Presentation of EPFL-Group for Fibre Optics:

Ultra-High Spatial Resolution in Distributed Fibre Sensing

Prof. Luc THEVENAZ

& co-workers

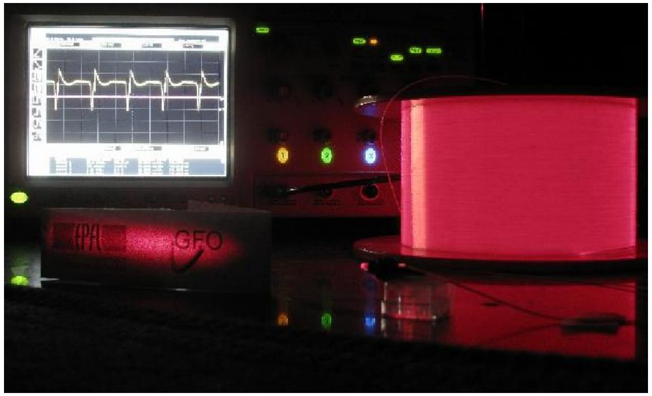
2 Postdoc, 4 PhD students, 3 visiting students

1/5 Adm. Assistant - 1/10 Technician

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

GFO

GFO Activities

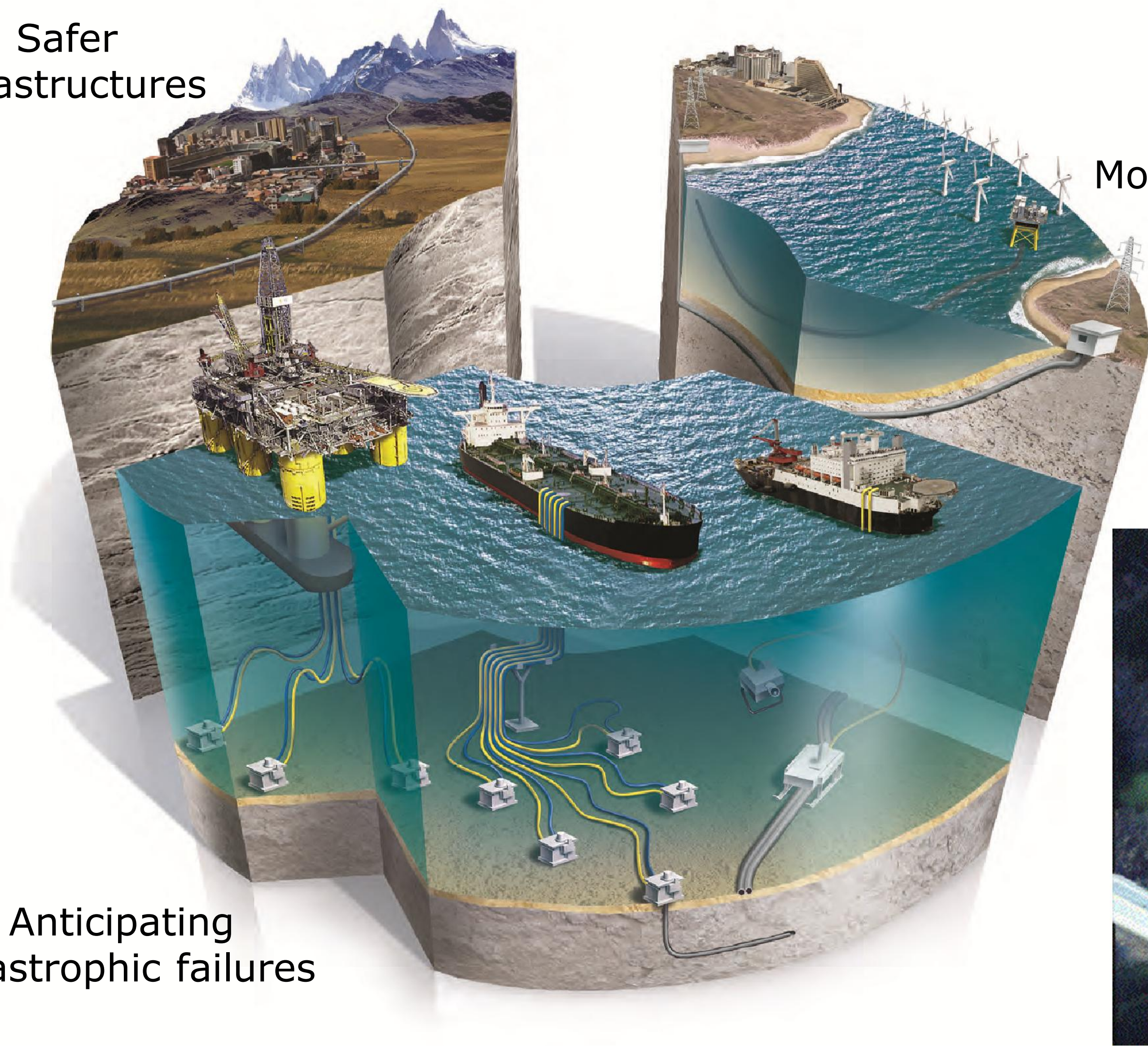


- Optical Fibre Sensors
  - Electrical current sensors (closed)
  - Distributed fibre sensing using stimulated Brillouin scattering (core research)
- Optical signal processing using Fibres
  - Slow & fast light, optical storage
  - Dynamic fibre gratings, microwave photonics
- Sensing using laser spectroscopy
  - Photoacoustic gas trace sensing (closed)
  - Photonic crystal fibres and waveguides

Fibre sensing, a response to a societal concern

Safer infrastructures

More efficient energy use

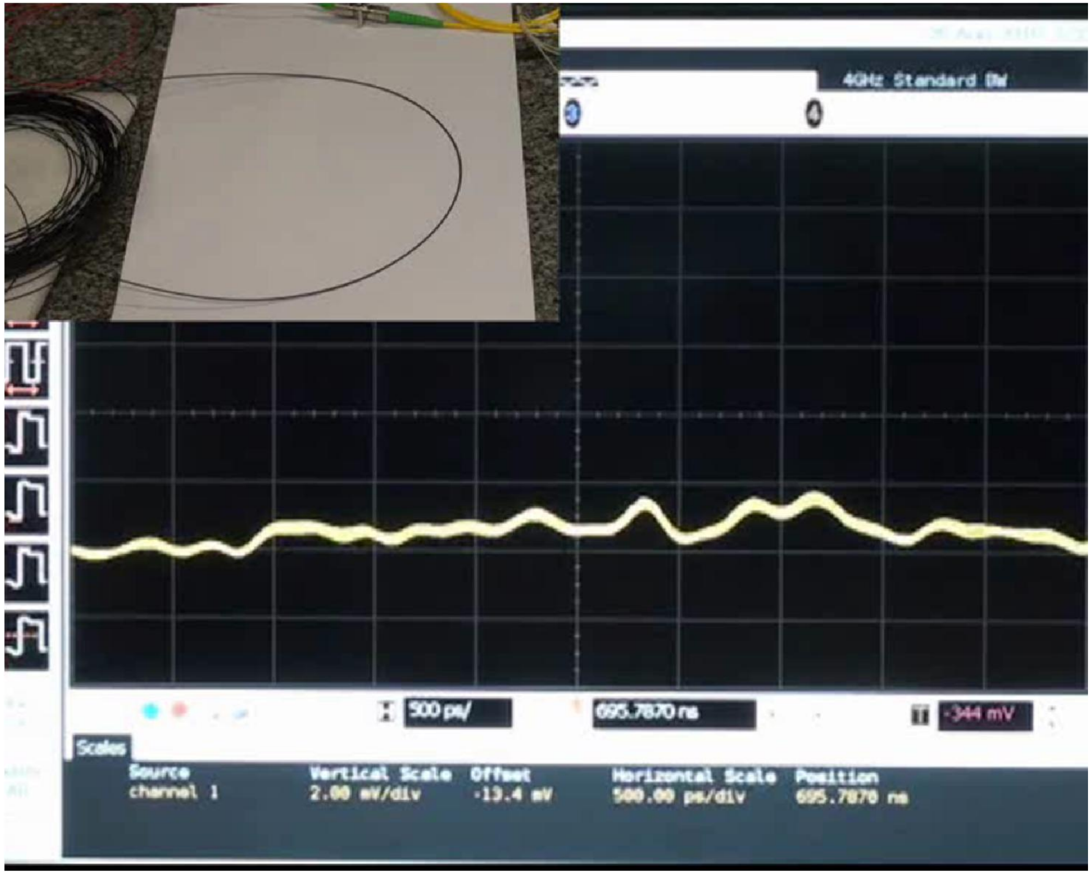


Environmental & human threats

Anticipating catastrophic failures

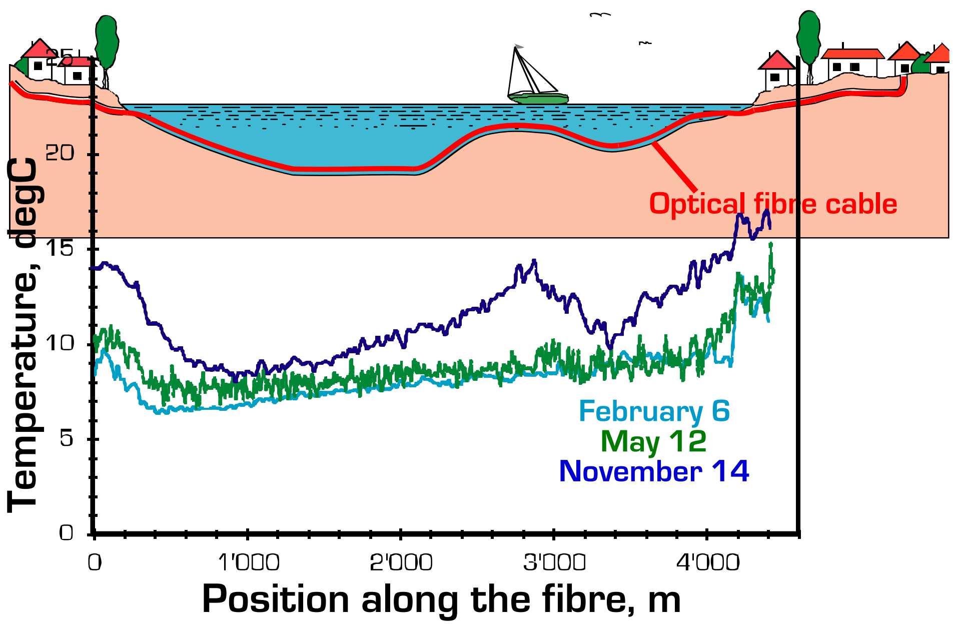
«Optical fibre nerves» a realistic answer to this concern

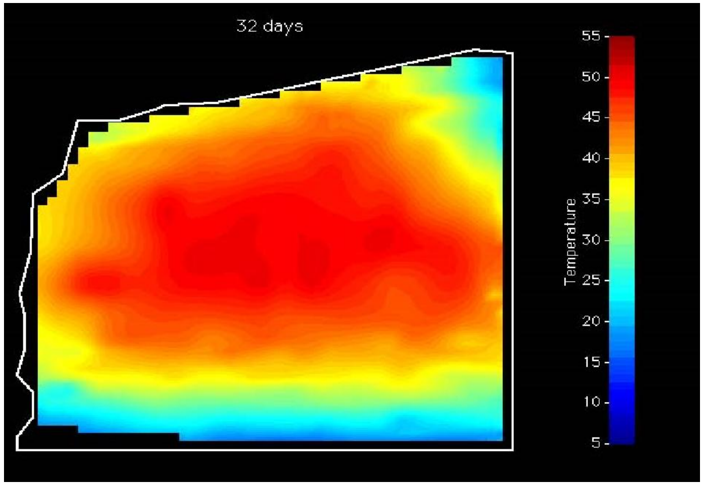
- The optical fibre can play the role of a sensitive nerve that is seamlessly and densely integrated in a structure or the environment
- The optical fibre can inform about the amplitude and the position of the «sensation»



Examples of distributed fibre sensing

A standard optical fibre is the sensing element and gives a value of measurand for each point along the fibre.

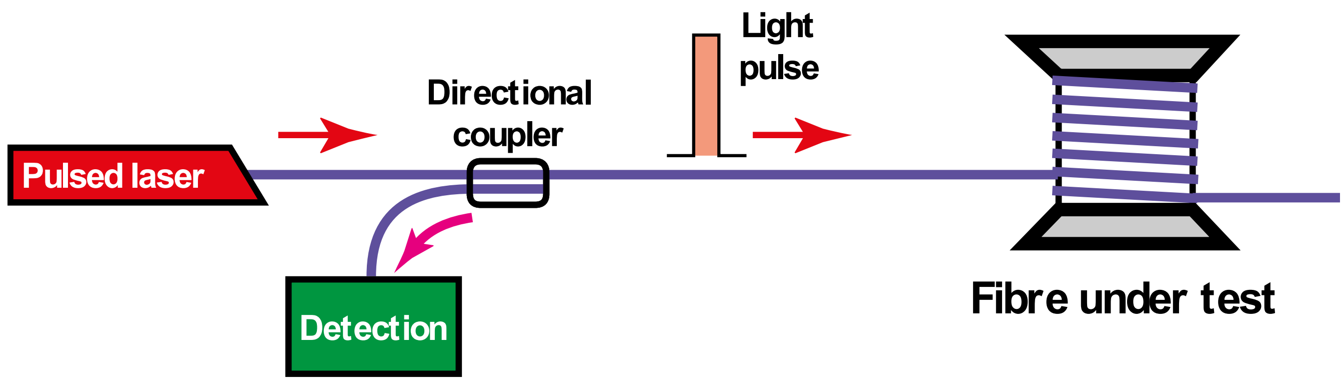


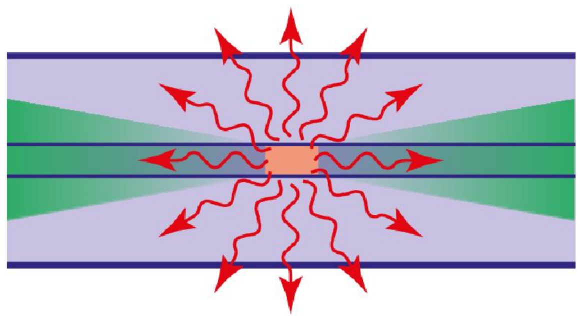


The optical fibre may replace many thousands of point sensors.

Range: 50 km, ext. to 150 km
Temperature resolution: 0.1 deg
Strain resolution: 0.001 %
Spatial resolution: 0.01-3 m (range dependent)

Spontaneous scattering-based sensors





$$P(z) = \frac{1}{2}\, v_{gr}\, P_o\, \tau\, S(z)\, \alpha_d(z)\, e^{-2\alpha z}$$

$$S(z) = \frac{3}{8}\left(\frac{\lambda_o}{n\,\pi\,\omega_o(z)}\right)^2$$: Recapture factor of the backscattered light (ω_o: mode radius)

$\alpha_d(z)$: Scattering coefficient

α : Attenuation

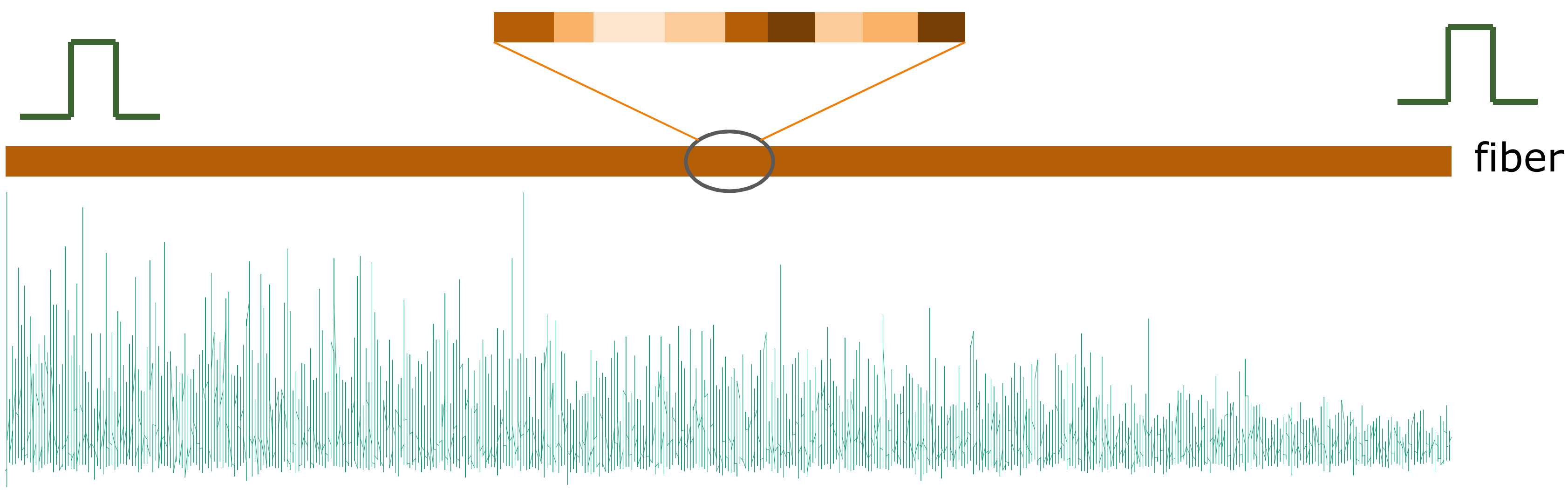
τ : Pulse temporal width

v_{gr} : Group velocity

Rayleigh-based sensing principle

Coherent optical time-domain reflectometry

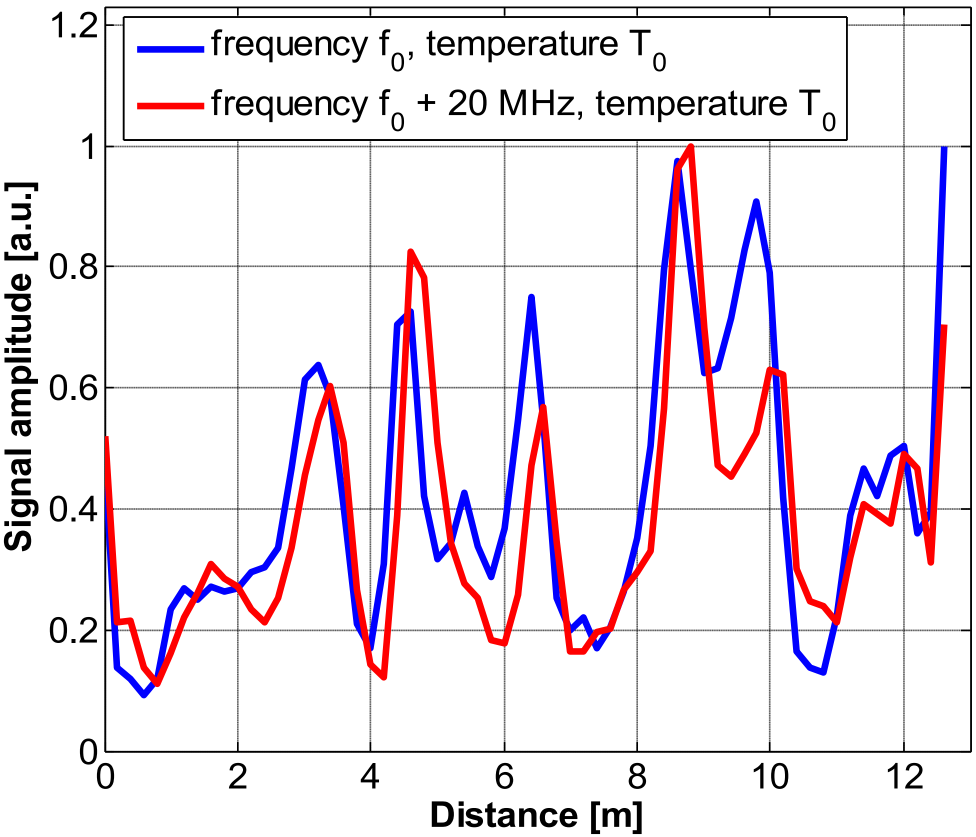
- An optical pulse is use to interrogate the fiber
- Backscattered light originated from the different scattering points interfere, resulting in a zigzag-shaped trace.



optical frequency, refractive index and pitch

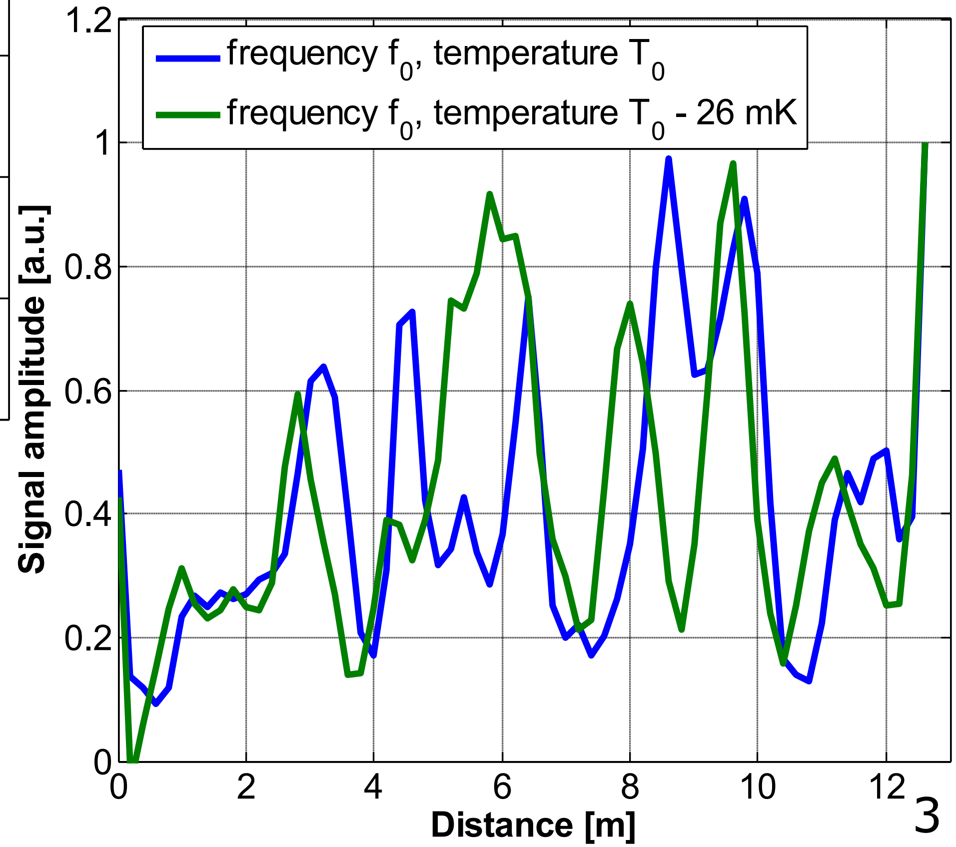
temperature and strain

Characteristic of Rayleigh traces



Frequency dependence

Temperature dependence

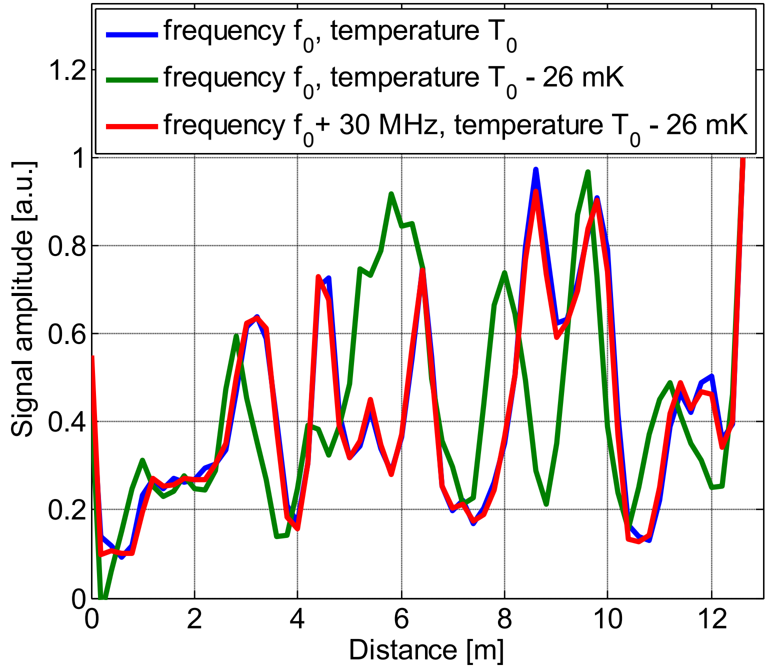


Rayleigh-based sensing principle

The shape change induced by temperature can be fully compensated by the effect of changing optical frequency.

restorability

relative temperature change



$$R_0(f_0,T_0) \xrightarrow{\text{temp change}} R(f_0,T_0+\Delta T) \xrightarrow{\text{freq change}} R'(f_0+\Delta f,T_0+\Delta T)$$

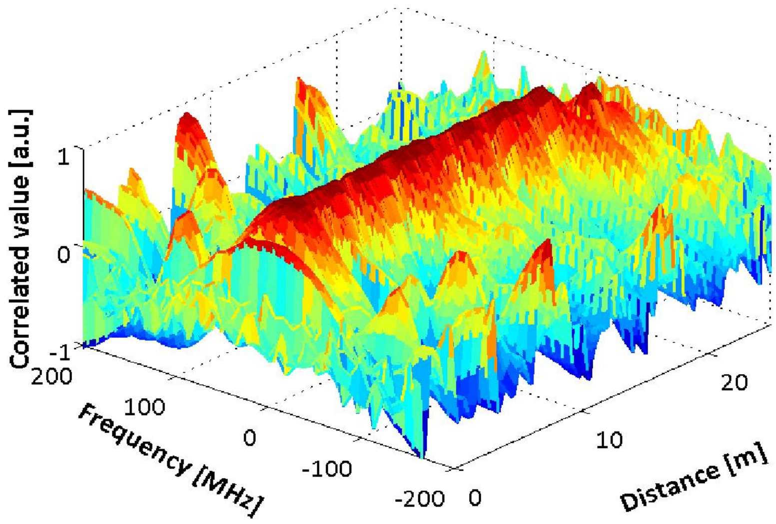
Trace comparison, $\Delta f \propto \Delta T$

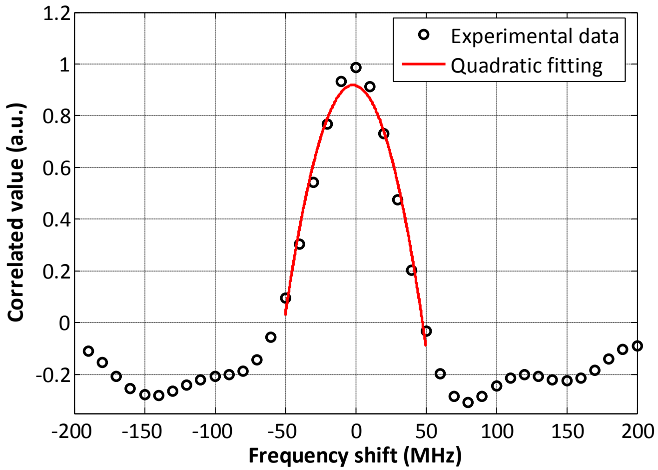
The similarity is determined by cross-correlation

$$R_0(f_0,T_0) * R'(f_0+\Delta f,T_0+\Delta T)$$

C-OTDR – Spectral measurements

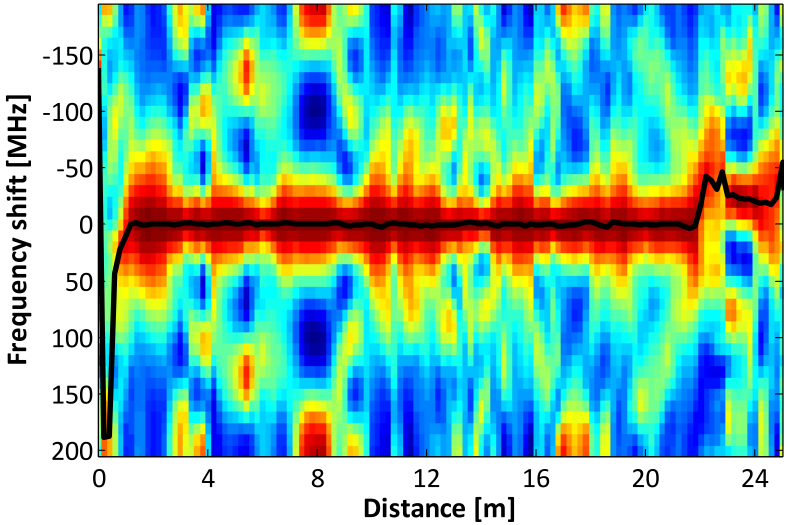
Spectral cross-correlation





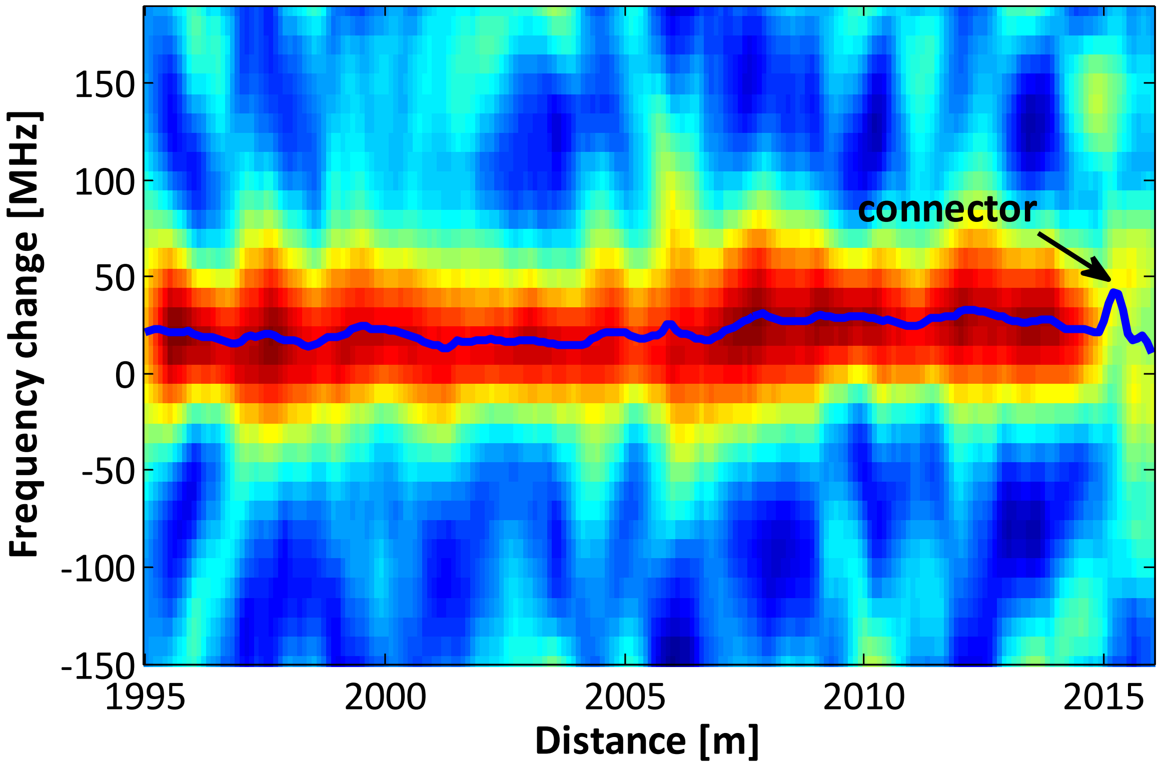
Frequency accuracy:

- 3 MHz (2mK @ 300K)
- 1k averages
- Scanning step: 10 MHz
- Time: 40s

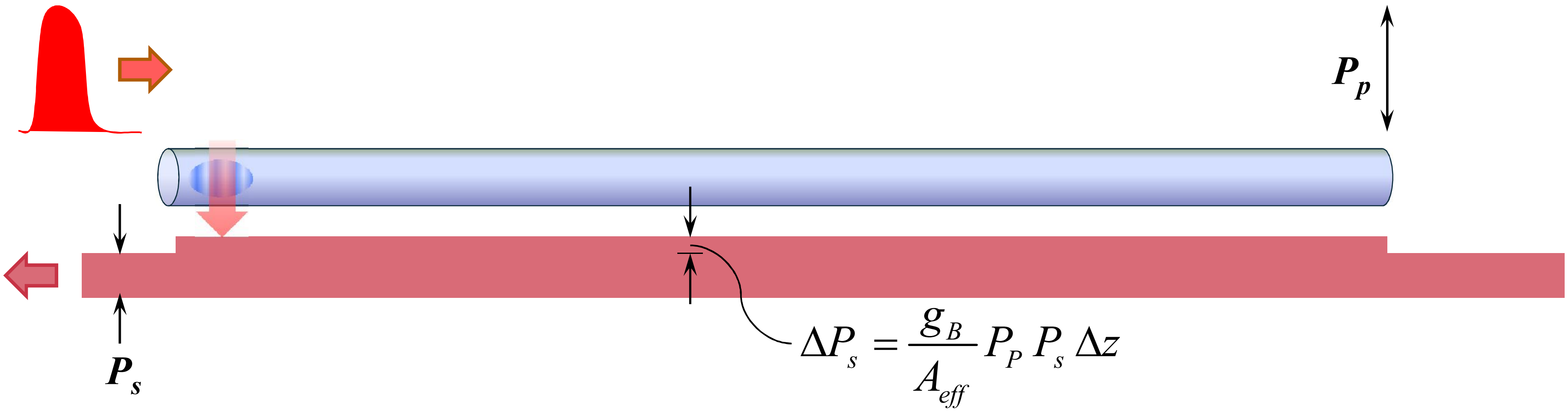


Km-range C-OTDR measurements

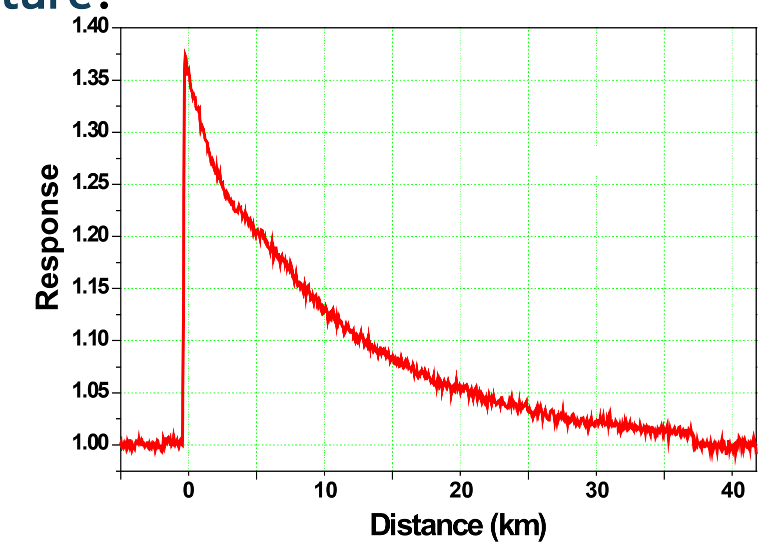
- Temperature change: -0.018 K (around 2-km distance)
  - Frequency shift in standard fibre: 18.96 MHz



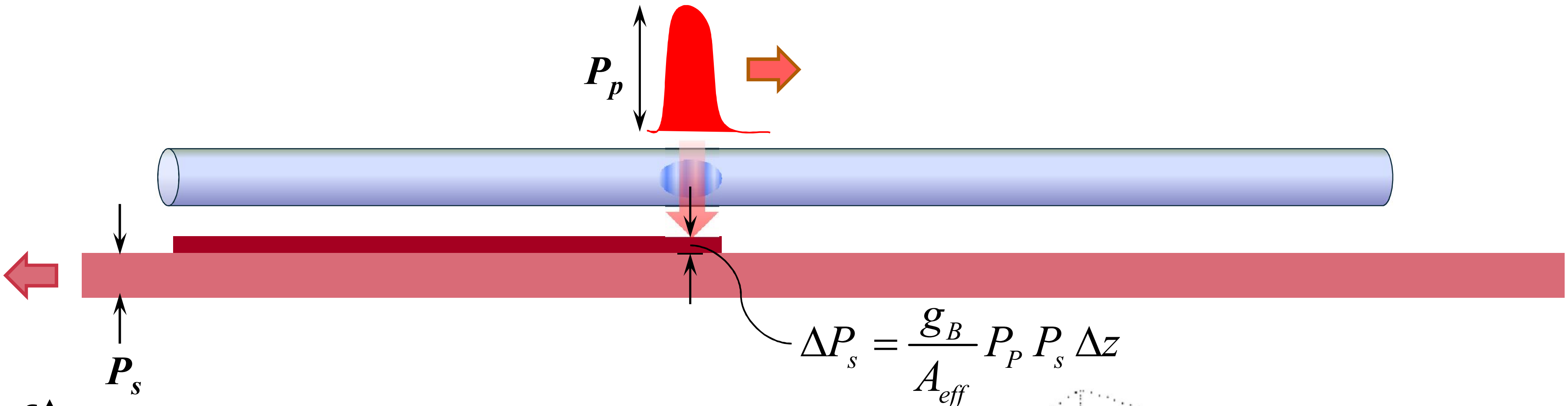
Nonlinear coupling-based sensors

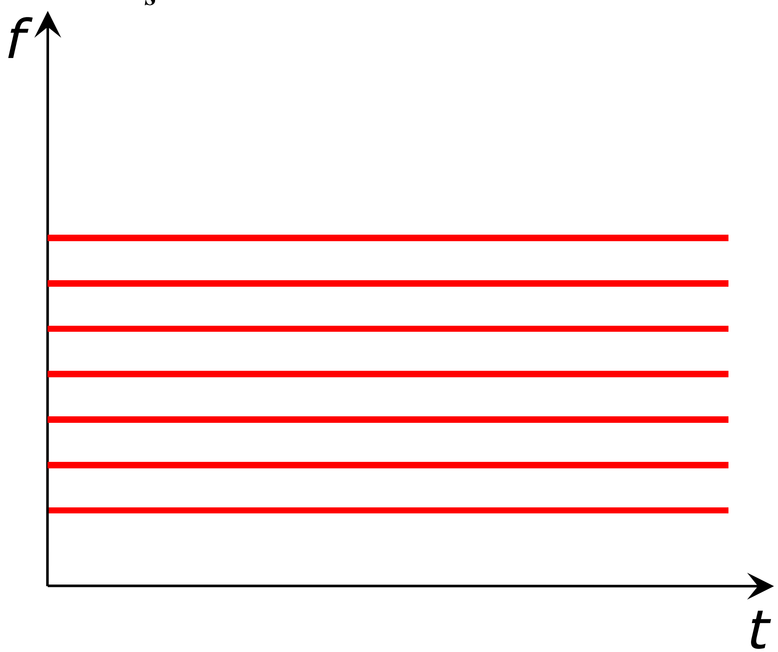


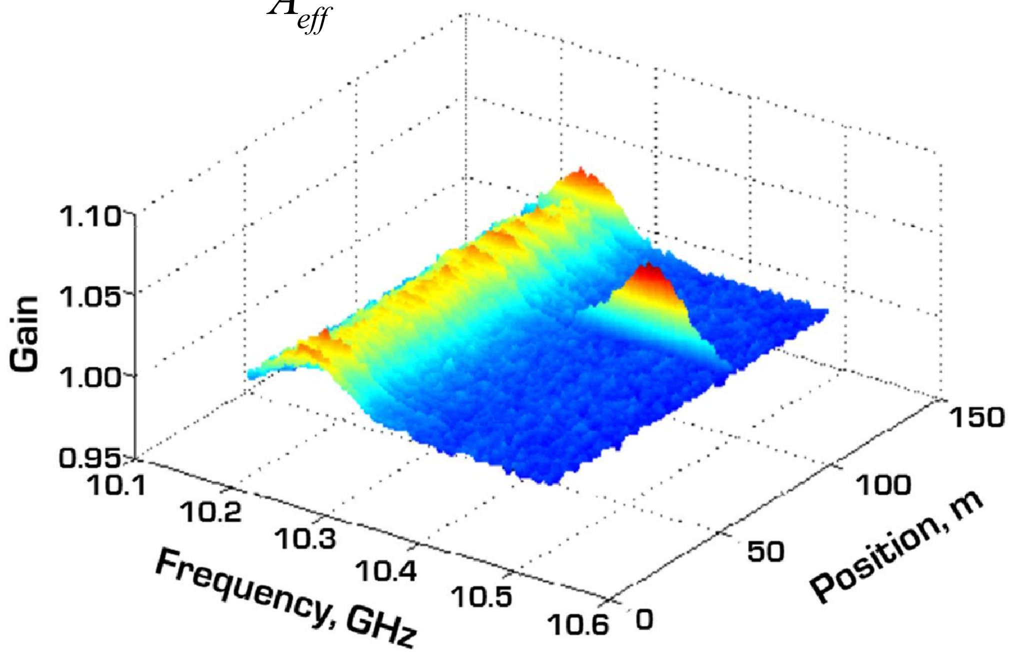
- The nonlinear interaction creates a dynamic Bragg grating and 100% of the diffracted light is back-coupled: ideal recapture!
- But the probe signal is needed to generate the dynamic grating and the response is on top of the CW probe signal.



Brillouin sensing principle

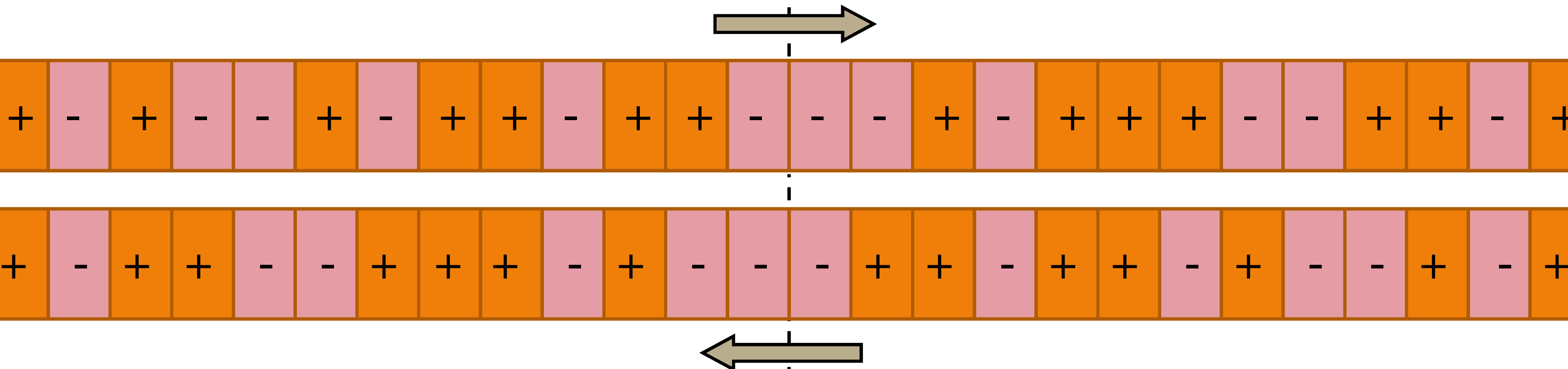






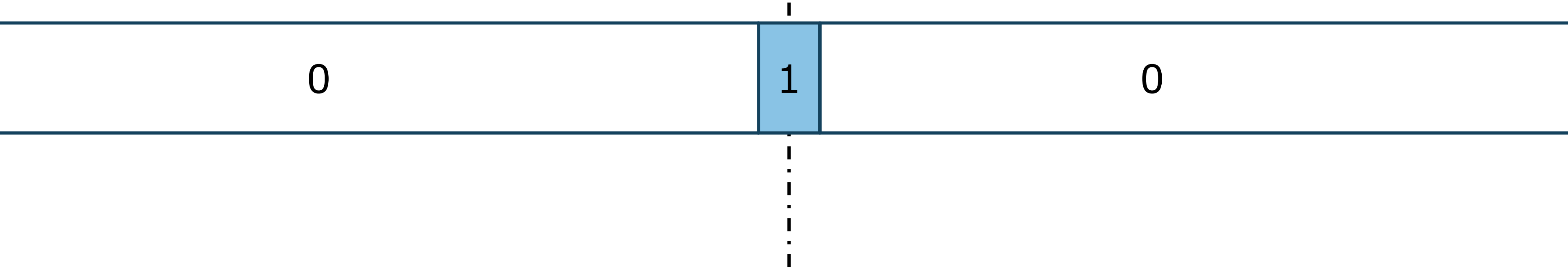
Generation of local stationary gratings

Signal phase-modulated by a PRBS or chaotic signal



The driving force for the acoustic wave ~ the product of the wave amplitudes

X (time averaged)



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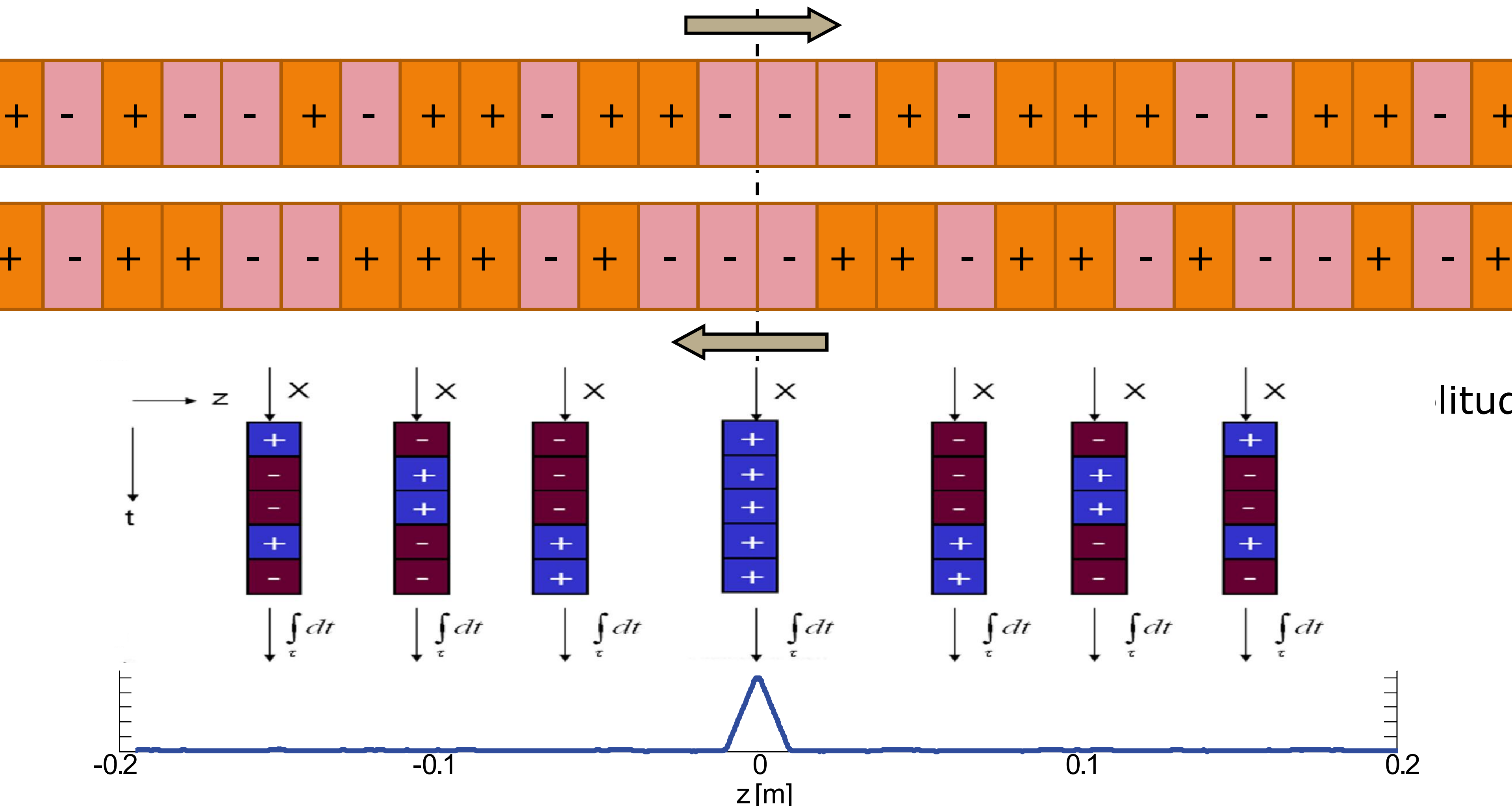

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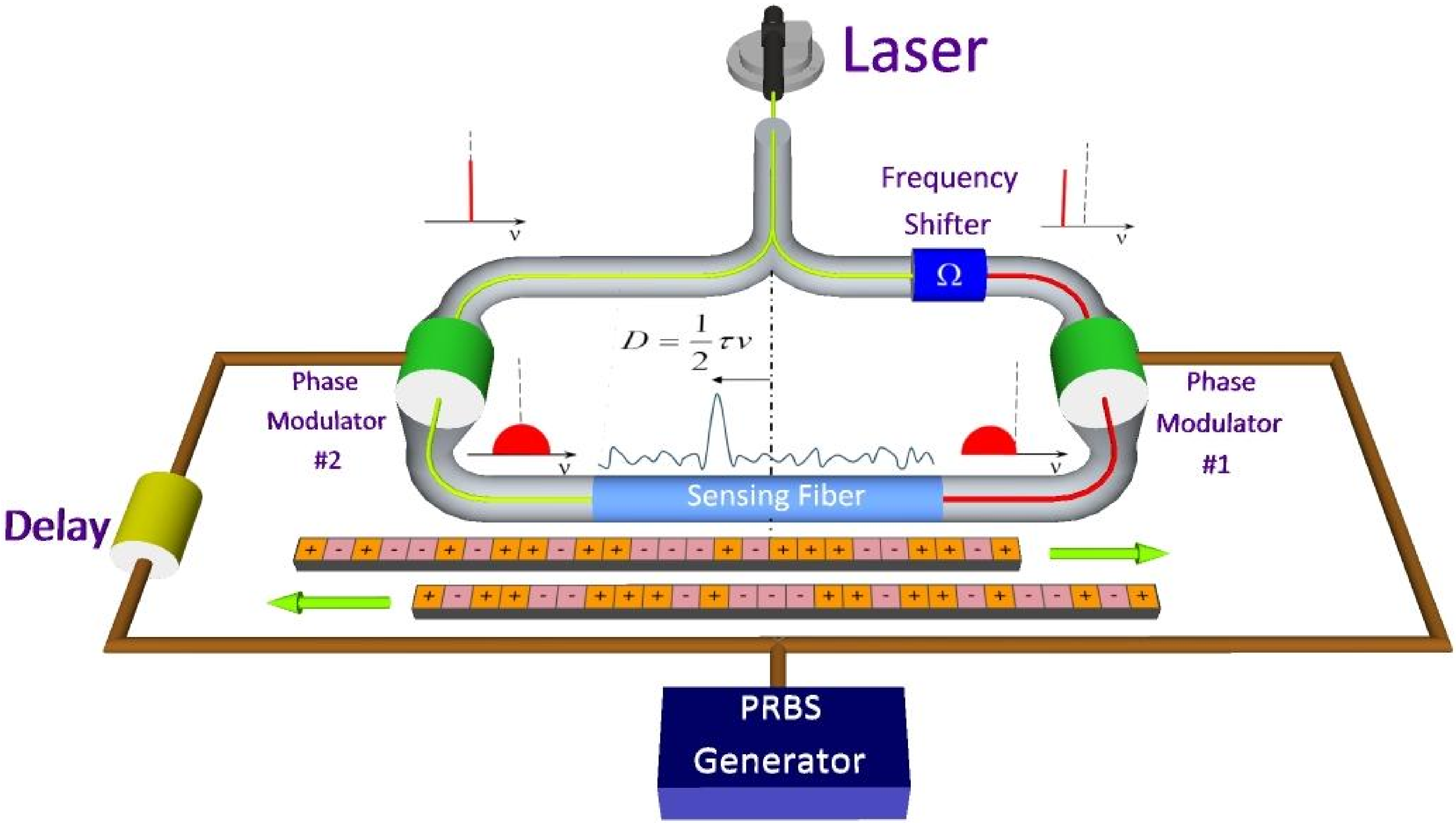
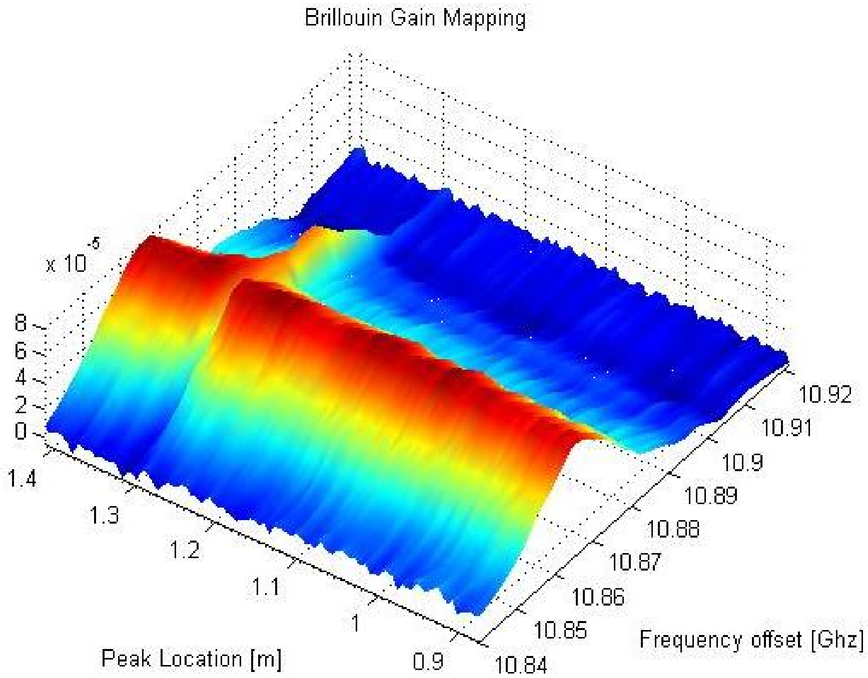
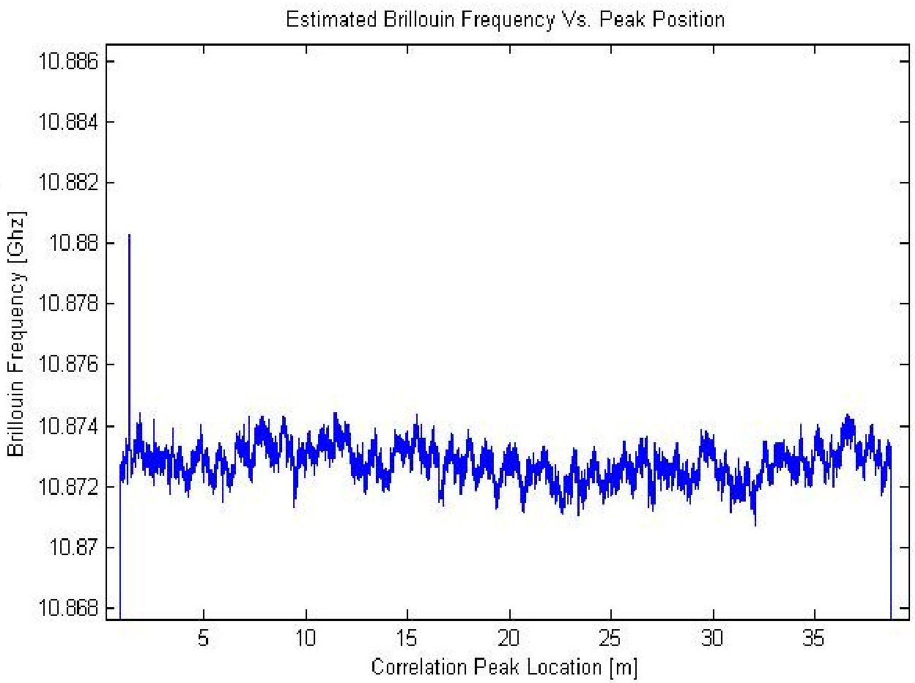


Results



- Fibre length: 40 m
- PRBS Clock rate: 8.14 GHz
  ➔ Spatial resolution: 1.2 cm
- PRBS length $2^{15}-1=32{,}767$ symbols



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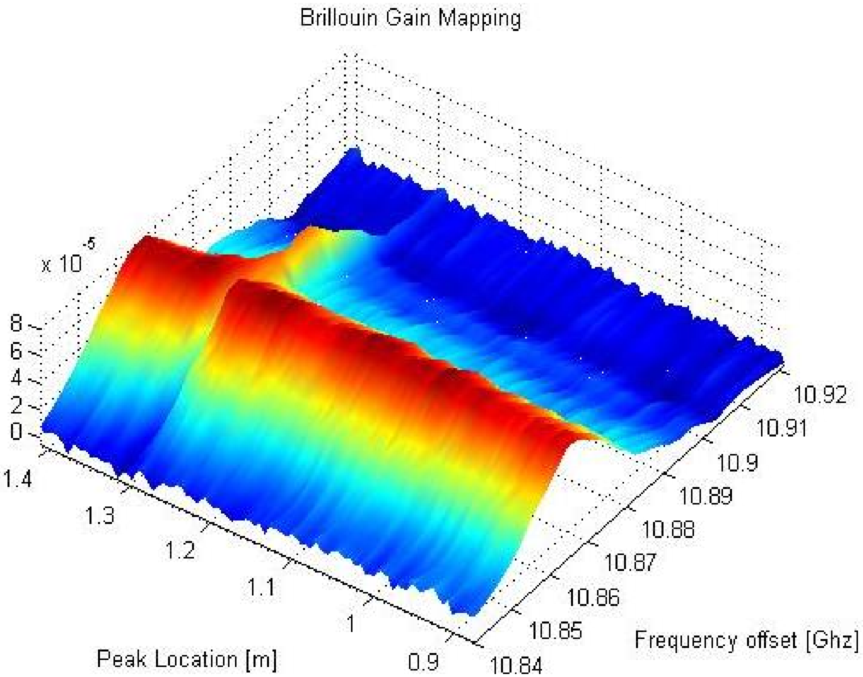

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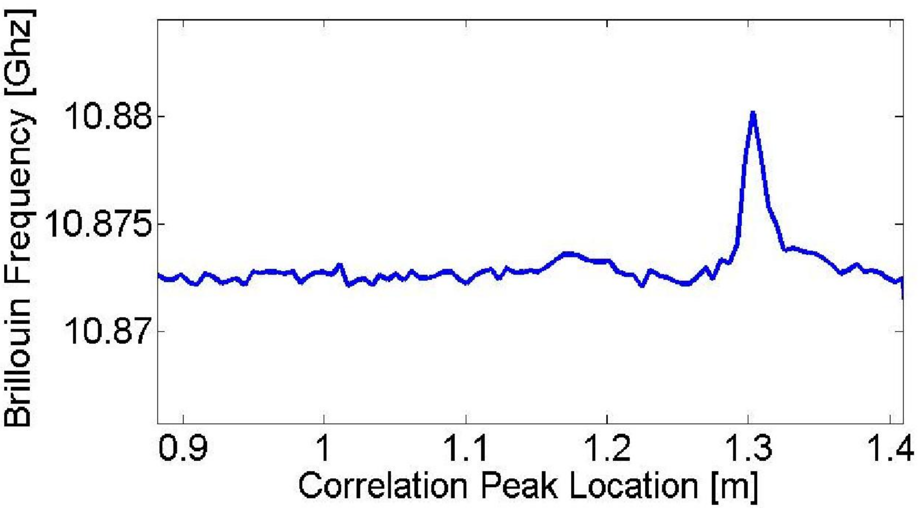
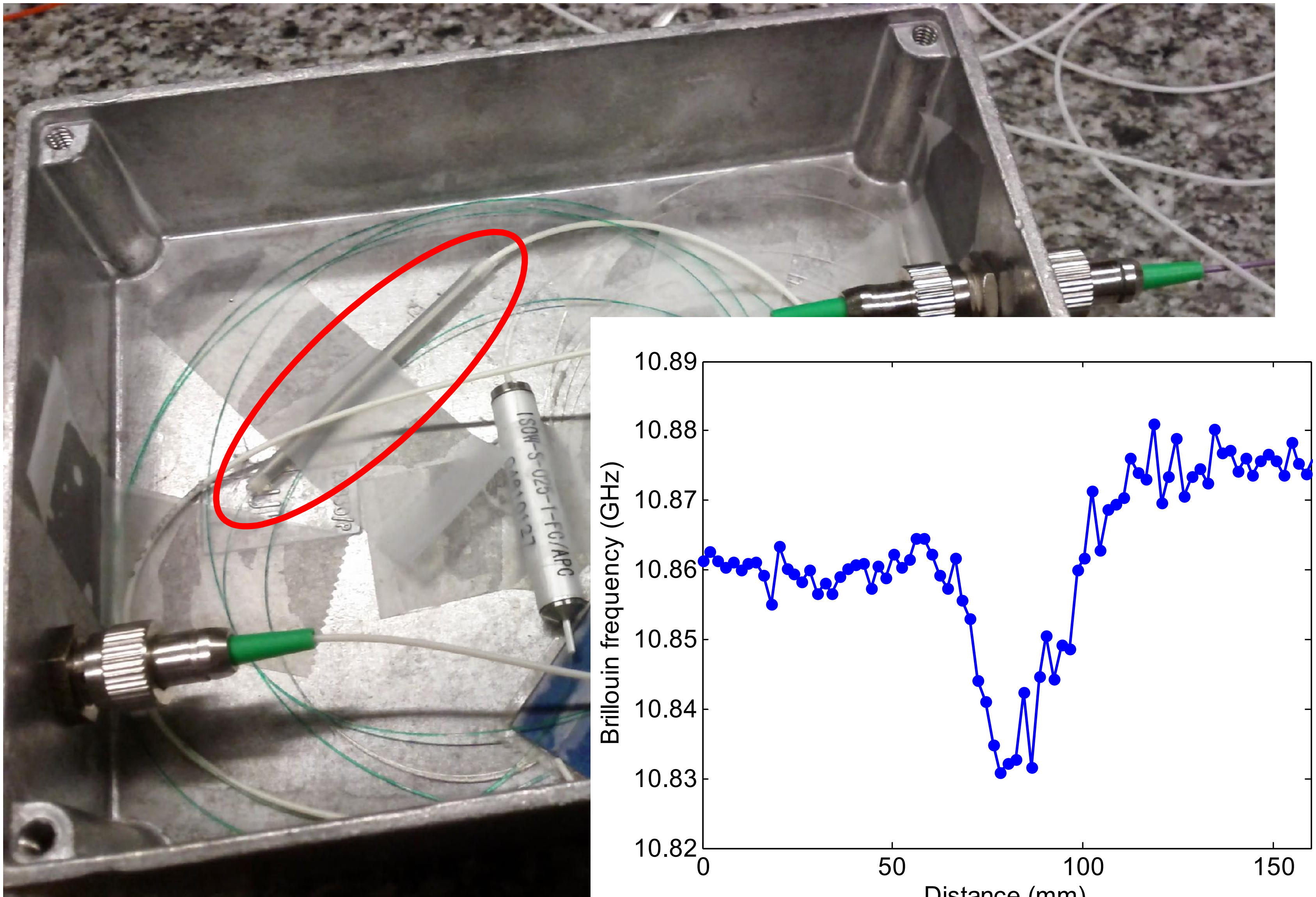


A. Zadok, Y. Antman, N. Primerov, A. Denisov, J. Sancho, and L. Thevenaz, "Random-access distributed fiber sensing," *Laser & Photonics Reviews,* online preview, 2012.

Examples of fibre components inspection



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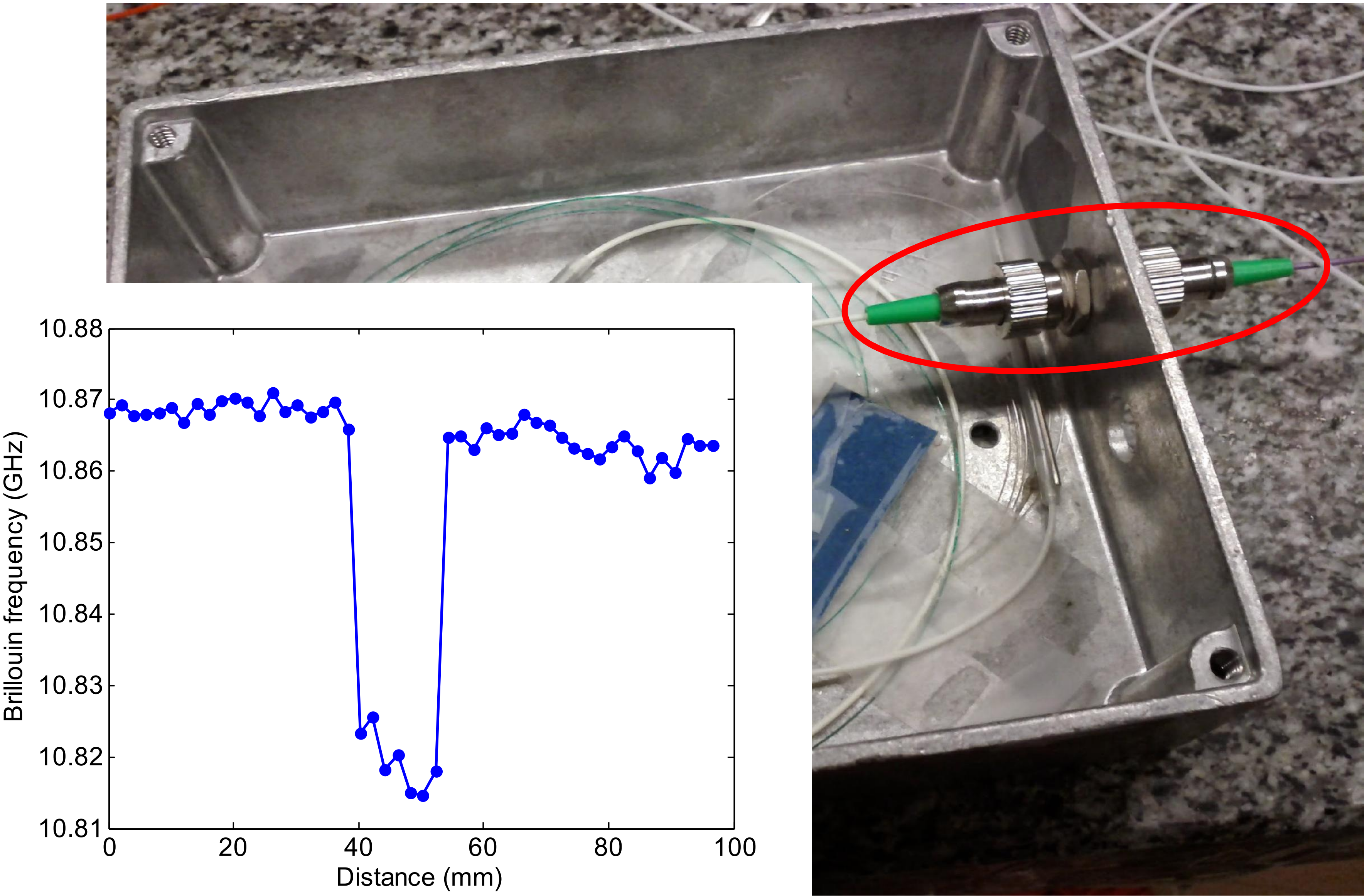

Perspectives

- State-of-the-art: distributed temperature and strain sensing over 50km with 1m spatial resolution

- Research art: >100km with 1m spatial resolution, 10km with 1 cm spatial resolution (1’000’000 resolved points).

- Future: Contact detection with instantaneous response

- Future: Distributed pressure sensing

- Future: Distributed sensing of magnetic field, illumination, radiation, etc…

- Future: Shape sensing