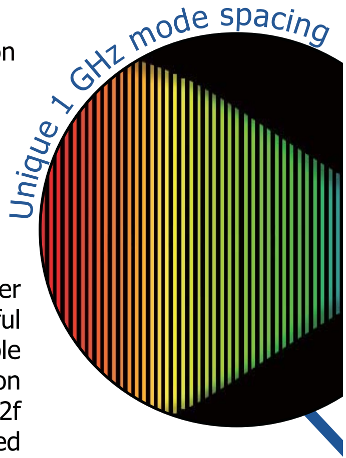
# taccor comb

## High-power frequency comb with 1 GHz mode spacing

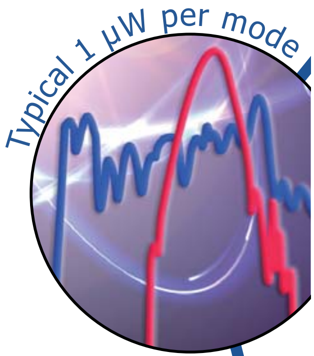
Laser Quantum

- Turn-key GHz femtosecond **taccor** laser
- Extension module for CEO frequency detection and stabilisation
- Repetition rate stabilisation via **TL-1000**
- Large mode spacing of 1 GHz
- High-power per mode (typ. 1 μW)
- Stable and robust



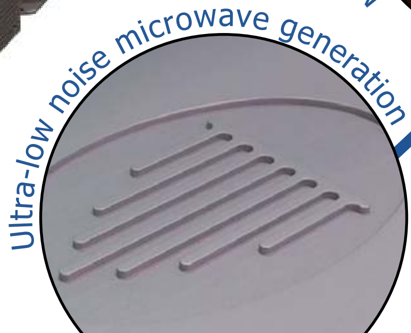

## Overview

To support applications of the **taccor** as a frequency comb, Laser Quantum has added the comb extension module to its successful range of 1 GHz lasers, now making the **taccor comb** available to the market. It consists of a matched dispersion compensation module, supercontinuum generation, and a nonlinear f-to-2f interferometer, all sealed in a compact housing which is attached to the turn-key femtosecond **taccor** laser system. The extension module consumes around 800 mW of the **taccor**'s output power so that up to 1 W can be made available for experiments via a dedicated exit port or can be further broadened to a supercontinuum spectrum using an optional second extension module.




In addition to the repetition rate RF signal at $f_R$, the **taccor comb** provides a long-term stable RF signal at the carrier-envelope offset (CEO) frequency $f_{CEO}$ (Fig. 1) with more than 35 dB signal-to-noise ratio (Fig. 2). Feedback electronics to stabilise $f_R$ and $f_{CEO}$ are provided in the form of Laser Quantum's **TL-1000** unit and the XPS800-E from our partner, Menlo Systems. The **taccor comb** provides the ideal solution for customers who seek to have a comb source with easy access to the visible and NIR spectral range at a high mode power level in a sealed, plug and play architecture. The high repetition rate of 1 GHz leads to a large mode spacing and high power per mode on the order of typically 1 μW after broadening (Fig. 3). The repetition rate of the **taccor comb** also enables generation of significantly more supercontinuum average power in a PCF compared to systems at 100 MHz (100 x more) or 250 MHz (16 x more) before significant coherence loss via nonlinear noise amplification is suffered (Fig. 4). This leads to a significantly enhanced signal to noise ratio for heterodyne beat measurements or direct frequency comb spectroscopy applications.





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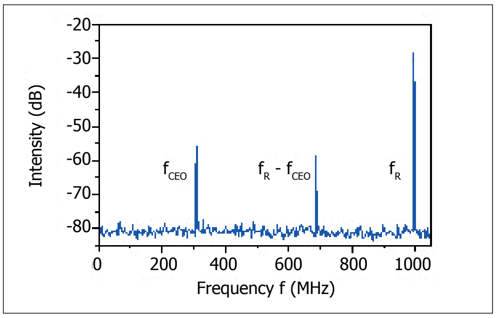


Fig. 1 RF output of the comb module (before amplification and filtering of $f_{CEO}$).

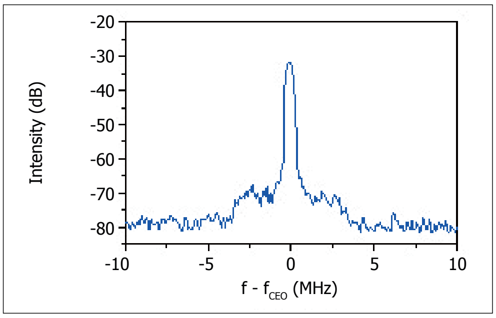


Fig. 2 Close-up of the unlocked $f_{CEO}$ signal after amplification and filtering showing a SNR larger than 35 dB measured with a resolution bandwidth of 100 kHz.

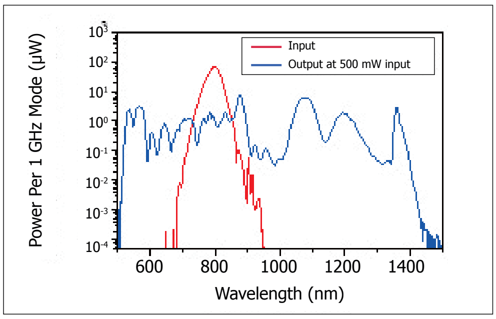


Fig. 3 Red: Typical **taccor** output spectrum used for CEO detection and comb applications. Blue: Output spectrum after 1 m photonic crystal fiber.

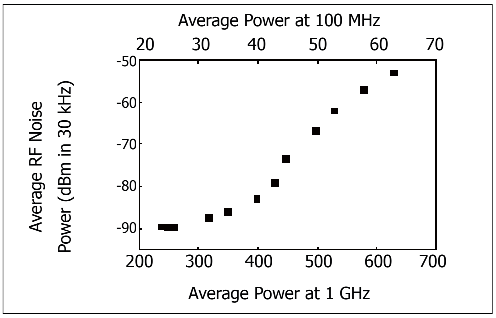


Fig. 4 Typical average RF noise in the CEO detection as function of power coupled through a PCF for supercontinuum generation for a 100 MHz laser (top scale) and a 1 GHz laser (bottom scale). Above a threshold pulse energy of around 30 pJ, nonlinear noise amplification quickly renders the PCF output incoherent, thus heavily favoring a 1 GHz system. Data taken from reference [1].

# Turn-key design for stable performance

The extension module in the **taccor comb** preserves the long-term stability of the turn-key **taccor** laser. The system delivers a stable RF output at $f_{CEO}$ over many days without realignment or signal loss. On a day-to-day basis the **taccor comb** is operated with minimal user interaction and a start-up time of <15 mins until locked in $f_R$ and $f_{CEO}$. The long term stability of $f_R$ and CEO beat lock are shown in Fig. 5a and 5b.

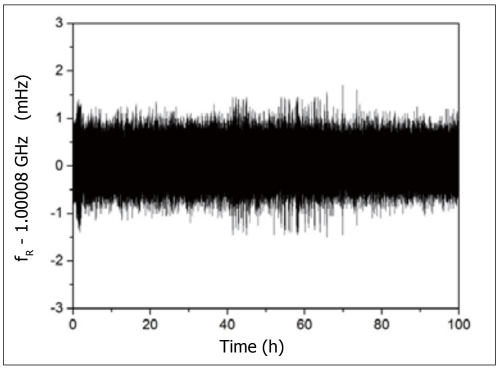


Fig. 5a Long term deviations of the stabilised **taccor** repetition rate over 100 h showing exceptional stability (limited by RF reference input).

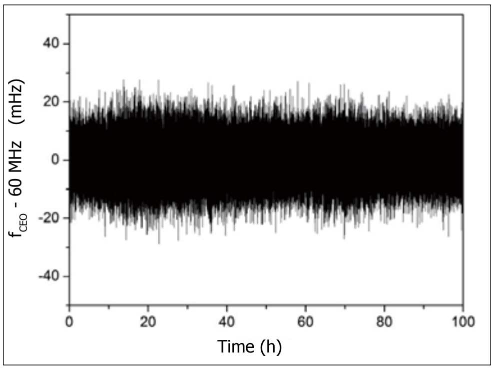


Fig. 5b Long term deviations from the lock point of a CEO beat stabilised at 60 MHz over 100 h showing exceptional stability (limited by RF reference input). No realignment is required for continuous operation of the **taccor comb** over several days.

# Carrier envelope phase stabilisation

The **finesse pure CEP** pump laser built within the **taccor** features our patented CEPLoQ™ technology and allows direct modulation of the 532 nm pump light leading to a faster and more stable response than traditional methods, e.g. using an AOM. Thus, a very high feedback bandwidth can be applied to phase-lock the CEO frequency to an external reference (see Fig. 6).

Phase detection between the measured $f_{CEO}$ and a given reference signal is performed and converted into a feedback signal to the finesse pure CEP input using the XPS800-E stabilisation unit (Menlo Systems). Tight locking of $f_{CEO}$ with a large feedback bandwidth enables the **taccor comb** to show residual integrated phase error of 300 mrad or less (see Fig. 7).

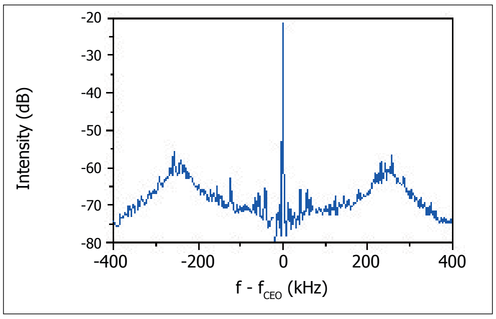


Fig. 6 Close-up of the phase-locked $f_{CEO}$. The data is acquired using a resolution bandwidth of 200 Hz. The servo bandwidth is about 250 kHz as indicated by the symmetrical peaks around the carrier.

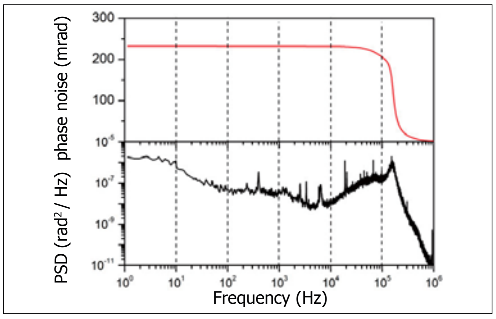


Fig. 7 Frequency resolved and integrated residual phase noise of the stabilised $f_{CEO}$ beat featuring 230 mrad (1 MHz – 1 Hz).

# Repetition rate stabilisation

Laser Quantum offers the timing stabilisation unit, **TL-1000**, as an accessory to the **taccor** series of high-speed femtosecond oscillators. The **TL-1000** allows the tight phase-lock of an oscillator's repetition rate to an external reference such as a synthesiser or another modelocked laser, with a residual timing jitter below 100 fs. A low timing jitter option is available that suppresses the timing jitter to typically below 10 fs (Fig. 8, 9 & 10). A suitable 10 GHz reference synthesiser must be provided by the customer. Stabilisation is performed at a higher repetition rate harmonic.

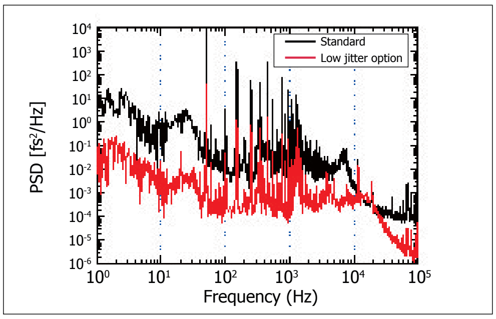


Fig. 8 Phase noise measurements of the **taccor** repetition rate $f_R$ stabilised using the **TL-1000**. Black and red graphs correspond to stabilisation using the standard and low jitter configurations of the **TL-1000** unit.

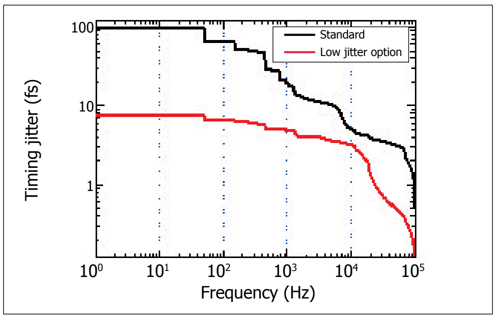


Fig. 9 Timing jitter as acquired by integrating the phase noise from Fig. 8. Stabilisation at the 10th harmonic of $f_R$ leads to a sub-10 fs timing jitter.

# Upgrades

The **taccor comb** can be upgraded by an additional extension module that can include one or two additional photonic crystal fibers for further broadening of the **taccor** laser output, e.g. if a specific supercontinuum spectrum is required for experiments.

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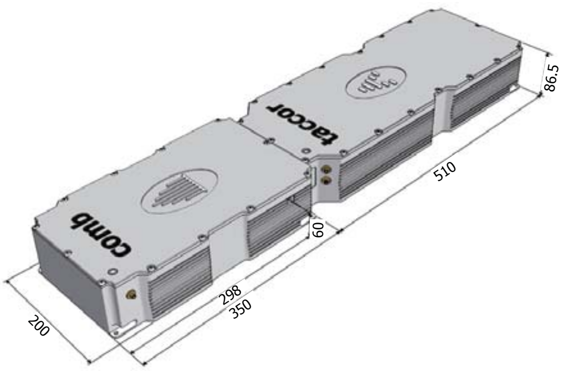
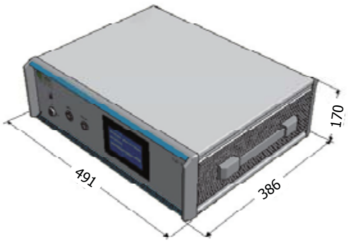
Laser QUANTUM

## Dimensions (mm)




## Other information

- Cooling system included
- f-to-2f interferometer included
- $f_{CEO}$ lock electronics included
- Weight: 50 kg


Drawings are for illustrative purposes only. Please contact Laser Quantum for complete engineer's drawings.

## Specifications*

| | power 8 | power 10 |
|---|---|---|
| Useable 800 nm power after $f_{CEO}$ stabilisation | 600 mW | 1000 mW |
| $f_{CEO}$ beat signal-to-noise (in 100 kHz bandwidth) | >35 dB | |
| Repetition rate/comb spacing | 1 GHz | |
| Tuneability of the comb mode position (@375 THz) | Up to 20 GHz | |
| Residual phase noise [1 Hz - 1 MHz] | Typ. 300 mrad | |
| Supercontinuum power per mode (typ.)* | 100 nW to 1 µW | |
| Supercontinuum wavelength coverage (typ.)* | 520 nm to 1200 nm | |
| Stability | $5x10^{-13}$** in 1 s, or <$2x10^{-17}$*** in 1s | |
| Accuracy | Same as reference**, <$8x10^{-20}$ *** has been demonstrated [2] | |

* With optional supercontinuum module. This option consumes the useable 800 nm power output not required for $f_{CEO}$ stabilisation.
** When $f_R$ is locked to a RF reference. A suitable RF synthesiser must be provided by the customer.
*** When $f_R$ is locked to an optical reference. A suitable optical reference must be supplied by the customer.

## References

[1] L. Hollberg et al., "Optical frequency standards and measurements", IEEE J. Quantum Electron. **37**, 1502 (2001)
[2] L.-S. Ma et al., "Optical frequency synthesis and comparison with uncertainty at the $10^{-19}$ level", Science. **303**, 1843 (2004)

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