High-power fiber lasers
/sources / amplifiers

KTH Winter School
Romme, Feb 5 2016

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Questions welcome
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- 100 km southwest of Heathrow
- 100 km west of Gatwick
- Please visit if you have a chance!
The Optoelectronics Research Centre

www.orc.soton.ac.uk

170 staff and research students
Research in photonics & optoelectronics
  Interaction between light and matter
  Fabrication, materials, and applications focused
  Physics, Optics, Quantum Electronics, Chemistry and Materials Science, Nanotechnology, Mathematics, Biology...
  Lasers, fibers, glass, planar, telecom, bio, meta-materials, plasmonics...
New fabrication facilities

- 150 million pound investment
- 944 m² Class 100-1K Cleanrooms
- 564 m² Class 1000 Cleanrooms
- 4 fiber draw towers/3 lathes
- New PECVD/FHD/PLD systems
- New activities/facilities:
  - Silicon photonics
  - Metamaterials
  - Nanophotonics
  - Biophotonics
- 30 new photonics laboratories
- Fully functional early 2010
- The Zepler Institute

Award from Royal Institute of British Architects!
Fiber fabrication at ORC

- Silica lathes
- Glass deposition
  - MCVD, OVD
- Draw towers
- Micro-structuring
- Soft glass
- RE-doping
- Etc.
Hollow core fibres

Transmission loss < 0.01 dB/m

MFD tailorable to any solid fibre  ➔ direct splicing possible

Low bend loss even at 100 µm MFD

Power in glass < 0.01%  ➔ γ ~ 0.001 W⁻¹km⁻¹

Can be made single moded  ➔ spatial filtering

Polarisation maintaining design possible
Fibers for high-power lasers

Size for power!

9/125 μm
100 W

40/650 μm
> 1 kW

single-mode signal fibre
multi-mode pump fibre
multi-mode pump fibre
GTWave fibre

Air clad

Micro-structured "holey" fiber

Multi core

Hi-bi

Ribbon

J. Nilsson, "High-power fiber lasers"
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Size matters!
Silica matters, too!

- **Large core** to facilitate:
  - power handling
  - minimization of nonlinear effects
  - high energy storage for pulsed application
  - efficient pump absorption & reduced device length

- Large inner cladding for launch of high-power pump beams

- Silica-based
  - Superb power-handling
  - Excellent control of parameters

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*Large size is the most important design feature of a high-power fibre laser*

9 / 125 µm
100 W

40 / 650 µm, > 1 kW
Schematic rare-earth-doped fibre laser

Dichroic mirror for pump / signal combination

Lens

Cavity feedback from perpendicular fibre cleave (4% Fresnel reflection)

Cavity mirror for external feedback

Rare-earth doped fibre

Laser output

Pump diode

Pump diode
Fiber power!
Many regimes!

Pump power limited in many cases!

Different wavelengths
Pulsed (fs – ns)
Single frequency…
Energy levels in rare-earth ions

- High-power fiber lasers are generally doped with rare earths
- Lots of energy levels and transitions in RE ions
- In silica, only four meta-stable levels can be pumped with high-power laser diodes
- Six transitions have been used for high-power cladding-pumped silica fiber lasers
  - Nd, Er, Tm, Yb, Ho

Figure from P. C. Becker, N. A. Olsson, and J. R. Simpson, Erbium-doped fiber amplifiers: fundamentals and technology (Academic Press 1999)
Simplicity of Yb$^{3+}$-ions makes YDFLs exceptionally efficient

- Only two energy levels
  → No upconversion or cross-relaxation
  → High concentrations can be used
  Very low quantum defect (can be below 10%)
- Pump at ~915 nm – 975 nm
- Emit at ~ 1060 nm

*Figure from P. C. Becker, N. A. Olsson, and J. R. Simpson, Erbium-doped fiber amplifiers: fundamentals and technology (Academic Press 1999)*
Yb-doped fiber sources

### Some record results

<table>
<thead>
<tr>
<th>What</th>
<th>Characteristics</th>
<th>Who</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highest-power fiber laser (MM)</td>
<td>100 kW</td>
<td>IPG</td>
<td>Yb-doped, 10xx nm, cw. Large number of (SM) fiber lasers bundled together so no inherent limitation.</td>
</tr>
<tr>
<td>Highest-power SM fiber laser</td>
<td>15 - 20 kW</td>
<td>IPG</td>
<td>Yb-doped, 10xx nm, cw, tandem-pumped with 1018 nm YDFLs (?)</td>
</tr>
<tr>
<td>Highest-power diode-pumped SM fiber laser</td>
<td>2 - 3 kW</td>
<td>IPG, Jena, ORC, Corning</td>
<td>Yb-doped, 10xx nm, cw</td>
</tr>
<tr>
<td>Highest-power Tm-doped</td>
<td>1 kW</td>
<td>Q-Peak / Nufern</td>
<td>2000 nm, SM, cw</td>
</tr>
<tr>
<td>Highest-power Er-doped</td>
<td>0.3 kW</td>
<td>ORC</td>
<td>1570 nm, cw, $M^2 = 3.9$</td>
</tr>
<tr>
<td>Highest-power 980 nm</td>
<td>0.1 kW</td>
<td>Jena, Bordeaux</td>
<td>Cw, nearly diffraction-limited, air:silica micro-structured fiber</td>
</tr>
<tr>
<td>Highest-power Bi-doped laser</td>
<td>~ 20 W (?)</td>
<td>FORC, General Physics Institute</td>
<td>~ 1150 nm, cw, SM, core-pumped by 10xx nm YDFL</td>
</tr>
</tbody>
</table>

These records may have been superseded in some cases. Many apologies for any left-out results.
### Some record results

#### Narrow linewidth

<table>
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<tr>
<th>What</th>
<th>Characteristics</th>
<th>Who</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highest-power narrow-line</td>
<td>1.7 kW</td>
<td>ORC</td>
<td>Yb-doped, 10xx nm, quasi-SM, cw, sub-GHz linewidth. Also highest-power high-gain MOPA.</td>
</tr>
<tr>
<td>Highest-power narrow-line polarization-maintaining</td>
<td>1.1 kW</td>
<td>ORC</td>
<td>Yb-doped, 10xx nm, quasi-SM, cw, 100-MHz-level linewidth.</td>
</tr>
<tr>
<td>Highest-power narrow-line “eye-safe”</td>
<td>0.6 kW</td>
<td>Northrop Grumman</td>
<td>Tm-doped, 2 µm, SM, cw, single-frequency</td>
</tr>
<tr>
<td>Highest-power narrow-line Er-doped</td>
<td>0.15 kW</td>
<td>ORC</td>
<td>1550 nm, SM, cw, single-frequency, tunable</td>
</tr>
</tbody>
</table>

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Some record results
Wavelength-converted

<table>
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<th>What</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Highest-power fiber Raman laser</td>
<td>1.3 kW</td>
<td>SIOM</td>
<td>1120 nm, core-pumped by 1080 nm YDFL. Also highest-power core-pumped fiber laser of any description.</td>
</tr>
<tr>
<td>Highest-power cladding-pumped fiber Raman laser</td>
<td>100 W</td>
<td>ORC</td>
<td>1120 nm, quasi-SM, cw, cladding-pumped by 1060 nm YDFL.</td>
</tr>
<tr>
<td>Highest-energy cladding-pumped fiber Raman laser</td>
<td>0.2 mJ</td>
<td>ORC</td>
<td>1120 nm, quasi-SM, cladding-pumped by 1060 nm YDFL.</td>
</tr>
<tr>
<td>Highest-power supercontinuum source</td>
<td>50 W</td>
<td>Imperial College</td>
<td>CW, core-pumped by 1070 nm YDFL. SC-generation in air:silica micro-structured fiber</td>
</tr>
<tr>
<td>Highest-power frequency-doubled fiber laser</td>
<td>80 W (530 nm)</td>
<td>ORC</td>
<td>530 nm, SM, pulsed (ps), frequency-doubled polarized Yb-doped fiber MOPA</td>
</tr>
</tbody>
</table>

These records may have been superseded in some cases. Many apologies for any left-out results.
### Some record results

#### Pulsed

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</tr>
</thead>
<tbody>
<tr>
<td>Highest-energy</td>
<td>82 - 113 mJ</td>
<td>Michigan U, Tsinghua U</td>
<td>0.2 mm core diameter, Yb-doped, 10xx nm Michigan 82 mJ, $M^2 = 6.5$, Tsinghua: 113 mJ, $M^2 = ?$</td>
</tr>
<tr>
<td>Highest-energy (quasi-) single-mode</td>
<td>22 mJ</td>
<td>Jena</td>
<td>Yb-doped, 10xx nm. “9-mJ pulse energy Q-switched large-pitch fiber laser system with excellent beam quality”, Paper 8237-31. 22 mJ reported at ASSP.</td>
</tr>
<tr>
<td>Highest-power fs. Also highest average power pulsed.</td>
<td>830 W</td>
<td>Jena</td>
<td>Yb-doped fiber MOPA, CPA, SM, polarized, 120 MHz, 640 fs, 12 MW (compressed).</td>
</tr>
<tr>
<td>Highest-power mode-locked fiber laser</td>
<td>65 W</td>
<td>Jena</td>
<td>Yb-doped, 10xx nm, 850 nJ. Compressed peak power 6 MW.</td>
</tr>
<tr>
<td>Highest in-fiber peak power</td>
<td>5 MW</td>
<td>Aculight</td>
<td>Yb-doped, 10xx nm, SM, 4.3 mJ, 1 ns. Air:silica micro-structured (“rod-type”) laser.</td>
</tr>
</tbody>
</table>

*Also some of the record results on earlier slides were pulsed!*

These records may have been superseded in some cases. Many apologies for any left-out results.
Optical fibres provide several fundamental advantages for lasers and amplifiers

- Confinement of pump and signal beams
  - High gain efficiency

- Long interaction length
  - RE-concentrations at quench-free level
  - Low heating per unit length
  - Simplified heatsinking

- Control of the propagation properties by the waveguide
  - Beam profile / single-mode output

- High gain
- High power
- High nonlinearities
  - Sometimes good, often bad
  - High gain & high nonlinearities → “interesting physics”
Interaction length: Bulk laser vs. fibre laser

Bulk: Not possible to maintain tight focusing over adequate length
→ High threshold, high thermal load

Fibre

Pump beam

Tight beam confinement and maximum intensity over arbitrary length.
→ Low threshold
→ High gain efficiency
→ Even three-level low-concentration systems lase (EDFA)
→ Low thermal load per unit length
An engineerable gain medium!

- The materials properties (spectroscopy) can be engineered to a degree with all gain media

- Fibers in addition open up for engineering of the geometry
  - Glass host with unique fabrication procedure

- This makes fibers much more amenable to engineering and they can have a high level of functionality
Engineering of fiber properties

- Spectral control
  - Distributed waveguide filtering
  - Bragg gratings in photosensitive fibers
  - Concentration & distribution of rare earths & co-dopants
- Spatial control
  - Single-mode propagation in multimode core
  - Mode filtering
  - Mode conversion
- Dispersion tailoring (temporal control)
- Nonlinearity

→ Altogether much greater control than with conventional non-waveguiding gain media
  - CO$_2$, Nd:YAG, Ti:Al$_2$O$_3$ ...

*Great advantage for sources in different regimes*

*Make the most of this*
Fibers provide many additional advantages

- Compact packaging & low weight
  - Can be coiled with cm-scale radius
- Compatibility with telecom technology
  - Telecom & fiber technology very sophisticated; still low cost
  - By far the biggest market for optics
- Thermal & mechanical stability, robustness
- Reliability and lifetime
  - High reliability and lifetime of telecom laser diodes and telecom devices
- Integrability
  - Fiber Bragg gratings, dyes, liquids, gases, nonlinearities... can be engineered into fiber
  - Fibers can be spliced together for added integration
    - Wavelength-selective couplers
    - Tapered fiber bundles
    - Fiberized components (modulators, isolators...)
  - Integration to complex systems with high functionality
Two dominating active fiber devices with very different characteristics

• Er-doped fibre amplifier for telecom
  – High gain efficiency
  – Long interaction length → low concentration for low quenching
  – Single-mode operation
  – Enabled the Internet
  – Laid the foundation for active fiber technology

• High-power Yb-doped fibre lasers and amplifiers
  – Low thermal load per unit length & simplified heat sinking
  – Single-mode operation
Power-scaling

Important points: High power fiber sources are,

- Cladding-pumped by multimode laser diodes
- Doped with rare-earth laser ions, notably Yb
- Silica-based
  (with few exceptions)

- The fibre converts the relatively low-brightness beam from a diode source to a much brighter beam with somewhat lower power
Principles of operation (amplifier)

- Optical **fibre doped with rare earth** in the core
- The RE ions are optically pumped to an excited state by **laser diode**
  The excited RE ions generate / amplify light via **stimulated emission**
- **Pump coupler** combines signal and pump
Example: Schematic end-pumped rare-earth-doped fibre laser

- In this example, fibre is really only the gain medium
- Similar to conventional bulk laser such as Nd:YAG
- Far from the ideal “all-fibre” laser without free-space paths
- Still, the fibre & waveguiding can provide many advantages!
Example: Amplifiers in different pumping configurations

**End-pumped**
- Pump not in same mode as signal
- “Space multiplexing”
- “All-fibre”
- Allows for continuous fibre path
- Robust

**Side-pumped**
- Pump not in same mode as signal

### Diagram
- Dichroic mirror
- Lens
- Rare-earth doped fibre
- Signal in
- Signal out
- Pump diode
- Pump diode
- Pump diode
- Pump diode
- Signal in (fibre)
- Signal out (fibre)
- Splice
- Pump couplers

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High-power pump diodes

**Diode stacks**

0.2 – 1 kW, 808, 915, 940, 980 nm

Alternatively, use lots of single-emitter diodes with combining network!

- Power up to ~ 10 W each

- Packages with several single-emitter diodes can provide > 100 W of fibre-coupled power
High-power pump diodes (II)

- High power
- Low cost (< $5/W)
- High efficiency
  - 80% reported
  - 50% – 60% standard pigtailed

- But, multimode = “low” brightness

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Why not simply use the diodes directly?

- Power is not enough
  - 100 W enough for lots of processing, but... don’t try it with a light bulb
- Power must be “concentrated” and ideally controllable
  - Spatially
  - Spectrally
  - Temporally (pulsed)
  - Brightness
- Fibres are very good for this at high powers
  - Long
  - Waveguide
- Also excellent amplifiers
  - MOPA

It’s not a lightbulb!!!!!!!
Brightness: key property of lasers

- Spatial brightness
- Related to focusability (beam quality, $M^2$) and intensity

$$B = \frac{P}{\Omega A} = \frac{P}{\pi^2 w^2 \theta^2} = \frac{P}{\lambda^2 (M^2)^2} = \frac{P}{\pi^2 w^2 NA^2}$$

$$\frac{P}{A} = I = B\Omega$$

$P$: Power
$A$: Area at focus
$\Omega$: Solid angle
$I$: Intensity

MM diodes:
High power
Poor beam quality
→ Limited brightness
Cladding-pumped fibre

- Cladding-pumping always leads to spatial concentration of light, from multimode diode to (nearly) diffraction-limited fibre laser output
- Enhancement of (spatial) brightness
Five orders of magnitude brightness-enhancement possible with cladding-pumping

- Launch low-brightness high-power diode into inner cladding of fibre!
- The converted output beam emerges from a much smaller core with much smaller NA than the inner cladding
  - Area up to 1000 times smaller in Yb-doped fibre laser
  - NA (angles) up to 10 times smaller
→ Brightness enhancement of over $10^5$ possible in Yb-doped fibre laser
  - Ideally $M^2_{out} = 1$; $M^2_{pump} > 300$ possible

$$\frac{B_{out}}{B_{pump}} = \left( \frac{P_{out}}{P_{pump}} \right) \left( \frac{w_{pump} NA_{pump}}{r_{core} NA_{out}} \right)^2 = \eta \left( \frac{w_{pump} NA_{pump}}{r_{core} NA_{out}} \right)^2$$
Brightness and power of Yb-doped fiber sources and diode sources


Pump launch

End-pumping
Side-pumping
Pros and cons of end-pumping

+ Simplest approach
  + Straightforward fibre fabrication, preparation and setup
+ High efficiency
+ Minimal pump brightness degradation
  – At most two pump launch points
  – Launch point becomes hot-spot – risk for failure
    – Multiple launch points or distributed pump injection preferable
  – Pre-empts splicing & “all-fibre” devices (without free-space path)
Side-pumping schemes
(more correctly, space (or mode) division multiplexing)

V-groove side-pumping
Keopsys

Rare-earth-doped core
V-groove
Outer cladding
Inner cladding
Focusing lens

IPG??

Silicone Coating

GTWave® SPI lasers

Side splice

Pump beam

Tapered fibre bundle
From C. Headley, OFS
Also Sifam, ITF...

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Tapered fiber bundle

- Buffer
- Inner-cladding
- Outer-cladding
- Core
- Splice
- Tapered bundle
- Fiber bundle

6 pump fibers & 1 signal fiber into 1 active fiber
## Pumping schemes pros and cons

<table>
<thead>
<tr>
<th></th>
<th>End-pumping</th>
<th>Tapered fiber bundle</th>
<th>V-groove side-pumping</th>
<th>GTWave</th>
<th>Side-splicing</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>End user ease of use and reconfigurability</strong></td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Ruggedness</strong></td>
<td>Limited</td>
<td>Good</td>
<td>Medium</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td><strong>Type of active fiber</strong></td>
<td>Any</td>
<td>Any</td>
<td>Any</td>
<td>Special (polymer-coated)</td>
<td>Polymer-coated (strippable)</td>
</tr>
<tr>
<td><strong>Signal launch efficiency</strong></td>
<td>Poor (free-space launch)</td>
<td>Good</td>
<td>Best (continuous fiber path)</td>
<td>Best (continuous fiber path)</td>
<td>Best (continuous fiber path)</td>
</tr>
<tr>
<td><strong>Active fiber size</strong></td>
<td>Arbitrary</td>
<td>125 – 500 µm?</td>
<td>Arbitrary (&gt; 200 µm?)</td>
<td>100 – 200 µm?</td>
<td>Arbitrary (&gt; 125 µm?)</td>
</tr>
<tr>
<td><strong>Size of pump fiber / emitter</strong></td>
<td>Arbitrary (same as active fiber)</td>
<td>125 – 200 µm</td>
<td>Arbitrary (same as active fiber)</td>
<td>100 – 200 µm?</td>
<td>100 µm??</td>
</tr>
<tr>
<td><strong>Pump launch efficiency</strong></td>
<td>Best</td>
<td>Excellent (?)</td>
<td>Good</td>
<td>Good</td>
<td>Good (?)</td>
</tr>
<tr>
<td><strong>Pump power handling</strong></td>
<td>Good (&gt; 3 kW)</td>
<td>Best (&gt;10 kW?)</td>
<td>Medium</td>
<td>Good (&gt; 1 kW)</td>
<td>Medium/good (?)</td>
</tr>
<tr>
<td><strong>Brightness preservation</strong></td>
<td>Best</td>
<td>Good</td>
<td>Poor</td>
<td>Good</td>
<td>Medium (?)</td>
</tr>
<tr>
<td><strong>Pump launch points</strong></td>
<td>2</td>
<td>2 – 18</td>
<td>Arbitrary</td>
<td>Distributed (Typically 4 ports)</td>
<td>Arbitrary</td>
</tr>
<tr>
<td><strong>Pump hot-spots?</strong></td>
<td>Yes</td>
<td>Yes</td>
<td>Yes (?)</td>
<td>No</td>
<td>No (?)</td>
</tr>
</tbody>
</table>

Notes: These are estimates. Published data are scarce.
Pump power handling of a single launch point is very good with end-pumping, but the number of launch points is limited to two.


Pump absorption: avoid circular symmetry

Pump absorption in 1 m long Er:Yb co-doped fiber with and without suppression of helical rays

But no need for pump absorption $> 20$ dB (?)
Multi-kilowatt single-mode Yb-doped fibre laser

> 2 kW of output power!

Spatial beam combination

Power supply & Diode controller

Diode stack @975 nm, 1.2 kW ORC

Diode stack @978 nm, 2 x 1.1 kW SPI

2 x Diode stack @978 nm, 2 x 1.1 kW SPI

Power supply & Diode controller

> 2 kW of output power!

Signal output
Multi-kilowatt single-mode Yb-doped fibre laser (II)

• Maximum output (> 2.1 kW) was limited by available pump power
  – Not limited by thermal effects!
• Diffraction limited beam quality: $M^2 = 1.2$
  – Five orders of magnitude brightness enhancement
• Excellent power handling indicates higher power possible
  – 10 kW?
2 kW YDFL / MOPA
IPG, 2005


YDF: 10 m, 10.6 µm MFD
Grating
Pump coupler
490 W @ 1090 nm
20 W x 36 976 nm LDs in total

YDF: 6 m, 12 µm MFD
Splice
1040 W
20 W x 36 976 nm LDs in total

YDF: 9 m, 14 µm MFD
20 W x 72 976 nm LDs in total
1960 W

Not really laser, but cascade of low-gain amplifiers (7 dB)
Total pumping 144 x 975 nm LDs with 20 W of power into 100 µm pigtail
-- Total pump power ~ 2880 W for 2 kW output power

SPI Lasers uses similar configuration

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Ytterbium-doping is best for power-scaling

- Highest fibre power (multi-kW)
- Highest efficiency (> 80% slope efficiency)
  – Reduces heat load
- Simple spectroscopy
- Emission wavelength 1 – 1.1 µm
- Pump wavelength 0.9 – 1 µm

- Yb can be incorporated in high concentrations
  – Fiber lengths 1 – 10 m rather than 10 – 100 m!
  – Allows for tandem-pumping for “ultra-low” thermal load
MOPAs bring out the best of high power rare earth doped fibres

Cladding-pumped RE-doped fibres offer unique \textit{combination} of
high power
high efficiency
high gain
broad bandwidth

→ \textbf{MOPAs} (master oscillator – power amplifiers) allow for
control, sophistication and high power at the same time
Versatile & rapidly reconfigurable
Why fibers for high-power, high brightness lasers?

Thermal effects enemy #1 for high power, high brightness lasers

$\Delta E = h\nu_p - h\nu_L \rightarrow$ Quantum defect heating

Excited-state absorption
Additional heating from nonradiative loss (e.g., cross-relaxation, impurities)

Pump power $\rightarrow$ Heating $\rightarrow$ Laser output

Heat removal $\rightarrow$ Temperature increase $\rightarrow$ Damage due to melting or burning

Temperature gradient $\rightarrow$ Thermal lensing/guiding $\rightarrow$ Thermally-induced stress
Fiber geometry unsurpassed for heatsinking

ROD

Heat

Heat

Laser

Pump

Pump

THIN Disc

Heat

Heat

SLAB

Heat

Laser

Heat

Heat

CLADDING PUMPED FIBRE

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Disadvantages

- **High nonlinearities**
  - Sometimes good, often bad
  - High gain & high nonlinearities $\rightarrow$ “interesting physics”

- **Low energy storage**
  - The flip side of high gain efficiency (& tight confinement)
    - Already a small stored energy creates a high gain, which leads to instabilities and large power losses to amplified spontaneous emission

- **Low damage threshold**
  - Especially in pulsed regime
## Limitations of fibers

**Optical damage**
- Large core
  - (New materials? Air-guided??)
  - All operating regimes

**Nonlinear degradation**
- Large core
  - Short fiber
    - Higher RE-concentration / new materials
    - Higher pump brightness
  - Spectral filter

- Primarily pulsed and narrow linewidth regimes

**SBS**
- Linewidth broadening of signal
  - SBS negligible for > 10 GHz linewidth
  - No SBS for pulses shorter than ~5 ns
  - Linewidth broadening of gain
    - Temperature, stress, compositional variations

- Very narrow linewidth
- Large core & short fiber helps, too!

**Energy storage**
- Large core

- High energy pulses

**Thermal degradation**
- Longer fibers
  - Better coatings
  - Improved heatsinking
  - Tandem-pumping
  - Smaller core?

Incl. TMI
- Longer fibers
  - Better coatings
  - Improved heatsinking
  - Tandem-pumping
  - Smaller core?

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- Longer fibers
  - Better coatings
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  - Smaller core?
Size matters!
Silica matters, too!

- **Large core** to facilitate:
  - power handling
  - minimization of nonlinear effects
  - high energy storage for pulsed application
  - efficient pump absorption & reduced device length

- Large inner cladding for launch of high-power pump beams

- Silica-based
  - Superb power-handling
  - Excellent control of parameters

Large core is the most important design feature of a high-power fibre laser

Typically a few hundred square microns

9 / 125 µm
100 W

40 / 650 µm, > 1 kW
Research on core area scaling
Single-mode operation of large cores

- **Rod fibre**
- **Straight, rigid, low NA**
- **Crystal fibre, Jena, Bordeaux, Aculight...**

- **Leakage channel fibre**
- **High leakage loss for higher order modes**
  - “Modal sieve”
- **U. Bath, IMRA**

- **Chirally coupled core**
- **High resonant coupling loss for higher order modes**
- **U. Michigan**

- **Higher order mode fibre**
- **Claim: Higher order mode more robust than the fundamental mode**
- **OFS**
Diffraction-limited large-core fibre lasers

Control of refractive index profile is essential

Conventional process

In large cores, the beam follows the index profile. The fundamental mode is NOT diffraction-limited with ring-shaped large cores.

Improved process

- More accurate RIP allows for diffraction-limited fundamental mode
- Precise control in large structures real challenge

Progress

Central dip
M² value ~ 3.2

No central dip
M² value ~ 1.4

J. Sahu, CLEO 2004

J. Nilsson, “High-power fiber lasers”
KTH Winter School, Romme, Feb 5 2016
But, core area scaling doesn’t end all problems

• 36.6 kW maximum output power with assumed parameters
  – Diode pumped Yb-doped fibre

For highest powers, we need to balance thermal effects and nonlinearities

- There are lots of different nonlinearities and thermal effects
  - Stimulated Raman scattering, self-phase modulation, stimulated Brillouin scattering...
  - Thermal lensing, thermal mode instabilities, thermal damage...
- Nonlinearities mitigated by short fibers and large core area
- Thermal effects mitigated by long fibers and small core area
- Possible to find optimum value of length / area
  - Compromise between SRS and thermal beam distortions
  - Maximum power a constant 36.6 kW on ridge
Why fibre is better than bulk

- Optimum value of length / area ~1000 times larger than the value of length / area for laser rod
  - Fundamentals of beam propagation (diffraction-limited beam & Gaussian optics) vs. materials constants (thermal conductivity, thermo-optic constants, nonlinear coefficients...)

→ Waveguiding helps! The fibre waveguide allows us to find best trade-off between nonlinearities and thermal distortions, as governed by fundamentally different materials parameters and physical aspects, whereas a rod laser doesn’t!
Applications
**Unique characteristics enable unique devices**

- High-gain broadband amplifiers for telecom
  - *Erbium-doped fibre amplifier* in particular, also Raman amplifiers
  - High gain efficiency and low threshold
  - Single-mode operation and low polarization-dependence crucial fibre attributes
- High-power *broadband ASE-sources*
  - Require high gain
- Amplifiers for *ultrashort pulses*
  - Require broad bandwidth
  - The controllable dispersion provides additional advantages
- Efficient high-power Nd-doped fibre amplifiers at 900 nm (Ti:Al₂O₃ replacement?)
  - Requires suppression of dominating 1100 nm transition
  - Possible with *distributed fibre filter*
  - Also S-band EDFAs
- **Distributed feedback fibre lasers** -- with FBGs written into the fibre
- **High-power MOPAs** with superb control of optical parameters
  - Impossible to obtain directly in high-power lasers
  - Fibre amplifiers work very well in high-power MOPA systems
- And many more, including high-power tunable fibre lasers

*And, of course... High efficiency and geometry of Yb-doped fibres ideal for high powers*
Application areas

- **Industrial**
  - Materials processing, welding, printing ...
- Aerospace & defence
  - Lidar, range-finding, directed energy, remote sensing...
- Pump sources
  - Lasers
  - Nonlinear converters
    - **UV** (lithography, etc.), X-rays, visible, supercontinuum...
- Medical
  - Imaging, laser surgery, cosmetics...
- Scientific
- Telecoms (?)
  - Raman lasers, high-power multi-port EYDFA, free-space communications, ...
- Displays (?)
  - Requires visible sources
Materials processing
most important application

M. N. Zervas & C. A. Codemard,
“High Power Fiber Lasers: A Review”,
Tm-doped fiber lasers  
(high power)

- After Yb, Tm may be most important dopant for high-power fiber lasers
- Emit at ~ 2000 nm
- Can be pumped with high-power diodes at ~ 800 nm
- Output power up to 1 kW
- Not nearly as good as Yb-doped fiber lasers, but potential may be greater
Tm$^{3+}$-doped silica fiber lasers at 2 $\mu$m: Spectroscopy

Efficient high-power diodes are only available at $\sim$ 800 nm, out of the possible pump wavelengths
Tm$^{3+}$-doped silica fiber lasers at 2 µm

- 2 for 1 cross-relaxation process improves efficiency beyond Stokes limit with 800 nm diode pumping
  - Requires short distance between Tm-ions
  - Works better at high concentrations
- 70% slope efficiency reported
- 170% quantum efficiency

Erbium:ytterbium co-doped fiber lasers for power-scaling in the 1.5 – 1.6 µm range

• The pump absorption of Er$^{3+}$:silica has been too low for high-power direct-diode cladding-pumping of Er-doped fibers (without Yb)
  • Core absorption limited to ~ 50 dB/m

• Ytterbium co-doping (sensitization) increases the pump absorption and enables cladding-pumping of Er-doped fibers with high-power diodes

• Erbium is tremendously important for telecom and probably the 3$^{rd}$ most important dopant for high-power fiber lasers

• Ytterbium sensitization (co-doping) used for high-power lasers and to some degree for telecom amplifiers with ~ 1 W of output power
Principles of Er:Yb co-doped fiber lasers

- Energy transfer between ions $\rightarrow$ concentrations need to be high
- Yb-concentration 5 – 20 times higher than Er-concentration
- Each Er-ion is
  - Likely to have nearby Yb-ion
  - Unlikely to have nearby Er-ion (avoids Er concentration quenching)
- Each Yb-ion must be able to transfer energy to nearby Er-ion
  - Sufficient Er-concentration
- The high Yb-concentration also allows for adequate pump absorption

EYDFL experimental set-up


**Fiber details:**
- Core 30 μm, NA 0.2
- Inner-cladding diameter 400 μm, NA ~0.48
- L = 4 m
- Pump absorption: 4.5 dB/m

Pump: 975 nm diode stack source
Launch coupling lens: \( f = 8 \) mm
Pump launch efficiency: > 80%
Fiber ends: perpendicularly cleaved → 4% - 4% feedback also at 1060 nm!

HT: high transmission, HR: high reflection
Er:Yb-doped DCFL – 120 W

Fiber Improvements:
Optimised Yb/Er ratio and fiber core composition to suppress ~ 1 µm lasing


0.3 kW EYDFL @ 1567 nm

High-power C-band & L-band tuning

C-band: Max. power > 40 W
Short fiber

L-band: Max. power > 70 W
Long fiber

All-fiber configuration utilizing a tunable FBG and tapered splicing technique


J. K. Sahu et al., CLEO 2004, paper CMK1
Bismuth-doped silica fiber lasers

Relatively new and unproven dopant for fiber lasers

Potential for amplification in elusive 1300 nm telecoms window

Power-scalable (?)
Bismuth-doped fiber basics

- Bismuth-doped silica
- Silica host opens up for power scaling
- Bismuth is not a rare earth
  - “Poor metal”
  - Multiple oxidization states with different spectroscopic properties are likely


http://www.nature.com/lsa/journal/v1/n5/full/lsa201212a.html
High power bismuth doped fiber laser

- 15 W output power
- Emission wavelength ~ 1150 nm
- Slope efficiency ~ 20%
- Pumped by Yb-doped fiber laser at around 1060 nm
- Low pump absorption (~ 0.3 dB/m)
  - Long fiber
  - Core pumping

**Broad gain bandwidth in bismuth-doped phospho-germanosilicate fiber**

Power still low, but several tens of watts now reported at 1.1 – 1.2 mm in aluminosilicate fibers.


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*From E. Dianov*

Arrows indicate pump wavelengths; laser and corresponding pump wavelengths are shown by lines of the same type.

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Power-scaling of fiber Raman lasers
Stimulated Raman scattering in silica is wavelength-agile

Flexibility in signal & pump wavelength
**kW-level fiber Raman laser**

- Core-pumped by YDFL at 1080 nm
  - No brightness-enhancement...

Results:
- $M^2 = 1.9$
- Output power: 6 W
- Slope efficiency 19%; Threshold: 33 W
- Efficiency limited by high background loss of tested fiber
- Order-of-magnitude brightness enhancement

Summary

- Thermal properties make fibres excellent for high-power, high-brightness operation
  - Low threshold helps, too
- Ytterbium-doped fibre lasers available at 10 – 20 kW
- Fibres are engineerable
- Beam combination (e.g., phased-array lasers) open up for multi-element diffraction-limited power-scaling
- MOPAs enable high control at kW level
  - Temporal
  - Spatial
  - Spectral

*It may be difficult to make a multi-kW fibre source with record-breaking performance but it is Very Easy to splice together a 10 W source that is very useful for your research!*
Books on Rare Earth Doped Fibre Amplifiers and Lasers

France, P. W., ed., *Optical fibre lasers and amplifiers* (Blackie 1991) -- *Old and thin but quite good.*


Digonnet, Michel J. F., ed., *Rare earth doped fiber lasers and amplifiers, 2nd ed.* (Marcel Dekker 2001) -- "Best coverage of fibre lasers and physics."


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