Scaling of fiber laser systems based on novel components and high power capable packaging and joining technologies

T. Schreiber, J. Limpert, A. Tünnermann
Fraunhofer IOF Jena, Germany and
IAP, Friedrich-Schiller-University Jena, Germany
Scaling of fiber laser systems based on novel components and high power capable packaging and joining technologies

Fraunhofer IOF Jena, Germany and IAP, Friedrich-Schiller-University Jena, Germany

Approved for public release, distribution unlimited

See also ADA564694. Mid-Infrared Fiber Lasers (Les fibres laser infrarouge moyen). RTO-MP-SET-171
Outline

- introduction
- packaging and joining technologies
  - Application to microchip lasers
- novel components
  - Applications to fiber laser system scaling
- example of MID-IR source
- possible further directions
Fiber Laser
Introduction

- fiber lasers and amplifiers
  - high gain, excellent and power independent beam quality

- all fiber setup for stability
Fiber Laser

Introduction

- rare-earth doped fibers, \textit{kW} average power levels available

\begin{itemize}
  \item long wavelength by heavy metal cation fibers (e.g. zirconium, ZBLAN fibers), which are not as "stable" as fused silica
\end{itemize}
Outline

- introduction
- **packaging and joining technologies**
  - Application to microchip lasers
- novel components
  - Applications to fiber laser system scaling
- example of MID-IR source
- possible further directions
Fiber Laser

Introduction

designing a (Mid-IR) source …

- power and nonlinearity handling, optical properties …
- short pulsed, …, cw, broadband
- packaging / joining
- Optomechanical requirements, stability for military/space, …

components
architecture

NLO
EUV
VIS
MID-IR
Overview of Joining Technologies for Optoelectronic Packaging

- Bonding of different materials always required
- Material, thermal or optical contact desired

Bonding of Optical Components

- **with** macroscopic intermediate layer / media
  - Adhesive Bonding
  - Laser Beam Soldering

- **without** macroscopic intermediate layer / media
  - Laser Splicing/Welding
  - Contact Bonding

Wafer Level Bonding
Mineralic, Fusion, Anodic, Eutectic, Glass-frit, liquid capillary...
Bonding and Packaging of Optical Components
Adhesive Bonding

- Alignment of a Micro Lens Array to a CCD Sensor
  - 6 degrees of freedom
  - Alignment step wide: 0.1 – 1 µm
Bonding and Packaging of Optical Components
Laser Soldering

- long term stability
- high temperature stability
- high radiation stability compared to adhesives
- good vacuum compatibility / no outgasing
- high thermal and electrical conductivity
- flux free processing due to sputtered thin film metallization
- flexible and automated assembly

laser beam soldered optics for lithography
Bonding and Packaging of Optical Components

Solder Bumping

- Example of fiber coupled diode
Bonding and Packaging of Optical Components

Mineralic Bonding

- Inorganic bonding at low temperatures (≤ 200°C) using special silicate solutions
- E.g. for high precision optical & mechanical systems
- High stability (intermediate layer <200nm)
  - Low stress
  - “Cold” bonding
  - No creep
  - No „out-gassing“
Bonding and Packaging of Optical Components
Laser based splicing and tapering

- Tapering and splicing device as well as process control developed
- easy adaptable
- very precise joints
- computer controlled process with high joining reproducibility
- mechanical stable welded joints
- high purity process without contaminations
- very low optical losses
- no consumables like process gas or filaments

Multimode fiber (ø720µm) with spliced end cap (ø1500µm)
**Bonding and Packaging of Optical Components**

**Direct bonding**

- Without additional material – surface activation
- Direct bond by a Waals forces
- Very small tolerances

- Joints are sensitive to shock
- Adjustment only within the plane of joining

- Assemblies tested under vacuum and cryogenic environment

≈ $250^\circ$ C
Scaling of fiber laser systems
Novel components and laser systems

- Microchip laser system using bonding technology

Diagram:
- AR coating
- Heat sink
- Laser crystal
- SESAM and Bragg mirror
Scaling of fiber laser systems

Novel components and laser systems

- Microchip laser system using bonding technology
- Unwanted jitter (typical for Q-switched lasers)

200 ps, Slope efficiency of ~ 35%, $E_p = 120 - 140$ nJ, Repetition rate up to 2 MHz
Scaling of fiber laser systems
Novel components and laser systems

- Microchip laser system using bonding technology
- Unwanted jitter (typical for Q-switched lasers)
- Self-injection seeding

Scaling of fiber laser systems
Novel components and laser systems

- Microchip laser system using bonding technology
- Unwanted jitter (typical for Q-switched lasers)
- Self-injection seeding
- Low cost alternative to mode-locked lasers

![Graph showing time and pulse duration vs. output power](image)

Outline

- introduction
- packaging and joining technologies
  - Application to microchip lasers
- novel components
  - Applications to fiber laser system scaling
- example of MID-IR source
- possible further directions
Scaling of fiber laser systems

Novel components and laser systems

- components:
  - novel fiber designs
Scaling of fiber laser systems
Novel components and laser systems

- components:
  - novel fiber designs = novel optical properties
  - endlessly single mode

- MFD independent of $\lambda$
- SM from 0.5 to 2.5 $\mu$m

Scaling of fiber laser systems

Novel components and laser systems

- components:
  - novel fiber designs = novel optical properties

![Ultra-broadband polarizing](image)

- Transmission [dB]
- Wellenlänge [nm]
Scaling of fiber laser systems
Novel components and laser systems

- components:
  - novel fiber designs = novel optical properties

extremely large dispersion shifts

![Graph showing dispersion D vs. wavelength (µm) with A=1.0 µm, d/Λ = 0.8, Ti:Sa, Nd:YAG, Yb, enhanced nonlinearity A_{eff} \sim 1..2 µm²]]
Scaling of fiber laser systems
Novel components and laser systems

- components:
  - novel fiber designs = novel optical properties

extremely large dispersion shifts

efficient nonlinearity $A_{eff} \approx 1..2 \, \mu m^2$
Scaling of fiber laser systems
Novel components and laser systems

- components:
  - novel fiber designs = novel optical properties
  - extremely low nonlinear interaction

![Diagram of fiber laser with labeled components: pump core (200 µm), active core (80 µm), air-clad, 1.5 mm outer cladding]
Scaling of fiber laser systems
Novel components and laser systems

- components:
  - novel fiber designs = novel optical properties
    - extremely low nonlinear interaction

- First GW fiber femtosecond system
- First kW average power fiber femtosecond system
Scaling of fiber laser systems
Novel components and laser systems

- components:
  - novel fiber designs = novel optical properties
  - fiber compatible components

  tapers and endcaps
Scaling of fiber laser systems  
Novel components and laser systems

- **components:**
  - novel fiber designs = novel optical properties
  - fiber compatible components

**tapers and endcaps**

- mJ, ns fiber laser systems
Scaling of fiber laser systems
Novel components and laser systems

- components:
  - novel fiber designs = novel optical properties
  - fiber compatible components

mode-stripper and high power connector
Scaling of fiber laser systems

Novel components and laser systems

- components:
  - novel fiber designs = novel optical properties
  - fiber compatible components

**Novel pump couplers**

- High reflectance at pumping wavelength
- High transmittance at lasing wavelength

![Diagram of novel pump couplers with labeled components]
Scaling of fiber laser systems
Novel components and laser systems

- components:
  - novel fiber designs = novel optical properties
  - fiber compatible components
  - High power components

![Graph showing diffraction efficiency vs. position on grating for TE and TM polarization.](image)
Scaling of fiber laser systems
Novel components and laser systems

- components:
  - novel fiber designs = novel optical properties
  - fiber compatible components
  - High power components

spectral beam combining of **narrow linewidth** sources
Scaling of fiber laser systems
Novel components and laser systems

- components:
  - novel fiber designs = novel optical properties
  - fiber compatible components
  - High power components

![Graph showing combined output power vs. total launched pump power](image)

Outline

- introduction
- packaging and joining technologies
  - Application to microchip lasers
- novel components
  - Applications to fiber laser system scaling
- example of MID-IR source
- possible further directions
- summary
Scaling of fiber laser systems
Novel components and laser systems

- Approach for a fiber based picosecond VIS and MIR source
Scaling of fiber laser systems
Novel components and laser systems

- Approach for a fiber based picosecond VIS and MIR source

### Degenerated FWM

<table>
<thead>
<tr>
<th></th>
<th>Equation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>a)</td>
<td>$2\omega_1 = \omega_2 + \omega_3$</td>
<td>Energy conservation</td>
</tr>
<tr>
<td>b)</td>
<td>$2k_{\text{pump}} = k_{\text{signal}} + k_{\text{idler}} + \gamma P_1 = 0$</td>
<td>Momentum conservation</td>
</tr>
<tr>
<td>c)</td>
<td>Low losses at $\omega_1$, $\omega_2$ and $\omega_3$</td>
<td>No attenuation of the waves</td>
</tr>
<tr>
<td>d)</td>
<td>$\text{MFD}<em>{\text{Signal}} \approx \text{MFD}</em>{\text{Pump}} \approx \text{MFD}_{\text{Idler}}$</td>
<td>Good overlap of the involved waves</td>
</tr>
</tbody>
</table>
Scaling of fiber laser systems
Novel components and laser systems

Approach for a fiber based picosecond VIS and MIR source

Condition a) \(2\omega_1 = \omega_2 + \omega_3\) + b) \(2k_{\text{pump}} = k_{\text{signal}} + k_{\text{idler}} + \gamma P_1 = 0\)

To get widely separated signals move the pump wavelength far away from the ZDW (in the normal dispersion regime)

Furthermore, the amplification bandwidth is given by:

\[
\Omega_A \approx \frac{\gamma P_0}{|\beta_2|\Omega_s}
\]

Thus, additionally to get narrowband signals we need:

- high dispersion
- high separation of the wavelengths

Nonlinear phase-matching diagram (Pump power = 40kWatt)
Scaling of fiber laser systems
Novel components and laser systems

- Approach for a fiber based picosecond VIS and MIR source

  Condition c) Low losses at $\omega_2$ and $\omega_3$

Analyze the phase-matching condition a) and b) and look for a material which transmission window fullfills c)

Transmission spectrum of fused silica

IR graded fused silica is a good candidate to use with tunable lasers from 1020-1090nm!
Scaling of fiber laser systems
Novel components and laser systems

- Approach for a fiber based picosecond VIS and MIR source

Condition d) \( \text{MFD}_s \approx \text{MFD}_p \approx \text{MFD}_i \)

Use an **endlessly single mode design** to ensure good mode field overlap for all involved wavelengths. E.g. an LMA-10 PCF.

Mode field distribution in LMA-10 fiber for signal, pump and idler waves:
Scaling of fiber laser systems
Novel components and laser systems

- Approach for a fiber based picosecond VIS and MIR source

30ps@1030nm
50 & 200ps@1064nm
0.2-1MHz

~100kW peak, 12W av.

1.4m LMA-10

Germanium Filter

1.4m
Scaling of fiber laser systems
Novel components and laser systems

- Approach for a fiber based picosecond VIS and MIR source

Slopes of the signal and idler wave average power with 200ps pulses and 1MHz rep. rate.

Av. power slopes of signal and idler

- ~37% efficiency
- ~6% eff.
Scaling of fiber laser systems
Novel components and laser systems

- Approach for a fiber based picosecond VIS and MIR source

Slopes of the signal and idler wave average power with 200ps pulses and 1MHz rep. rate.

![Graph showing photon flux vs. pump power](image-url)
Outline

- introduction
- packaging and joining technologies
  - Application to microchip lasers
- novel components
  - Applications to fiber laser system scaling
- example of MID-IR source
- possible further directions
Packaging and Joining Technologies for fiber lasers – further directions

- using other NLO-elements + high power silica fiber lasers
  - e.g. quasi phase-matching (orientation-patterned GaAs)
  - transparent (low absorption), nonlinear materials + bonding process (for thermal contact)
- anti-reflection properties on MID-IR fibers
  - effective media directly bonded to fiber end facet
- fiber bragg gratings
  - written by femtosecond pulses
    (for non UV-sensitive fibers)
...
Scaling of fiber laser systems based on novel components and high power capable packaging and joining technologies

Thank you for your attention!