SILICON PHOTONICS ENABLED LASER DOPPLER VIBROMETRY AND ITS APPLICATION IN CARDIOVASCULAR MEDICINE

Roel Baets, Yanlu Li

Optimess 2019, Antwerp

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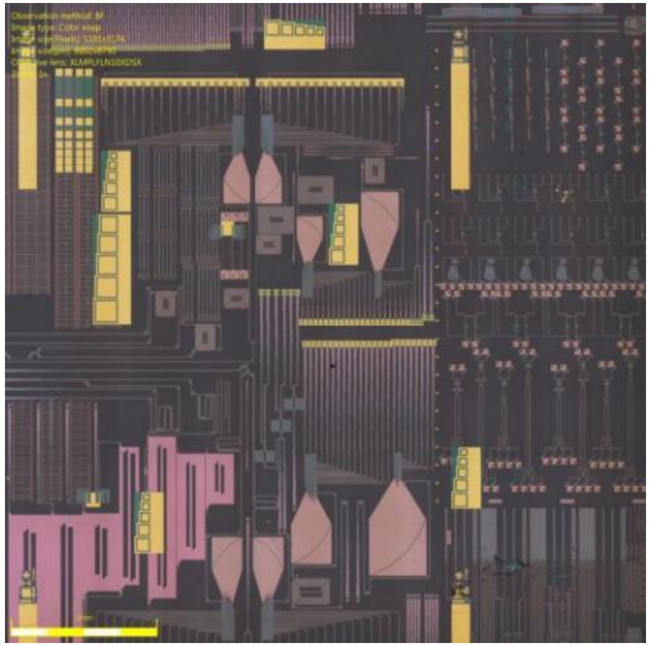
embracing a better life

What is silicon photonics?

The implementation of high density photonic integrated circuits by means of CMOS process technology in a CMOS fab





Pictures, courtesy of imec

Enabling complex optical functionality on a compact chip at low cost

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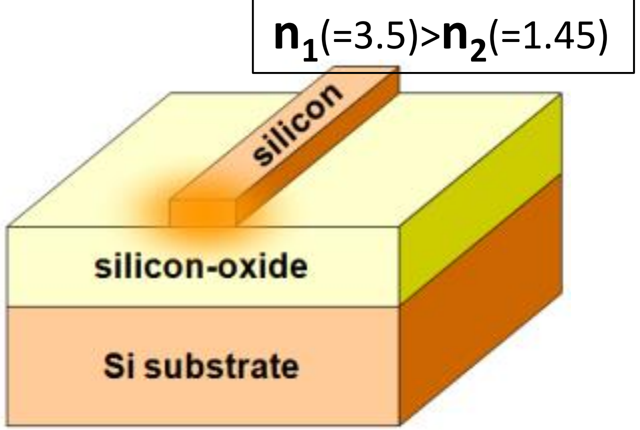
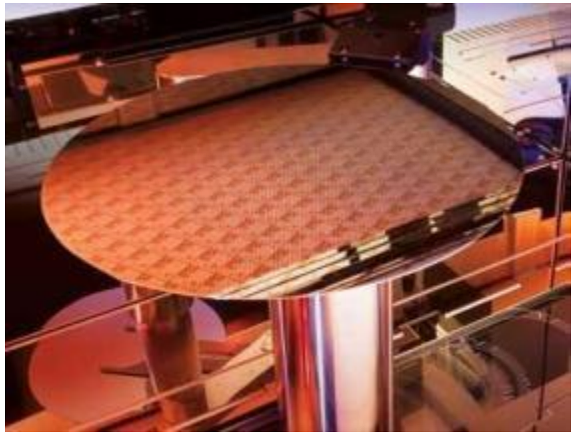
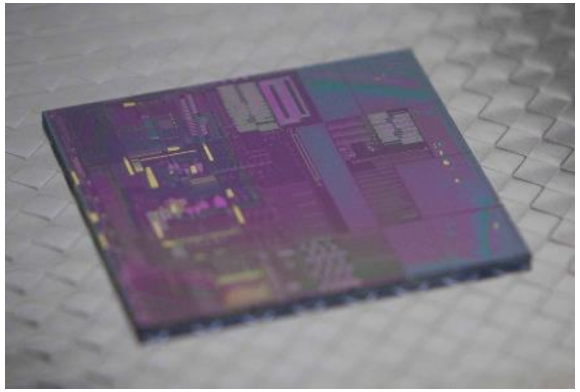
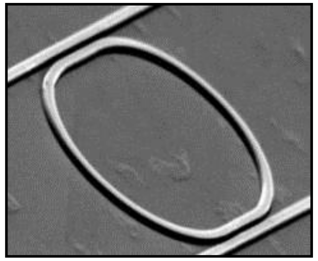
WHY SILICON PHOTONICS

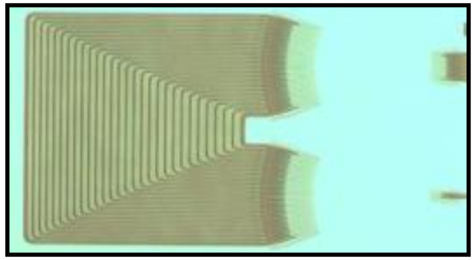
- High index contrast ⇒ very compact PICs
- CMOS technology ⇒ **nm-precision, high yield, existing fabs, low cost in volume**
- High performance passive devices
- High bitrate Ge photodetectors
- High bitrate modulators
- Wafer-level automated testing
- Hierarchical set of design tools
- Light source integration (hybrid/monolithic?)
- Integration with electronics (hybrid/monolithic?)

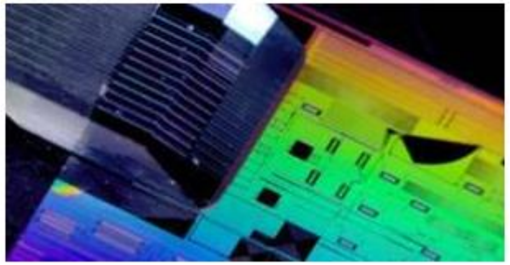






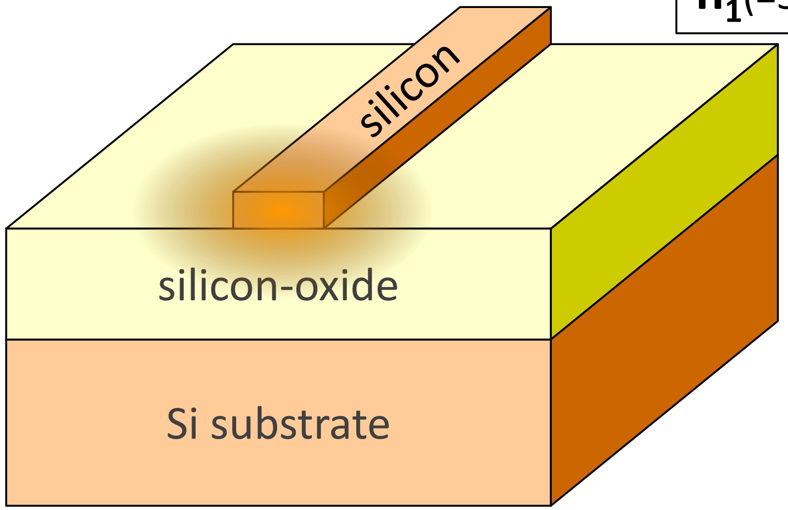


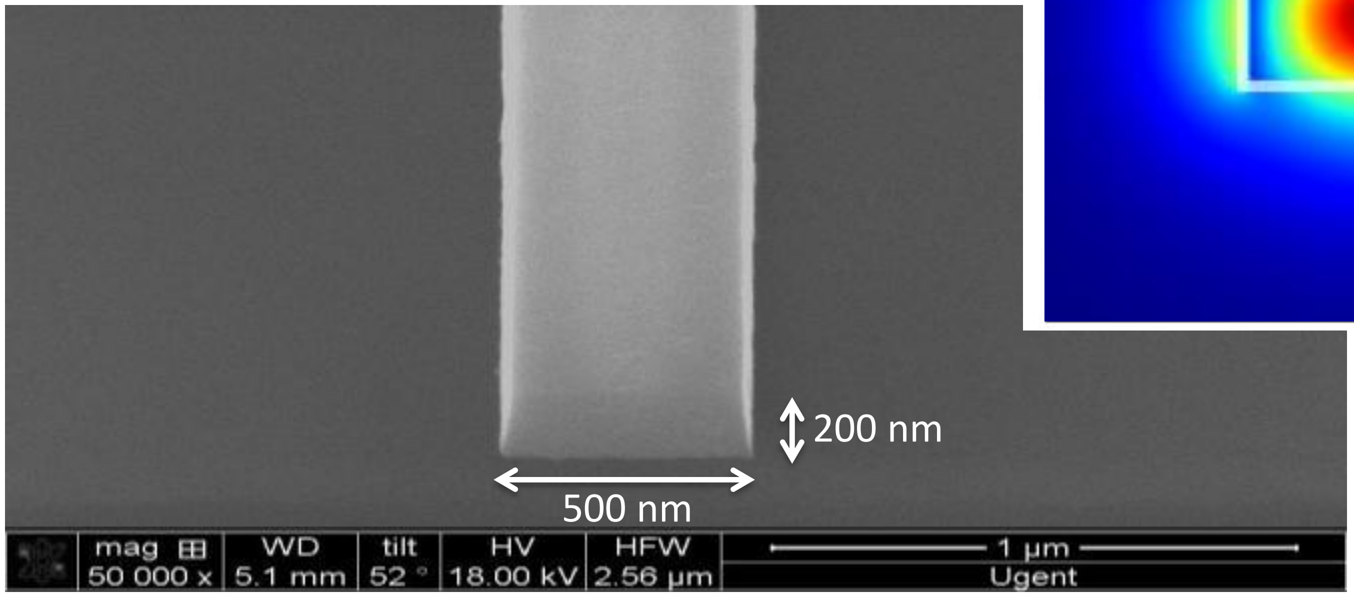


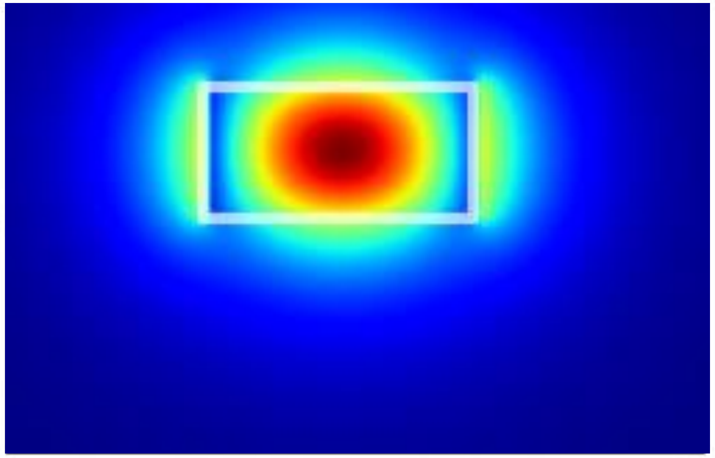


SILICON PHOTONIC WIRES

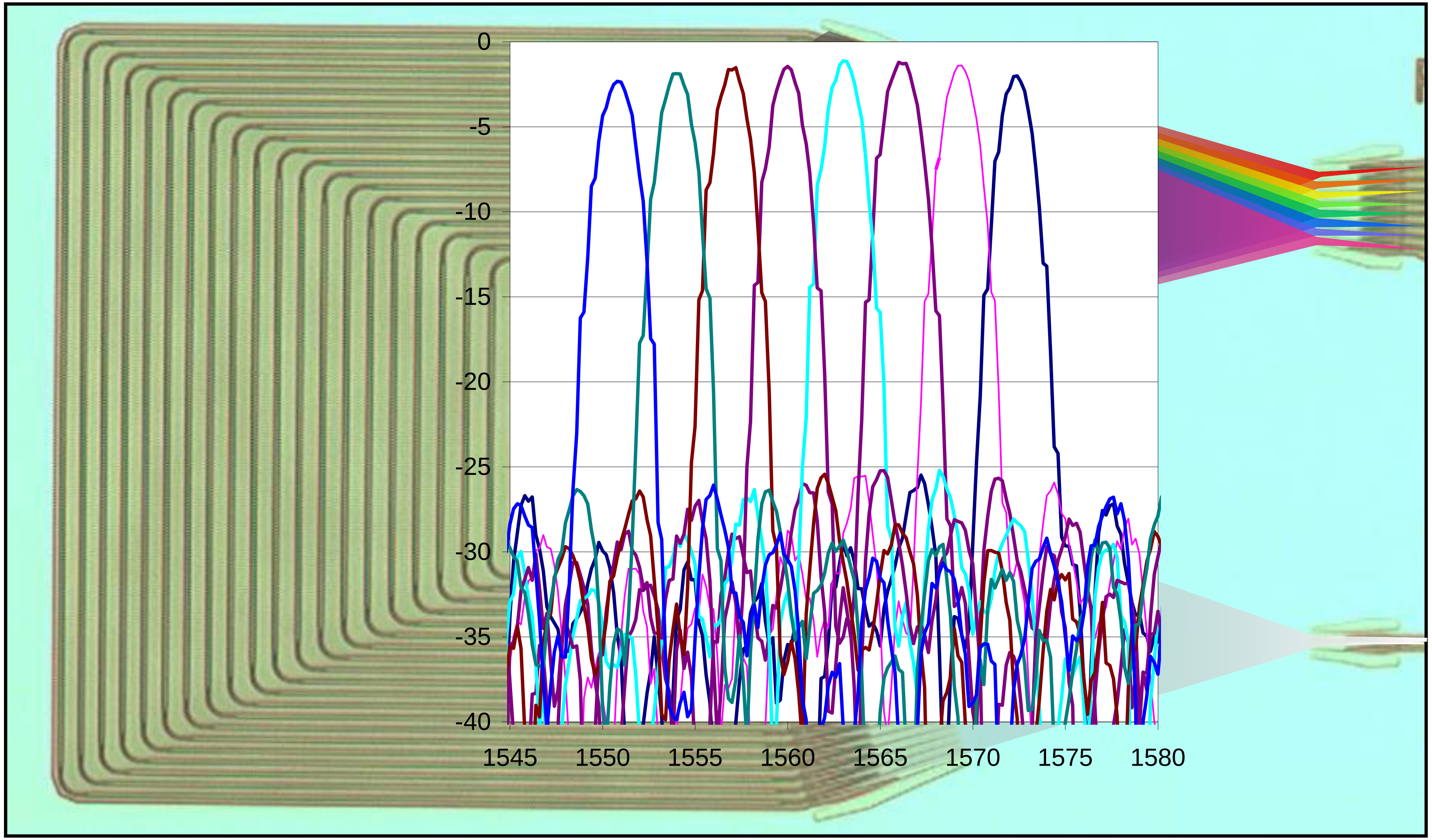
$n_1(=3.5)>n_2(=1.45)$



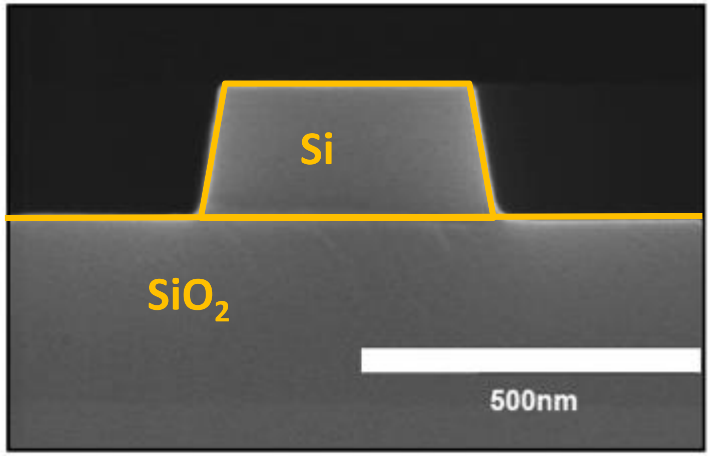




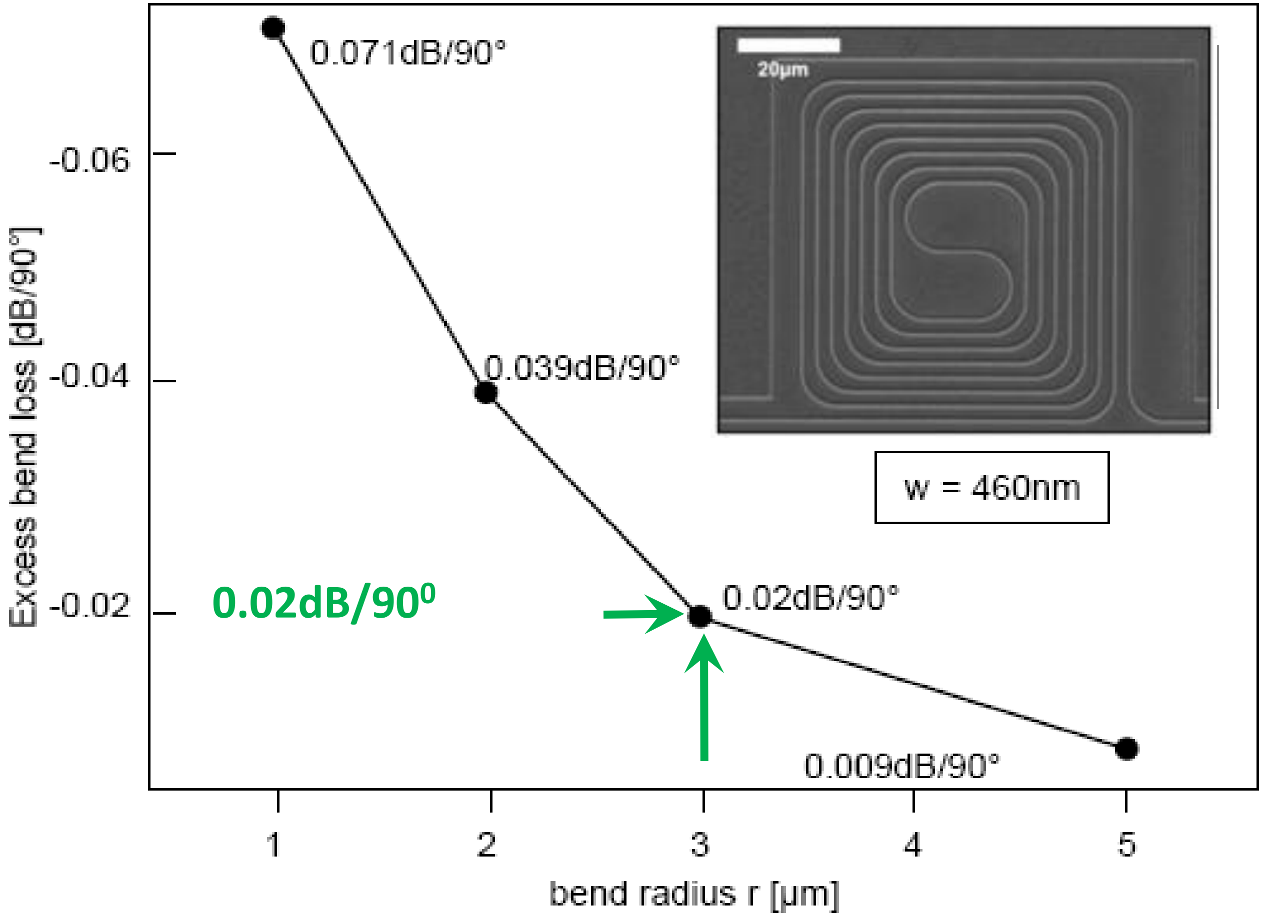
On-chip AWG spectrometer (200 x 350 µm^2)



BEND WAVEGUIDE



S.K. Selvaraja, JLT 27, p.4070 (2009)



THE PAST 5-10 YEARS: STUNNING INDUSTRIAL DEVELOPMENT IN SILICON PHOTONICS

- active optical cables (eg PSM4: 4x28 Gb/s on parallel fibers)
- WDM transceivers (eg 4 WDM channels x 25 Gb/s on single fiber)
- coherent receiver (eg 100 Gb/s PM-QPSK)
- fiber-to-the-home bidirectional transceiver (eg 12 x 2.5 Gb/s)
- monolithic receiver (eg 16x20Gb/s)
- 40Gb/s, 50Gb/s and 100 Gb/s Ethernet (future: 400Gb/s)
- …

Medicine and Life science

Enormous challenges:

- Ageing society
- Keep ever more performant health care affordable for society
- More focus on preventive medicine

Technology can help:

- Low-cost personal, bed-side and point-of-care medical devices
- Minimally invasive devices (cathetered approaches, implants, electronic pills)
- Rapid diagnostics (immuno-assays based on disposable use-once chips)

Assets of silicon photonics for medicine and life science

Low cost (even in moderate volume)

Very compact devices

Can address needs from visible to mid IR

Mature supply chain

Chip cost in a CMOS fab (order of magnitude)

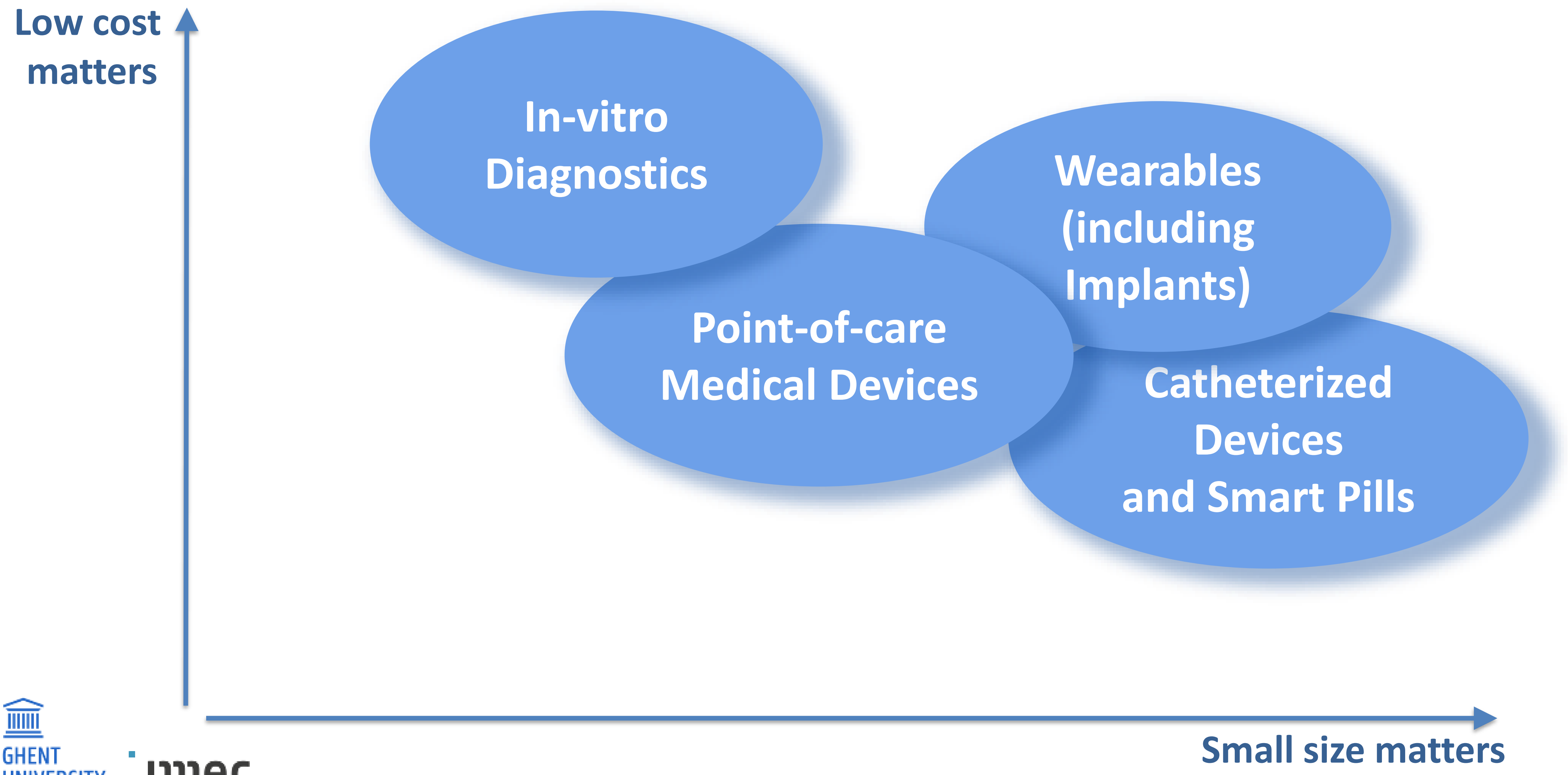
	Simple photonic chip	Complex photonic chip
Very low volume (**MPW**) (~ 100-1000 chips)	100€	1000€
Low volume (1K - 10K chips)	10€	100€
Moderate volume (10K – 1M chips per year)	3€	30€
High volume (>1M chips per year)	<1€	<10€

In high volume, the chip is "for free"

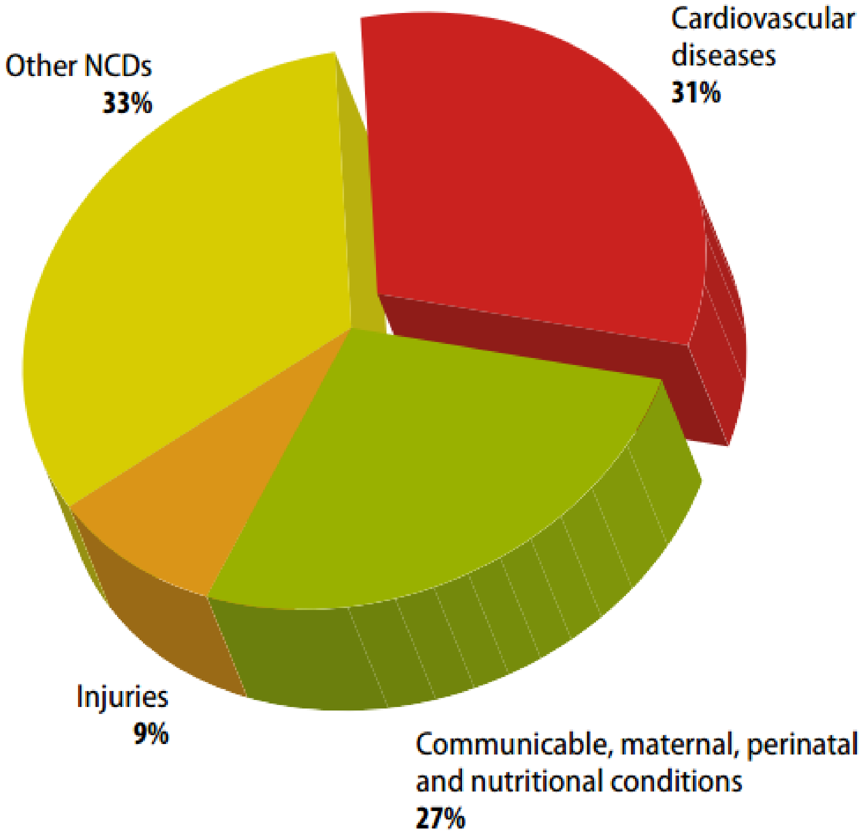
Even in moderate volume the cost per chip is low

Even in low volume the chip can have a high value for money

Main applications of Silicon photonics in Medicine



CARDIOVASCULAR DISEASES



Distribution of major causes of death including CVDs

Cardiovascular disease: The biggest killer in the world, responsible for **30%** of deaths (WHO, 2011)

Cardiovascular Disease (CVD)

Arteriosclerosis: stiffening of arterial walls

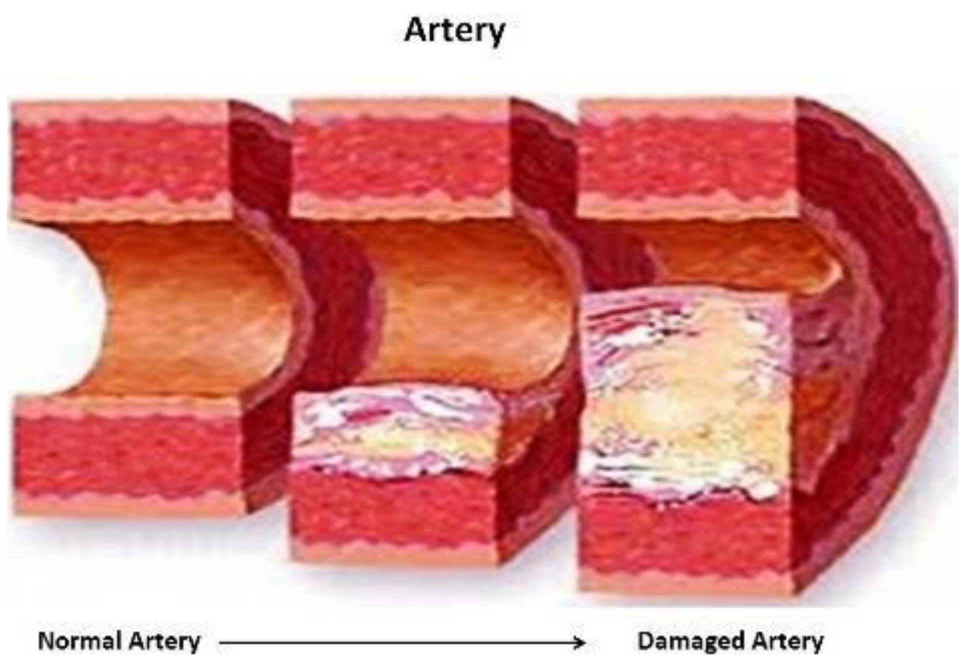
Atherosclerosis: deposition of plaque on the inner arterial walls (which can lead to stiffening)

Stenosis: abnormal narrowing in a blood vessel

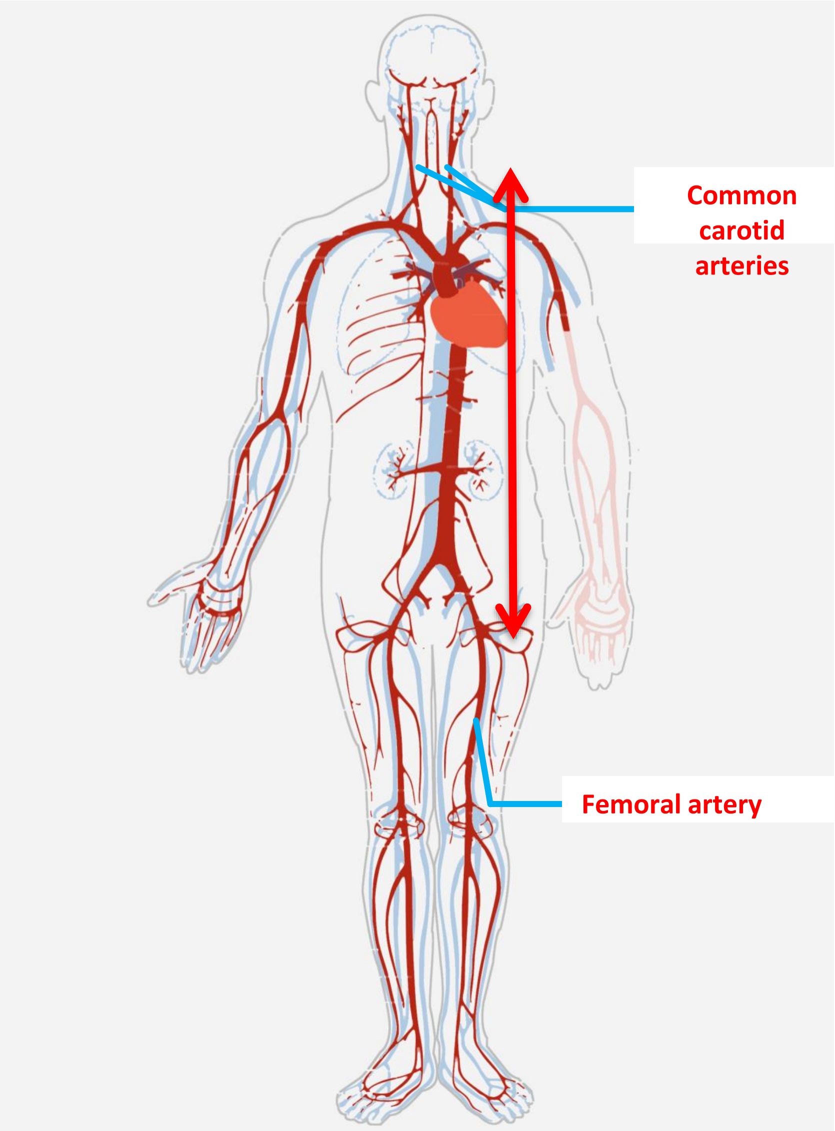
Heart Dyssynchrony: left and right part of the heart are not triggered synchronously

A **map of the skin displacement** above arteries can help for early diagnosis of these pathologies.

- Method: laser Doppler vibrometry
- Technology: silicon photonics
- Use: by general practitioner



Pulse wave velocity (PWV): marker for arterial stiffness

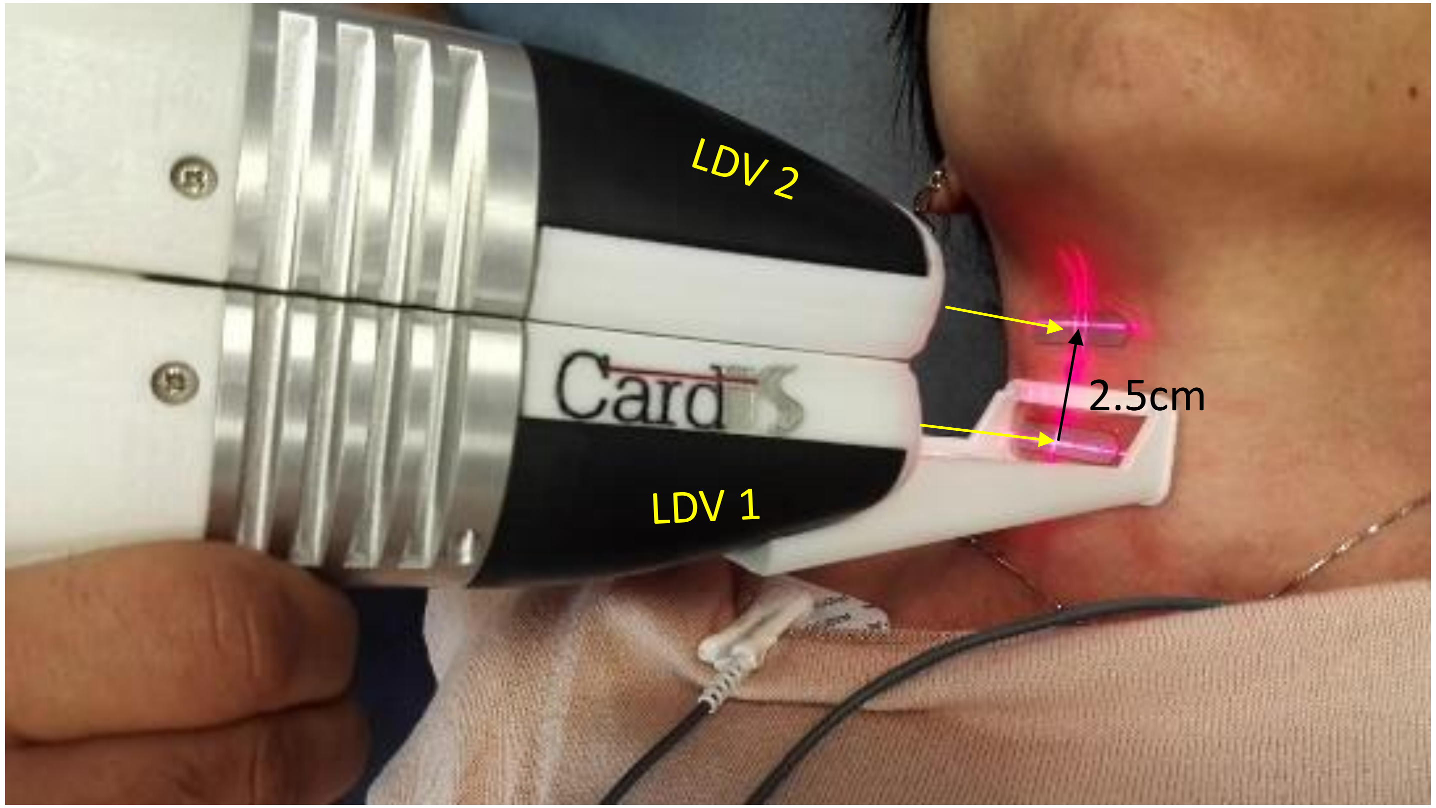


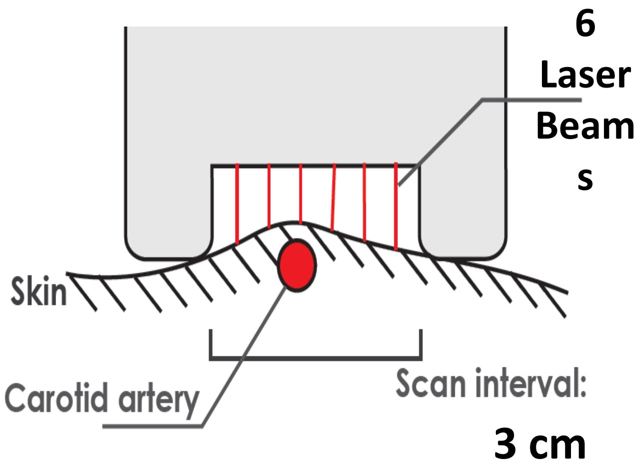
Pulse Wave Velocity: speed by which the pressure wave caused by a heart beat travels in the arteries

$$PWV = \frac{pulse\ travel\ distance}{pulse\ travel\ time}$$

Larger PWV ->
Higher arterial stiffness ->
Higher risk of cardiovascular events

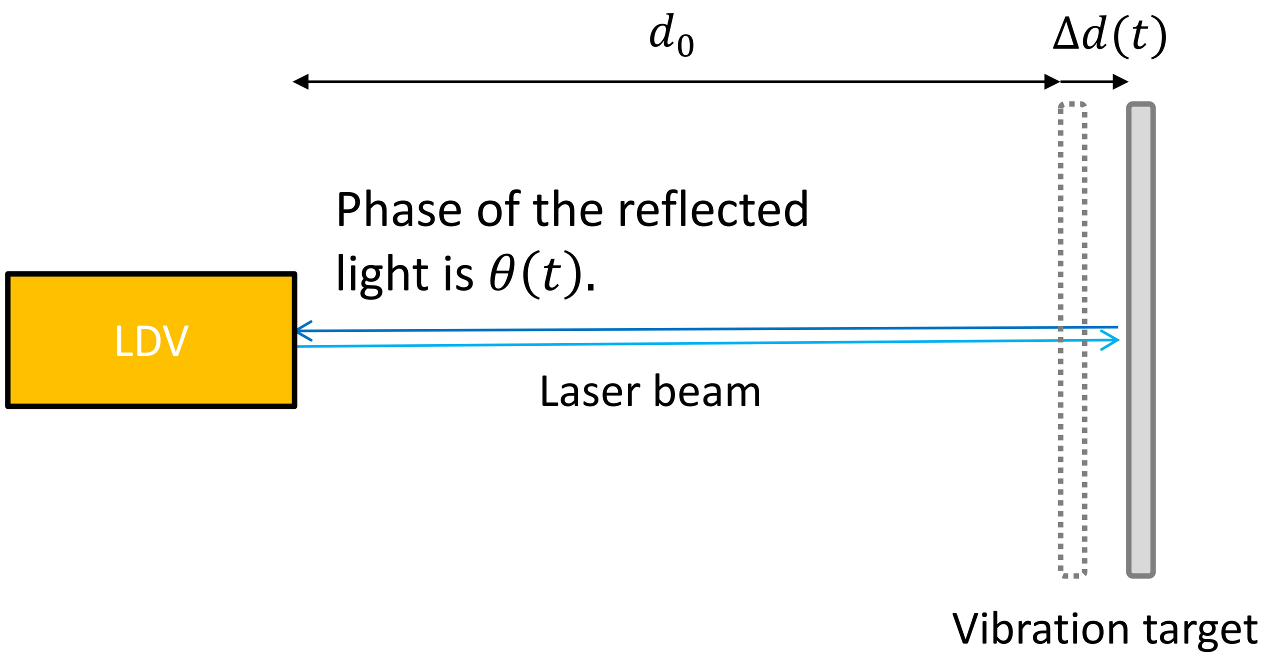
APPROACH: MEASURE LOCAL COMMON-CAROTID PWV





Method used: measure skin movement by Laser Doppler Vibrometry (LDV)

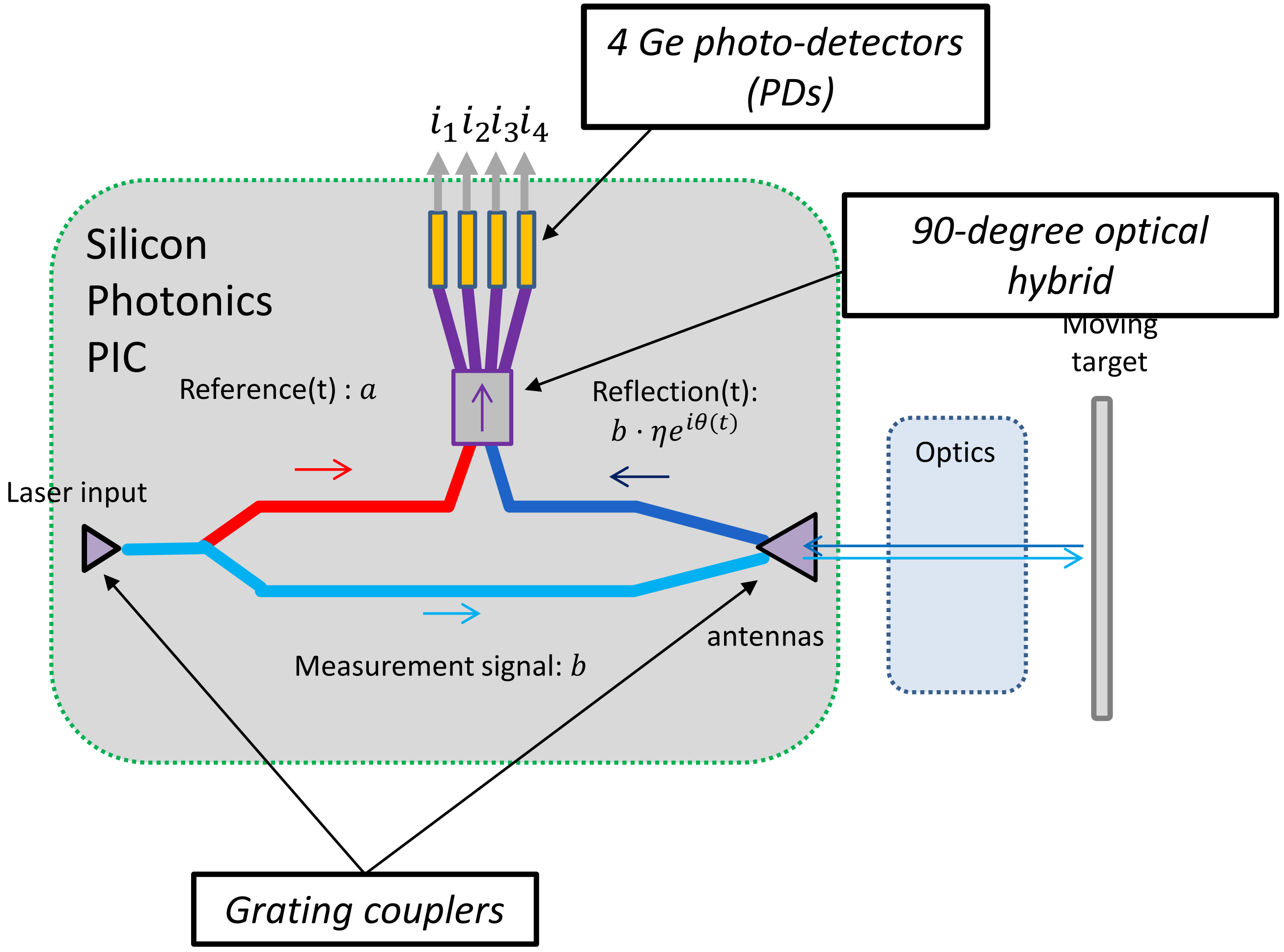
WORKING PRINCIPLE OF LDV

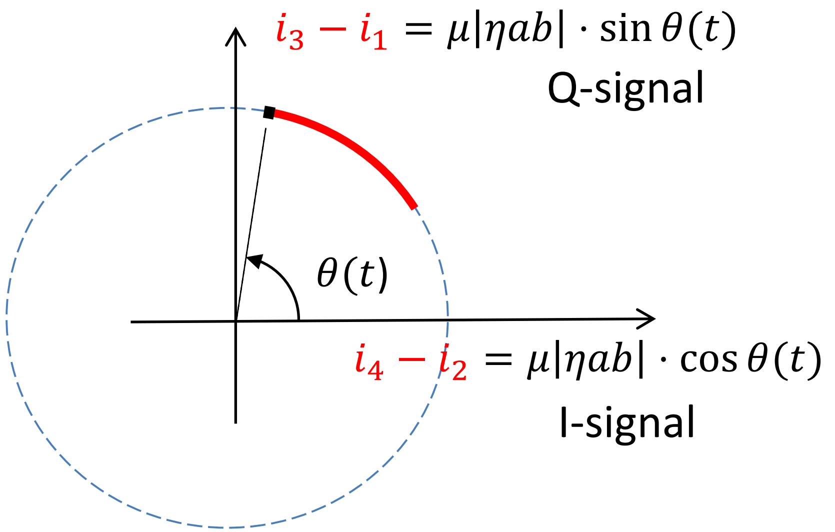


The displacement $\Delta d(t)$ can be retrieved by measuring $\theta(t)$, based on the relation

$$\theta(t) = \frac{2\pi}{\lambda_0} \cdot 2\Delta d(t) + \text{const.}$$

Working principle of LDV: homodyne detection

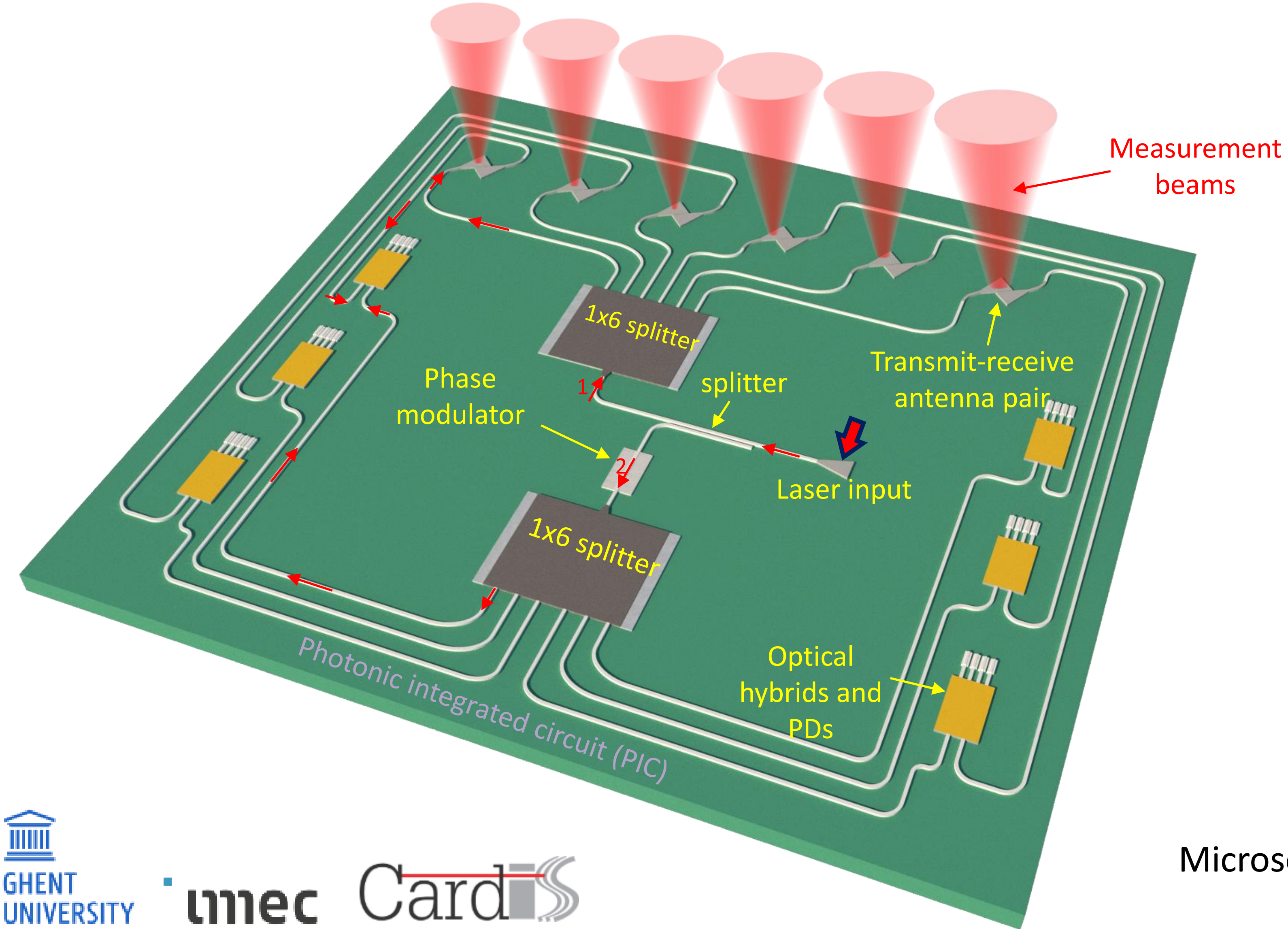


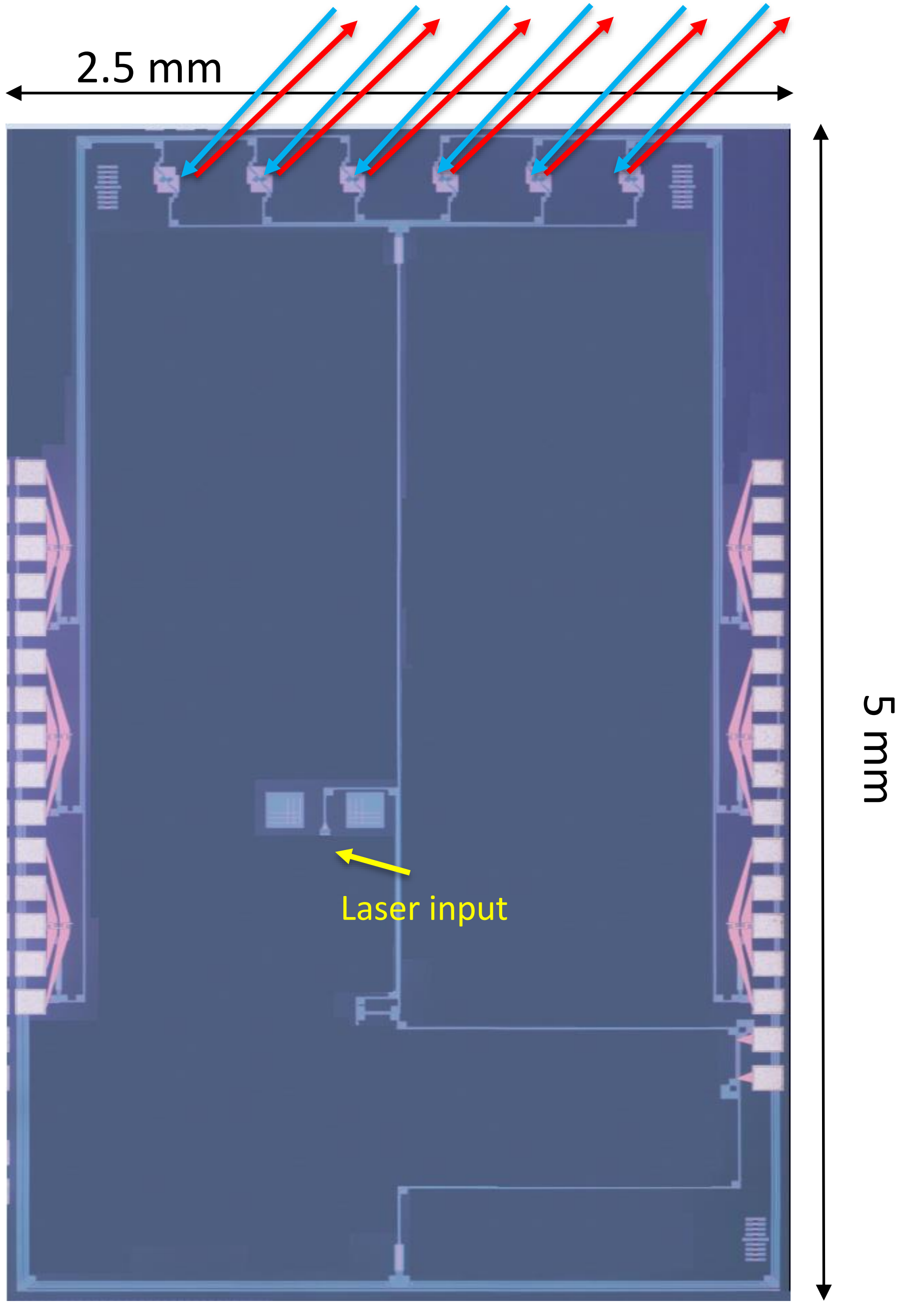


Demodulation method:

$$\theta(t) = \arctan\left(\frac{i_3 - i_1}{i_4 - i_2}\right)$$

Realization of a six-beam LDV on silicon chip

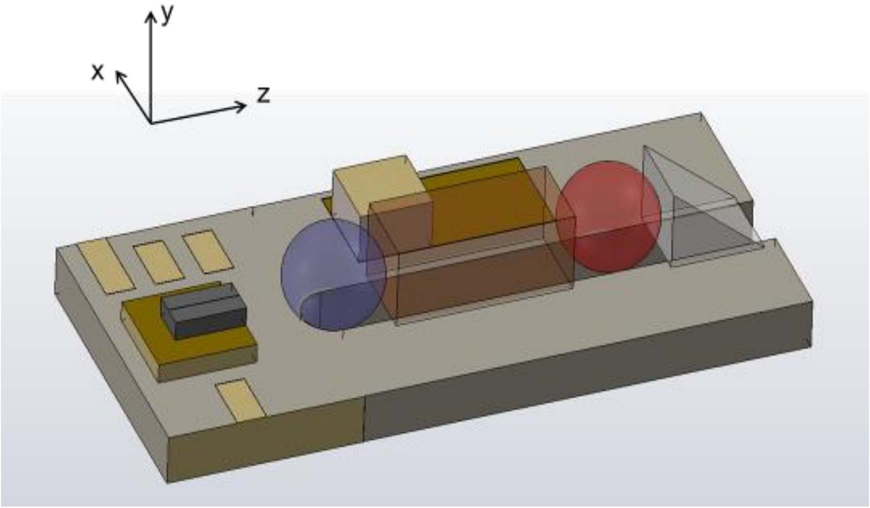




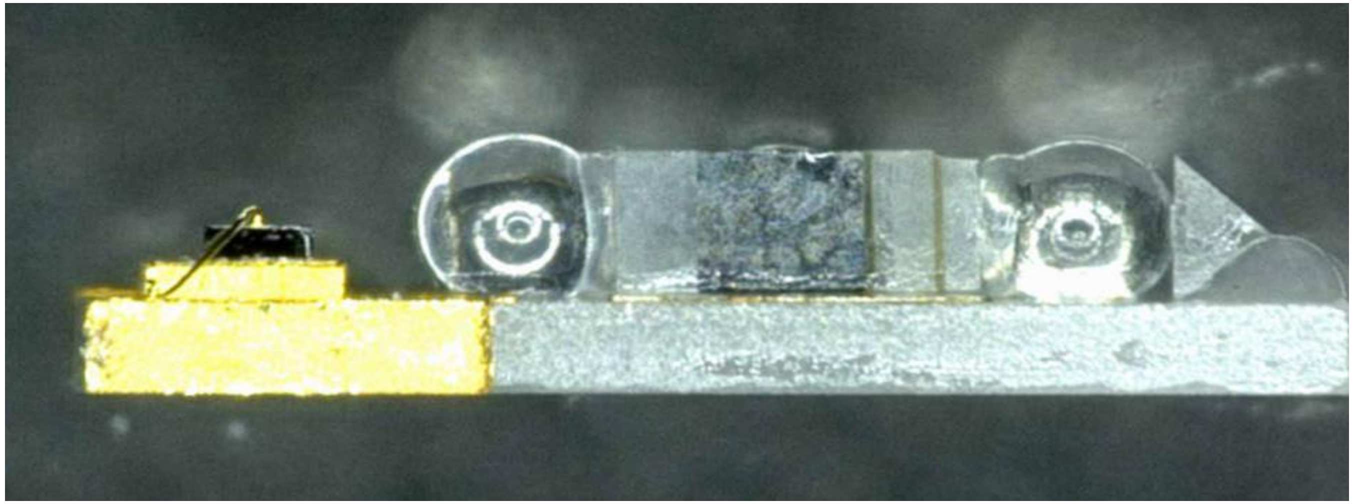
Microscope image of the photonic integrated circuit (PIC) in a silicon-on-insulator platform

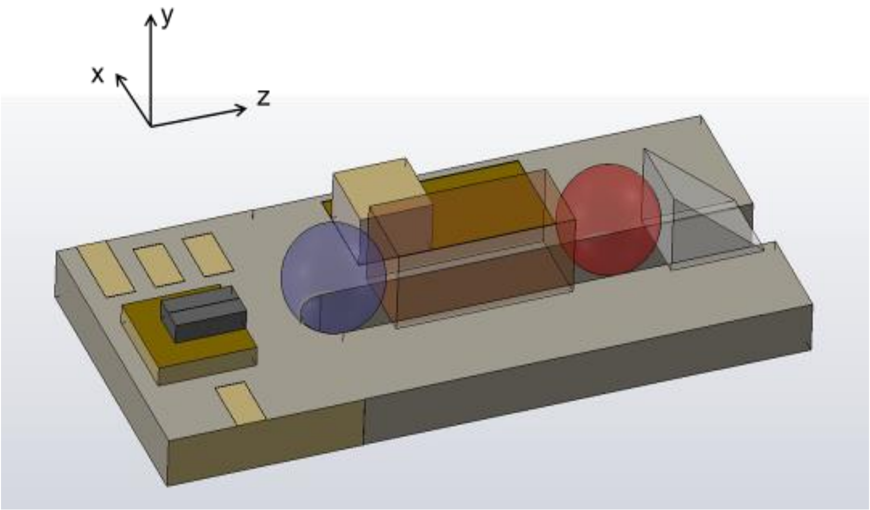
Photonic integrated circuits (PICs)

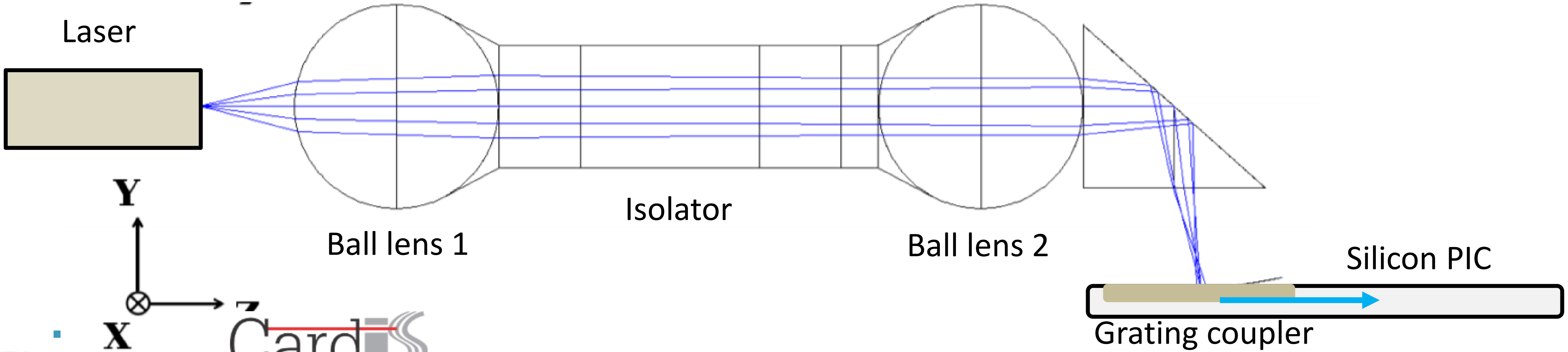
- PICs fabricated through Europractice MPW-service
- iSiPP50G SOI process at imec
- Laser diode is mounted on a Micro-Optic Bench (MOB) which is attached to the PIC



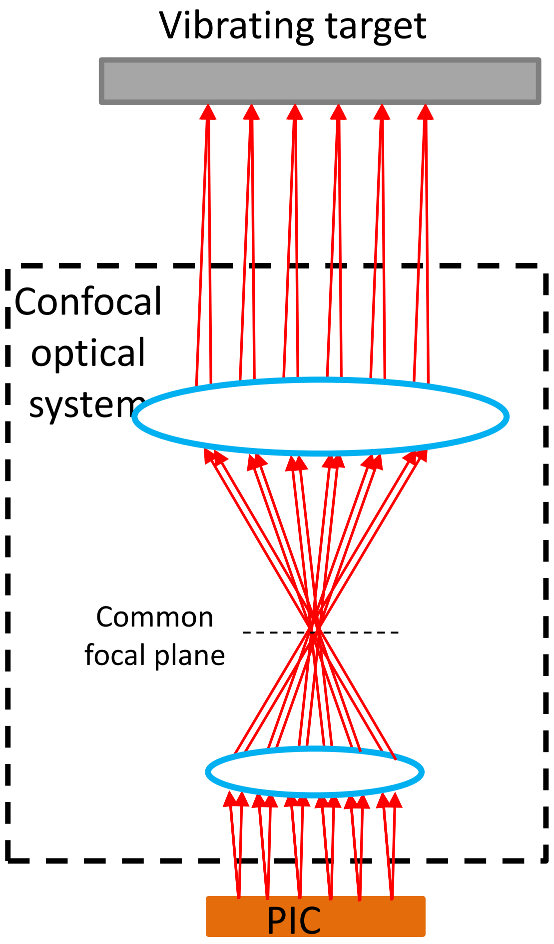
Hybrid laser integration: Micro-optic bench approach



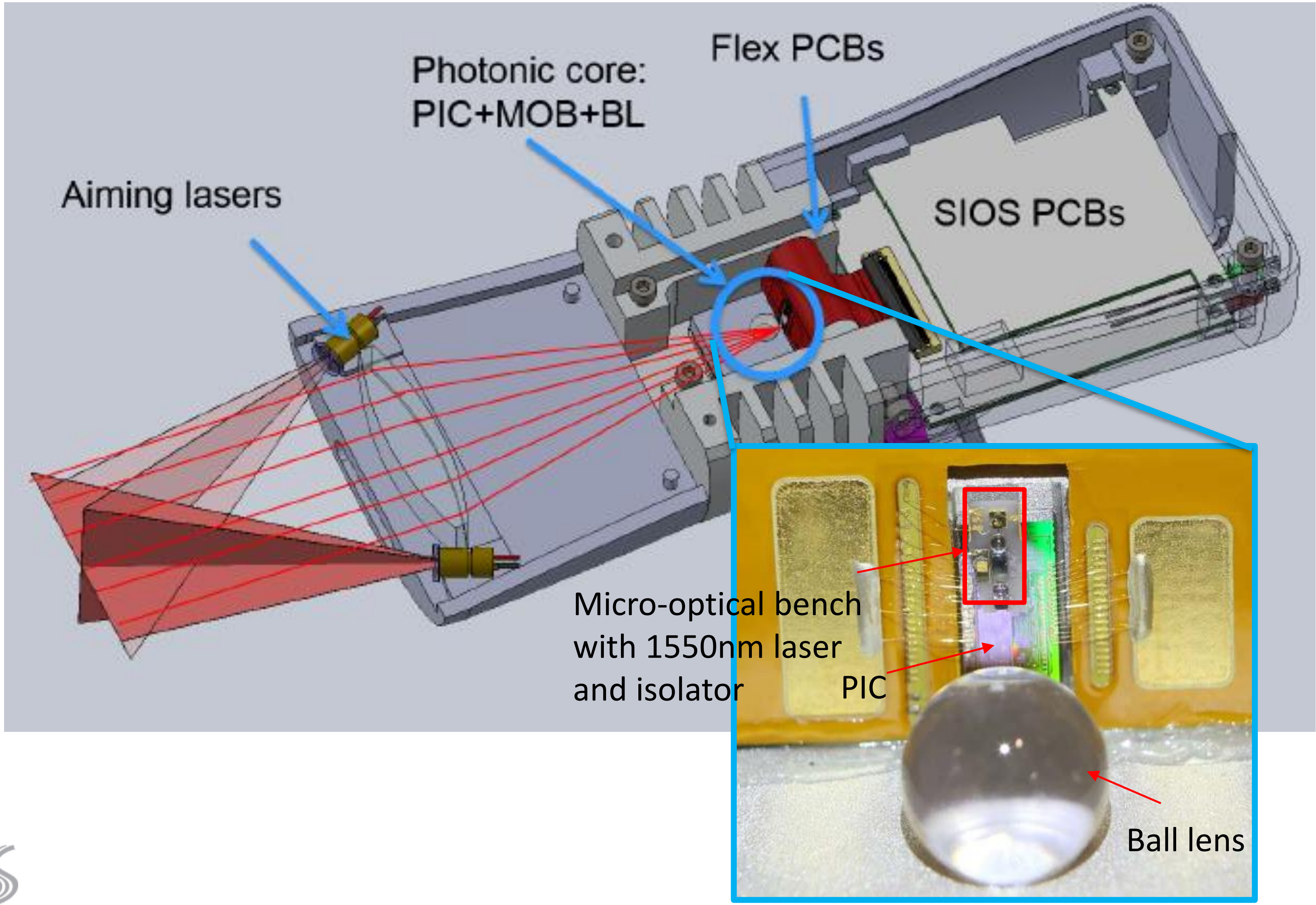




Packaging of the 6-beam LDV



PIC and external optics



THE EXTERNAL VIEW OF THE MULTI-BEAM LDVS

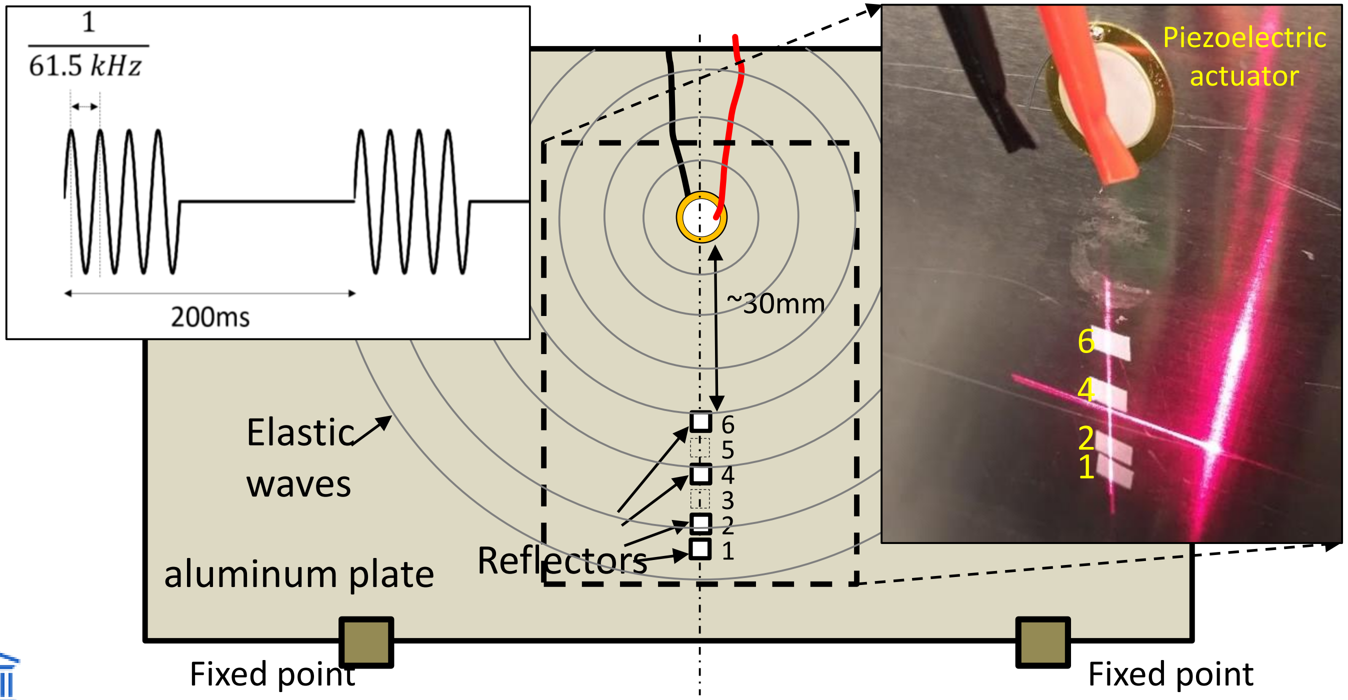
Y. Li, J. Zhu, M. Duperron, P. O'Brien, R. Schuler, S. Aasmul, M. De Melis, M. Kersemans, R. Baets, Six-beam homodyne laser Doppler vibrometry based on silicon photonics technology, Optics Express, 26(3), p.3638-3645 (2018)

Performance specification of the CARDIS demo

Parameters	Value	Note
Working wavelength	1550 nm	
Spacing of channels	5 mm	
Number of channels	6 x 2	
Sampling rate	100 ksps	
Output power (each beam)	20 µW – 40 µW	At the target side
Displacement resolution	< 10 pm/sqrt(Hz)	When the target is at the focusing position, and with retroreflective tape
Working distance	71 mm	
Laser linewidth	800 kHz	DFB laser, with passive cooler

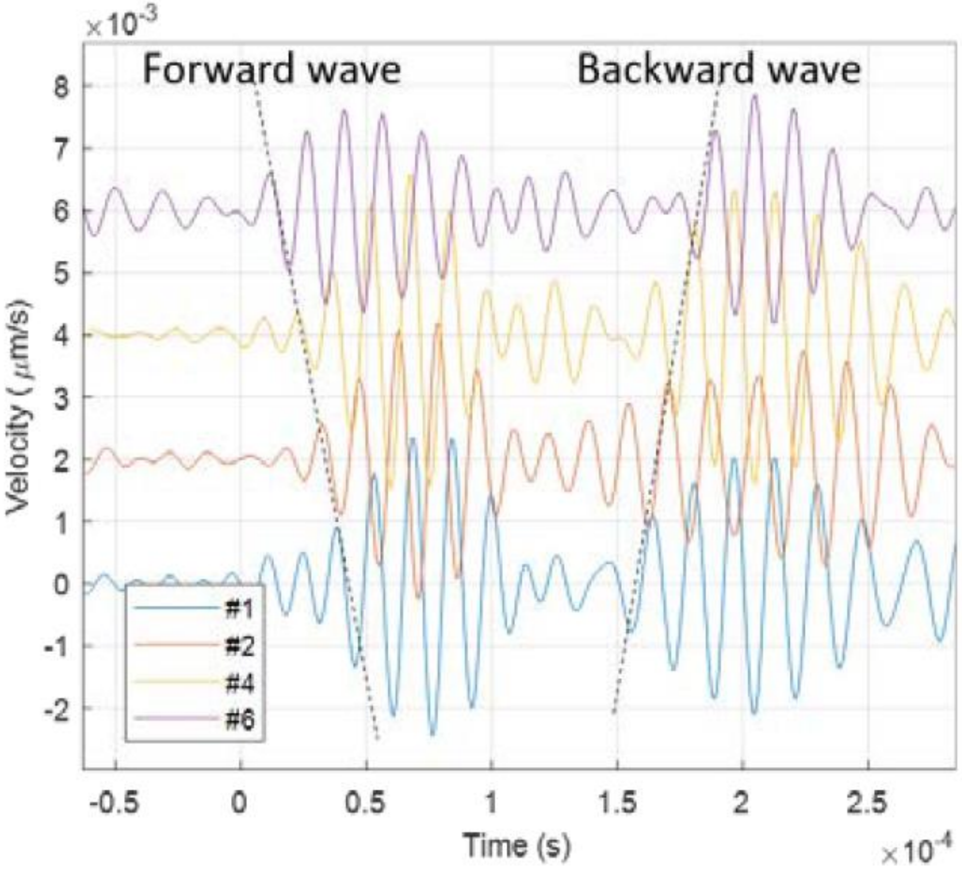
ONE DEMONSTRATION: LAMB-WAVE VELOCITY MEASUREMENT

- A Lamb wave is generated on an Al plate by using a PZT actuator with a sine-burst voltage
- Vibrations at six points are simultaneously measured with our 6-beam LDV.
- Using a DAQ with a higher sampling rate (1Msps) to capture the Lamb wave.

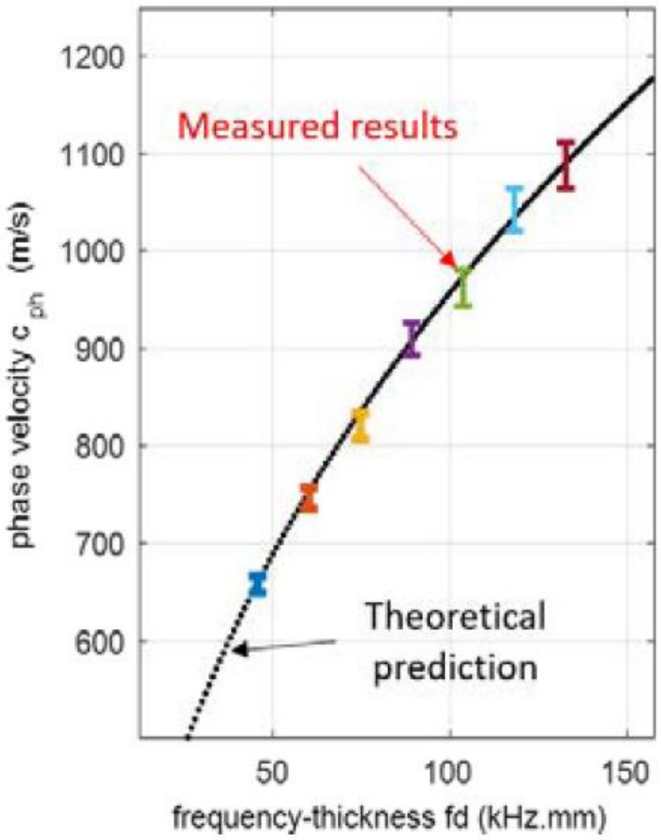


Parameter	Value
Al plate thickness	1.45 mm
Central frequencies	31.5kHz, 41.5kHz, … 91.5kHz
Cycle number	4
PZT voltage amplitude	150 Vpp
Spacing reflectors	5 mm

DISPERSION CURVE: MEASUREMENT VS CALCULATION



The plotted signals correspond to central frequency of 61.5kHz (after a band-pass filter of 20 kHz)



The phase velocities are retrieved with a band-pass bandwidth of 2 Hz.

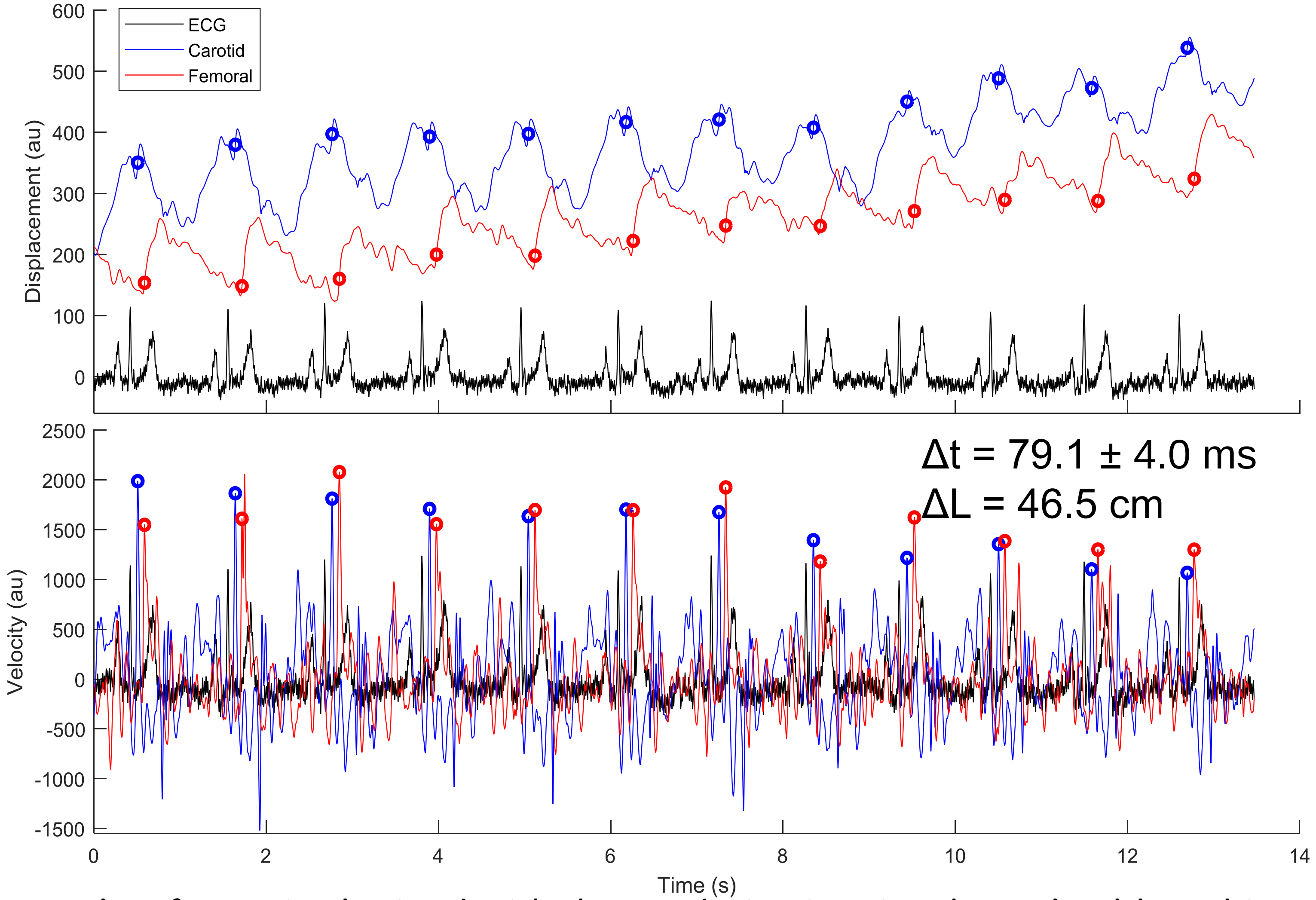
The phase velocities of the Lamb waves are calculated, with the assumptions:

- density ρ = 2700 kg/m^3
- Young's modulus E = 70 GPa
- Poisson coefficient ν = 0.33

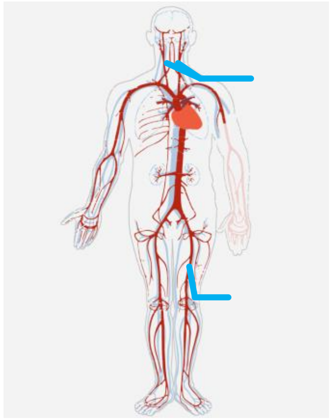
The calculated results fit very well with the measured results (the error bars are caused by the sampling resolution)

Clinical Feasibility Study at INSERM, Paris

Carotid-femoral (cf) PWV measurement



The cf-PWV is obtained with the 1st derivative signal on a healthy subject.



Sensor	cf-PWV
CARDIS LDV	5.88 ± 0.30 m/s
Commercial cf-PWV meter (Sphygmocor)	5.96 ± 0.40 m/s

The cf-PWV measured by the CARDIS LDV is very similar to that measured by a commercial PWV meter.

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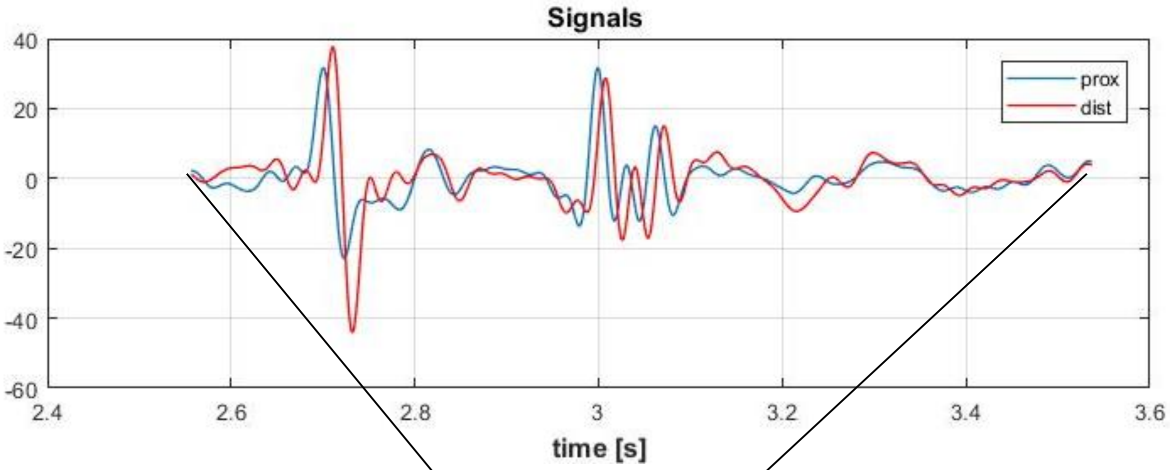
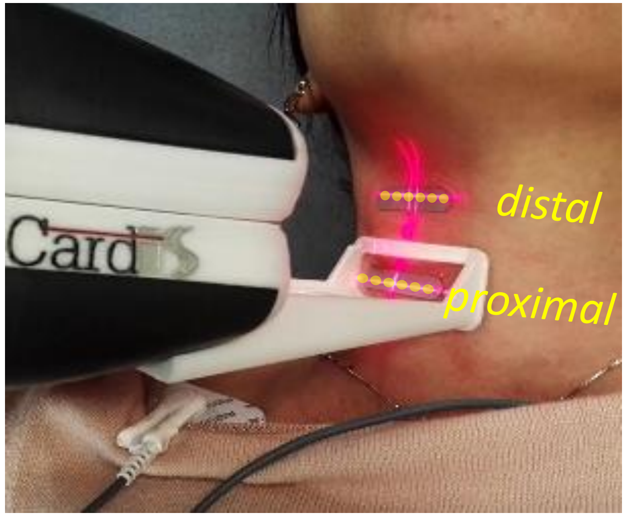
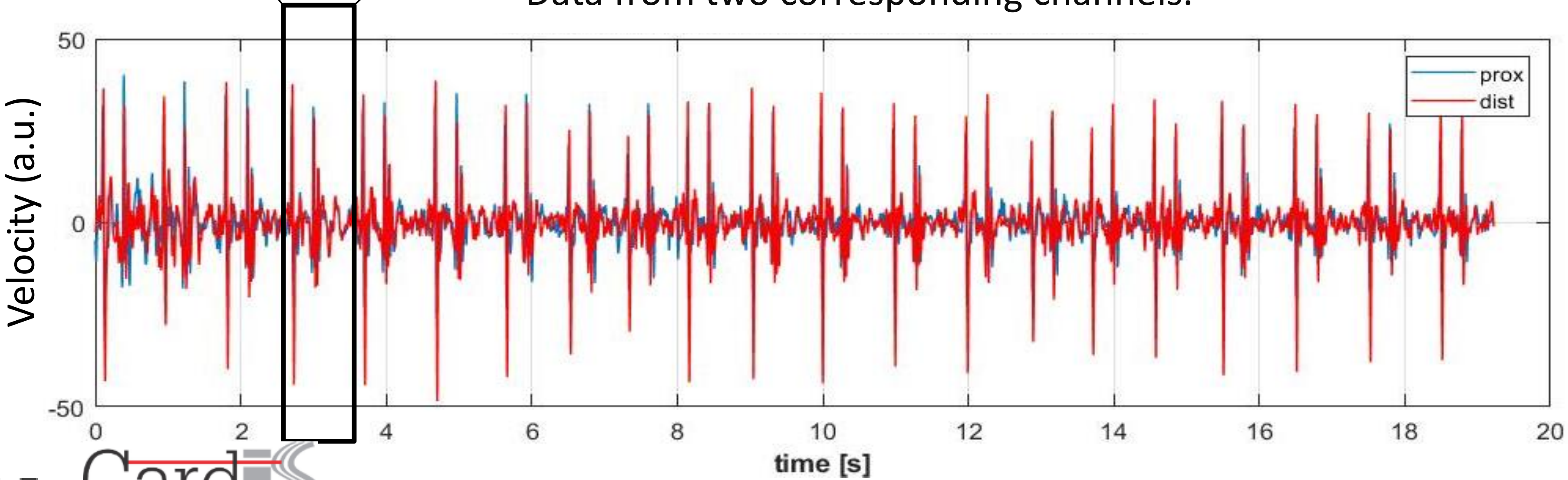
COMMON-CAROTID (CC) PWV MEASUREMENT RESULTS

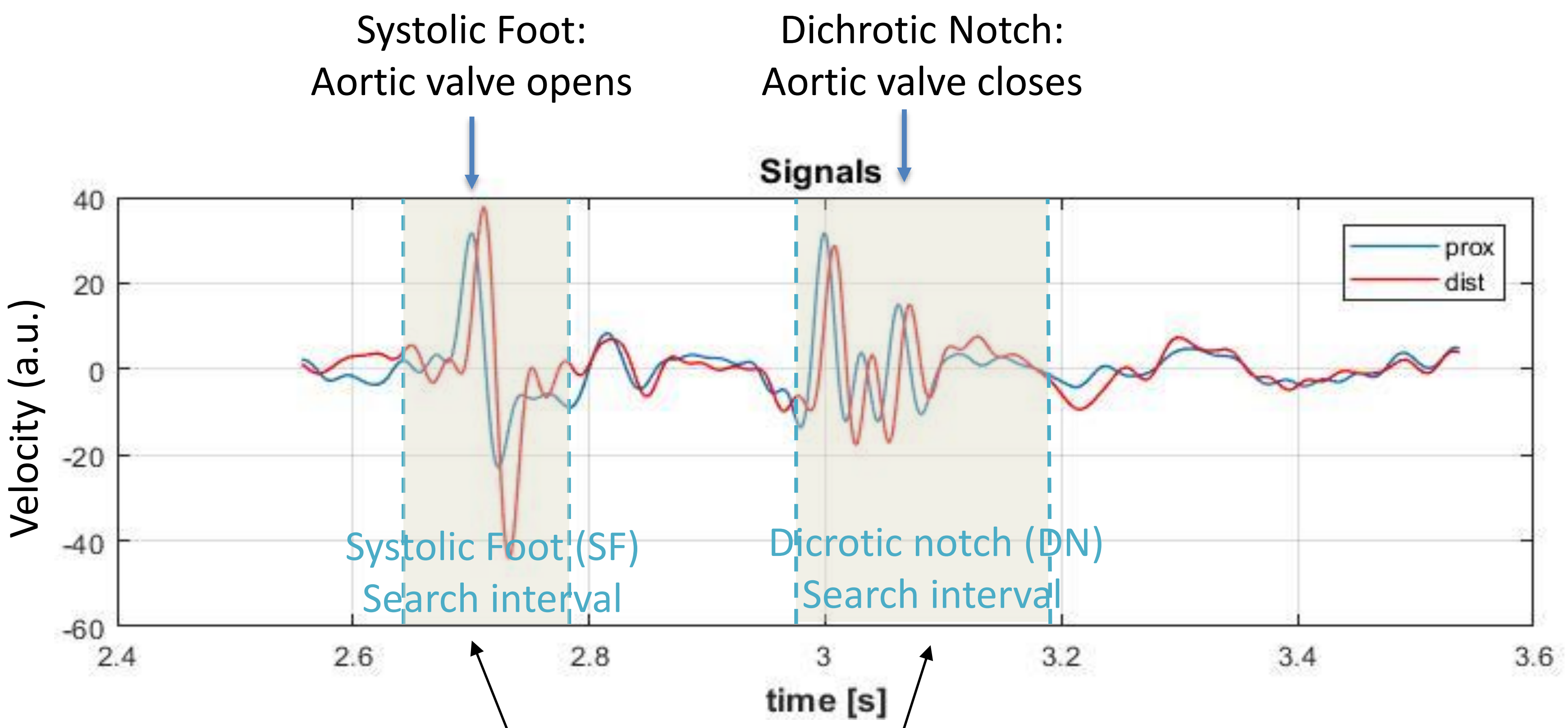




Data from two corresponding channels.



MEASURED CC-PWV VALUES



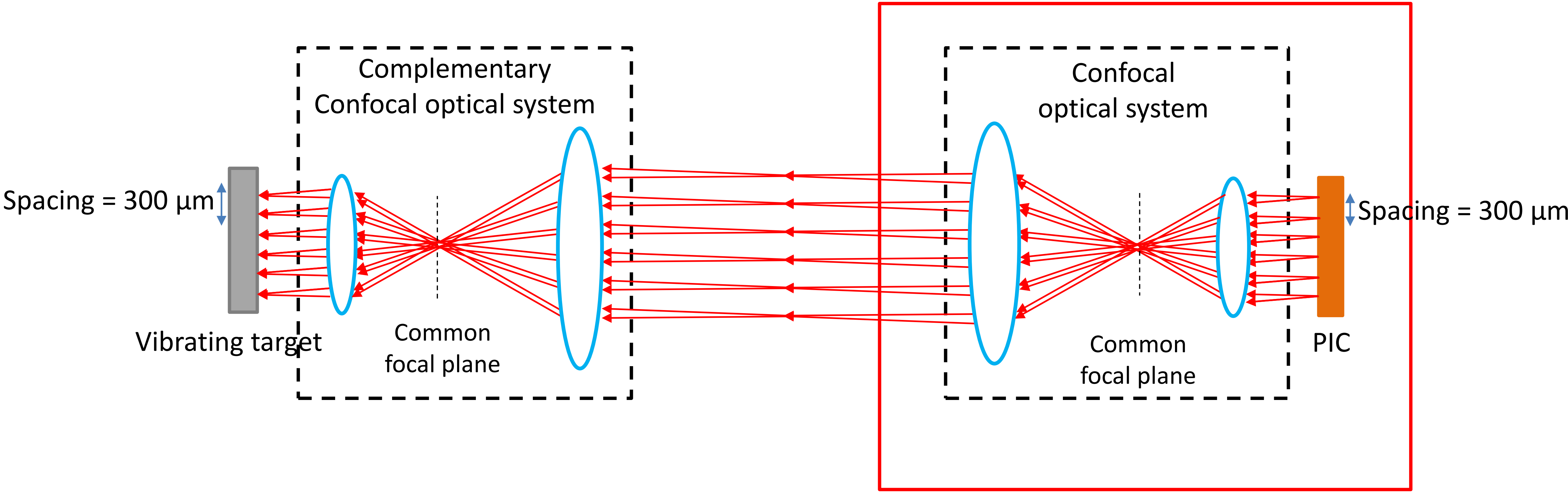
The time delays are calculated by using a cross-correlation method in these intervals.

FUTURE DEVELOPMENTS

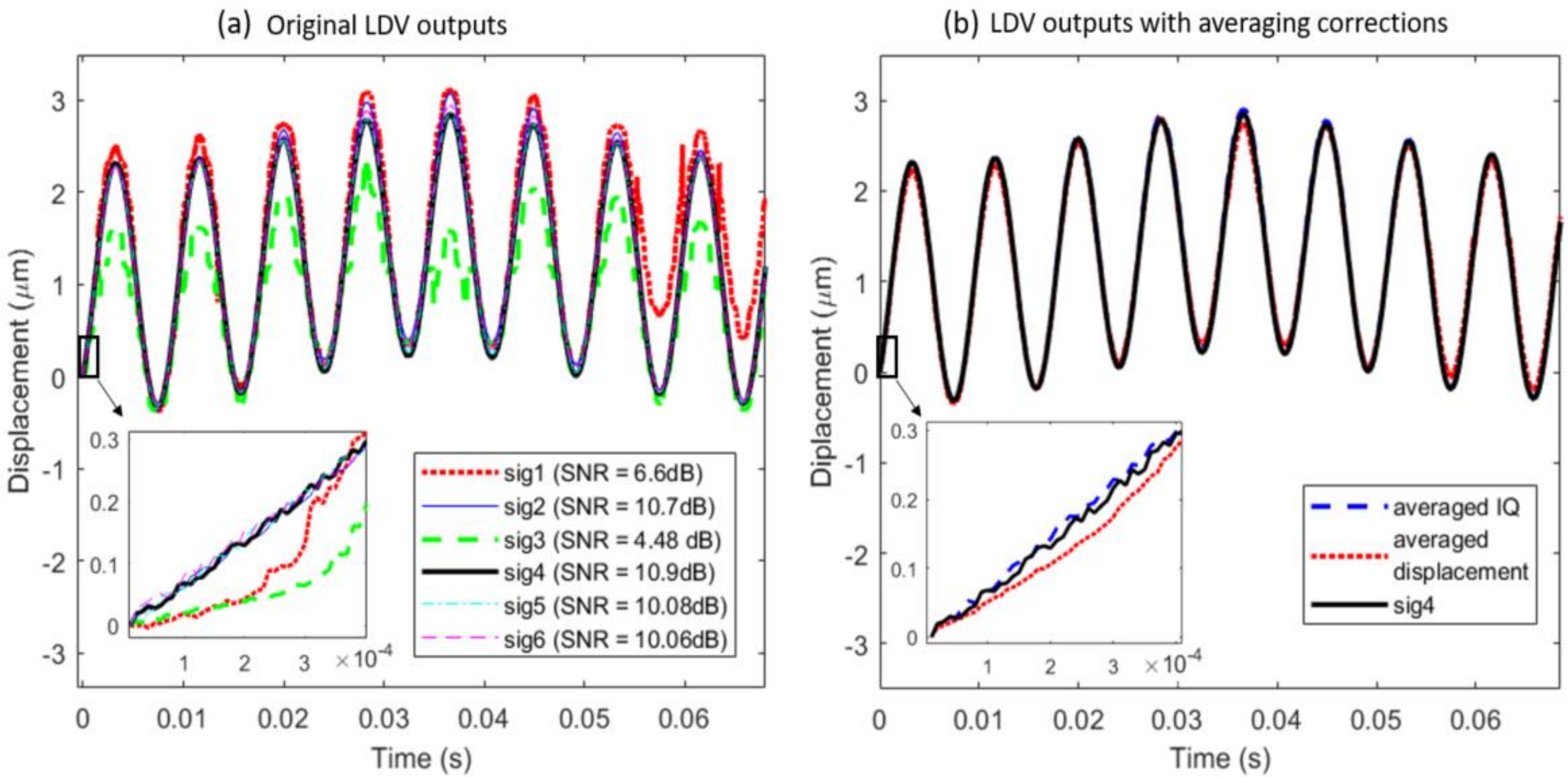
- Measure without retroreflective tape
    - Improve SNR (higher power, move to shot noise limit)
    - Change wavelength
- Reduce speckle noise
    - Average between several beams; select best beam…
    - Rapid beam scanning (easy to realize on-chip)
- Increase number of beams (1x6 → 10x10 → 100x100…)

THE MEASUREMENT SETUP FOR THE BEAM AVERAGING

To ensure we can demonstrate the beam averaging effect, we add an extra lens system to ensure the six beams are measuring the same vibration.



Despeckle results with averaging methods



- The signal with the best SNR (sig4) is used as the benchmark.
- Two averaging methods: average to the IQ signals (before demodulation) or to the displacement signals (after demodulation).
- It is shown that the averaging method works, and the IQ averaging provide better results.

Y. Li, et al, Speckle mitigation in laser Doppler vibrometry based on a compact silicon photonics chip, CLEO 2018

Conclusions & Outlook

Silicon photonics has the potential of serving many medical applications, in particular for point-of-care, in-the-body devices and in-vitro diagnostics

Key assets: compact size and volume; low cost

Case discussed here: Pulse Wave Velocity (PWV) measurement

- Excellent performance for carotid-femoral PWV
- Work in progress for local carotid PWV

On-chip LDV has a lot of potential for advanced NDT applications whenever performance, cost or device volume matters

ACKNOWLEDGEMENTS

Funding

Collaborations (on Laser Doppler Vibrometry)

Video

Louise Marais and colleagues, Inserm

Photonics Research Group of Ghent University – imec

imec Silicon Photonics platforms (SOI and SiN)

University of Antwerp

MBL meets OPTIMESS 2019

Abstract submission is still running till 30 May 2019. Below is the list of contributions which have been accepted up till now.

Current Contributions

Name	Title	Affiliation
Song Zhang	High-speed 3D shape measurement and applications	Perdue University
Erwin Hack	Optical measurement techniques	EPFL Lauzanne
Christian Rembe	State of the Art of Laser-Doppler-Vibrometry and Future Trends	Clausthal University
Giancarlo Pedrini	Digital Holography digital holography for erosion measurements under extreme environmental conditions inside the ITER tokamak	Institut für Technische Optik at the University of Stuttgart
Roel Baets	Silicon photonics enabled Laser Doppler Vibrometry and its application in cardiovascular medicine	UGent
Adriana Nava	Ear recognition using fringe projection technique	Unidad Interdisciplinaria de Ingenierias, Mexico