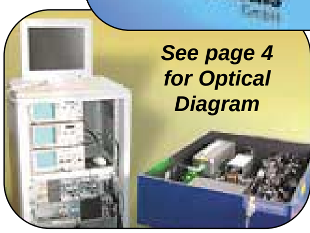
www.menlosystems.com

MenloSystems GmbH



Menlo Systems GmbH was founded in 2001 as an outgrowth of Prof. Theodor Hänsch's optical measurement research at the Max Planck Institute for Quantum Optics in Munich Germany. The founding partners are Theodor Hänsch, of Max Planck and Ludwig Maximilian's University, Alex Cable President/Founder of Thorlabs, Michael Mei, Ronald Holzwarth, and Bruno Gross, all of the Max Planck Institute for Quantum Optics. The company's expertise is in extraordinarily precise optical measurement techniques and instrumentation.

FC8003 Optical Frequency Synthesizer

The FC8003 Optical Frequency Synthesizer allows the user access to optical frequency measurement techniques with unprecedented accuracy and flexibility. This novel, extraordinarily precise technology can be implemented in applications such as frequency chain generation, optical atomic clocks and ultra high precision spectroscopy.

- Measures/generates optical frequencies with unprecedented accuracy (up to 14 digits) and stability (up to $4x10^{-13}$ in 1s).
- Optical Frequency Comb Generation
  Provides 500,000 precise laser lines with variable spacing.
- The FC8003 multiplies a radio frequency reference into the optical region.

Specifications for the FC8003 femtosecond laser based optical frequency synthesizer are detailed below:

Comb frequency spacing:	1GHz
Accessible optical range:	532, 633, 780, 800 or 1064nm (one at a time)
Accuracy:	10^{-14} or same as reference, whichever applies first.
Stability:	$4x10^{-13}$ in 1 sec. or same as reference, whichever applies first.
Wavemeter unit:	Absolute accuracy: 1GHz, Resolution: 300MHz

When beating the comb with an SM-diode laser (output > 2mW) or any other comparable optical signal to be measured, an SNR of >30dB in 100kHz bandwidth will be achieved.

Operating principle

The **FC8003** technology is based on a femtosecond laser frequency comb. To understand the mode structure of a femtosecond (fs) frequency comb, and the techniques applied for its stabilization, one can look at the idealized case of a pulse circulating in a laser cavity with length L with a carrier frequency ω_c as shown below in Figure 1.

The output of this laser is a sequence of pulses that are essentially copies of the same pulse separated by the round trip time $T=v_g/2L$ where v_g is the cavity's mean group velocity defined by the round trip time and the cavity length. The pulses, however, are not quite identical. This is because the pulse envelope $A(t)$ propagates with v_g while the carrier wave travels with its phase velocity.

As a result the carrier shifts with respect to the pulse envelope after each round trip by a phase angle $\Delta\varphi$ as shown in Figure 1. Unlike the envelope function, which provides us with a more rigorous definition of the pulse repetition time $T = \omega_r^{-1}$ by demanding $A(t)=A(t-T)$, the electric field is, in general, not expected to be periodic in time. If the periodicity of the envelope function is assumed, the electric field at a given place outside the laser resonator can be written as:

$$E(t) = \mathrm{Re}(A(t)\exp(-i\,\omega_c\, t)) = \mathrm{Re}(\textstyle\sum_n A_n \exp(-i\,(\omega_c+n\omega_r)\,t)) \qquad \text{Eq. 1}$$

Where A_n are Fourier components of $A(t)$. This equation shows that, under the assumption of a periodic pulse envelope, the resulting spectrum consists of a comb of laser modes that are separated by the pulse repetition frequency.

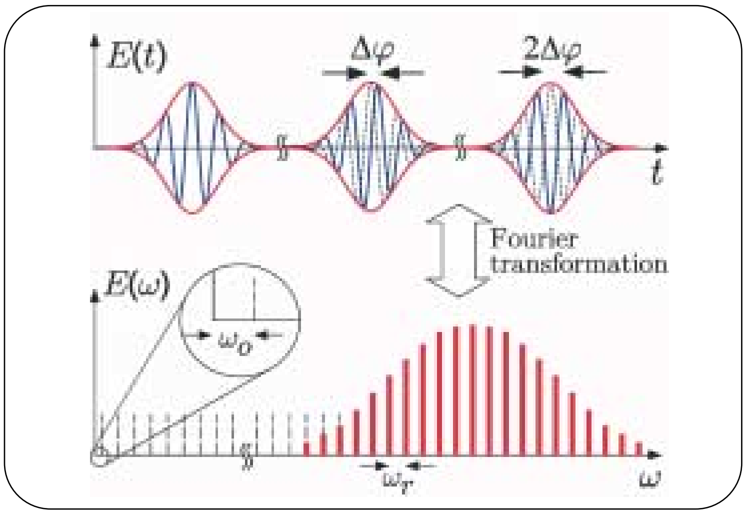


Figure 1

Figure 1: Consecutive pulses of the pulse train emitted by a mode locked laser and the corresponding spectrum, see top view of Figure 1. As the carrier wave at ω_c moves with the phase velocity, while the envelope moves with a different group velocity, the carrier wave (shown in blue) shifts by $\Delta\varphi$ after each round trip with respect to the pulse envelope (shown in red). Bottom view of Figure 1: This continuous shift results in a frequency offset $\omega_o=\Delta\varphi/T$ of the comb, hence exact harmonics of the pulse repetition frequency ω_r are not obtained, see bottom view of Figure 1 and Equation 2 on the next page [9,10,34,35,36].

Since ω_c is not necessarily an integer multiple of ω_r, the modes are shifted from being exact harmonics of the pulse repetition frequency by an offset that can be chosen to obey $\omega_o < \omega_r$ simply by renumbering the modes:

$$\omega_n = n\omega_r + \omega_o \qquad \text{Eq. 2}$$

where n is a large integer ($\approx 10^6$). This equation maps two radio frequencies ω_r and ω_o onto the optical frequencies ω_n. While ω_r is readily measurable, and usually lies between a few 10's of MHz and a few GHz, depending on the length of the laser resonator, ω_o is not easy to access unless the frequency comb contains more than an optical octave.

The intuitive picture given here can even cope with a frequency chirp, i.e. a carrier frequency that varies across the pulse. In this case the envelope function becomes complex in value and the comb structure derived above stays valid provided the chirp is the same for all the pulses. Under this assumption, which is reasonable for a stationary pulse train, $A(t)$ remains a periodic function.

Spectral broadening due to self phase modulation via the intensity dependent index of refraction in an optical fiber is used to increase the width of the frequency combs.

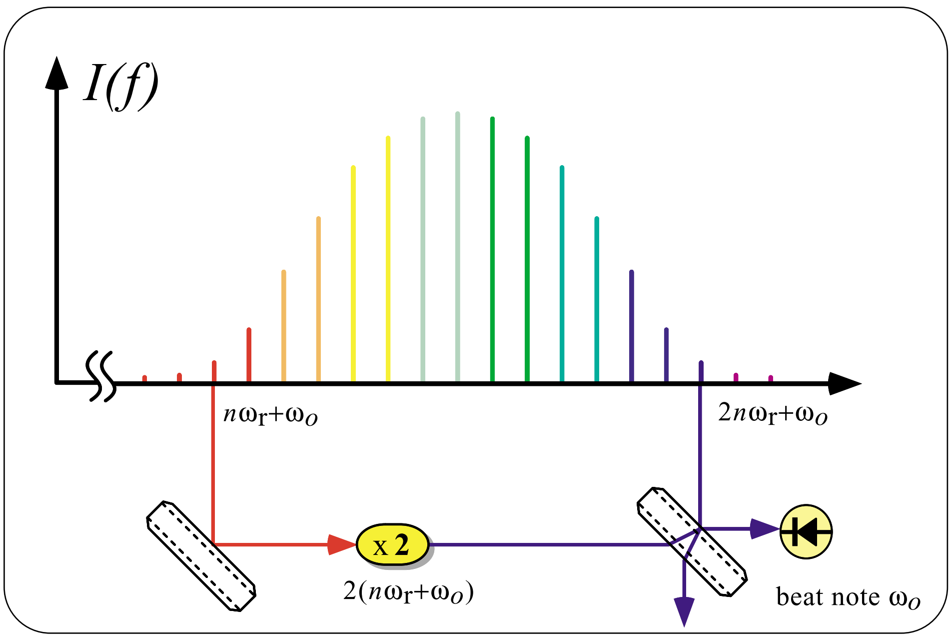


Figure 2

Figure 2: The principle of the optical frequency synthesizer: A mode with the mode number n at the red wing of the comb and whose frequency is given according to Equation 2 by $\omega_n = n\omega_r + \omega_o$ is frequency doubled in a non-linear crystal. If the frequency comb covers a full optical octave a mode with the number $2n$ should oscillate simultaneously at $\omega_n = 2n\omega_r + \omega_o$. The beat note between the frequency doubled mode and the mode at $2n$ yields the offset frequency $2(n\omega_r + \omega_o) - (2n\omega_r + \omega_o) = \omega_o$.

To achieve a stabilized frequency comb two free parameters, i.e. the comb spacing and the comb offset have to be stabilized. To gain access to the offset frequency we frequency double the infrared part of the comb and observe a beat with the blue part (see figure). This is done in a nonlinear interferometer. Both parameters are subsequently phase locked by controlling the cavity length and the pump power.

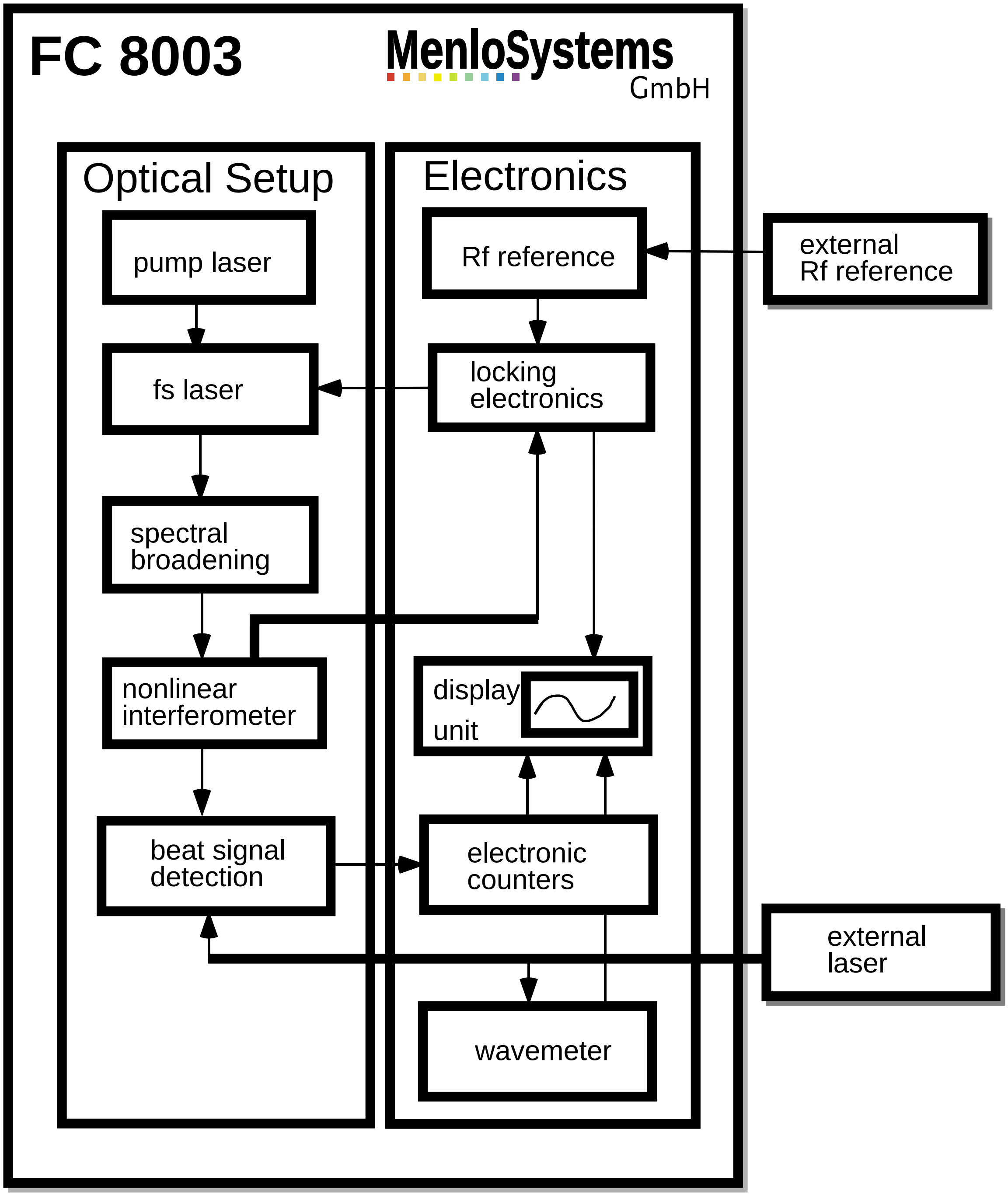
The **FC8003** system has been developed and fully characterized in the Frequency Chain Lab at the Max-Planck-Institute for Quantum Optics (MPQ) in Munich,Germany; see reference Holzwarth et al., PRL 85, 2264, 2000.

System Description

The **FC8003** is housed in a compact box measuring 900mm x 700mm x 300mm. This system includes the following major components:

- Femtosecond laser system
- Green pump laser (Coherent, Inc, model Verdi)
- Photonic crystal fiber for spectral broadening
- Nonlinear interferometer creating the second harmonic of the infrared part of the pulse a and generating a beat signal with the green part thereby giving access to the offset frequency of the frequency comb.
- AOM and driver for amplitude modulation of the pump beam
- Phase detector to phase lock the offset frequency
- Lock boxes (PI circuits) to phase lock the repetition frequency and the offset frequency to a radio frequency reference provided by the customer.
- Counter without dead time to check the phase locks for lost cycles and count the beat signal with the external source to be measured.
- High voltage source for piezo actuator and avalanche photo diodes.
- Intelligent display units.
- Computer read out of the counter units and the optional wavemeter.
- All other mechanical, optical and electronical parts are provided for trouble-free self assembly, including temperature stabilization and cycle slip counter.

Note: GPS controlled radio frequency oscillator and wavemeter for coarse frequency determination can be provided as an option.



Menlo Systems GmbH • Schellingstr. 4 • D-80799 Munich/Germany
www.menlosystems.com • Phone: +49 (0)89 32905 295 • Fax: +49 (0)89 32905 255

In the U.S., contact our partners at:

Thorlabs, Inc. • 435 Route 206 • P.O. Box 366 • Newton, NJ 07860
www.thorlabs.com • Phone: 973-579-7227 • Fax: 973-300-3645
Thorlabs contact – Amy Eskilson at aeskilson@thorlabs.com