Fiber lasers: The next generation

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kW fibre laser

No connection!
After the telecoms EDFA
The fibre laser – another fibre revolution?

Fibre laser 1985

Fibre laser 2006

21th anniversary of the invention of the diode-pumped silica fibre laser
Gapontsev’s Law
Fiber Laser Power doubles every year

Major Players:
• SPI
• ORC
• IPG
• Jena

Power output limited by available diode pumps, not by fiber
Fiber lasers withstand heat because:

- Large surface area
- Core is close to heatsink
- Guided mode resists thermal distortion
- Silica has excellent heat resistance

**What is a fibre laser?**

Fiber lasers withstand heat because:

- Large surface area
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- Silica has excellent heat resistance
Approaches to heat resistance
Fibre Laser or Disk Laser?
The two newcomers

Long and thin? Or short and fat?
Why can a fiber take so much power?
Scaling the core size for high power handling

Core area can be 400 times larger than for telecoms
Non-linear effects and damage scale with core area

Max power: 1.36 kW @1090 nm
Slope efficiency: 83%
Beam quality M²: 1.4

10 kW should be possible!
Unique advantages of fibre lasers

- Superb beam quality and pointing accuracy at kW's
- Excellent pulse stability
- High gain permits MOPA's

- High efficiency (>30% wall plug)
- Ease of thermal management
- Low-cost medium

- Monolithic robust structure
- Small footprint
- Can be mobile/airborne

Applications:
- Stent manufacture
- Welding
- Printing/gravure
- Marking
- Pacemakers
- Cutting
Perfect Beam Quality:
Smaller spot, greater target intensity or larger working distance

Users have never before had a tool with such beam precision at high power
The advantages of beam quality
Welding at a distance
Disadvantages of Fiber Lasers

Long and thin gives:

- Very high core intensity – damage, nonlinear limitations for pulsed applications (Brillouin, Kerr and Raman)
- Small active volume – low pulse energy (~10mJ)
- Very high gain – can be difficult to stop spurious lasing
- Photodarkening (if you are not careful!)
- And - are they scalable to very high powers?

But – we can use all the low cost fiber telecom tricks Special fibers, filters, compression, couplers, etc
Some fibre tricks:
All silica double-clad fibres for high power

- **Circular geometry**
  - 100nm struts give NA > 0.6

- **Square geometry**
  - 2μm struts give NA = 0.1
What is a Cladding-Pumped Fiber Laser?

Rare-earth-doped core converts multimode pump energy to high brightness, *diffraction-limited*, signal beam.
An elegant solution to pump injection: GTWave™ Double-Clad Fiber

Common low-index polymer cladding

Pump Fibers (Silica)

Yb-Doped (signal) fiber

3 x preforms

Furnace

Coating applicator

Diam ~1mm
Power Scaling using a MOPA Chain

- Add one or more amplifiers
- Retain all-fibre approach
- Scalable to >1000W

Further power scaling currently requires spatial beam combination and loss of beam quality
400W GTWave module

What is the optimum module power before beam combining?
Recent results at Southampton

**CW laser Configuration**
- 1.36 kW Yb-doped fibre laser ($M^2=1.4$)
- 633 W PM Yb-doped fibre laser
- 188 W 1550 nm Er/Yb co-doped fibre laser ("eye safe")
- 75 W 2 µm Yb-sensitized Tm-doped fibre laser

**CW MOPA Configuration**
- 402 W / 511 (PM / Non-PM) single-frequency Yb-doped fibre MOPA
- 151 W 1562 nm single-frequency Er/Yb co-doped fibre MOPA

**Pulsed**
- 120 W Q-switched Yb-doped fibre laser (0.6/8.4 mJ/pulse)
- 60 W 4 ps 10 GHz Er/Yb codoped fibre MOPA (1550 nm)
- 321 W 20 ps 1 GHz Yb-doped fibre MOPA (1060 nm)

All pumped with 915 - 980nm laser diodes
More wavelengths:

‘Eye-safe’ wavelengths > 1.5µm are important

Technology alert
Latest 293W ‘Eye-safe’ Er/Yb co-doped fibre laser

Diode stack @975 nm, 1.2 kW

Double-clad Er/Yb-doped fibre

Signal output @1567 nm

Emission @~1 μm

Unabsorbed pump

293 W

Er/Yb co-doped core ~30 μm
Fiber OD 600 μm
Length 6 m
High-power pulsed operation

- Fiber lasers typically limited to a few mJ and ~10kW peak power
- A very large core volume increases stored energy
- Leads to questions over packaging and mode control
- Beam combination may be the answer
- What can we do?
Pulsed 1550nm EYDF MOPA’s

4 ps 60W 10GHz
Amplified gain-switched diode

100ns High-energy
Amplified Q-switched fibre laser

Latest results: 321W (1060nm) 20ps 1GHz and now 300fs
321 W average power, 1 GHz, 20 ps, 1060 nm pulsed fibre MOPA source

Gain-switched diode (Master-oscillator)

1 GHz

DC Bias

Gain-switched diode (Master-oscillator)

20 ps (after CFBG)

975 nm pump

90/10 coupler

Seed Laser

50/50 coupler

CFBG

Double-clad YDF

HR@1060 nm
HT@975 nm

Unabsorbed pump

321 W

Peak power 13kW
Pulse energy 0.26 μJ
Slope efficiency 78%

975 nm pump

490 μW

5 mW

200 mW

Core-pumped YDFA

Cladding-pumped YDFA GTWave®

Double-clad YDF

HR@975 nm
HT@1060 nm

HR@1060 nm
HT@975 nm

Normalized amplitude

Time delay [ps]
For higher peak power we can use pulse compression tricks

Parabolic pulse amplification (fs)

- Broad gain bandwidth of Yb allows amplification of ultrashort (~100fs) pulses
- Parabolic pulse formation exploits fiber gain/nonlinearity to give high-power linearly-chirped pulses that can be compressed

>5MW peak power ~100fs pulses at 25W average power
Pulsed: Higher average power

160W 300fs MOPA

Passively mode-locked 1055-nm VECSEL
and Yb-fiber power amplifier
Amplified VECSL 160W fs source

4 ps, 910 MHZ pulses at 1055nm from a VECSEL

Fiber amplification up to 160 W plus temporal compression to 330 fs
More colours

80 W average power green from a frequency-doubled picosecond Yb-doped fiber MOPA source
80W Green laser

Pulsed laser diode

120MHz, 80ps, 1060nm seed

975 nm Pump LD

47% conversion efficiency
Diffraction limited (M2 ~ 1.15)

80W 530 nm

180W 0.5nm polarised beam M2<1.1

1060 nm

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The $300 laser lamp for projection displays?

Supercontinuum generation in highly nonlinear holey fibres

Megalumens!
The Power Limits

How High Can We Go?
Thermal limits of single fiber lasers

Assumptions:

- JAC fiber, NA~0.44, 20μm air-gap.
- Surface temperature maintained at 25°C by cooling.
- Uniform heat dissipation along 10m device length.
- Core and Inner Cladding dimensions scaled to maintain pump and signal intensities at a known safe level.
Further Power Scaling: Fiber Design Is The Key

Size matters!

9/125 mm 100W

40/650 mm > 1kW

GTWave multi-port fiber

single-mode signal fiber

multi-mode pump fiber

GTWave fiber

multi-mode pump fiber

Photonic Bandgap

Multi core

Air clad

Ribbon

Hi-bi
Towards a Megawatt CW?

- Fiber lasers are ideal for power scaling by beam combination because of their near-perfect beam profiles and coherence.
- Important to maintain beam quality ($M^2 \sim 1$).
- Wavelength beam combination for industrial?
- Coherent beam combination looks attractive for military (Requires single-frequency and polarised beams).

Where have we got to?
Who is interested?

[Image of a military vehicle with labeled components: Laser Chiller, Beam Control, Prime Power, Laser Device, Fire Control]
Future Steerable 1 MW Design?
Multi-path MOPA

Lengths matched to within coherence length of source

DFB fiber laser

1000 W
1000 W
1000 W

Phase-coherent output for synthetic-aperture source

Single-mode
Single-frequency
Single-polarization
511W Single-Frequency MOPA

Output Power

Backward Signal Power

Slope efficiency: 80%
Max. power: >500 W

fiber Length 9m
OD 650µm
Core 43µm

Linewidth <60kHz
M² <1.6

But why was the Brillouin limit so high?
Wavelength-combining for high power industrial lasers?

- Could combine tens of fiber lasers as in telecom DWDM
- Retains beam quality
- An advantage to have numerous pump diode injection points
Conclusions: A view from the cutting edge

- Fibre lasers are challenging conventional laser technology and continue to gain market share.

- Fiber circuitry provides a unique high-gain environment for robust designs. Stable, reliable and reproducible.

- The single-fiber laser will reach 10kW sooner than you think!

- MOPA configuration allows highly-controllable pulse and single-frequency operation.

- With beam combination, the ideal laser for both industrial and defence applications.