Developments in new high power fiber lasers and ultrafast lasers

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Townes Laser Institute at UCF

New Florida Center of Excellence at the University of Central Florida

Dedicated May 4 2007

~ 57,000 students
2nd largest university in USA

High power fiber lasers
Lasers in Medicine, Advanced Manufacturing & Defense.
Economic Development

Collaboration Agreement with Fraunhofer Institute for Laser Technology Aachen – Industrial Laser Materials Processing

COLLEGE of OPTICS & PHOTONICS
Current Faculty 45
Graduate students ~ 180
Space ~ 105,000 sq ft
Budget ~ $12M/yr
Axel Schulzgen
Professor
(ex Univ. Arizona, Humbolt Univ.)
Multi-structured optical fibers
Phosphate fibers, Fiber lasers, NLO fibers

Ayman Abouraddy
Assistant Professor
(ex MIT, Boston Univ)
Multifunctional fibers, CG, polymer and photon band-gap fibers
Biomed fibers

Rodrigo Amezcua-Correa
Research Assistant Professor
(ex Southampton & Bath Universities)
PCF fibers. Silica fibers
Outline

Advances in High Tm fiber lasers
  Spectral control and tuning
  Pulsed laser operation in ns, ps and fs regimes

Towards multi-kW power levels with spectral beam combining
  GMRF-line controlled lasers
  Dense spectral packing within Tm linewidth (1850 – 2150 nm)

Atmospheric transmission tests over 1 km
  Spectral tuning through water absorption lines

First LIBS detection of organic signatures with Tm fiber lasers
  Advantages of Detection

Next generation of high power ultrafast lasers
  CEP and quasi single cycle
Control of the spectral regime
narrow linewidth output
tunable emission
stable frequency control

Pulsed operation at 2 um
Q-switched ns regime
ps pulses with
fs pulse mode-locking

kW powers through beam combining
initial demonstration
dense wavelength stacking

Applications of cw and pulsed Tm fiber lasers
High power beam propagation
Spectral sensing technologies
Medical applications
High Harmonic Generation

\[ V\text{-parameter} \sim \lambda^{-1} \]
\[ \text{SRS}_{\text{thresh}} \sim \lambda^{-1} \]
\[ P_{\text{crit}} \text{ (self-focusing)} \sim \lambda^{-2} \]
Thulium laser characteristics

- Many Potential Pump Bands
  - Different applications call for different bands
- 790 nm pumping highly efficient
  - High diode powers available
- Cross Relaxation process
  - Quantum defect 40% → CR allows >75% efficiency
  - Multi-polar interaction between adjacent thulium ions allows energy transfer between them
  - Single pump photon can generate two laser photons
- Optimum doping
  - High Tm doping levels needed
  - Use of Al to minimize clustering in silica host which causes energy transfer up-conversion
Propagation near 2 μm offers inherent benefits of increased MPE and reduced aerosol absorption.

Blue: Atmospheric transmission between 0.8 and 2.2 μm  
Green: aerosol absorption (α = 0.18 km⁻¹ at λ = 1 μm)  
Black: Relative laser Gain in Yb, Er–Yb and Tm short length silica fiber lasers  
Red: Maximum Permitted Energy for 100 ns pulse (log scale).

Spectral control of the large Tm bandwidth

Volume Bragg Gratings (VBG)
*Glebov Group @ CREOL*
high efficiency >95%
tunable (100 pm)

Guided-Mode Resonant Filter (GMRF)
*Eric Johnson Group @ UNCC*
fixed wavelength by design
linewidth (50 pm)

Fiber Bragg Grating (FBG)
*Nufern Inc*
all-fiber, monolithic fabrication
linewidth ~2.5nm
B. Sampson
Nufern

Slope efficiency ~55%
~110W output power at 2050nm (FWHM ~2.5nm) from a grating based laser cavity
E-O efficiency = 17% at 110W with 793 nm bars

\[ V_{\text{eff}} = 2.61 @ 2.05\mu m \text{ for } 25/400 \text{ fiber} \]

70W output at 1908nm

\[ E_{\text{qua}} = A + Bx + Cx^2 \]

\[ \begin{align*} A &= 54.35216 \quad 56.77923 \\ B &= -0.13454609 \quad -0.13972182 \\ C &= 8.34772E-05 \quad 8.616E-05 \\ R^2 &= 0.99853 \quad 0.9984 \end{align*} \]
300 W Stable, Tunable MOPA

Power Amplifier Performance

- 8 W seed power
- Up to 220 W power
- Example slope at 1.967 μm (65%)
- >1 hr Stability
- Tuning from 1.927 μm – 2.097 μm
- FWHM <200 pm (MO limited)
- $M^2 < 1.2$

\[ y = 0.6467x - 7.9751 \]
Volume Bragg Grating High Power Oscillator

VBG Reflectivity

Normalized Reflectivity (a.u.)

Wavelength (nm)

~5 m 25/400 TDF

VBG or HR 25/400 UDF 0.09 NA

L1 M1 L2

L3 L2

Grating tilted 0.6° in two axes

VBG Front Surface Uncoated

5 mm 6 mm

VBG Schematic

Volume Bragg Grating

High Power Oscillator
- 159 W VBG Stabilized Power at 2053 nm
- 54% Slope (~5% less than for HR due to no AR coating on VBG)
- Stable spectrum < 1nm 10dB width (linewidth limited by VBG)
- $M^2<1.2$ in all cases, independent of feedback
- >1 hr stable operation time. Power limited by onset of parasitic lasing
- Rotation of VBG changes wavelength
- 50 W VBG Tunable Power
- 47-54% Slope
- >100 nm tuning range (1947-2053nm)
- Range limited by onset of parasitic lasing due to VBG design and fiber length
Fiber Lasers based on Guided Mode Resonance Filters

**Pump diode:** 790nm 400 μm, 0.22 NA fiber, 30 W; 11 cm coiling diameter on heatsink

**GMRF provided by collaboration with Eric Johnson (UNCC)**

![Diagram of Fiber Laser System with GMRF](image)

**GMRF Spectral Reflectivity**

*Transmission ~ 50 pm linewidth*
Fiber Lasers based on Guided Mode Resonance Filters

GMRF provided by collaboration with Eric Johnson (UNCC)


> 10 W with GMRF linewidth < 100 nm
Dense wavelength packing of Tm fiber lasers

**Principle Elements**

Dense stacking of narrow line (~100 pm) wavelength-specific lasers under effective bandwidth of 200 nm

Beam Combiner utilizes high damage resistant Dielectric Edge Mirrors (DEM)s

Q-switched 2 um Tm fiber laser LIBS sensing

**Tm fiber laser:**
- Wavelength: 1992 nm
- Duration: 200 ns
- Energy: 100 uJ
- Repetition rate: 20 kHz

**Focusing optics:**
- 0.3 NA asphere
- Diameter: 10um
- Irradiance: 600 MW/cm²

**Spectrometer:**
- Acton HRE Echelle
- Range: 200-900 nm
- Resolution: 0.04 nm

**Acquisition:**
- Delay: 0ns
- Duration: 300 ns

Matthieu Baudelet et al., Optics Express 18 7905 (2010)
Co-pumped LMA (23/250 TDF) “all-fiber” amplifier
~0.5 W Average power; Amplified at full 46 MHz
~11 nJ pulse energy; Limited by feedback to modelocked laser due to poor isolation

- **Improvements in Process**
  - Use Isolator for correct wavelength
  - Higher seed power/preamp for better saturation and energy extraction
  - More seed power -> higher efficiency
  - Pulse down counter -> more per pulse energy

- **Goals**
  - Reach microJoules level in conventional fiber
  - Reach 10’s W average power
  - Compare nonlinear thresholds to similar Yb lasers
Towards an all-fiber fs Tm laser

Average Power 12.8 W
182 nJ uncompressed pulses 60 nm Bandwidth

Sims et al ASSP 2011
Innovative Science & Technology Experimentation Facility (ISTEF)

- A fully equipped laser ranging facility on Cape Canaveral Air Force Station
- Full laser and telemetry support
- 1 km (fully secure) range
- 5 km and 10 km ranges
- Many different receivers

Beam image at ~300 m on 1 km range
A 50 mm lens is used to collimated the beam from the fiber facet along a 1 km laser range.

- Beam diameter measurements along the 1 km range confirm nearly diffraction-limited beam divergence.
- The centroid moved between 6.5 – 7.5 % of the full beam diameter corresponding to pointing variation of <45 μrad including beam distortion from atmospheric turbulence.
Initial 2 μm Tm fiber laser propagation tests

Beam images after 1 km propagation with identical initial power, confirming atmospheric transmission MODTRAN simulations
<table>
<thead>
<tr>
<th>Laser Type</th>
<th>Details</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>TW Laser</td>
<td>100 fs 850 nm CPA Cr:LiSAF 300 mJ 0.1 Hz 1 J single shot</td>
<td>High intensity laser plasmas, Hard X-ray generation &amp; imaging, Air filamentation studies</td>
</tr>
<tr>
<td>MFL 2004–2010</td>
<td>40 fs 800 nm CPA Ti:Sapphire 40 mJ 10 Hz 2 mJ 1 kHz</td>
<td>LIBS sensing studies, Femtosecond spectroscopy, Air filamentation studies</td>
</tr>
<tr>
<td>MTFL 2010</td>
<td>40 fs 800 nm CPA Ti:Sapphire 400 mJ 10 Hz</td>
<td>Air filamentation studies, LIBS sensing studies, Standoff spectroscopy</td>
</tr>
<tr>
<td>HERACLES 2010-</td>
<td>5 fs 800 nm OPCPA CEP Hybrid 2 mJ 10 kHz</td>
<td>Attoscience, EUV generation &amp; applications, THz studies</td>
</tr>
<tr>
<td>PhaSTHEUS 2011-</td>
<td>5 fs 800 nm OPCPA CEP Hybrid 100 mJ 1 Hz</td>
<td>Attoscience, EUV generation &amp; applications, Stand-off THz studies, Air filamentation studies</td>
</tr>
</tbody>
</table>
Energy scaling of few cycle systems

HERACLES: High Energy Repetition-rate Adjustable Carrier Locked to Envelope System

PhaSTHEUS
Herrmann et al
ASSP 2009

HERACLES
Witte et al., Opt. Expr 2006

Krausz et al. CLEO, 2007
Tünnermann et al., Opt. Expr 2009
Chalus et al., Opt. Expr 2009

100 mJ
10 mJ
1 mJ
100 µJ
10 µJ
1 µJ

1 Hz 10 Hz 100 Hz 1 kHz 10 kHz 100 kHz 1 MHz +

Mid-IR systems
800 nm systems
Architecture of HERACLES

- CEP stabilization
- Ultra broadband Ti:Sapphire oscillator
  - 85 MHz
  - 5 pJ
  - 1064 nm

- Dual stage pre-amplifier
  - 85 MHz
  - 2 nJ
  - 25 ps

- Pulse picker
  - 85 MHz
  - 2 nJ
  - 2 ps

- Regenerative amplifier
  - 1-10 kHz
  - 2 nJ
  - 0.7 mJ
  - 85 ps

- Single pass amplifier
  - 1-10 kHz
  - 2.2 mJ
  - 85 ps

- OPA #1
  - 40 pJ
  - 45 ps

- OPA #2
  - 15 mJ
  - 85 ps

- Compressor
  - 1-10 kHz
  - 9 fs
  - 1.5 mJ

- Multi pass booster amplifier
Technique implemented on HERACLES limits losses in compressor

\[ \text{low loss compressor enables higher output energy at low cost} \]
mJ, multi-kHz, TEM$_{00}$ pump beam generation
Amplified spectrum supporting a 7.3 fs transform-limited pulse
The high energy beam line

CEP stabilization

Ti:Sapphire

Yb fiber preamplifier

Stretcher

1 nJ
20 ps
1 Hz

Nd:YAG regenerative amplifier

Nd:YAG double pass amplifier

Nd:YAG single pass amplifier

Nd:YVO₄ regenerative amplifier

Nd:YVO₄ single pass amplifier

Nd:YAG multi-pass amplifier

OPA #1

OPA #2

OPA #3

Compressor

20 pJ
20 ps
1 Hz

20 pJ
20 ps
1-10 kHz

1 nJ
20 ps
1 Hz

1 nJ
20 ps
1-10 kHz

100 mJ
85 ps
1 Hz

10 mJ
85 ps
1-10 kHz

1 mJ
8 fs
1-10 kHz
1 Hz

10 mJ
8 fs
1 Hz
New laser technologies are breathing new concepts into ultra-fast laser technologies

Many new applications opening for ultra-short pulse lasers

In addition to pressing to higher powers, we are pushing to towards shorter pulses, higher efficiencies, more compact and rugged systems.

After 50 years of lasers
After 25 years of ultrafast

This field offers so much for the next generation of scientists and engineers
<table>
<thead>
<tr>
<th>Educational Programs in Laser Materials Processing</th>
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<tbody>
<tr>
<td><strong>NSF International REU Program in Optics, Lasers Photonics and Optical Materials</strong></td>
</tr>
<tr>
<td>International summer internship program for undergraduates</td>
</tr>
<tr>
<td>1998 – present</td>
</tr>
<tr>
<td>&gt; 70 students</td>
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<tr>
<td>2 year program</td>
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<tr>
<td><strong>NSF Materials World Network Program</strong></td>
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<tr>
<td>In novel IR fibers</td>
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<tr>
<td>Clemson University, UCF, Bordeaux University, Turin University, Adelaide University</td>
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<tr>
<td>2007 – 2012</td>
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<tr>
<td>Mobility program</td>
</tr>
<tr>
<td>~ 20 students</td>
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<tr>
<td><strong>ATLANTIS-MILMI</strong></td>
</tr>
<tr>
<td>University Central Florida, Bordeaux University, Clemson University, Friedrich-Schiller Univ.</td>
</tr>
<tr>
<td>2008 – present</td>
</tr>
<tr>
<td>International MS degree</td>
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<tr>
<td>Lasers and Materials Interaction Science</td>
</tr>
<tr>
<td>~ 16 students</td>
</tr>
<tr>
<td><strong>Co-tutelle doctoral degree Program in Laser Materials Processing and Optical Materials</strong></td>
</tr>
<tr>
<td>University Central Florida, Clemson University, Bordeaux U.</td>
</tr>
<tr>
<td>2004 – present</td>
</tr>
<tr>
<td>Joint Ph.D</td>
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<tr>
<td>7 graduates expansion</td>
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</table>
Acknowledgements

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Spireon
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NUFERN
Thank you!