Modern 2020

Overview of Optical Fiber Technologies for Radioactive Waste Disposal Site Monitoring

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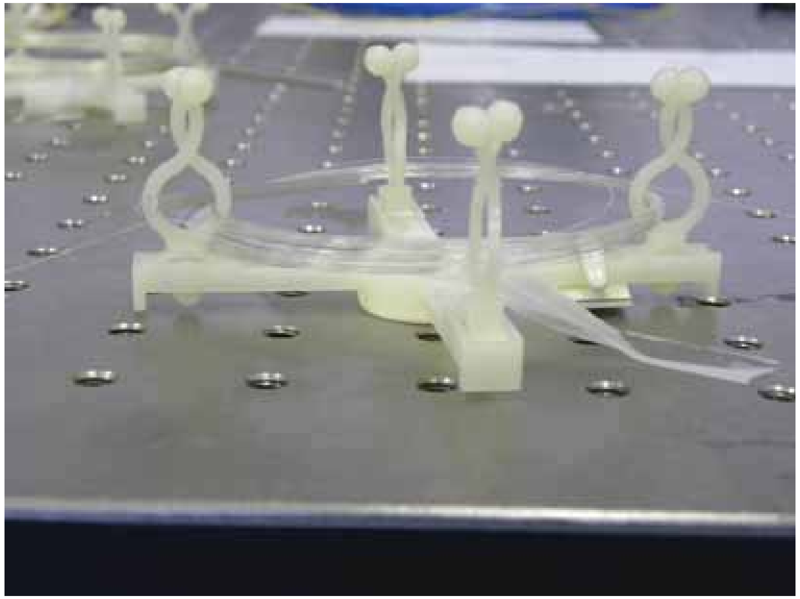
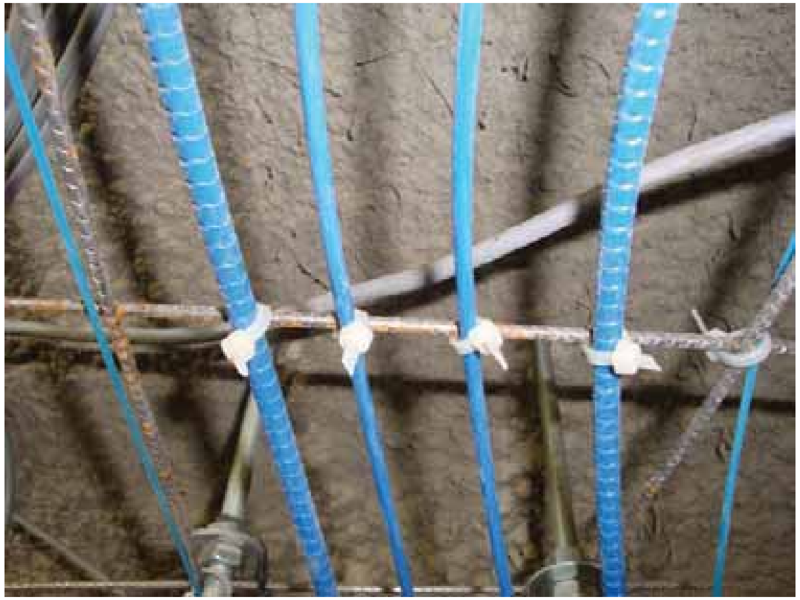
Packaging design is essential to move from optical fibers to monitoring cables



- core: 4 µm to 62.5 µm
- cladding: 125 µm (= hair)



- temperature, strain, radiation, hydrogen release,

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Introduction

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Many parameters can be monitored in nuclear waste geological repositories. Is optical fiber sensing possible?

Parameters	Typical range	Target sensitivity	Target spatial resolution
Temperature	20 to 90 °C	0.1 °C	20 cm
Displacement	0.5 to 2.5 mm m^{-1}	1 µm m^{-1}	10 cm
Strain in concrete	10 µm m^{-1}	3 µm m^{-1}	10 cm
Concrete cracks	200 µm		10 cm
Gap evolution inside cell	10 mm (in 100 years)	0.5 mm	1 m
Hydrogen	0 to 4 % with a sensitivity of 500 ppm 4 to 10 % with a sensitivity of 1 %	100 ppm <1 %	1.5 to 3 m
Gamma radiation	0.1 to 1 Gy h^{-1} TID of 10 MGy on 100 years	50 mGy	1.5 m
Dry density of bentonite	1000 to 2000 kg m^{-3}	10 kg m^{-3}	1 m
pH	7 to 13	0.5	1 m

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Optical scatterings

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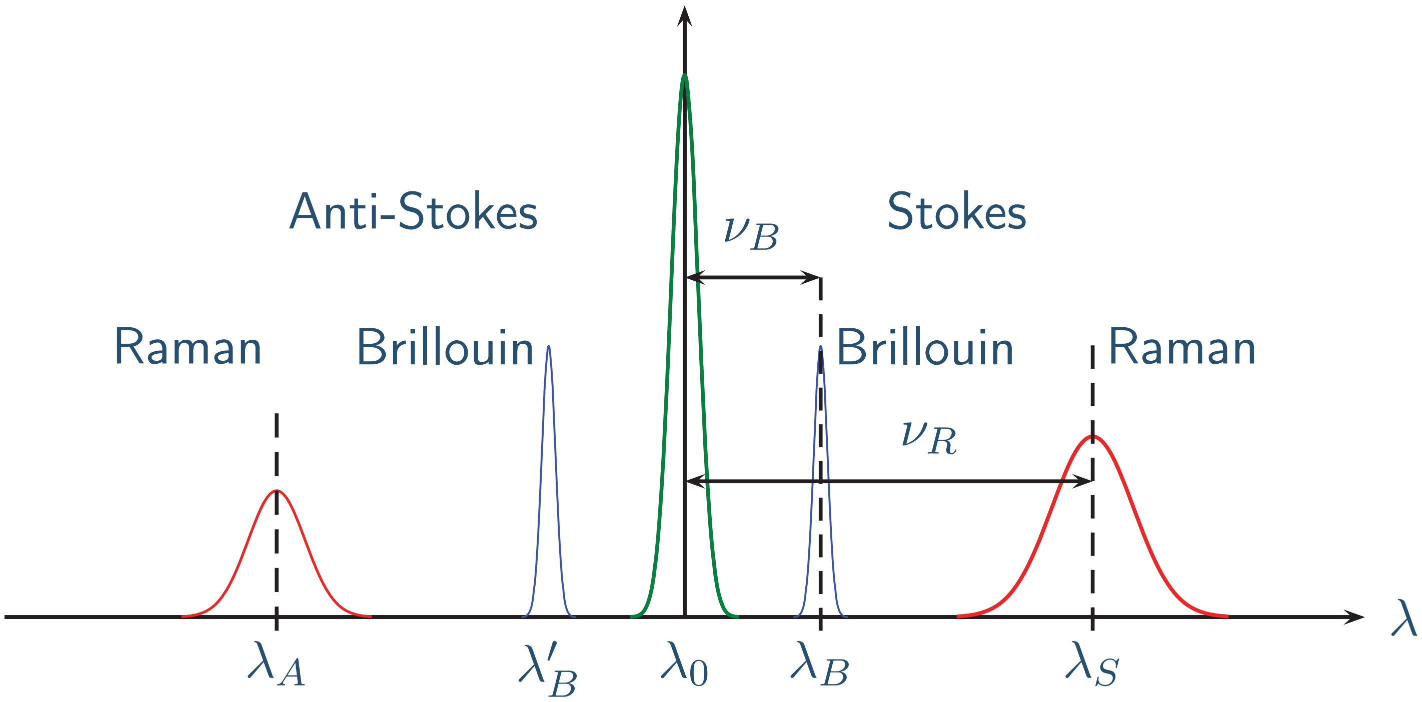
There are 3 scattering mechanisms used for optical sensing

Rayleigh scattering: elastic scattering ($\lambda_0 \to \lambda_0$), sensitive to **temperature** and **strain** ($\lambda_0 \approx 194$ THz)

Raman scattering: inelastic scattering ($\lambda_0 \to \lambda_S$, λ_A), sensitive to **temperature** ($\nu_R \approx 13$ THz)

Brillouin scattering: inelastic scattering ($\lambda_0 \to \lambda_B, \lambda'_B$), sensitive to **temperature** and **strain** ($\nu_B \approx 11$ GHz)



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Reflectometry principles

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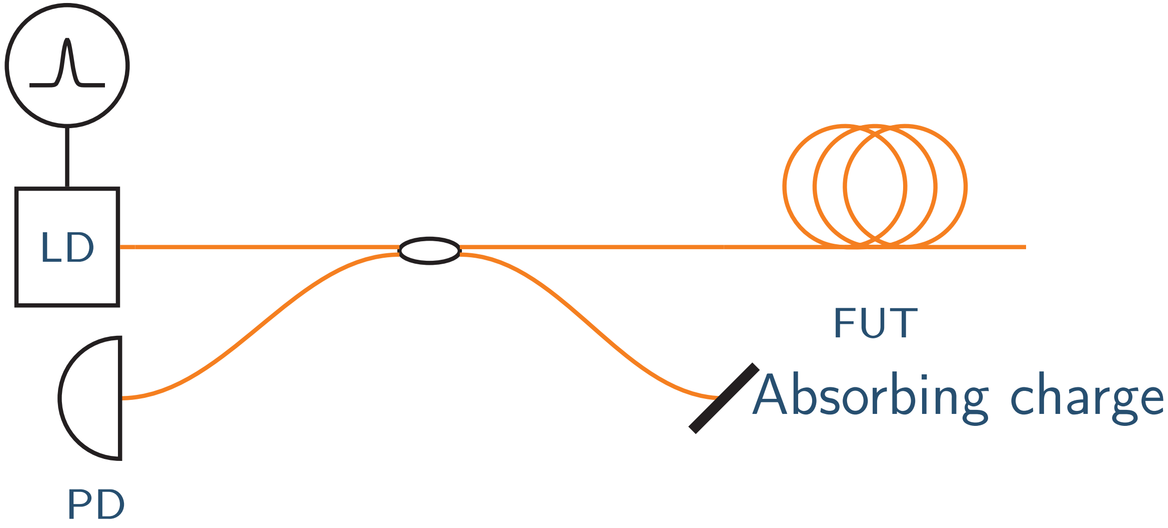
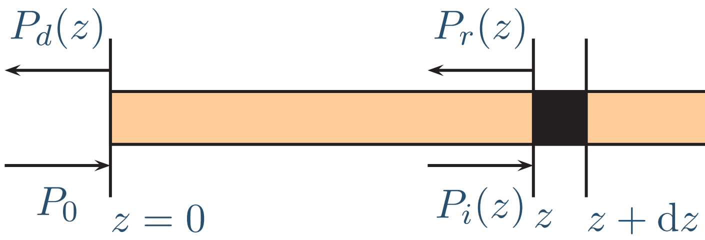
OTDR is a very simple and interesting tool that consists of analyzing a backscattered pulse





- pulse width D (in time)
- pulse peak power P_0
- Rayleigh attenuation coeffient $\alpha_s = \frac{C}{\lambda^4}$

$$P_r(z) = P_i(z)\alpha_s F \mathrm{d}z \Rightarrow P_d(z) \approx \frac{v_g \alpha_s F}{2} P_0 D e^{-2\alpha z}$$

$$\Rightarrow 5 \log P_d(z) = K - az$$

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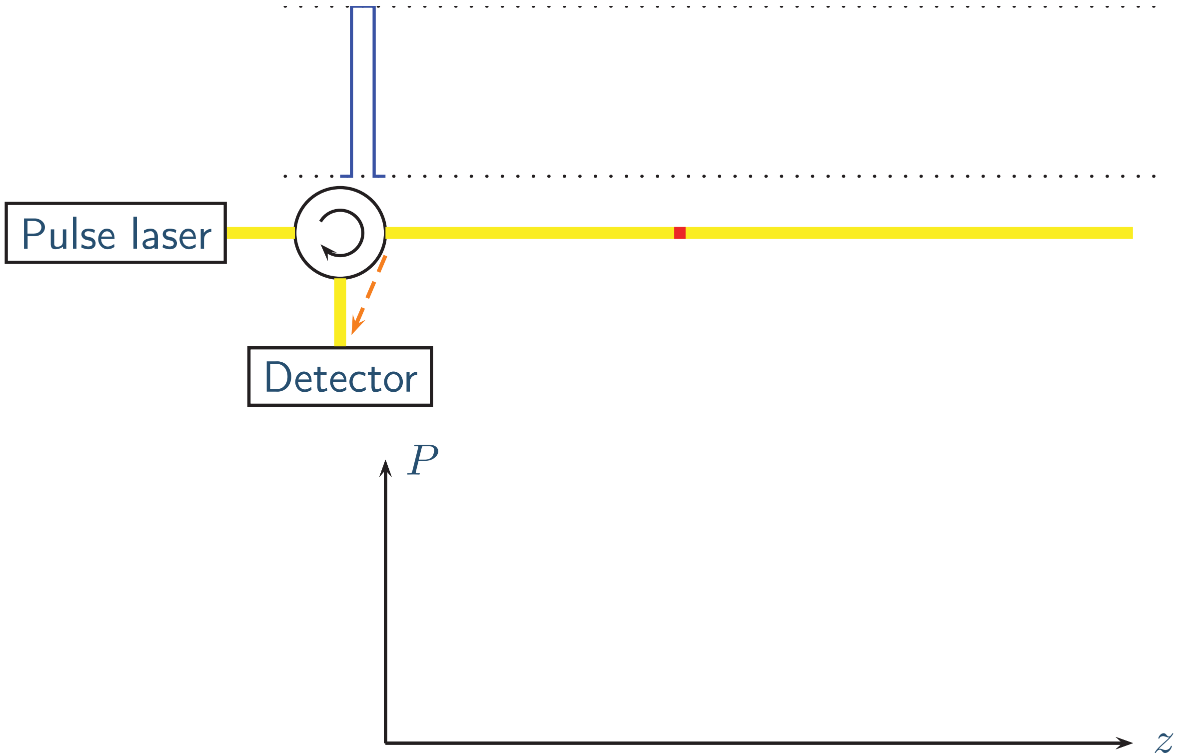
OTDR is a very simple and interesting tool that can be used with FBG



Rmk: If there are FBGs along the fiber, they will create strong reflections that will be visible in the curve like any reflective event.

- access to one end only
- simple set-up
- laboratory and **field** measurements
- information on spatial behavior
- precision less than other techniques
- 1300, 1550 and 1625 nm
- P_0 around 10 mW with repetition rate 1 kHz (long fibers) and 20 kHz (short fibers)
- D in the range ns to μs
- kilometer range and meter spatial resolution

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By combining reflectometry with Rayleigh, Raman and Brillouin scatterings, distributed measurement is possible

- OTDR/OFDR uses Rayleigh backscattering to measure distributed temperature/strain by cross-correlation analysis with one reference trace:

$$\Delta\nu_R = C_T^R \Delta T + C_\epsilon^R \Delta\epsilon$$

- RDTS (Raman Distributed Temerature Sensor) measures the ratio:

$$R(T) = \left(\frac{\lambda_S}{\lambda_A}\right)^4 \exp\left(-\frac{h\nu_R}{k_B T}\right)$$

versus the fiber length.

- BOTDA (Brillouin Optical Time Domain Analysis) extracts:

$$\Delta\nu_B = \nu_B - \nu_{B0} = C_T^B \Delta T + C_\epsilon^B \Delta\epsilon$$

versus the fiber length to get distributed measure of temperature/strain.

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Rayleigh, Raman and Brillouin based sensors have complementary properties

	Rayleigh	Brillouin	Raman
Diffusion type	elastic	inelastic	inelastic
Fiber type	singlemode	singlemode	multimode singlemode
Measuring distance	20 km (OTDR) 70 m (OFDR)	30 km	30 km
Spatial resolution	20 cm (OTDR) 10 mm (OFDR)	10 cm	1 m
Temperature sensitivity	$C_T^R = -1.5\,\text{GHz}\,°\text{C}^{-1}$	$C_T^B = 1\,\text{MHz}\,°\text{C}^{-1}$	0.1 °C
Strain sensitivity	$C_\epsilon^R = -0.15\,\text{GHz}\,\mu\epsilon^{-1}$	$C_\epsilon^B = 0.05\,\text{MHz}\,\mu\epsilon^{-1}$	insensitive
Measuring time	10 min (OTDR) 10 s (OFDR)	10 min	1 min
Power budget	10 dB (OTDR) 70 dB (OFDR)	10 dB	10 dB

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Fiber Bragg gratings

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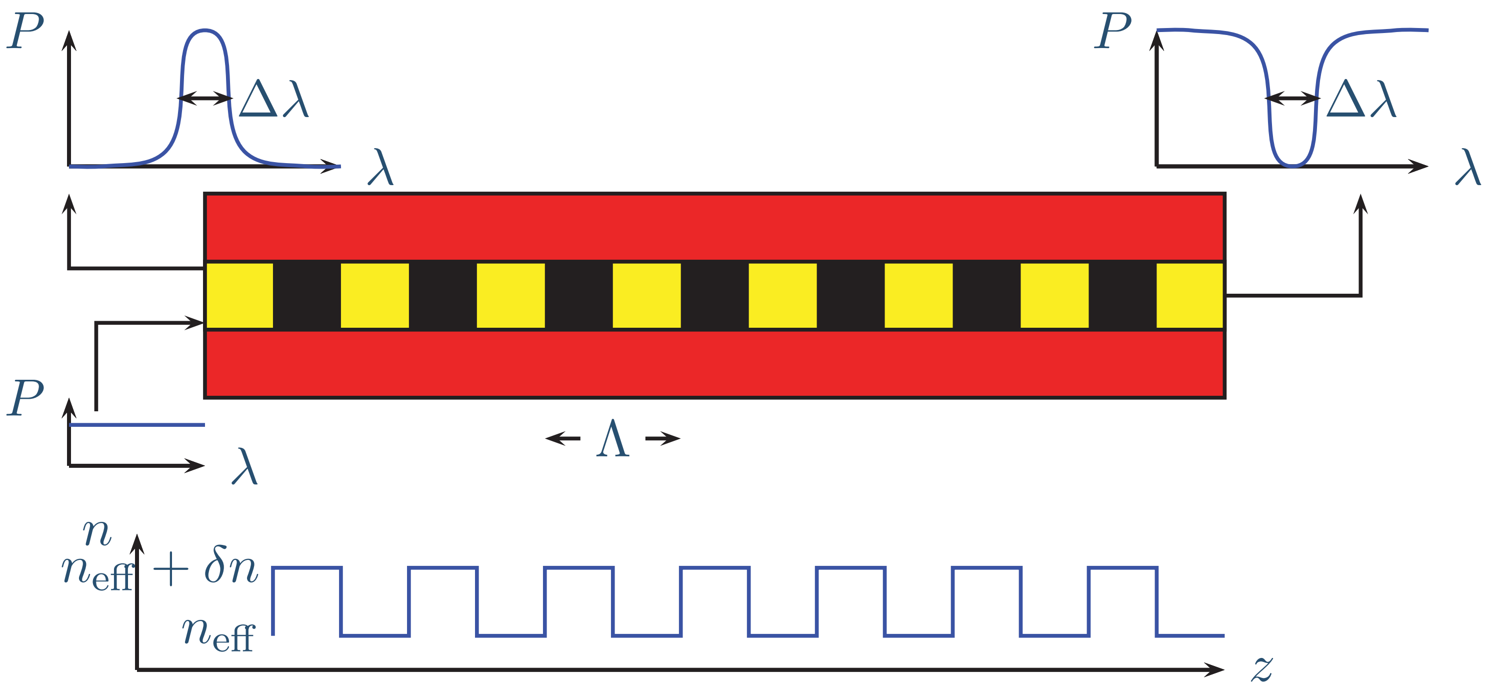
A fiber Bragg is a z-periodic modulation of the refractive index



- Periodic modulation of $n \Rightarrow$ coupling between forward and backward waves $\Rightarrow \lambda_B = 2n_{\text{eff}}\Lambda \quad \lambda_{\max} = 2(n_{\text{eff}} + \delta n)\Lambda$
- $0.5 \leq \Lambda \leq 100\,\mu\text{m}$, $10^{-5} \leq \delta n \leq 10^{-3}$, $1\,\text{mm} \leq L \leq 1\,\text{m}$
- R can be as high as 100% and $0.1\,\text{nm} < \Delta\lambda < 100\,\text{nm}$

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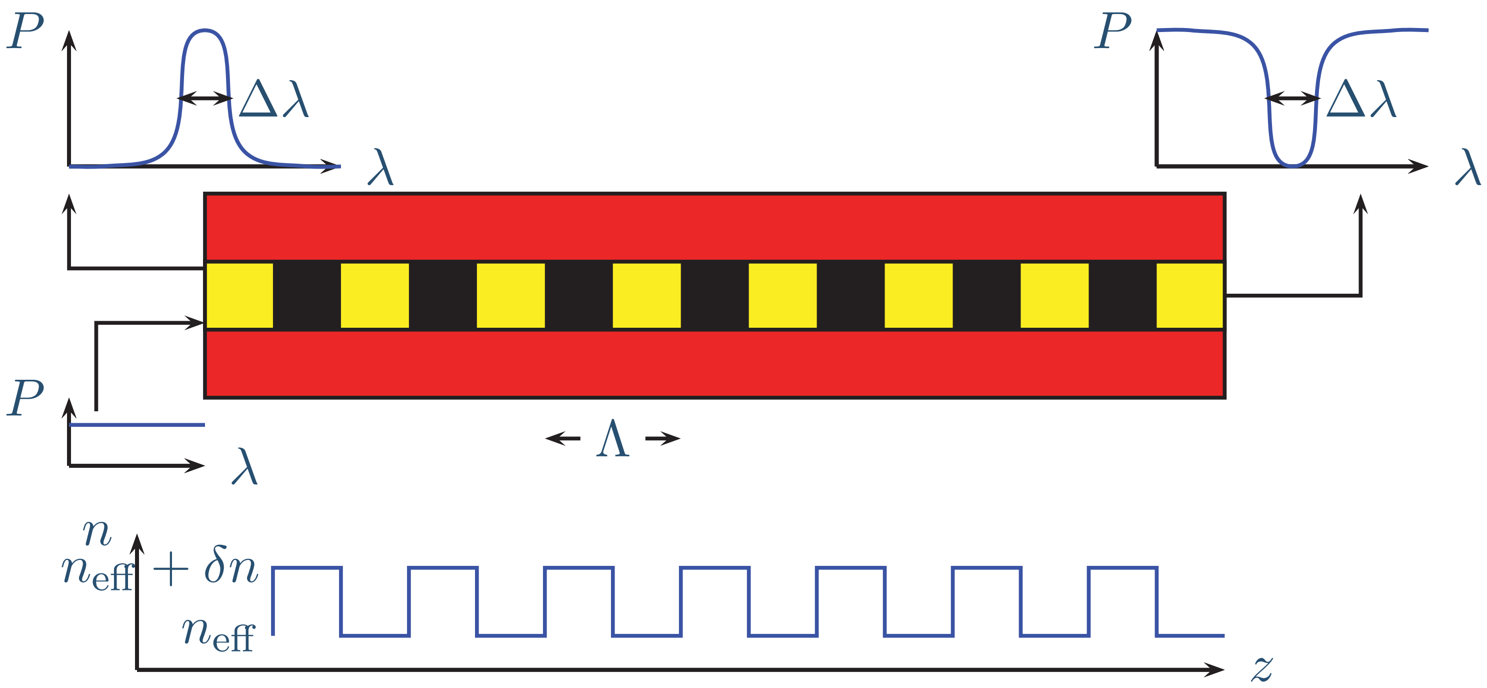

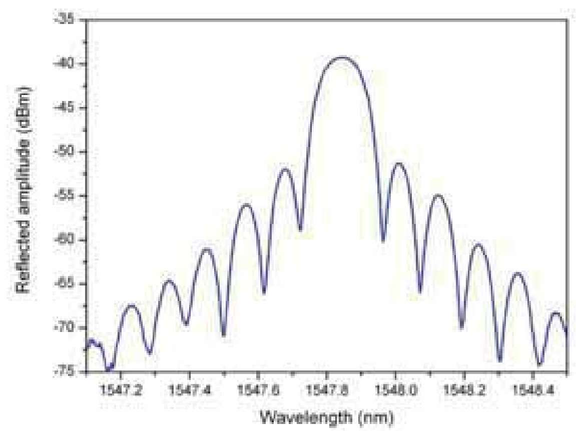

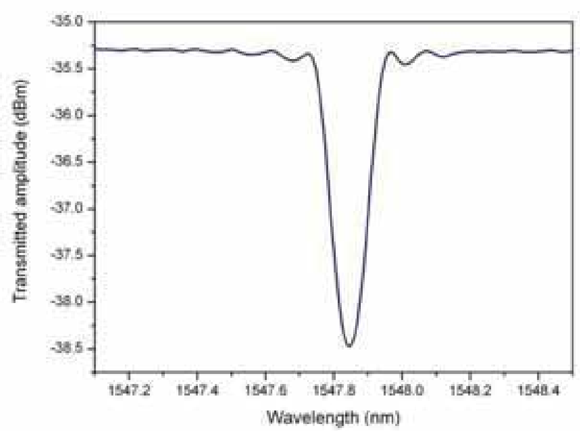

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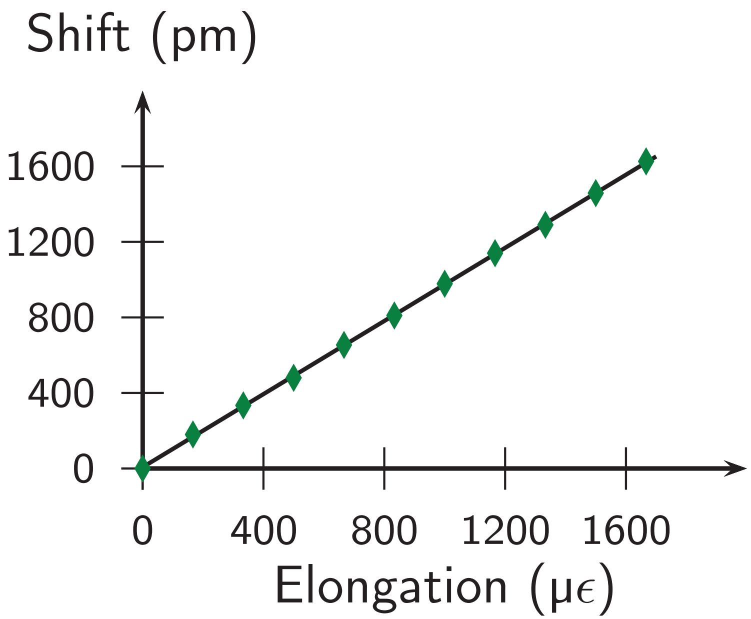
FBGs are excellent sensors because λ_B changes linearly with strain and temperature variations (no hysteresis)

$$\frac{\Delta\lambda_B}{\lambda_B} = \left\{ \frac{1}{n_{\text{eff}}} \frac{\partial n_{\text{eff}}}{\partial \epsilon} + \frac{1}{\Lambda} \frac{\partial \Lambda}{\partial \epsilon} \right\} \epsilon = (1 - p_e)\epsilon$$

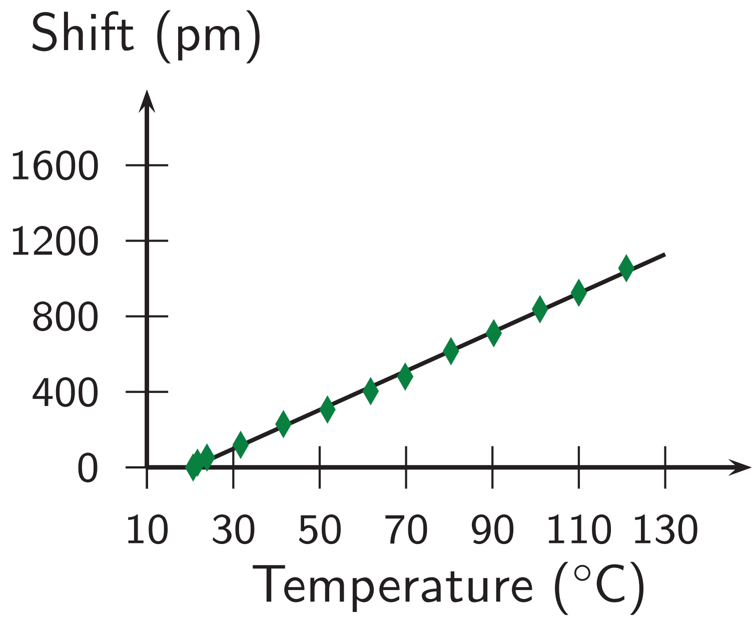
$$\frac{\Delta\lambda_B}{\lambda_B} = \left\{ \frac{1}{n_{\text{eff}}} \frac{\partial n_{\text{eff}}}{\partial T} + \frac{1}{\Lambda} \frac{\partial \Lambda}{\partial T} \right\} \Delta T = (\xi + \alpha)\Delta T$$

- $\epsilon = \Delta\ell/\ell$
- $p_e \approx 0.22 \times 10^{-6}\ \mu\epsilon^{-1}$

- $\xi \approx 8.6 \times 10^{-6}\ ^\circ\mathrm{C}^{-1}$
- $\alpha \approx 0.55 \times 10^{-6}\ ^\circ\mathrm{C}^{-1}$



$\Delta\lambda_B/\Delta\epsilon = 0.97\ \mathrm{pm}/\mu\epsilon$



$\Delta\lambda_B/\Delta T = 10.3\ \mathrm{pm}/^\circ\mathrm{C}$

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Hydrogen and pH sensing

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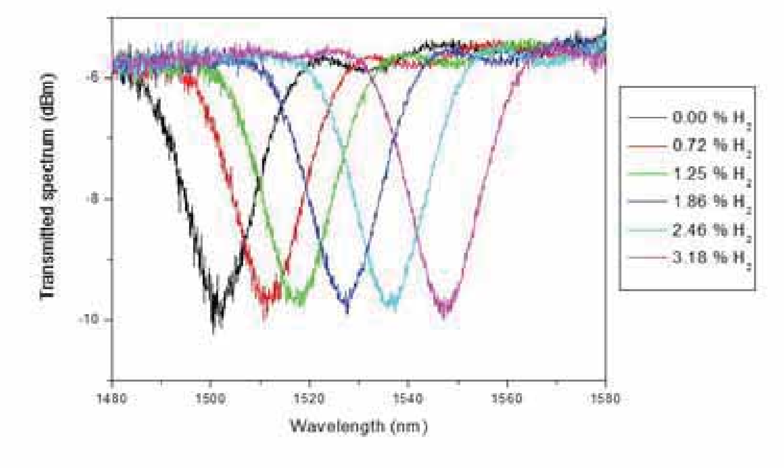
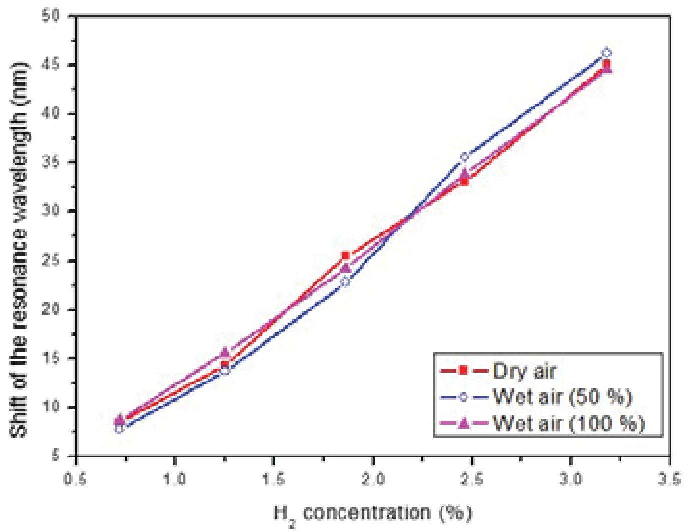
A sensitive layer is added around an FBG and the measurement is the wavelength shift

H_2 sensing

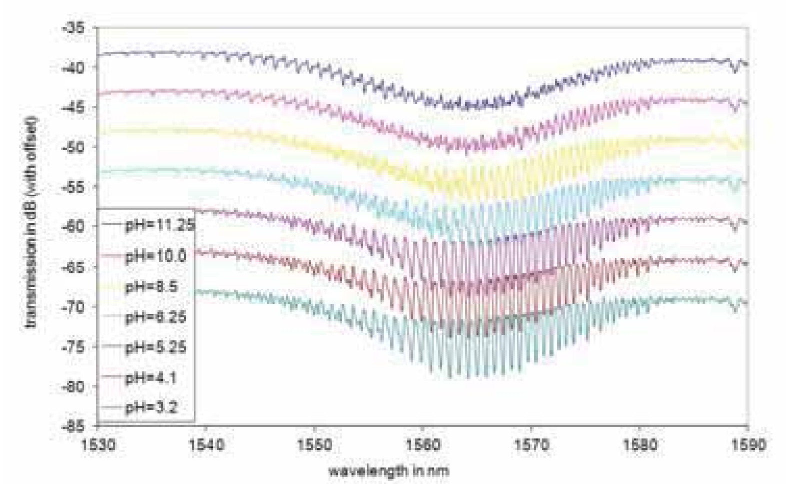
$$WO_3 + H_2 \longleftrightarrow WO_2 + H_2O$$
$$WO_2 + \frac{1}{2} O_2 \longleftrightarrow WO_3$$

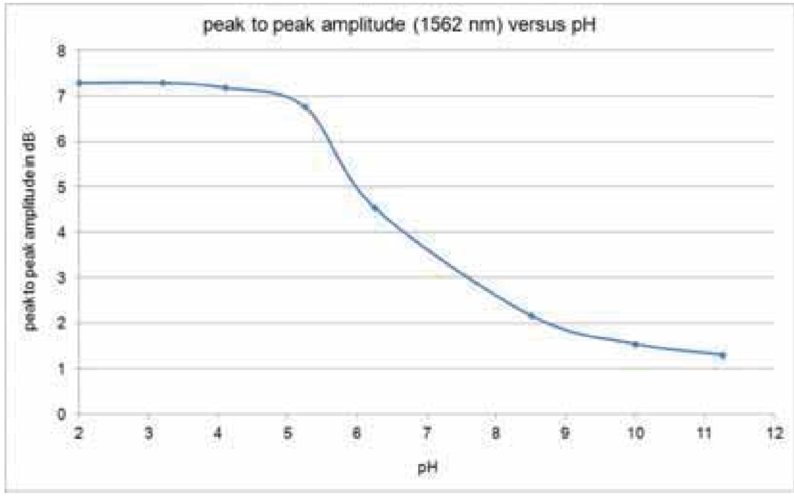




pH sensing

micro-porous bromophenol blue silica sol-gel layer





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Results

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For temperatrure and strain, TRL = 9 in classical environments but only 6 in radioactive waste disposals

1. Temperature is retrieved from Raman scattering in a multimode fiber
   - carbon-primary coating is mandatory to prevent hydrogen diffusion
   - F-doped fiber is mandatory to reduce the RIA
   - double-ended configuration proved to be efficient, at the expense of temperature uncertainty, which reaches 5 °C at 1 MGy
   - cross-sensitivities with H_2 and radiation.
2. Strain is retrieved from Brillouin scattering in a singlemode fiber
   - carbon-primary coating is mandatory to prevent hydrogen diffusion
   - F-doped fiber is mandatory to reduce the RIA and Brillouin frequency shift
   - temperature reduces the negative impact of radiation on distributed sensors
   - The frequency shift is in the order of 4 MHz at 1 MGy for the Ge-doped fiber and only 2 MHz with the F-doped fiber, which approximately corresponds to 80 μm m^{-1} and 40 μm m^{-1} maximal errors in strain measurement

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TRL is 3 for distributed radiation sensors, hydrogen detection, and pH sensing around 7 (but only 1-2 for in the basic range 11 to 13)

3. Rayleigh scattering has proved to be a very promising solution for strain sensing
   - less affected by radiation than Brillouin scattering
   - with F-doped fibers, the influence of radiation on Rayleigh frequency shifts is as small as −3.75 GHz, or 25 $\mu m\,m^{-1}$ error, whatever the working temperature (80 to 120 °C)
4. For distributed radiation sensing, fiber dopant is a key parameter:
   - Al-doped sample is clearly the most radiation-sensitive
   - Ge-doped sample is the less sensitive
   - a combination of different fibers should be deployed to measure the radiation spatial distribution on the MGy range.
5. Special cable to measure bentonite properties through distributed Raman temperature has been designed and proved to be a viable solution.
6. Hydrogen sensing has been obtained by palladed silica optical fibers paired with Brillouin scattering and by functionalized fiber Bragg gratings.

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Conclusion

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Optical fiber monitoring is feasible but still needs research and funding to be fully qualified for long-term monitoring

Optical fiber monitoring is feasible:

- for distributed temperature with specialty fibers and reflectometry techniques
- for point monitoring of temperature, strain with fiber Bragg gratings
- TRL is 6 for temperature and strain
- TRL is only for 3 radiation, and 2 for pH and H_2

To probe further: see posters

- Polymer optical fibre Bragg gratings for nuclear waste repositories, C. Broadway, UMONS
- Calibration of heated fiber-optic cable for monitoring dry density and water content in granulated bentonite mixture in the Full-scale Emplacement experiment, T. Sakaki, Kyoto University
- Distributed pore pressure monitoring with a DOFS-system – Prototype test, B. Frieg, NAGRA
- Toward long-term hydrogen monitoring with specialty optical fibers, G. Humbert, XLIM
- Qualifying distributed strain sensing systems based on optical fiber for the monitoring of radioactive waste repository, A. Piccolo, ANDRA

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