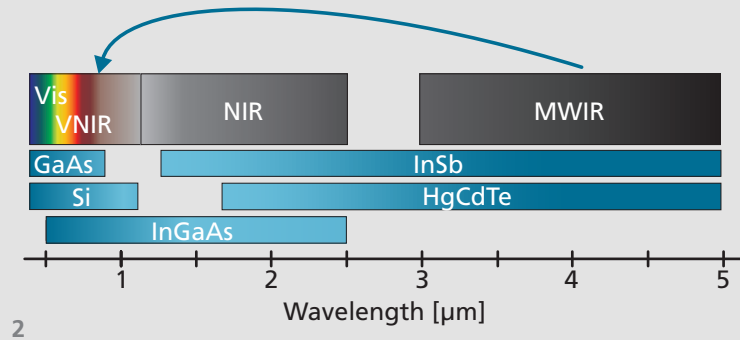




1

- 1 Mid-infrared spectroscopy – convenient as a fiber coupled visible spectrometer with the help of non-linear-optical upconversion.
- 2 Nonlinear optical upconversion helps to overcome limitations of available mid-infrared (MWIR) detectors by transferring incoming signals into the visible or very-near-infrared (VNIR) range.



2

MID-INFRARED SPECTROMETER WITH KHZ ACQUISITION RATES VIA NONLINEAR OPTICAL UPCONVERSION

Infrared spectroscopy is a universal tool for substance detection, materials characterization and quality control. The strongest and most selective spectral features are to be found in the mid-infrared region (MWIR) with wavelengths between 3 and 12 μm . To date mid-infrared analysis is mostly used in a laboratory environment with Fourier transform infrared spectrometry (FTIR) as the standard method, complemented by tunable interband- or quantum-cascade laser spectrometers. FTIR offers a wide spectral coverage and high signal-to-noise ratios. However, FTIR mostly relies on mechanical scanning and is thus limited in its acquisition speed. Laser-based spectrometers excel in spectral resolution, e.g. for gas sensing, but are often specific to a single line and work with scanning acquisition as well. For highly dynamic processes, such as reaction monitoring and rapid inline inspection and sorting, significantly faster and more robust spectroscopic methods are required. Grating

spectrometers with array detectors, widespread in near-infrared applications, enable the robust acquisition of complete spectra in a single shot. In the mid-infrared regime, however, limitations are imposed by noise properties and cooling requirements of available detector materials. Therefore, grating spectrometers are rather uncommon in this range.

Nonlinear optical upconversion into the very-near-infrared range

Nonlinear optical upconversion into the very-near-infrared (VNIR) range via sum frequency generation enables low-noise and fast detection of mid-infrared radiation. This allows one to harness the superior properties of readily available silicon array detectors. Fraunhofer IPM has developed a solution, combining a wavelength conversion unit for the mid-infrared with a custom-

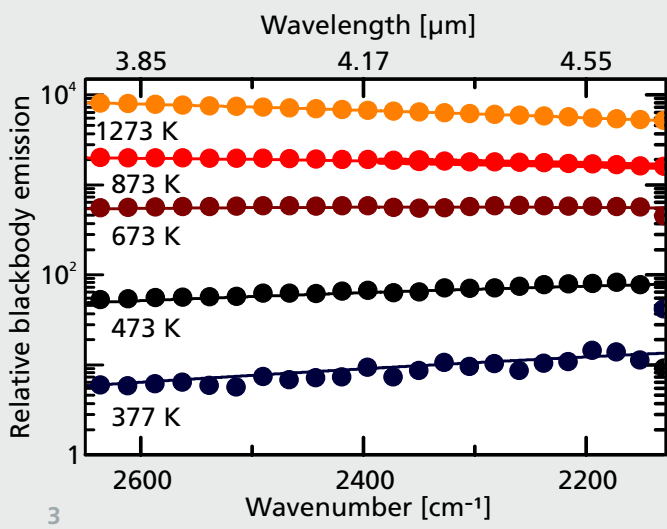
Fraunhofer Institute for Physical Measurement Techniques IPM

Heidenhofstrasse 8
D-79110 Freiburg, Germany

Contact

Dr Frank Kühnemann
Spectroscopy and Process Analytics
Phone +49 761 8857-457
frank.kuehnemann@ipm.fraunhofer.de

www.ipm.fraunhofer.de/en



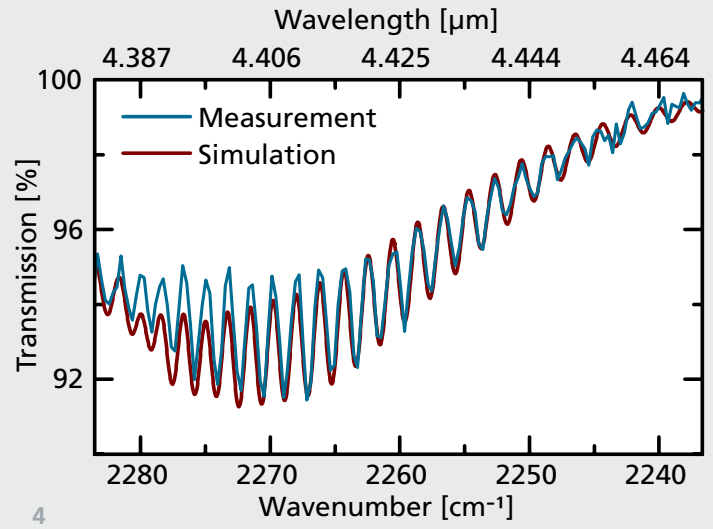
3 High dynamic range: Blackbody radiation at different temperatures measured with the upconversion spectrometer (dots) in comparison with the corresponding theoretical values (solid lines), displaying over five orders of magnitude.

4 High spectral resolution: Transmission spectrum of CO₂ diluted in air. Upconversion spectrometer measurement (cyan) and simulation (red, modelled with a 1.1 cm⁻¹ instrument function) showing resolved ro-vibrational lines.

built spectrometer unit based on a silicon camera in line mode. The system combines wide spectral coverage in the mid-infrared range with high sensitivity, high frame rates and the practicability of a fiber coupled grating spectrometer.

Physical principle: Sum frequency generation

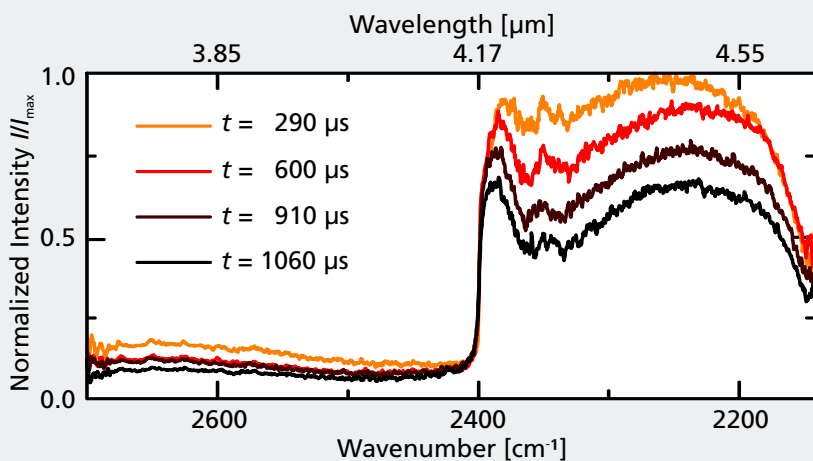
For the purpose of upconversion, infrared signals are mixed with the beam of a strong pump laser in a nonlinear optical crystal. From the nonlinear response of the crystal to the incoming light field, a third wave emerges with its frequency being the sum of the incident light frequencies. A MWIR signal between 3 and 5 μm wavelength, mixed with a Nd:YVO pump laser of 1064 nm wavelength is transferred to wavelengths between 780 and 880 nm – ideal for detection with silicon CMOS sensors. MIR input signals can be converted to the shorter wavelength range whilst fully preserving their spectral information. High conversion efficiencies are achieved by resonantly enhancing the pump laser wave in a high-finesse cavity.



Design flexibility: Meeting application requirements

Due to its modularity, system properties can be adapted to different application requirements: Modifying the converter layout allows one to increase the sensitivity at the expense of the spectral bandwidth or vice versa. In principle, the spectral windows can also be shifted as a whole. Frame rate and spectral resolution can be adapted by individually combining grating, optics and image sensors. Furthermore, light collection can be customized to the individual needs of measurement scenarios and process environments.

The nonlinear optical upconversion module presented here can act as a translating link in any combination of mid-infrared methods and very-near-infrared instrumentation.



High-speed spectroscopy: Hot gas emission spectra during solid fuel combustion captured with a time resolution of 150 μs. Upconversion spectroscopy allows acquisition of spectra well beyond kilohertz rate.

OUR SPECIFICATIONS

- **Spectral coverage**
2100 ~ 2700 cm⁻¹ (3.7 ~ 4.7 μm)
- **Spectral resolution**
1.1 cm⁻¹ (1.5 ~ 2.4 nm)
- **Maximum acquisition rate**
6500 spectra / s
- **Noise equivalent power (NEP)**
below 1 pW / Hz^{1/2}

OUR PORTFOLIO

- Service measurements and application studies
- System design for spectrometers according to customer requirements
- Development and manufacturing of complete measurement systems