Ultra low timing jitter performance & characterization of Origami femtosecond laser series

White Paper

P/N 09-001
Revision 1.2
December 2016

I. Introduction

Compact, industrial-grade optical pulse sources with very low timing jitter and sufficient power are becoming a key building block in many advanced applications. High data rate communication systems, optical sampling systems used for high-speed analog-to-digital conversion, precise frequency comb generation and long-range radio frequency (RF) clock distribution via fiber-optic links, to name a few, are increasingly depending on the commercial availability of reliable, industrial-grade optical pulse sources with ultra-low amplitude and phase noise properties.

Using passively mode-locked laser sources is the natural choice for the generation of ultra-short pulses exhibiting low phase and amplitude noise. Mode-locked lasers emit a train of equidistant pulses, the optical spectrum of which is an equidistant comb in the optical frequency domain.

Particularly, the recent advances in the measurement and control of the carrier-envelope offset frequency have greatly expanded the range of possible applications of such frequency combs, enabling e.g., extremely precise optical frequency measurements in a wide spectral region, and phase coherent links between microwave and optical frequency standards, as required for the next generation of atomic clocks.

Therefore, the off-the-shelf availability of industrial-grade femtosecond and picosecond optical pulses sources is vital for wide application areas. In respond to this imminent need, Onefive GmbH has released a series of ultra-short pulsed lasers qualified for industial applications. These lasers are based on the successful Origami-platform which has already been adopted industry-wide.

The laser design supports a wide range of pulse repetition rates with high output power, compact size, low power consumption and continuous 24/7 operation under changing environmental conditions. A built-in piezo allows for synchronization of the repetition rate to an external radio frequency (RF) clock. Direct access to the pump power ensures the ability to control the carrier-envelope offset independently of the cavity length.

With a well designed laser head in place, a crucial role for the ultra low noise performance of the system is greatly affected by the laser driver and control electronics used, because noise on the pump light can modulate the phase and amplitude of the laser output. To address this circumstance, Onefive GmbH has developed a new line of linear laser controllers, delivering ultra-quiet current and control mechanisms in order to unfold the full potential of the laser itself.

II. Origami laser and low noise laser controller

The Origami laser series is a passively mode-locked soliton laser platform, based on either Er/Yb doping for 1550-nm operation or Yb doping for operation in the 1-µm wavelength range.

The hybrid laser setup, consisting of state-of-the-art polarization maintaining (PM) fiber technology and free-space sections for advanced dispersion control, allows for high pulse energy generation while supporting perfectly transform-limited soliton pulses without spectral ripples, excess of optical bandwidth, Kelly-sidebands or temporal pedestals or satellite pulses. The mechanical implementation of the laser is accomplished in a rigid housing, minimizing mechanical vibrations, acoustic noise pickup and susceptibility to environmental temperature changes.

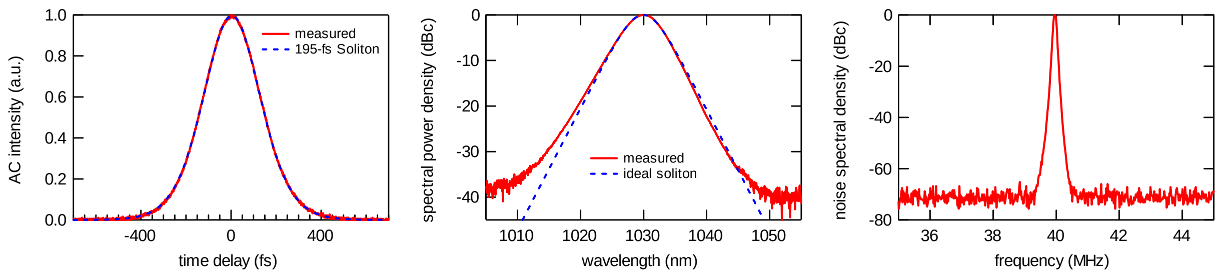

Fig. 1: Typical output from a 40-MHz Origami laser at 1030 nm, 5.7 nm FWHM optical bandwidth, 195 fs pulse duration at 200 mW average output power, corresponding to about 5 nJ pulse energy or 23 kW pulse peak power respectively.

Usually, Onefive lasers come with a very compact and highly efficient laser controller, based on switched mode technology. Even with these controllers, which are optimized for OEM applications (power consumption, reliability, and size), timing and amplitude jitter of the lasers are very low. For high end applications requiring even lower noise, we have developed a special low noise laser controller pushing the timing jitter from below a few tens of femtoseconds to a few femtoseconds only.

The low noise laser controller consists of linearly regulated power supplies with specially filtered and shielded power lines and a linear laser driver circuitry. Passive air cooling of the lower efficient linear stages is ensured by proper heat sink design. Altough the laser driver is designed for stand-alone 24/7 operation, all functions can also be controlled remotely via TTL signal inputs, thus enabling easy and straight-forward OEM integration into any system.

Advanced packaging of the laser and control electronics ensures sustained performance under 24/7 operation and changing environmental conditions. The use of a single Telcordia-qualified pump module minimizes the overall mean-time-to-failure of the laser and ensures very long lifetime.

In case the repetition rate needs to be locked to an external RF clock, the Origami laser family can be upgraded with an internal piezo-based cavity extension. The repetition rate can then be locked to the external RF clock by a simple phase-locked loop (PLL) module. Onefive supplies a very compact, state-of-the-art digital PLL module named “SYNC”.

It is packaged in a single compact box with all the necessary electronics and drivers built in. The high mechnical stability of the hybrid laser cavity leads to very low drift and fluctuations of the repetition rate in free running operations. Power supplies and piezo driver electronics can be designed in a compact package with high efficiency, ensuring low power consumption, small footprint and high easy of use. The SYNC module can be remotely controlled via the TTL interface of the laser controller, allowing OEM integrators to upgrade their system very easily at a later point.

III. Timing jitter

Pulse trains exhibit deviations of the temporal pulse positions from those in a perfectly periodic pulse train. This phenomenon is called timing jitter. Timing errors may be quantified in different ways:

- as a power spectral density of the timing deviation or of the timing phase
- with an root-mean-square (RMS) value obtained by integration over a certain measurement bandwidth

In the absence of technical noise, the jitter of a mode-locked laser is limited by quantum noise. However, additional technical noise in the form of vibrations, drifts of the laser resonator length and noise on the pump source can easily lead to stronger timing jitter, unless a very stable laser setup is made.

An optimized laser setup can exhibit extremely small timing jitter. Particularly over short time scales, this can be substantially smaller than that of expensive high-quality electronic oscillators. A detailed analysis based on analytical and numerical modeling can be found in Refs. [1,2]. The results of this analysis carried out with a focus on pure solid-state lasers are also applicable to soliton mode-locked fiber lasers and hybrid systems. They indicate that a laser like the Origami has the potential for particularly low timing jitter, as will be confirmed by the measurements presented in this white paper. Additional information on timing jitter can be found on [3].

Measurement of timing jitter

There are different methods for measuring the timing jitter of mode-locked lasers (e.g. Ref. [4,5]). Here we use an Agilent signal source analyzer (SSA) 5052B [6]. The applied measurement technique of the Agilent SSA is based on analyzing the phase noise power spectral density of the signal under test (SUT). The SSA locks two ideally similar and low phase noise electronic oscillators to the SUT with a very low loop bandwith (~1 Hz). The mixed signals from each oscillator with the SUT are then compared to each other. Correlated phase noise terms correspond to the phase noise of the SUT, uncorrelated phase noise terms correspond to the phase noise of the electronic oscillators and cancel each other. With this measurement method one gains about 20 dB (assuming a sufficiently long correlation time) in system noise floor compared to the noise floor of each individual oscillator.

Laser

The laser under test is an Origami femtosecond laser, running at 214 MHz repetition rate and delivering sub-180-fs pulses at 1562-nm center wavelength with about 120 mW average output power. The laser's repetition rate is **not** locked to an external RF clock, i.e. the laser is free running. The power supply and control electronics are based on Onefive's advanced 19" rack-mount low noise laser controller model "Laser Controller LP Linear".

Measurement setup

For the measurement, the optical output from the PM fiber of the pigtailed laser was detected with a commercially available U^2T photodetector, supplied with a constant current power supply [7]. The optical power had to be attenuated to about 5 mW in order to avoid saturation and damage of the photodetector. After a DC block, the RF signal passed a narrow-band filter at the 14th harmonic of the laser's repetition frequency, i.e. 2998 MHz. The filtered RF signal at 2998 MHz was then amplified with a low noise amplifier (LNA) and analyzed with the Agilent 5052B signal analyzer (see Fig. 2).

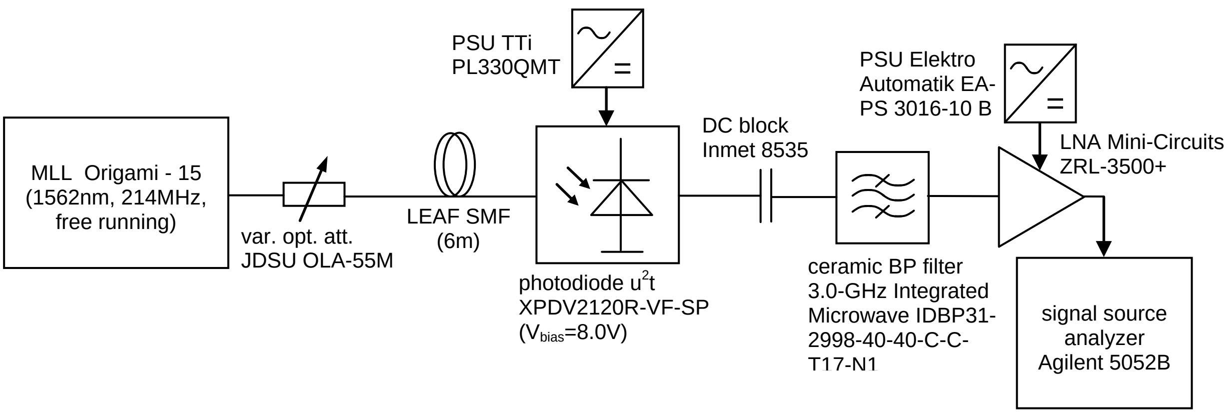

Fig. 2: Phase noise measurement setup: MLL, mode-locked laser; VOA, variable optical attenuator; SMF, single mode fiber; PSU, power supply unit; BP, band pass; LNA, low – noise amplifier.

The integration time for each individual measurement was set to the maximum number of 10'000 correlations. A rough estimate gives a measurement limitation of the phase noise to about 2 fs RMS in the frequency regime of interest (1 kHz – 10 MHz).

IV. Results

The results in Fig. 3 show the single sideband (SSB) phase noise curve in units of dBc/Hz versus the offset frequency from the carrier at 2998 MHz. The span covers the offset frequency range from 1 kHz up to 10 MHz. Integration over this range leads to a measured RMS phase noise of 62.8 μrad, which corresponds to 3.34 fs rms timing jitter.

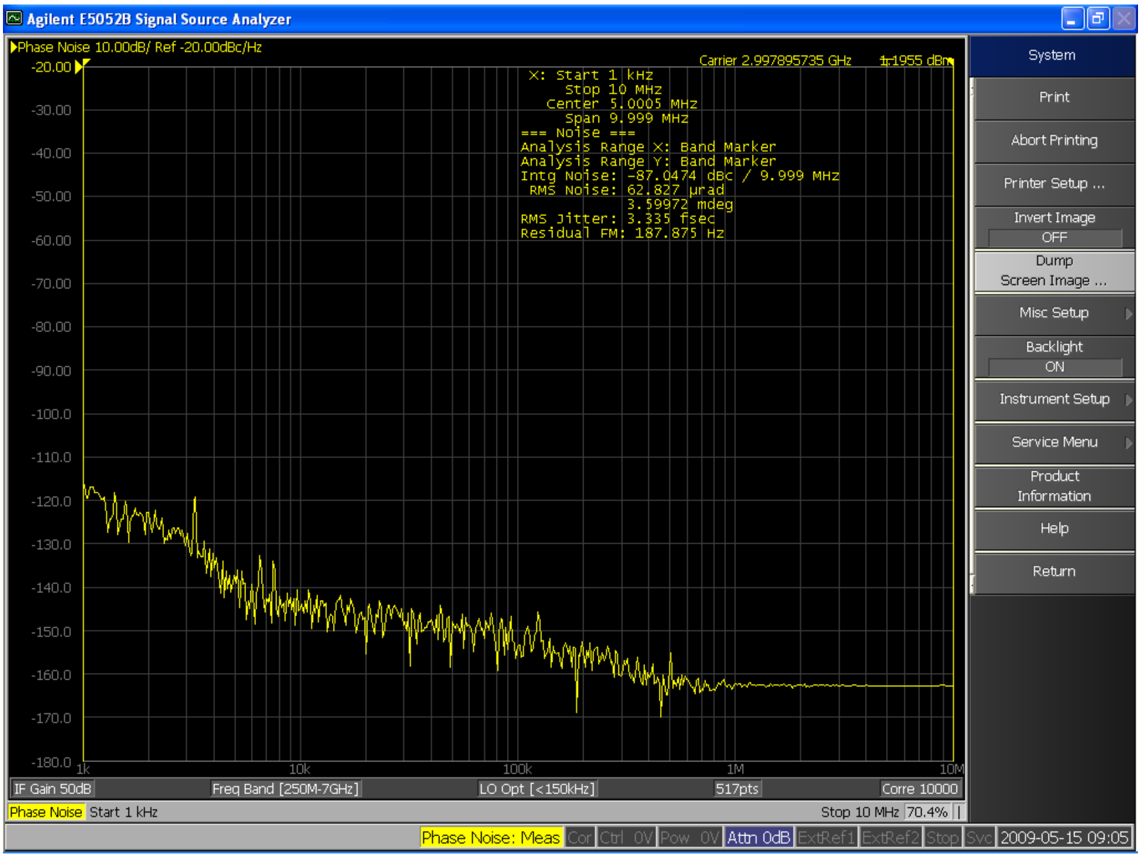

Fig. 3: Measured timing jitter of 3.34 fs, integrated from 1 kHz to 10 MHz with 10'000 correlations.

Repeated measurements over days and weeks yielded very similar results with a timing jitter always below 4 fs rms.

Phase noise components with frequencies below 1 kHz are of only little interest, as the piezo-option integrated in the laser has several kHz of bandwidth and can thus correct for timing drifts in this frequency regime. This allows locking of the laser's repetition rate to an external RF clock with a PLL of sufficient bandwidth. In this case, the phase noise in the frequency regime below 1 kHz will follow the RF phase noise of the input reference clock.

V. Further optimizations

Further optimizations of this specific measurement setup and the laser design are possible. Currently, the limitations are the following

Measurement setup

- Photodetector bias voltage is limited to 8.0 V: An improved photodetector design could significantly improve the signal-to-noise ratio.
- Internal photodiode termination resistor: Removal will reduce the noise floor.
- Analyzer noise floor: Probably the main contribution to system noise floor.
- Low noise amplifier has approximately 3 dB noise figure: Use different type with lower noise figure.

Laser design

- Battery power supply instead of linear AC/DC converter is expected to slightly improve the phase noise.
- Further improved packaging to reduce accoustic noise pickup.
- Further improvement of the laser driver towards higher loop bandwidth for advanced amplitude stabilization techniques and more quiet control electronics.

Other measurement techniques, based on optical cross correlation of two ideally identical lasers have a much lower intrinsic noise floor and could potentially reveal the true phase noise of the laser system across a wider frequency range [8].

VI. Conclusions

With the advent of passive mode locking, improved packaging of ultra-short pulsed lasers and advanced laser controller electronics, the availability of off-the-shelf industrial-grade femtosecond and picosecond lasers exhibiting ultra low phase noise performance became a reality.

Onefive’s high performance femtosecond and picosecond laser sources are the best choice for any timing-sensitive application and deliver unprecedented phase noise performance in a compact, industrial-grade package.

Contact Us

For more information on our ultra low noise pulsed laser series Origami or any other product from Onefive GmbH, please contact us.

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