Low Noise Frequency Stable Fiber Lasers for Optical Remote Sensing Applications

Jens Engholm Pedersen

Oct 22, 2012

NKT Photonics A/S
Denmark
NKT Photonics

**Crystal Fibre**
- High Peak Power Pulsed Lasers
  - Material Processing
  - Military & Defense
  - High-end research & development
  - Gyroscope

**aeroGAIN**
- Advanced sensing
  - Wind LIDAR
  - Seismic
  - Security
  - SHM

**Koheras**
- Replacement of conv. multiple lasers
  - Imaging (bio.)
  - Inspection (semicon.)
  - High-end R&D

**SuperK**
- Spectroscopy
  - Military & Defense
  - High-end research & development

**Argos**
- Advanced sensing
  - Wind LIDAR
  - Seismic
  - Security
  - SHM
Fiber lasers for remote sensing:

1. Laser source requirements for remote sensing
2. What’s on the market?
3. Fiber DFB laser:
   a) general operational principles
   b) noise
   c) new class of frequency stabilized fiber lasers
4. Applications
5. Summary
## Laser based remote sensing

<table>
<thead>
<tr>
<th>Security</th>
<th>Seismic</th>
<th>Structural Health Monitoring</th>
<th>Vibrometry</th>
<th>Wind LIDAR / Ranging</th>
<th>PDV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Water pipes</td>
<td>Laser Doppler vibrometry</td>
<td>Wind turbines</td>
<td>Shock wave analysis</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Oil and gas pipes</td>
<td></td>
<td>Wind assessment</td>
<td>@ km/ sec velocities</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Other</td>
<td></td>
<td>Airports</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Atmospheric sensing</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Aircraft monitoring</td>
<td></td>
</tr>
</tbody>
</table>

fiber interferometry
Laser source requirements for remote sensing applications

• Fiber optic sensing: low levels of change in phase, frequency or intensity
  ⇒
• low noise laser source – low phase & amplitude noise
• compact
• fiber coupled
• maintenance free
• frequency tuneability for some applications

Example: Wind LIDAR
• back scatter coefficient from atmospheric aerosols <10^{-14}
  (depending on aerosol concentration (clean air is a problem!))
• => good signal-to-noise ratio requires high power + low noise
Compact low noise laser sources

**NPRO** laser has set the standard for compact low noise lasers for years.

Last 10 years: **new class of laser products** for fiber optic and remote sensing.

- greater wavelength selection
- compact (similar foot print)
- fiber coupled
- maintenance free
- single frequency
- narrow linewidth
- low phase noise – some comparable to NPRO

**SCL: RIO** (talk later this session), Teraxion

**Fiber lasers:** Orbits Lightwave, NP Photonics, NKT Photonics
Focus: Distributed Feed-Back Fiber Laser – UV processing

Laser wavelength:

\[ \lambda_B = \Lambda_B \cdot n(\lambda_B, \varepsilon, T) \]

Pump light

\[ \delta I_{gap} = \frac{\lambda_B}{4} \]

Stimulated laser emission at a wavelength \( \lambda_B \)

Typical length: 2 - 10 cm

UV-BEAM
Distributed Feed-back fiber laser - packaging

Fiber laser grating mounted under tension on substrate.

$$\lambda_B = \Delta_B(\varepsilon,T) \cdot n(\lambda_B,\varepsilon,T)$$

Fiber laser **wavelength** determined by grating pitch, tension, temperature

10 – 50 mW
Single mode operation

Phase shifted FBG of DFB fiber laser:
- strong grating with narrow spectral width (< 100 pm)
- DFB cavity: FSR > grating bandwidth => robust single mode operation
- single mode operation un-changed during frequency tuning

- Polarization modes - degeneracy lifted through:
  - residual fiber birefringence
  - UV-induced birefringence
- Laser polarization modes discriminated through differential Q-values
## Wavelength ranges

<table>
<thead>
<tr>
<th>RE dopant</th>
<th>DFB fiber lasers</th>
<th>Wavelength range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yb</td>
<td></td>
<td>980-1200 nm</td>
</tr>
<tr>
<td>Er</td>
<td></td>
<td>1500-1620 nm</td>
</tr>
<tr>
<td>Tm</td>
<td></td>
<td>1730-2100 nm</td>
</tr>
</tbody>
</table>
Spectral linewidth

self-heterodyne linewidth measurement w. 25 km delay:

E15 fiber laser sub-coherent linewidth < 500 Hz @ 120 µsec.
Coherence length

- E15 fiber laser (free running)
  - ~ 56 km

- E15 fiber laser (locked)
  - ~ 8000 km
Phase noise

Combination of fiber waveguide properties, FBG cavity and long rare earth lifetimes account for a very low level of phase noise

Key to optical remote sensing (Fiber Optic interferometric sensing)

E15 phase noise spec

Slavik et al, Southampton, OFS 2011
Lower phase noise – higher frequency stability:
A new class of frequency stabilized fiber lasers

**Frequency-lock fiber laser to compact & stable frequency reference:**

- Frequency stabilized laser output
- Compact & stable frequency discriminator
- Laser frequency control (piezo tuning)

---

frequency stabilized fiber DFB laser module (X15)
Frequency noise reduction

Frequency-locking fiber laser on stabilized frequency locker (stable interferometer)

- reduce phase noise by approx 20 dB
- Meet requirements for Geo-seismic fiber optic sensing: low phase noise @ low frequencies
Locked laser shows clear improvement in frequency stability over time

Frequency drift < 1 MHz/10 hours
Frequency stability – Allan Variance analysis

Allan variance: E15PM BasiK and X15PM

\[ \sigma_y(t) = \frac{1}{2} \langle (\nu_{n+1} - \nu_n)^2 \rangle \]

Sample period (s)

- E15 S/N 09220147 & 09220149
- X15 S/N 12110179 & 12110180
- X15 S/N 12110179 & 12110181
- X15 S/N 12110179 & 12110182
- X15 S/N 12110179 & 12110182 unlocked
Fiber DFB laser frequency tuning

\[ \lambda_B = \Lambda_B(\varepsilon, T) \cdot n(\lambda_B, \varepsilon, T) \]

Laser grating bonded to substrate
=>
change wavelength by changing substrate length

Slow tuning - thermal tuning – mount fiber laser grating on e.g. aluminum substrate:

1. Fiber laser wavelength tunes as:

\[ \frac{1}{\lambda} \cdot \frac{d\lambda}{dT} = \alpha_{\text{substrate}} + \frac{1}{n} \cdot \frac{\partial n}{\partial T} + \frac{1}{n} \cdot \frac{\partial n}{\partial \varepsilon} \cdot \alpha_{\text{fiber}} \]

2. Tuning range approx. 1 nm or 125 GHz @ 1550nm

3. Slow tuning: approx. 1 GHz/sec

4. Single mode operation maintained during tuning
Fast tuning - piezo frequency tuning

1. Piezo electric transducer built into substrate

2. Fiber laser wavelength tunes with $\Lambda_B (U_{\text{piezo}})$

2. **Tuning range.** 25 - 500 pm or 3 - 62 GHz @ 1550nm depending on piezo type

3. **Tuning speed**

4. Single mode operation maintained during tuning

![Graph showing wavelength tuning (MHz/V) vs. modulation frequency (Hz) with a peak at 10 GHz @ 200 V]
Frequency tuneable FL: application in Frequency-conversion PDV

Frequency-conversion PDV:

“Limiting performance can be achieved at any (measurable) velocity!”

ref.: D.H.Dolan, PDV Workshop, Sept. 2010
Koheras Laser Solutions

- BoostiK System
  - 10 W @ 1550
  - Low to high power
  - Single to multi wavelengths
  - Laser properties are the same

- AcoustiK System
  - 1 W @ 1550

- BoostiK Module
- AdjustiK System
- BasI Module
  - 10 – 50 mW @ 1550

Incremental Performance
Multi-channel source

AcoustiK System

up to 32 channels multiplexed in a single PM fiber
# Koheras Laser Key Applications

<table>
<thead>
<tr>
<th>Security</th>
<th>Seismic</th>
<th>Structural Health Monitoring</th>
<th>Vibrometry</th>
<th>Wind LIDAR / Ranging</th>
<th>Injection seeding</th>
<th>Scientific Instrumentation</th>
<th>Space</th>
<th>Fusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Security Seismic</td>
<td>Vibrometry</td>
<td>Wind LIDAR / Ranging</td>
<td>Injection seeding</td>
<td>Scientific Instrumentation</td>
<td>Space</td>
<td>Fusion</td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Water pipes</td>
<td>Wind turbines</td>
<td>Airports</td>
<td>High power YAG lasers</td>
<td>Spectroscopy</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Oil and gas pipes</td>
<td>Wind assessment</td>
<td>Atmospheric sensing</td>
<td>Aircraft monitoring</td>
<td>Atomic physics</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind turbines</td>
<td>Wind assessment</td>
<td>Atmosphere sensing</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>Navy</td>
<td>Other</td>
<td>Laser Doppler vibrometry</td>
<td>Wind assessment</td>
<td>Airports</td>
<td>Aircraft monitoring</td>
<td>Fusion energy</td>
<td></td>
</tr>
</tbody>
</table>

**Sensor interferometry**

**LIDAR**

**Instrumentation & Science**

[Image of Koheras Laser Key Applications table]
Summary

The DFB Fiber Laser is a perfect match for fiber optic sensing applications:

- compact, fiber coupled laser source
- single mode – also under frequency tuning
- low phase noise & narrow linewidth ~ long coherence length
- fast & wide range frequency tuning - 10’s of GHz tuning @ kHz speed
- high power (up to 10 W @ 1550nm)
- multi-wavelength systems
- remote digital control
Questions?
Application slides ......
• Laser radiation scatters from atmospheric aerosols
• Aerosol movement follows the wind
• Scattered radiation is ‘Doppler’ shifted by the wind speed
• Measure ‘in-line’ component of wind speed
CW LIDAR: ranging

A CW LIDAR lacks the ranging that is inherent to a pulsed system.

CW LIDAR range information:
- Dominant contribution to scattering comes from focus region (within Rayleigh length).
- Range resolution depends on distance.
- Max range limited to a few x 100 m.
LIDAR & laser noise

spurious reflections in LIDAR optics
⇒
• coherent white noise floor
• magnitude depends on spectral linewidth of LIDAR laser
• level may increase beyond shot noise
⇒
sensitivity of CW LIDAR system depends on laser linewidth
CW Wind LIDAR: Natural Power ZephIR

Courtesy of Natural Power
PDV vs wind LIDAR – laser noise requirements

PDV: probe return $10^{-4}$
Wind LIDAR: return $10^{-14}$

=> noise impact:
Wind LIDAR requires shot noise limited detection (RIN shot noise limited, narrow linewidth to reduce coherent noise from residual reflections and non-perfect isolation in system)
Frequency-conversion PDV

- Two wavelengths
  - One illuminates target
  - One serves as a reference
- Advantages
  - Always beating
  - Provides direction information
  - Utilizes the power of the FFT
- Avoids low frequency shoulder

Tune wavelengths to get any desired beat frequency

Limiting performance can be achieved at any (measurable) velocity!
The main disadvantage of the heterodyne system compared to the Fabry-Perot or VISAR techniques is the limited maximum velocity of the heterodyne method. The velocity range of the Fabry-Perot or VISAR may be adjusted to arbitrarily high velocity by the choice of etalons. The heterodyne system described here is limited by the bandwidth of the high-sample-rate digitizer.

“A Novel System for High-Speed Velocimetry Using Heterodyne Techniques”
O. T. Strand, D. R. Goosman, C. Martinez, T. L. Whitworth, W. W. Kuhlow
Review of Scientific Instruments 2005

The phenomenon of shock waves reaching the measurement surface is known as shock breakout. The time from detonation to shock breakout is about 1 to 2 μsec.

The primary goal of velocimetry is to capture the initial details of the shock breakout. Unfortunately, these measurements are the most difficult to achieve. A secondary goal is to capture the evolution of surface velocities in the first 15 mm of travel, as the target begins to spall.

“Design, construction, alignment, and calibration of a compact velocimetry experiment”
Morris I. Kaufman*a, Robert M. Malonea, Brent C. Froggeta, David L. Esquibel, Vincent T. Romeroa, Gregory A. Larea, Bart Briggsa, Adam J. Iversona, Daniel K. Frayera, Douglas DeVorea, Brian Catanab, David B. Holtkamb, Mark D. Wilkeb, Nick S. P. Kingb, Michael R. Furlanettob, Matthew E. Briggsb, Michael D. Furnishc
DOE/NV/25946--250
Acoustic sensing: Geo-seismic sensing for Oil & Gas

Geoseismic sensing: airgun + hydrophone array.
- Systems traditionally based on electric transducers (e.g. piezo electric hydrophones)
- Systems based on fibre optical sensors now available

Search for new oilfields (streamers)

Permanent reservoir monitoring (e.g. this conference presentation SWA1)
Fiber optical hydrophones

- Laser used as interrogator for phase changes in fiber optical interferometer
- Key laser parameter: LOW PHASE NOISE
- Fiber Lasers ideal candidates for fiber optic geoseismic sensor systems

Grating based interferometry
(Optoplan / this conf.: SWA1)

Fiber optic un-balanced Mach-Zender interferometer
Acoustic sensing: Fiber laser direct hydrophone element

- A DFB fiber laser is used directly as the sensing device.
- Diode laser provide pump energy to several fiber laser elements.
- Serial arrangement enables WDM multiplexing.
- Transducer converts acoustic field into optical laser frequency modulation.

Fiber laser hydrophone
L=70mm, Φ=4mm

Courtesy of: FOI
Fiber laser hydrophone – basic configuration

pump laser, $\lambda_{\text{pump}}$

isoler

WDM $\lambda_{1-4}$

demodulators

fiber cable

fiber laser sensors $\lambda_1 \lambda_2 \lambda_3 \lambda_4$

base unit

 Courtesy of: FOI
Acoustic sensing: Pipeline Monitoring / perimeter security

- Distributed fiber sensor, ~ 100 km
- Long base-line interferometers
- DFB fiber laser: long coherence length
- Observing phase-shift of signal
- Acoustic "Finger print" of intruder

Oil or Gas Pipe | Fence/Borders | Perimeter/tunnels

Reference: Future Fibre Technologies, Australia
FFT Microstrain Locator Technology

Bidirectional fibre optic Mach Zehnder interferometer with counter-propagating signals.

Event location resolved by measuring time difference between counter propagating signals.

Requires highly coherent laser (low phase noise)