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Acoustic Sensing with Correlation and Coherent Detection using an Integrated Coherent Transceiver

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Motivation

Acoustic fiber sensing systems based on coherent-OTDR are costly in current implementations:

- Ultra-low phase noise laser
- Processing of high data volumes – signal feature extraction
- **Coherent transceiver**

Novel contribution:

- In-house designed highly integrated coherent transceiver based on silicon photonics to realize a coherent OTDR interrogator
- Proof of concept demonstrating acoustic sensing after 20 km fiber span

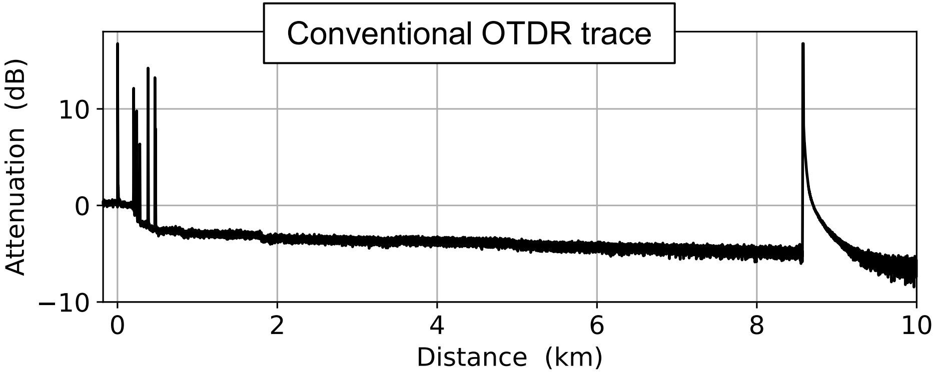
Outline

1. Introduction to fiber sensing with OTDR and its applications
2. CC-OTDR component requirements
3. Integrated coherent transceiver based on silicon photonics
4. Testbed and acoustic sensing results
5. Conclusion

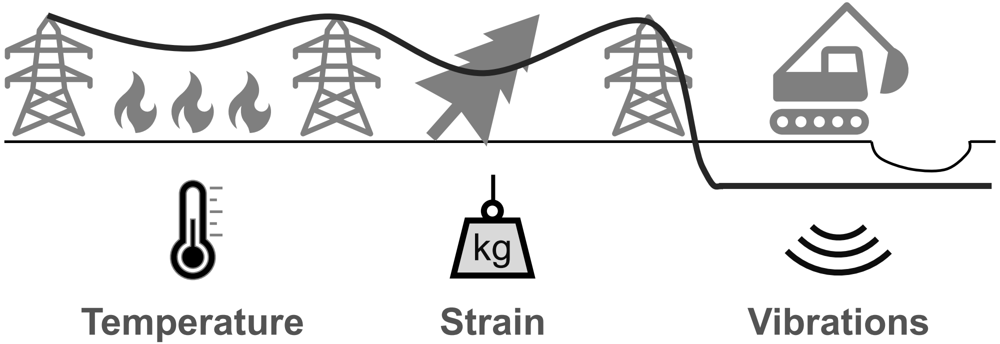
Outline

Introduction to fiber sensing with OTDR

Fiber integrity monitoring
- Fiber break, fiber tapping etc.
- Attenuation along the fiber



Optical fiber as a sensor
- Monitoring of the fiber environment
- Events influence: effective refractive index, length, coating



Monitor communication fiber for external threats - “Joint Communication & Sensing”

Introduction to fiber sensing with OTDR



Distributed temperature and strain monitoring along

- Tunnels, bridges
- Pipelines, water pipes, power grids
- Reactor skin,
- …



Distributed vibration sensing for

- Oil and gas evaluation,
- Perimeter and border protection,
- Traffic monitoring,
- …

Distributed monitoring of slow and fast effects

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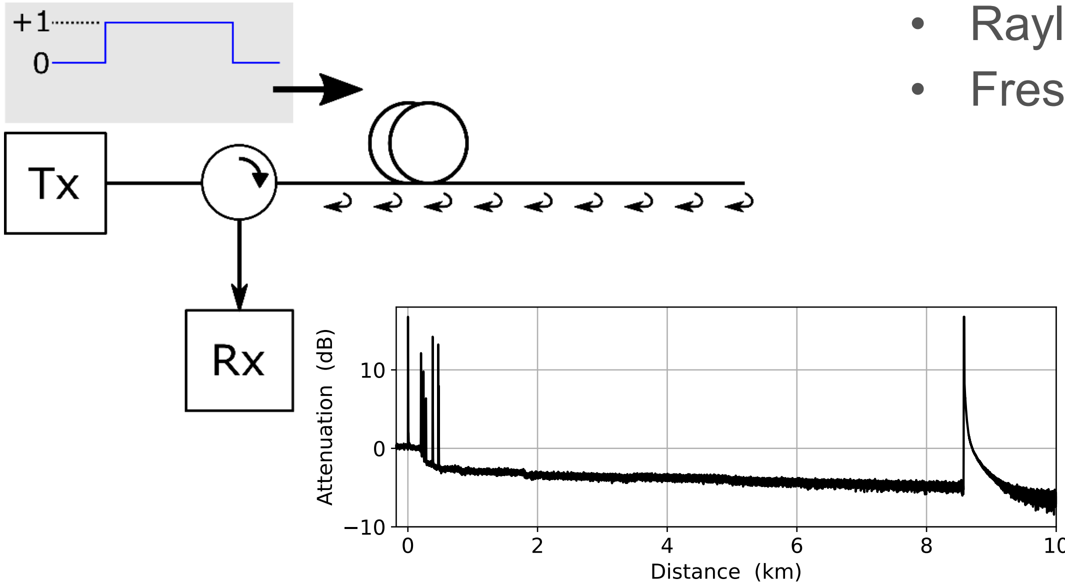
Introduction to fiber sensing with OTDR



Distributed sensing based on

- Rayleigh back-scattering
- Fresnel reflection

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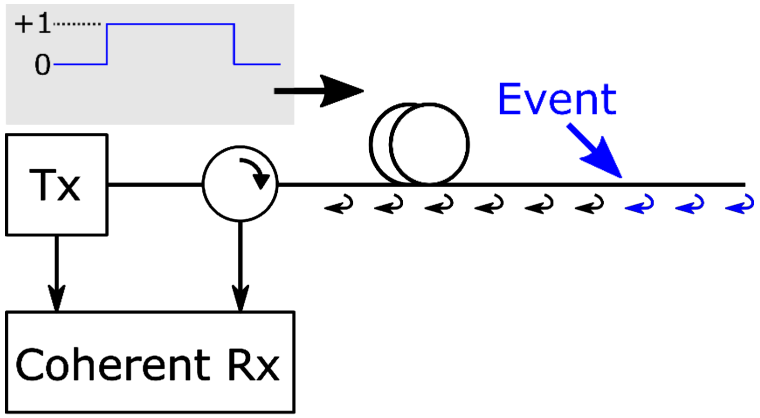
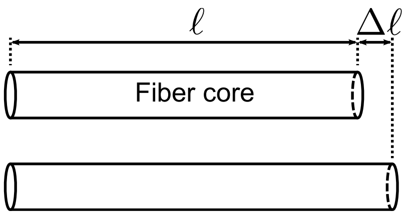
Introduction to fiber sensing with OTDR





$$\varepsilon = \frac{\Delta\ell}{\ell}$$

Distributed sensing based on

- Rayleigh back-scattering
- Fresnel reflection

Coherent Rx gives:

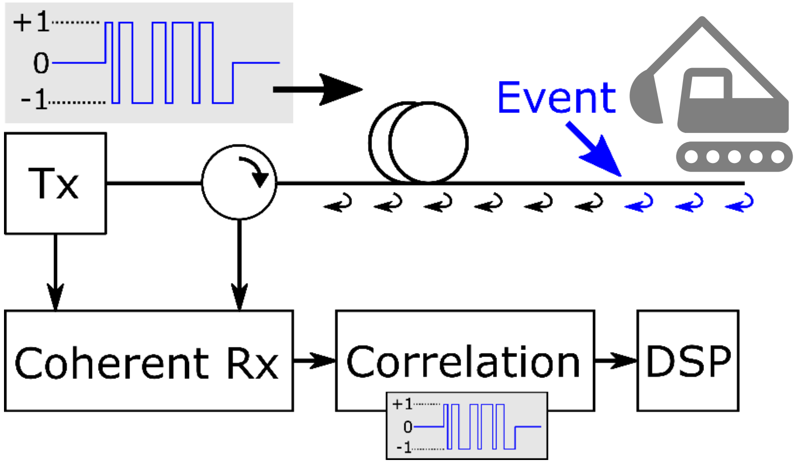
Amplitude, phase and polarization information

Highly sensitive to environmental influences

Strain applied to a fiber section:

Delay change	3.87 ps/(km·με)
Phase change	4706 rad/(km·με)

Introduction to fiber sensing with OTDR



Distributed sensing based on

- Rayleigh back-scattering
- Fresnel reflection

Coherent Rx gives:

Amplitude, phase and polarization information

Highly sensitive to environmental influences

Pulse coding with correlation:

Improved spatial resolution or higher pulse energy

Coherent detection and correlation are combined in CC-OTDR

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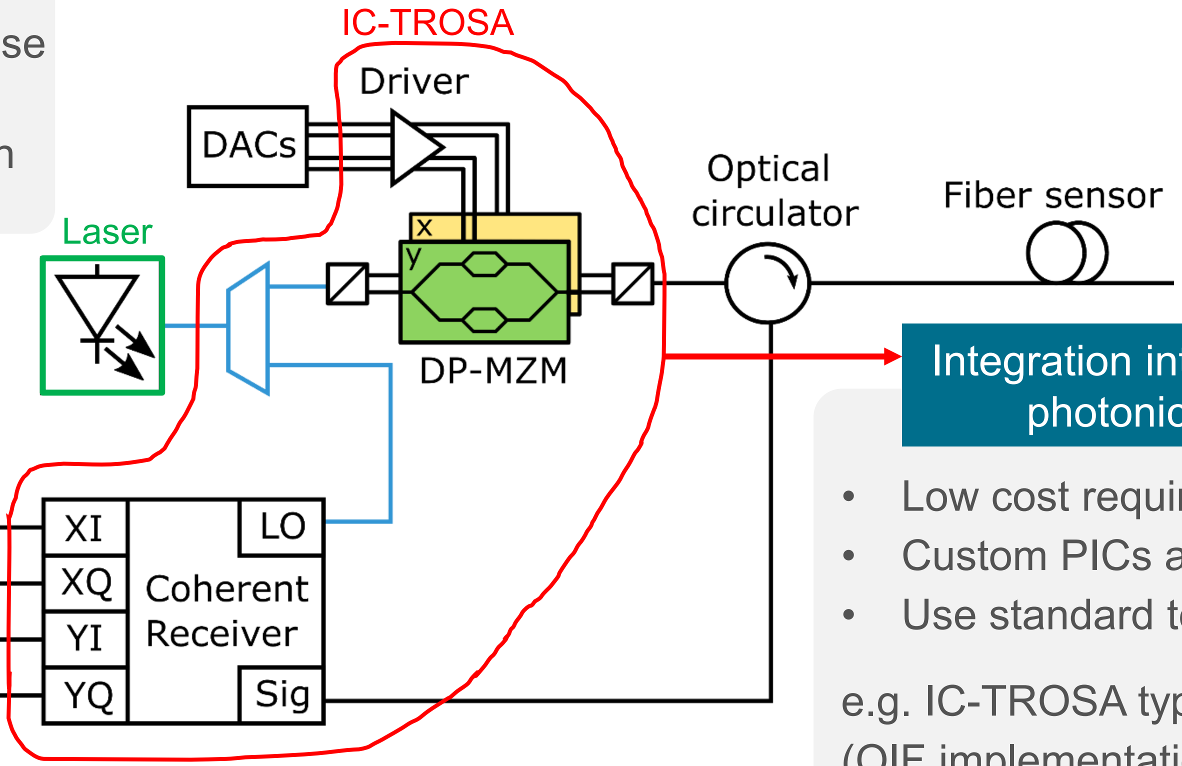
CC-OTDR component requirements

External laser input

- Telecom laser‘s phase noise is too high
- Lorentzian line-width commonly > 25 kHz



Integration into a single photonic chip

- Low cost required
- Custom PICs are too costly
- Use standard telecom chip

e.g. IC-TROSA type 1 (OIF implementation agreement)

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CC-OTDR component requirements

Laser phase noise needs to be low

- Measure phase changes from environmental effects rather than phase noise

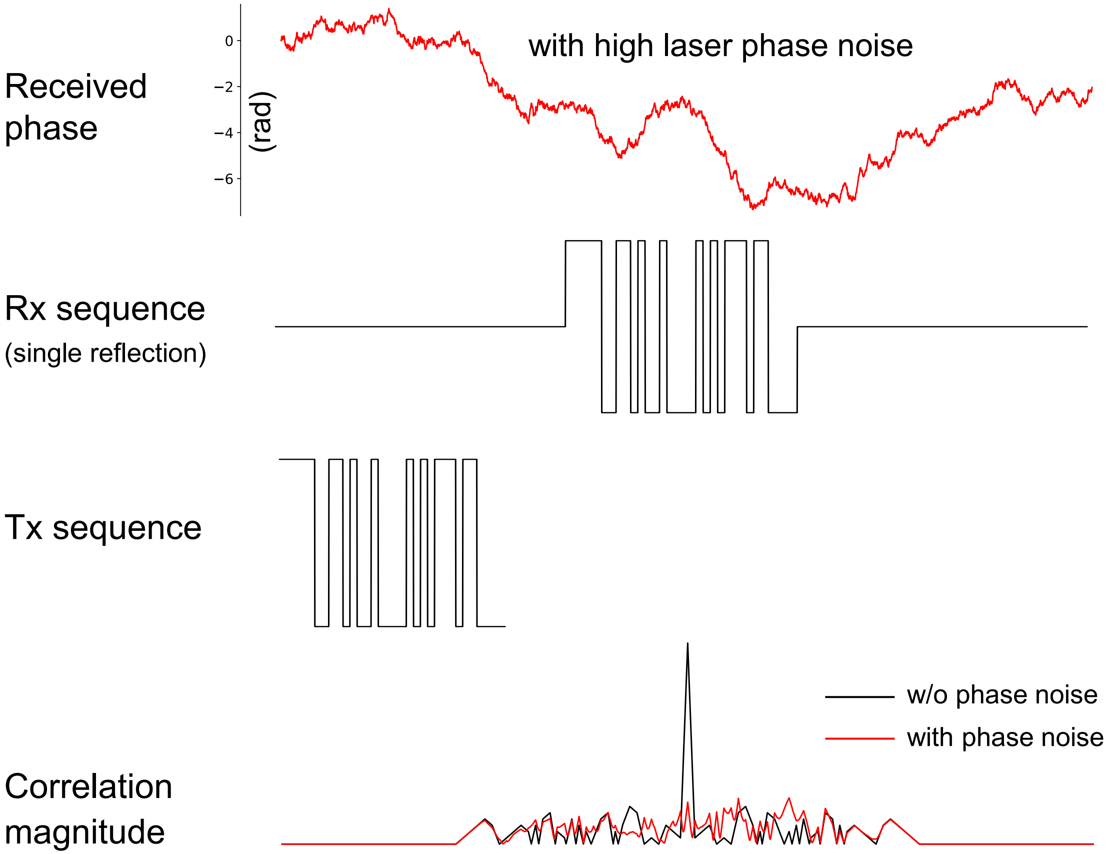
Received phase difference

$$\varphi_{\text{Rx}}(t) = \varphi(t) - \varphi(t - \tau)$$

- stable over sequence duration

Laser power and sequence duration determine energy of the probe signal

Higher sequence duration → higher laser phase noise stability required



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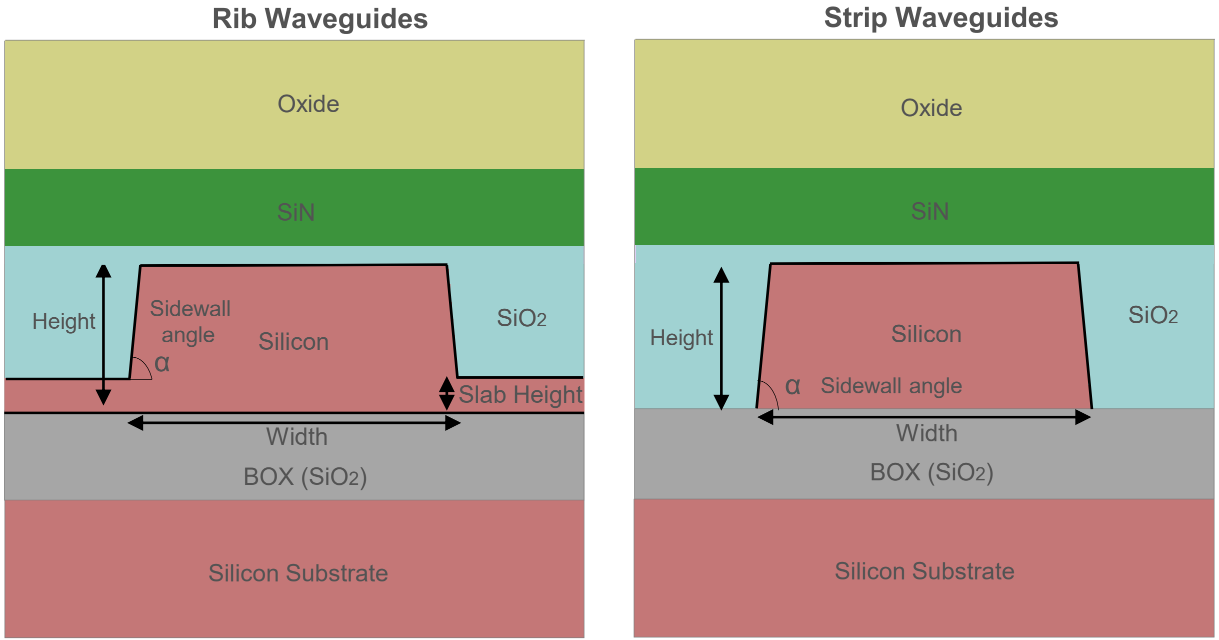
Integrated coherent transceiver

Silicon waveguide cross-section



Refractive index @ 1550 nm

Si 3.49

SiO_2 1.44

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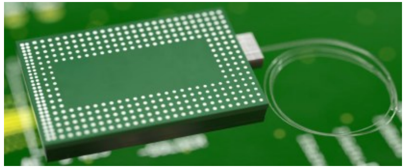
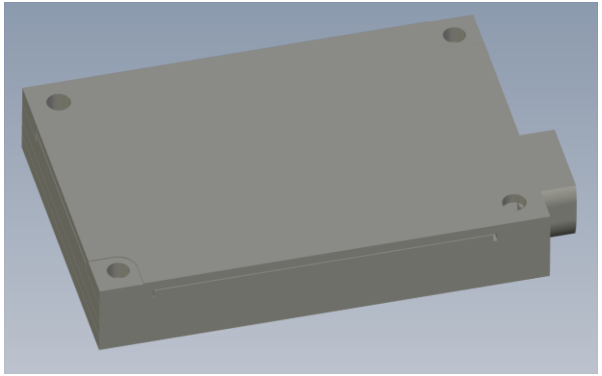
IC-TROSA

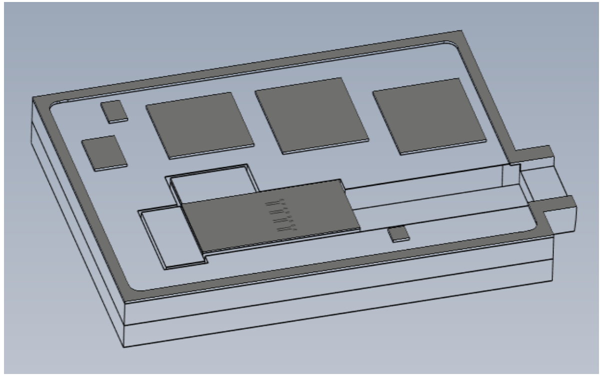
Integrated coherent transceiver

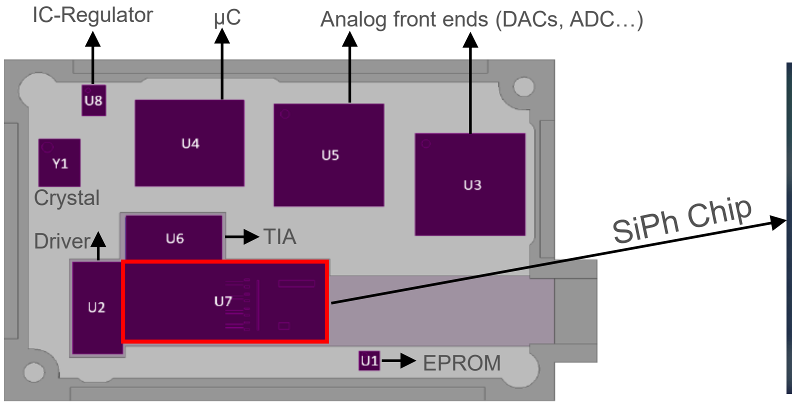


Module

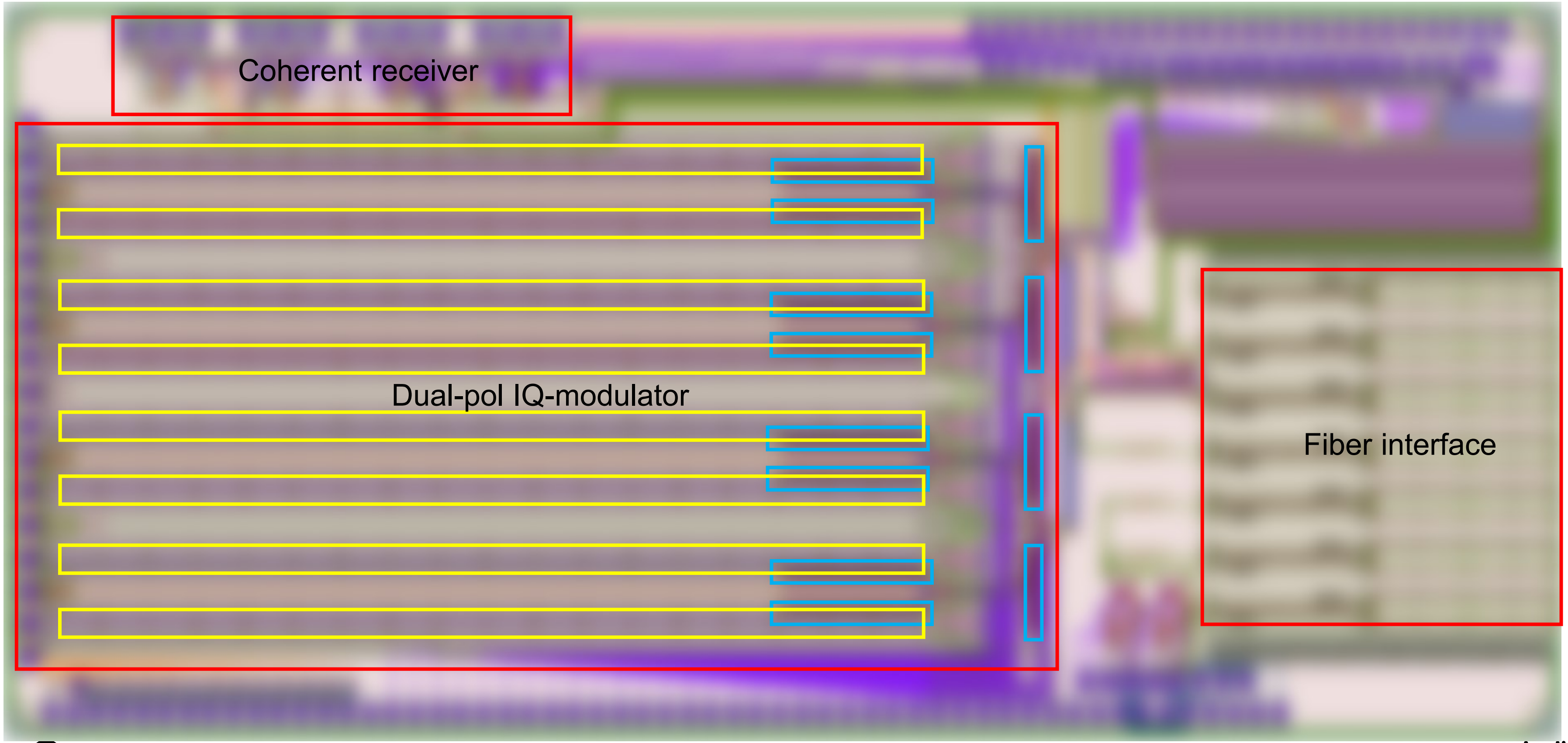


Cross-Section



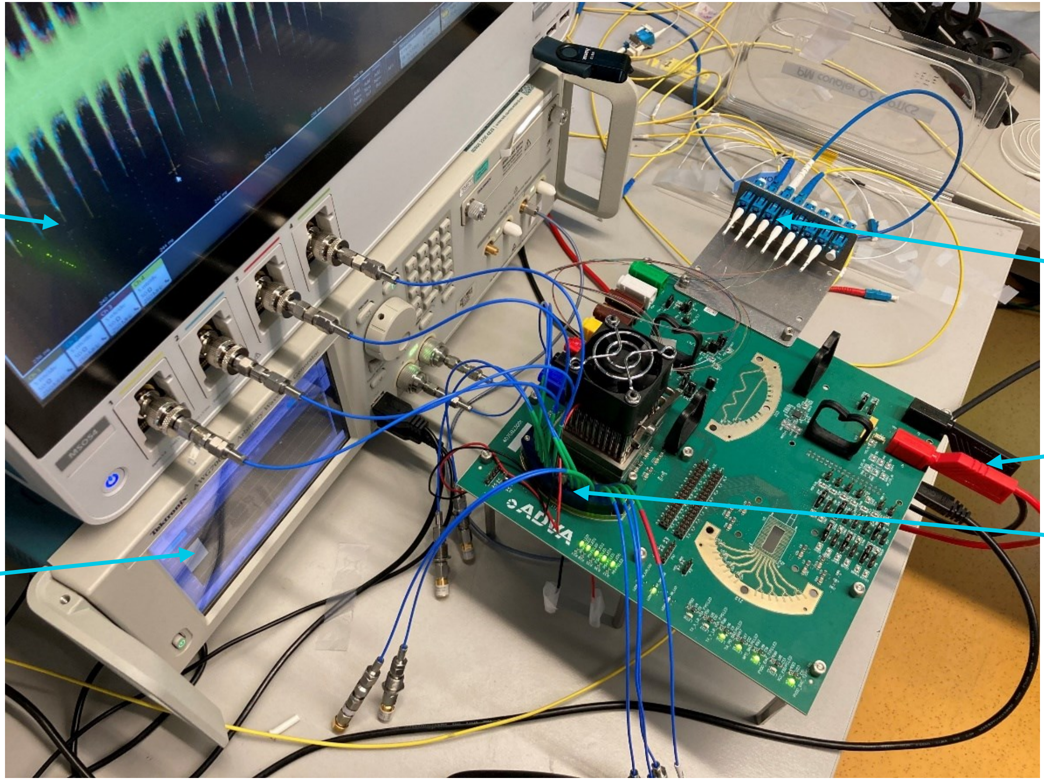


Integrated coherent transceiver



Integrated coherent transceiver

IC-TROSA on evaluation board in the acoustic sensing setup



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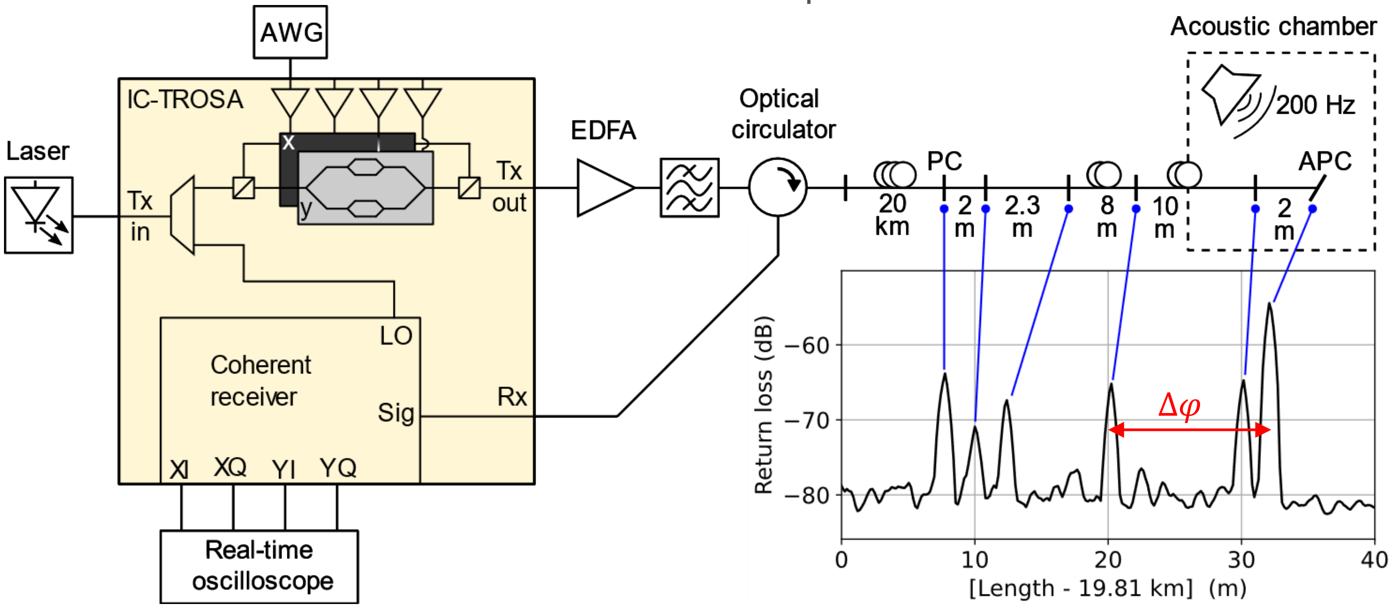
Testbed and acoustic sensing results

PRBS 8191	-1	27500 zero padding

Binary phase shift keying @125 MBaud
Pattern repetition rate: 3.5 kHz



LO… Local oscillator
Sig… Signal input
(A)PC… (Angled) physical contact connector

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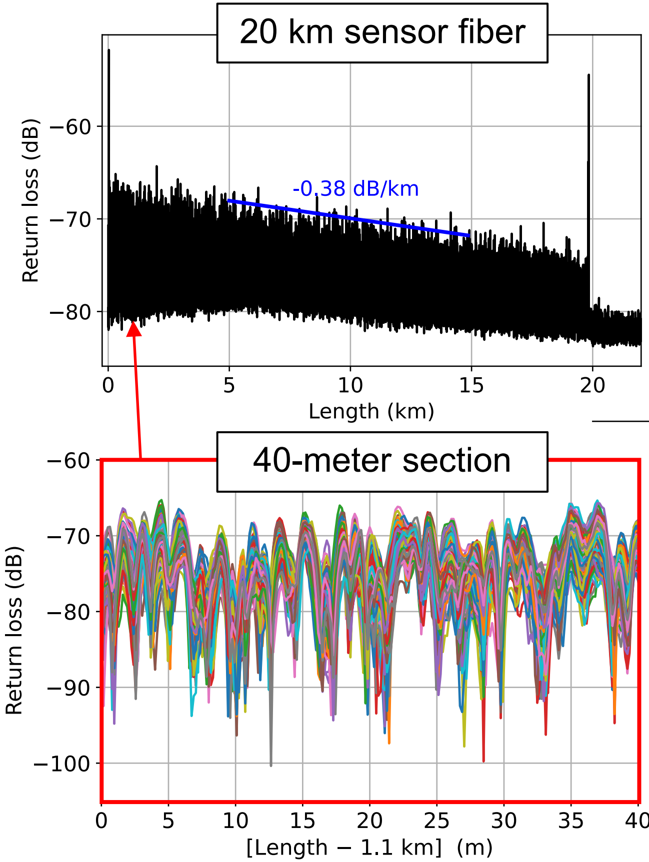
Testbed and acoustic sensing results



- Averaged fingerprint (over all frames)
- Round trip attenuation 0.38 dB/km (0.19 dB/km single-pass)

- Fingerprint of individual frames
- Rayleigh back-scattering region
- Overlap shows time-invariance of the fading pattern (in constant environmental conditions)
- Changes of fingerprint indicate events

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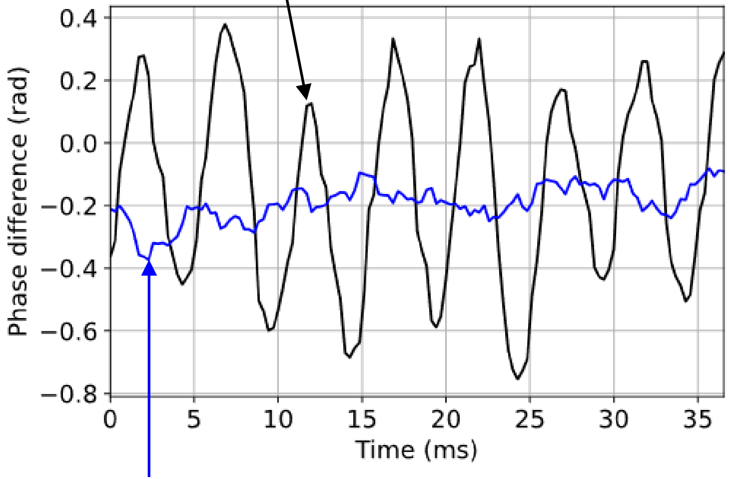
Testbed and acoustic sensing results

- Phase difference of the last 12-meter fiber section
- Difference is taken to avoid phase unwrapping issues

with 200 Hz acoustic signal



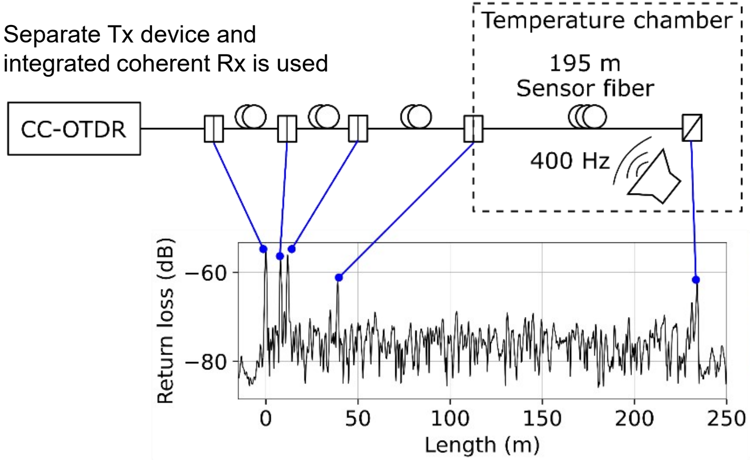
without acoustic signal

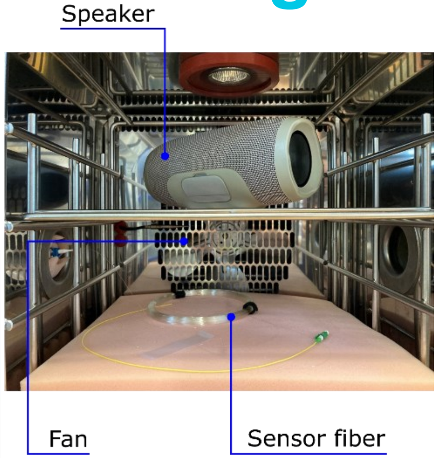
Remaining noise

- Environment
  - Acoustic noise/ lab noise
  - Airflow
  - Thermal changes
- Interrogator
  - Laser phase noise
  - Thermal noise

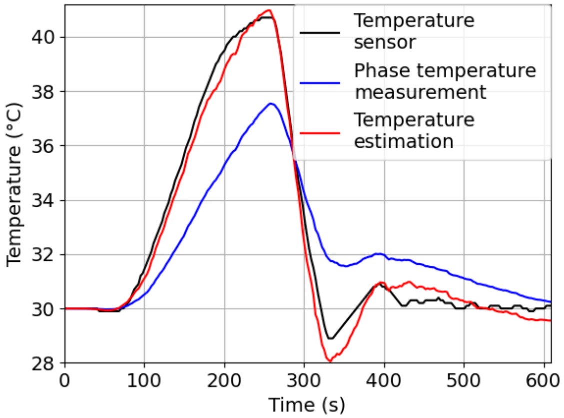
Testbed and acoustic sensing results

Separate Tx device and integrated coherent Rx is used

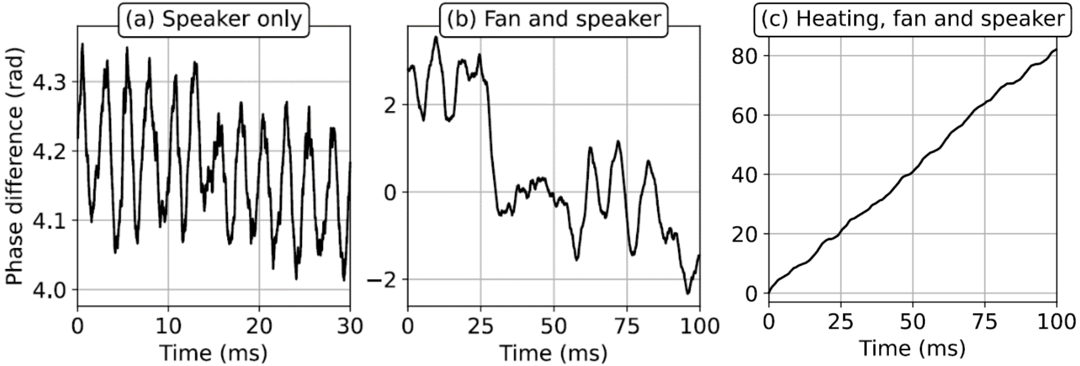




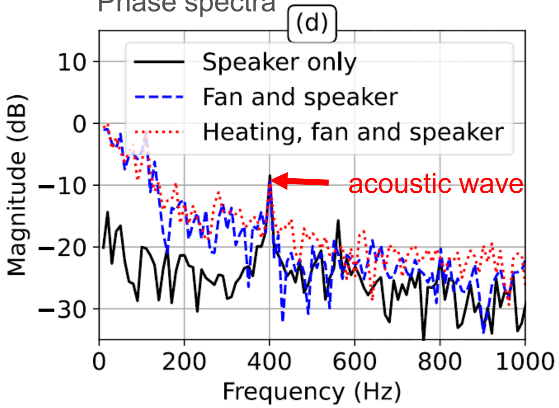
Measured temperature



Time-domain phase evolutions



Phase spectra



*A. Sandmann, F. Azendorf, and M. Eiselt, “Simultaneous Temperature and Acoustic Sensing with Coherent Correlation OTDR,” OFC 2023

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Outline

Conclusion

Single-chip coherent transceiver used for acoustic sensing with CC-OTDR

- In-house designed SiPh chip optimized for telecom applications
- Highly integrated and energy efficient chip

Proof of concept:

- Detection of an applied 200 Hz acoustic signal after 20 km fiber demonstrated
- Based on evaluating phase information of light reflected back to the interrogator

Integrated SiPh transceiver is suitable for acoustic sensing applications

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Thank you

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