Mid-IR-Sensorik mithilfe von verschränkten Photonen im Mikromodul

K. Paschke
Ferdinand-Braun-Institut
Leibniz-Institut für Höchstfrequenztechnik (FBH)
April 2024

Ferdinand-Braun-Institut: semiconductors for new applications & markets

- Microwave & optoelectronic components & systems – key devices for:
  - Health & nutrition, climate & energy, mobility, security, communications, quantum technologies …
- International competence center with full value chain
  - MMICs & power electronic devices
  - High-power diode lasers (NIR to UV spectral range) & UV light-emitting diodes
  - Photonic components & modules as well as systems for applications incl. quantum technology, sensors & health care
- Successful in knowledge and technology transfer:
  - University cooperation (joint labs)
  - Strategic partner of the industry
  - Spin-offs
- Facts & figures:
  - Staff: 370
  - Budget 2021: 44.3 M€ (incl. 25.6 M€ third-party funds)



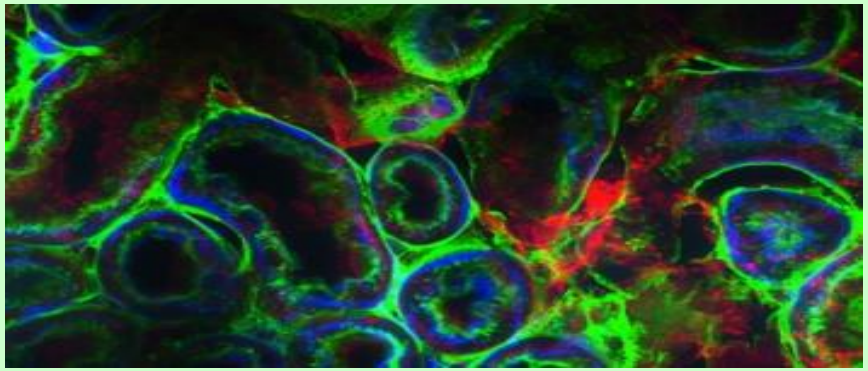
Laser Modules Lab:
Development of high-power miniaturized laser modules for…

Optical measurement



- High-coherent 632.82 nm laser to replace HeNe lasers ***(FINDLING)***
- Quantum-OCT with entangled photons in the mid-infrared ***(QUIN)***
- Spectral infrared microscopy with entangled photons for micro-plastic detection ***(SIM-QPIa)***

Medical & life science



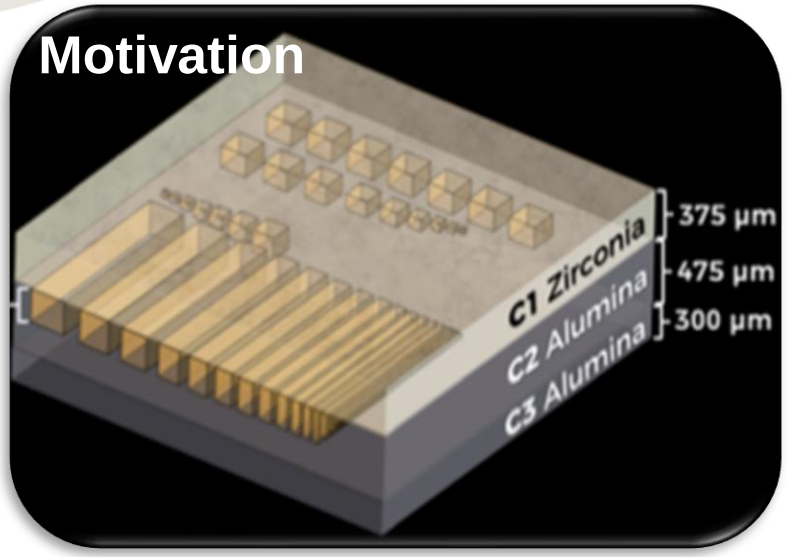
- Ophthalmology 2W cw @ 532…574 nm, Confocal Microscopy and multiphoton Microscopy ***(YELLOW)***
- Fluorescence spectroscopy / STED ps-laser sources @ 532…589 nm
- Laser modules 30 W @ 978 nm for pumping of Er:YAG-lasers for drug penetration through skin & fs- Laser for Assisted Cataract Surgery ***(MiFeM)***
- Entangled photons for new imaging for biomarker detection ***(QEED)***

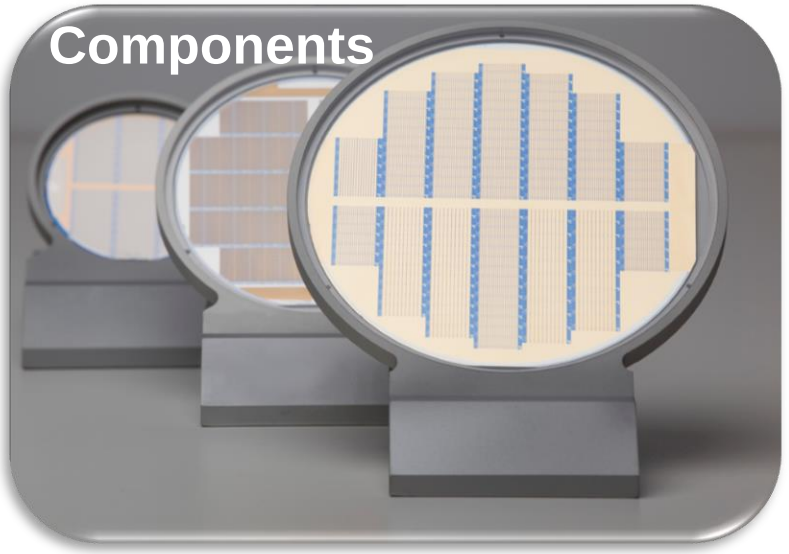
Display & Printing

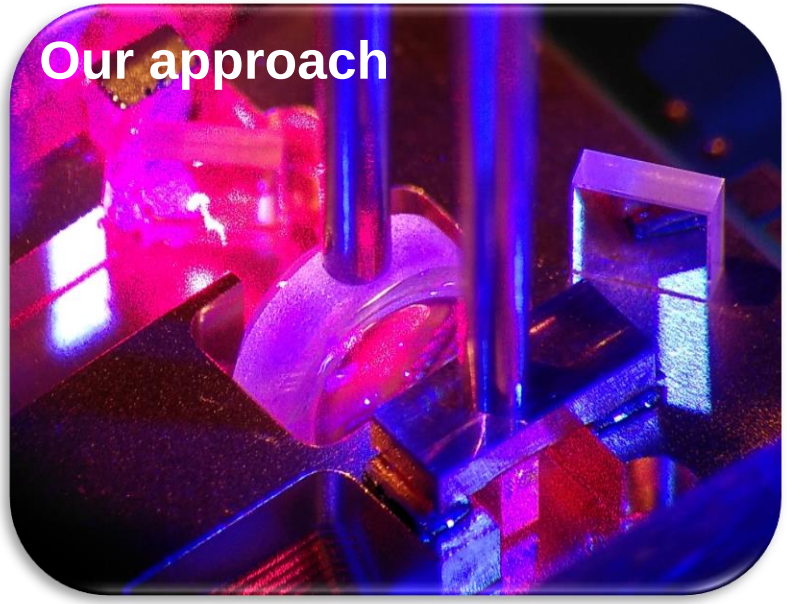


- 3D-laser television based on holography – RGB ***(DisKo)***
- Color space enhancement with Yellow
- RGB for Economic Holographic Laser Printer ***(Echolas)***
- Solutions for miniaturized laser systems for laser marking and engraving

Outline


Motivation
C1 Zirconia
C2 Alumina
C3 Alumina
375 µm
475 µm
300 µm


Components

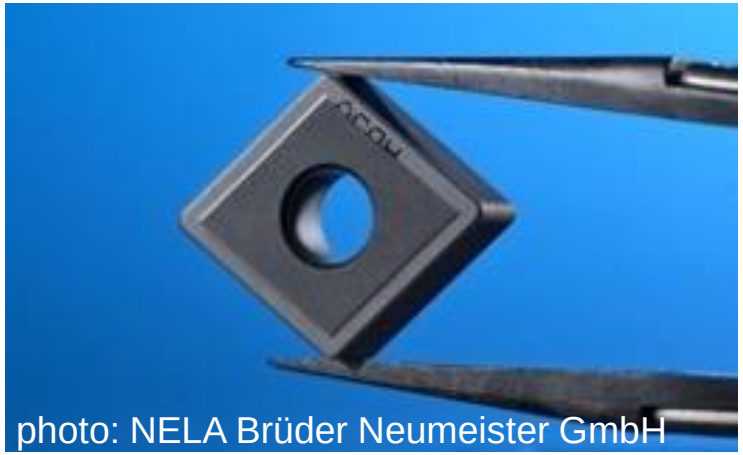

Our approach


Results & Outlook
QUIN

Motivation

How to detect masked defects or buried structures in highly scattering materials

- Strongly scattering media: ceramics, paints, micro-porous or micro-fibrous materials
- Interesting for: non-destructive testing in optical testing and sorting machines, quality control of pharmaceutical coatings, investigation of products made of polymers & composite ceramic–polymer materials, dentistry…
- mid-IR Light (3 - 5 µm) allows strong-scattering materials to be penetrated in order to measure structures located below the surface.

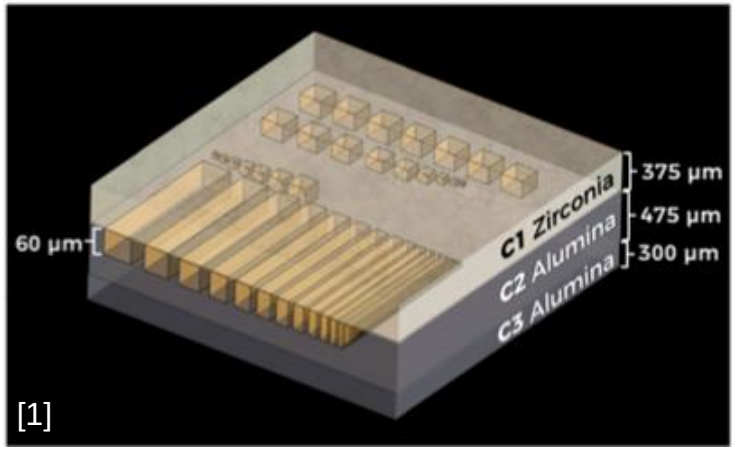

photo: NELA Brüder Neumeister GmbH

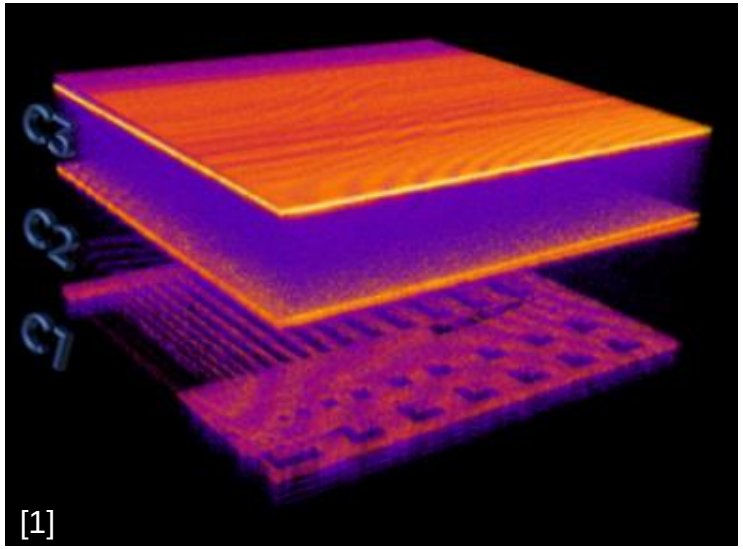
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- mid-IR Light (3 - 5 µm) allows strong-scattering materials to be penetrated in order to measure structures located below the surface.
- One optical method: optical coherence tomography (OCT).





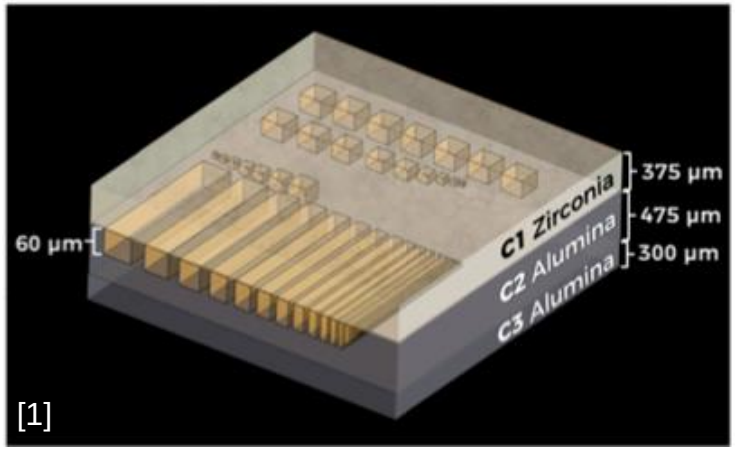
[1] N.M. Israelsen et al. "Real-time high-resolution mid-infrared optical coherence tomography," Light: Science & Applications 8 (2019).

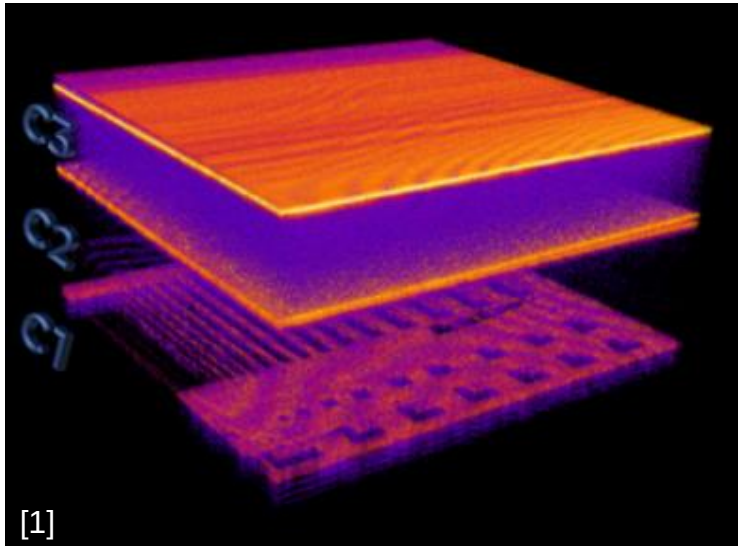
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Motivation

How to detect masked defects or buried structures in highly scattering materials

- However, so far mid-IR OCT has not been widely implemented, as both suitable detectors and laser sources are very expensive and subject to noise.





[1] N.M. Israelsen et al. "Real-time high-resolution mid-infrared optical coherence tomography," Light: Science & Applications 8 (2019).

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Motivation

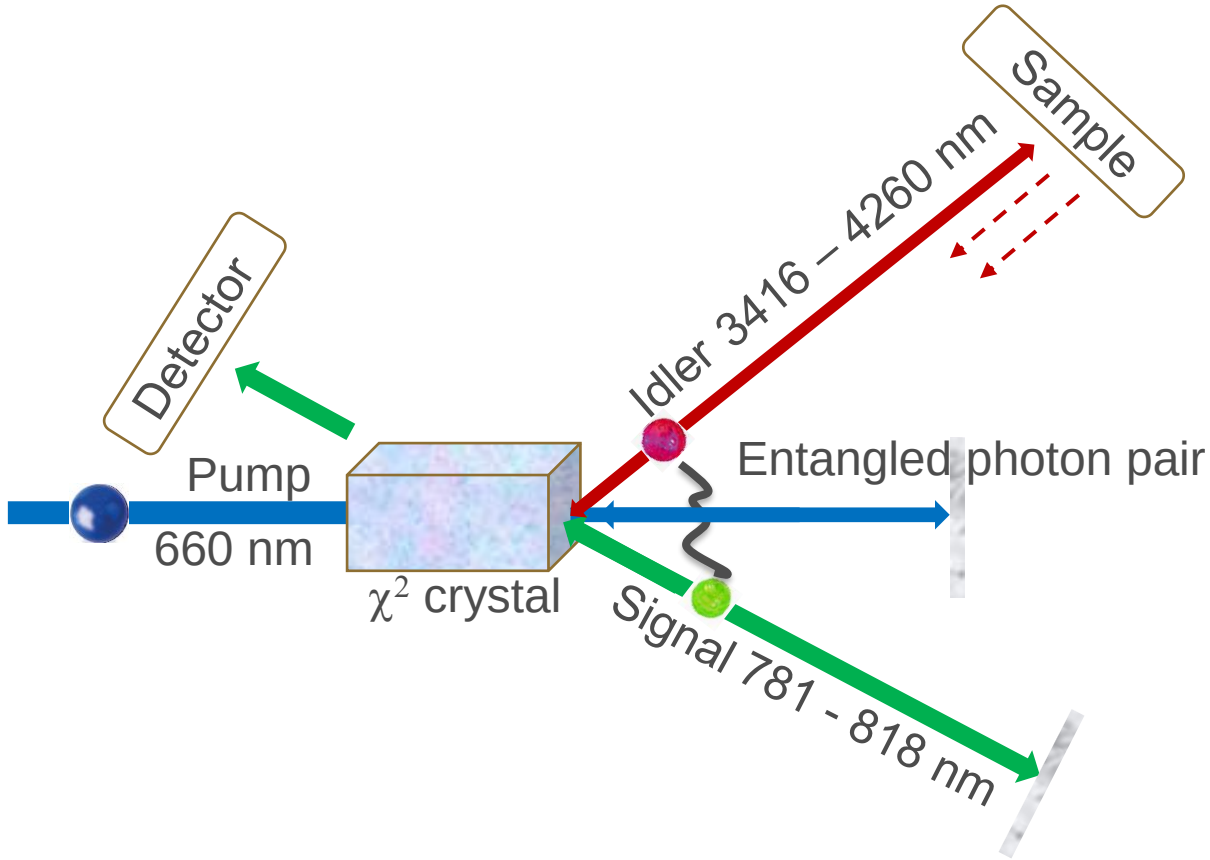
Solution: Novel approach using quantum technology

- Entanglement [1]: NIR- and a mid-IR photon, which is created in SPDC (spontaneous parametric down conversion) process

- Mid-IR light (idler) directed onto sample → in parts scattered back
- NIR and the pump on a reference path

- Backscattered and reference light travel back to SPDC crystal and interfere → Due to the entanglement information from mid-IR transferred to NIR (quantum interference)

- NIR- photon detected with low-noise silicon detectors, while it gives the picture of the entangled mid-IR photons.

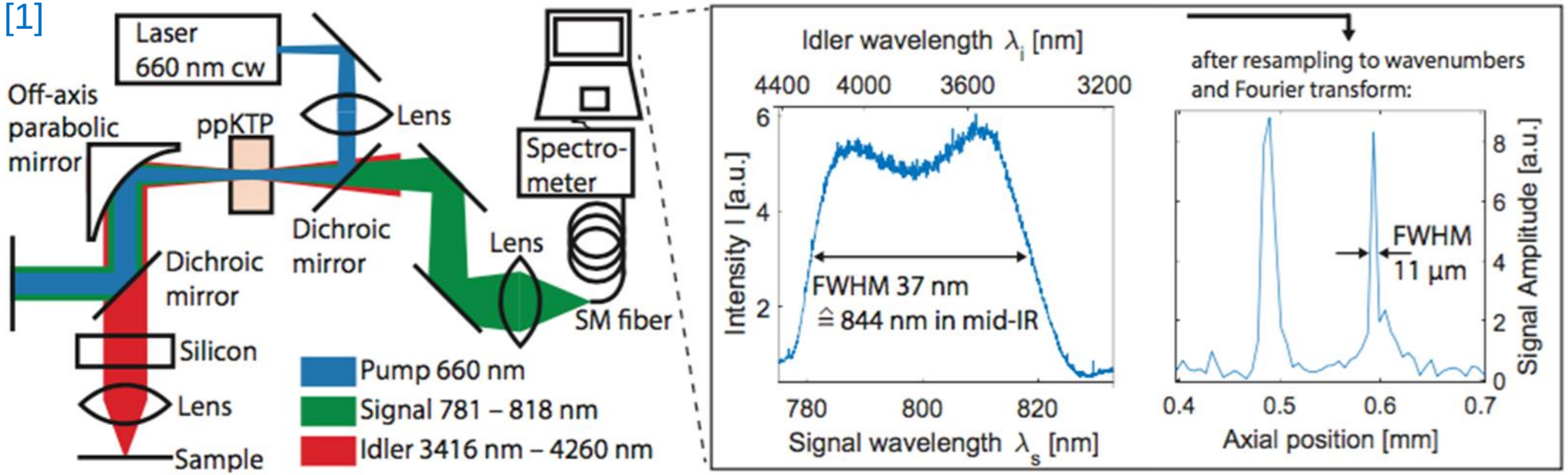


[1] Alain Aspect / John F. Clause / Anton Zeilinger "for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science“, **Nobel prize for Physics (2022).**

Motivation

Solution: Novel approach using quantum technology

[1]



This quantum-OCT with undetected photons will allow imaging application in the mid-IR and maybe even the far-infrared currently not accessible with classical optics.

[1] A. Vanselow et al. "Frequency-domain optical coherence tomography with undetected mid-infrared photons," Optica 7 (12), pp. 1729-1736 (2020).

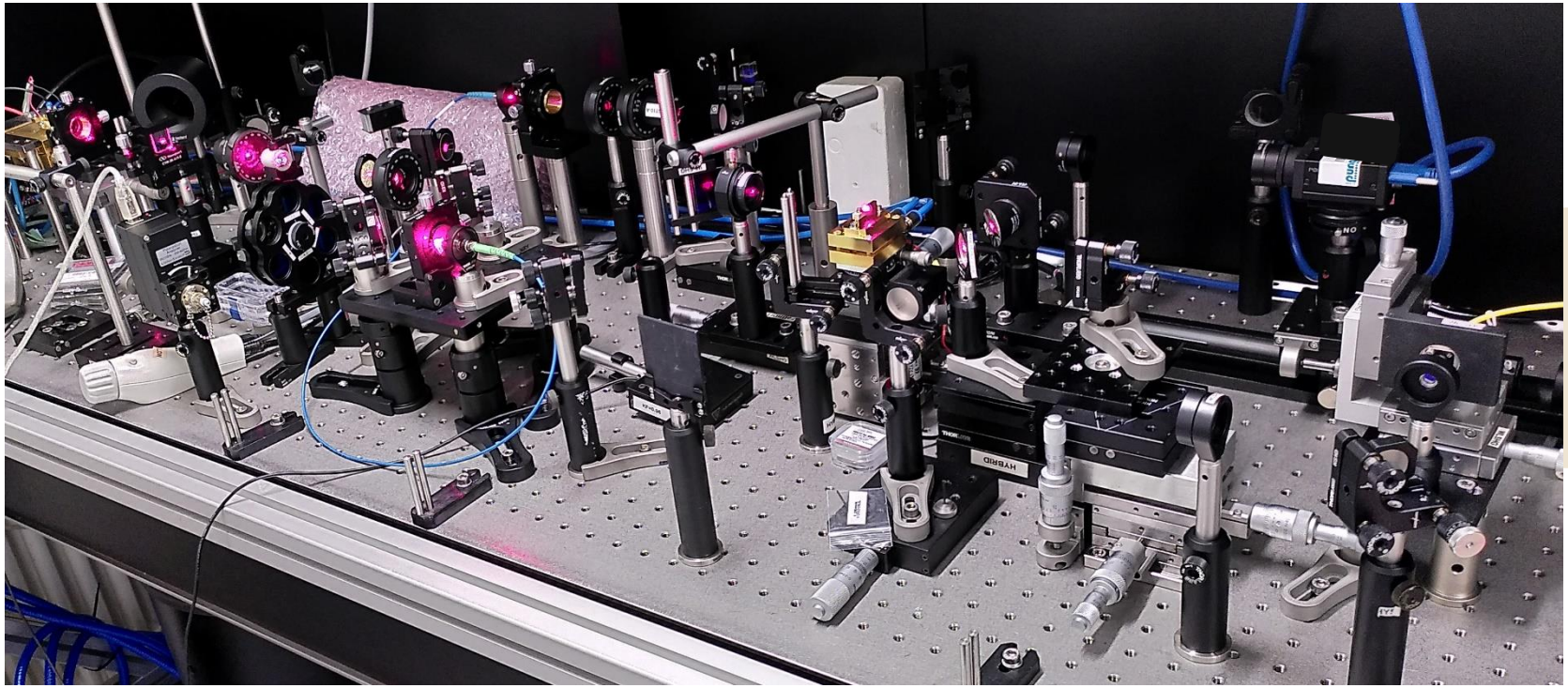
Motivation



Copyright

Aim: Make complex laboratory experiment industry compatible

Move quickly from feasibility study to application

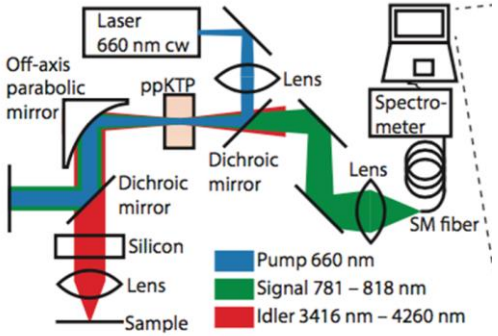


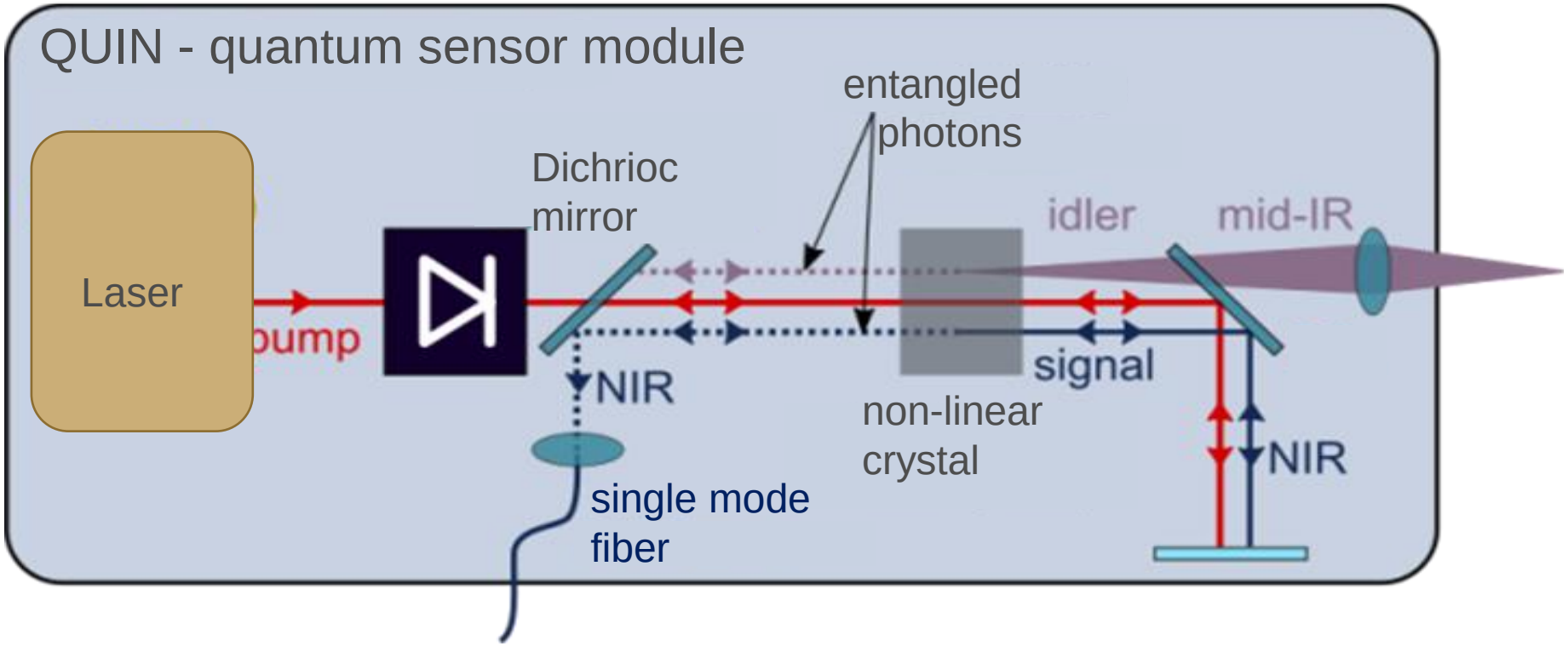


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Motivation

Concept for mid-IR OCT with entangled photons

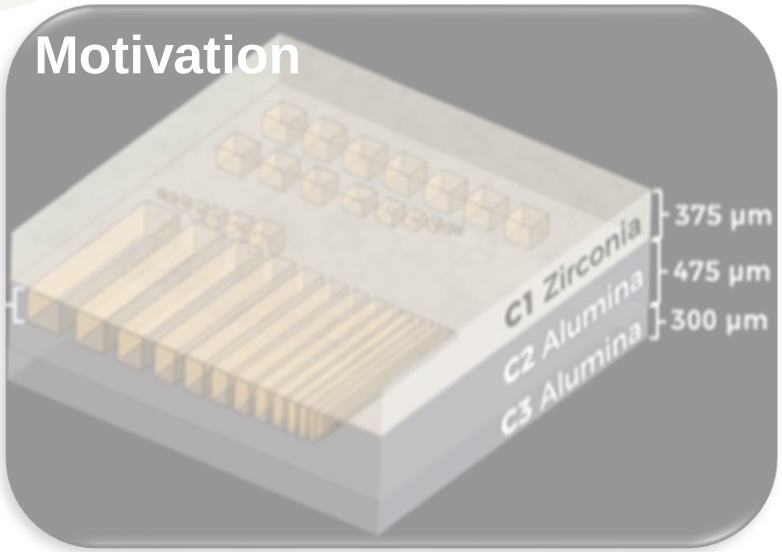


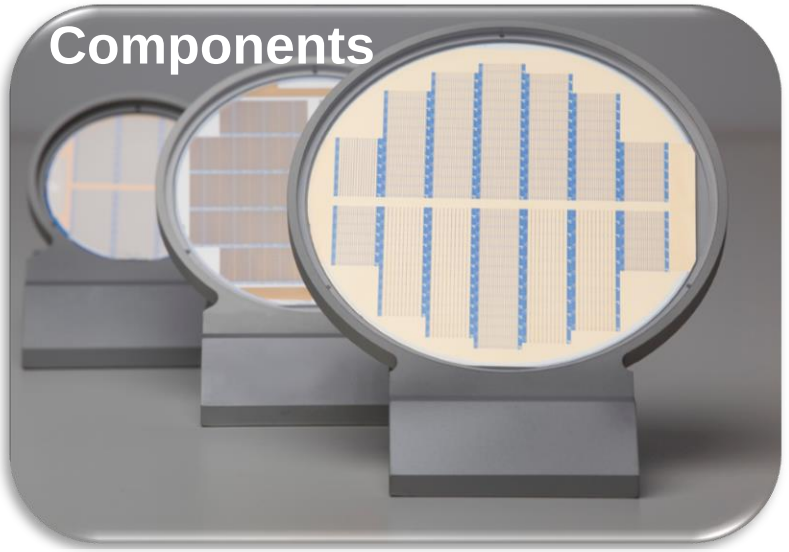


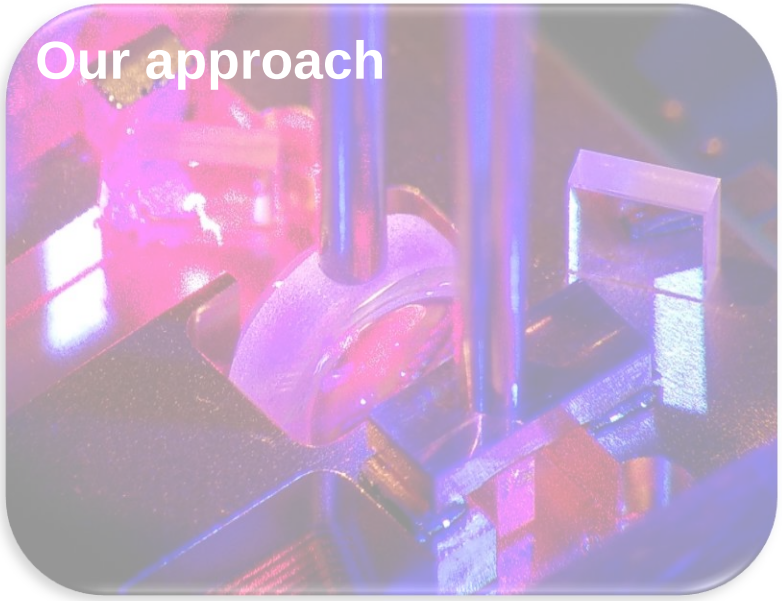
Photonenrate	10^{10} photons/s(2.5 nW)
Spektrale Breite	15 THz
Interferenzkontrast	50%

- **Replacing the laser source**
- **Shrinking of the setup**

Outline


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C1 Zirconia
C2 Alumina
C3 Alumina
375 µm
475 µm
300 µm


Components


Our approach


Results & Outlook
QUIN

Components-
Replacing the laser source

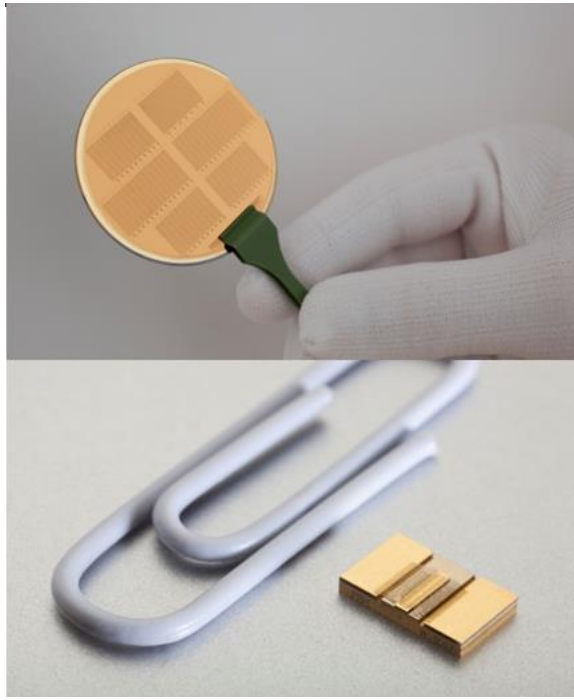
State of the art

- Solid state lasers (DPSS)
- Frequency converted fiber lasers



Semiconductor source

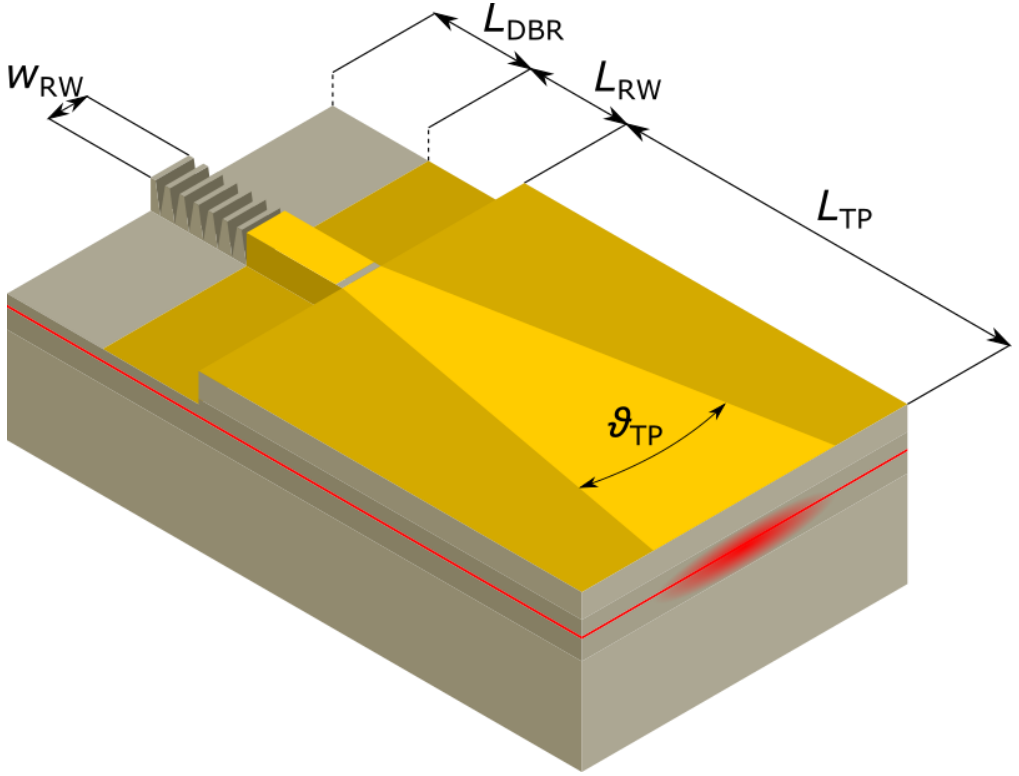
- Small size
  - Capability of micro integration
- High power conversion efficiency
  - Peak values > 70%; typically > 50...65%
- Wide wavelength range directly delivered
  - Central wavelength freely selectable
- Capability of mass production
  - Full 3…4” wafer processing enables low cost manufacture (low €/W)
- Extremely reliable and robust
  - Qualified for most demanding environment (space, sub-sea)
- Easy excitation (electrically driven)
  - Direct modulation possible



Components-
Replacing the laser source

Laser source requirements for mid-IR quantum OCT

- Red-emitting laser diode $\lambda \sim 660$ nm
- High output power $P > 1$ W
- Suitable coherence length $L_c > 50$ cm ($\Delta\nu < 500$ MHz)
- Mainly fundamental mode $M^2 \leq 2$
- Small size for capability of micro integration



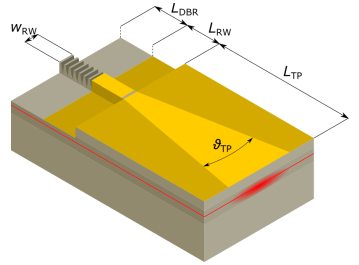
Device: DBR tapered diode laser[1]

- Output power: taper area (θ_{TA},L_{TP})
- Beam quality: RW (L_{RW}, w_{RW}, Δn_{eff})
- Spectral purity: DBR (R_{DBR}, L_{DBR})

[1] B. Sumpf and K. Paschke, "Spectrally stabilized high-power high-brightness DBR-tapered lasers in the VIS and NIR range“, Proc. SPIE 10518, 1051817 (2018).

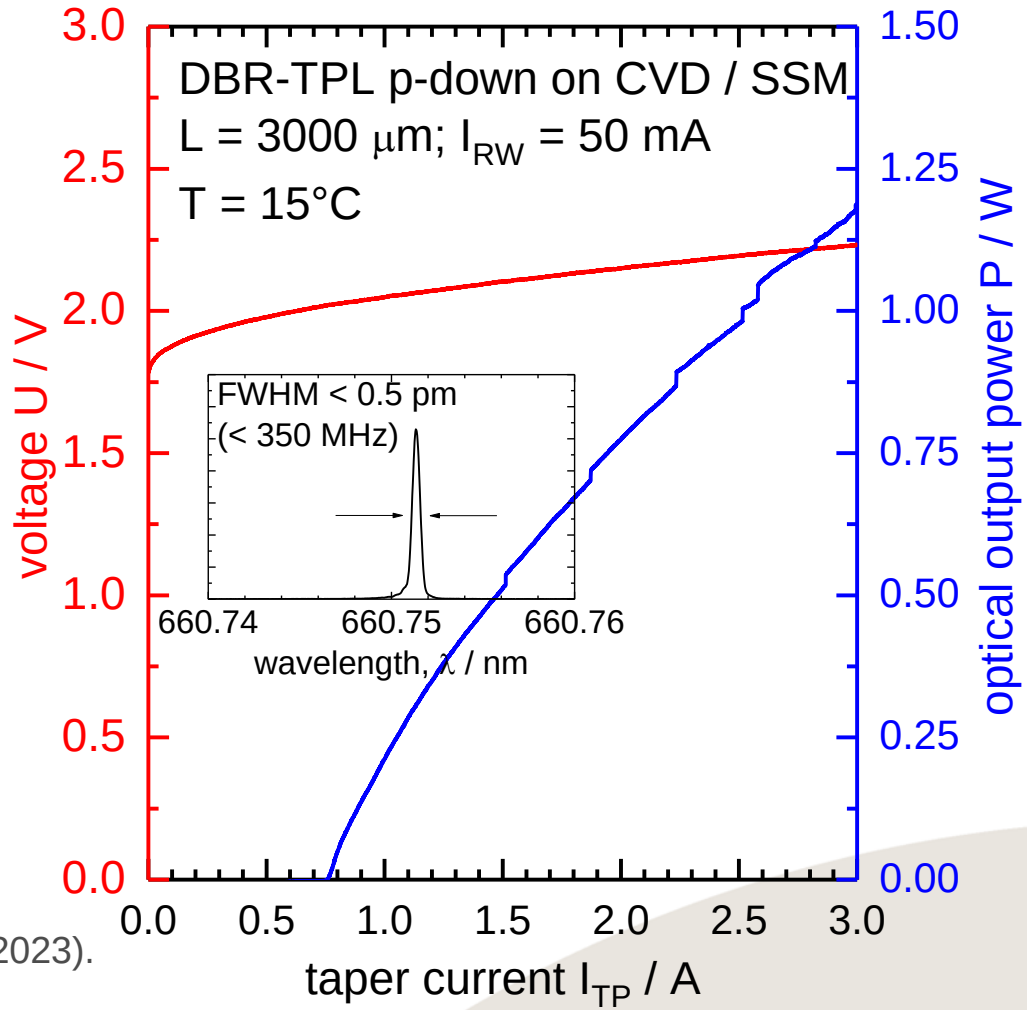
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Components-
Replacing the laser source



Development of a worldwide unique laser diode, as a source for nonlinear process

- Red-emitting laser diode $\lambda \sim 660$ nm
- High output power $P > 1$ W
- Mainly fundamental mode $M^2 \leq 2$
- $\Delta\lambda < 0.5$ pm ($\Delta\nu < 350$ MHz) → $L_c > 80$ cm

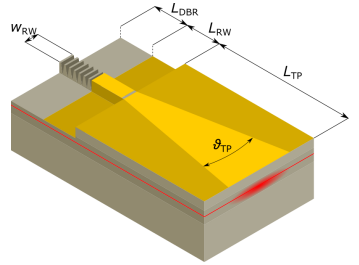


[1] G. Blume, et al. "Single mode 660 nm DBR tapered laser with 1 W optical output power Proc. of SPIE, vol. 12402 (2023).

[2] G. Blume, et al. CLEO presentation tomorrow

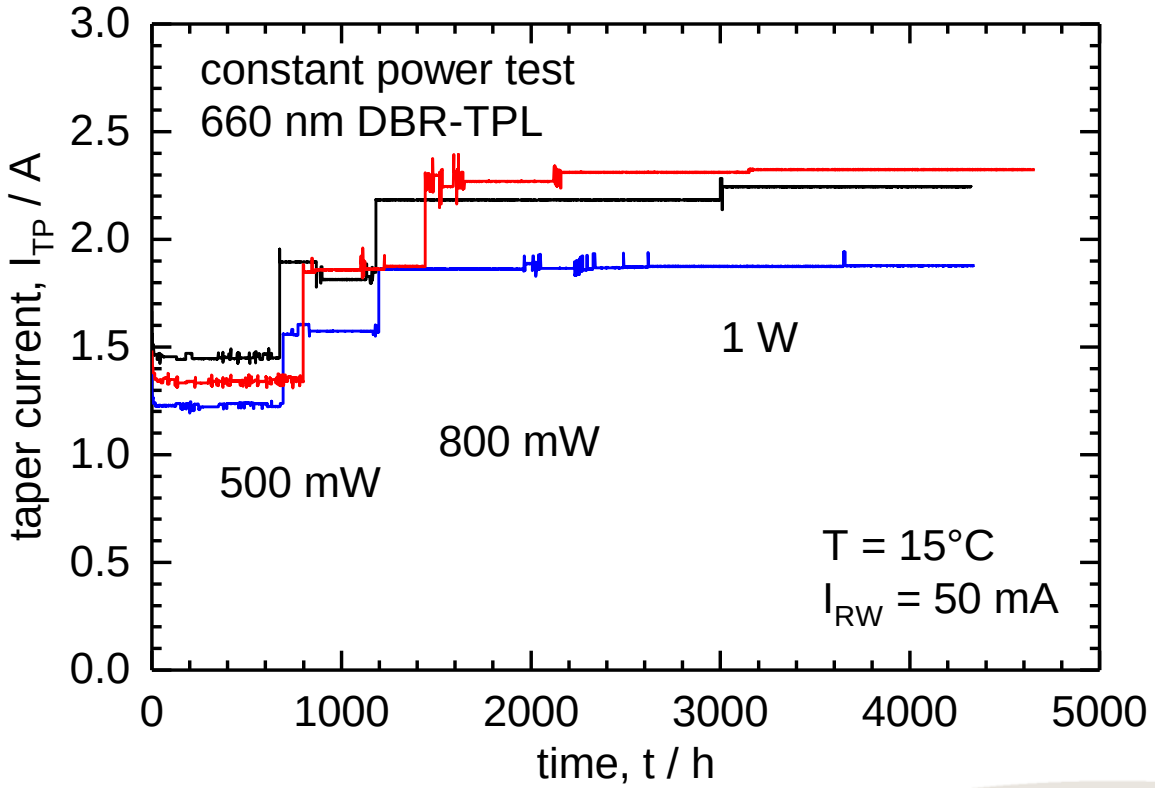
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Components-
Replacing the laser source



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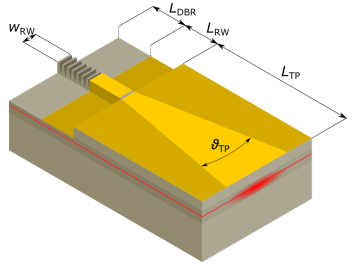
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- Reliability: can be operated at 1.0 W for > 3000 h



[1] G. Blume et al. "Single mode 660 nm DBR tapered laser with 1 W optical output power," Proc. SPIE, 1240205 (2023).
[2] G. Blume et al. "Design strategies to optimize 660 nm DBR tapered laser performance," CLEO Munich CB11.5 (2023-06-29).

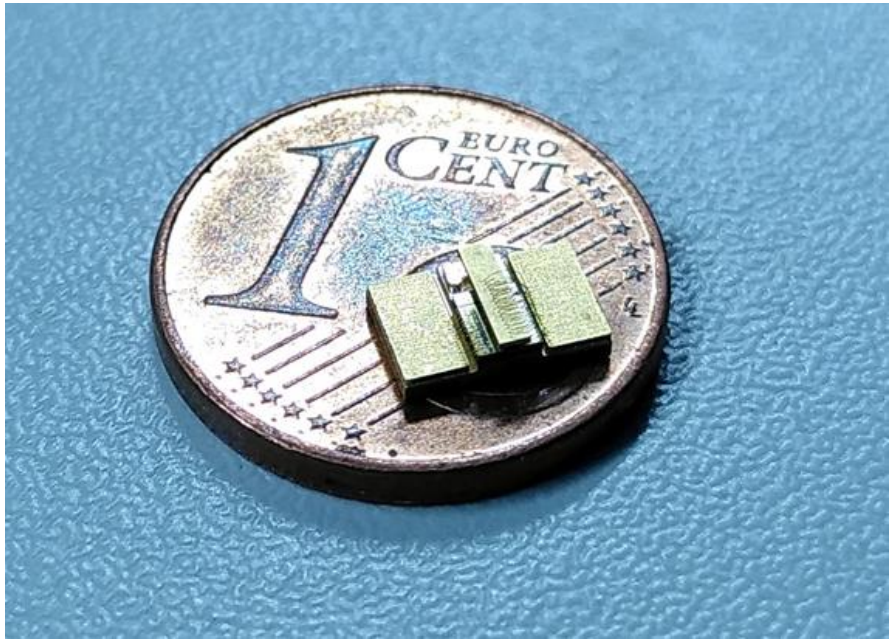
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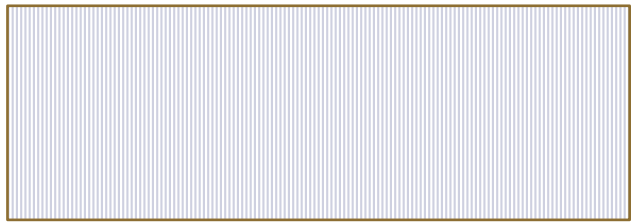
[1] G. Blume et al. "Single mode 660 nm DBR tapered laser with 1 W optical output power," Proc. SPIE, 1240205 (2023).
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Components-
Shrinking of the setup

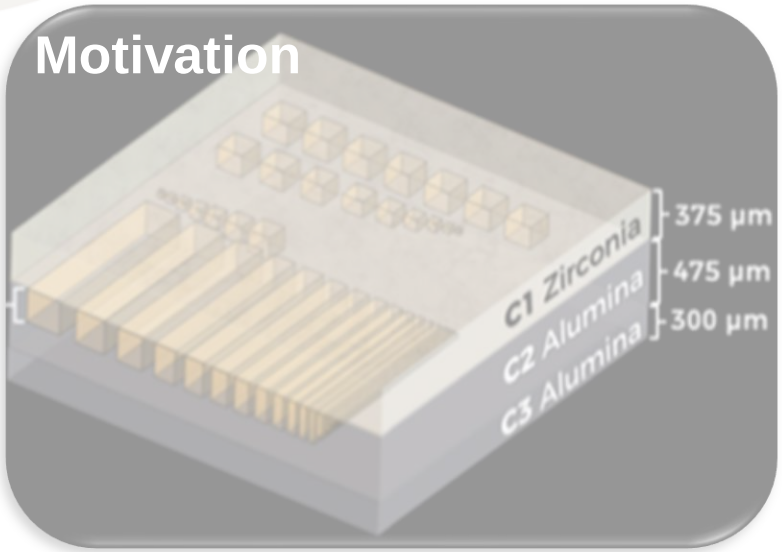
Design of the crystal in collaboration with the HUB

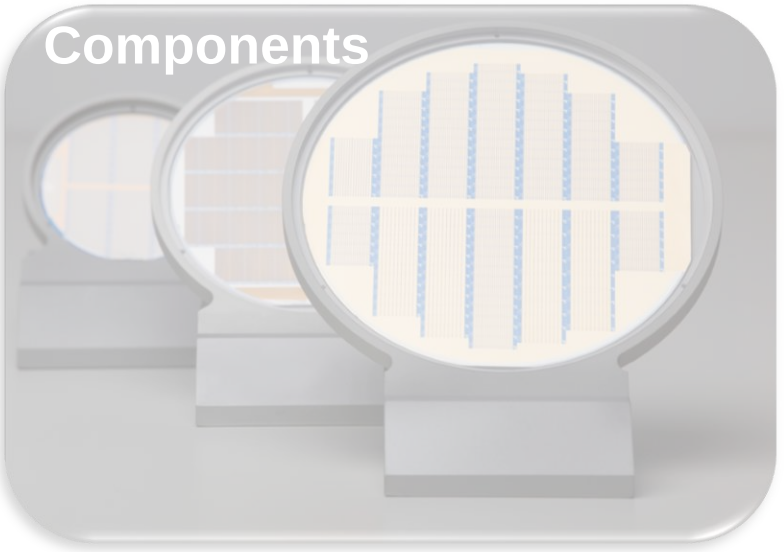
- 660nm to 789-820nm and 3400-4300nm
- PP KTP
- bulk
- L = 2,5mm

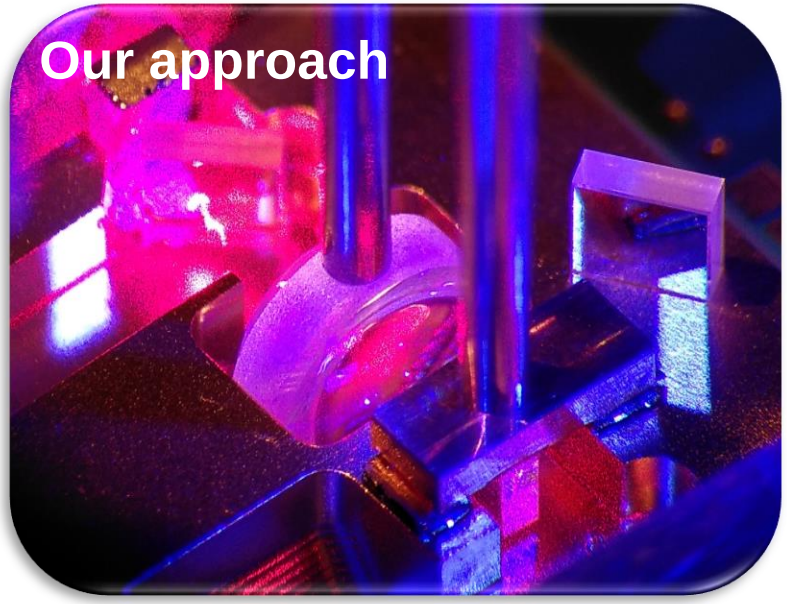


SPDC-Kristall

Outline





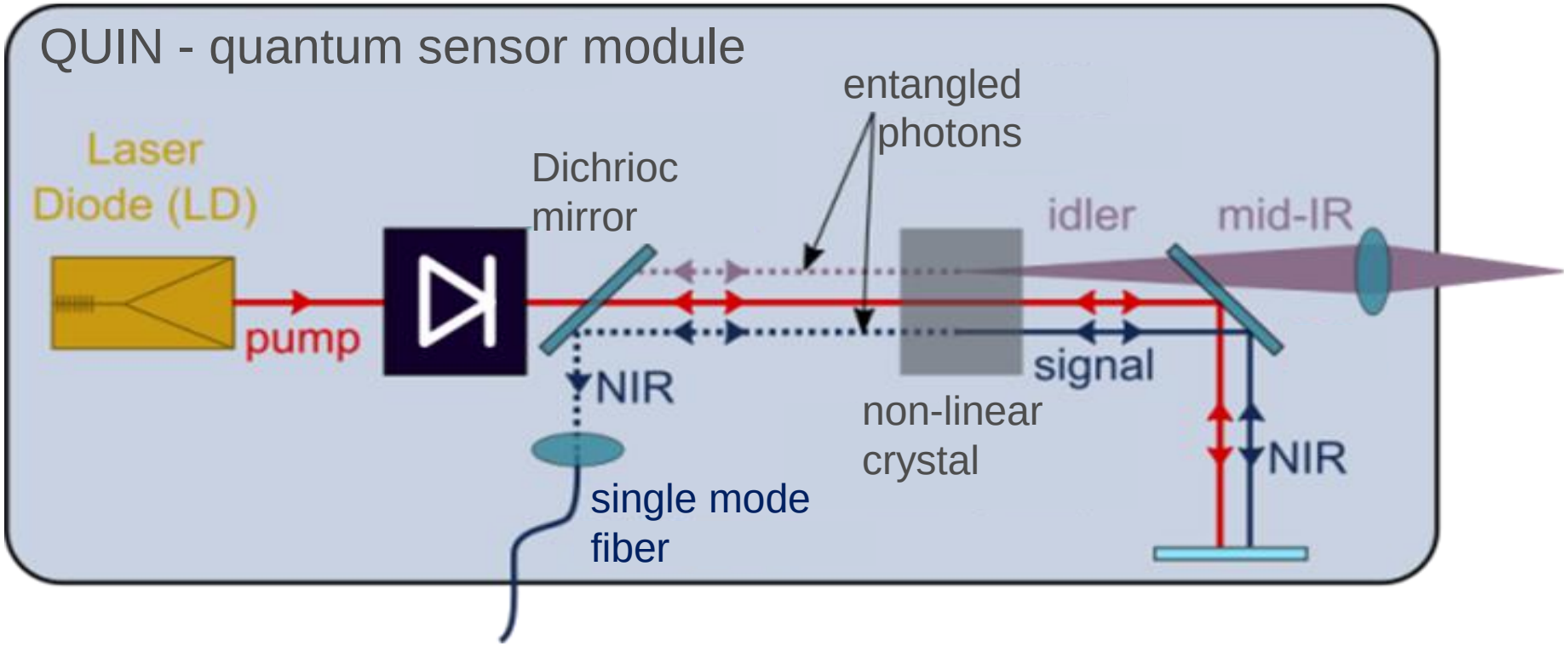


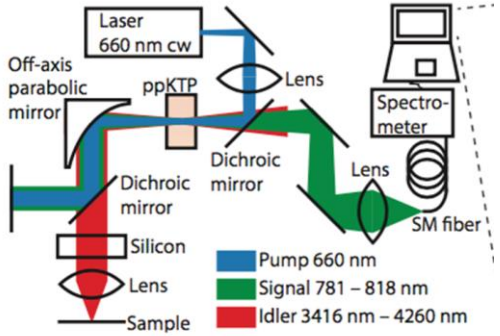


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Our approach -
Opto-mechanical design for miniaturized quantum sensor module

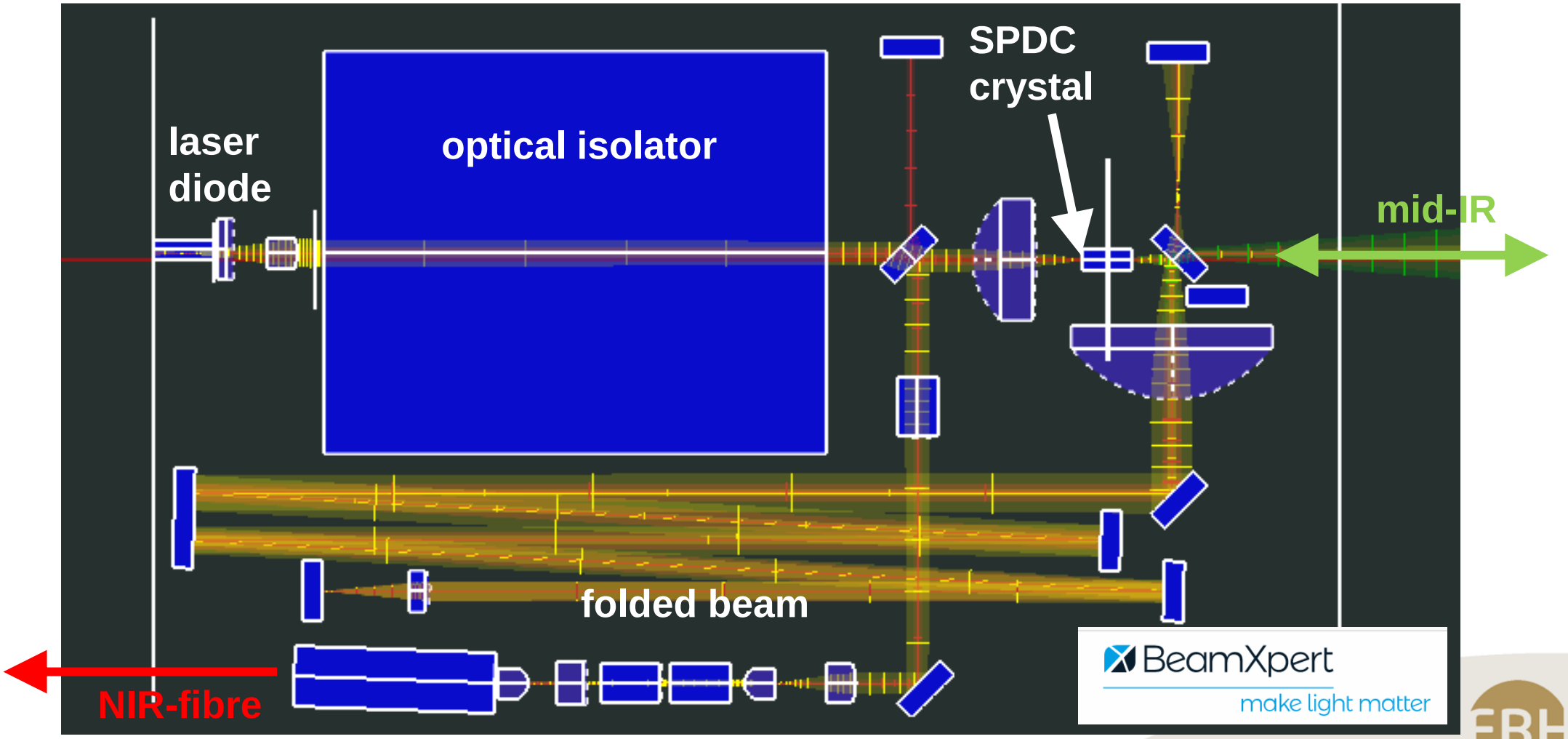
Concept for mid-IR OCT with entangled photons





Our approach -
Opto-mechanical design for miniaturized quantum sensor module

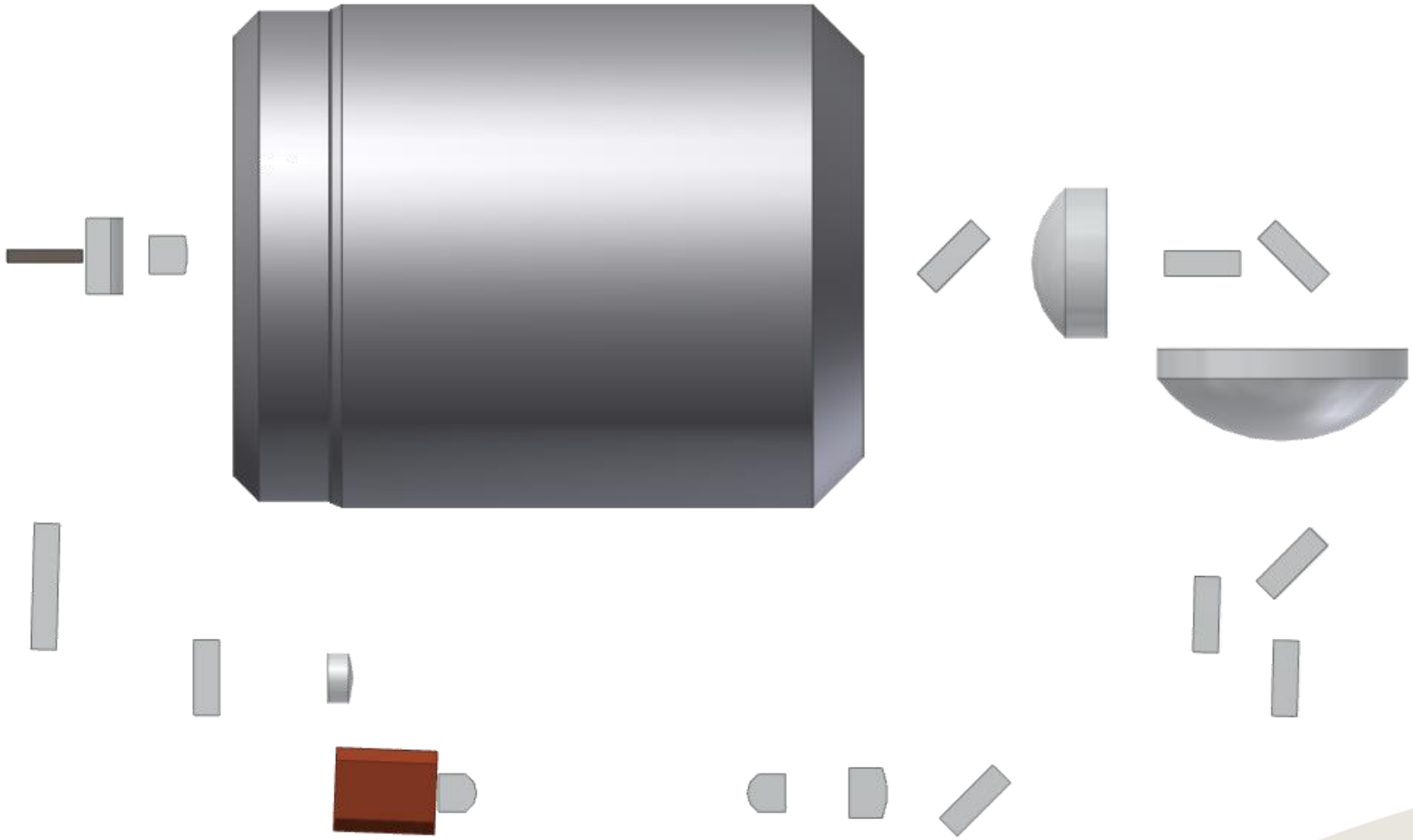
Optical simulation of the beam path



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Our approach -
Opto-mechanical design for miniaturized quantum sensor module

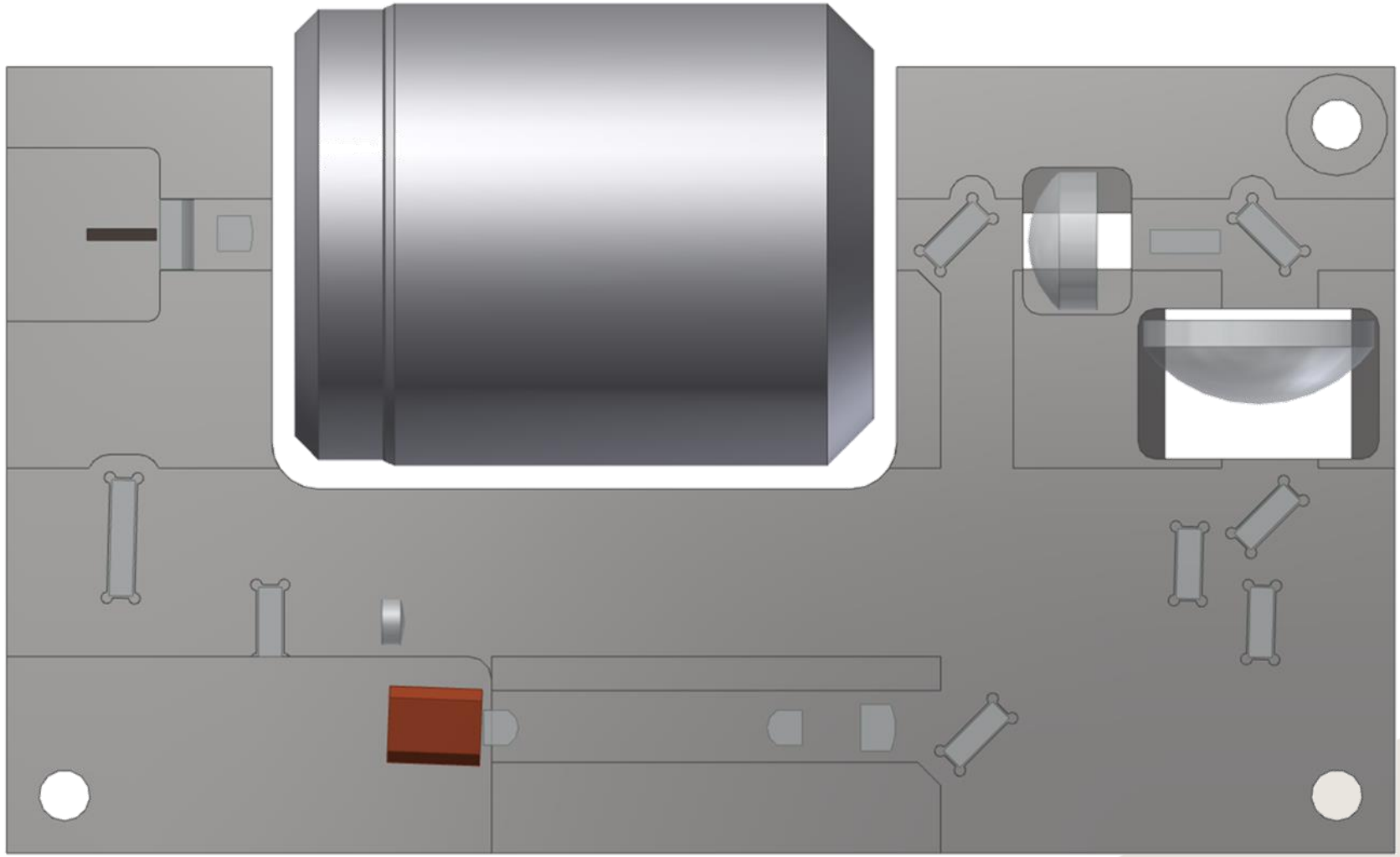
Simulation to drawing



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Our approach -
Opto-mechanical design for miniaturized quantum sensor module

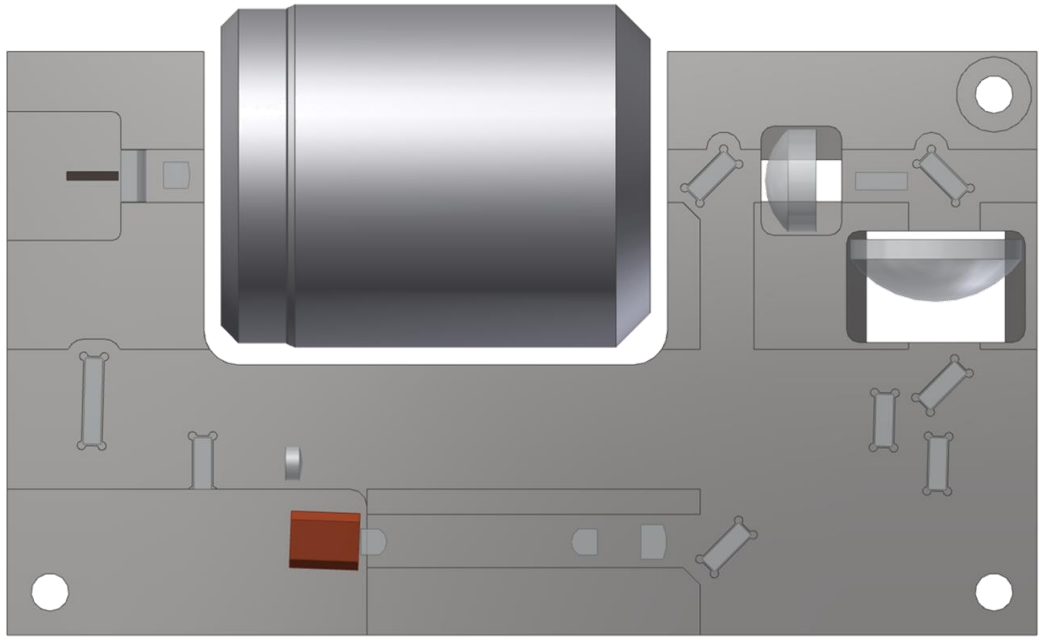
Drawing of mounting platform (inlay)



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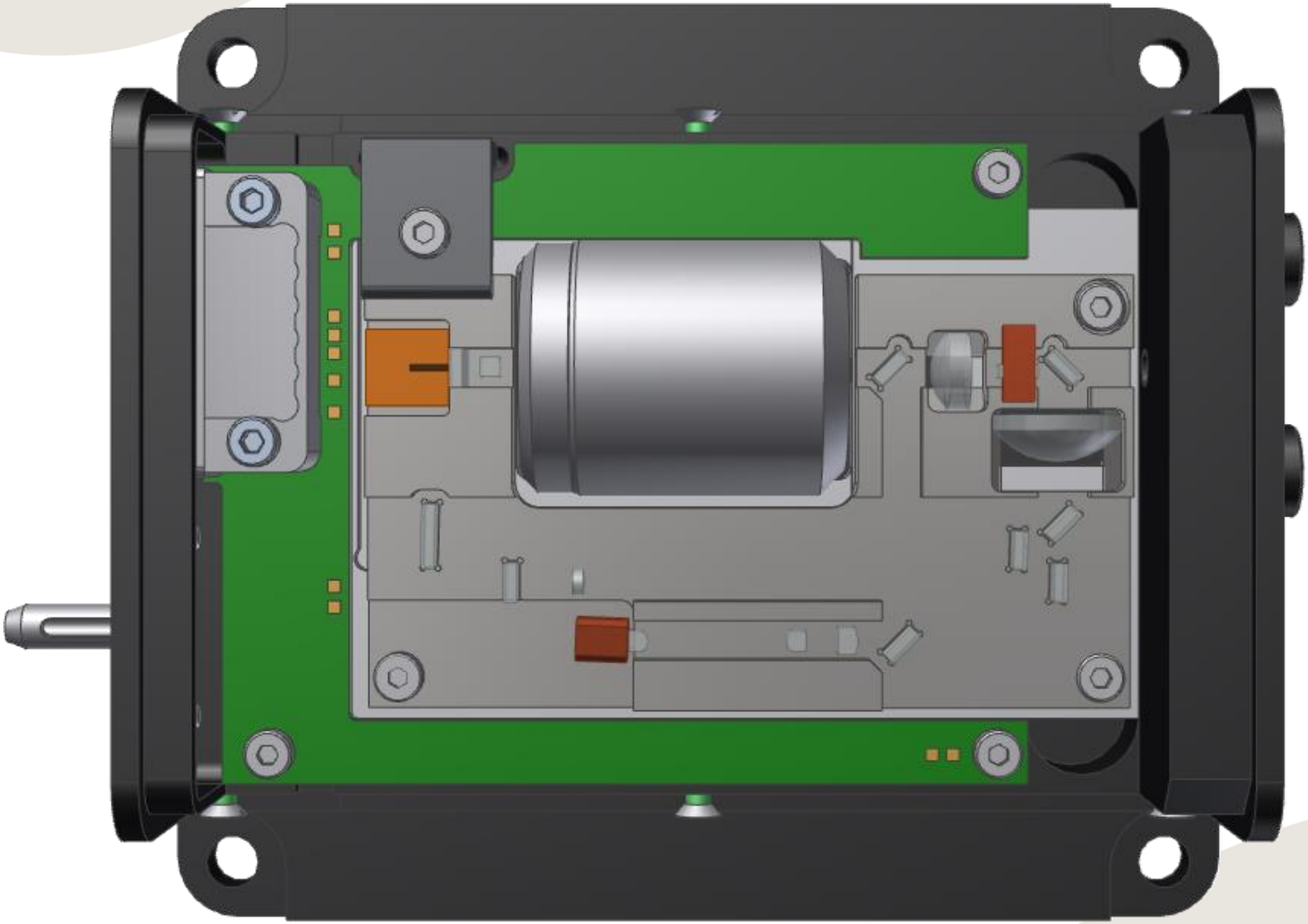
Our approach -
Opto-mechanical design for miniaturized quantum sensor module

Drawing of mounting platform (inlay)



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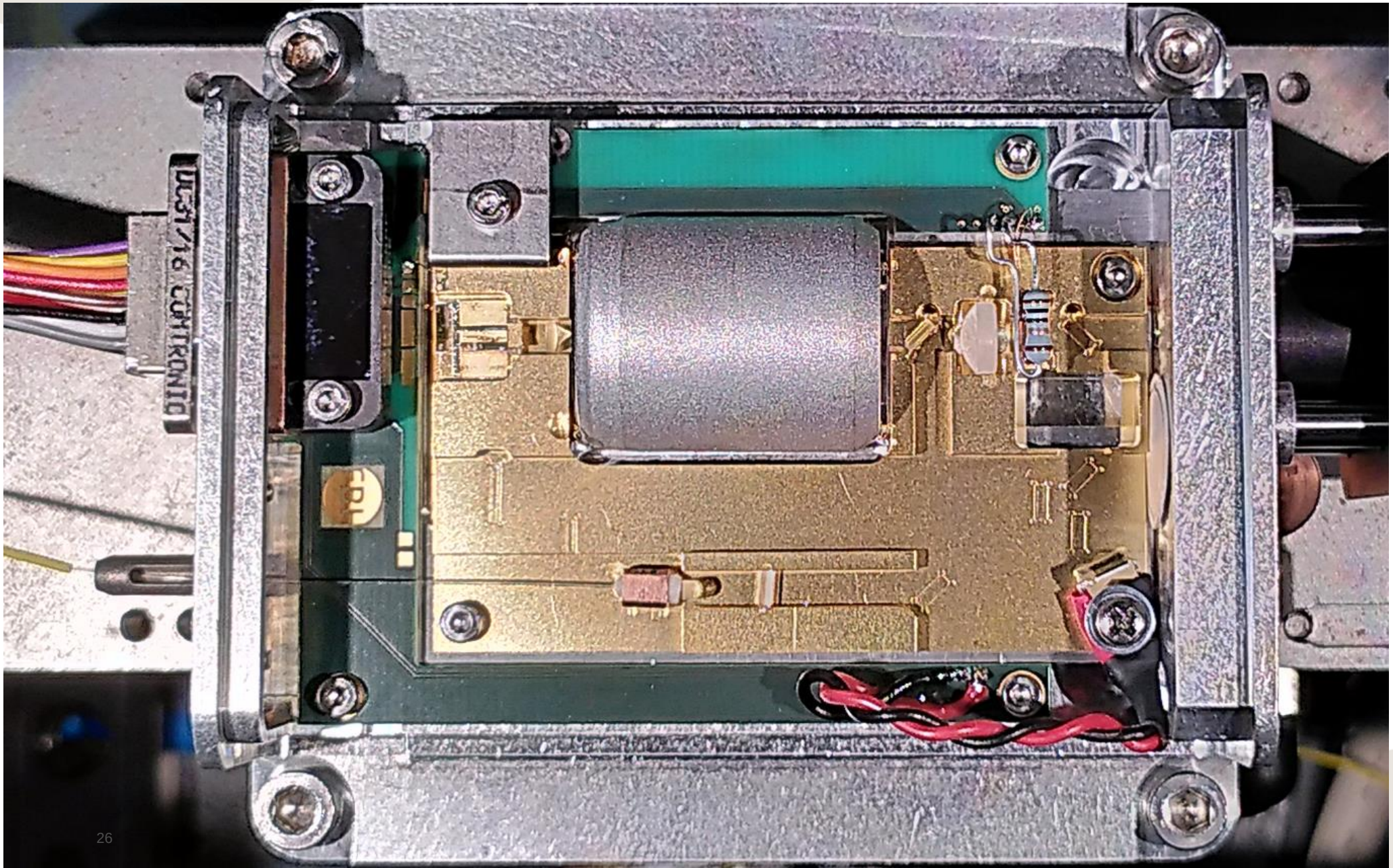
Our approach



Drawing of the connectors, circuit boards, base plate, which exactly fit the inlay

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Our approach

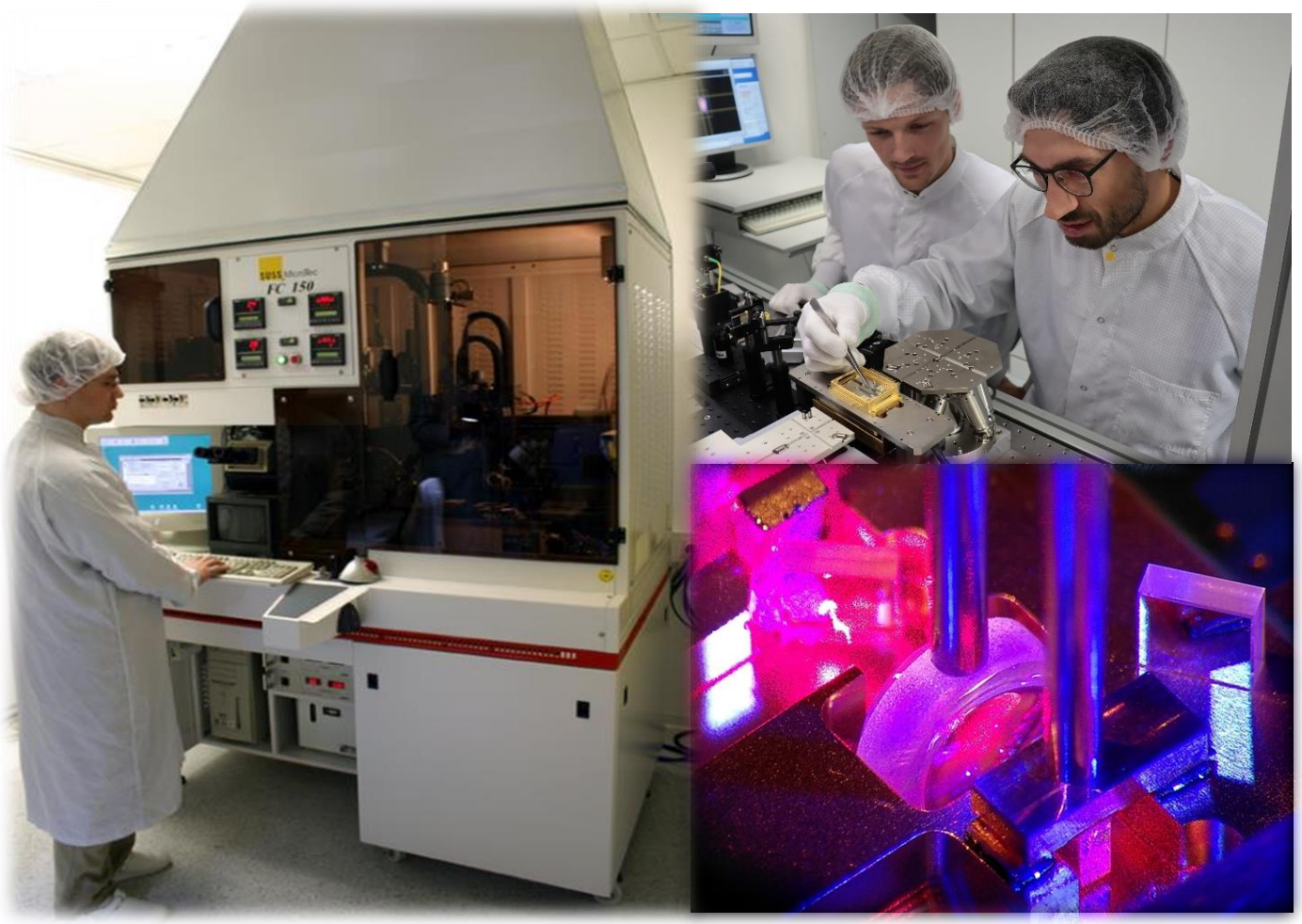


Inlay:

1:1 Translation of the simulation into a device

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Our approach -
Opto-mechanical design for miniaturized quantum sensor module



Simultaneous high precision active alignment of multiple components:

- Passive installation of DBR-TPL using FC-Bonder 150
- Active integration of micro-lenses, mirrors, beam splitters, SPDC-crystal, wave-plates, fiber ferrules, …) with high stability (mechanical, power, wavelength, reliability) using Micro manipulators
  - Resolution: 1 nm / 1 µrad,
  - Sensitivity: 10 nm / 10 µrad
  - Accuracy: 100 nm / 100 µrad

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Our approach -
Opto-mechanical design for miniaturized quantum sensor module

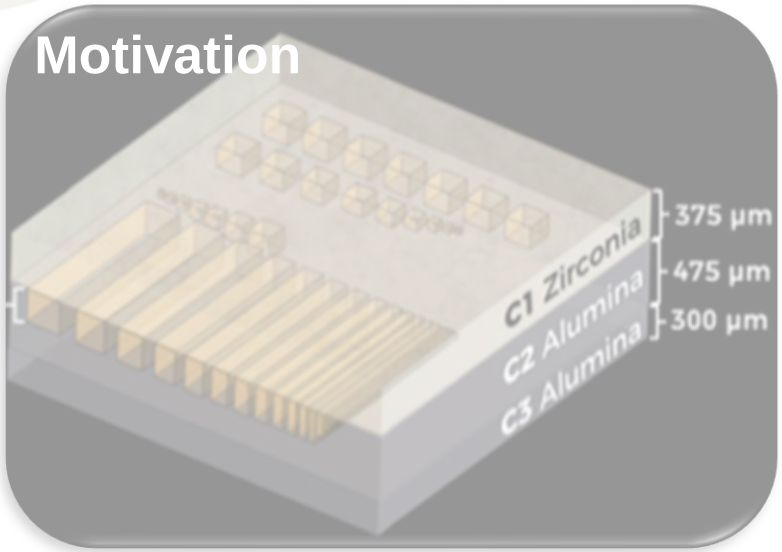
Drawing of the housing, which exactly fits the inlay

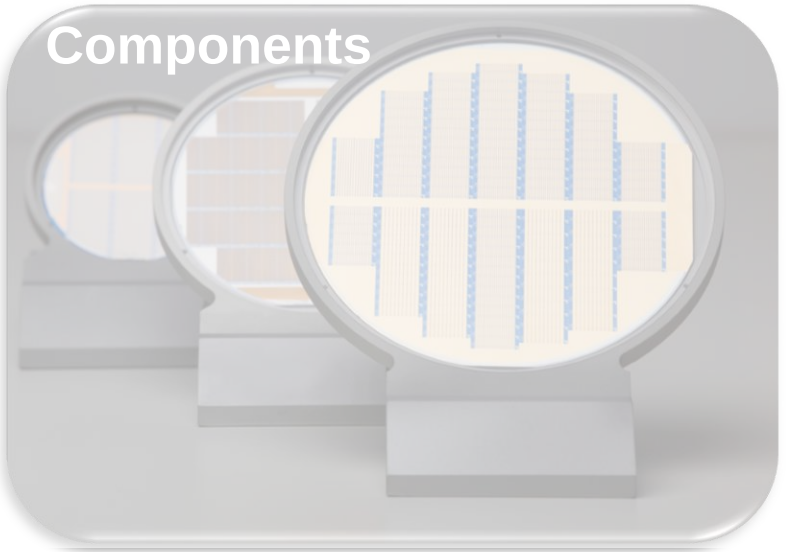


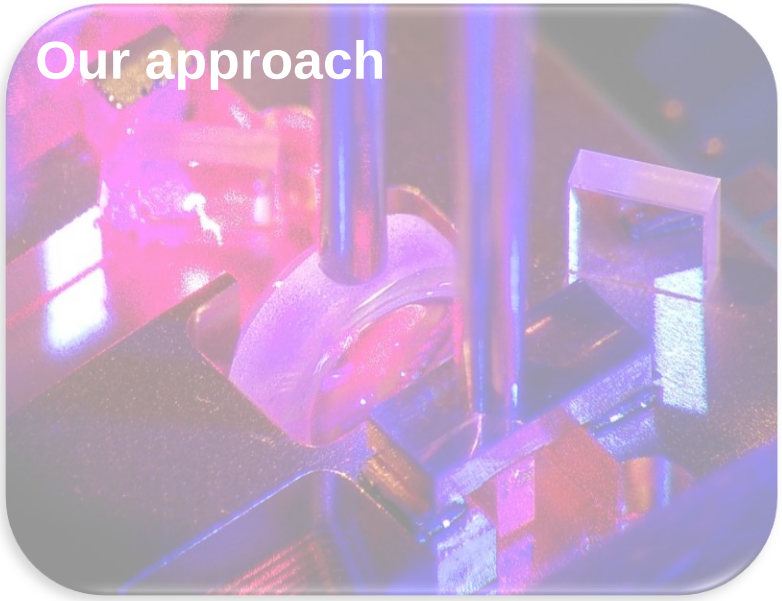


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Outline

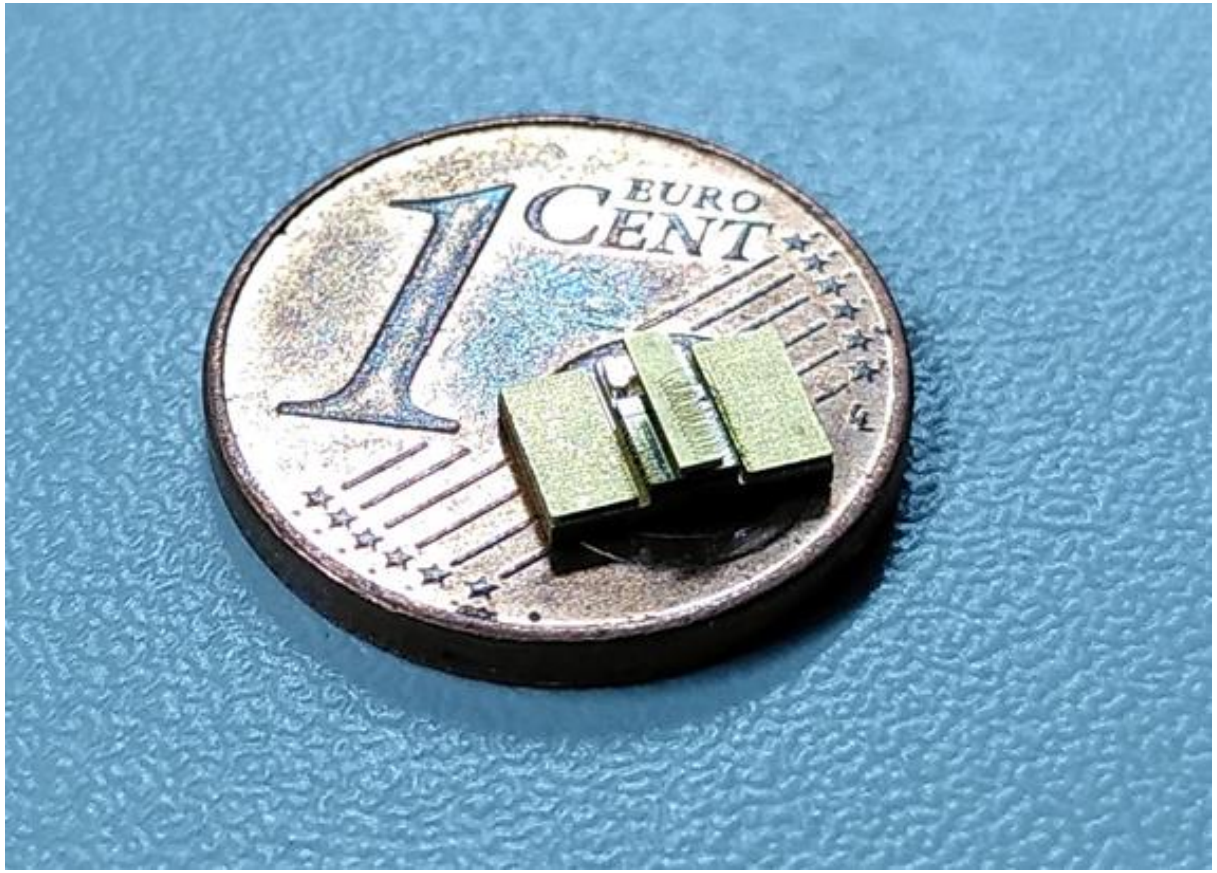

Motivation
375 µm
475 µm
300 µm
C1 Zirconia
C2 Alumina
C3 Alumina


Components


Our approach


Results & Outlook
QUIN

Results & Outlook
Micro-source entangled photons for mid-IR OCT



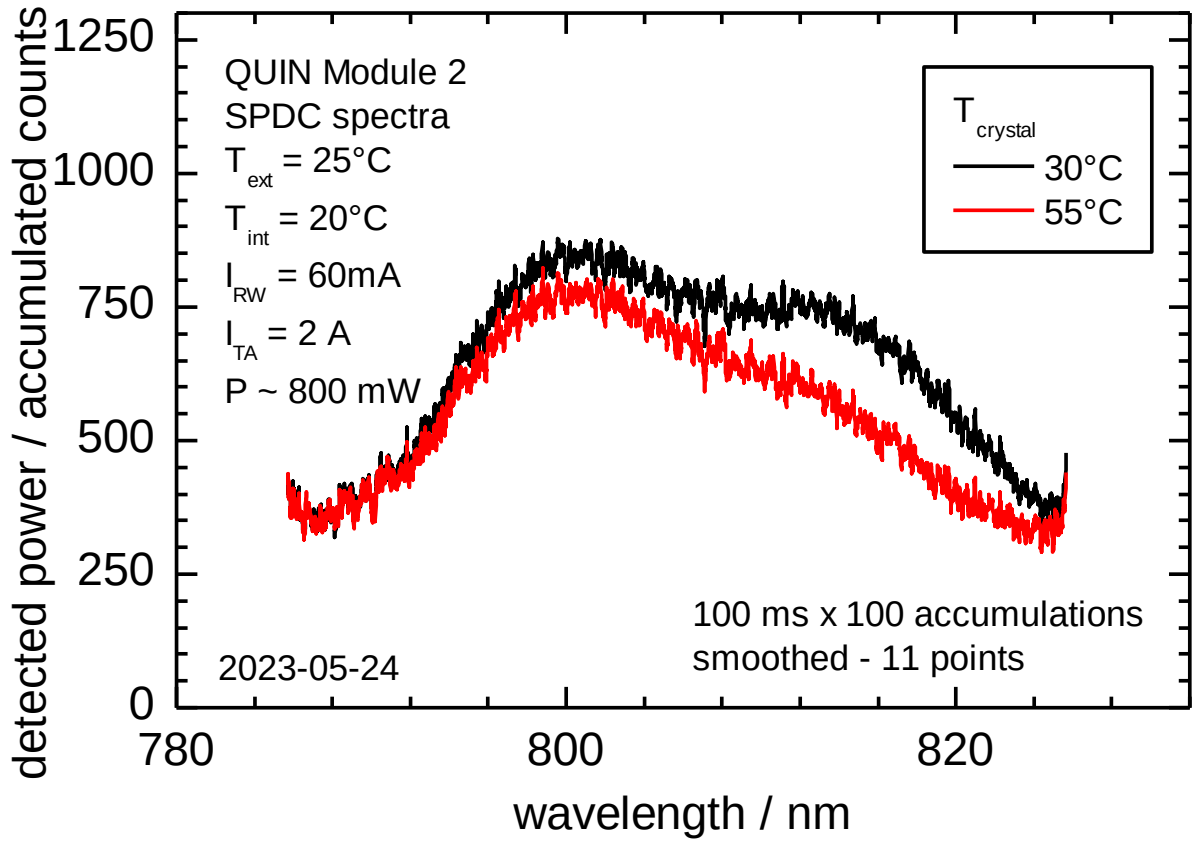
Aim → Results:

- Miniaturization and thus usable for industry ✓
- Replacing the laser source with a worldwide unique laser diode @ 660 nm ✓

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Results & Outlook
Micro-source entangled photons for mid-IR OCT

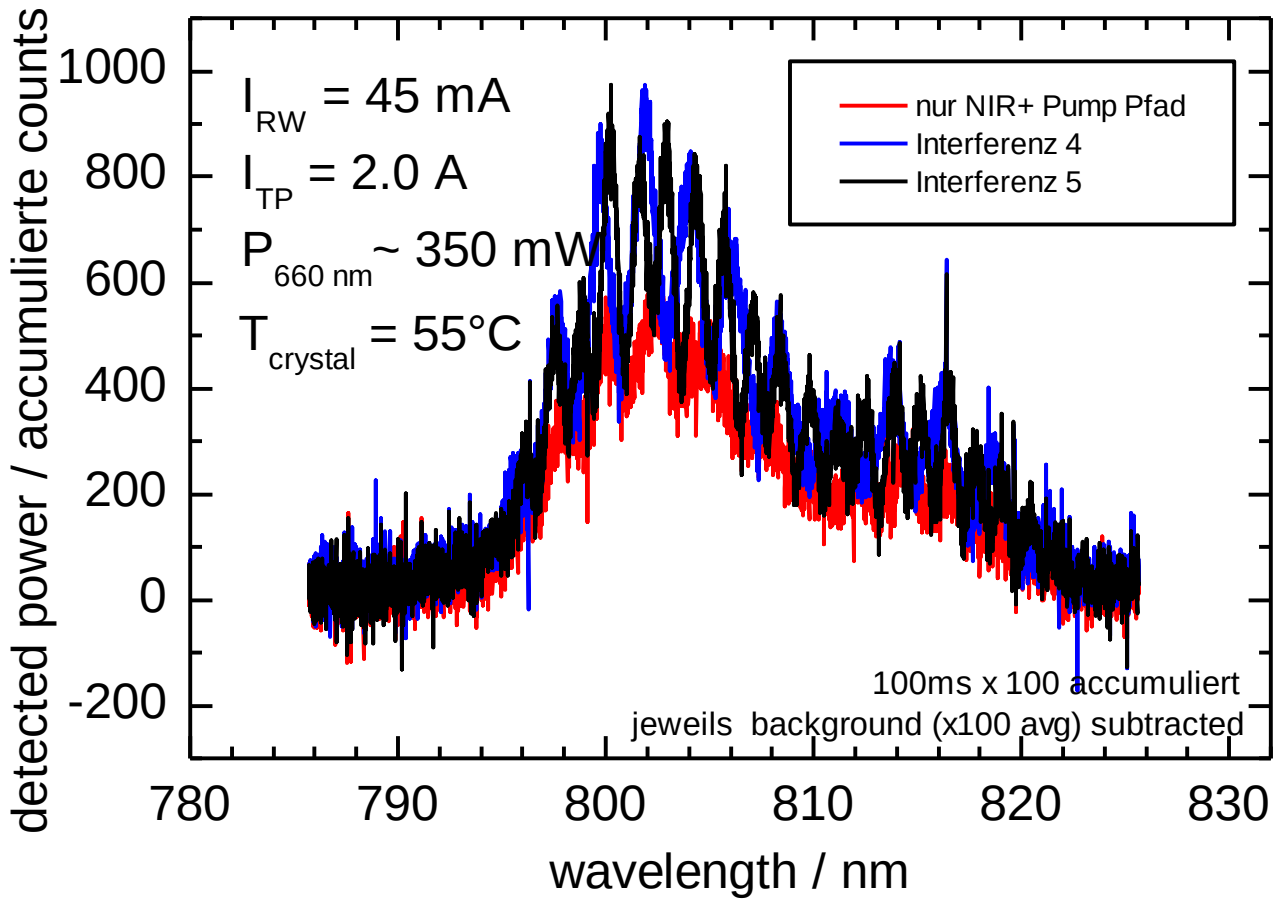
First SPDC experiments with 660 nm DBR-TPL pump light produced entangled detected NIR (~800 nm) and “undetected” mid-IR (~3.7 µm) photons



Aim → Results:

- Miniaturization and thus usable for industry ✓
- Replacing the laser source with a worldwide unique laser diode @ 660 nm ✓
- SPDC: entangled detected NIR & undected MIR photons ✓

Results & Outlook
Micro-source entangled photons for mid-IR OCT

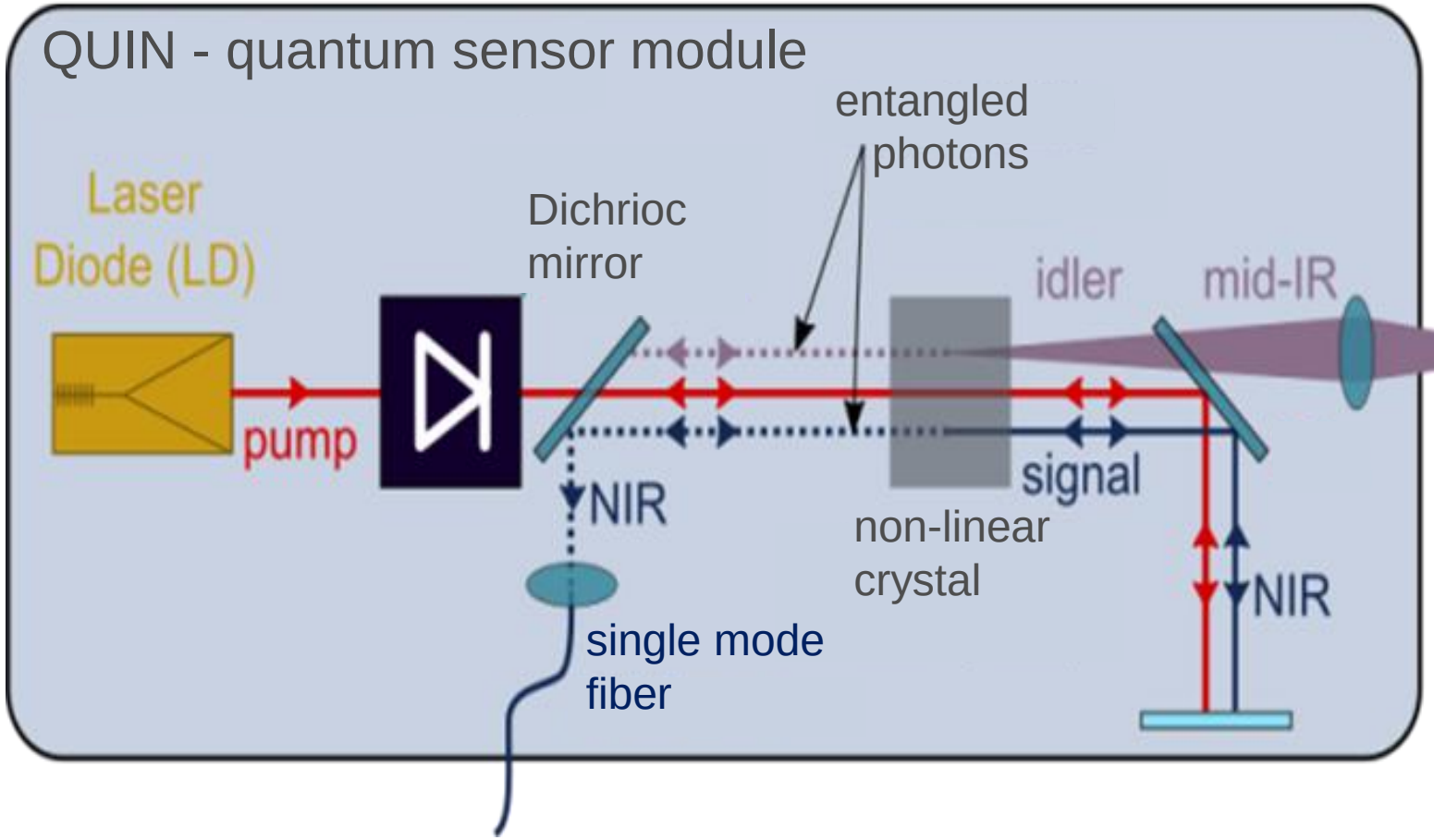


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- Miniaturization and thus usable for industry ✓
- Replacing the laser source with a worldwide unique laser diode @ 660 nm ✓
- SPDC: entangled detected NIR & undected MIR photons ✓
- Integration of quantum interference in the module ✓

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Results & Outlook
Micro-source entangled photons for mid-IR OCT



Aim → Results:

- Miniaturization and thus usable for industry ✓
- Replacing the laser source with a worldwide unique laser diode @ 660 nm ✓
- SPDC: entangled detected NIR & undected MIR photons ✓
- Integration of quantum interference in the module ✓

Outlook:

- Assembly into a complete system
- Exploring the limits or possibilities of the concept (penetration depths, resolution...)

Acknowledgment

The authors would like to thank

- The German Federal Ministry of Education and Research (BMBF) for financial support of the project QUIN (FKZ 13N15403)

GEFÖRDERT VOM

Bundesministerium für Bildung und Forschung

- All colleagues at the FBH, who were involved in
  - Technical support,
  - Sample preparation and
  - Measurements



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Thank you.

Katrin, Paschke
Ferdinand-Braun-Institut
Leibniz-Institut für Höchstfrequenztechnik
Linz, 2024