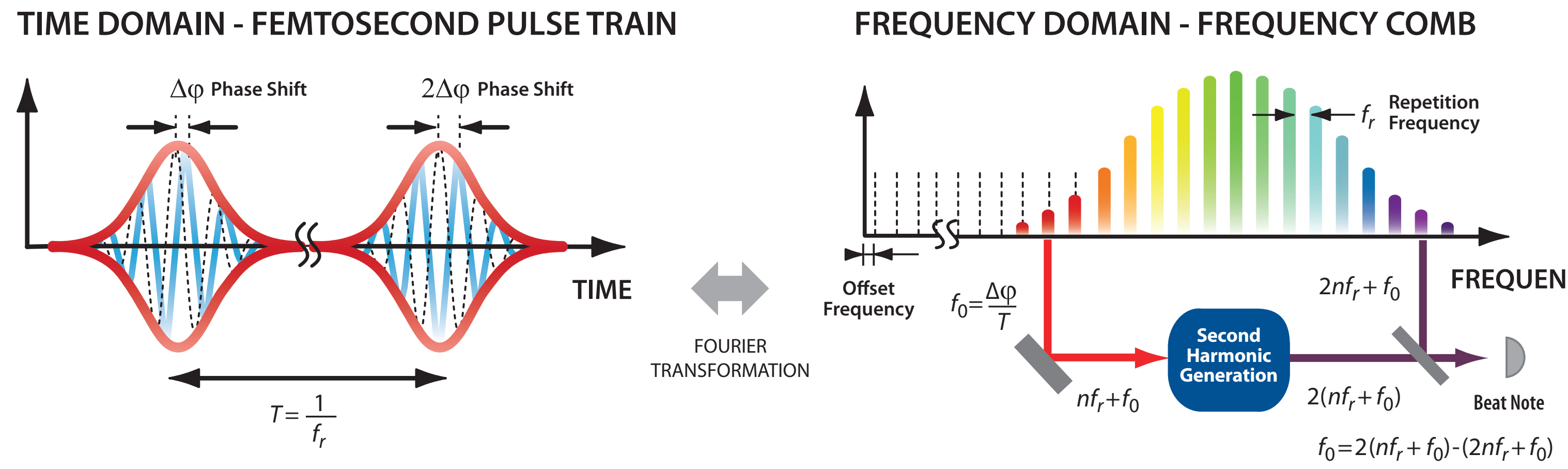
20 YEARS OF OPTICAL FREQUENCY COMBS

Optical frequency combs are emitted by mode-locked femtosecond lasers. Consecutive pulses of the laser pulse train in the time domain can be described in terms of a Fourier series, which corresponds to a series of frequency modes in the frequency domain. The separation between the modes is equal to the repetition frequency f_r. The comb modes, however, are located not at exact integer multiples of the repetition frequency, but are shifted by an arbitrary offset frequency f_0.

The frequency of each mode can be written as $f_n = nf_r + f_0$. This equation maps two radio frequencies f_r and f_0 onto the optical frequencies f_n. The frequency comb can act as a ruler in the frequency space once the two critical frequencies, the repetition frequency and the offset frequency, are known and stabilized. The repetition frequency is readily measureable with a photodiode and usually lies between a few tens of megahertz and a few gigahertz.

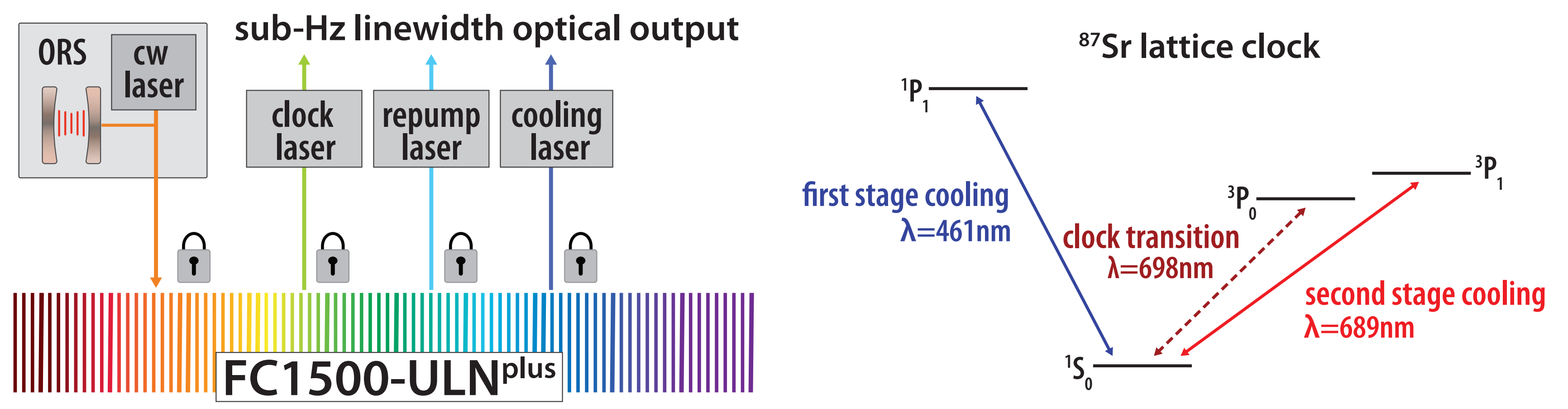
With a comb spanning more than an octave, it is particularly easy to determine the offset frequency. A mode with the number n at the red end of the spectrum can be sent through a nonlinear crystal to generate its second harmonic frequency, which is now displaced by twice the offset frequency. A beat note between this frequency doubled mode and an original comb mode with the number $2n$ at the blue end of the spectrum directly reveals the offset frequency $2(nf_r + f_0) - (2nf_r + f_0) = f_0$.



speed of light in vacuum $c = 299{,}792{,}458\ \frac{m}{s}$	**light velocity** $c = f \cdot \lambda$	**bandwidth conversion** $\Delta f = \frac{c}{\lambda^2} \cdot \Delta\lambda$ e.g. at 633 nm $\Delta\lambda = 1$ nm corresponds to $\Delta f = 748$ GHz
pulse period $T = \frac{1}{f_r}$	**offset frequency** $f_0 = \frac{\Delta\varphi}{T}$	**frequency comb equation** $f_{cw} = n \cdot f_{rep} \pm f_0 \pm f_{beat}$

QUANTUM TECHNOLOGY FOR THE NEXT CENTURY

Menlo Systems' complete solution for optical lattice clocks



FC1500-ULN^{plus} Optical Frequency Comb
accuracy: 1 x 10^{-18} (τ >100 s); stability: 5 x 10^{-18} in 1 s, 5 x 10^{-19} in 1000s;
operational range: 500 nm to 2 µm

ORS Ultrastable Lasers
state-of-the-art linewidth <1Hz and stability <7 x 10^{-16} Hz

Optical clock transitions for the most accurate definition of the second

strontium clock transition f = 444.779 THz λ = 674.025 nm absorbing ion $^{88}Sr^+$, $5\ ^2S_{1/2} - 4\ ^2D_{5/2}$	**calcium clock transition** f = 455.986 THz λ = 657.459 nm absorbing atom ^{40}Ca, $^1S_0$ - $^3P_1$, $\Delta m_J = 0$
strontium lattice clock transition f = 429.228 THz λ = 698.446 nm absorbing atom ^{87}Sr, $5\ ^1S_0 - 5\ ^3P_0$	**ytterbium lattice clock transition** f = 518.296 THz λ = 578.420 nm absorbing atom ^{171}Yb, $6\ ^1S_0 - 6\ ^3P_0$

TIMELINE

First Envisioned in 1997

"By March 30 of 1997, I had written a confidential six-page proposal for a universal optical frequency comb synthesizer '...which produces a wide comb of absolutely known equidistant marker frequencies throughout the infrared, visible, and ultraviolet spectral range. To this end, a white light continuum with a pulse repetition rate f_r is produced by focusing the output of a mode-locked femtosecond laser into an optical fiber or bulk medium with a third-order nonlinear susceptibility. The rate of phase slippage of the laser carrier relative to the pulse envelope, f_{CEO}, is monitored by observing a beat signal between the white light continuum and the second harmonic of the laser. The envisioned self-referencing scheme could find the carrier-envelope offset frequency f_{CEO} without any auxiliary laser.' I asked Thomas Udem and Martin Weitz in our laboratory to witness and sign every page on April 4, 1997, since this might become important for later patent applications."

– From the Nobel Lecture of Theodor W. Hänsch 2005

1999 **First Absolute Optical Frequency Measurement**
The measurement of the hydrogen 1S–2S transition frequency using an optical frequency comb yielded a new value accurate to 1.8 parts in 10^{14}, surpassing all earlier optical frequency measurements by more than an order of magnitude.

2000 **First Demonstration**
With a few weeks difference, John L. Hall at JILA and the team of Hänsch at the Max Planck Institute for Quantum Optics demonstrated the first octave-spanning self-referencing laser frequency comb.

2001 **Menlo Systems**
Menlo Systems was founded with the aim to
accelerate the advancement of optical technology for precision measurements and their applications from the table tops of research laboratories to standard use in communication and high technology industries. The first commercial system based on a Ti:sapphire laser was delivered in 2001.

2005 **Nobel Prize**
Hänsch and Hall were awarded the Nobel Prize for their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique. Menlo Systems released the first fiber based Optical Frequency Comb.

2014 **Figure 9® Mode Locking Technology**
Menlo Systems' proprietary figure 9® mode locking technology enabled a new generation of reliable, robust, and long term stable metrology equipment for applications outside the optical laboratory.

2017 **Compact Optical Frequency Comb**
The fully autonomous SmartComb in a 19" housing makes Hänsch's 2001 vision of a compact and portable Optical Frequency Comb reality, a mile stone for field applications in frequency metrology.

2019 **World's Most Precise Optical Frequency Comb**
With the FC1500-250-ULN^{plus} Menlo Systems provides an Optical Frequency Comb with a demonstrated accuracy at the 20th decimal place.

APPLICATIONS

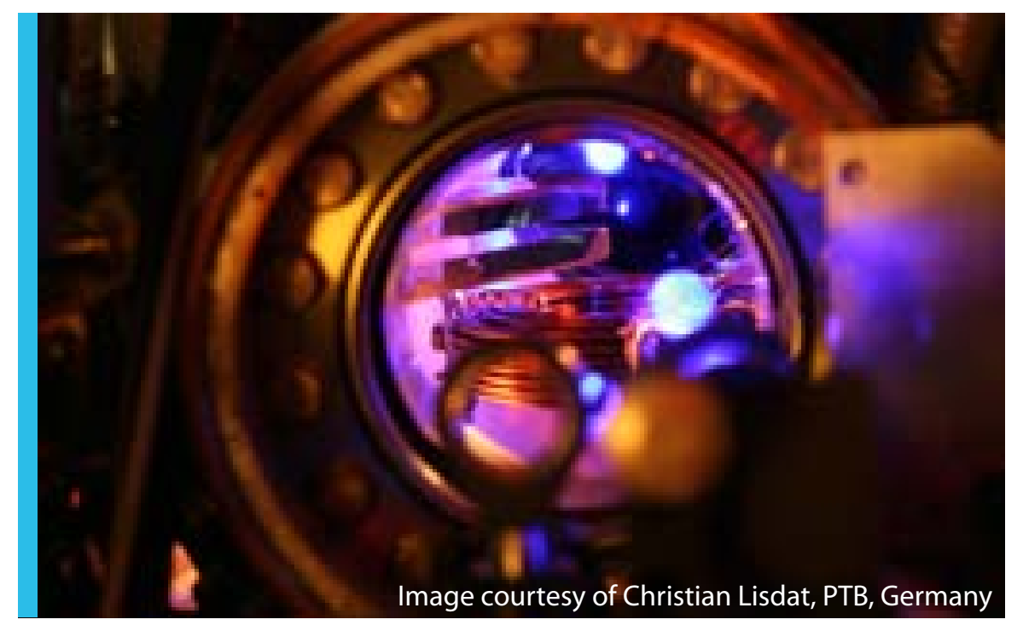


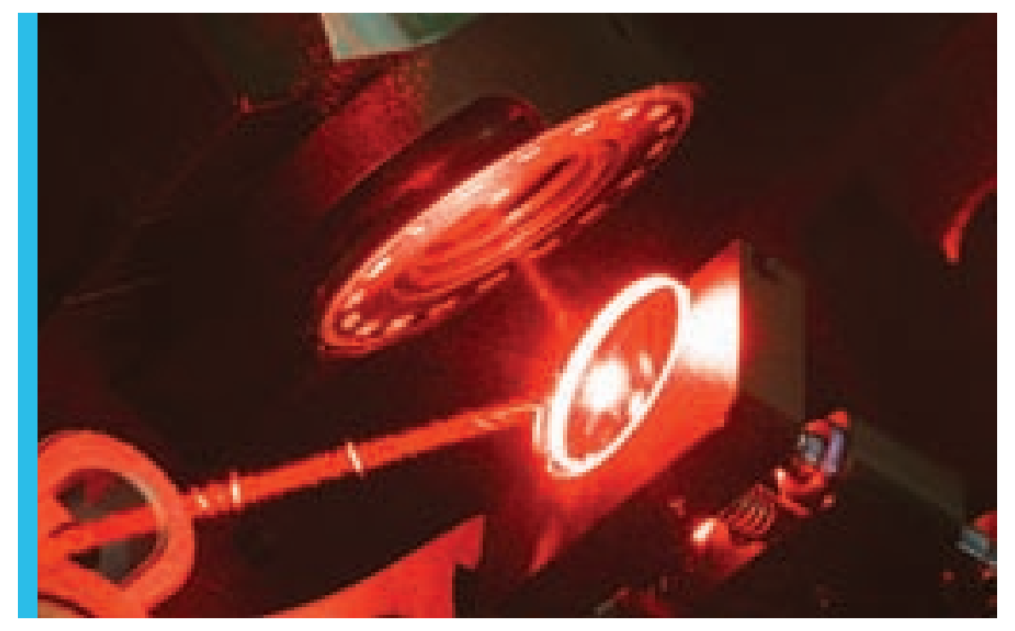
Image courtesy of Christian Lisdat, PTB, Germany

Optical clocks

The formal SI definition of the second is currently the 9,192,631,770 multiple of a transition between two hyperfine states in a cesium atom. With an accuracy of one part in 10^{16} latest generation cesium clocks err by less than one second in 30 million years. By increasing the oscillation frequency from the microwave to the optical region of the electromagnetic spectrum the accuracy is improved by several orders of magnitude. Today's most accurate optical lattice clocks with a precision in the range of 10^{-18} reduce the error to less than 1 second in 15 billion years, the estimated age of the universe. In the hunt for the highest precision, optical frequency combs are an indispensable tool for the comparison of different optical clocks. They provide the gear for the conversion between optical and microwave frequencies in order to make them measurable. With an accuracy and stability of 10^{-18} or better they present a suitable clockwork operating in the testing of physical theories or in relativistic geodesy.

Dimensional metrology

According to the SI definition, the meter is the length of the path traveled by light in vacuum during a time interval of 1/299,792,458 of a second. In a practical realization of the meter, a stable metrology laser with an accurately determined frequency is used to convert its wavelength into a path length by means of optical interferometry. Besides uncertainties arising from the interferometer resolution and the refractive index determination, the uncertainty in the laser frequency is limiting the accuracy of the length measurement. Since an optical frequency comb allows for a direct and absolute frequency measurement with highest accuracy, this uncertainty is decreased to a non-relevant value in the length determination. Cumbersome periodic intercomparison campaigns of the optical laser frequency used in different national metrology laboratories have become obsolete.



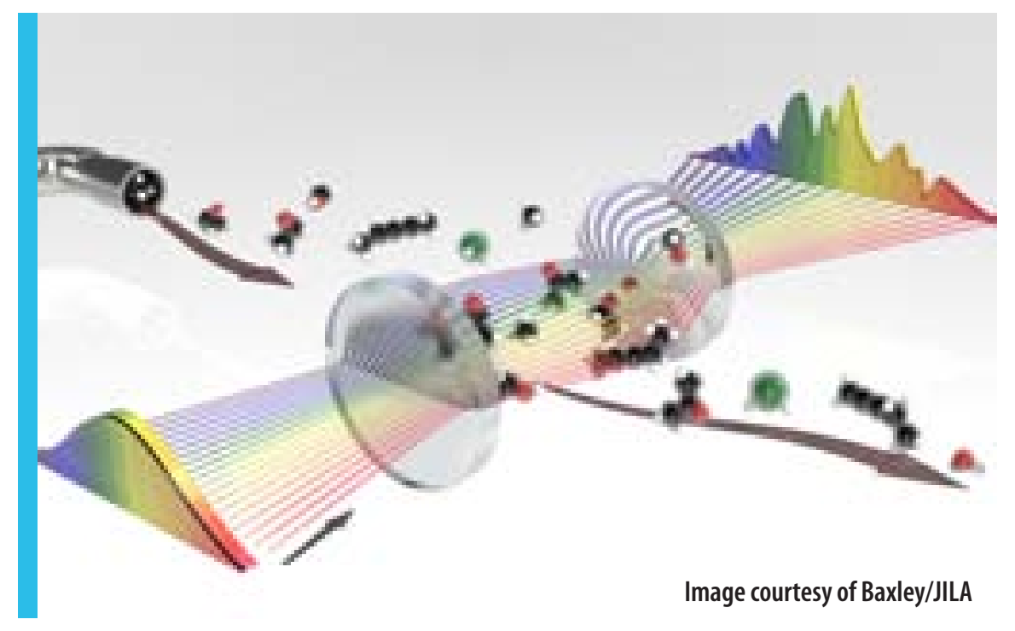


Image courtesy of Baxley/JILA

Molecular fingerprinting in the mid-infrared

Rotational and vibrational transitions of molecules are energetically located in the mid-infrared region of the electromagnetic spectrum. By exactly determining position and intensity of their absorption lines, molecular species and their concentrations within a mixture are unambiguously identified. The accuracy and sensitivity of such spectroscopic measurements were limited by the lack of suitable light sources in the past. Optical frequency combs covering a broad spectrum extended into the mid-IR region enable novel spectroscopic approaches for the direct and absolute measurement of molecular fingerprints. Methods such as Fourier transform spectroscopy or cavity enhanced detection achieve the high sensitivity necessary for the analysis of chemical trace amounts. Dual comb spectroscopy further enhances sensitivity and precision, at the same time decreasing the recording time and the requirements for optical detectors.

High-resolution spectroscopy

Precision laser spectroscopy of atomic transitions is the most powerful tool for accurate testing of physical theories and for determining the values and conceivable drifts of fundamental constants. Sophisticated techniques for laser stabilization and sample preparation allow for probing of ultra narrow transitions with smallest systematic error and potentially very high relative accuracy. These experiments naturally require the comparison of the probing laser light either against some optical reference or against the SI second realized by atomic clocks. Optical frequency comb synthesis is the enabling technique for this comparison, ensuring highest spectral purity in the transfer of the reference stability to the spectroscopy laser. The advantage of the several hundred thousand ultra stable and precisely tuned cw lasers operating at once in a frequency comb also facilitates experiments with sensitivity for the tiniest amounts of molecules in the gas phase, such as performed e.g. for atmospheric trace gas monitoring.


Image courtesy of ESO/B. Tafreshi (twanight.org)

Astro-combs

The extremely accurate and fine grid of the frequency ruler provided by an optical frequency comb is used to calibrate high resolution astronomical spectrographs. With the laser lines superimposed on the star's spectral lines the latter are readily measured with the accuracy of an atomic clock. At the same time, uncertainties from practical spectroscopic experiments are eliminated. As the calibration is absolute, even if different combs are used to calibrate spectra from different telescopes at different epochs, those spectra can be compared. Astro-combs enable observations that previously were unachievable, such as the quest for exoplanets or the characterization of quasars. They also facilitate the investigation whether the expansion of the universe is accelerating. Such a direct observation could be decisive on whether or not dark energy, together with general relativity, constitute the proper model, or if we have to seek out new explanations.

Frequency metrology in space

State-of-the-art optical frequency combs are qualified for operation under microgravity and vacuum conditions, which are essential requirements for their mission in space. Satellites flying in formation need to hold their relative position accurate to few microns. The European Space Agency is investigating frequency combs as a unique technology to measure distances of several hundred meters with micrometer and even nanometer accuracy. Likewise global navigation systems will profit from increased precision of their on-board atomic clocks, while space-born or lunar observatories would enable high resolution astronomical spectroscopy free of atmospheric impact such as absorption, blurring, wind loading or vibrations. In fundamental research experiments optical frequency combs perform absolute frequency measurements on space missions probing the equivalence principle.

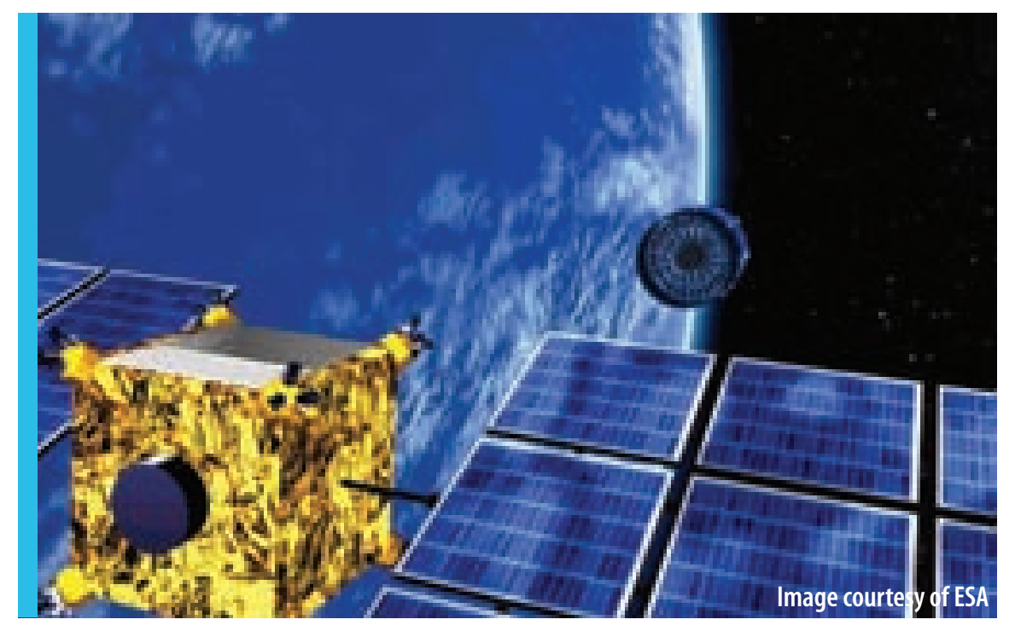


Image courtesy of ESA

PRECISION IN PHOTONICS. TOGETHER WE SHAPE LIGHT.

MenloSystems

Menlo Systems is a leading developer and global supplier of instrumentation for high-precision metrology. If you want to find out more about our frequency comb technology call us at +49 89 189 166 0, email us at sales@menlosystems.com or visit our website www.menlosystems.com.