High peak power single-frequency MOPFA for lidar applications

Applications of wind lidars

Wake vortices monitoring
Lidar developments and tests on international airports (CREDOS, FIDELIO EU projects)

Turbulence & windshear monitoring
Turbulence & Wind mapping algorithms (UFO EU project)

Airborne sensors
Lidar developments for true air speed (AIM2 EU project)

Windfarm optimization
Use lidar information for wind mills optimization, feed-forward turbine control (Leosphere)

Onera investigates most of those lidar applications
- by developing the wind lidar
- by developing **the laser source**

Courtesy from S. Wolf, IFALPA

Courtesy from Leosphere

2016-06 CLRC, High peak power single-frequency MOPFA for lidar applications
Wind lidar principle

\[ v_{\text{Doppler}} = \frac{2V_r}{\lambda} = V_r \times 1.3 \text{ MHz/(ms}^{-1}) \times 1.55\mu\text{m} \]

\[ \Delta v + v_{\text{Doppler}} \Rightarrow V_r \]

Detected beat signal

\[ \Delta v + v_{\text{Doppler}} \]

Time ↔ distance

Pulse launch

Local Oscillator

50/50 Coupler

Amplifier

AOM

\[ \lambda = 1.55 \mu\text{m} \]

Detector

Signal processing

\[ \text{LASER} \]

\[ v_0 \]

\[ v_0 + \Delta v + v_{\text{Doppler}} \]

\[ v_0 + \Delta v \]

\[ v_0 + \Delta v + v_{\text{Doppler}} \]

\[ V_{\text{air}} \]

\[ V_r \]
Wind lidar principle

Why fiber lasers?

- **High efficiency** laser/amplifier sources,
- **Compact** lasers and amplifiers,
- No optical **alignment** for all-fiber systems,
- **Low cost**.
- MOPFA allows **versatile** pulsed sources: single-mode, single-frequency, long-pulse (10ns – 1µs)

**BUT:** peak power limited by SBS for narrow linewidth

Typical architecture MOPFA
Master oscillator power fiber amplifier

\[ v_0 + \Delta v \]

**MO**

Pulse shape control

+100MHz

**AOM**

Fiber amplifier(s)

\[ \cos(\Delta v + v_{\text{Doppler}}) \]

\[ \Delta v + v_{\text{Doppler}} = V_r \]
Example application
Wind field monitoring around airport
10 km range; refresh rate: 1 mn for 360°

Source requirements:
- Narrow linewidth: $\Delta v < 1 \text{ MHz}$
- High beam quality: $M^2 < 1.3$
- Pulse duration: $t_{\text{pulse}} = 0.5$ to $1 \mu\text{s}$
- Maximum PRF = 10-15 kHz
- Pulse energy $E = 100'$s $\mu\text{J}$
  $\Rightarrow P_{\text{peak}} = 100 - 1\text{ kW}$
Wind lidar requirements => laser source requirements

Typical architecture MOPFA
Master oscillator power fiber amplifier

MO  AOM
Pulse shape control  Fiber amplifier(s)

+100MHz

Catastrophic when:
P_{\text{peak}} > P_{\text{th}}

Typical Brillouin gain spectrum at 1550nm

Typical Brillouin gain spectrum at 1550nm

P_{\text{th}} = 21 \frac{A_{\text{eff}}}{g_B L_{\text{eff}}}

- A_{\text{eff}}: effective core area
- L_{\text{eff}}: effective fiber length
- g_B: Brillouin gain

Pump wave at $v_p$

Stokes wave at $v_s = v_p - v_B$

Acoustic wave at $v_B$

pump wave + Stokes wave $\rightarrow$ acoustic wave $\rightarrow$ Stokes wave

$\Delta v_B \approx 30\text{MHz}$
$g_B \approx 2.10^{-11}\text{m/W}$
$v_B \approx 11\text{GHz}$

Power (a.u.)

Time (µs)

Pulse
Stokes (SBS)
$P_{\text{th}}$

2016-06 CLRC, High peak power single-frequency MOPFA for lidar applications
How to mitigate SBS in optical fiber?

**Sample SBS threshold:**
- $P_{th} \sim 100$ W in singlemode fibers
- $P_{th} \sim 300$ W in commercial large mode area (LMA) fibers
- $P_{th} \sim 2$ kW demonstrated in specialty fibers$^{1,2}$

Longitudinal variation of Brillouin frequency using temperature, fiber compositions, strain… Compatibility with other requirements (beam quality…)?

Use of **highly doped** short fibers
High efficiency?

Use of **LMA with MFD > 30 µm**
Compatibility with good beam quality?

\[
P_{th} = 21 \frac{A_{eff}}{g_{B}L_{eff}}
\]
Why is this not so simple to increase $A_{\text{eff}}$?

- Fiber doping: Er and Er:Yb at 1.55 µm
- Beam quality in large core fibers
- Increase $A_{\text{eff}}$:
  - 1. MFC fibers
  - 2. PAS fibers: large core

**Alternative way: decrease $L_{\text{eff}}$ with strain**

- Strain principle
- 3. Application on LMA fiber

**Coherent combining**

- of 2 singlemode amplifiers
- of 7 cores of a multicore fibers
Doping for 1.5µm laser amplification: Er vs Er:Yb

**erbium only (Er)**

- \(4I_{9/2}\)
- \(4I_{11/2}\)
- \(4I_{13/2}\)
- \(4I_{15/2}\)

**erbium + ytterbium codoping (Er:Yb)**

- \(4I_{9/2}\)
- \(4I_{11/2}\)
- \(4I_{13/2}\)
- \(4I_{15/2}\)

---

**Good beam quality**
- Direct pumping => no P doping, low core NA possible

**Low pump absorption**
- Er doping <10³ ppm => avoid inter-ions energy transfer

**Fiber/setup design/cost**
- Need for small cladding size and high brightness pump

---

**High pump absorption**
- High Yb doping

**Parasitic emission at 1µm**
- Power limited by Er-Yb back transfer + non participating Yb

**Challenging beam quality**
- P doping => central dip in refractive index profile
Increase $A_{eff}$: Beam quality in large core fibers

Standard step index profile

LMA step index profile. Diam. 30µm / ON 0.10

Er:Yb doped fibers: large NA and central dip

Singlemode fiber

Multimode fiber
State of the art of narrow linewidth 1.5µm fiber sources

- a compromise has to be made between efficiency and peak power
- strategies are required to maximize efficiency and peak power
1. maintain uniform core profile

Microstructured core fiber (IPHT/ONERA collaboration)

Erbium Ytterbium large mode area fiber

Modeling

Measurements


M^2 \sim 1.3

A_{eff} \sim 800 \mu m^2

P_{th} = 2 kW

G. Canat, et al.
CLEO’09, paper JTuB3 (2009)
2. chose co-dopants (Al, P)

Phospho-alumino-silicate (PAS) LMA 30µm (Er,Yb:AIP)

Brillouin threshold $P_{\text{peak}} \sim 770W$ at 650ns pulse duration and 10kHz PRF Slope efficiency 26%
Brillouin threshold $P_{\text{peak}} \sim 1120W$ at 108ns pulse duration and 5kHz PRF Slope efficiency 19%

W. Renard, et al. CLEO 2015
• **Why is this not so simple to increase** $A_{\text{eff}}$?
  • Fiber doping: Er and Er:Yb at 1.55µm
  • Beam quality in large core fibers
  • Increase $A_{\text{eff}}$:
    • 1. MFC fibers
    • 2. PAS fibers: large core
• **Alternative way: decrease** $L_{\text{eff}}$ **with strain**
  • Strain principle
  • 3. Application on LMA fiber
• **Coherent combining**
  • of 2 singlemode amplifiers
  • of 7 cores of a multicore fibers
Strain: principle (1)

Absence of strain, $\delta(z)=0$ everywhere

Unstrained fiber

With strain distribution, $\delta(z)$

Unstrained fiber | 1% Strain

1 single peak
Maximum Brillouin strength

2 peaks in the spectrum, Brillouin threshold increases by x 2

To gain more: continuous distribution

15 2016-06 CLRC, High peak power single-frequency MOPFA for lidar applications
Absence of strain, $\delta(z)=0$ everywhere

Unstrained fiber

With strain distribution, $\delta(z)$

Unstrained fiber | 1% Strain

2 peaks in the spectrum, Brillouin threshold increases by x 2
3. Use of strain distribution to increase the SBS threshold

Experiment: 1579nm high peak power single frequency MOPFA

Spectral broadening

SBS threshold increase

23% efficiency
• Why is this not so simple to increase $A_{\text{eff}}$?
  • Fiber doping: Er and Er:Yb at 1,55µm
  • Beam quality in large core fibers
  • Increase $A_{\text{eff}}$:
    • 1. MFC fibers
    • 2. PAS fibers: large core

• Alternative way: decrease $L_{\text{eff}}$ with strain
  • Strain principle
  • 3. Application on LMA fiber

• Coherent combining
  • of 2 singlemode amplifiers
  • of 7 cores of a multicore fibers
Coherent combining principle

- 1 Master oscillator (pulsed or continuous, narrow linewidth)
- N amplifiers with brightness: \( B_{\text{ampli}} = \frac{P}{(M^2)^2} \) (P power, \( M^2 \) beam quality)
- Phase controller compensates for phase variations
- Sum of power of N lasers with same spatial, spectral, temporal characteristics

\[
B_{\text{final}} = N \cdot B_{\text{ampli}}.
\]
4. Peak power improvement by Pulse Coherent Combining

- Amp1 and Amp2 amplify the common MO
- Amp1 and Amp2 outputs overlap and interfere on a 50/50 beam splitter
- A CW multi-dithering phase controller is used (LOCSET) to minimize O₂ output (⇔ maximize O₁ output)
- The setup is adapted to pulse operation using a leak between pulses.

Overall beam combining efficiency: 95%

Pulse Coherent Combining in a Wind Lidar

• 3 Configurations to check CBC impact on instrument:
  - Single pulse amplifier (30W)
  - Coherently combined pulse amplifiers (30W)
  - Coherently combined pulse amplifiers (96W)

<table>
<thead>
<tr>
<th></th>
<th>Amp 1</th>
<th>Amp 2</th>
<th>Output</th>
<th>CBC</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>49 W</td>
<td></td>
<td>29.5 W</td>
<td>OFF</td>
</tr>
<tr>
<td>B</td>
<td>18.5 W</td>
<td>10.6 W</td>
<td>29 W</td>
<td>ON</td>
</tr>
<tr>
<td>C</td>
<td>49 W</td>
<td>51 W</td>
<td>96 W</td>
<td>ON</td>
</tr>
</tbody>
</table>

• Procedure: 10 min in each configuration
• Comparison of measurements:
  - Carrier to Noise Ratio (CNR) (quality of the signal)
  - Estimated frequency (wind speed)
  - Instrument noise floor
Lidar performance comparison – CNR and estimated frequency

Results:

- **CNR is equivalent** for CBC ON and CBC OFF
- CNR @ 96W is **+5dB** compared to CNR @ 29W (expected **5.2dB**)
- **Noise floor is equivalent** for CBC ON and CBC OFF

First demonstration of wind lidar based on coherent combining!

5. Coherent combination of a multicore fiber

Several Fibers

- Easily increase the number of channel
- One pump and one phase modulator per channel

Multicore Fiber

- Common pump and phase modulator
- Common environment
4. Coherent Beam Combining: some experimental results

- Residual phase fluctuations $\sim \lambda/27$
- Combining efficiency 63%
- 3.7 meters
Onera has investigated various strategies to mitigate SBS

- Generating uniform core by microstructuration
- Adjusting fiber composition in PAS fibers
- Applying strain on the fiber
- Coherent combining

Based on new specialty fibers and new architecture, high peak power single frequency MOPFA are available at 1.55 µm for wind lidar applications.
Long range wind speed measurements

Horizontal measurement on a typical day. Wind speed ~ 40 km/h

Horizontal measurement during « Hermann » storm. Wind speed up to 110 km/h