Integrated optical ultrasound transducers on thick SOI waveguide platform

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Outline

- Ultrasound imaging
- Optical ultrasound transducer
- Why thick SOI?
- Fabrication
- Results
- Conclusions
- Acknowledgements

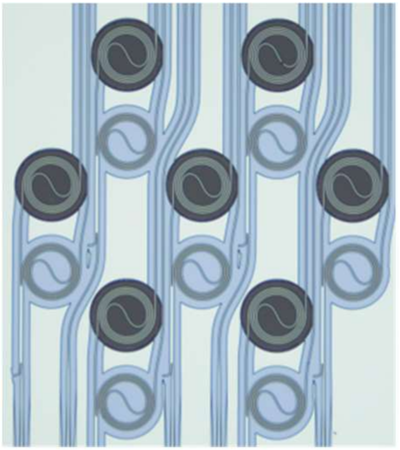
Ultrasound imaging

- Ultrasound is used in medical diagnosis to create an image of internal body structures/organs, to measure characteristics (e.g., distances/velocities) or to generate informative audible sound.
- A major parameter to improve the ultrasound image quality (to allow better and more specific diagnosis) is the signal-to-noise-ratio (SNR).
- Increase in SNR yields improved detection at larger depths.
- More sensitive transducers are needed to increase the SNR.

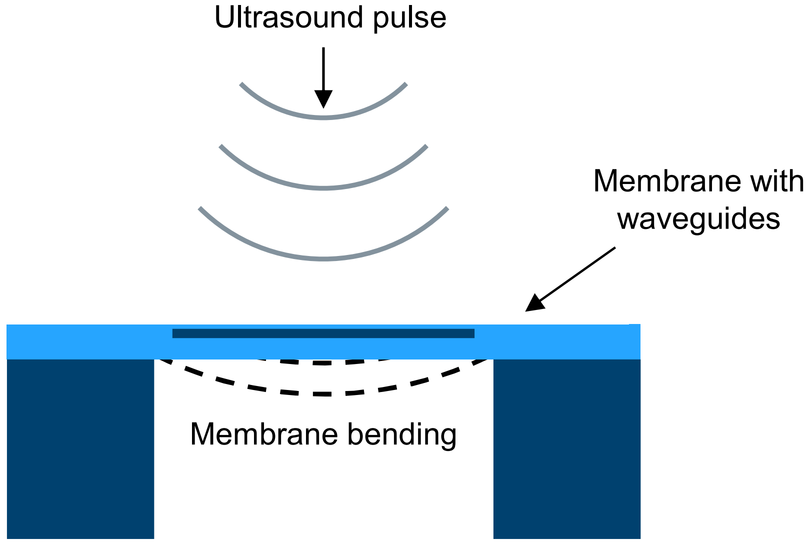
Ultrasound imaging

- Current state-of-the-art transducer technologies are piezotransducers, capacitive Micromachined Ultrasound Transducers (cMUTs) and piezoelectric Micromachined Ultrasound Transducers (pMUTs).
  - Noise effective pressure (NEP) ~ 0.5 Pa @ 1 MHz

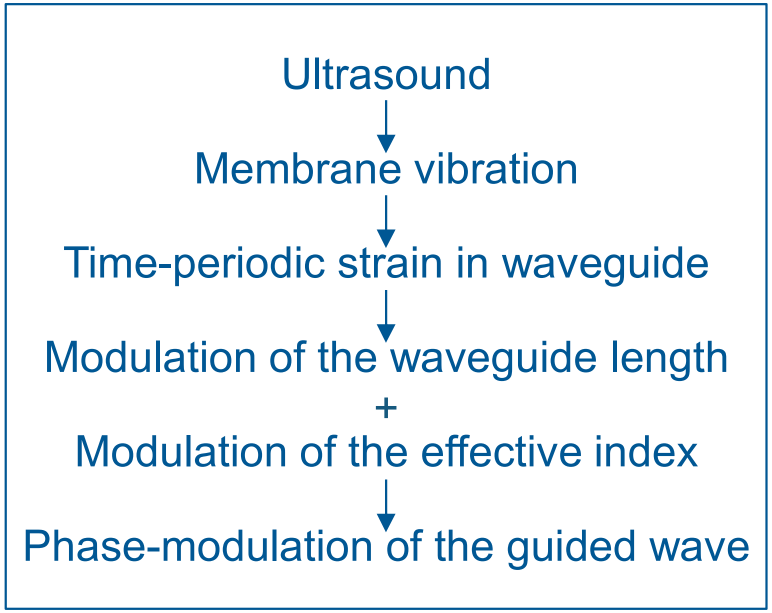
HEU project Med-IPUT is developing advanced integrated photonic ultrasound transducer (IPUT) with a primary focus to improve the sensitivity of the transducers with impact in improved image resolution and diagnostic accuracy.



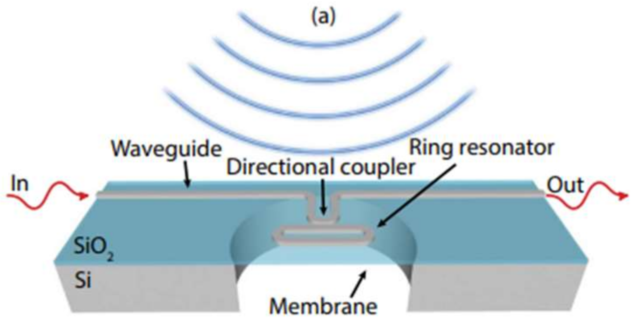
Principle of an integrated optical ultrasound transducer



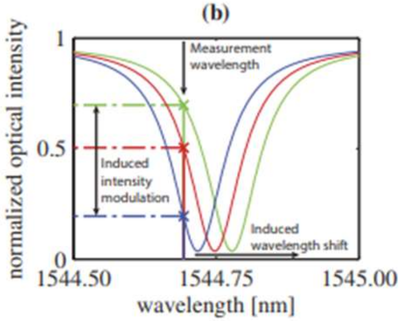
Interferometric measurement principle used to detect the phase-modulation of the guided wave.



Ring-resonator based detection



Micro-RR sensor on a membrane structure

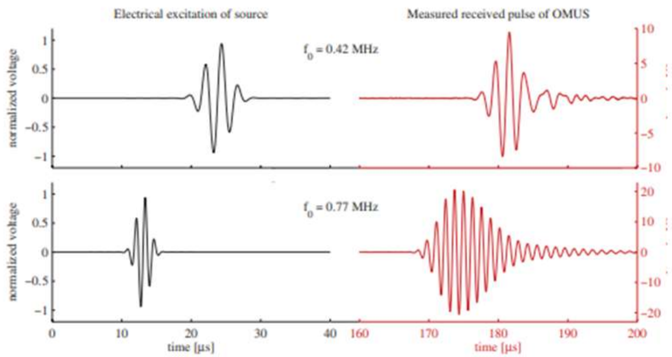


Sketch of intensity curves at the end of the micro-RR output waveguide.

Time-dependent intensity in the micro-RR output

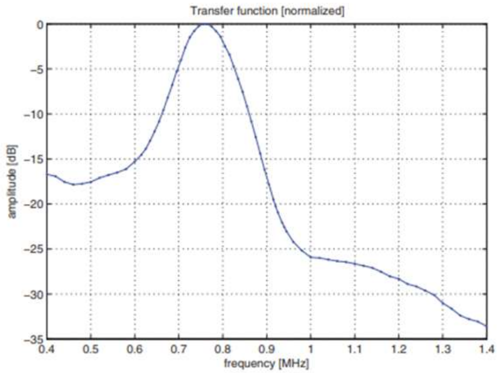
$$I(\lambda_l, t) = T(\lambda_l) I_0 \approx T_0(\lambda_l + \Delta\lambda(t)) I_0,$$

Ultrasound-induced optical wavelength shift



Transmitted acoustical pulses

Time responses of the OMUS



Normalized transfer function

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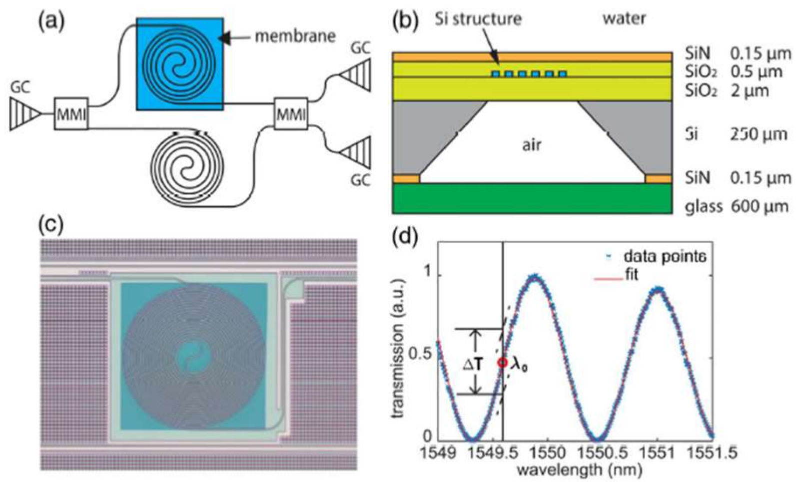
A sensitive optical micro-machined ultrasound sensor (OMUS) based on a silicon photonic ring resonator on an acoustical membrane

S.M. Leinders[1], W.J. Westerveld[2,3,†], J. Pozo[3,†], P.L.M.J. van Neer[3], B. Snyder[4], P. O'Brien[4], H.P. Urbach[2], N. de Jong[1,5] & M.D. Verweij[1]

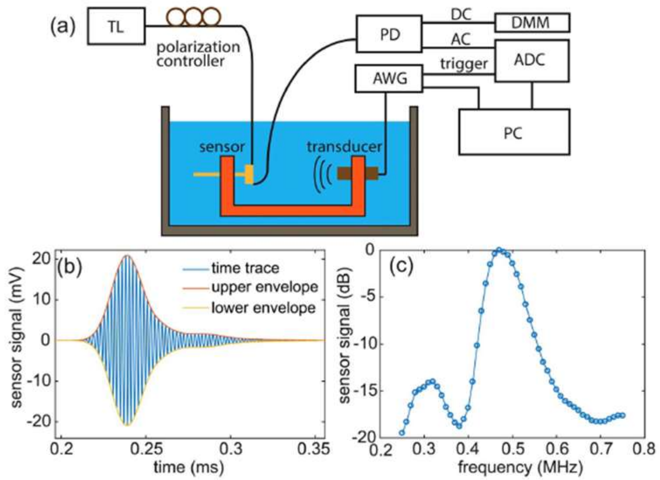
MZI based detection

MZI sensor　　Membrane structure



Microscope image; membrane size 121x121 µm^2

Normalized transmission spectrum



Response to a Gaussian ultrasound pulse at 0.45 MHz

Normalized transfer function

Amplitude of the phase modulation of the mode in the MMI input

$$\Delta\varphi(\lambda_0, L_s, L_s^*) = \frac{2\pi}{\lambda_0}\left(\int_{L_s^*} n_e^*(\lambda_0, l)\,\mathrm{d}l - \int_{L_s} n_e(\lambda_0, l)\,\mathrm{d}l\right)$$

Maximally strained　　Strainless

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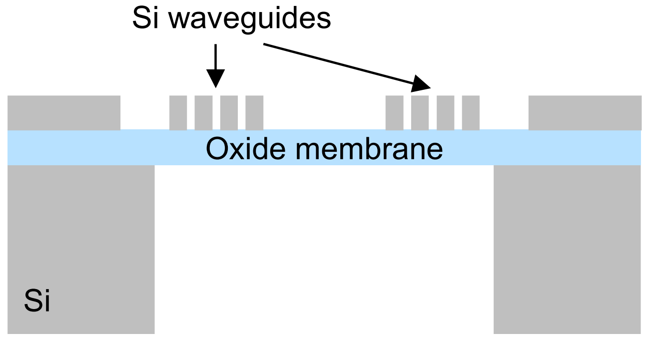
Optics Letters

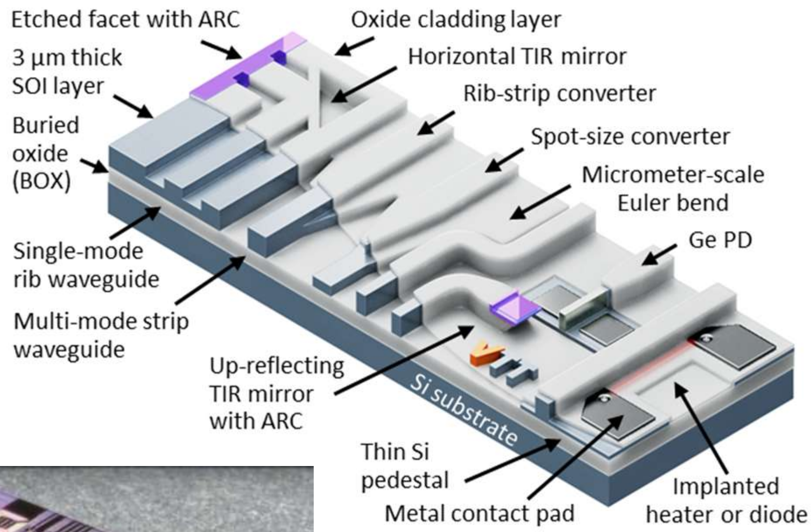
On-chip silicon Mach–Zehnder interferometer sensor for ultrasound detection

Boling Ouyang,[1,*] Yanlu Li,[2,3] Marten Kruidhof,[1] Roland Horsten,[1] Koen W. A. van Dongen,[1] and Jacob Caro[1]

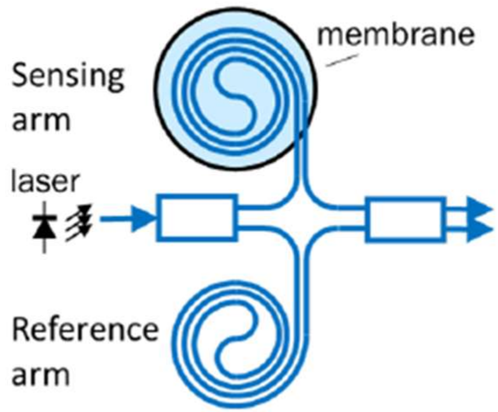
Why to use thick SOI for IPUTs?

- Low loss waveguide technology and dense integration
  - Demonstrated 0.02-0.15 dB/cm
  - Allows longer spiral waveguides and cascading of multiple membranes in a single sensor
- Waveguides on the top of the membrane
  - Enabling high sensitivity
- Buried oxide can be used as a membrane
  - Thicker oxide allows higher ultrasound frequency
- Cavity-SOI technology
  - Better size and shape control of membranes

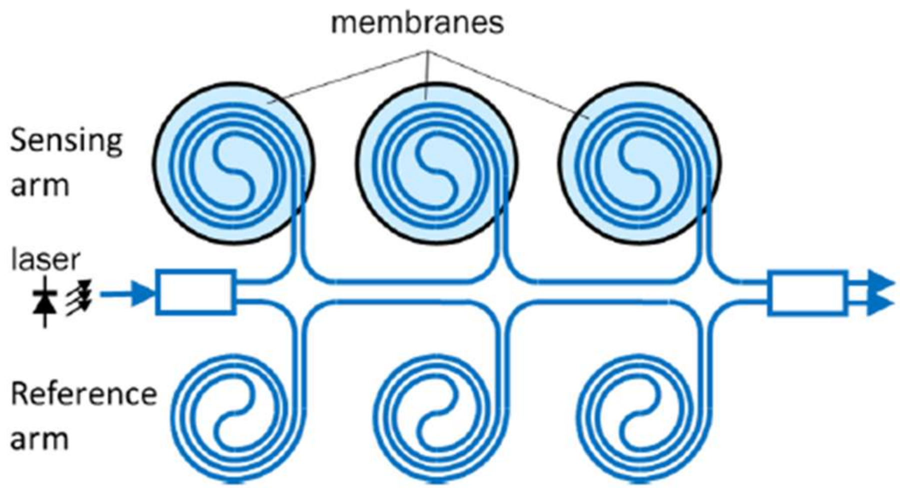




MZI based ultrasound sensor on thick SOI



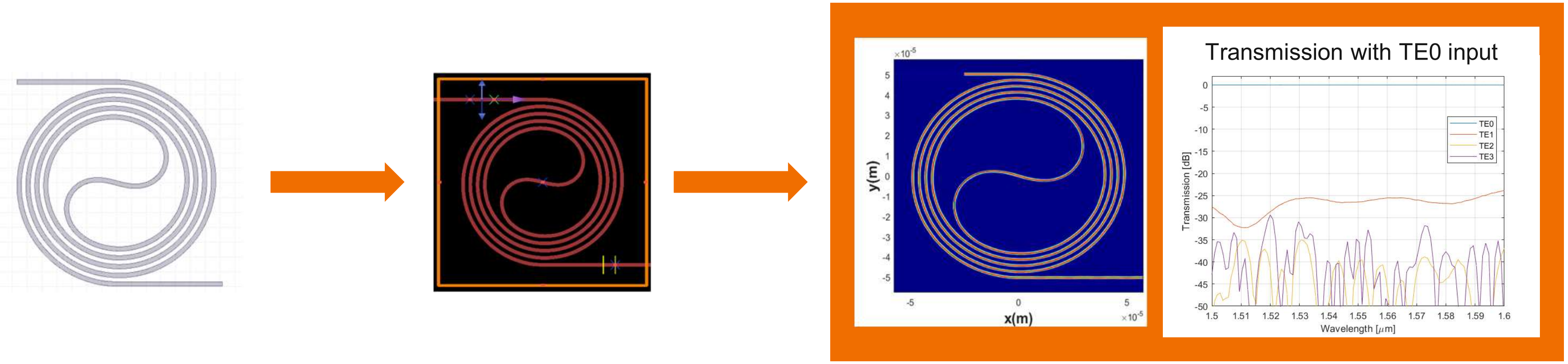
long sensing branch
provides high
sensitivity



Cascaded membranes
provides further
increase in sensitivity

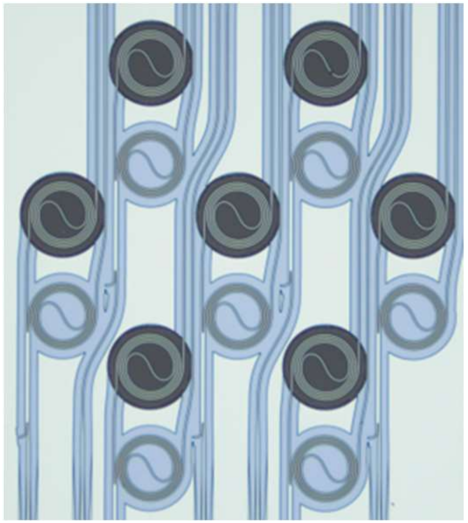
Optimization of the sensing waveguide layout

- Optical performance of the sensing waveguides optimized with extensive simulations to secure high extinction ratio between the fundamental mode and higher order modes in a long spiral

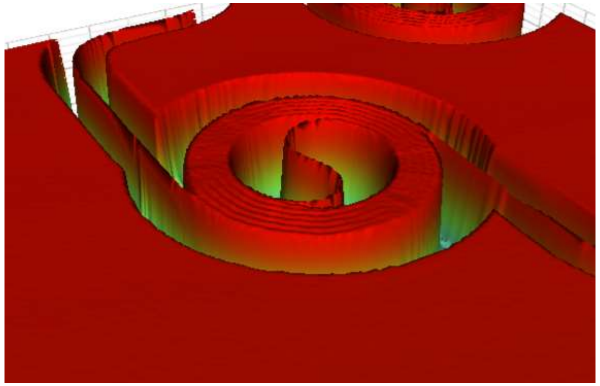


Processing

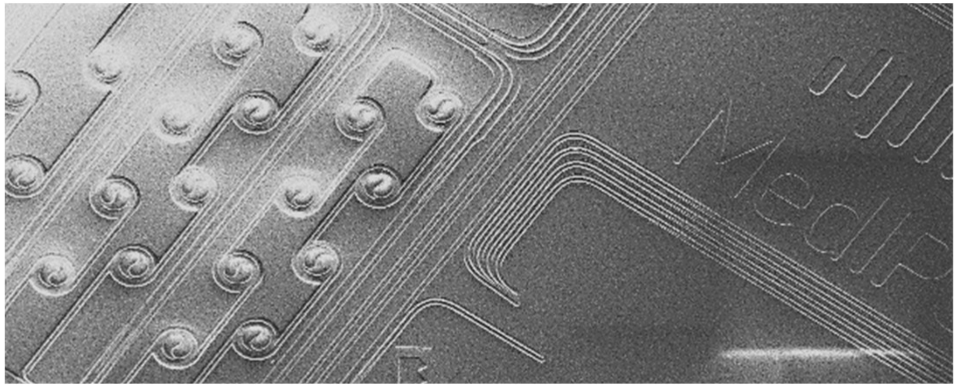
- IPUT waveguides were fabricated using VTT's standard 3 µm SOI waveguide process
- Membranes were formed with backside etching through the substrate
- Devices with up to 20 membranes in cascade have been fabricated



Optical microscope



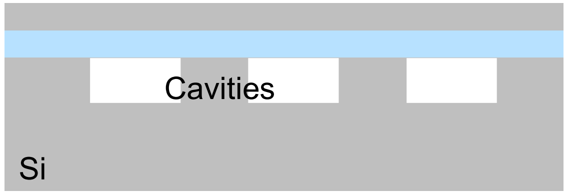
Optical profilometer



Scanning electron microscope (SEM)

Membrane processing

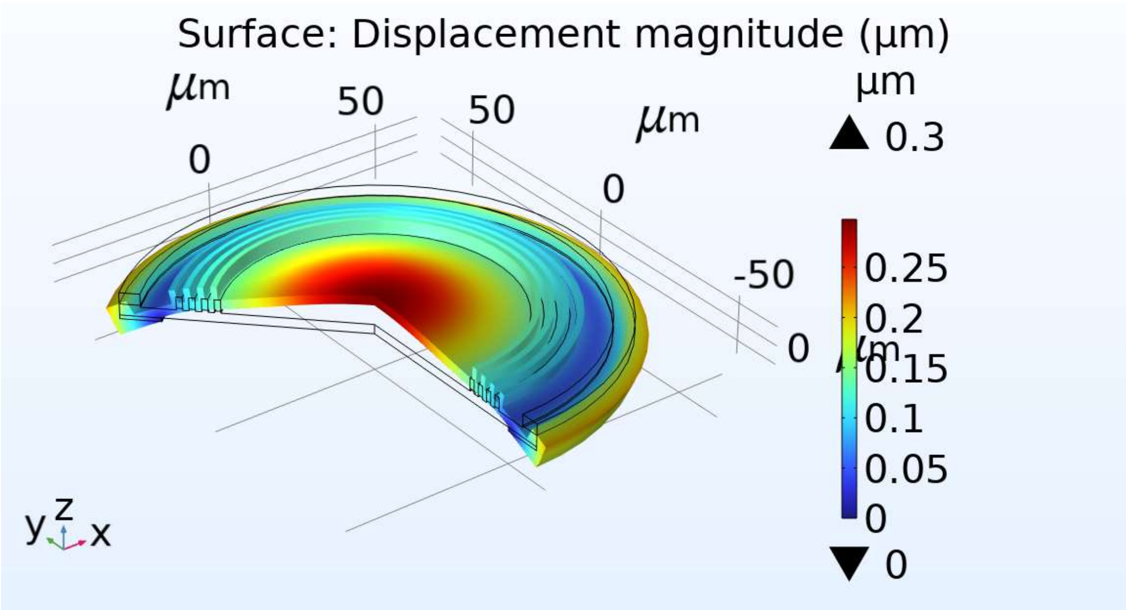
- Membranes have been fabricated with backside through silicon etching
- Substrate thickness create challenges to achieve high quality membrane structures
  - Reduction in alignment accuracy
  - Size and shape control
  - Sidewall quality (striations)
- Process optimized to achieve good alignment accuracy, size control and sidewall quality
- Further development on-going to use cavity SOI structures to solve most of the issues related to the backside through-wafer etching



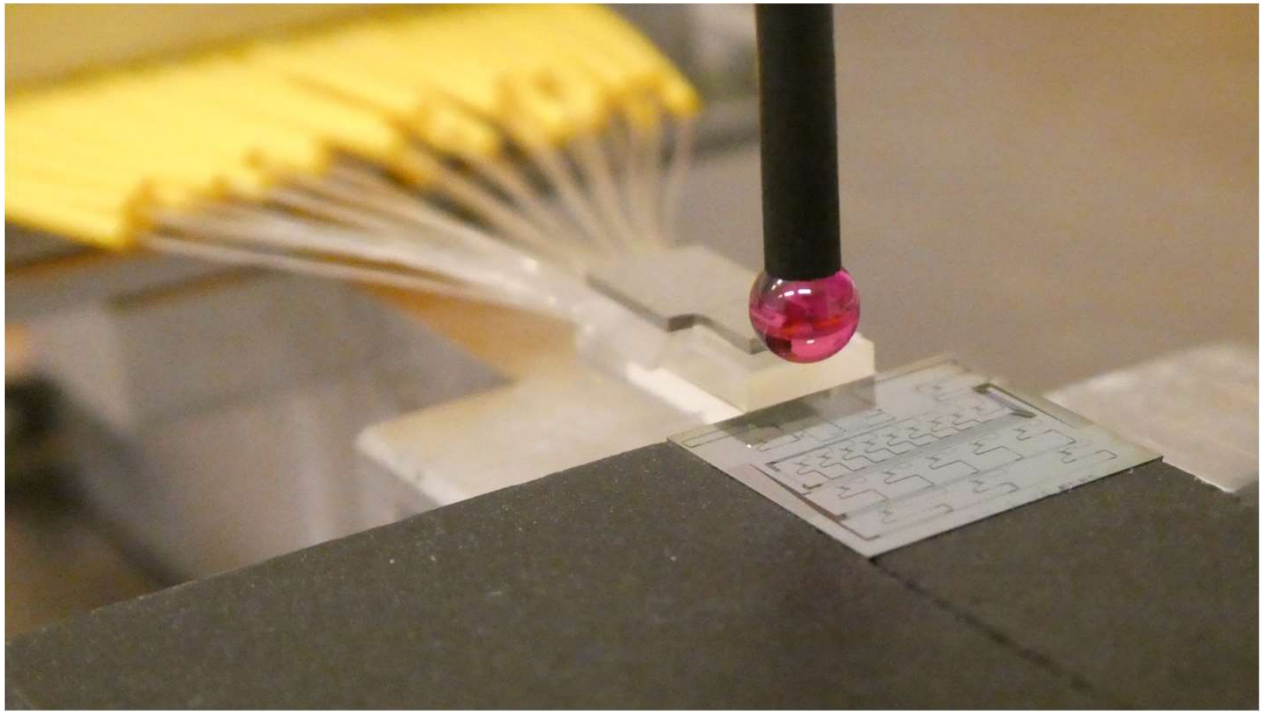
SOI wafer with premade cavities

Membrane modelling

- Mechanical modelling (COMSOL) of the membrane structure has been made to support the device processing

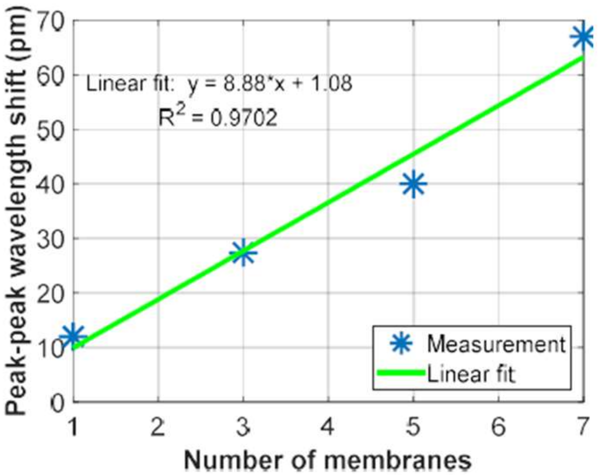


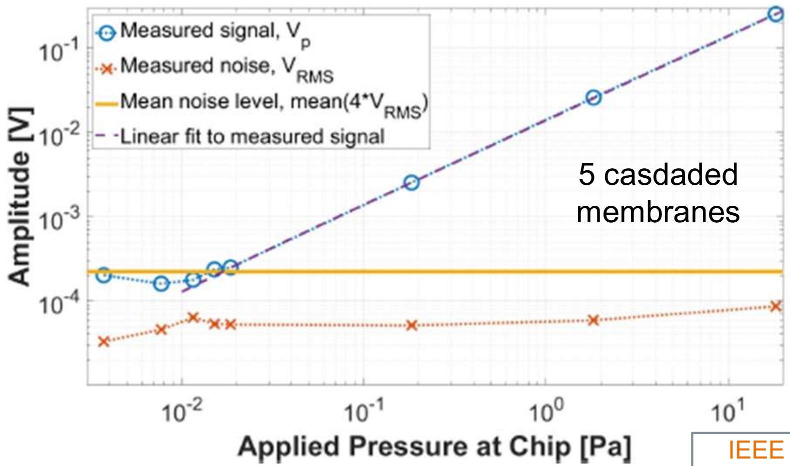
Chip assembly for measurements

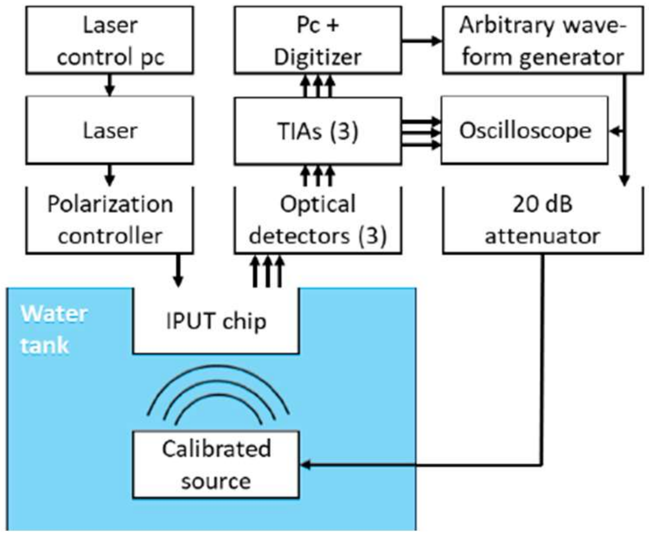


Characterization

- Characterization of the fabricated IPUTs was made at TNO
- Measured noise effective pressure (NEP) was 0.0043 Pa @ 0.53 MHz center frequency
  - SOTA transducers: typically ~0.5 Pa @ 1 MHz
  - Leinders (optical, RR): 0.4 Pa @ 0.76 MHz
  - Ouyang (optical, MZI): 0.38 Pa @ 0.47 MHz







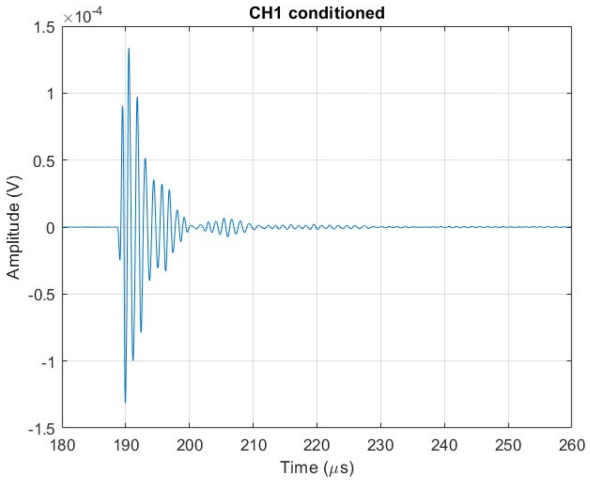
IEEE Ultrasonics, Ferroelectrics, and Frequency Control Joint Symposium
Taipei, Taiwan, Sept. 22 – 26, 2024, Paper 7331

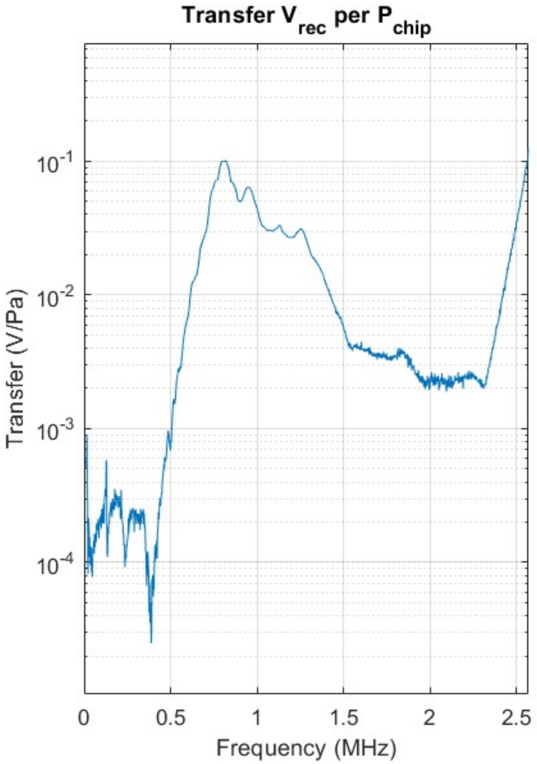
Ultra-Sensitive Cascaded Integrated Photonic Ultrasound Transducers (IPUTs)

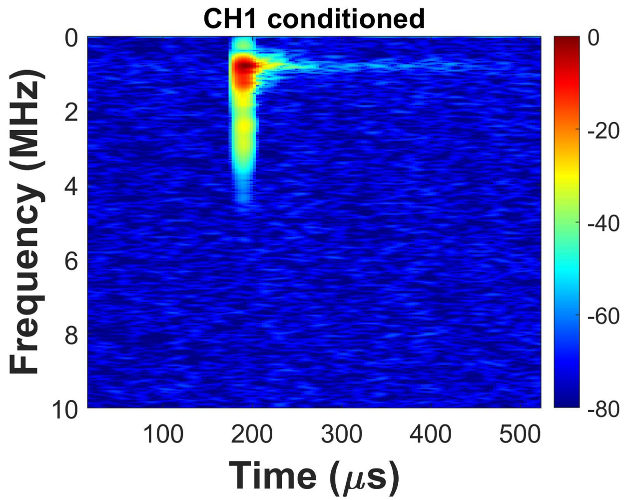
P.L.M.J. van Neer[1], P.J. Harmsma[2], A.M. Gerritsma[1], R.K. Altmann[2], S.V. Vallapil[3], M.P. Oderwald[2], D. Piras[4], B.A.J. Quesson[1], S. Bhat[5], M. Harjanne[5], S. Ylinen[5], Y. Marin[5], P. Heimala[5], T.H. Jansen[2], M.D. Verweij[3], M.S. van der Heiden[1]

Characterization

- Example of the response of a device with 20 cascaded membranes to an ultrasound pulse and its normalized transfer function







Conclusion

- VTT's thick SOI platform has certain benefits in fabricating membrane based ultrasound transducers, including low propagation loss and dense integration.

- Initial results show that high sensitivity transducers can be achieved on the platform
  - ~90x improvement in NEP compared to the published optical ultrasound transducers (Leinders and Ouyang)

- Further development is on-going to improve the fabrication process and to design and fabricate IPUT devices that can be tested for ultrasound imaging.

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MedIPUT

https://med-iput.eu/

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beyond

the obvious

Thank you!

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