COMP-ECO Workshop

Smart structures – health monitoring and self-sensing capabilities of composites

26th October 2023 in Delft, the Netherlands

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TU Delft

Aero NDT

Smart Structures – Health Monitoring & Self-sensing Capabilities of Composites

MAIN FOCUS OF WORKSHOP

- Fibre optic sensing for smart structures
- Guided wave ultrasonic sensing for smart structures

SCHEDULE

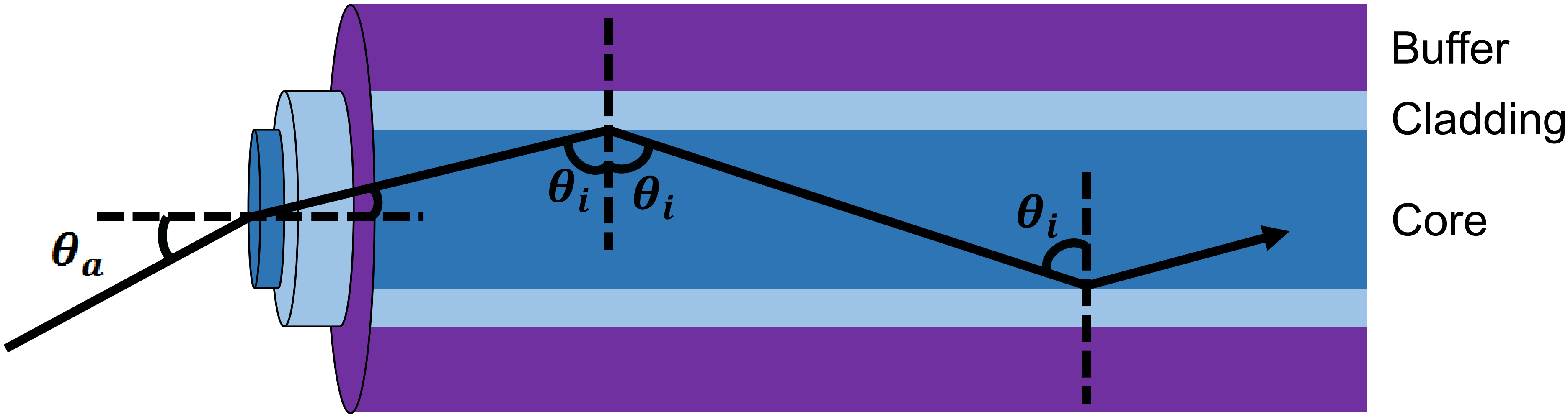
- 13:30 Lecture on Fibre optic sensing (Lecture Room F)
- 14:15 Coffee Break
- 14:30 Lecture on Guided wave ultrasonic sensing (Lecture Room F)
- Lab Demonstrations
    - 15:30 Group 1: Fibre Optic Sensing; Group 2: Ultrasonic Sensing
    - 16:00 Group 1: Ultrasonic Sensing; Group 2: Fibre Optic Sensing
- 16:30 Round-up of Smart Structures workshop (Lecture Room F)

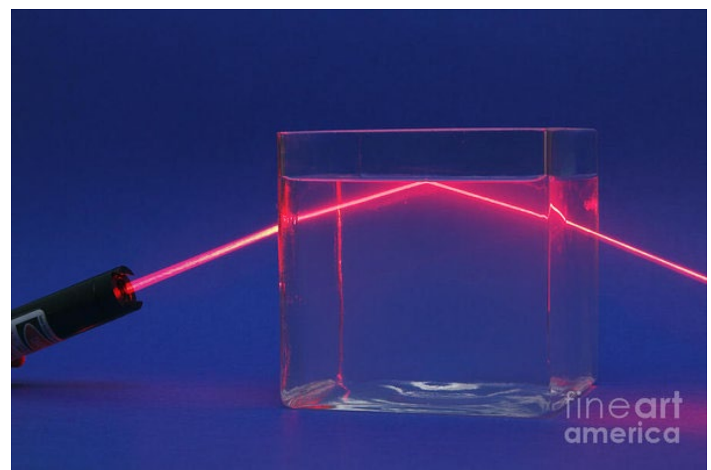
Part 1: Fibre optic sensing for smart structures

Total Internal Reflection

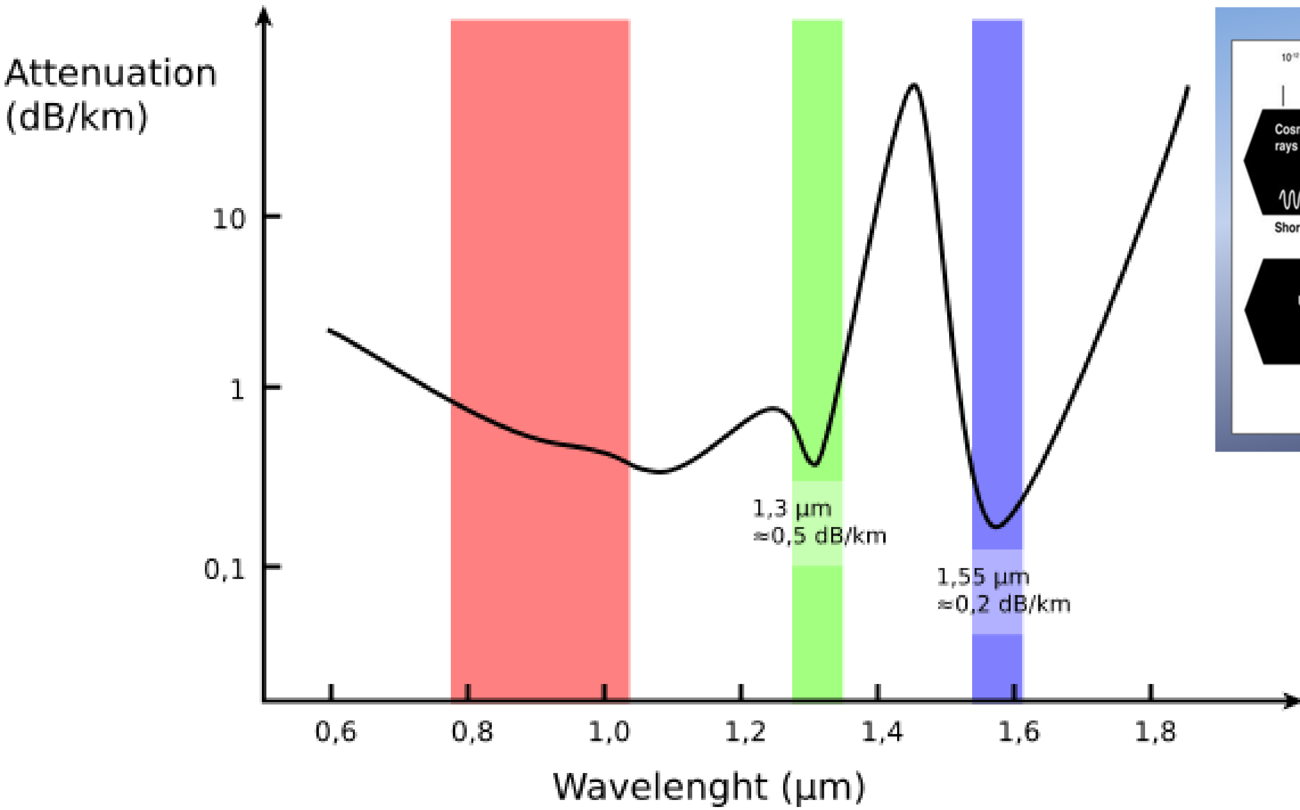
$n_{core} > n_{cladding}$

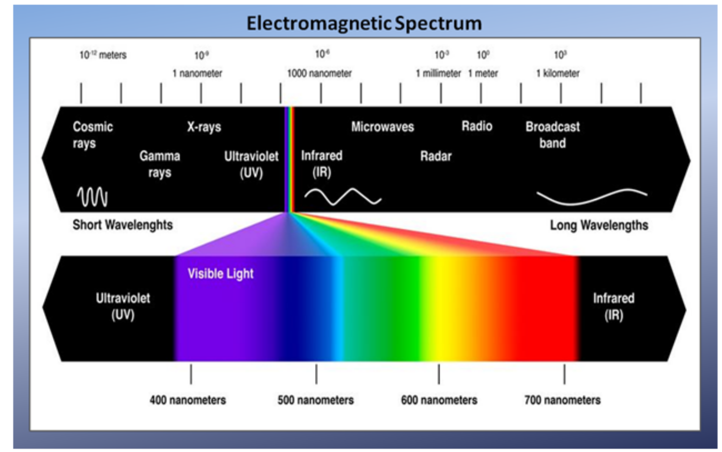
- $\theta_i > \theta_c \rightarrow \sin\theta_c = n_{cladding}/n_{core}$



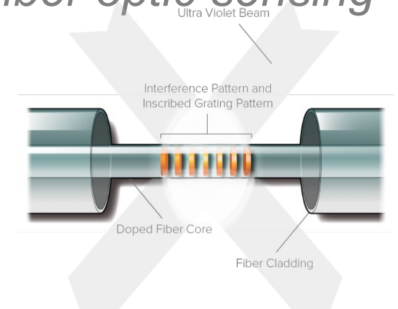


Attenuation of light in optical fibers





- 3dB = 50%
- 1 dB = 10%



Fibre optic sensing principles

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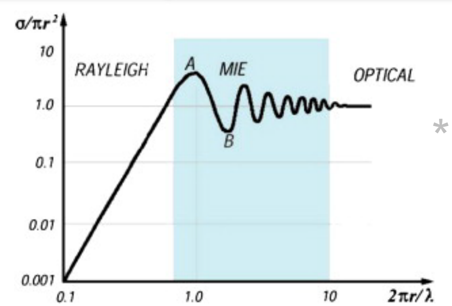
Types of Fibre Optic Sensors

Fibre Optic Sensors (FOS)

- Interferometric sensors
- Grating-based sensors
- Distributed sensors
  - Raman scattering — Temperature
  - Brillouin scattering — Temperature, Strain
  - Rayleigh scattering
  - Mie scattering

Structural Health Monitoring with FOS [1]

- Strain-based shape reconstruction
- Strain monitoring in structure elements
- Damage Detection



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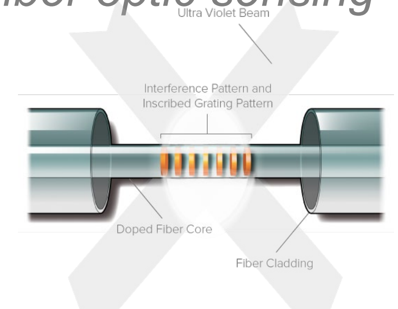
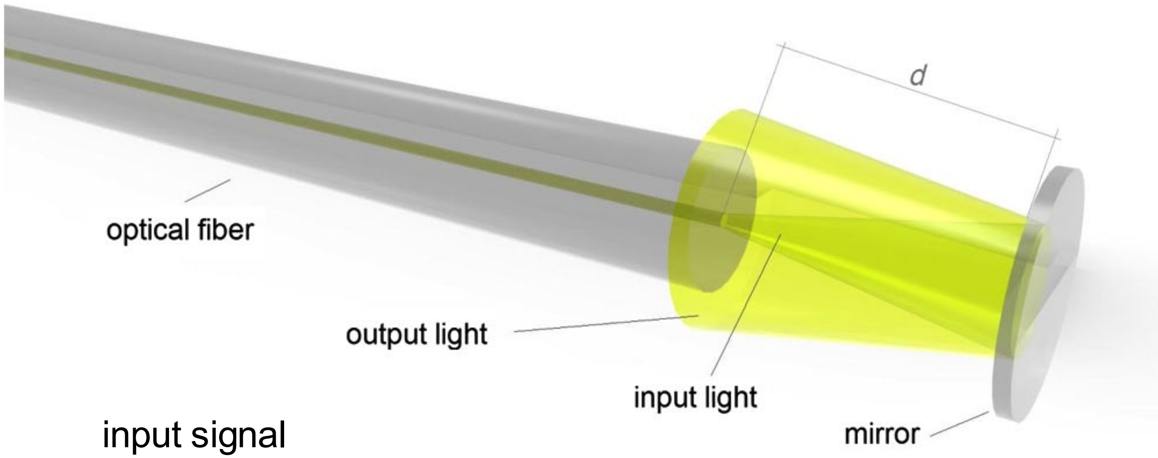
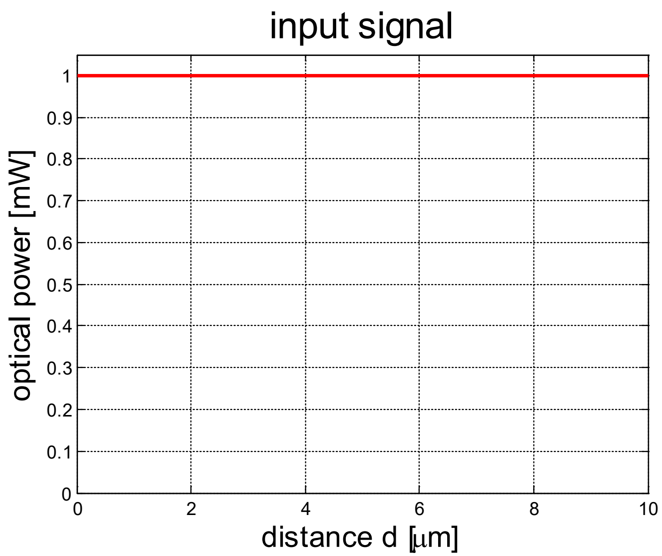
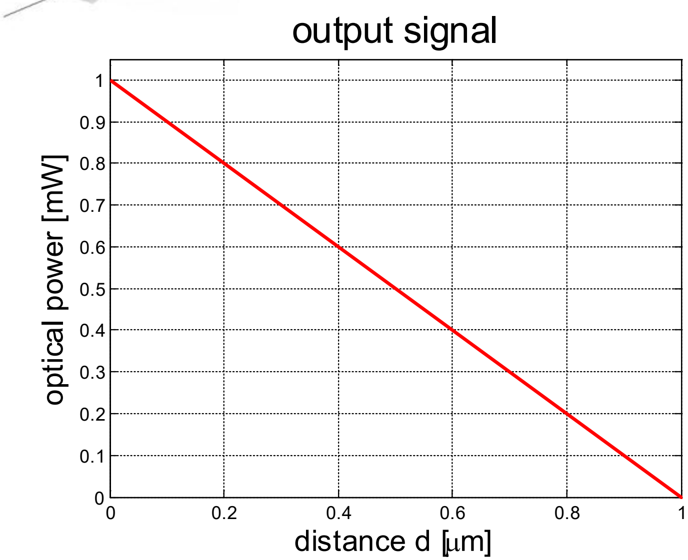
[1] R. Di Sante, "Fibre Optic Sensors for Structural Health Monitoring of Aircraft Composite Structures: Recent Advances and Applications," pp. 18666–18713, 2015.

Optical fiber intensity sensor

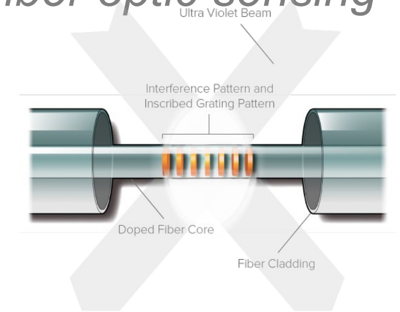


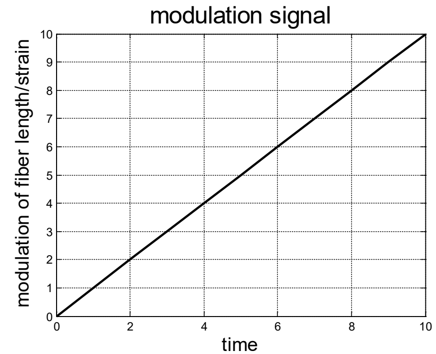


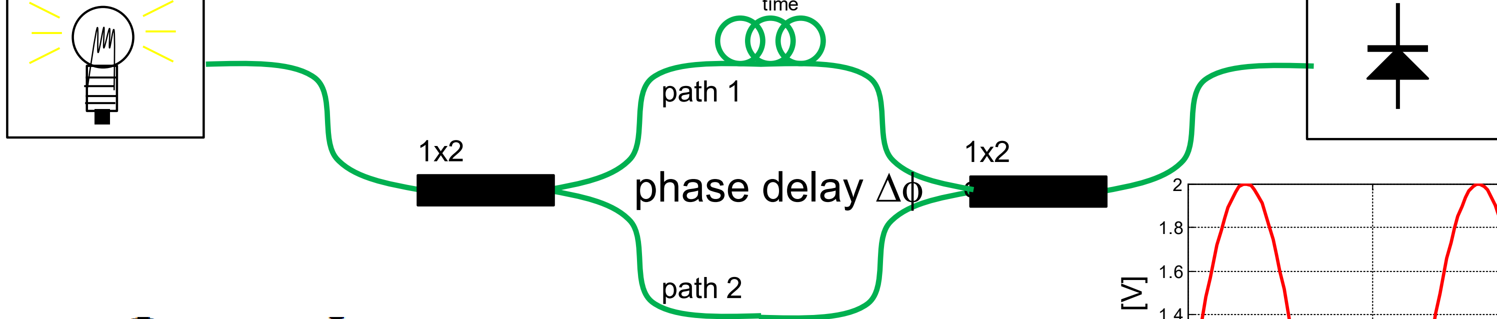


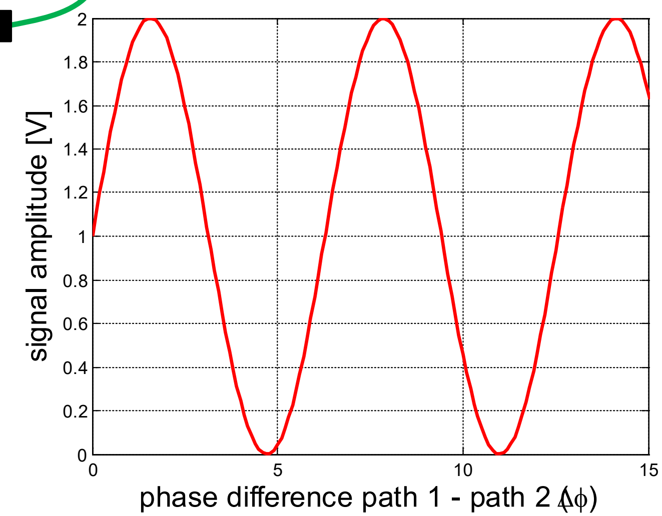


Optical fiber phase sensor









L = |path1 – path2|

$$\phi = \frac{2\pi \cdot n \cdot L}{\lambda}$$

$$\delta\phi = \frac{2\pi}{\lambda}\delta(n \cdot L)$$

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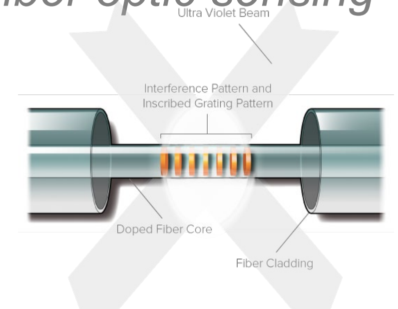
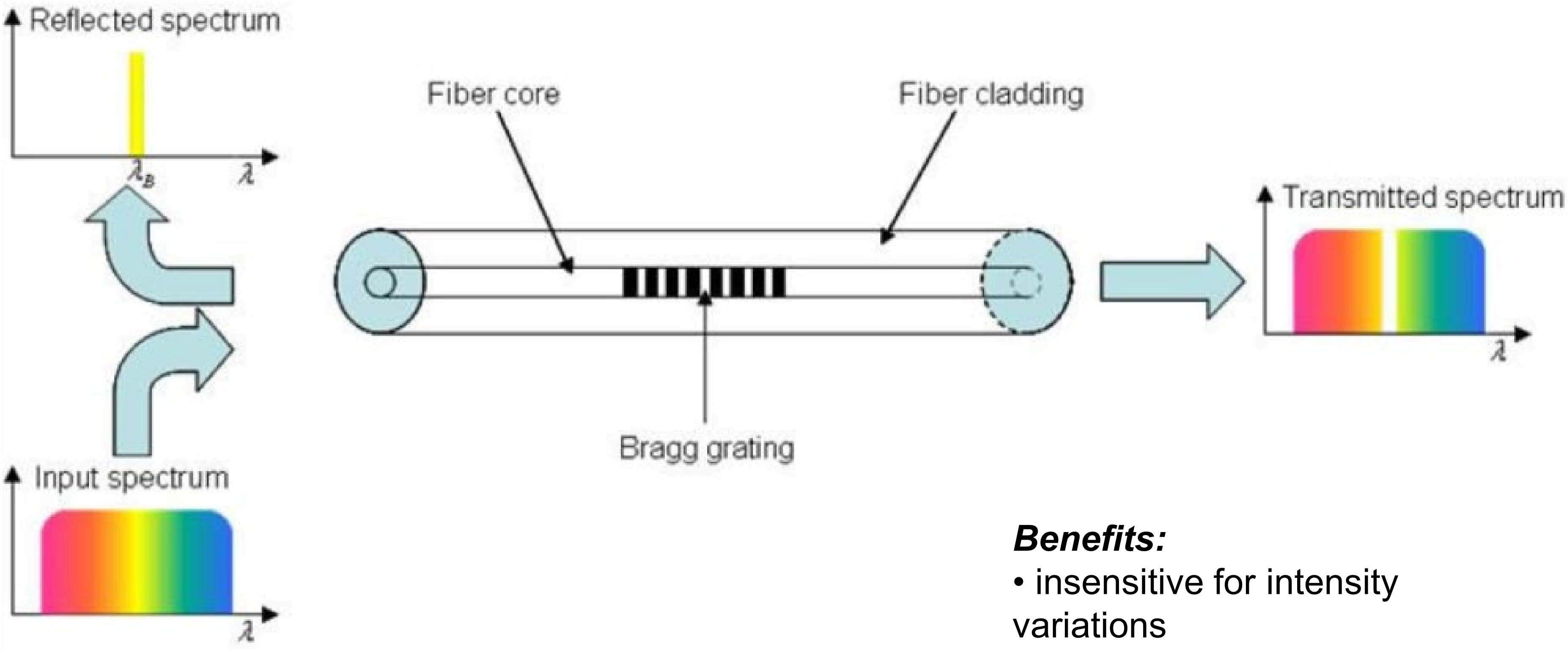


Optical fiber wavelength sensor

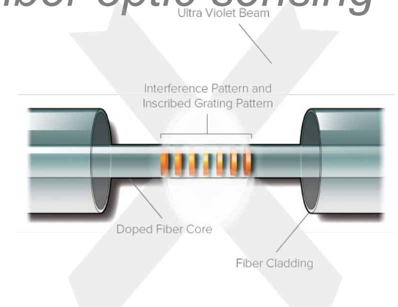
Fiber Bragg Grating (FBG)



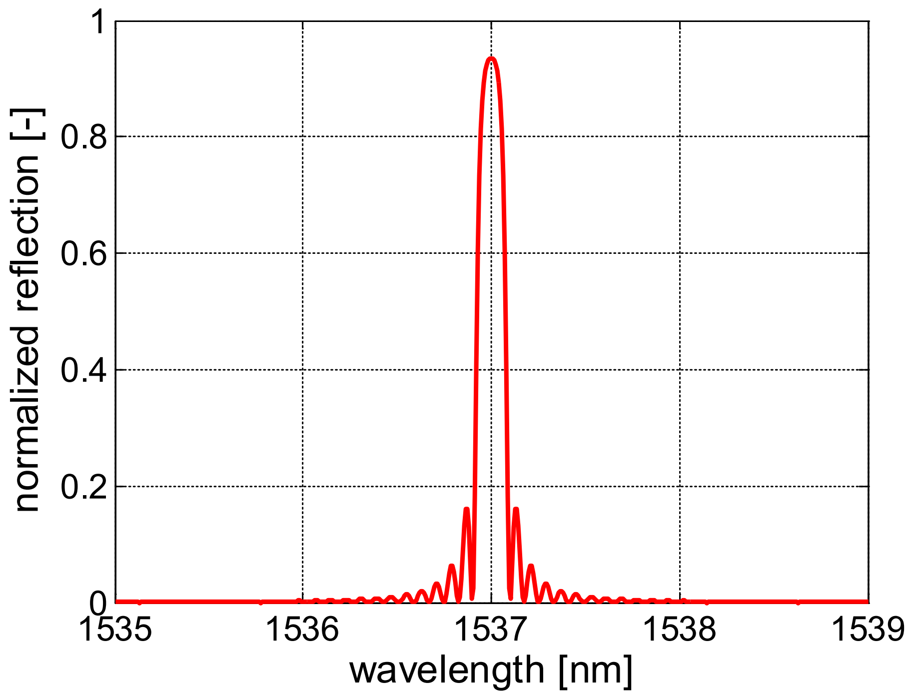
Benefits:
- insensitive for intensity variations
- multiplexing capabilities

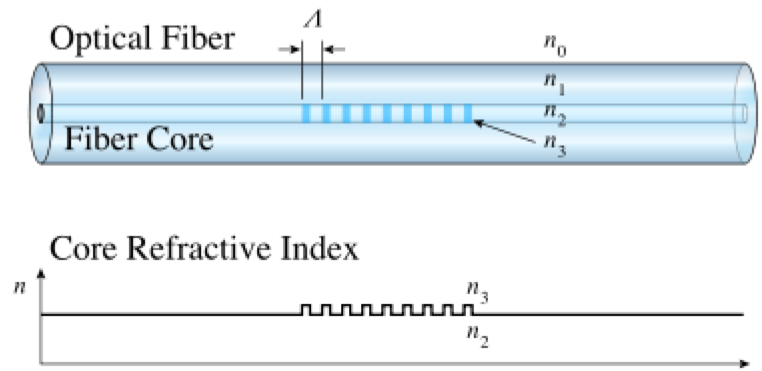
Drawbacks:
- expensive read out equipment

Optical fibre sensor – focus on FBG's

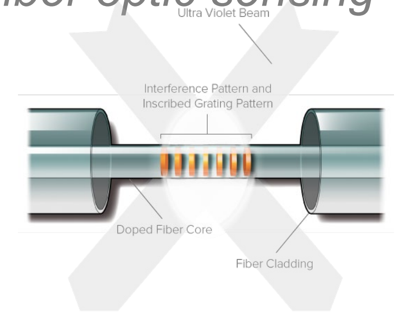


$$\lambda_B = 2 \cdot n_{eff} \cdot \Lambda$$





Optical fibre sensor – focus on FBG's



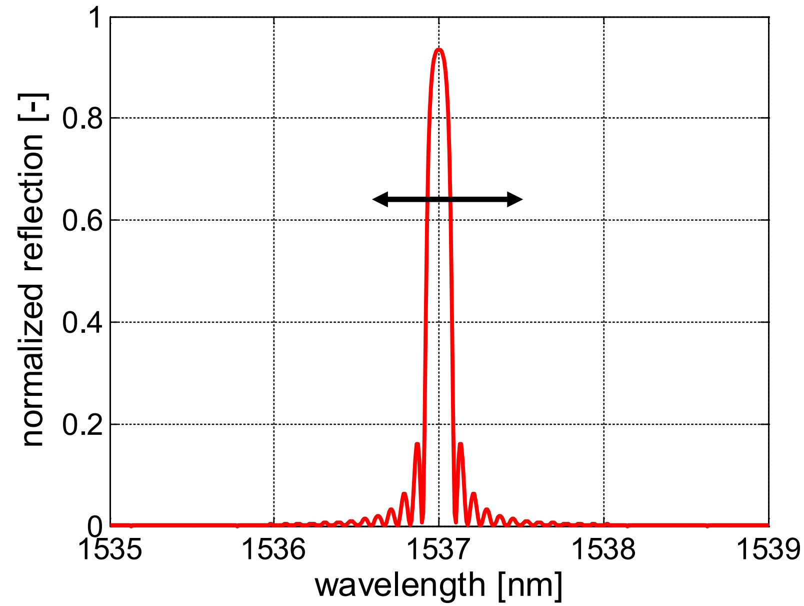
$$\lambda_B = 2 \cdot n_{eff} \cdot \Lambda$$

strain (ε) sensitivity :

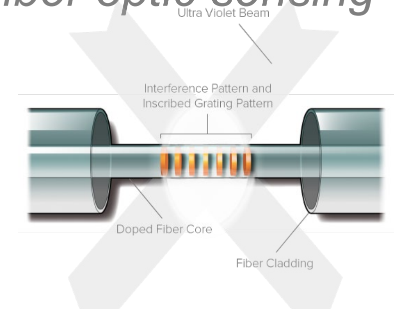
- $$\frac{\Delta L}{L} = \varepsilon \rightarrow \frac{\delta \lambda_B}{\delta \varepsilon} = 1.2 \, {}^{pm}/_{\mu\varepsilon}$$

temperature (K) sensitivity:

- $$\frac{\delta \lambda_B}{\delta T} \approx 10 \, {}^{pm}/_{K}$$

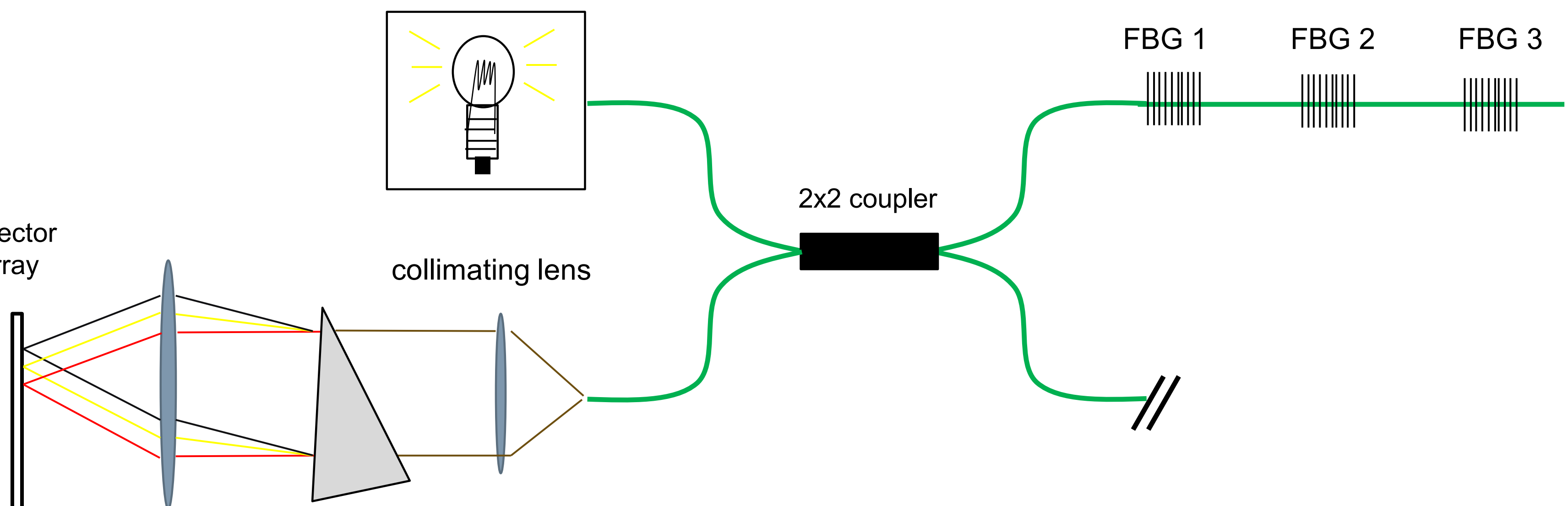


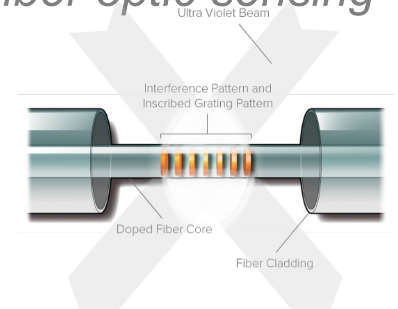
λ_B



Optical fibre sensor – Wavelength detection

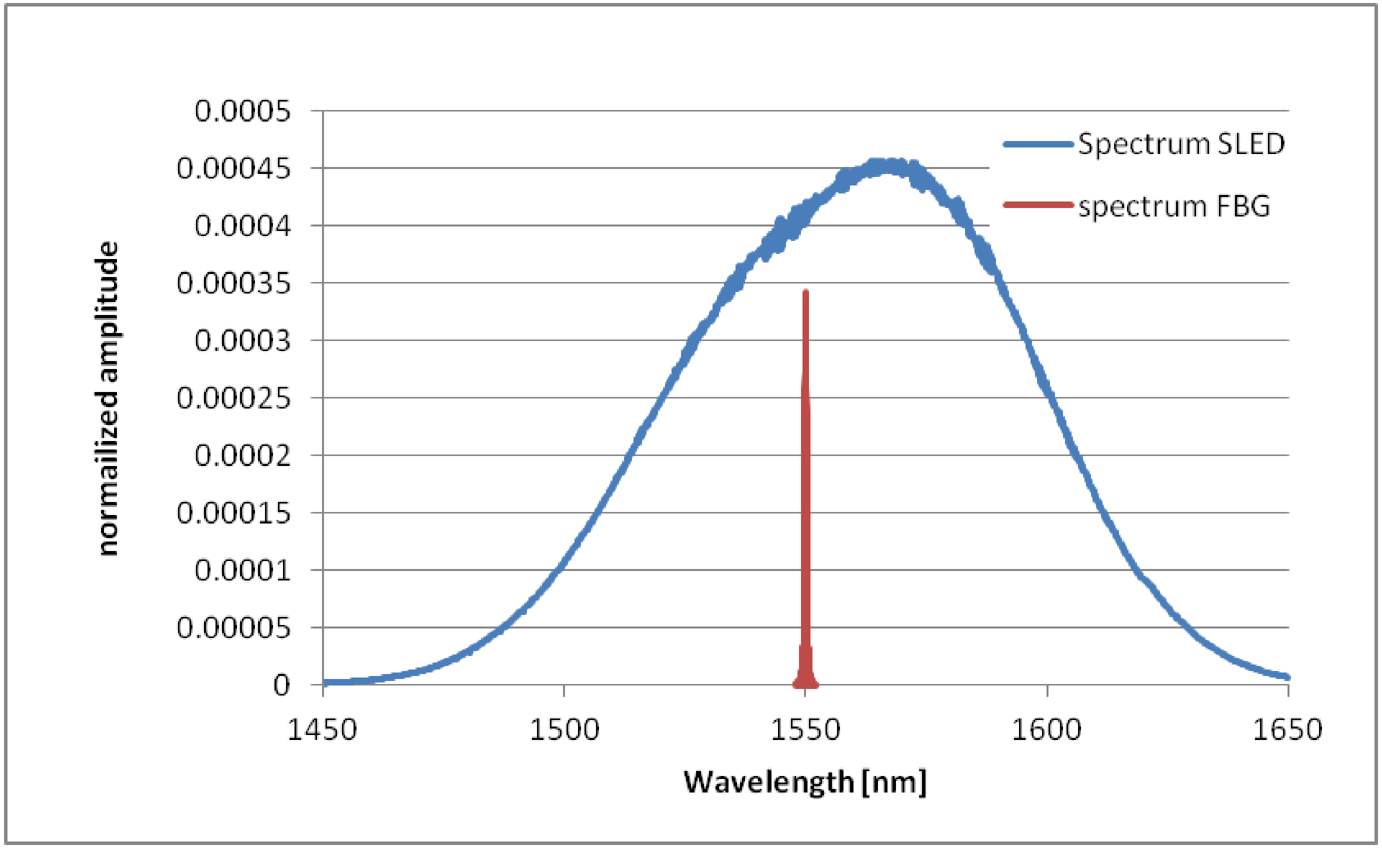
interrogator concept 1: *spectrometer design*





Optical fibre sensor – Wavelength detection

spectrometer design



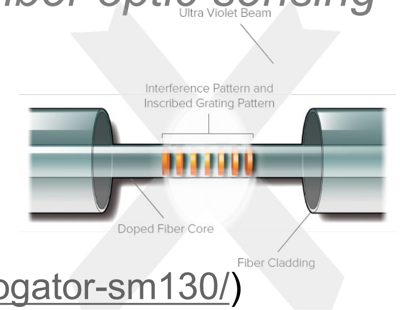
Benefits:

• all FBG's interrogated simultaneously

Drawbacks:

• >99% of the light is lost

Optical fibre sensor – Wavelength detection

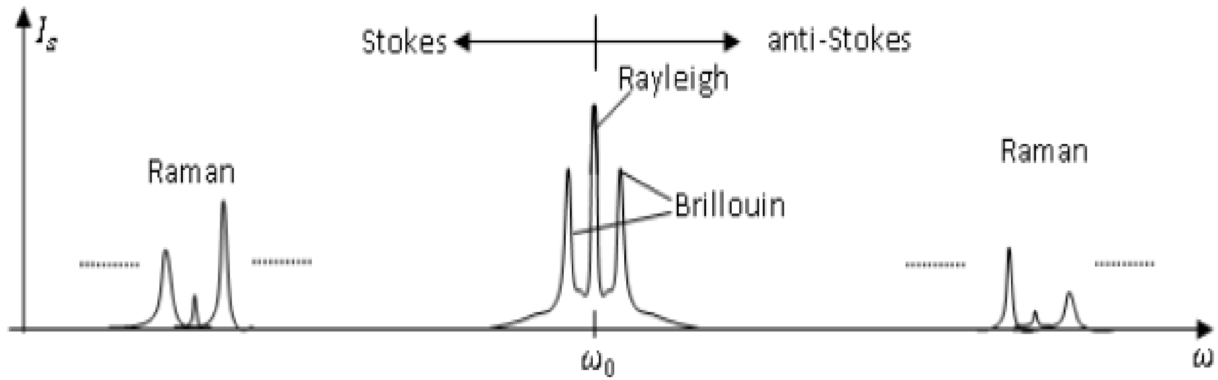


Many different commercial interrogators available:

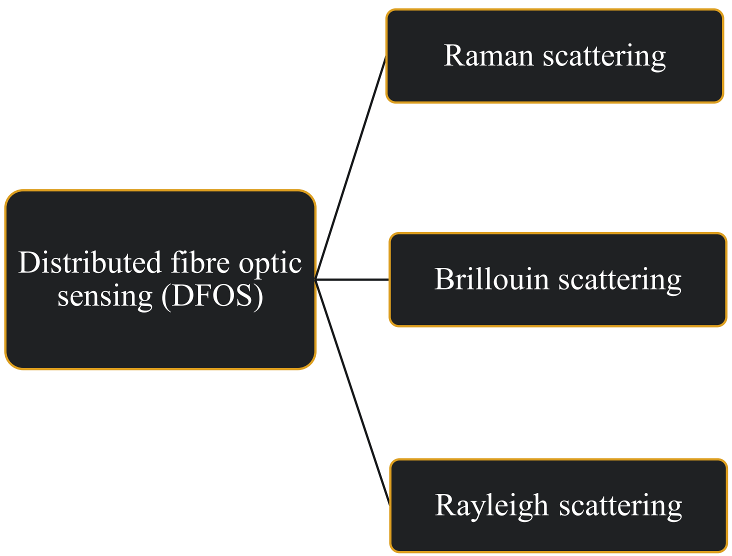
- MicronOptics (http://www.micronoptics.com/product/dynamic-optical-sensing-interrogator-sm130/)
- SmartFibres (https://www.smartfibres.com/docs/SmartScan.pdf)
- HBM FiberSensing (https://www.hbm.com/en/2322/optical-interrogators-from-hbm-fibersensing/)
- Redondo (http://www.redondooptics.com/FBGT_060209.pdf)
- National Instruments (http://sine.ni.com/nips/cds/view/p/lang/nl/nid/209012)
- FAZtechnology (http://www.faztechnology.com/products/interrogators/fazt-v4/)
- Technobis (http://www.technobis.com/index.php/products/extreme-fiber-sensing/gator-basic-fbg-interrogator/)
- ATgrating (http://www.atgrating.com/en/productview.asp?id=87)
- Bayspec (http://www.bayspec.com/telecom-fiber-sensing/fbg-interrogation-analyzer/)
- Proximion (http://www.proximion.com/fiber-optic-sensors/)
- Epsilonoptics (http://www.epsilonoptics.com/interrogators.html)
- and many more ....

Note: >95% of the interrogators are based on concept 2 – scanning laser


Rayleigh, Raman and Brillouin Scattering



[1]



$$\frac{I_{AS}}{I_S} = (\frac{\lambda_S}{\lambda_{AS}})^4 e^{-\frac{\hbar\omega_M}{k_B T}}$$ [1]

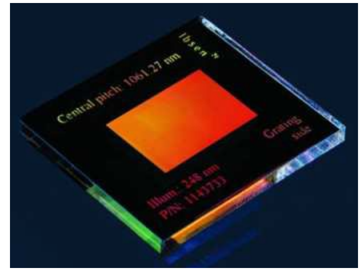
$$\Delta\upsilon_B = C_T \Delta T + C_\varepsilon \Delta\varepsilon$$ [1]

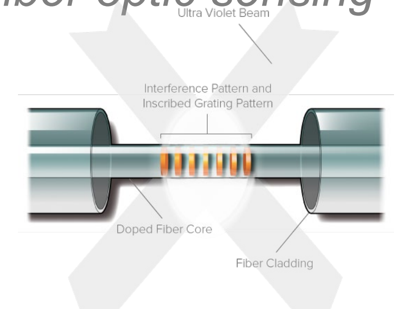
$$\frac{\Delta\lambda}{\lambda} = K_T \Delta T + K_\varepsilon \Delta\varepsilon$$ [2]

[1] X. Bao and L. Chen, “Recent Progress in Distributed Fiber Optic Sensors,” Sensors (Switzerland), vol. 12, no. 7, pp. 8601–8639, 2012.

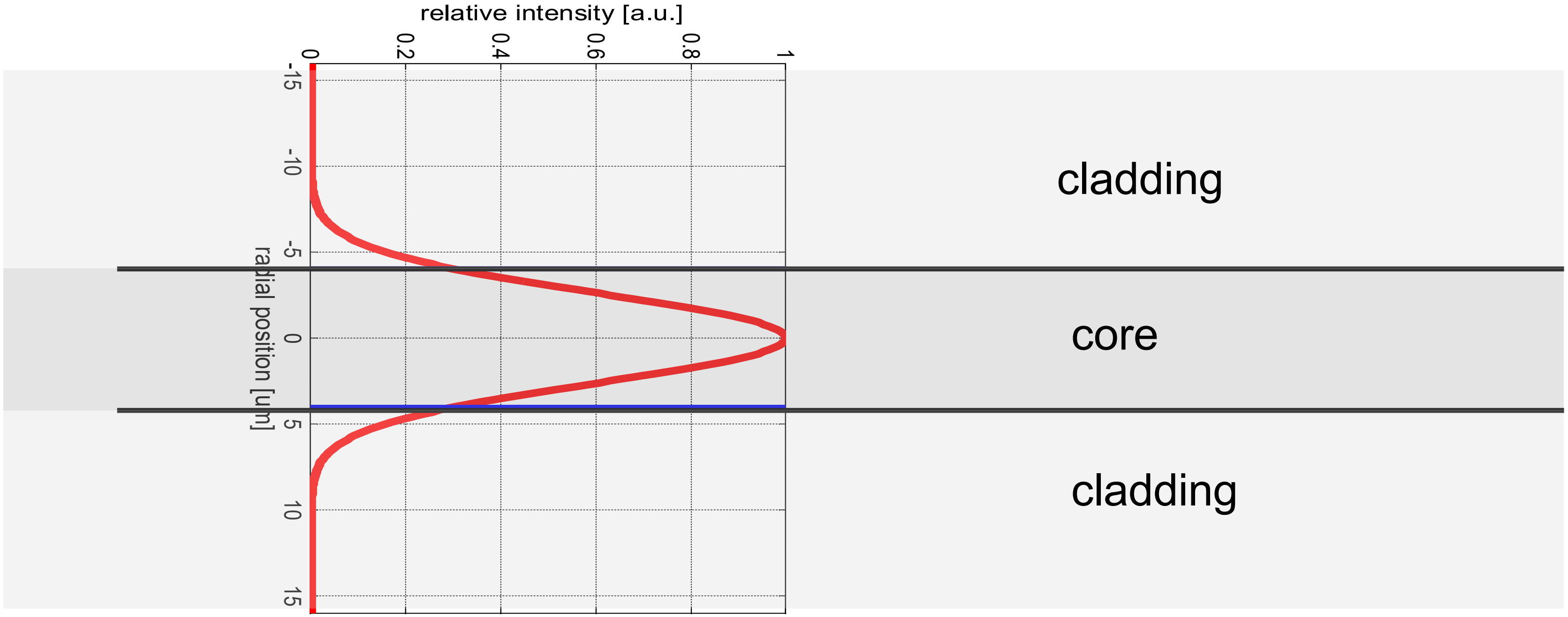
[2] S. T. Kreger, A. K. Sang, D. K. Gifford, and M. E. Froggatt, “Distributed strain and temperature sensing in plastic optical fiber using Rayleigh scatter,” Fiber Opt. Sensors Appl. VI, vol. 7316, no. April 2009, p. 73160A, 2009.

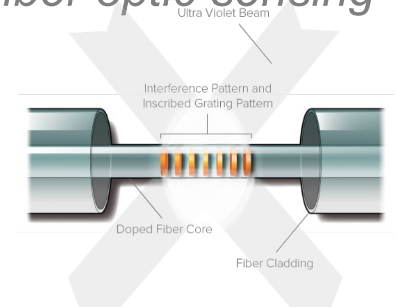
RI modulation



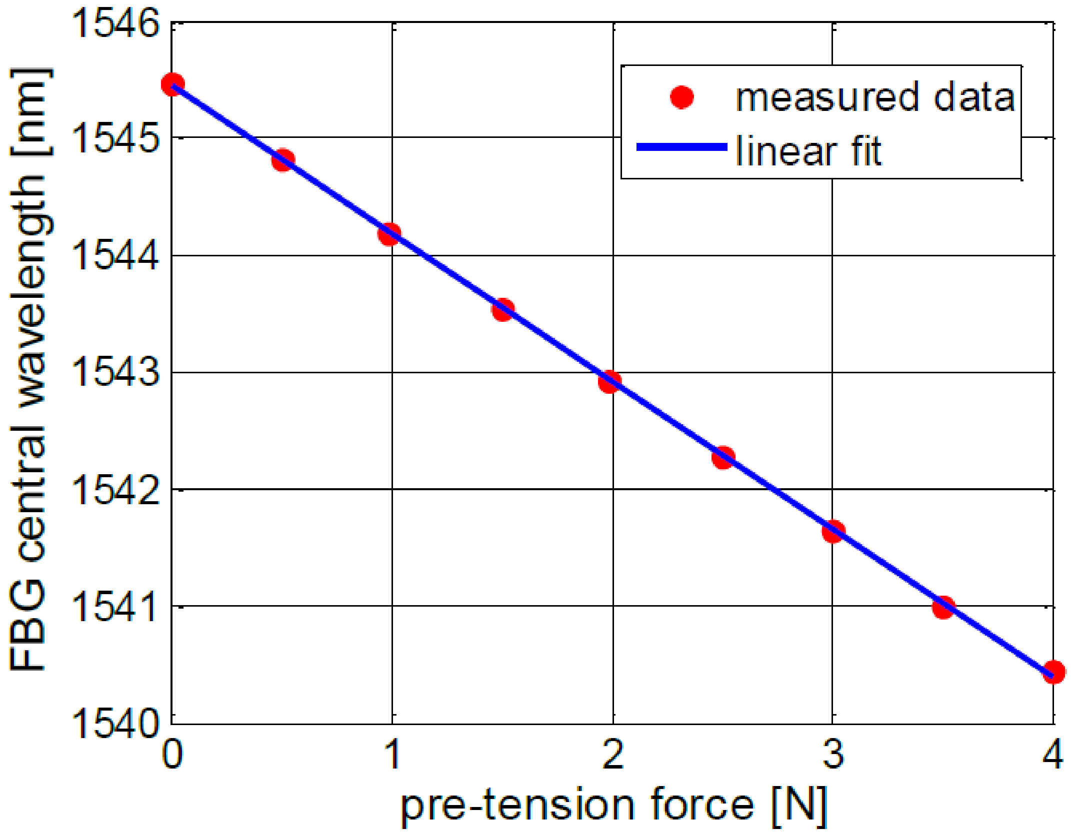


$$\lambda_B = n_{eff}(\lambda) \cdot \Lambda_{pm}$$





Fibre pretension



~5nm λ_B correction

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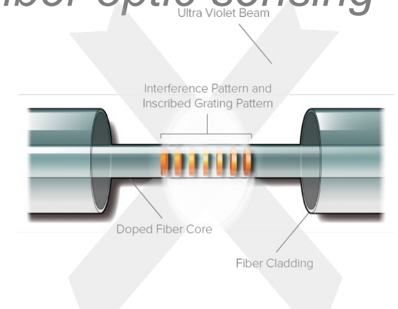
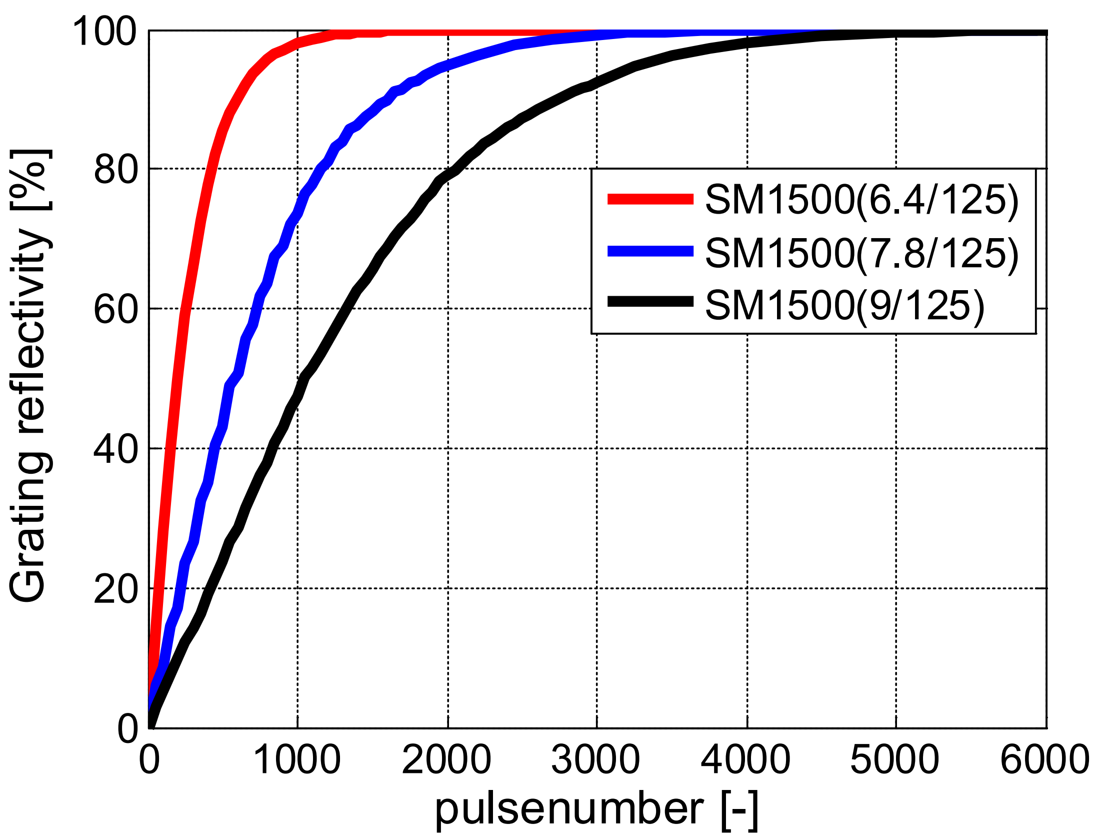
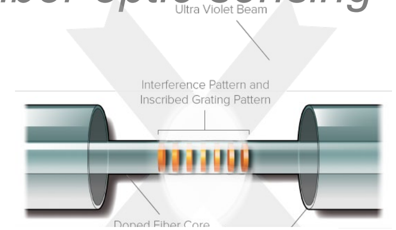
Reflectivity

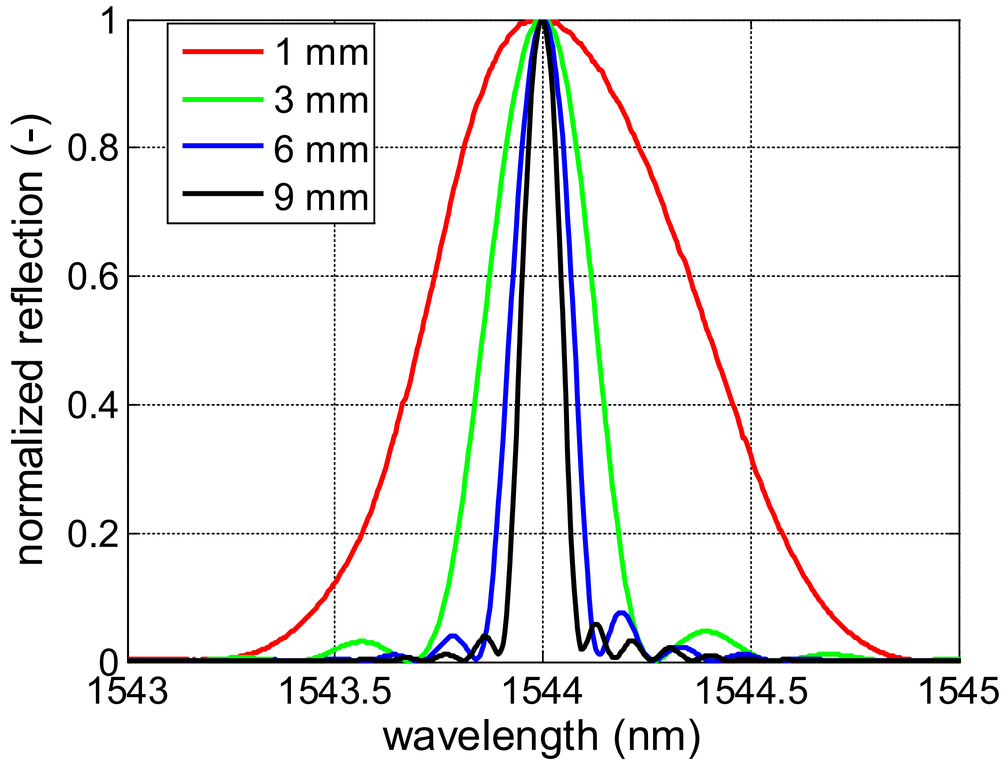


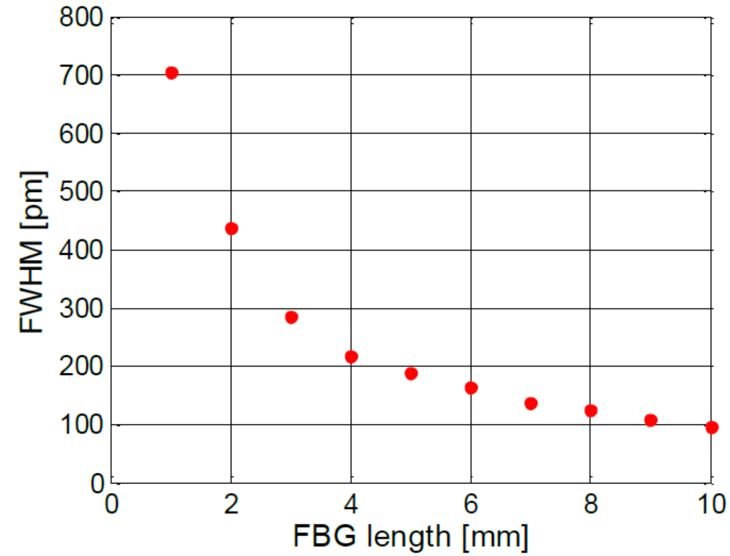


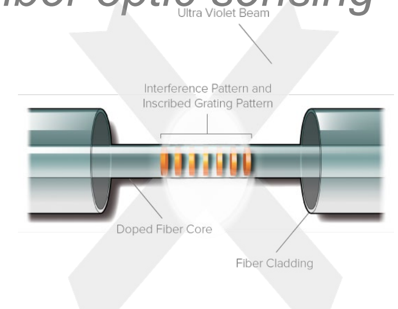
- Repetition rate of UV laser is 500 Hz

Grating length









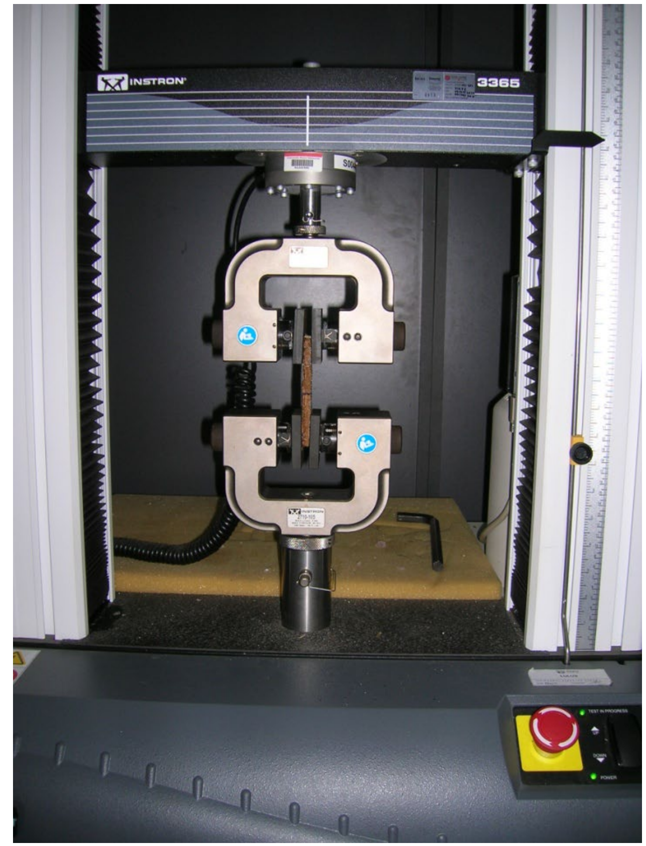
Fibre break strength

- Break strength of pristine fiber ~60N

- Stripping and recoating reduces fiber strength to
  ~10-15 N

$$\varepsilon = \frac{F}{E \cdot A}$$

- ε — fiber strain
- F — force on fiber
- E — Youngs modulus (72GPa)
- A — fiber surface = $(\pi/4)\cdot\text{diameter}^2$



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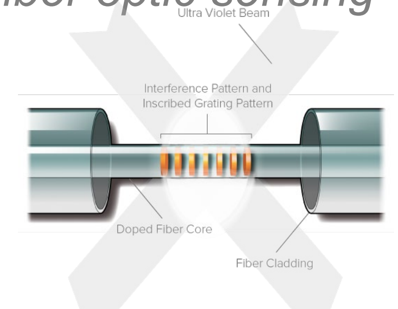
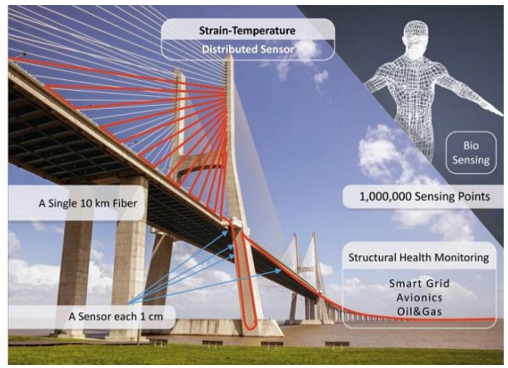


Fibre optic sensing applications

Introduction

Fibre optic sensing can obtain parameters such as strain, temperature, etc. for Structural Health Monitoring.



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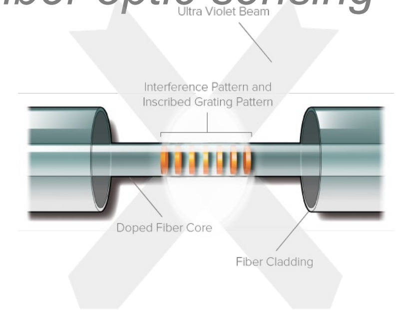


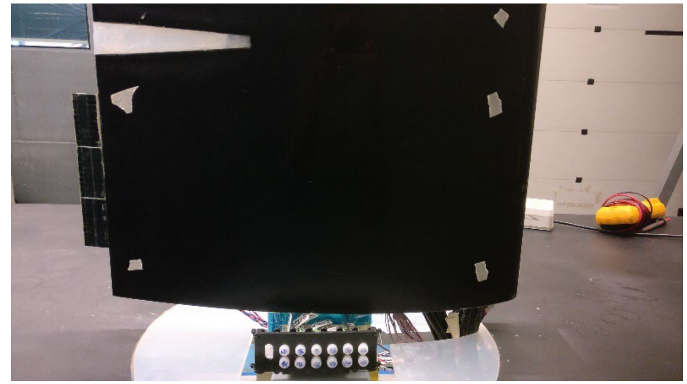
Research of PhD Nakash Nazeer

SmartX Morphing Wing

6 individual morphing sections

Section #1

Upper wing section view
Morphing section #1



Lower wing section view
Morphing section #1

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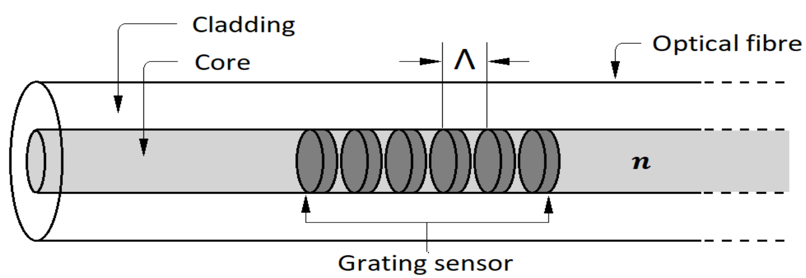
Sensor Principles

Bragg Grating

$$\lambda_B = 2n_{eff}\Lambda$$

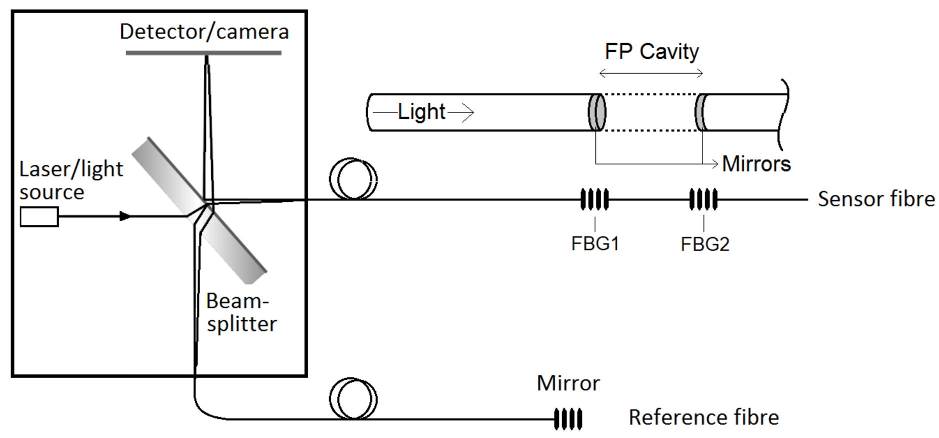


Λ: Periodic spacing
λB: Grating wavelength
$neff$: Core refractive index

Fabry-Pérot

$$\Delta\varepsilon = \frac{\Delta\lambda_{BS}}{(1-\rho_a)\lambda_B}$$

$$\varepsilon = \frac{\Delta d}{L}$$



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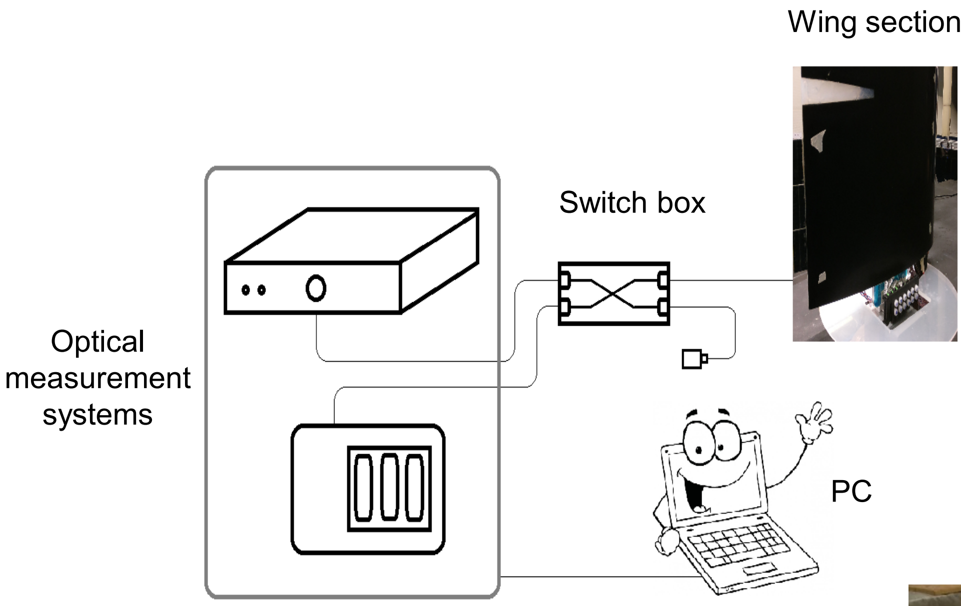
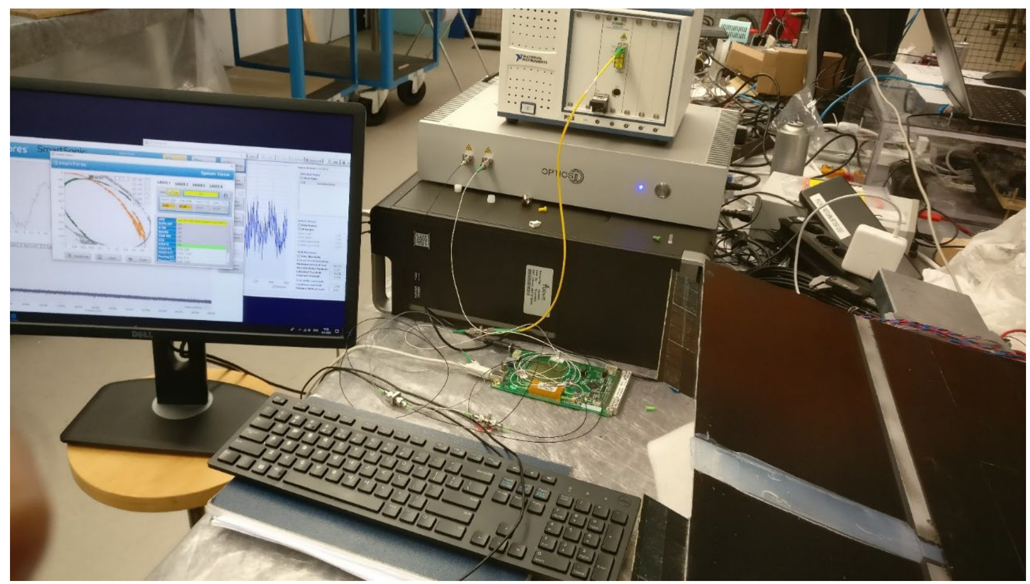
Experimental Setup



Test conditions

- Static tests
- Only morphing section #1 considered
- Offline measurement (Not in the wind tunnel)



Bend up and bend down

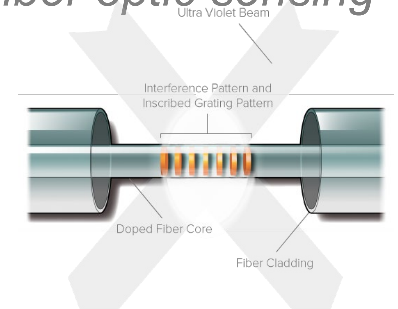
Bend up	(NI) ε FBG		(O11) ΔL				
Actuator input (deg)	FBG_2 (μ)	FBG_3 (μ)	ΔL FP_1-2 (μm)	ΔL FP_3-4 (μm)	**Tip deflection (mm)**	**Estimated tip deflection (mm)**	Error (mm)
5	143,17	144,00	-7,6	-7,598	**2**	**2,1**	0,1
10	300,31	306,72	-25,2	-25,414	**6**	**1,93**	-4,07
15	441,64	443,60	-78,4	-79,386	**9**	**8,48**	-1,69

Bend down	(NI) ε FBG		(O11) ΔL				
Actuator input (deg)	FBG_2 (μ)	FBG_3 (μ)	ΔL FP_1-2 (μm)	ΔL FP_3-4 (μm)	**Tip deflection (mm)**	**Estimated tip deflection (mm)**	Error (mm)
5	-138,00	-137,00	8,4	8,346	**5**	**3,16**	-1,84
10	-287,32	-280,00	29,0	27,178	**10**	**11,58**	1,58
15	-427,14	-423,00	86	85,6	**15**	**13,31**	-1,69

Twist

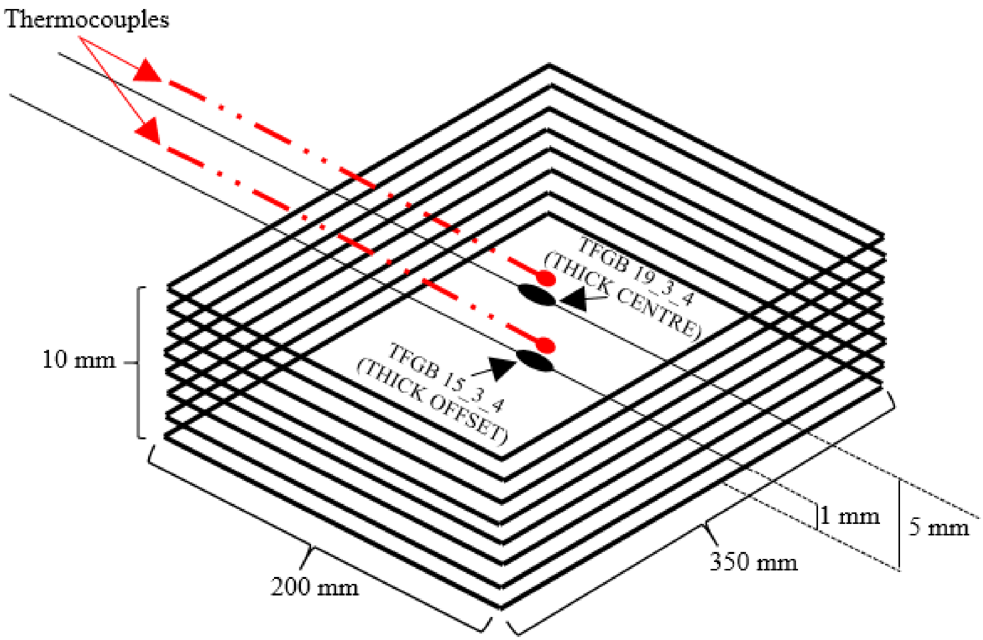
Right	(NI) ε FBG		(O11) ΔL				
Actuator input (deg)	FBG_1 (μ)	FBG_4 (μ)	ΔL FP_1-2 (μm)	ΔL FP_3-4 (μm)	**Tip deflection (mm)**	**Estimated tip deflection (mm)**	Error (mm)
5	-24,05	23,8	-5	6	**2**	**0.66**	-1.34
10	-53,65	51,3	-8,5	16	**4**	**5.18**	1.18
15	-101,75	100	-11	25	**6**	**5,98**	-0.02

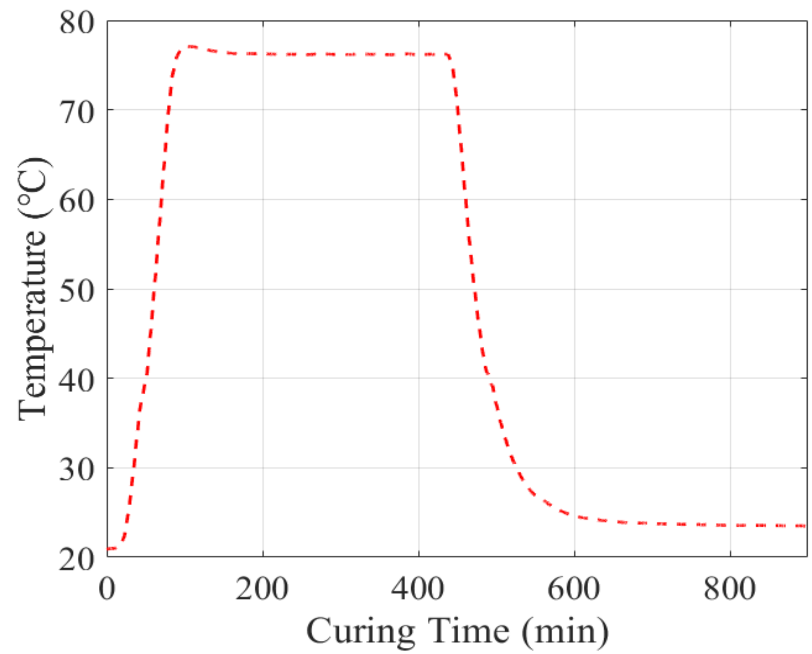
Left	(NI) ε FBG		(O11) ΔL				
Actuator input (deg)	FBG_1 (μ)	FBG_4 (μ)	ΔL FP_1-2 (μm)	ΔL FP_3-4 (μm)	**Tip deflection (mm)**	**Estimated tip deflection (mm)**	Error (mm)
5	-24,05	23,8	-5	6	**2**	**1.25**	-0.75
10	-53,65	51,3	-8,5	16	**4**	**4.65**	0.65
15	-101,75	100	-11	25	**6**	**5.97**	-0.03



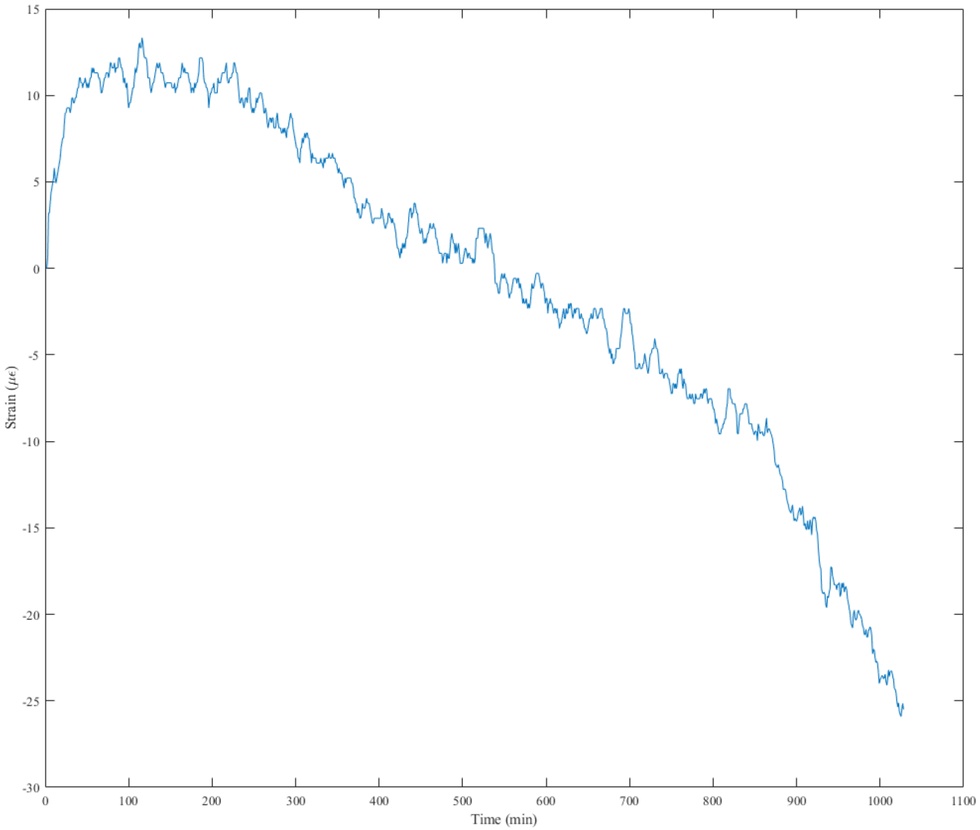
Research of PhD Luigi Fazzi

Thermoset composites curing with tilted FBG sensors

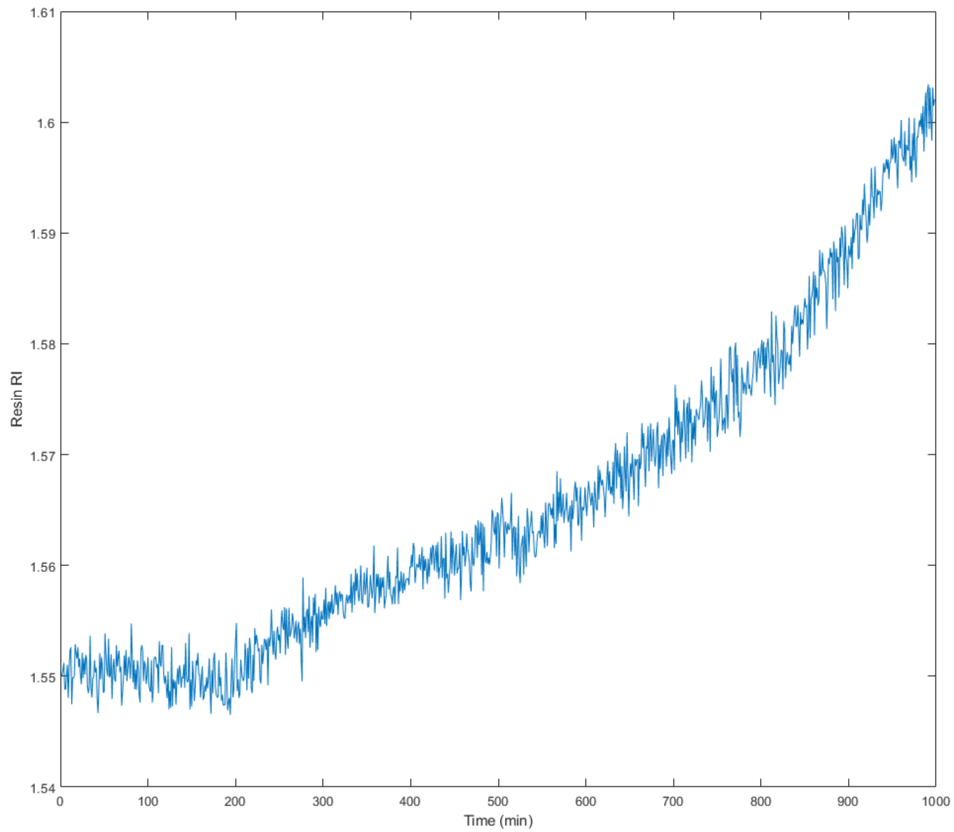




5 mm GFRP (curing at room temperature)

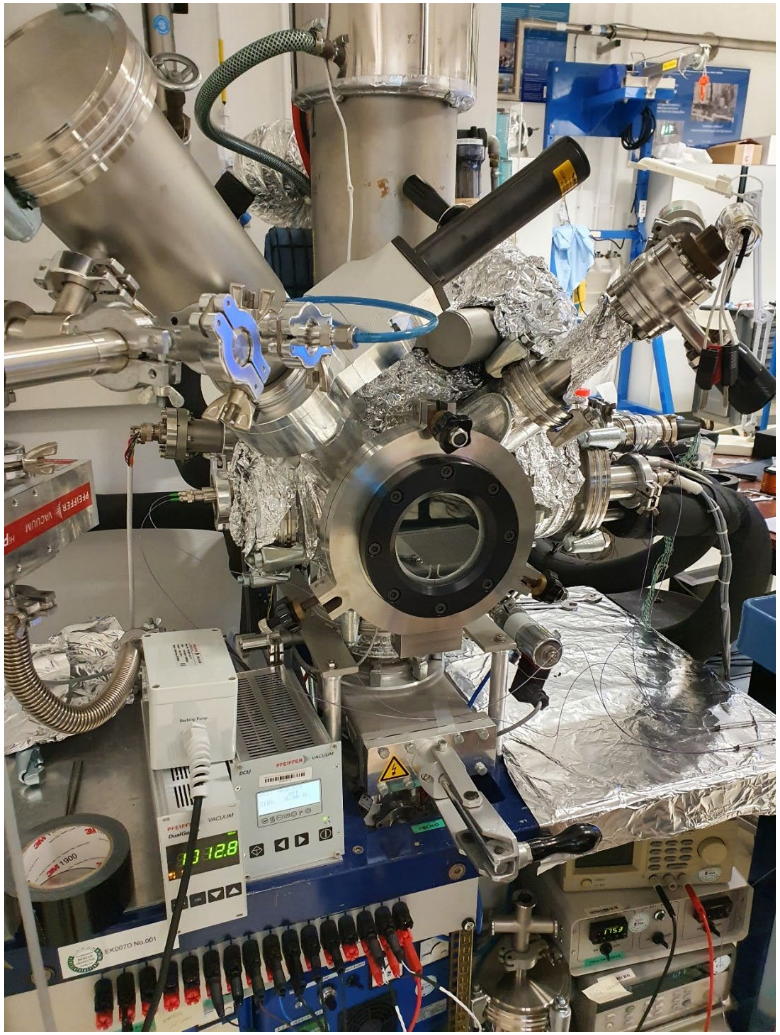


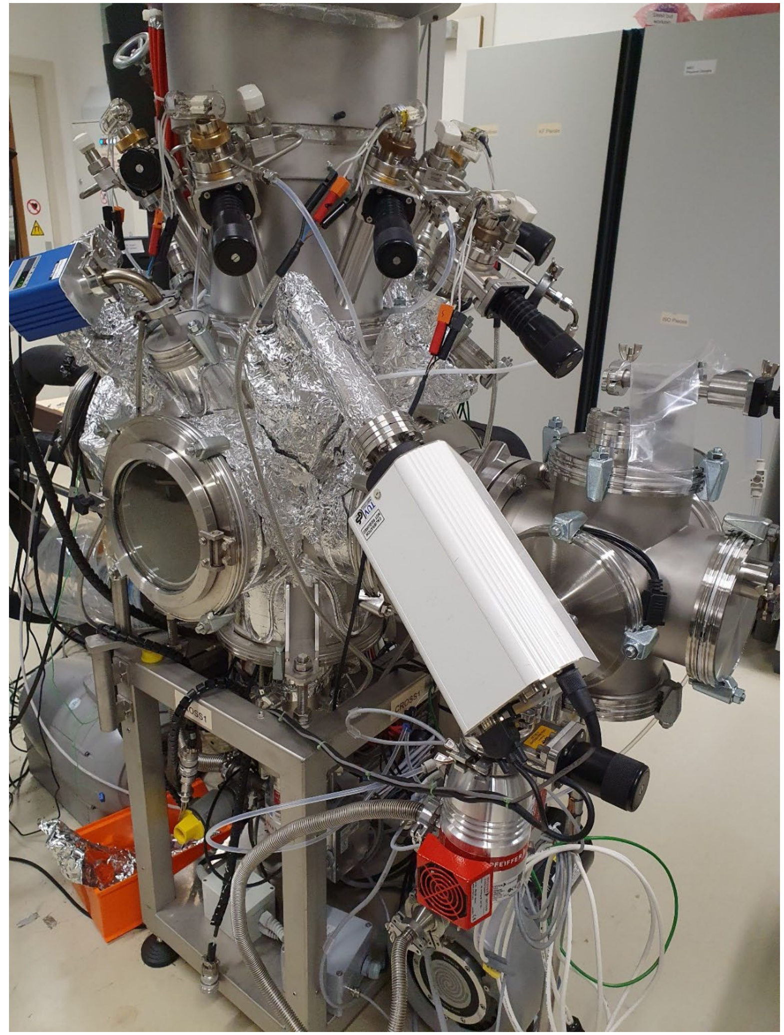
Strain vs time



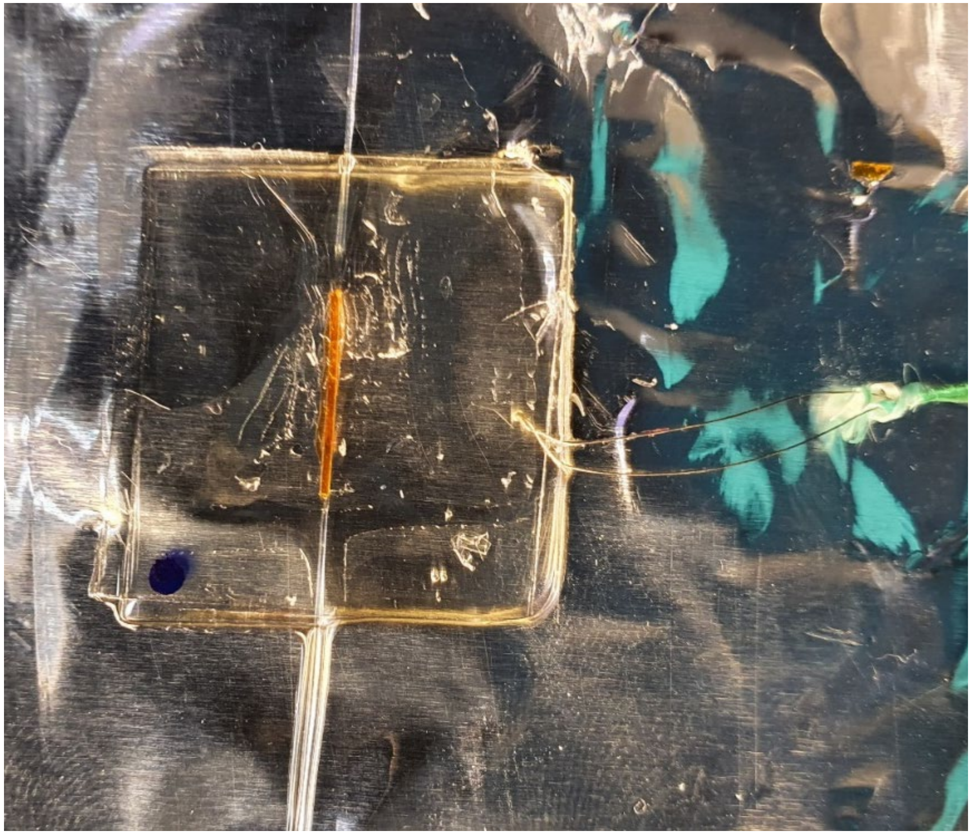
Resin RI vs time

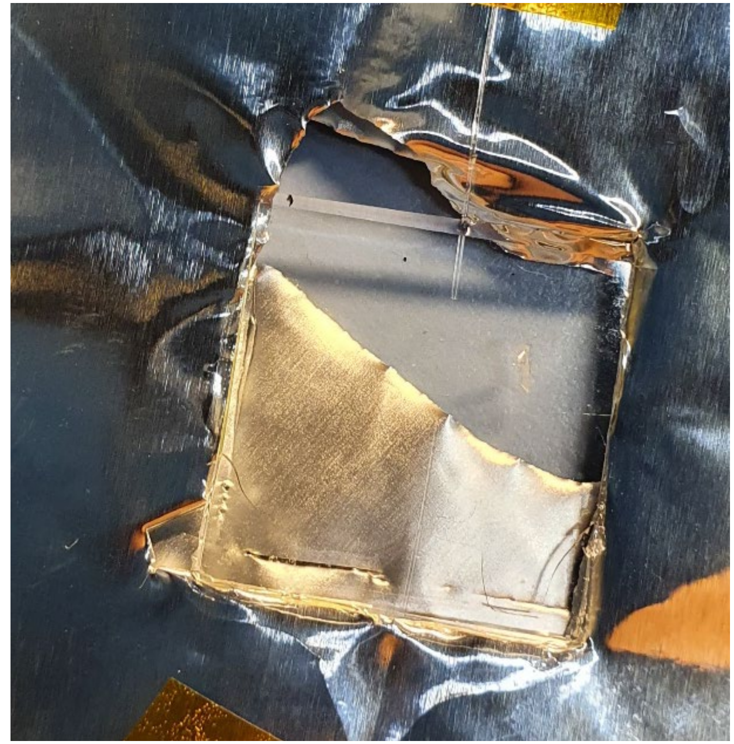
Simulated space enviroment





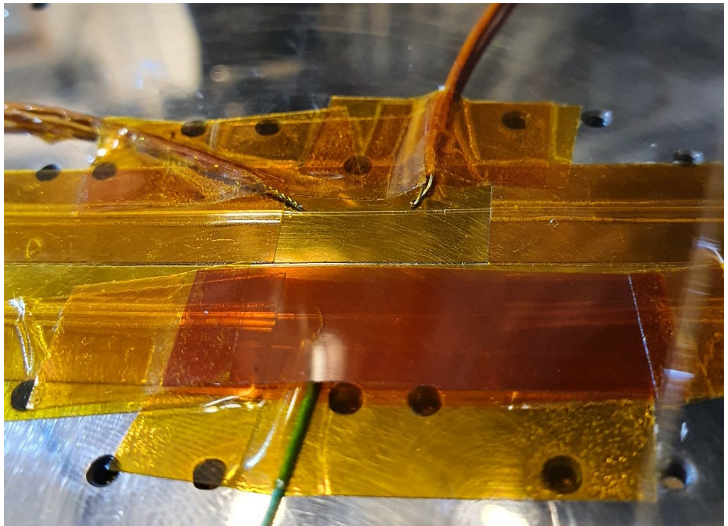
Solar cell samples

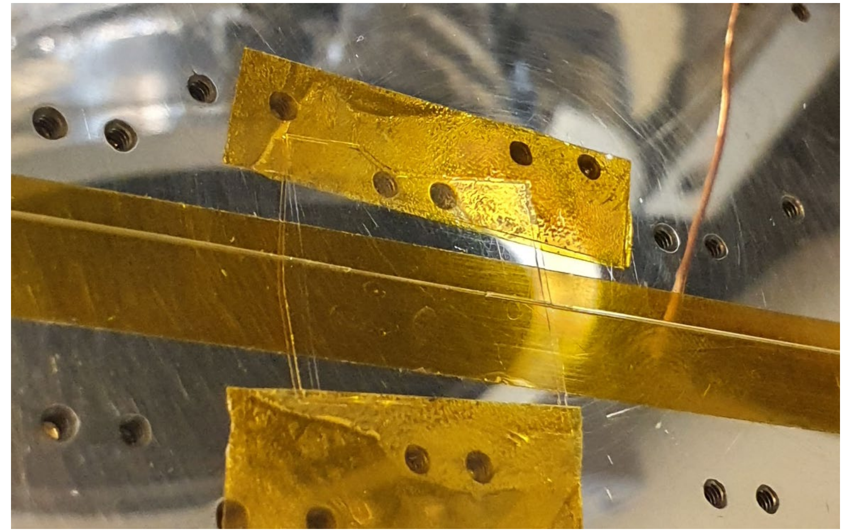


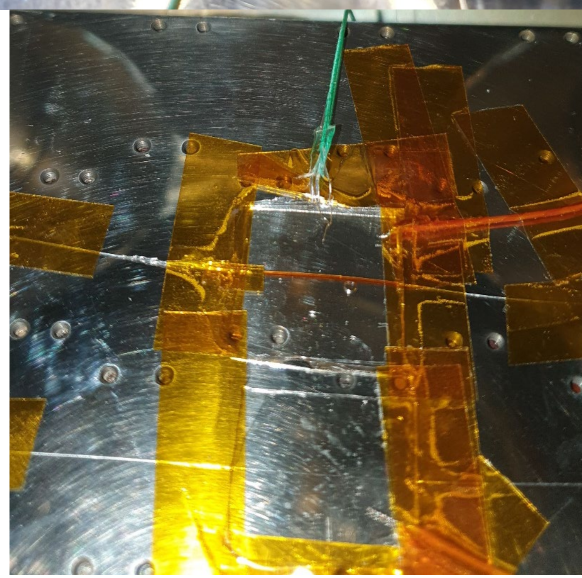


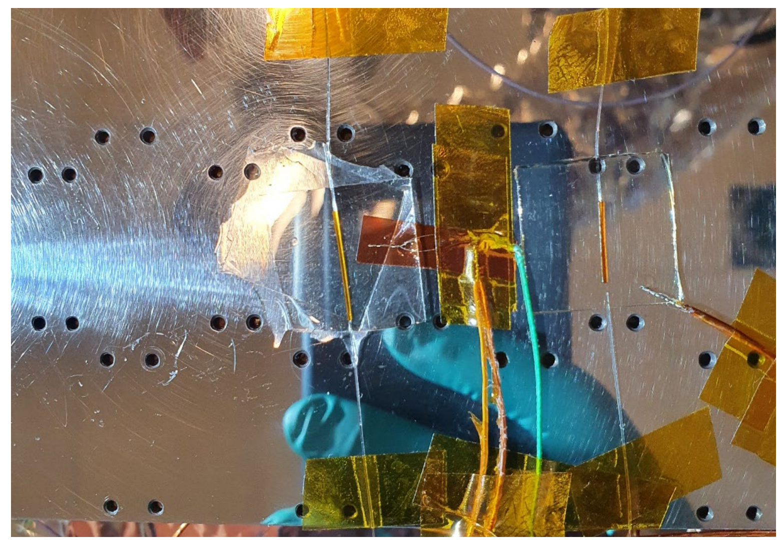
TU Delft AeroNDT

Samples inside vacuum test chamber

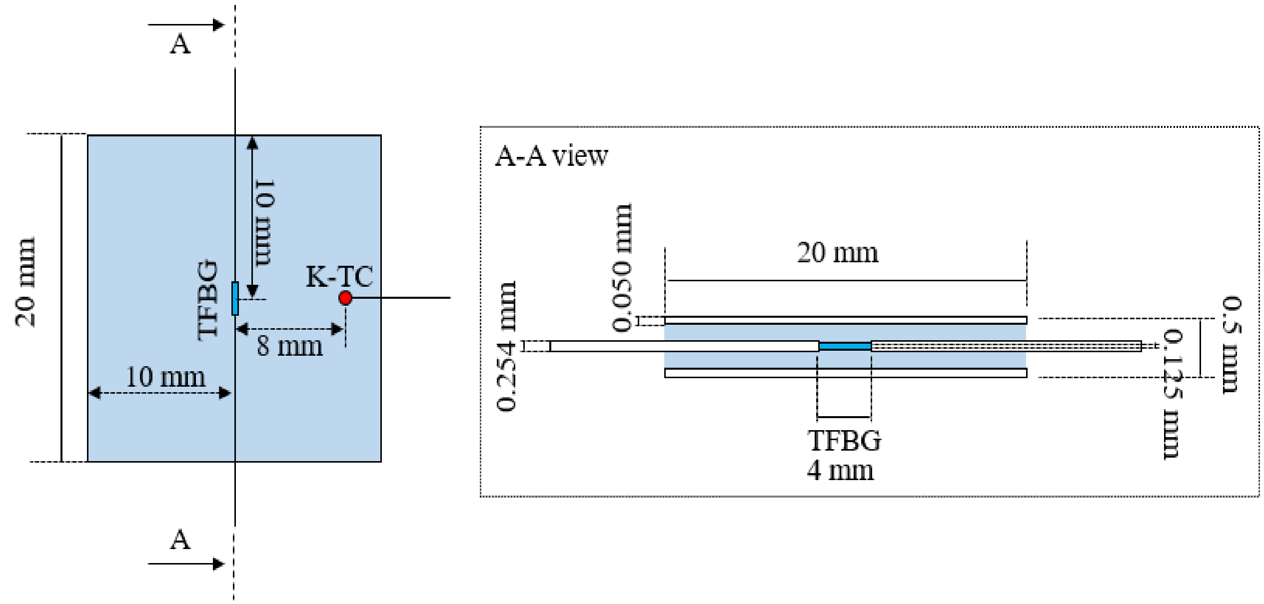


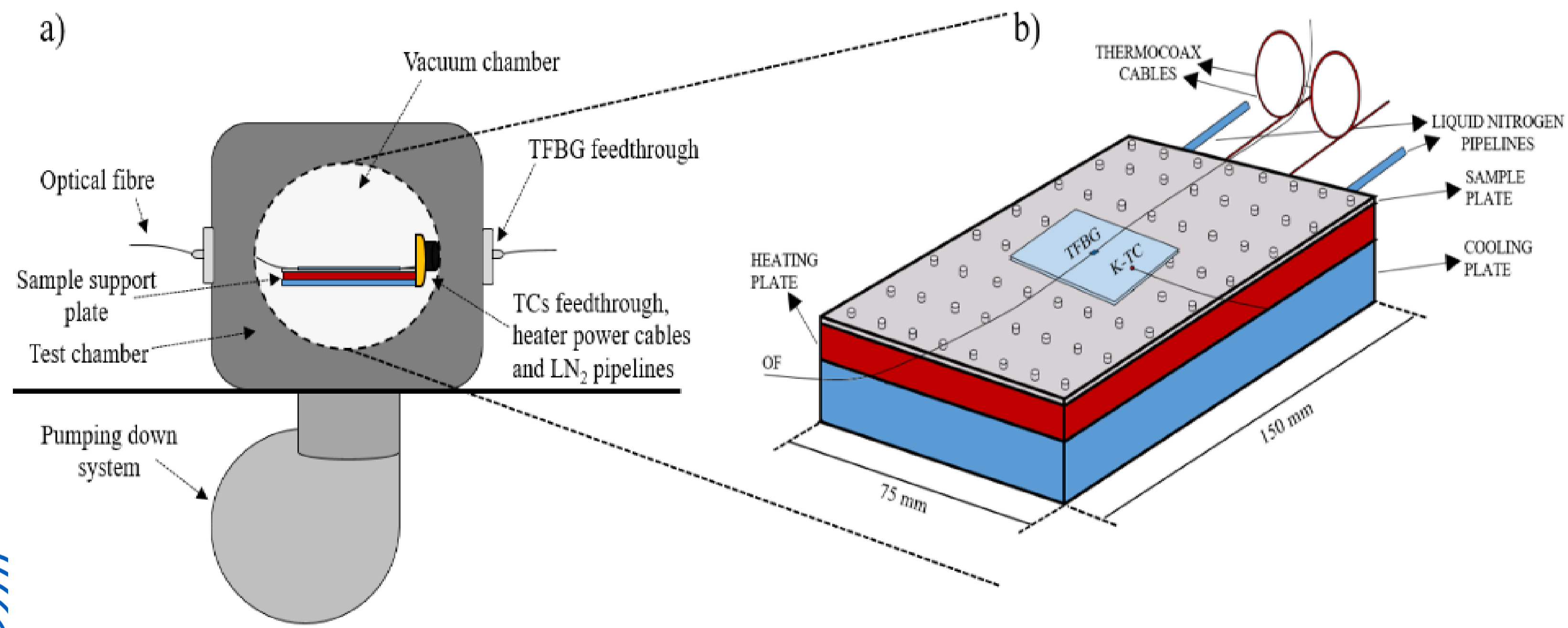




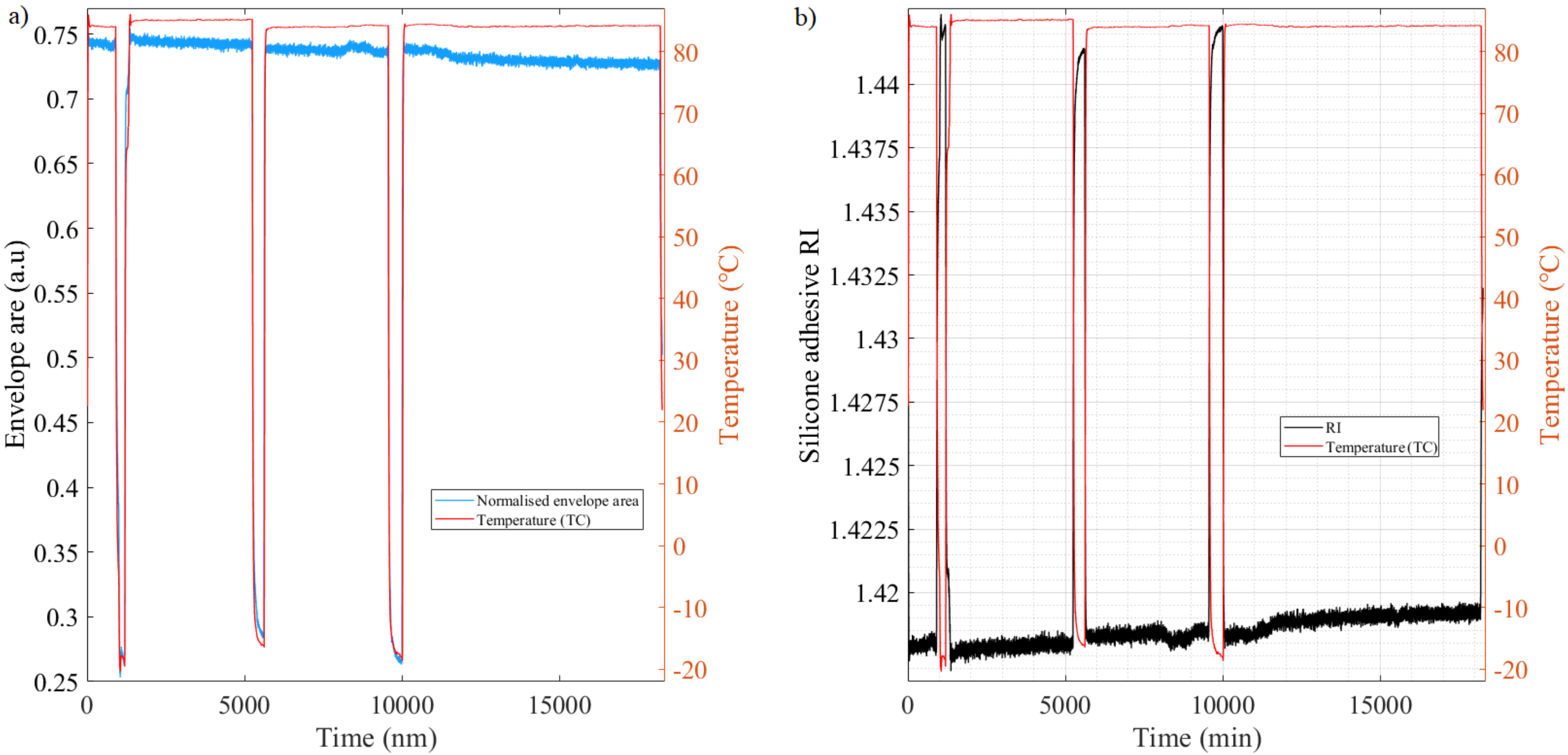


Experimental setup

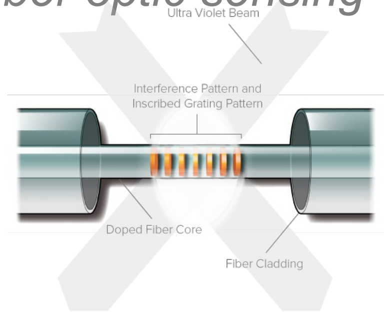




Results



The starting RI was ~1,43. The final RI is ~1,432.

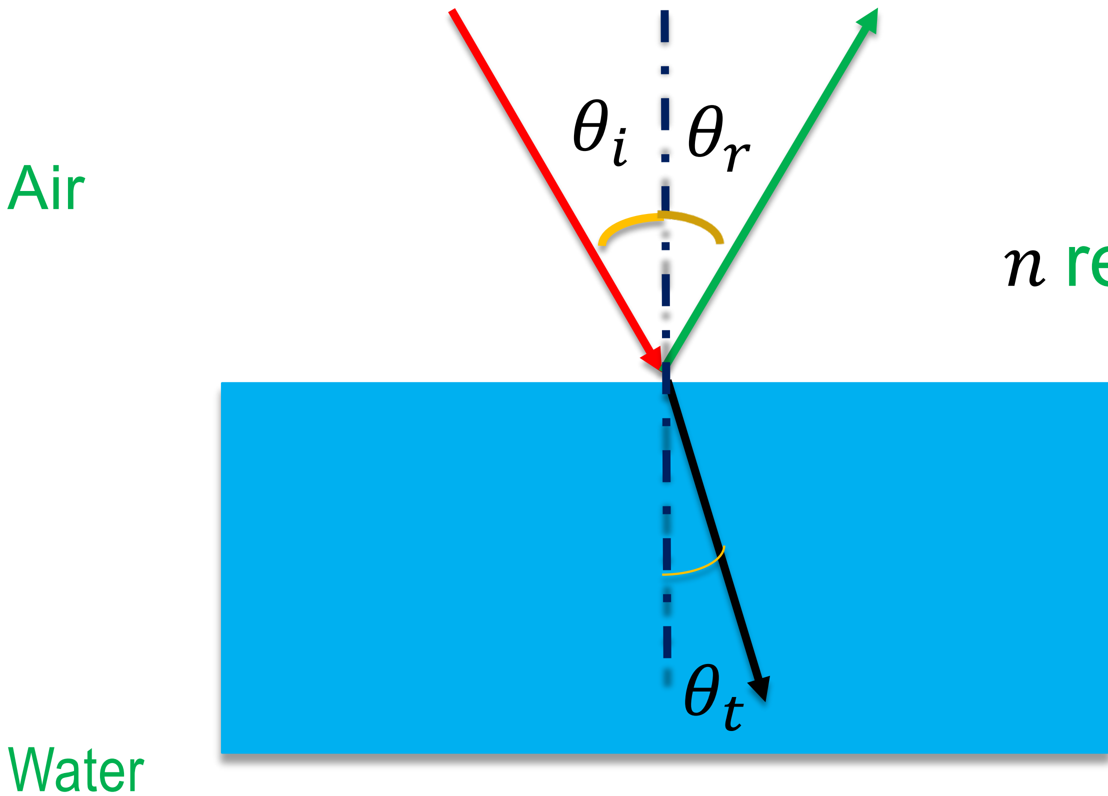


End of Part 1 - Fibre optic sensing for smart structures

- Fibre optic sensing theory
- Research of PhD Nakash Nazeer on fibre optic shape sensing of morphing aircraft wing
- Research of PhD Luigi Fazzi on fibre optic sensing during composite manufacturing and in a simulated space environment

Part 2: Ultrasonic wave propagation

How to visualize waves in two different media?



Snel's Law:

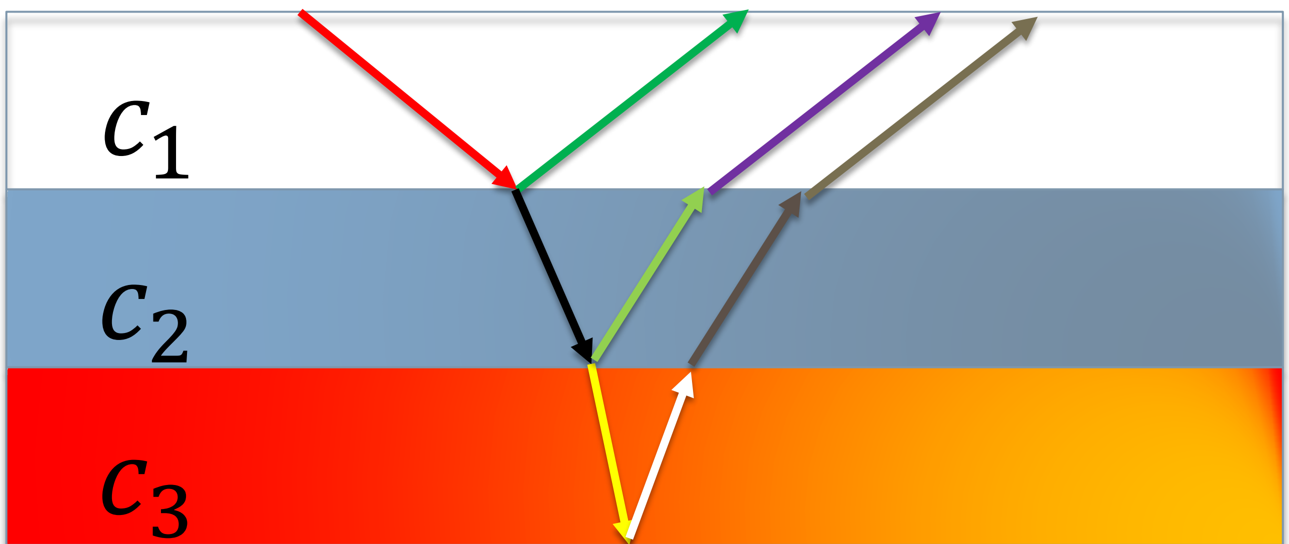
$$\frac{sin\theta_i}{sin\theta_t} = \frac{n_t}{n_i} = \frac{c_i}{c_t}$$

n refractive index

‘Multiple reflection scenario?

3 layers

1st reflections



Transmission

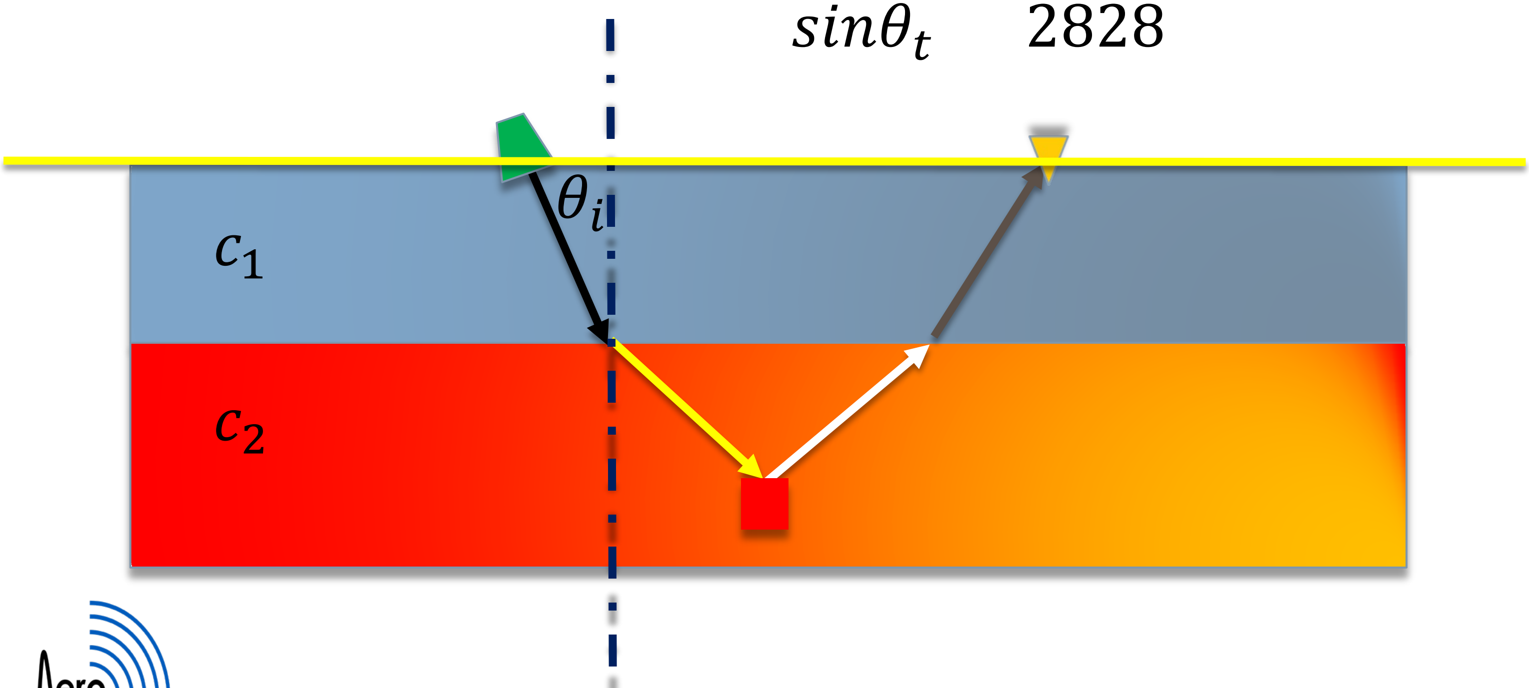
$c_1 > c_2 > c_3$

Q1 Can we detect this damage at the surface?

c_1= 2000m/s
c_2= 2828m/s

YES!

$$\theta_i = 30^o \rightarrow \frac{sin30}{sin\theta_t} = \frac{2000}{2828} \rightarrow \theta_t = 45^o$$



Can we detect this damage at the surface (note different materials!)?

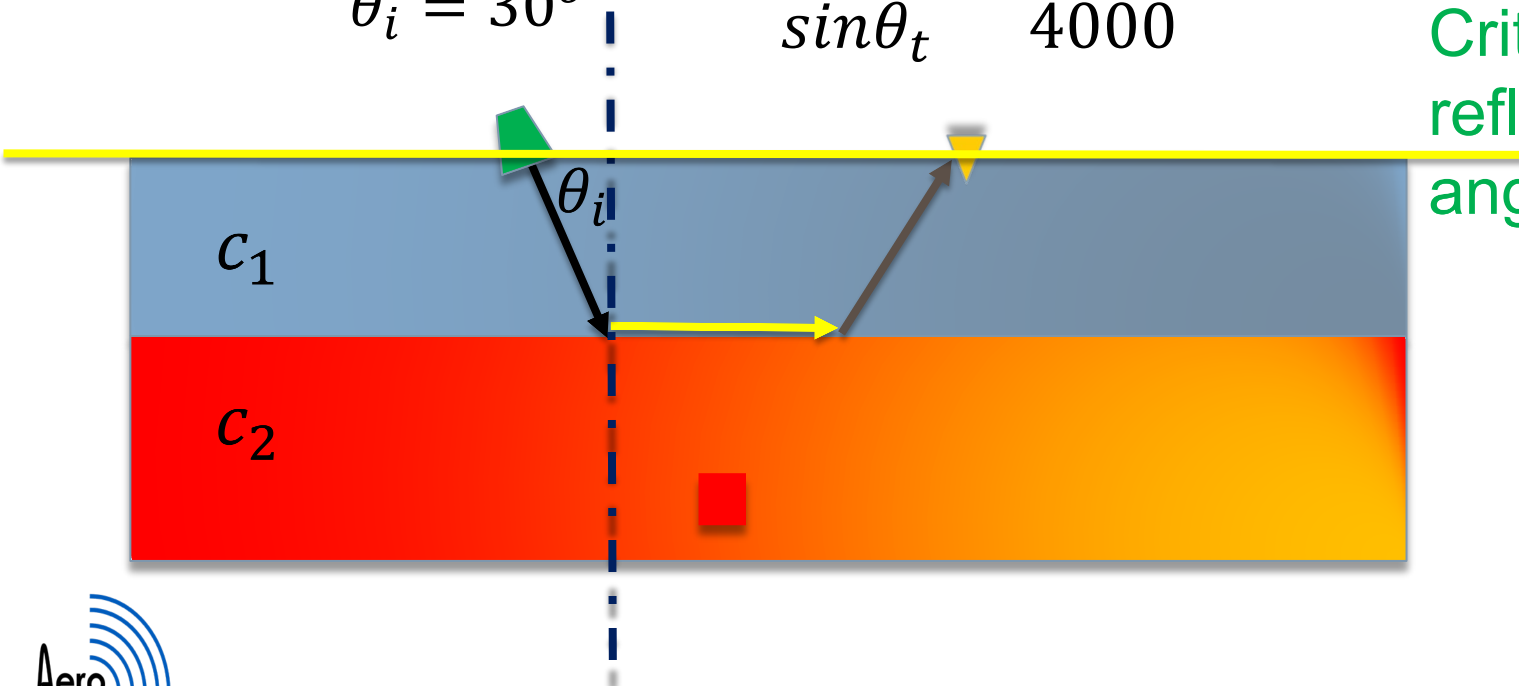
No!

c_1= 2000m/s
c_2= 4000m/s

$\theta_i = 30^o$

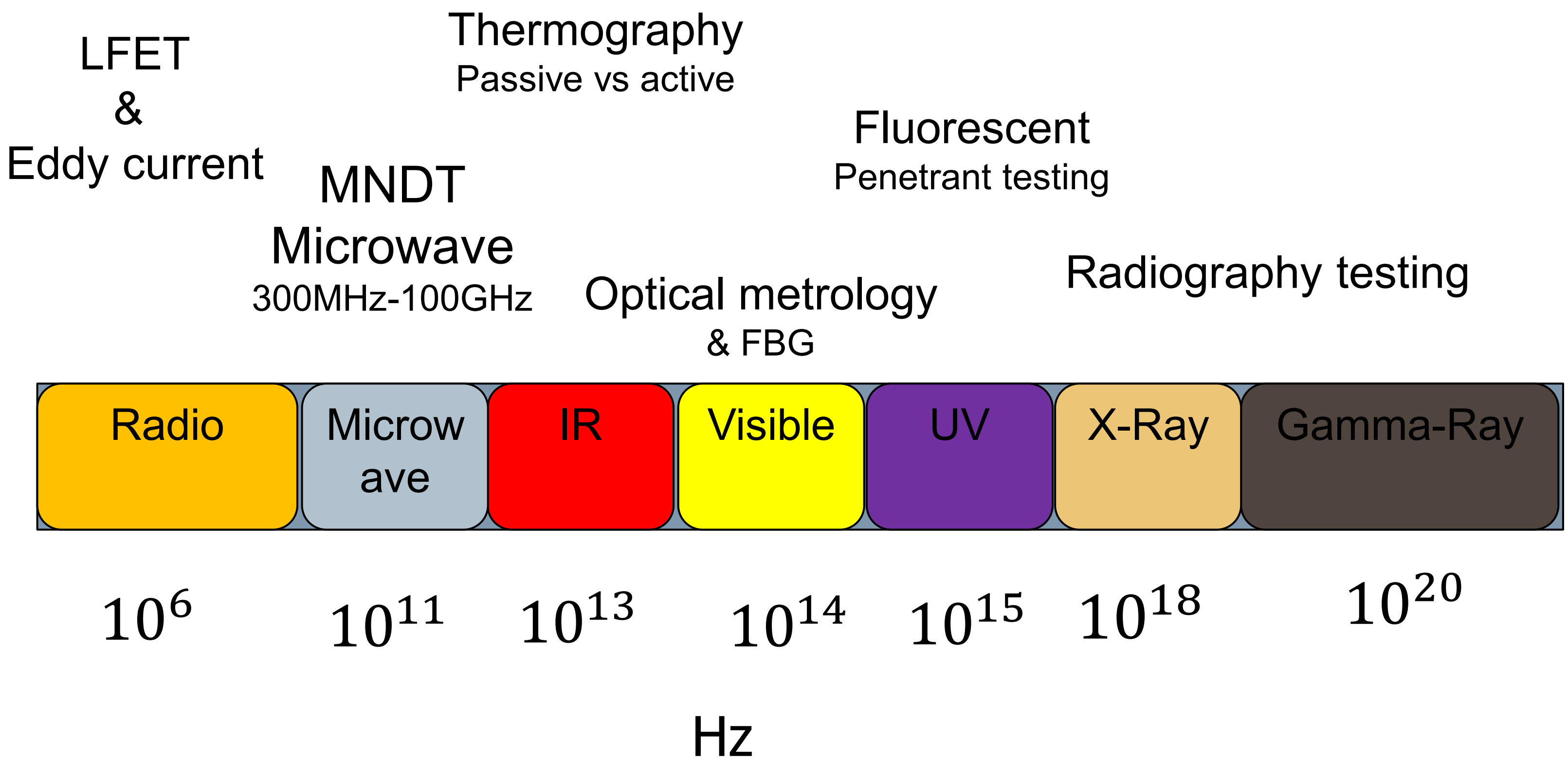
$\rightarrow \frac{sin30}{sin\theta_t} = \frac{2000}{4000} \rightarrow \theta_t = 90^o$

Critical reflection angle

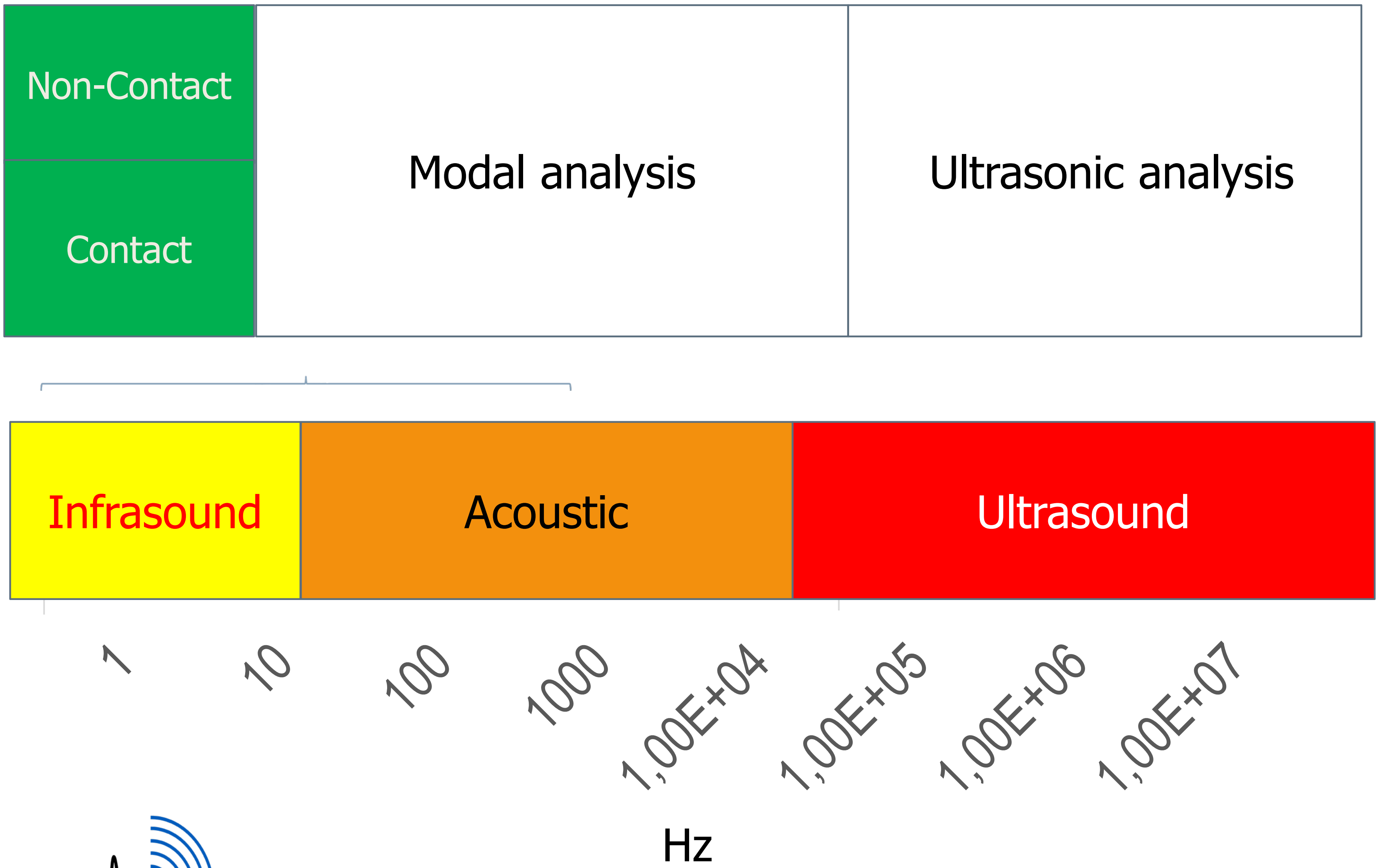


Ultrasonic wave modes

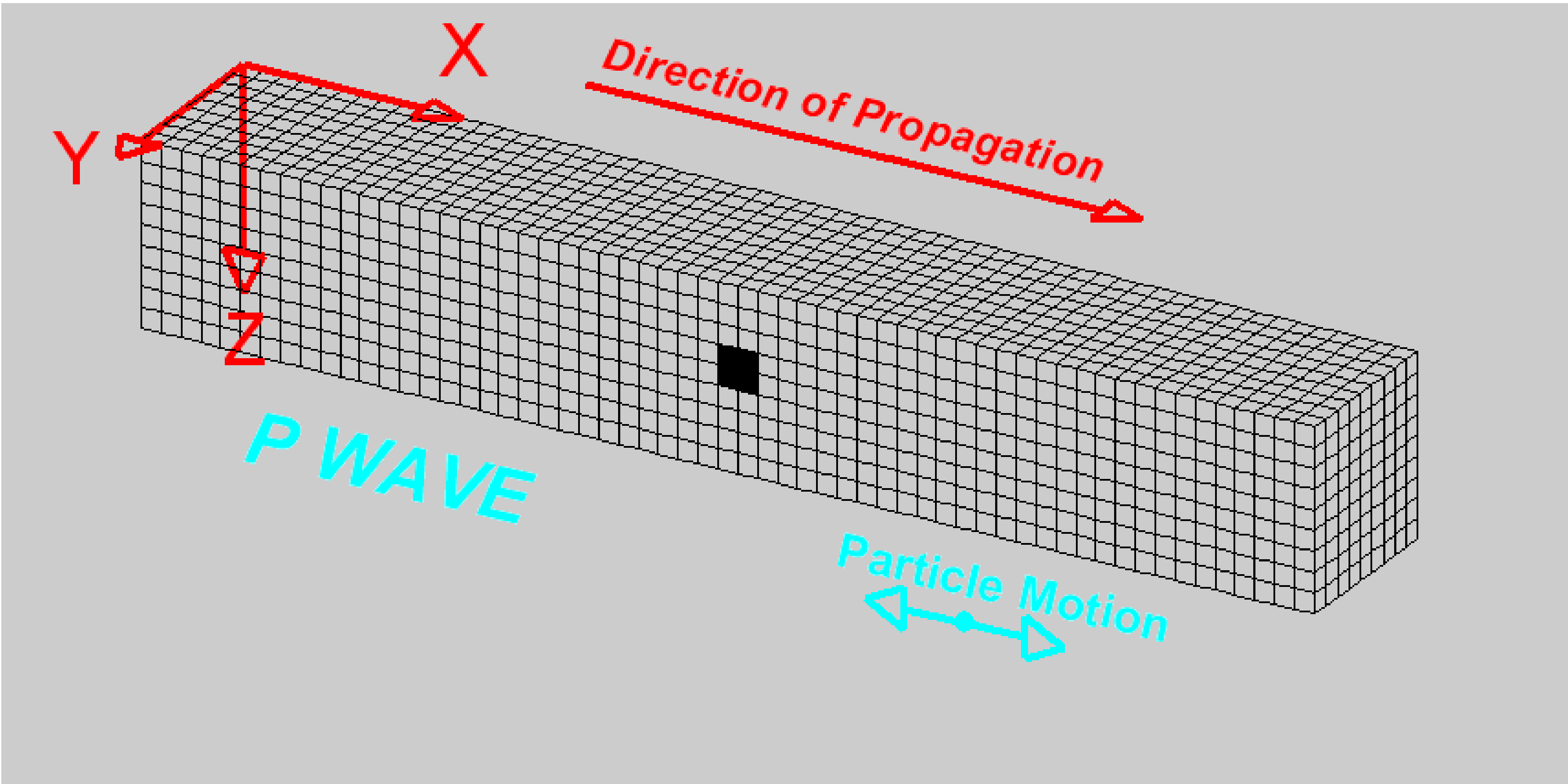
Electromagnetic wave spectrum



Mechanical wave spectrum

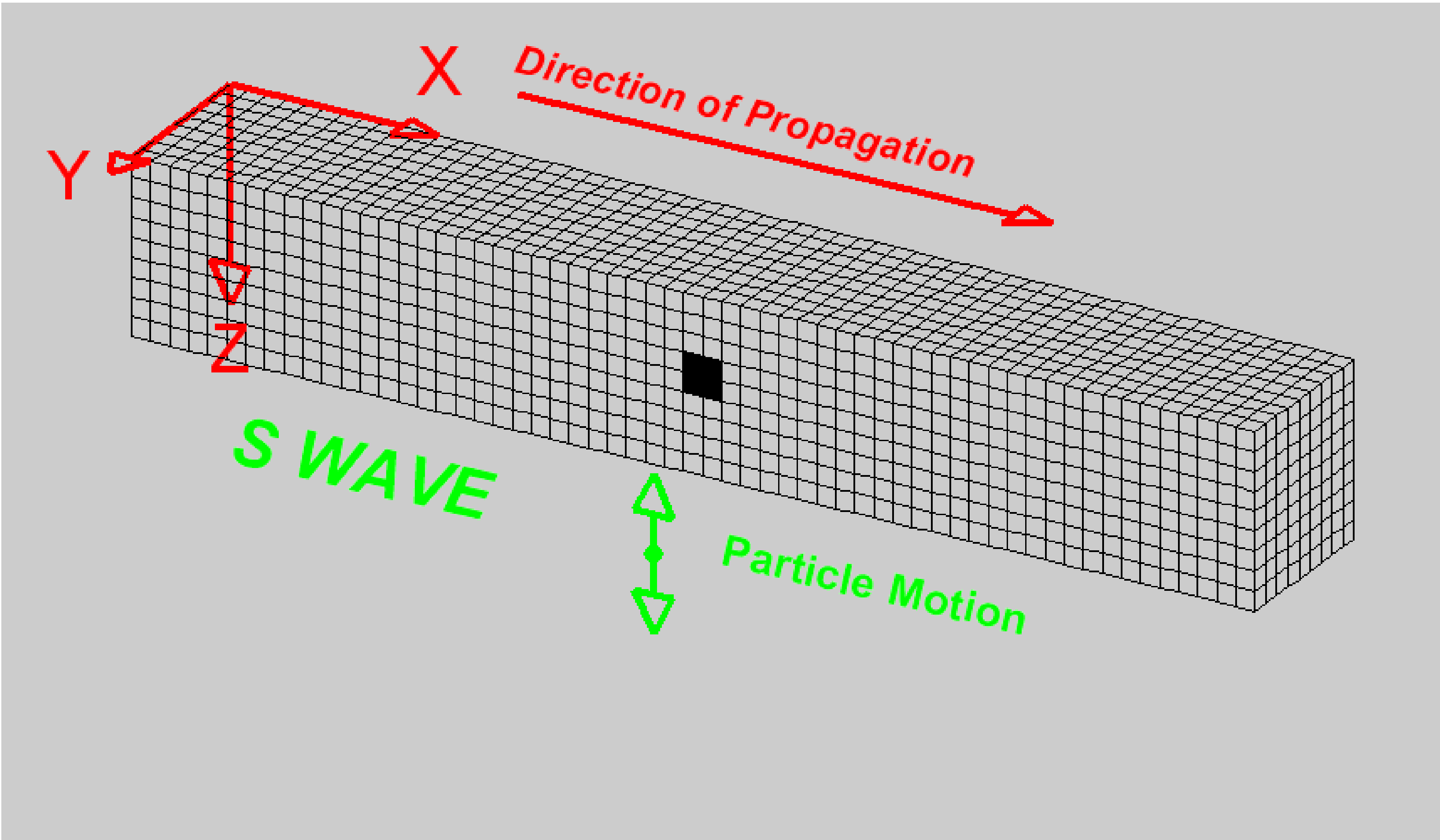


Longitudinal aka P-waves



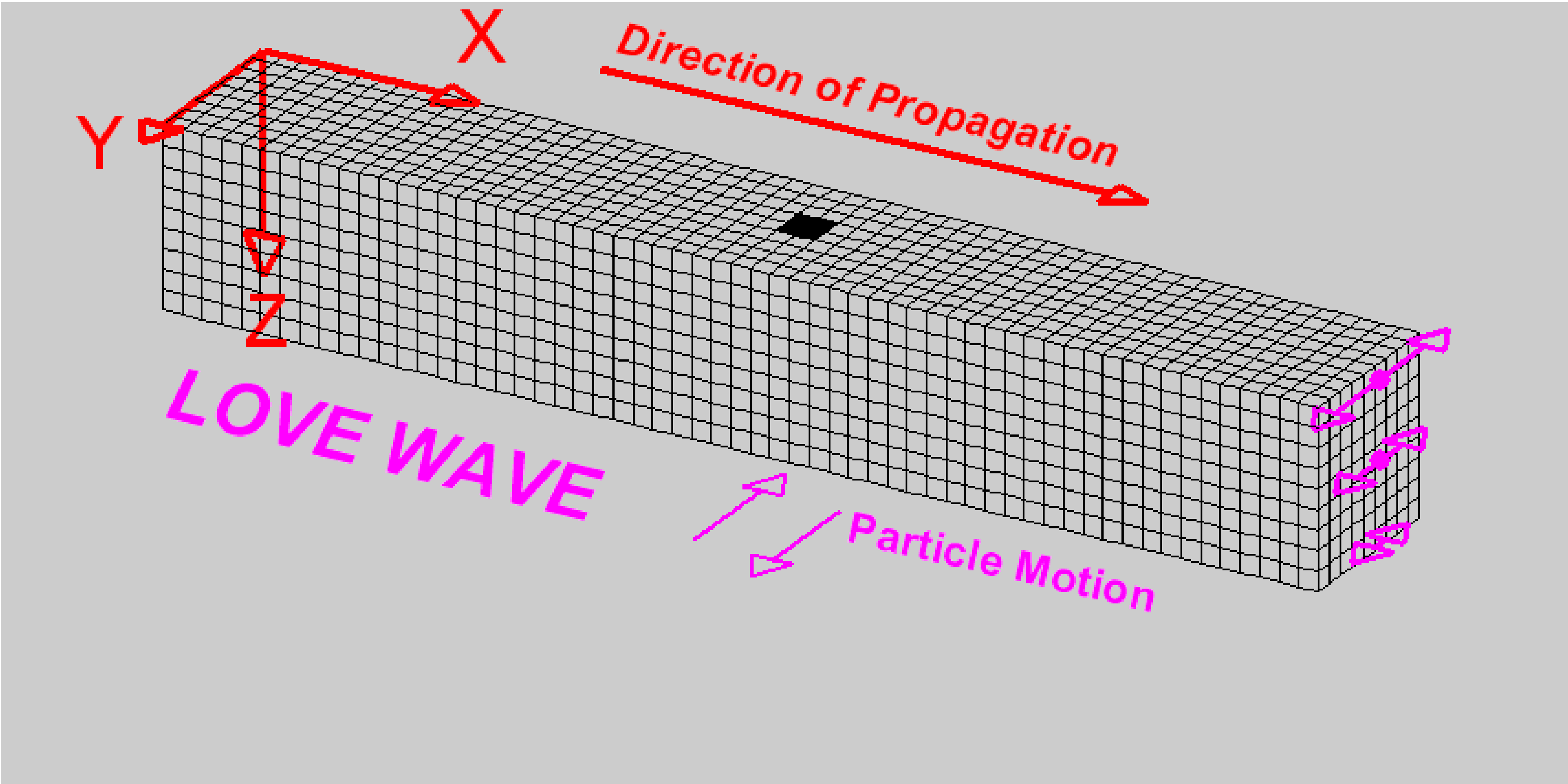
http://www.geo.mtu.edu/UPSeis/images/P-wave_animation.gif

Shear, S_y- and S_z-waves



http://www.geo.mtu.edu/UPSeis/images/S-wave_animation.gif

Surface Love waves



http://www.geo.mtu.edu/UPSeis/images/Love_animation.gif

Surface Rayleigh waves

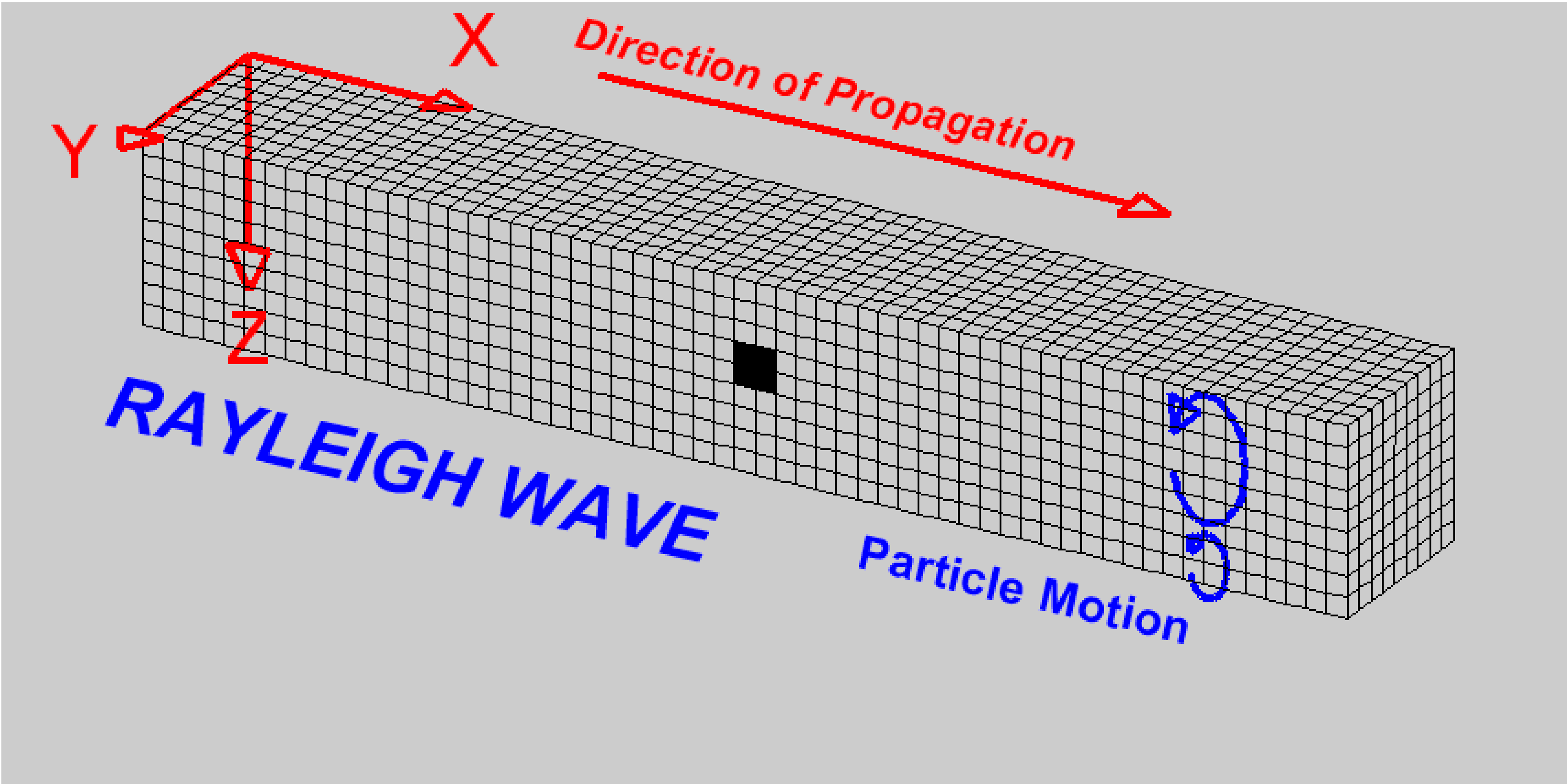
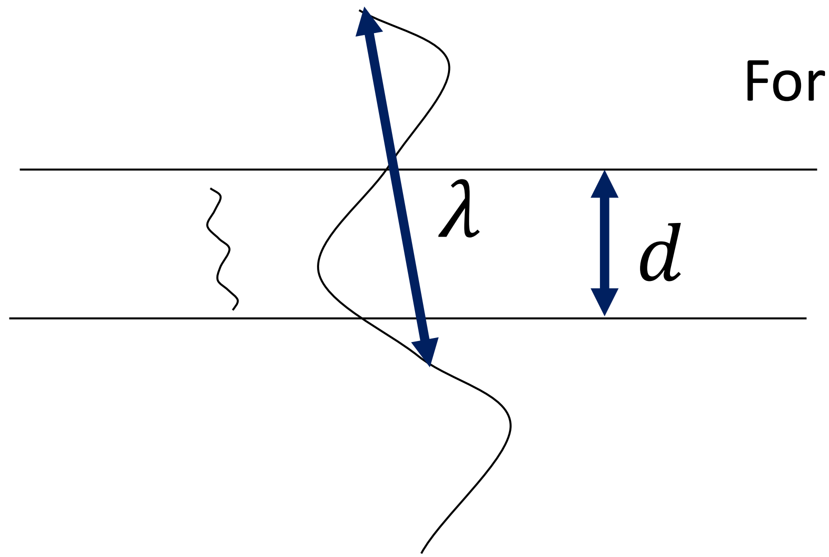
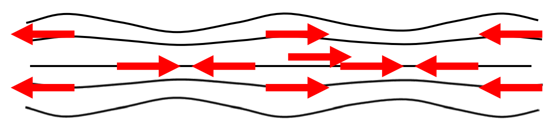


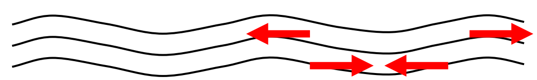
Plate waves – Lamb waves



For $\frac{d}{\lambda} \leq 1$ Lamb waves occur



Symmetric, S_0, S_1, …



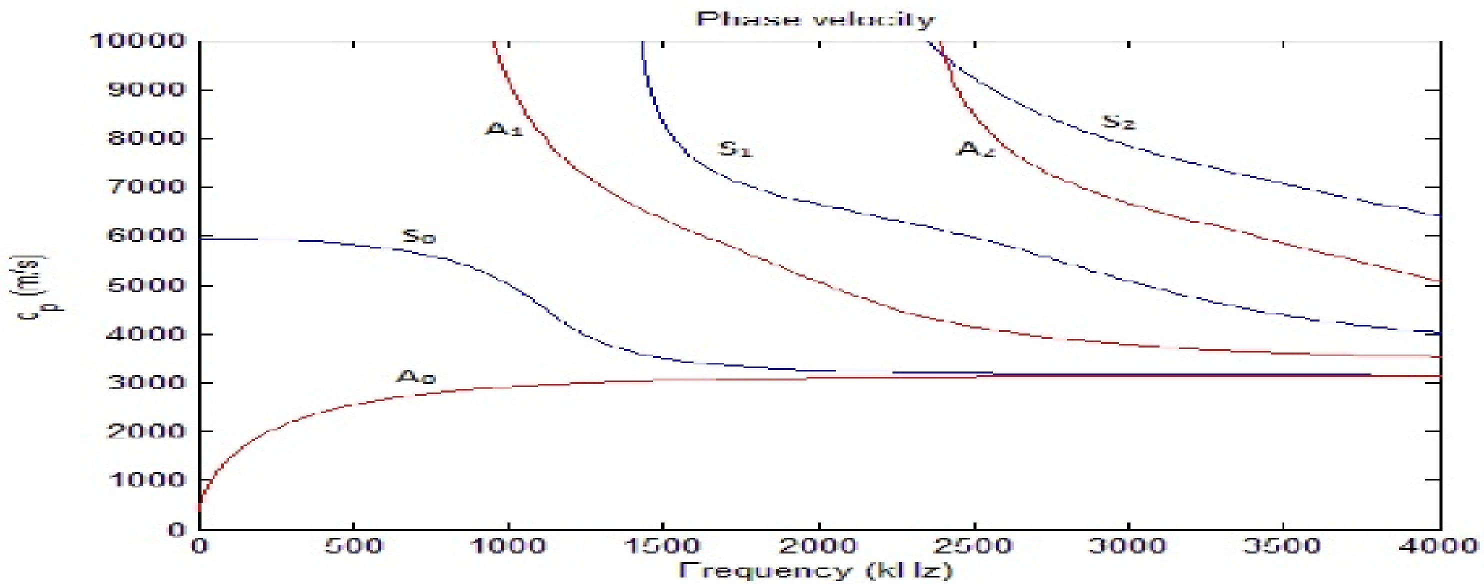
Asymmetric A_0, A_1, …

Phase and group velocity

Phase velocity C_P : Velocity of the carrier wave

Group velocity C_G: Velocity of the wavepacket

- Phase =Group velocity for isotropic material



- Wave velocity can change as function of frequency, known as 'dispersion'

Ochôa, P., Infante, V., Silva, J.M., Groves, R.M., "Detection of multiple low-energy impact damage in composite plates using Lamb wave techniques", Composites Part B, 2015.

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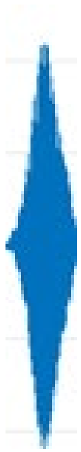
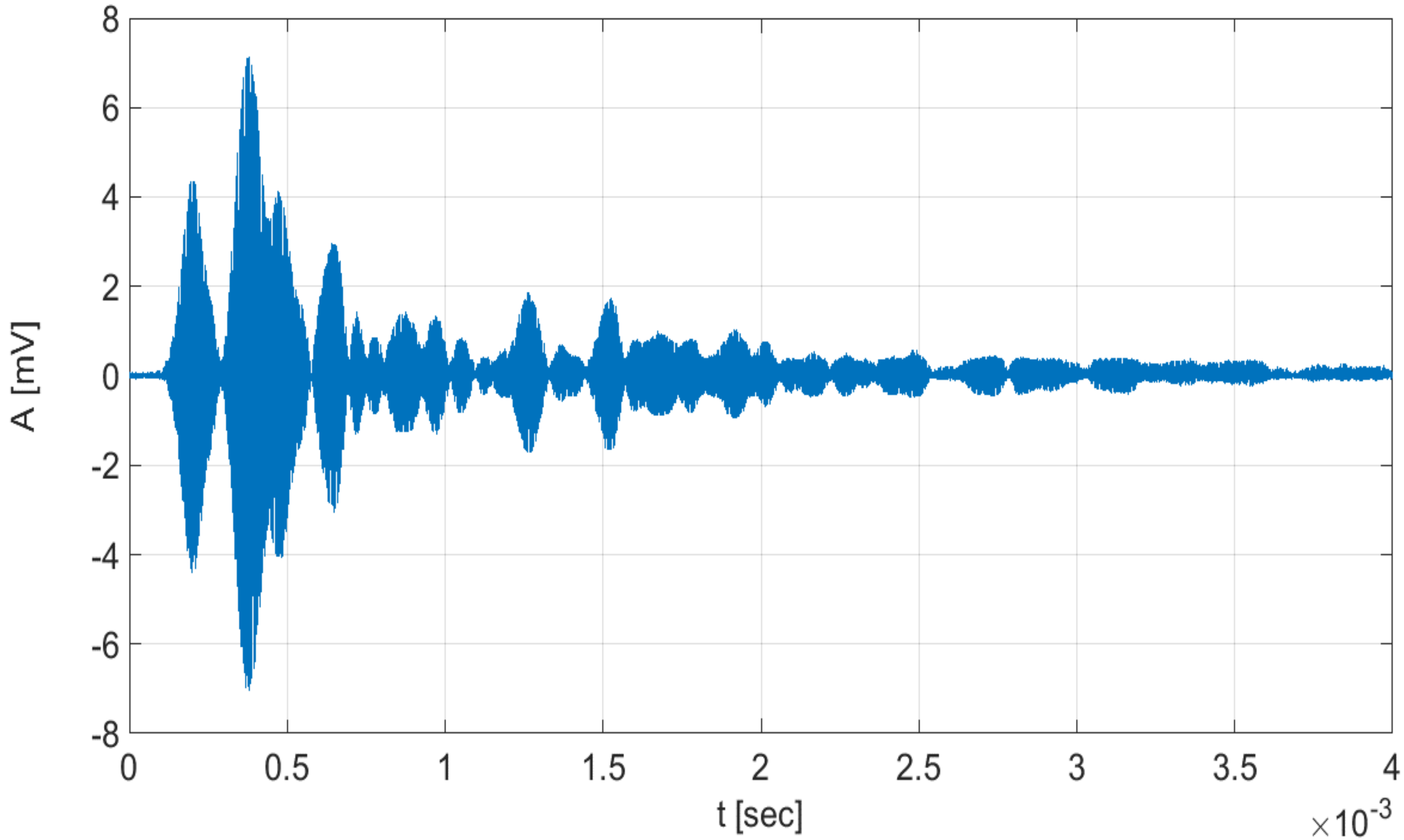
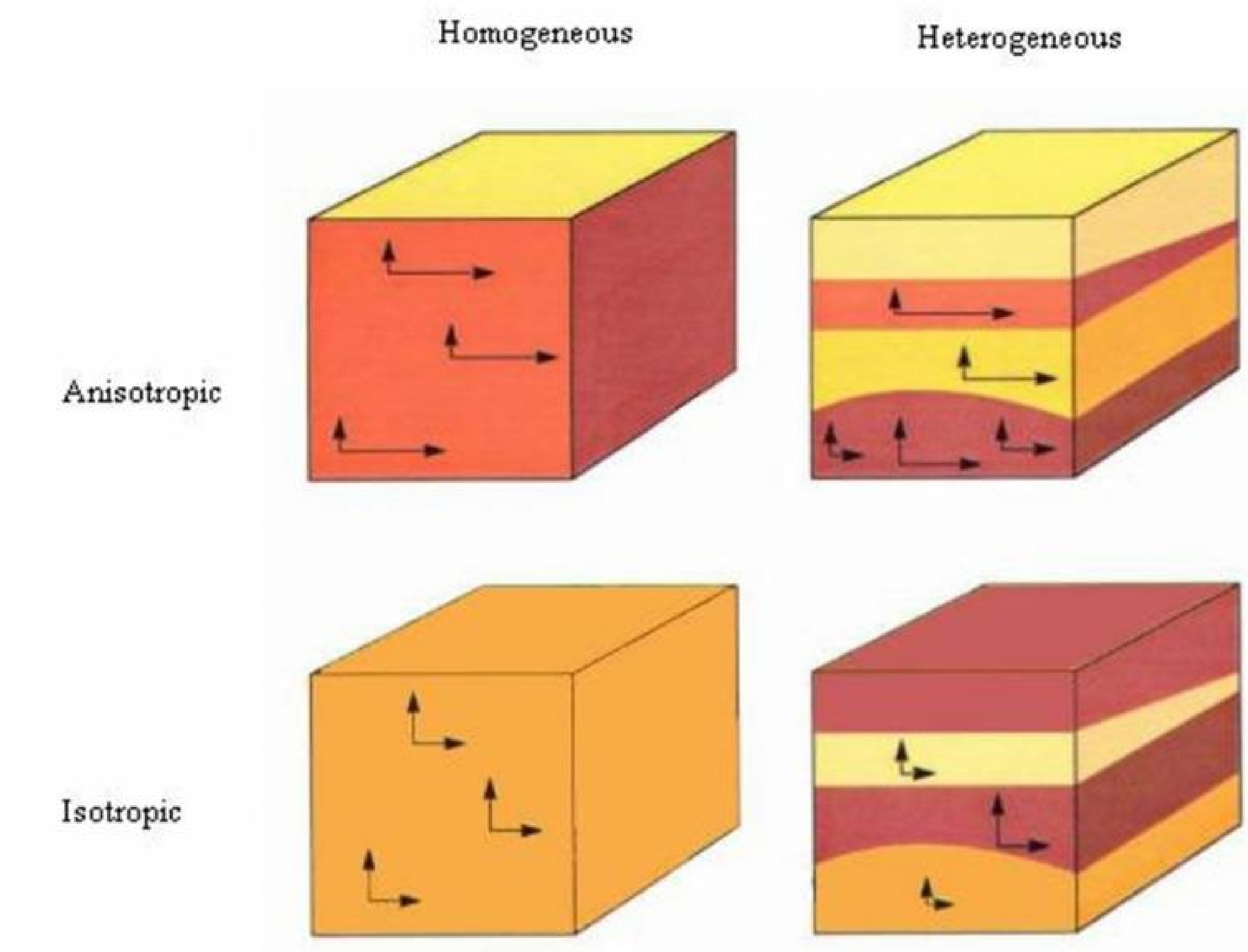
Time of flight of waves



Input wave



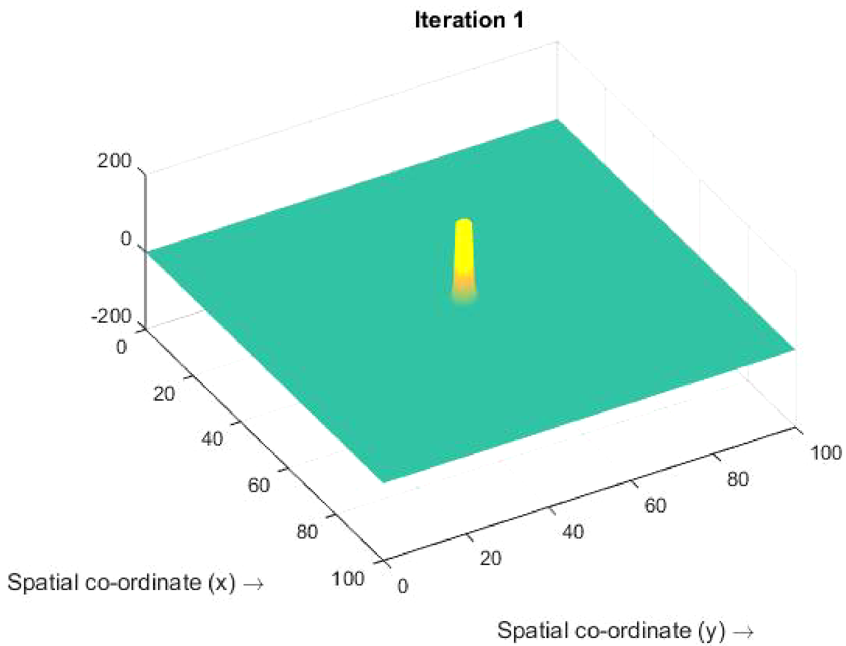
Homogeneous/ heterogeneous & anisotropic/ isotropic



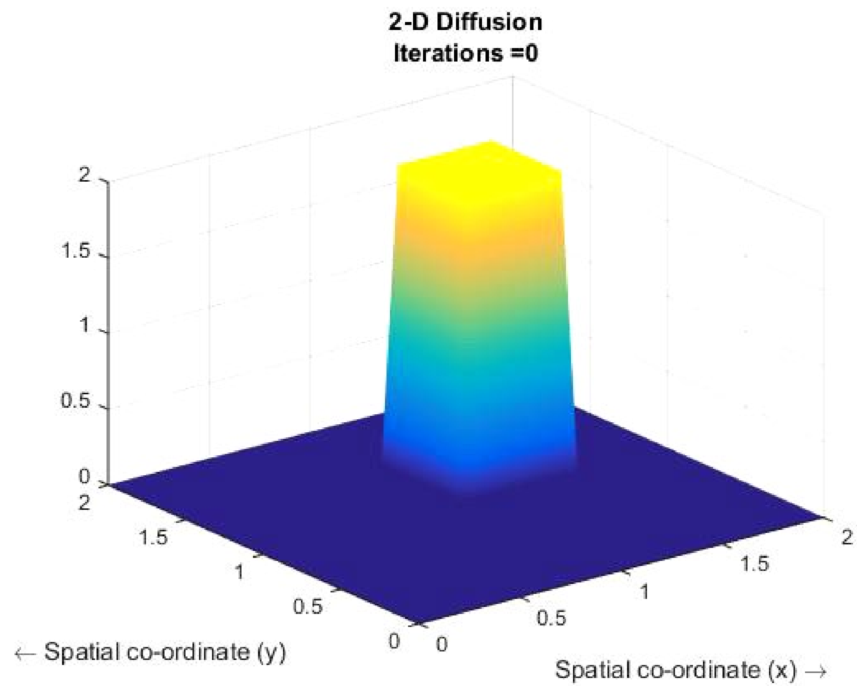
http://petroleumgeophysics.com/images/contributions/Figure-230.jpg

Ultrasonic wave properties

Wave propagation vs diffusion



Like rock in water



Heating an object with a torch (temporarily)

Properties of waves

$$\frac{\partial^2 U}{\partial t^2} = c^2 \frac{\partial^2 U}{\partial x^2} \qquad \frac{\partial U}{\partial t} = \alpha \frac{\partial^2 U}{\partial x^2}$$

Property	Wave	Diffusion
Velocity	Finite c=?? m/s	Infinite
Well posed t>0	Yes	Yes
Well posed t<0	Yes	No
Behavior for $t \to \infty$	Does not decay	Decays to zero
Information	Transported	Decays gradually

http://www.math.ucsb.edu/~grigoryan/124A/lecs/lec11.pdf

Wave velocities in homogeneous isotropic materials -1

$$c_s = \sqrt{\frac{G}{\rho}}$$

c_s shear wave velocity, ρ the solid density

&

$$\nu = \frac{c_p^2 - 2c_s^2}{2(c_P^2 - c_s^2)}$$

c_p compressional velocity

http://www.diss.fu-berlin.de/diss/servlets/MCRFileNodeServlet/FUDISS_derivate_000000001276/02_kaselowch2.pdf?hosts=

Wave velocities in homogeneous isotropic materials -2

$$E = 2G(1 + \nu)$$

With E the Elasticity modulus

Alternative

$$c_p = \sqrt{\frac{K + \frac{4}{3}G}{\rho}}$$

where $K = \frac{E}{3(1-2\nu)}$ bulk modulus, & ν Poisson ratio

http://www.diss.fu-berlin.de/diss/servlets/MCRFileNodeServlet/FUDISS_derivate_000000001276/02_kaselowch2.pdf?hosts=

Acoustic Impedance

$$Z = \rho \cdot c$$

Reflection : $R = \frac{Z_2 - Z_1}{Z_2 + Z_1}$

Z_2 Impedance material 2

Z_1 Impedance material 1 $[kg/(m^2 \cdot s)] \rightarrow [Pa \cdot s/m]$

R Reflection coefficient [%]

Transmission : $T = 1 - R$

Ultrasonic sensing technology

Frequency and accuracy

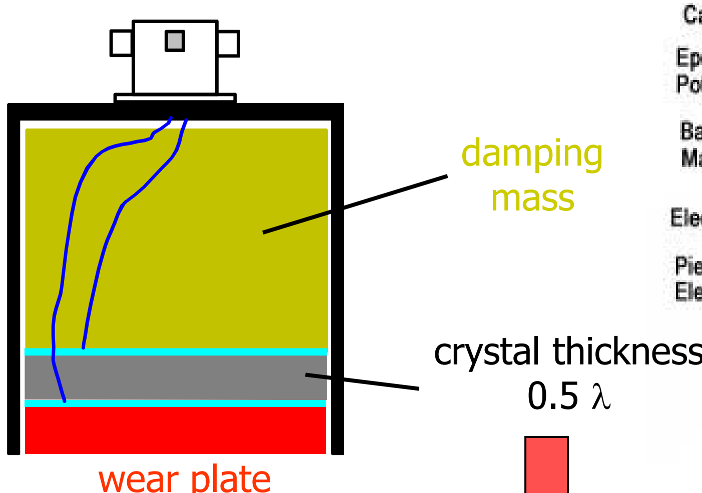
Wave measurements are in general more accurate, but also more time consuming.

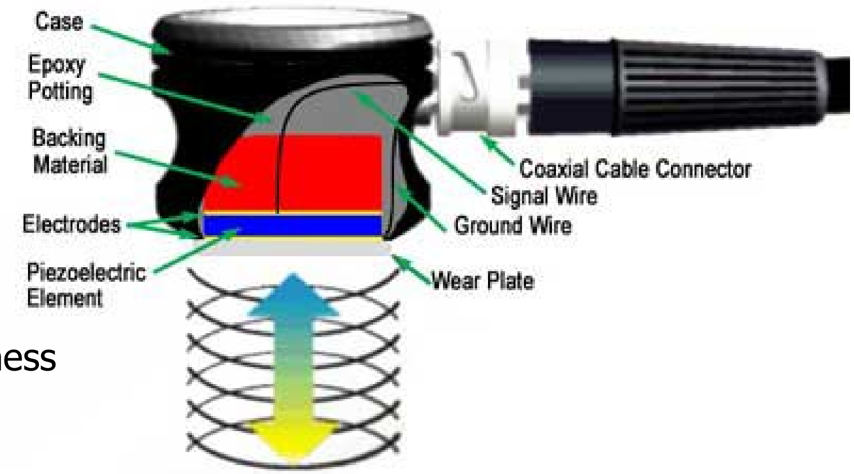
Lower ‘frequencies’ also means deeper penetration of materials (music through a wall, you mainly will hear the lower frequencies).

Acoustic Wave PZT

Excitation pulse requires 25 V to 600 V

Available up to 150 MHz centre frequency



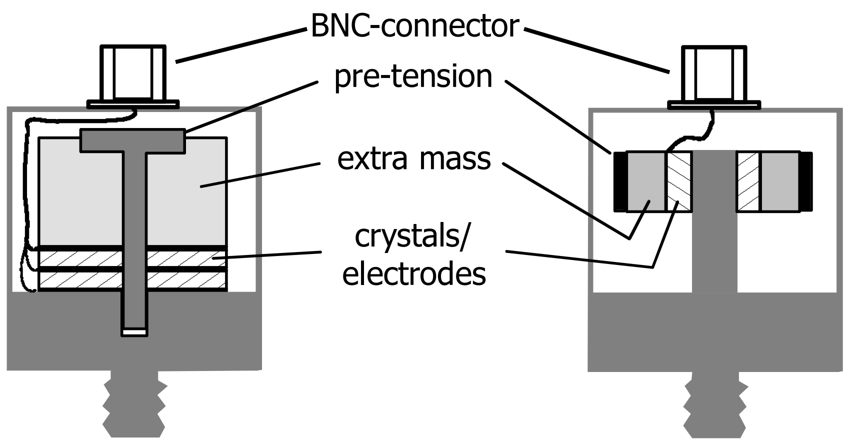


For example made of lead zirconate niobate (PZN) or lead titanate (PT)

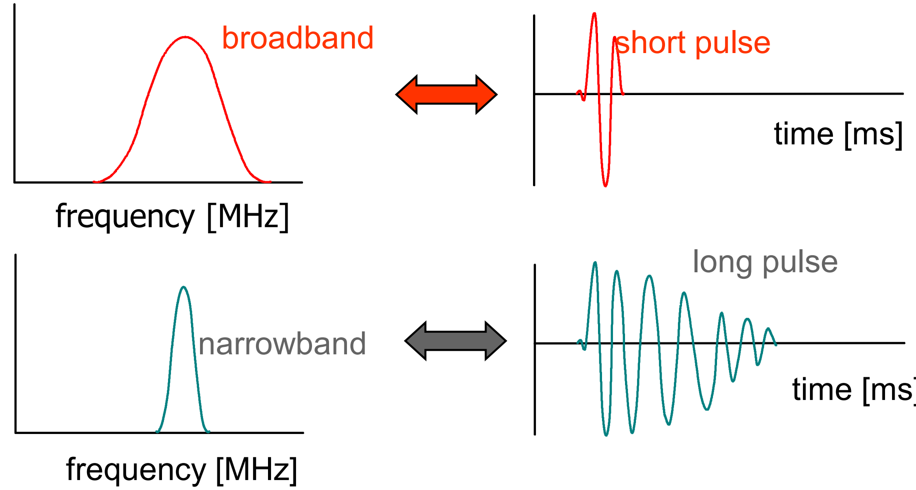
These man-made materials are more sensitive and also cheaper than quartz

Shear and Pressure transducers

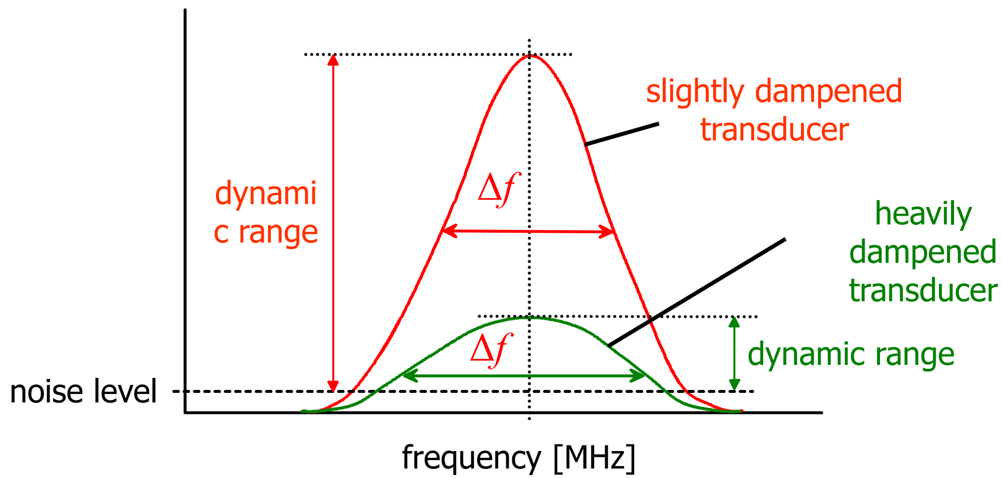
pressure-type **shear-type**



Bandwidth vs Pulse Time

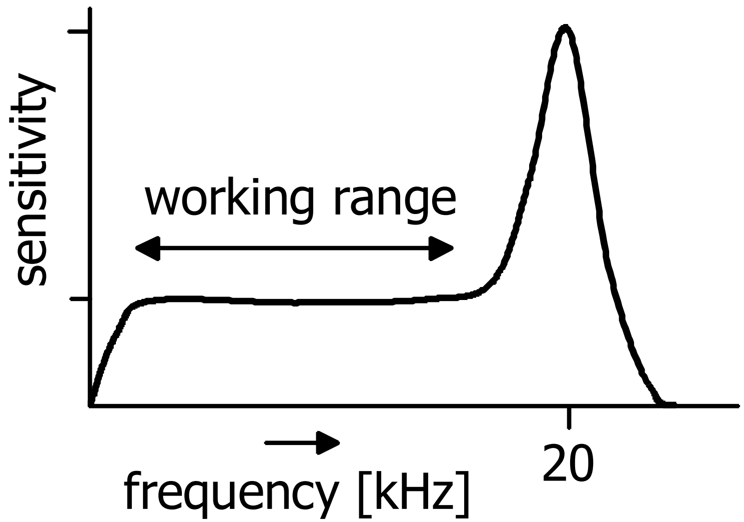


Damping of PZTs

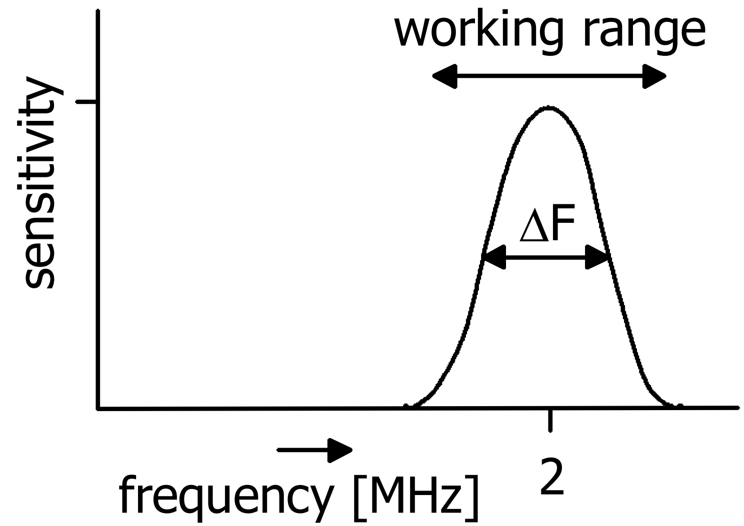


Increased damping (more attenuating mass) increases transducer bandwidth at the cost of dynamic range

Accelerometer vs wave transducer

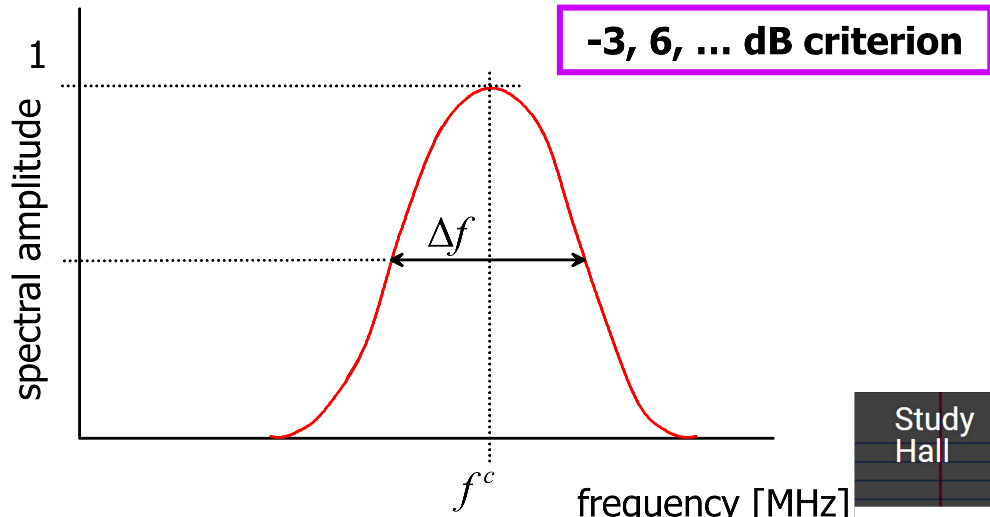


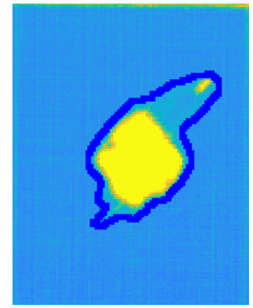
Accelerometer



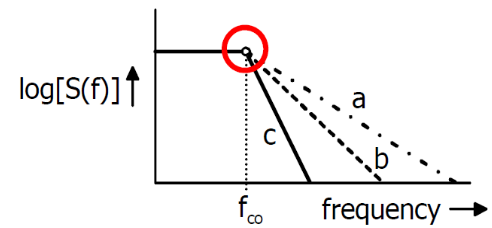
Wave transducer

Bandwidth of Acoustic Wave PZTs





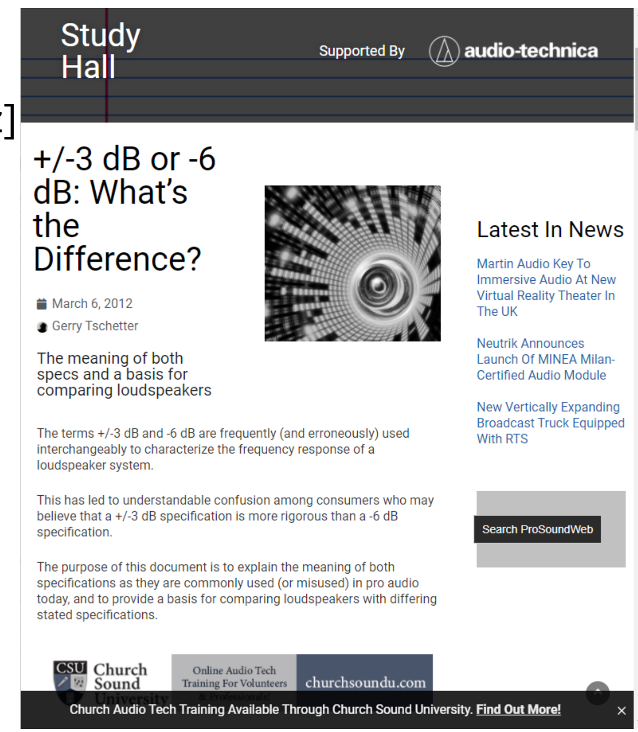
Ultrasonics



Cut-off frequency

Relative bandwidth: $\dfrac{\Delta f}{f^c} 100\%$

Bandwidths of commercial transducers between 5% - 150%



Study Hall

Supported By audio-technica

+/-3 dB or -6 dB: What's the Difference?

March 6, 2012

Gerry Tschetter

The meaning of both specs and a basis for comparing loudspeakers

The terms +/-3 dB and -6 dB are frequently (and erroneously) used interchangeably to characterize the frequency response of a loudspeaker system.

This has led to understandable confusion among consumers who may believe that a +/-3 dB specification is more rigorous than a -6 dB specification.

The purpose of this document is to explain the meaning of both specifications as they are commonly used (or misused) in pro audio today, and to provide a basis for comparing loudspeakers with differing stated specifications.

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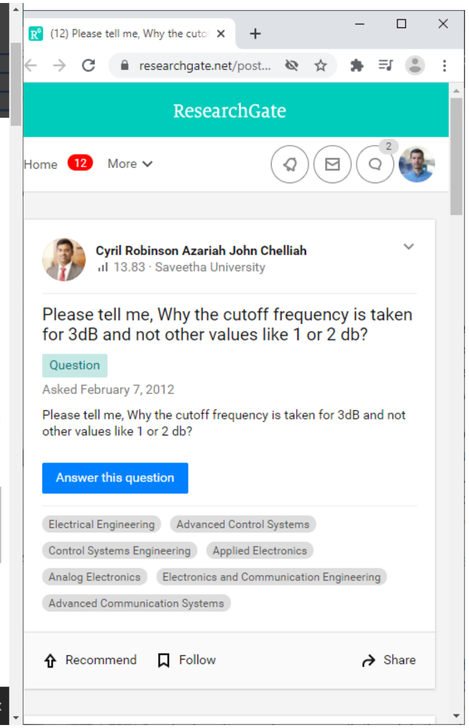

(12) Please tell me, Why the cuto

researchgate.net/post...

ResearchGate

Home 12 More

Cyril Robinson Azariah John Chelliah

13.83 · Saveetha University

Please tell me, Why the cutoff frequency is taken for 3dB and not other values like 1 or 2 db?

Question

Asked February 7, 2012

Please tell me, Why the cutoff frequency is taken for 3dB and not other values like 1 or 2 db?

Answer this question

Electrical Engineering | Advanced Control Systems | Control Systems Engineering | Applied Electronics | Analog Electronics | Electronics and Communication Engineering | Advanced Communication Systems

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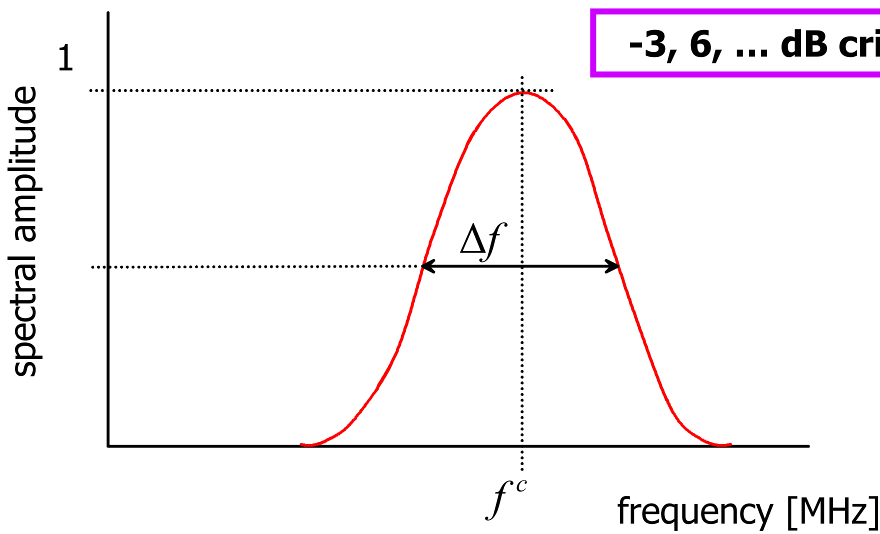
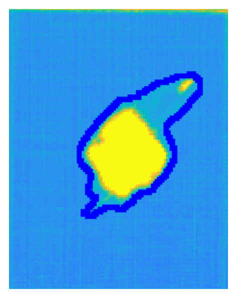
3/6 dB

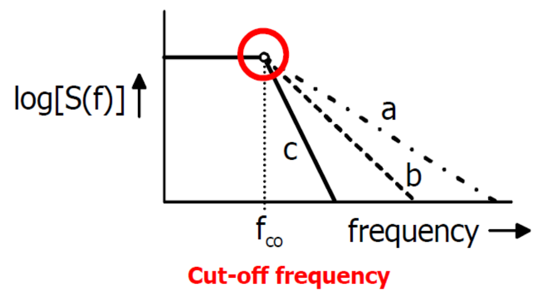
- What is the physical meaning of -3 dB?
- What is the physical meaning of -6 dB?
- Which one to use for the bandwith?

- In groups
- 4 minutes



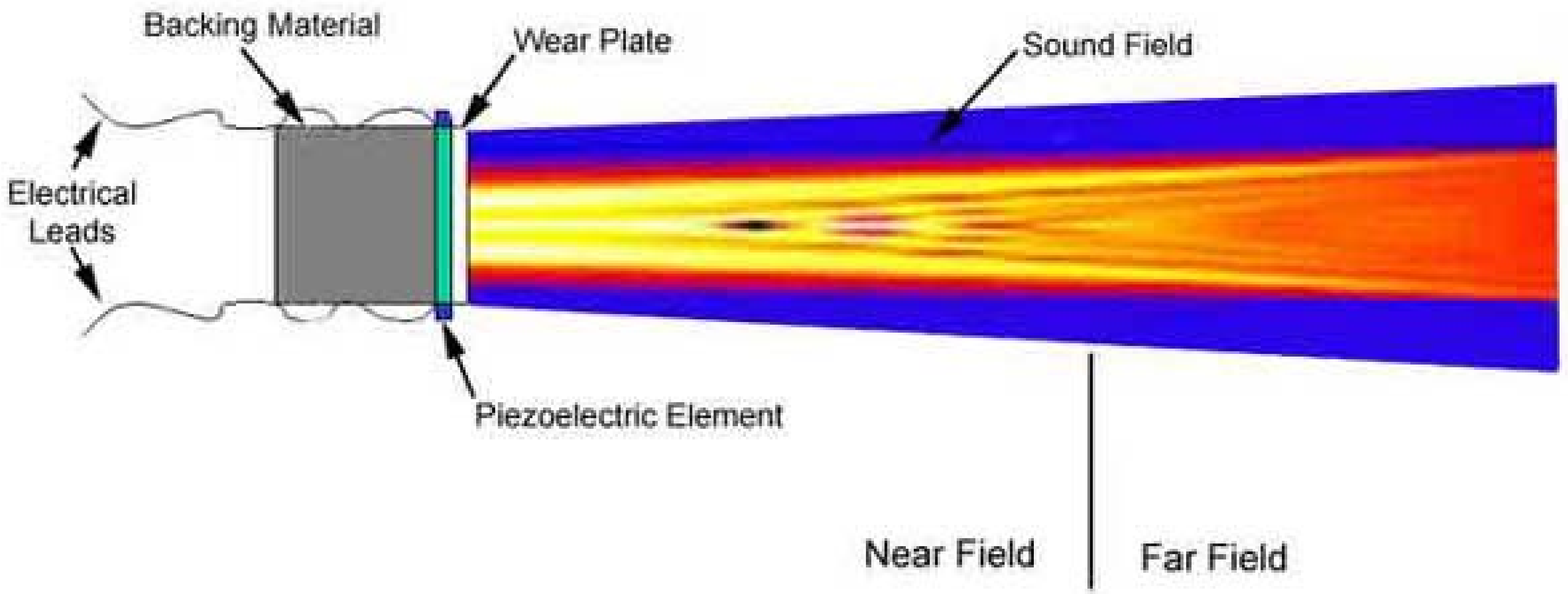


Ultrasonics



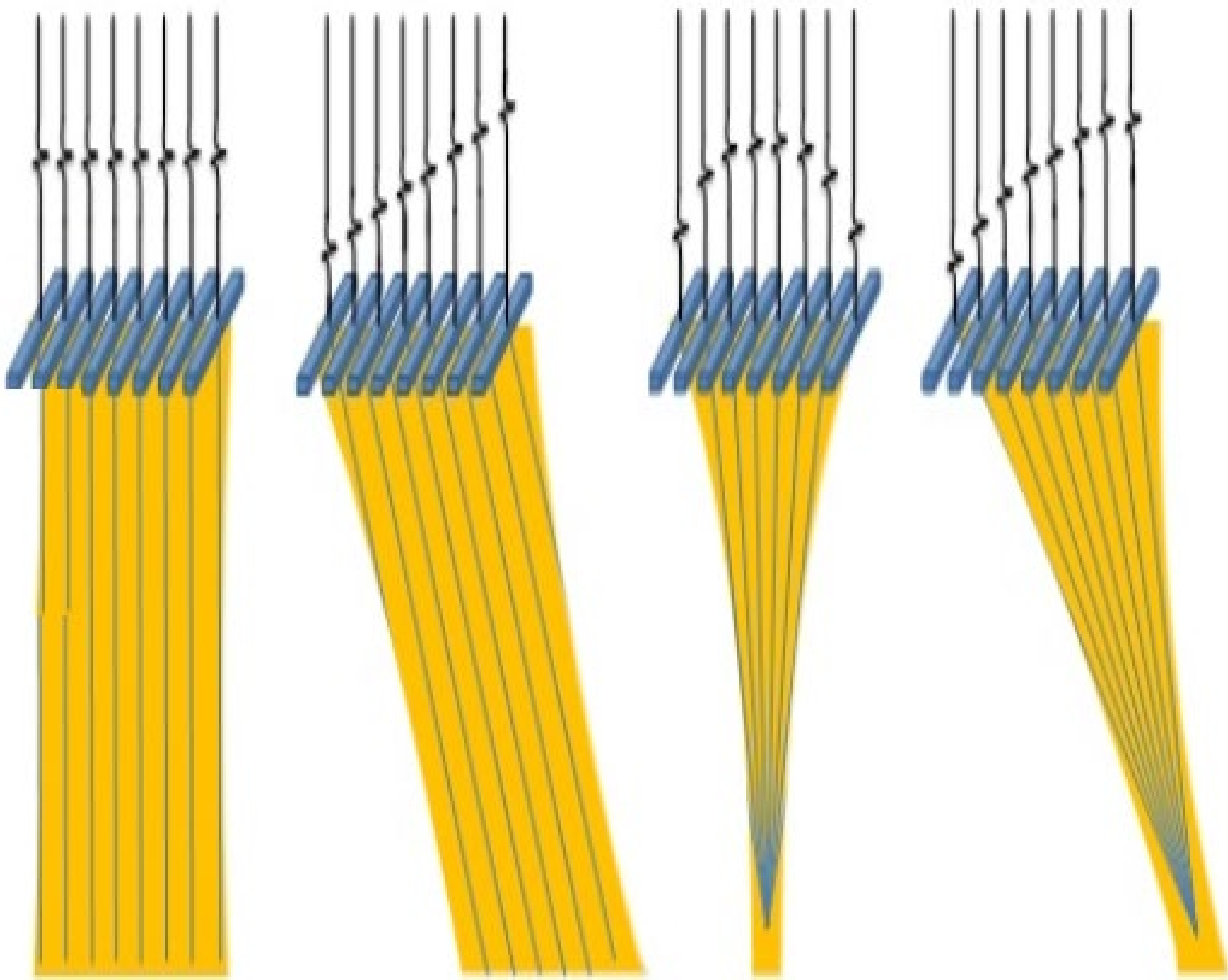
Phased array ultrasonics

Visualising an ultrasonic beam



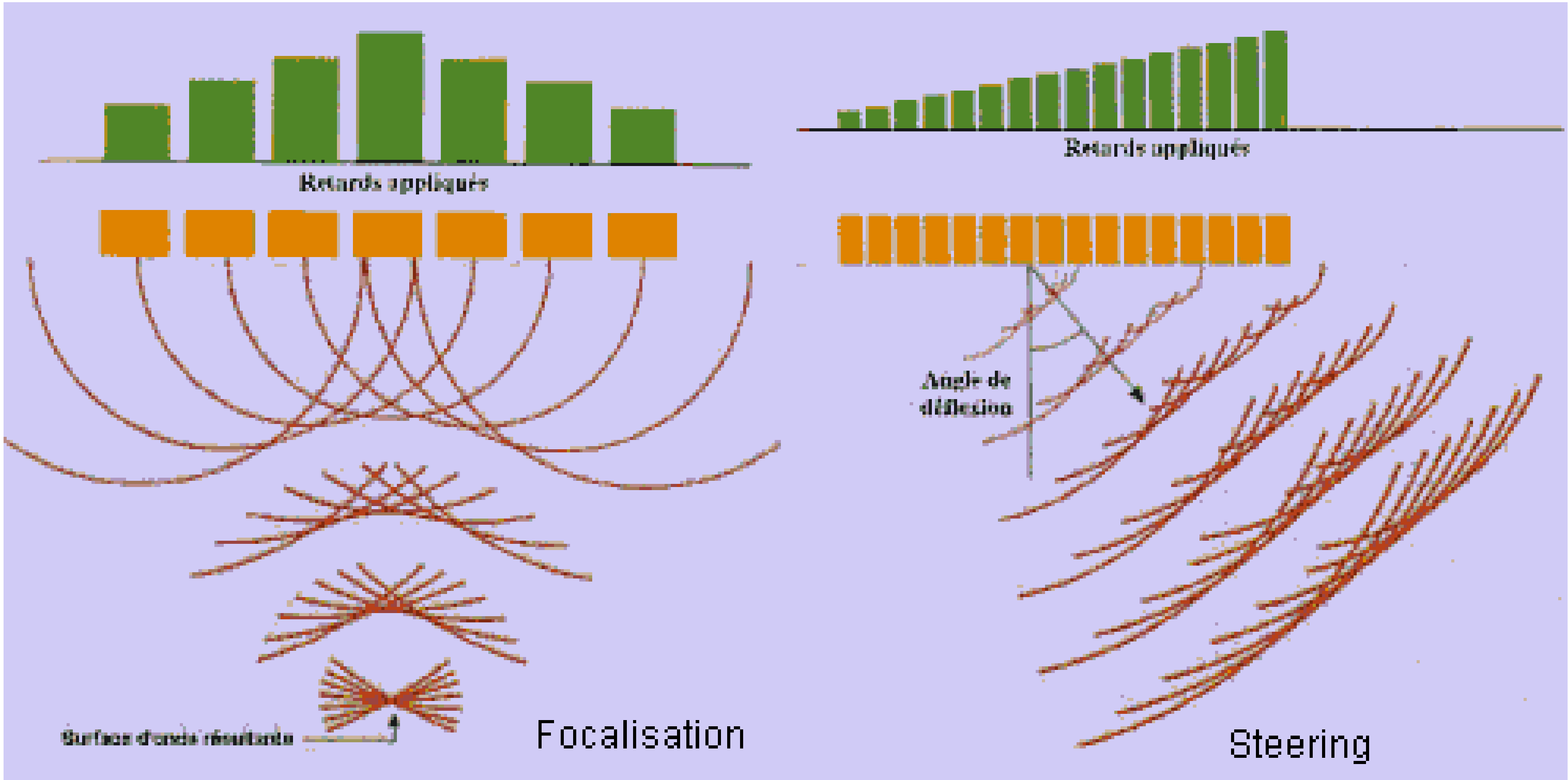
Near field distance
= 2x wavelength

Phased array ultrasonic beams



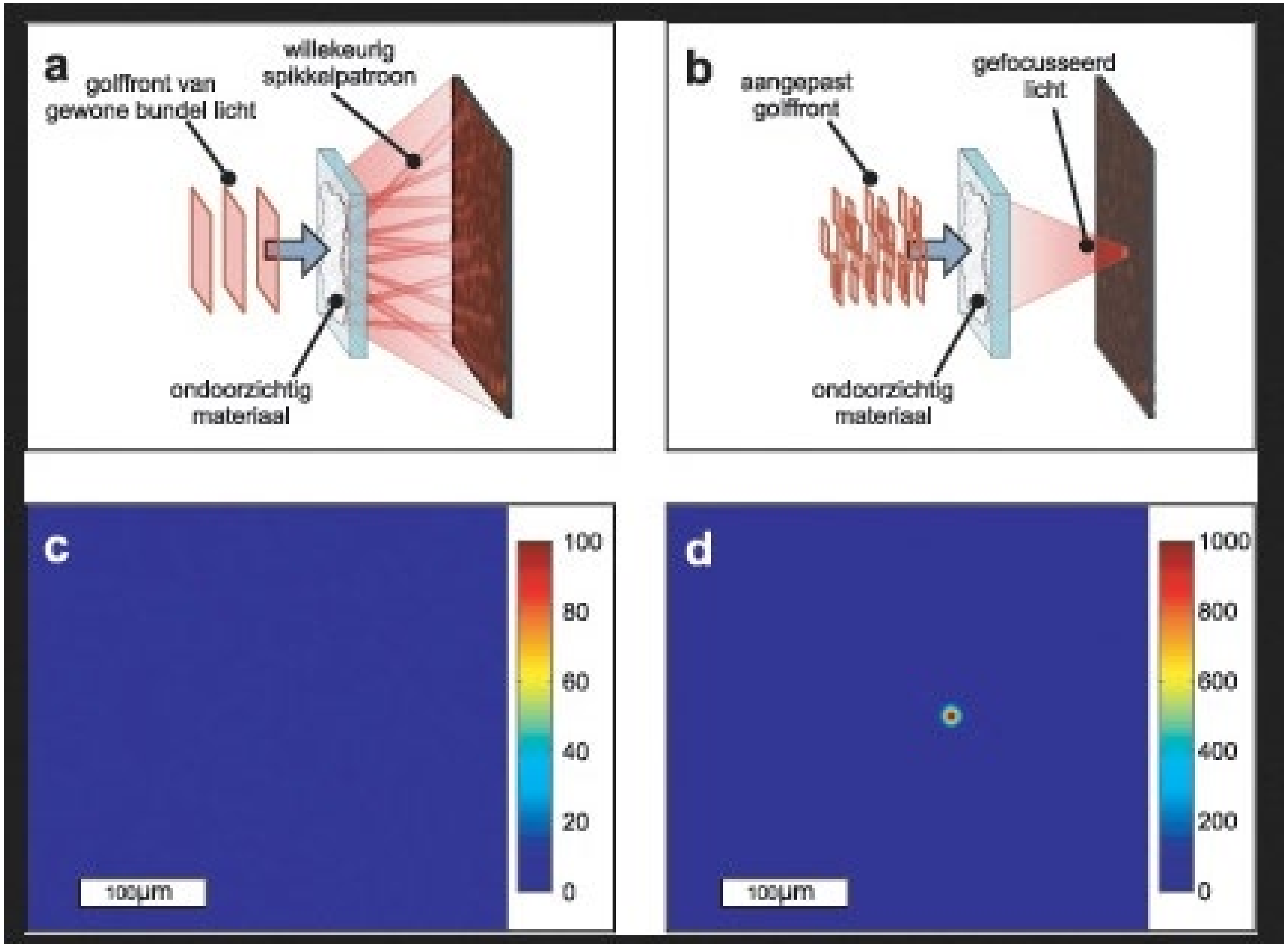
http://sine.ni.com/cs/app/doc/p/id/cs-14014#prettyPhoto[gallery]/0/

Focusing and steering PAUT beams



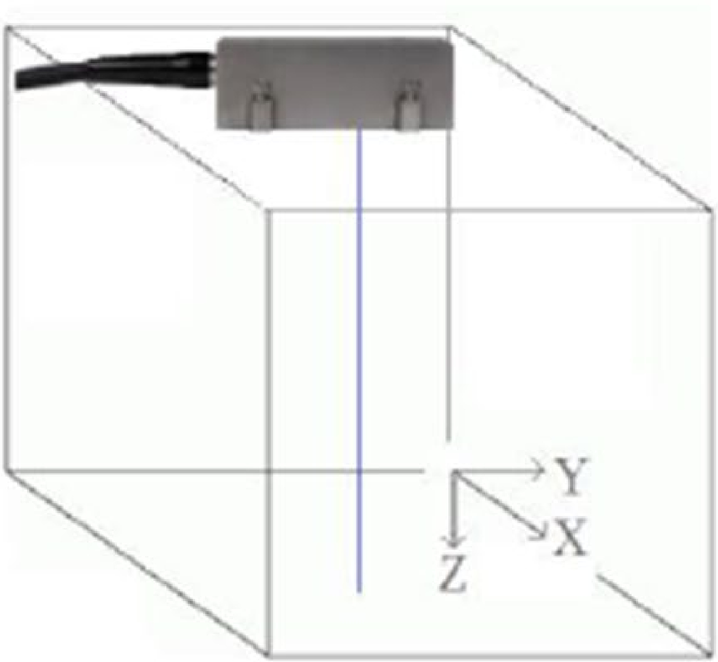
http://www.ndt.net/article/wcndt00/papers/idn009/idn009.htm

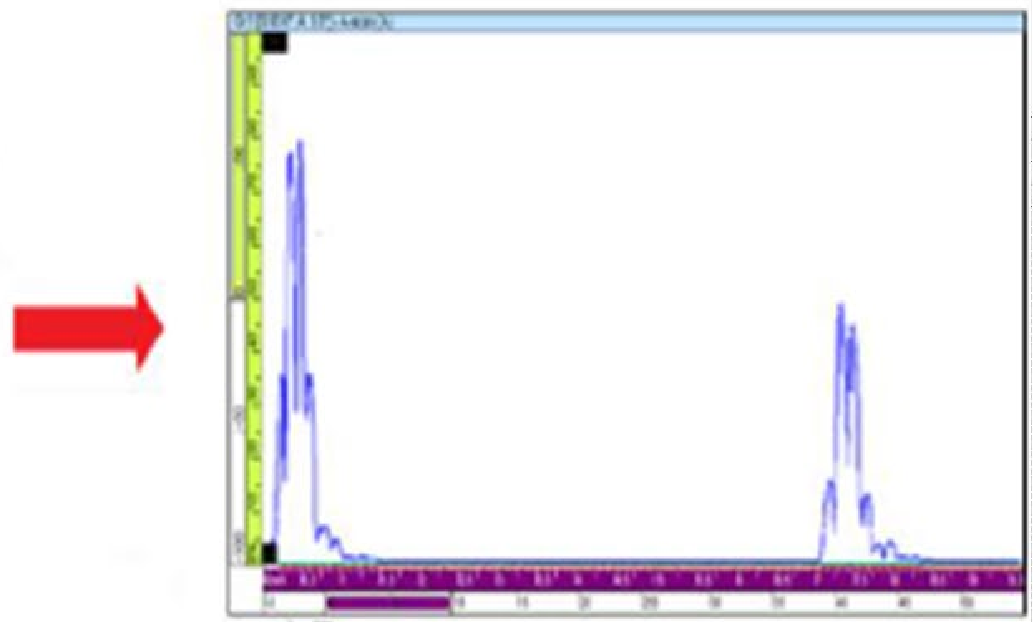
Adapting the waveform for the material under test



http://www.ndt.net/article/wcndt00/papers/idn009/idn009.htm

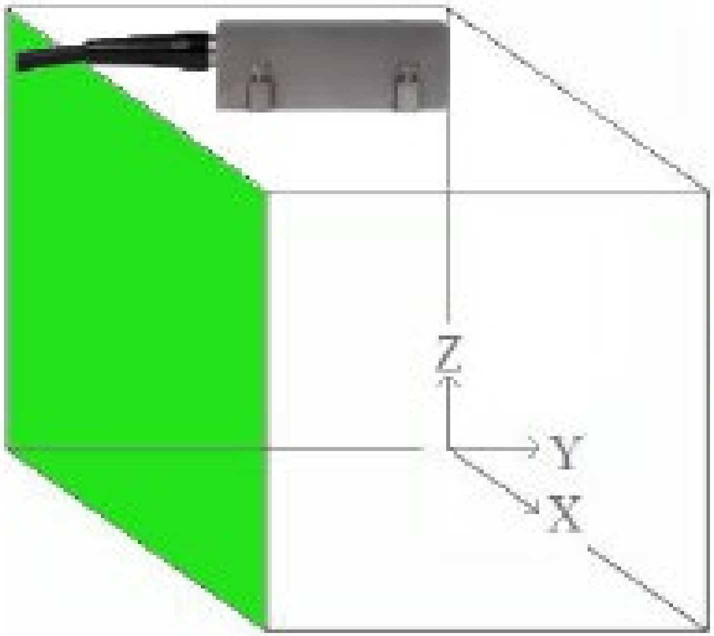
A-Scan

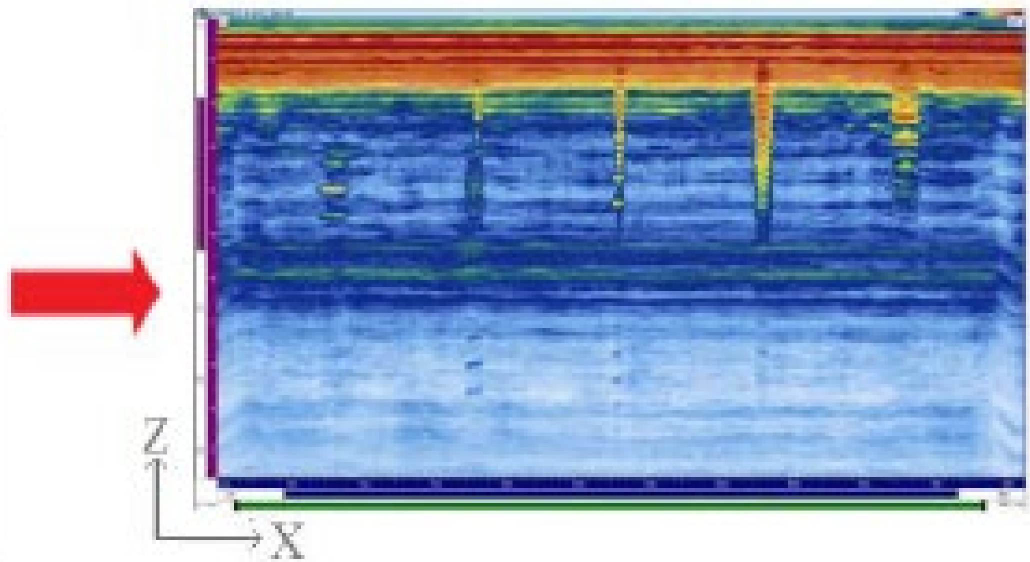




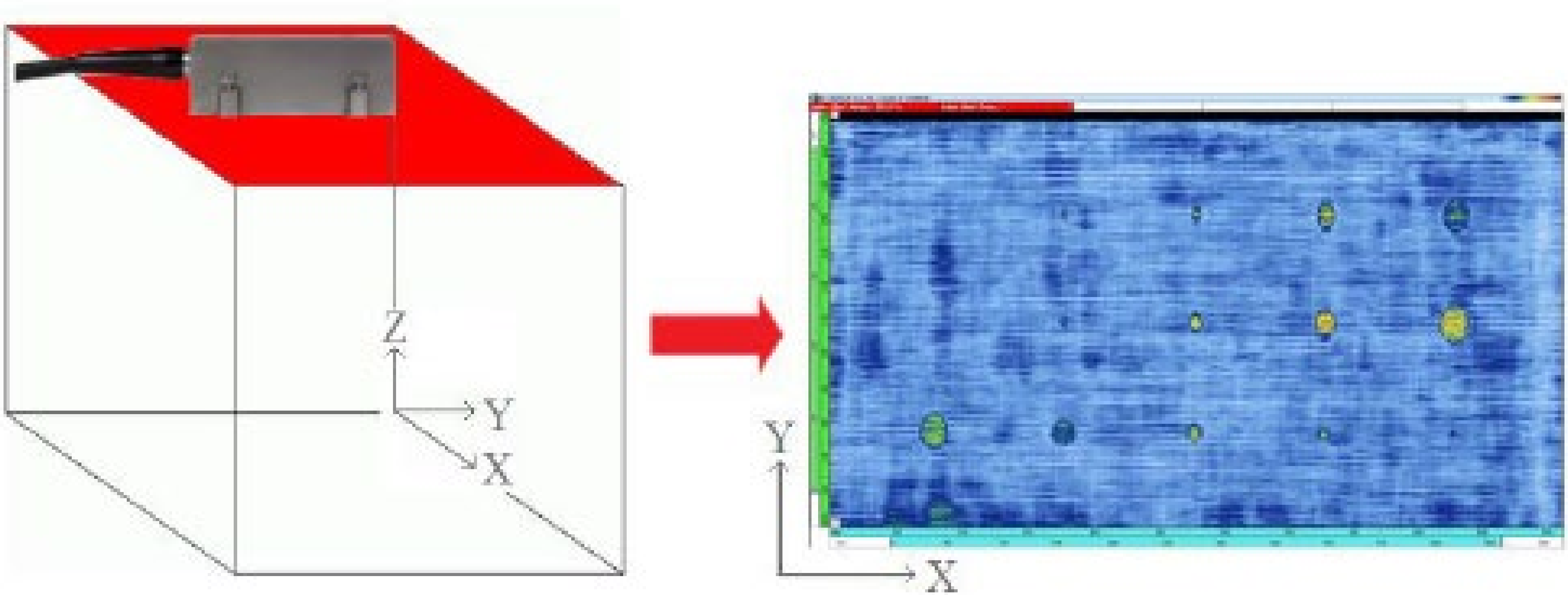
R. Groves, *AE4ASM108, experimental & NDT techniques* ,2015,

B-Scan

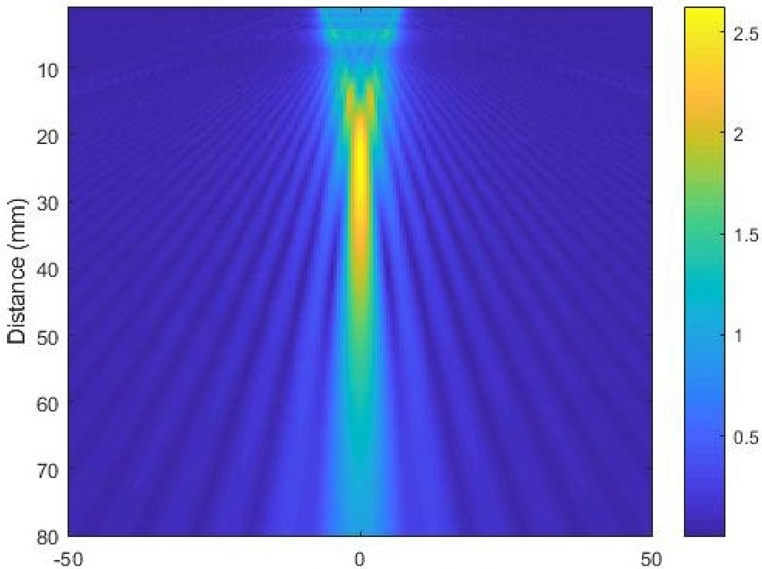




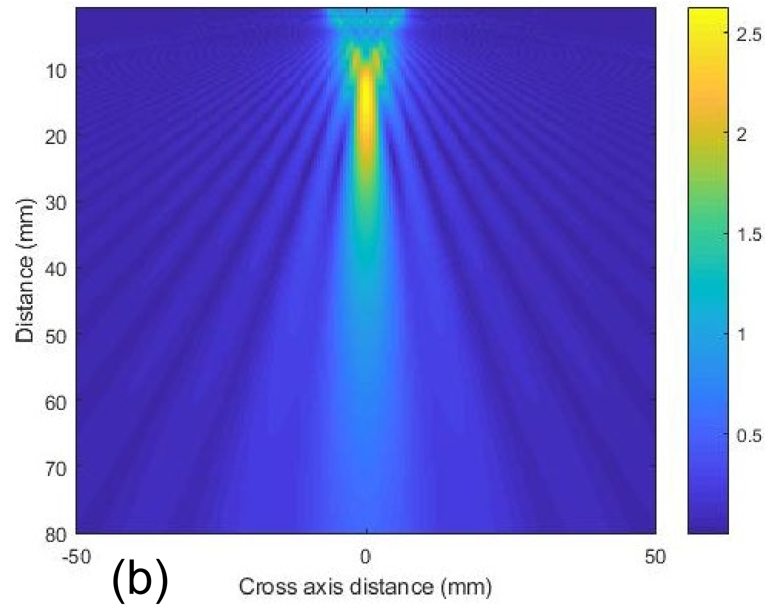
C-Scan



Beam focusing in anisotropic materials

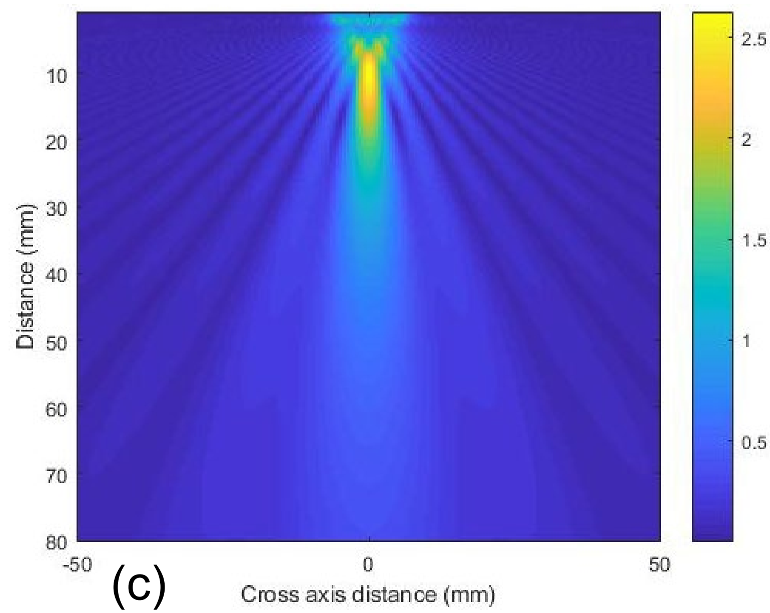


(a)



(b)

Beam field: (a) C = E = 0, (b) C = E = −2.5 mm/μs, and (c) C = E = −4.9 mm/μs.



(c)

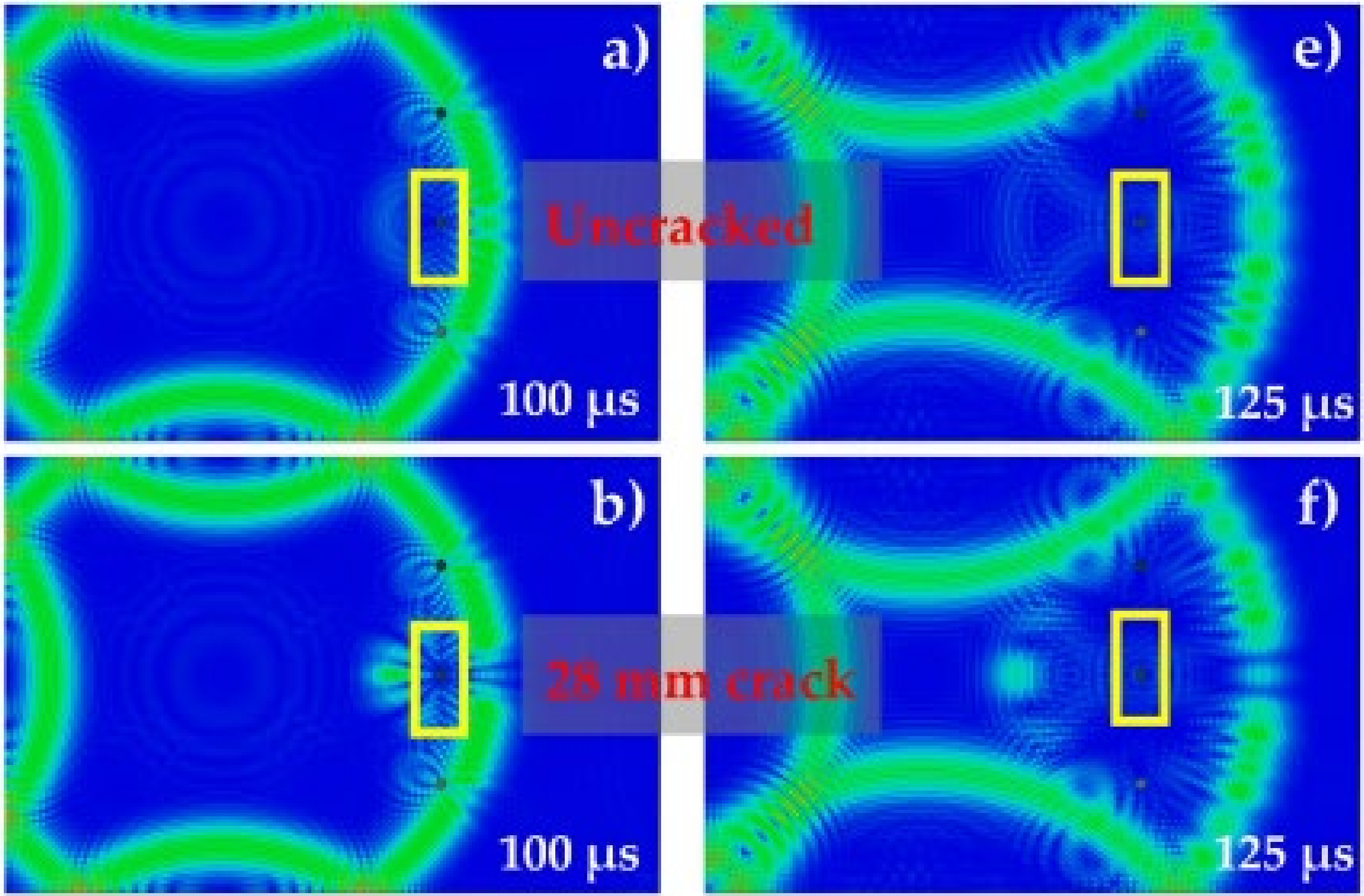
Anand C, Delrue S, Jeong H, Shroff S, Groves RM, Benedictus R. Simulation of Ultrasonic Beam Propagation from Phased Arrays in Anisotropic Media using Linearly Phased Multi Gaussian beams. IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, 67(1), pp. 106 – 116, 2020.

TUDelft Aero NDT

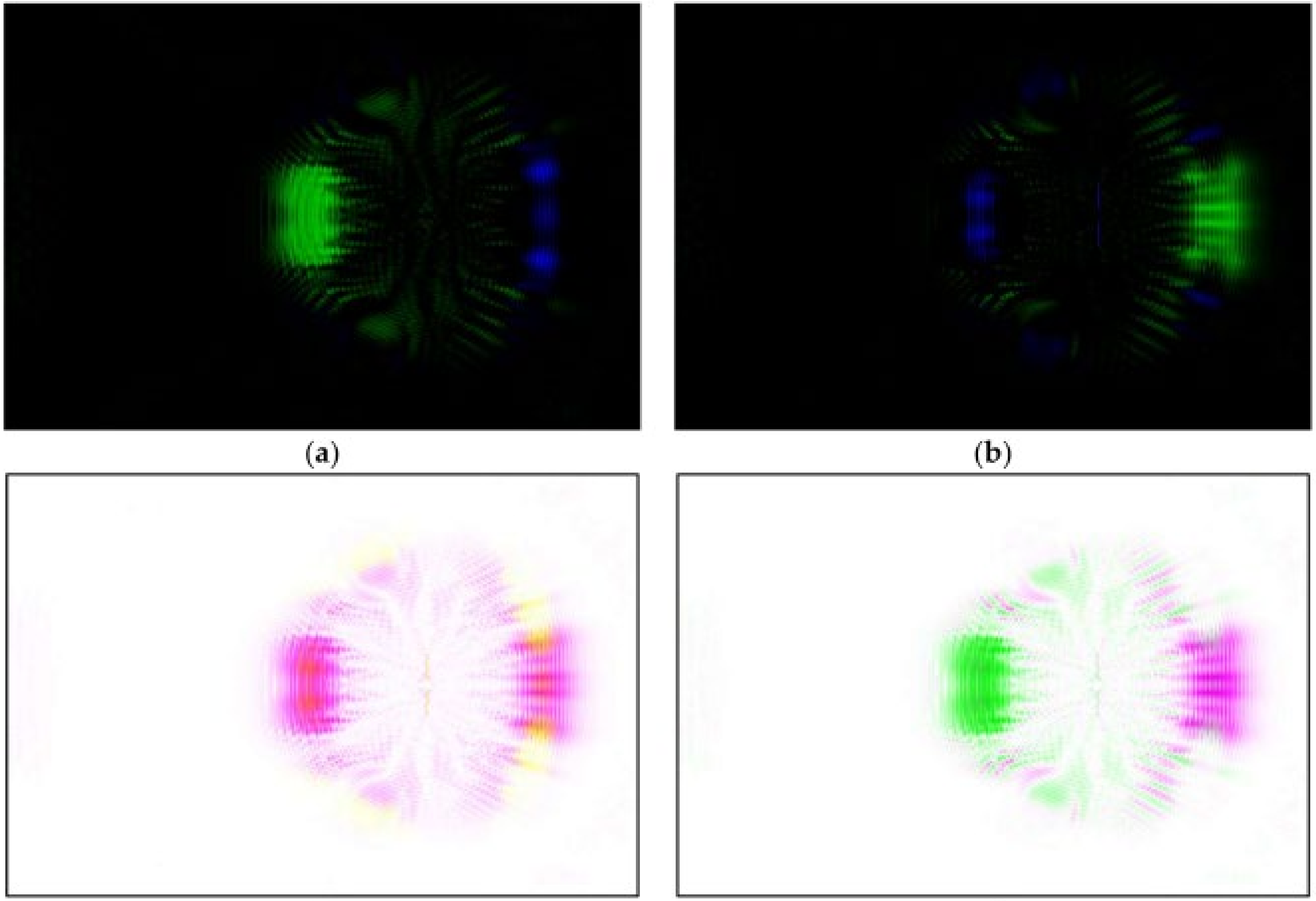
Guided wave ultrasonics for SHM

TU Delft Aero NDT

Guided waves for no defect and 38 mm crack

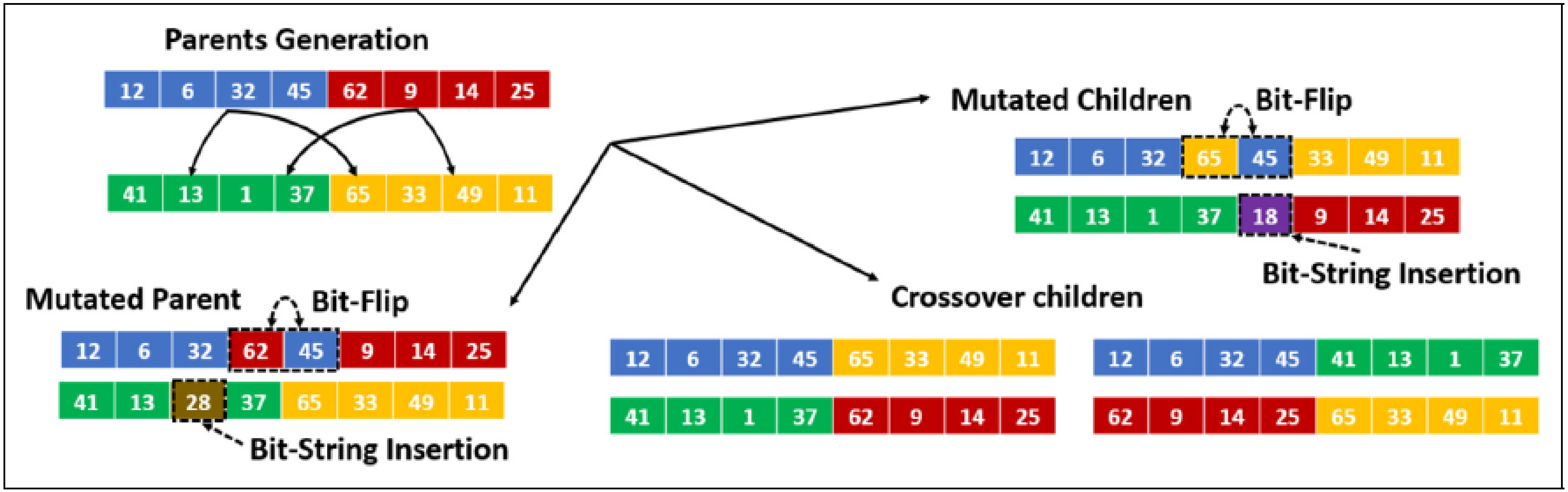


Difference between defect / no defect images



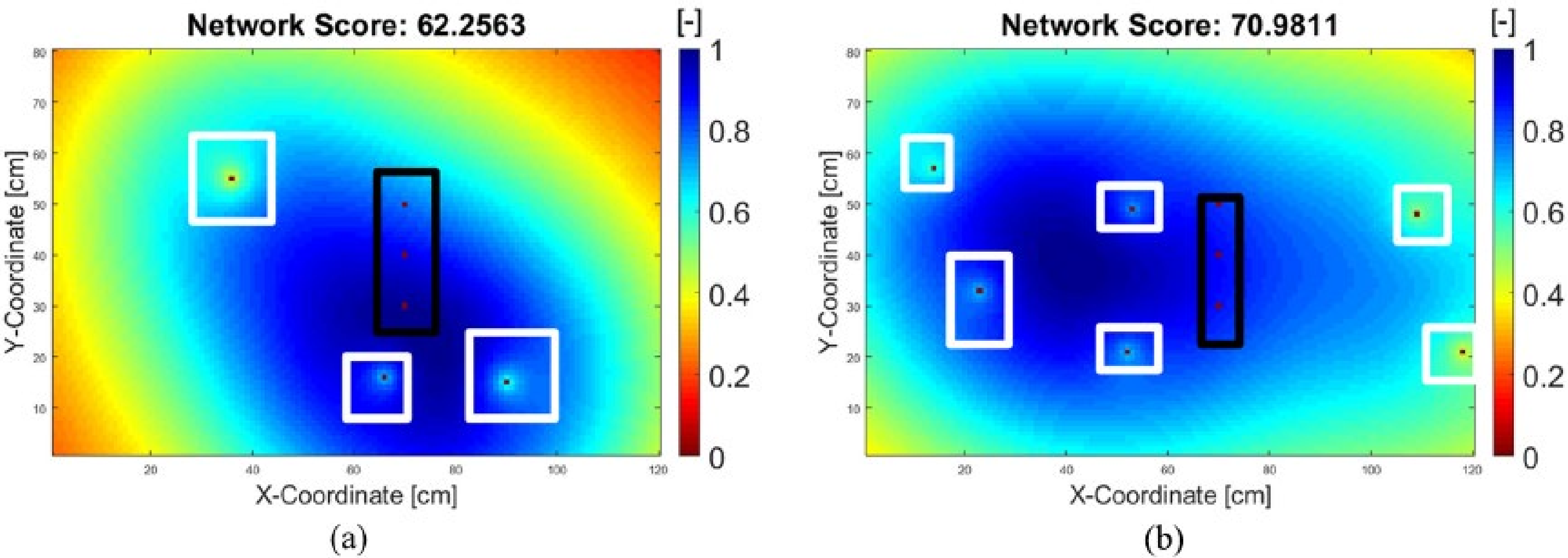
AI Methods

1. Random algorithm
2. Greedy algorithm
3. Genetic algorithm



TU Delft AeroNDT

Network score as a metric



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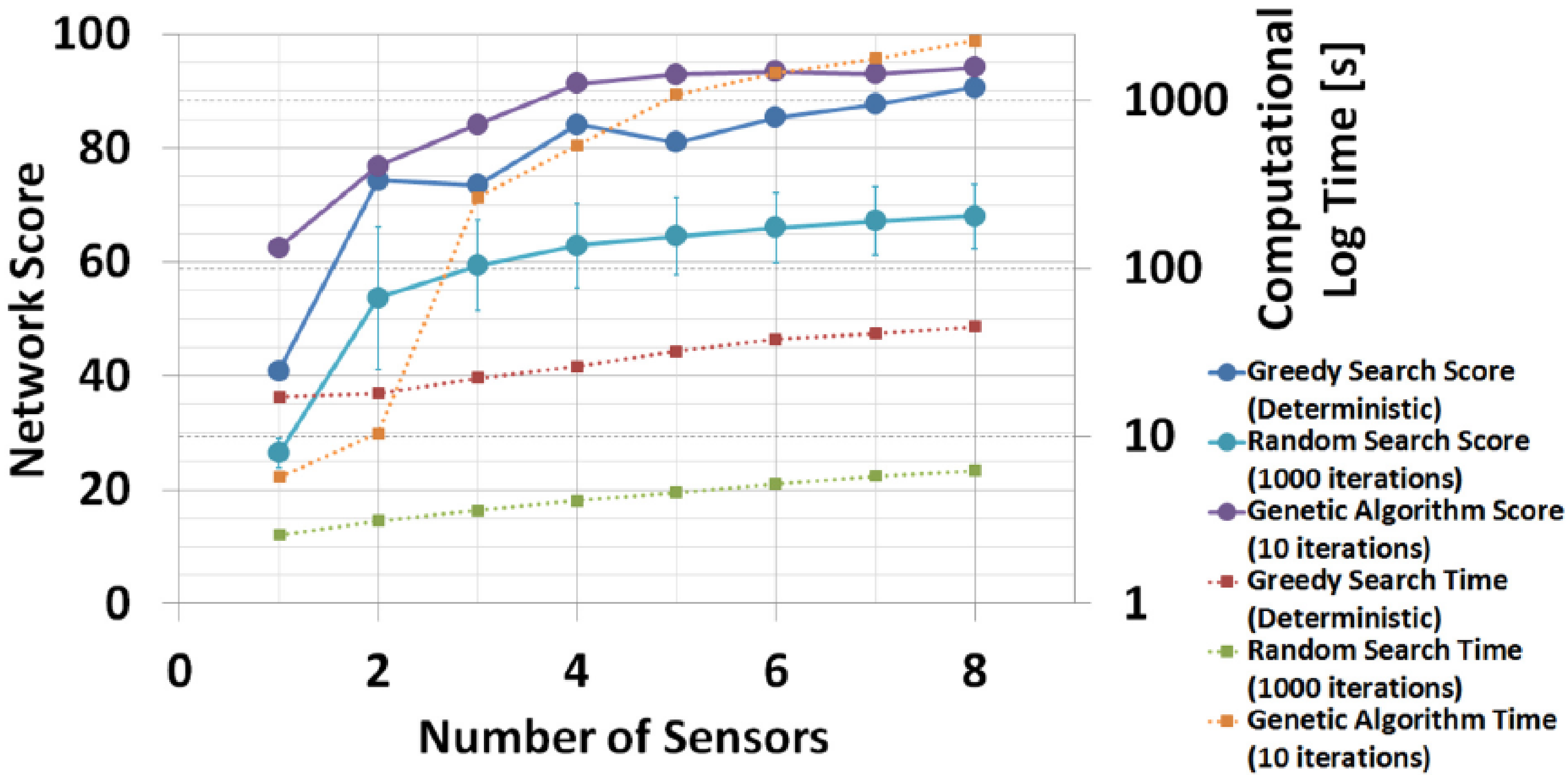
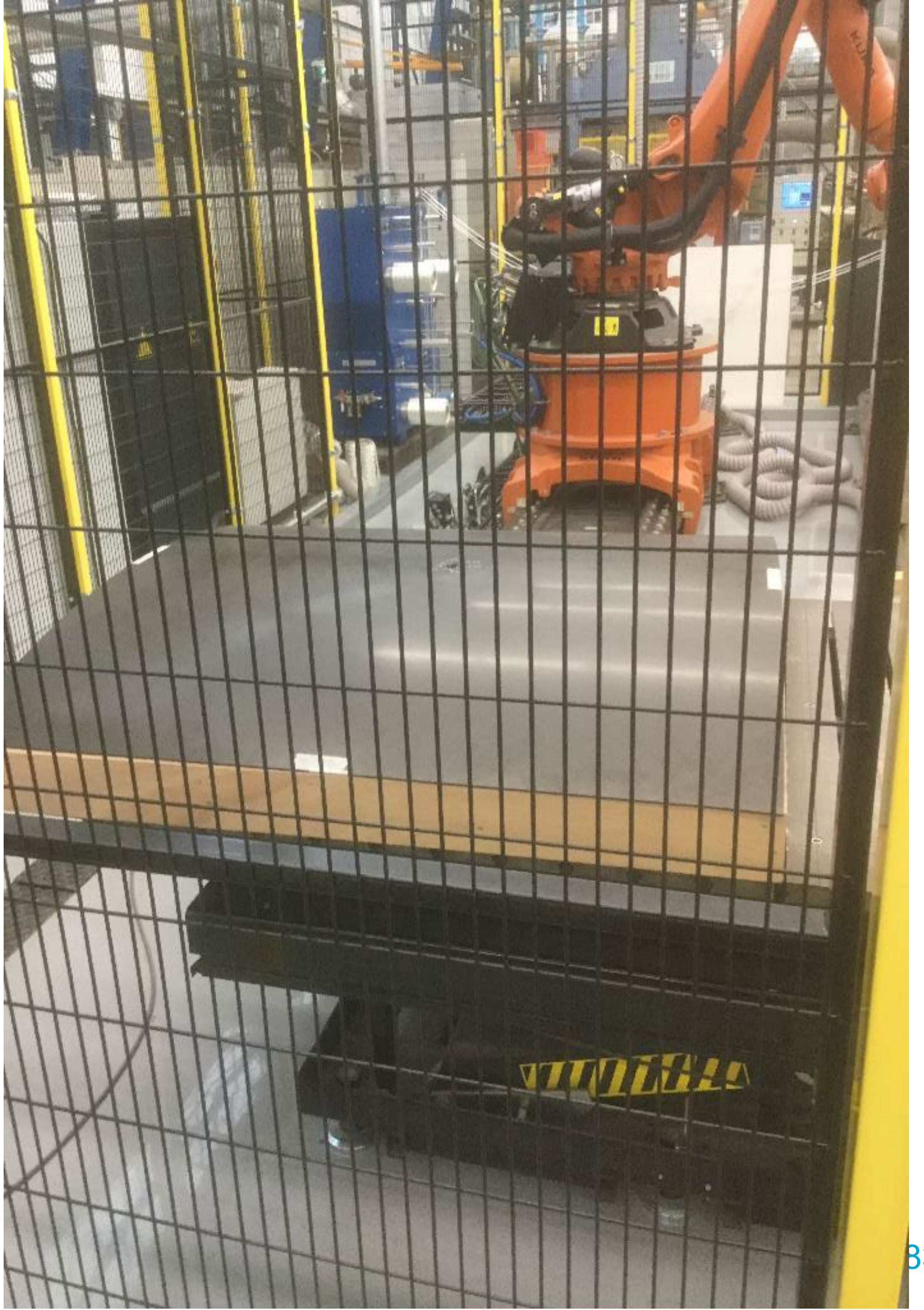
Comparing AI algorithms



Thank you for your attention!



TUDelft AeroNDT