Low Noise Frequency Stable Fiber Lasers for Optical Remote Sensing Applications

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NKT Photonics

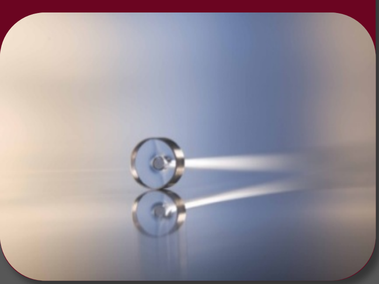
Crystal Fibre	*aeroGAIN*	*Koheras*	*SuperK*	*Argos*

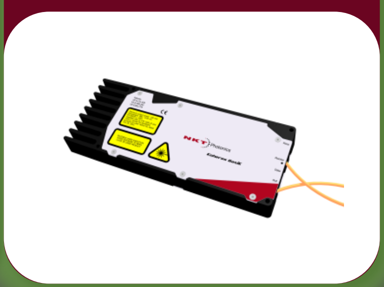
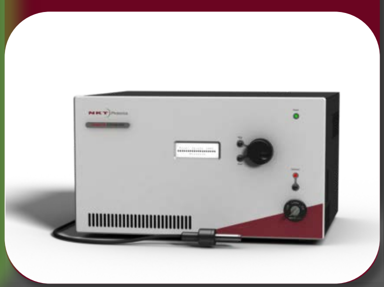
High Peak Power Pulsed Lasers (*Crystal Fibre*, *aeroGAIN*)
- Material Processing
- Military & Defense
- High-end research & development
- Gyroscope

Advanced sensing (*Koheras*)
- Wind LIDAR
- Seismic
- Security
- SHM

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

Spectroscopy (*Argos*)
- Military & Defense
- High-end research & development

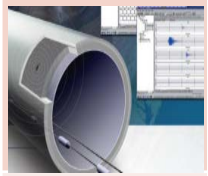
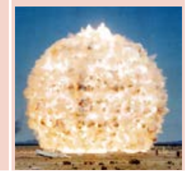



Fiber lasers for remote sensing:

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

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

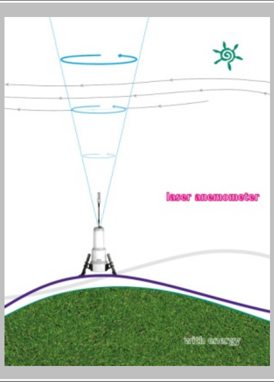
fiber interferometry

Laser source requirements for remote sensing applications

- Fiber optic sensing: low levels of change in phase, frequency or intensity $\Rightarrow$
- 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

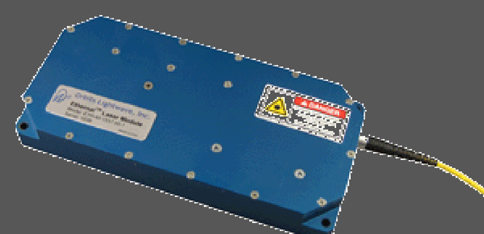
NPRO laser has set the standard for compact low noise lasers for years.

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

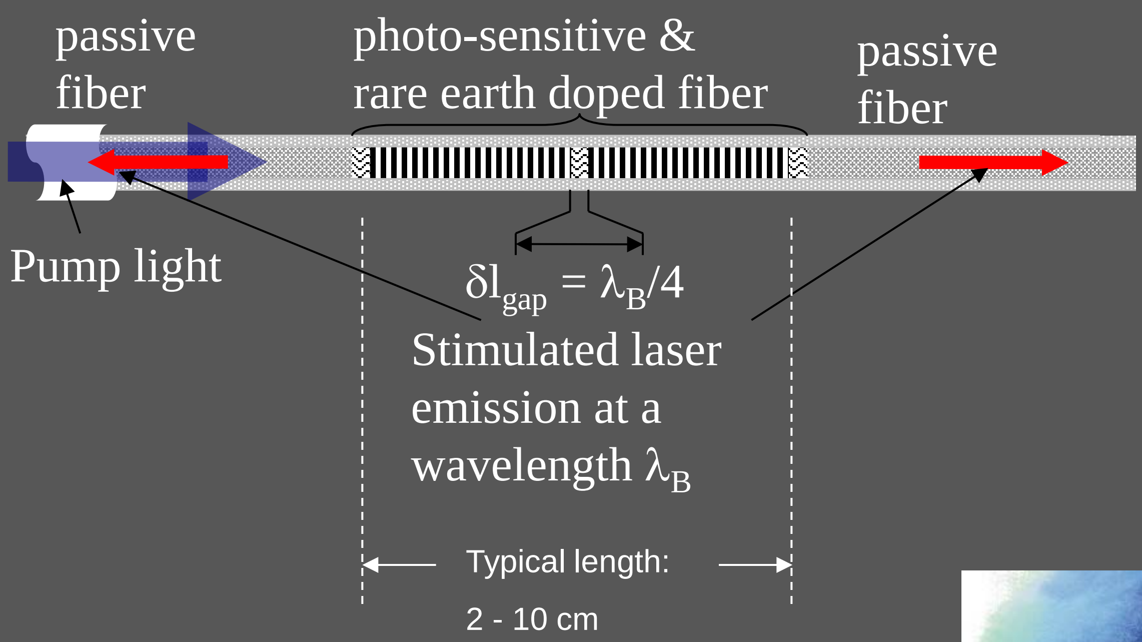
- greater wavelength selection
- compact (similar foot print)
- fiber coupled
- maintenance free
- single frequency
- narrow linewidth
- low phase noise – some comparable to NPRO

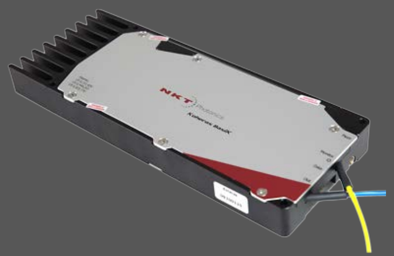
SCL: RIO (talk later this session), Teraxion

Fiber lasers: Orbits Lightwave, NP Photonics, NKT Photonics



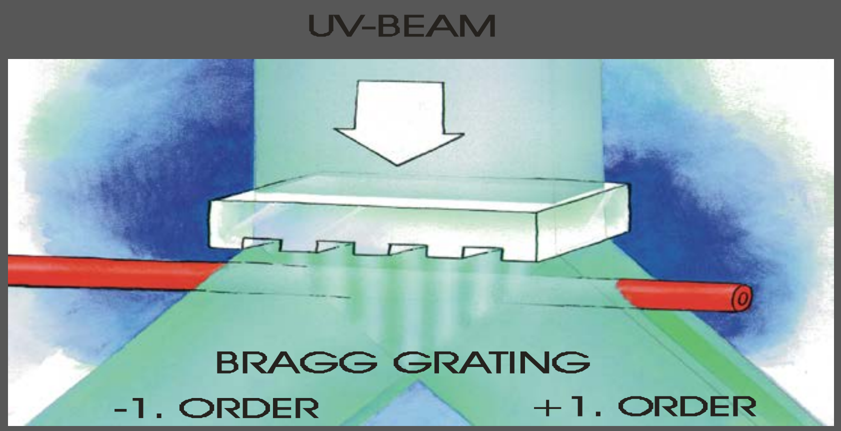
Focus: Distributed Feed-Back Fiber Laser – UV processing



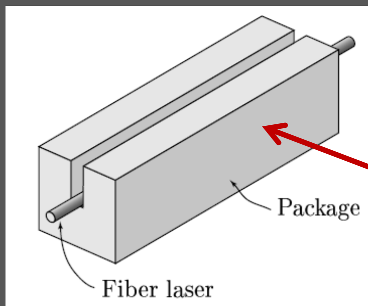


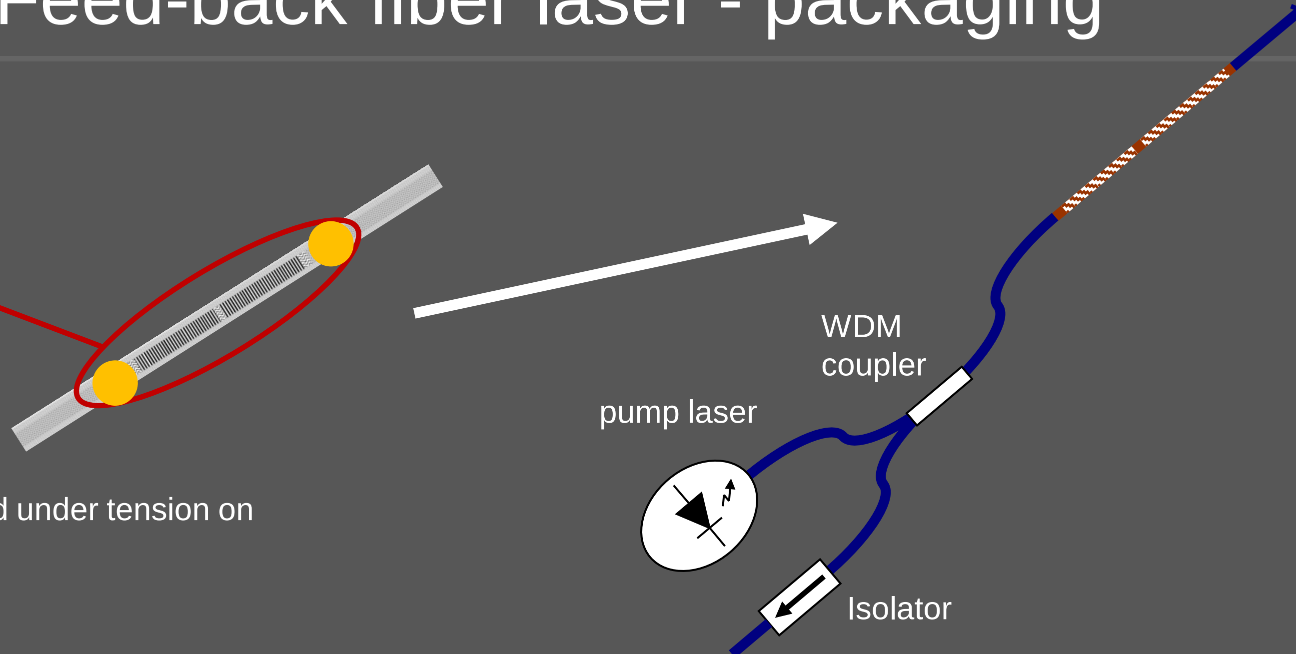
Laser wavelength:

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



Distributed Feed-back fiber laser - packaging





Fiber laser grating mounted under tension on substrate.

$\boldsymbol{\lambda_B = \Lambda_B(\varepsilon,T) \cdot n(\lambda_B,\varepsilon,T)}$

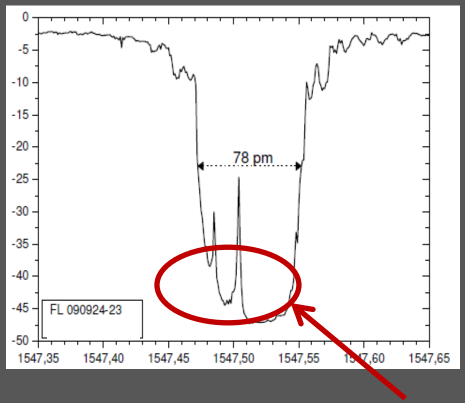
Fiber laser **wavelength** determined by grating pitch, tension, temperature

10 – 50 mW

Single mode operation

Phase shifted FBG of DFB fiber laser:

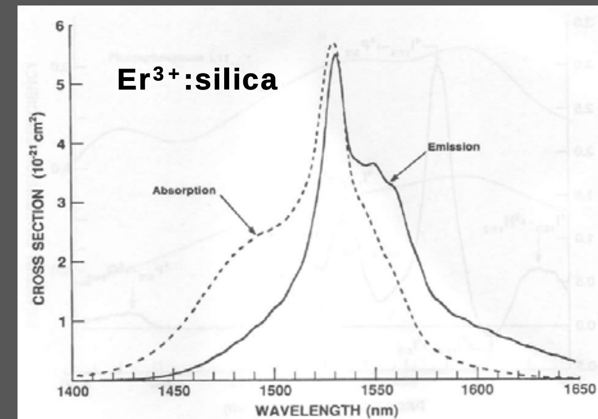
- strong grating with narrow spectral width (< 100 pm)
- DFB cavity: FSR > grating bandwidth => robust single mode operation
- single mode operation un-changed during frequency tuning

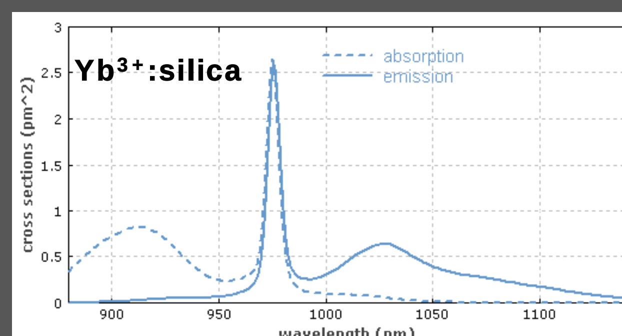


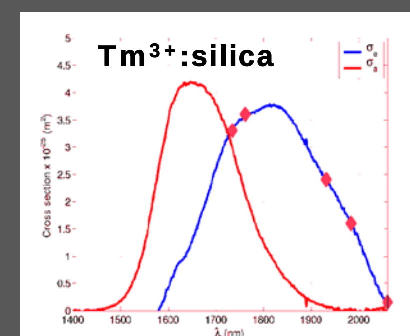
- Polarization modes - degeneracy lifted through:
  - residual fiber birefringence
  - UV-induced birefringence
- Laser polarization modes discriminated through differential Q-values

Wavelength ranges

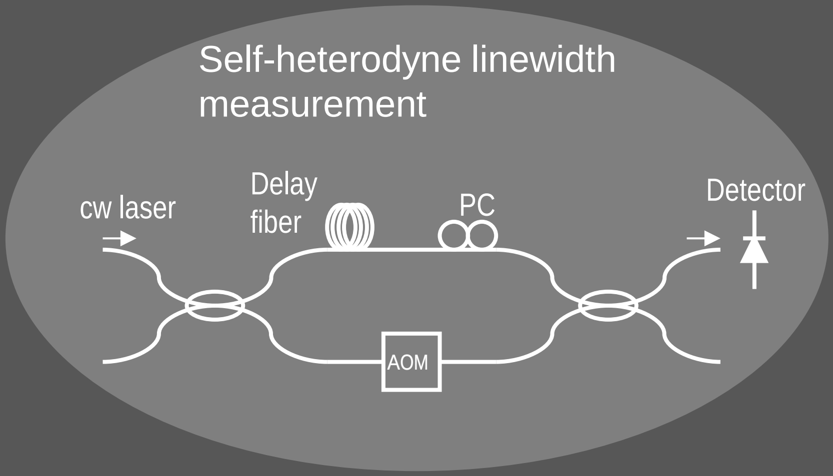
DFB fiber lasers	
RE dopant	Wavelength range
Yb	980-1200 nm
Er	1500-1620 nm
Tm	1730-2100 nm

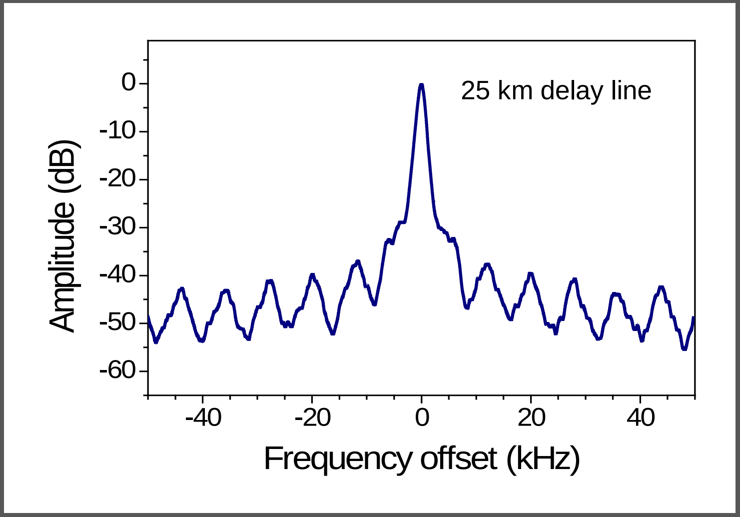






Spectral linewidth

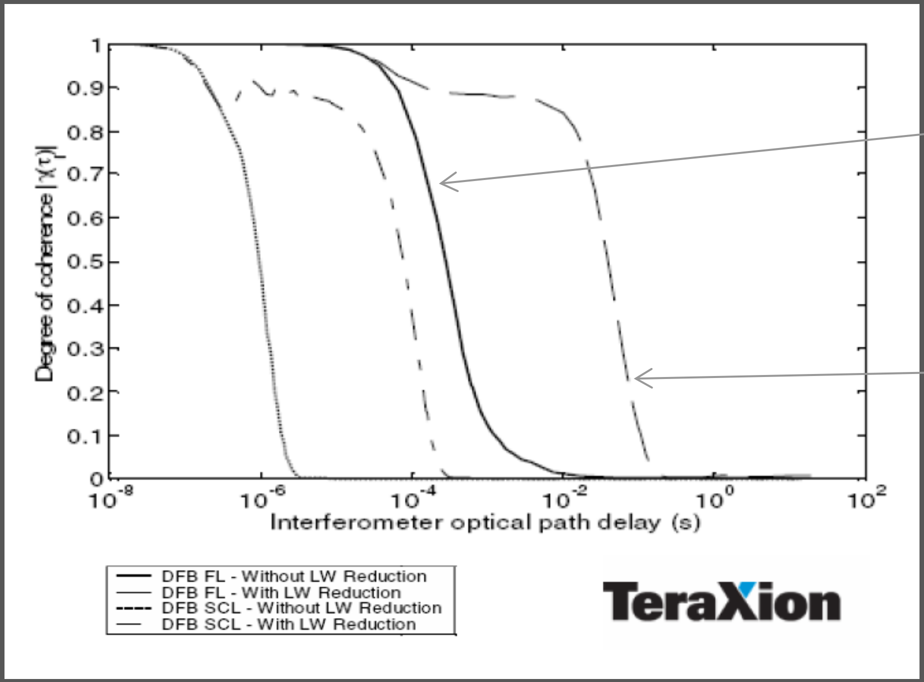




self-heterodyne linewidth measurement w. 25 km delay:

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

Coherence length



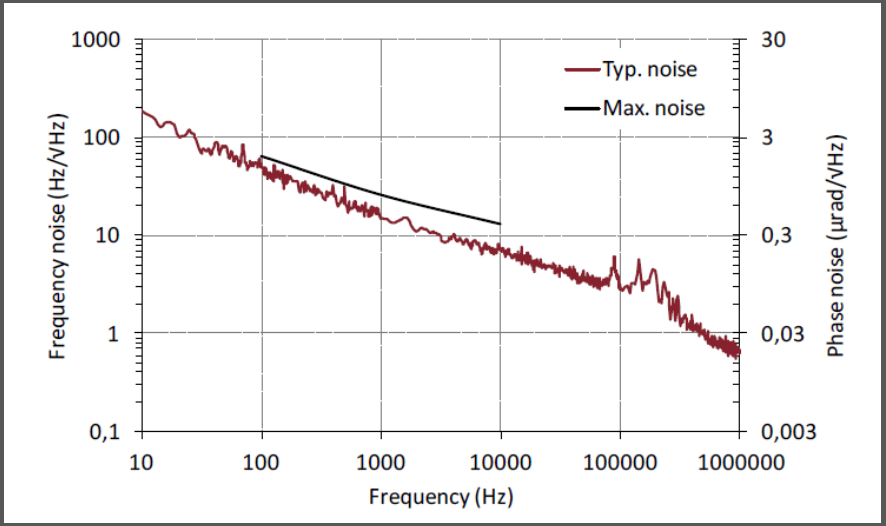
E15 fiber laser (free running)
~ 56 km

E15 fiber laser (locked)
~ 8000 km

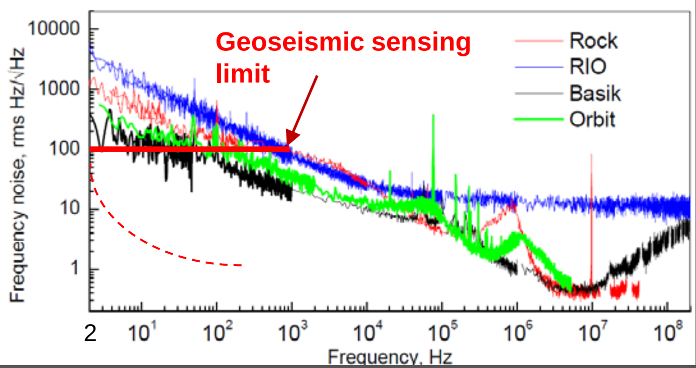
Phase noise

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)



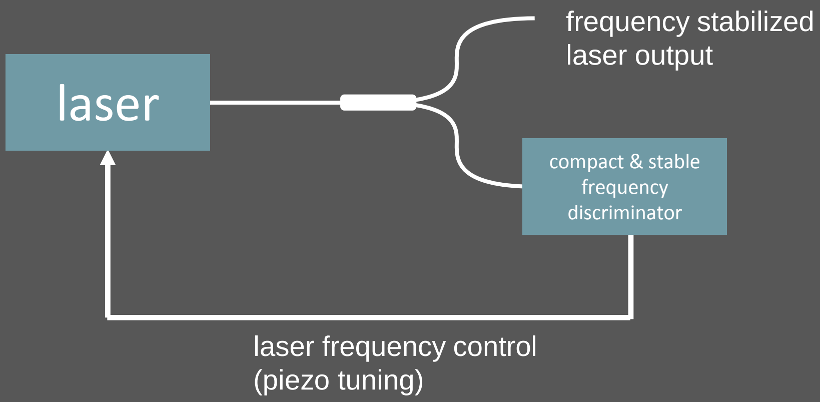
E15 phase noise spec



Slavik et al, Southampton, OFS 2011

Lower phase noise – higher frequency stability:
A new class of frequency stabilized fiber lasers

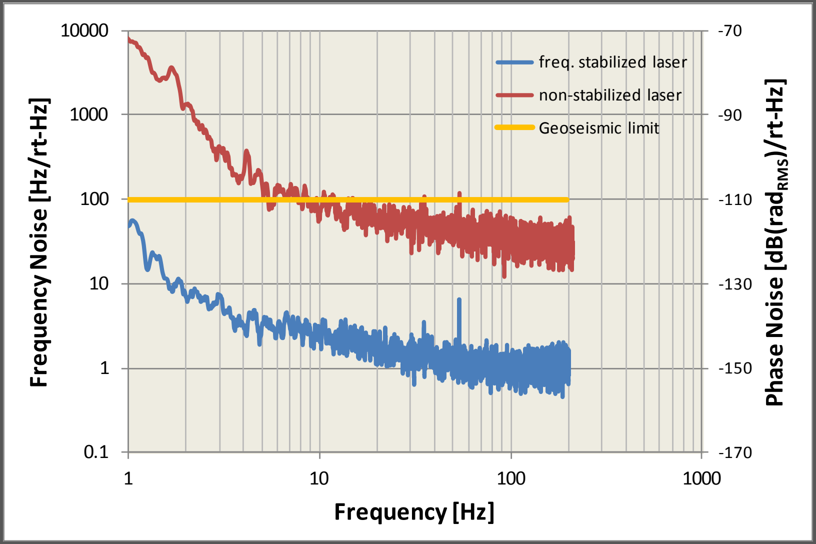
Frequency-lock fiber laser to compact & stable frequency reference:



frequency stabilized fiber DFB
laser module (X15)

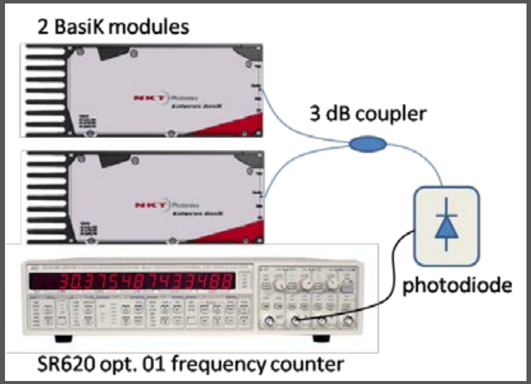
Frequency noise reduction

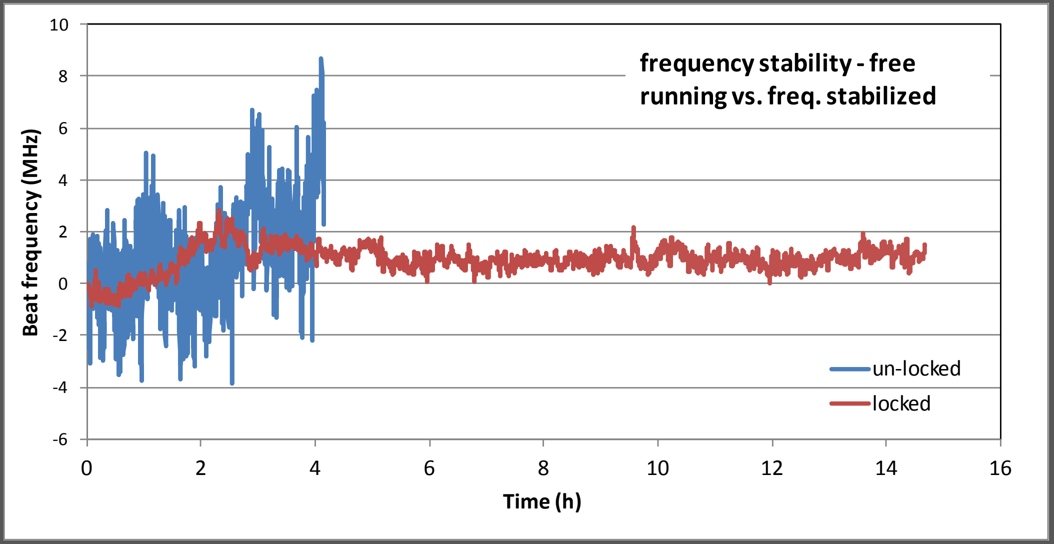
Frequency-locking fiber laser on stablized frequency locker (stable interferometer)



- reduce phase noise by approx 20 dB
- Meet requirements for Geo-seismic fiber optic sensing: low phase noise @ low frequencies

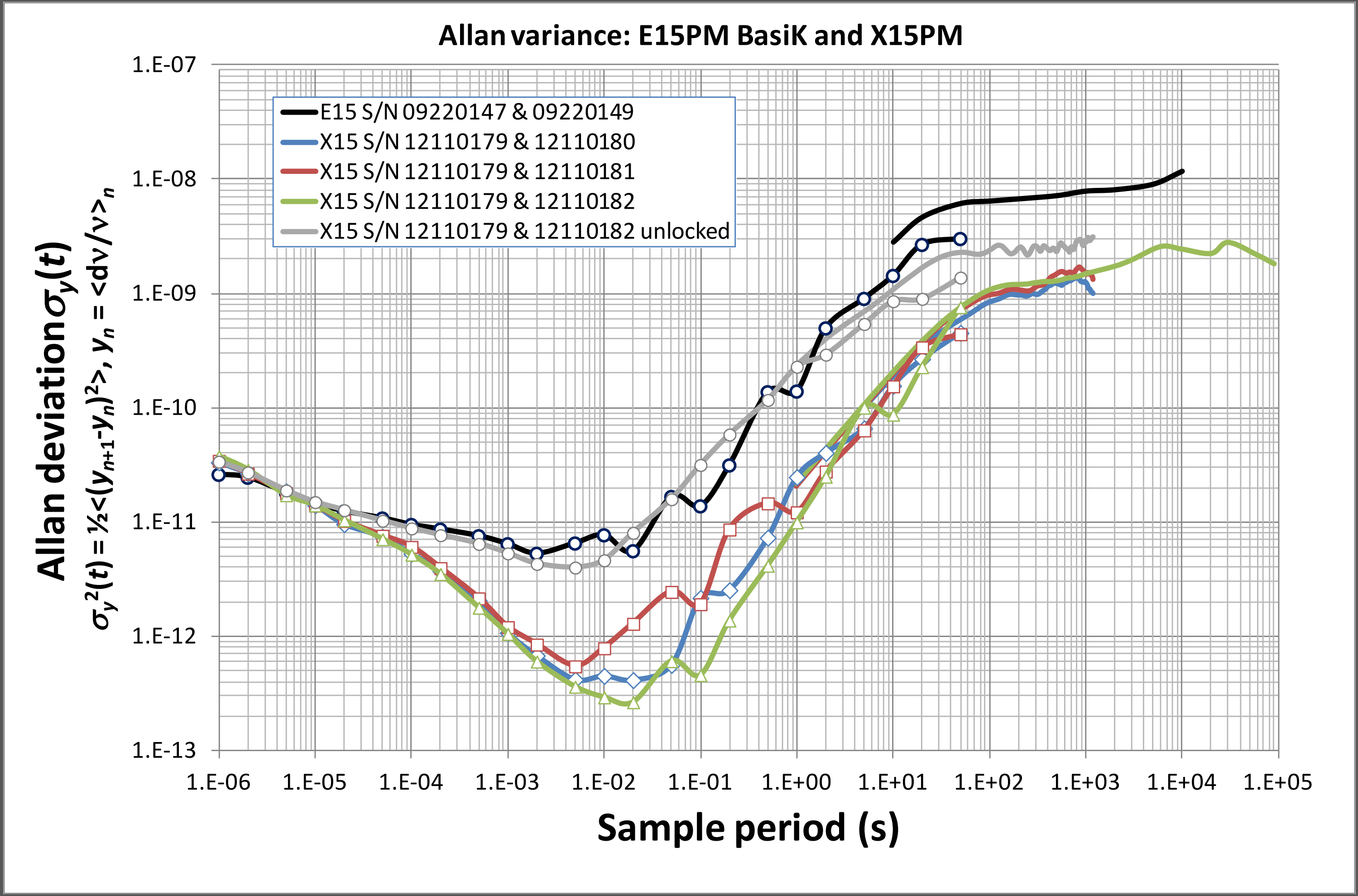
Frequency stability over time





- Locked laser shows clear improvement in frequency stability over time
- Frequency drift < 1 MHz/10 hours

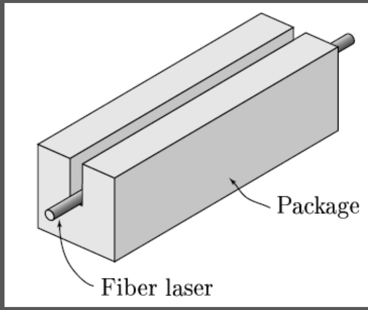
Frequency stability – Allan Variance analysis



Fiber DFB laser frequency tuning

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

Laser grating bonded to susbtrate
=>
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:

$$\frac{1}{\lambda} \bullet \frac{d\lambda}{dT} = \alpha_{substrate} + \frac{1}{n} \bullet \frac{\partial n}{\partial T} + \frac{1}{n} \bullet \frac{\partial n}{\partial \varepsilon} \bullet \alpha_{fiber}$$

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

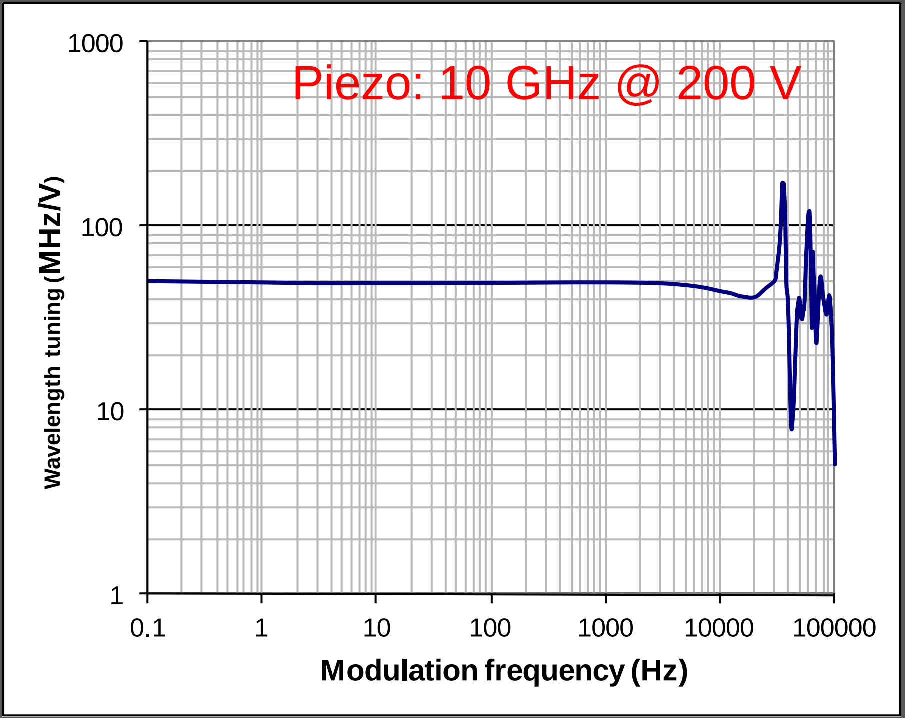
1. Piezo electric transducer built into substrate

2. Fiber laser wavelength tunes with Λ_B **(U_{piezo})**

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

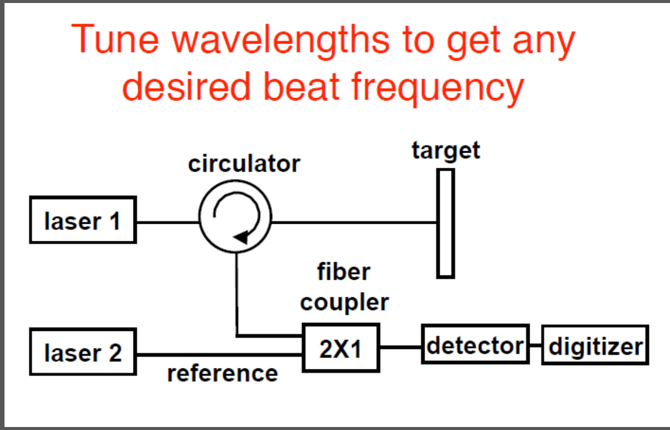
3. Tuning speed

4. Single mode operation maintained during tuning



Frequency tuneable FL: application in Frequency-conversion PDV

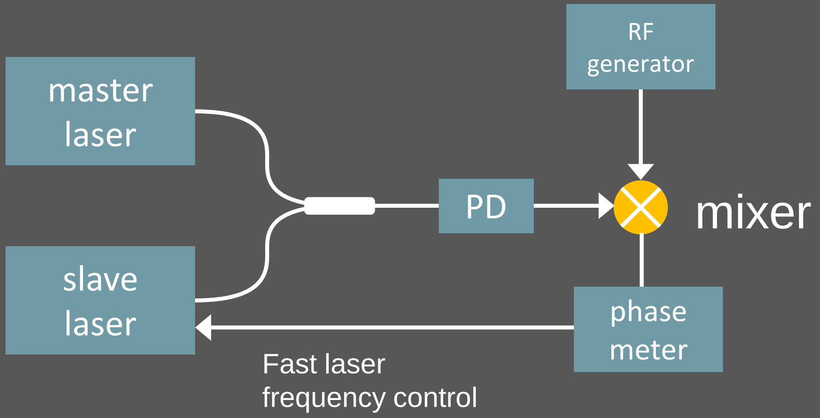
Frequency-conversion PDV:



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

ref.: D.H.Dolan, PDV Workshop, Sept. 2010

Lock reference laser (laser 2) to pre-set frequency offset from target laser (laser 1) using PZT frequency tuning:



Koheras Laser Solutions

10 W @ 1550

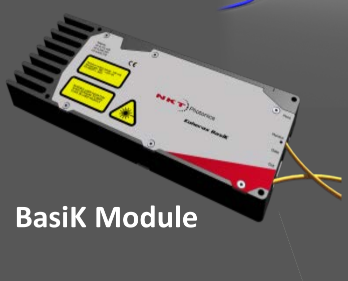
BoostiK System

AcoustiK System

1 W @ 1550

BoostiK Module

AdjustiK System



BasiK Module

Incremental Performance

10 – 50 mW @ 1550

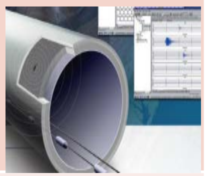
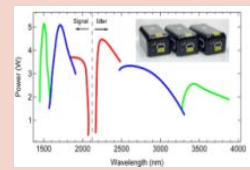
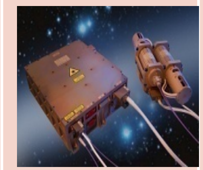
- Low to high power
- Single to multi wavelengths
- Laser properties are the same

Multi-channel source

AcoustiK System

up to 32 channels multiplexed in a single PM fiber

Koheras Laser Key Applications

Security	Seismic	Structural Health Monitoring	Vibrometry	Wind LIDAR / Ranging	Injection seeding	Scientific Instrumentation	Space	Fusion
								
Data	Navy	Water pipes Oil and gas pipes Other	Laser Doppler vibrometry	Wind turbines Wind assessment Airports Atmospheric sensing Aircraft monitoring	High power YAG lasers	Spectroscopy Atomic physics	Magnetic field surveys Gravitational wave detection Telescope radio antennas	Fusion energy

Sensor interferometry LIDAR Instrumentation & Science

Summary

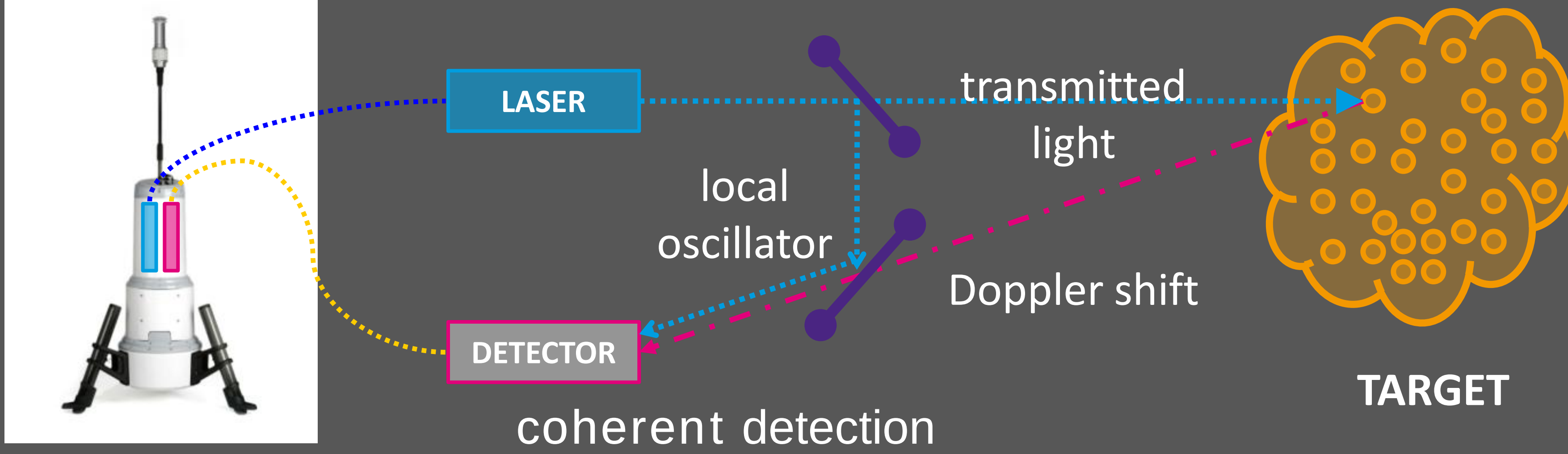
The DFB Fiber Laser is a perfect match for fiber optic sensing applications:

- 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 ....

CW LIDAR: Wind speed measurement



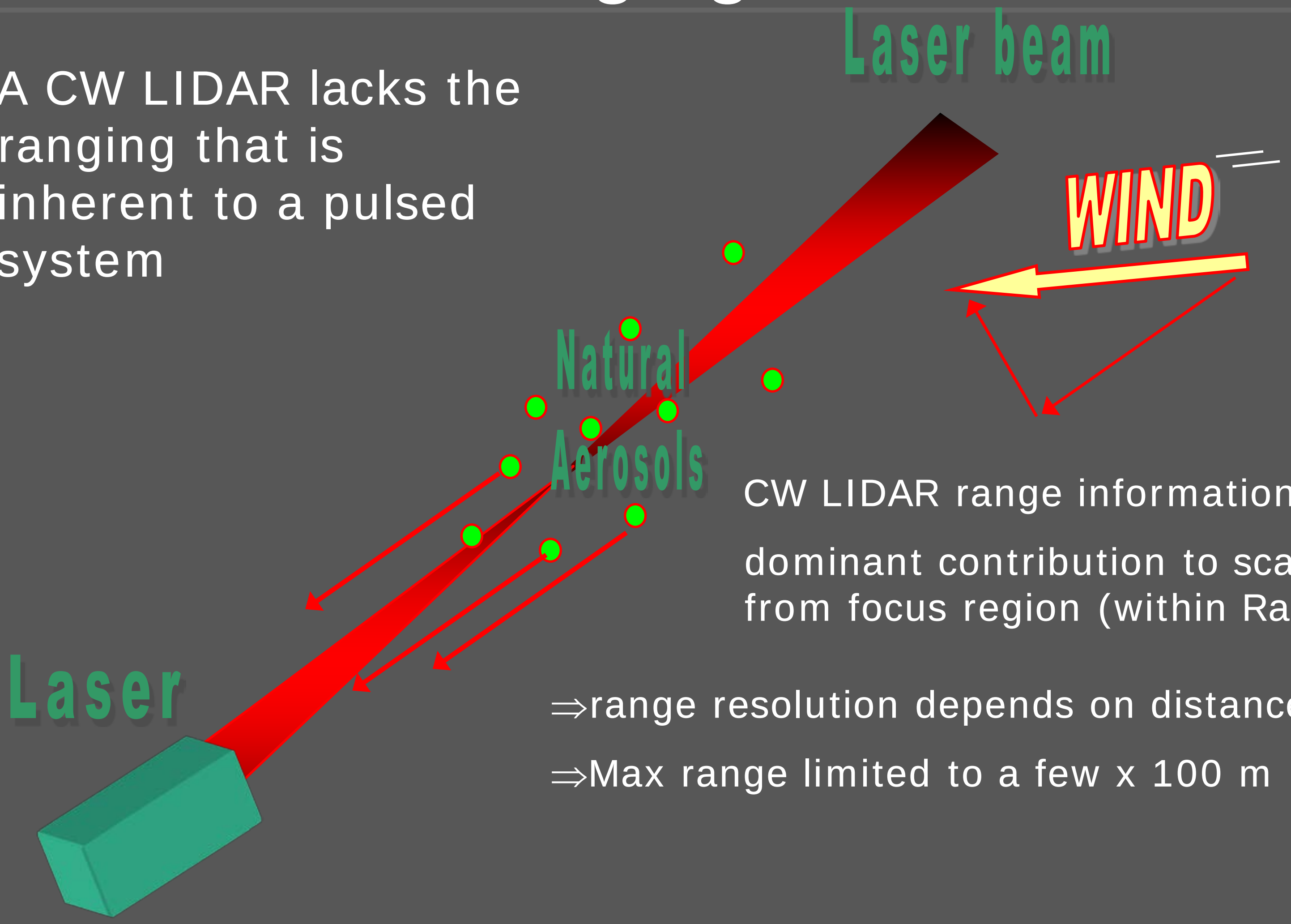
- Laser radiation scatters from atmospheric aerosols
- Aerosol movement follows the wind
- Scattered radiation is 'Doppler' shifted by the wind speed
- Measure 'in-line' component of wind speed

Courtesy of:

natural power

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

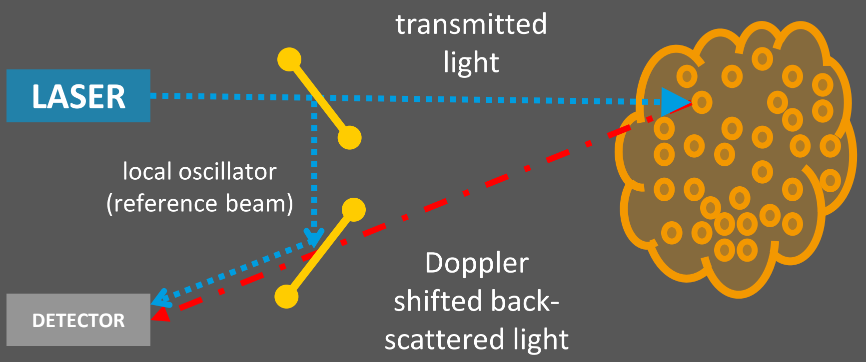
spurious reflections in LIDAR optics

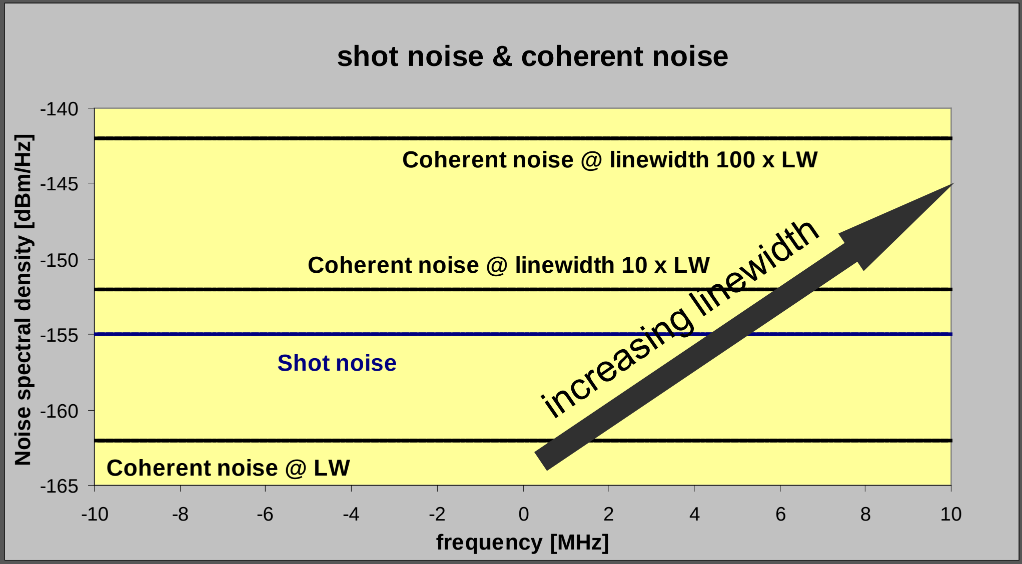
⇒

- 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

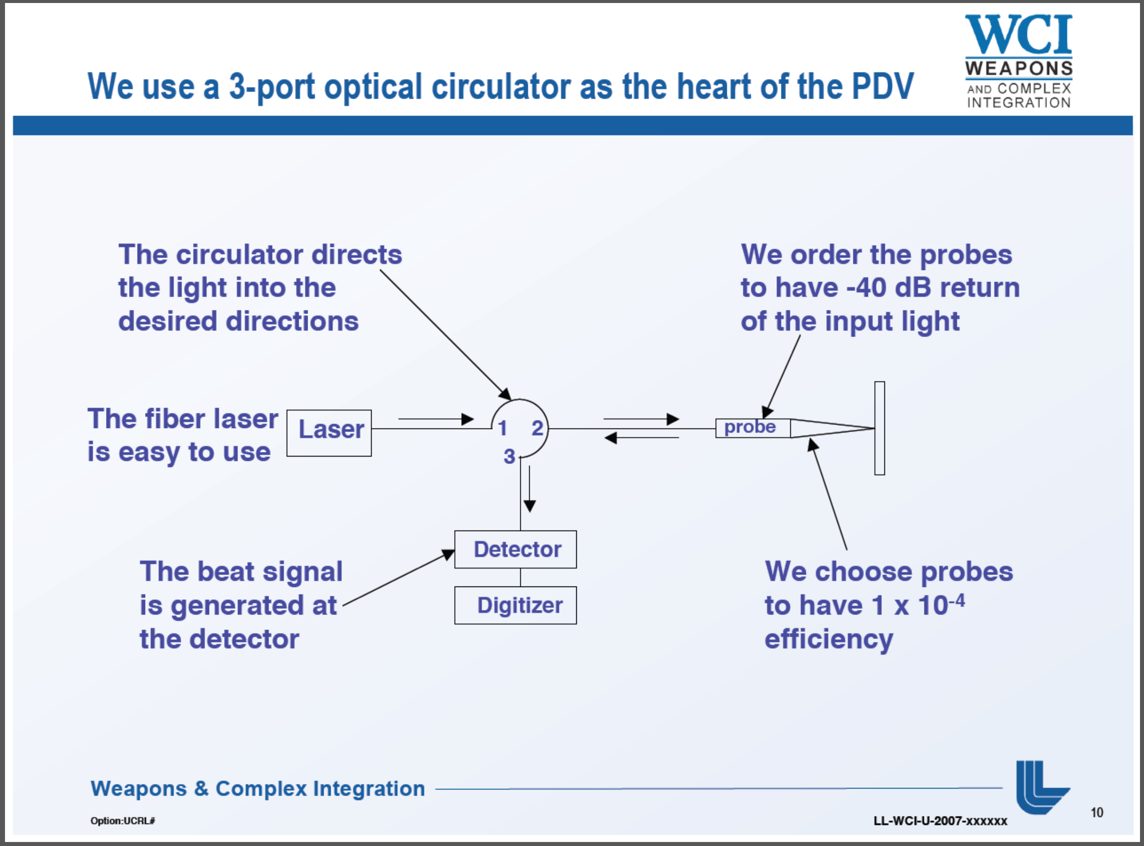
PDV vs wind LIDAR – laser noise requirements

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)

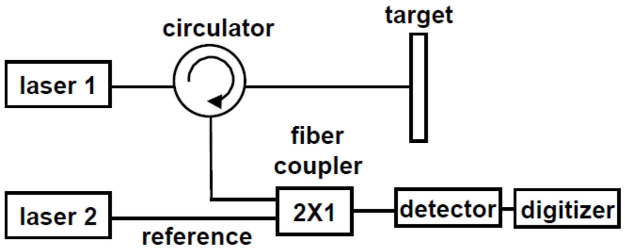


PDV vs wind LIDAR

Frequency-conversion PDV

- Two wavelengths
  - One illuminates target
  - One serves 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!

PDV & laser requirements

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.

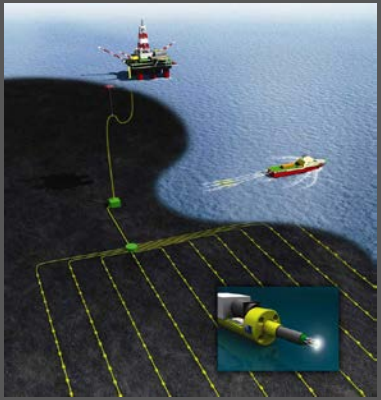
The primary goal of velocimetry is to capture the initial details of the shock breakout. Unfortunately, these measurements are the most difficult to achieve. A secondary goal is to capture the evolution of surface velocities in the first 15 mm of travel, as the target begins to spall.

"Design, construction, alignment, and calibration of a compact velocimetry experiment"
*Morris I. Kaufman*a, Robert M. Malonea, Brent C. Froggeta, David L. Esquibela, Vincent T. Romeroa, Gregory A. Larea, Bart Briggsa, Adam J. Iversona, Daniel K. Frayera, Douglas DeVorea, Brian Cataa, David B. Holtkampb, 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

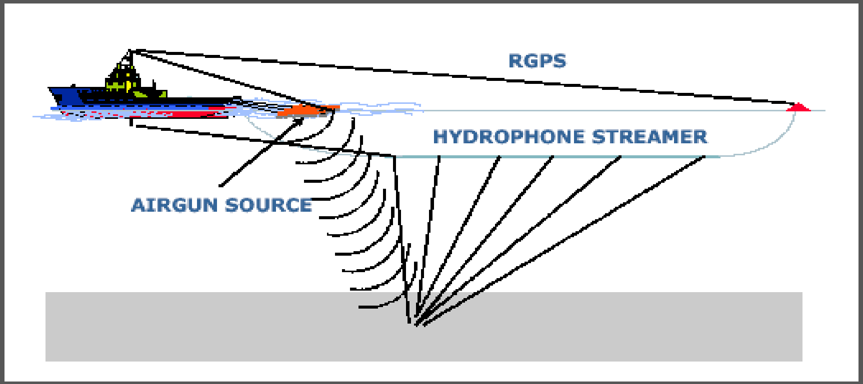
Geoseismic sensing: airgun + hydrophone array.

- Systems traditionally based on electric transducers (e.g. piezo electric hydrophones)
- systems based on fibre optical sensors now available



Search for new oilfields (streamers)

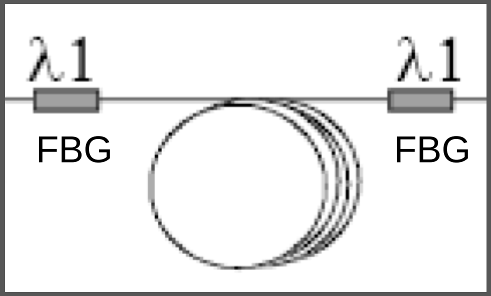
Permanent reservoir monitoring (e.g. this conference presentation SWA1)



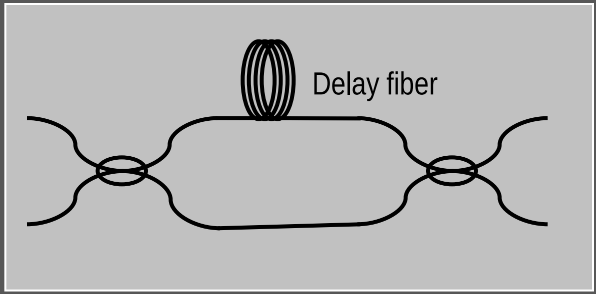
Fiber optical hydrophones

- 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

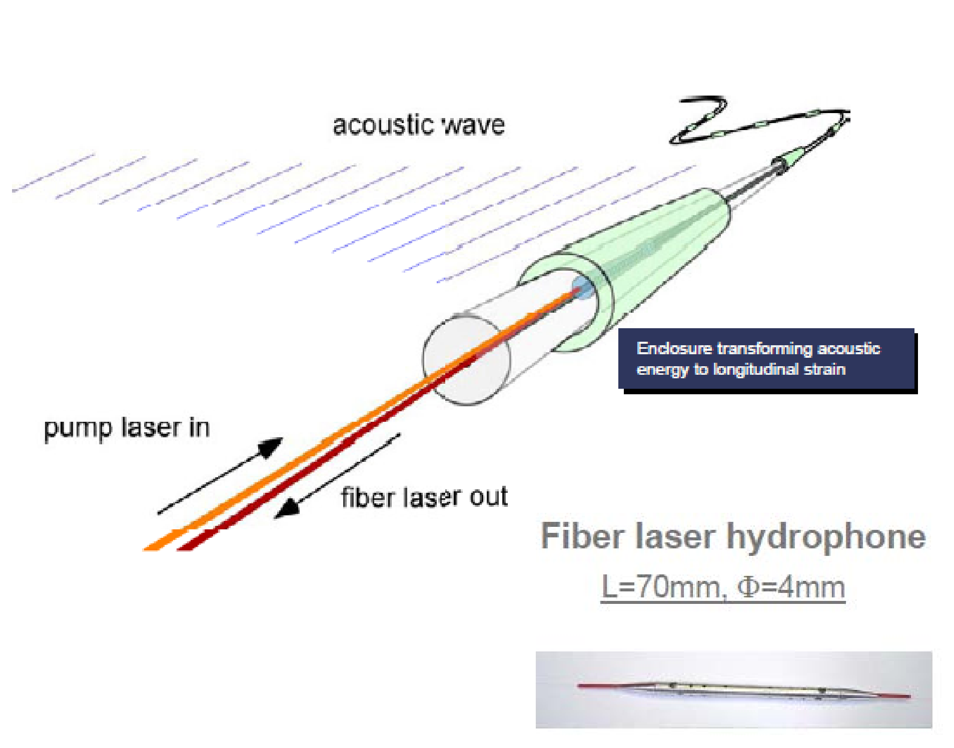
Grating based interferometry (Optoplan / this conf.: SWA1)



Fiber optic un-balanced Mach-Zender interferometer



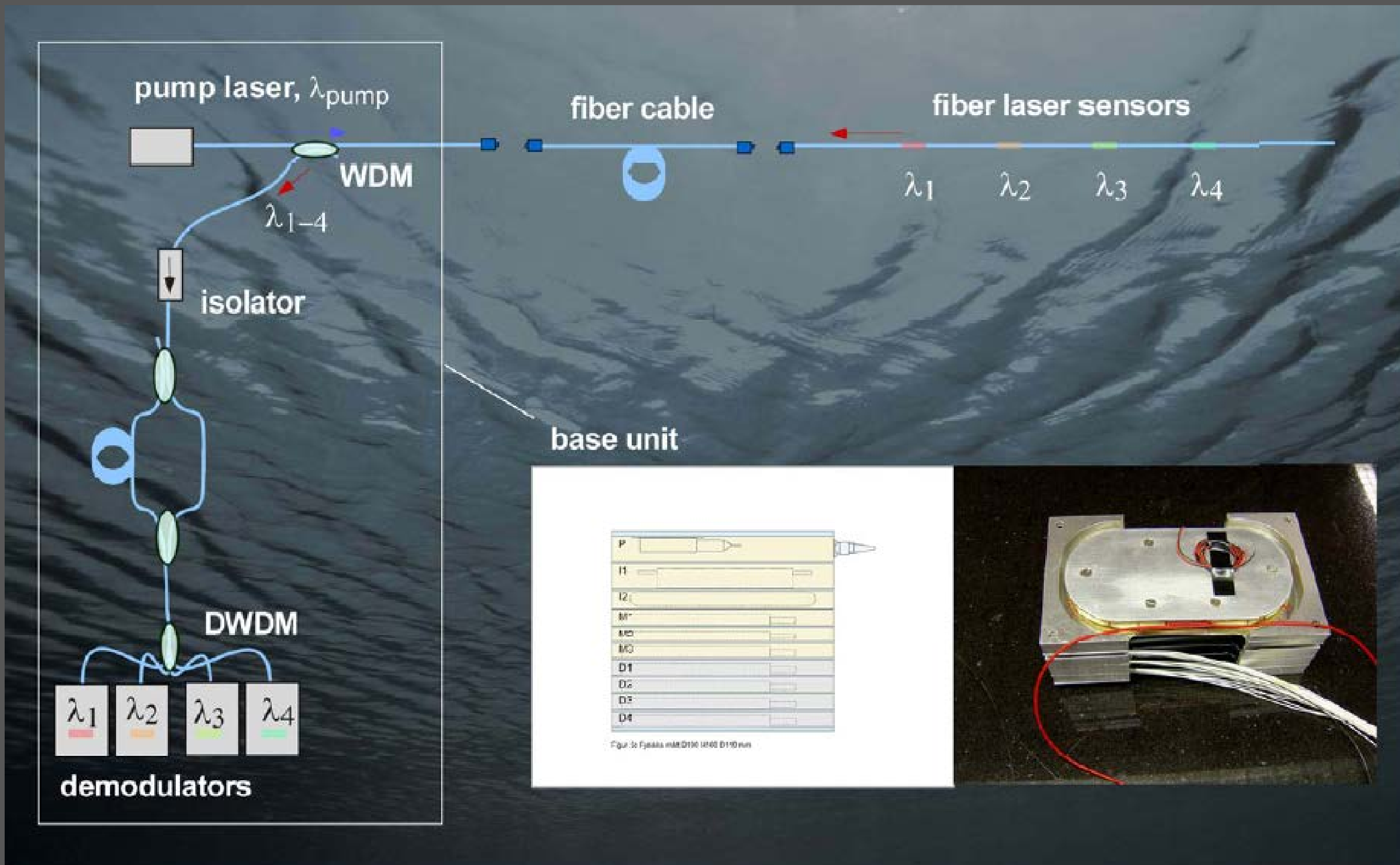
Acoustic sensing: Fiber laser direct hydrophone element



- 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

Courtesy of: FOI

Fiber laser hydrophone – basic configuration



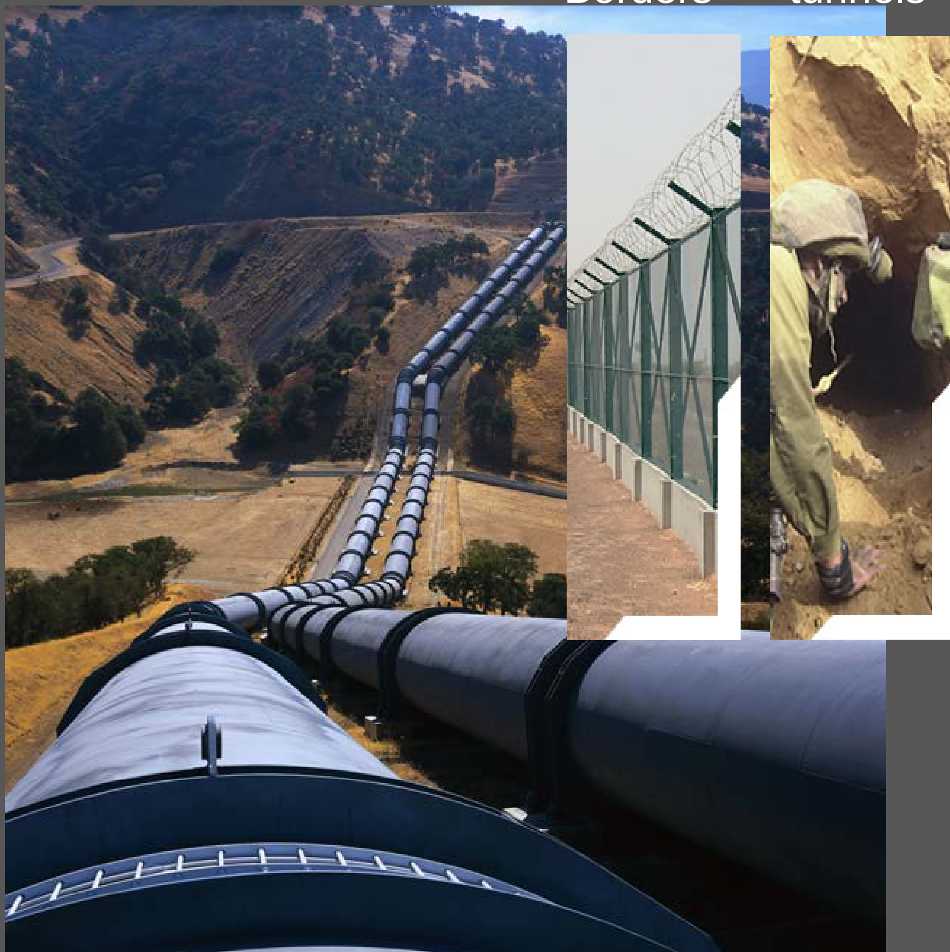
Courtesy of:

Acoustic sensing: Pipeline Monitoring / perimeter security

Oil or Gas Pipe

Fence/ Borders

Perimeter/ tunnels



- 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

FFT Future Fibre Technologies™
Light years ahead in sensing and security

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)