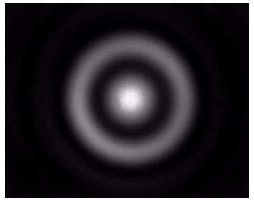
Sensing with undetected mid-infrared photons for prospective non-destructive testing



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Quantum Austria: 3. Vernetzungstreffen

05.03.2025

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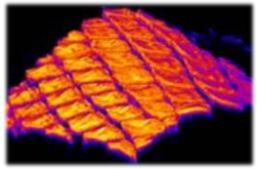
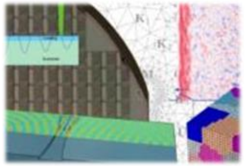
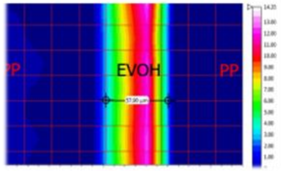
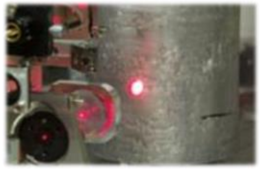




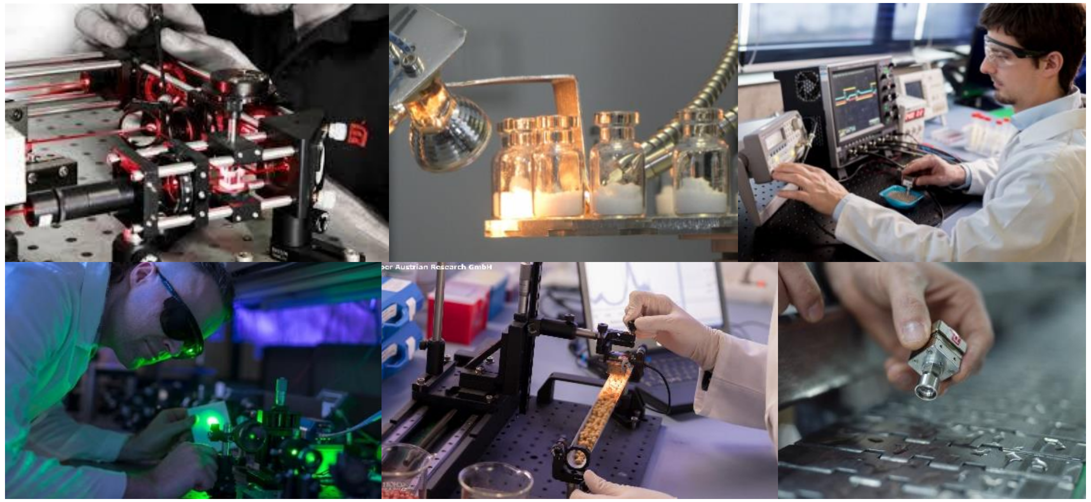




Research **Ce**nter for **N**on-**D**estructive **T**esting

Linz, Austria

Science Park @Johannes Kepler University



Founded in 2009 (UAR)
around 40 employees

www.recendt.at

Research Groups:

Optics

- Infrared & Raman Spectroscopy
- Optical Coherence Tomography
- **Quantum sensing - New**
- Terahertz Technology

Acoustics

- Laser Ultrasonics
- Photoacoustics
- Physical & Computational Acoustics

Challenges of direct mid-IR sensing

Conventional mid-IR sources exhibit trade-offs in one or more of the sensing-related parameters:

bandwidth, cost, footprint, brightness

Globar

- ✓ broadband
- ✓ cost-effective
- ✗ low brightness

Supercontinuum

- ✓ bright
- ✓ broadband
- ✗ spectral and intensity fluctuation
- ✗ large footprint and energy consumption
- ✗ expensive

Quantum cascade laser

- ✓ bright
- ✓ small footprint
- ✗ limited bandwidth
- ✗ fragile
- ✗ often require cooling

Synchrotron

- ✓ bright
- ✓ broadband
- ✗ large footprint
- ✗ expensive

Detectors in the mid-IR suffer from:

- high cost
- low pixel count
- low efficiency
- high noise *(can be helped with cooling)*

compared to silicon-based visible detectors (400-1000nm)

The potential to get mid-IR information using well-developed visible and near-IR technology is of great practical interest

Quantum optics provides a solution!

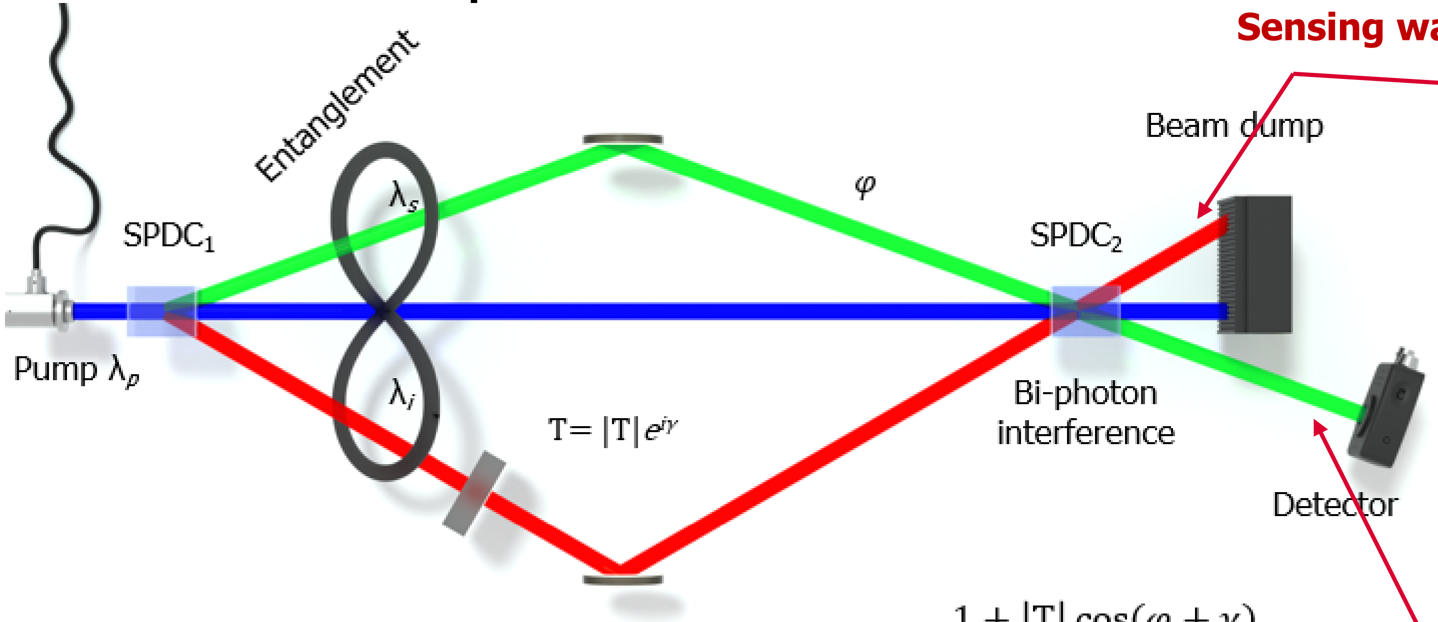
Sensing with undetected photons in a nutshell

Induced coherence without induced emission for sensing with mid-IR undetected photons:

- A common pump (λ_p) illuminates two nonlinear crystals,
- **Spontaneous parametric down-conversion** (SPDC) processes generate correlated (energy-entangled) photon pairs (λ_s and λ_i) in each crystal, so that $\omega_p = \omega_i + \omega_s$ where frequencies of generated photons can be broadly non-degenerate
- **Which-source information is erased** at the second crystal, the coherence between two SPDC sources is induced

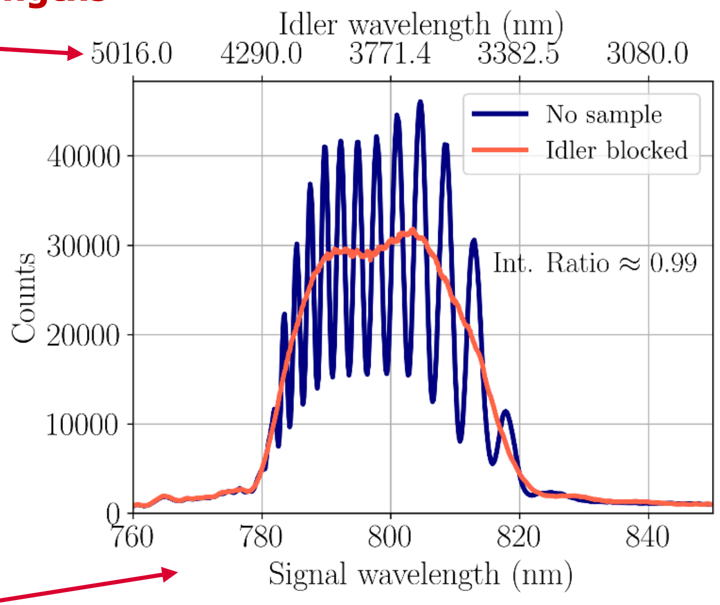
→ observable **interference** for the photons from the first and second SPDC sources due to the **indistinguishability of the photon paths**

→ interferometric sensing with undetected photons, **as the interference pattern ($\mathcal{R}s$) can be detected with photons that never interacted with the sample T**.



$$\mathcal{R}_s = \frac{1 + |T|\cos(\varphi + \gamma)}{2}$$

Sensing wavelengths



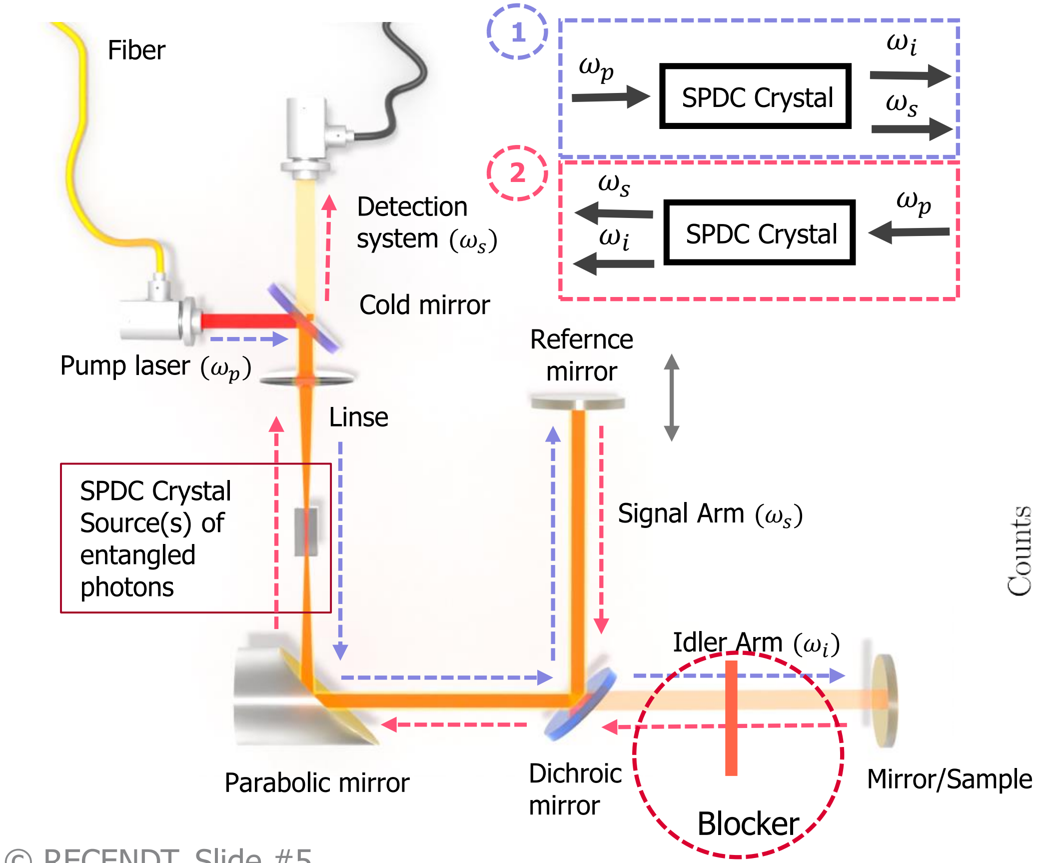
Detection wavelengths

Nonlinear interferometer in practice

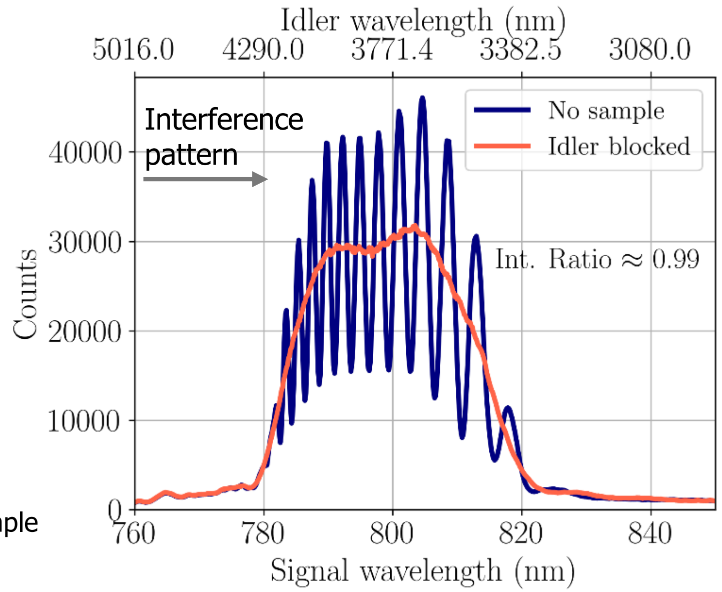
Low power acting on the sample is ~ 60 pW

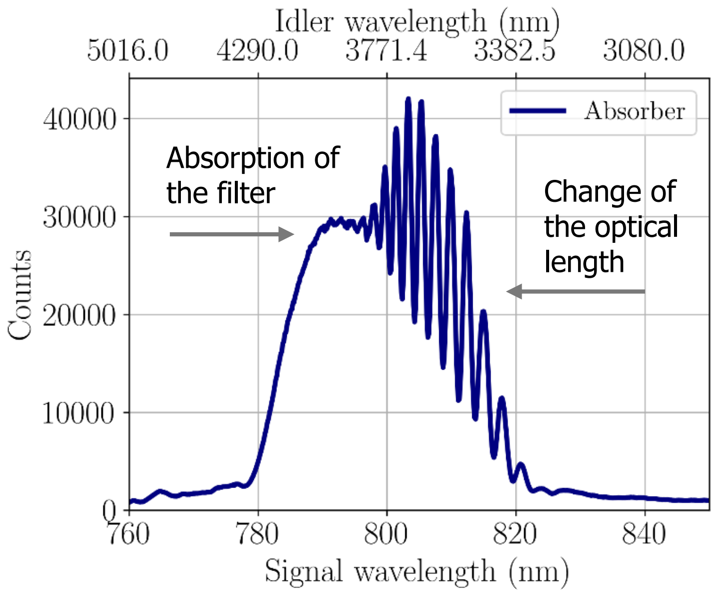
Nonlinear interferometer (Michelson configuration)

- Dichroic mirror instead of beam splitter
- Two sources are folded in one—double pass through the same crystal
- Only ω_s photons are measured



- Entangled photon pairs are created in the forward- and back-propagation
- **Interference** occurs when the interferometer is perfectly aligned (photon paths overlap)
- Principle of **Indistinguishability** → It is not possible to distinguish whether ω_s were generated in the forward- or back-propagation → causes interference between ω_s photons
- If one of the entangled photons $\boldsymbol{\omega_i}$ is absorbed/scattered (or acquires phase information) in the back propagation, then ω_s are distinguishable in the detector arm → **Loss (change)** of **Interference**





Quantum Fourier Transform Infrared Spectroscopy

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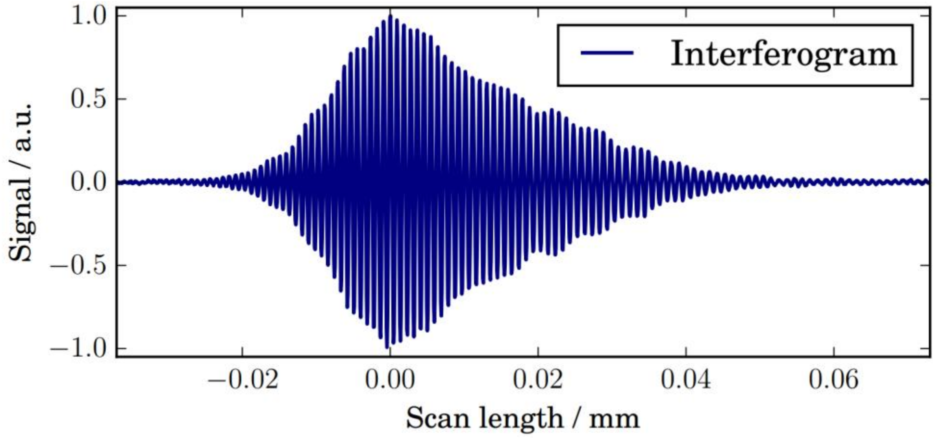
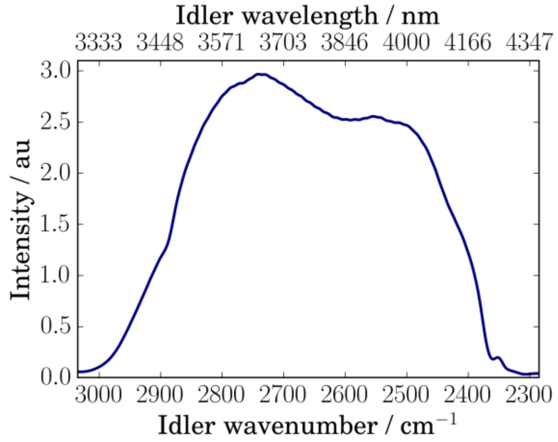
Q-FTIR: akin to standard FTIR but built on principles of quantum optics and sensing with undetected photons

Towards Chemical Analysis

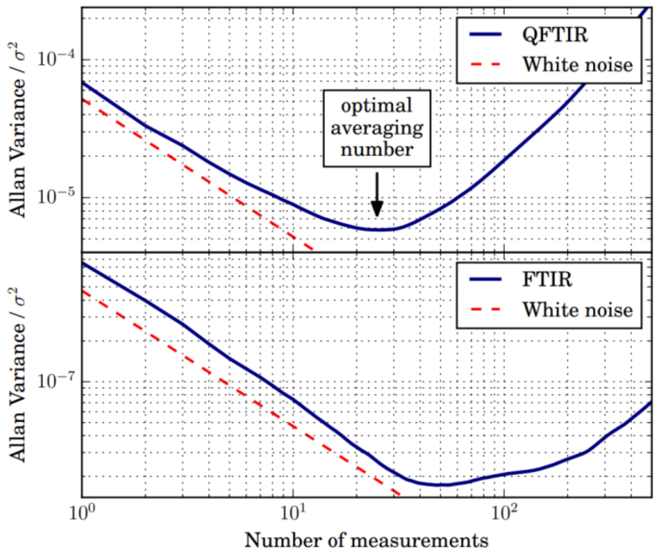


Fourier transform



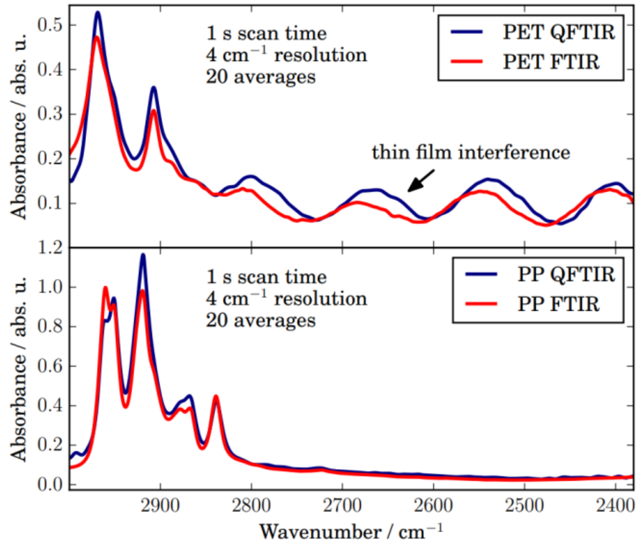
Emission spectrum of the SPDC: undetected mid-IR part used for spectroscopic studies (vibrational spectroscopy)

Work towards QFTIR microscopy is ongoing



Comparable long-term stability

Orders of magnitude higher SNR per milliwatt of optical power



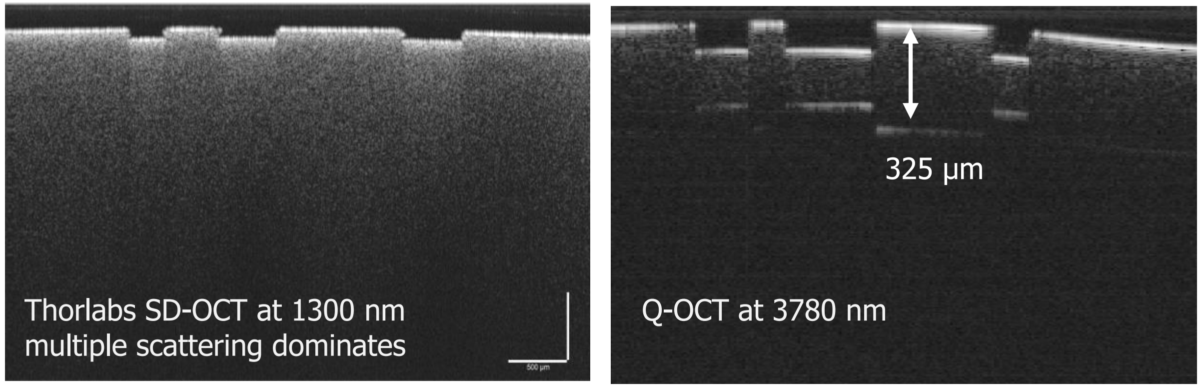
Molecular spectra of Polymers (CH vibrations)

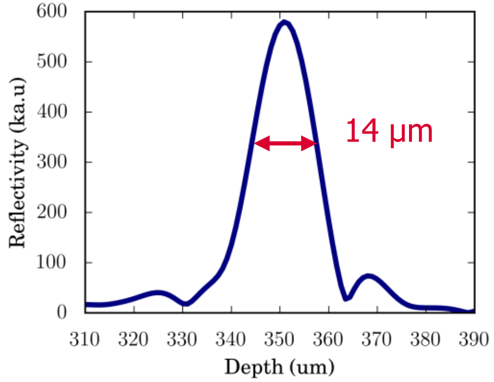
Obtained with a classical instrument (FTIR) and quantum FTIR (QFTIR) with **no mid-IR sources and detectors**

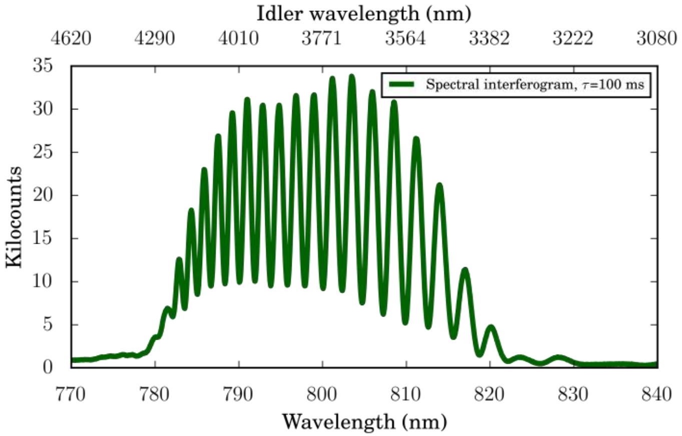
Quantum Optical Coherence Tomorgraphy (QOCT)

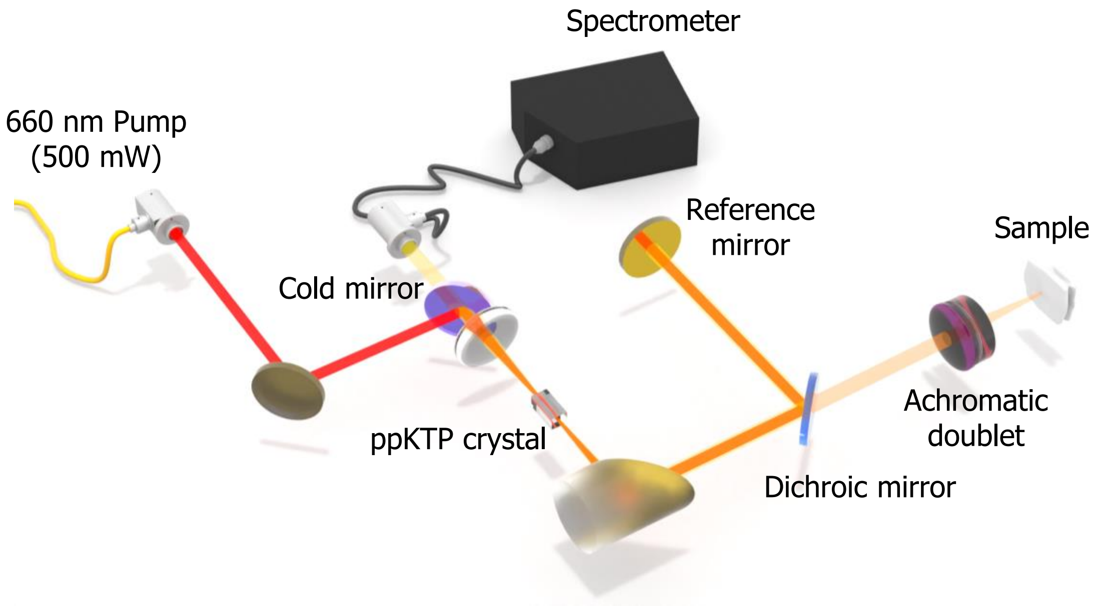
- **Q-OCT**: implemented in spectral domain configuration (grating spectrometer, fixed arms lengths)
- Implemented in the mid-IR spectral range, can compete with classical systems due to shortcomings of mid-IR components
- Interesting for high scattering applications or use cases requiring low incident powers such as **biomedical imaging, additive manufacturing (polymerization sensitive) and cultural heritage**

LCM ceramics **4.59%** porosity, 1450° sintering temperature









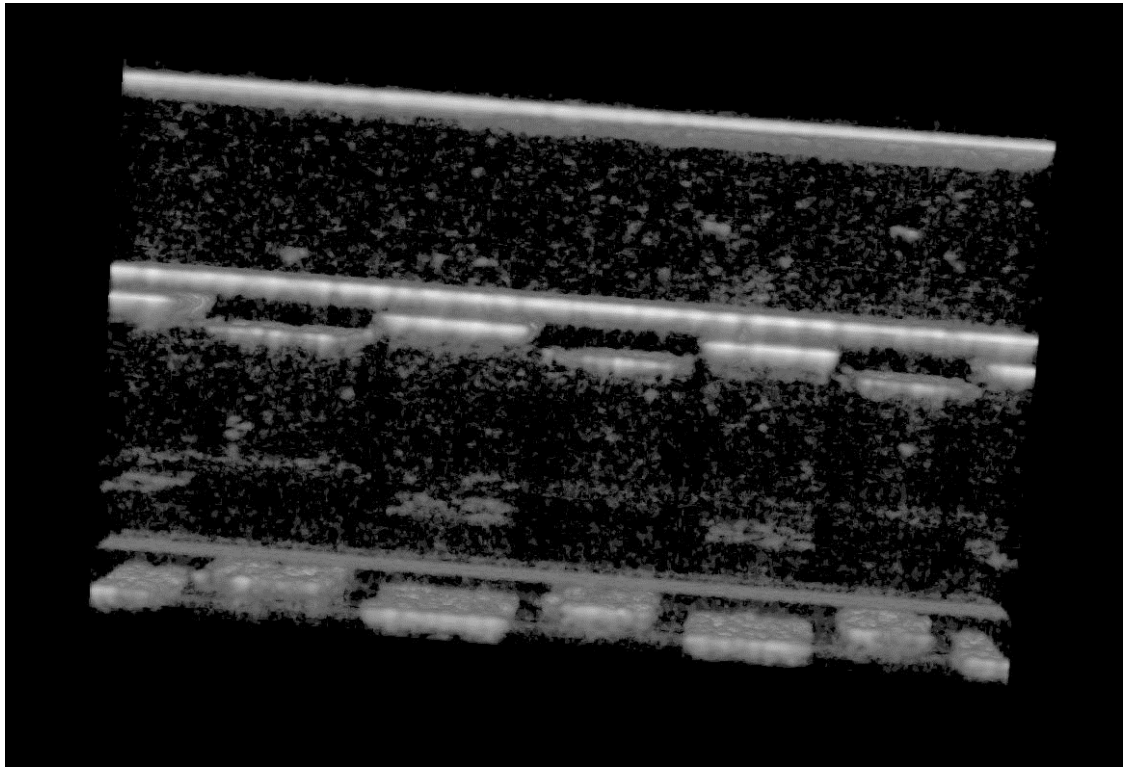
Specifications:

1. >58 dB SNR (i_s^2/i_n^2)
2. 14 µm axial PSF
3. ~40 µm lateral PSF

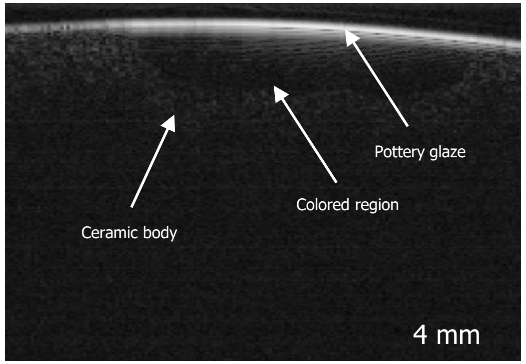
60 pW mid-IR sensing power $(\sim 1000 \cdot 10^6 \text{ ph/s})$

Quantum Optical Coherence Tomorgraphy (QOCT)

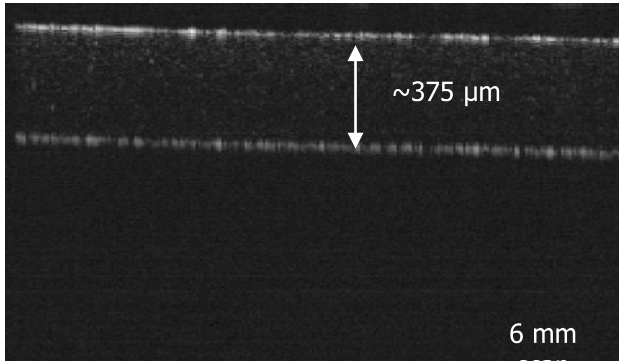
High porosity industrial ceramics – QOCT Volumetric scan



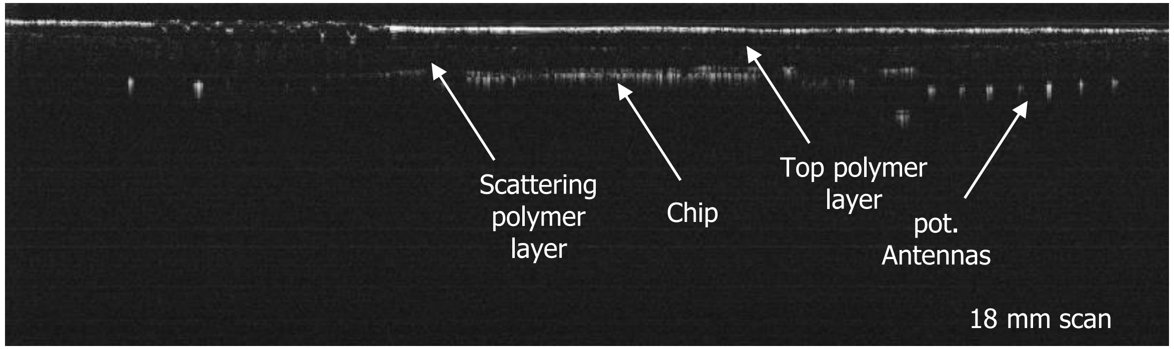
Gmundner Keramik Porcelain



Sintered industrial alumina (tilted)
~2% porosity



Bank card chip region



- High probing depth and mid-IR OCT performance at lower costs: the price of the whole system is **half of the price of a mid-IR OCT capable classical source (industrial applications)**
- Ultra-low probing power levels, **9 orders of magnitude** lower than classical systems (niche applications, such as art inspection)

Thank you for listening!

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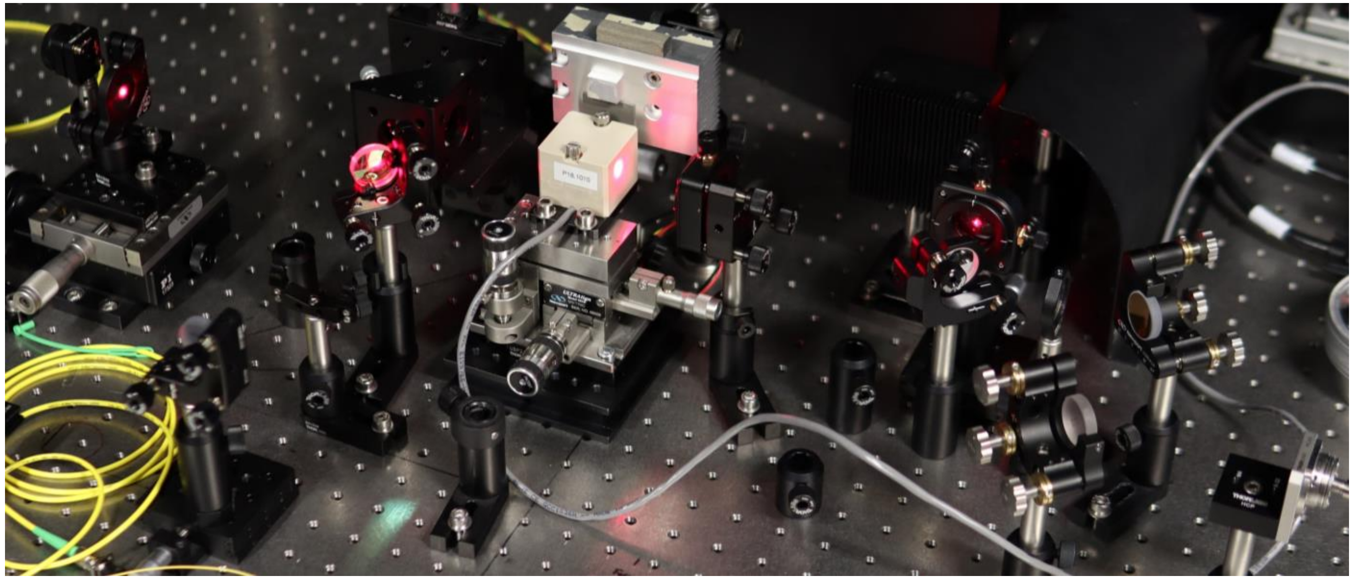

- The quantum system is currently being advanced towards chemical imaging modality
- OCT and QFTIR miniaturization is feasible and on the list
- Ideas for multiple increase in the number of generated photons in development enhancing signal-to-noise ratio to surpass classical methods
- New application cases under investigation

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