Whitepaper

The **taccor comb** - high power frequency comb with 1 GHz mode spacing

***Abstract**: Optical frequency combs based on femtosecond lasers have become invaluable tools in optical metrology and spectroscopy due to their unique ability to phase-coherently, linking the microwave and optical frequency domains. Combs based on lasers with 1 GHz repetition rate provide a unique combination of large mode spacing and high power coherent super-continuum generation. Laser Quantum has introduced the **comb** extension to its successful range of **taccor** 1 GHz femtosecond lasers to provide a professional and complete solution to the market.*

The strictly periodic pulse train emitted by a mode-locked femtosecond laser leads to a perfectly uniform comb in optical frequency space and enables a phase-coherent link between the microwave and optical domains in a stunningly simple manner. This concept has led to the award of the physics nobel prize to Theodor Hänsch and John Hall in 2005 [1].

The Fourier transformation of the electric field emitted by a femtosecond laser yields the relationship

$$f_n = f_0 + n \times f_R$$

for the optical frequencies f_n emitted by the laser. These frequencies are spaced by the laser repetition rate f_R and carry integer mode numbers n with typically 6 to 7 digits. For example, a typical Ti:Sapphire laser with 1 GHz repetition rate, such as the Laser Quantum **taccor** (figure 1), has about 20,000 modes under its spectral envelope with mode numbers around 375,000. The existence of the carrier-envelope offset frequency f_0 is owed to the fact

Figure 1: Laser Quantum's **taccor**

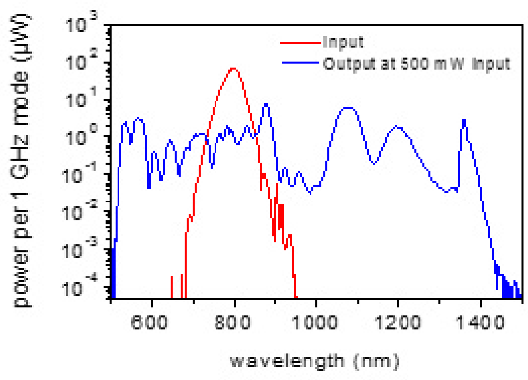

Figure 2: Red: Typical **taccor** output spectrum used for CEO detection and comb applications. Blue: Output spectrum after 1 m photonic crystal fiber.

that the carrier wave (375 THz for an 800 nm Ti:Sapphire laser) travels at the phase velocity while the pulse envelope travels at the group velocity. As these two are usually not equal, the relative position of the carrier under the envelope slips at a rate given by f_0 and the modes are offset from the integer harmonic of f_R by f_0.

The potency of the femtosecond laser frequency comb (FLFC) originates from the simple fact that the optical frequencies f_n are defined by two easily measureable radio-frequencies (f_0 and f_R). Optical frequency measurements relative to the Cs clock have become simpler in recent times and no longer require the expertise of a National Facility with specialty equipment occupying an entire laboratory [2]. In essence, the FLFC provides a ruler for optical frequencies with the precision of the Cs clock.

In the early years of the FLFC, following the first demonstrations in 1999, applications were mostly for measurements, comparisons of optical frequencies or to function as clockworks in optical atomic clocks in Optical Frequency Standard Laboratories such as PTB in Germany, NPL in the UK or NIST in the USA [3-6]. Later FLFCs found more widespread applications, such as direct frequency comb spectroscopy [7], arbitrary waveform generation [8], dual-comb FTIR spectroscopy [9] or CARS microscopy [10] and the calibration of astronomical spectrographs [11].

Almost all FLFC applications benefit from a repetition rate around 1 GHz for several reasons. The much larger mode-spacing, compared with other solid-state lasers or fiber lasers with f_R between 70 and 250 MHz, allows easier identification of the mode number, as

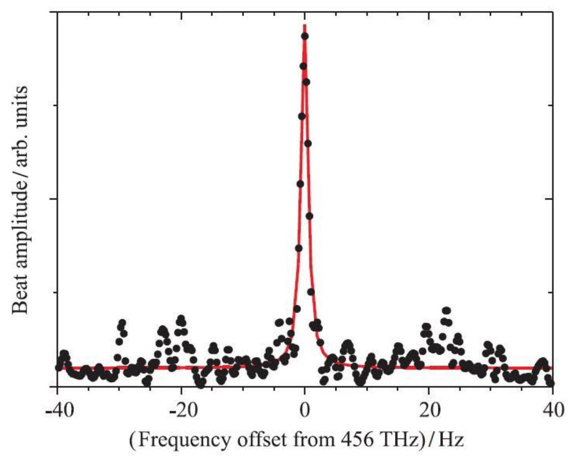

Figure 3: Heterodyne beat between two ultrastable cw lasers at 532 THz and at 456 THz via a Laser Quantum 1 GHz Ti:Sapphire laser recorded at the U.S. National Institute of Standards and Technology.

required for all frequency measurements. At the same time, radio-frequency (RF) filtering of the relevant beat signals is less demanding when the forest of modes is less dense to begin with. A less dense comb also leads to more power available in each mode, i.e. a 1 GHz laser has 10 times more power per mode than a 100 MHz laser at a given average power (typically between 100 mW and 1 W for commonly used lasers). A further advantage, again by a factor of 10 at 1 GHz, is related to the commonly used nonlinear photonic crystal fibers (PCF) used for super-continuum generation in typical FLFC setups (see figure 2 for a typical super-continuum at 1 GHz mode spacing). It has been shown that above a threshold of a few 100 pJ of pulse energy, the coherence of the frequency comb is heavily reduced or even lost entirely at the output of the fiber due to nonlinear noise amplification [12].

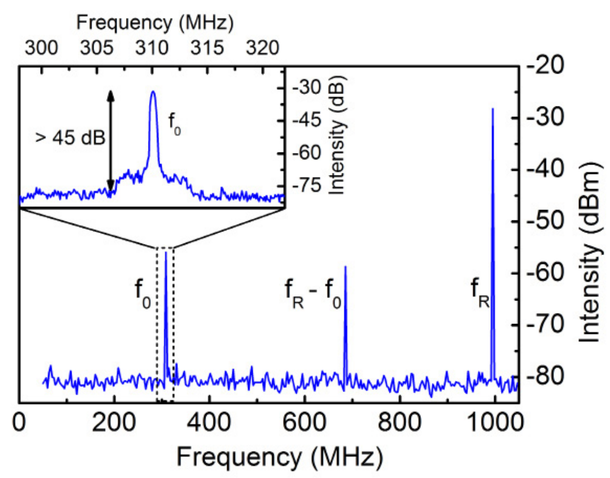

Figure 4: Carrier-envelope offset beat obtained from the **taccor comb**. The signal-to-noise ratio is limited by the RF spectrum analyzer. The close-up in the inset reveals the true signal-to-noise ratio of >40 dB in 100 kHz of bandwidth.

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This means there is a limit to the pulse energy that can be launched through the fiber, typically around 300 pJ. In a 1 GHz pulse train, this corresponds to 300 mW of average power versus 30 mW in a 100 MHz train. So in total, the useful power per mode in a coherent super-continuum scales with the square of the repetition rate, giving a 1 GHz system 100-fold advantage over a 100 MHz system. Finally, a higher repetition rate means a lower pulse-to-pulse separation causing the dead-time in dual comb FTIR, CARS or similar applications to be less, therefore more data acquisition time is spent on gathering useful data and less time is spent acquiring 'zeros'.

Laser Quantum's 1 GHz femtosecond lasers have found widespread use in frequency metrology in many National Laboratories and other research groups around the world. In an international comparison between four independently constructed systems, each using a Laser Quantum laser, these lasers have been shown to support optical frequency measurements at the 10^{-19} accuracy level with stability at the 10^{-17} level in 1 s of averaging time and mode linewidths below 1 Hz [13,14], see figure 3. Hence, for the foreseeable future, these lasers are capable to support even the world's most accurate and stable optical atomic clocks as optical clockwork and will not be a limiting factor in the most demanding optical frequency measurements [15]. Furthermore, applications in ultralow-noise microwave generation have been shown [16].

To support applications of the **taccor** as a frequency comb, Laser Quantum has recently developed the comb extension to its successful range of 1 GHz lasers, now making the **taccor comb** available to the market, see figure 5. It consists of a matched dispersion compensation module, super-continuum generation and a nonlinear f-2f interferometer. The **taccor comb** provides a long-term stable RF signal at the carrier-envelope offset frequency with more than 40 dB signal-to-noise ratio in 100 kHz bandwidth, as shown in figure 4. Phase detection between the measured f_{CEO} and a given reference signal is performed and converted into a feedback signal using the XPS800-E stabilisation unit by Menlo Systems GmbH. This feedback signal controls the intensity of the **finesse pure CEP** pump laser built within the **taccor**, in order to stabilise the **comb's** f_{CEO} signal. The **finesse pure CEP** laser features our patented CEPLoQ™ technology and allows direct modulaton 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 of up to 250 kHz can be applied to phase-lock the CEO frequency to an external reference (figure 6 & figure 7).

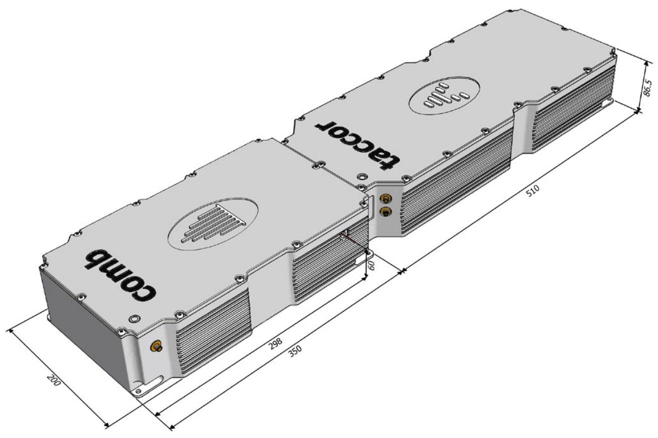

Figure 5: Laser Quantum's **comb** extension showing dimensions.

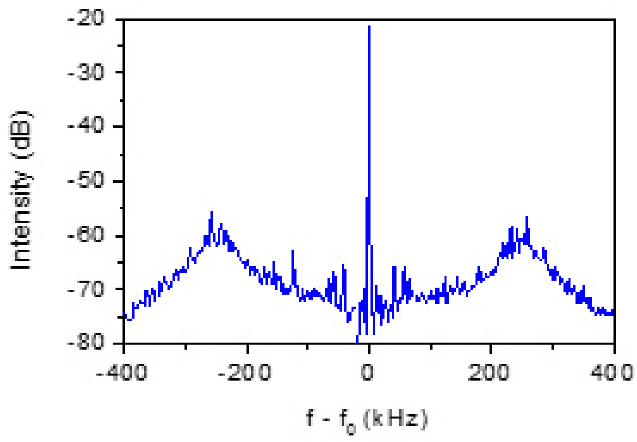

Figure 6: Close-up of the phase-locked f_{CEO}. The data is acquired using a resolution bandwidth of 200 Hz. The servo bandwidth is about 250 kHz as indicated by the symmetrical peaks around the carrier.

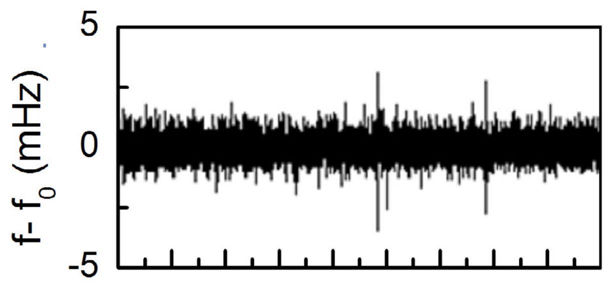

Figure 7: Long term deviations from the lock point of a CEO beat stabilised at 310 MHz over 25 h showing exceptional stability (limited by RF reference input).

Acknowledgements:

Thanks to Albrecht Bartels and Matthias Beck of Laser Quantum.

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