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Industrial Paper

Versatile GHz burst-mode operation in high-power femtosecond laser for industrial applications

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Abstract

A new versatile patent-pending method to form ultra-high (2.2 GHz) repetition rate bursts of ultrashort laser pulses, overcoming many limitations encountered by other fiber-based techniques, is introduced in this work. The developed method was based on the use of an all-in-fiber active fiber loop which enabled to form bursts of laser pulses with any desired pulse repetition rate (PRR), which does not depend on the initial PRR of a fiber oscillator. The bursts of ultrashort laser pulses containing any number of pulses in a burst (from 2 pulses to thousands of pulses inside the burst) with identical intra-burst pulse separation were demonstrated. The experimentally constructed 30 W-level average power ultrashort (sub-1 ps) pulse laser system operated in single-pulse and GHz-burst operation regimes.

Keywords: GHz burst; active fiber loop; ultrashort pulse; high-power laser

1. Introduction

Ultrashort light pulses are highly applicable in science, medicine, and industry. The discoveries of new light–matter interaction regimes stimulate the development of lasers with increased functionality and vice versa. A recently developed technique that uses gigahertz (GHz) bursts of ultrashort pulses attracted a lot of attention by demonstrating the superior performance of the laser system and its application (Kerse et al., 2016). That prompted a further investigation and optimization of laser parameters (Žemaitis et al., 2019; Žemaitis et al., 2020; Bonamis et al., 2020).

Common methods for producing GHz bursts of pulses may be implemented in commercial lasers, however, only a few of them can provide significant improvements with a unique set of features and parameters. The methods to generate bursts of pulses have some limitations associated with the principle of the method itself. The complexity and size of the free-space arrangements of burst formation setups may be the main drawbacks for them to be successfully integrated into commercial laser systems. Meanwhile, fiber-based GHz burst formation by pulse repetition rate (PRR) multiplication techniques based on splitting and delaying ultrafast radiation from the MHz master oscillator are a convenient solution successfully demonstrated experimentally (Kerse et al., 2016; Eidam et al., 2016; Zhao et al., 2006). Moreover, these techniques are of a high potential to be easily implemented in the all-in-fiber design to provide compact, stable, and robust ultrafast lasers for the industry.

PRR multiplication technique based on the approach of cascaded fiber couplers in combination with fiber delay lines allows achieving ultra-high pulse repetition rates (Kerse et al., 2016). However, one of the drawbacks of this PRR multiplication technique is the difficulty to maintain equal pulse energies (pulse amplitudes) and equal temporal separations between the pulses due to coupling efficiency asymmetries of the fiber couplers and the difficulty to ensure precise fiber lengths. Another disadvantage is ultrashort pulse duration variation within a burst since dispersion is not controlled in this solution. The more PRR cascades are used, the higher pulse temporal distortion is obtained for broadband radiation. Furthermore, a minimal width of the bursts was limited to 15 ns consisting of 50 pulses by a response (rise and fall times) of the acousto-optic modulator which was used in the presented system after the PRR multiplier to select the desired width of the burst from a GHz pulse train. The

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dispersion of different length fibers in each pulse multiplication stage was compensated and equal pulse durations of laser pulses within a burst were obtained, in a modified multiplication technique (Eidam et al., 2016). However, this solution only solved the issue of pulse duration variation inside the burst, but all the other aforementioned drawbacks remained.

Pulse repetition rate can be increased by using a pulse multiplication technique based on the configuration of passive fiber loops (Zhao et al., 2006). Using this method, the initial pulse from the laser source is coupled in the passive fiber loop which is formed by connecting one input and one output port of the 2x2 fiber coupler. The pulse circulates inside the loop while its energy is steadily reduced by the fiber coupler resulting in a formation of a burst of pulses with decaying amplitude at the output of the passive fiber loop. The pulse multiplication methods of multiple passive fiber loops with no additional elements have several drawbacks. The synthesized bursts contain laser pulses of unequal amplitudes, which can be hardly matched. The burst envelope is adjusted only by selecting the splitting ratios of the fiber couplers. No other control of pulse amplitudes is provided. This technique is not suitable for synthesizing long bursts of ultrashort pulses as broadband radiation circulating many round-trips inside the fiber loops would experience the influence of the dispersion which would lead to the pulse duration variation inside the burst. Furthermore, the highest possible PRR that can be achieved by the aforementioned approach is about 2 GHz as it is defined by the length of the shortest fiber loop and a minimum length of two fiber pigtails (approximately 5 cm each) that is required to accomplish the splicing with a fiber splicing machine.

In this work, a new versatile patent-pending method to form ultra-high PRR (>2 GHz) bursts of ultrashort laser pulses with identical pulse separation and adjustable amplitude is presented. The developed new technique based on the use of the active fiber loop (AFL) allows to overcome many limitations encountered by other techniques. The formation of 2.2 GHz intra-burst PRR bursts with the AFL and their amplification in an industrial-grade 30 W-level average output power hybrid – an Yb-doped fiber and Yb:YAG – power amplifier, was demonstrated.

2. Experimental results and discussion

The technique based on the AFL is a very versatile method suitable to form bursts of ultrashort laser pulses (Bartulevicius et al. (2020)). The AFL is the key element for burst formation which is depicted in Fig. 1 (left).

The whole operation and burst formation can be explained by observing the propagation of single pulses with pulse separation T_0 of the initial pulse train. The first pulse from the initial pulse train coupled into the fiber coupler is divided into two replicas. One pulse is outcoupled through the first output port *OUT1* and another replica of the pulse is delivered into the AFL through the second output port *OUT2*. The pulse replica propagating through the AFL returns to the fiber coupler a little bit later (time delay T_2) than the second pulse from the initial pulse train arrives. They form the first burst containing two pulses. Further, one replica of the pair of pulses is outcoupled through the first output port and another replica containing two pulses is delivered into the loop again. After the second round-trip, a burst containing three pulses will be formed. After N round-trips, the burst of $N+1$ pulses will be formed at the output of the AFL. Experimentally measured 2.2 GHz intra-burst PRR burst of pulses containing 2 and 20 pulses is depicted in Fig. 1(a-b). Long bursts of 20–1000 ns widths, as shown in Fig. 1(c–d), can be synthesized using the described method along with an additional temporal modulation of the initial pulse train.

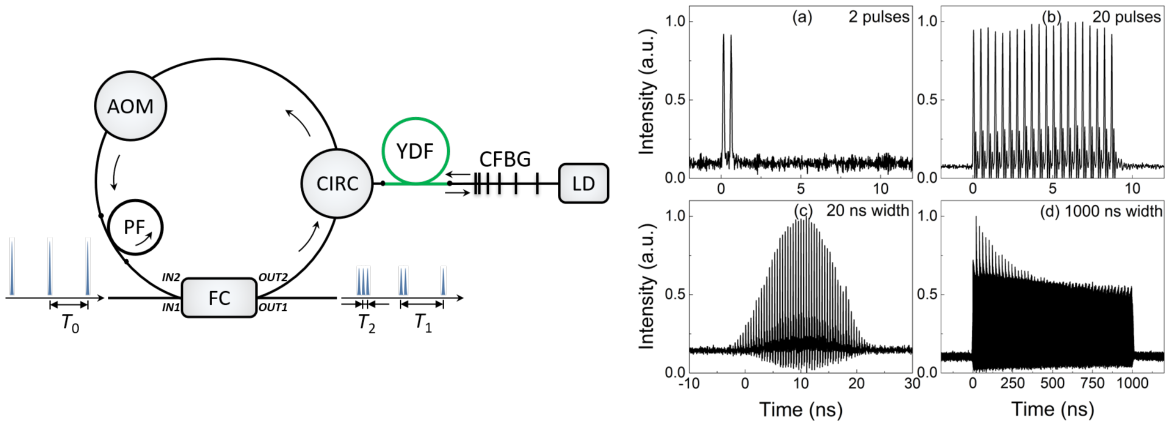

Fig. 1. Left: Schematic setup of an active fiber loop. FC - 2x2 fiber coupler (50/50 splitting ratio), CIRC - optical circulator, YDF – ytterbium-doped fiber, CFBG - chirped fiber Bragg grating, LD - single-mode laser diode, AOM - acousto-optic modulator, PF - a segment of a passive optical fiber. *IN1,2* - input ports of the fiber coupler, *OUT1,2* - output ports of the fiber coupler. Time delays: T_0 - between input pulses, T_1 - between a delayed replica of an input pulse and an undelayed replica of the pulse, T_2 - intra-burst pulse separation. Right: Experimentally measured 2.2 GHz intra-burst PRR burst of pulses containing a different number of ultrashort pulses: (a) 2, (b) 20, (c) ~40, and (d) ~2200.

The burst formation technique based on the use of the AFL is a very versatile method as it allows to overcome many limitations encountered by other fiber-based techniques. First of all, short bursts, from 2 pulses in a burst, and long bursts, even up to 1000 ns width, can be formed with identical pulse separation (Bartulevicius et al. (2020)). Secondly, any desired intra-burst PRR can be achieved independently from the initial PRR. Moreover, the loss and dispersion compensation mechanisms are employed in the AFL. It has the property to adjust the shape of the amplitude envelope of the short bursts by the amplification conditions of the YDF amplifier. The dispersion compensation in the developed AFL ensures the formation of GHz bursts of ultrashort laser pulses.

The AFL was integrated into the industrial-grade 30 W-level average power femtosecond laser (*FemtoLux 30, EKSPLA*). The laser system consisted of an all-in-fiber seed source, the AFL with auxiliary acousto-optic modulators for temporal control of GHz bursts, fiber and solid-state power amplifiers, and a pulse compressor. The AFL produced the sequence of bursts with a different number of pulses of 2.2 GHz intra-burst PRR as described above. The laser system was able to operate in the single-pulse operation regime (MHz-level PRR) when the AFL was inactive.

Laser pulses in the single-pulse and GHz-burst regimes were amplified to more than 30 W average output power in hybrid Yb-doped fiber / Yb:YAG power amplifiers. The GHz bursts of 0.2–1 MHz burst repetition rate (BRR) containing from 2 to approx. 1100 pulses (500 ns width) were amplified up to 31.5 W average output power resulting in a burst energy from 31.5 µJ up to 140 µJ burst energy. The desired rectangular-like GHz burst shapes were achieved by pre-shaping the burst before amplification in the power amplifiers. Measured rectangular-like burst shape at the output of the system are depicted in Fig. 2. Autocorrelation functions (ACF) of the compressed pulses in the GHz burst operation regime are shown in the insets of Fig. 2. The average ACF width (a full-width at half-maximum, FWHM), was in the range from 511 fs for a 2-pulses-burst to 1369 fs for a 500 ns width burst.

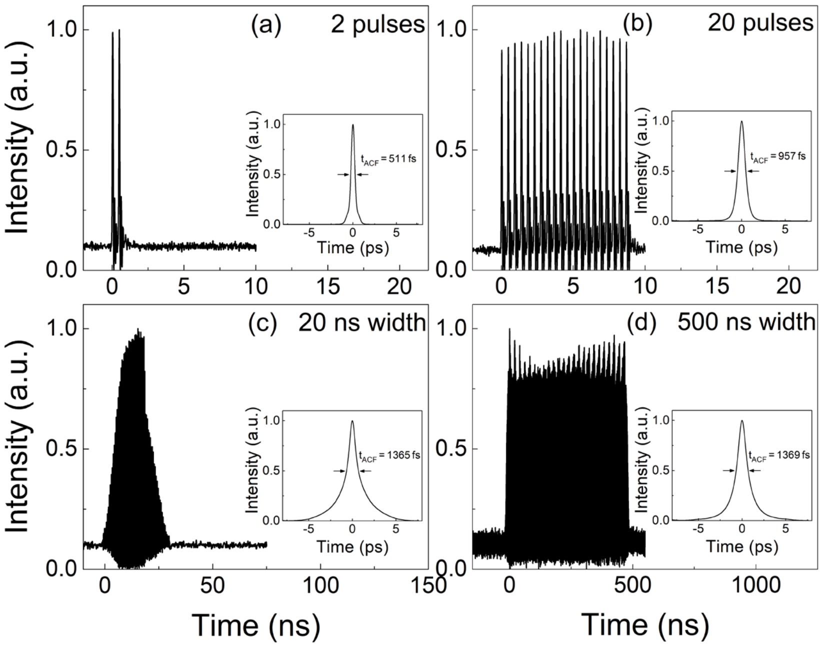

Fig. 2. Measured 2.2 GHz pre-shaped bursts containing from 2 to approx. 1100 pulses at 233 kHz BRR and 31.5 W average output power for the desired rectangular-like burst shape at the output of the system. Inset: Measured autocorrelation functions of compressed pulses.

The largest increase of the average ACF width was attributed to the narrowing of the pulse spectrum caused by the bell-shaped reflectivity profile of the chirped fiber Bragg grating (CFBG) used for dispersion compensation in the AFL (Fig. 3). A higher-order dispersion mismatch in the AFL components may be another reason for the difference in the measured ACFs of the compressed pulses. A Fourier-transform-limited (FTL) pulse duration derived from the measured pulse spectrum increased from 330 fs to 540 fs in the GHz-burst regime of bursts containing from 2 to approx. 1100 pulses (Fig. 3). A flat-top CFBG design must be used in the AFL to avoid the pulse spectrum narrowing. Nevertheless, ultrashort pulse duration of sub-1 ps for Gaussian-shaped pulse was achieved in the GHz-burst operation regime. In the single-pulse regime (at 2 MHz PRR, 30.6 W average output power, and 15.3 µJ pulse energy), the measured ACF had a width of 519 fs (FWHM) which corresponded to high-quality 368 fs pulse duration for Gaussian-shaped pulse.

A detailed description of a new pulse multiplication technique and the demonstration of its versatility in industrial-grade high-power laser will be provided at the conference.

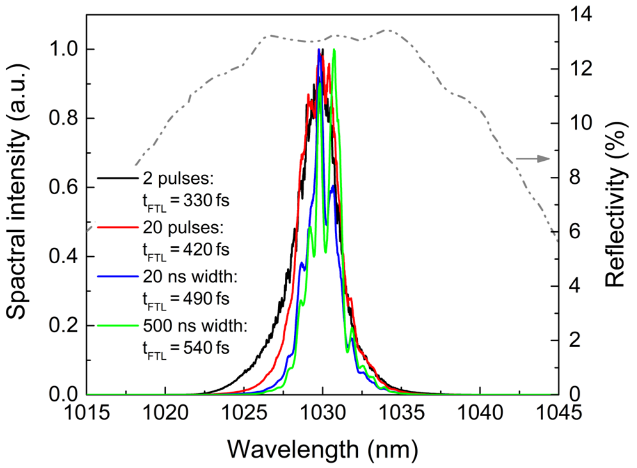

Fig. 3. Pulse spectra at the output of the system in the GHz-burst regime. Reflectivity profile of the CFBG used in the AFL for dispersion compensation in grey dash-dotted line.

Conclusions

In this work, a versatile method to form GHz bursts with identical pulse separation, any predefined intra-burst PRR, and amplitude envelope using the AFL was demonstrated. It allowed to form 2.2 GHz bursts containing from 2 up to approximately 2200 pulses (1000 ns burst width) in the bursts. The AFL was integrated into the industrial-grade 30 W-level average power femtosecond laser (*FemtoLux 30, EKSPLA*) operating in the single-pulse and GHz-burst regimes. The laser system delivered high-quality 368 fs duration (FWHM) pulses of 15.3 µJ pulse energy and 30.6 W average output power at 2 MHz PRR in the single-pulse regime. In the GHz-burst regime, bursts of 2.2 GHz intra-burst repetition rate were formed and amplified to more than 30 W average output power. The laser system was able to deliver bursts of GHz pulses at 0.2–1 MHz BRRs obtaining the highest burst energy of about 140 µJ. The ultrashort pulse duration of sub-1 ps for Gaussian-shaped pulse was achieved in all GHz-burst regimes for different burst widths despite the evident pulse spectrum narrowing in the AFL. The developed laser can offer unique set of features and parameters and be very attractive for most material processing applications.

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