High power fiber lasers emitting at 1030 nm and 976 nm

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1. Introduction

2. Fiber lasers at 1030 nm
   ✓ Sub 300 fs: Fiber CPA
   ✓ Sub 100 fs: Direct amplification
   ✓ Sub 10 fs: Few cycles with OPCPA

3. Fiber lasers at 976 nm
   ✓ Main issues
   ✓ High power: CW laser
   ✓ High energy: Q-switch
   ✓ High peak power: Mode-lock systems
   ✓ Blue Light
   ✓ High brightness pumping of Yb-doped materials
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   - High brightness pumping of Yb-doped materials
A revolution in laser technology: fiber lasers

- Large amplification bandwidth
- Limited thermo-optical problems
- Excellent beam quality
- Efficient diode pumping operation
- High single pass gain
- Large variety of doping ions
- Compactness
Diode pumped solid-state laser evolution

**End pumped bulk laser**

- Laser Diode
- HR-Mirror
- Output coupler
- Gain medium
- Laser beam
- Lens

**Side pumped bulk laser**

- Laser Diode
- HR-Mirror
- Output coupler
- Gain medium
- Laser beam
- Lens
Diode pumped solid-state laser evolution

Stress-induced birefringence

Beam distortions

Low power

High power

Thermal lensing

Quantum defect = 24 %
Diode pumped solid-state laser evolution

Disk Laser
- Laser Diode
- Lens
- Disk
- Cooling
- HR-Mirror
- Laser beam
- Output coupler

Slab Laser
- Slab
- HR-Mirror
- Lens
- Laser Diode
- Laser beam

Fiber Laser
- Fiber
- Laser Diode
- HR-Mirror
- Lens

reduced thermo-optical distortions
Diode pumped solid-state laser evolution

Heat is spread over long distances in fibers
Standard single mode active fiber

- Core size < 10 µm
- Requires single mode pumping diodes
- Pumping limited to 1 W
- Length: 10..100 m (non linear effects)

Not compatible with high power
Double clad fiber

- High power multimode pumping diodes
- but higher core doping: \( \frac{\Phi_{co}}{\Phi_{cl}} \)

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E. Snitzer et. al., Optical Fiber Communication Conference, PD5, 1988

E. Cormier CMDO 2010
Step index vs air-clad microstructured fibers

Double-clad fiber

- Polymer pump clad
- Polarization-maintaining

Air-clad fiber

- Higher NA for pump core
- No pump radiation in the polymer clad
- Larger MFD while singlemode
Typical microstructured fibers used in our systems

- Large core diameter with diffraction limited operation

80 μm (NA < 0.02)

- Air-clad microstructures for pump propagation (NA = 0.6)

- Polarization maintaining design for environmentally stable operation

40 μm (NA < 0.01)

Flexible fibers

Rod type fiber
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Chirp Pulse Amplification

- Reduced peak power
- Reduced nonlinear effects

\[ I = \frac{E}{A \cdot \tau} \]

CPA fiber amplifier: sub 300 fs

\[ E = 100 \, \mu J \]
\[ T = 270 \, \text{fs} \]
\[ f = 300 \, \text{kHz} \]
\[ P = 340 \, \text{MW} \]
\[ \Delta \lambda = 7.2 \, \text{nm} \]
\[ P_{\text{av}} = 30 \, \text{W} \]

Y. Zaouter et al, Optics letters 33, 1527 (2008)
J. Boullet et al, Optics letters 34, 1489 (2009)
CPA fiber amplifier: sub 300 fs

J. Boullet et al, *Optics letters* 34, 1489 (2009)
Direct amplification: sub 100 fs

Yb:KYW oscillator

Diodes
60 W @ 976 nm

Microstructured rod-type 80/200 fiber

Transmission grating
1740 l/mm

Output
Direct amplification: sub 100 fs

- Gain: \( I(z) = I_0 \exp(\alpha z) \)
- SPM: \( \omega(t) = \omega_0 \left(1 - \frac{\ln^2}{c} \frac{dI}{dt}\right) \)
- asymmetric gain

Spectrum extends up to 60 nm
Modulations smoothed out due to amplification
Direct amplification: sub 100 fs

12.5 W (1.25 µJ)

66 fs

8.6 W (0.86 µJ)

47 fs

18 MW: 1.25 µJ @ 65 fs

10 MHz

Y. Zaouter et al, Optics letters 33, 107 (2008)
Y. Zaouter et al, Optics express 15, 15, 9372 (2007)
FCPA pumped OPCPA : sub 10 fs

- Signal source
- Pump source
- Signal stretcher
- Yb Fiber CPA pump
- Parametric amplifiers
- Compressor
FCPA pumped OPCPA : sub 10 fs

- 7 fs Ti:Sapph Oscillator
- 300 nm @ -10dB
- CEP stabilized

Rainbow
FCPA pumped OPCPA : sub 10 fs
FCPA pumped OPCPA: sub 10 fs

- CEP stabilized Modelocked source
- Signal stretcher
- Yb Fiber CPA pump
- Parametric amplifier
- Compressor

Flow:

- FCPA Pump
- Rainbow signal
- BBO Type I
- SF10 prisms
- To SHG-FROG
FCPA pumped OPCPA : sub 10 fs

• Spectrum

$\Delta \lambda = 68 \text{ nm}$

1 µJ
68 nm amplified bandwidth @ 720 nm
10 fs (3.6 cycles)

• Duration

$\Delta \tau_{\text{field}} = 10 \text{ fs}$

100 kHz

J. Nillon, et al, ASSP 2009, [Post Deadline], Denver USA
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Yb-doped fiber lasers operating at 976 nm

Configuration 1

$\lambda_p = 976 \text{ nm}$

$\lambda_s = 1030 \text{ nm}$
Yb-doped fiber lasers operating at 976 nm

Configuration 1

Yb-doped fiber

\[ \lambda_p = 976 \text{ nm} \]

\[ \lambda_s = 1030 \text{ nm} \]

Configuration 2

Yb-doped fiber

\[ \lambda_p = 976 \text{ nm} \]

\[ \lambda_s = 1030 \text{ nm} \]

915 nm

976 nm

1030 nm
Yb-doped fiber lasers operating at 976 nm

Issue #1: Transparency:

$$\sigma_s^{\text{em}} \sim \sigma_s^{\text{abs}}$$

Bleaching is achieved if:

$$\frac{n_{\text{trans}}}{n_{\text{Tot}}} = \frac{\sigma_s^{\text{abs}}}{\sigma_s^{\text{abs}} + \sigma_s^{\text{em}}} \approx 50\%$$

for a pump intensity of:

$$I_p^{\text{trans}} = \frac{h \nu_p}{\left( \frac{\sigma_s^{\text{abs}}}{\sigma_s^{\text{abs}}} - \sigma_s^{\text{em}} \right) \tau_{\text{fluo}}} \approx 30 \text{ kW/cm}^2$$

Transparency at 1030 nm achieved for inversion ~5% …
Yb-doped fiber lasers operating at 976 nm

Issue #2: Gain competition between quasi and true 3-level laser operation:

\[ G_{1030} = 0.25 \, G_{976} + 0.72 \alpha_p \beta \]

- Pump absorption
- Clad to core area ratio

- Rod type U-LMA PCF: 80 / 200 μm

- \( \beta = 6.2 \): \( \alpha_p = 9 \) dB \( \Rightarrow \) \( G_{1030 \text{ nm}} < 50 \) dB

- \( \Phi_{\text{clad}} = 200 \) μm \( \Rightarrow \) \( P_p \sim \text{several 100W} \)
High power CW laser at 976 nm

Rod type fiber:
Microstructured
Double clad Yb doped
80µm/200µm
Absorption: 10 dB/m
Length: 1.2 m

1. $P_{trans}^p = 11$ W
2. $\beta = 6.2$, losses = 60 dB

Boulet et al., OE 16, 17891 (2008)
High power CW laser at 976 nm

Efficiency:
- Slope Efficiency = 48%
- $P_{\text{thresh}} = 18\text{W}$

Spectrum:
- 977.5 nm

Beam quality:
- $M^2 = 1.35$

Parasitic lasing suppression:
- 35 dB

Boulet et al., OE 16, 17891 (2008)
High energy Q-switch laser at 976 nm

MOPA: Master Oscillator Power Amplifier

Boulet et al., OL 35, 1650 (2010)
High energy Q-switch laser at 976 nm

Slope efficiency ≈ 35 %
Amplification threshold = 27 W

78 W @ 190 KHz, 32 ns
Or
1 mJ @ 10 KHz, 12 ns

M² < 1.4

Boulet et al., OL 35, 1650 (2010)
High peak power mode-lock laser at 976 nm

Mode-Locking:
non-linear polarization evolution
All-normal dispersion

$\Delta\lambda_{1/2} = 5 \text{ nm}$

$\Delta\lambda_{1/e^2} = 10 \text{ nm}$

Lhermite et al., OL 35, 3459 (2010)
High peak power mode-lock laser at 976 nm

Output pulses

\[ \Delta \tau = 1.44 \text{ ps} = 1.41 \times 1.02 \text{ ps} \]

Compressed pulses

\[ \Delta \tau = 402 \text{ fs} = 1.41 \times 285 \text{ fs} \]

- \( P_{av} = 480 \text{ mW} \)
- \( \nu = 40.6 \text{ MHz} \)
- \( E = 11.8 \text{ nJ} \)
- \( \Delta \lambda = 5 \text{ nm} \)
- \( \Delta \tau = 285 \text{ fs} \)
- \( E_{\text{compressed}} = 6 \text{ nJ} !!! \)
- \( P_{\text{peak}} = 21 \text{ kW} \)

50% compressor efficiency only!! Potentially 37 kW

Lhermite et al., OL 35, 3459 (2010)
Blue light generation at 488 nm

High energy fiber laser
59 W @ 977 nm

LBO crystal
\(\lambda/2\), \(\lambda/4\)

DM
\(\omega\), \(2\omega\)

36 % efficiency

16.1 W at 488 nm

Boulet et al., Europhoton (2010)
Blue light generation at 488 nm

Applications of high brightness intense sources at 488 nm
- Replacement of Ar ion lasers
- Laser surgery
- Dermatology
- Biophotonics
- Laser light shows and laser display RGB

Bouilet et al., Europhoton (2010)
High brightness pumping of Yb-doped material

Single-mode laser

\[ d_0 = \frac{4\lambda f}{\pi D_0} \]

Multi-mode diode

\[ d_0 = M^2 \frac{4\lambda f}{\pi D_0} \]

Brightness:

\[ B = \frac{P}{S\Omega} \]
High brightness pumping of Yb-doped material

High power fiber laser

High power diode

Yb:CaF$_2$

High brightness optical pumping of Yb materials
High brightness pumping of Yb-doped material

ASE source at 976 nm

$\text{TEM}_{00}$

Up to 40 W
High brightness pumping of Yb-doped material

- Small signal gain up to 10 expected with long crystals
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