NOVA UNIVERSIDADE NOVA DE LISBOA

NOVA SCHOOL OF SCIENCE & TECHNOLOGY

ACADEMIA NDT INTERNATIONAL

Science, Technology and Diagnostics in Non-Destructive Testing

The essence of NDT: the intelligent use of physical phenomena to save lives

Telmo G. Santos

General Assembly, Budapest, Hungary, 15-17.10.2022

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FCT NOVA Location

UNIVERSIDADE NOVA DE LISBOA

THE UNIVERSITY

9 Schools

DEGREE PROGRAMMES

28 Bachelor

12 Integrated Masters

103 Masters

84 Doctorate

RESEARCH

40 Research Units

ACADEMIC AND RESEARCH STAFF

2 355 Faculty and Researchers

Top 8 of young universities in Europe in Engineering & Technology

NOVA
UNIVERSIDADE NOVA DE LISBOA

Research & Innovation Oriented School

NOVA
NOVA SCHOOL OF SCIENCE & TECHNOLOGY

NDT Lab at FCT NOVA

Facilities for Non-Destructive Testing

Main NDT methods:

- Visual Inspection (endoscopy, digital microscopy);
- Dye penetrant / Magnetic particles
- Thermography
- **Electromagnetic Methods (Eddy currents, others)**
- Ultrasound (Conventional and Air-coupled)
- Low intensity digital X-ray
- Terahertz
- Other customized NDT techniques
- NDT innovations based on bacterial cells
- Homemade equipment & Other commercial equipment…

Main Research Areas

https://www.scopus.com/authid/detail.uri?authorId=7004578662

Santos, Telmo Gomes

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Metrics overview

104
Documents by author

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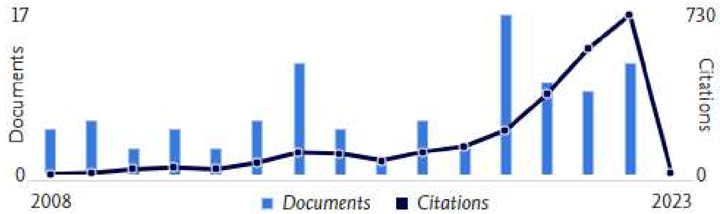
Citations by *1893* documents

26
h-index: View *h*-graph

Document & citation trends



Analyze author output | Citation overview

Most contributed Topics 2017–2021

Microstructure; Titanium Alloy (TiAl6V4); Inconel (Trademark)
8 documents

Gas Metal Arc Welding; 3D Printers; Wire
6 documents

Eddy Current Testing; Nondestructive Methods; Defects
4 documents

View all Topics

104 Documents | Cited by 1893 Documents | 2 Preprints | 144 Co-Authors | 23 Topics | 0 Awarded Grants (Beta)

Looking at the history of NDT…

Since 1940´s: No new NDT methods, from the ***physical phenomena*** point of view…

PAST / TODAY NDT NEEDS

Railway * Big Casting * Welds * Aircraft´s Fuselage…

EMERGING **NDT NEEDS**

New materials, manufacturing, products

Requiring: new and different NDT methods.

1850´s — **Capillary action** (dye penetrant)

1860´s — **Magnetic field** (magnetic-particle)

1920´s — **Electromagnetic Radiation** (x-ray, micro waves, IR, THz)

1930´s — **Mechanical vibration** (ultrasound, PA, laser US)

1940´s — **Electromagnetic induction** (eddy currents)

Bacteria

New physical phenomena for NDT?

2020´s — **Biologic phenomena?**

Hypothesis: Can we use non pathogenic bacteria as a defect detector?

Note 1: The dates presented refer to the industrial implementation of the NDT and not to the discovery of the physical phenomena.

Note 2: Physical phenomena are the target, but not NDT techniques (eg. microwave and thermography NDT are considered in Electromagnetic Radiation phenomena).

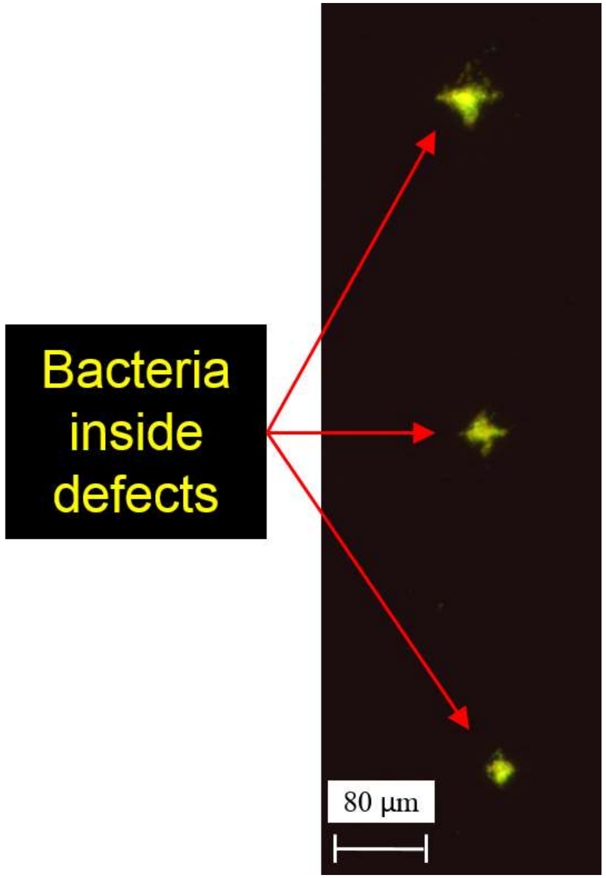
Why using bacterial cells?

Bacterial cells preferentially adhere to surface irregularities, such as: roughness, cracks and voids.

Can it allowing the identification of these defects?

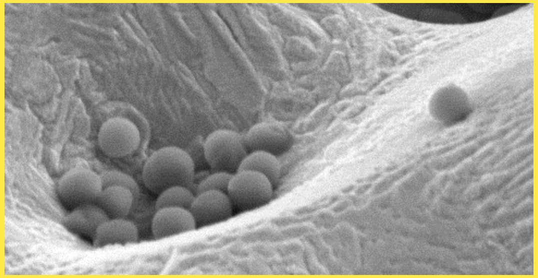
The mais Idea is to explore the:
- *Live* attributes;
- Natural *intentionality*

i) small dimension (< 1 μm)
ii) high penetration capacity (due biosurfactants)
iii) motility (flagella, gliding…)
iv) adherence
v) reproducibility and death
vi) fluorescence
vii) endothermic /exothermic
viii) susceptibility to electric and magnetic fields.



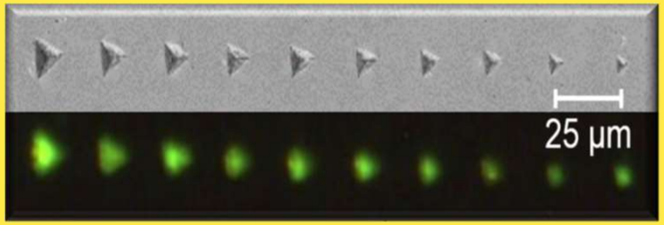
PROOF OF CONCEPT

1. DEFECT AFFINITY



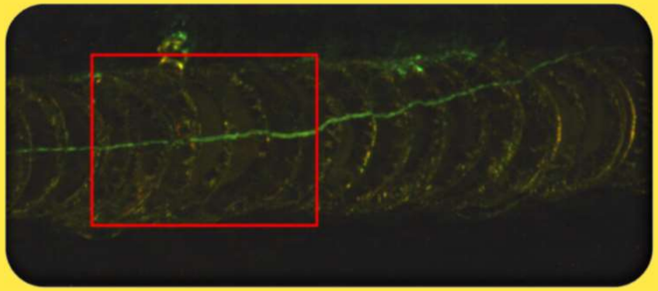
2. DEFECT DETECTION

Artificial



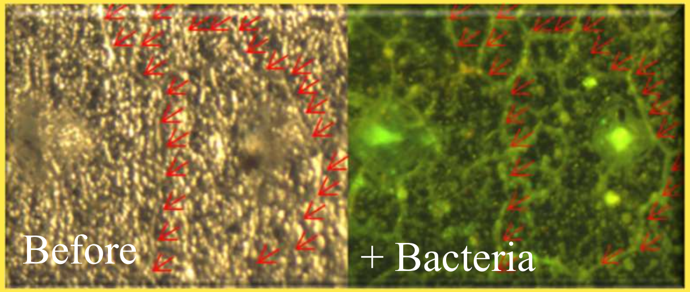
Bacteria in nano indentations

Real

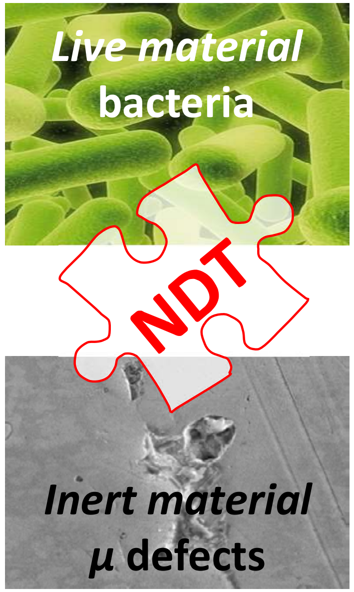


laser weld in NiTi

3. REVEALING SURFACE MORPHOLOGY



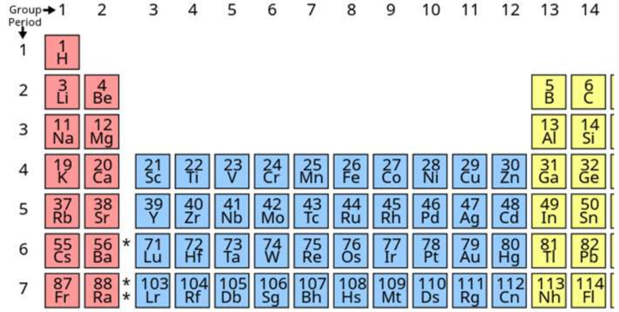
Anodized pattern in aluminium



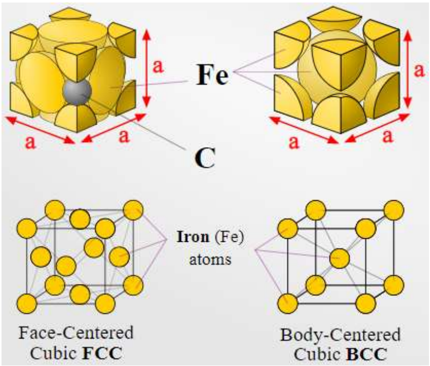
Main Idea: link ***live*** and ***inert material*** in NDT

4 main factors governing the technique

The compatibility, the interaction and the adhesion mechanisms between materials and bacteria are interesting, complex and interdependent of multi factors:



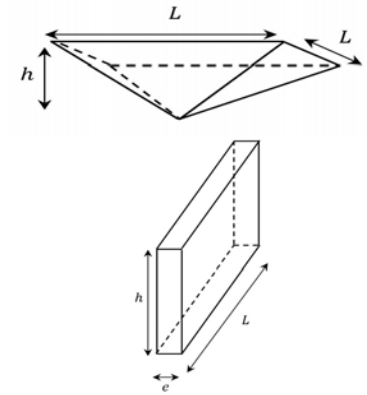
Chemical composition of the surfaces



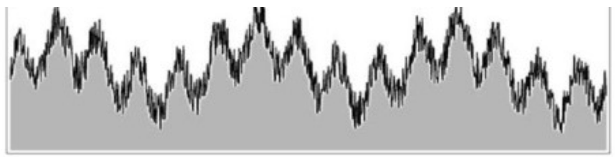
Crystalline structures of existing phases

Interaction mechanisms between <u>bacteria</u> and <u>materials</u>

Defects geometry



Surface Topography



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Scientific Aspects Detailed

NDT&E International 63 (2014) 43–49

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A new NDT technique based on bacterial cells to detect micro surface defects

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Developments in micro- and nano-defects detection using bacterial cells

Telmo G. Santos[a,*], R.M. Miranda[a], M. Teresa Vieira[b], A. Rita Farinha[b], Telma J. Ferreira[b], Luísa Quintino[c], Pedro Vilaça[d], Carla C.C.R. de Carvalho[e]

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Soldagem & Inspeção. 2015;20(2):253-259 Artigos Convidados

http://dx.doi.org/http://dx.doi.org/10.1590/0104-9224/SI2002.12

Nova Técnica de END Baseada em Células Bacterianas para Detecção de Micro e Nano Defeitos Superficiais

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Resumo: Trabalhos recentes têm demostrado que filmes com células bacterianas (CB) podem ser usados como uma nova técnica de Ensaios Não Destrutivos (END) fiável para a deteção e caracterização de micro e nano defeitos superficiais. As CB podem ser usadas também numa perspetiva de caracterização da textura e topografia de superfícies. Esta nova técnica de END pretende explorar a intencionalidade e os atributos de vida das CB, nomeadamente: a sua reduzida dimensão, elevada capacidade de penetração, mobilidade, aderência, fluorescência,

Weld World

DOI 10.1007/s40194-015-0249-9

RESEARCH PAPER

Surface discontinuity detection using bacterial suspensions

Telmo G. Santos[1] · R. M. Miranda[1] · F. Nascimento[2] · Luísa Quintino[2] · Pedro Vilaça[3] · Carla C. C. R. de Carvalho[4]

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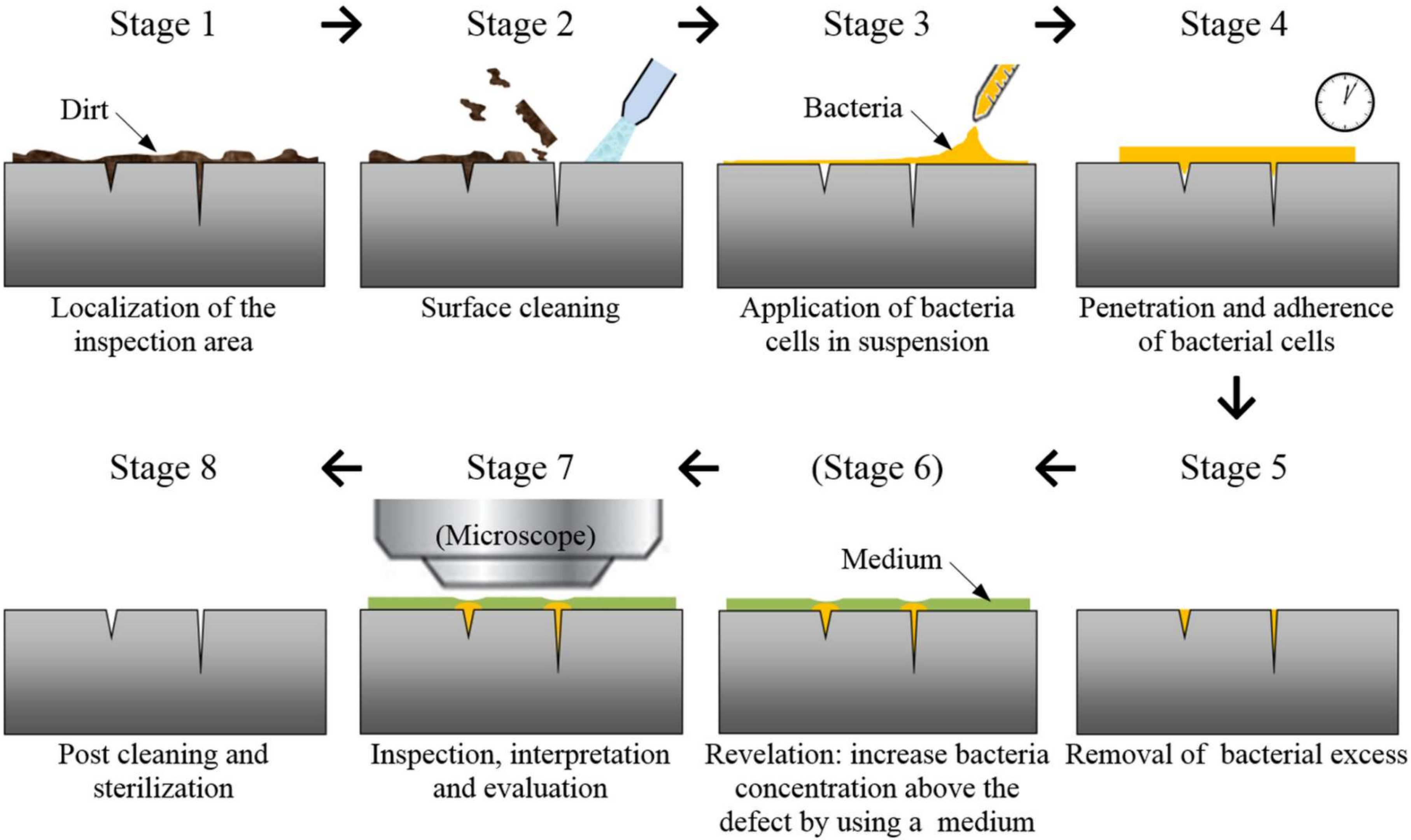
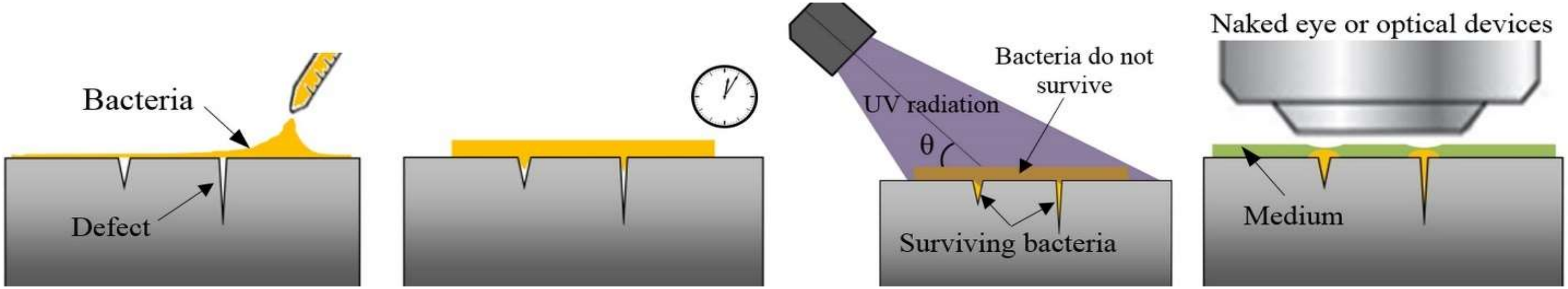
Abstract The main problem when detecting microsurface discontinuities in the microfabrication scale is the poor sensitivity of existing nondestructive testing (NDT). Although advanced techniques to detect microdiscontinuities based on ultrasonic testing (UT) or eddy current testing (ET) methods exist, these are not suitable for microcomponents, since the ... the technique and its application to the detection of discontinuities to different materials.

Keywords (IIW Thesaurus) Surface conditions · Defects · Size · Other NDT methods · Nondestructive testing

Stages: analogy with Dye Penetrant



Set-Up inspection process



deposition

penetration
only 4 min

An electrical or magnetic field can be applied to improve the bacteria mobility and migration into defects.

excess removal
non intrusive

observation

Allowing the visibility by naked eye

- The technique is totally innocuous;
- No biological risks to the operator;
- Only non-pathogenic bacterial are used (Biosafety Level 1);

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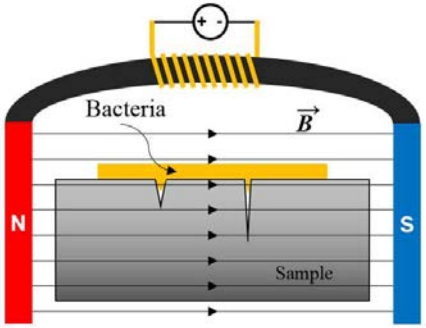
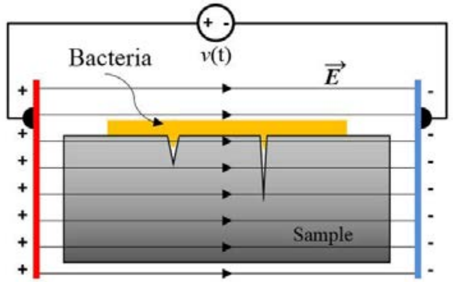
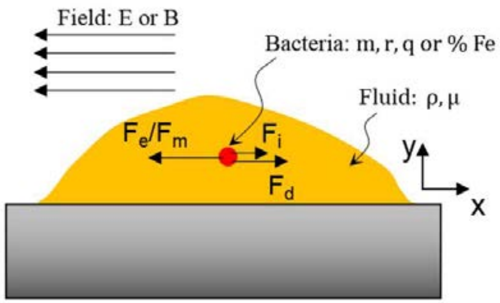
Susceptibility to electric and magnetic fields







Forces:

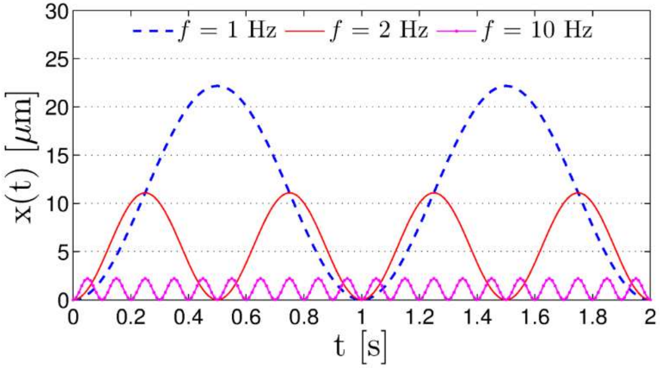
Electric $\vec{F}_e = \vec{E} \cdot q$

Magnetic $\vec{F}_m = \frac{\mu_r V}{\mu_0} \cdot B \cdot \frac{dB}{dx}$

Drag $\vec{F}_d = 6 \cdot \pi \cdot r \cdot \mu \cdot \frac{\partial x}{\partial t}$

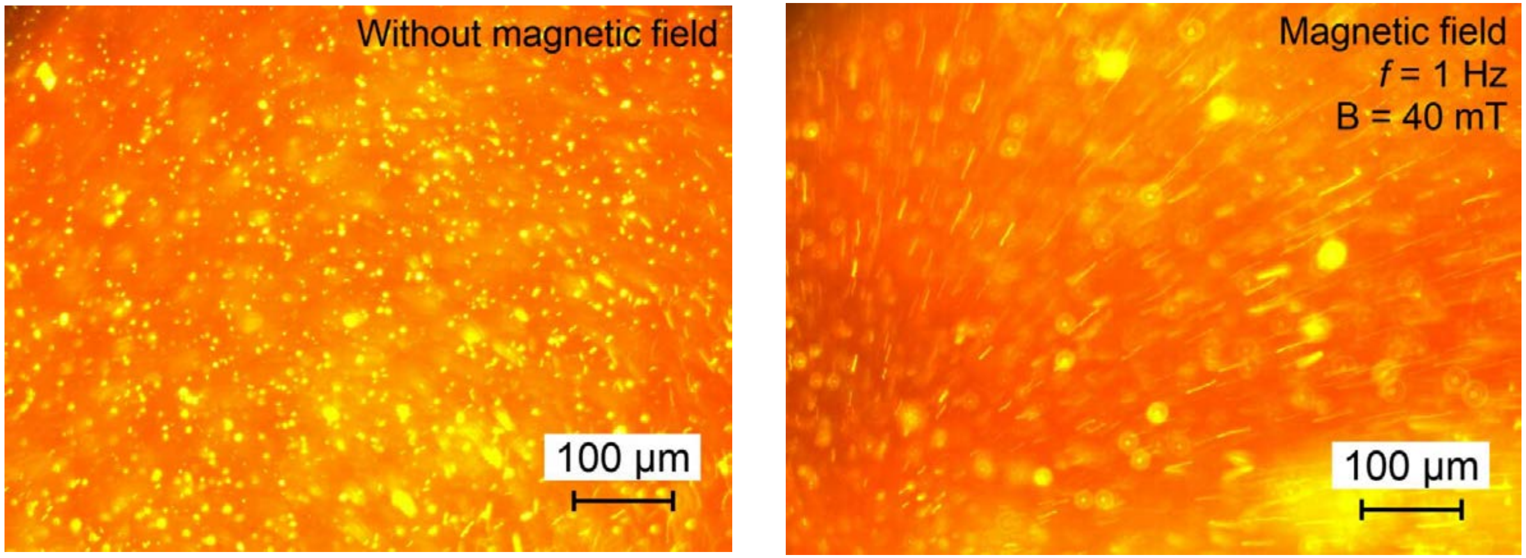
Inertial $\vec{F}_i = m \cdot \frac{\partial^2 x}{\partial t^2}$

$$m \cdot \frac{\partial^2 x}{\partial t^2} + c \cdot \frac{\partial x}{\partial t} = F \cdot \sin(\omega t)$$



$$x(t) \approx \frac{F \cdot (1 - \cos(\omega t))}{c \cdot \omega}$$

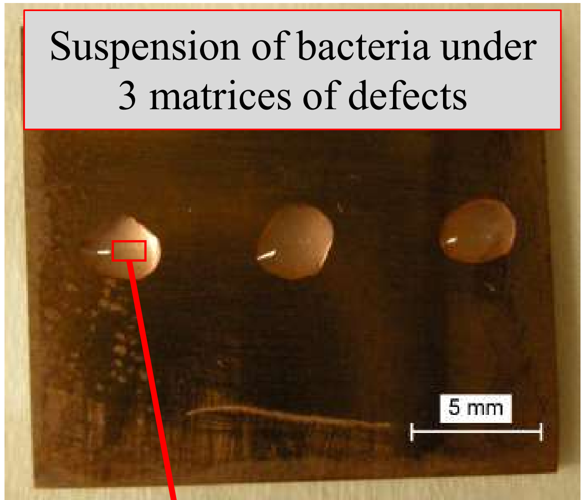
Susceptibility to electric and magnetic fields

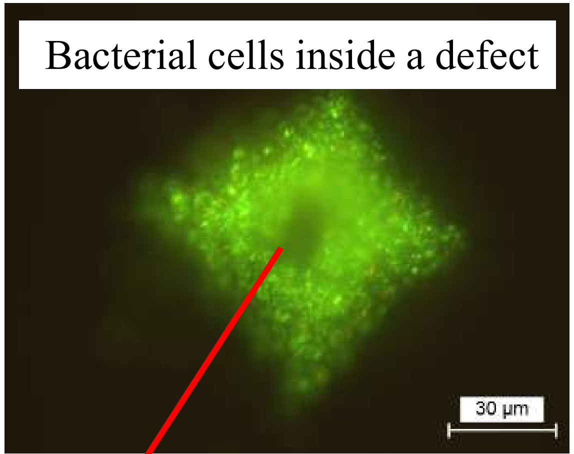


Effect of a magnetic field on *S. aureus* cells movement.
The cells were observed during an exposure time of 10 s at a magnification of 150x, in the absence (a) and in the presence (b) of a alternating magnetic flux density with a frequency of 1 Hz and an amplitude B = 40 mT.

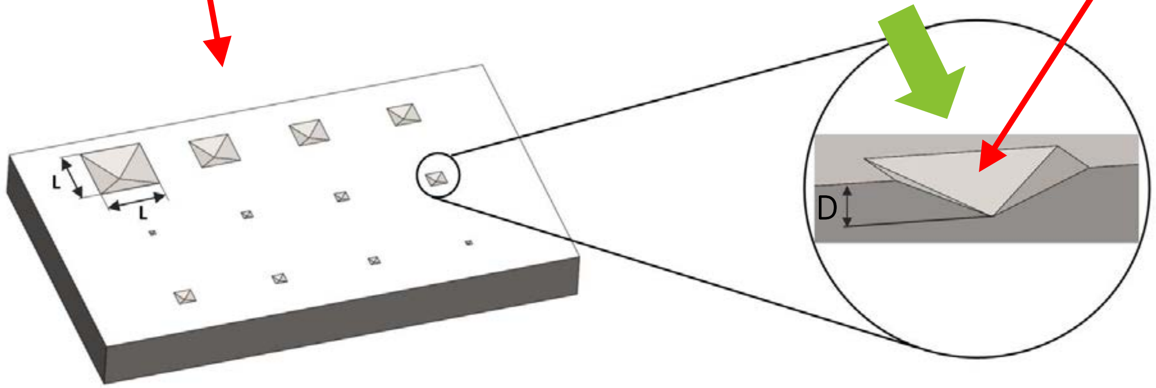
Experimental Results

Micro surface defects were produced using a micro hardness indenter with a Vickers pyramid.





Morphology of the artificial defects



Bacterial cells used:

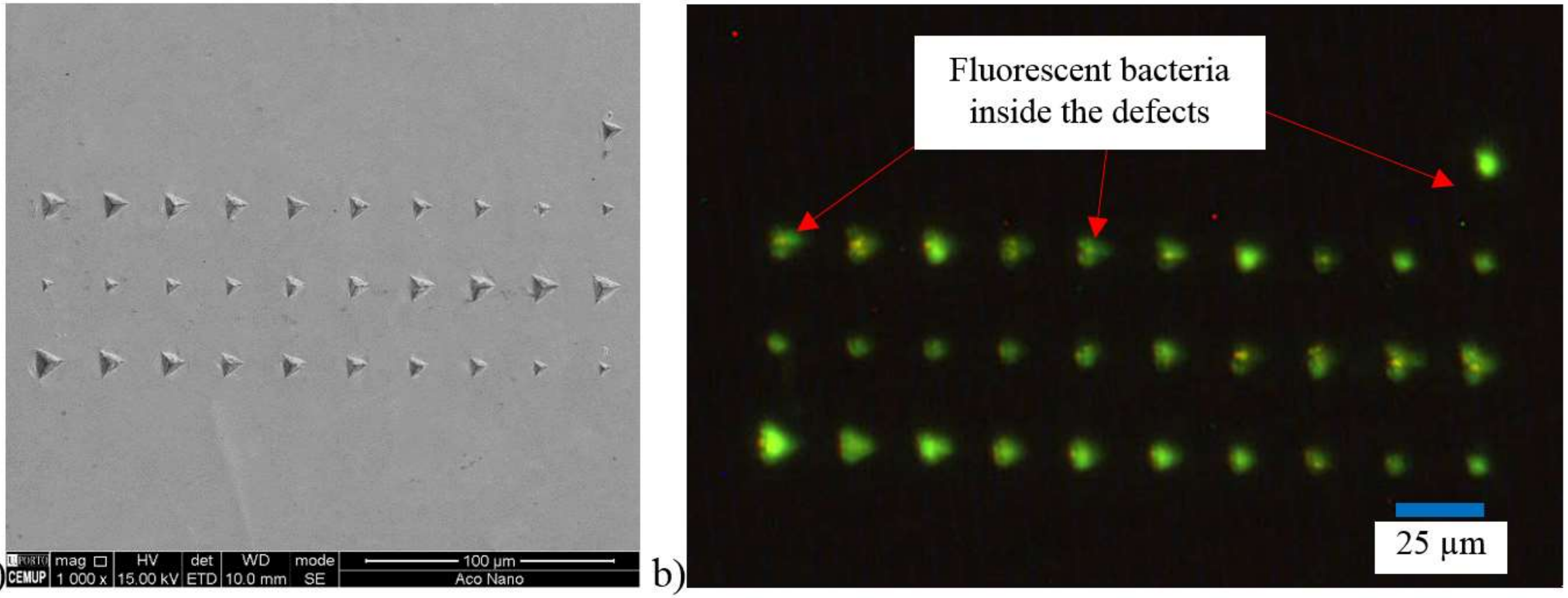
- *Rhodococcus erythropolis* (0.92 µm long)
- *Staphylococcus aureus*
- *Staphylococcus hominis*

Depth of defects produced with different loads in the materials under test.

Defect reference	Load (N)	Defect depth (*d*) and side length (*L*): [*d*/*L*] (µm)		
		Aluminium	Steel	Copper
A	100	25.5/126.0	19.5/96.5	21.0/103.9
B	50	18.7/92.5	13.9/68.9	15.0/74.0
C	30	14.4/71.1	10.5/52.0	11.6/57.3
D	20	11.5/56.9	8.5/41.9	9.5/47.1
E	10	7.9/39.1	5.9/29.3	6.8/33.4
F	5	5.7/28.2	4.1/20.1	5.0/24.6
G	2.5	4.3/21.3	2.9/14.4	3.5/17.3
H	1.0	2.6/12.7	1.8/8.7	2.0/9.7

Experimental Results

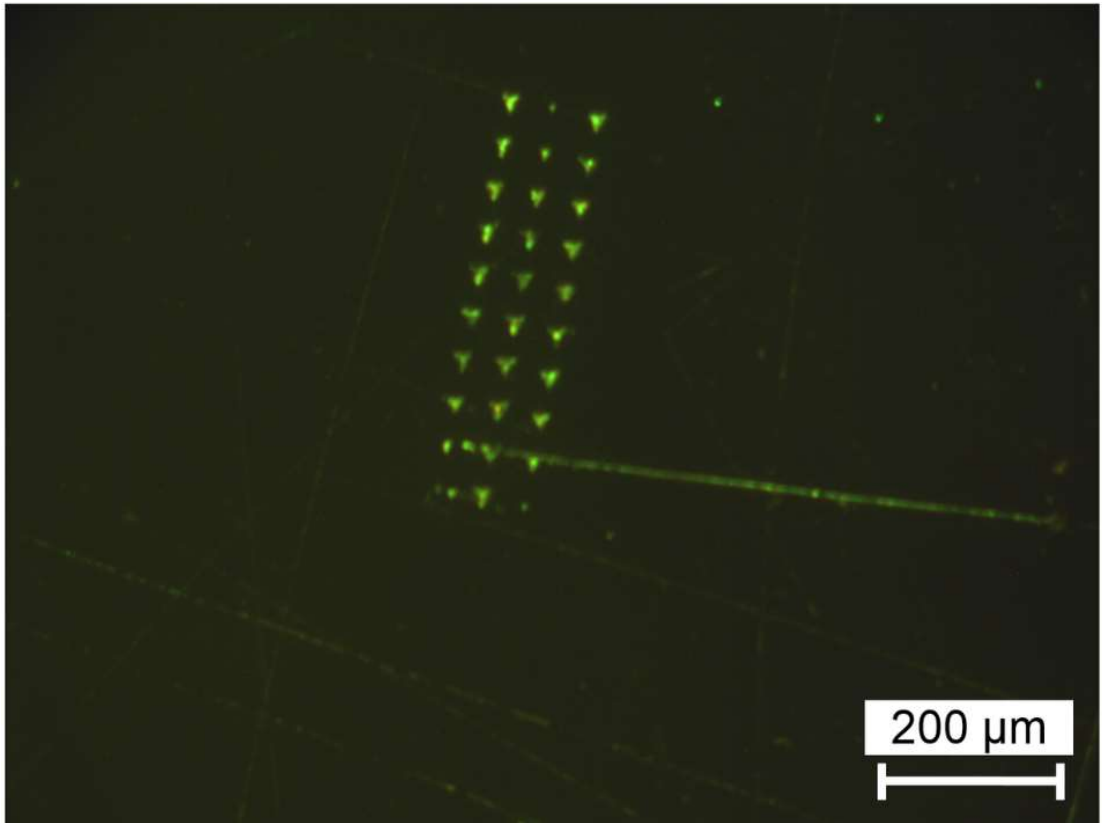
Nano Indentations



a) b)

Matrix of nano indentations produced in AISI 316L observed under SEM (a) and optical microscopy after testing with *R. erythropolis* without magnetic fields (b).

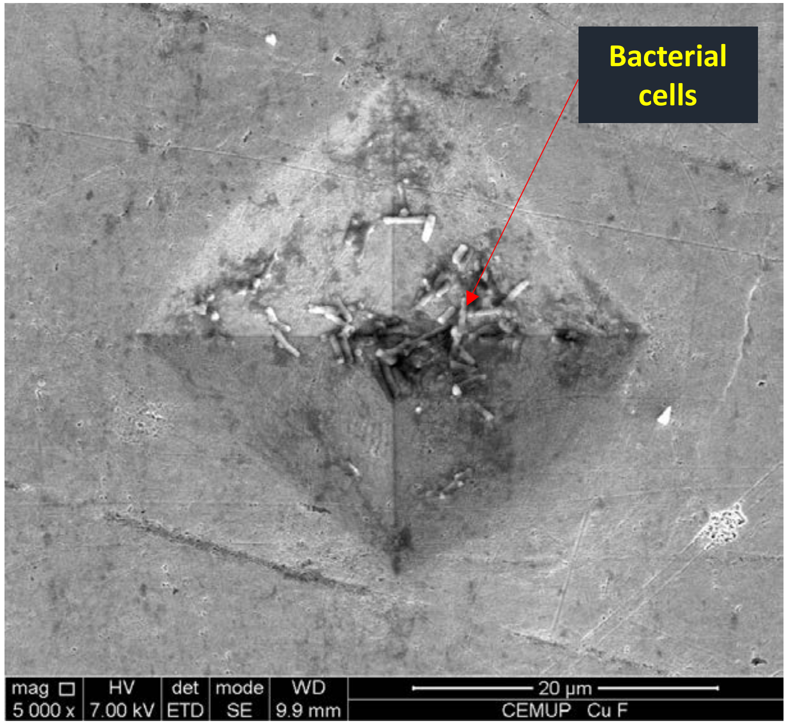
The side length range was 12–5.3 µm and the depth was 1.4–0.6 µm.



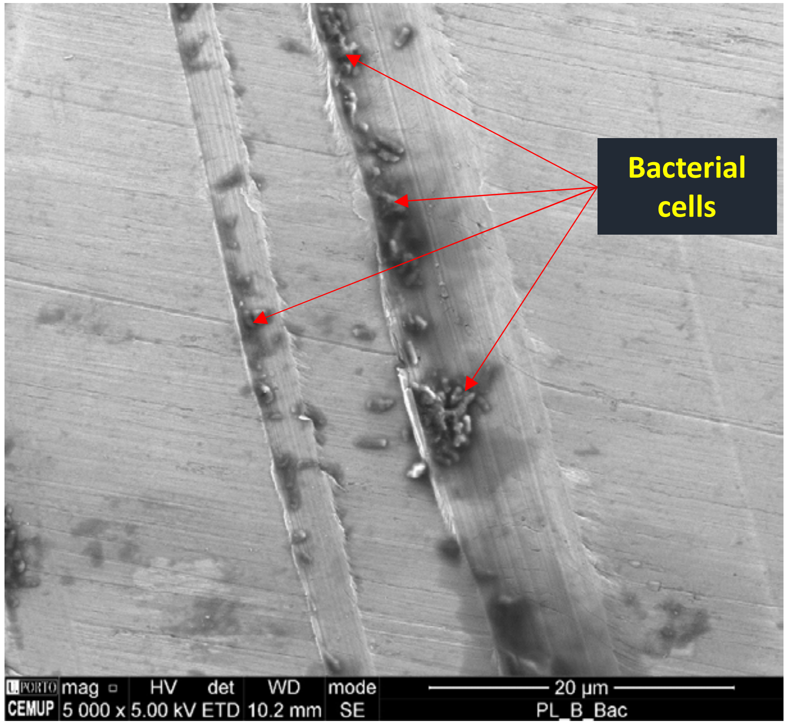
Berkovich nano indentations in 24 kt Gold inspected with *Rhodococcus erythropolis*.

Experimental Results

Scanning electron microscope (SEM) images of the bacteria inside a defect.



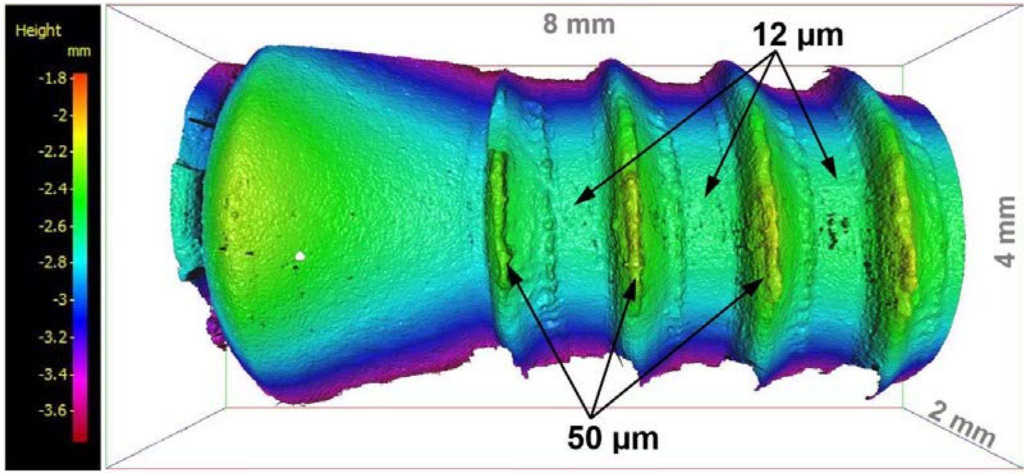
Defect: Vickers pyramidal indentation

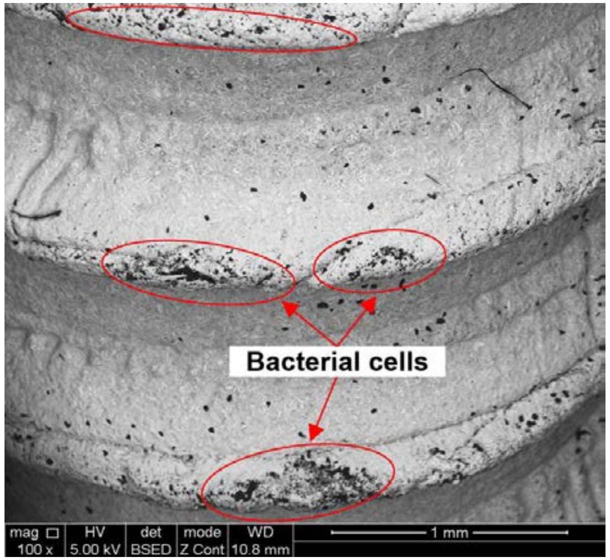


Defect: Groove

Micro manufactured components
(Metallic screw obtained by µPIM)

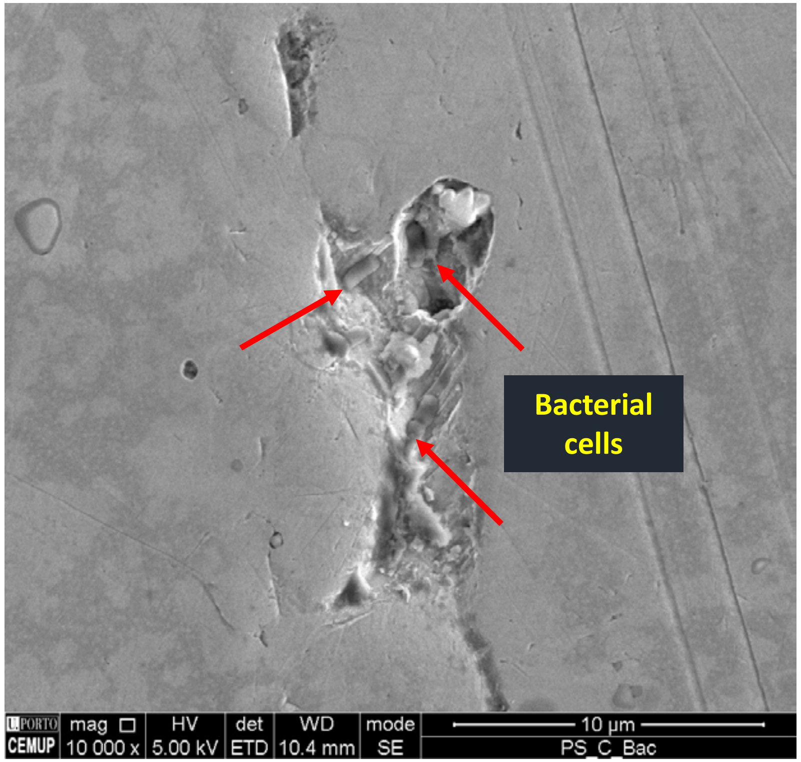
Height profile

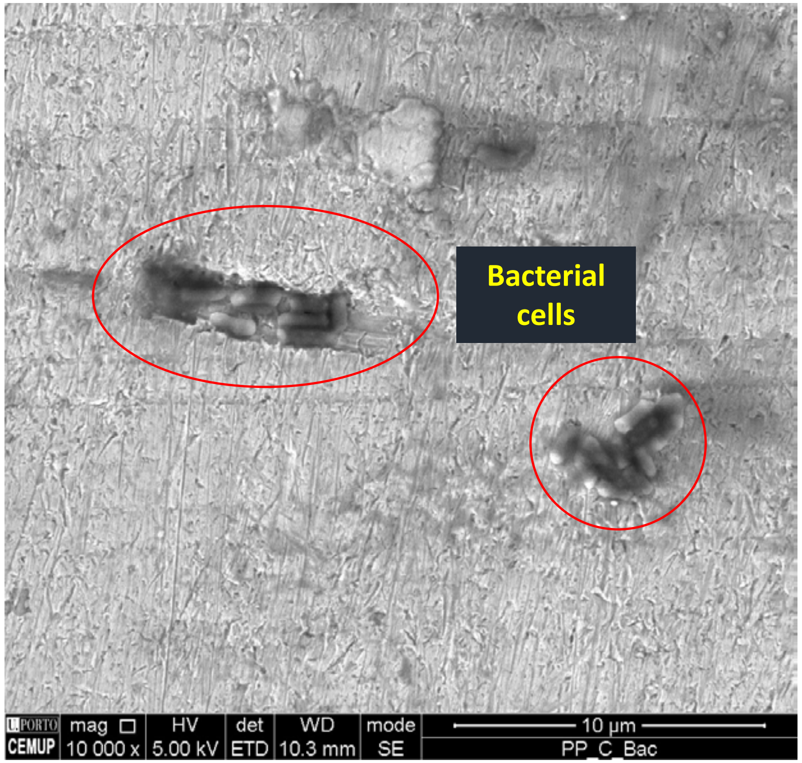




SEM micrograph highlighting bacteria on the external thread crest.

Scanning electron microscope (SEM) images of the bacteria inside a defect.

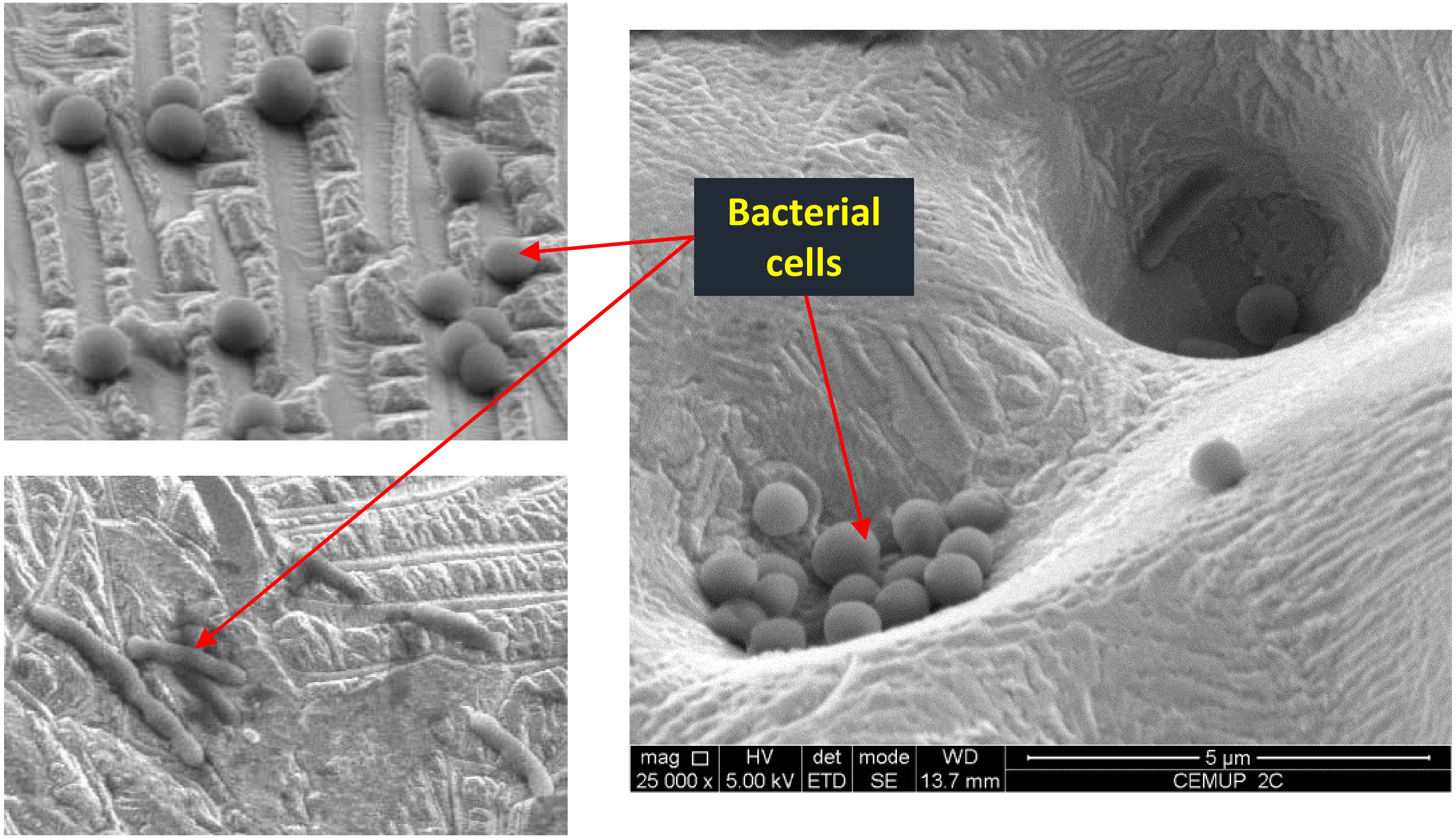




Real defect: Micro manufactured components

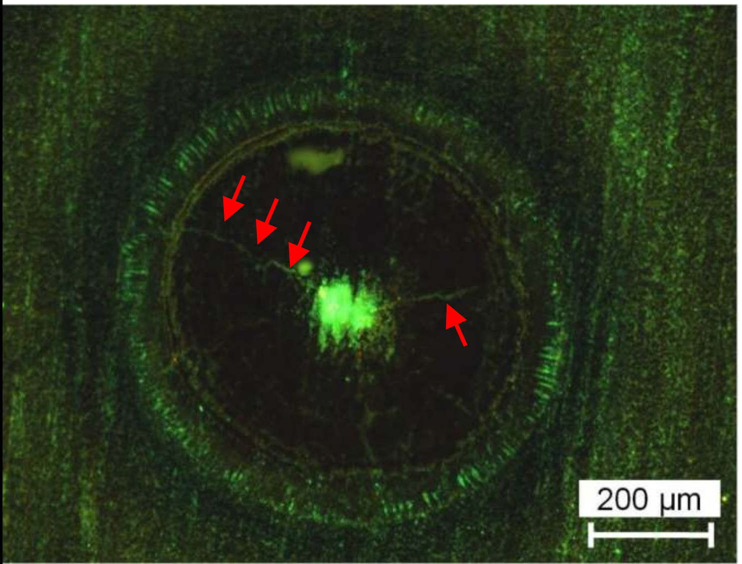
Experimental Results

Scanning electron microscope (SEM) images of the bacteria inside a defect.

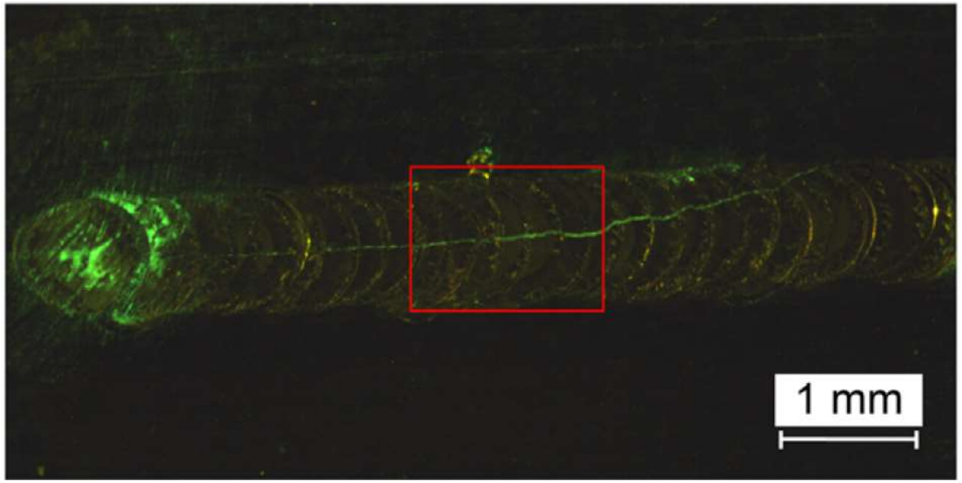


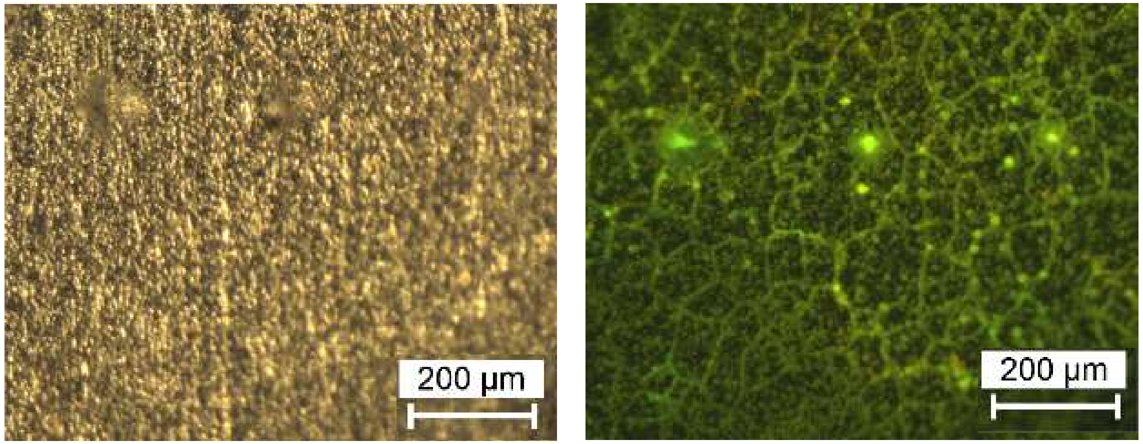
Experimental Results

Micro-laser weld of NiTi



Laser spot welding in Ti
Bacteria reveals the radial cracks





Bacterial cells can reveal some topographic surface attributes not visible by optic microscopy

Anodized AA2xxx with micro indentations

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Wishes for the future of END?

1) Lower the detectability threshold (Smaller defects)
2) Increase reliability (PoD and ROC)
3) Reduce inspection time and cost

What else is needed in 22' of Sec. 21?

Image
Automatable
Contactless

IAC-NDT

Non contact
(Less Intrusive)

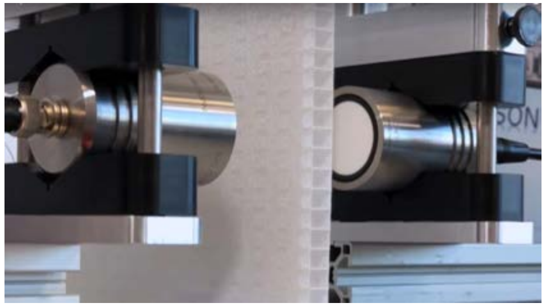
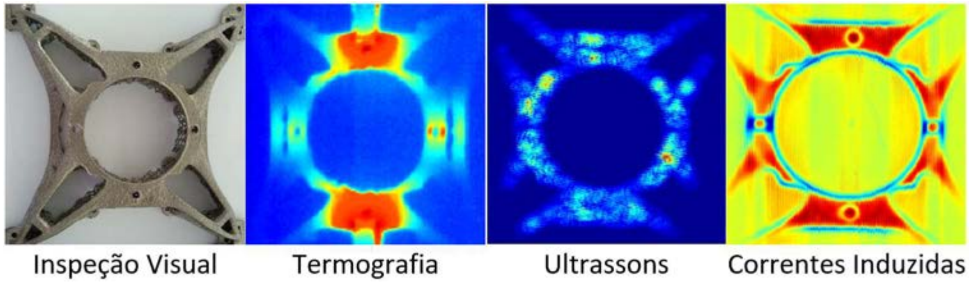


Image (Digital)
(Ease of Interpretation)



Automatable
(Reduce operator intervention)

Eligible methods for IAC -NDT?

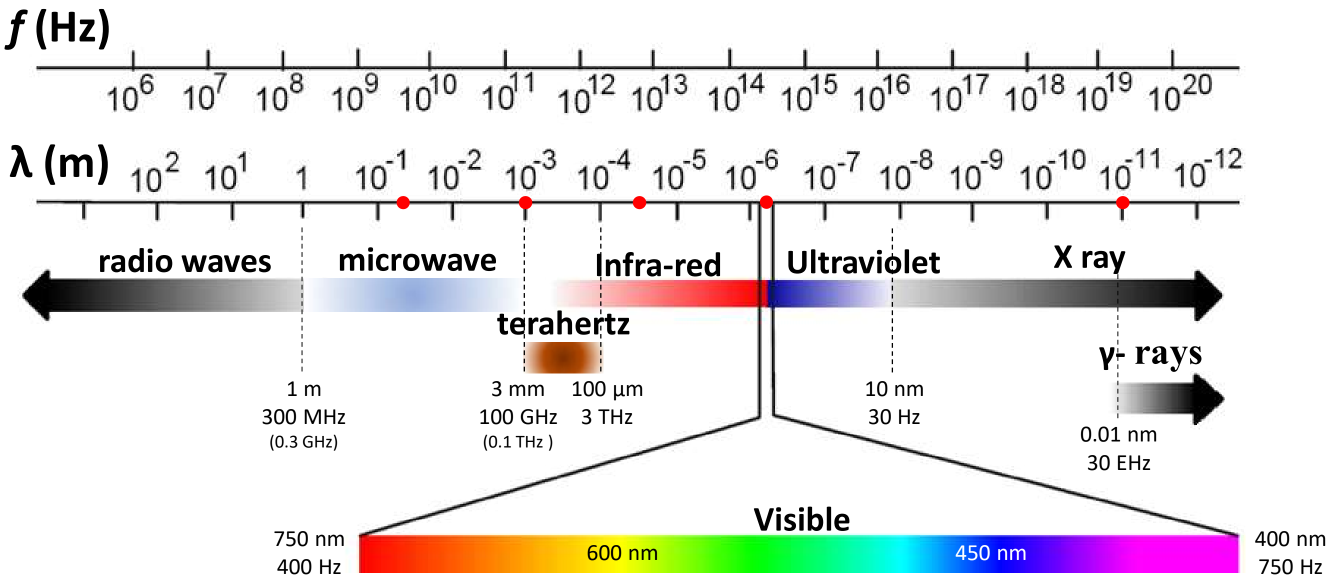
Criteria		Visual inspection	Dye Penetrants	Magnetic particles	Radiology **EM Radiation**	Ultrasound	Eddy Currents
Defects	Surface	✓	✓	✓	✓	(✓)	✓
	Sub-surface	✗	✗	(✓)	✓	(✓)	(✓)
	Volume	✗	✗	✗	✓	✓	✗
Material	$\sigma \approx 0$	✓	✓	✓	✓	✓	✗
	$\mu \approx 1$	✓	✓	✗	✓	✓	✓
Access to 1 surface only		✓	✓	✓	✗	✓	✓
No contact		✗	✗	✗	✓	(✗)	(✓)
Automatable		(✓)	✗	✗	✓	✓	✓
Produces image		✗	✗	✗	✓	(✓)	(✓)

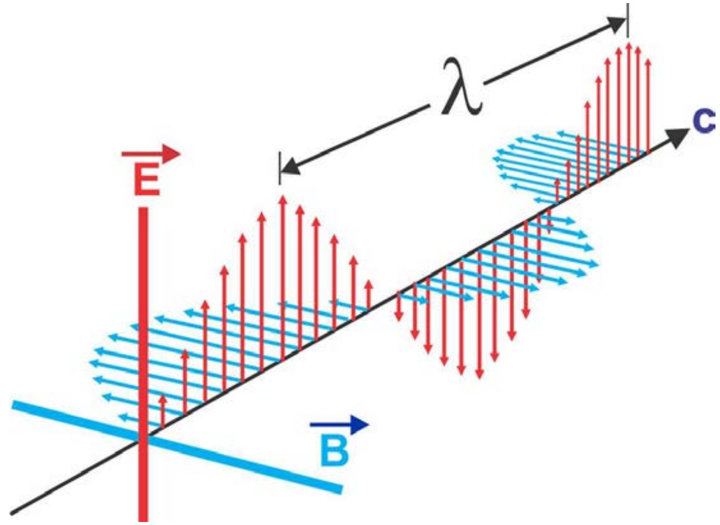
THz

$$3\ \text{THz} \leqslant f \leqslant 0.1\ \text{THz}$$

$$100\ \mu\text{m} \leqslant \lambda \leqslant 3\ \text{mm}$$

$$1\ \text{THz} = 1\times10^{12}\ \text{Hz}$$

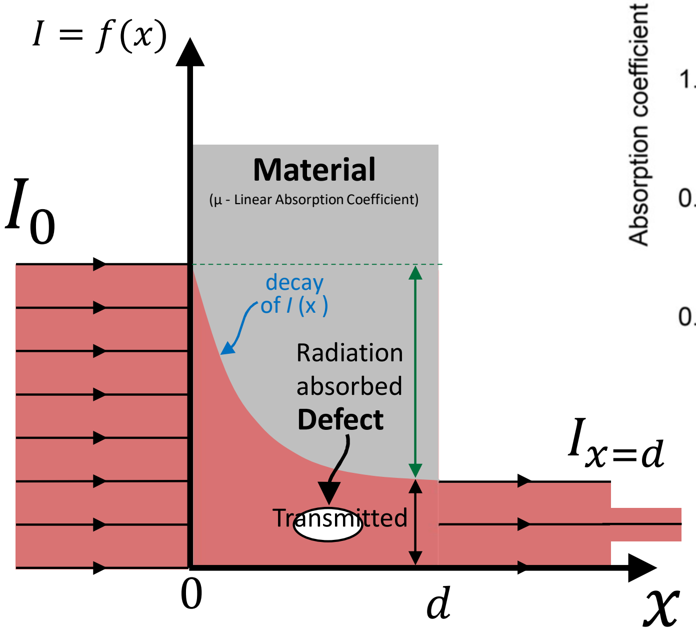


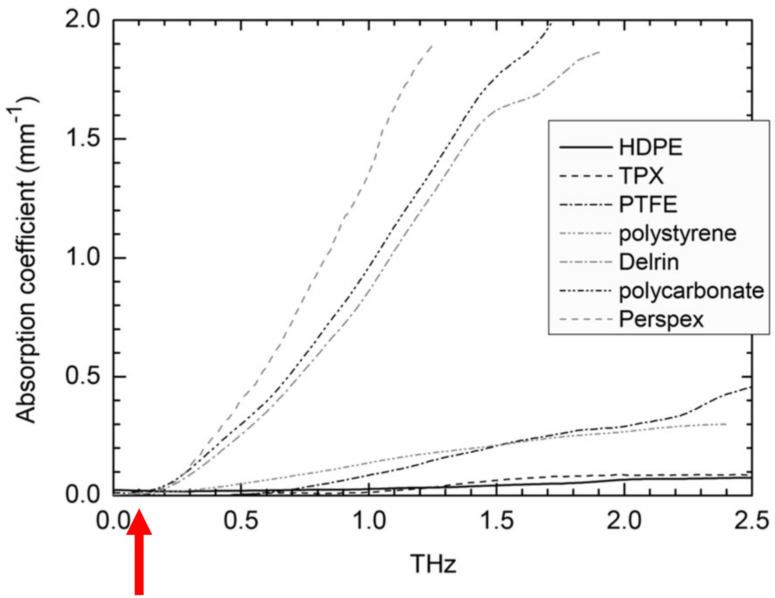


How do THz interact with materials?

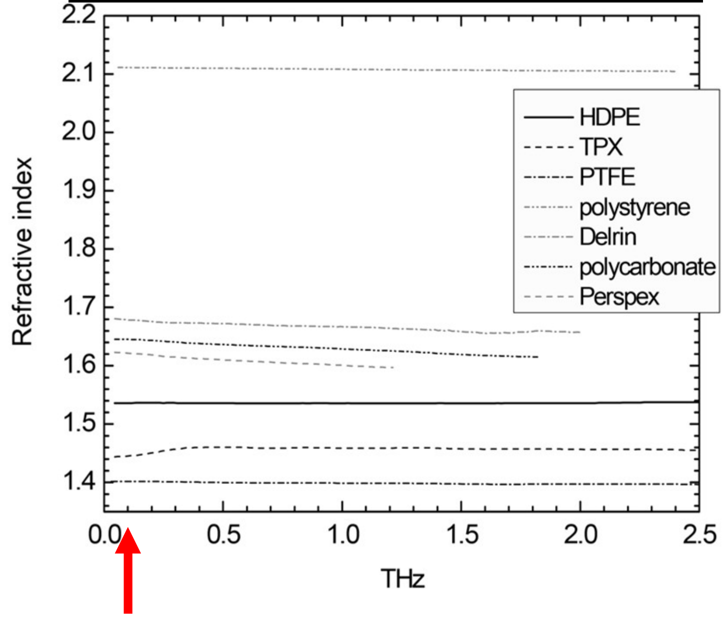
Atenuation

$$I_x = I_0 \cdot e^{-\mu \cdot x}$$



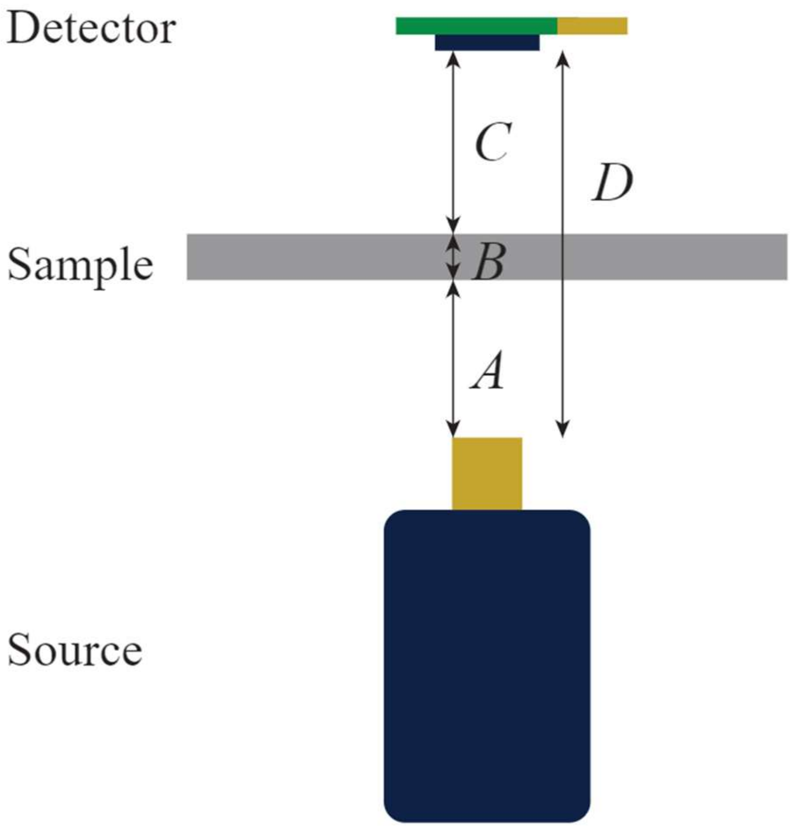


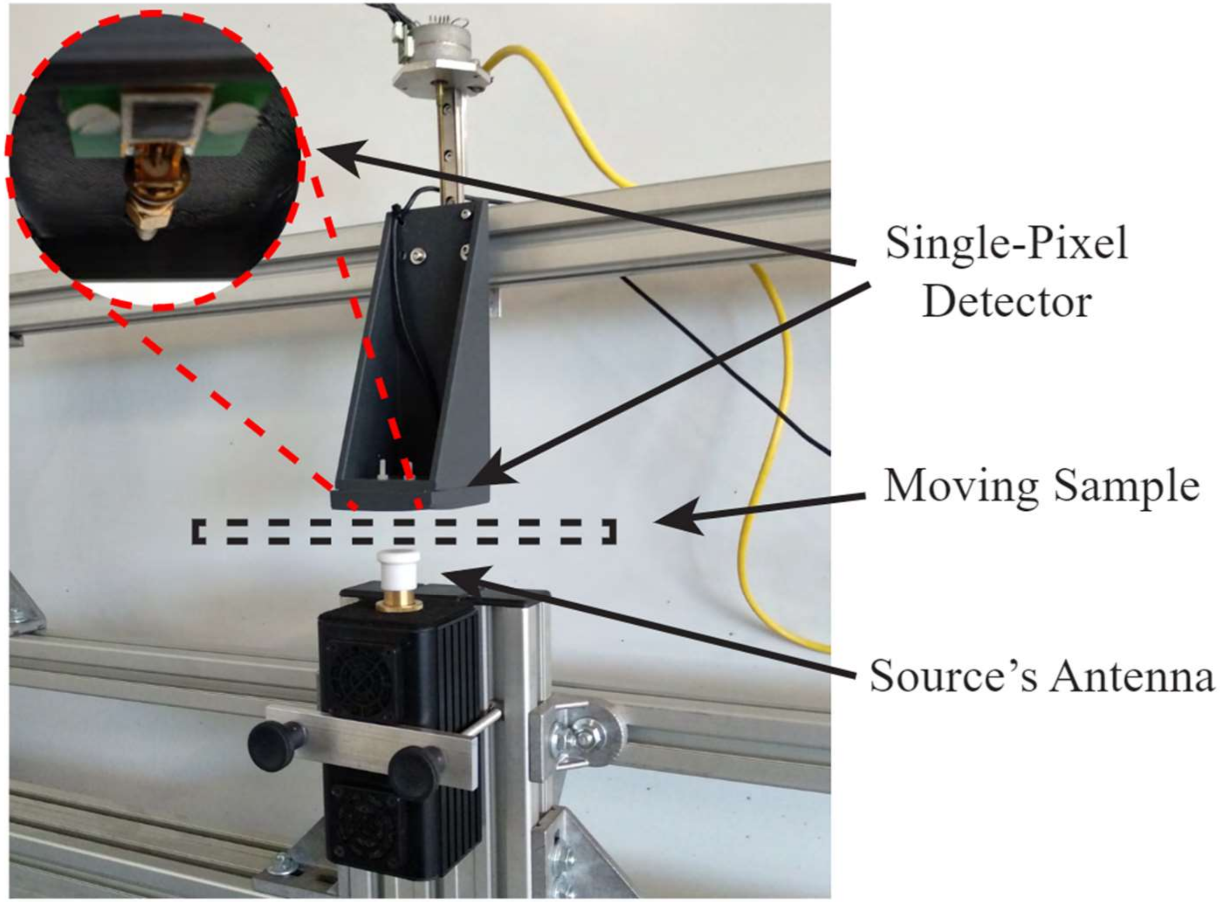
Refractive index (n = c/v)



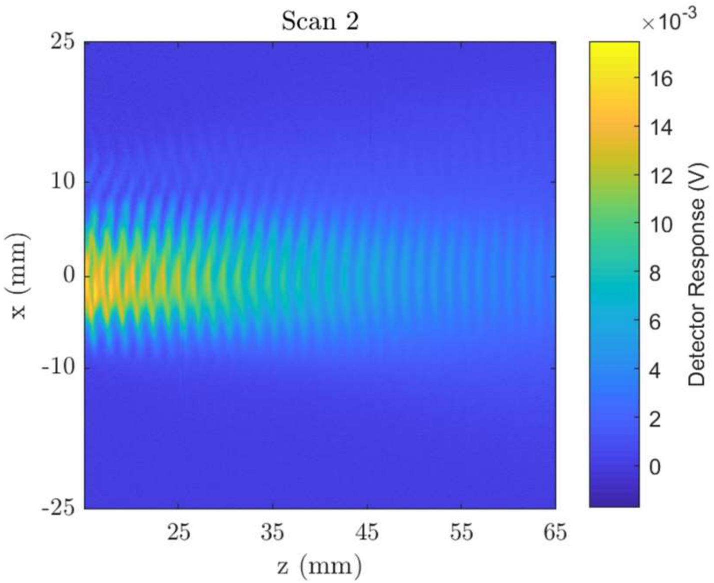
Reflect on the conductors!
It is absorbed by water!

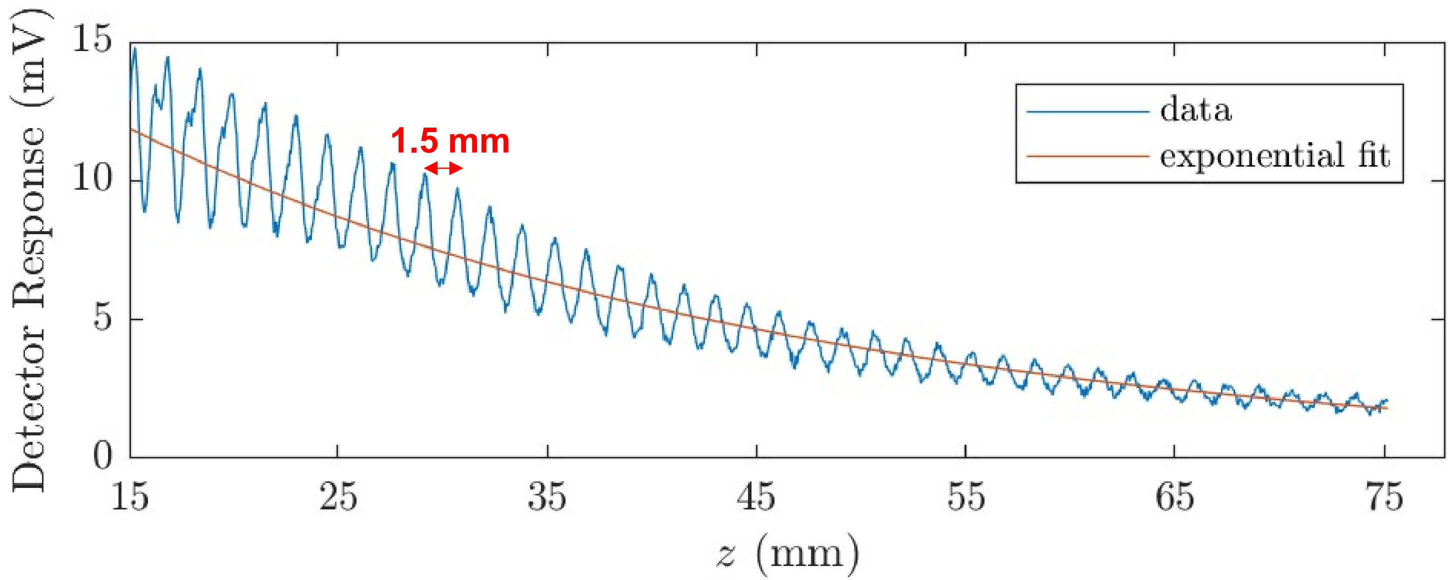
Setup: Source, Sensor and Setup

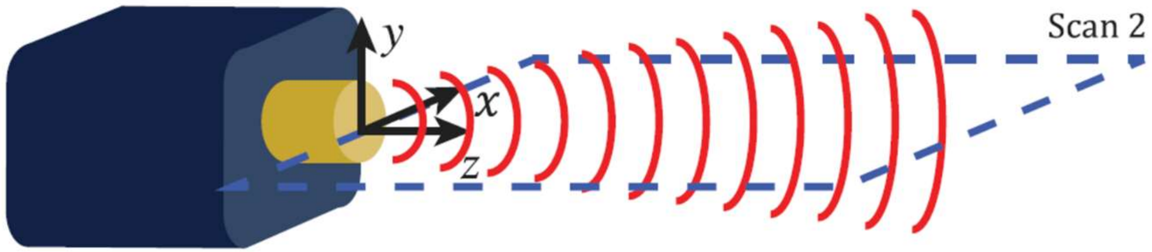




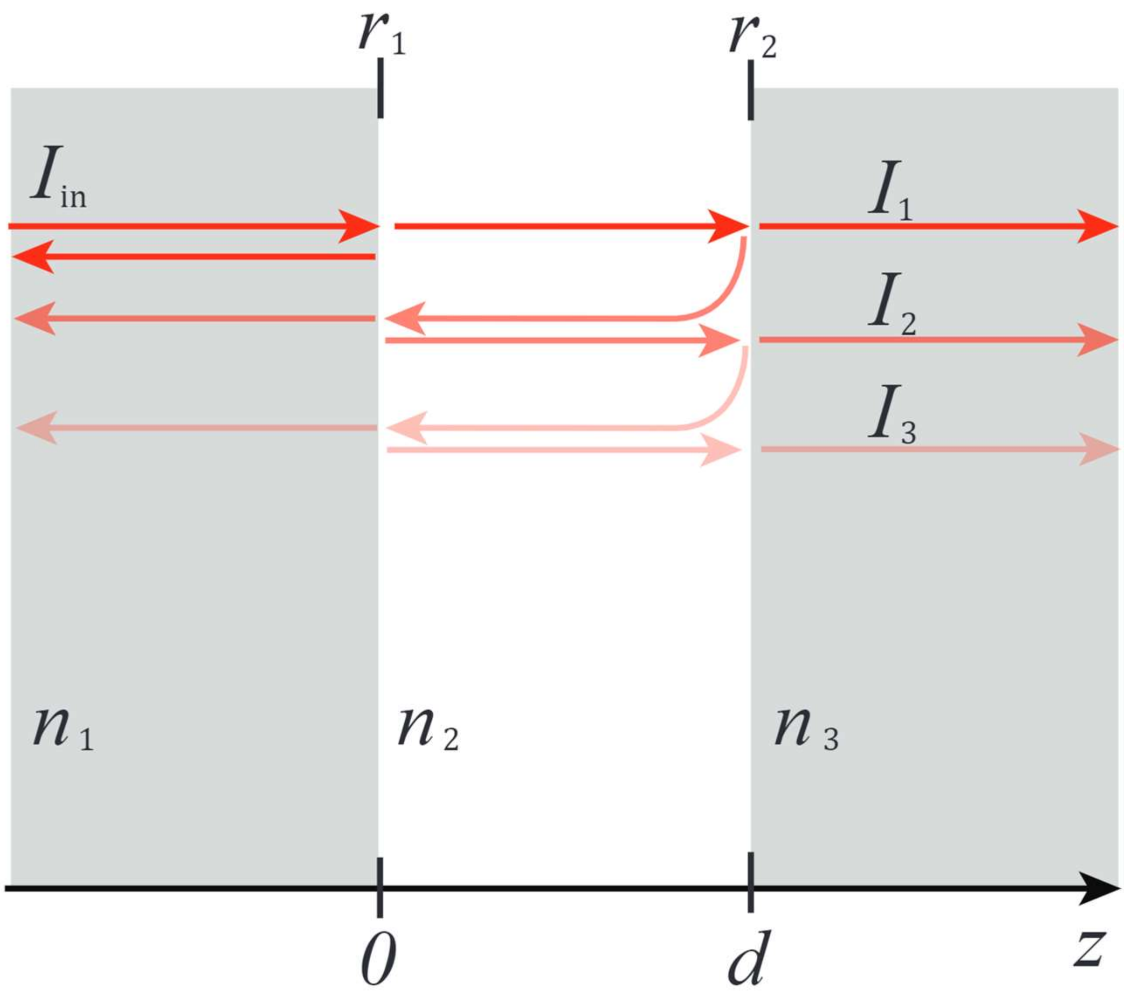
Source Characterization + Sensor



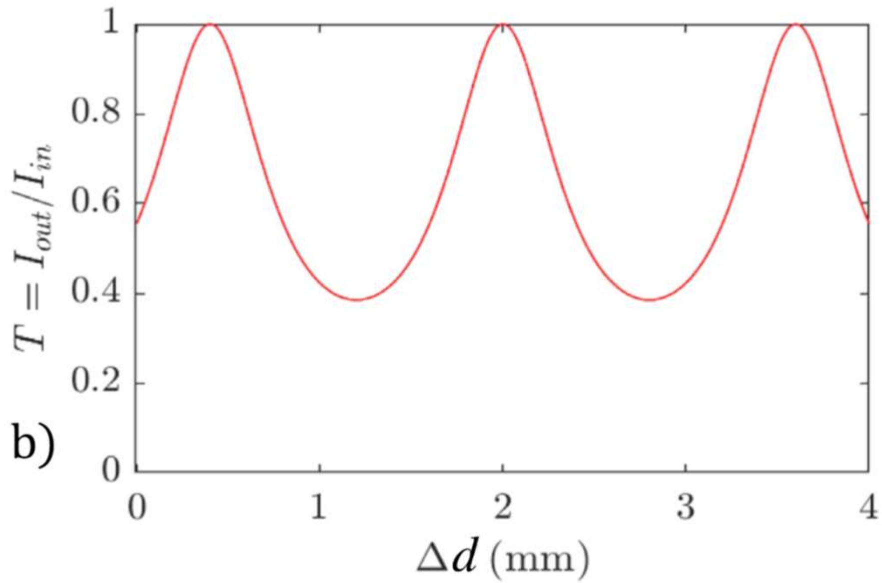




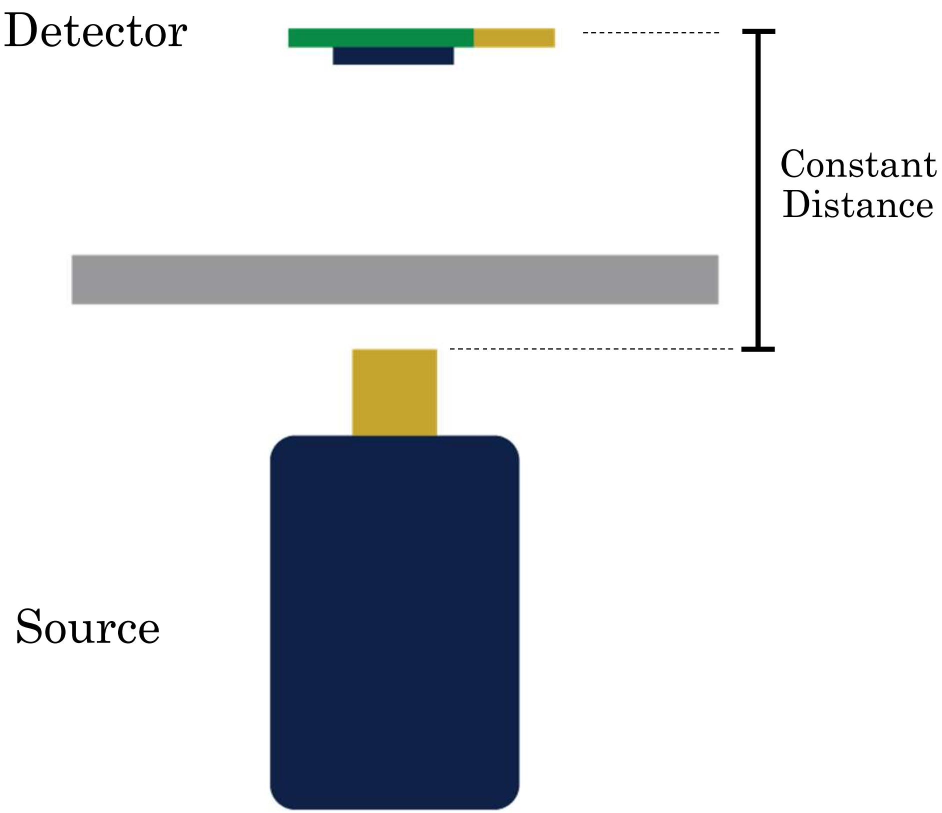
Fabry-Perot Effect

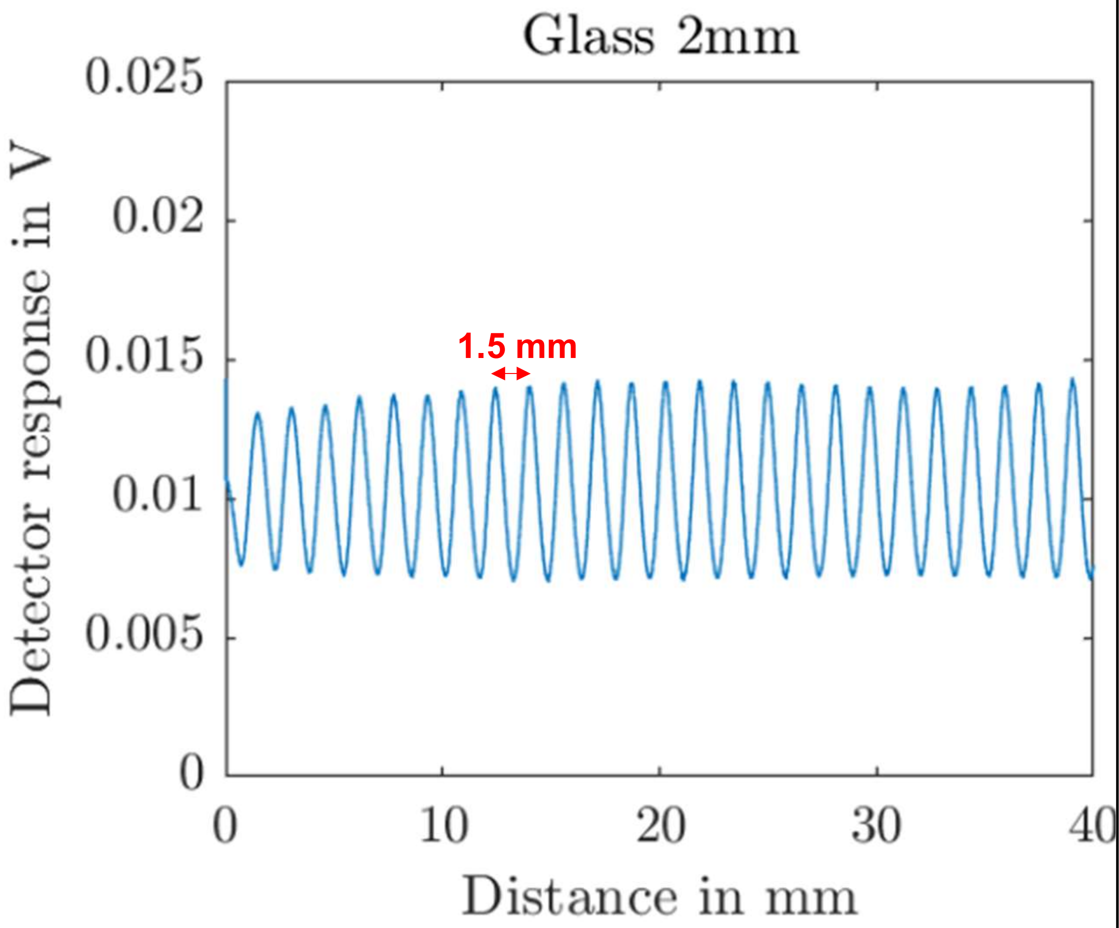


$$T = \frac{I_{out}}{I_{in}} = \frac{(1 - r_1 r_2)^2}{(1 - r_1 r_2)^2 + 4 r_1 r_2 sin^2(\frac{2\pi d}{\lambda})}$$

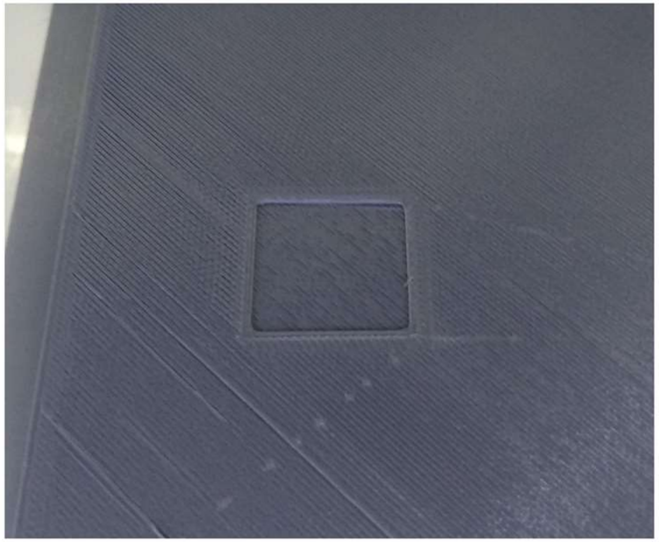


Fabry-Perot Effect

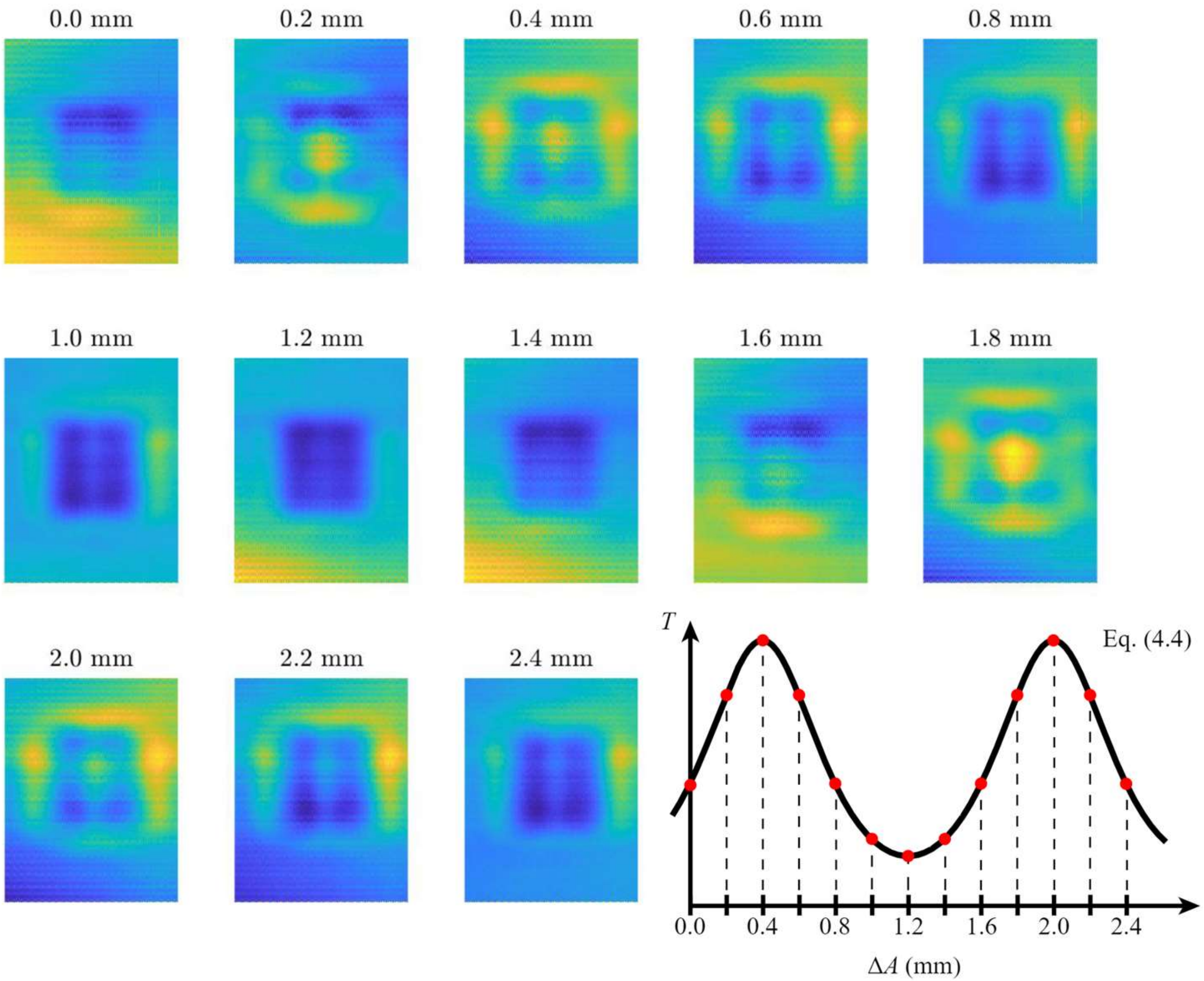




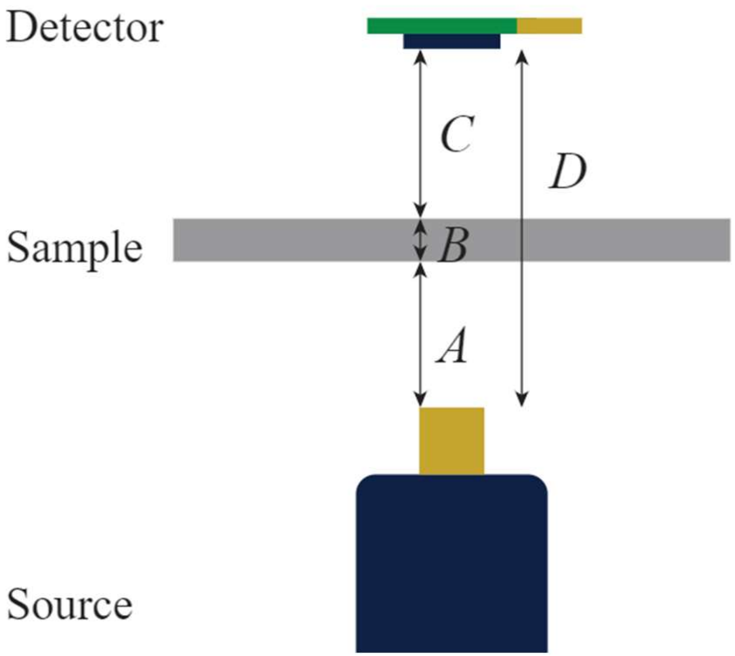
C-Scan on 3D Printing PLA with a defect

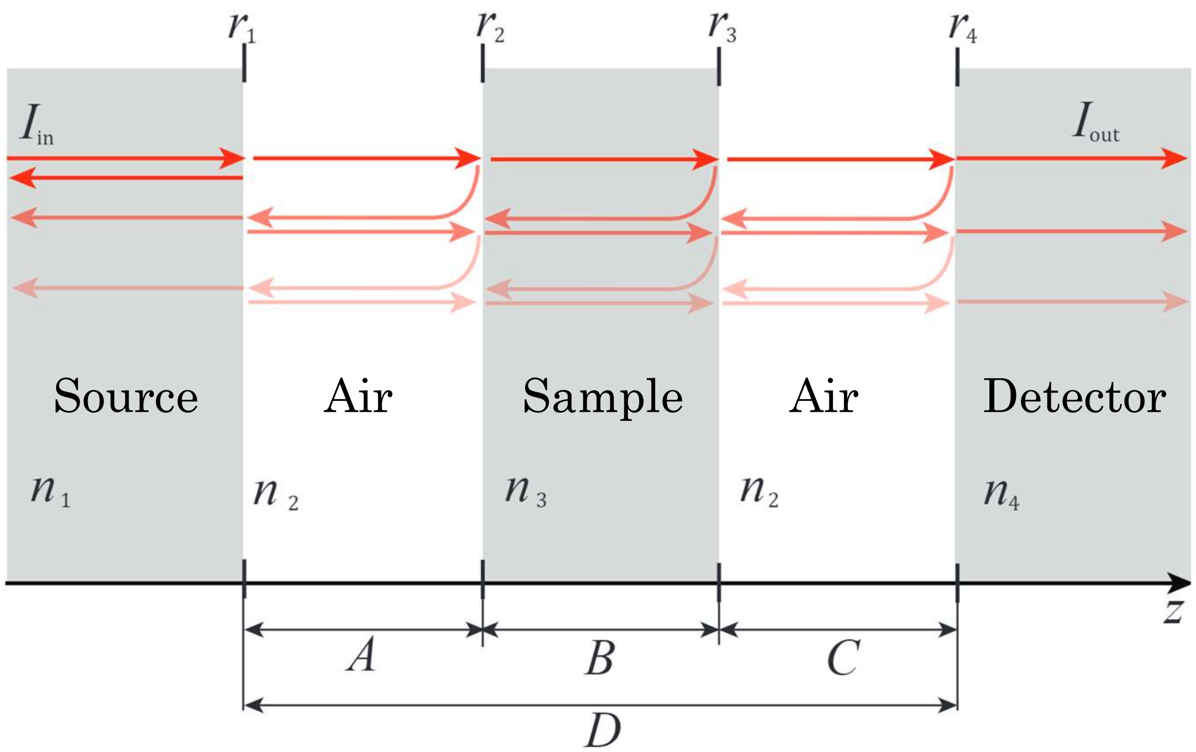


20x20x0.5 mm defect on a 4 mm thick PLA sample.



Fabry-Perot Effect



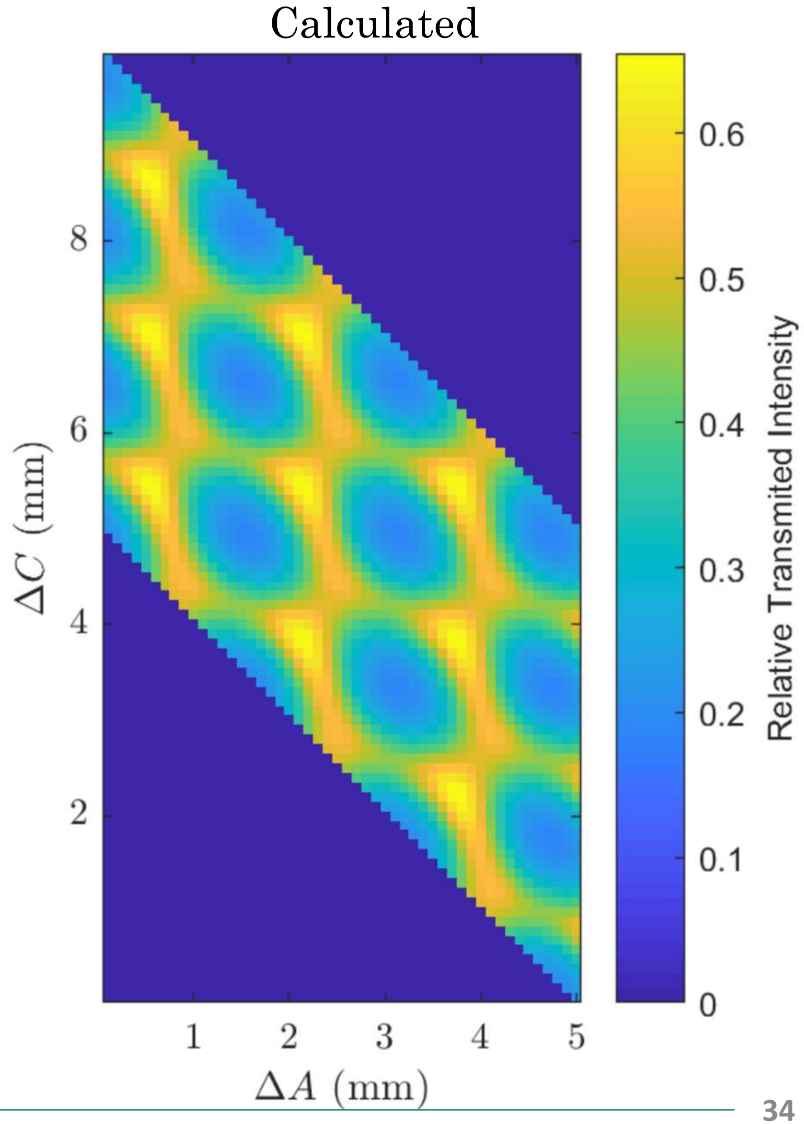


$$T = \tau\tau^*$$

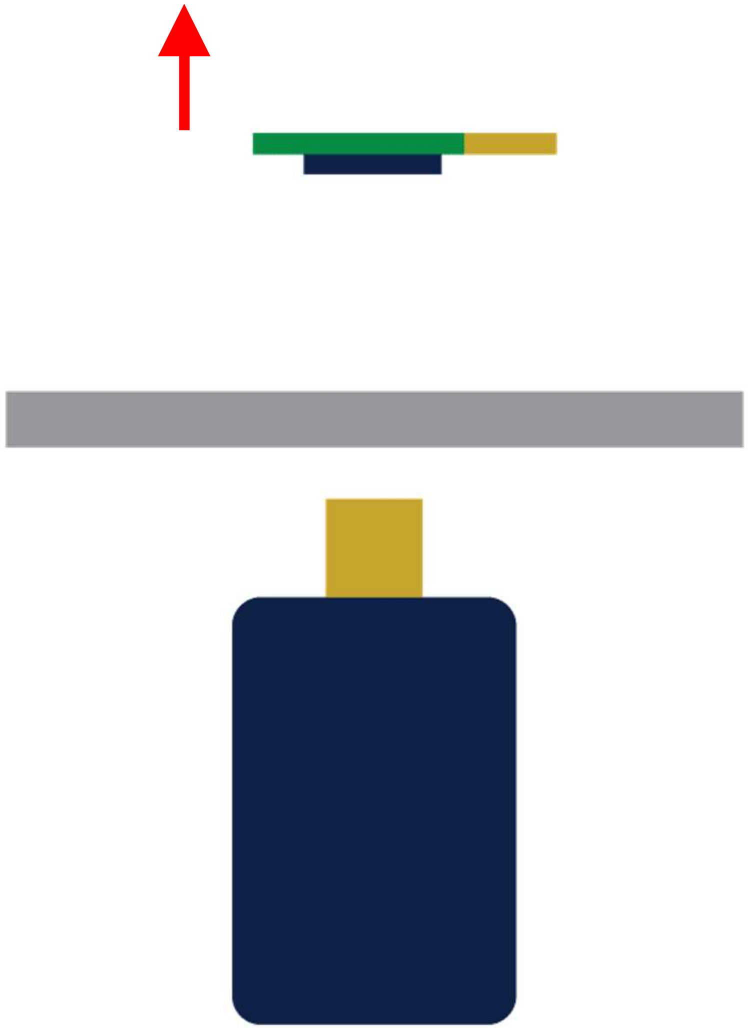
$$\phi_i = \frac{2\pi L_i n_i}{\lambda}$$

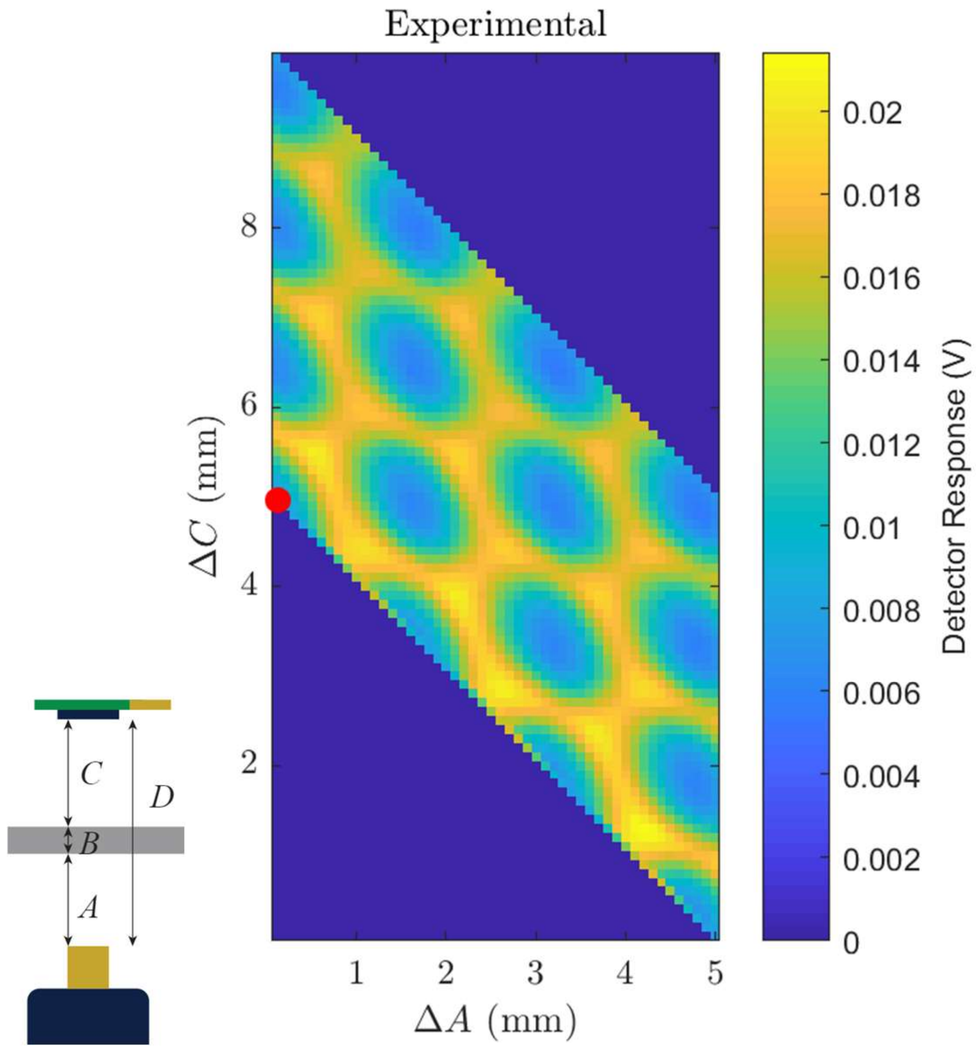
$$r = \frac{|n_1 - n_2|}{n_1 + n_2}$$

$$\begin{aligned}\tau = \tau_1\tau_2\tau_3\tau_4/\{&exp[j(-\phi_1-\phi_2-\phi_3)]\\
&+ (at_1)^2\, r_1r_2\, exp[j(+\phi_1-\phi_2-\phi_3)]\\
&+ (at_2)^2\, r_2r_3\, exp[j(-\phi_1+\phi_2-\phi_3)]\\
&+ (at_1)^2(at_2)^2\, r_1r_3\, exp[j(+\phi_1+\phi_2-\phi_3)]\\
&+ (at_3)^2\, r_3r_4\, exp[j(-\phi_1-\phi_2+\phi_3)]\\
&+ (at_1)^2(at_2)^4(at_3)^2\, r_1r_2r_3r_4\, exp[j(+\phi_1-\phi_2+\phi_3)]\\
&+ (at_2)^2(at_3)^2\, r_2r_4\, exp[j(-\phi_1+\phi_2+\phi_3)]\\
&+ (at_1)^2(at_2)^2(at_3)^2\, r_1r_4\, exp[j(+\phi_1+\phi_2+\phi_3)]\}.\end{aligned}$$

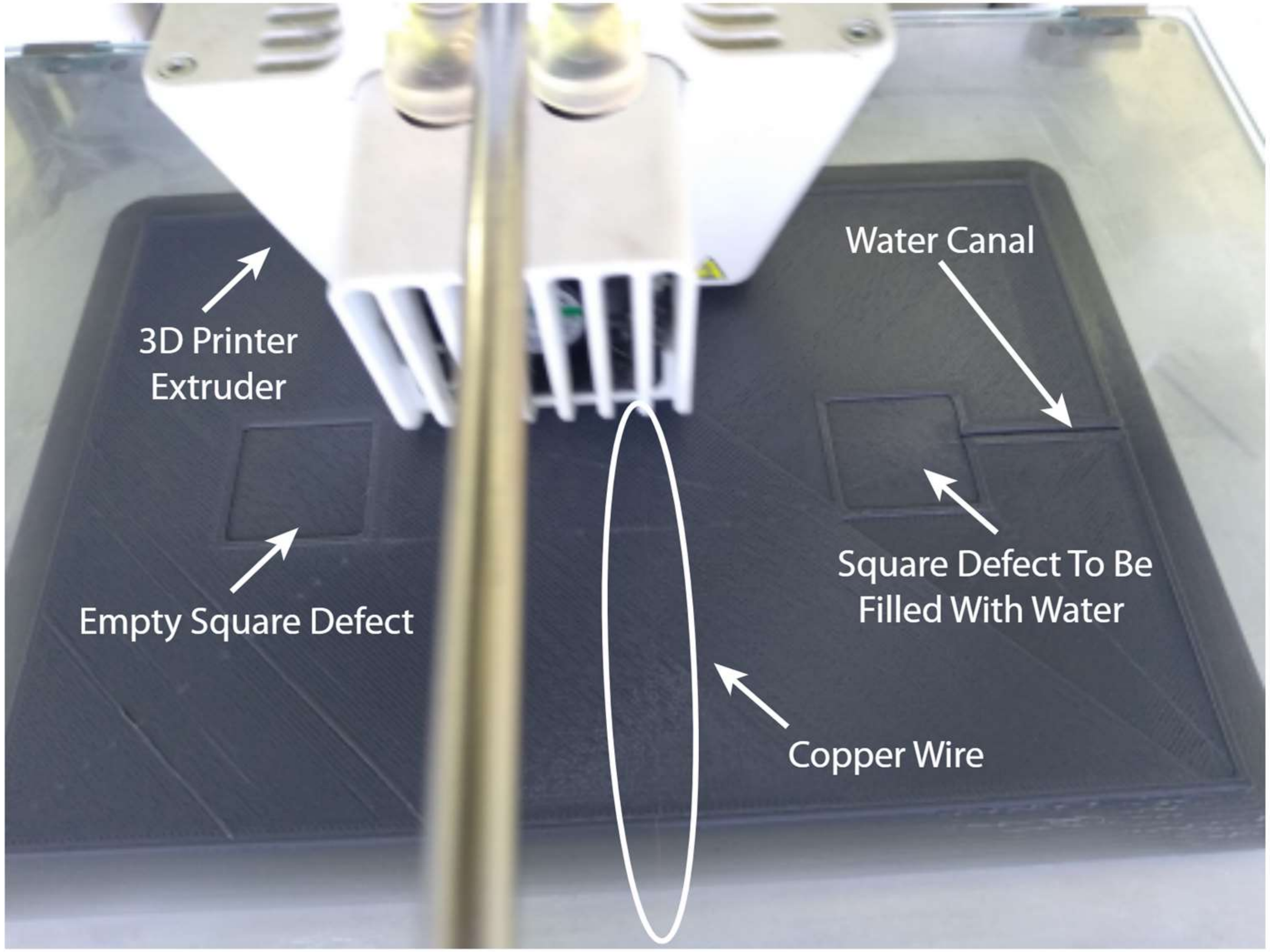


Fabry-Perot Effect

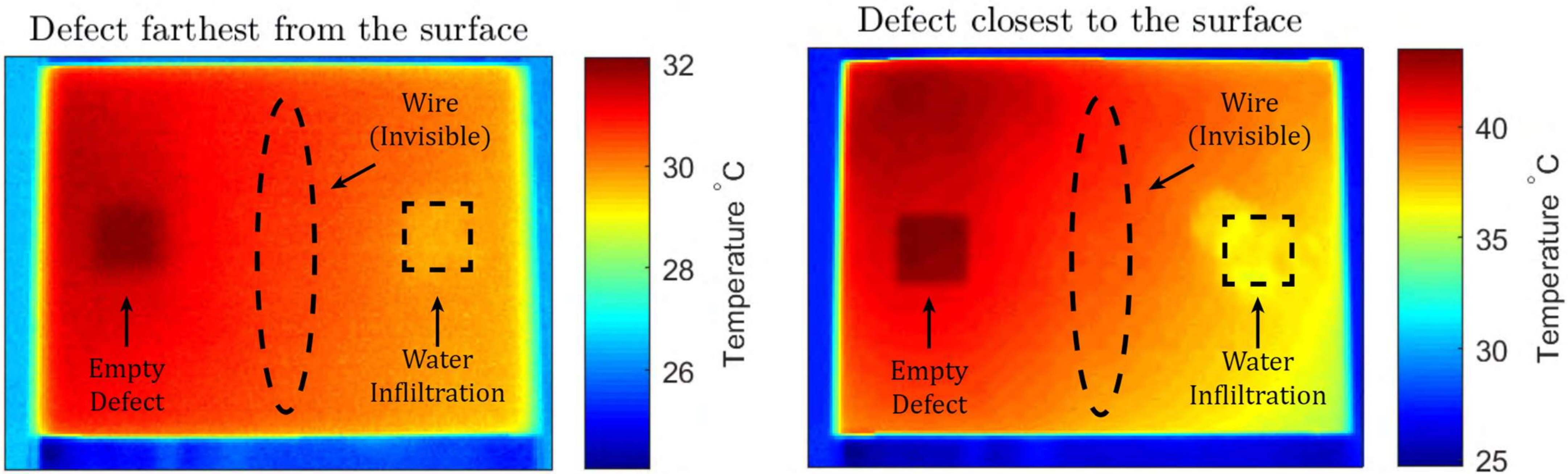


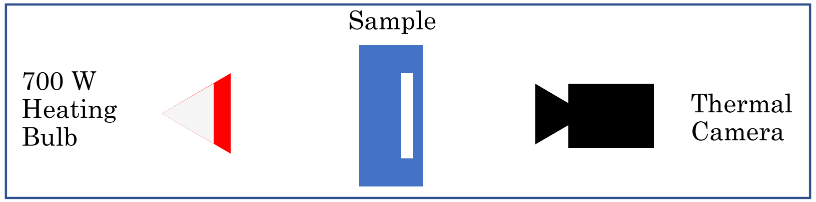


Benchmarking: THz vs US, IV, Rx

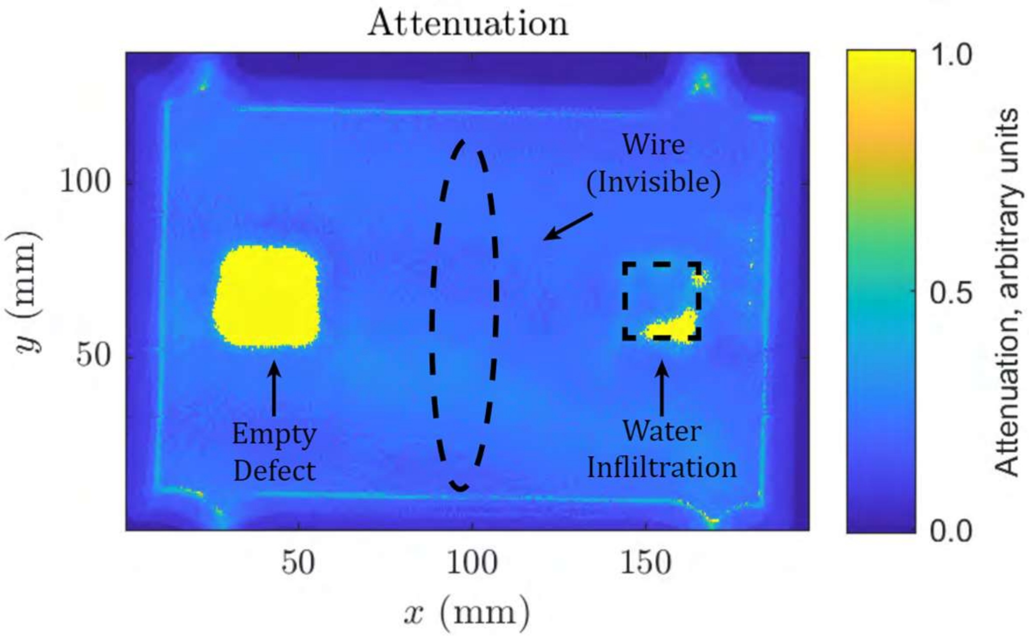


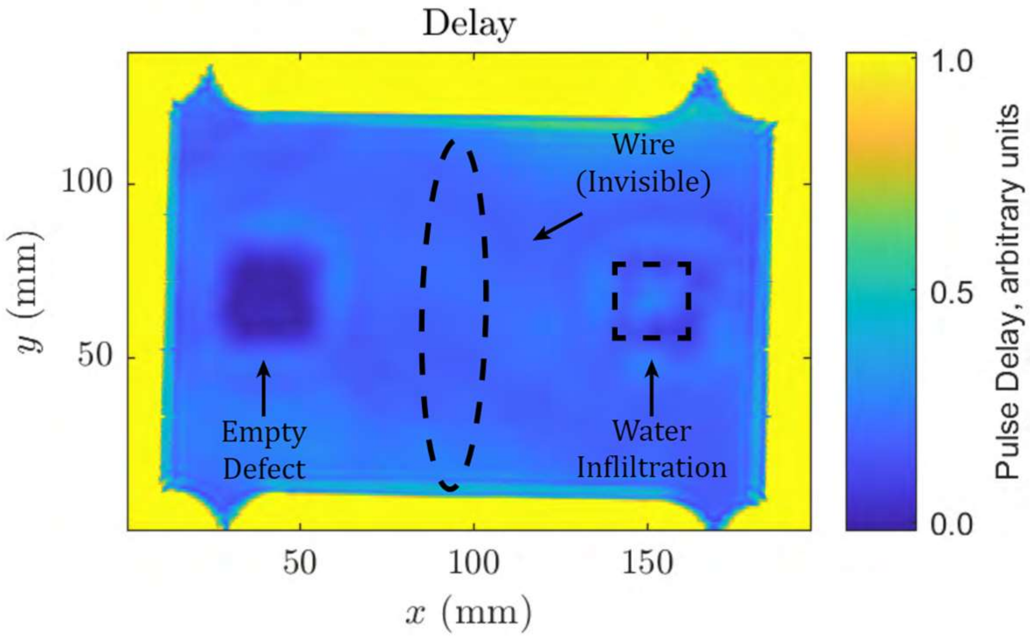
Active Transient Thermography



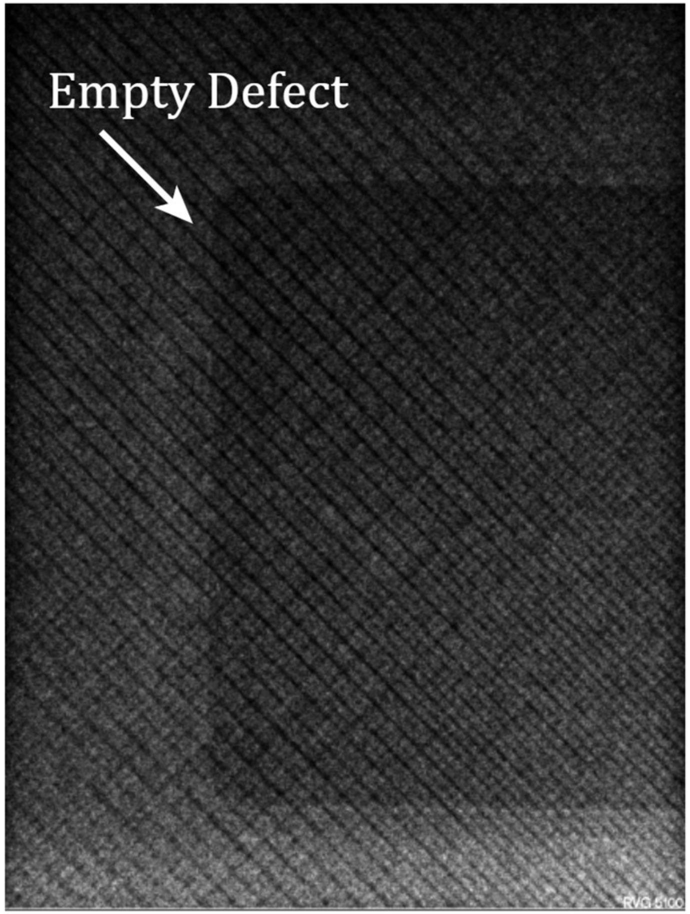


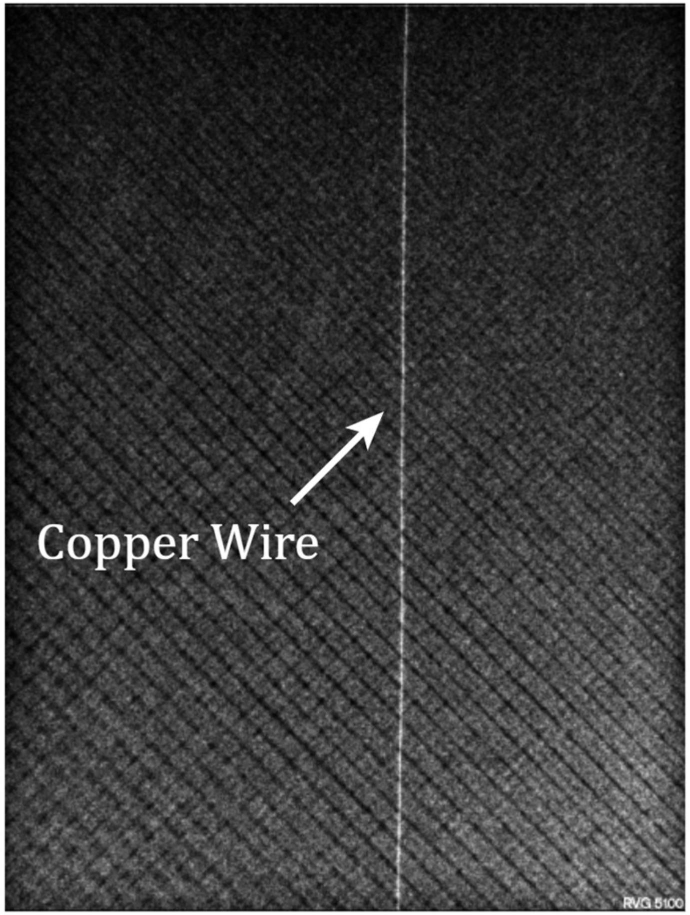
Ultra-Sound Air-Coupled (200 kHz)

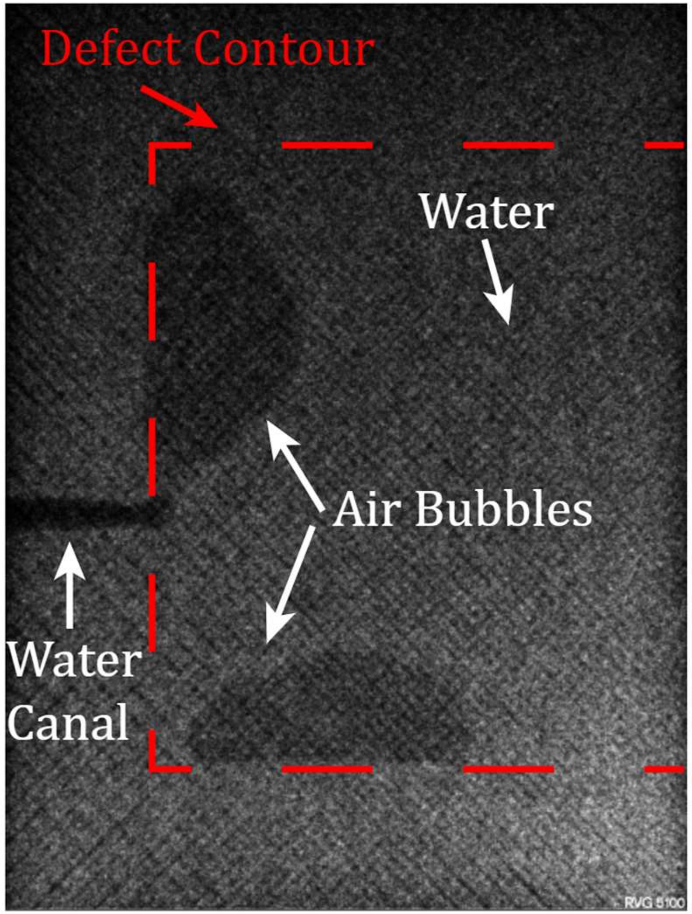




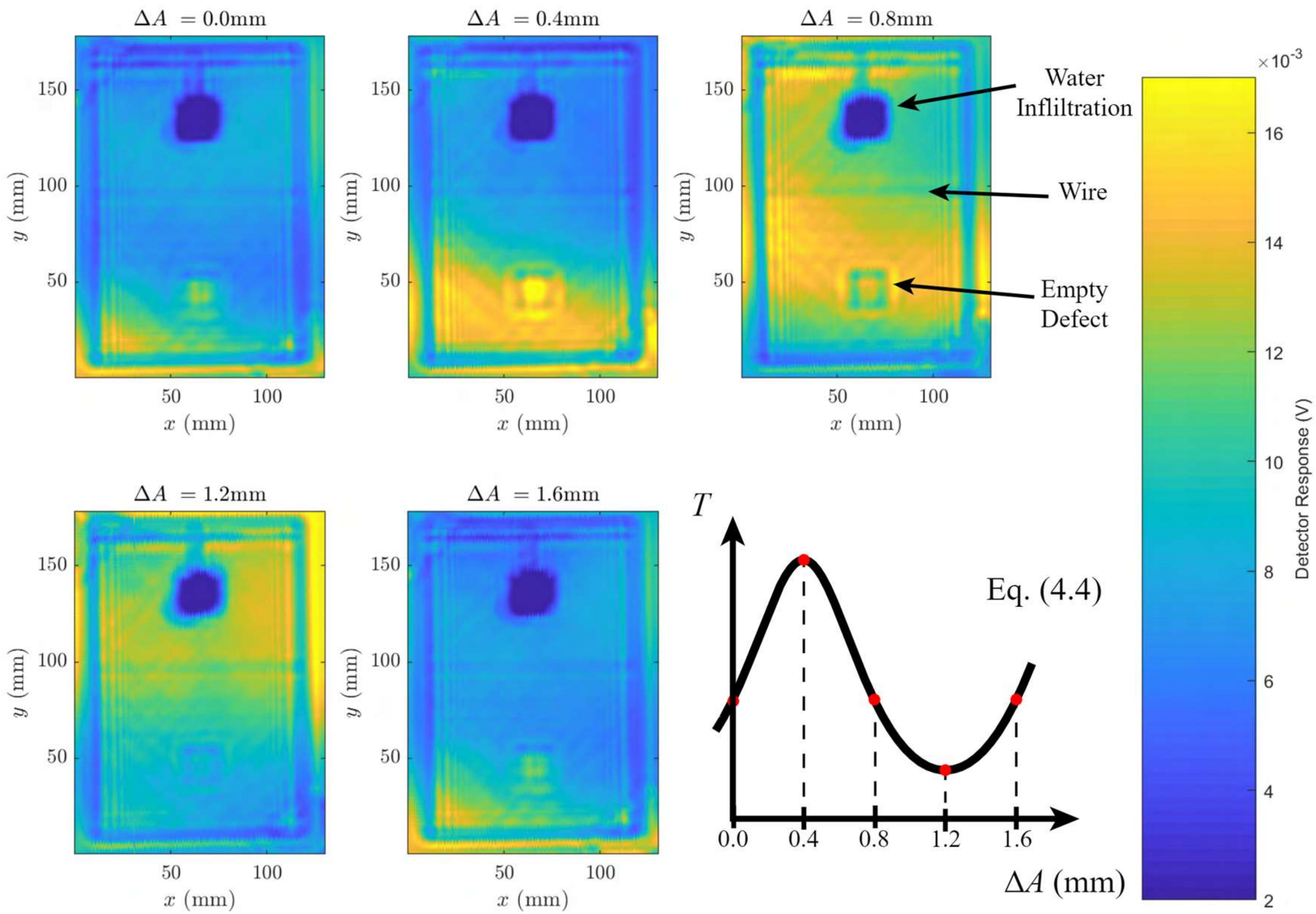
Digital X-Ray







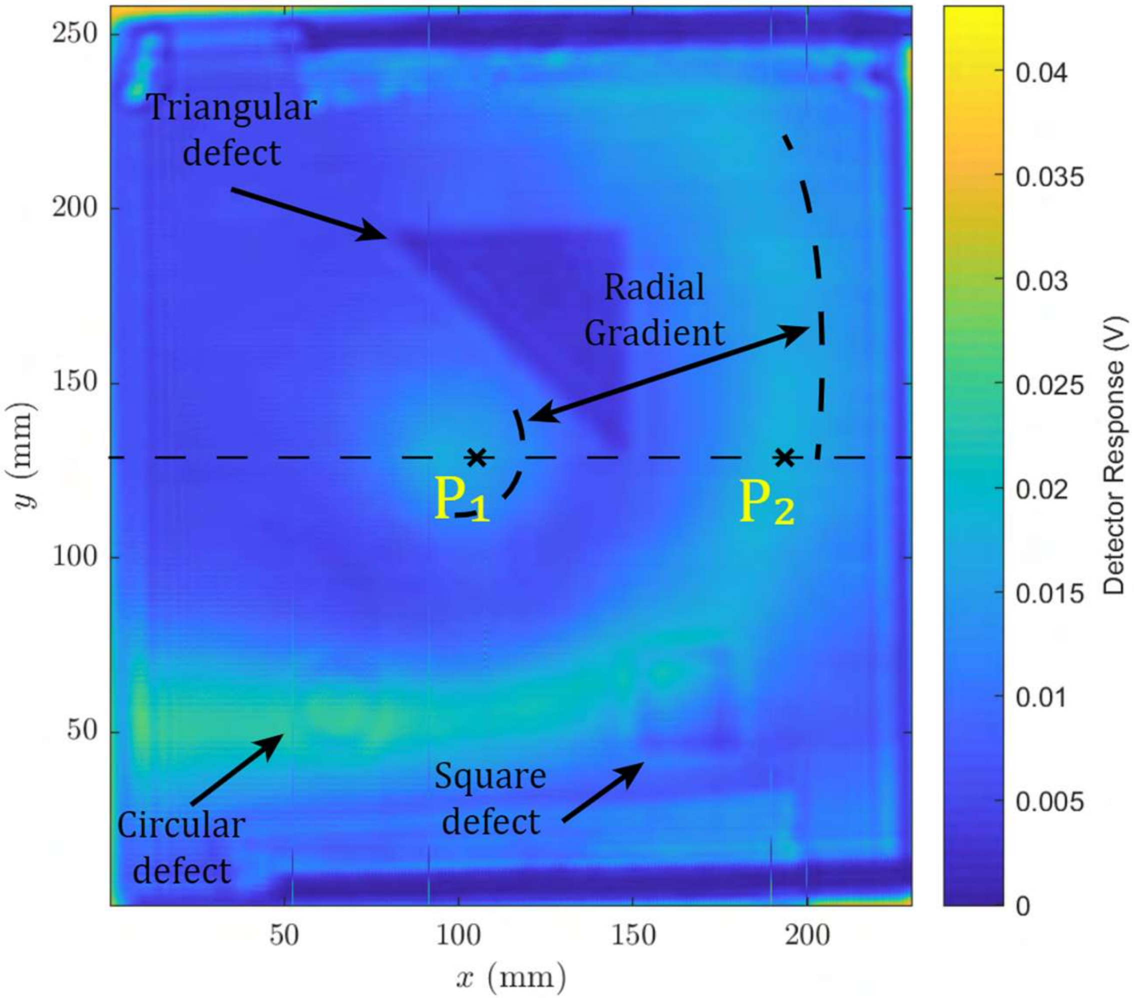
THz

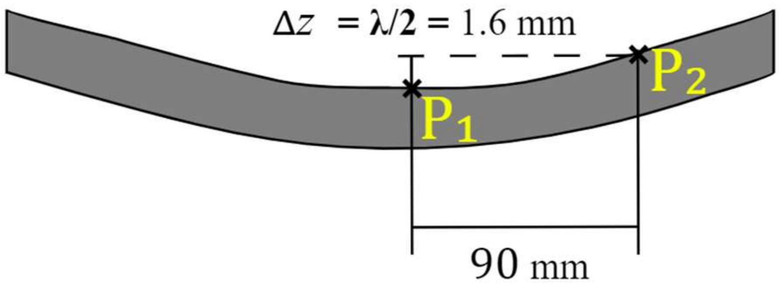

ΔA = 0.0mm
ΔA = 0.4mm
ΔA = 0.8mm
ΔA = 1.2mm
ΔA = 1.6mm
y (mm)
x (mm)
Water Infiltration
Wire
Empty Defect
T
Eq. (4.4)
0.0
0.4
0.8
1.2
1.6
ΔA (mm)
×10^-3
Detector Response (V)
2
4
6
8
10
12
14
16

Benchmarking

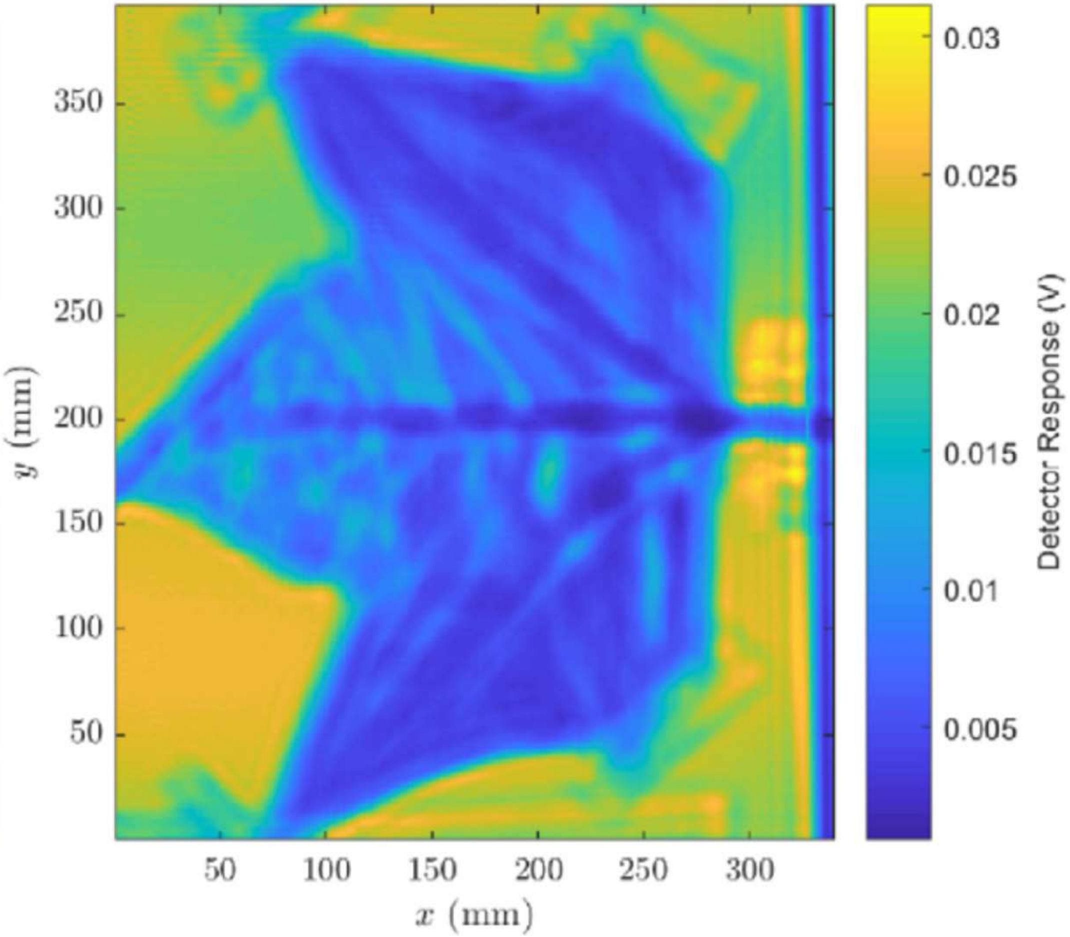
	Empty Defect	Water Infiltration	Metallic Wire	Health Safety
CW Terahertz Imaging	✓	✓✓✓	✓	✓
Air-Coupled Transmission US	✓	✓	✗	✓
Active Transient Thermography	✓	✓*	✗	✓
Digital X-Ray Imaging	✓✓✓	✗	✓✓✓	✗

Thin metallic wires

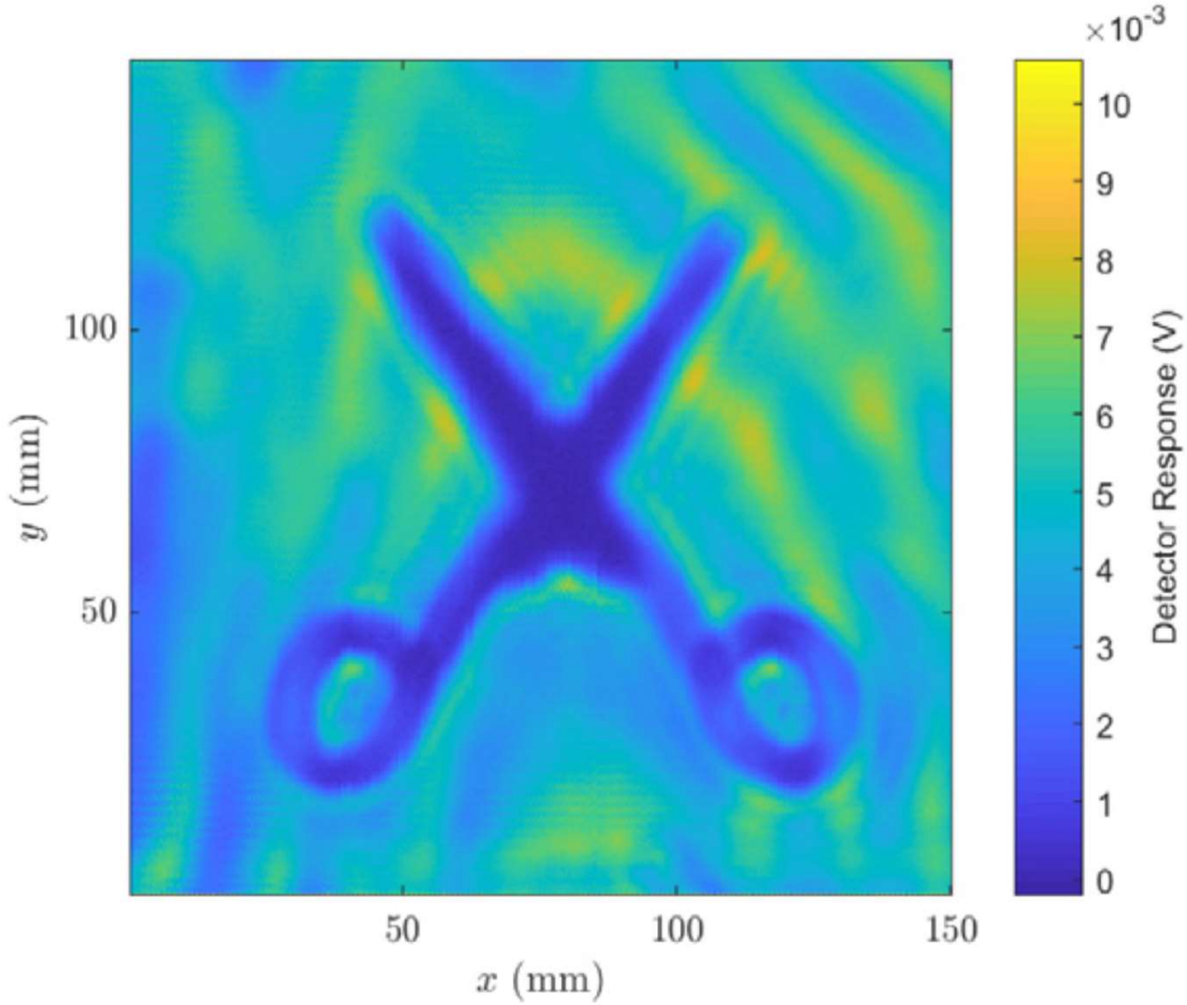




Other THz applications

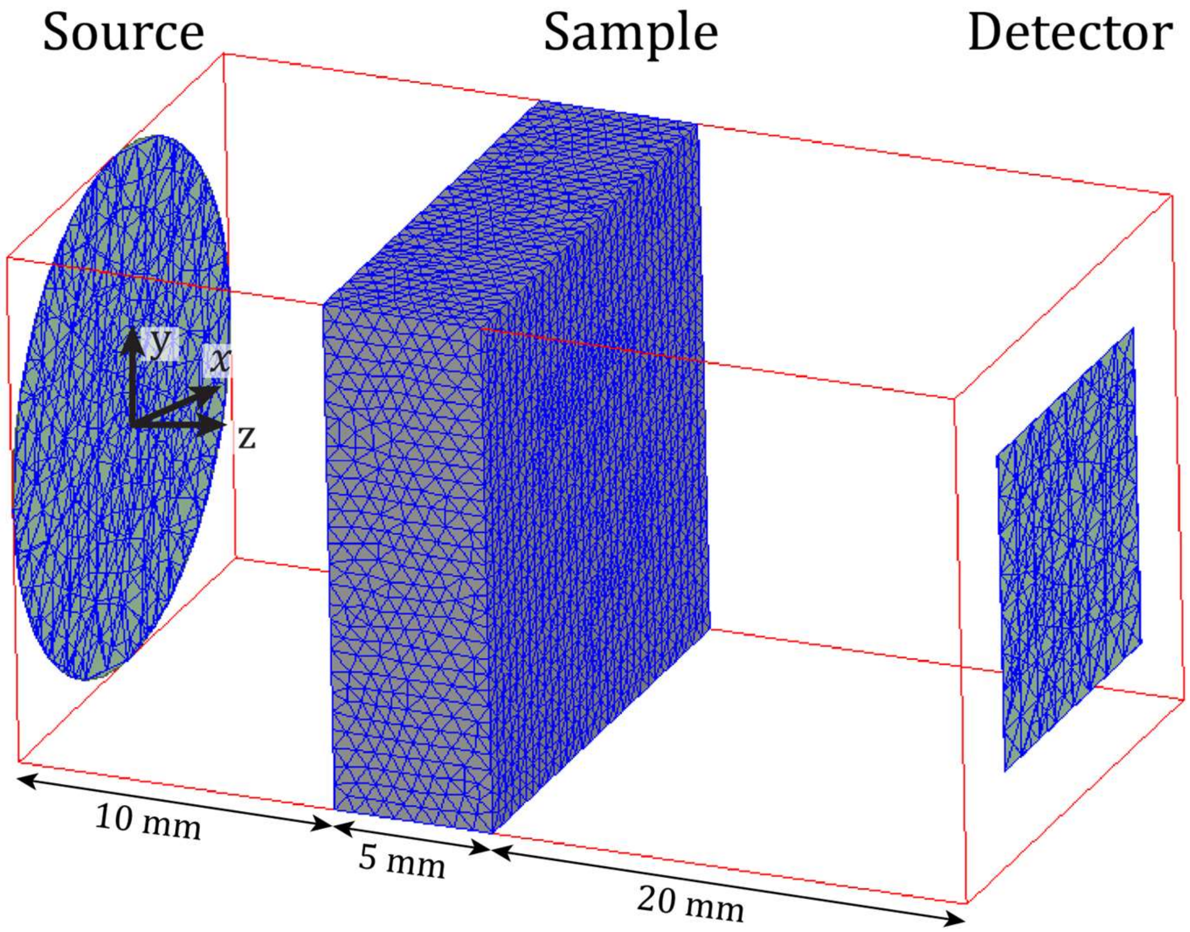


Other THz applications

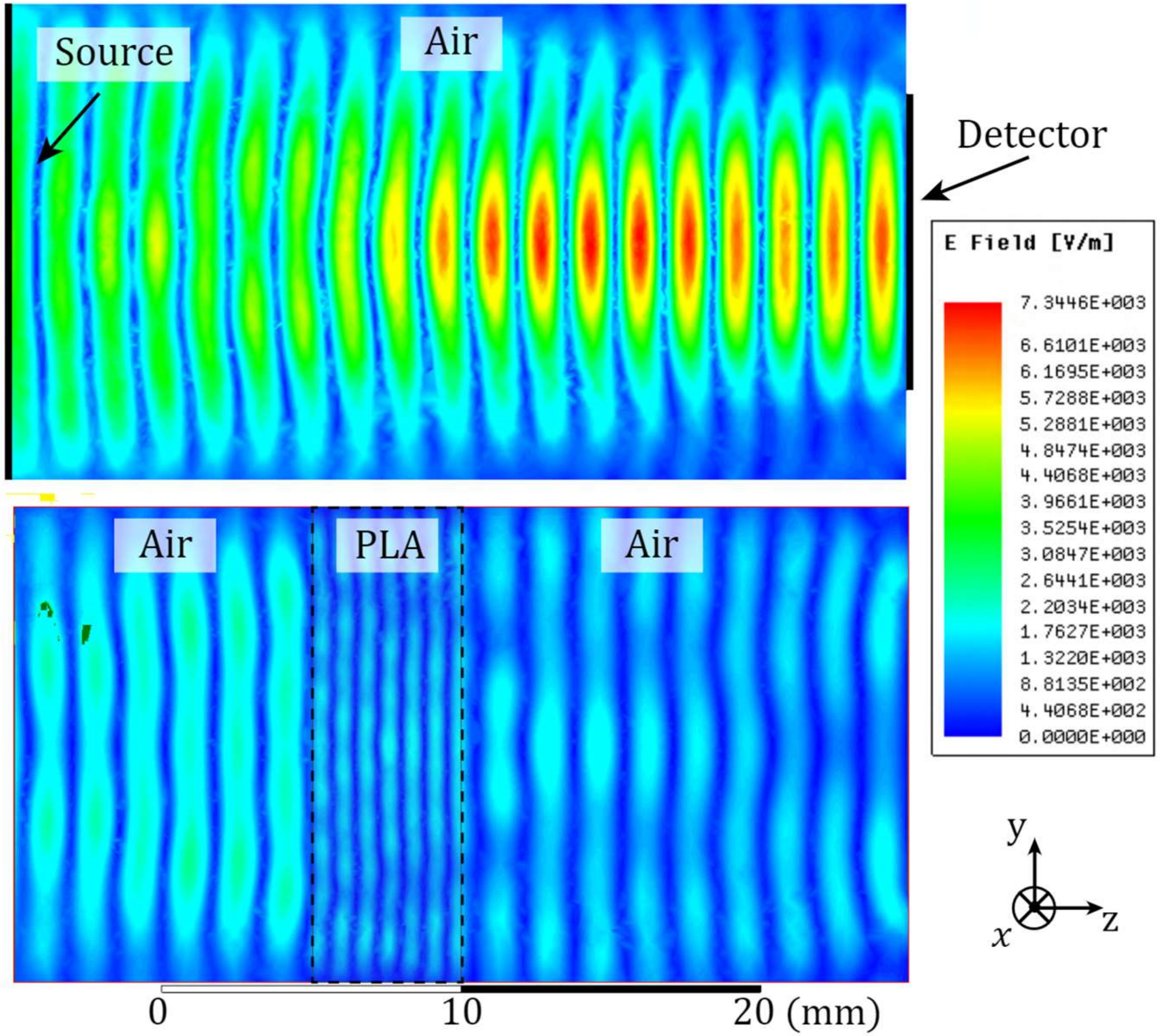


Numerical Simulations

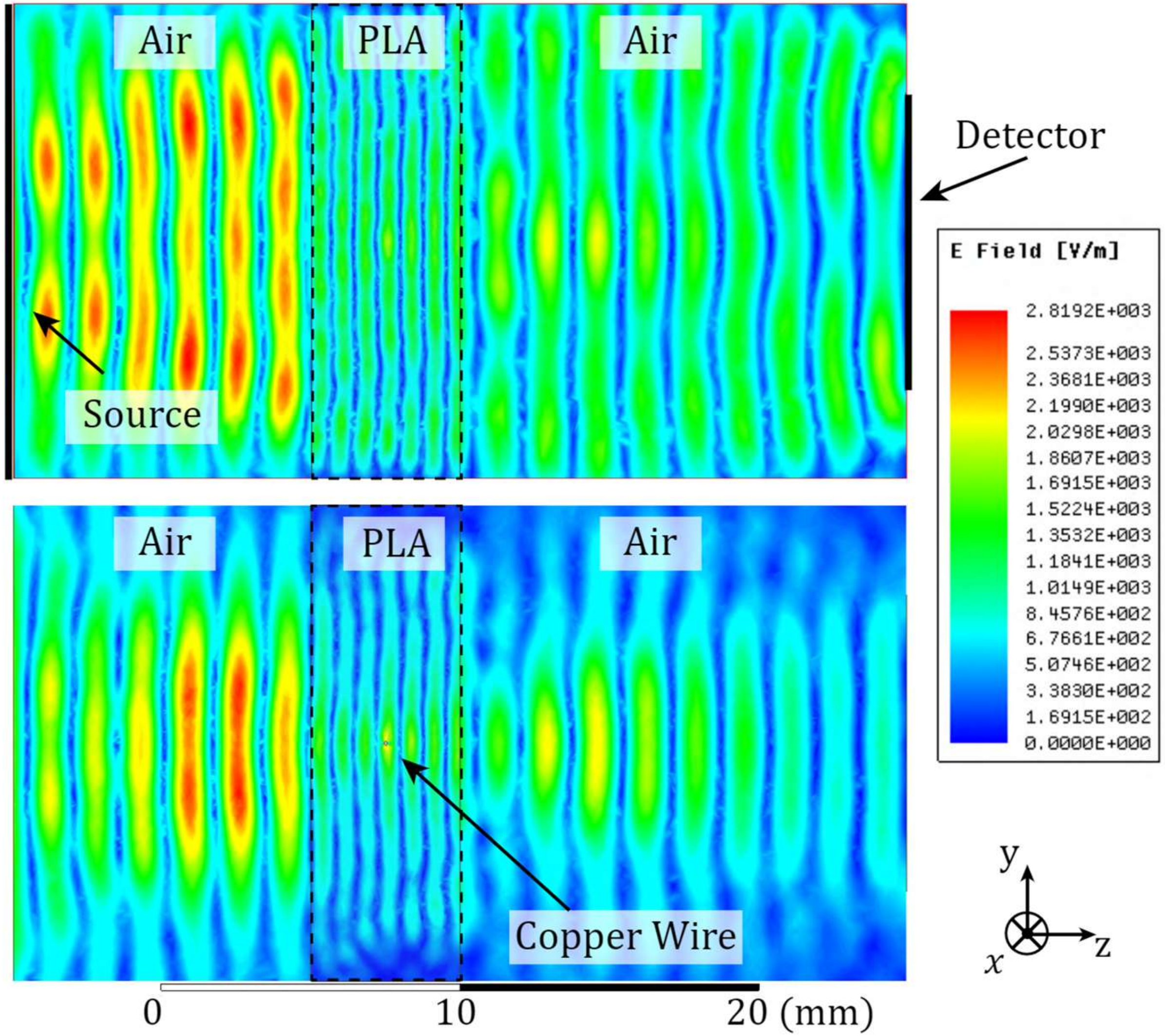
- Finite Element Method.
- Ansys HFSS.
- Mesh with 500 000 tetragonal elements.



Numerical Simulations

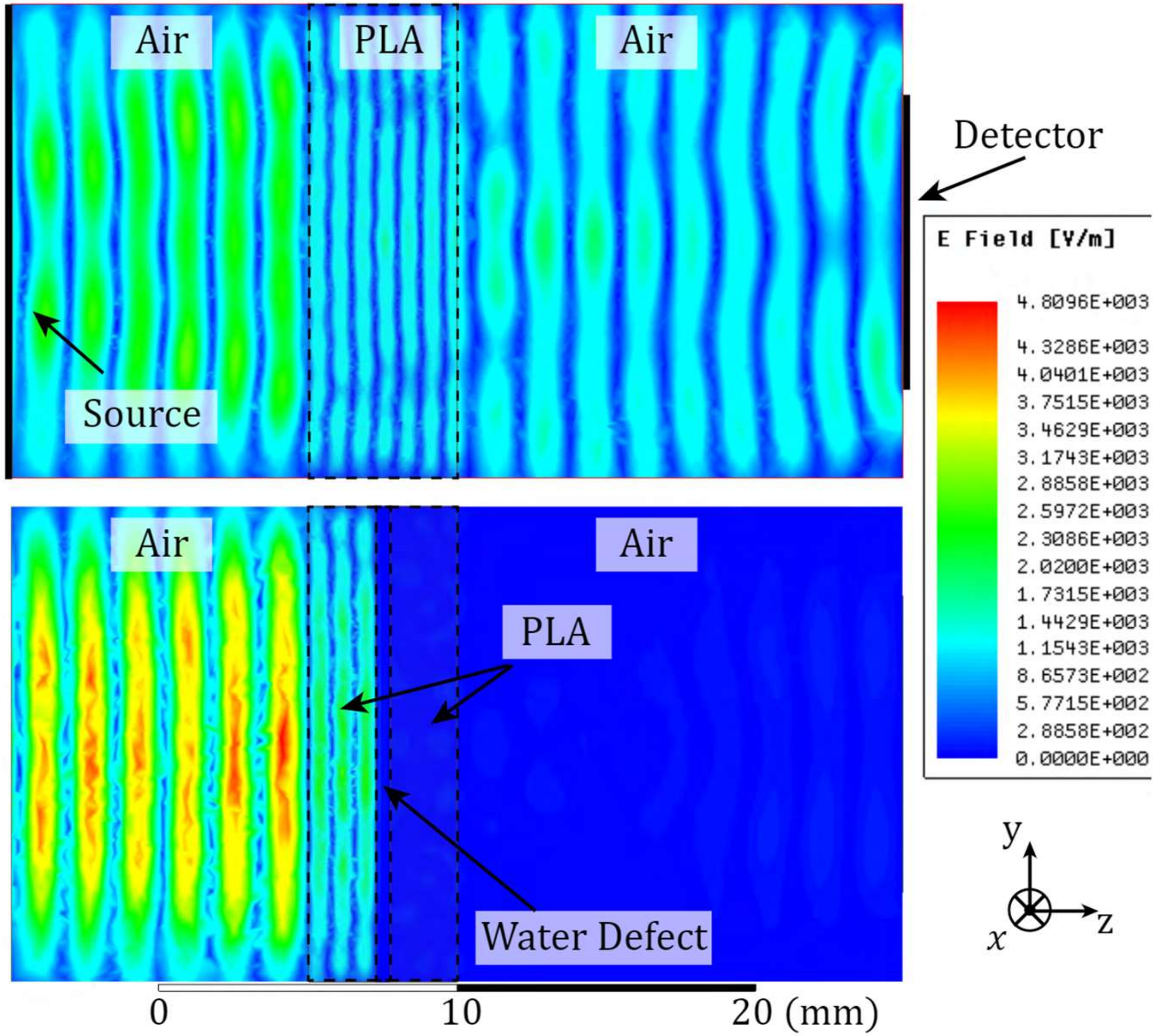


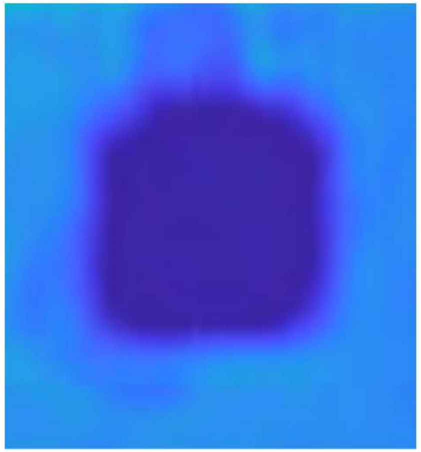
Numerical Simulations



Copper Wire Image

Numerical Simulations





Water Infiltration
THz Image

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Continuous wave terahertz imaging for NDT: Fundamentals and experimental validation

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Polymers

ABSTRACT

Continuous wave terahertz (CW THz) imaging, is a variant of terahertz imaging that has been gaining scientific and technological relevance in multiple areas. In this paper the fundamental phenomena of CW THz were studied and a mathematical model was developed that successfully describes the Fabry–Perot interference for such a system, opening the possibility for measurement of thicknesses and surface curvatures. The capabilities of the system were tested using different types of defects, such as voids, water infiltrations and thin metallic wires. The interactions between different materials, features and the radiation beam were numerically studied using finite element method and the results agreed with the experiments. By comparing the results with other Non-Destructive Testing methods, it was found that CW THz imaging is particularly interesting to image water infiltrations and composite materials that incorporate conductive wires.

ECNDT 2023

FINAL ABSTRACT SUBMISSION DEADLINE

31 OCTOBER 2022

Thank you!

Telmo G. Santos
Full Professor
Advanced Manufacturing and Non-Destructive Testing

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