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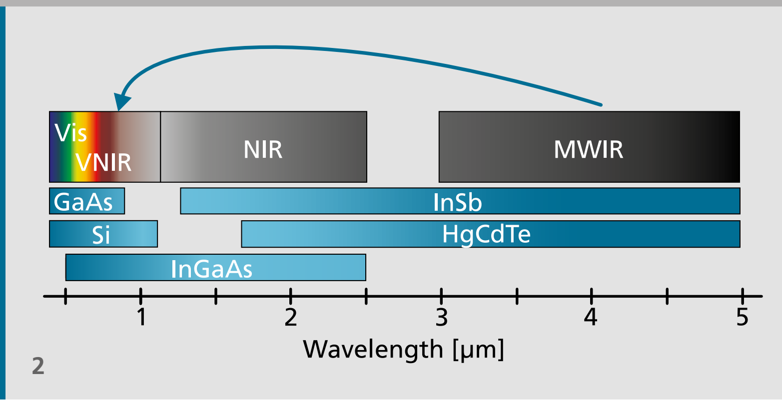


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1 *Mid-infrared spectroscopy – convenient as a fiber coupled visible spectrometer with the help of non-linear-optical upconversion.*

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.*


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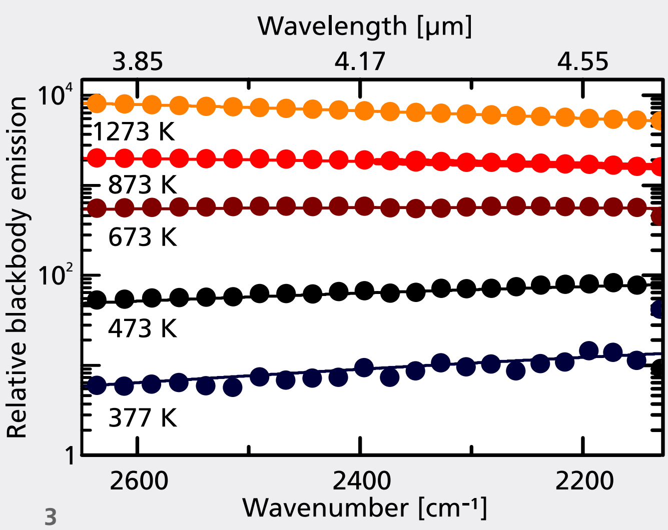
# MID-INFRARED SPECTROMETER

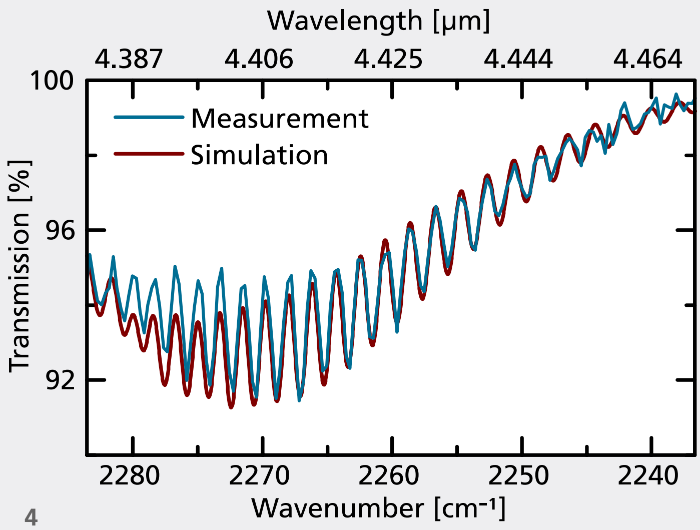
## WITH KHZ ACQUISITION RATES VIA NONLINEAR OPTICAL UPCONVERSION

Infrared spectroscopy is a universal tool for substance detection, materials characterization and quality control. The strongest and most selective spectral features are located 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-built spectrometer unit based on a silicon array detector. The system combines wide




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 $CO_2$ diluted in air. Upconversion spectrometer measurement (cyan) and simulation (red, modelled with a 1.1 $cm^{-1}$ instrument function) showing singly-resolved rotational lines.*

spectral coverage in the mid-infrared range with high sensitivity, high frame rates and the practicability of a fiber coupled grating spectrometer – a powerful tool, e.g. for high-speed emission MIR spectroscopy of combustion processes.

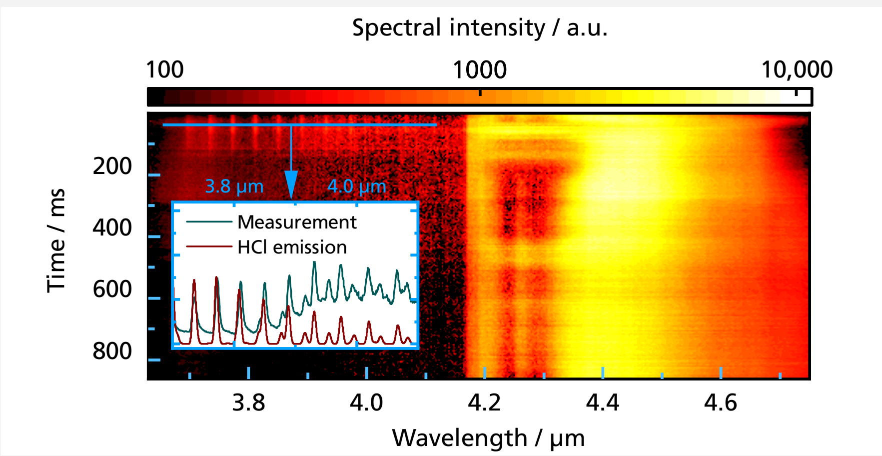
**Physical principle: Sum frequency generation**

Upconversion from the mid-infrared is realized by three-wave-mixing in a nonlinear-optical crystal. The interaction of two light waves generates a third wave with a frequency equal to the sum of the incident waves' frequencies. MWIR signals between 3 and 5 µm wavelength are mixed with a pump laser of 1064 nm wavelength and transferred to wavelengths between 780 and 880 nm by upconversion, perfectly suited for detection with silicon CMOS sensors 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.




5 ***High-speed emission spectroscopy****: Time series of hot gas emission spectra during solid fuel combustion captured with a temporal resolution of 150 µs. In this demonstration, the emergence of hydrochloric acid (HCl) as a combustion product is localized to the first 100 ms after ignition. The time slice in the inset shows the characteristic HCl fingerprint in the 3.7–4.1 µm region.*

**Demonstrator 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 / $Hz^{1/2}$*

**Service**

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