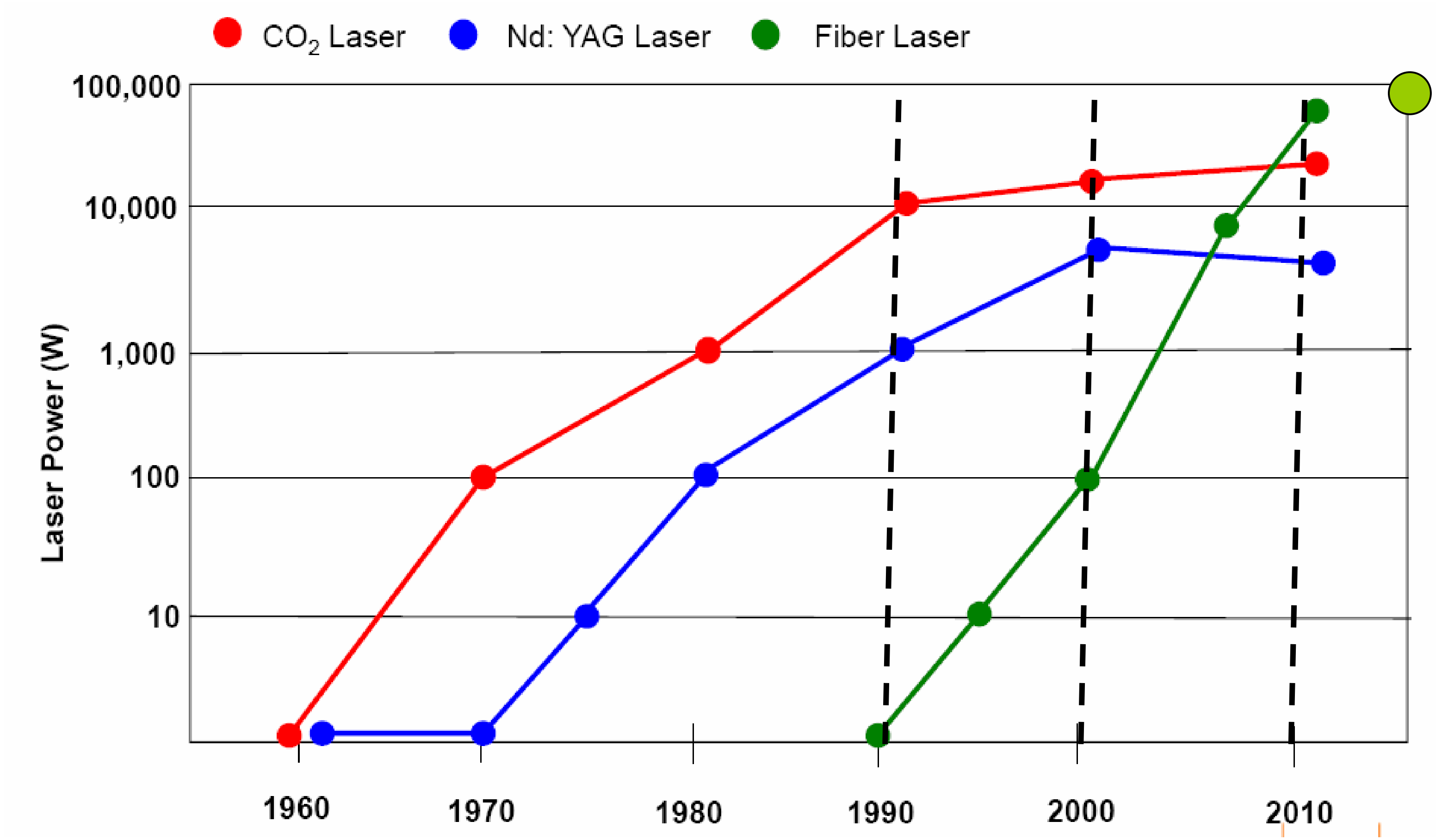
Türenschweißen mittels ***RoboScan***, Brennweite 500 mm; 49 Nähte in unterschiedlichen Ebenen, Taktzeit 19 s

*Door welding with **RoboScan**, focal distance 500 mm, 49 seams in different planes, cycle time 19 s*



Türenschweißen mittels ***RoboScan***, Brennweite 1500 mm; 22 Nähte in einer Ebene, Taktzeit 5,8 s

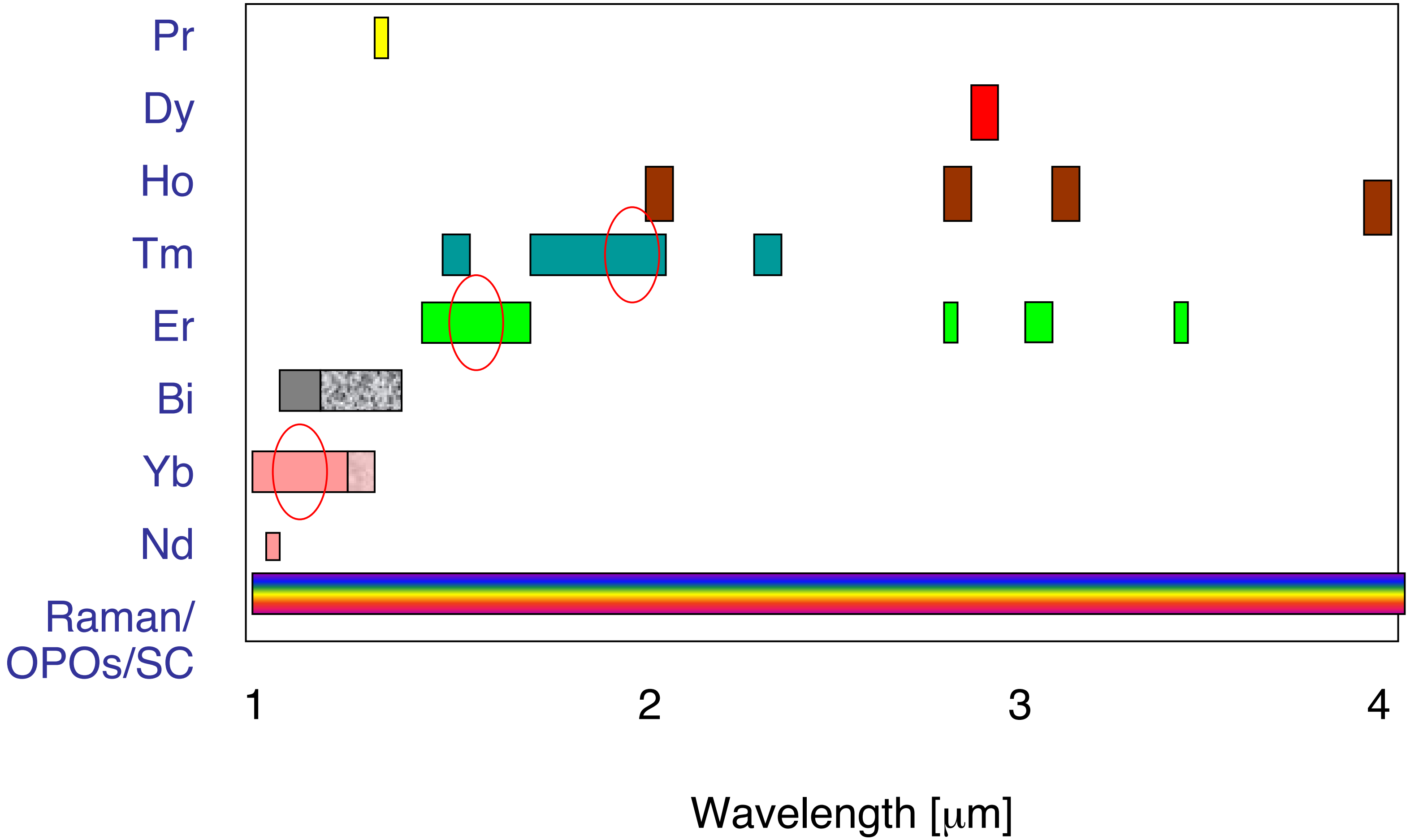
Maximum power (1 micron)



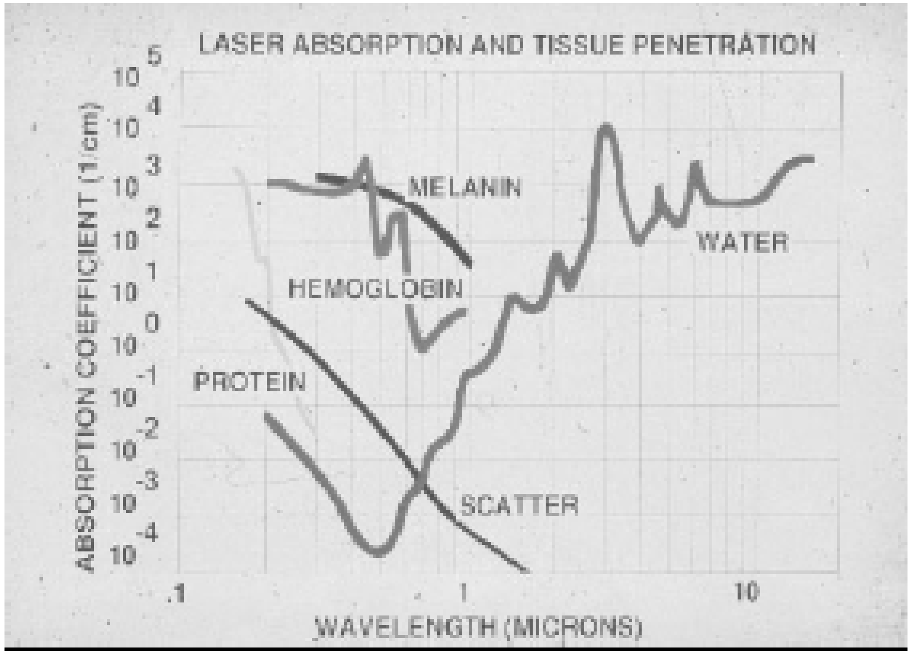
Source: IPG 7/2011

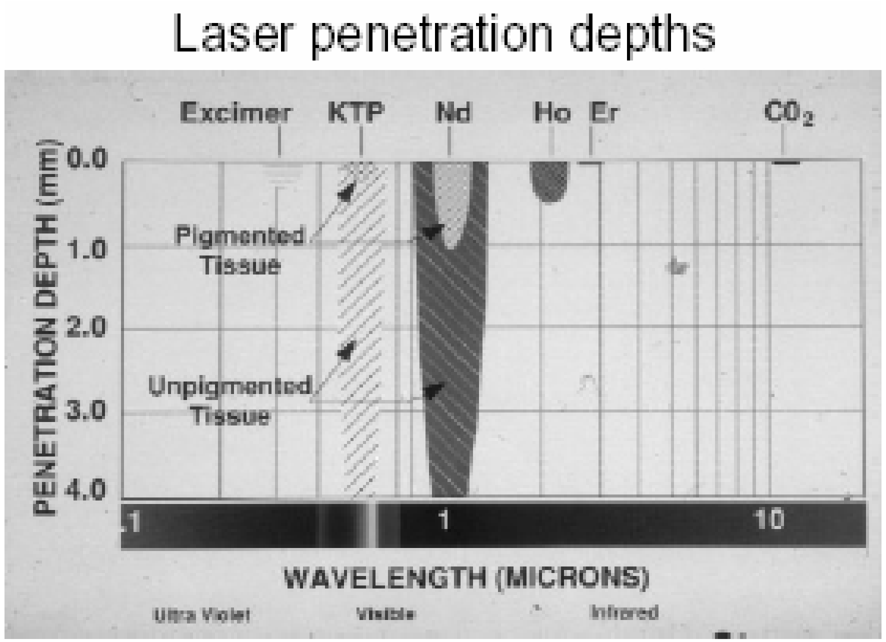
Active Material

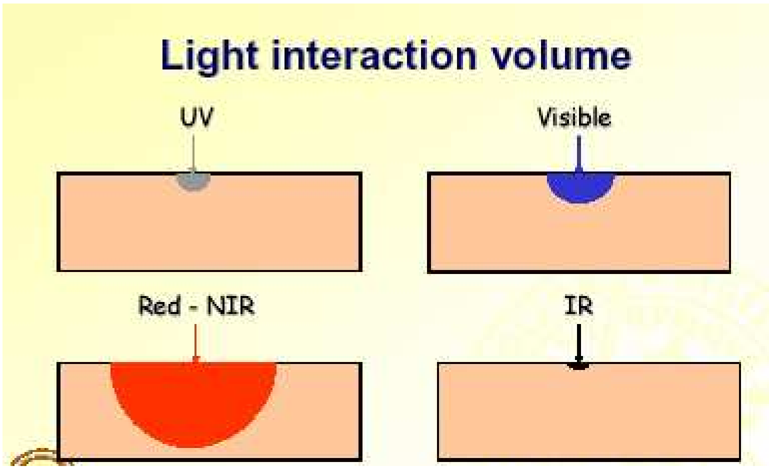
Emission Wavelength



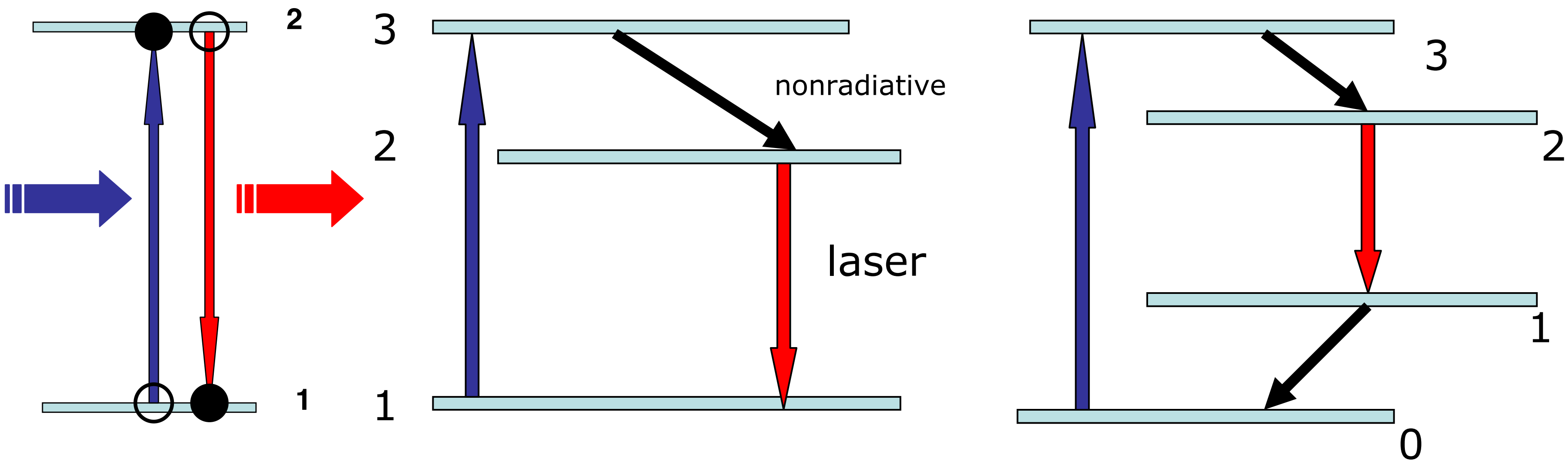
Example of Importance of right λ: Tissue absorption







ACTIVE IONS – Direct Pumping



2 – Levels

Yb (Er)

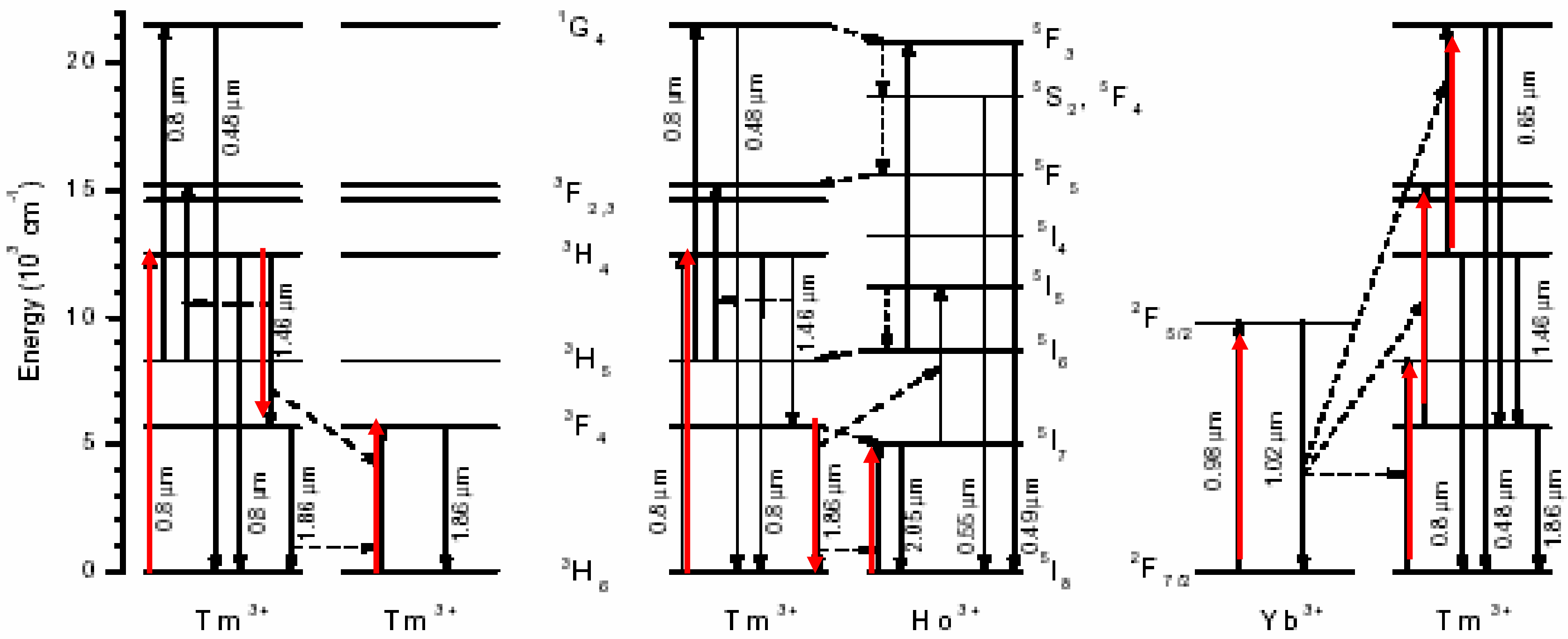
3 – Levels

Er

4 – Levels

Nd

ACTIVE IONS – Pumping Schemes



Cross-relaxation

Tm

Energy transfer

Tm:Ho, Yb:Tm, Yb:Er

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Mid-Wave IR and Long-Wave IR Laser Potential of Rare-Earth Doped Chalcogenide Glass Fiber

L. B. Shaw, B. Cole, P. A. Thielen, J. S. Sanghera, and I. D. Aggarwal

Pr Doping

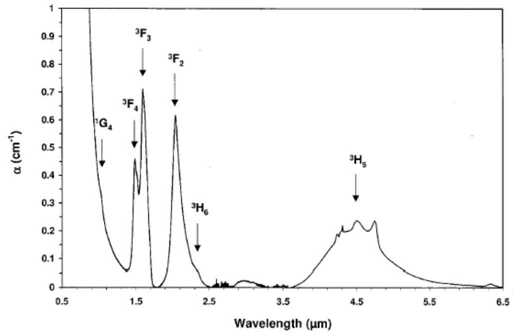


Fig. 3. Absorption spectrum of 1000-ppm Pr^{3+}-doped GAGSe glass.

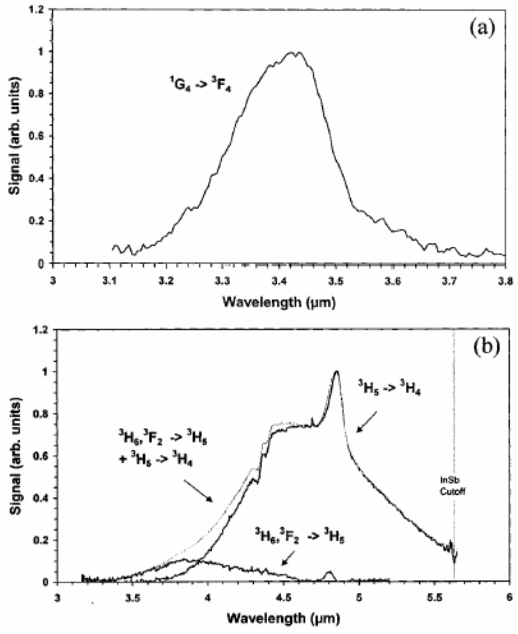
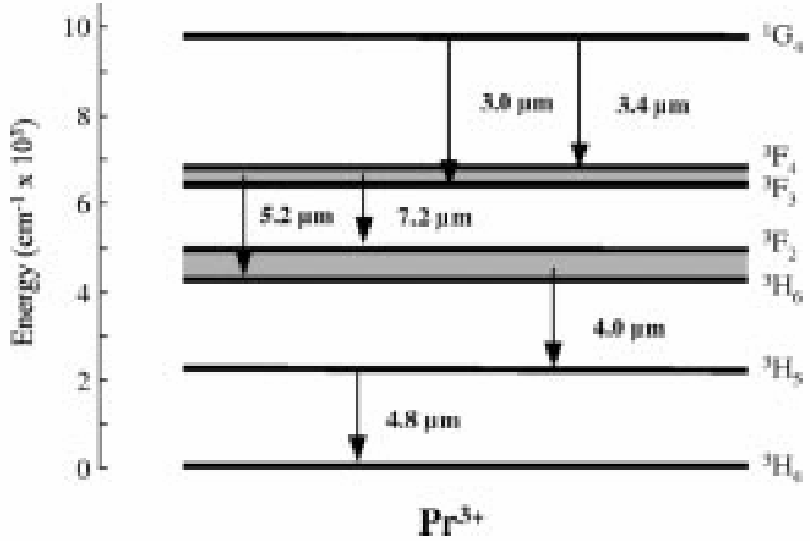


Fig. 5. Room-temperature fluorescence spectra of the MWIR transitions in Pr^{3+}. (a) $^1G_4 \rightarrow {}^3F_4$ uncorrected fluorescence spectra. (b) The 3–5-µm emission from the ($^3H_6$, $^3F_2$) and $^3H_5$ levels in Pr^{3+}-doped GAGSe under 1.97-µm pumping. The contribution from the ($^3H_6$, $^3F_2$) $\rightarrow$ $^3H_5$ and $^3H_5 \rightarrow {}^3H_4$ transitions are shown in grey.

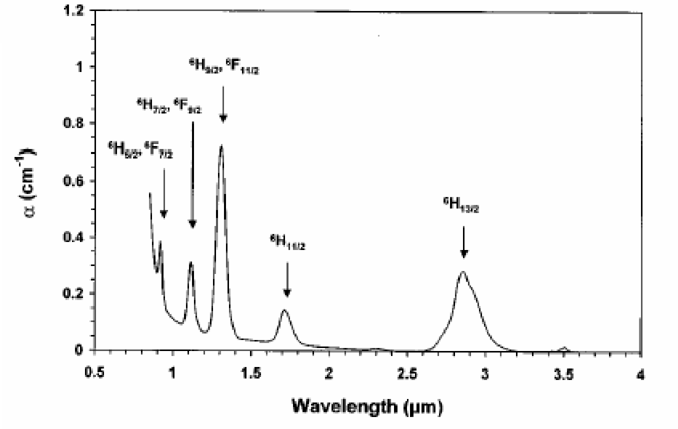


Transition Initial state	Final state	λ (µm)	τ_{rad} (ms)	τ_{exp} (ms)	η (%)	β	Δν (cm^{-1})	σ_{em} (x 10^{-20} cm^2)
$^3H_5$	$^3H_4$	4.8	15.0	12	80	1	394	0.80
($^3H_6$,$^3F_2$)	$^3H_5$	4.0	3.4	4.2	100	0.42	436	0.76
($^3F_3$,$^3F_4$)	$^3H_6$	5.2	0.29	0.25	86	0.034	-	-
	$^3F_2$	7	0.29	0.25	86	8 x 10^{-4}	-	-
$^1G_4$	$^3F_4$	3.4	0.36	0.22	61	0.043	210	1.26

2 micron pumping?

Mid-Wave IR and Long-Wave IR Laser Potential of Rare-Earth Doped Chalcogenide Glass Fiber

Dy Doping



val

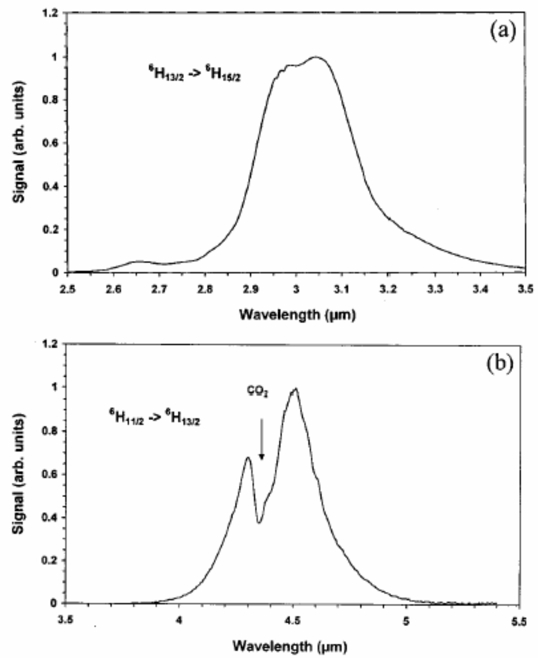


Fig. 9. Room-temperature fluorescence spectra of the MWIR transitions in Dy^{3+}. (a) $^6H_{13/2} \rightarrow {}^6H_{15/2}$ uncorrected fluorescence spectra. (b) $^6H_{11/2} \rightarrow {}^6H_{13/2}$ uncorrected fluorescence spectra. The dip at ~4.3 μm is due to atmospheric CO_2 absorption.

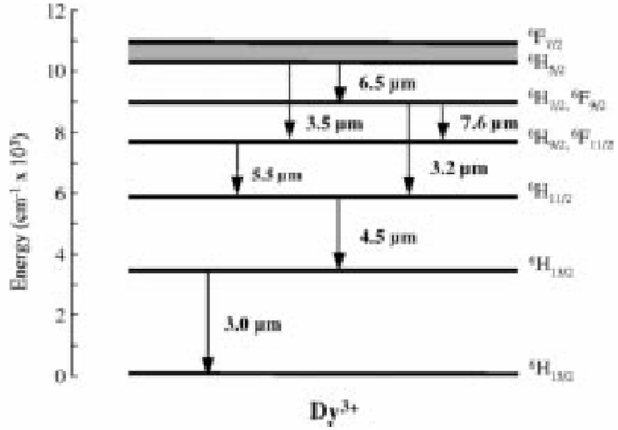


Fig. 6. Rare-earth energy diagram of the lower lying levels of Dy^{3+} with energies <12 000 cm^{-1}. Potential MWIR and LWIR laser transitions are marked. Levels expected to be thermally coupled at room temperature are shaded.

Transition Initial state	Final state	λ (μm)	τ_{rad} (ms)	τ_{exp} (ms)	η (%)	β	Δν (cm^{-1})	σ_{em} (x 10^{-20} cm^2)
$^6H_{13/2}$	$^6H_{15/2}$	3.0	6.2	6	97	1	309	0.93
$^6H_{11/2}$	$^6H_{13/2}$	4.5	2.4	2	83	0.10	200	0.82
$^6H_{9/2}$, $^6F_{11/2}$	$^6H_{11/2}$	5.5	0.38	0.31	82	0.04	-	-
$^6H_{7/2}$, $^6F_{9/2}$	$^6H_{9/2}$, $^6F_{11/2}$	7.6	0.37	<0.025	< 7	0.018	-	-
	$^6H_{11/2}$	3.2	0.37	<0.025	< 7	0.12	-	-

1.8 micron pumping?

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Mid-Wave IR and Long-Wave IR Laser Potential of Rare-Earth Doped Chalcogenide Glass Fiber

ggarwal

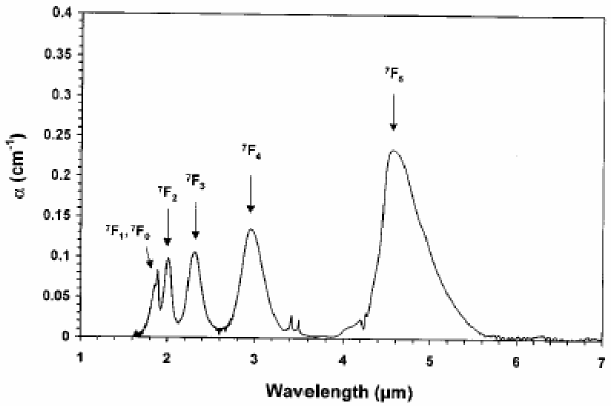
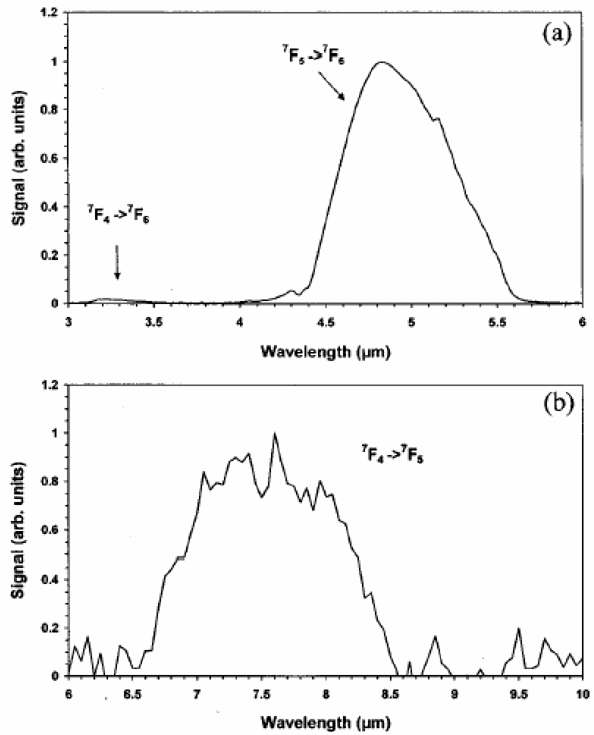


Fig. 11. Absorption spectrum of 1000-ppm Tb^{3+}-doped GAGSe glass.



Tb Doping

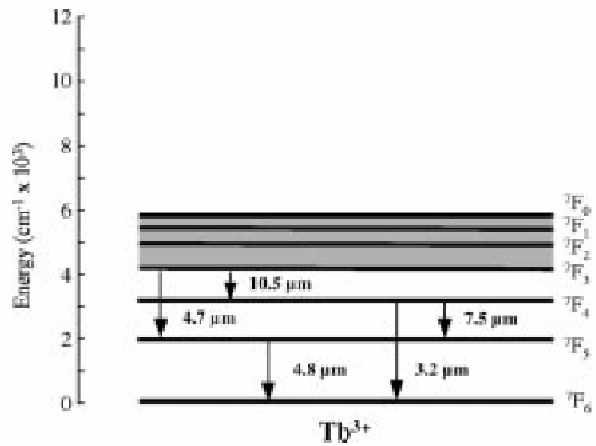


Fig. 10. Rare-earth energy diagram of the lower lying levels of Tb^{3+} with energies <12 000 cm^{-1}. Potential MWIR and LWIR laser transitions are marked. Levels expected to be thermally coupled at room temperature are shaded.

Transition: Initial state	Transition: Final state	λ (μm)	τ_{rad} (ms)	τ_{exp} (ms)	η (%)	β	Δν (cm^{-1})	σ_{em} (x 10^{-20} cm^2)
$^7F_5$	$^7F_6$	4.8	15.0	11	73	1	305	1.05
$^7F_4$	$^7F_6$	3.1	8.0	0.012	0.15	0.88	195	1.37
	$^7F_5$	7.5	8.0	0.012	0.15	0.12	248	0.83
$^7F_3$	$^7F_5$	4.7	4.1	-	-	0.17	-	-
	$^7F_4$	10.5	4.1	-	-	0.02	-	-

3 micron pumping?

Spectroscopic properties and Judd-Ofelt theory analysis of Dy^{3+} doped oxyfluoride silicate glass

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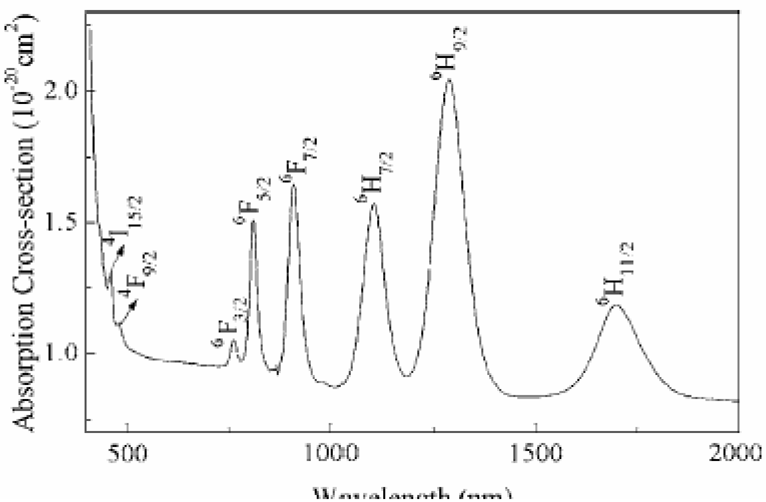
Dy Doping



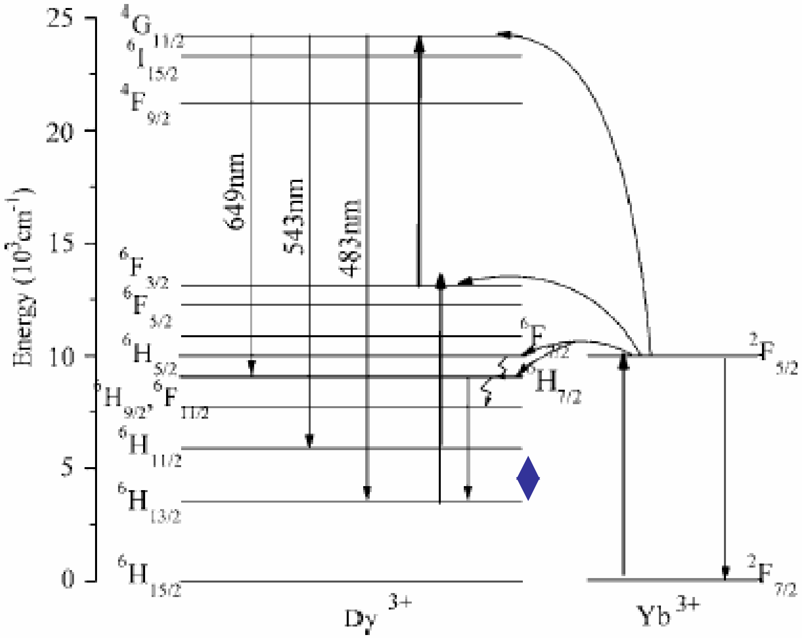
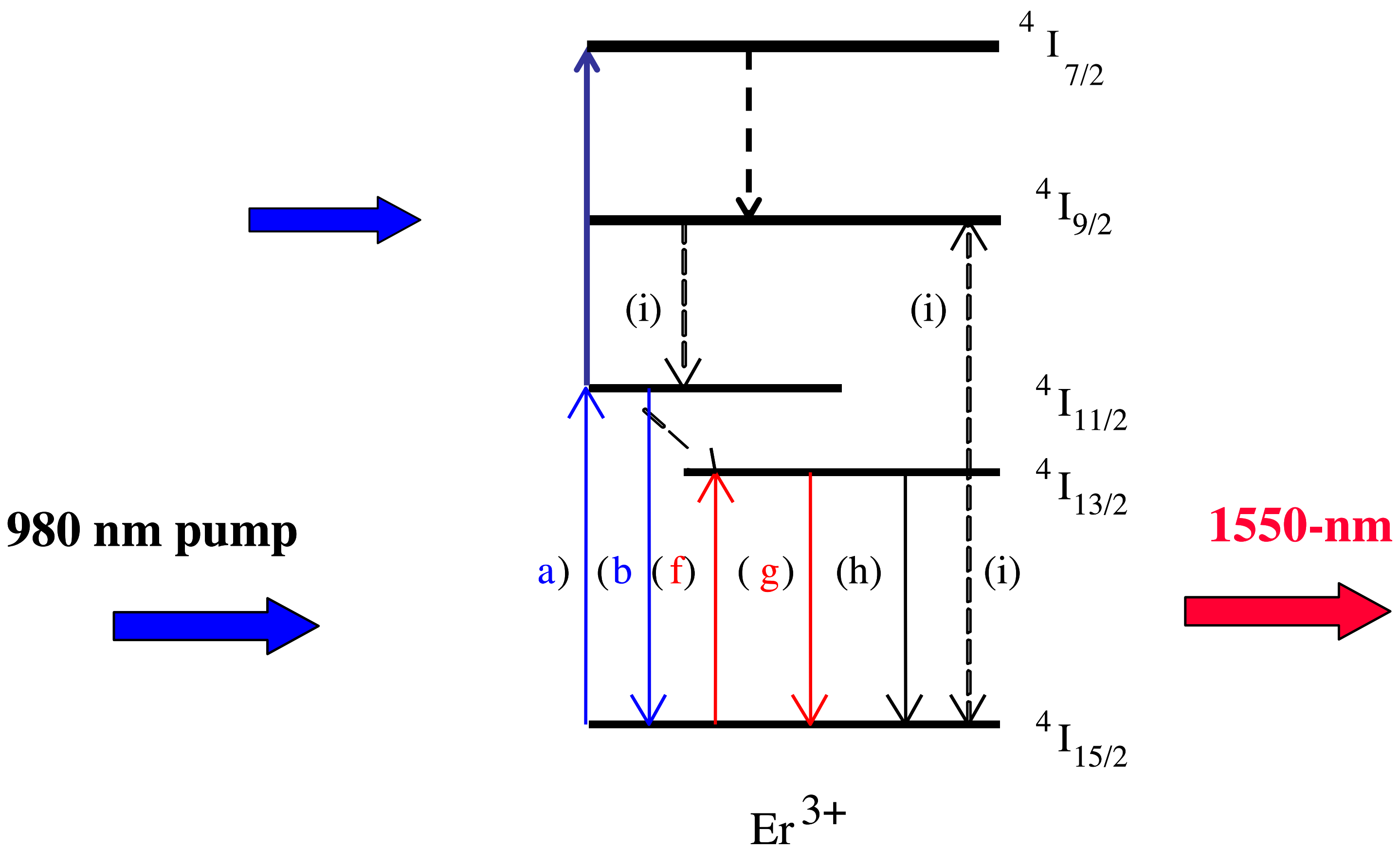


TABLE III. Calculated transition probability, fluorescence branching ratio, and radiative lifetime of Dy^{3+} in oxyfluoride silicate glass

Transition	Energy (cm^{-1})	A_{ed} (s^{-1})	A_{md}	β	τ_{rad} (μs)
$^6H_{9/2}+^6F_{11/2}\rightarrow ^6H_{11/2}$	1913	9.57	53.98	0.052	810
$^6H_{9/2}+^6F_{11/2}\rightarrow ^6H_{13/2}$	4299	136.66		0.110	
$^6H_{9/2}+^6F_{11/2}\rightarrow ^6H_{15/2}$	7830	1034.17		0.838	

Low gain: long length (50 mm is enough?)

Rate-equations (3-level)



We can introduce co-operative upconversion… and many others.. Like excited state absorption

Full Rate-equations (3-level) system below threshold

$$\frac{dN_3}{dt} = \sigma_{a13} F_p N_1 - \sigma_{e31} F_p N_3 - \frac{N_3}{\tau_{32}} - \frac{N_3}{\tau_{31}}$$

$$\frac{dN_2}{dt} = \sigma_{a12} F_s N_1 - \sigma_{e21} F_s N_2 - \frac{N_2}{\tau_{21}} + \frac{N_3}{\tau_{32}}$$

$$\frac{dN_1}{dt} = -\sigma_{a13} F_p N_1 + \sigma_{e31} F_p N_3 - \sigma_{a12} F_s N_1 + \sigma_{e21} F_s N_2 + \frac{N_2}{\tau_{21}} + \frac{N_3}{\tau_{31}}$$

$$N_1 + N_2 + N_3 = N = 1$$

From second equation, neglecting ASE photons and decay from level 3 to level 1 and imposing steady-state condition (derivative=0) we have

$$0 = -\frac{N_2}{\tau_{21}} + \frac{N_3}{\tau_{32}}$$

$$\frac{N_2}{\tau_{21}} = \frac{N_3}{\tau_{32}} \; therefore \; N_3 = \frac{\tau_{32}}{\tau_{21}} N_2$$

To avoid to waste inversion in an useful level the pump level should rapidly decay to the upper laser level: $\tau_{32} << \tau_{21}$

Rate-equations above threshold: steady-state

$$\begin{cases} 0 = Wp\, N_1 - qB\left(N_2 - N_1\right)\dfrac{N_2}{\tau} \\ 0 = q\left[V_a B\left(N_2 - N_1\right) - \dfrac{1}{\tau_c}\right] \end{cases}$$

$$condition: N_2 + N_1 = N_T$$

Photons within resonator (from solving first equation)

$$\boxed{q_0 = \frac{V_A}{2\tau}\left(N_T + \Delta N_{th}\right)\tau_c\left(x-1\right)}$$

Rate-equations (3-level) above threshold

Laser output power (assuming output only from Mirror #2)

$$P_L = \frac{V_A}{2\tau}\left(N_T + \Delta N_{th}\right)h\nu \frac{\gamma_2}{2\gamma}\left(x-1\right)$$

$$x = \frac{P_P}{P_{p,th}}$$

$$P_L = \frac{V_A}{2\tau}\left(N_T + \Delta N_{th}\right)h\nu \frac{\gamma_2}{2\gamma}\left(x-1\right) = \frac{q_0}{\tau_c}\left(h\nu\right)\left(\frac{\gamma_2}{2\gamma}\right)$$

x represent the ration between pump power and power at threshold. If x=1 laser power is obviously zero

Host Materials

Silica (Al-silicate) glass is the most common host glass

Pros: Excellent quality, Telecom Know-how, Thermal conductivity

Cons: Low doping level (below 1%),

Phosphate glass:

Pros: High-doping level (5% and above), high phonon energy (efficient codoping). No Photodarkening

Cons: Difficult splicing with silica fiber, low thermal conductivity

Unsuitable for Telecom grade C-band amplifiers

Tellurite Glass, ZBLAN

Pros: transparent in the 1-5 micron window, low phonon energy. (good for IR transition above 2 micron).

Cons: Thermal dissipation, splicing

Chalcogenaide Glass

Pros: transparent up to 10 micron

High-non linear coefficient

Cons: Absorb 1 micron radiation, soft glass

Pumping: fficiency

Optical Optical-to to-optical efficiencies (typical):
1 micron: Yb-doped fused silica fibers: 70% – 80%
2 micron: Tm-doped fused silica fibers: 50%- 75%
1.5 micron: Er and Er/Yb doped silica fibers: 20% - 40%

Electrical Electrical-to to-optical efficiencies:
Typical ~25%; maximum reported 40%

Pumps 9xx nm (-60%)
Pump 1480 nm (-40%)
Pumps 780 nm (40%-50%)

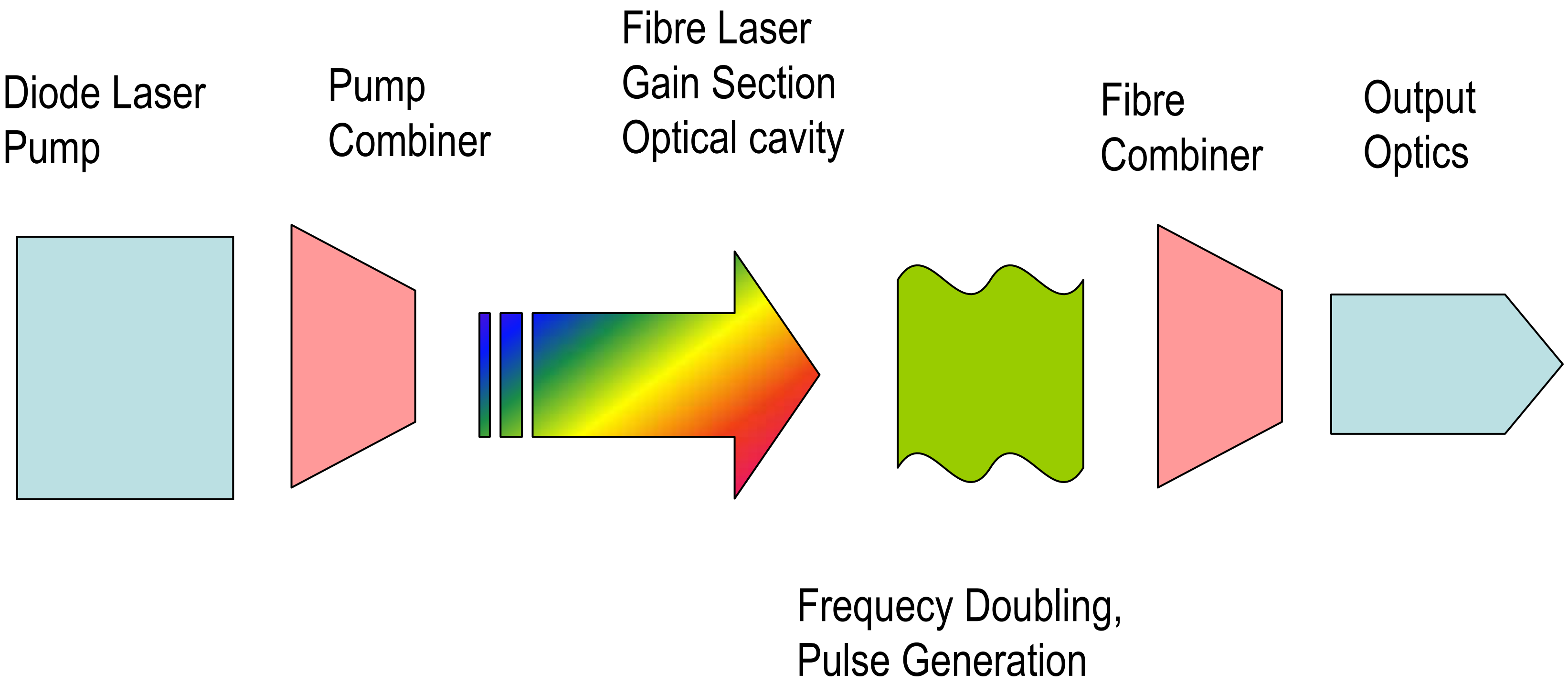
Pumping scheme and Heat Removal

Quantum defect = λ_p/λ_L

	Lasing	Pump	QD	Heat removal from 10kW laser
Yb:	1070	945	11%	1.1 KW
Er:	1550	980	37%	3.7 kW
Er:	1550	1480	4%	0.4 kW
Tm	1800	780	28%	2.8 kW
Tm	1800	1600	11%*	1.1 kW (fiber pumped)
Ho	2100	1800	14%	1.4 kW (fiber pumped)

Components

Components

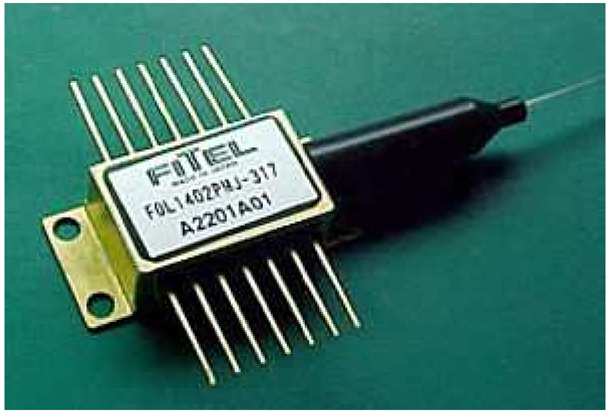


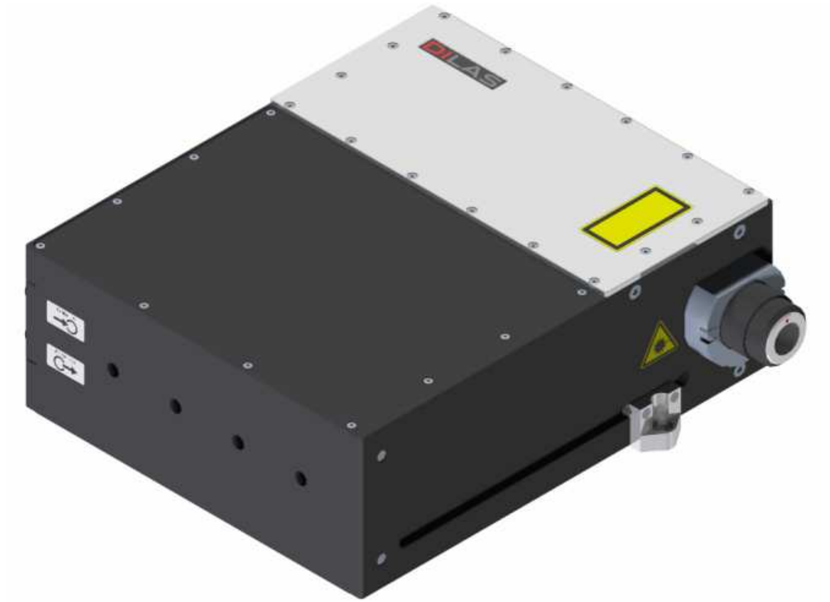
Diode Laser
Pump
Pump
Combiner
Fibre Laser
Gain Section
Optical cavity
Fibre
Combiner
Output
Optics
Frequecy Doubling,
Pulse Generation

Pumping system

Need to deliver pump power into active fiber:

Power level from 100s mW into SMF to kWs into double cladding fibers (+100 microns diameter)

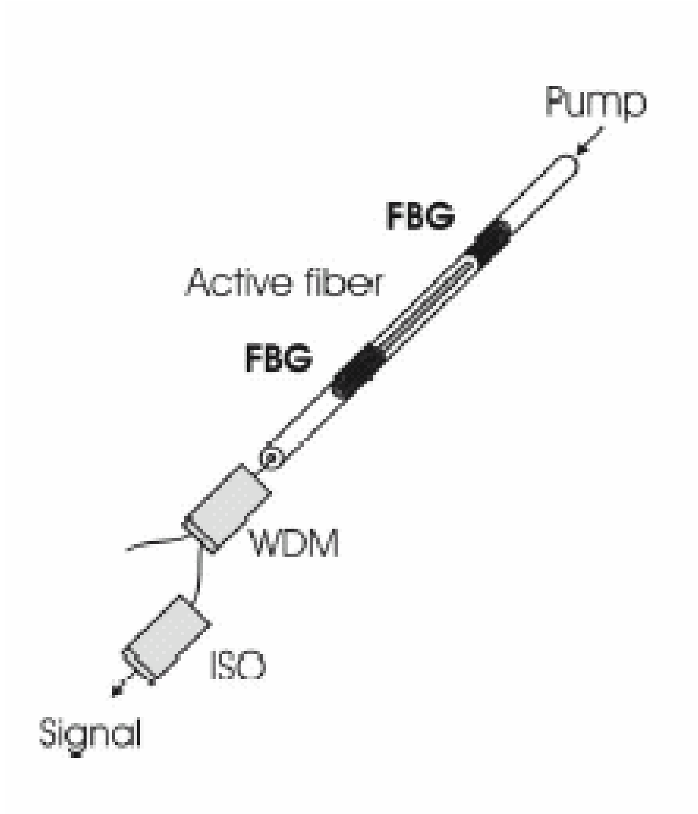


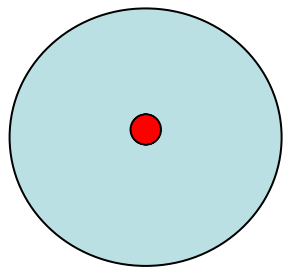


Source: DILAS

Fiber

Single-mode fiber (core pumped) are telecom type.

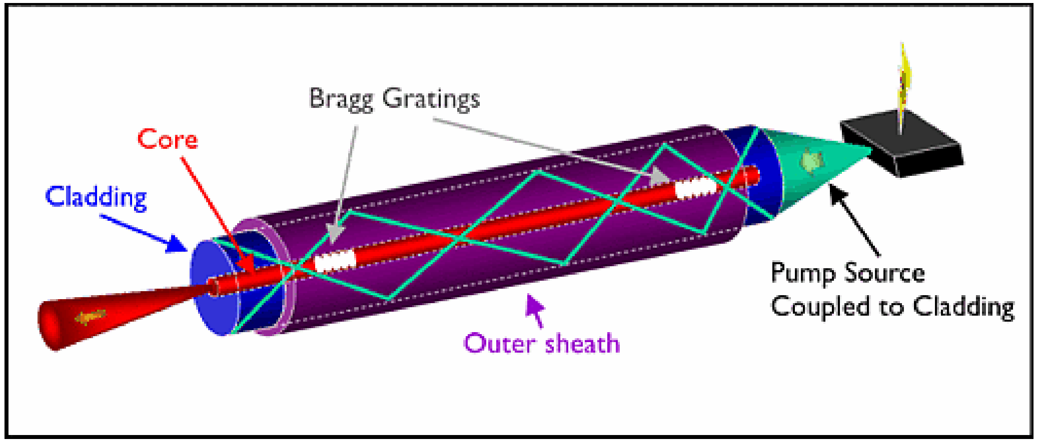


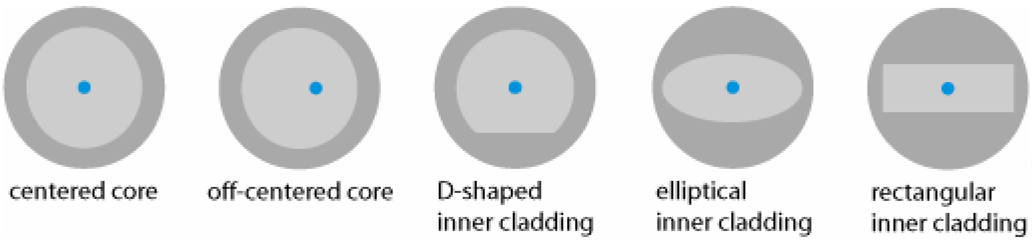


Fiber

For high-power we need to increase active volume and optimize pump absorption:

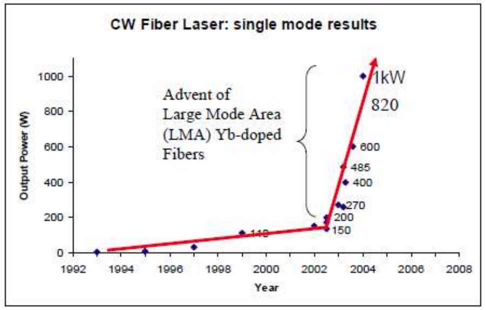
Double cladding pumping scheme





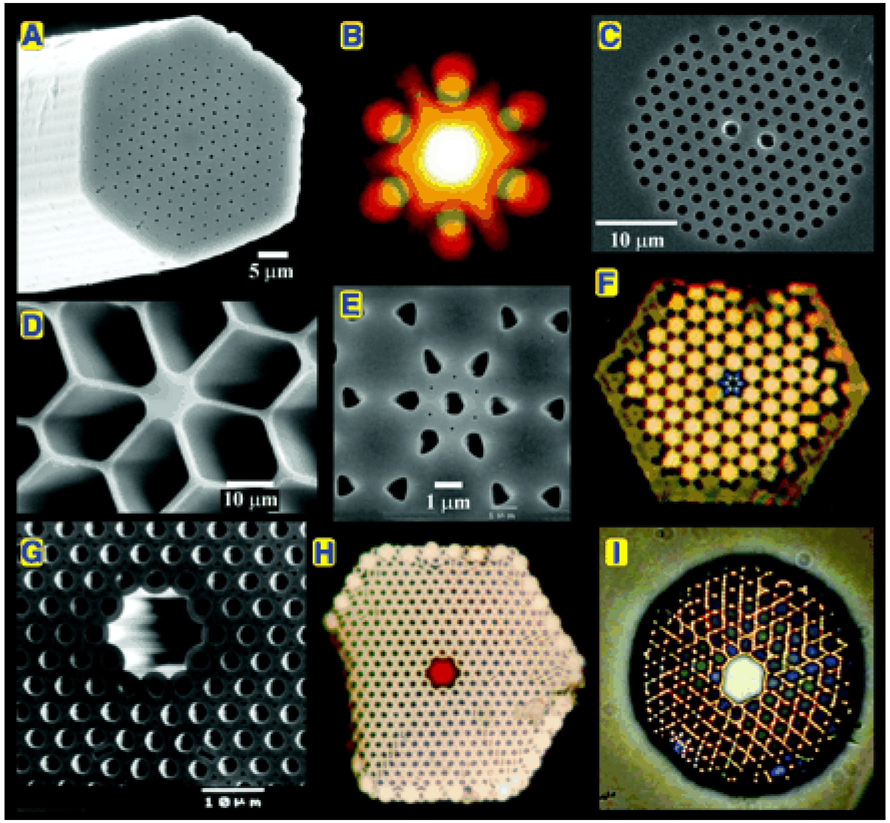
Core diameter 15 micron SM, 20 (max 25 micron) slightly MM

High-order suppression techniques (e.g. bending)



Source: ORC Southampton

Microsctructured Fiber

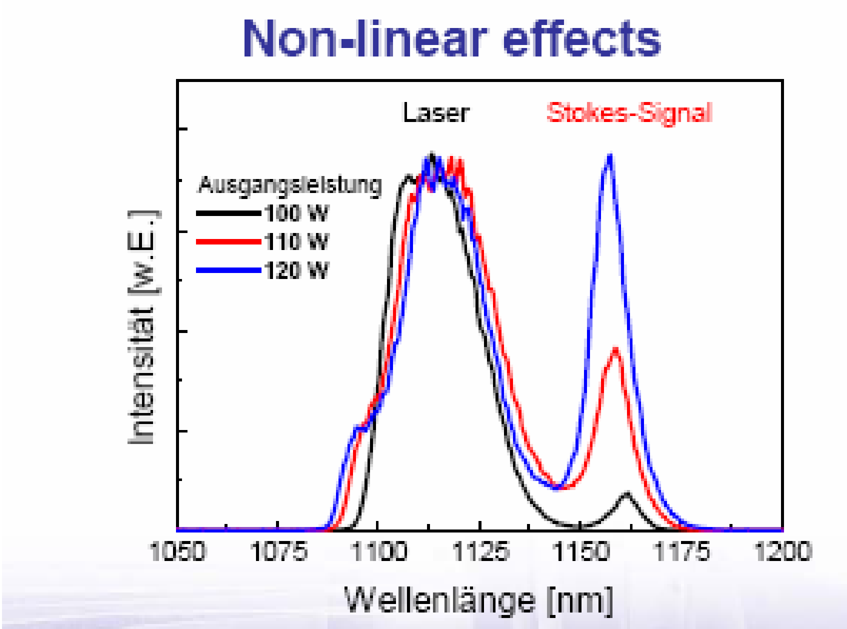


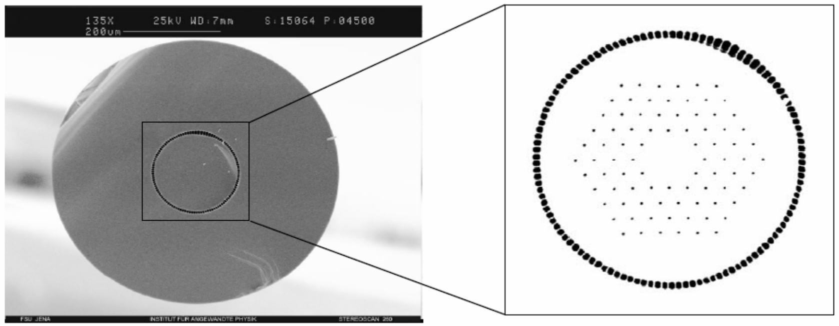
P. Russell, Science 17 January 2003:

$$V_{PCF} = \frac{2\pi}{\lambda} \cdot \Lambda \cdot \sqrt{n_{core}^2(\lambda) - n_{cladding}^2(\lambda)}$$

Endlessy single-mode, dispersion management, management of non-linearity (LMA Fibers)

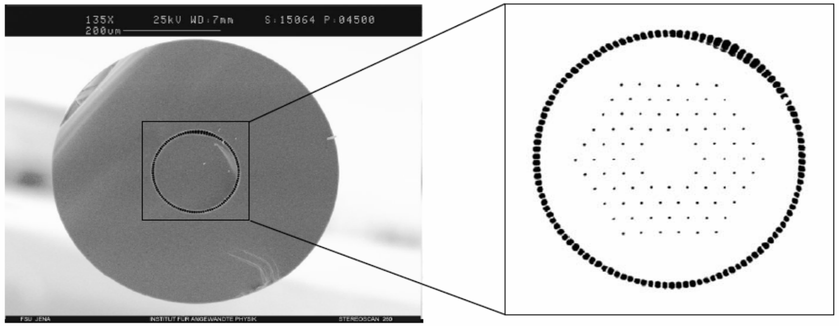
Microsctructured Fiber: LMA





J. Limpert et al. Opt. Express **12,** 1313-1319 (2004).

Fiber



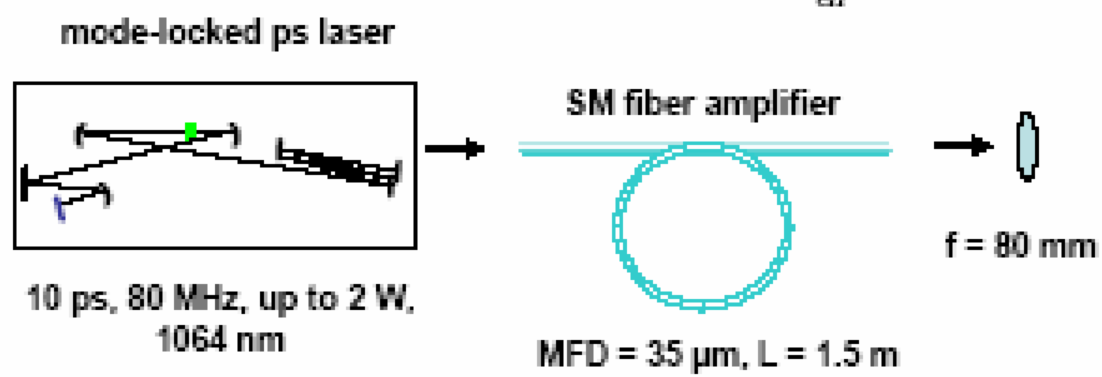
40 μm core (7 missing holes) and 200 μm air-cladding.

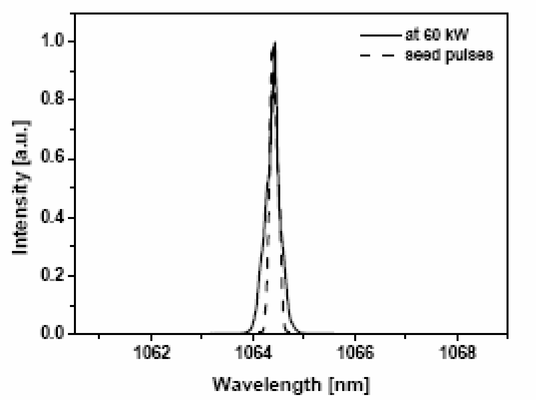
About 1000 μm^2 area

Use: Amplifier stage: 10 ps to 60kW Peak power

Air-cladding region. Bridges width is small than laser wavelength. High N.A. Low non-linearity

$$\Delta\lambda_{SPM} \propto \frac{P_{peak} \cdot L_{eff}}{\Delta\tau \cdot A_{eff}},$$



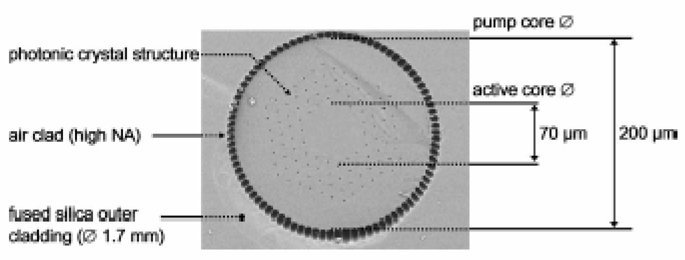


J. Limpert et al. Opt. Express **12,** 1313-1319 (2004).

Fiber (rod-type)

In Q-switched laser pulsewidth is proportional to cavity length (fiber are not so good therefore….). Typical value of pulsewidth in Q-switched fiber laser is 100 ns.

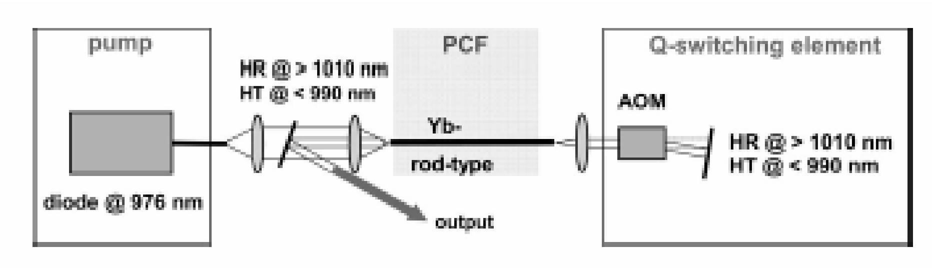
Rod type. High Volume with guided light

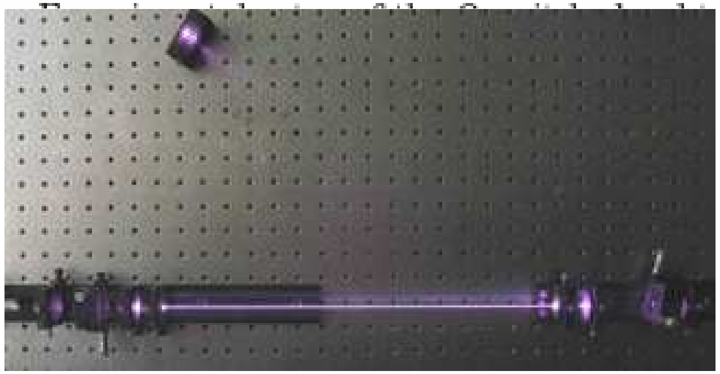


STIFF Fiber

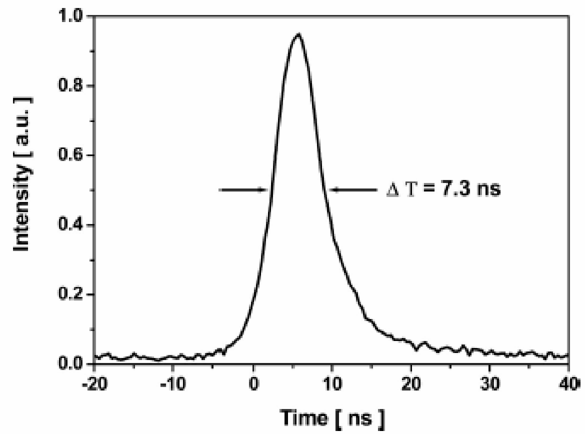
58 μm MFD (19 missing holes) and 200 μm air-cladding.

Possibility of large volume (high-energy) in short fiber.



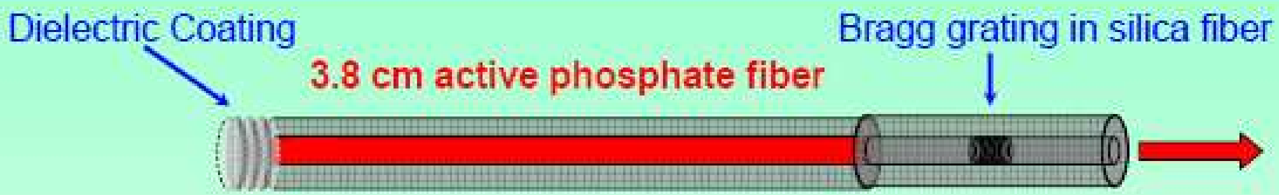


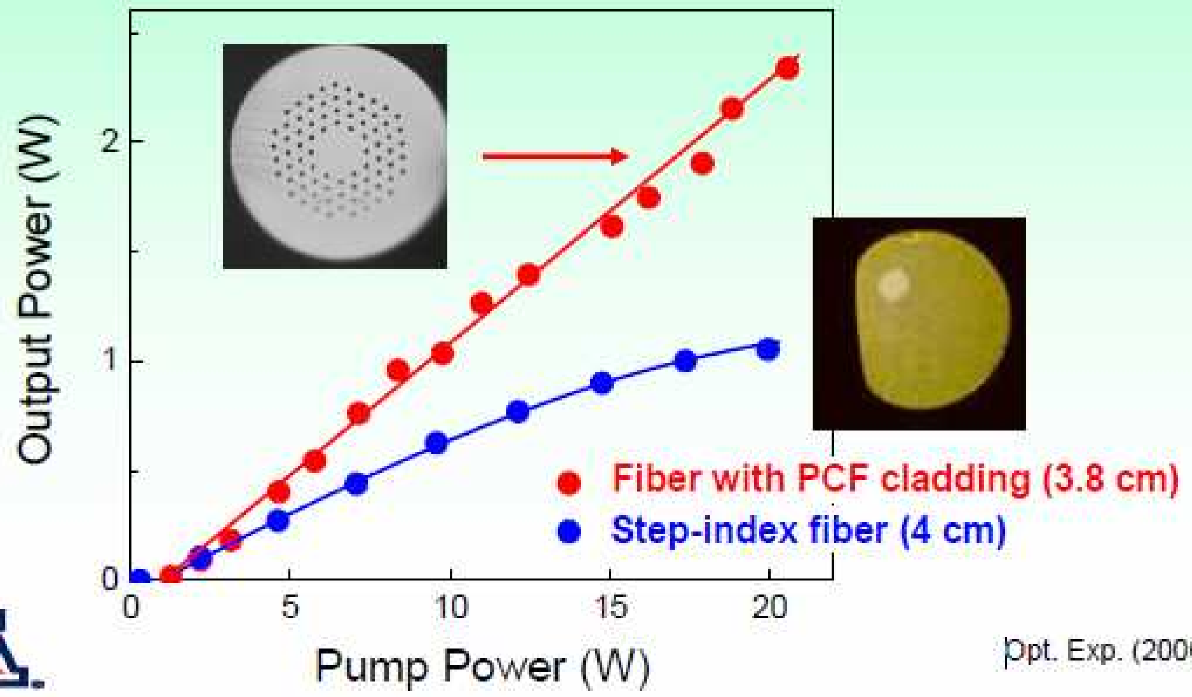
2 mJ, 100 W pulsewidth down to 7 ns
Pump cladding diameter: 200 mm N.A. =0.6
Outer cladding: 1.7 mm
MFD 58 mm



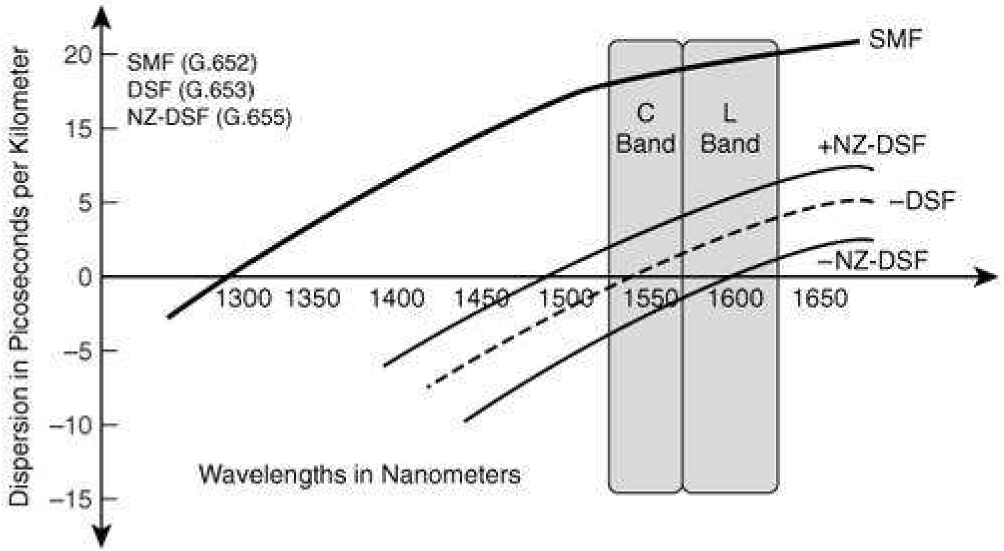
O. Schmidt, Jet al., "Millijoule pulse energy Q-switched short-length fiber laser," Opt. Lett. 32, 1551-1553 (2007)

Single-Frequency Microstructured Fiber Lasers

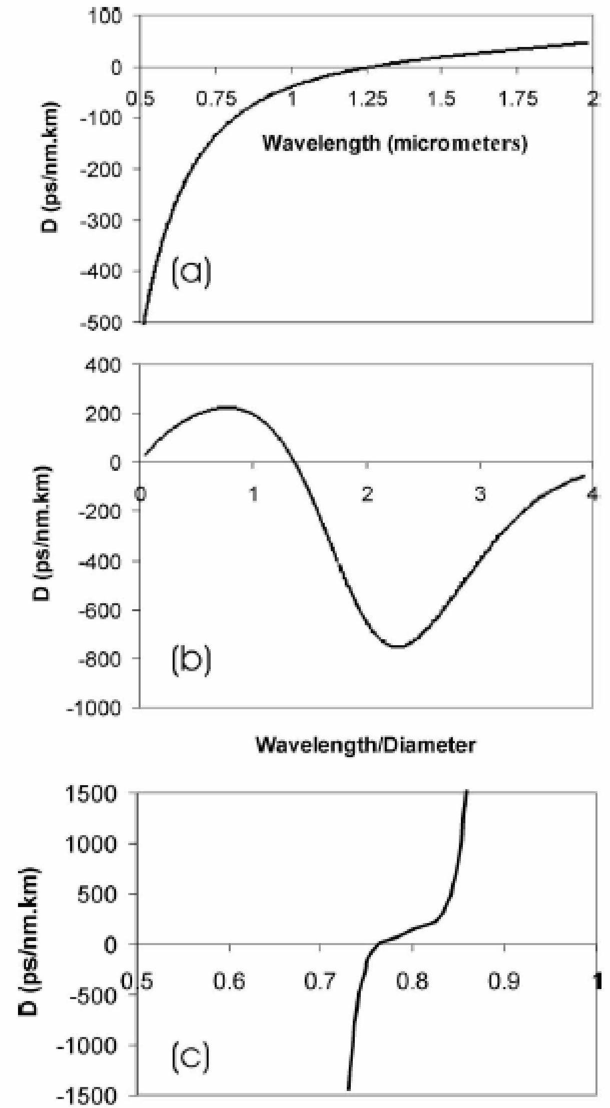




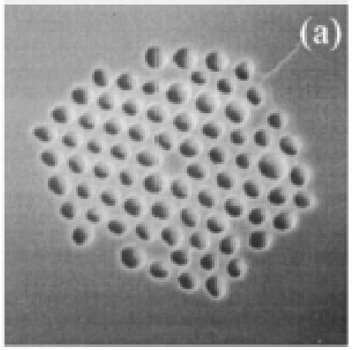
Opt. Exp. (2006)

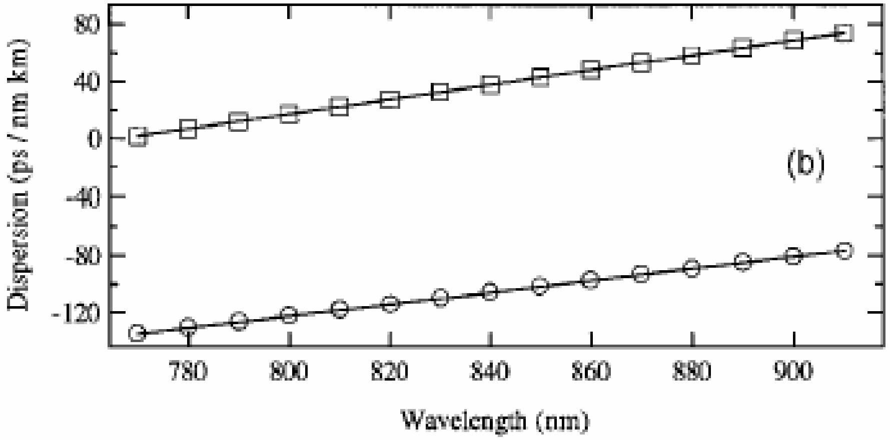


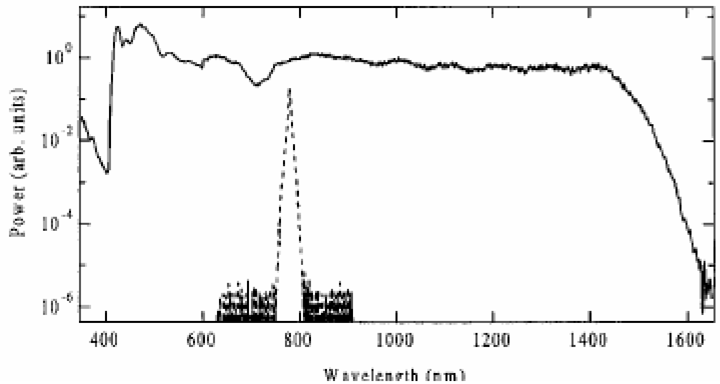
SMF
SMF (G.652)
DSF (G.653)
NZ-DSF (G.655)
C Band
L Band
+NZ-DSF
–DSF
–NZ-DSF
Dispersion in Picoseconds per Kilometer
Wavelengths in Nanometers
20
15
5
0
–5
–10
–15
1300 1350 1400 1450 1500 1550 1600 1650

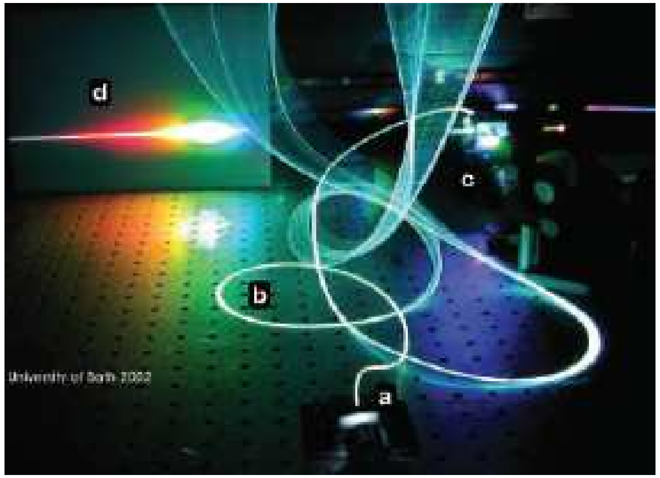


D (ps/nm.km)
Wavelength (micrometers)
(a)
0.5 0.75 1 1.25 1.5 1.75 2
100 0 -100 -200 -300 -400 -500
D (ps/nm.km)
(b)
0 1 2 3 4
400 200 0 -200 -400 -600 -800 -1000
Wavelength/Diameter
D (ps/nm.km)
(c)
0.5 0.6 0.7 0.8 0.9 1
1500 1000 500 0 -500 -1000 -1500

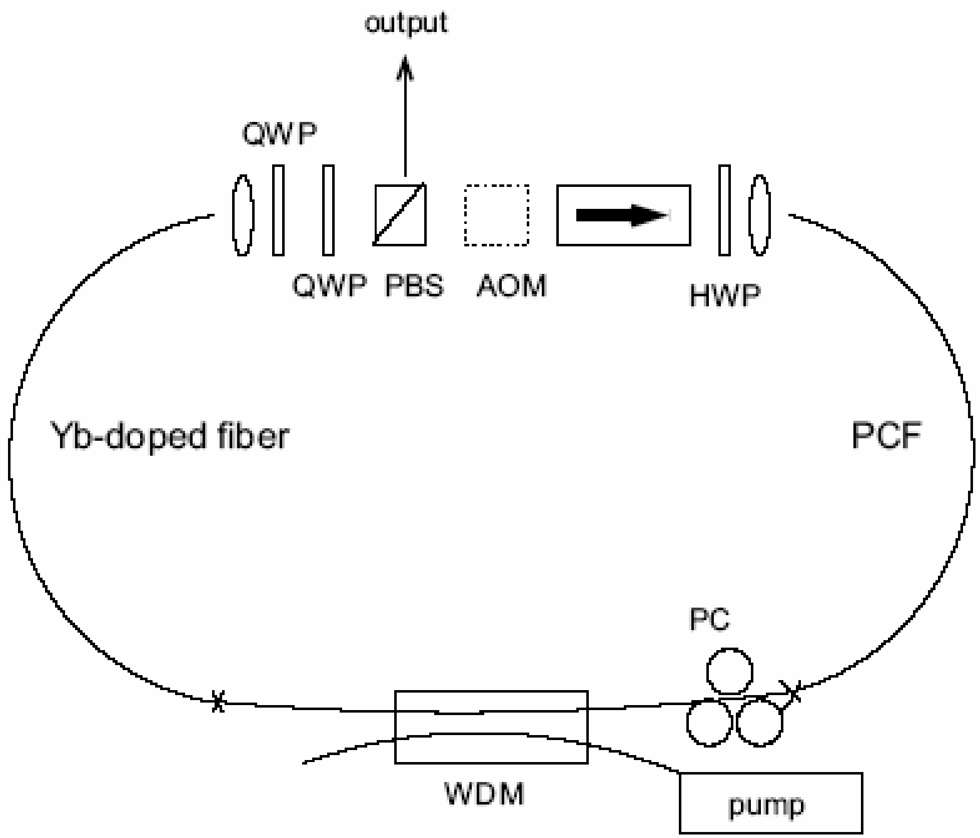




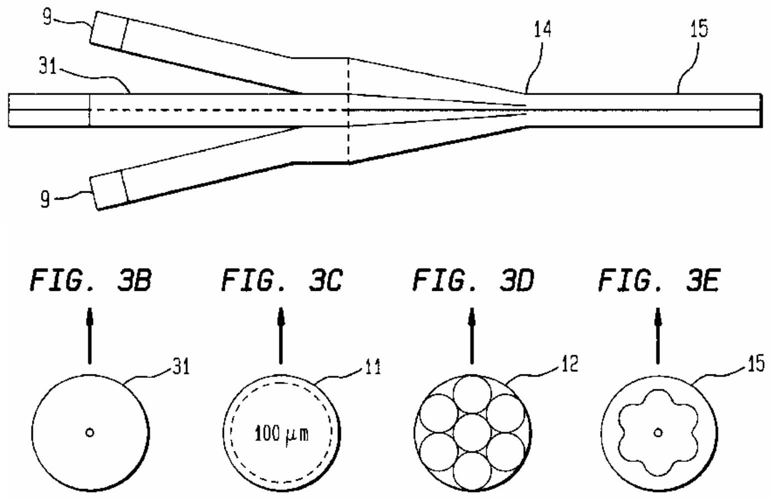




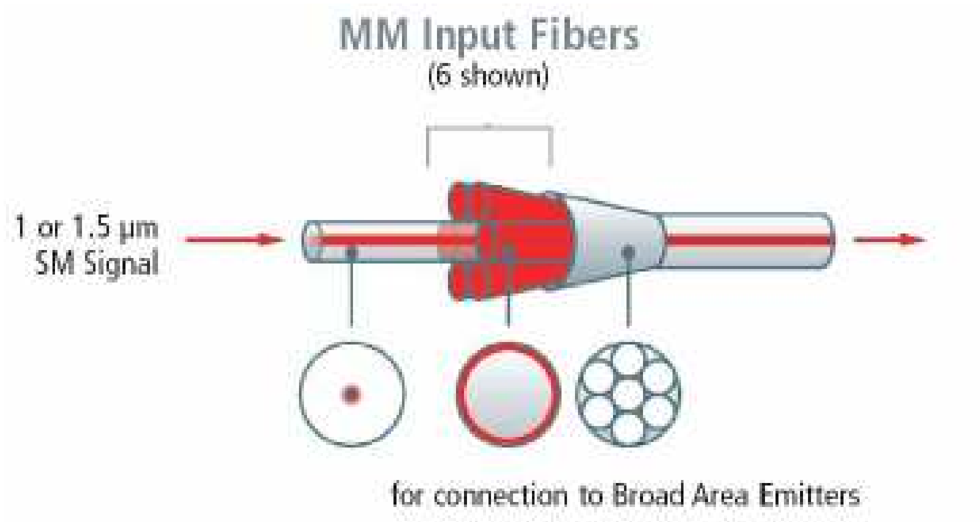
J. K. Ranka *et al.*,", [Opt. Lett. 25 (1), 25 (2000)]


output
QWP
QWP
PBS
AOM
HWP
Yb-doped fiber
PCF
PC
WDM
pump

Pump combiner



(US patent # 5,864,644)



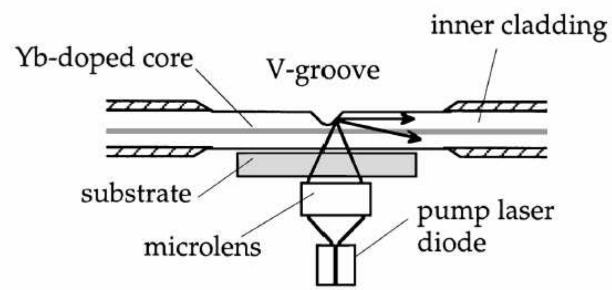
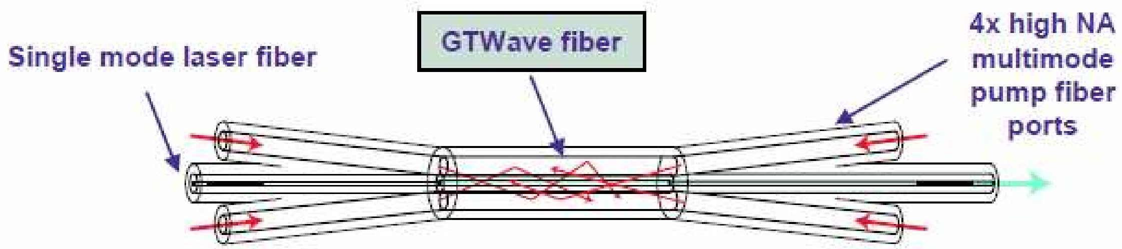


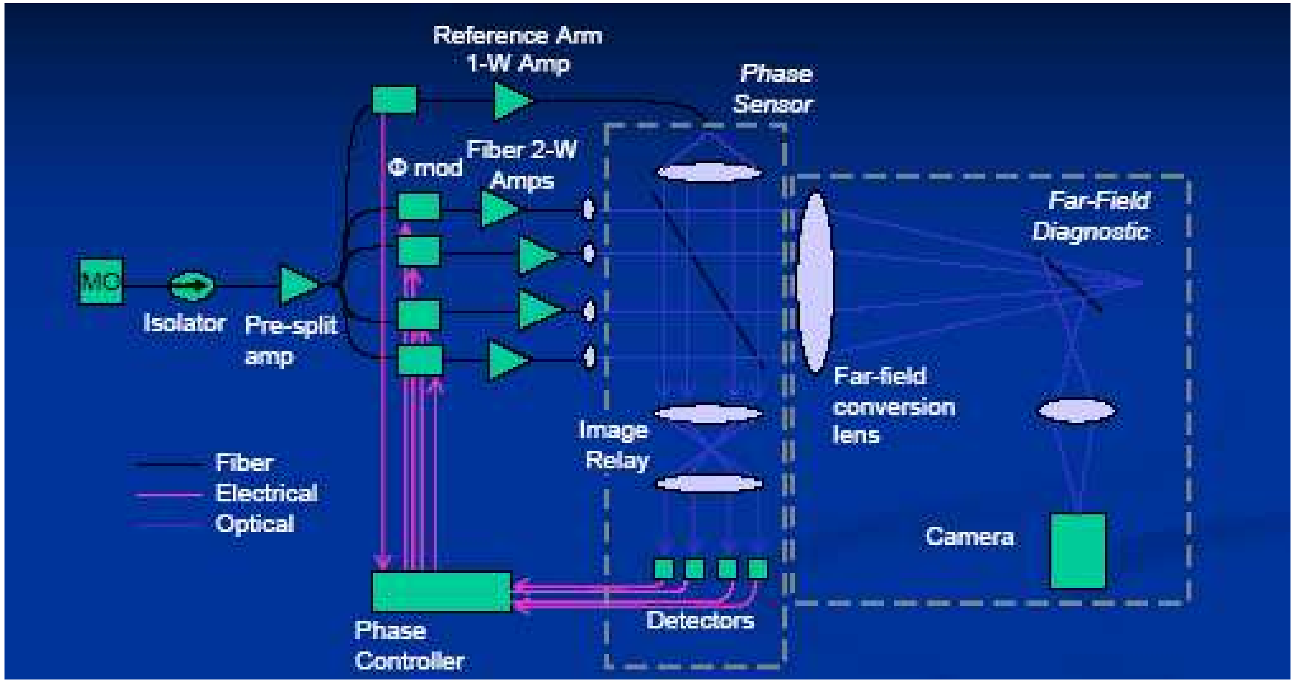
Fig. 1. V-groove side-pumping arrangement.

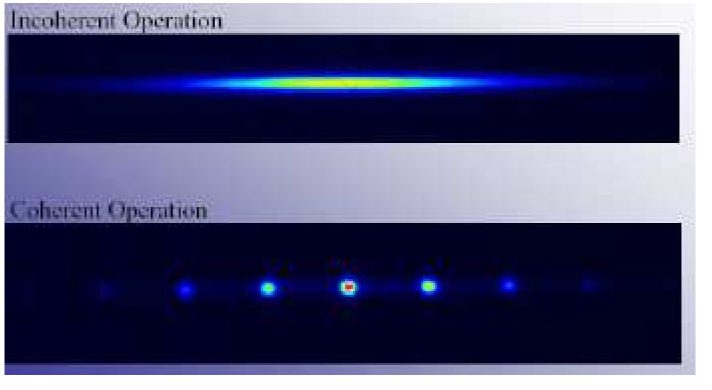
(Goldberg, Opt. Lett. 1999)



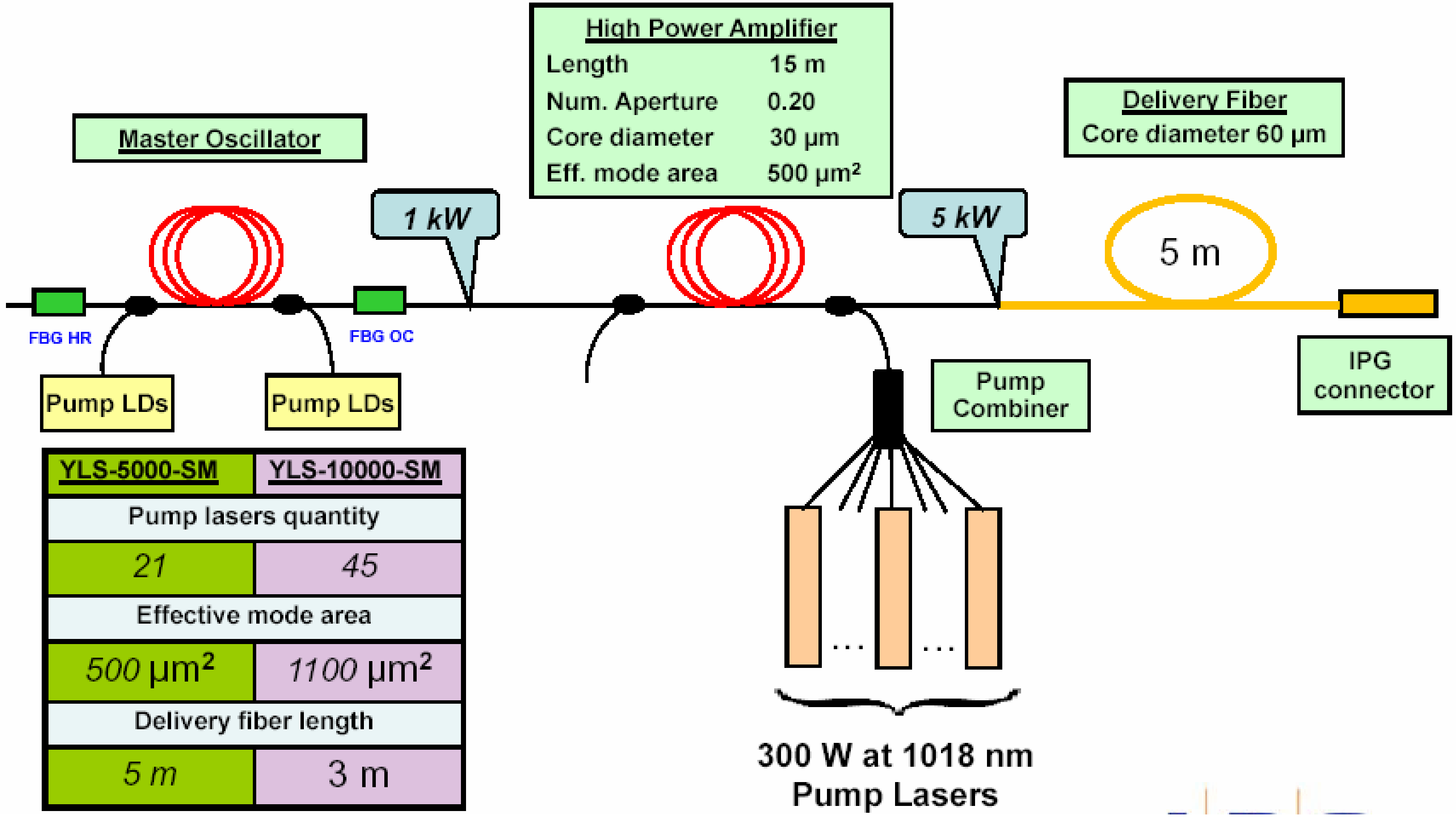
GTWave technology (credit: D. Payne)

Laser combiner





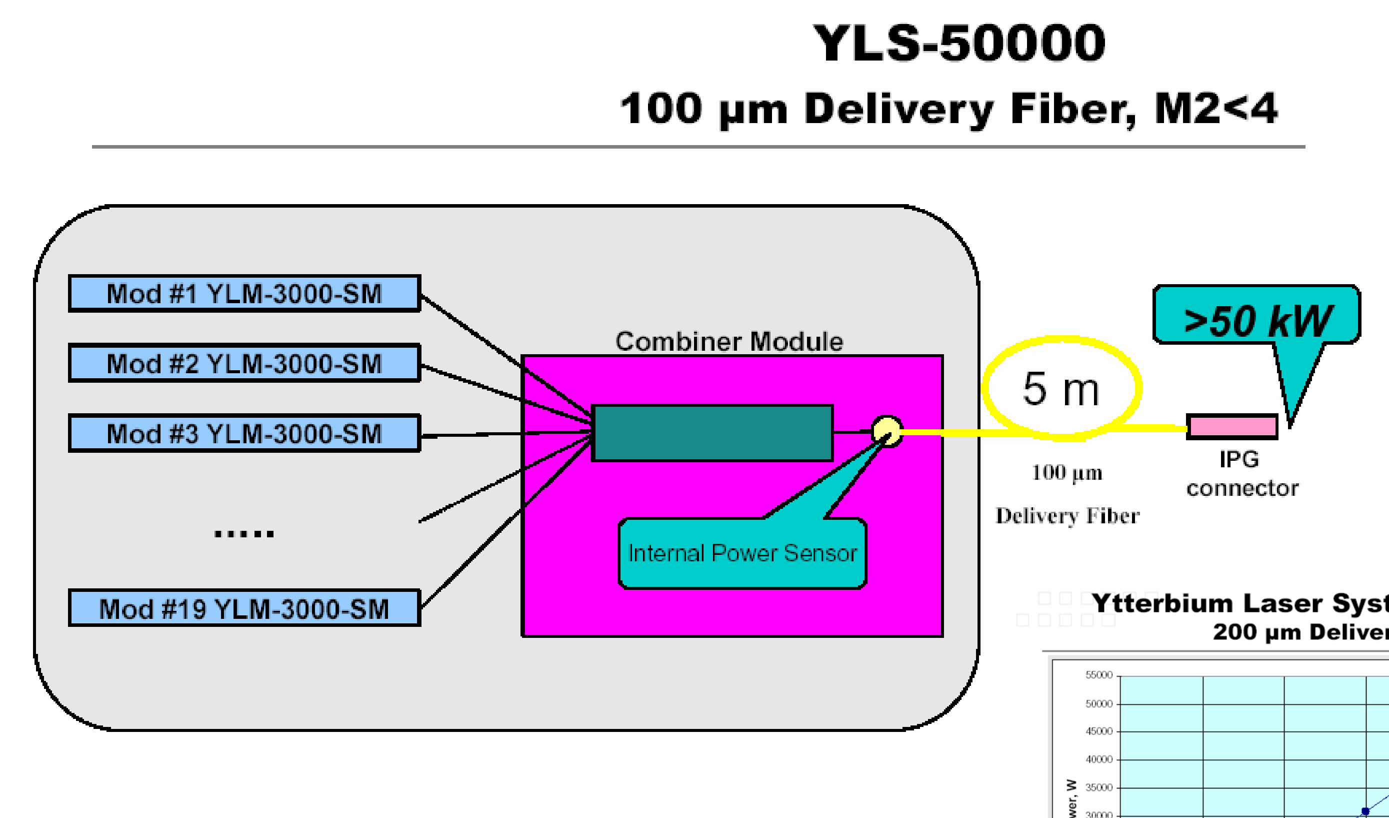
cw lasers

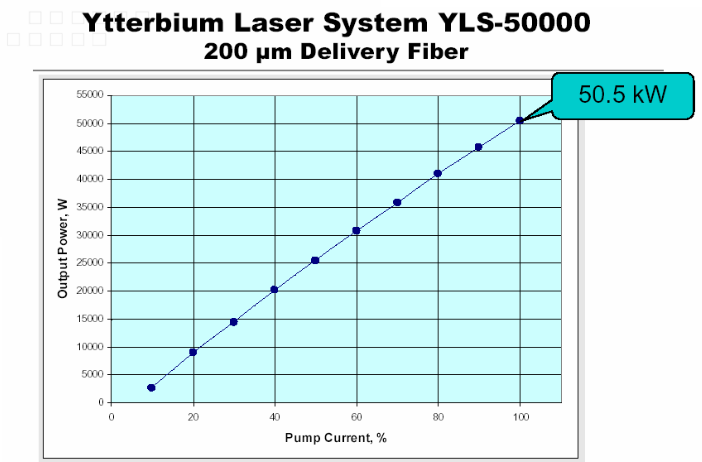


YLS-5000-SM	YLS-10000-SM
Pump lasers quantity	
21	*45*
Effective mode area	
500 μm^2	*1100* μm^2
Delivery fiber length	
5 m	3 m

Source: IPG

cw lasers





Source: IPG

DESIGN LIMITS

Nonlinear Schrodinger Equation

Loss Dispersion SPM

$$\partial_z A + \frac{\alpha}{2} A + i\frac{\beta_2}{2}\partial_t^2 A - i\gamma|A|^2 A = 0$$

A(z,t) is the complex slowly varying pulse envelope in a frame of reference moving with the pulse at the group velocity $v_g = 1/\beta_1$.

α accounts for linear absorption at carrier frequency ω_0.

$\gamma = 2\pi n_2 = (\lambda Aeff)$

Raman

$$\frac{dI_s}{dz} = g_R I_p I_s - \alpha_s I_s$$

$$\frac{dI_p}{dz} = -g_R \frac{\omega_p}{\omega_s} I_p I_s - \alpha_p I_p$$

What are the limits for fiber lasers?

1: Available pump power (especially to pump active ions other than Yb!)

2: Output wavelength: only few are covered by standard ions

3: (Pulsed) Length: looking for new glasses

4: (HP) Heat dissipations (water cooling, etc.)
CW bulk damage @ ~100-kW (anticipation)

5: (HP and pulsed) Non-linear effects (**χ(3)** nonlinearity)
Self-Phase-Modulation (SPM)
Stimulated Raman Scattering (SRS)
management –increase core size
Stimulated Brillouin Scattering (SBS) for narrow-linewidth
management – increase core, SBS suppression techniques

6: Photodarkening:
management: low doping (silica), alternative glasses

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CW bulk damage @ ~100-kW (anticipation)

5: (HP and pulsed) Non-linear effects (χ(3) nonlinearity, silica is symmetric)
Self-Phase-Modulation (SPM)
Stimulated Raman Scattering (SRS)
management –increase core size
(SF) Stimulated Brillouin Scattering (SBS) for narrow-linewidth
management – increase core, SBS suppression techniques

6: Photodarkening:
management: low doping (silica), alternative glasses

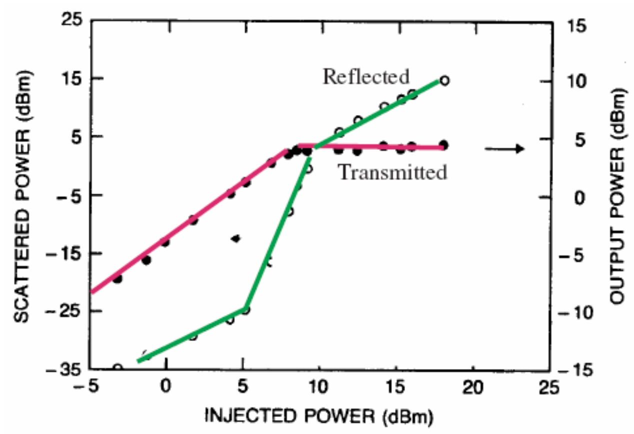
Stimulated Brillouin Scattering (SBS)

Stimulated Brillouin Scattering (SBS) is the dominant non-linear effect for narrow-linewidth laser (below 10 MHz). SBS ha narrow gain bandwidth.

Scattering of light from acoustic waves.

Becomes a stimulated process when input power exceeds a threshold level.

$$P_{th} \approx \frac{21}{g_B}\frac{L_{eff}}{A_{eff}} \qquad L_{eff} = \frac{1}{x}L\left(1 - e^{-xL}\right)$$



G. P. Aggarwal, “Non-linear Fiber Optics”, Academic Press, 2006

Management: Short Fiber, Large Mode Area. Linewidth Broadening, Fiber straining (broadening SBS gain).

Currently: Threshold at 100s W SF laser (limit 1 kW)

Broadening at 10 GHz for kW class laser

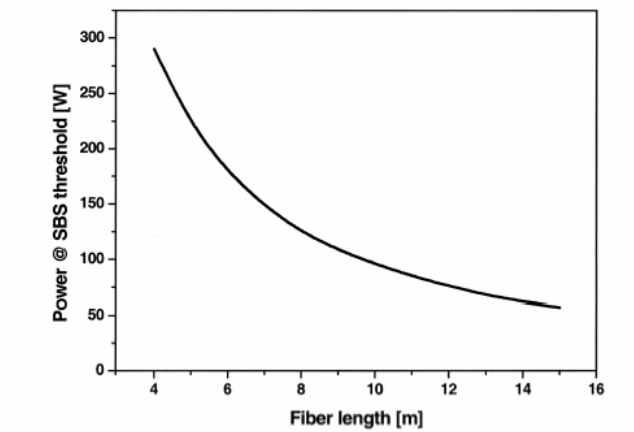


Fig. 4. Brillouin threshold power as a function of fiber length (mode-field diameter is 23 μm).

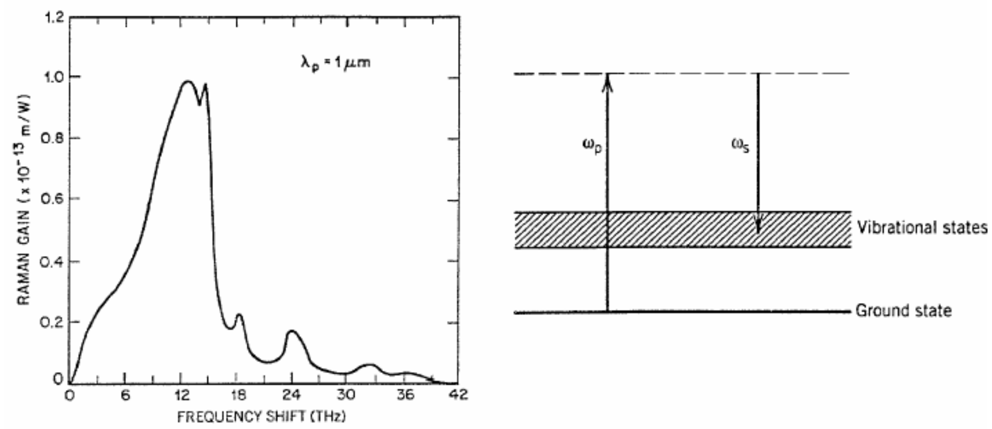
A. Liem, et al. "100-W single-frequency master-oscillator fiber power amplifier," Opt. Lett. **28**, 1537-1539 (2003)

Stimulated Raman Scattering (SRS)

Scattering of light from vibrating (silica) molecules. Since we are in glass the vibrational state is a band

Gain extends to tens of THz with peak (silica) at 13 THz (i.e. SRS at 1.5 mm is about 100 nm)

$$P_{th} \approx \frac{16}{g_R} \frac{A_{eff}}{L_{eff}}$$



Telecom fiber(50 m^2 A_{eff}): 1 W

Active Fibers (10 m, 20 micron core): 10 kW (100 ns, 1 mJ!),

Affects; Q-Swicthed laser for marking! Pulsed laser in general, HP CW lasers

Management:

increase core size, short fiber (high-doping)

SRS: only Bad?

Bad for laser and amplifiers

Good for “*Raman* Laser” and “*Raman* Amplifiers”: allow to shift wavelength and cover neighborough wavelength intervals where no active ions are available!

$$\frac{dI_s}{dz} = g_R I_p I_s - \alpha_s I_s$$

$$\frac{dI_p}{dz} = -g_R \frac{\omega_p}{\omega_s} I_p I_s - \alpha_p I_p$$

Self-phase modulation (SPM)

Based on Kerr effect: refractive index depends on optical intensity.

$$\phi(t) \approx k\, n_2 \frac{L_{eff}\, P(t)}{A_{eff}}$$

Limits:
100 ns pulses: 10W on LMA fiber: 1 mJ
10 ps: 1 μmJ
100 fs: 10 nJ

Management:
increase core size, short fiber (high-doping)

Good or Bad:
Bad for pulse amplification
Good for supercontinuum generation

Bulk damage

Bulk damage inside fiber core: depends in on Intensity and effective area

$$P_{Max} \approx \frac{A_{eff}}{\sqrt{\tau}}$$

For ps to ns pulses. Thermal damage by melting/heating.
Below tens of ps *ablation* occurs.
Process becomes almost insensitive from pulsewidth

$$E_p P_{Max} \approx 2\, mJ\, \frac{W}{\mu m^4}$$

Expected 100kW threshold for CW lasers

Management: Increase core size. Interplay pulse duration and pulse peak power.

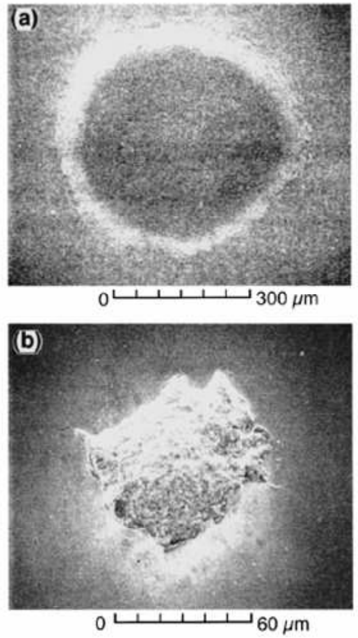


FIG. 4. Laser damage spots on fused silica created by (a) long pulse, 900-ps, 300-μm diameter; (b) short pulse, 0.4-ps, 500-μm diameter.

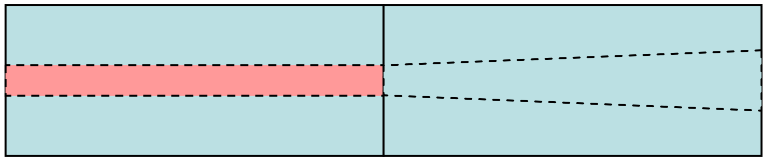
B. C. Stuart, et al. “Nanosecond-to-femtosecond laser-induced breakdown in dielectrics”, PRL, 74.2248,1995.

Surface damage

Weakest point. Threshold can be 1 order of magnitude below bulk damage threshold. About 10-20 W μm^2 at 1 μm wavelength (pure silica).
Decrease for doped glass

Limits for single fiber lasers (10 kW)

Management: Undoped coreless endcaps.

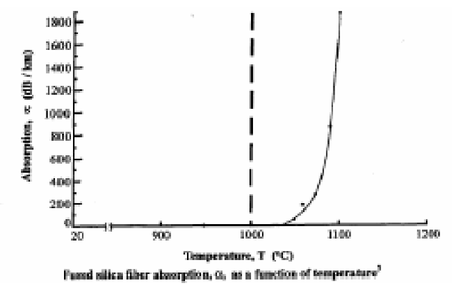


Other “real-world” limits

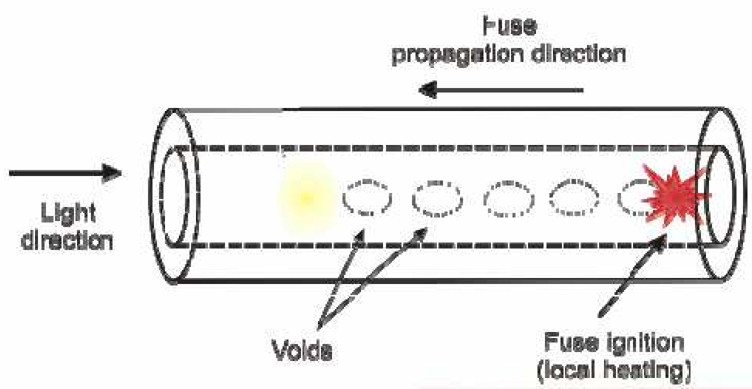
Self-pulsation: An amplifier left without seed will generated large pulse destroying (even evaporate) the fiber core and damaging inline components (Yb-doped amplifiers)

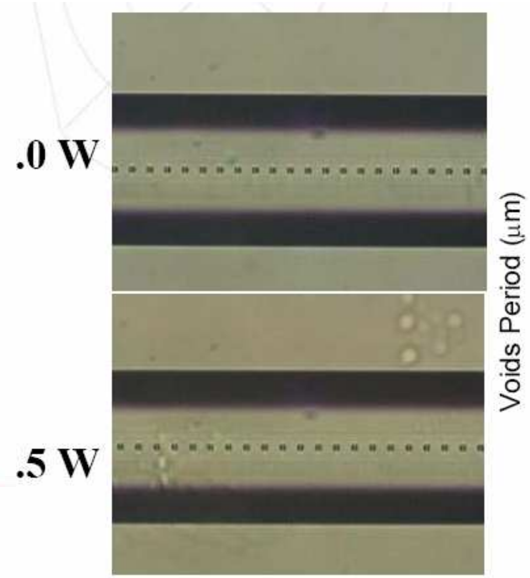
Fiber Fuse Effect: Travelling hot-spot generate by defects or even dirty connectors. Threshold of few Ws.

Generated by local defect. Absorption enhanced temperature rise



D. D.Davis et al, SPIE Vol. 2966, 0277-786X, 1997

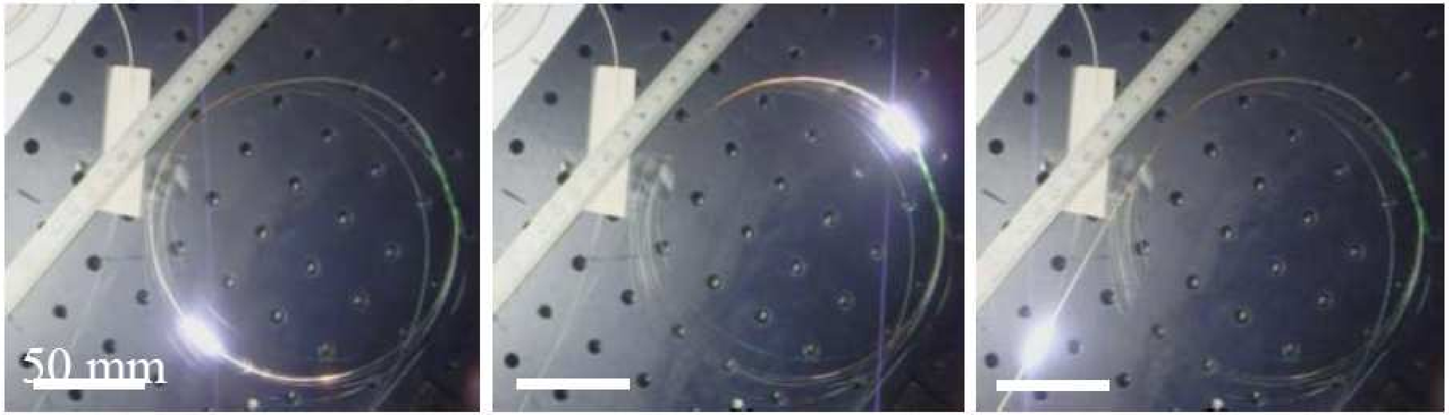




Courtesy: P. Andre’, Univ. of Aveiro, Portugal

Fuse fibre effect

• Photogram's with a period of 0.4 s, for an optical power of 3.0 W.

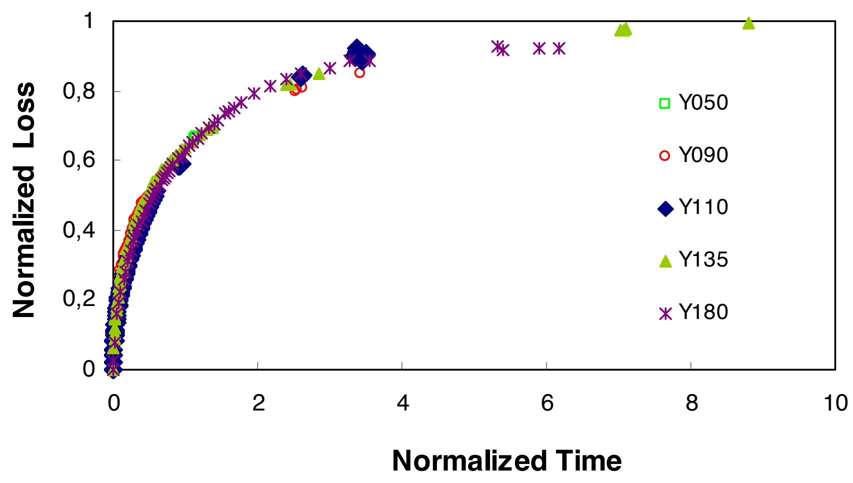


Velocity = 0.43 ± 0.03 m.s^{-1}

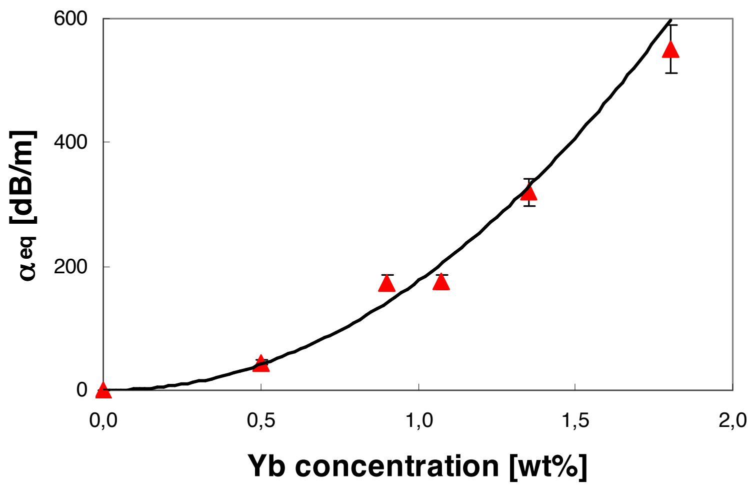
Courtesy: P. Andre', Univ. of Aveiro, Portugal

Photodarkening

Self-similarity



Quadratic vs. Doping Level



$$\alpha_{eq} = k\, N_{Yb}^{\;2}\; N_{2,Yb} = k\, N_{Yb}^{\;3}\; \tilde{N}_{2,Yb}$$

Overall trends

Does it help if we increase:	Length	A_{eff}	"Doping level"
Stimulated Raman Scattering (SRS)			
SBS			
SPM			
Thermal Management			
Photodarkening			
Detrimental effect (cluster)			
High Power			
Q-switching short pulse			
High Quality Beam			
Single-Frequency operation			

A Fiber laser design is always a compromise!

What are the limits for cw fiber lasers?

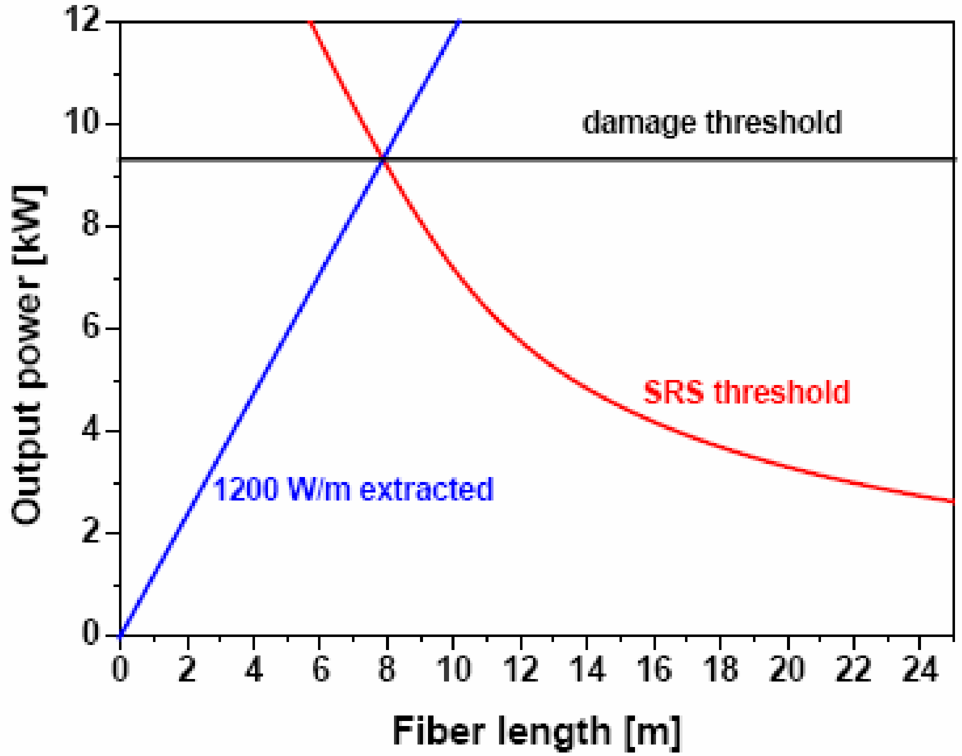


Fig. 7: Summary of thermal, damage and nonlinearity limits of a continuous-wave fiber laser with a 35-μm MFD core.

J. Limpert et al. “Fiber Lasers”, Jena University

How far we are from limits?

Yb-doped laser (silica) are……

………….almost close to physical limits!

Type of Devices

Fibre devices

CW Lasers

- Single-frequency, Linearly Polarized, High-power

Pulsed lasers

- ns regime
- ps regime
- ultrashort laser

Amplifiers

- CW
- Pulsed

Continuum generation

Waveguide laser

Fibre devices

CW Lasers

Single-frequency, Linearly Polarized, High-power

Pulsed lasers

ns regime

ps regime

ultrashort laser

Amplifiers

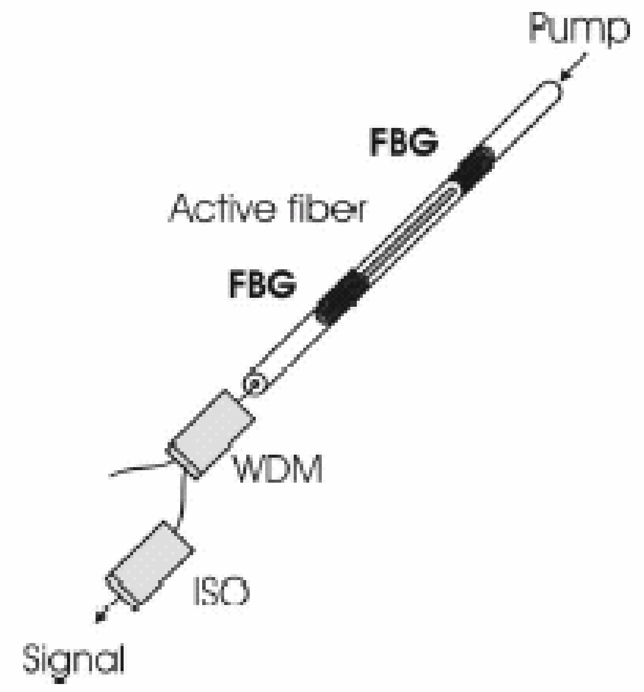
CW

Pulsed

Continuum generation

Waveguide laser

cw fiber lasers



High-power cw fiber lasers

High power cw fiber laser divide into three categories

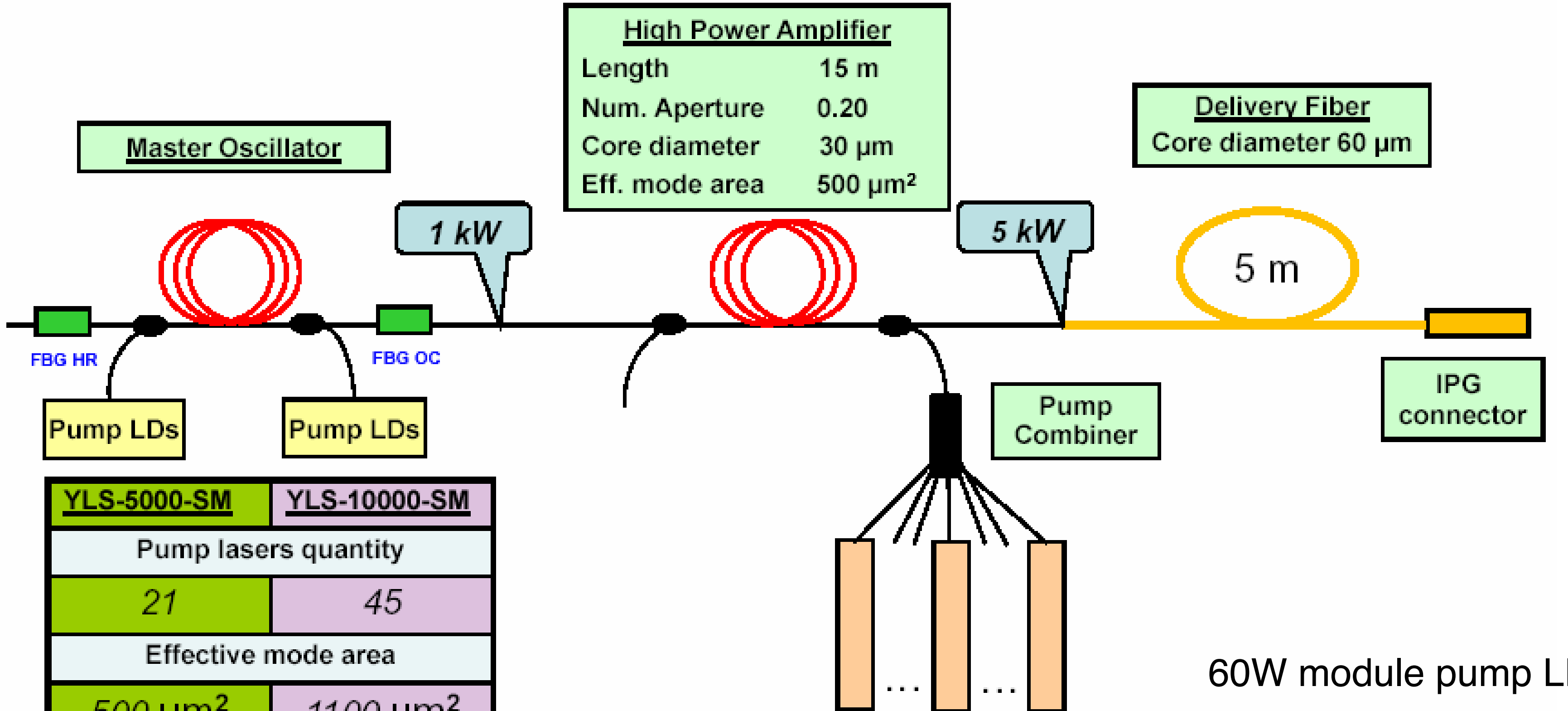
Laser fiber (Only a fiber laser): power is limited to about 1 kW

MOPA configuration (seeder + amplification stages): power up to 5 kW, possibility of linear polarization. Single mode. M^2 close to 1.

MOPA configuration offers also possibility of single-frequency and linearly polarized output, as well as pulsed operation

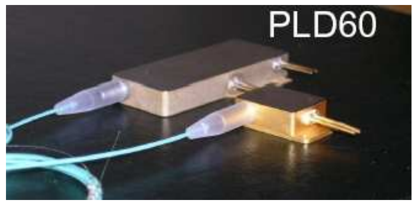
Combining of several laser into the same fiber or in free space (beam combining). Power up to 100 kW. M^2 approaching 5.

cw lasers



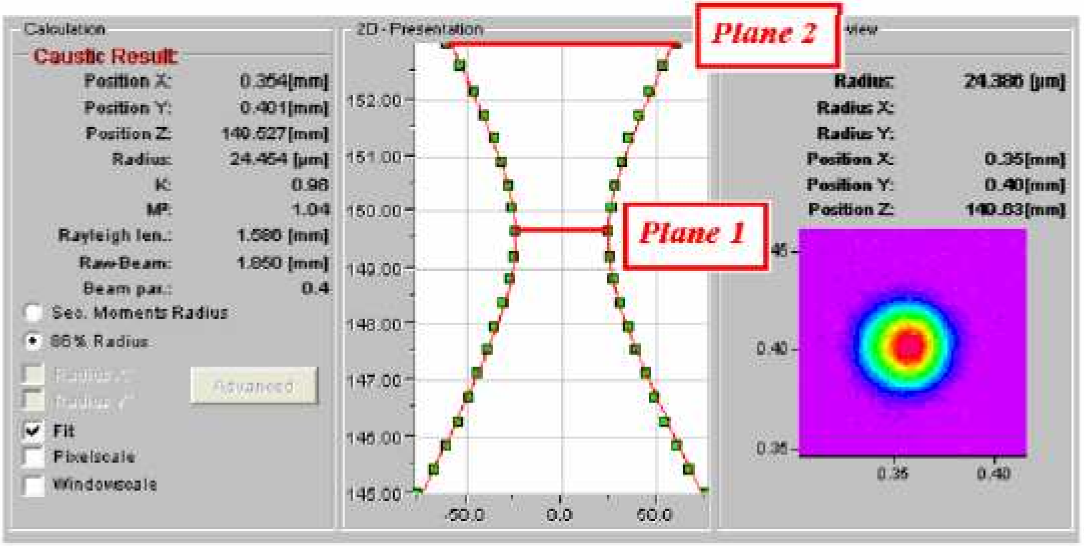
YLS-5000-SM	YLS-10000-SM
Pump lasers quantity	
21	45
Effective mode area	
500 μm^2	1100 μm^2
Delivery fiber length	
5 m	3 m

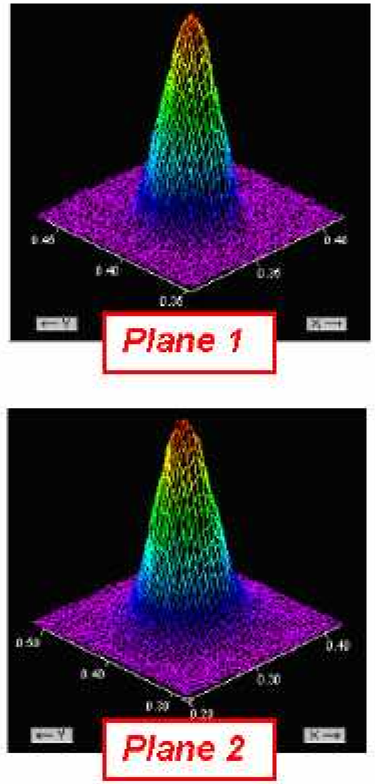
60W module pump LDs



Source: IPG

YLS-5000-SM Beam Quality





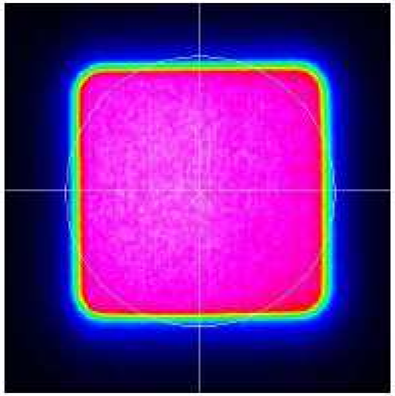
M^2 value = 1.04

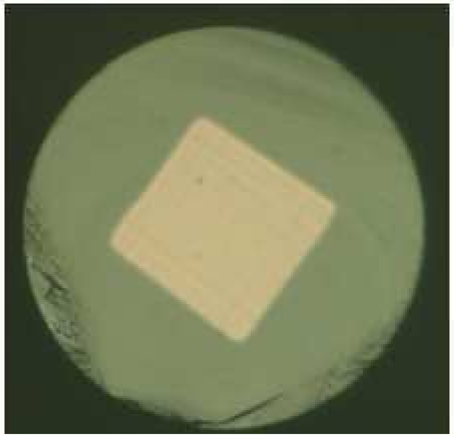
measured with Primes Laser Quality Monitor (LQM)

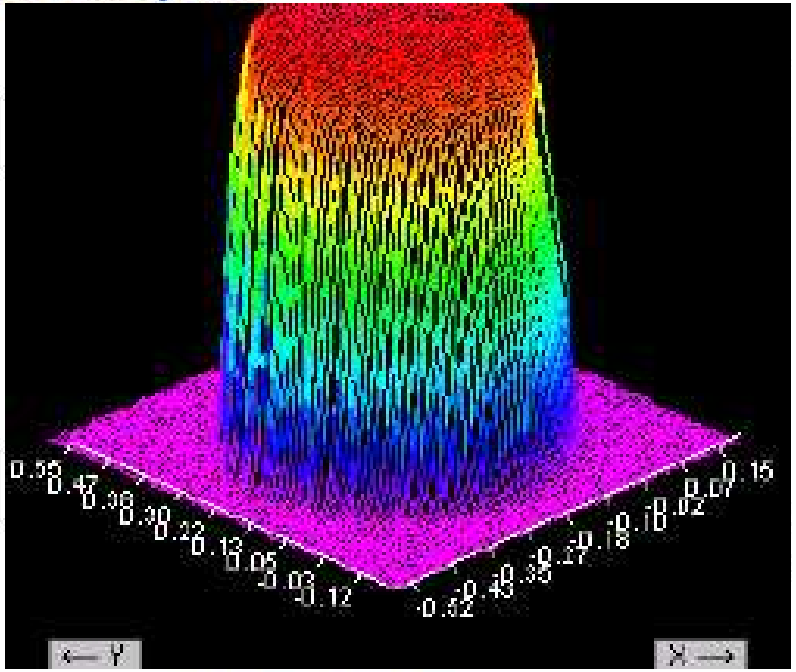
Source: IPG

Beam Shape

Square core delivery fiber



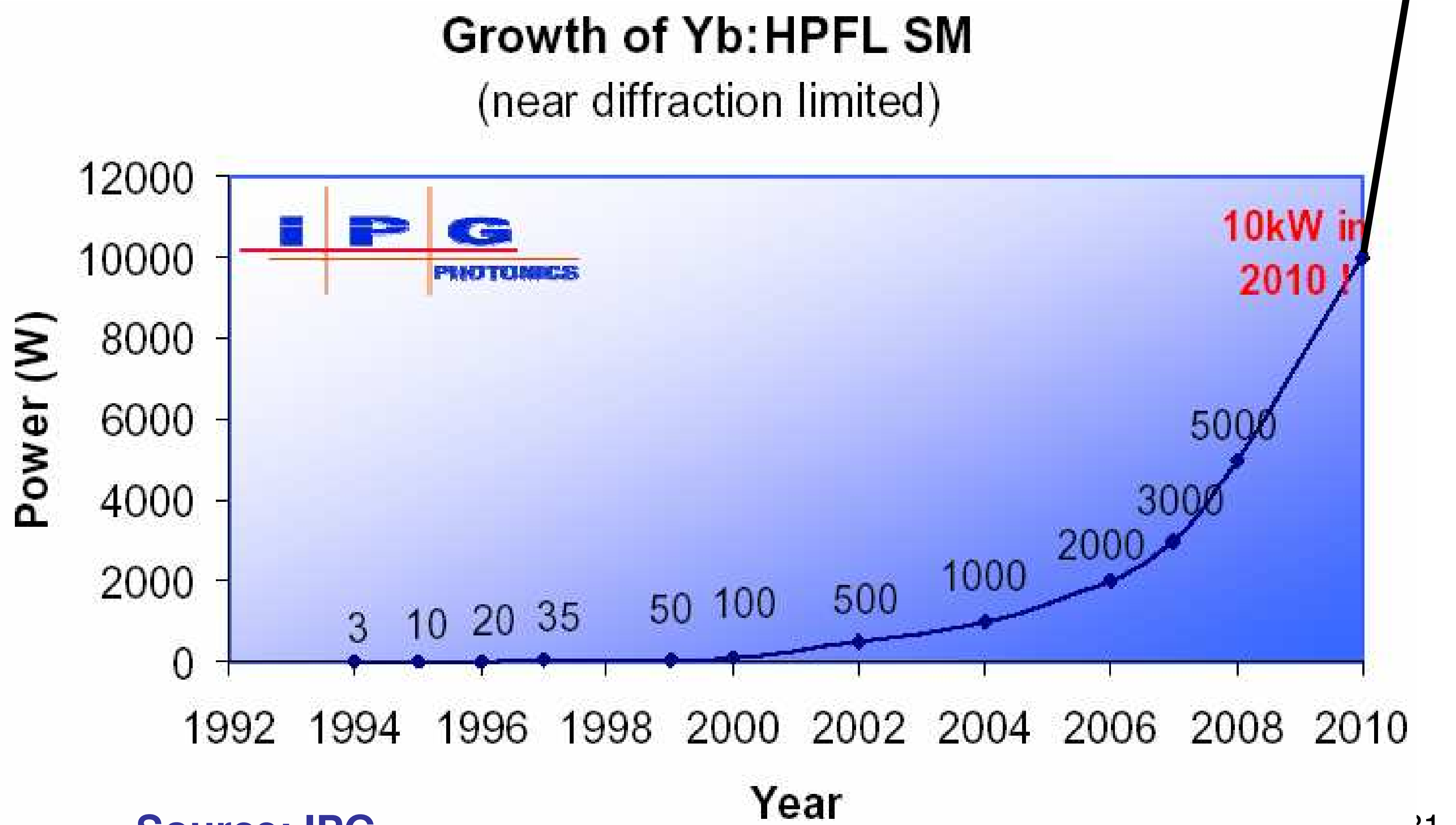




- Square shape image
- Uniform intensity distribution
- Process traces with sharp edges

Source: IPG

High-power fiber lasers

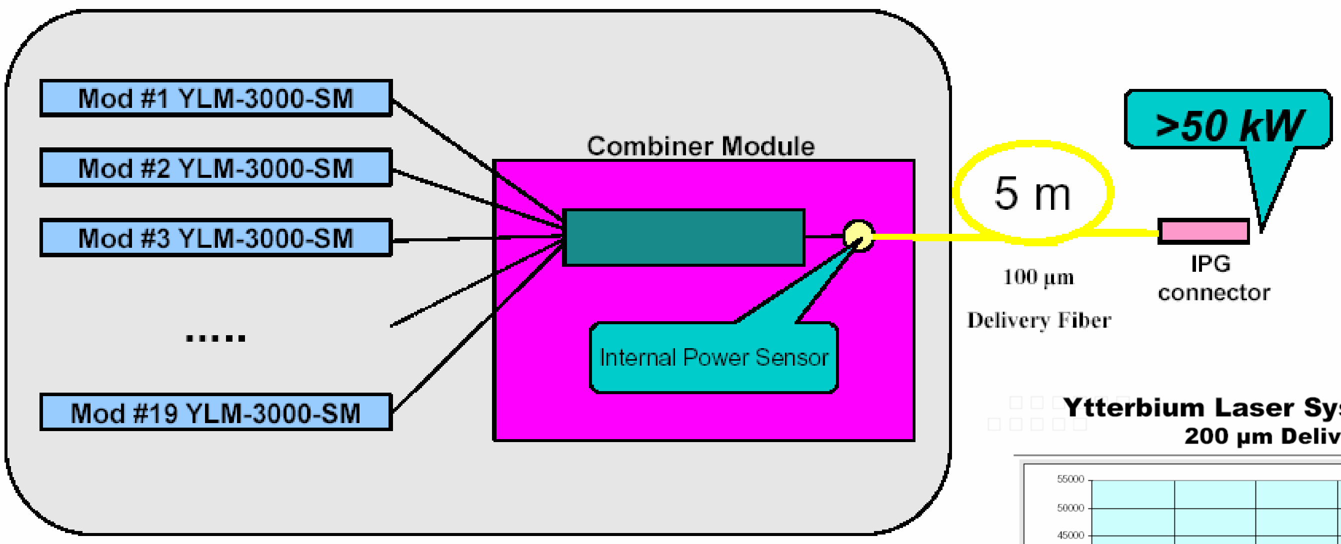


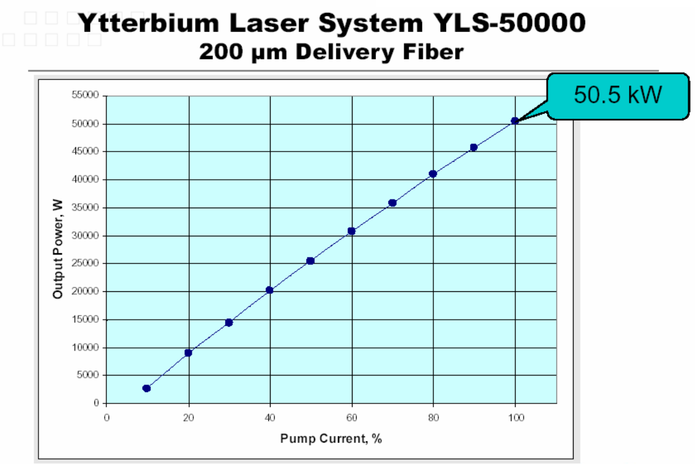
Source: IPG

cw lasers

YLS-50000

100 µm Delivery Fiber, M2<4



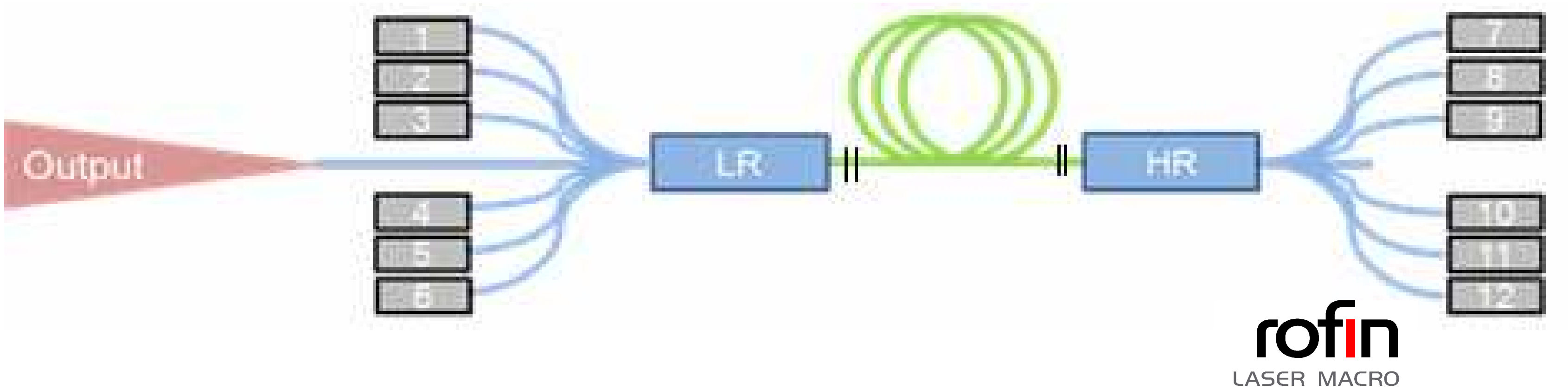


Source: IPG

cw lasers

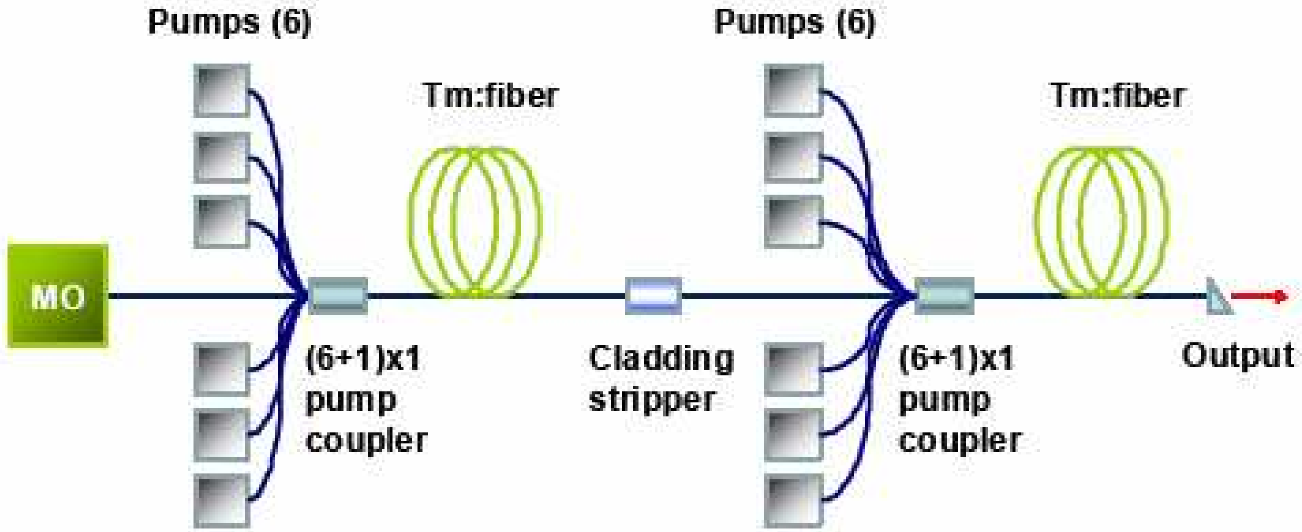
Results

1,9 kW fundamental mode, dual side pumped fiber laser oscillator:



Source: ROFIN

Two-stage power amplifier



MO

50 Watts at 2045-nm

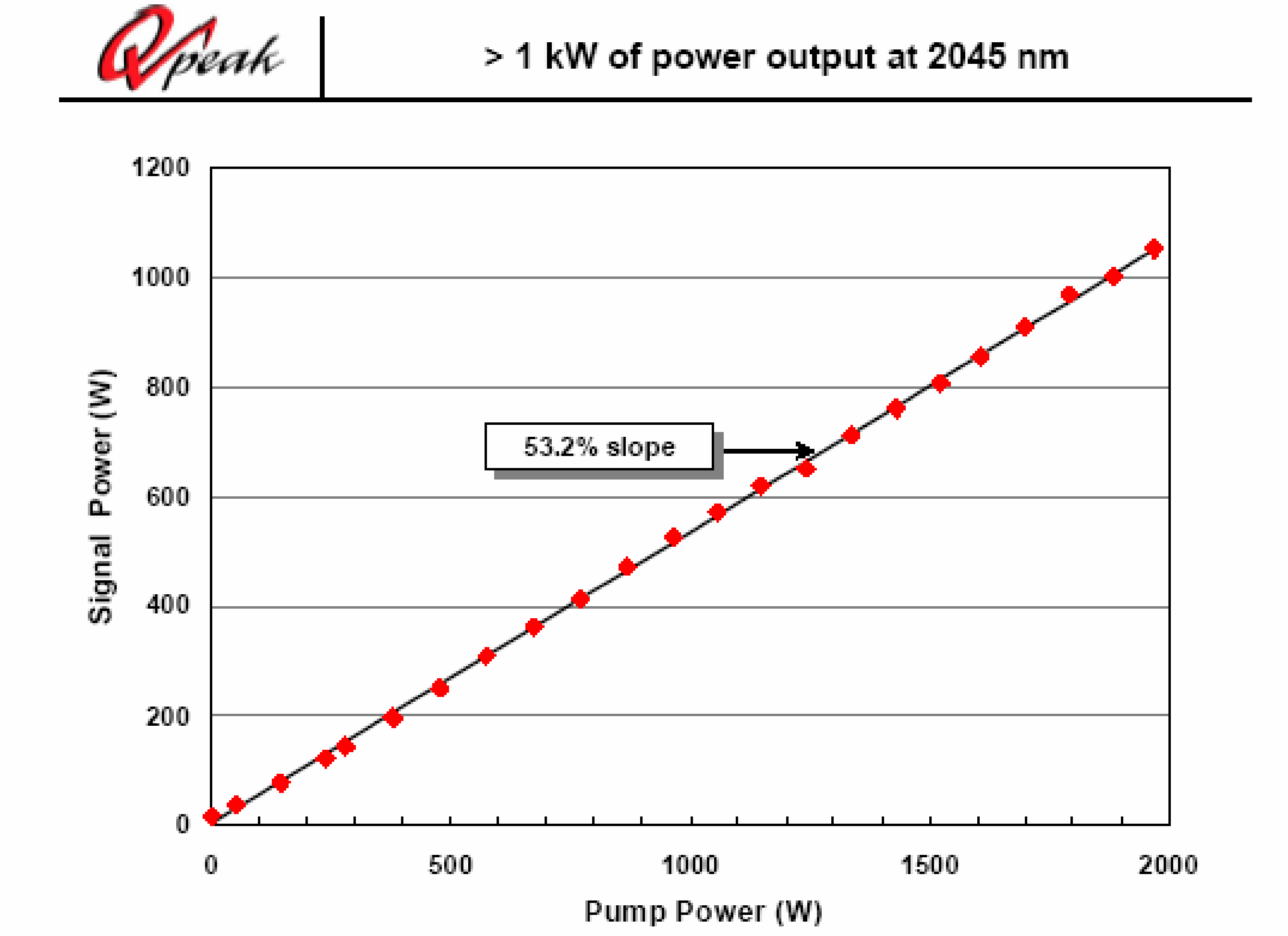
1st Stage

12m LMA-TDF-20/400 active fiber

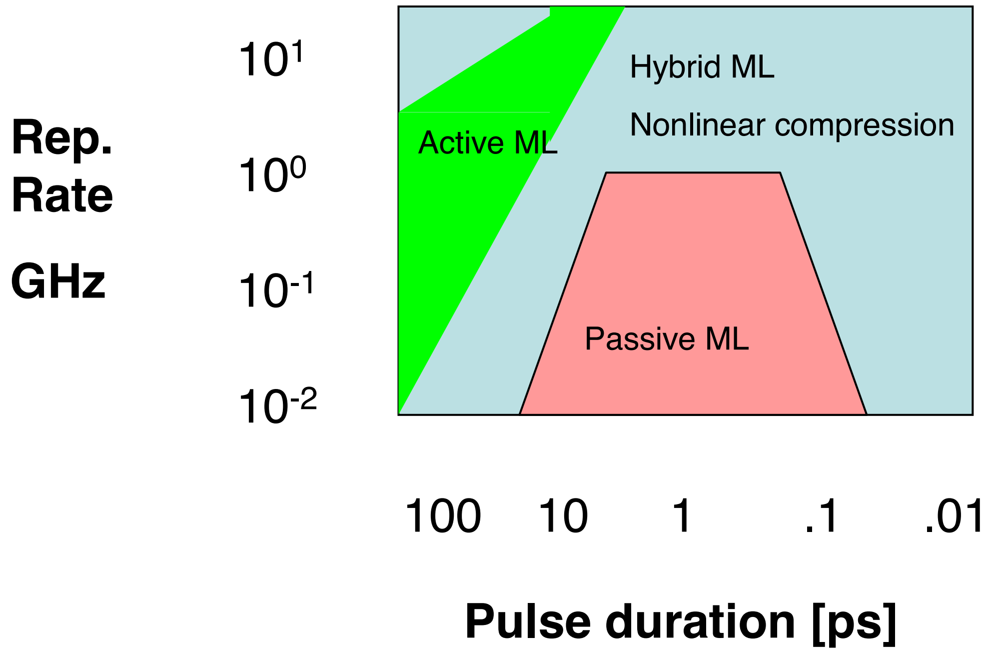
2nd Stage

12m LMA-TDF-20/400 active fiber

ISLA project aims to expand applications of 2-micron fiber laser technology



Pulsed lasers

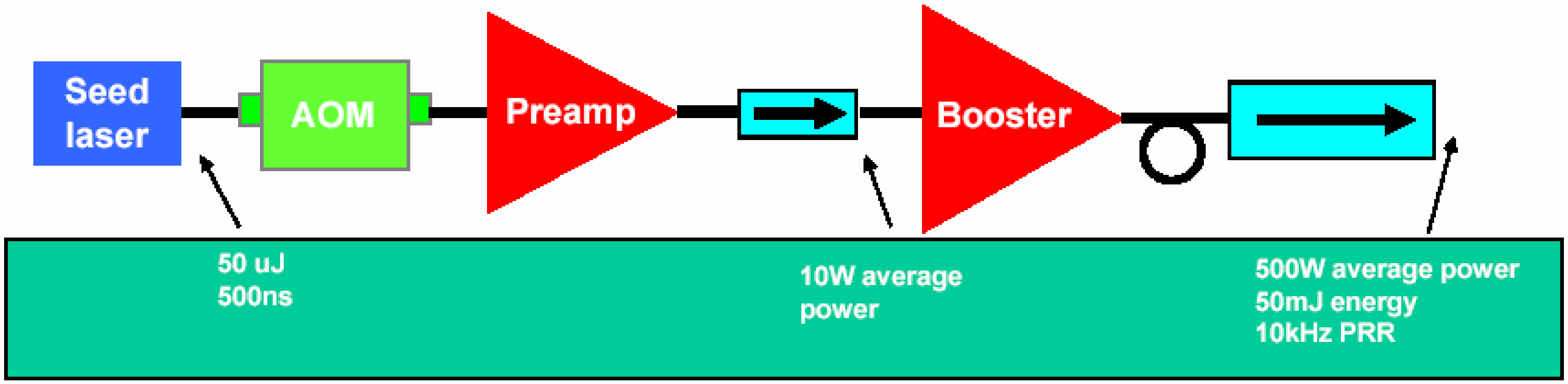


For fs pulses Basic Osillator 10 pJ-1 nJ

Direct Amplification 1nJ – 1 μJ

Chirped Pulsed Amplification 1μJ – 1 mJ

Pulsed lasers

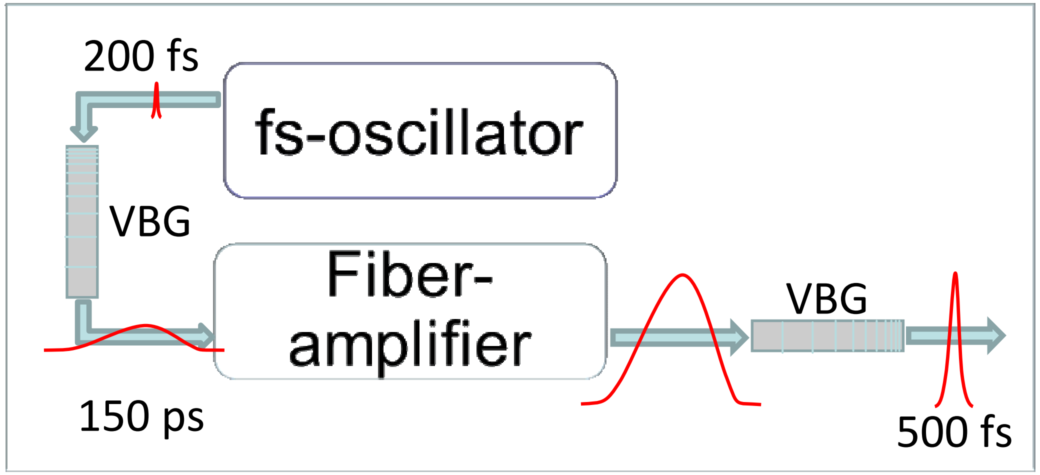


Source: ORC

Pulsed fibre Laser

Objective Femtosecond MOPA (master-oscillator amplified system)

Parameter		
Average power	200	W
Pulsewidth	< 500	fs
Pulseenergy /rep.rate	> 100	µJ @ 2 MHz
Beam quality (M^2)	< 1.2	(TEM_{00})



Source: LIFT

pulsed fibre Laser

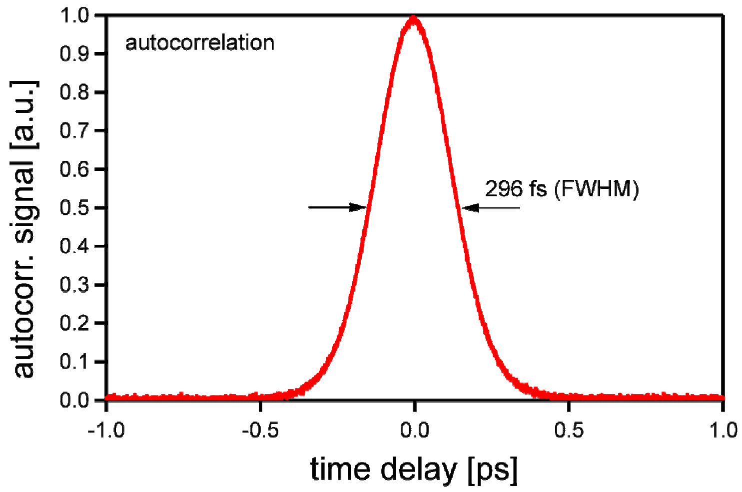
Challenge Femtosecond MOPA (master-oscillator amplified system)

- High-energy pulses out of fibre amplifier
  - Nonlinear effects
  - Damage threshold of bulk material
- Dispersion management (temporal pulse shape)
- Beam quality (TEM_{00} at high average power)

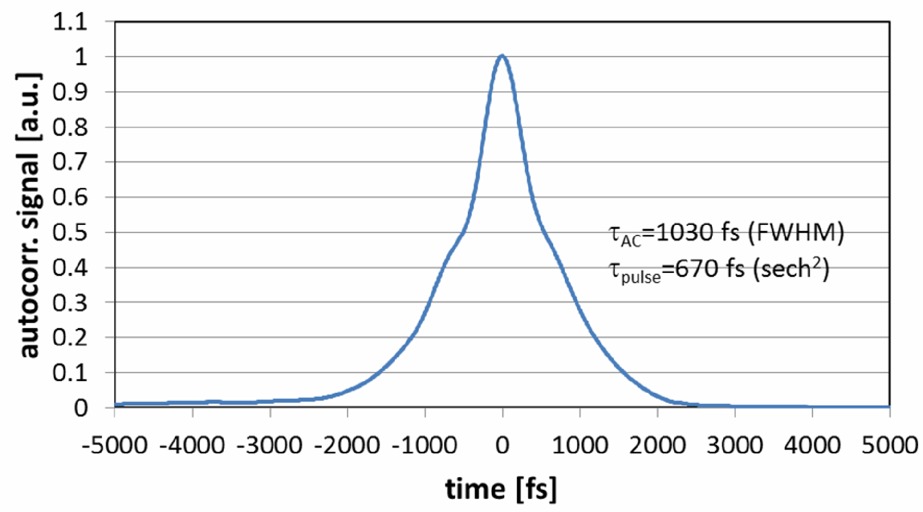
Source: LIFT

pulsed fibre Laser

Results Femtosecond MOPA (master-oscillator amplified system)



Master-oscillator (MO) output



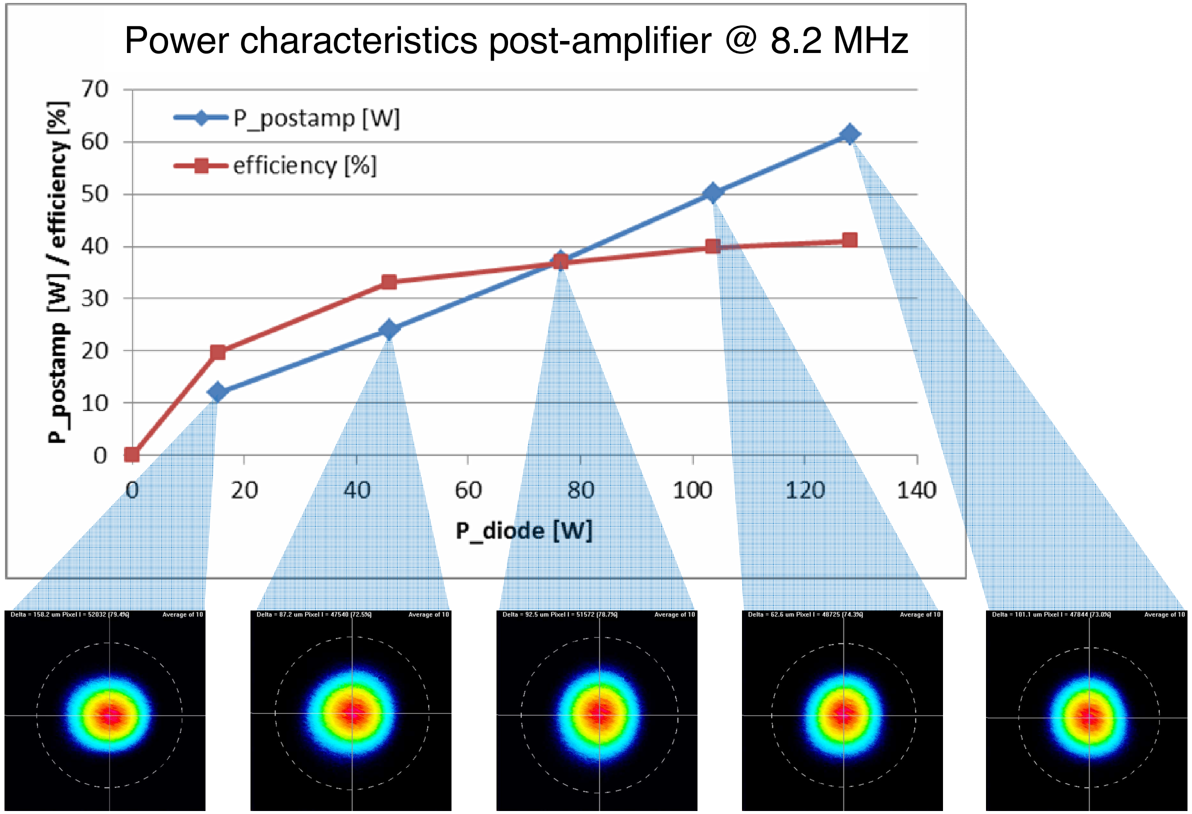
Power-amplifier (PA) output

Source: LIFT

pulsed fibre Laser

Femtosecond MOPA (master-oscillator amplified system)

Results



Source: LIFT

LIMITS

(Visible/UV)

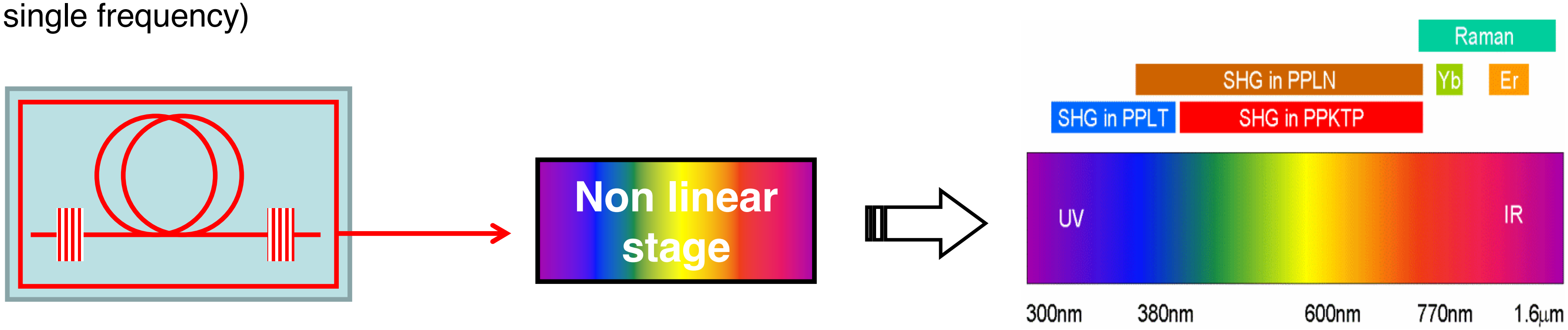
cw visible lasers

Wavelengths for specific medical treatments (532nm, 577nm, 633 nm, …)
Apply the advantages of fibre lasers to the medical area (beam quality, higher power, new wavelengths accessible, low maintenance lasers, …)
New laser tools for Ophthalmology (1 to 5 Watt range) and Dermatology (10 to 20 W range)

Challenges & tasks

Laser Concept

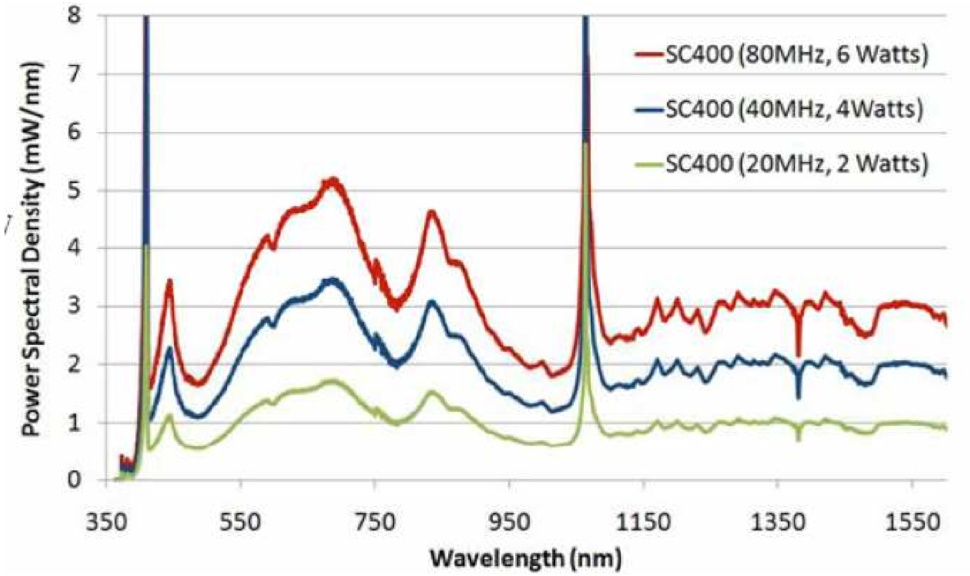
IR linearly polarized CW Fiber laser (narrow linewidth or single frequency)



- Architecture based on Fiber laser in the infrared then frequency-doubled using periodically poled crystals (non-linear stage)
- Single pass configuration for SHG (much better stability)

Source: LIFT

UV/Visible Continuum generation



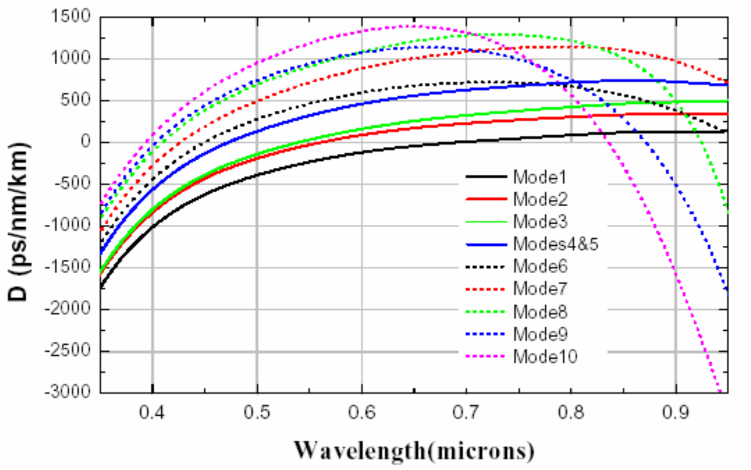
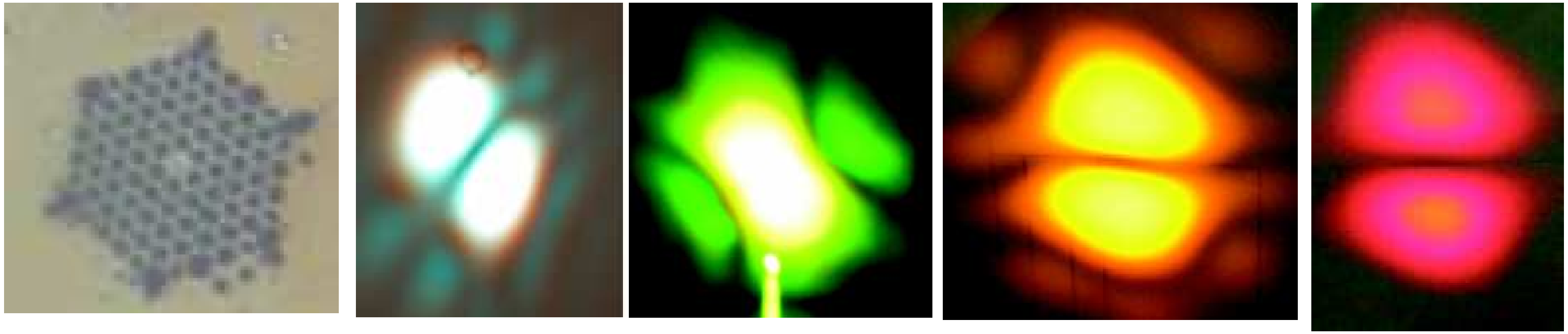


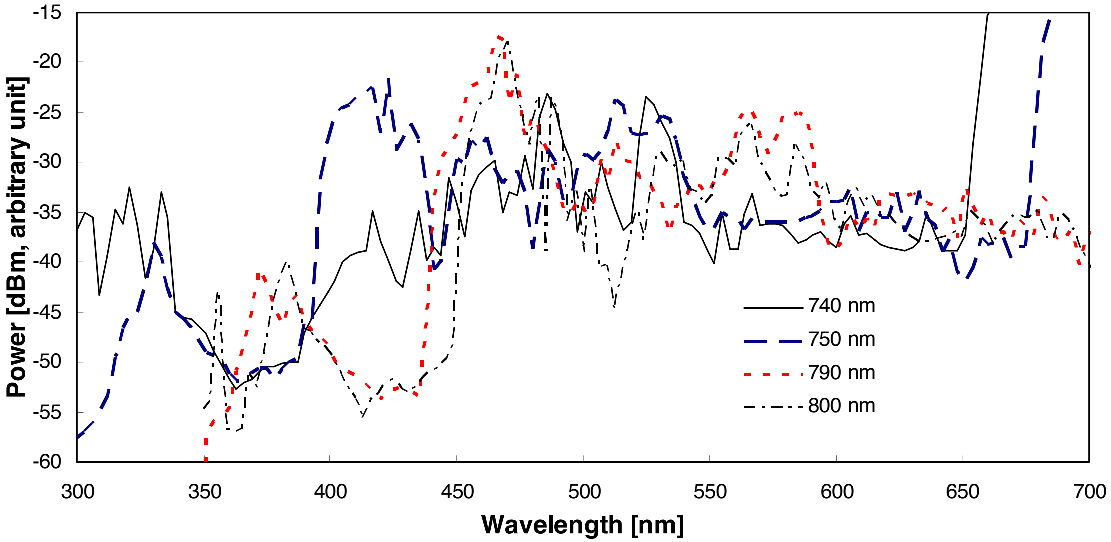
Fig. 9. Calculated dispersion profiles of the first 10 modes of a 1.6 μm MOF. Solid curves: lowest order modes having only one zero-dispersion point in the visible. Dashed curves: higher-order modes which have another zero-dispersion point in the infrared.

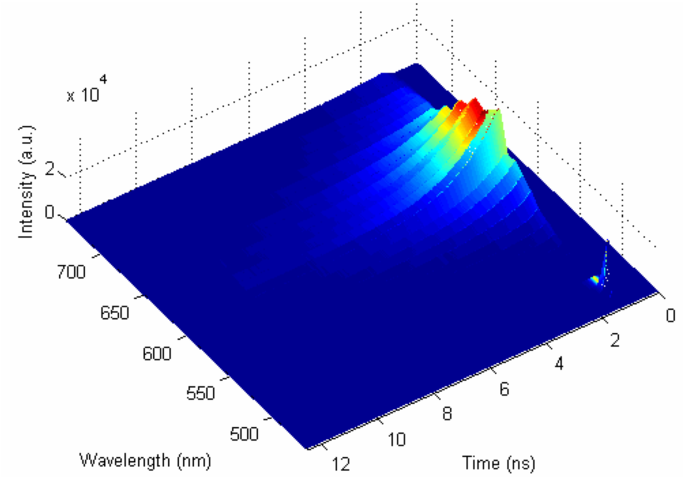
From J. Hecht, LFW 2011 Webcast

A. Efimov et at, "Nonlinear generation of very high-order UV modes in microstructured fibers", Opt. Express, 11 (918) 2003. (Los Alamos National Laboratory and University of Bath)

UV/Visible Continuum generation



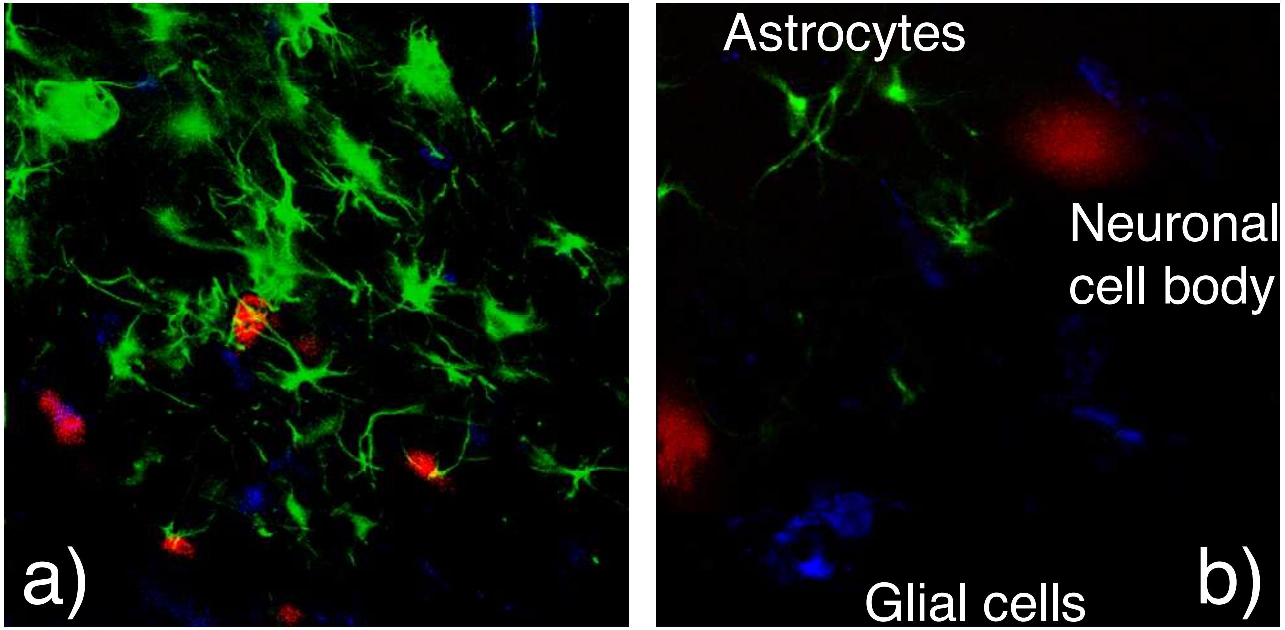




Swansea University
Prifysgol Abertawe

Confocal laser scanning microscopy measurement

RGB Confocal image of rat neuronal cells



BLUE: glial cells excited at 630 nm,
RED: neuronal cellular body excited at 550 nm.
GREEN: astrocytes excited at 458 nm

Constant pump power. Different excitation wavelength chosen by a monochromator

THANK YOU