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    - iBeam smart PT
  - Single Frequency Lasers
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    - TopMode
    - TopWave 266
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    - UV / RGB Solutions
  - Tunable Diode Lasers
    - ECDL/DFB Lasers
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    - Frequency Converted Lasers
      - SHG pro
      - DL-SHG
      - DL TA-SHG pro
      - DL TA-FHG pro
      - TOPO
    - Amplified Lasers
      - TA pro
      - BoosTA pro
      - BoosTA
    - Laser Driving Electronics
      - DLC pro
      - DC 110: □□□□□
    - Laser Locking Electronics
      - DigiLock110: □□□□□□□□□□□□□□
      - FALC 110: □□PID□□□□□□□
      - PDH/DLC pro: Pound-Drever-Hall
      - PDD 110: Pound-Drever-Hall□□□□□
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      - DLC pro Lock
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    - FemtoFiber smart

    - FemtoFiber smart 780
    - FemtoFYb 1030-400
    - FemtoFYb 1030-800
    - PicoFYb 1030
    - PicoFYb 1064
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    - FemtoFiber FluoLife
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    - FemtoFiber Quantum Microscopy
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    - GaAs□InGaAs □□□□□□□
  - Time-Domain
    - TeraFlash
    - Imaging Extension
    - TeraSpeed
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  - Accessories
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- Frequency Combs
  - DFC CORE / DFC CORE+
  - DFC Extensions

    - DFC BC / DFC MD
    - Complete DFC Systems
    - DFC SDL
  - Multi-Laser Engines
    - iChrome CLE
    - iChrome MLE
  - Customized Solutions
    - SodiumStar
    - TeraFlash smart
    - 633 nm High Power
    - 213 nm 10 mW cw
    - 193 nm sub-mW
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      - FiberDock
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      - Fabry-Perot
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    - Ion-Laser-Cooling-&-Trapping
    - Degenerate-Quantum-Gases(BEC,DFG)
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  - Optical Microscopy
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    - Raman-Microscopy
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- FemtoFiber ultra
    - FemtoFiber ultra 920
- FemtoFiber dichro
- FemtoFiber customized

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    - TeraBeam
- Time-Domain
    - TeraFlash
    - Imaging Extension
    - TeraSpeed
- Accessories

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- DFC BC / DFC MD
- Complete DFC Systems
- DFC SDL

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Direct Frequency Comb Spectroscopy

Beyond optical clocks – Frequency comb as versatile spectroscopic tool

- Dual comb spectroscopy
- Cavity enhanced comb spectroscopy
- Mid-IR comb spectroscopy
- Coherent control
- Remote sensing

Frequency combs were originally developed to serve as frequency counters for optical frequencies and clockwork in the field of optical frequency metrology. Beside this early purpose, frequency combs can also be used directly for spectroscopy. Their outstanding accuracy, high spectral purity, and broad spectral coverage make them a very useful and unique spectroscopic tool.

There is a variety of different kinds of direct frequency comb spectroscopy methods. Examples include dual comb spectroscopy, cavity enhanced comb spectroscopy, mid-IR comb spectroscopy, coherent control or remote sensing, to name only a few of these techniques. All of these techniques are usually based on analyzing the light generated by a frequency comb after it has interacted with a sample.

Dual comb spectroscopy for example uses two frequency combs of slightly differing line spacing. From each pair of optical lines, one from each comb, a radio frequency beat note is generated on a detector. This way, optical frequencies are converted into radio frequencies such that amplitude and phase changes caused by the interaction of one of the combs with a sample can be detected[1,2].

In **cavity enhanced comb spectroscopy**, every optical line is efficiently coupled into a high finesse cavity mode. Doing this, multiple parallel channels for ultrasensitive detection of molecular dynamics and trace analysis can be generated. The main advantages are large spectral bandwidths, high spectral resolution, and high sensitivity combined with fast spectral acquisition times. Beside many other applications, this is particularly attractive for attosecond science. By a careful design of the cavity mirrors, cavity enhanced comb spectroscopy can also be used in combination with an offset-free comb as pump laser. This has advantages with respect to stability and enables the generation of attosecond pulses at multi-10-MHz repetition rates[3].

Mid-IR comb spectroscopy faces the challenge that there are no efficient detector arrays available in the Mid-IR region. The solution is to use Fourier transform spectroscopy in the form of Michelson-based or dual-comb spectroscopy. The Mid-IR domain, with its strong molecular fingerprints, is of special interest for direct frequency comb spectroscopy which features short acquisition times, high sensitivity and high accuracy over a broad bandwidth[4].

A particularly intriguing application of **direct comb spectroscopy** is **coherent control** of the **quantum state** of cold particles, for example of trapped ions. Entangling quantum logic gates with high fidelity have been performed and even operations faster than the trap frequency are feasible with direct comb spectroscopy[5].

Remote sensing of greenhouse gases can be performed using direct frequency comb spectroscopy in a dual comb configuration[6]. Here, precise and continuous measurements of small gas enhancements over long ranges can increase the understanding of regional greenhouse gas transport, sources, and sinks. In the future, portable systems will enable regional monitoring.

- Related Products
    - DFC CORE / DFC CORE+
    - DFC Extensions
    - DFC BC / DFC MD
    - Complete DFC Systems
- Related Literature
    - 1. Ideguchi et al., Adaptive real-time dual-comb spectroscopy, Nature Communications 5 (2014)
    - 2. Coddington et al., Dual-comb spectroscopy, Optica 3 (2016)
    - 3. Holzberger et al., Enhancement cavities for zero-offset-frequency pulse trains, Opt. Lett. 40 (2015)
    - 4. Schliesser et al., Mid-infrared frequency combs, Nature Photonics 6 (2012)
    - 5. Hayes et al., Entanglement of Atomic Qubits Using an Optical Frequency Comb, Phys. Rev. Lett. 104 (2010)

    - 6. Rieker et al., Frequency-comb-based remote sensing of greenhouse gases over kilometer air paths, Optica 1 (2014)
- Related Applications
    - Microwave-Generation

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