NON-CONTACT PHOTOACOUSTIC IMAGING USING SILICON PHOTONICS-BASED LASER DOPPLER VIBROMETRY

Emiel Dieussaert Supervisors: Prof. Yanlu Li, Prof. Roel Baets

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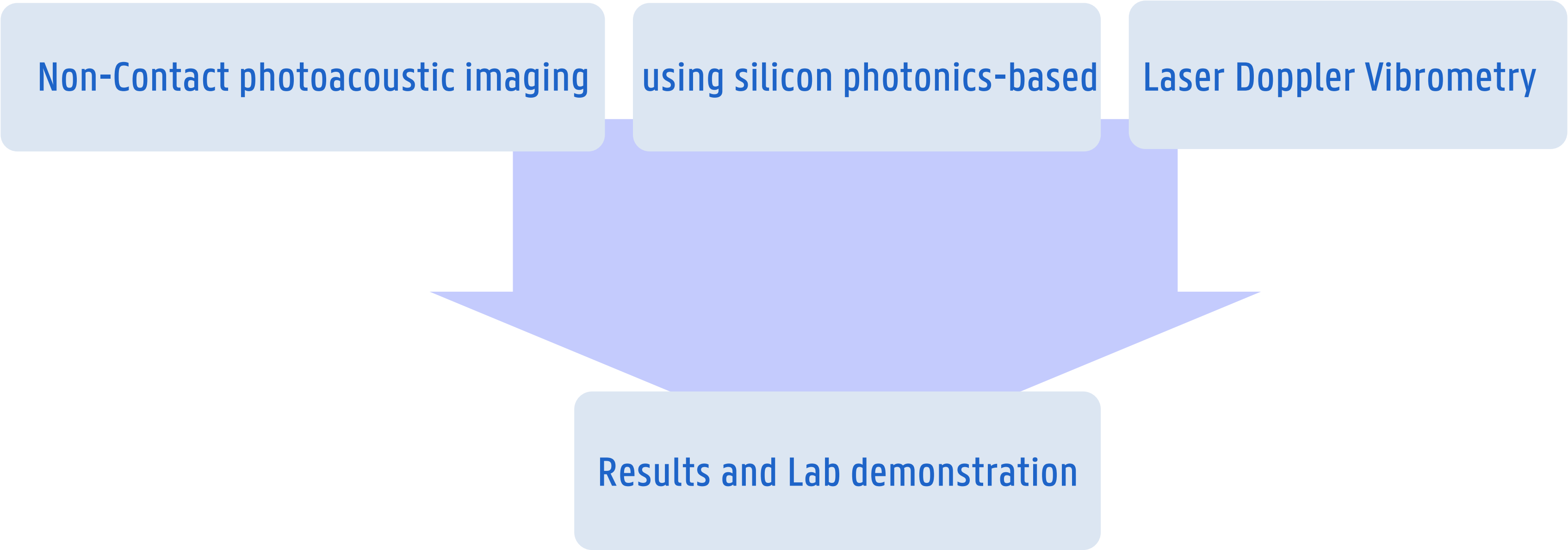
embracing a better life

CONTENT



Non-Contact photoacoustic imaging

using silicon photonics-based

Laser Doppler Vibrometry

Results and Lab demonstration

CONTENT

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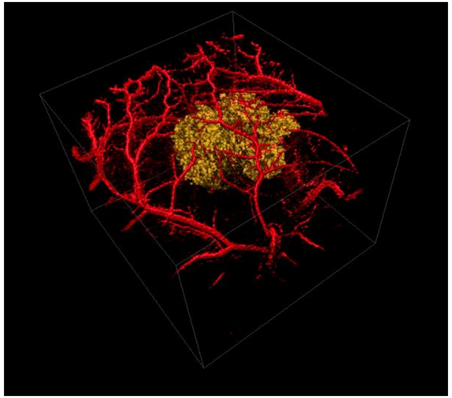
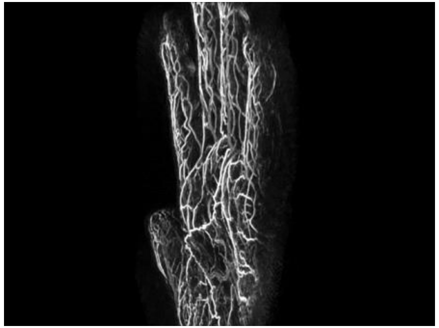
MEDICAL IMAGING TECHNIQUES

Photoacoustic imaging is a relatively new biomedical imaging technique

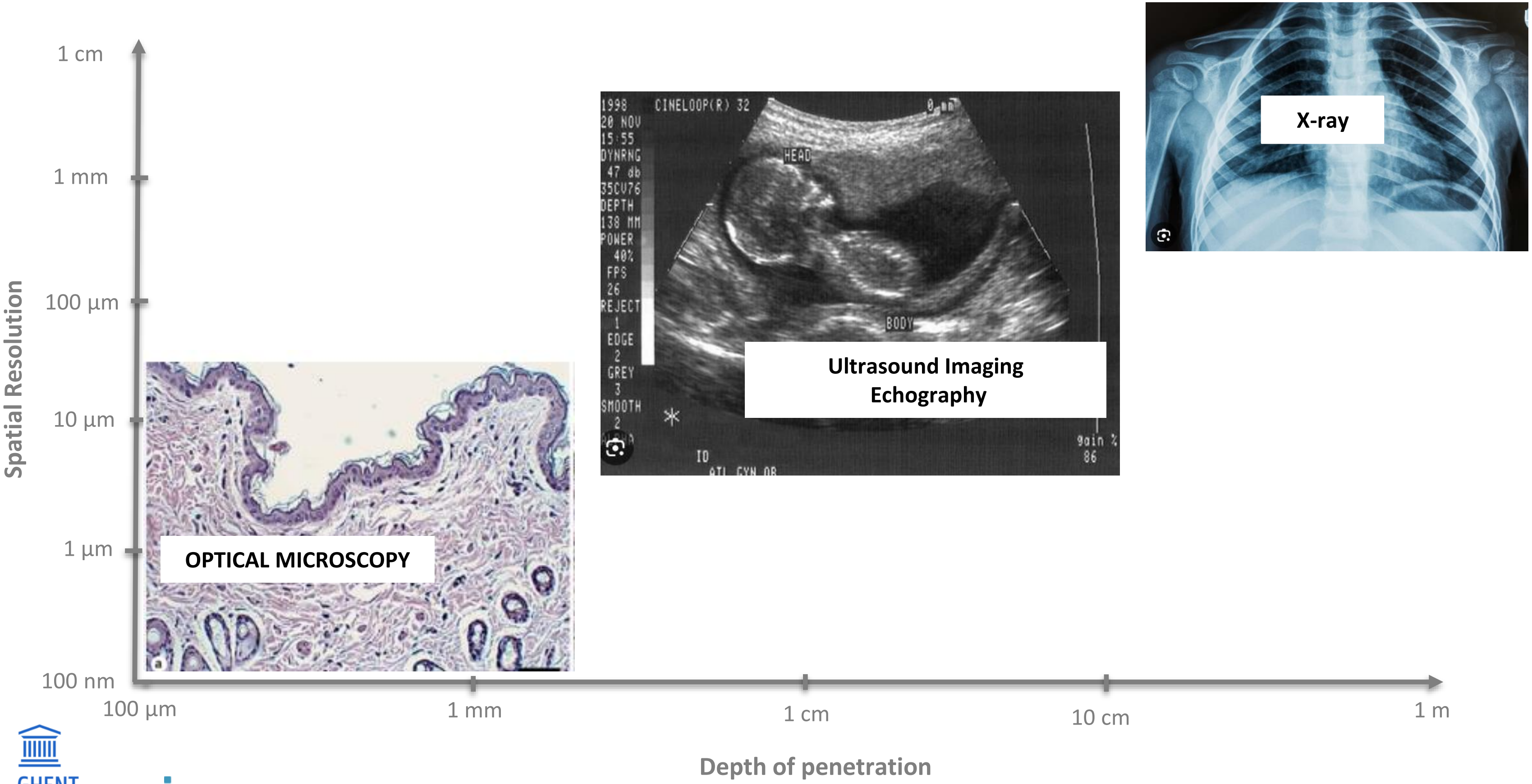




Why is biomedical imaging important ?

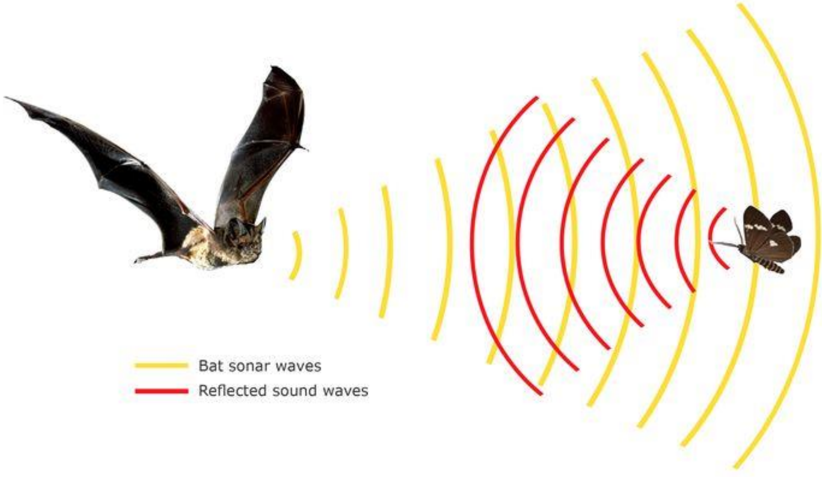
Diagnoses and follow-up of injuries, diseases, cancer,…

MEDICAL IMAGING TECHNIQUES: SOME EXAMPLES



MEDICAL IMAGING TECHNIQUES: SOME EXAMPLES

Ultrasound Imaging
Echography

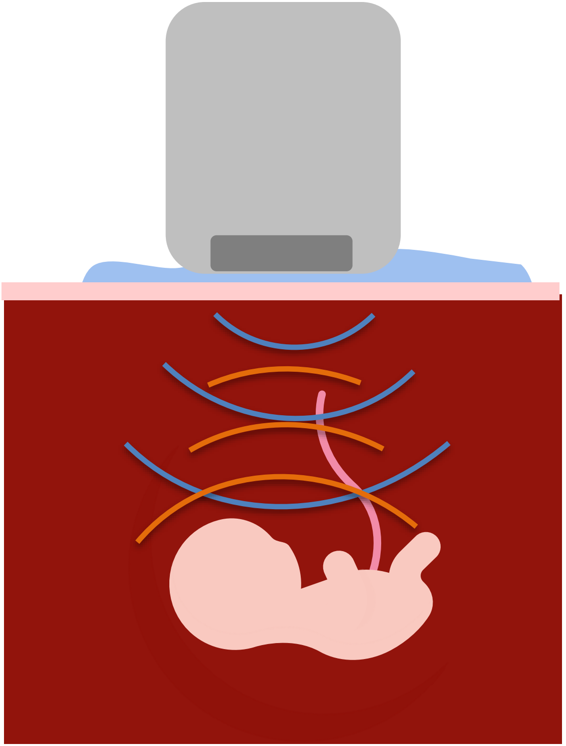


Large imaging depth

No optical contrast

MEDICAL IMAGING TECHNIQUES: SOME EXAMPLES

Ultrasound Imaging
Echography



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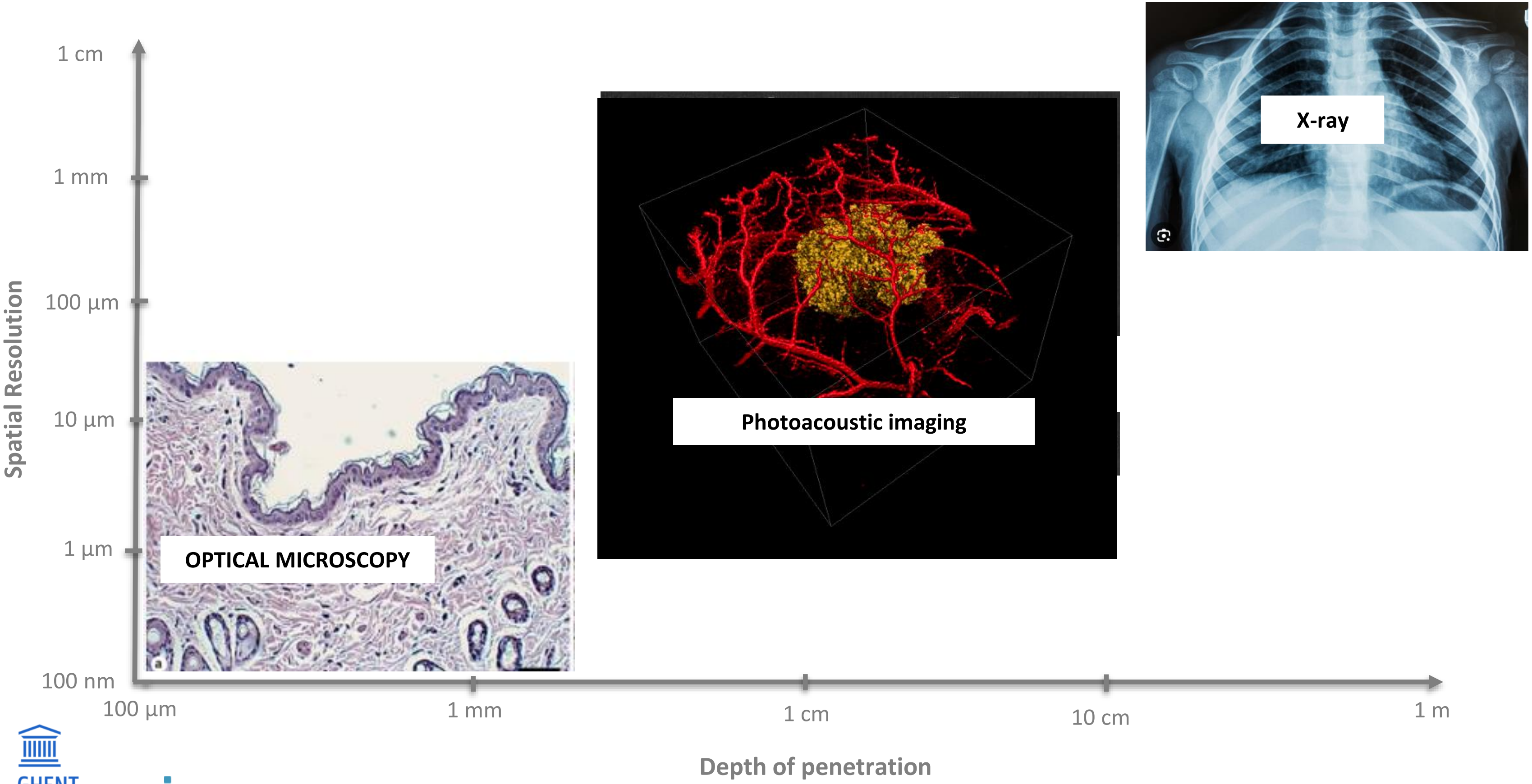
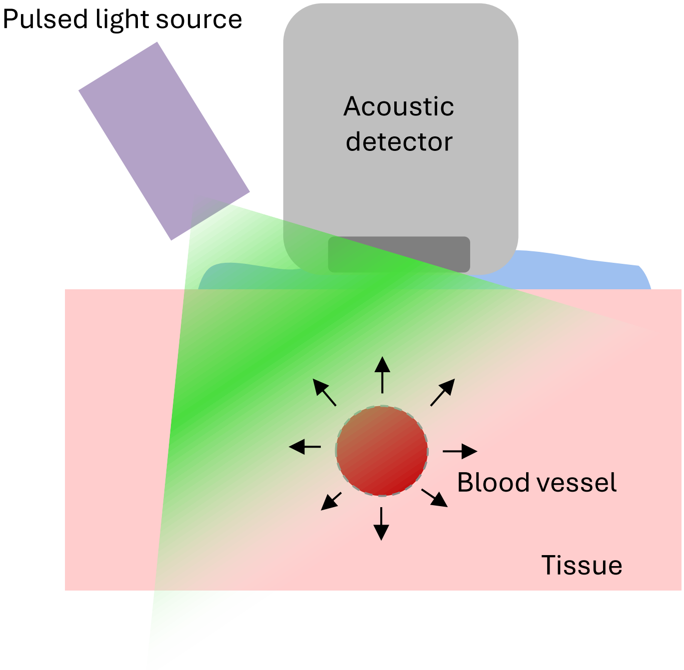
MEDICAL IMAGING TECHNIQUES: SOME EXAMPLES



PHOTOACOUSTIC IMAGING

A COMBINATION OF OPTICAL AND ACOUSTIC METHODS



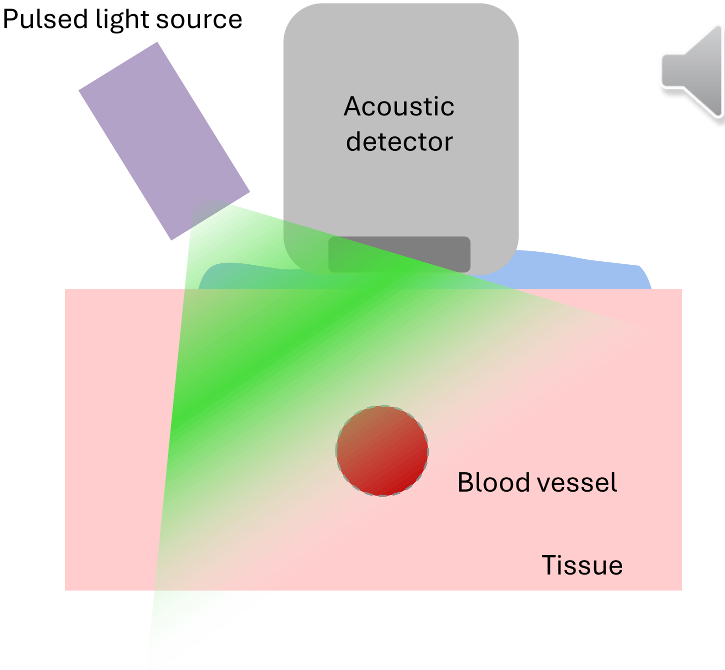
Pulsed laser excitation and local absorption

Local heating and thermal expansion

Acoustic wave propagation and ultrasound detection

PHOTOACOUSTIC IMAGING

A COMBINATION OF OPTICAL AND ACOUSTIC METHODS



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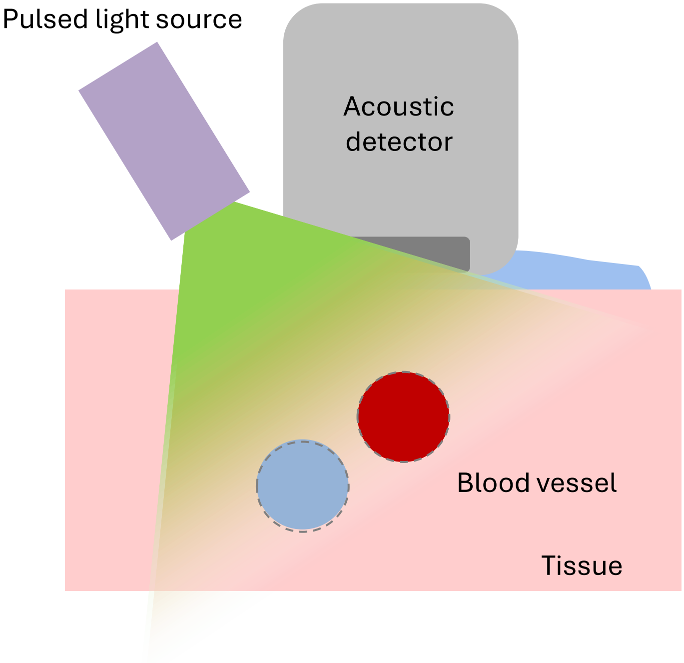
A COMBINATION OF OPTICAL AND ACOUSTIC METHODS



Pulsed laser excitation and local absorption

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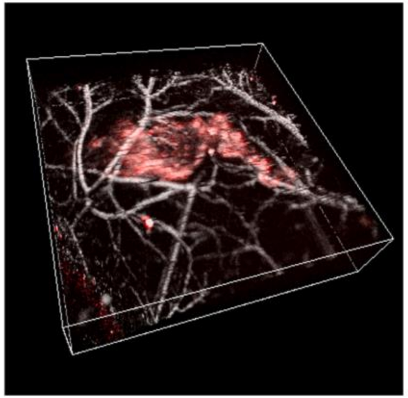
PHOTOACOUSTIC IMAGING

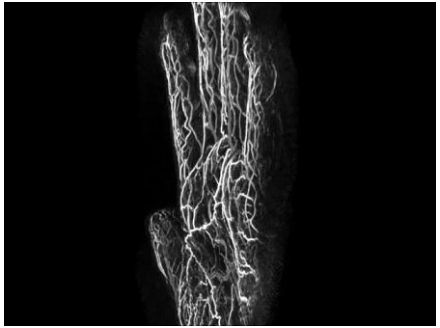
A COMBINATION OF OPTICAL AND ACOUSTIC METHODS

We can discern different types of tissue

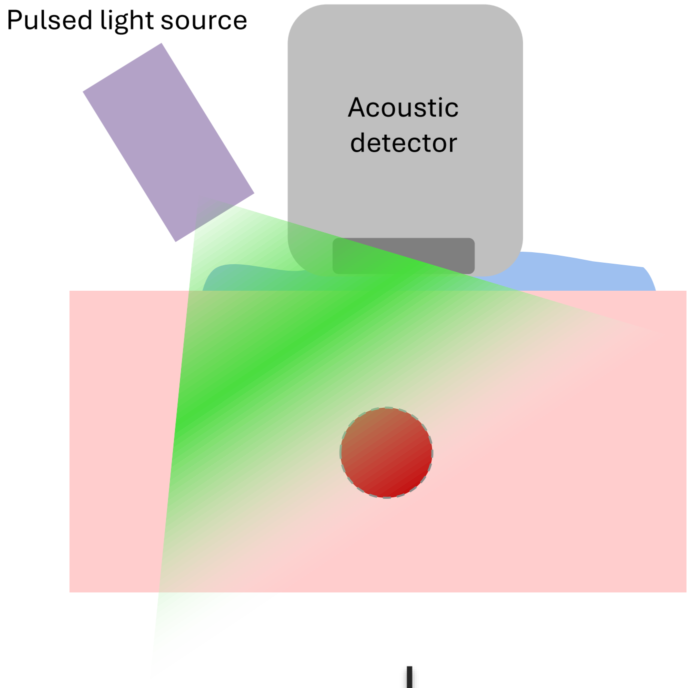


[2] Soon-Woo Cho, (2023), Photoacoustics

Large depths (up to couple cm)



[1] Y. Matsumoto, (2018), Scientific reports



Pulsed light source

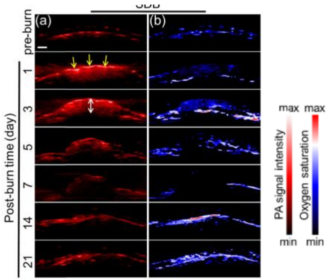
Acoustic detector

Contact based method

→ Risk of reaction or infection of the sample

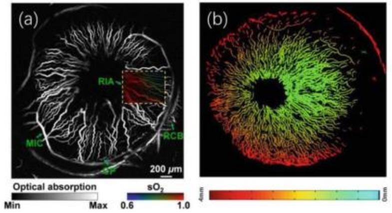
→ Inconvenient for many applications

Wound imaging



Zhiyou Wu et al., Biomedical Optics Express (2019)

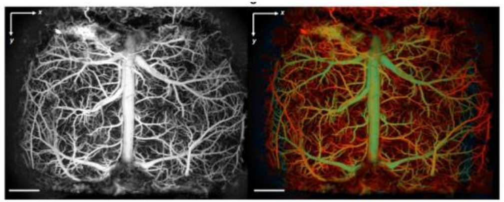
Eye-imaging



Hu S et al., Optics Letters, (2010)

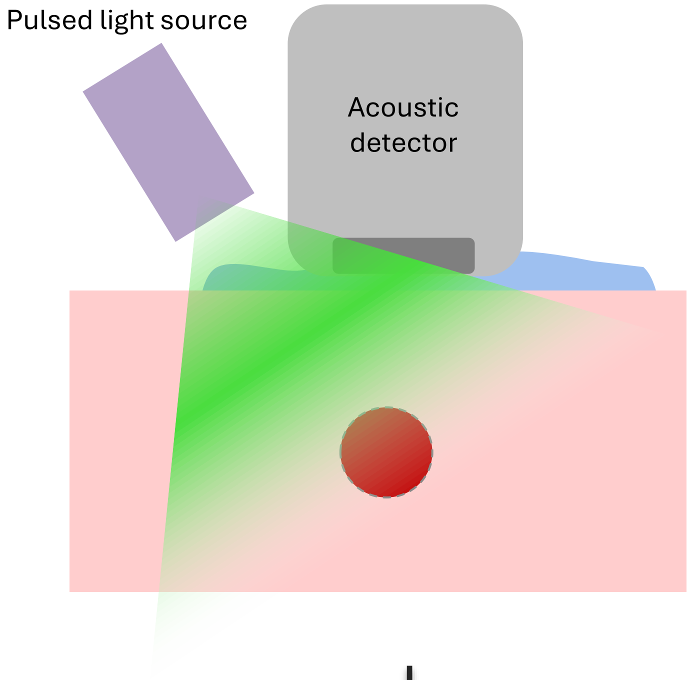
Zhao H et al., JBO, (2018)

Brain imaging



Zhu et al. Light: Science & Applications (2022) 11:138

During surgery,...



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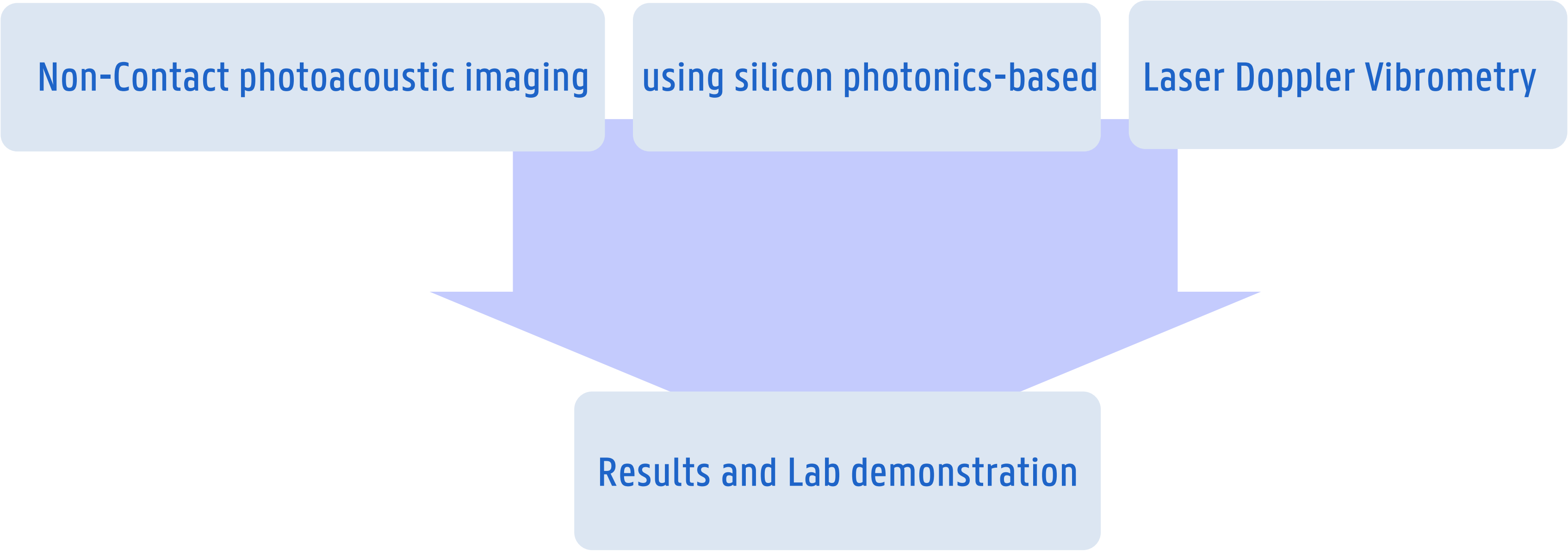
Contact based method

Is there a method to detect acoustic waves without contact?

↓

Laser Doppler Vibrometry

CONTENT



Non-Contact photoacoustic imaging

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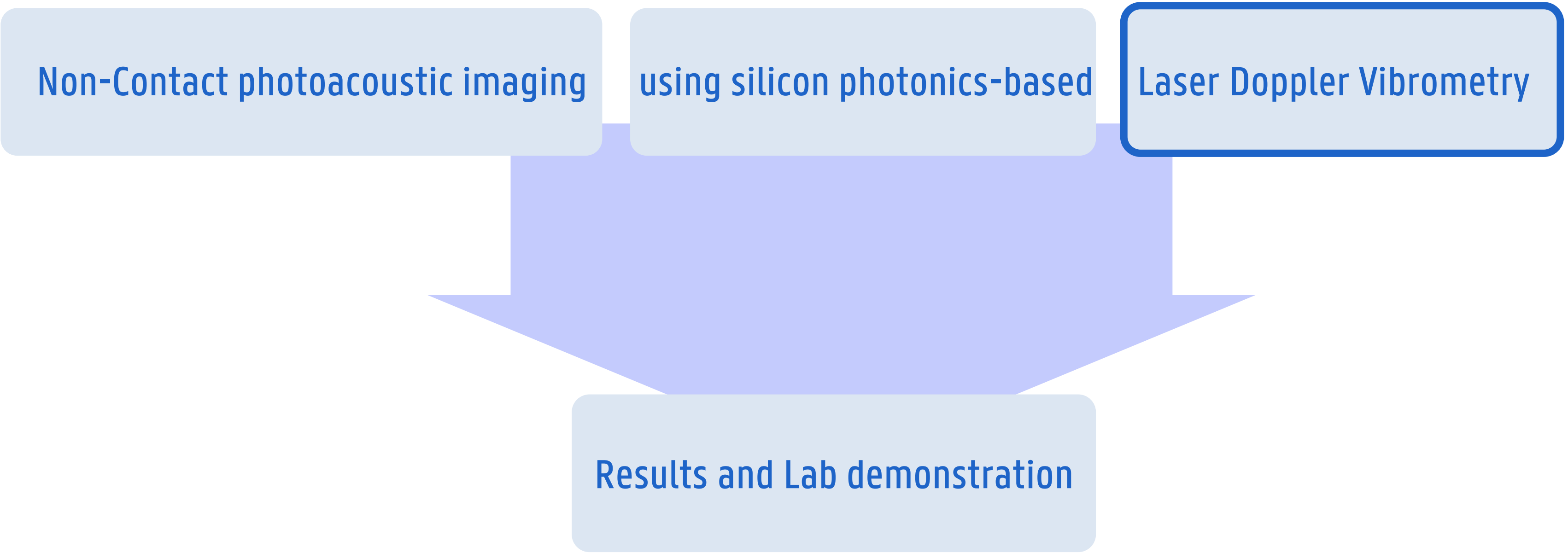

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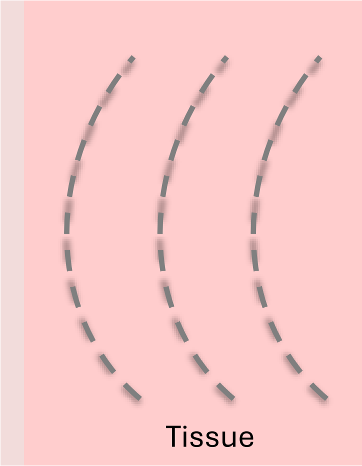
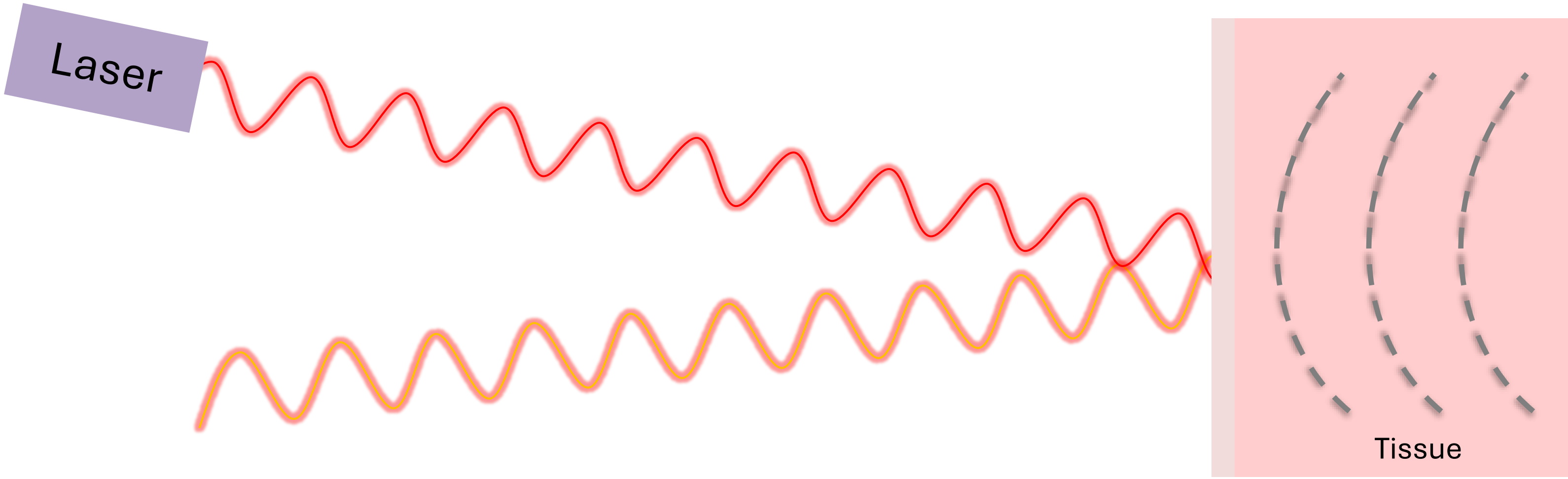
LASER DOPPLER VIBROMETRY – NON CONTACT ULTRASOUND DETECTION

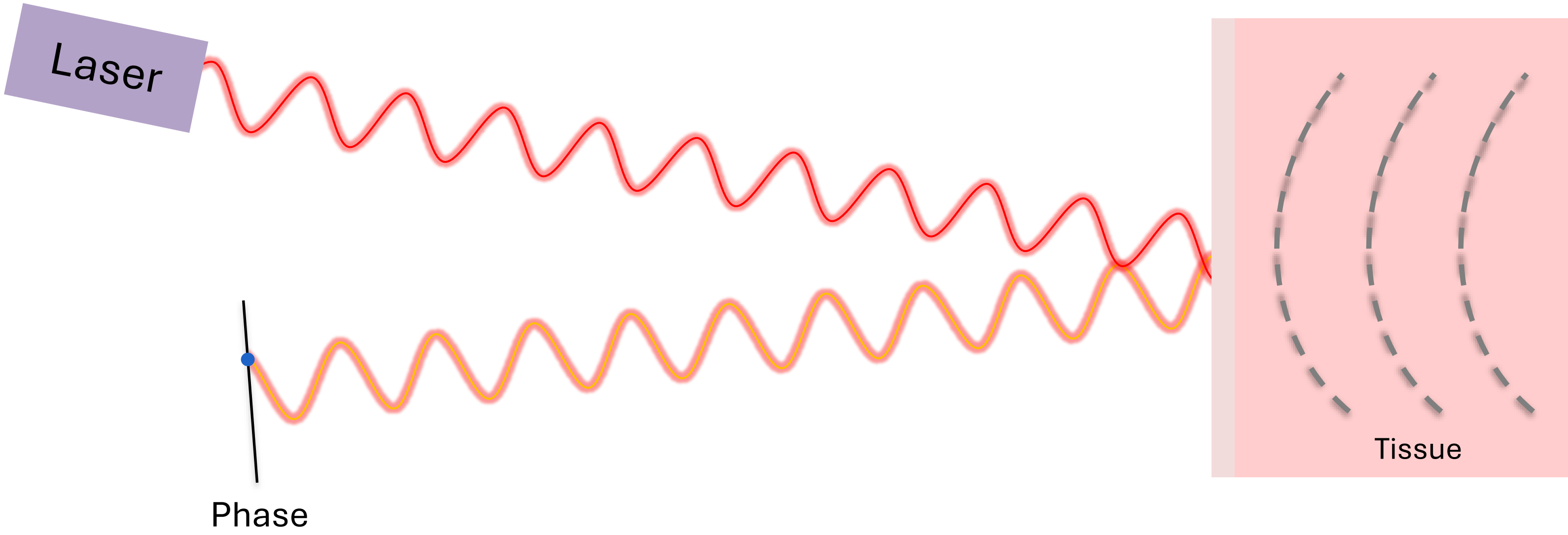


Ultrasounds induces surface movement

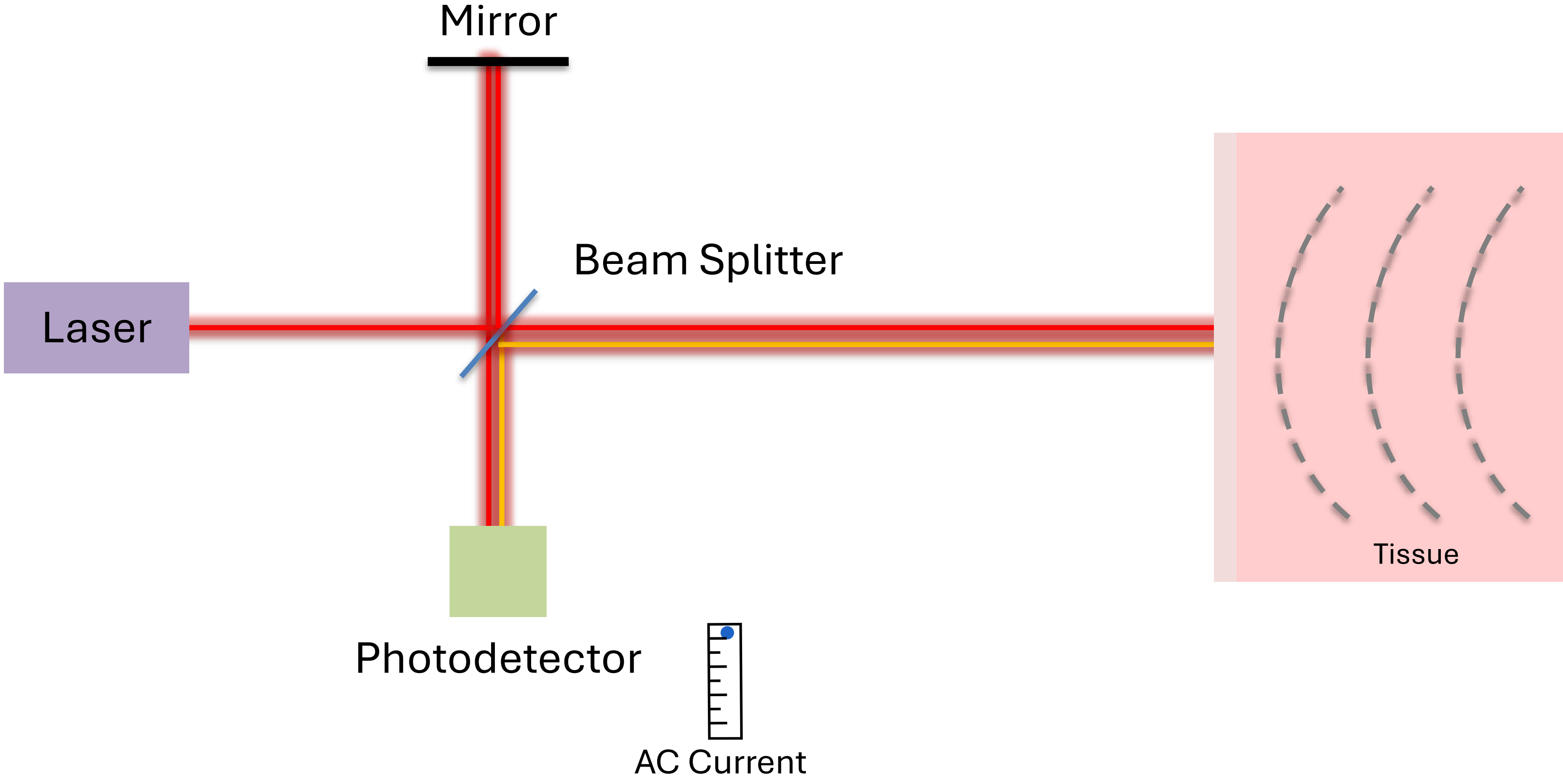
LASER DOPPLER VIBROMETRY – NON CONTACT ULTRASOUND DETECTION



LASER DOPPLER VIBROMETRY – NON CONTACT ULTRASOUND DETECTION



LASER DOPPLER VIBROMETRY – NON CONTACT ULTRASOUND DETECTION



COMMERCIAL SCANNING LDV

→ **Bulky and expensive**

CONTENT

Non-Contact photoacoustic imaging

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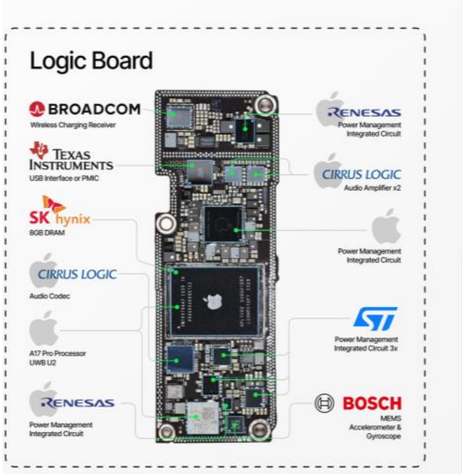
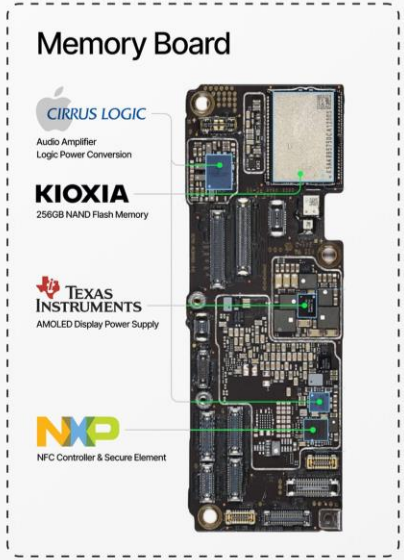
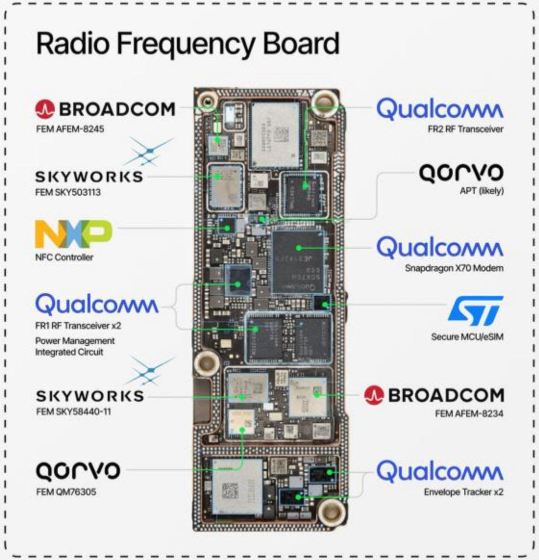
SILICON CHIPS EVERYWHERE



+-160 different chips





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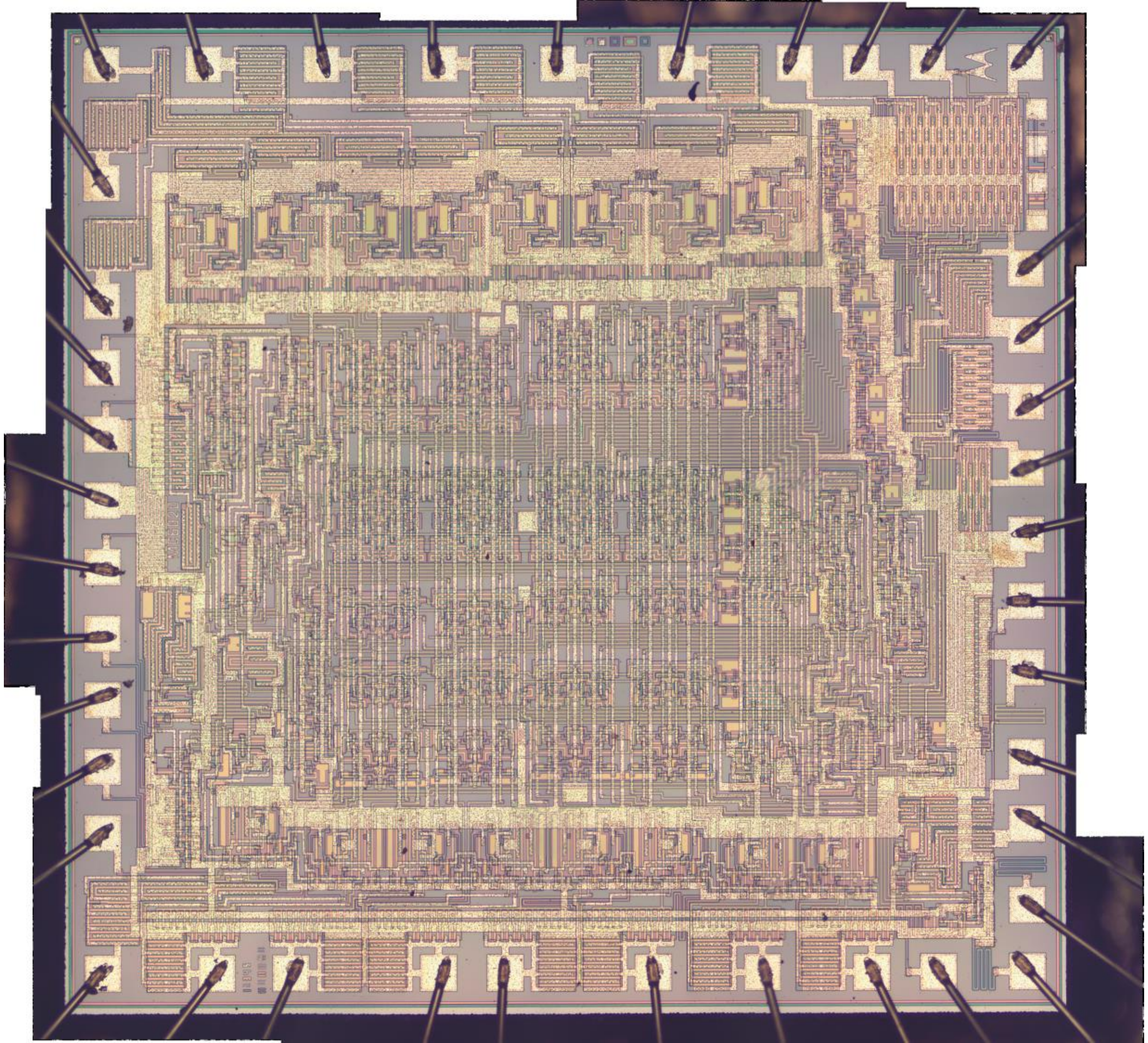
Silicon Chips everywhere - **Electronics**

+-3500 different chips

Motorola chip
1976



Current chips are
x1 000 000
More complex

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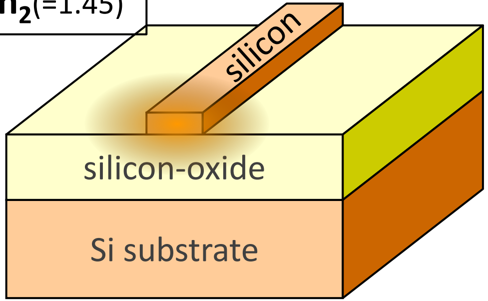
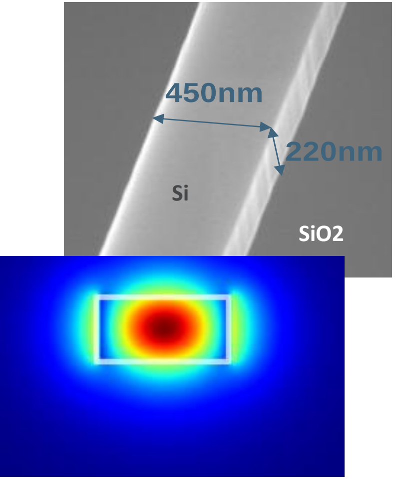
SILICON PHOTONICS

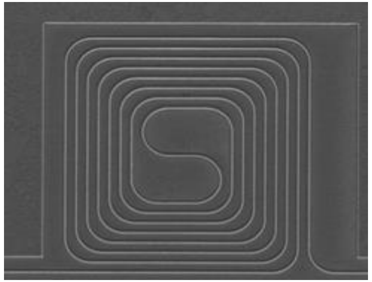
Manipulating light with microstructures

Waveguides

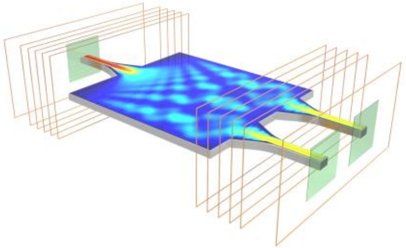
$n_1(=3.5)>n_2(=1.45)$



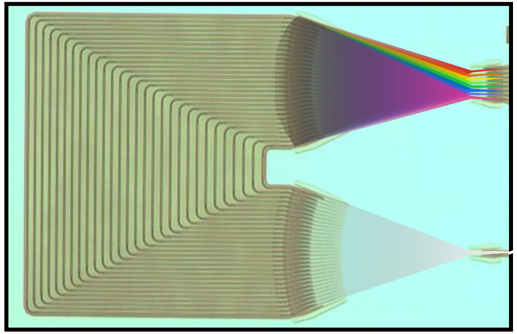




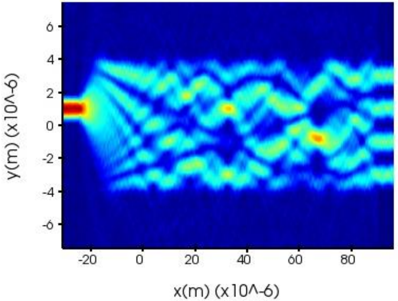
Splitters



Arrayed Waveguide grating



Optical Hybrid

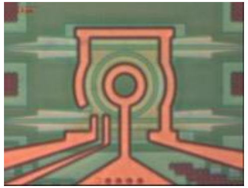


And more…

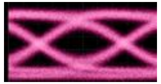
SILICON PHOTONICS

IMEC ISIPP200 platform

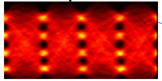
56-160Gbps
Silicon Ring Modulator



56Gbps NRZ

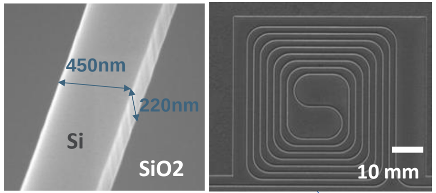


160Gbps PAM-4

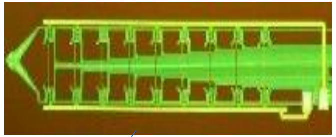


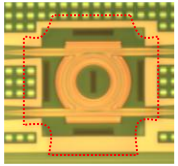
Y. Tong et al., PTL 2020

High-density Si Waveguides *(0.5-2dB/cm)*



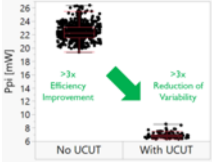
Silicon WDM filters



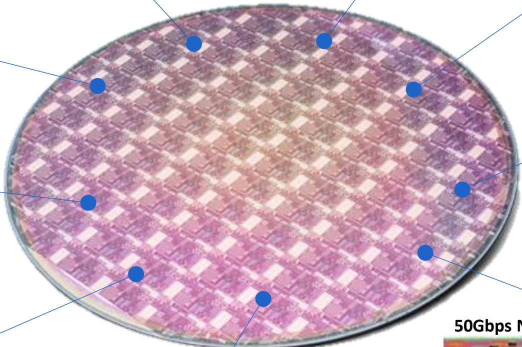


Efficient Thermo-Optic Phase Tuners

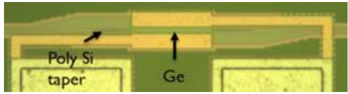
Undercut

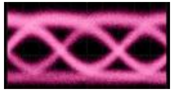


Low Thermo-Optic Powe Consumption

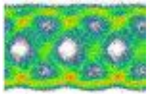


56-128Gbps GeSi Electro-Absorption Modulator

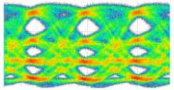




56Gbps NRZ

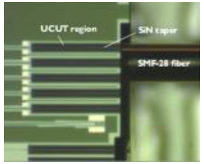


100Gb/s NRZ

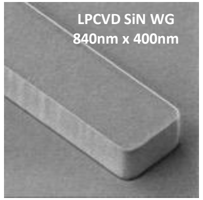


128Gb/s PAM-4

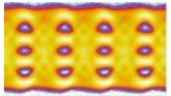
Integrated LPCVD / PECVD SiN Waveguides



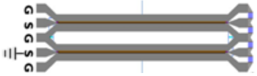
SiN Edge Coupler 9um MFD (<3dB)

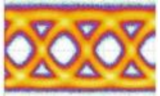


56-106Gbps Silicon Mach-Zehnder Modulator



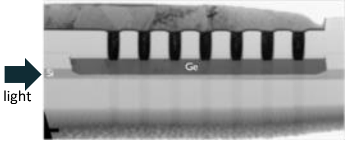
106Gbps PAM-4



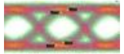


56Gbps NRZ

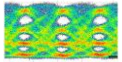
56-128Gbps Ge Photodetector



50Gbps NRZ

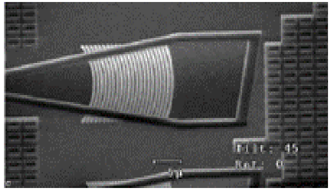


128Gbps PAM-4

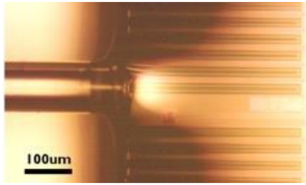


100Gb/s NRZ

SMF Grating Coupler *(<2dB)*

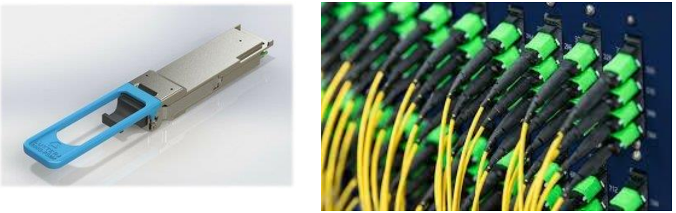


High-NA *(<2dB)* &
SMF Edge Couplers *(<3dB)*



SILICON PHOTONICS APPLICATIONS

Datacom

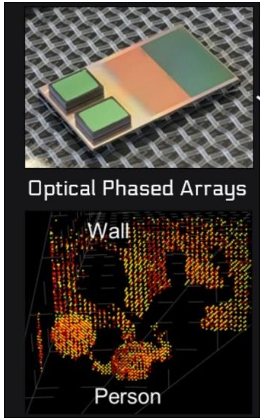


Photonic Computing, AI

Quantum applications:

Quantum computing, sensing, communication

LIDAR

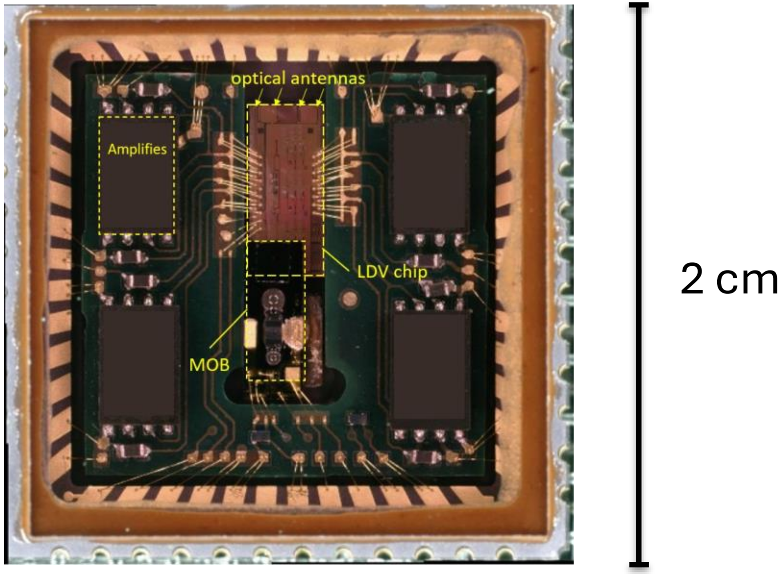


Sensing

SILICON PHOTONICS

Commercial LDV

Silicon Photonics based LDV



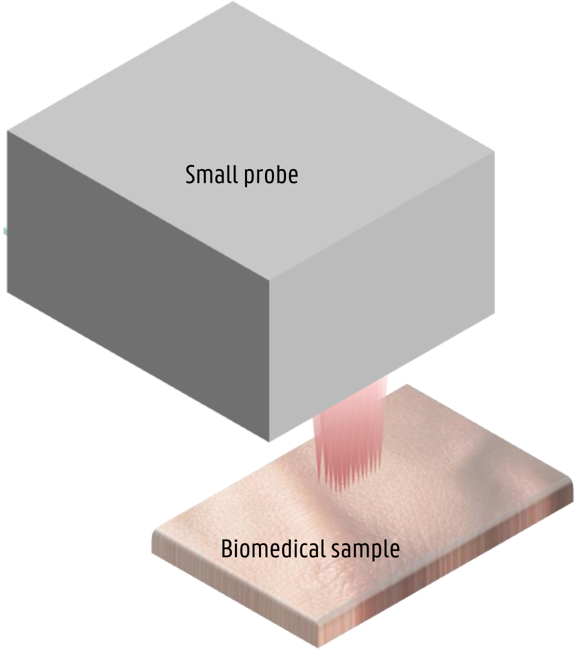
VISION

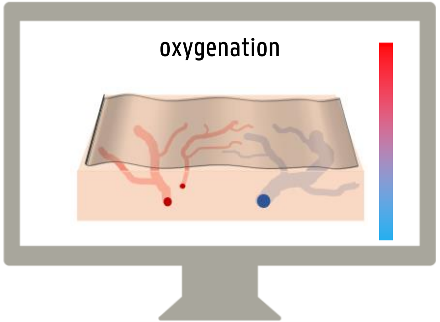
Photoacoustic Imaging

Silicon Photonics

Laser Doppler Vibrometry

VISION: SMALL CONTACTLESS DEVICE FOR PHOTOACOUSTIC IMAGING





RESULTS AND LAB DEMONSTRATION

Theoretical analysis LDV for Photoacoustics

E. Dieussaert, Y. Li, G. Morthier, R. Baets, “Influence of optical amplifiers for on-chip homodyne laser Doppler vibrometers,” *Journal of Physics: Conference Series*, 2021

E. Dieussaert, R. Baets, Y. Li, “Proposal for non-contact photoacoustics using silicon photonics-based Laser Doppler Vibrometers” *IEEE Benelux Annual Symposium*, 2022.

Proof of concept experiment

E. Dieussaert, R. Baets, H. Jans, X. Rottenberg, Y. Li “Non-contact photoacoustic imaging with a silicon photonics-based Laser Doppler Vibrometer,” *Scientific Reports*, 2024

E. Dieussaert, R. Baets, Y. Li, “Silicon photonics-based laser doppler vibrometer for non-contact photoacoustic sensing,” *Smart Photonic and Optoelectronic Integrated Circuits 2023*, SPIE, 2023.

E. Dieussaert, X. Rottenberg, R. Baets, Y. Li, “Miniature and non-contact photoacoustic system using silicon photonics-based Laser Doppler Vibrometer and compact excitation source,” *ECIO*, 2023.

Scalable architecture

E. Dieussaert, R. Baets, Y. Li, “On-chip multi-beam frequency shifter through sideband separation,” *Optics Express*, 2023.

E. Dieussaert, R. Baets, Y. Li, “Photonic integrated circuit for multiple frequency shifting of light,” publication number: US20240168223A1, U.S.

E. Dieussaert, R. Baets, Y. Li, “Scaling Silicon Photonics-based Laser Doppler Vibrometry with Multi-Beam Frequency Shifters,” *IEEE Silicon Photonics Conference,* 2024

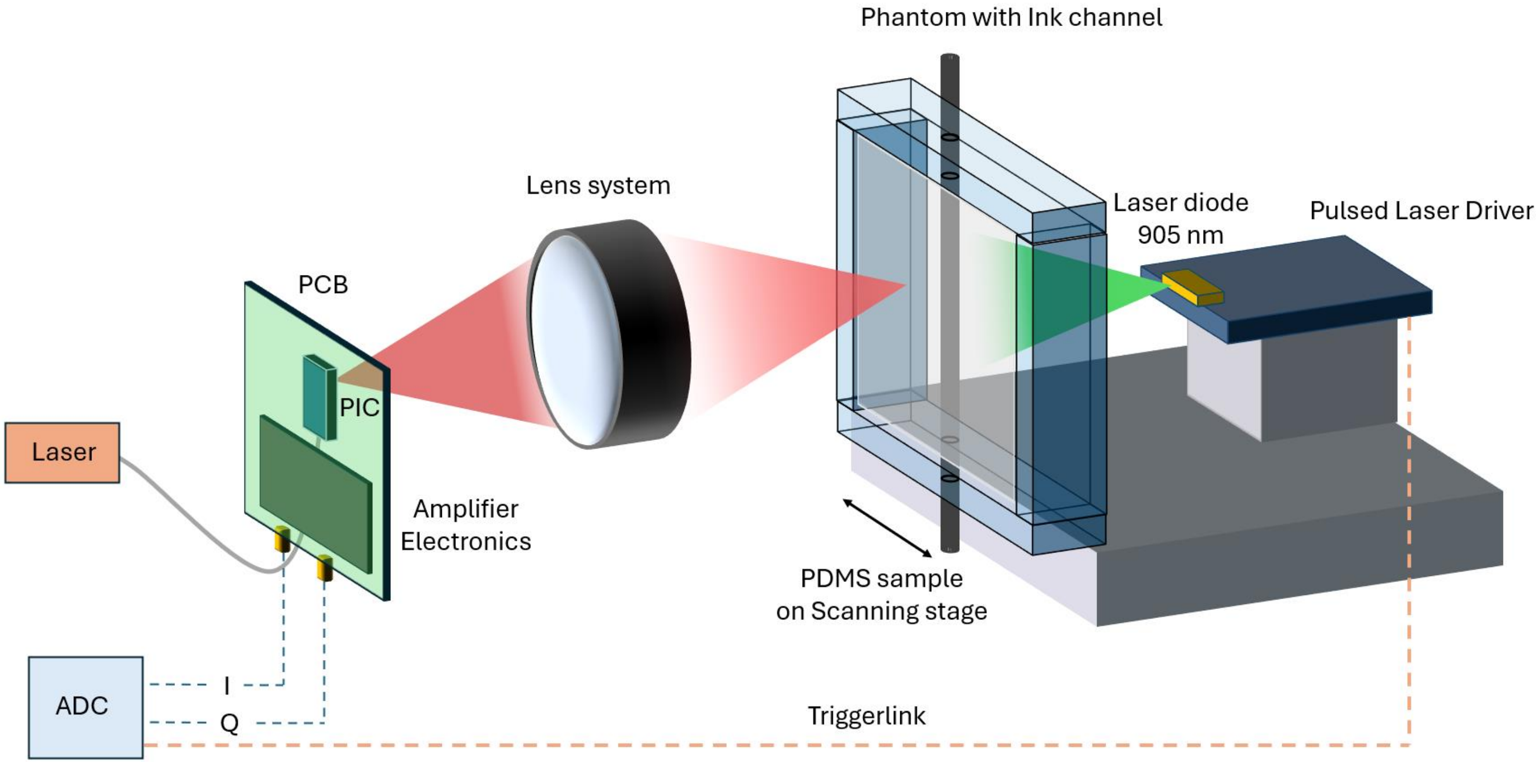
Proof of concept experiment

Scalable architecture

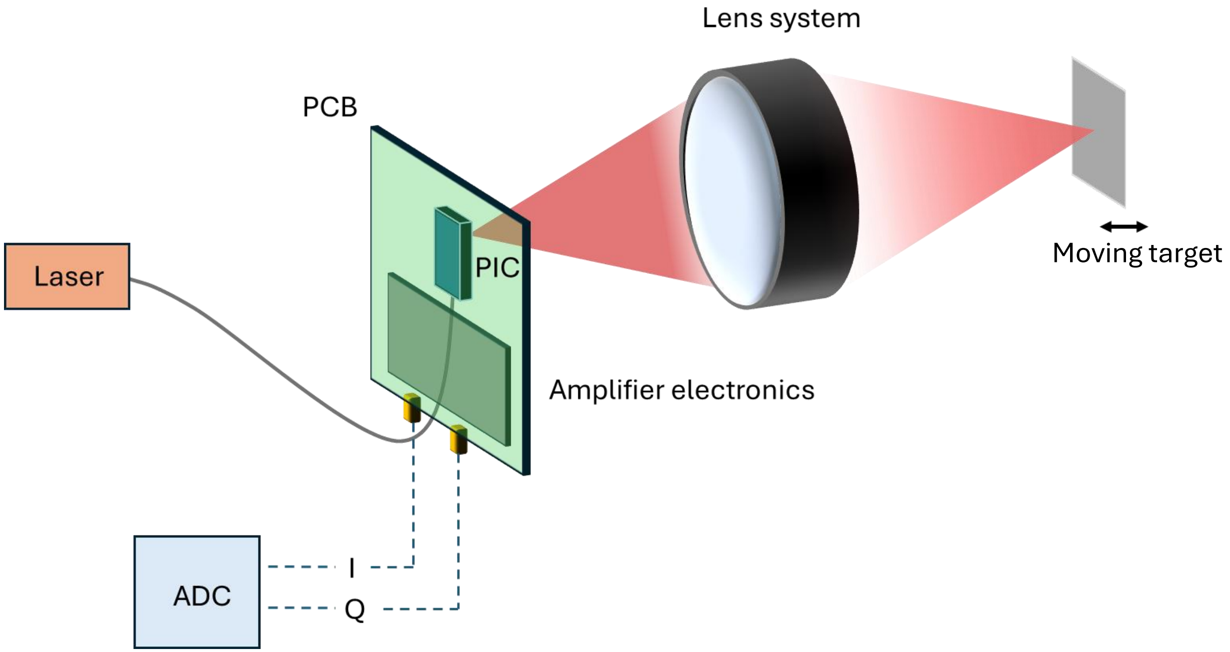
Proof of concept experiment

Scalable architecture

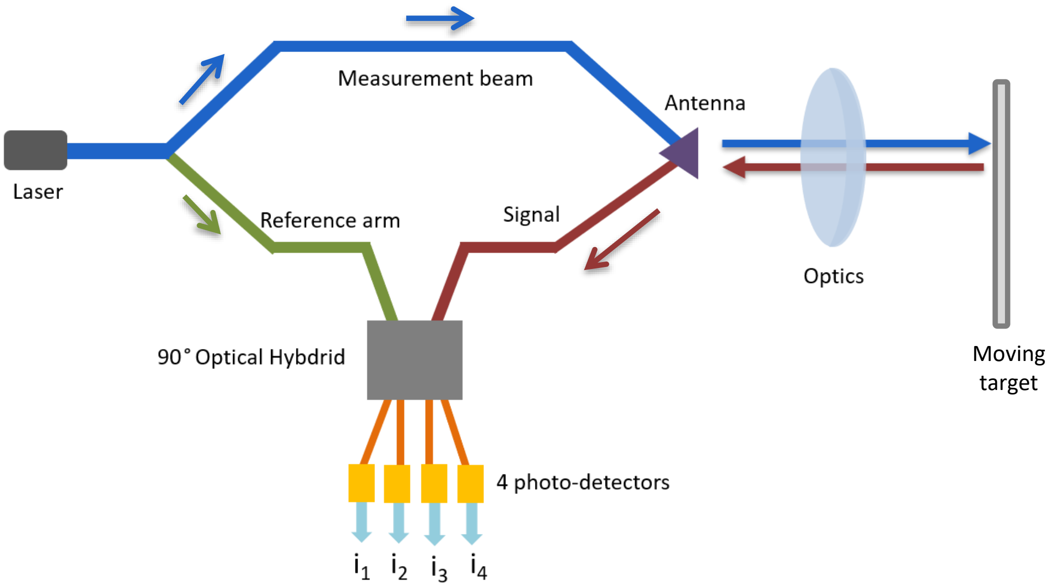
PROOF OF CONCEPT EXPERIMENT

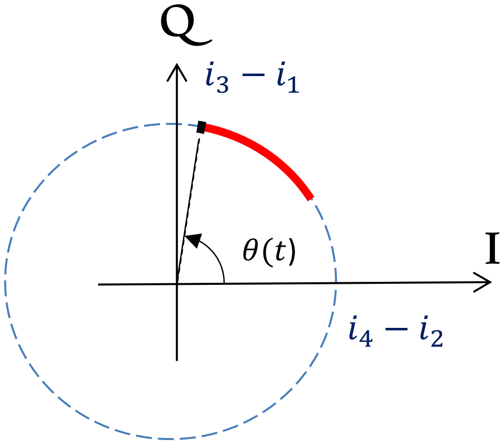


SILICON PHOTONICS-BASED LDV



SILICON PHOTONICS-BASED LDV





$$i_1 \propto |\text{Reference(t)} + 1 \cdot \text{Signal}(t)|^2$$

$$i_2 \propto |\text{Reference(t)} + i \cdot \text{Signal}(t)|^2$$

$$i_3 \propto |\text{Reference(t)} - 1 \cdot \text{Signal}(t)|^2$$

$$i_4 \propto |\text{Reference(t)} - i \cdot \text{Signal}(t)|^2$$

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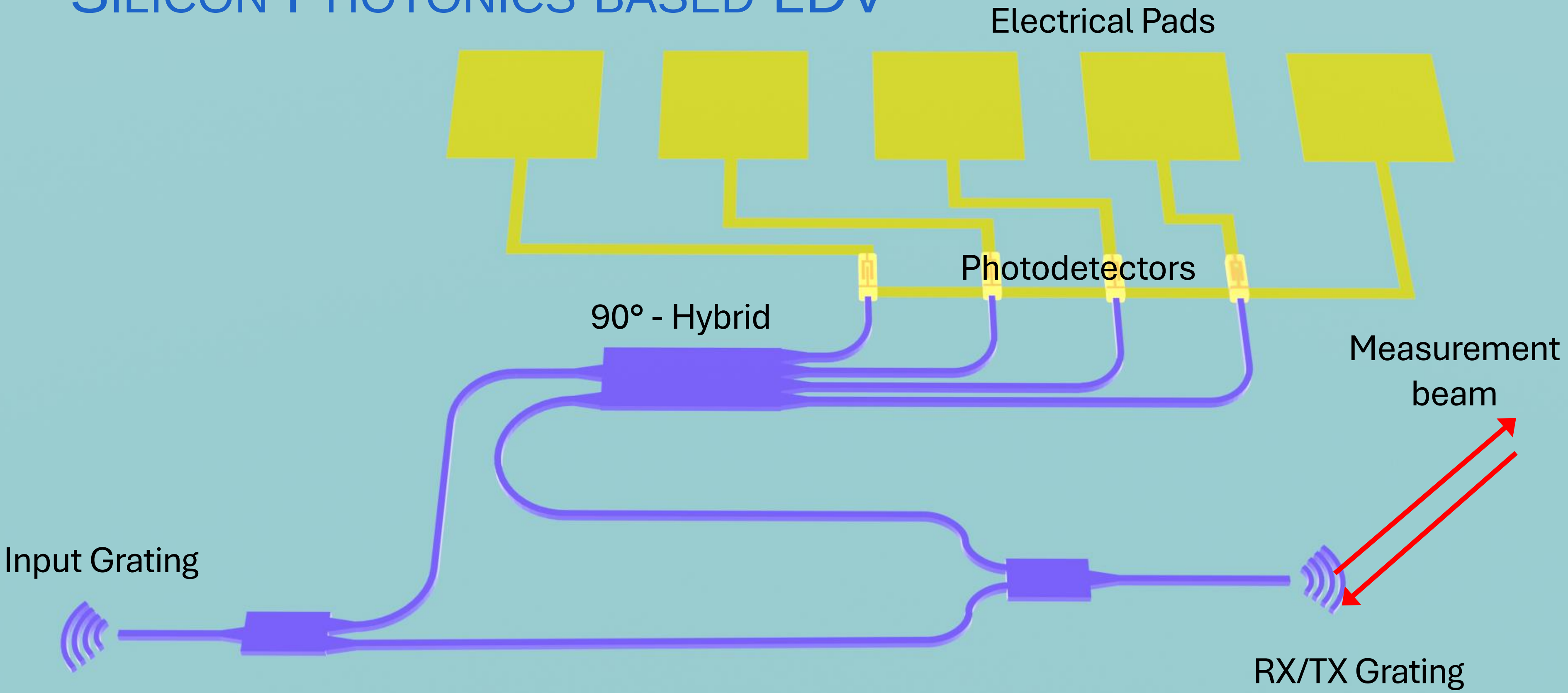
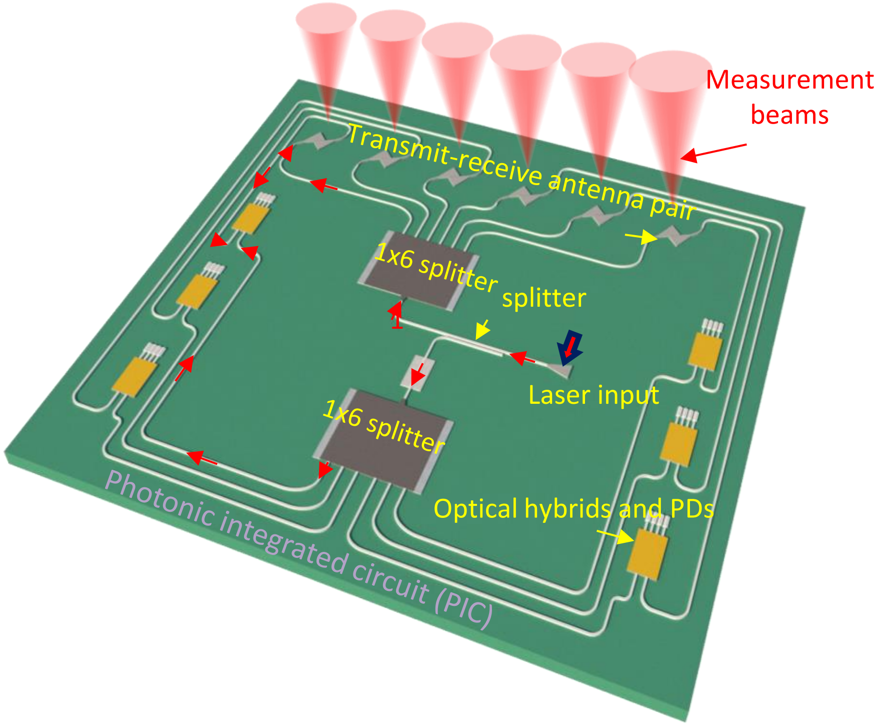
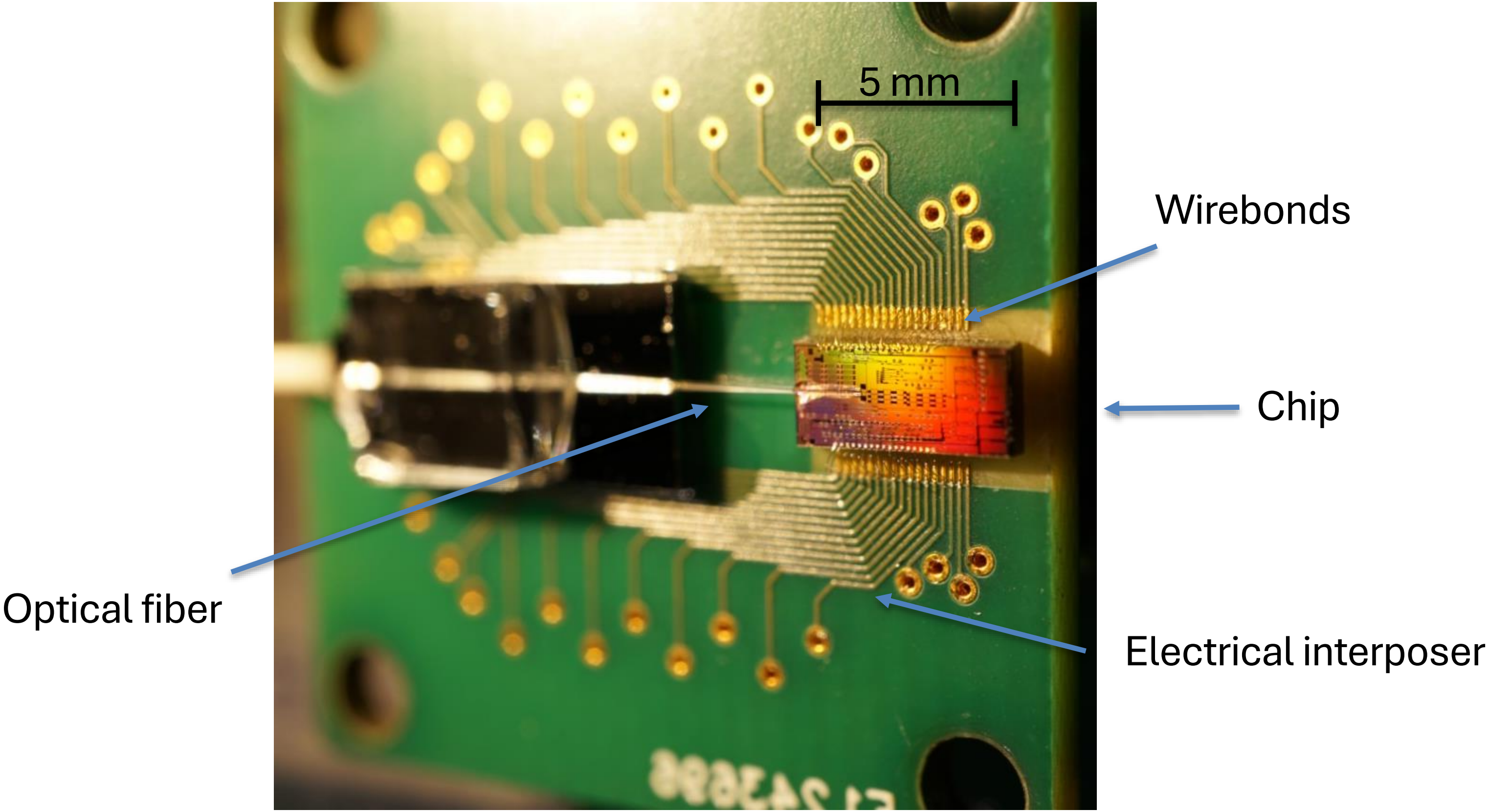
SILICON PHOTONICS BASED LDV



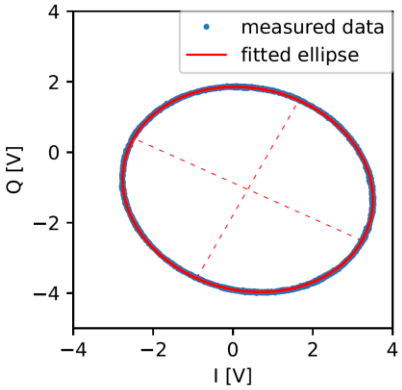
MULTIBEAM SILICON PHOTONICS BASED LDV

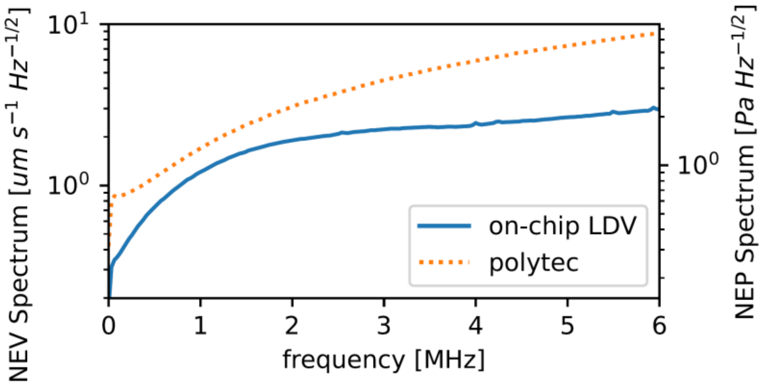


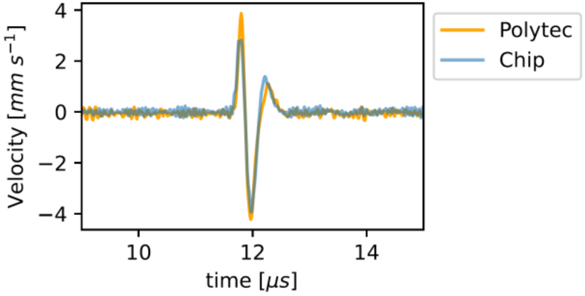
SILICON PHOTONICS BASED LDV

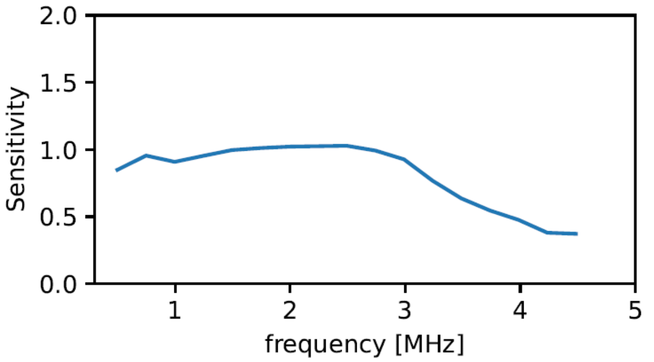


PERFORMANCE OF THE LDV

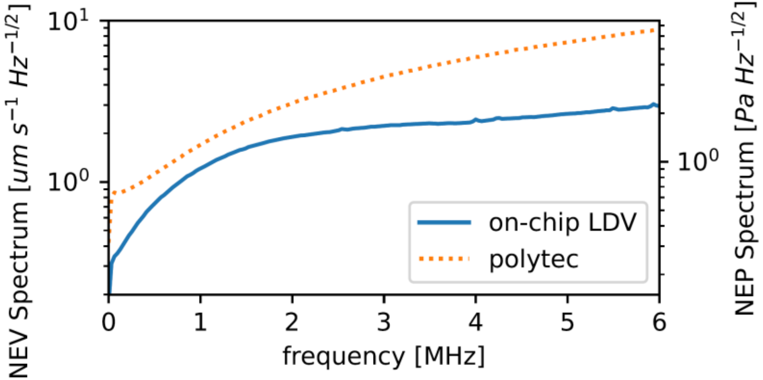






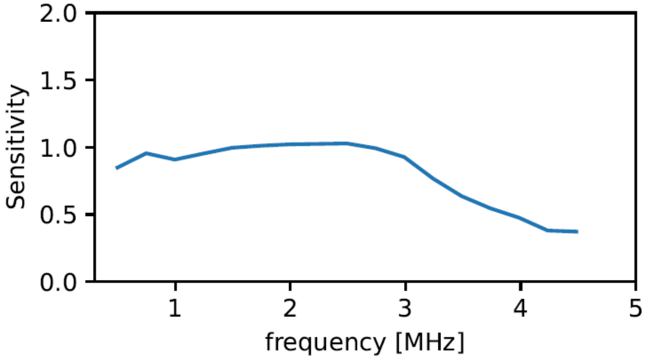


PERFORMANCE OF THE LDV

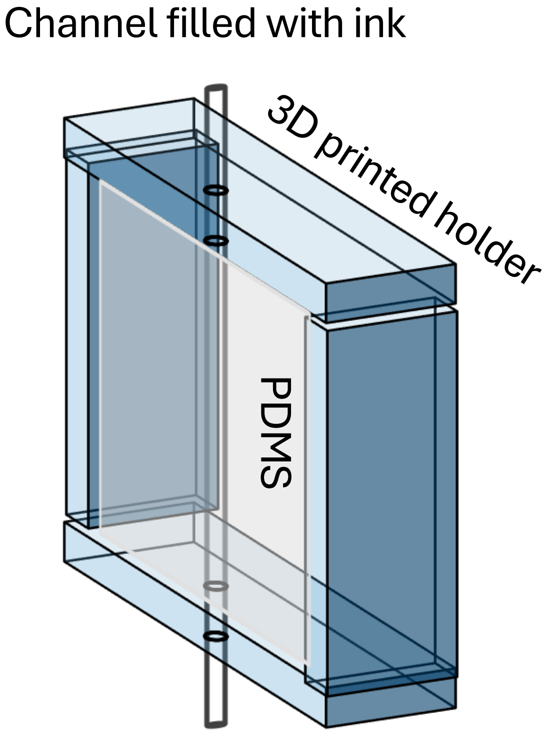


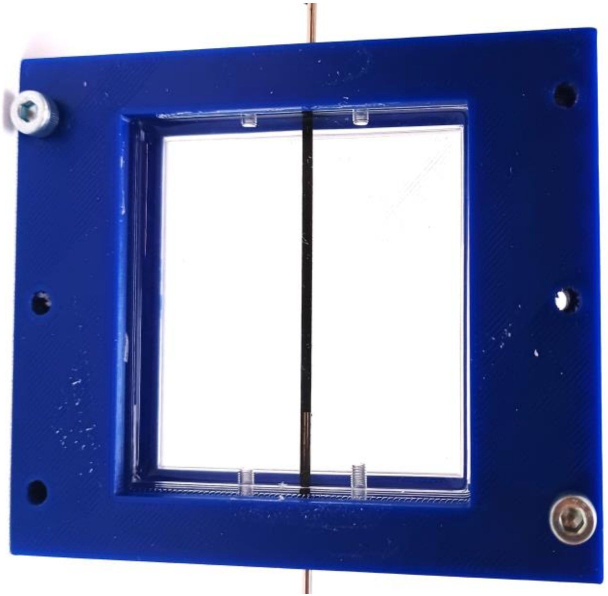
Conclusion:

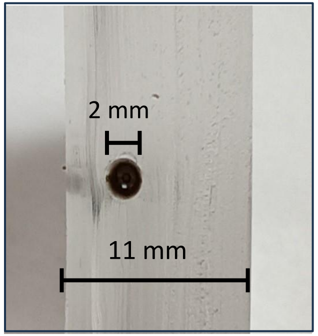
The detection system with the on-chip LDV has been successfully adapted to detect ultrasounds



SAMPLE







EXCITATION SOURCE

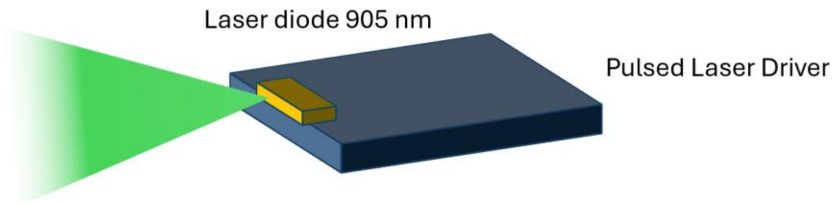
Conventional photoacoustic systems

High pulse power

Bulky & expensive

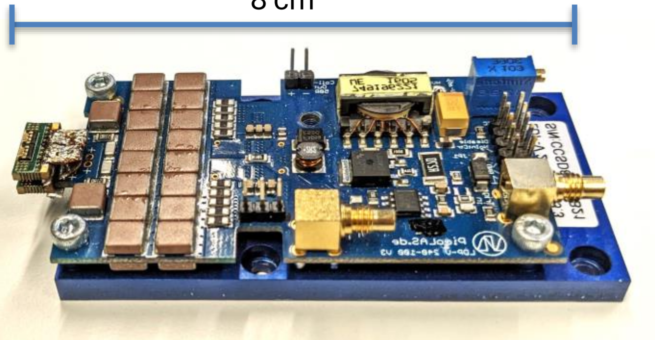
EXCITATION SOURCE

Compact excitation source



EXCITATION SOURCE

Compact excitation source



Lower pulse power

Compact and cheap

High repetition rate

EXCITATION SOURCE

Compact excitation source

Laser diode

or

Laser Bar

+-900 nm

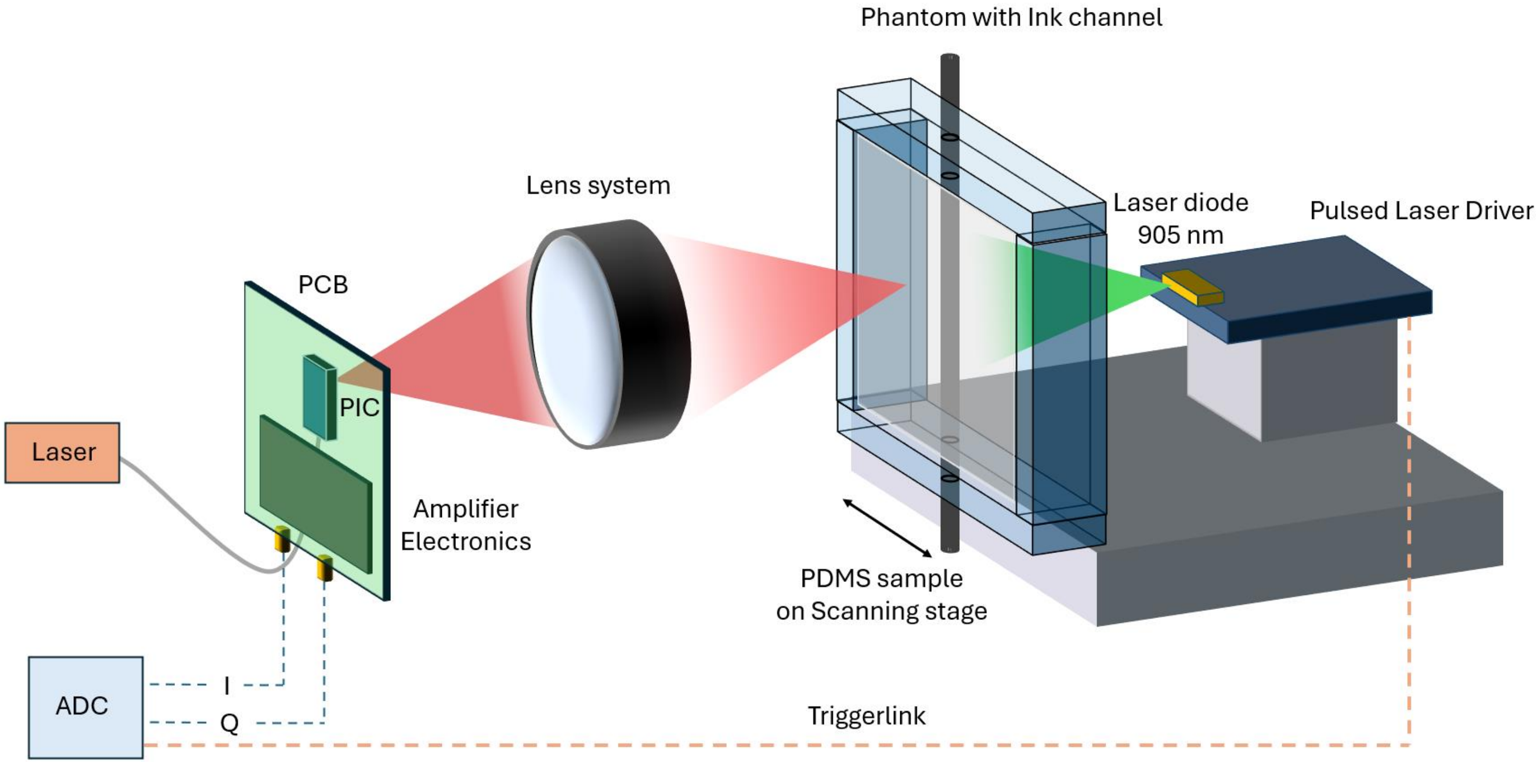
Commercial pulsed laser driver

100 – 200 uJ/pulse

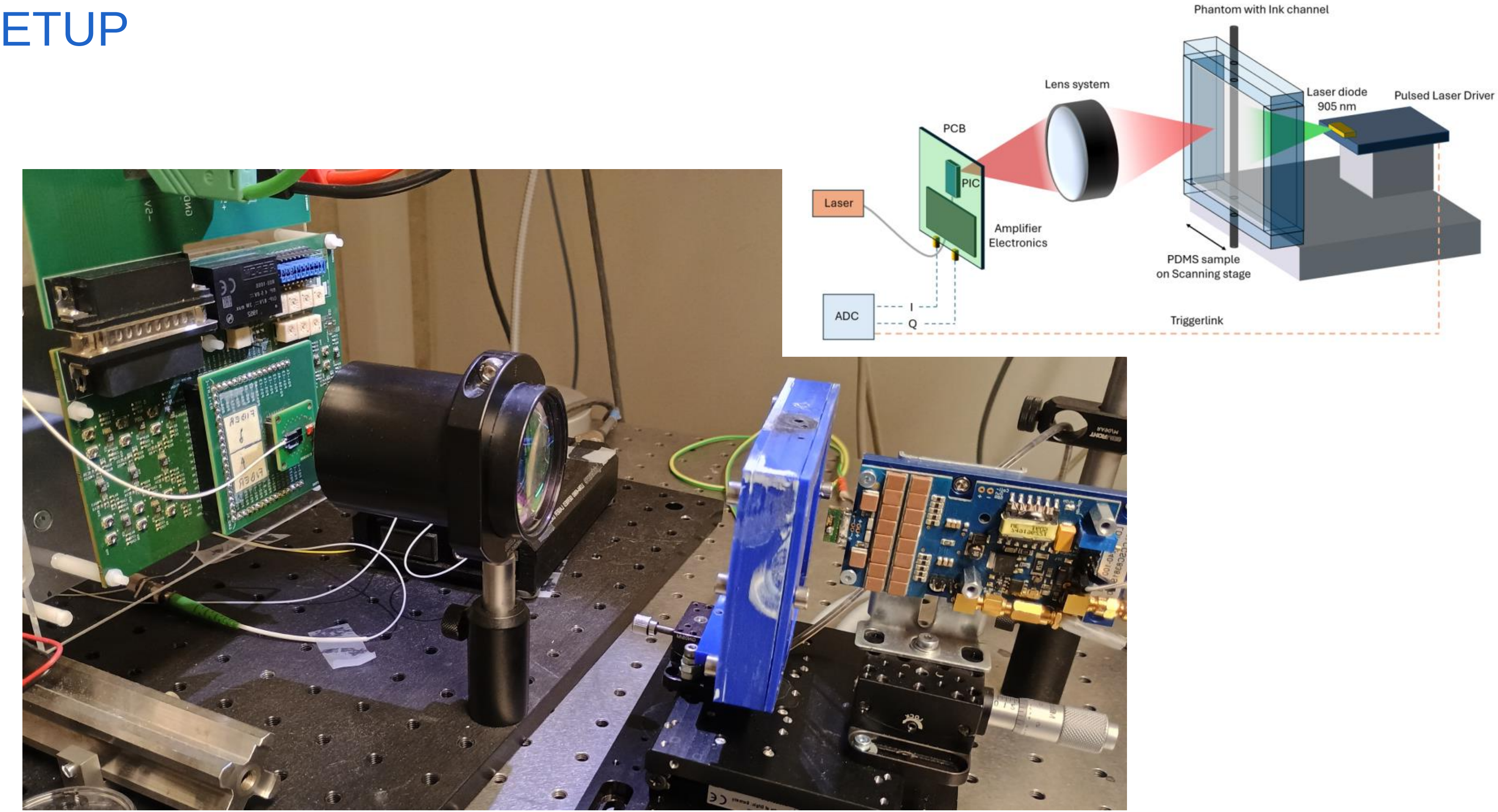
500 ns

1 kHz repetition rate

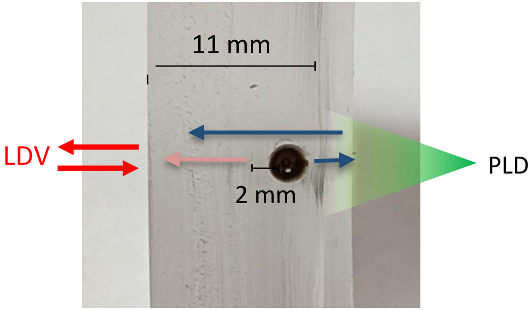
SETUP

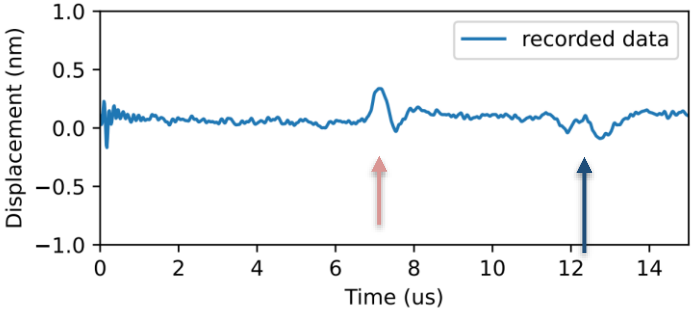

Phantom with Ink channel
Lens system
Laser diode
905 nm
Pulsed Laser Driver
PCB
PIC
Laser
Amplifier
Electronics
PDMS sample
on Scanning stage
ADC
I
Q
Triggerlink

SETUP


Phantom with Ink channel
Lens system
Laser diode
905 nm
Pulsed Laser Driver
PCB
PIC
Laser
Amplifier
Electronics
PDMS sample
on Scanning stage
ADC
I
Q
Triggerlink

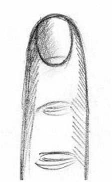
On-chip LDV and photoacoustics



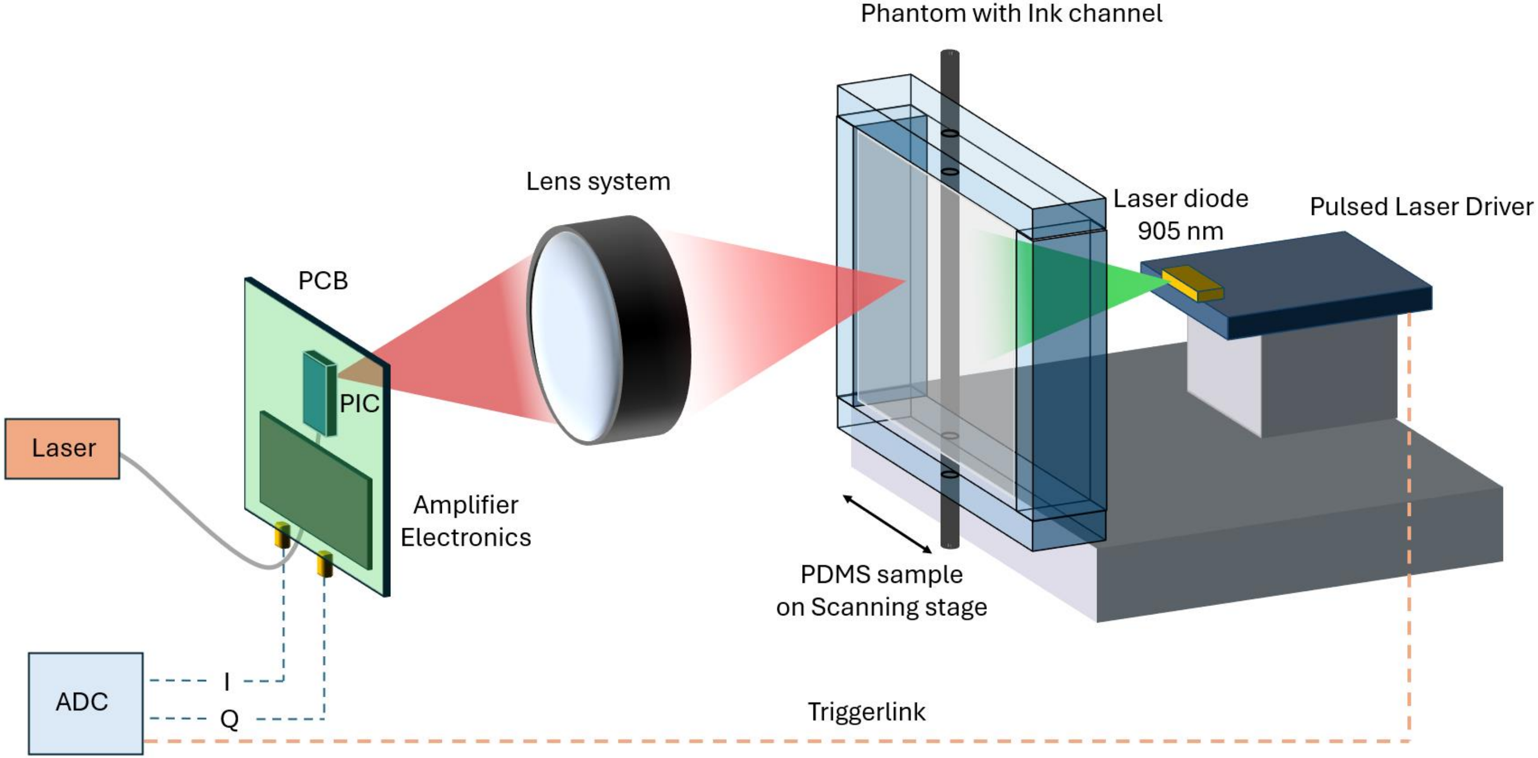


1 s average

Nail grows ±1 nm/s



SETUP



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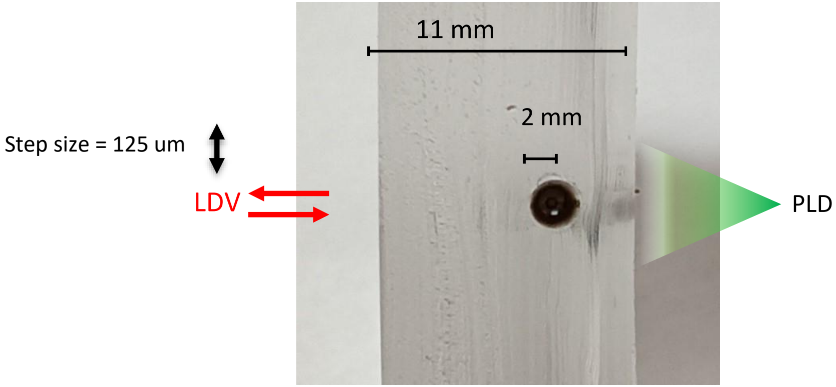
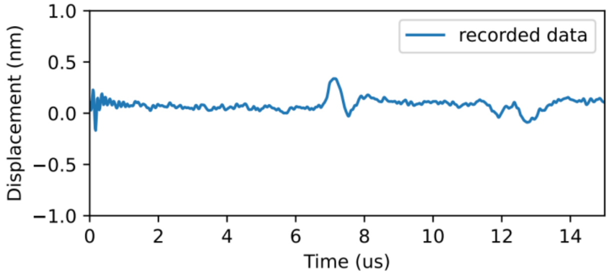
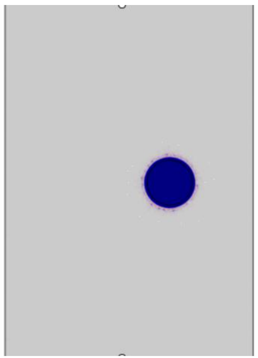
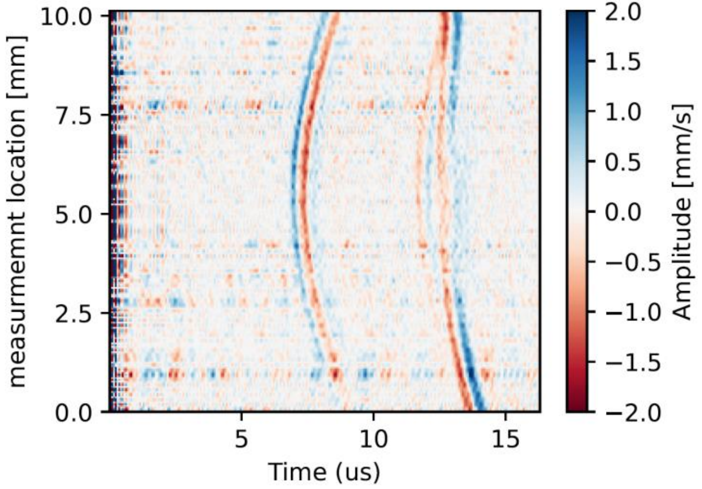
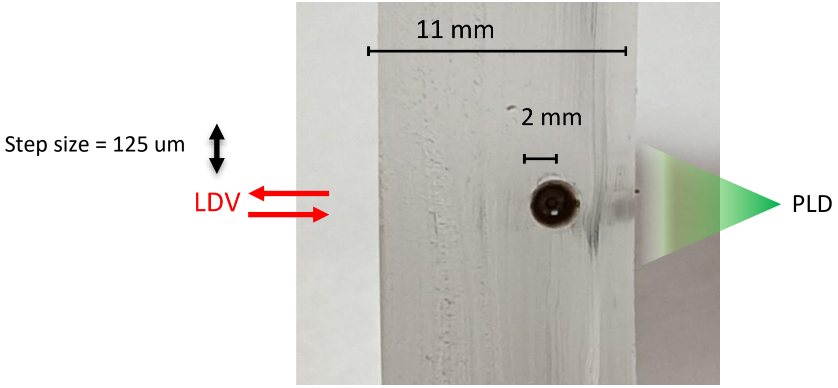
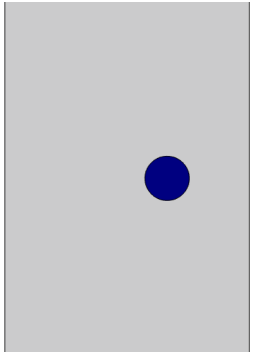

11 mm
2 mm
Step size = 125 um
LDV
PLD

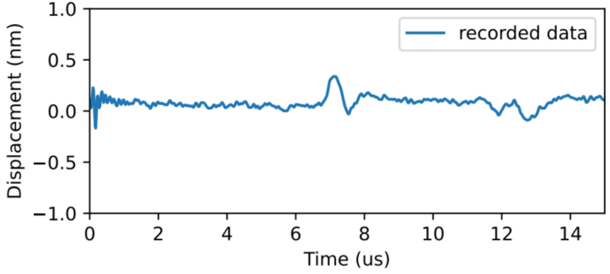

recorded data
Displacement (nm)
1.0
0.5
0.0
−0.5
−1.0
Time (us)
0
2
4
6
8
10
12
14

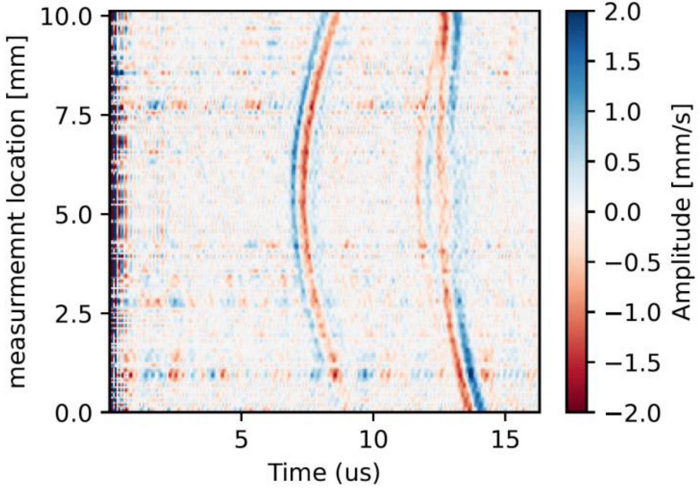


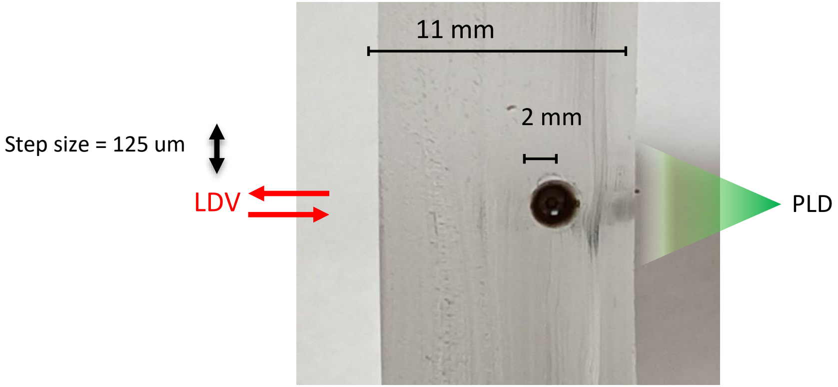

measurememnt location [mm]
10.0
7.5
5.0
2.5
0.0
Time (us)
5
10
15
Amplitude [mm/s]
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0

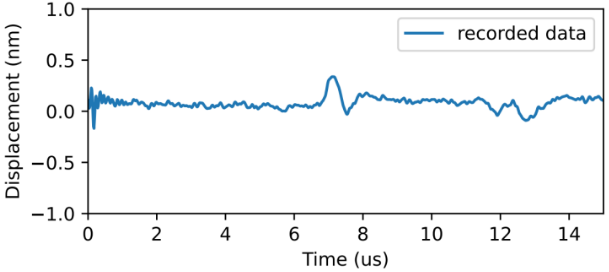

11 mm
2 mm
Step size = 125 um
LDV
PLD

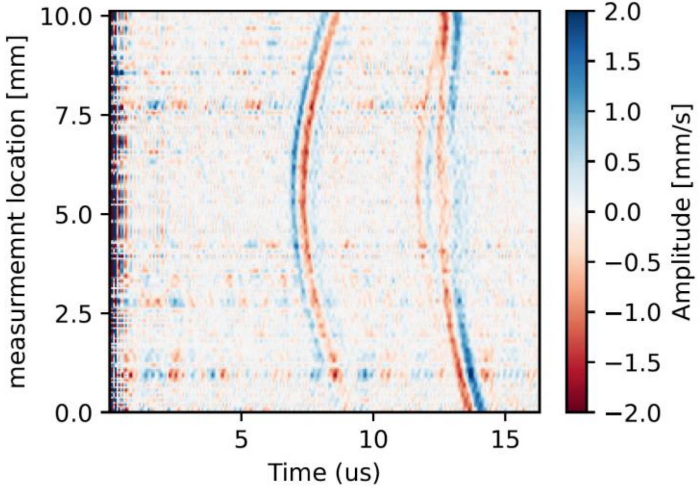


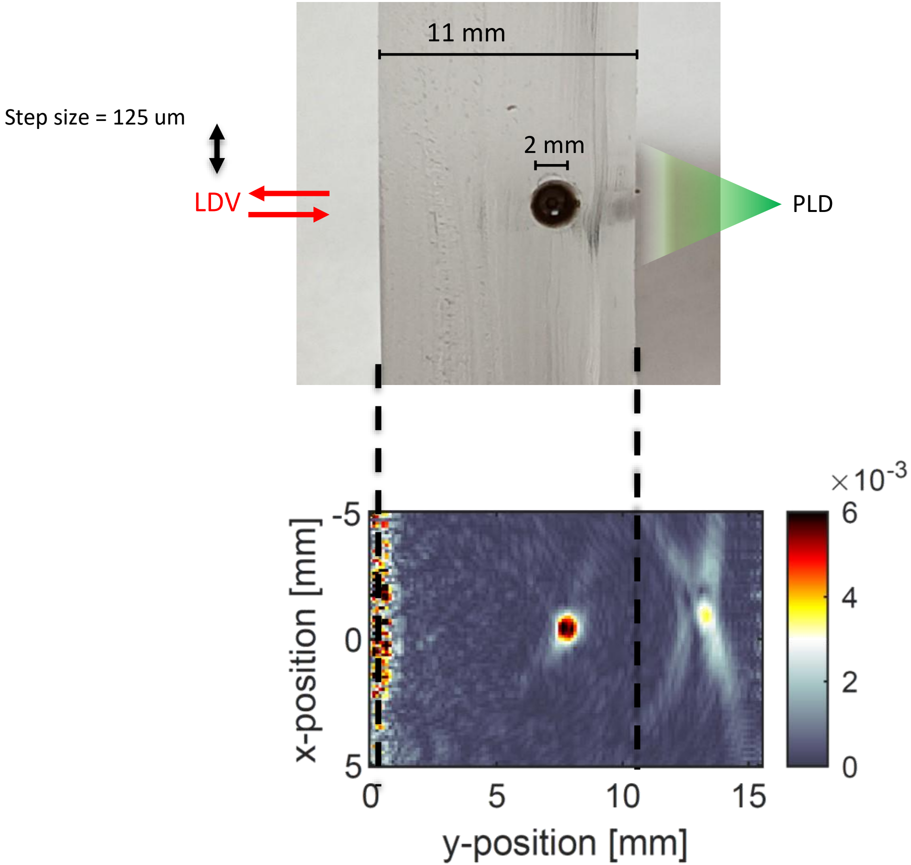

recorded data
Displacement (nm)
1.0
0.5
0.0
−0.5
−1.0
0
2
4
6
8
10
12
14
Time (us)

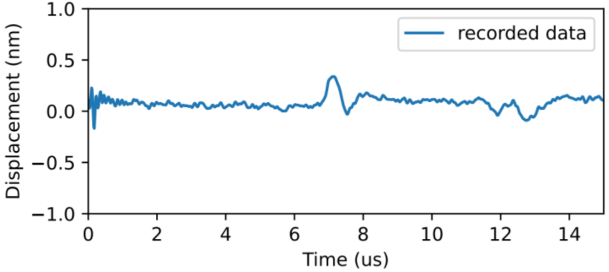

measurmemnt location [mm]
10.0
7.5
5.0
2.5
0.0
5
10
15
Time (us)
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
Amplitude [mm/s]

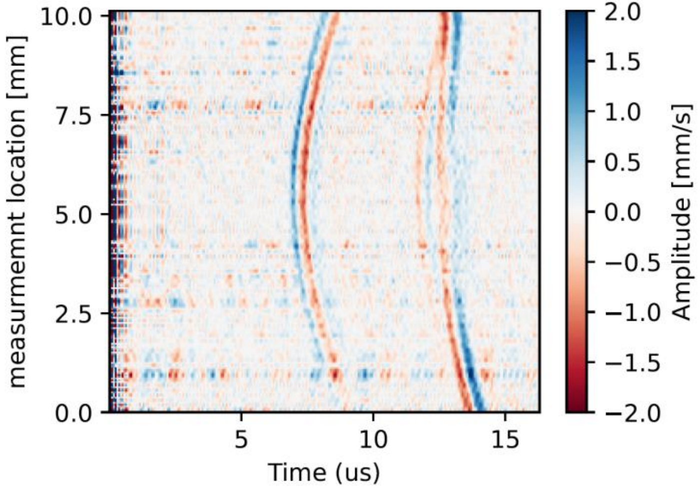

11 mm
2 mm
Step size = 125 um
LDV
PLD


Displacement (nm)
1.0
0.5
0.0
−0.5
−1.0
recorded data
0
2
4
6
8
10
12
14
Time (us)

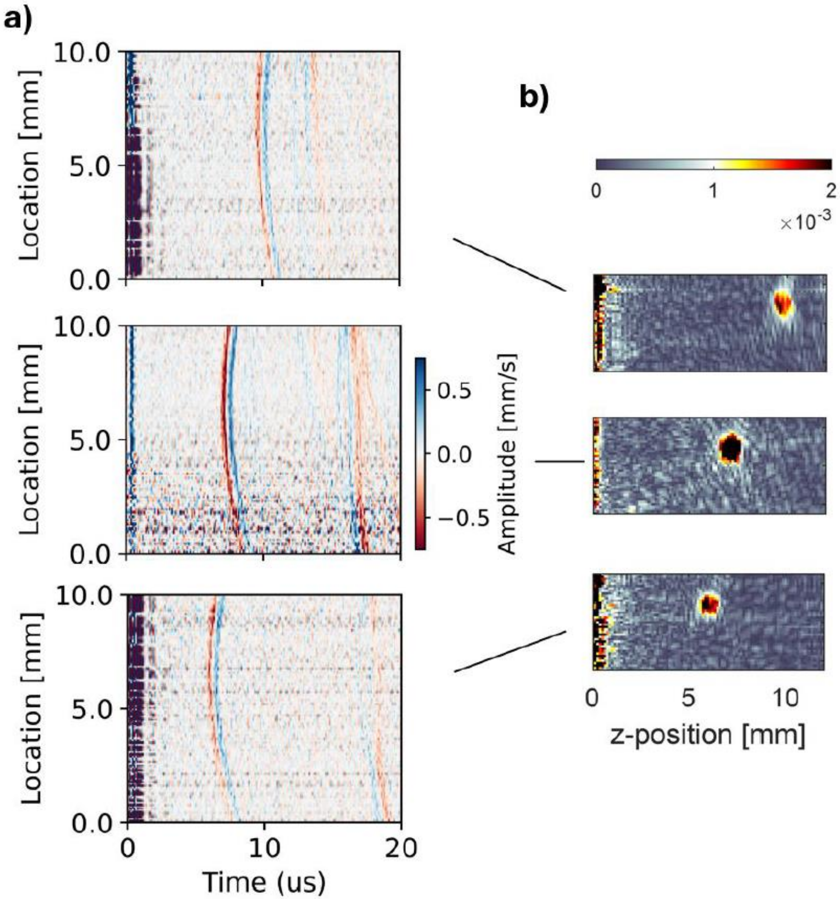

measurememnt location [mm]
10.0
7.5
5.0
2.5
0.0
5
10
15
Time (us)
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
Amplitude [mm/s]


Step size = 125 um
LDV
11 mm
2 mm
PLD
×10⁻³
6
4
2
0
-5
0
5
x-position [mm]
0
5
10
15
y-position [mm]

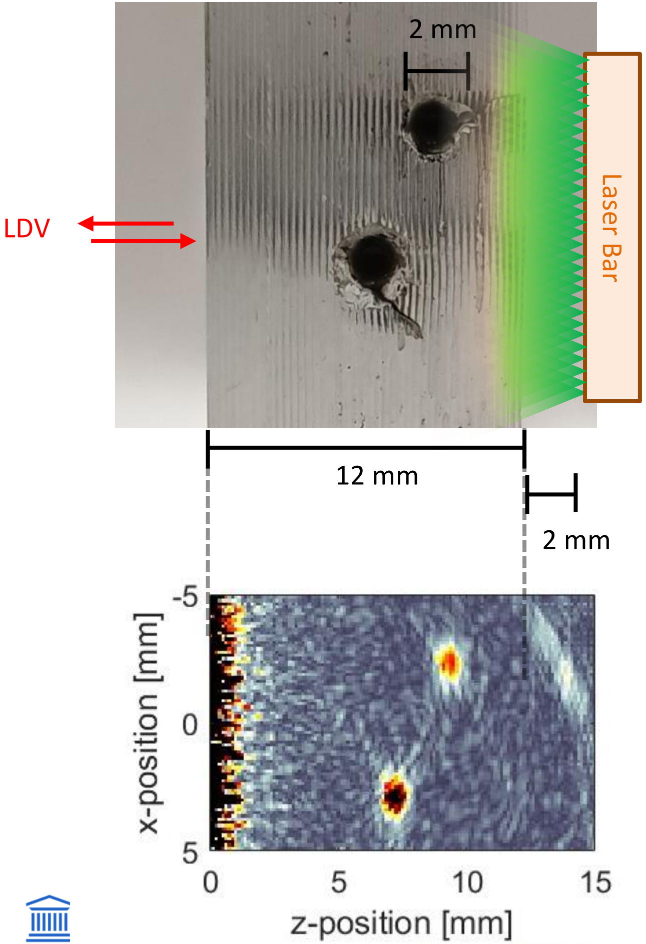

1.0
0.5
0.0
−0.5
−1.0
Displacement (nm)
0
2
4
6
8
10
12
14
Time (us)
recorded data

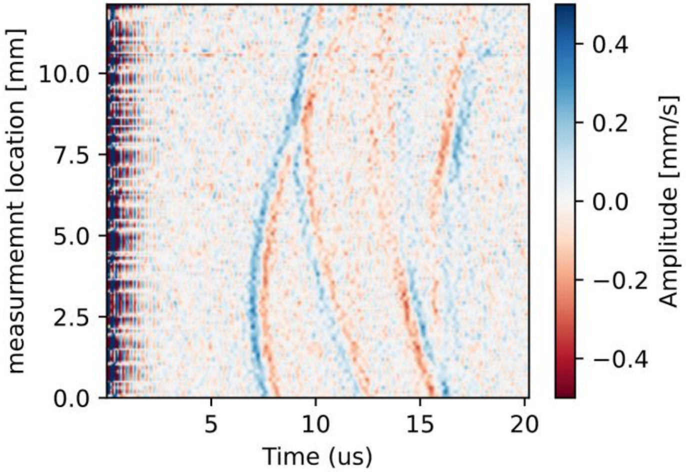

10.0
7.5
5.0
2.5
0.0
measuremnt location [mm]
5
10
15
Time (us)
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
Amplitude [mm/s]

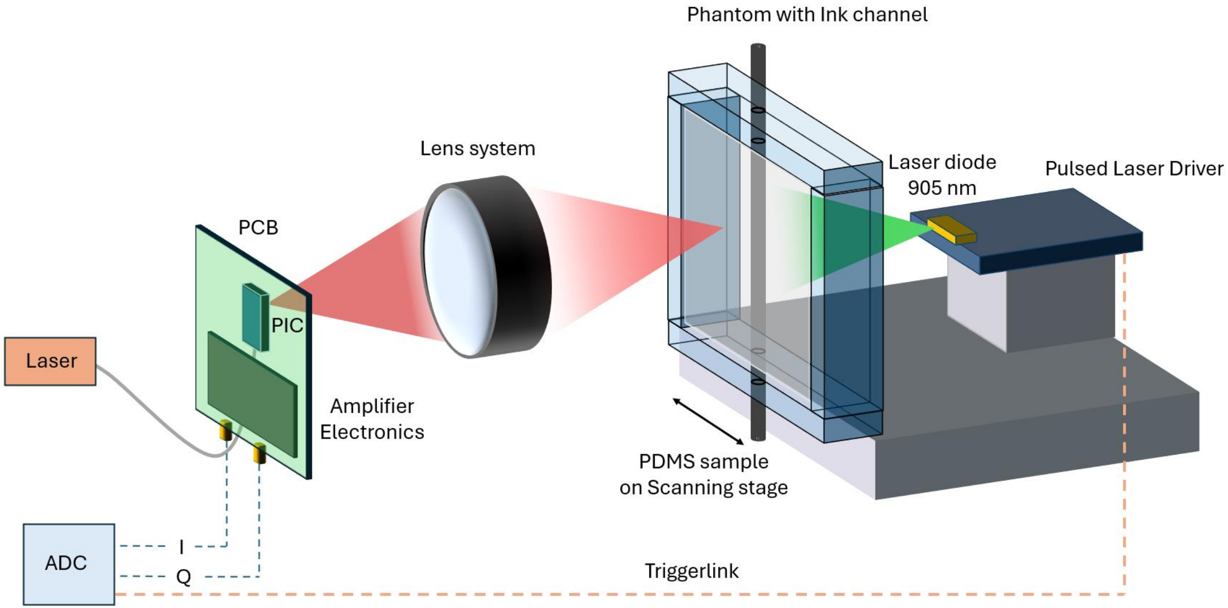
DIFFERENT DEPTHS



TWO CHANNELS







Conclusion: This first of its kind demonstration shows contactless, compact photoacoustic imaging with on-chip LDV

But there are still considerable challenges to move to in vivo samples: skin reflection, signal amplitude

CONTENT

Proof of concept experiment

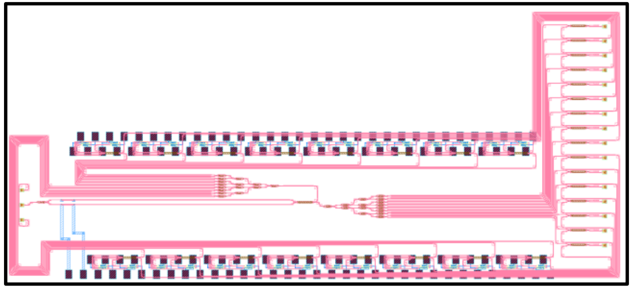
Scalable architecture

CONTENT

Proof of concept experiment

Scalable architecture

Number of beams : 16 , contact pads: +-80



How do we scale towards 100s or 1000s of beams?

NEW ARCHITECTURE

SYNTHETIC ARRAY HETERODYNING

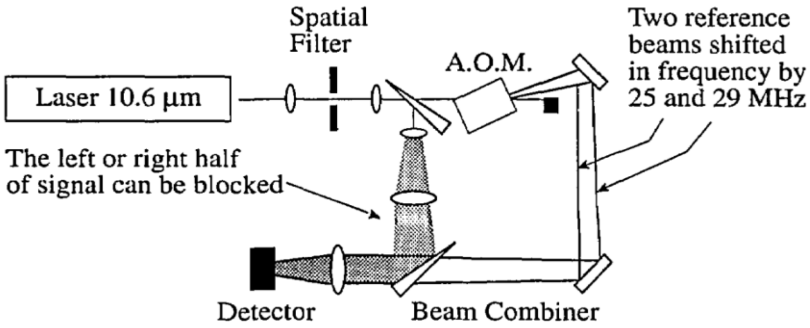
October 15, 1994 / Vol. 19, No. 20 / OPTICS LETTERS 1609

Synthetic-array heterodyne detection: a single-element detector acts as an array

Charlie E. M. Strauss

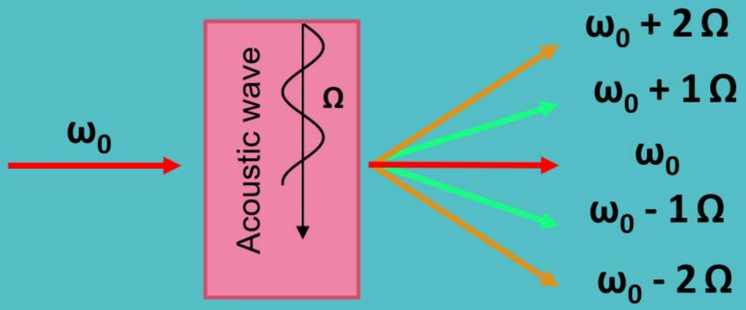
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

Received June 10, 1994

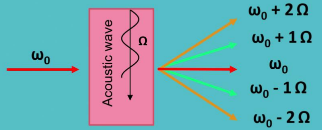


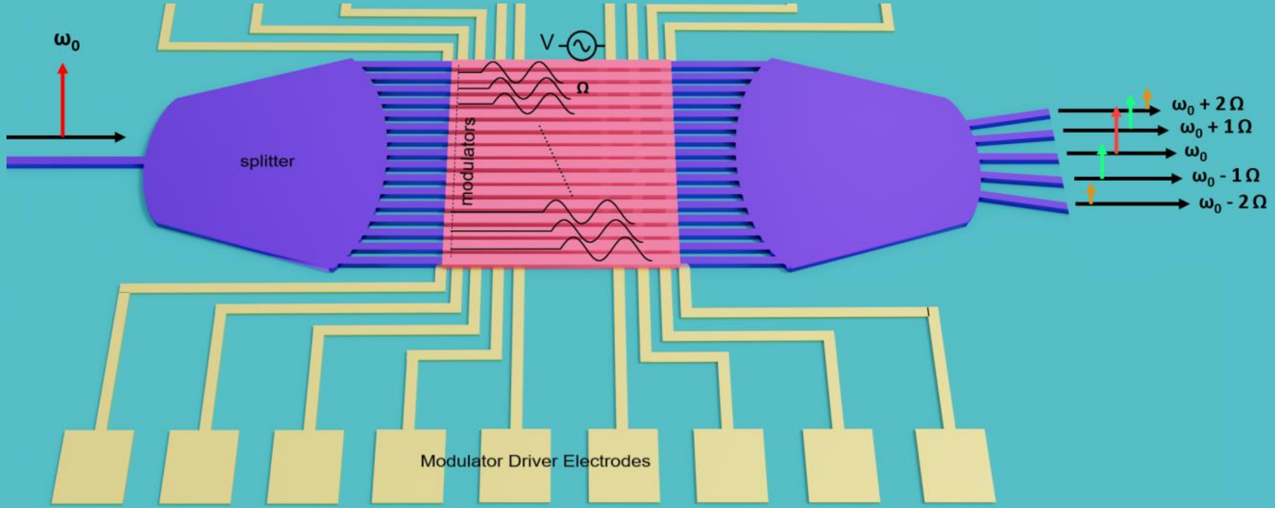
NEW COMPONENT: MULTIBEAM FREQUENCY SHIFTER

Acousto optic modulator



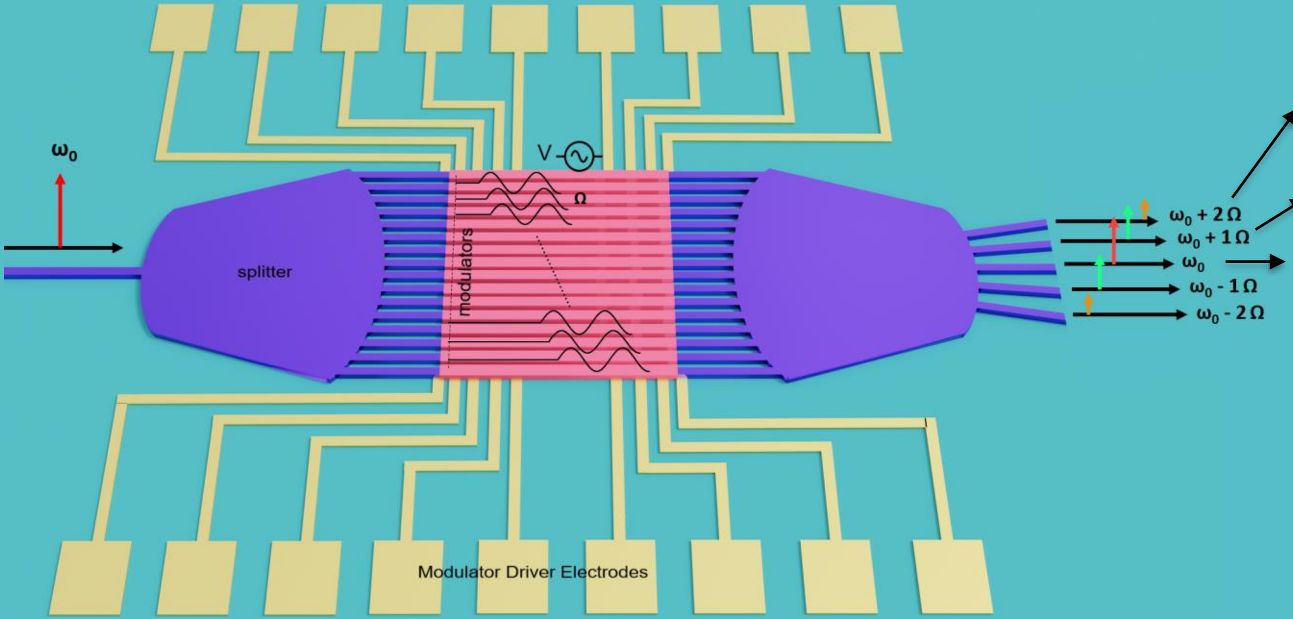
NEW COMPONENT: MULTIBEAM FREQUENCY SHIFTER

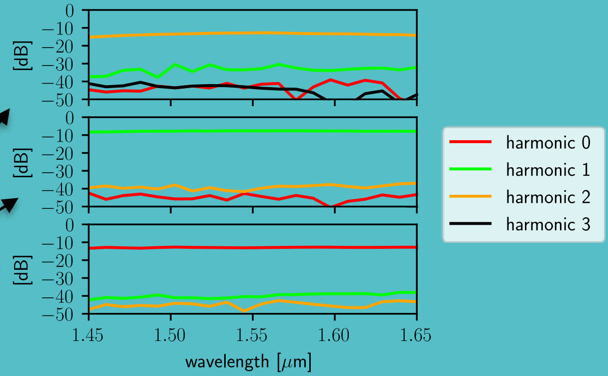




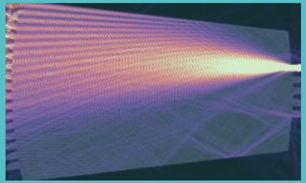
E. Dieussaert, On-chip multi-beam frequency shifter through sideband separation, Optics Express, 2023
+ patent application

NEW COMPONENT: MULTIBEAM FREQUENCY SHIFTER





2D FDTD



E. Dieussaert, On-chip multi-beam frequency shifter through sideband separation, Optics Express, 2023
+ patent application

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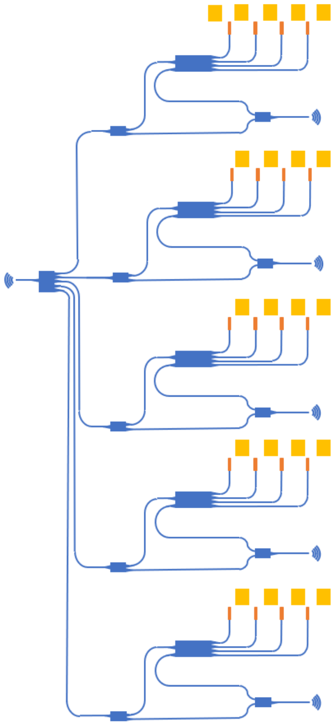
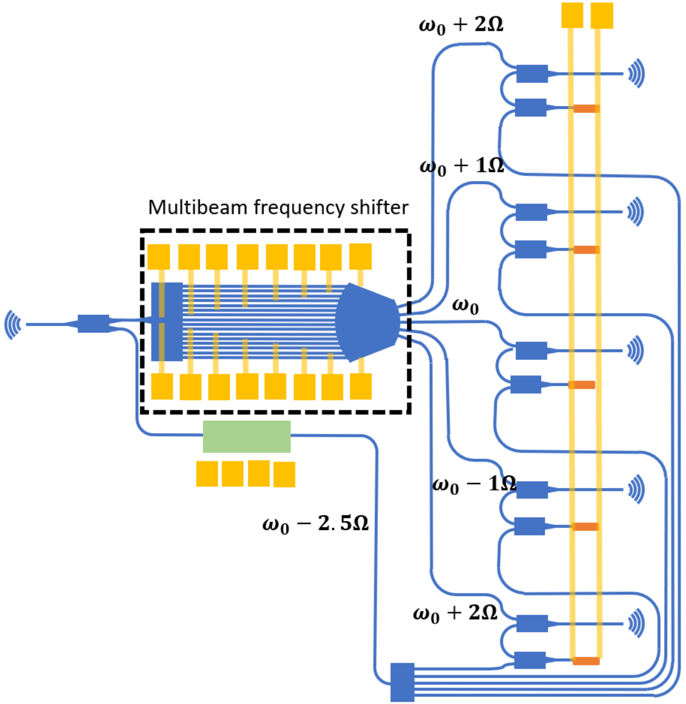
Current architecture

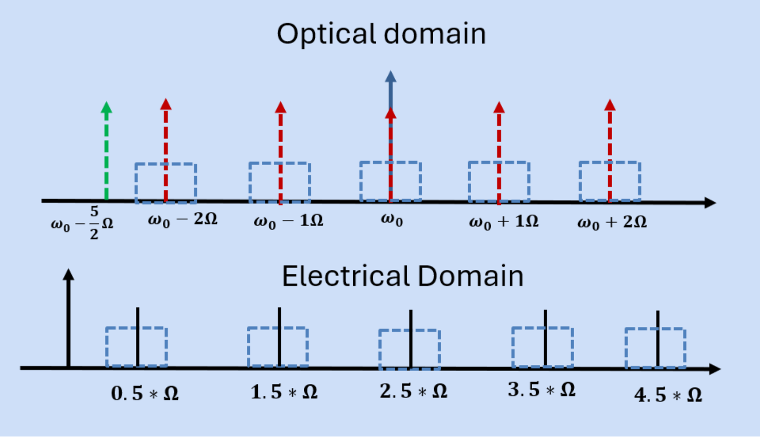


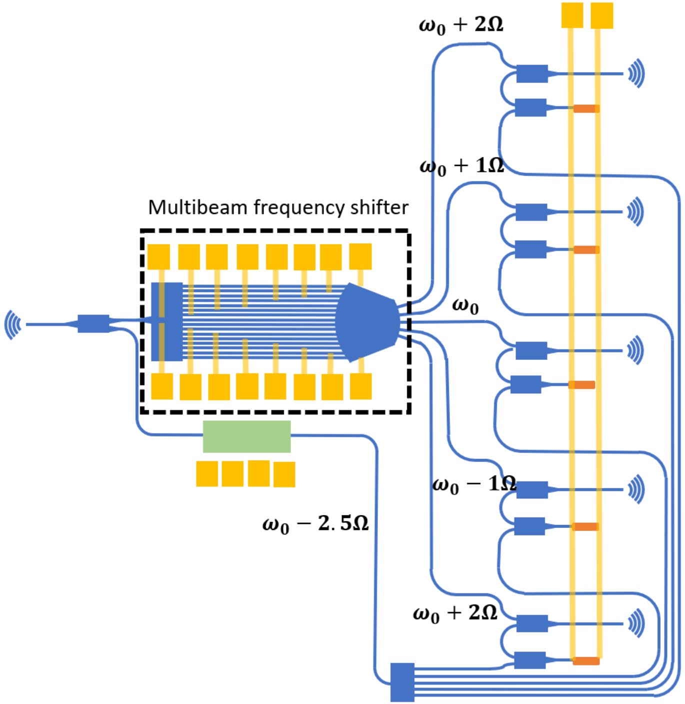
5 beams, 10-20 pads

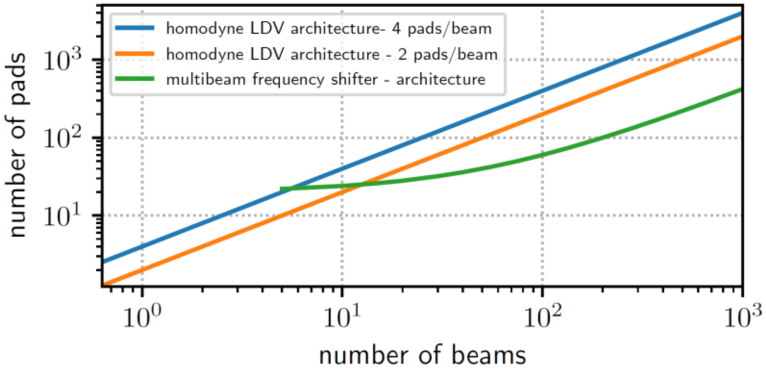
New architecture

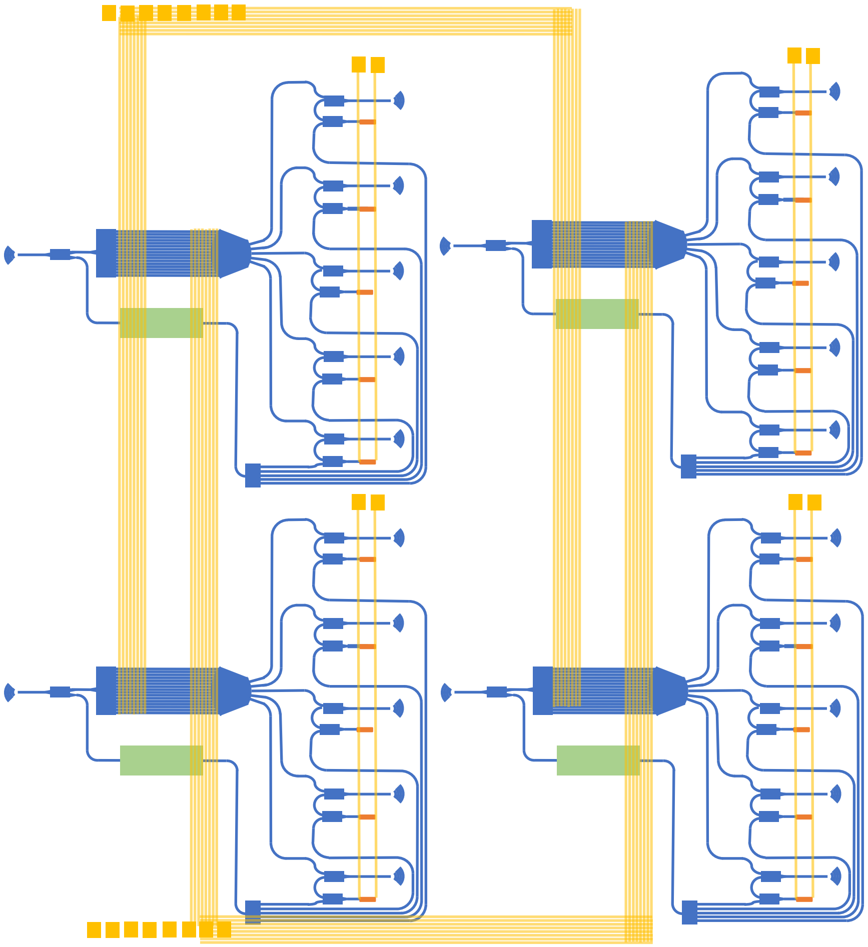


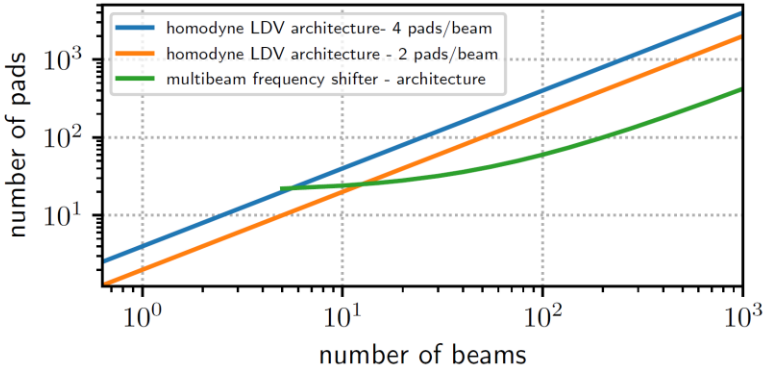
New architecture






homodyne LDV architecture- 4 pads/beam
homodyne LDV architecture - 2 pads/beam
multibeam frequency shifter - architecture
number of pads
10^3
10^2
10^1
10^0
10^1
10^2
10^3
number of beams





Conclusion:

The proposed architecture reduces the required number of pads by a factor of x5 or x10

SUMMARY

The on-chip LDV system was adapted to measure ultrasound

First lab demonstration of Non-contact Photoacoustic imaging with on-chip LDV

Scalable architecture and new component