TECHNO-CLS

G.A. 101046458

WP4 - CLS TECHNOLOGY 2ND YEAR REPORT

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Objectives

- O4.1 Fabrication of high-quality bent and periodically bent crystals (silicon, germanium) by means of surface modification techniques. Extensive characterization of samples via XRD in parallel with their fabrication.
- O4.2 Optimization and characterization of the PLM (Pulsed Laser Melting) process to fabricate surface localized stressor alloys on Si and Ge surface; realization of PLM processed PC and PBC optimised for gamma emission.
- O4.3 Experimental determination of AW generation and propagation in crystals; monitoring dynamic bending of the crystals.
- O4.4 Feasibility studies on laser pulse AW generation and propagation; monitoring the dynamic bending of the crystals. ->completed in the 1st year
- O4.5 Periodically bent Si-Ge superlattices with parameters suitable for channeling experiments with e- and e+-beams -> see Rébecca Dowek's talk

Objective O4.1-2
Static BC and PBC

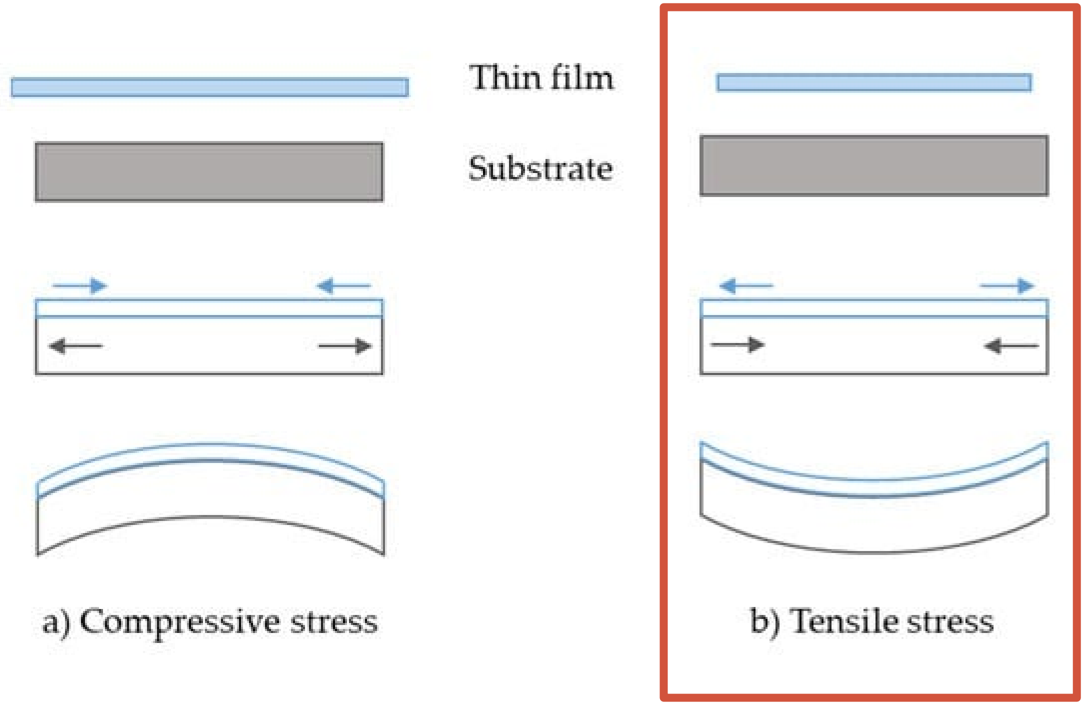
- **O4.1 Fabrication of high-quality bent and periodically bent crystals (silicon, germanium) by means of surface modification techniques. Extensive characterization of samples via XRD in parallel with their fabrication.**
- **O4.2 Optimization and characterization of the PLM (Pulsed Laser Melting) process to fabricate surface localized stressor alloys on Si and Ge surface; realization of PLM processed PC and PBC optimised for gamma emission.**
- O4.3 Experimental determination of AW generation and propagation in crystals; monitoring dynamic bending of the crystals.

Bent Crystals by surface modification (BCs)

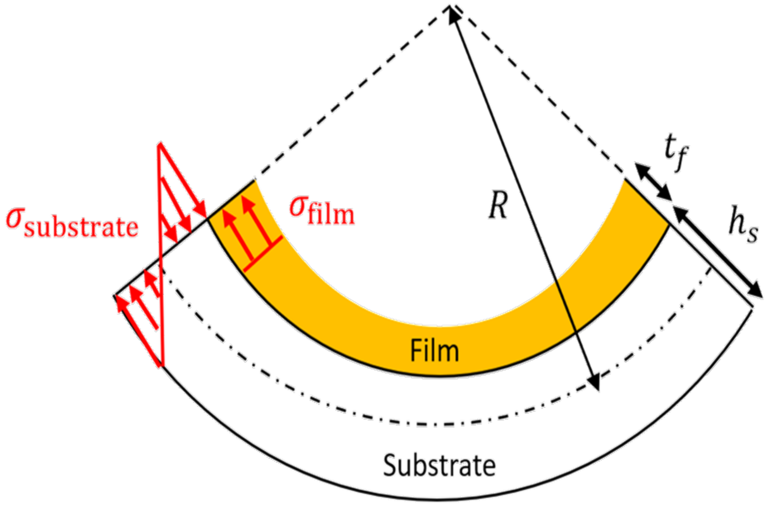
BCs

Thin film deposition:

Si_3N_4 - INFN&UNIFE



Lanzoni, Mazzolari, Guidi, Tralli, Martinelli, «On the mechanical behaviour of a crystalline undulator», Int. J. Eng. Sci., Volume 46, Issue 9, (2008)



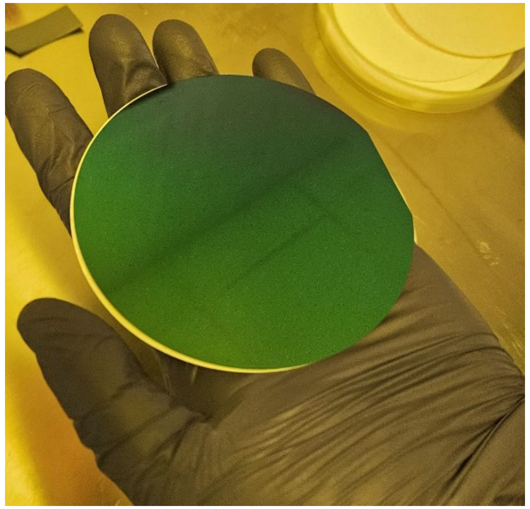
- **Deposition of thin layer of Si_3N_4 (Silicon Nitride) occurring at high temperature (~1000 °C)**
- Mismatch in Thermal Expansion Coefficient between Si substrate and thin film give raise to a thermal stress following the Stoney law:

$$\sigma_f = \frac{\overline{E_s} h_S^2}{6 R t_f}$$

BCs

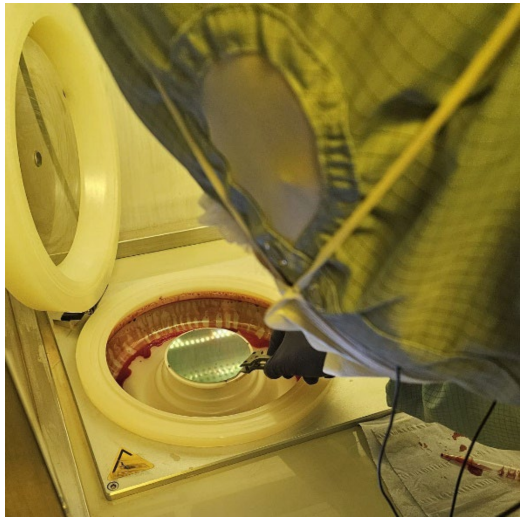
Bent Crystals with self-standing curvature

Evaluation of film deposition:



2 Sides Si_3N_4

Photoresist
1 side
+
BHF solution



1 Side Si_3N_4

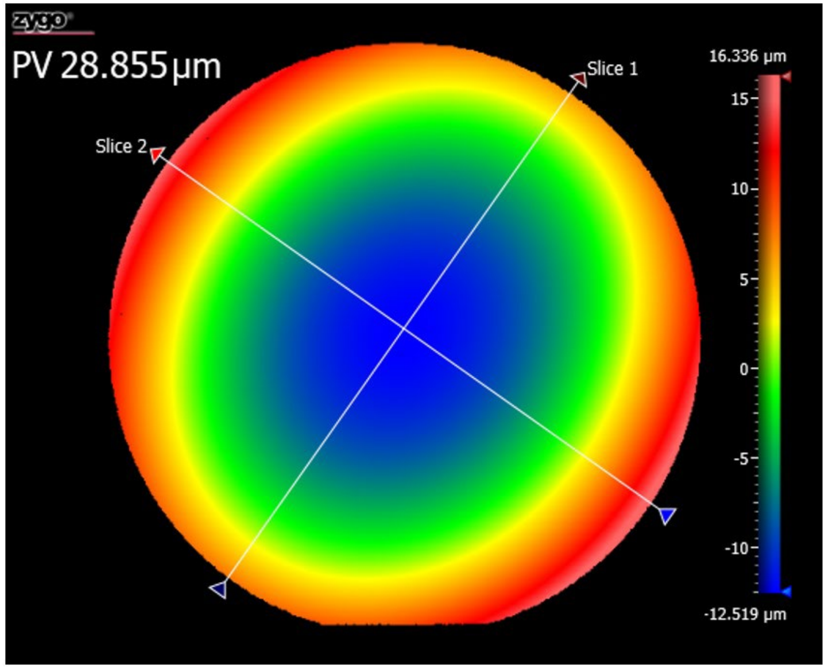
Optical Interferometry Zygo NX2:
Profile analysis of the physical surface of the sample with vertical precision ~ 1 nm

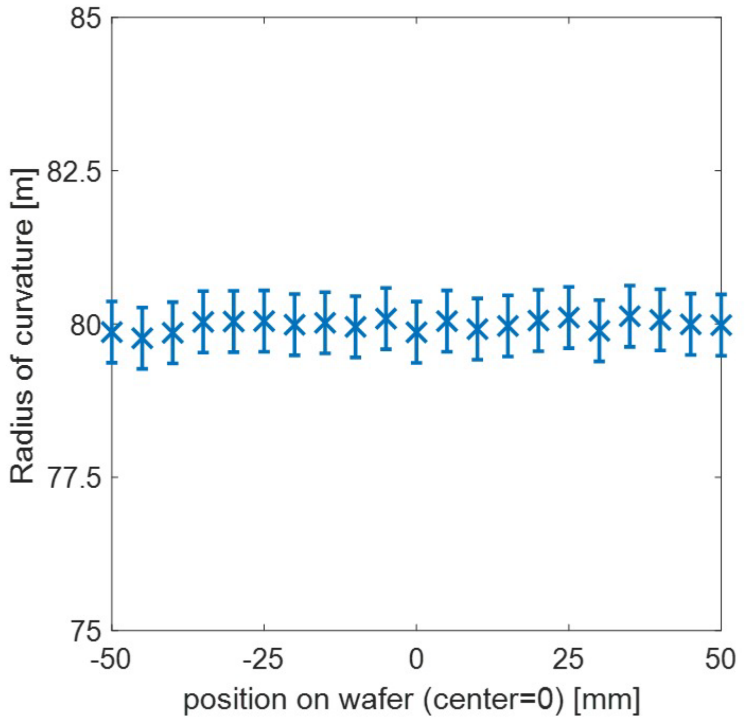
Quality control of film deposition:
Thickness of Silicon Nitride $\approx 400nm$

* Strauss Model: On the mechanical behaviour of a crystalline undulator, L. Lanzoni, A. Mazzolari, V. Guidi, A. Tralli, G. Martinelli, International Journal of Engineering Science, 46, 917-928 (2008)

Bent Crystals with self-standing curvature

- Profile of the wafer surface was measured with Zygo VeriFire HDX interferometer
- X-rays diffraction with HR-XRD allowed quantitative analysis of the lattice planes of the wafer

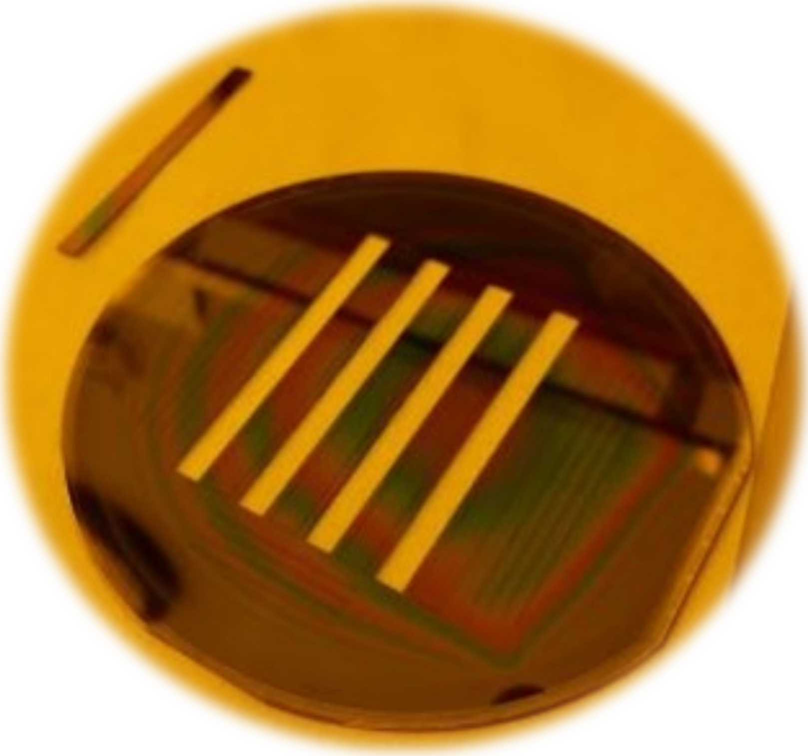


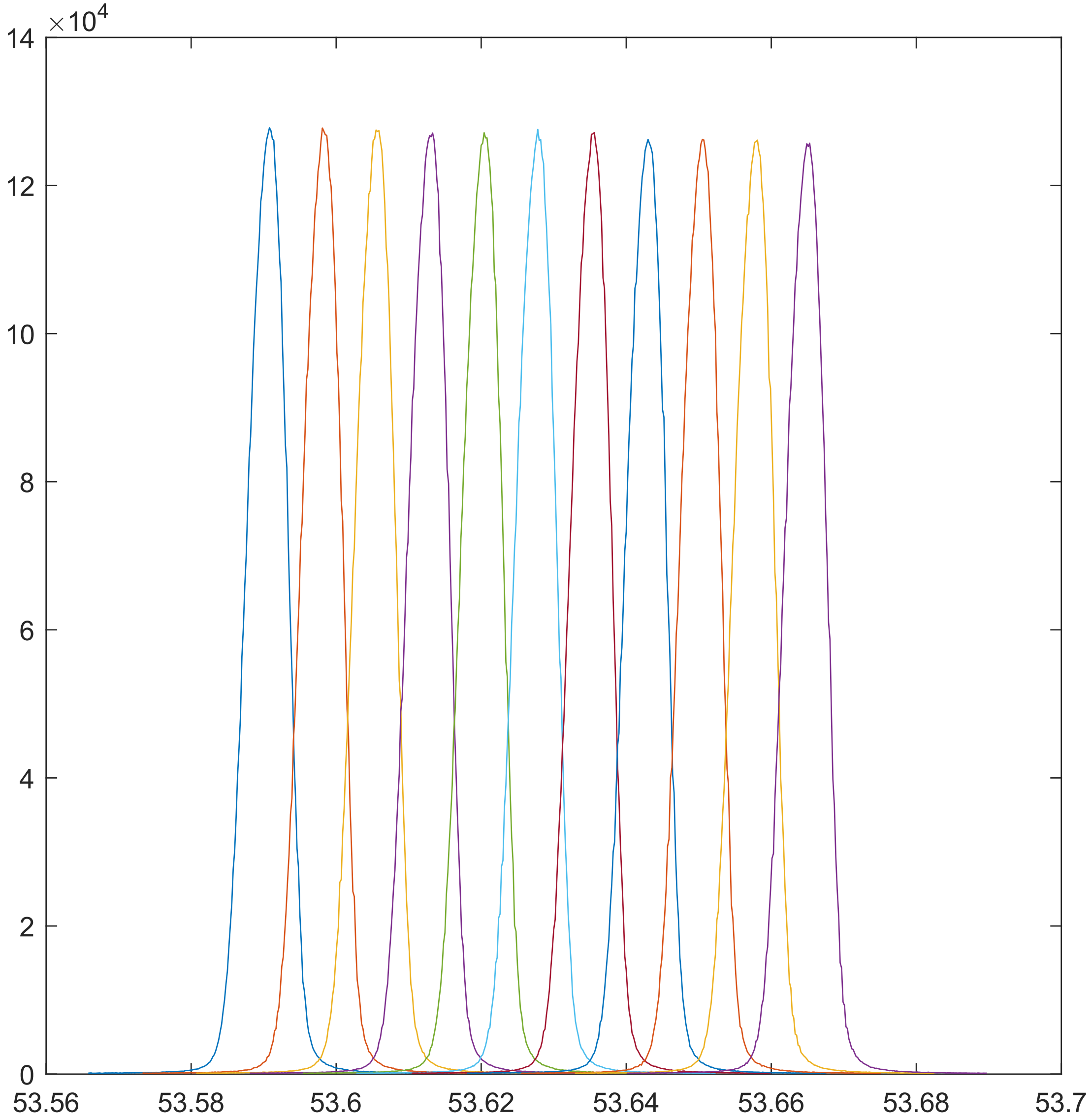


Bent Crystals with self-standing curvature

BCs

Silicon sample produced 0.5x4x55m^3, bending characterized with HR-XRD: predicted channeling deflection of the beam of 60μrad (adapted for multi-GeV beams)

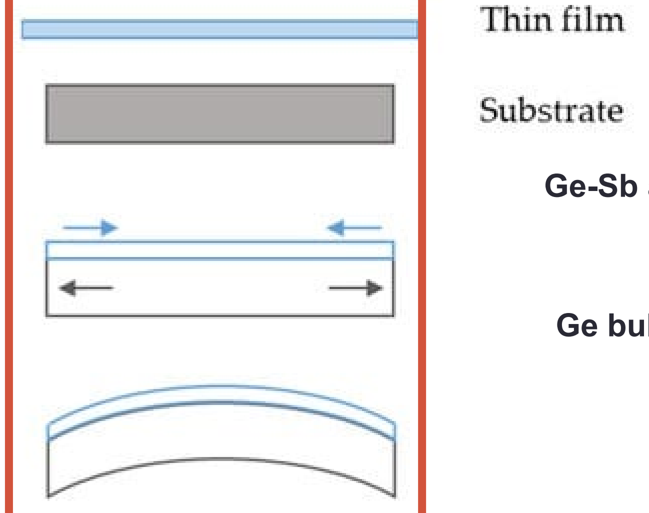




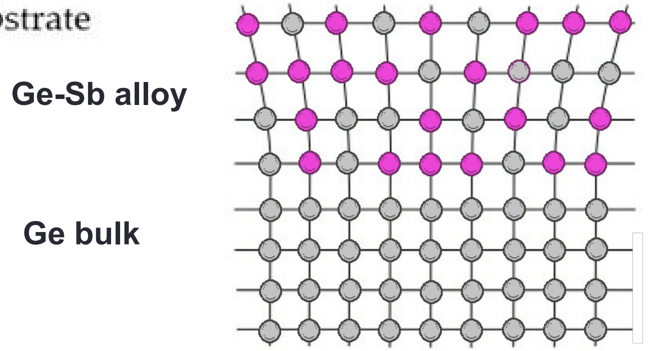
Ge Bent Crystals by PLM surface modification (BCs)

BCs

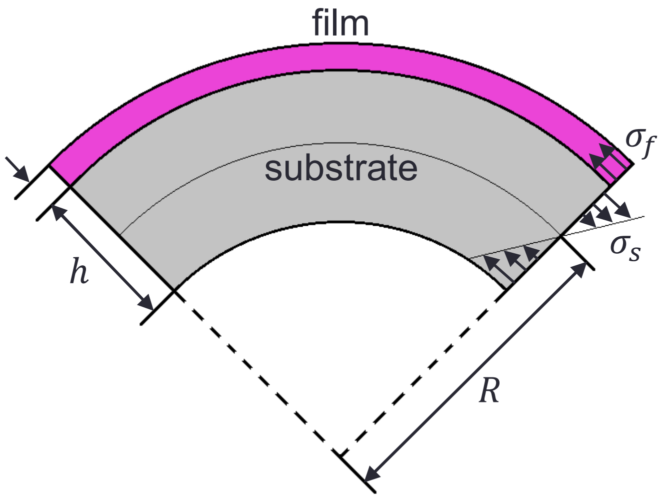
Sb_xGe_{1-x} - UNIPD



a) Compressive stress



$$f = \frac{a_f - a_s}{a_s}$$

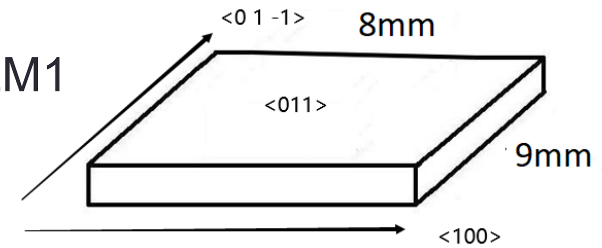


- **Creation of a Sb_xGe_{1-x} thin film by Sb sputtering and Pulsed Laser Melting process that forms a coherent epitaxial constraint.**
- Integrated misfit between the film and the Ge substrate induces curvature:

$$\int f \, dt_f = \frac{h_S^2}{6R}$$

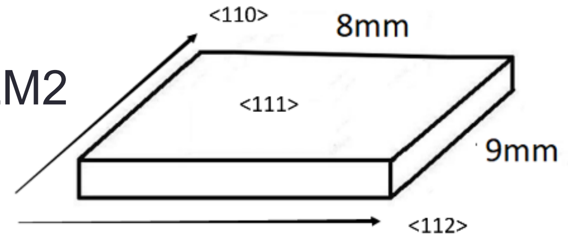
UNIPD – PLM self-standing curved crystals

BC-Ge-PLM1



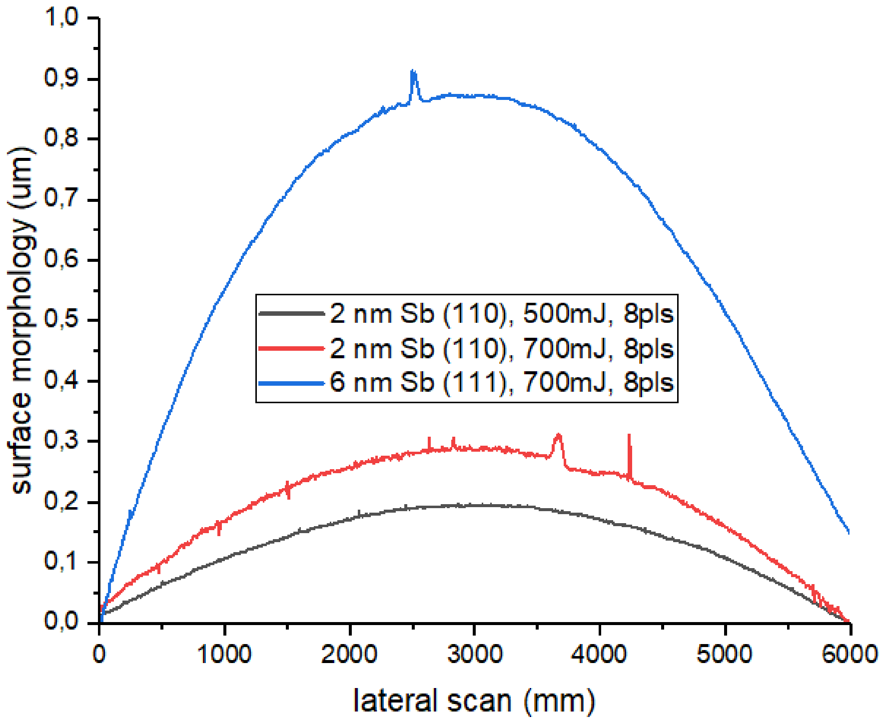
Ge (110)

BC-Ge-PLM2



Ge (111)

Crystal id.	Plane	Max $\int f dt_f$ (HRXRD) nm	h_S (mm)	R (Stoney + HRXRD) m	R (Stylus prof.) m
BC-Ge-PLM1	(110)	0.46	0.20	14.5	16.6
BC-Ge-PLM2	(111)	0.80	0.15	4.6	4.5

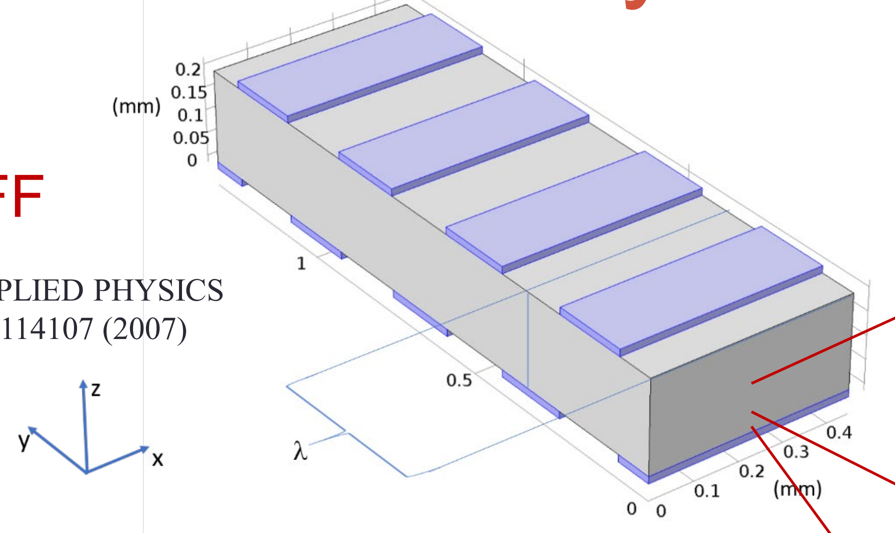


Periodic stressor layers: 2 patterning designs for
STATIC Periodically Bent Crystal

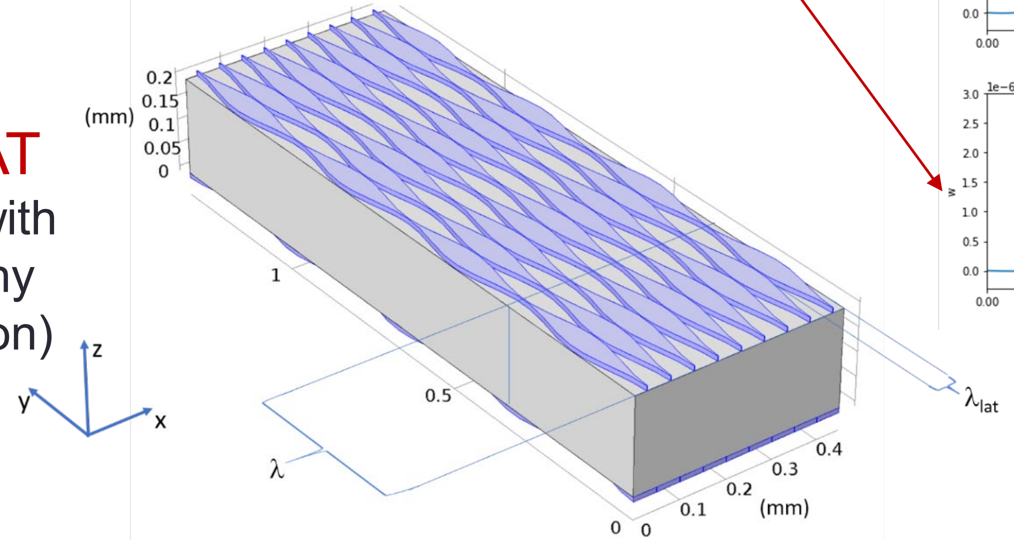
PBCs

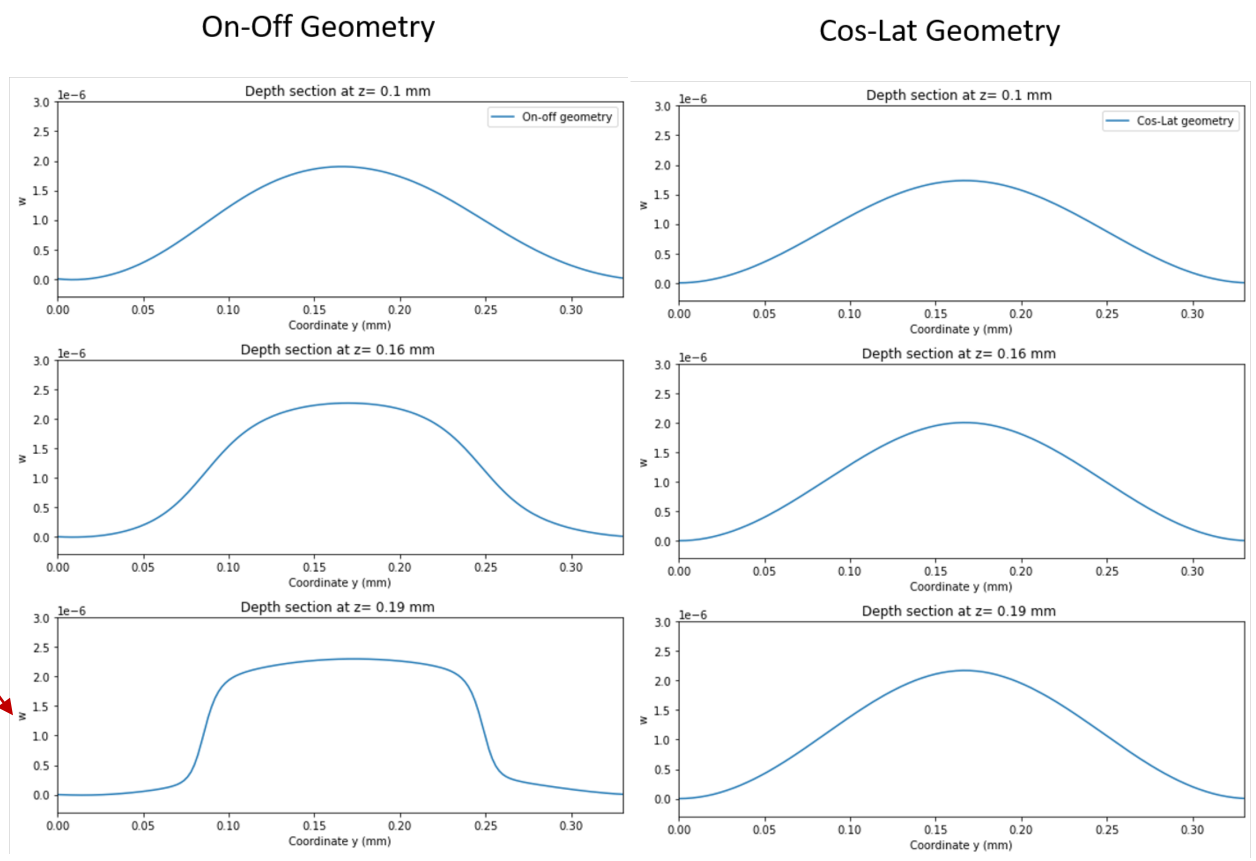
ON/OFF

V. Guidi et al. APPLIED PHYSICS LETTERS **90**, 114107 (2007)



COS/LAT
(feasible with lithography optimization)





λ_{Lat}=25 μm

Patenting of Cos-Lat design with UNIPD, UNIFE, INFN technology transfer offices has been started

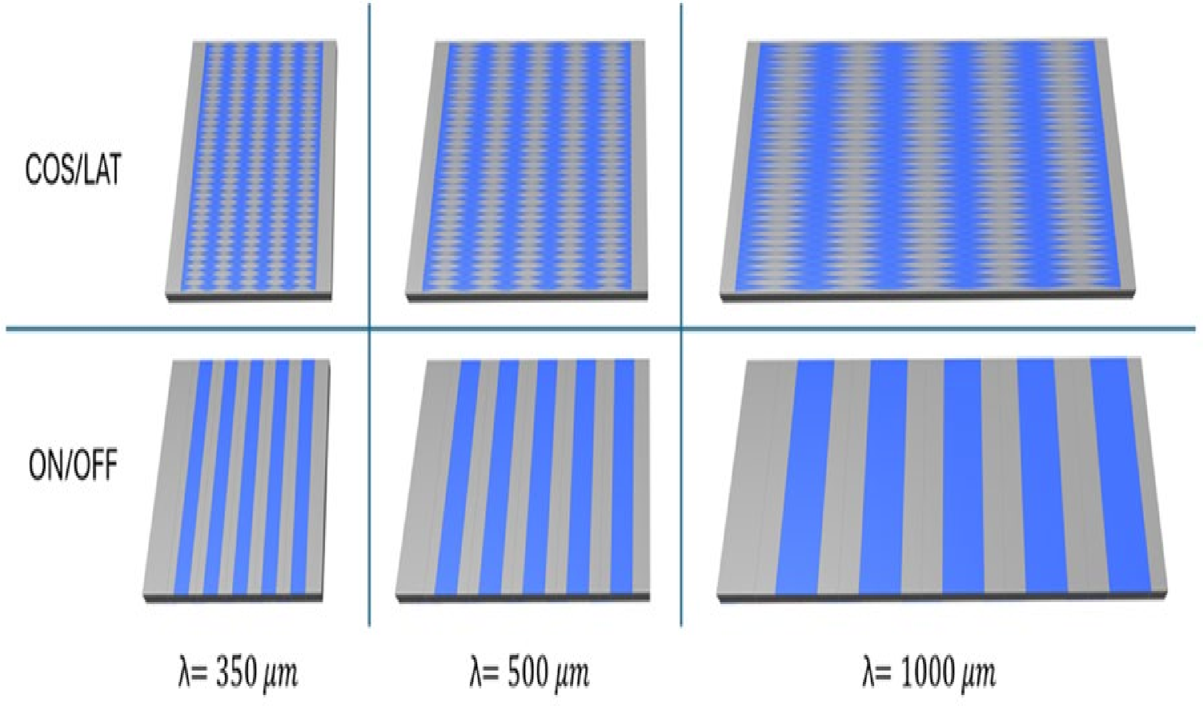
Periodically bent crystals (PBCs)

PBCs

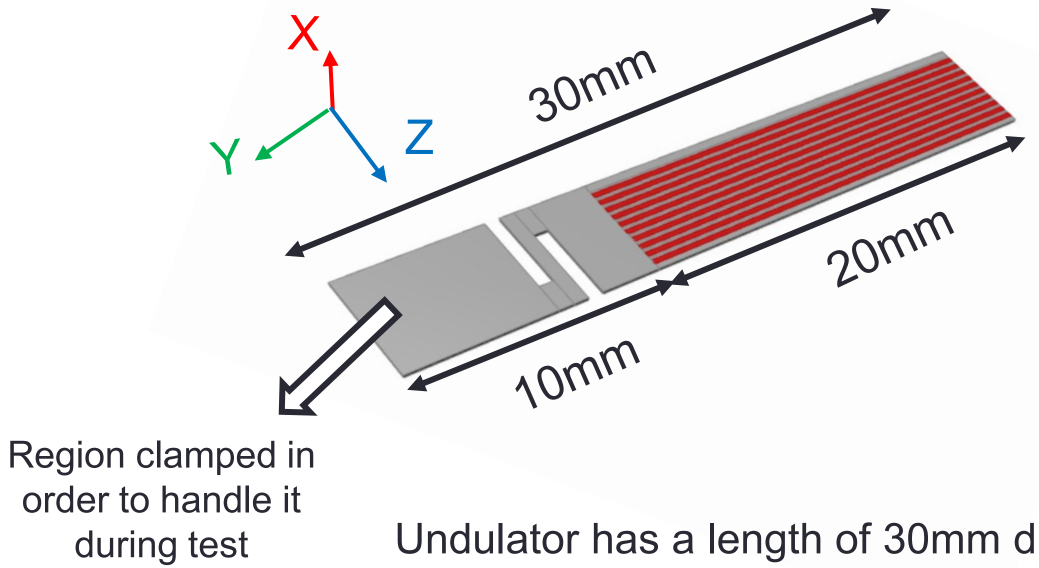
Prototypes manufacturing with both design patterning.

- $\lambda_{undulator}$ **from 300 to 1000 micron (>>** $\lambda_{channeling}$**)**
- **Amplitude from 10*d to 100*d** (d is the lattice constant)
- **Suitable for positron beam with energy > 1 GeV**

Optimization of parameters is obtained via FEM simulation both for ON/OFF and COS/LAT patterning



Example of real undulator design:



Undulator has a length of 30mm divided in:
- Support region of 10mm
- Active region periodically bent of 20mm

Periodically bent crystals (PBCs)

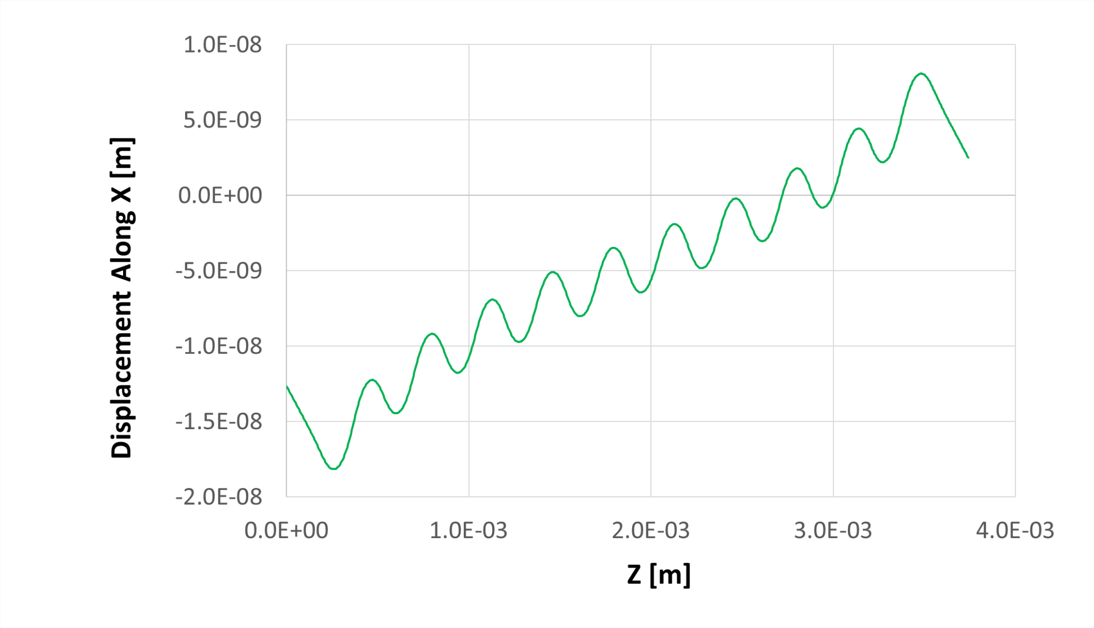
PBCs

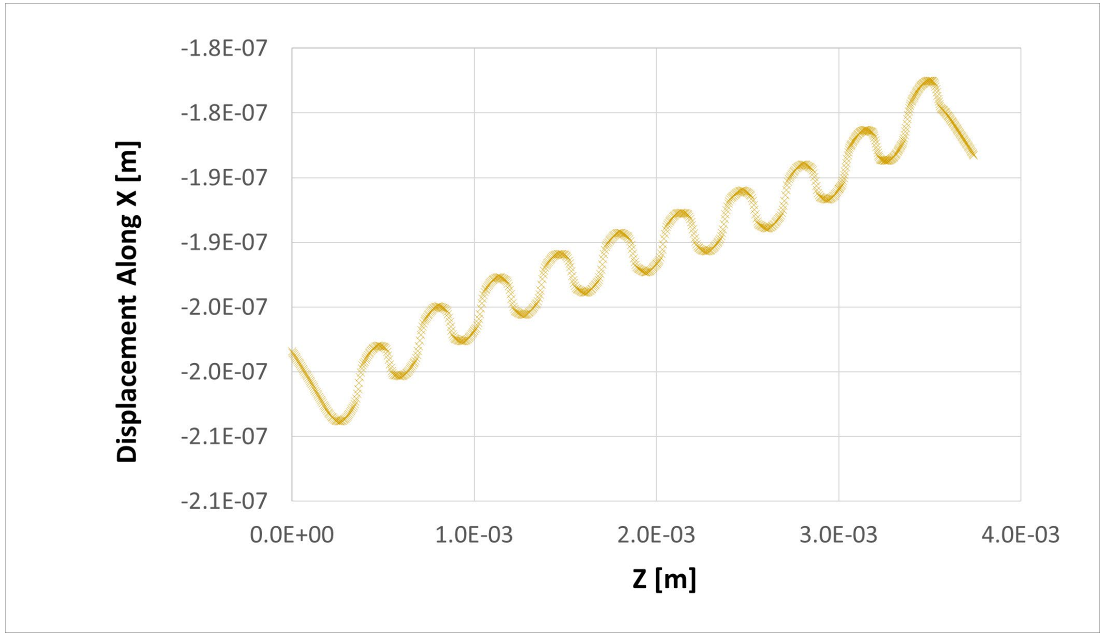
FEM simulation to obtain spectrum emission:

Activity in synergy with WP2

Example of deformation for ON/OFF undulator:

Middle height of undulator → harmonics ↑ → At 200um to the surface of undulator





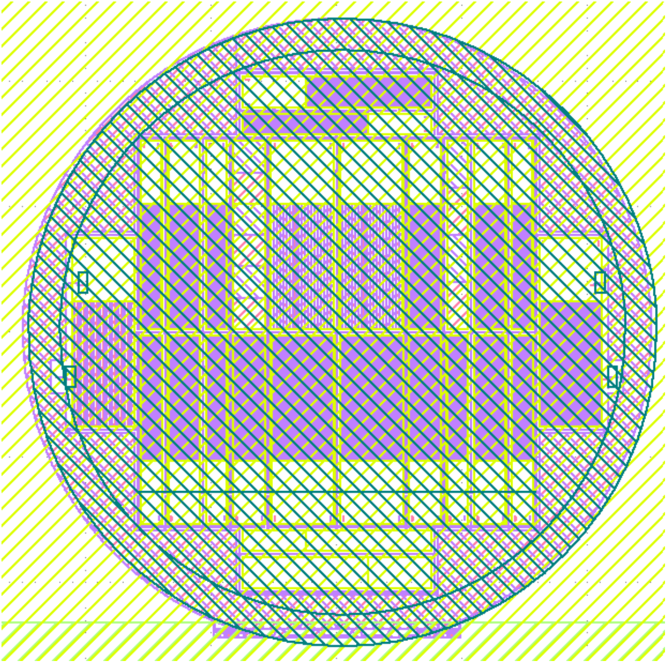
For each undulator has been performed FEM simulation obtaining the deformation amplitude at different height (0 to 160um) along the beam direction in order to simulate **the emission spectrum using MBN software for 10-20 GeV positrons (LALP CU)**

Litography of Silicon Nitride tensile PBCs

PBCs

Prototypes of mask for photolithography:

For one wafer 2 masks, one for each sides is necessary →
In order to produce all different prototypes, 4 masks have been manufactured



Masks 1A+1B:

Number of periods:	Period (um)	334	500	1000
10	ON/OFF	5	5	3
	COS/LAT	5	5	3

Masks 2A+2B:

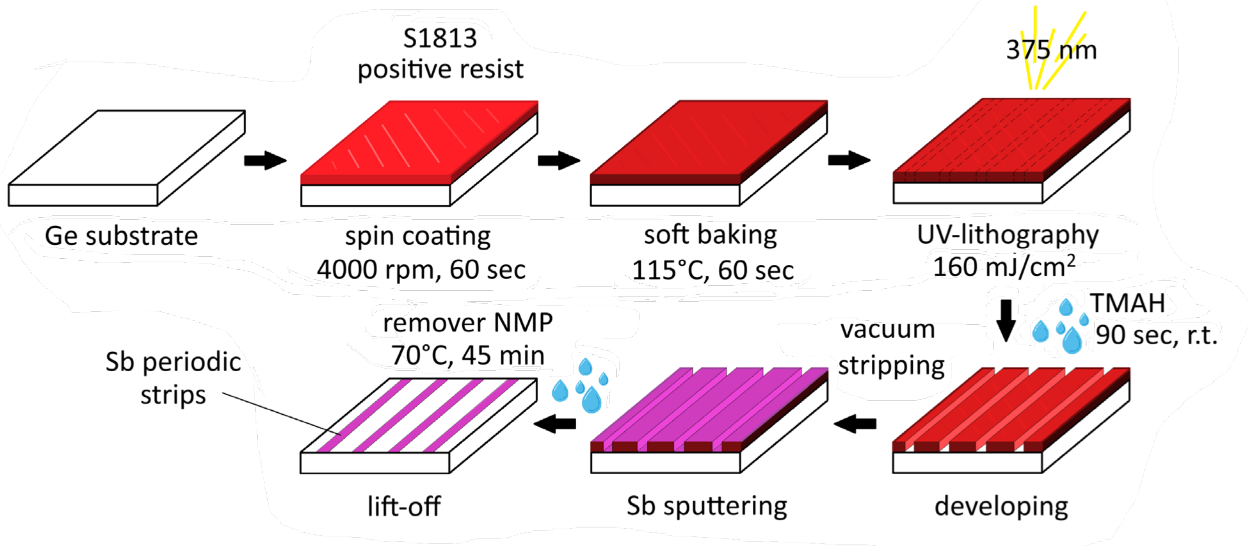
Number of periods:	Period (um)	334	500	1000
5	ON/OFF	3	3	3
	COS/LAT	4	3	3

Number of periods:	Period (um)	334	500	1000
3	ON/OFF	3	4	3
	COS/LAT	4	3	3

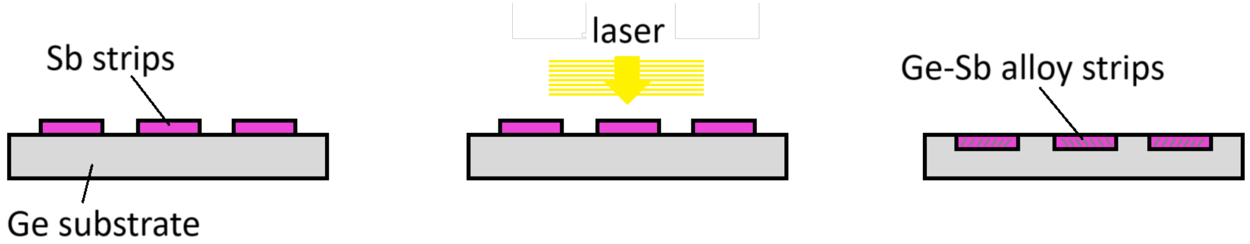
1 undulator of 4 periods of 7.5mm
1 undulator of 6 periods of 5mm
→ To evaluate the agreement with FEM simulation and validate it by interferometer measurements

Number of periods:	Period (um)	334	500	1000
2	ON/OFF	3	4	3
	COS/LAT	4	3	3

PLM PBC patterning: processing design and optimization



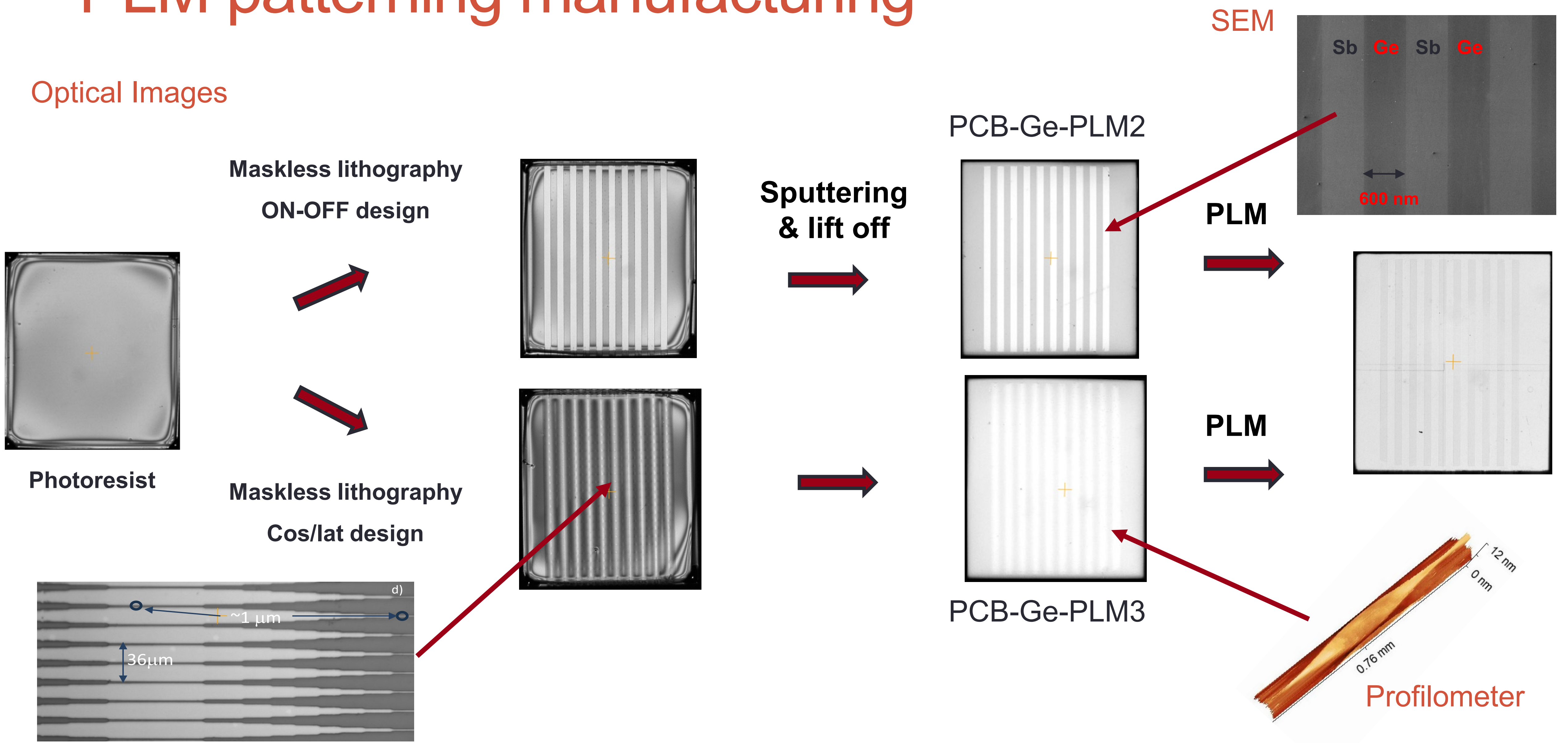
Lithographic process (S1813 commercial resist) adapted and optimized for our system



PLM treatment: optimized laser parameters from self-standing curvature study

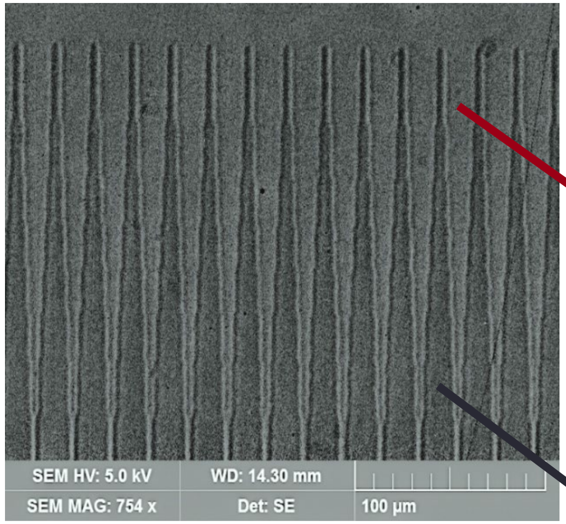
Rotate the sample and **repeat** again the same procedure on the **other face** with a controlled offset (half period)

PLM patterning manufacturing

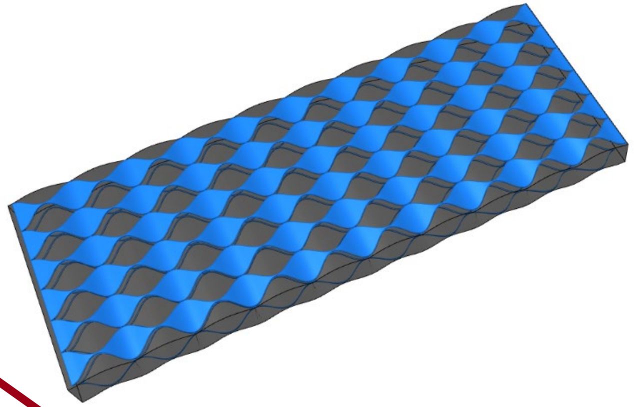


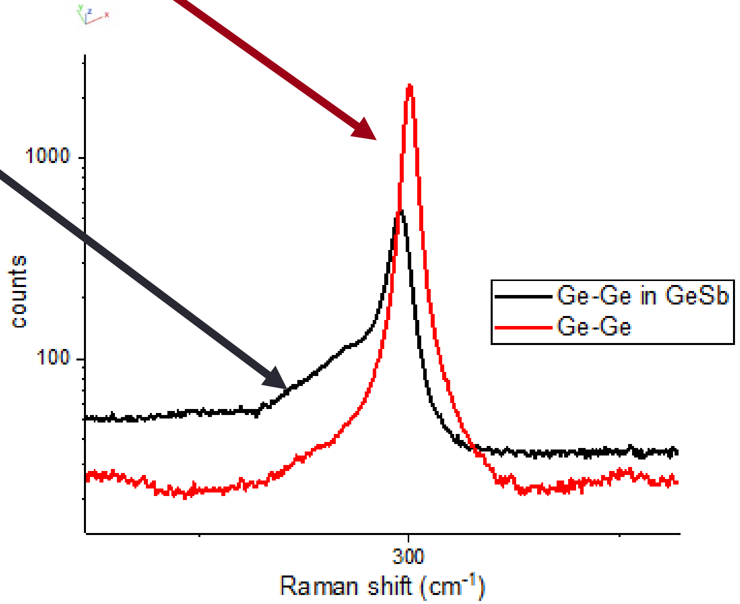
UNPD undulator characterizations

The local strain can be monitored by looking the raman shift of Ge-Ge streching peak.

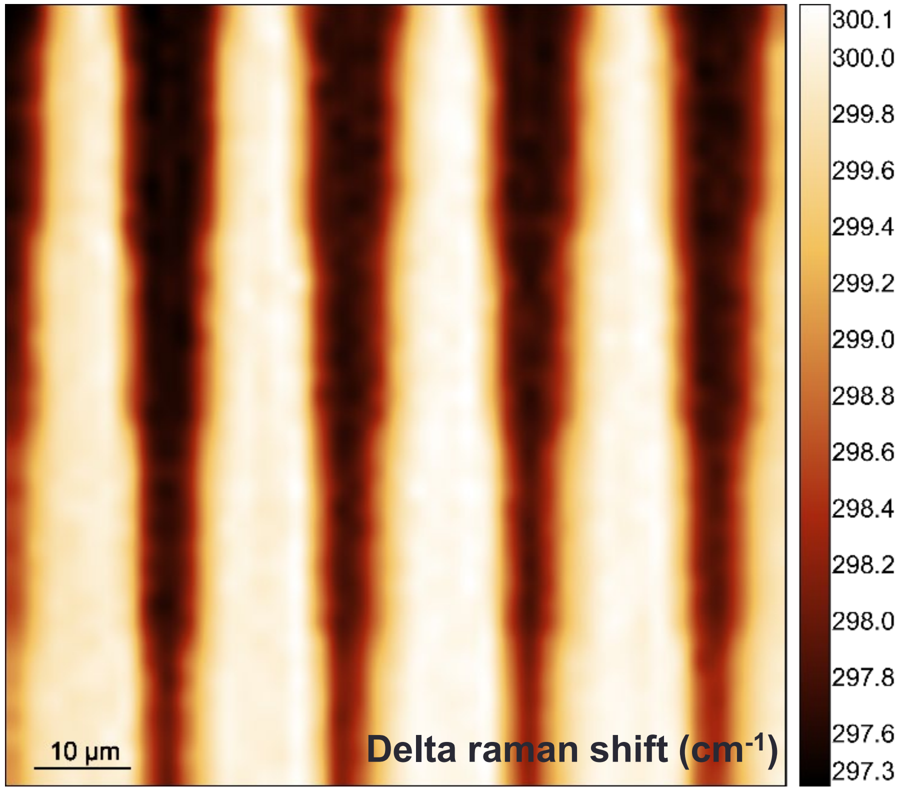


SEM imaging after PLM





RAMAN MAP



Leader

HELLENIC MEDITERRANEAN UNIVERSITY

Objective O4.3 Dynamic PBC

- O4.1 Fabrication of high-quality bent and periodically bent crystals (silicon, germanium) by means of surface modification techniques. Extensive characterization of samples via XRD in parallel with their fabrication.
- O4.2 Optimization and characterization of the PLM process to fabricate surface localized stressor alloys on Si and Ge surface; realization of PLM processed PC and PBC optimised for gamma emission.
- **O4.3 Characterization of crystalline samples under sinusoidal excitation at various frequencies from 1MHz to 15MHz and 25MHz to 60MHz**

Acoustic Wave Crystalline Undulators

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- Experimental detection and characterization of acoustically induced modulation of the lattice in crystal samples

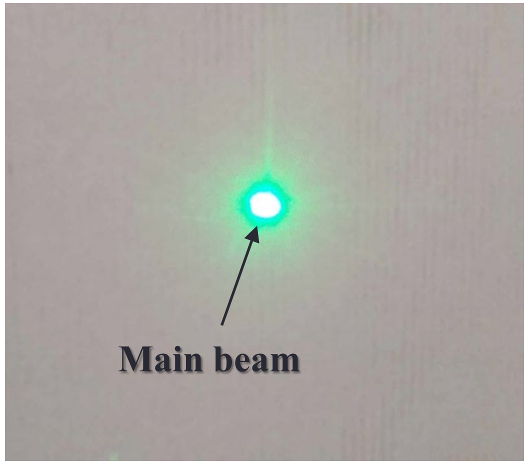
- Development and calibration of diagnostic systems
  - ***Acoustic wave detection***
    - *CW laser beam deflection*
    - *CW laser optoacoustic Bragg scattering*
  - ***Acoustic wave characterization***
    - *Nanosecond laser interferometry*
    - *Nanosecond laser refractive imaging*
      - *Computational model*

Development of Acoustic wave detection techniques

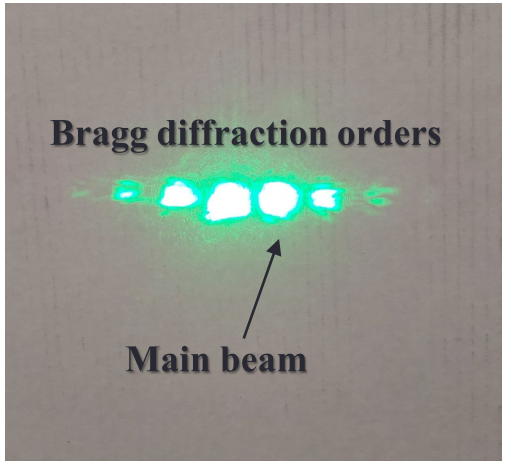
Detection of Traveling Acoustic Waves (AWs) in crystals generated by MHz piezoelectric transducers

a) CW Laser Bragg diffraction by MHz acoustic grating

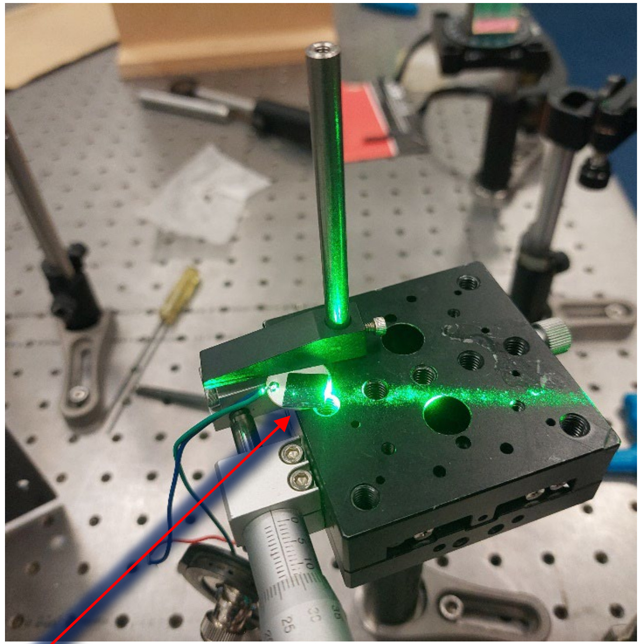
No excitation

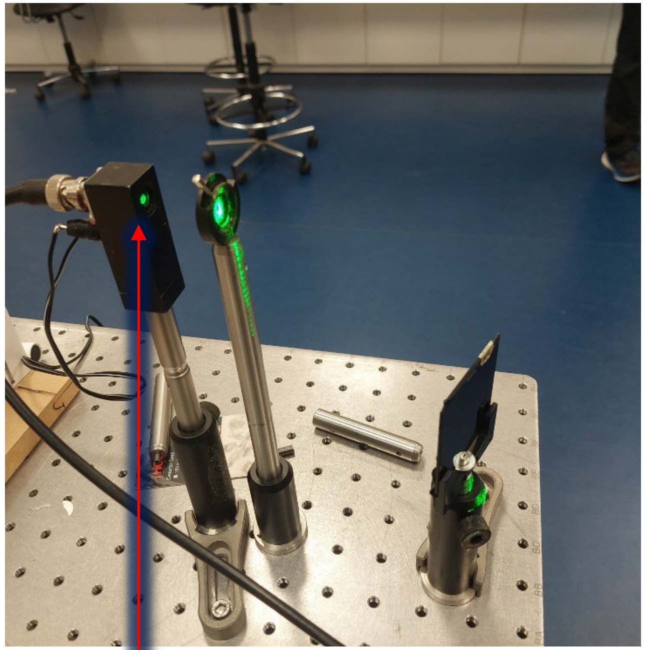


With excitation



b) CW Laser beam deflection by MHz oscillating piezos





532 nm laser beam deflection from Si crystal

Ultrafast picosecond photodiode

Imaging of Travelling MHz AWs by Nanosecond Laser Interferometry:

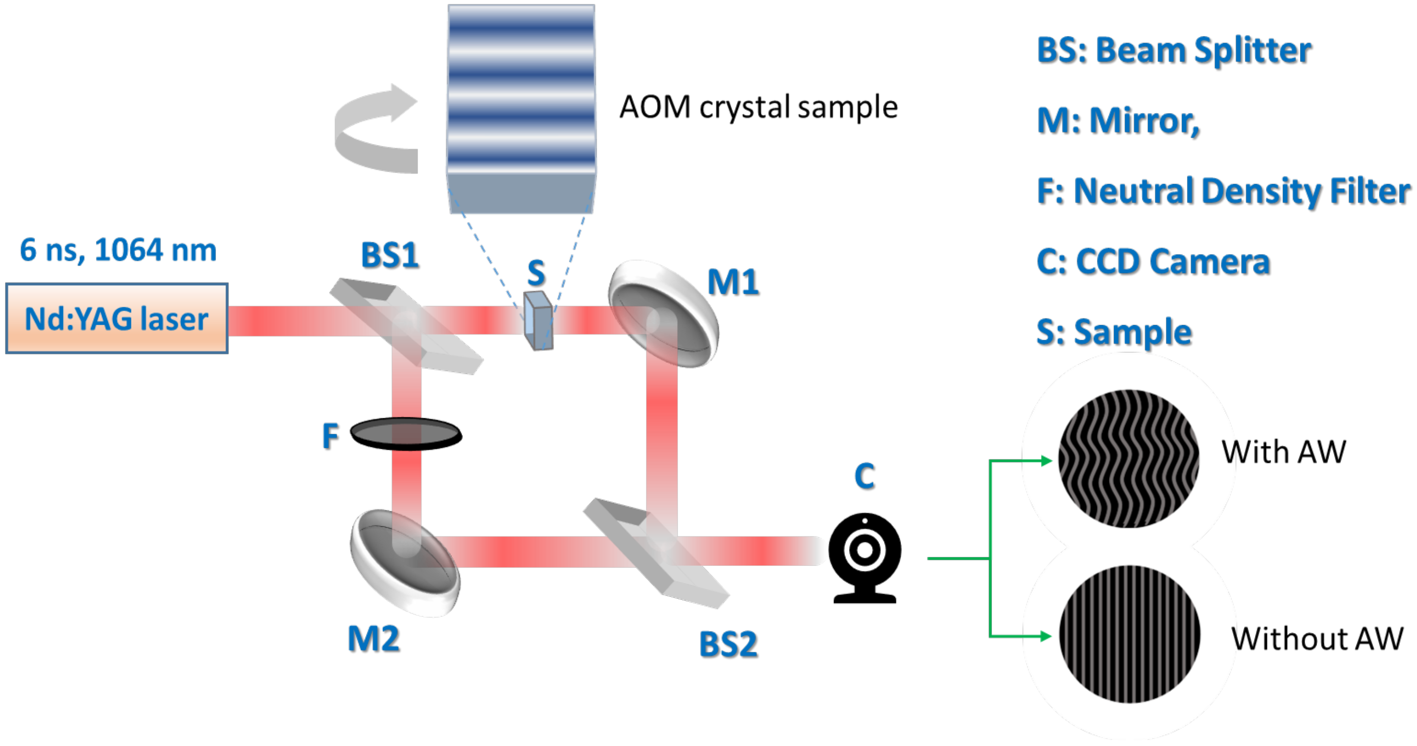
Principle of operation and setup

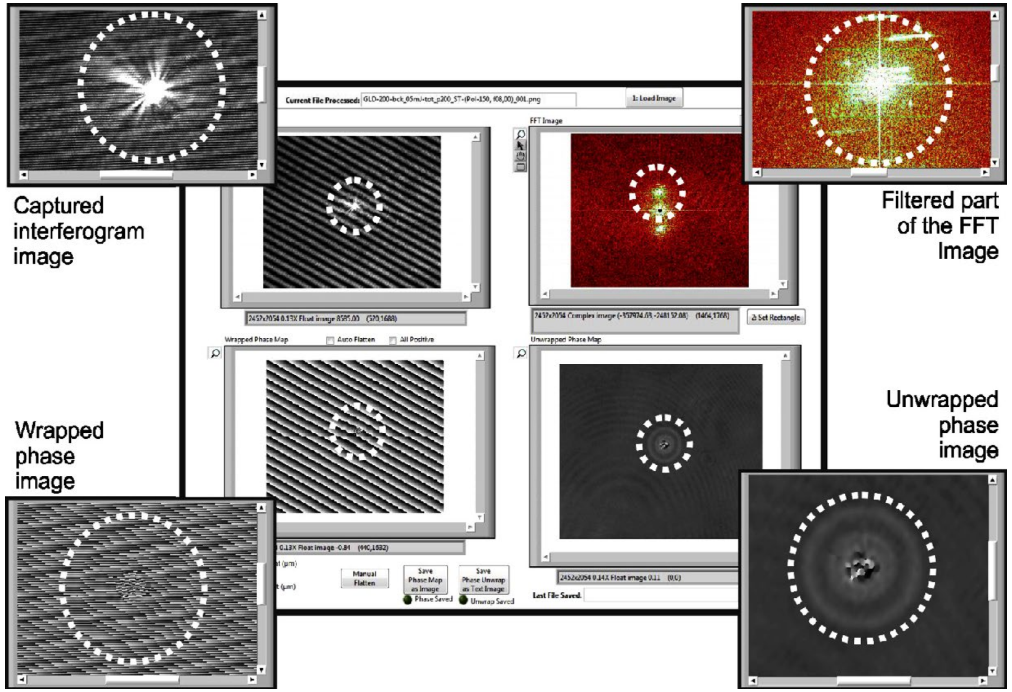
- **Imaging Optical interferometry system based on the Mach–Zehnder setup**
- **High-resolution 2D imaging of the dynamic lattice modulation**

Fast probing with 6ns laser pulses

Capturing of effectively FROZEN travelling waves!!!

Schematic diagram of a nanosecond Mach Zehnder interferometer





Interface and process of fringe analysis software

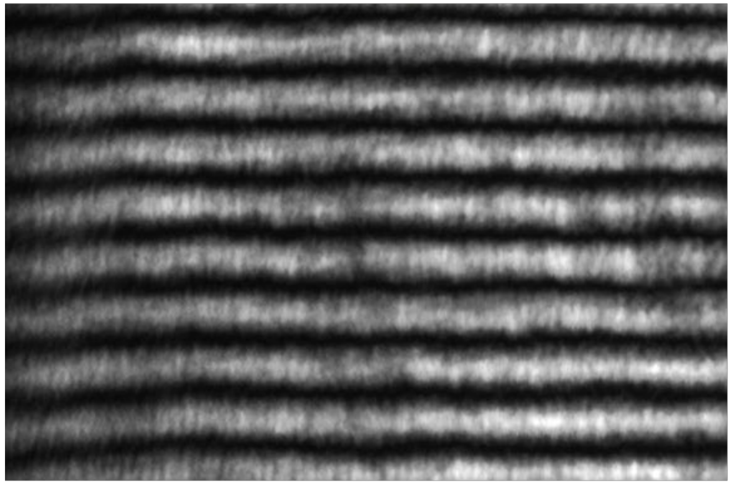
Imaging of Travelling AWs by Nanosecond Laser Interferometry:

Typical Proof of Principle Experimental Results on 5 cm Quartz Crystal

Analysis via in-house Image processing Software

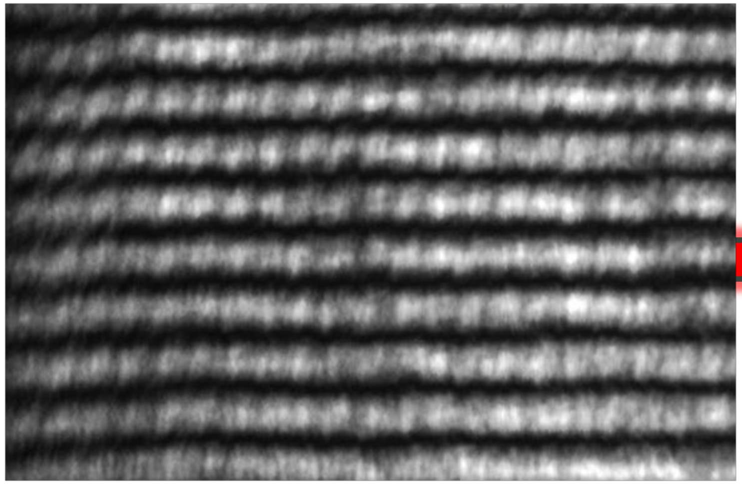
Acoustically excited Quartz crystal at 40.65 MHz

No excitation (Reference)



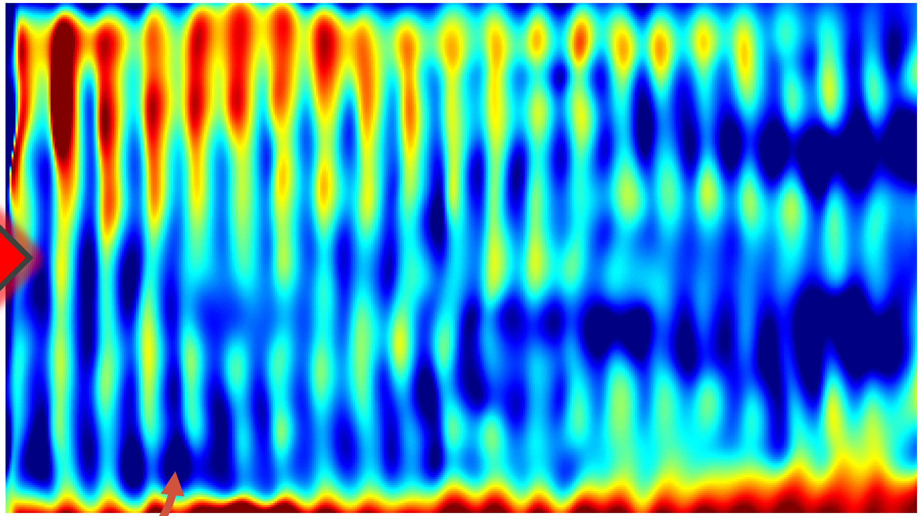
Unmodulated fringes

With excitation (Signal)



Modulated fringes

f = 40.65 MHz, λ = 140 μm



Detected acoustic waves

FROZEN travelling AWs!!

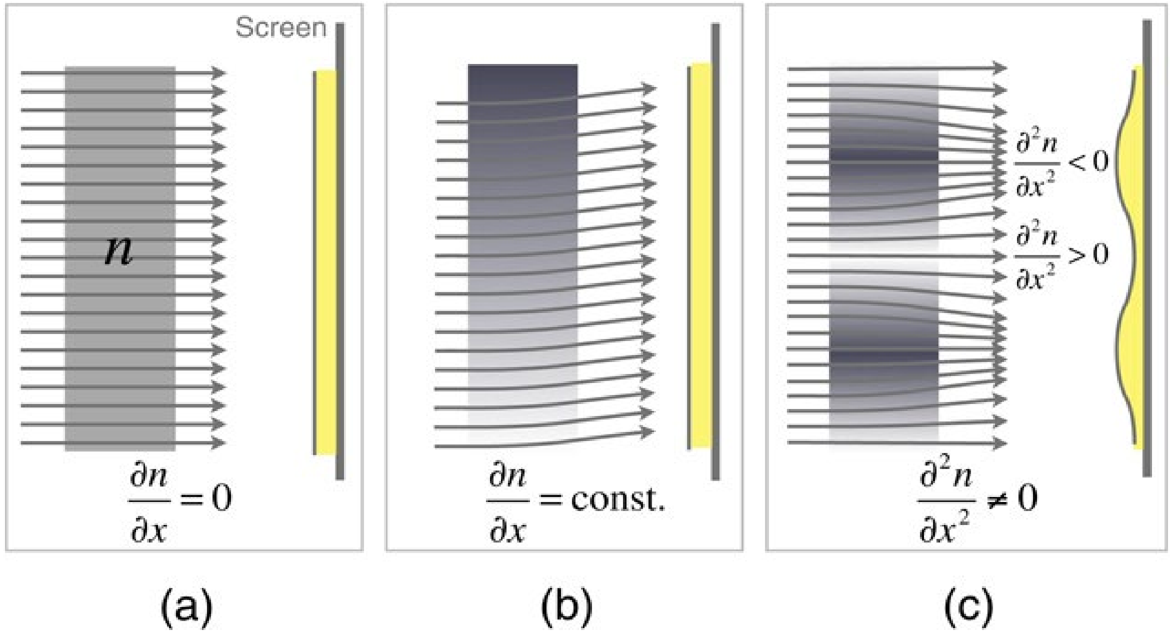
Nanosecond Refractive imaging of travelling AWs:

Principle of operation

a) *Homogenous refractive index*
   - *No laser deflection → Uniform illumination*

b) *Refractive index with homogenous gradient*
   - *homogenous laser deflection → Uniform illumination*

c) *Inhomogeneous refractive index gradient*
   - *Inhomogeneous laser deflection → Non-Uniform illumination*



*Nobuki Kudo 2015 Jpn. J. Appl. Phys. 54 07HA01

Acoustic waves propagation inside the crystal →

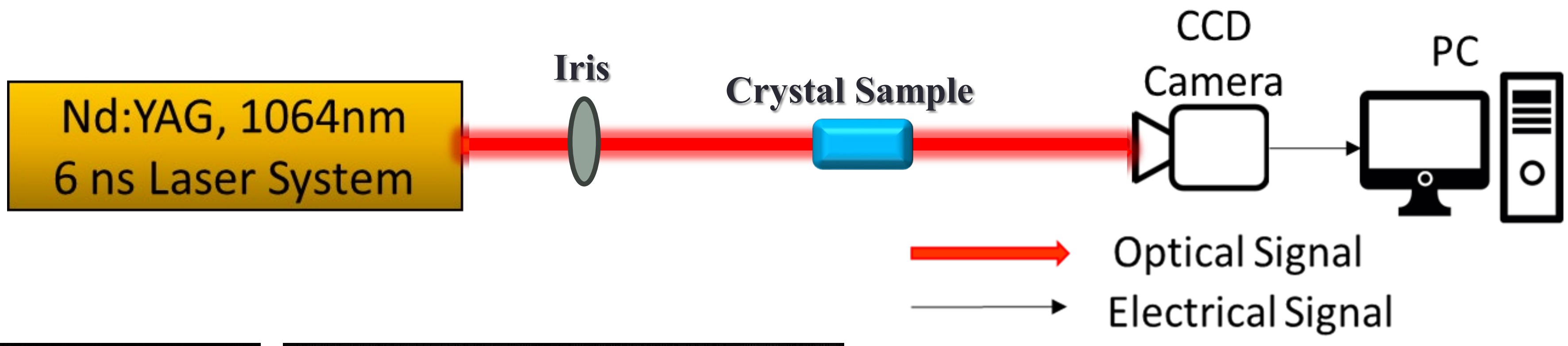
Sinusoidal modulation of the refractive index perpendicularly to the probe beam propagation axis →

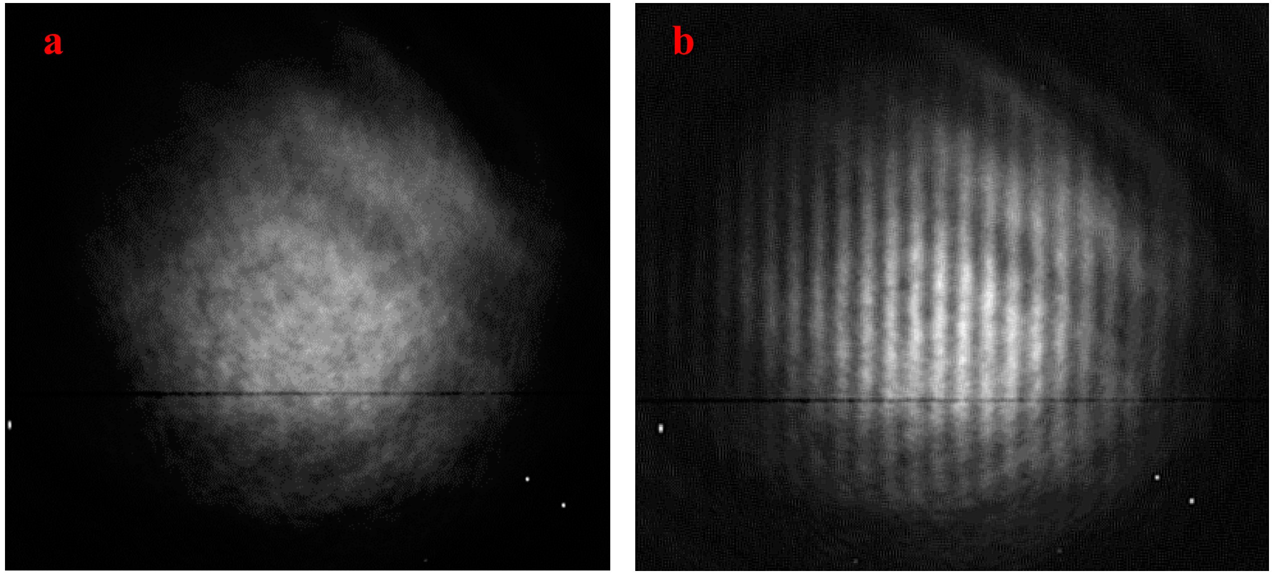
Modulation of the laser intensity distribution on the camera!

Nanosecond Refractive imaging of travelling AWs:

Typical Experimental Results on thick Crystal

Schematic diagram of the nanosecond refractive imaging technique setup





Intensity distribution on imaging camera of

a) Unmodulated Quartz crystal

b) Acoustically modulated Quartz crystal

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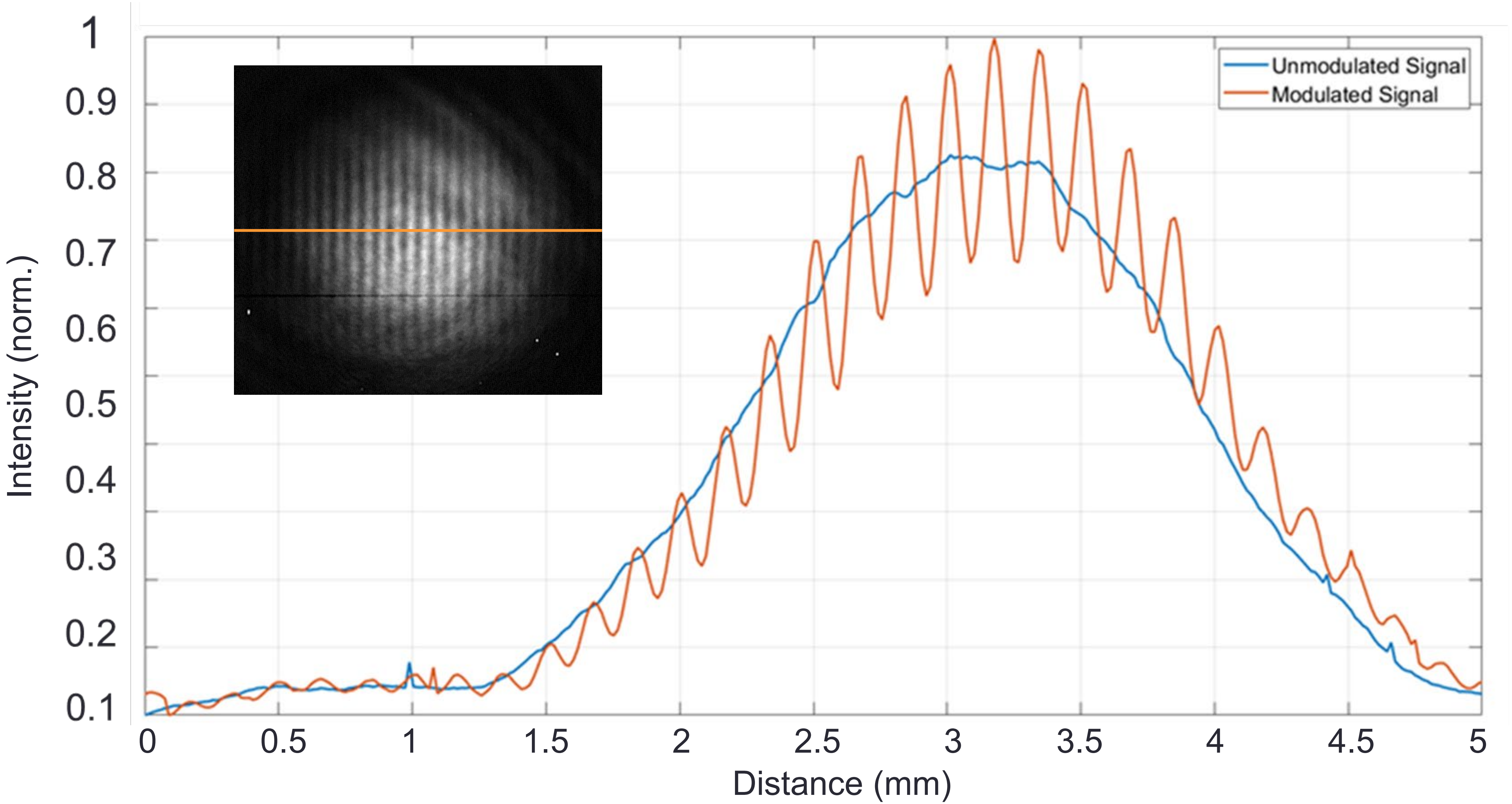
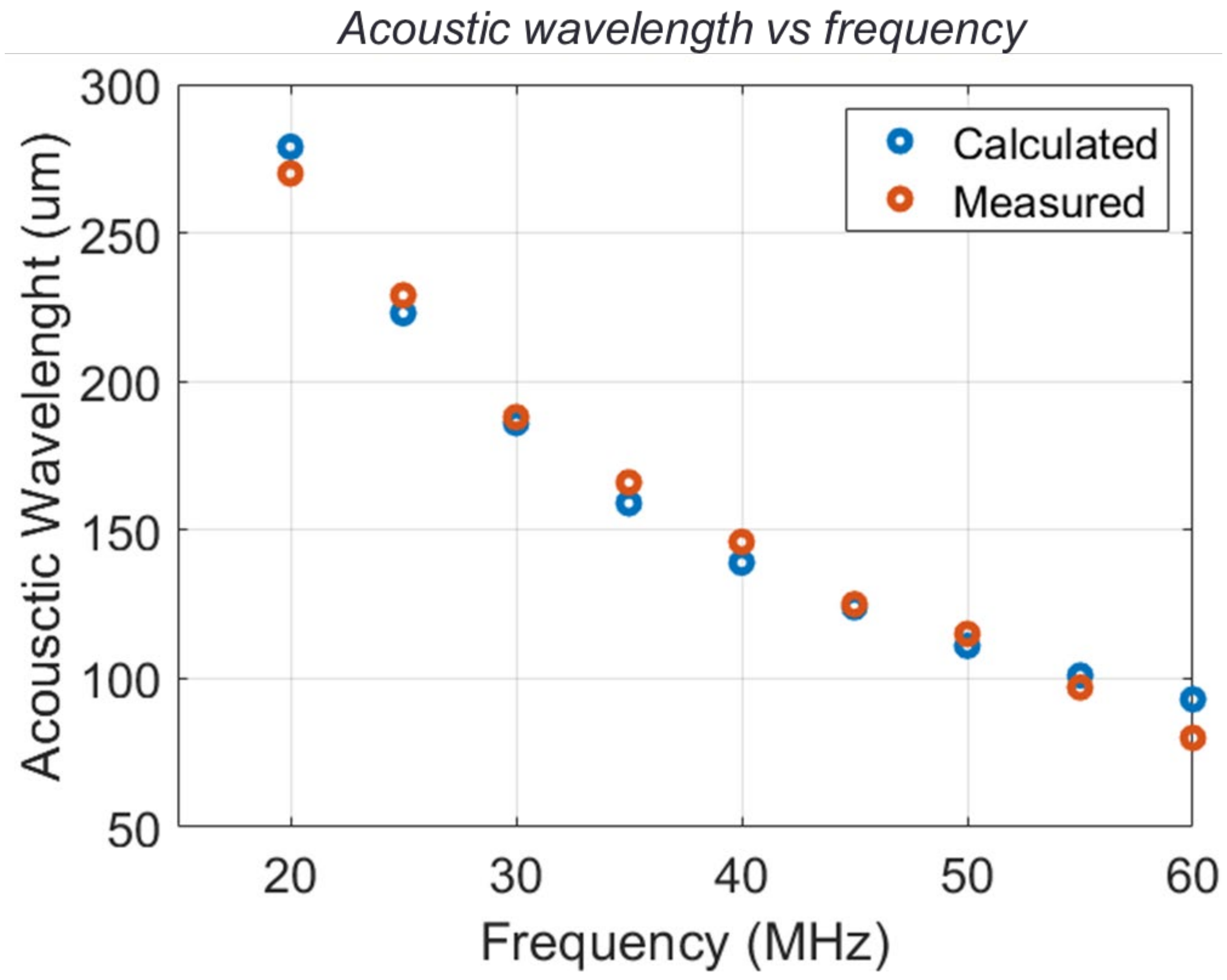
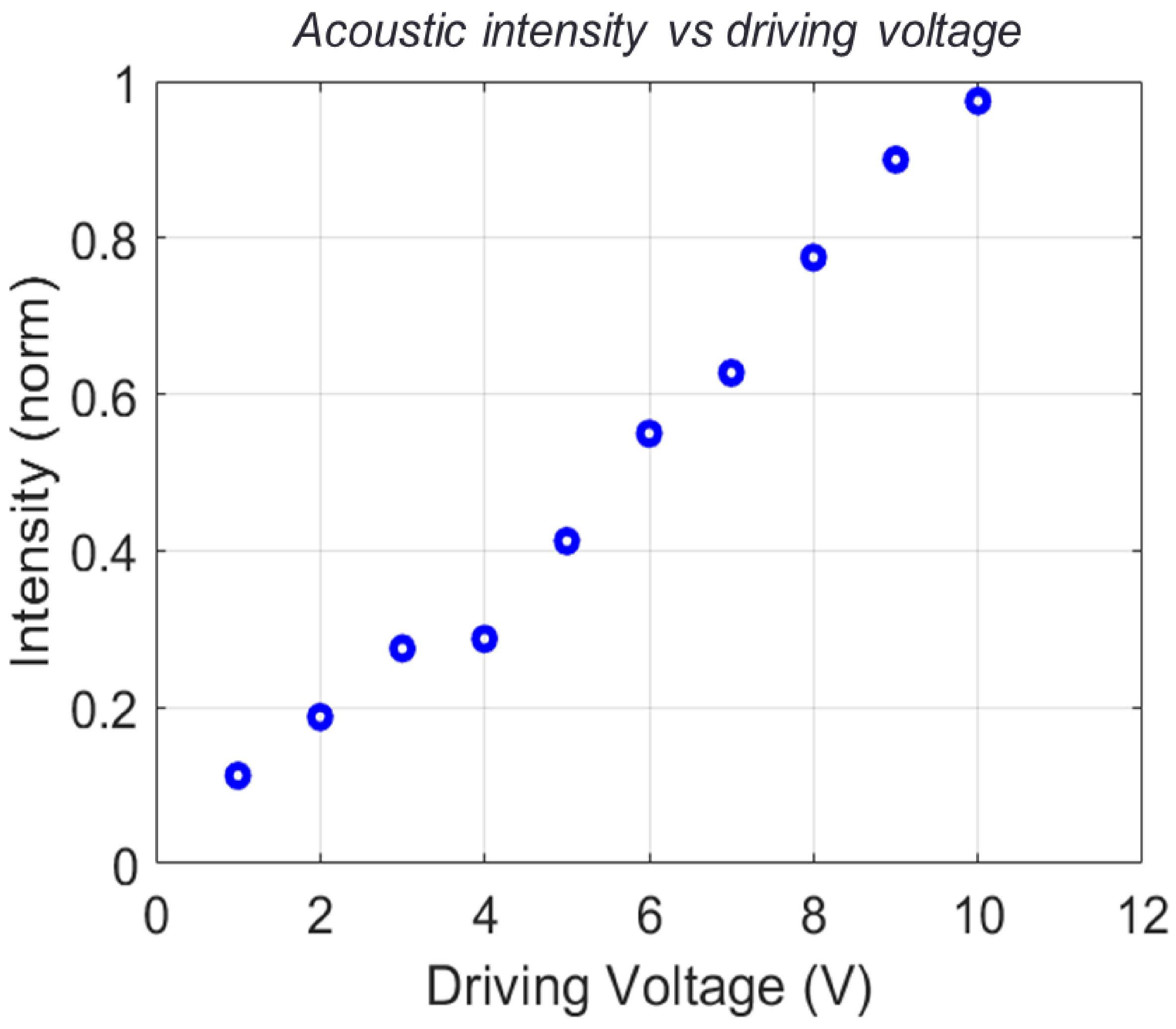
Nanosecond Refractive imaging of travelling AWs: Typical Experimental Results analysis



Nanosecond Refractive imaging of travelling AWs: Typical Experimental parametric study

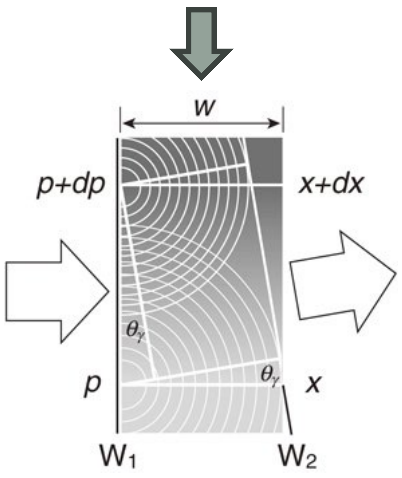


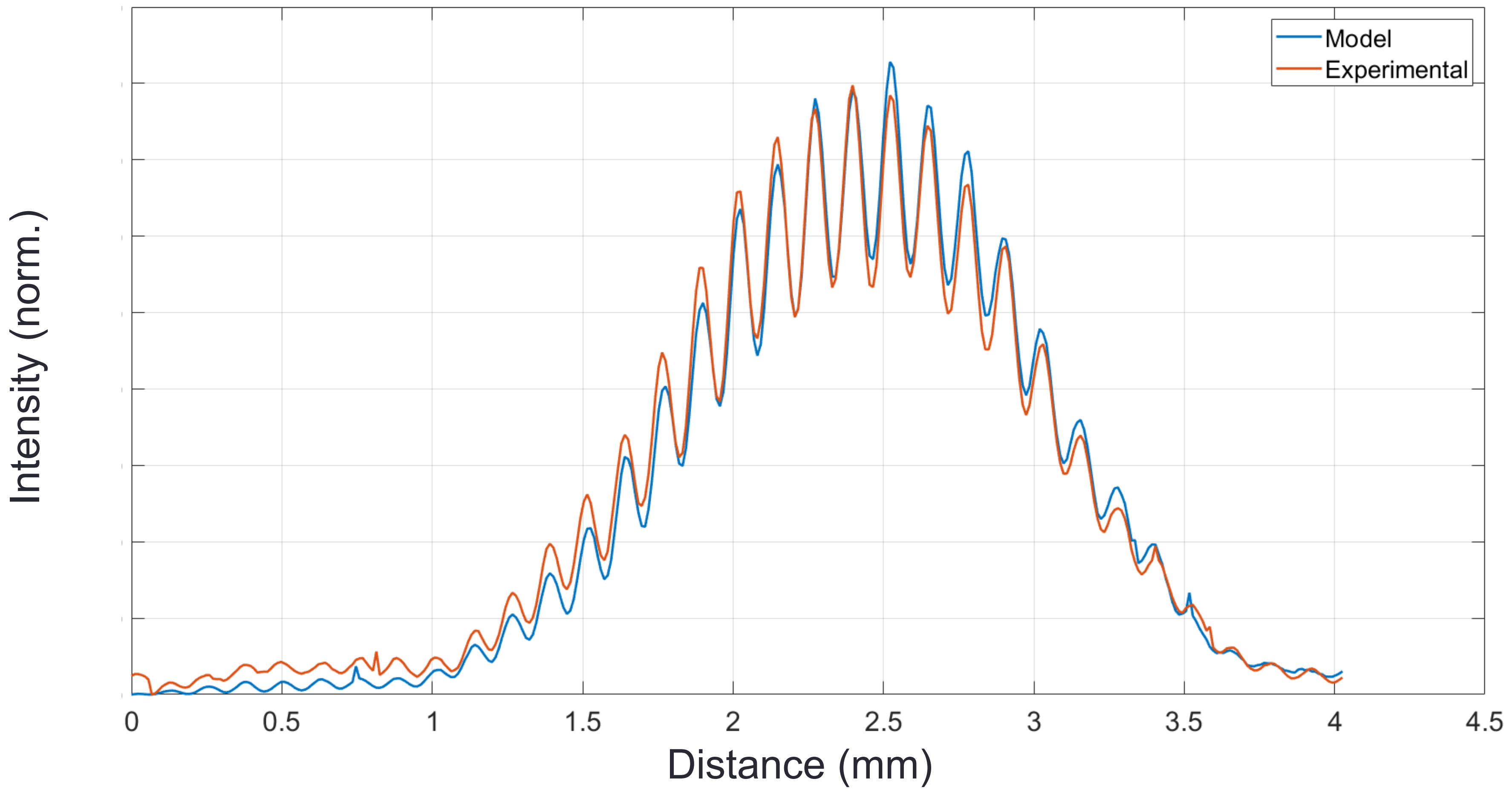


Nanosecond Refractive imaging of travelling AWs:

Experimental Results vs Computational Model

Computational model Principle





Summary of 2nd year activity for WP4

- Fabrication and characterization of first prototype of BC with tensile film of silicon nitride
- Parametric simulation of optimal pattern shape for silicon nitride PBCs optimized for positron with 10-20 GeV energies and started the fabrication of first prototypes of PBCs

- Fabrication of BC samples via PLM
- Set-up of lithography to produce PLM PBC-CU -> samples realized
- Progress in the optimization of pattering design in term of experimental constraints (stressor strength and lithography resolution)

- Started patenting procedure of the novel design, i.e., COS/LAT, for static PBC-CU

- Development of laser diagnostics systems for fast imaging of travelling AWs
- Proof-of-Principe characterization of travelling acoustic waves in Quartz crystal
- Parametric study of AW control via driving frequency and voltage
- Computational model development for AW pressure calculation in nanosecond laser refractive imaging

JOINT ACTIVITY WITH WP2 for gamma-ray emission simulation

Prospect for next years

O4.1 & O4.2

- Realize different samples of static PBC via Surface modification with Silicon Nitride deposition and Pulse Laser Melting with parameters adapted for high-energy positron beams > GeV.
- Select the best sample for possible experiments.
- Compare the two techniques for static PBC to define the best method in terms of performance as CU.

O4.3

- Development of a Ge-based A-CU suitable for high energy positron beams $\geq 20\ \mathrm{GeV}$
- Development and characterization of a Si- and Ge-based A-CU for lower-energy positron beams (~0.5 GeV) – Scheduling of experiments at MAMI

Work in synergy with both WP2 and WP3