High peak power Erbium-Ytterbium MOPFA for coherent Lidar anemometry

ONERA, France

S. Jetschke, S. Unger, J. Kirchhof,
IPHT Jena, Germany
1.5μm laser technologies for compact coherent detection lidar

- Erbium-Ytterbium LMA master oscillator power fiber amplifiers
- Multifilament core fibers
Monolithic compact lasers for coherent lidar anemometry

- **Required properties:**
  - Good atmospheric transmission (1.5 µm or 2 µm)
  - Eyesafe wavelength
  - Compact, simple, cheap laser

- **Solutions at 1.5µm:**
  - Semiconductor MOPA (CW regime)
  - Pure Erbium MOPFA (CW/pulsed)
  - Erbium-Ytterbium MOPFA (CW/pulsed)
All semi-conductor MOPA for coherent lidar (1/2)

P = 0.9 W
\( \Delta \nu < 100 \text{ kHz} \)
\( M_{\text{fast}}^2 = 1.16 / \)
\( M_{\text{slow}}^2 = 1.43 \)

Limited to CW regime
Single frequency regime
Broad band phase noise ?

Measurement on rotating diffusing target for 5 days
MOPFA with LMA fibers

- **Injection:** CW low power laser with very good spectral and spatial qualities
- **Modulation:** arbitrary shape and arbitrary high repetition rate (> 10 kHz)
- **Amplification:** monolithic fiber medium with high gain

Amplification @ 1.5 µm => Erbium doping
Stimulated Brillouin Scattering in optical fibers

\[ \omega_s = \omega_p - \Omega_B \]

\[ P_{\text{seuil}} \approx 21 \frac{A_{\text{eff}}}{g_B L_{\text{eff}}} \]

Singlemode fibers \( @ 1.5 \, \mu \text{m} \) \( P_{\text{th}} L = 880 \, \text{W.m} \) without gain. \( P_{\text{th}} = 80 \, \text{W} \) for an amplifying fiber of a few meters.
Erbium-Ytterbium fibers

$^{2}F_{5/2}$  $^{2}F_{7/2}$

Pump @ 975 nm

Ytterbium

Erbium

$^{4}I_{11/2}$  $^{4}I_{13/2}$  $^{4}I_{15/2}$

Signal @ 1550 nm

Quantum defect
~ 33%
High peak power amplification in Er-Yb fibers

High peak power amplification requires:

⇒ Large core diameter
⇒ Low NA (otherwise multimode)

ErYb doped fibers: problem of refractive index dip

⇒ Bad fundamental mode shape,
⇒ Bad mode discrimination
⇒ ErYb doped LMA fibers limited to ~25µm
Resonant pumping of pure Erbium doped fibers

\[ ^4I_{11/2} \]

\[ ^4I_{13/2} \]

\[ ^4I_{15/2} \]

Pump @ 1535 nm

Signal @ 1560 nm

Quantum defect ~ 3% only!


Global efficiency still low, long fiber length required, low non-linear threshold
Outline

- 1.5µm laser technologies for compact coherent detection lidar
- Erbium-Ytterbium LMA master oscillator power fiber amplifiers
- Multifilament core fibers
A high energy amplifier multistage MOPFA for the FIDELIO project

DFB Laser Diode
\(\lambda = 1545\,\text{nm}\)

PRF = 4 kHz
Pulse duration 1 \(\mu\)s

Acousto-optic modulator

SM/PM Er doped
SM/PM DC/ErYb doped
LMA PM DC/ErYb doped
DC/LMA ErYb doped PM IPHT

4 \(\mu\)J
30 \(\mu\)J
\(~250\,\mu\)J
\(~1000\,\mu\)J

Pedestal Multifilament core fiber
Principle of pedestal fibers
MOPFA detailed architecture

- 1545nm DFB
- AOM → WDM → ASE filter → TFB1 → TFB2
- Pump: 1x250mW @ 980nm
- EDF1: PM-SM 3m
- EYDF1: PM-SM 3m
- Pump: 1x2W @ 980nm
- Pump: 4x4W @ 980nm
- EYDF2: PM-LMA 3.5m

Graphs:
- Average Power (W) vs. Pulse Energy (µJ)
- Amplitude (A.U.) vs. Time (µs)
- Repetition frequency (kHz) vs. Average Power (W)
3rd Stage: $M^2$ measurement

$M^2 \sim 1.2/1.4$

![Graph showing diameter vs position with $M^2 \sim 1.2/1.4$.]
Modes superposition

\[ a = \sqrt{1 - \alpha} \cdot E_{LP01} + \sqrt{\alpha} \cdot E_{LP11y} \]

Relative phase

Relative power

\[ \Rightarrow -M^2 \text{ always } > 1.7 \]

-Instable
SWAN lidar characteristics:

- Fibered PM Laser **100µJ**
- Real time signal processing
- Eye safe laser
- 1D scanning pattern
CREDOS vortex measurement campaign (2007)
Outline

• 1.5µm laser technologies for compact coherent detection lidar

• Erbium-Ytterbium LMA master oscillator power fiber amplifiers

• Multifilament core fibers
**Multi Filament Core fibers**

**Global core**
- Core Diameter: 24 µm by 32 µm
- Birefringence: $10^{-4}$
- Core Losses: 0.38 dB/m @ 1200 nm (mostly due to diffusion on filaments-silica interfaces)
- Pump Abs.: 0.9 dB/m @ 915 nm, 3.4 dB/m @ 976 nm

**Filaments in the Core**
- Fil. number: 37
- Fil. diameter: 1.8 µm
- Fil. period: 5.1 µm
Modeling: guided optical modes

- Only one guided mode (there is not 1 mode/filament but 1 global mode because of strong filament interaction)
- Expected $M^2 = 1.5$, $A_{\text{eff}} = 1100 \, \mu\text{m}^2$

« Multifilament-core fibers for high energy pulse amplification at 1.5 $\mu\text{m}$ with excellent beam quality », Opt. Lett., 33 pp. 2071-2073 (2008)
Pulsed amplifier performances

1545nm DFB

AOM

Pre-amp

200µJ

5-30kHz 800ns pulses

250W peak power

MFC fiber

HT @ 1550 nm

HR @ 975 nm

38W 975nm pump

Photodiode

Camera

Powermeter

Polar. analyzer

940 W peak power

(a)

Energy (µJ)

Pulse frequency (kHz)

(b)

Energy (µJ)

Launched pump power (W)
SBS threshold measurement in the MFC fiber

\[ P_{th} \approx 2 \text{ kW peak power} \]

\[ C_B \approx \frac{21}{P_{th} L_{eff}} \approx 4 \times 10^{-3} \text{ W}^{-1} \text{ m}^{-1} \]

\[ g_B = \frac{C_B A_{eff}}{K} \]

Leff and Aeff are calculated by simulations and K=1

\[ g_B \approx 4 \times 10^{-12} \text{ m.W}^{-1} \]
Conclusion

- Intrinsic difficulties of Erbium-Ytterbium fibers due to homogeneities and large NA.

- With pedestal fibers beam quality can be kept good enough to extract 250 W peak power, 100 µJ, make a Lidar for 400 m range vortex measurements

- New special fiber structure is the Multifilament Core Fibers: ~2 kW peak power $M^2 \sim 1.5$ single mode, 1 mJ
ONERA lidar range increase

- **Range (m)**
- **Laser energy (mJ)**


- 1.5 µm fiber lidar range increase
We would like to acknowledge for fundings provided by Region Ile de France, European Union FP6 projects FIDELIO, CREDOS
See talk of C. Besson in Session 8 on Wednesday about FIDELIO project “Pulsed 1.5 µm LIDAR for axial aircraft wake vortex detection”