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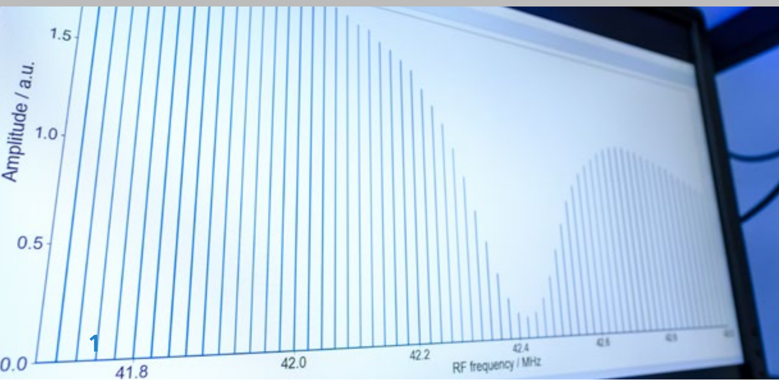

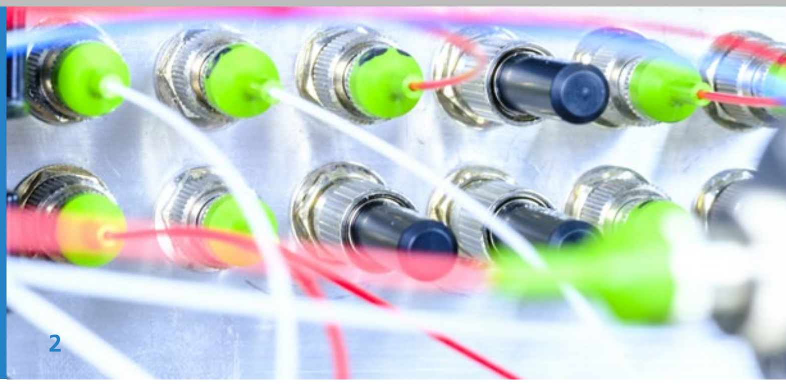

1 Zoom-in on a dual-comb spectrum resolving individual comb teeth.
2 Optical module of the Dual-Frequency Comb Spectrometer by Fraunhofer IPM.
3 Line strengths of common gas species in exhaust or air in the mid-infrared spectral range (simulated with HITRAN API). Insets: measured transmission spectra of CO_2 and CO, N_2O and CH_4.
4 Measured transmission spectrum of N_2O and CO_2 in air.

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DUAL-COMB SPECTROSCOPY

BRIDGING THE GAP BETWEEN FTIR AND QCL/ICL

Molecular spectroscopy in the mid-infrared spectral range (MIR) provides sensitive methods for gas sensing, material characterization and gas analysis with applications in security, process control, automotive engineering and life sciences. Today's systems use Quantum/Interband-Cascade-Lasers (QCL/ICL) for highly sensitive spectroscopy, whereas Fourier-Transform-IR (FTIR) spectrometers excel in spectral bandwidth.

Fraunhofer IPM has developed a spectrometer based on frequency combs that fills the gap between classical FTIR and QCL/ICL-based spectrometers and combines the advantages of both domains.

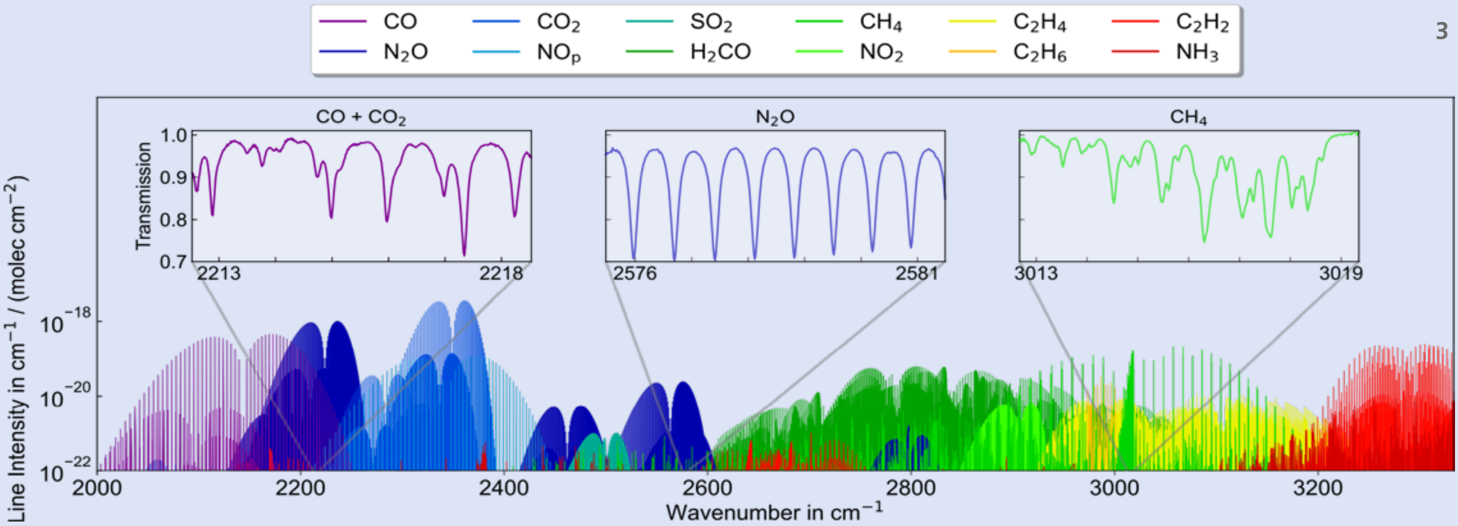
Principle of dual-comb spectroscopy

Frequency combs are lasers, which emit a large number of coherent and equally spaced modes. For spectroscopic applications, collecting the information from all comb teeth simultaneously is of primary interest. By superimposing two synchronized combs with slightly different »tooth spacing« the full optical information sampled by the combs is encoded into a radio frequency signal – easily measured with a single photodetector.

Combs with large mode spacing (tens to hundreds of GHz) are used for the analysis of solids and liquids, while combs with narrow spaced lines (hundreds of MHz) are utilized for high resolution molecular spectroscopy and gas analysis. As the resolution is given by the mode spacing it is possible to overcome the limits of traditional spectrometers.

A versatile demonstrator for mid-infrared gas spectroscopy and analysis

The spectrometer is composed of two modules: Dual-comb generator and MIR-converter. For comb generation, a single



continuous-wave laser at 1.55 µm is split into two beams and the combs are initialized via electro-optic modulation at slightly different frequencies. The resulting intrinsic coherence of the two combs and the use of standard fiber-optic components reduce the system's complexity, which facilitates ease of operation and lowers costs. More importantly, the coherent detection improves the signal-to-noise ratio and hence sensitivity.

To access spectral regions of interest, the near-infrared comb is transferred to the MIR via difference-frequency mixing using an in-house developed single-frequency optical parametric oscillator (OPO). Tuning the OPO between 1.0 and 1.3 µm, the output covers the wavelength range between 3 and 5 µm without modification of the setup.

Next to the optical setup the system comprises a specialized operation software for system control, data acquisition and data processing, allowing for continuous measurements, efficient data compression and real-time analysis. Adding spectral analysis software is simple and allows for turn-key systems that can be operated by non-specialists.

Flexibility for many applications

The Fraunhofer IPM spectrometer system excels through its versatility. The measurement window can be freely set in the full MIR range between 3 and 5 µm. Virtually any infrared-active gas species can be addressed in that region.

Full control over the measurement parameters allows for in-depth adaptation to the requirements of vastly different measurement tasks: rapidly acquiring spectra with up to 20 kHz, stretching the instantaneous window bandwidth over 20 cm^{-1} or narrowing the spectral resolution down to 250 MHz (< 0.01 cm^{-1}) for sensitive low-pressure spectroscopy. The system also offers the possibility of averaging time spans of hundreds of seconds for high-precision spectroscopy, which enables detecting even the faintest absorption in a sample.

This way, the system can serve a wide field of applications from rapid combustion analysis and fine-tuned process control over gas mixture certification to exhaust gas analysis (N_2O and CO_2, see fig. 4) or the determination of the stable carbon isotopes ratio (^{12}C and ^{13}C) in the greenhouse gases CO_2 and CH_4. Further potential applications include multi-component atmospheric monitoring (CH_4, CO_2, N_2O, …) and, as a new topic of growing relevance, the characterization and quantification of contaminants in hydrogen (H_2).

The dual-comb spectrometer features superior properties for many measurement tasks. Its flexibility makes it a valuable tool in prototyping, referencing and developing spectroscopic methods and systems.

Please contact us to find out what we can do for *your* application.

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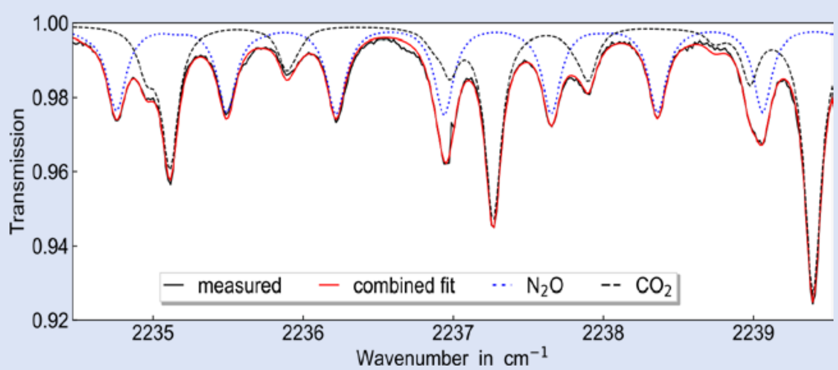

Characteristic properties

Spectral coverage
3 – 5 µm (2000 – 3333 cm^{-1})

Optical bandwidth
200 – 700 GHz (7 – 23 cm^{-1})

Optical sampling/ mode spacing
250 – 500 MHz (0.008 – 0.016 cm^{-1})

Acquisition rate
up to 20 kHz

Typical concentration resolution
2 ppb (at 330 ppb N_2O and 10 s acquisition time)

Noise equivalent absorption
$3 \cdot 10^{-3}$ (10 s acquisition time)

Number of spectral features (comb lines)
500 – 2000