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-Cascade-Lasers (QCL) for highly sensitive spectroscopy, whereas Fourier-Transform-IR spectrometers excel in spectral bandwidth.

Fraunhofer IPM developed a spectrometer based on two frequency combs that combines the advantages of both domains and enables broadband sensitive spectroscopic measurements at high acquisition rates. The spectrometer can be used to analyze complex gas mixtures with high time and frequency resolution, addressing the typical challenges caused by cross-sensitivity together.

**Dual-comb principle**

Frequency combs have become a dominating method for metrology. They can be used as a ruler in the optical frequency domain. Frequency combs feature multiple coherent and equally spaced modes defining the resolution, tunable from hundreds down to tens of MHz. The simultaneous use of two combs, where one samples the second, is of particular interest for spectroscopic applications. It results in a beat signal that encodes all spectral information. If one or both combs undergo attenuation due to a probe, this is recovered in the combined spectrum. A single photodetector is sufficient to detect the beat signal; the spectrum can be calculated efficiently by using a Fourier-transformation. As the resolution is given by the mode spacing it is possible to overcome the resolution limits of traditional spectrometers.
Mutual coherence

A key topic for dual comb systems is to ensure coherence and keep phase instabilities between the two combs at a minimum. This requires either complex analysis software and synchronization hardware or active stabilization. Due to their high complexity, such systems can only be operated by specialists in a laboratory. The Fraunhofer IPM system generates two frequency combs via separate sideband modulations from the same ultra-narrow-linewidth laser. These primary combs are spectrally broadened by nonlinear effects as they pass a fiber. Using one seed laser ensures a stable beat signal, i.e., the carrier-envelope offset phase remains sufficiently constant. The intrinsically coherent combs make lower demands on the hardware, which leads to both, a reduction of costs and enhanced ease of operation.

Mobile and versatile demonstrator setup

Fiber-coupled components from the telecommunications sector are employed for the system, which guarantees high quality and robustness as well as durability. The full system operates autonomously in a 18 HU, 19” rack and offers multiple fiber ports emitting dual-frequency comb or receiving such for detection.

A GUI allows to control the system and adjust the data acquisition parameters to different types of measurements. This enables continuous measurements, data compression and real-time analysis. Thus, switching arbitrarily between two scenarios becomes possible: averaging over hundreds of seconds to gain a high precision spectrum on the one hand and spectra acquisition rates in the kilohertz range to investigate dynamic processes like in exhaust systems or human respiration on the other hand. Adding spectral analysis software is simple and allows for turn-key systems which can be operated by non-specialists.

Outlook: full MIR tuning

One important extension of the technique currently under development is the frequency-agile transfer of the C-band combs to the MIR range by nonlinear-optical frequency conversion. The combs can be tuned over the full 3 – 5 µm wavelength range, which provides access to the fundamental absorption bands of hydrocarbons, CO, CO₂, nitric oxides, and a host of other molecular gases. In a second step, the tuning will be extended to the 7 – 10 µm range in order to address the very selective fingerprint spectral region. Due to the system’s broadband capability, absorption lines can be freely chosen for increased sensitivity without disturbance by other gas species that occur in the same spectral region.

Example specifications

- Optical bandwidth: > 500 GHz
- Optical resolution: < 100 MHz
- Optical power: > 50 mW
- Spectra acquisition rate: > 1 kHz
- Detectable absorption: in 10⁻³ range
- Gaussian beam profile out of a single mode fiber