MenloSystems

ULTRAFAST SOLUTIONS

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- large mode spacing
- widely tunable carrier envelope offset phase

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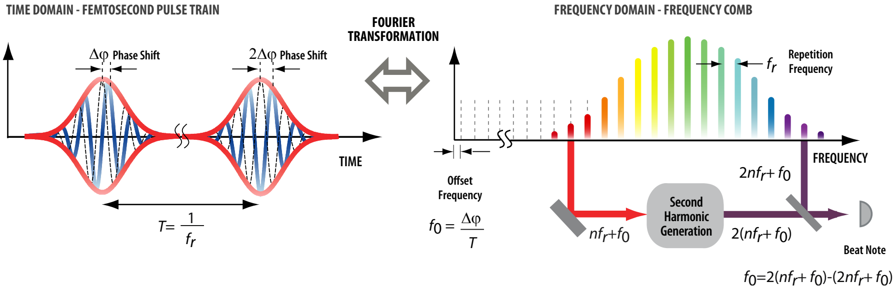
OPTICAL FREQUENCY COMBS



PRECISION MEASUREMENT AT THE HIGHEST LEVEL

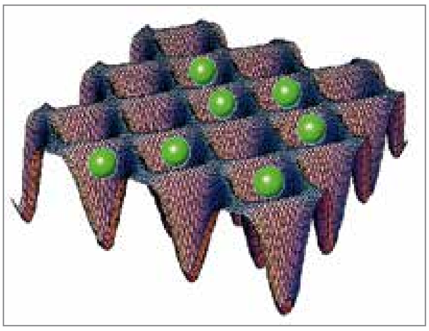
The control of the broadband frequency comb emitted from a mode-locked femtosecond laser has permitted a wide range of scientific and technological advances – ranging from the counting of optical cycles in high-accuracy optical clocks to measurements of phase-sensitive high-field processes. A unique advantage of the stabilized frequency comb is that it provides, in a single laser beam, about hundreds of thousand optical modes with very narrow linewidths and very well-known absolute frequency positions.

Frequency combs are simple and compact systems that phase coherently connect the radio frequency domain (below 100 GHz) with the optical domain (above 140 THz). They greatly simplified high precision optical frequency measurements and provide the long awaited clockwork mechanism for an all-optical atomic clock.

OPTICAL CLOCKS

The second is currently defined as the time taken to complete 9,192,631,770 oscillations between two energy levels in a cesium atom. The current generation of cesium clocks has an accuracy of 10^{-16} – equivalent to an error of less than one second in 30 million years. Scientists are looking for ways to create an even more accurate clock. One way of doing this is to increase the rate at which the clock ticks. This can be realized if optical transitions were used to measure time rather than microwave transitions in cesium. The main challenge when building an optical clock is to relate these optical frequencies to the much lower microwave frequencies that are used to define the second. Frequency combs are the indispensable tool providing the gear for this conversion.

The optical lattice clock proposed by Hidetoshi Katori from the University of Tokyo locates the atoms at lattice sites, thus minimizing mutual interaction without limiting the signal-to-noise ratio (in *Nature Vol. 435: 321-324, 2008*).

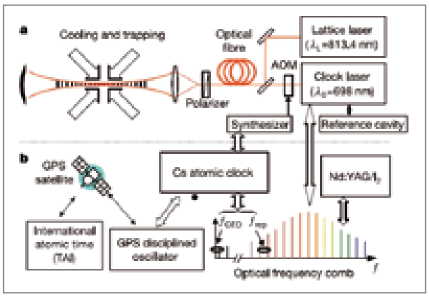


Spatial interference pattern of lasers can produce periodic trapping potentials for ultracold neutral atoms, called an optical lattice.

Image credit: Hidetoshi Katori/University of Tokyo

Other approaches focus on the enhancement of the detection scheme for single particle signals. Today, optical clocks reach accuracy beyond the 10^{-17} level and currently no limit is foreseen for what can be reached. Harald Schnatz, working on the frequency measurement of optical clocks based on a single Yb+ ion in a Paul trap or Sr atoms confined in an optical lattice at Physikalisch-Technische Bundesanstalt in Braunschweig, believes that "the time is ripe to prepare for secondary realizations of the second, which, later, could possibly lead to a new definition of the second."

State-of-the-art metrology system, the FC1500-250-WG Optical Frequency Synthesizer – seeded with the 250-MHz M-Comb Erbium-doped fiber oscillator.



Experimental configuration for the Sr lattice clock.
Image credit: Hidetoshi Katori/University of Tokyo

FIBER LASERS AT THE HEART OF THE MOST PRECISE CLOCKS

The accuracy of the frequency combs has reached a level that does not limit the overall accuracy of the optical clock when they are employed as an optical clockwork. Our laser systems have been engineered for the demanding metrology applications and have the following features:

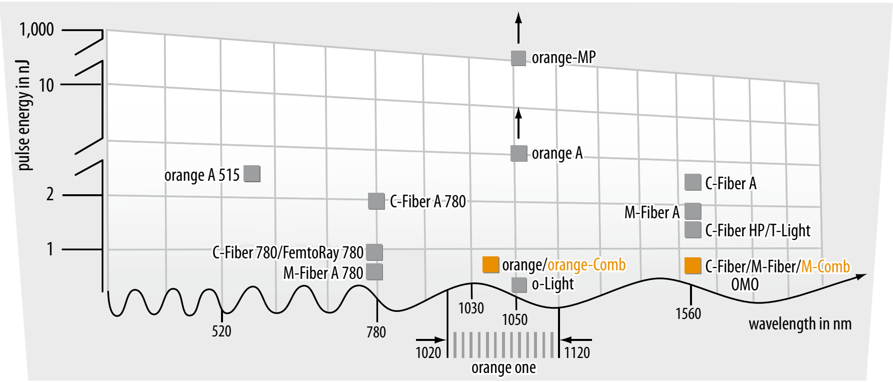
Klaus Hartinger from Menlo Systems in the Laboratory of Photonics and Quantum Measurements at the Swiss Federal Institute of Technology (EPFL) in Lausanne, Switzerland, working with an FC1500-250-WG Optical Frequency Synthesizer.

- low phase noise Erbium- and Ytterbium-doped fiber oscillators
- high repetition rate of 250 MHz for wide spacing between the individual comb lines
- large tuning range of the cavity length and of the carrier envelope offset frequency for long-term stable operation
- electro-optic intracavity modulator – integrated in the oscillator for high-performance phase locking to an optical reference
- all-fiber-coupled f:2f interferometer for the offset frequency detection ensuring adjustment free and robust operation
- seeding up to five additional amplifiers for multiple measurement ports at user-defined frequencies and spectral ranges

The latest generation of our Erbium FC1500-250-WG and the recently released Ytterbium FC1000-250 Optical Frequency Synthesizer find applications in the following fields:

- high resolution spectroscopy
- optical clocks
- dimensional metrology
- low-noise microwave synthesis
- transfer of ultrastable timing signals and frequency standards

MENLO SYSTEMS’ LASER SELECTOR



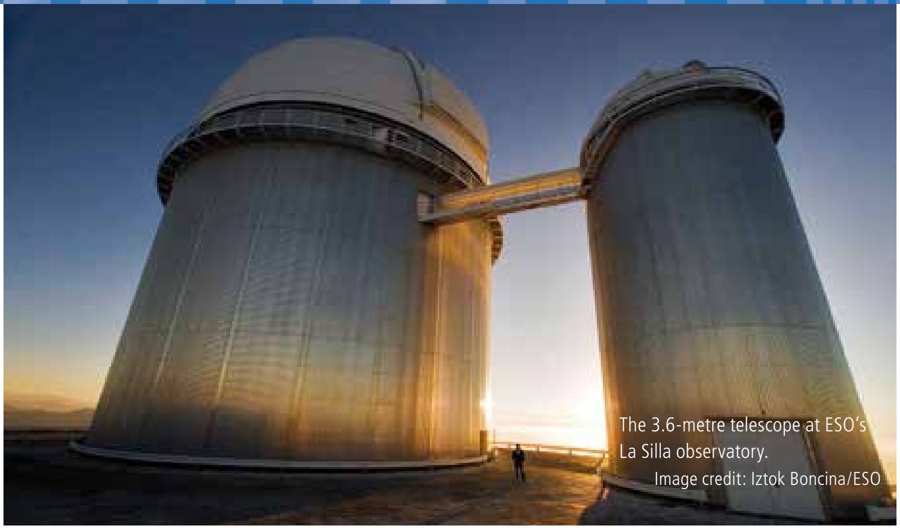
ORDERING INFORMATION

FC1500-250-WG
Erbium-based Optical Frequency Synthesizer

FC1000-250
Ytterbium-based Optical Frequency Synthesizer

FC8004
Ti:Sa-based Optical Frequency Synthesizer

ASTRO COMBS



The 3.6-metre telescope at ESO's La Silla observatory.
Image credit: Iztok Boncina/ESO

MEASURING COSMIC VELOCITIES

Spectrographs connected to telescopes are used to identify planets around stars outside our solar system. Astronomical spectrographs are typically calibrated against Thorium-Argon lamps or Iodine absorption cells. A more precise way of calibration should make it possible to explore deep space more accurate than ever before, making identification of Earth-sized planets or direct detection of cosmic acceleration possible.

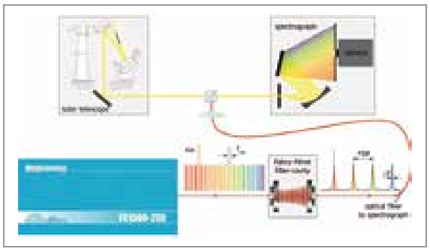
Traditional calibration techniques are subject to uncertainties that unavoidably degrade the wavelength resolution: lines are not evenly distributed in the spectral range of interest, have a wide range of intensities and sometimes appear blended. The frequency comb technology may offer a solution.

A RULER MADE OF COMB MODES

When laser pulses pass through a spectrometer, the regular train of modes is overlapped with the light collected by the spectrograph and hence can be used as a perfect ruler to calibrate the apparatus with unprecedented resolution.

The main challenges are to generate a frequency comb with a sufficiently large mode spacing that can be resolved by the astronomical spectrograph and to have sufficient comb light in the full spectral operating range.

Fabry-Pérot cavities can serve as mode filters to increase the fundamental mode spacing. Using more than one filter cavity has the advantage of achieving a higher suppression of the unwanted modes. Power losses due to the rejected modes of the filter stages need to be replenished to ensure sufficient light intensity for non-linear processes such as frequency doubling and spectral broadening necessary to match the frequency comb spectrum to the optical bandwidth of the spectrograph.



A solar telescope collects light that is superimposed with the frequency comb light. Together they are fed to a spectrometer. Since the original mode separation of the frequency comb (250 MHz) is too close to be resolved by the spectrometer, the light is first filtered using a Fabry-Pérot filter cavity to 15 GHz.

TAILORING THE YTTERBIUM FIBER COMBS

The FC1000-250 Optical Frequency Synthesizer is an ideal choice for such a system. Based on an Ytterbium-doped fiber laser, it allows for amplification to high power levels. The automated ASTRO Extension Package can be configured to meet the individual requirements posed by high performance astronomical instruments in need of high-precision calibration.

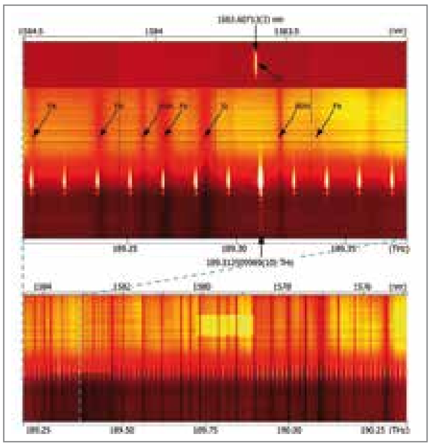
ONE OF ASTRONOMERS' DREAMS FULFILLED

Menlo Systems teamed up with scientists from the Max Planck Institute of Quantum Optics in Germany and the European Southern Observatory to develop calibration instruments

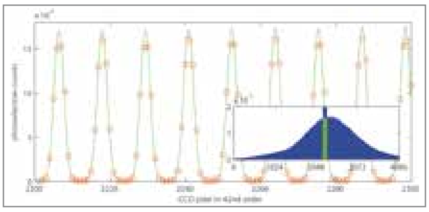
Tilo Steinmetz from Menlo Systems and Constanza Araujo-Hauck set-up the comb mode filter cavity at the VTT optical laboratory, in Tenerife.
Image credit: ESO

specially designed for high resolution spectrographs. After successful tests in the laboratory, in 2008 the team has successfully tested a prototype device using the laser comb at the Vacuum Tower Telescope (VTT) solar telescope in Tenerife, measuring the spectrum of the Sun in infrared light. For more information on this proof of principle campaign see Steinmetz et al. in *Science Vol. 321: 1335-1337, 2008*.

Current work focuses on the calibration of the HARPS planet-finder instrument on ESO's 3.6-metre telescope at La Silla in Chile.
Recently published results by Wilk et al. (in *Monthly Notices of the Royal Astronomical Society Vol. 405: L16–L20, 2010*) announce an era of a promising technique to achieve the accuracy needed to study the big astronomical questions.

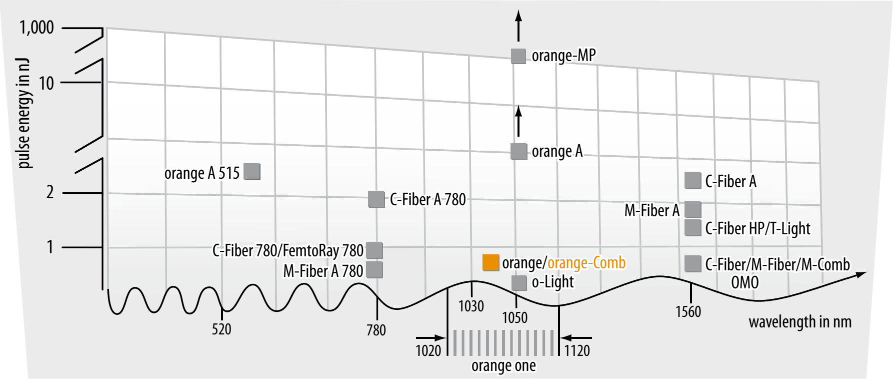


The solar spectrum measured at the VTT on Tenerife. A section is magnified on top; the dark lines are caused by absorption of gaseous elements in the photosphere of the Sun and by absorption in Earth's atmosphere. The spectral lines of the frequency comb appear as bright streaks that are used as precise calibration lines for the entire solar spectrum.



The laser frequency comb calibration spectrum is determined by fitting individual comb modes with Gaussians, which serve as a good approximation of the spectrometer point spread function. A section of the extracted comb spectrum (red dots) is shown together with a sum of Gaussians fitted to the data (green line). The inset shows one full echelle order (out of 72) with the spectral envelope of the frequency comb. The range of the zoomed region is highlighted.

MENLO SYSTEMS' LASER SELECTOR



ORDERING INFORMATION

FC1000-250
Optical Frequency Synthesizer

ASTRO
Extension Package for Mode Spacing
in the GHz range

SYNCHRONIZATION AND TIMING DISTRIBUTION ON THE FEMTOSECOND LEVEL

The latest optical technology allows for synchronization and timing distribution with accuracies down to the femtosecond level. Some of our recent product developments were inspired by the requirements for a nearly drift-free synchronization and timing distribution within the facilities of upcoming light sources such as the FERMI light source at the ELETTRA facility and FLASH light source at the DESY facility.

FOLLOWING A REFERENCE SIGNAL WITHIN 10 fs

The conventional method of distribution of reference signals via RF-cabling allows for synchronization on the order of 100 fs rms value long-term at best. Entering the regime of sub-10 fs requires new solutions based on optical techniques. For background information, see e.g. Kim J. et al. *Nature Photonics Vol. 2: 733-736, 2008*.

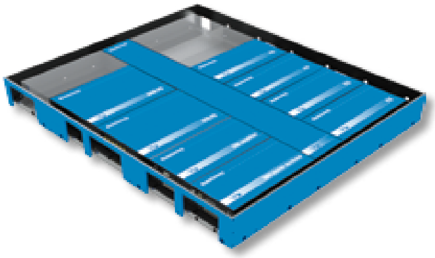
The essential technologies that are required for the sub-10 fs regime are:

- low phase-noise sources
- drift-free optical-to-optical synchronization
- RF-to-optical synchronization
- dispersion compensation modules to disseminate a reference throughout the facility via stabilized fiber-optic links

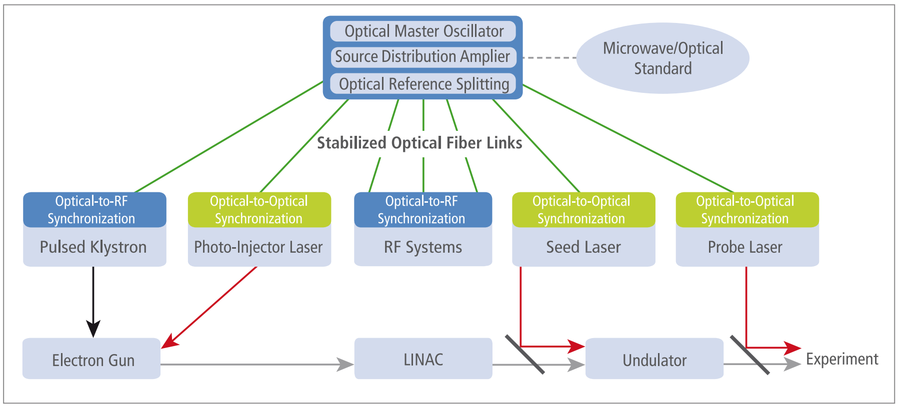
NEXT GENERATION TIMING SYSTEM

In a joint forces project with Idesta Quantum Electronics Inc., Menlo Systems developed new modules around our femtosecond fiber lasers and our synchronization and stabilization techniques. When combined to a timing system, record low jitter and drift values between master and client RF and optical signals can be achieved. The result is a complete solution for a long-term stable, pulsed optical timing distribution and synchronization system.

The first timing system of its kind has been implemented in 2010 at the newly built FEL facility at the FERMI light source at ELETTRA.



The main building blocks of the timing system are a highly stable Optical Master Oscillator (OMO) that is synchronized to the master RF clock, a splitting and amplification unit to provide multiple optical signals to be distributed to the various clients, dispersion compensated fiber links, and detection and stabilization electronics to provide the error signals and the stabilization thereof.



Schematic overview of the timing system. A master signal has to be distributed to multiple clients in order to achieve perfect synchronization between the events.

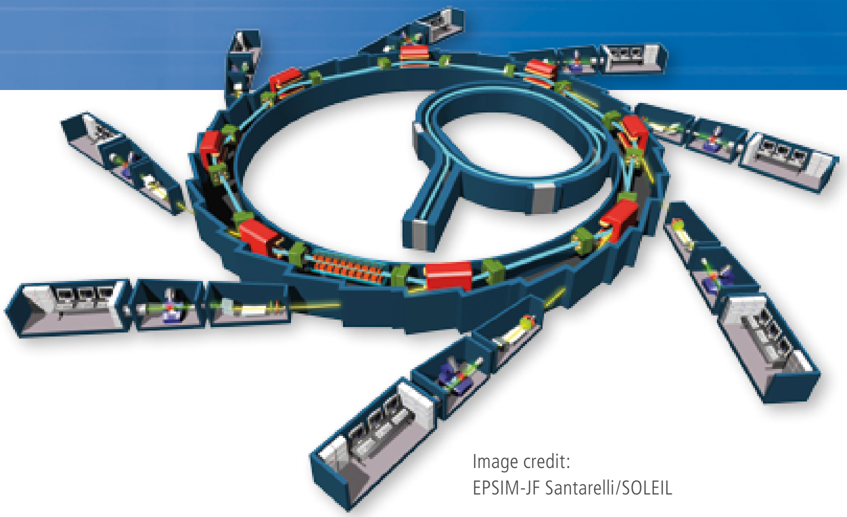


Image credit:
EPSIM-JF Santarelli/SOLEIL

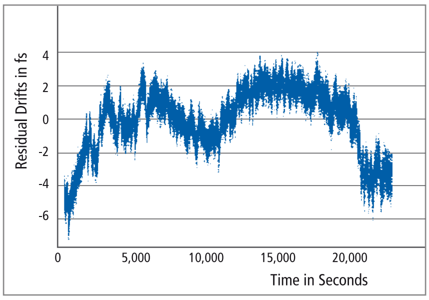
After the engineering and the installation at FERMI were completed, we started a measurement campaign in order to do a full characterization of the system under real life conditions. We characterized the performance of the link ends hundreds of meters away from the master source by comparing one remote link output to one of the outputs of the master system.

A TAILORED SOLUTION FOR EACH TIMING TASK

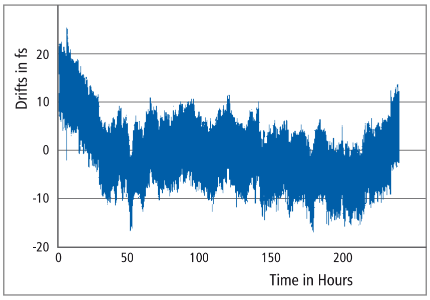
As the timing system is engineered in a modular way, it turns out that many of the individual building blocks can be exploited in a variety of demanding applications like:

- implementation of a low-phase noise optical source to serve as reference clock
- synchronization of lasers by means of the high-resolution, long-term stable phase detectors
- synthesis of very low-noise RF and microwave signals
- distribution of a reference signal and stable trains of femtosecond pulses at remote locations by means of stabilized, dispersion compensated fiber-optic links

In this joint effort, we could realize a nearly drift-free timing distribution and synchronization system that operates 24h/7d with lowest long term drifts in a large scale facility.

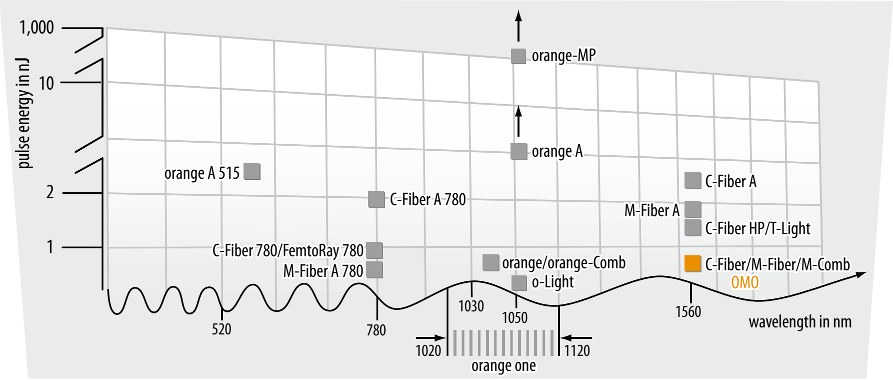


The residual out-of-loop drift between the OMO and the RMO over eight hours, measured with a balanced optical microwave detector, is as low as 2 fs rms.



The out-of-loop drift of the link output compared to a splitter box output port, recorded over 10 days, is 5.3 fs rms.

MENLO SYSTEMS' LASER SELECTOR



ORDERING INFORMATION

OMO
Optical Master Oscillator

SDA
Source Distribution Amplifier

SPBOX
Optical Reference Splitting

LFC
Link Fiber Connection Transmitter and Receiver Module

ASYNCHRONOUS OPTICAL SAMPLING

The turn-key ASOPS TWIN 250 Asynchronous Sampling System, consisting of two phase-locked fs lasers and the electronics for locking and trigger signal generation.

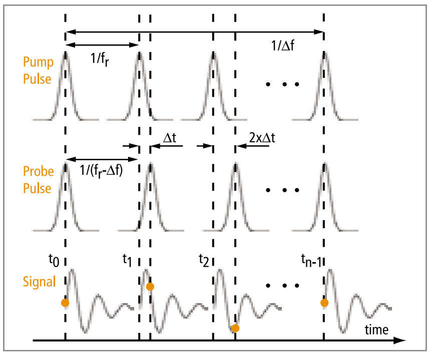
FOR HIGH-SPEED AND HIGH-PRECISION MEASUREMENTS

In time-resolved pump-probe experiments an ultrafast laser pulse triggers a reaction and a second pulse takes a snapshot of the induced change. By shifting the arrival time of the probe pulse with respect to the pump pulse the stimulated process can be followed in time. Similarly, the THz Time-Domain Spectroscopy (THz-TDS) technique uses femtosecond pulses in combination with nonlinear crystals or photoconductive switches, together with field-resolved detection.

Typically, in the time-resolved pump-probe and the THz-TDS technique the weak probe pulse is split off from the original laser beam and then delayed against the pump pulse with a mechanical delay line. Though this scheme has been widely used over the past decades it nevertheless has some distinct disadvantages. These drawbacks can be overcome by using two synchronized lasers with slightly different but stabilized pulse repetition rates. This method discarding the need for a mechanical delay line is called Asynchronous Optical Sampling (ASOPS).

HIGH-SPEED SCANNING OVER SOME NANOSECONDS

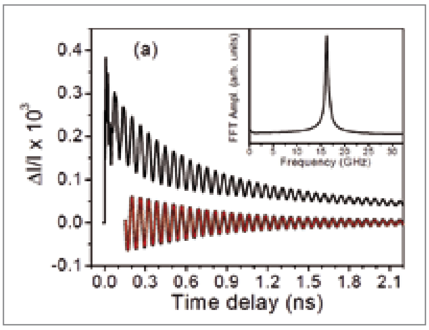
The ASOPS scheme uses two synchronized lasers with slightly different but stabilized pulse repetition rates. Both ultrafast lasers delivering the pump and probe pulses are locked together at a tunable repetition rate difference.



The repetition rate of the first laser (pump laser) is slightly offset from the repetition rate of the second laser (probe laser) by a fixed offset frequency Δf. If the pulses from both lasers are emitted simultaneously at the time t_0 then the following pulses at time t_1 are separated by $\Delta t = |1/f_{pump} - 1/f_{probe}| = \Delta f/(f_{pump} \cdot f_{probe}) \approx \Delta f/f_{pump}^2$, i.e. the probe pulse is delayed with respect to the pump pulse. With each laser pulse this difference increases until the pulses are again emitted simultaneously at the time 1/Δf. This way the time window $1/f_{pump}$ between two successive pump laser pulses is sampled by the probe laser pulses with a time resolution of Δt within a time 1/Δf.

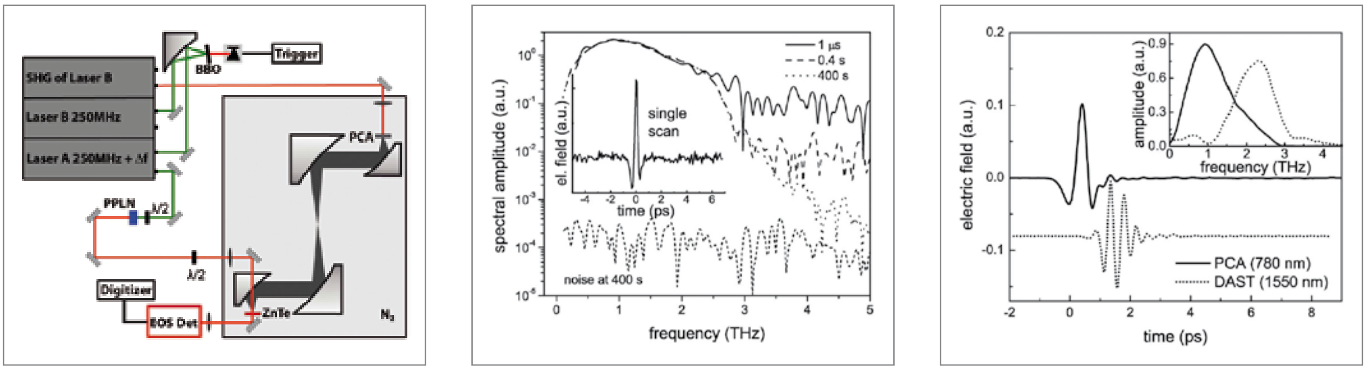
Advantages of the ASOPS technique over conventional sampling techniques requiring a mechanical delay stage include faster data acquisition times, increased temporal measurement windows, and the absence of limitations that are common to moving components e.g. beam pointing instability. Depending on the fundamental repetition rate, the time window of the measurements can extend up to 10 ns. To realize such a wide measurement window with the conventional method, a 1.5-m long motorized delay line would be required. The actual scan range of mechanical delay lines is typically limited to 100 ps or less. Even if robust and stable delay lines were available the data acquisition time would exceed 1 h, assuming 66,667 steps on the delay line with 0.1 s–0.2 s per step. In comparison, the scan time of our 100 MHz ASOPS system with 1 kHz offset frequency amounts to only 1 ms.

Scientists of the FOCUS Center at the University of Michigan took advantage of this extraordinary temporal dynamic range to connect the fast and slow time scales in the observation of dissipation and decoherence processes in the study of transient solid-state dynamics. Vladimir A. Stoica et al. in *Optics Express, Vol. 16: 2322-2335, 2008,* demonstrated optical time-domain spectroscopy from femtoseconds to nanoseconds using our



Coherent magnetization oscillation measurement for (110) Fe/Ge sample. Long-lived coherent magnetization oscillations could be resolved for time delays of up to 9 ns, although only the first 2.2 ns are displayed in the plots shown.

Image credit: Stoica et al./OSA



Layout of the THz spectrometer and the THz data measured using our ASOPS TWIN 250 system.

Image credit: Stehr et al./OSA

ultrafast dual-fiber-laser system with kilohertz continuous scanning rates. Utilizing different wavelengths for the pump and probe beams, they exploited the broad ranges of time scales provided by the ASOPS system for quantitative studies of thermal transport and the detection of coherent spin and lattice excitations in epitaxial magnetic thin films.

SCANNING A NARROW RANGE OF INTEREST

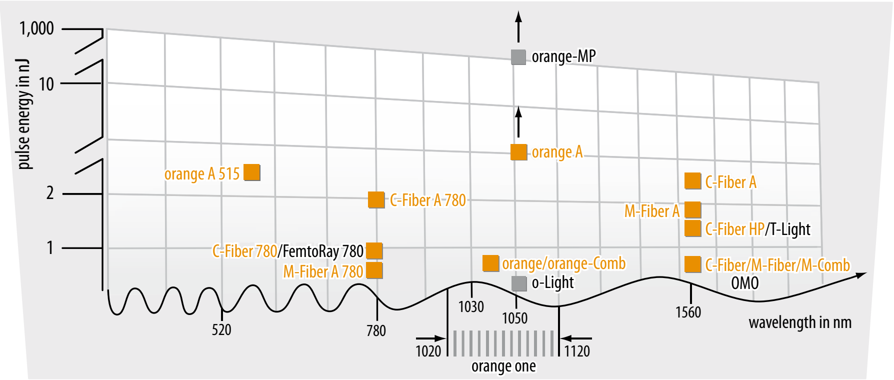
Alternatively, with the ASOPS electronics one can realize the adjustable delay between the two lasers by alternating the sign of the offset frequency on a time scale much shorter than 1/Δf. Thus, a significantly narrower time window for the measurements can be achieved.

At the Institute for Terahertz Science and Technology of the University of California Santa Barbara, a group of scientists developed a high-performance THz spectrometer based on our ASOPS TWIN 250 Asynchronous Optical Sampling System. Stehr et al. in *Optics Letters, Vol. 35: 3799-3801, 2010*, applied a triangular voltage signal at a rate of 2.5 kHz to the phase and scanned a time window of just 20 ps, without acquisition of unneeded data points. They acquired THz spectra extending to 3 THz within 1 µs at a signal-to-noise ratio of the electric field of better than 20. Signal averaging results in a dynamic range of more than 60 dB, and frequency components of more than 4 THz could be detected.

WHAT IS YOUR APPLICATION?

We offer versatile ASOPS solutions. All our scientific fiber lasers can be combined in an ASOPS system. The wide range of available optical wavelengths and the broad temporal dynamic range ensured by the fast electronic sampling technique make our ASOPS system a powerful tool for spectroscopic applications.

MENLO SYSTEMS' LASER SELECTOR



ORDERING INFORMATION

ASOPS TWIN 250

Asynchronous Optical Sampling System

ASOPS DUAL COLOR

1560/780 Asynchronous Optical Sampling System

TERAHERTZ TIME-DOMAIN SPECTROSCOPY (THZ-TDS) AND IMAGING

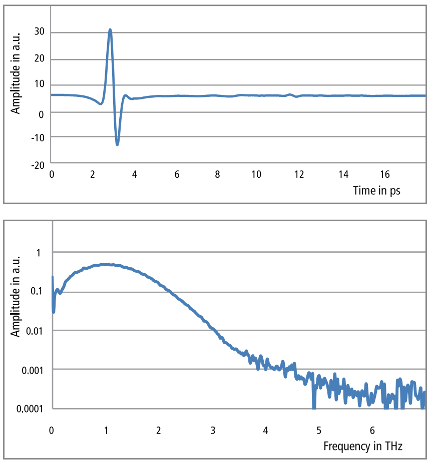
CLOSING THE GAP BETWEEN THE INFRARED AND MICROWAVES

The unique properties of terahertz electromagnetic radiation open up a novel approach in material investigation. Located in the frequency range between 100 GHz and tens of THz, terahertz waves are non-ionizing and therefore safe to use. They are reflected by metals and have a large penetration depth in various materials such as polymers, paper or some liquids, which makes them ideally suited for non-destructive imaging application. If applied in spectroscopy, a characteristic fingerprint of chemical substances is obtained due to the frequency-dependent transparency and refractive index of materials in the terahertz range.

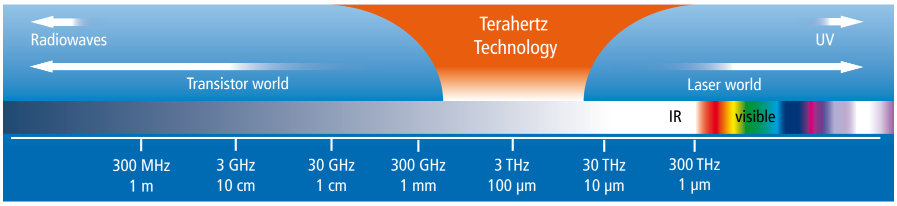
The underlying physical phenomena observed at THz frequencies represent an interface between electronics and photonics. Efficient THz generation technologies have been developed in the recent years. The radiation properties vary according to the generation mechanism. Moreover, specially designed optical components are needed to maintain the full potential of the application such as THz bandwidth, beam quality and intensity.

APPLICATION FIELDS OF THZ-TDS AND IMAGING

- characterization of biological, chemical or pharmaceutical samples
- quality control in food industry
- material inspection in synthetic material production
- homeland security
- THz-ASOPS
- ultrafast processes in solid state physics



Temporal shape of a THz pulse (above) translated into the spectral domain via Fourier transformation; obtained with TERA 8-1 THz emitter and detector modules.



MENLO SYSTEMS TECHNOLOGY FOR BROADBAND-THZ APPLICATIONS

Our THz products incorporate our expertise in femtosecond lasers based on Erbium-doped fiber technology. Together with our collaboration partners from the Fraunhofer Society, we continually work on the development of photoconductive antennas for THz generation. We distinguish between two different technologies, with LT-grown GaAs antenna substrates for the 800 nm laser wavelength and novel InGaAs/InAlAs multilayer mesa structures for 1560 nm lasers.

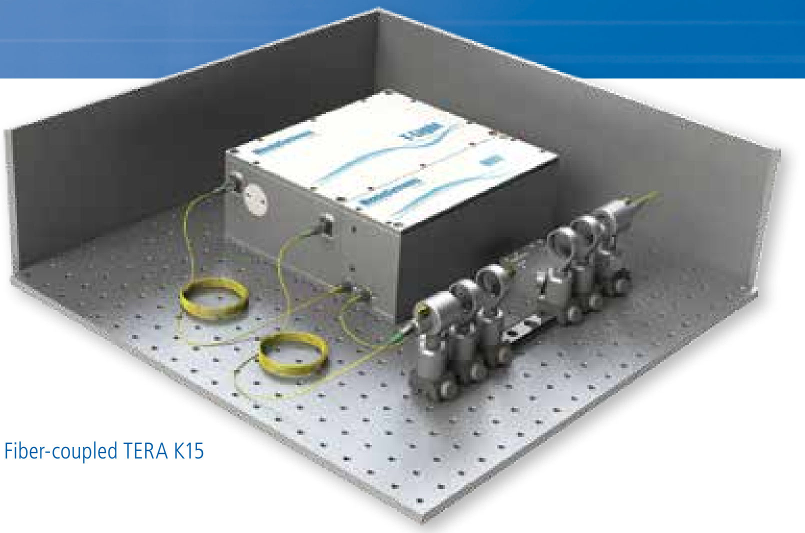
In order to best meet our customers' experimental demands, our THz spectrometers can be operated flexibly in transmission and reflection geometry. Fully automated measurement, data acquisition and evaluation are integrated into the setup.

FIND THE PERFECT SOLUTION FOR YOUR MOST DEMANDING APPLICATION

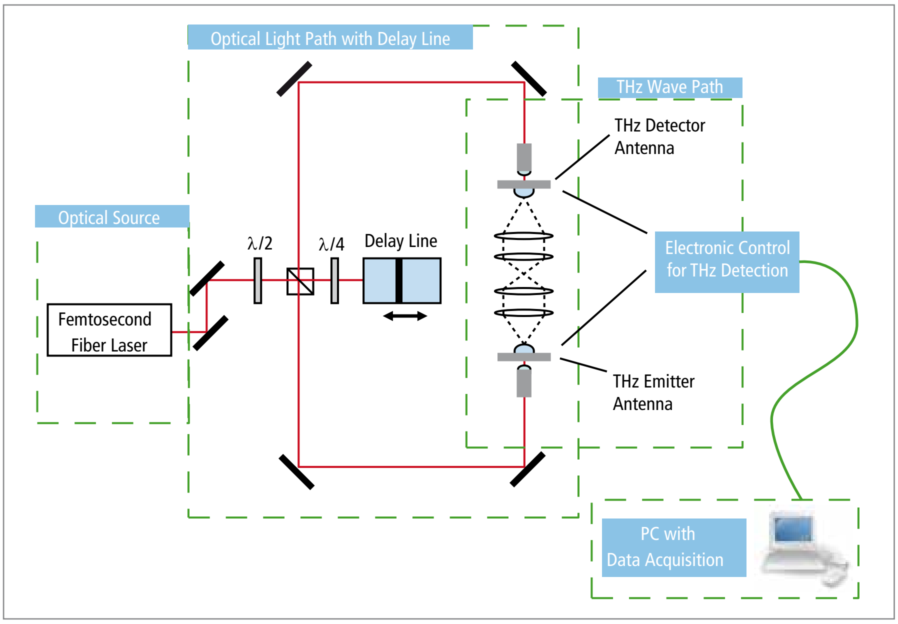
Menlo Systems provides complete solutions for THz time-domain spectroscopy and imaging. Choose your system and we configure the setup for optimal performance.

THZ-TDS DATA EVALUATION SOFTWARE

Menlo Systems' novel THz software, the TeraLyzer developed by LyTera, empowers the characterization of sub-100 µm and multilayer samples for extraction of the thickness and THz parameters n, α, κ, ε' and ε'' in a standard THz-TDS setup. The software is compatible with our TERA K15 and TERA K8 terahertz spectrometers.

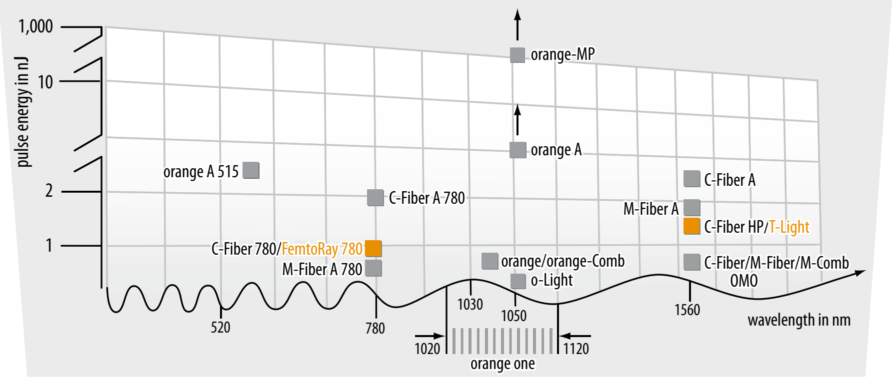


Fiber-coupled TERA K15



Schematic layout of the TERA K8 system: the laser output pulses are split and delayed with respect to each other. The laser light is focused onto the THz antenna for emission and detection. The sample is placed in the focus of the THz path, the transmission spectrum of a sample is recorded with data acquisition electronics.

MENLO SYSTEMS’ LASER SELECTOR



TERA K15:

- all-fiber coupled solution for high flexibility of measurements with minimal alignment effort
- easy switching between transmission and reflection geometry
- integrated laser model: T-Light

TERA K8:

- scientific open-platform kit
- highest bandwidth performance
- integrated laser model: T-Light 780

TERA Image:

- fully automated THz-imaging unit
- non-destructive visualization of sample material quality and composition
- optional upgrade for both our terahertz kits

ORDERING INFORMATION

TERA K15

Complete All-fiber-coupled THz System

TERA K8

Complete THz System using Free Space Optics

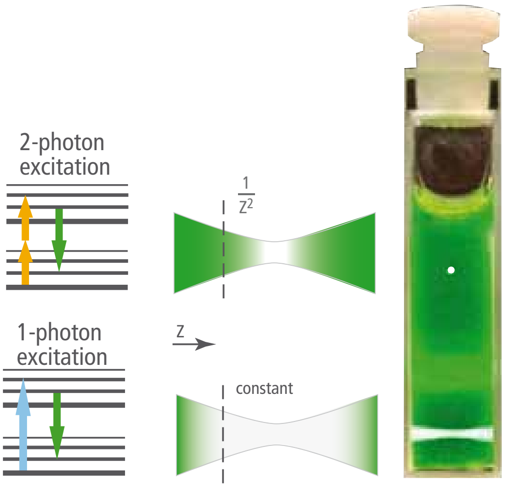
TERA IMAGE

Fully Automated Extension Unit for THz Imaging

TERALYZER

THz-TDS Data Evaluation Software

MULTIPHOTON APPLICATIONS

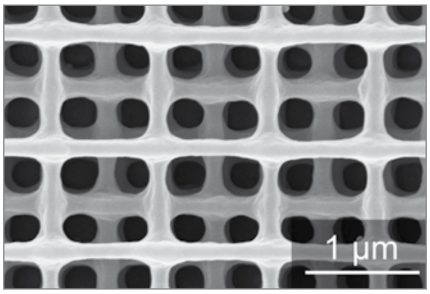


NANOMETER SCALE RESOLUTION

Laser material processing and investigation with sub-micrometer resolution requires a confined energy deposition volume of the light into the specimen. With multiphoton effects an in-plane sub-micrometer resolution is combined with an equally high lateral resolution enabling three-dimensional (3D) nanometer precision of the application, ranging from clean ablation profiles on surfaces to biological tissue imaging. Furthermore, due to the energy selectivity of the processes triggered by multiphoton interaction, a larger penetration depth, reduced photobleaching and phototoxicity open up novel application fields such as 3D polymer nanostructuring and in-vivo biological treatment.

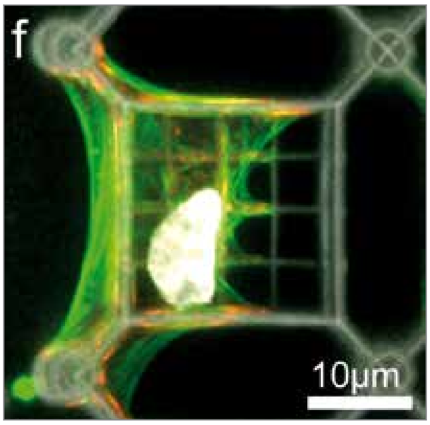
3D LASER LITHOGRAPHY

The direct laser writing process makes use of laser pulses with energy below the absorption threshold of the photosensitive material. The illuminated material is transparent for the light. Only by focusing the ultrashort light pulses to a small focal spot, multiphoton absorption processes in a very localized volume can be triggered. The process allows engineering almost arbitrary 3D structures out of various photosensitive materials such as SU-8, Ormocere, PDMS, and chalcogenide glasses. Furthermore, these structures can act as templates for replication (positive–positive) or inversion (positive–negative) processes into other materials like e.g. silica, and silicon. Main applications include the fabrication of 3D photonic crystal structures, the generation of 3D scaffolds and microfluidic channels for biological sciences.



Wood pile photonic crystal out of SU-8.

Image credit: Nanoscribe GmbH

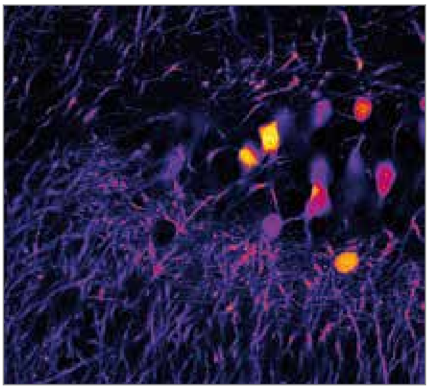


3D tailored environment for the investigation of cell sensitivity to its surroundings.

Image credit: Nanoscribe GmbH

TWO-PHOTON MICROSCOPY

Due to low scattering of the NIR laser radiation and low illumination power, the combination of a large penetration depth and reduced phototoxicity makes two-photon microscopy a key tool for 3D imaging of biological tissue samples. Various fluorescence markers with similar absorption spectra but different fluorescence wavelengths can be used for discrimination of cell organelles.

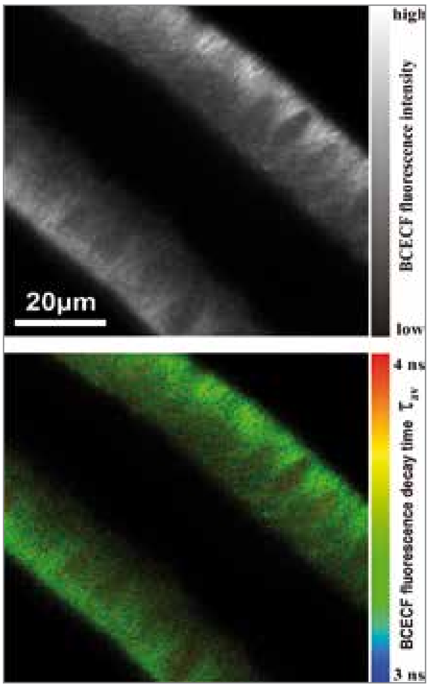


Two-photon image of a mouse brain slice. Various markers can be used to obtain a color coded picture.

Image credit:
Christian Seebacher/BioImaging Zentrum LMU

TWO-PHOTON FLUORESCENCE LIFETIME IMAGING

Fluorescence lifetime imaging microscopy (FILM) offers spectral and fluorescence lifetime discrimination and is a non-invasive



Intracellular pH imaging in cockroach salivary duct cells using 2P-FLIM.

Image credit: Carsten Hille/University of Potsdam

method for lifetime-based sensing. When utilizing the 2P process, fluorescence lifetime can be mapped much more accurately, as contamination with residual fluorescence from the surroundings is eliminated by confining the excitation region. Hille et al., in *Analytical and Bioanalytical Chemistry Vol. 391:1871-1879, 2008,* demonstrated efficient 2P excitation in combination with fluorescence lifetime imaging microscopy.

MENLO SYSTEMS FEMTOSECOND FIBER LASER TECHNOLOGY

The crucial parameters for multiphoton applications are met by ultrashort laser pulses, rendering high peak power and low average power. Menlo Systems provides reliable and affordable femtosecond pulse sources based on fiber laser technology. The key features are:

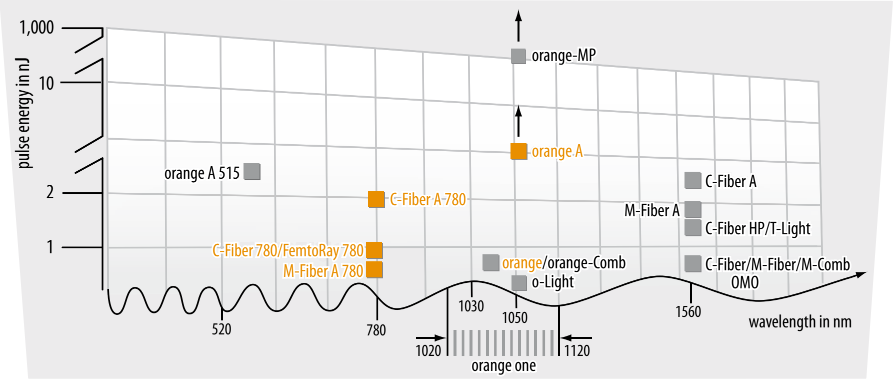
- turnkey-operation by self-starting mode-locking mechanism
- pulse duration well below 100 fs
- high average output power
- ultrastable performance
- low maintenance
- small footprint

FIND THE SOLUTION FOR YOUR APPLICATION

Choose between different output wavelengths from our Erbium and Ytterbium-doped fiber lasers and various classes of output power. The high repetition rate allows for fast processing, customized laser models with lower repetition rates for delicate samples are available on request.

We offer our expertise in ultrafast physics and are ready to become your technology partner in exploring multiphoton applications.

MENLO SYSTEMS' LASER SELECTOR



ORDERING INFORMATION

FEMTORAY 780

Femtosecond Erbium Laser with Frequency Doubler

C-FIBER A 780

Femtosecond Erbium Laser with Frequency Doubler

orange

Femtosecond Ytterbium Laser

MICROJOULE FEMTOSECOND FIBER LASERS

LASER MICROMACHINING

Laser micromachining is defined as laser cutting, drilling, etching, stripping, and skiving materials such as plastic, glass, ceramic, thin metal, and biological tissue with dimensions ranging from 1 µm to 1 mm. To drive such processes with micrometer resolution, not only a very precise control of the machining tool and sample is required, but also processes like heat diffusion must be limited to these dimensions.

Ultrashort laser pulses have durations below 1 ps, typically between 100 fs and a few hundred fs. At this time scale new possibilities emerge. Precision machining of nearly all materials becomes available. Whereas in most areas picosecond or even nanosecond lasers still dominate the market there are applications in medical and, most recently, also industrial machining where femtosecond lasers seem to be most promising candidates to achieve better results.

To understand the difference between processes induced by ns/ps lasers on the one hand and fs lasers on the other, one has to look at the interaction process between an ultrashort laser pulse and matter. This process can be divided into four main sections: in the first section the laser pulse hits the target and its energy is deposited in the target. Second, the affected area is undergoing rapid phase transitions forming a plasma. In the third section ablation takes place where the hit material is ejected from the target. Finally, in the fourth section, the plasma is expanding into the surrounding area.

For ultra short pulses, the pulse duration is much shorter than the relaxation time of the electrons in the sample after the energy is deposited. Coupling between the electrons and the lattice can be neglected on this time scale. There is a direct phase transition from the solid state to the plasma. No heat diffusion into surrounding areas is taking place. As a consequence a very precise interaction can take place, which is truly limited to the area hit by the pulse. Further, it can be shown that the ablation depth depends logarithmically on the absorbed laser power. Due to this weak dependence, the ablation depth can be controlled very precisely by varying the pulse intensity.

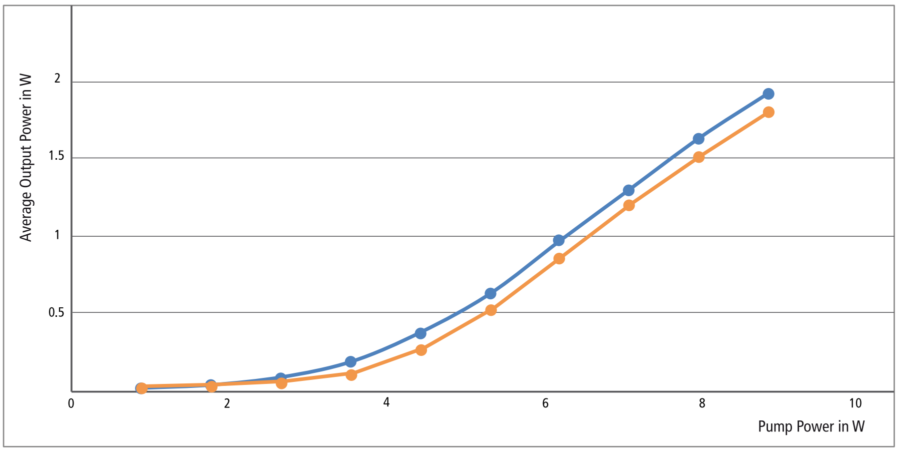
For picosecond lasers, the interaction time is already on the order of the electron relaxation time. Therefore, the heat diffusion to neighboring areas cannot be neglected anymore. In drilling, for example, this leads to effects that smear out the area of the laser interaction.

Applications range from the fabrication of computer chips to real-time contact-free treatment of biological tissue, as in cell dissection and eye surgery. In a technique called laser-based nano-dissection the gentle and contact-free manipulation of cells and cell structures has become available with the advances in fs laser sources.

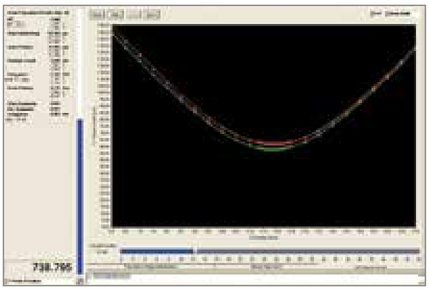
MENLO SYSTEMS' FIBER-BASED SOLUTION FOR HIGH ENERGY FEMTOSECOND PULSES

There are several laser architectures such as solid state or dye lasers generating microjoule ultrashort pulses. Menlo Systems' approach is based on an Ytterbium-doped Master Oscillator Power Amplifier (MOPA). Starting with a Ytterbium-doped fs fiber oscillator with MHz repetition rate and low pulse energy we reduce the repetition rate to the kHz regime and increase the pulse energy to the microjoule level in a multiple step, pulse picking and amplification process.

Menlo Systems' high energy solution. A pulse picking unit is gating the output pulses such that the repetition rate is decreased. An amplifier stage increases the energy to the microjoule regime.



Average output power for different pump powers at 1 MHz (blue) and 100 kHz (orange). By reducing the repetition rate the energy is concentrated in the remaining pulses.

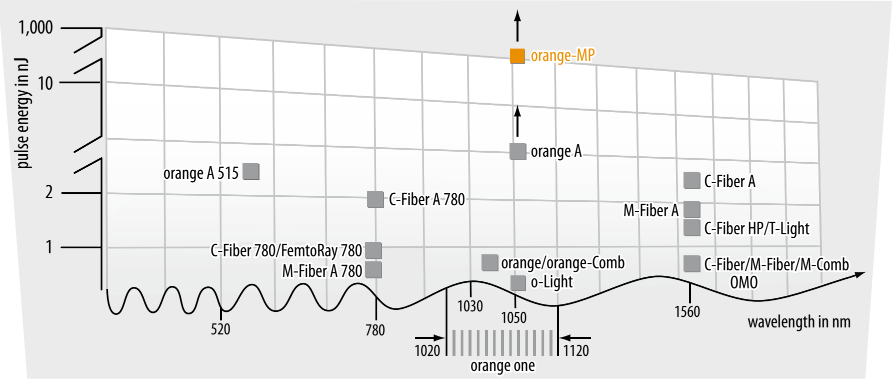


Beam quality analysis of the amplified laser output, measured M^2 value is <1.05.

All steps are realized in fiber technology except for the final step, where the pulse length is compressed to the 100 fs regime in a free space compressor. The whole system uses integrated diodes as pump sources. The fiber approach allows for a robust setup with minimal footprint.

In summary, the fiber technology seems to be ready for a revolution in laser micromachining. Currently still missing is the availability of reliable, truly industrial and cost effective fs laser sources. We do our best to make these sources available to our customers.

MENLO SYSTEMS' LASER SELECTOR



ORDERING INFORMATION

ORANGE-MP

Ytterbium Fiber Laser System

COOLING ATOMS AND IONS

ULTRASTABLE SINGLE FREQUENCY LASERS

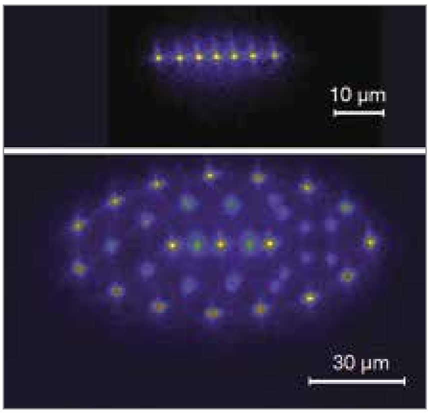
The fields of ultrafast and continuous wave (cw) lasers were nearly separate studies for many years. However, with the invention of the frequency comb, both of these communities have recently come back together to explore new scientific fields.

For many experimental applications, such as laser cooling and trapping of atoms and ions, a narrow line width, a stable frequency and performance of the laser are crucial. In cooling mechanisms, e.g. Doppler cooling or Sisyphus cooling, the desired transition energy needs to be precisely addressed, while in trapping, the (multiple) potential minimum created is used to localize the particles.

In many cases the atoms or ions that need to be cooled cannot be addressed directly or have transitions that decrease the efficiency of a direct cooling method. This can be overcome if the excess energy is deposited onto a different species of efficiently cooled ions, by the principle of sympathetic laser cooling. It makes use of either vibrational coupling or Coulomb interaction and the centrifugal force in a rotating RF-trap, where heavier ions form a shell confining lighter ions in the center of the trap. Energy is removed from the particles in the center indirectly via the surrounding heavier particles by the cooling laser.

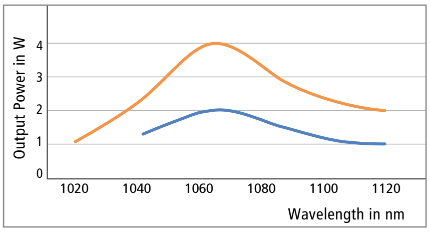
SYMPATHETIC ION COOLING WITH MG+ IONS

Mg+ ions are often used for sympathetic cooling as their cooling transition can be reached by frequency doubling an 1120 nm laser twice to 280 nm. In particular, this is a useful application for cooling lighter charged atoms such as Li and Be. Although Li has atomic transitions that would allow it to be laser cooled directly, cooling Li sympathetically using Mg+ has the advantage of not having a strong (high power) cooling beam of the same wavelength as the investigating laser beam. Furthermore, the atomic transitions in Be are difficult to address directly due to the lack of suitable optical sources, while sympathetic cooling enables experiments.



Strong optical transitions of Mg+ can be used for laser cooling. Shown are two ion crystals within a Paul trap after Doppler cooling. Having lasers with a narrow linewidth and a precisely controllable frequency, the motional ground state can be reached by sideband cooling – opening the door for quantum information processing with Mg+ ions (work done by the Schätz group at MPQ). Other ion species, like Li may not allow for effective laser cooling but can be cooled sympathetically by Mg ions within the same trap.

Image credit: Tobias Schätz/Max-Planck-Institute of Quantum Optics



The wavelength selectability of the orange one-2 laser model (orange curve) and orange one-1 (blue curve) with 1–4 W continuous wave output in the wavelength range between 1020 and 1120 nm.

LEARNING FROM EXPERIENCE AND BUILDING NEW TECHNOLOGY

Menlo Systems has listened to the experts in both the ultrafast and the cw world. Combining the experience on fiber lasers and the frequency comb technology, our cw fiber laser is the missing link between these fields. We have designed a two-stage amplifier system which is seeded by an ultra narrow line width, single frequency fiber laser module. The result is the ***orange one*** product line, delivering up to 4 W of optical output power in the wavelength range of 1020 nm–1120 nm with an optical line width below 100 kHz.

DEVELOPING CONVENIENT AND RELIABLE STANDARD PRODUCTS

The extremely narrow line width of the orange one laser combined with its low noise and stable performance makes it an ideal tool for many atomic physics experiments.

In constant dialogue with researchers in the field we learn about the demands of the latest scientific experiments. Some of our customers who bought our ***orange one*** model frequency doubled the output to 560 nm using an LBO crystal. In response, we developed the orange one-SHG where the IR-output is frequency doubled in a fiber coupled waveguide. A further doubling of the frequency finally allows access to the 280 nm transition in Mg+.

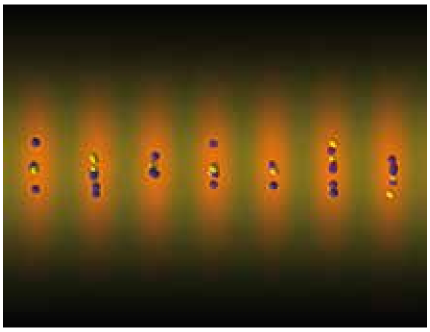
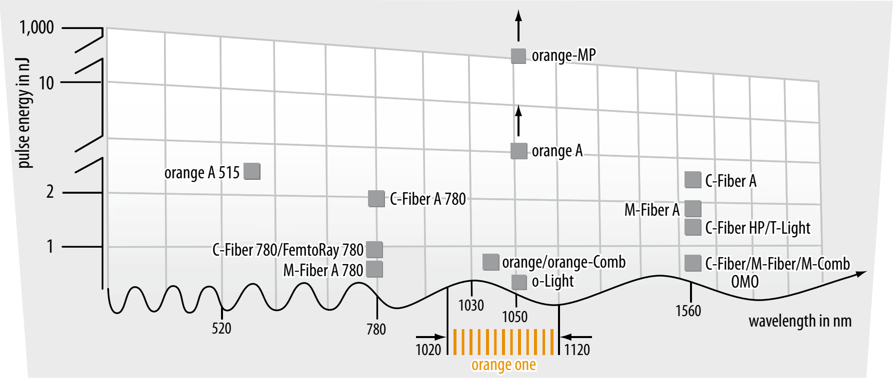


Illustration of a lattice of laser beams trapping small numbers of atoms in pancake-shaped "wells." The laser excites the atoms so that they switch between lower (blue) and higher (yellow) energy levels.

Image credit: NIST

MENLO SYSTEMS' LASER SELECTOR



ORDERING INFORMATION

ORANGE ONE-1PM
Single Frequency Laser with PM Output

ORANGE ONE-SHG
Single Frequency Laser with Frequency Doubler

ORANGE ONE-1
Single Frequency Laser >1 W Power

ORANGE ONE-2
Single Frequency Laser >2 W Power

LASERS BEHIND THE SOLUTIONS

ROBUST SYSTEMS BASED ON FIBER TECHNOLOGY

The Menlo Systems fiber-based femtosecond laser sources integrate latest achievements in fiber technology into easy-to-use instruments for R&D and industrial applications.

The fiber based ring cavity uses a highly doped fiber as gain media. This gain medium is pumped by fiber coupled laser diodes. The diodes are telecom rated ensuring long life time and trouble-free operation.

To achieve mode-locking and the generation of ultrashort pulses, the intracavity polarization of the laser is controlled and maintained with the help of an embedded microcontroller. The passive mode-locking scheme ensures stable mode-locking over long periods. Changing ambient conditions, vibrations and other external noises and disturbances are counteracted by means of active control. E.g. the laser head is temperature stabilized to suppress the effects of changes in the temperature of the surrounding environment.

FLEXIBLE SYSTEM CONFIGURATIONS

Menlo Systems originally developed the femtosecond fiber lasers to serve as pump sources for its Optical Frequency Synthesizers. The lasers were engineered for and field-tested in high-precision metrology applications. Besides the requirement for low phase-noise operation, parameters such as the repetition rate of the femtosecond pulse train and the phase relation between carrier and envelope of the pulses need to be controlled with an extreme precision allowing for frequency measurements with an accuracy of 10^{-14} or even beyond with the Optical Frequency Synthesizer.

Current product lines combine multiple output ports, high output powers, ultrashort pulses and frequency conversion into different spectral domains. This flexibility is crucial for having a versatile laser system, which enables easy reconfiguration for a wide range of tasks.

Two product lines of pulsed laser systems are available. One is based on Erbium as active gain fiber with a broad emission spectrum around 1560 nm. The other is based on Ytterbium where the emission is centered around 1030 nm.

STANDARD MODELS

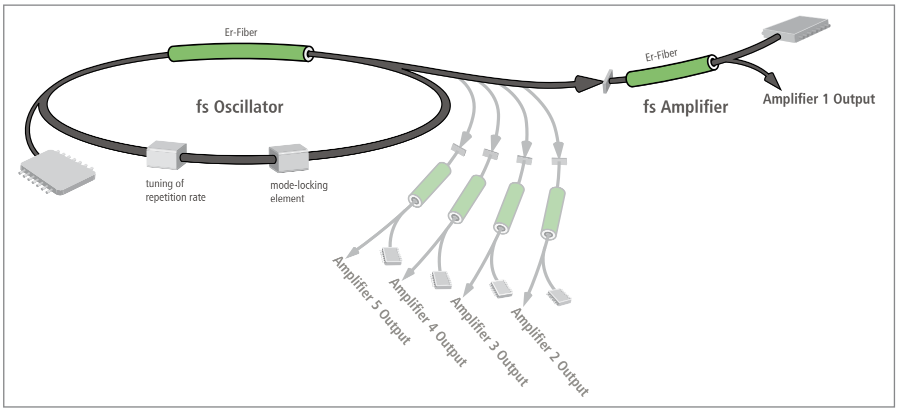
In addition to laser systems tailored for specific user demands, we marked out a number of standard models, see Laser Selector on opposite page.

KEY PARAMETERS AT A GLANCE

Repetition Rate:
- 50 MHz, 100 MHz, 250 MHz
- free-running & phase-locked operation available, user-defined repetition rates available

Center Wavelength:
- fundamental wavelengths at 1560 nm or 1030 nm
- frequency doubled output to 780 nm or 515 nm
- supercontinua in the NIR and VIS spectral range
- output shifted to user-defined wavelengths

Pulse Duration: 50-200 fs



Schematic illustration of the fiber ring oscillator, capable of seeding up to five amplifiers.

The compact laser models (T-Light, FemtoRay 780 and o-Light) are coming with set parameters and their minimalistic approach makes them the most economic choice in the market. The benefits are most obvious in the context of industrial applications where reliability, compact size and economic use become key factors.

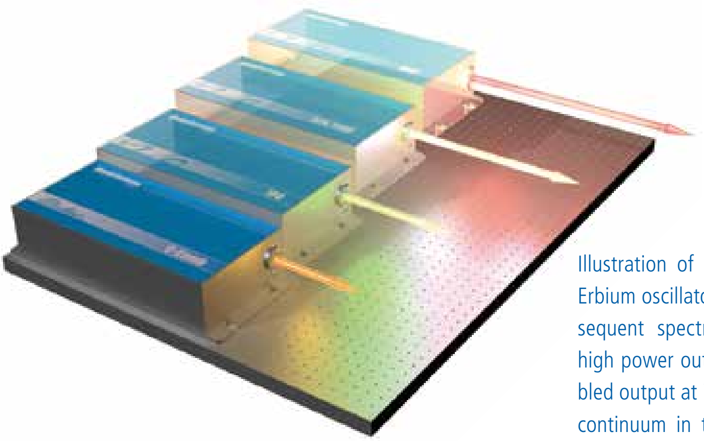
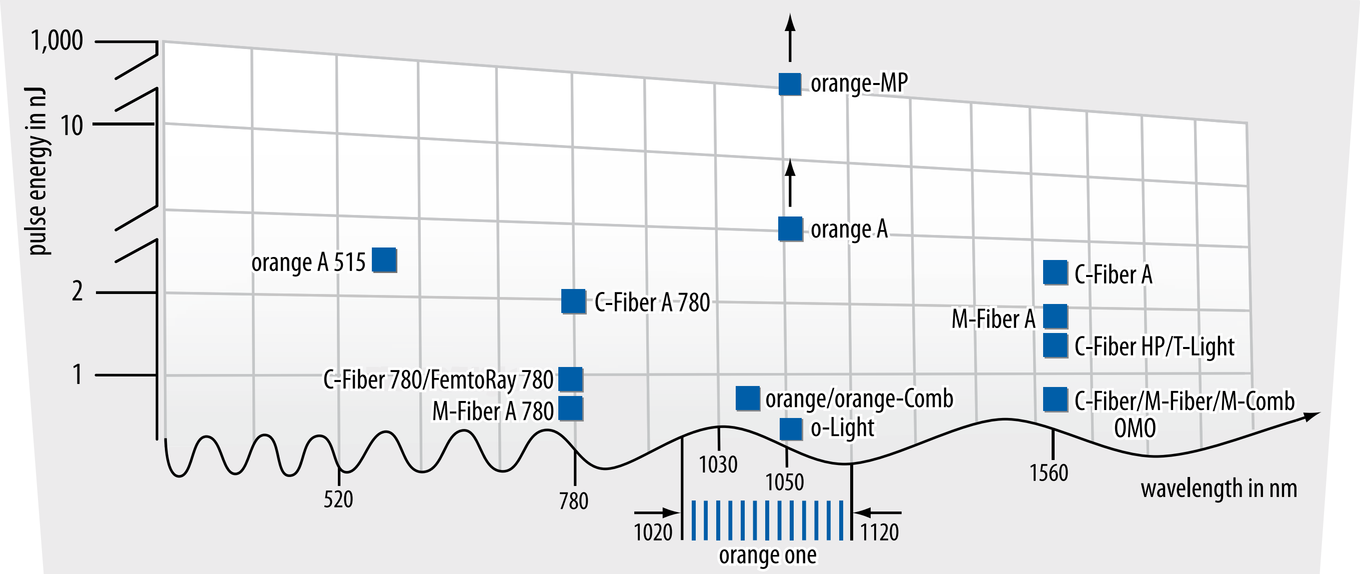


Illustration of a fiber laser system based on an Erbium oscillator with optional amplifiers and subsequent spectral conversion modules providing high power output at 1560 nm, a frequency-doubled output at 780 nm, an octave-spanning supercontinuum in the 1–2 µm range and a Raman-shifted output in the near infrared to a wavelength beyond 1560 nm.

MENLO SYSTEMS' LASER SELECTOR

The laser chart below facilitates selecting the most suitable source. The available wavelengths are plotted horizontally, while the vertical positions correspond to the energy levels in a single laser pulse. After locating the model of interest, please refer to the online data sheets at www.menlosystems.com or contact us.

MENLO SYSTEMS' LASER SELECTOR



NARROW LINEWIDTH CONTINUOUS WAVE LASERS

Over the years many customers have approached us for narrow linewidth, high power fiber lasers. Combined and locked to the Optical Frequency Synthesizers such lasers allow e.g. for manipulation of cold atoms with highest precision. This has been the start for our third product line within the fiber lasers that features an integrated, narrow linewidth, single frequency fiber laser which is followed by a multiple step amplification scheme. This allows for several W of output powers within the Ytterbium gain spectrum. We have specialized on the longer end of the gain spectrum going to wavelengths up to 1120 nm. Frequency conversion into the visible spectral range is available by an integrated second harmonic generation (SHG) module with highest conversion efficiency using fiber technology.

Current work focuses on extending the wavelength range to 2 µm, using Thulium-doped fiber as gain medium.

Again, for latest specifications please refer to the online data sheets at:
www.menlosystems.com or contact us.

A SHORT STORY ABOUT MENLO SYSTEMS

Menlo Systems GmbH is a spin-off from the renowned Max-Planck-Institute for Quantum Optics. Professor Theodor W. Hänsch, director of the institute, and his co-workers have pioneered a revolutionary and simple technique for measuring the frequency of light: the Optical Frequency Synthesizer. This invention has been called "...the biggest advance in precision electromagnetic measurements since people began to measure laser frequencies in the seventies..."

In 2001, Professor Hänsch, Dr. Ronald Holzwarth, and Dr. Michael Mei founded Menlo Systems GmbH. The founding was guided by the dream and vision of establishing optical frequency comb technology as the most precise measurement tool.

The commercial success story started with the first product in 2002: the Optical Frequency Synthesizer. It enables the user to measure optical frequencies with the highest accuracy with a table top instrument. Numerous world records in precision measurements have been achieved with its base technology, e.g. in the determination of the Rydberg constant.

The headquarters of Menlo Systems in Martinsried outside Munich.

Second in the product line were the femtosecond fiber lasers. The state-of-the art instruments focus on ease-of-use without sacrificing performance. Various models for applications like medical diagnostics, terahertz spectroscopy, seeding of amplifiers, and test and measurement applications are available.

The ongoing dialog with our customers encourages us to venture into new areas. As a result, whole new products keep emerging and the range of our products now includes THz systems as well cw fiber lasers.

Menlo Systems opened its US subsidiary in late 2006 to establish a direct line to its customers in North America. Located in Newton, New Jersey the new US office helps to grow the company and to continue its success in the American market.

In 2011, starting with more than 60 employees into the second decade of its operation, Menlo System will continue having a strong presence in Europe, North America and Asia.

Femtosecond optical frequency combs have led to a revolution in our ability to measure the frequency of light. This new approach vastly enhanced and simplified optical metrology, and enables new directions in physics.

Michael Mei and Ronald Holzwarth

The management team of Menlo Systems consists of Dr. Mei and Dr. Holzwarth. Strong business building expertise is added by Alex Cable, the founder and president of Thorlabs.

Menlo Systems still has a strong bond to the research community centered around Professor Hänsch, who is heading the scientific advisory board of Menlo Systems. The board supports and provides valuable counsel for us on achieving our mission 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, which mission has been our driving force over the years.

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

Theodor W. Hänsch

First demonstrated in 1999

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. 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 in 2005.

Excitement is not measurable. Light is.

Menlo Systems, a leading developer and global supplier of instrumentation for high-precision metrology, was founded in 2001 as a spin-off of the Max Planck Institute for Quantum Optics, with the foremost aim to commercialize optical measurement technologies and make it available to newly emerging application fields. Menlo Systems maintains a strong bond to co-founder Theodor W. Hänsch, who pioneered precision laser techniques.

Known for the Nobel Prize-winning optical frequency comb technology, the Munich-based company offers complete solutions based on ultrafast lasers and synchronization electronics. Applications for our products and solutions span from research laboratories to truly industrial tasks. The patented technology is recognized by global laser manufacturers to whom we deliver OEM solutions for integration into cutting-edge products.

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www.frequencycomb.com

Version 5