Università degli Studi di Napoli Federico II — itee PhD information technology electrical engineering — DIETI — UNINA

PhD Barbara Rossi

Optical Fiber Devices for Precision Medicine

Tutor: Prof. Antonello Cutolo

Cycle: XXXVIII Year: III

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My background

- **M.Sc**. In Biomedical Engineering – 25th March 2022
- **OptoPower Lab** – DIETI
- **Tutor**: prof. Antonello Cutolo
- PhD started and end dateds : 01/11/2022 – 31/10/2025
- Scholarship funded by **UNINA**
- **Abroad Research:** Technical University of Denmark
- **Collaborations**: the Optoelectronic Division, Engineering Department, University of Sannio, the CNOS center (Nanophotonics and Optoelectronics Centre for Human Health, BN, Italy), IIT(Italian Institute of Technology) of Lecce

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Summary of study activities

PhD Year	Courses	Seminars	Research	Tutoring/Supplementary Teaching
1st	28	10.4	35	--
2nd	8	2.3	45	2.4*
3rd	4	5.2	60	1*

Tutorship Fisica I e Fisica II

PhD school:

- China-Italy Joint Laboratory on Advanced Manufacturing (CI-LAM);
- FIT4MEDROB International Seasonal School.

Main Attendend Courses:

- Optical Components and Circuits (MSc course) – Prof. A. Capozzoli;
- Optics and Microwave Engineering (MSc course) – Prof. A. Capozzoli;
- Numerical Methods for Thermal Analysis, Modeling and Simulation: Application to Electronic Devices and Systems (Ad hoc course) – Dr. A.P. Catalano

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Research products 1/2

[C1]	B. Rossi, M. Giaquinto, M. A. Cutolo, A. Cusano, A. Cutolo, "*Advanced integrated optical devices for ultrasound diagnostics*", Springer Nature, Proceedings of SIE 2023 - 54th Annual Meeting of the Italian Electronics Society, A Springer book series Lecture Notes in Electrical Engineering (Poster Presentation).
[C2]	B. Rossi, M. Giaquinto, M. A. Cutolo, A. Cusano, "Advanced Integrated Optical Devices for Ultrasound Diagnostics," *Progress in Electromagnetics Research Symposium (PIERS) 2024*, Chengdu, China.
[C3]	B. Rossi, M. A. Cutolo, G. Breglio, A. Cusano, M. Giaquinto, A. Cutolo, "Advanced Lab-on-Tip Devices for Ultrasound Diagnostic: A Numerical Investigation," *International Conference of Photonics (ICOP 2024)*, Florence, Italy.
[C4]	B. Rossi, M. Giaquinto (**invited**), M. A. Cutolo, A. Cusano, G. Breglio, "Optical Fiber Based Devices: From Biosensing to Ultrasound Applications," *2025 Photonics & Electromagnetics Research Symposium Abstracts, Abu Dhabi, UAE.*

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Research products 2/2

[C5]	C. Qvotrup, B. Rossi, M. De Vittorio, "Numerical Simulation of Photoacoustic Ultrasound Pulses for Neural Applications," *Optogen 2024*, Copenhagen, Denmark.
[P1]	B. Rossi, P. M. Aiello, M. A. Cutolo, M. Giaquinto, A. Cusano, G.Breglio, A. Cutolo, "*Polymer-Based Lab-on-Tip Microstructures For Ultrasound Medical Diagnostics*," *2024 IEEE Sensors Applications Symposium (SAS)*, Naples, Italy, 2024, pp. 1-6, doi: 10.1109/SAS60918.2024.10636662.
[P2]	B.Rossi, M.A Cutolo, M. Giaquinto, G.Breglio, A.Cusano, *Curved Fabry-Perot Ultrasound Detectors: Optical and Mechanical Analysis*, Sensors, *25(4), 1014, 2025*, https://doi.org/10.3390/s25041014.
[P3]	Rossi, B., Cutolo, M. A., Aiello, P. M., Breglio, G., Cusano, A., & Giaquinto, M. ," *All-polymer multilayer Lab-on-Fiber structures for photoacoustic applications in biomedical field* ," Sensors, (**submitted**).

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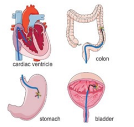
Research field of interest

The necessity to develop novel personalized techniques for patient treatments has gradually become a key factor in the optimization of a wide range of clinical applications, particularly in oncology and neuroscience.

To this aim, the '***precision medicine***' is following two main strategies:

- **SPECIFIC CLINICAL TREATMENTS PERSONALIZED FOR EACH PATIENT**

- **COMPACT NON-INVASIVE DEVICES FOR LOCALIZED DIAGNOSTICS AND THERAPY**



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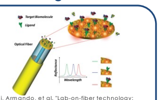
Research field of interest

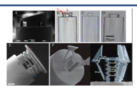
Optical Fiber can be functionalized using the Lab-on-fiber Technology.

CHEMICAL AND BIOLOGICAL Sensing Surface

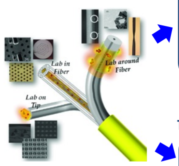


Ricciardi, Armando, et al. "Lab-on-fiber technology: a new vision for chemical and biological sensing." *Analyst* 140.24 (2015): 8068-8079.

OPTO-MECHANICS STRUCTURE

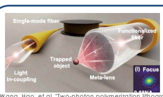


Xiong, Cong, et al. "Optical fiber integrated functional micro-/nanostructure induced by two-photon polymerization." *Frontiers in Materials* 7 (2020): 586496.



Vaiano, Patrizio, et al. "Lab on fiber technology for biological sensing applications." Laser & Photonics Reviews 10.6 (2016): 922-961.

METASURFACES INTEGRATION



Wang, Hao, et al. "Two-photon polymerization lithography for imaging optics." *International Journal of Extreme Manufacturing* 6.4 (2024): 042002.

THERMO-PLASMONIC EFFECT

Principe, Sofia, et al. "Thermo-plasmonic lab-on-fiber optrodes." *Optics & Laser Technology* 132 (2020): 106502.

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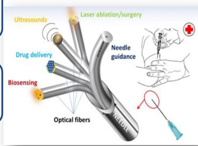
Research field of interest

A multifunctional device for *in vivo* medical applications given by the integration of functionalized Lab-on-Fiber probes in a medical needle

Localized biosensing for detecting molecular biomarkers directly in tissue

Targeted drug delivery via microfluidic channels integrated into optical fibers

Ultrasound generation and detection for imaging, therapy, and drug activation



Cutolo, Antonello, et al. "Ultrasound waves in tumors via needle irradiation for precise medicine." Scientific Reports 12.1 (2022): 6513.

Laser-based ablation and surgery through precise light delivery

Raman spectroscopy for high-resolution biochemical fingerprinting in situ

Real-time needle tracking and navigation using optical or optoacoustic feedback

Within the Hospital in the Needle project, this study is focused on ultrasound probes

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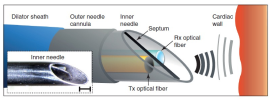
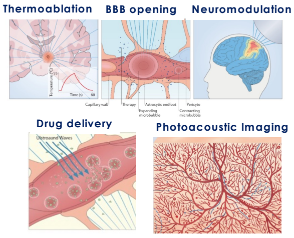
All-optical Ultrasound Transducer

All-optical ultrasound transducer



Localized Ultrasounds Applications



The system is composed of two optical fibers:
- Generation fiber;
- Detection Fiber

Advantages
- Compact size;
- High resolution;
- Use of non-ionizing signals;

This thesis is divided into two main parts, exploring both generation and detection.

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PhD thesis overview

❑ **Problem**
- Existing fiber-optic ultrasound probes are promising, but their full potential remains largely unexplored.

❑ **Objective**
- Explore and exploit modern fabrication techniques, novel materials, and design strategies to engineer high-performance all-optical ultrasound probes.

❑ **Methodology**
- MATLAB simulations for preliminary modeling
- COMSOL Multiphysics simulations for optical, acoustic, and mechanical analysis

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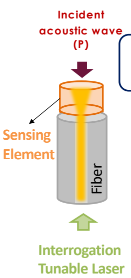
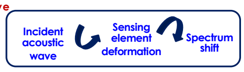
Optical fiber Ultrasound detectors

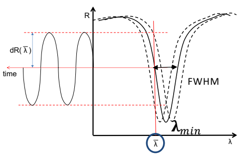
The sensing element realized on the optical fiber tip essentially works as **an interferometer.**



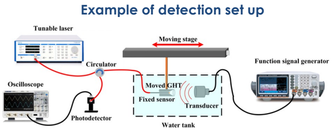
WORKING PRINCIPLE



Ansari, Rehman, et al. "All-optical forward-viewing photoacoustic probe for high-resolution 3D endoscopy." *Light: Science & Applications* 7.1 (2018): 75.



Example of detection set up



Wei, Heming, et al. "3D printed Fabry-Perot acoustic probe with a glass horn tube." *Optics & Laser Technology* 168 (2024): 109977.

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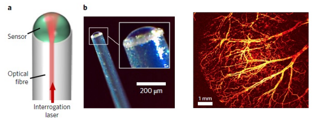
Sensing Element



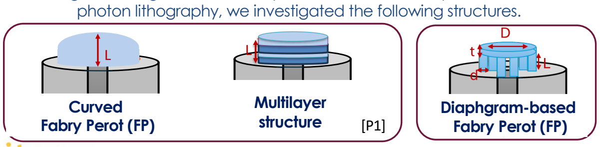
Guggenheim, James A., et al. "Ultrasensitive plano-concave optical microresonators for ultrasound sensing." *Nature Photonics* 11.11 (2017): 714-719

STATE OF THE ART

A polymeric curved structure with two reflective layers on the top and bottom realized on the fiber tip with two.

- The structure is realized using the **dip coating** technique, which results **in poor dimensional control.**
- It suffers from an intrinsic **trade-off in bandwidth and sensitivity.**

Taking advantage of the maturity of fabrication techniques such as two-photon lithography, we investigated the following structures.



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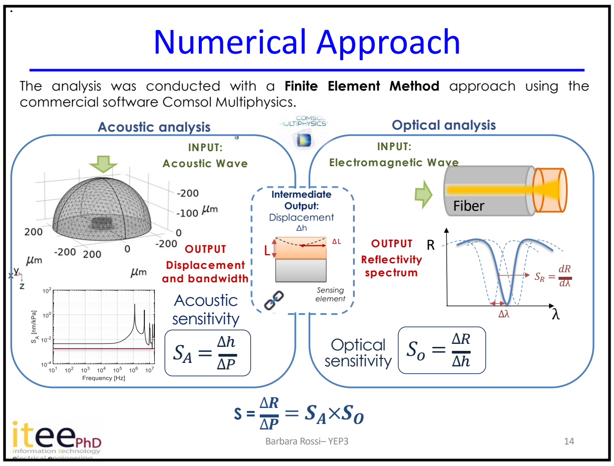
Numerical Approach
The analysis was conducted with a Finite Element Method approach using the commercial software Comsol Multiphysics.
Acoustic analysis
INPUT: Acoustic Wave
Optical analysis
INPUT: Electromagnetic Wave
Fiber
Intermediate Output: Displacement Δh
OUTPUT Displacement and bandwidth
OUTPUT Reflectivity spectrum
Acoustic sensitivity
$S_A = \frac{\Delta h}{\Delta P}$
Optical sensitivity
$S_O = \frac{\Delta R}{\Delta h}$
$S_R = \frac{dR}{d\lambda}$
S = $\frac{\Delta R}{\Delta P} = S_A \times S_O$
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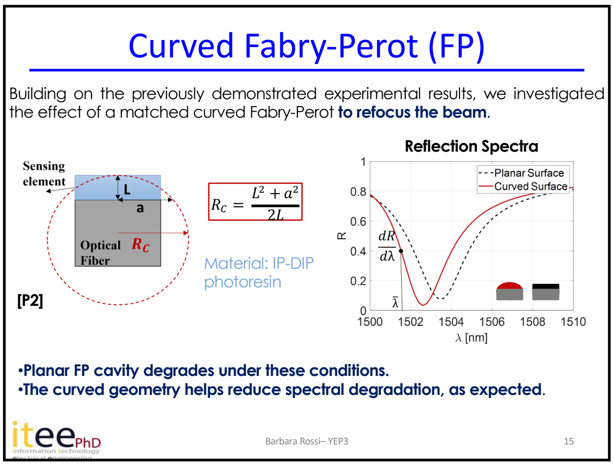
Curved Fabry-Perot (FP)
Building on the previously demonstrated experimental results, we investigated the effect of a matched curved Fabry-Perot to refocus the beam.
Sensing element
Optical Fiber
$R_C = \frac{L^2 + a^2}{2L}$
Material: IP-DIP photoresin
[P2]
Reflection Spectra
Planar Surface
Curved Surface
$\frac{dR}{d\lambda}$
λ [nm]
•Planar FP cavity degrades under these conditions.
•The curved geometry helps reduce spectral degradation, as expected.
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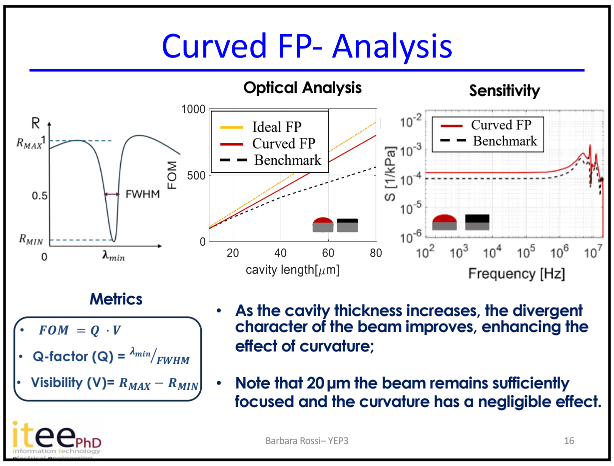
Curved FP- Analysis
Optical Analysis
Sensitivity
FWHM
Ideal FP
Curved FP
Benchmark
cavity length[μm]
S [1/kPa]
Frequency [Hz]
Metrics
• $FOM = Q \cdot V$
• Q-factor (Q) = $\lambda_{min}/FWHM$
• Visibility (V)= $R_{MAX} - R_{MIN}$
• As the cavity thickness increases, the divergent character of the beam improves, enhancing the effect of curvature;
• Note that 20 μm the beam remains sufficiently focused and the curvature has a negligible effect.
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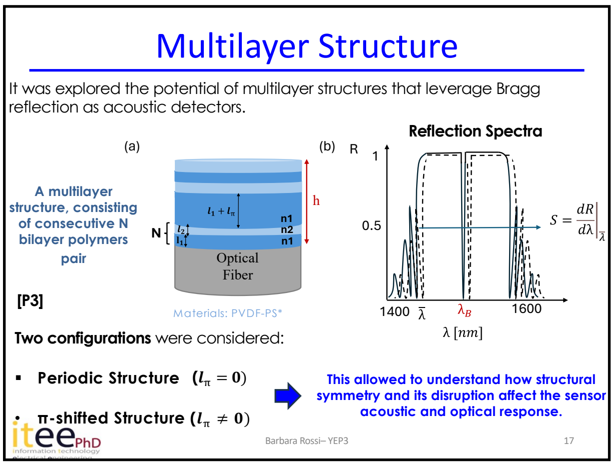
Multilayer Structure
It was explored the potential of multilayer structures that leverage Bragg reflection as acoustic detectors.
A multilayer structure, consisting of consecutive N bilayer polymers pair
Optical Fiber
Materials: PVDF-PS*
[P3]
Reflection Spectra
$S = \frac{dR}{d\lambda}\Big|_{\bar{\lambda}}$
λ [nm]
Two configurations were considered:
▪ Periodic Structure ($l_\pi = 0$)
▪ π-shifted Structure ($l_\pi \neq 0$)
This allowed to understand how structural symmetry and its disruption affect the sensor acoustic and optical response.
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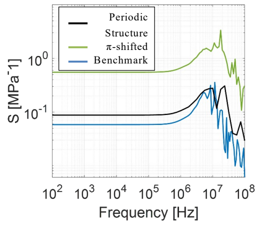
Multilayer Structure – Final Results



Design	Geometry Parameters	S [kPa⁻¹]	f_0 [MHz]	fcut-off [MHz]
Periodic Structure	l_1 = 0.218 μm, l_2 = 0.26 μm, L = 30 μm	0.23×10^{-3}	13	30
π-shifted Structure	l_1 = 0.218 μm, l_2 = 0.26 μm, l_π = 0.26 μm	0.15	9	25
Benchmark	L = 30 μm	0.10×10^{-3}	12	26

- **the π-shifted design, thanks to the introduction of symmetry breaking, further enhances sensor sensitivity up to 7-fold without reducing bandwidth;**

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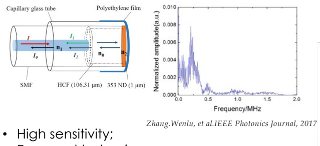
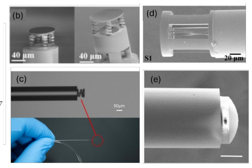
Membrane Structure

FP Cavity membrane



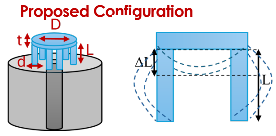
Potentialities offered by 3D micro-printing based on two photon lithography



- High sensitivity;
- Resonant behaviour;
- Trade-off sensitivity – band;
- Bulk solution;

Proposed Configuration

A polymeric flexible membrane integrated on the fiber tip



[C2,P1]

Material: IP-DIP photoresin

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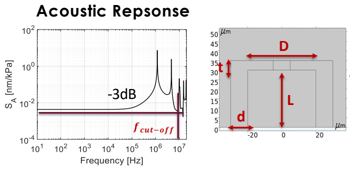
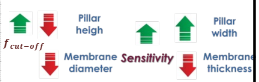
Membrane – Analysis

Acoustic Repsonse

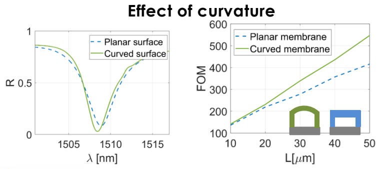


Parametric Analysis



Rossi, Barbara, et. al. "Advanced Lab-on-Tip ultrasound detectors: A numerical analysis." Results in Optics 9 (2022): 100312.

Effect of curvature



Up to 20μm the effect of curvature start to impact on the overall sensor performance

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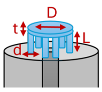
Membrane – Final Results

Geometrical Parametrs



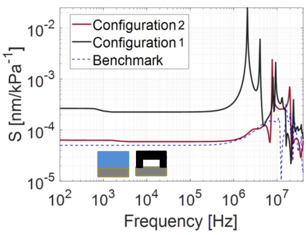
Configuration 1

L = 30 μm; D = 60 μm; t = 5 μm; d = 7 μm

Configuration 2

L = 10 μm; D = 12 μm; t = 5 μm; d = 7 μm

SENSITIVITY



PERFORMANCES

- ***Enables tuning frequency range up to tens of MHz.***
- Ideal solution for detecting *narrow-band acoustic waves*.

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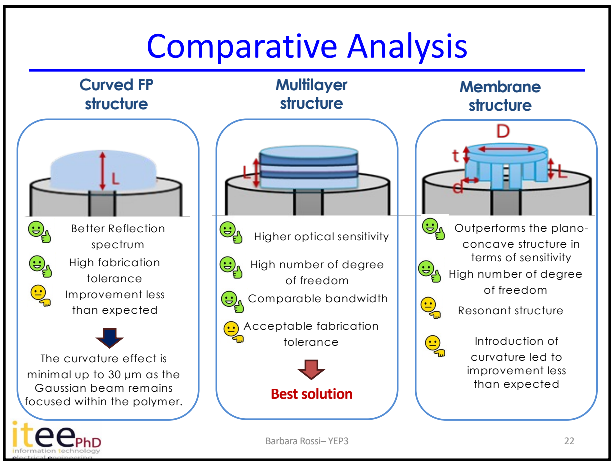
Comparative Analysis
Curved FP structure
Multilayer structure
Membrane structure
L
D
t
d
Better Reflection spectrum
High fabrication tolerance
Improvement less than expected
The curvature effect is minimal up to 30 µm as the Gaussian beam remains focused within the polymer.
Higher optical sensitivity
High number of degree of freedom
Comparable bandwidth
Acceptable fabrication tolerance
Best solution
Outperforms the plano-concave structure in terms of sensitivity
High number of degree of freedom
Resonant structure
Introduction of curvature led to improvement less than expected
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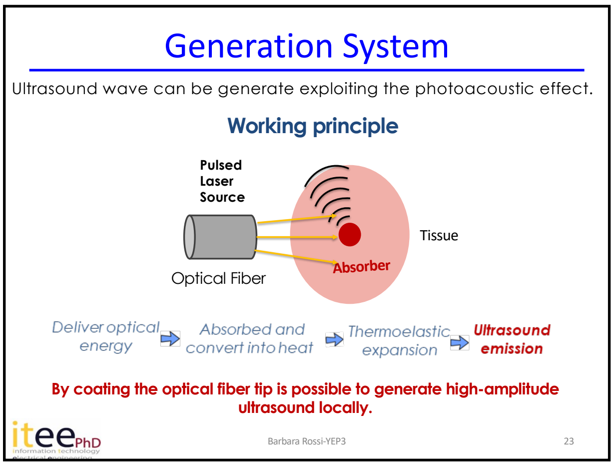
Generation System
Ultrasound wave can be generate exploiting the photoacoustic effect.
Working principle
Pulsed Laser Source
Tissue
Absorber
Optical Fiber
Deliver optical energy
Absorbed and convert into heat
Thermoelastic expansion
Ultrasound emission
By coating the optical fiber tip is possible to generate high-amplitude ultrasound locally.
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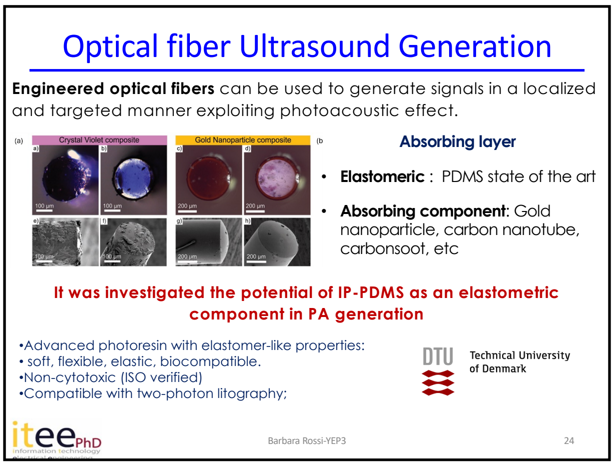
Optical fiber Ultrasound Generation
Engineered optical fibers can be used to generate signals in a localized and targeted manner exploiting photoacoustic effect.
Crystal Violet composite
Gold Nanoparticle composite
Absorbing layer
Elastomeric : PDMS state of the art
Absorbing component: Gold nanoparticle, carbon nanotube, carbonsoot, etc
It was investigated the potential of IP-PDMS as an elastometric component in PA generation
•Advanced photoresin with elastomer-like properties:
• soft, flexible, elastic, biocompatible.
•Non-cytotoxic (ISO verified)
•Compatible with two-photon litography;
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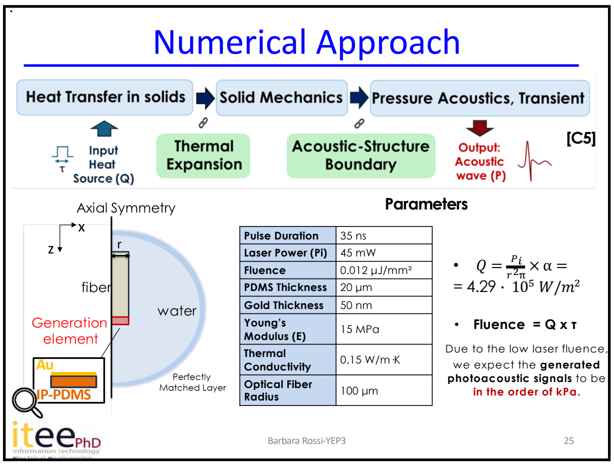
Numerical Approach
Heat Transfer in solids
Solid Mechanics
Pressure Acoustics, Transient
Input Heat Source (Q)
Thermal Expansion
Acoustic-Structure Boundary
Output: Acoustic wave (P)
[C5]
Axial Symmetry
x
z
r
fiber
water
Generation element
Au
IP-PDMS
Perfectly Matched Layer
Parameters
Pulse Duration 35 ns
Laser Power (Pi) 45 mW
Fluence 0.012 µJ/mm²
PDMS Thickness 20 µm
Gold Thickness 50 nm
Young's Modulus (E) 15 MPa
Thermal Conductivity 0.15 W/m·K
Optical Fiber Radius 100 µm
• $Q = \frac{P_i}{r^2\pi} \times \alpha =$
$= 4.29 \cdot 10^5\ W/m^2$
• Fluence = Q x τ
Due to the low laser fluence, we expect the generated photoacoustic signals to be in the order of kPa.
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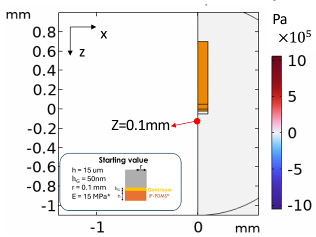
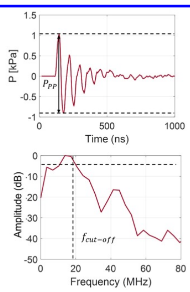
Numerical Model – Preliminary Analysis

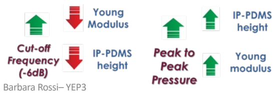
Acoustic Pressure Field Map





Evaluation metrics:

- Peak to peak pressure (P_{PP});
- $f_{cut-off}(-6dB)$.



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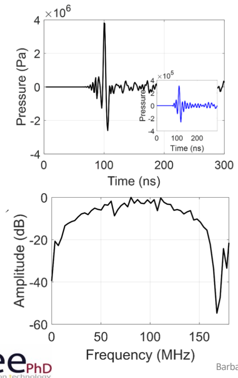
Final Design



Pulse Duration	6 ns
Laser Power	10 W
Fluence	0.12 μJ/mm²
IP-PDMS Thickness	20 μm
Gold Thickness	50 nm
Optical Fiber Radius	100 μm

- **The probe exhibits a peak-to-peak pressure in the MPa range and a bandwidth extending up to 100 MHz.**
- **It outperforms conventional PDSM devices of one order-of-magnitude.**

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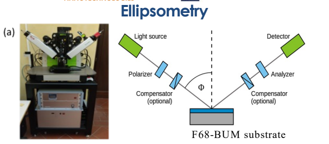
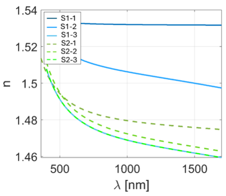
Advanced Material Characterization

IP-PDMS has potential applications also as **fiber-based acoustic sensors. However,** the **optical behavior of these materials in the infrared (IR) and near-infrared (NIR) ranges** remains largely uncharacterized.

ISTITUTO ITALIANO DI TECNOLOGIA CENTER FOR BIOMOLECULAR NANOTECHNOLOGIES — UNIVERSITÀ DEGLI STUDI DEL SANNIO

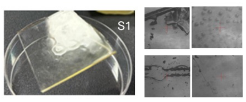
Ellipsometry





Accurion EP4 Ellipsometry

- 5 % Laser power
- 40° and 50° Angle of incident
- 2 samples (s1 and s2)
- 27x27cm



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Research results and Future Perspectives

This thesis focuses on the investigation of all-optical ultrasound probes exploiting novel materials and fiber-based technologies for miniaturized and non-invasive sensing.

- Analysis of fiber-based detector configurations, evaluating advantages and limitations related to fabrication method, material, and geometry;
- Investigation of fiber-optic ultrasound generators using novel material IP-PDMS;
- Optical characterization in the NIR region of IP-PMDS;

❑ Experimental validation of both generation and detection elements;

❑ Design and realization of advanced architectures through Lab-on-Fiber technology, enabling enhanced functionality in compact systems.

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