From Innovation to Prism Award: What Lies Beyond the Technologies of FemtoLux 30 Laser

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1. Introduction

Ultrashort laser pulses find wide applications in the fields of laser science, and industry. Many micro- and nano-machining tasks require the use of femtosecond or picosecond lasers due to their exceptional performance, superior precision, and minimal heat impact provided by ultrashort light pulses [1,2]. Certain material processing mechanisms respond exclusively to femtosecond pulses due to their significantly higher peak power compared to nanosecond pulses with the same energy. Despite their ability to concentrate energy in a small volume, femtosecond pulses typically result in low ablation efficiency per pulse. On the other hand, nanosecond lasers offer high throughput in material processing using high-energy laser pulses [3]. The ideal laser parameters, including pulse duration, for material processing depend on the material's characteristics. Carefully adjusting laser parameters and operation regimes may ensure optimal laser application outcomes. Lasers with enhanced functionality and a unique set of features can stimulate research in new fields and the development of novel laser techniques.

In this work, we present an ultrafast laser *FemtoLux 30 (Ekspla)* with enhanced functionality that can offer different operation regimes and a unique set of pulse parameters in a single laser source, which earned global recognition by winning the prestigious *"SPIE Prism Award 2024"* in the category of *Lasers*. This study introduces the feasibility of innovative and versatile technologies integrated into the *FemtoLux 30* laser. Firstly, a pulse-on-demand (PoD) mode in the conventional single-pulse operation regime was developed. This feature enabled the laser to fire a pulse only when required with a timing jitter as low as 20 ns (peak-to-peak). Precise control over the laser's output results in higher efficiency, accuracy, and quality of the laser processing. Secondly, this study introduces a versatile active fiber loop (AFL) technology enabling new operation regimes in ultrashort pulse lasers. The AFL technology enabled the most versatile GHz burst mode overcoming many limitations encountered by other fiber- and/or solid-state-based techniques. Any desired pulse repetition rate (PRR), any number of pulses in a burst (ranging from 2 pulses to thousands of pulses inside the burst) with identical intra-burst pulse separation can be obtained [4-6]. Moreover, the AFL allowed the tuning of pulse duration from a few hundred femtoseconds to picoseconds and even up to the nanosecond range [7]. The developed laser offers a unique set of features and parameters and can be beneficial for most laser applications as it can operate in precisely controlled single-pulse and flexible GHz-burst (short-, long-bursts, GHz-bursts-in-MHz-bursts) regimes, with the ability to tune pulse duration. Moreover, the mJ-level pulse energy version of the *FemtoLux 30* laser and the options for second- and third- harmonic generation are accessible, making such laser an indispensable tool for most scientific and industrial laser applications.

2. Results and discussion

The flexibility of the developed single laser source to operate in precisely controlled and widely tuneable single-pulse and GHz-burst regimes is based on the innovative and versatile laser technologies used in this system.

A PoD mode, achieved by the precise control of single laser pulses, expanded laser operation capabilities in the common single-pulse regime. This capability is particularly valuable in various micromachining applications where high processing speed, constant energy, and accuracy are essential. To follow complex curvature at high speeds while maintaining equidistant spacing, it is necessary to adjust the repetition rate of the pulses. Attempting to achieve these requirements through position-based laser triggering may lead to jitter ranging from several microseconds to tens of microseconds, due to laser system limitations, resulting in random pulse spacing. Conversely, utilizing time-based laser triggering can lead to overheated areas due to excessive pulse overlap. Therefore, the PoD feature with a jitter as low as 20 ns can tackle all the challenges and maximize process efficiency, precision, and quality at the high speed of laser processing.

A versatile AFL technology has enabled the exploration of new operation regimes in the ultrashort pulse laser, facilitating the generation of GHz bursts of ultrashort pulses and allowing for pulse duration tuning from a few hundred femtoseconds up to the nanosecond range. The all-in-fiber AFL comprised the main components responsible for burst formation and temporal control of the pulses/bursts (achieved through acousto-optic modulators), pulse amplification (using ytterbium-doped fiber (YDF) amplifier), dispersion compensation and accumulation (utilizing chirped fiber Bragg gratings), and selection of different operation modes (using optical switch). The GHz burst formation technique is based on splitting and delaying ultrafast pulses from the MHz master oscillator. One of the main advantages of this versatile technique is the capability to form bursts of laser pulses containing any number of pulses within a burst with identical pulse separation. The AFL enables the formation of the bursts of any desired fixed intra-burst PRR which does not depend on the initial PRR of a fiber oscillator. Furthermore, the amplitude of pulses in a burst is controlled by amplification conditions in the YDF amplifier. The ultrafast laser with integrated AFL produced the sequence of bursts with a different number of pulses of 2.2 GHz intra-burst PRR and was able to operate in the flexible single-pulse (MHz-level PRR, high temporal quality 300 fs pulses) and GHz burst (short-, long-bursts, GHz-bursts-in-MHz-bursts) operation regimes (Fig. 1). Laser pulses in the single-pulse and GHz-burst regimes (bursts containing from 2 to approx. 1100 pulses (500 ns width)) were amplified to more than 30 W average output power.

The AFL was utilized for a wide pulse duration tuning in an ultrashort pulse laser, as well. The pulse duration tuning technique relied on controlled dispersion accumulation during each round-trip inside the AFL. The duration of a single pulse passing through the AFL increased after each round-trip, forming a sequence of pulses with varying durations outside the AFL. A discrete linear increase in pulse duration was achieved, reaching 1 ns after 13 round trips. Pulses that did not propagate through the loop maintained a duration of 300 fs at the output of the system (Fig. 1). Therefore, this approach allowed for pulse duration tuning within a range from 300 fs up to 1 ns in the ultrafast laser. The envelopes of the different duration pulses are presented in Fig. 1.

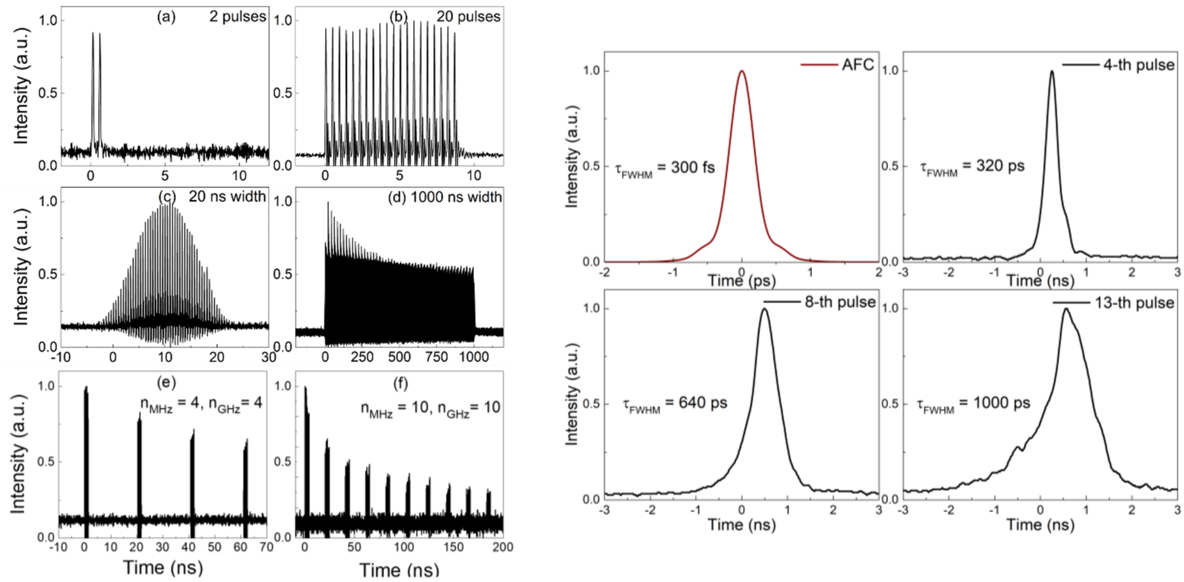

Fig. 1: Left: The measured 2.2 GHz intra-burst PRR bursts containing different number of pulses in a-b) short-, c-d) long-, e-f) burst-in-burst formation regimes. Right: Different duration pulses at the output of the laser utilizing the AFL for pulse duration tuning.

In conclusion, the flexibility of the demonstrated single laser source to operate in a widely tunable single-pulse and GHz-burst regimes gives unprecedented freedom to determine the most suitable combination of ultrafast radiation parameters for a certain material processing application and makes such laser indispensable for most scientific and industrial laser applications. A detailed description of the operation of the *FemtoLux 30* laser and the demonstration of its versatility along with accompanying technologies will be presented at the conference.

3. References

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