DE GRUYTER Adv. Opt. Techn. 2021; 10(4–5): 277–283

Research Article

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High-power ultrafast fiber lasers for materials processing

https://doi.org/10.1515/aot-2021-0033
Received July 15, 2021; accepted September 27, 2021;

Abstract: State-of-the-art fiber-laser systems can deliver femtosecond pulses at average powers beyond the kilowatt level and multi-mJ pulse energies by employing advanced large-mode-area fiber designs, chirped-pulse amplification, and the coherent combination of parallel fiber amplifiers. By using sophisticated coherent phase control, one or even several output ports can be modulated at virtually arbitrary power levels and switching speeds. In addition, an all-fiber setup for GHz-burst generation is described allowing to access an even wider range of laser parameters. The combination of all these approaches together with the robustness, efficiency, and excellent beam quality inherent to fiber-laser technology has the potential to strongly improve existing materials-processing applications.

Keywords: coherent combination; fast switch; fiber lasers; GHz-burst; materials processing; ultrafast.

1 Introduction

In the last decades, fiber lasers and amplifiers have become versatile tools for a plethora of state-of-the-art materials-processing applications [1–3]. Their success is based on the wave-guiding properties of the fiber technology resulting in an excellent average-power capability while maintaining diffraction-limited beam quality, high wall-plug efficiency, and maximum compactness, reliability, and robustness. These advantages come into play not only for high-power continuous-wave and short-pulse laser systems but also for low- and medium-power ultrafast systems with pulse durations in the range of ps to fs. However, not only serving the important but also most demanding market segment of ultrafast laser systems, requesting simultaneously high energies in the μJ to mJ range and average powers beyond the kW level, is still extremely challenging for all laser technologies.

In this contribution, we will focus on the capabilities but also the limitations of state-of-the-art ultrafast fiber technology. We will introduce the concept of a coherent combination that allows us to bypass existing physical limitations and to realize laser parameters that have been inaccessible even a few years ago. Figure 1 shows the parameter range of commercially available ultrafast fiber lasers emitting at 1 and 2 μm central wavelength, i.e. fiber-laser systems based on ytterbium- and thulium-doped fused silica, respectively. As can be seen from the figure, for both wavelengths coherent-combination systems with kW-level average powers and multi-mJ pulse energies are readily available, i.e. parameters beyond the capability of single-emitter systems. Moreover, laboratory setups have recently crossed the 10 kW barrier for ultrafast laser systems, ultimately demonstrating the capabilities of the coherent-combination technology [4]. Finally, a novel external modulation possibility based on the coherent combination and the fiber-based generation of GHz pulse bursts [5–7] will be briefly described. The combination of all these technologies will allow to access unprecedented laser parameters and flexibility and will be able to revolutionize ultrafast materials processing.

2 State-of-the-art ultrafast fiber amplifiers

For ultrafast applications such as surface structuring [8] and micromachining [9, 10], requirements on state-of-the-art laser technology can be extremely demanding and typically depend on the specific application. In general, the desired light-matter interaction requires minimum pulse energy

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within a given pulse duration to be initiated. Secondly, the repetition rate and therewith the average power defines throughput and process efficiency assuming the availability of laser scanners with sufficient deflecting speed and high-power optics. Today, the majority of market-relevant applications are driven by laser systems with a few tens of Watts of average power with a trend toward multi-100 W laser systems. It can be anticipated that there will be a demand for ultrafast laser systems at the kW level and beyond within the near future. These power requirements typically come with the request for pulse energies in the μJ to mJ range, an excellent beam quality, and, of course, compactness, stability, and robustness.

The three most prominent solid-state laser technologies capable of generating the highest power levels are based on active media with thin disks [11], Innoslab [12], or fiber geometry [13, 14]. In comparison, thin disk and Innoslab geometries allow for higher pulse energies in the ultrafast regime resulting from their reduced nonlinear interaction of the amplified laser pulses with the active medium. Fibers, on the other hand, are superior in terms of achievable average power while preserving diffraction-limited spatial beam quality even in the femtosecond-pulse regime [15–18]. However, in fibers, the tight transverse confinement of the optical pulses over considerable lengths eventually results in nonlinear pulse distortions and damage at high peak intensities. This can be circumvented to a certain degree by employing fibers with large mode-field areas [19] in combination with a chirped-pulse-amplification scheme (CPA) [20]. State-of-the-art pulse stretchers and compressors allow temporal extension of femtosecond pulses up to duration of several nanoseconds and enable fiber-based systems to produce pulse peak powers of up to 3.8 GW at 2.2 mJ pulse energy out of a single main-amplifier channel [21]. However, after decades of successful power scaling, a further increase in available average output power and pulse energy becomes increasingly challenging due to the proximity of different technological limitations. Regarding the case of ultrafast fiber technology, for example, the most prominent limitations are optically induced damage and the occurrence of nonlinear effects resulting in a degeneration of the spectral and temporal pulse properties. In principle, the stretched pulse duration in the CPA regime could be further increased but is practically limited to about 10 ns by the footprint of the laser system, the available grating size, cost, and regarding multipass-approaches, by the grating efficiency. Moreover, for large-mode-area fibers, single-mode operation becomes extremely challenging for mode-field-diameters exceeding 80 μm due to unavoidable production tolerances during fiber drawing. Finally, even in terms of average power, the traditional strength of fiber technology, novel effects such as transverse-mode instabilities seem to set an ultimate limit at highest output powers [22].

One solution to overcome (or actually bypass) such a fundamental barrier of scaling a physical system beyond its intrinsic limitations is parallelization. Thus, instead of pushing laser technology step by step toward its fundamental limitations, the idea is to operate the amplifiers well below these limits and add more identical amplifiers operating in parallel. Finally, the individual output emissions of the parallel amplifiers are coherently combined into a single output beam. The implication of this change in paradigm is significant: achievable laser parameters are not limited anymore by the different limiting effects discussed above, but only by the number of parallel channels, i.e. by system size and cost.

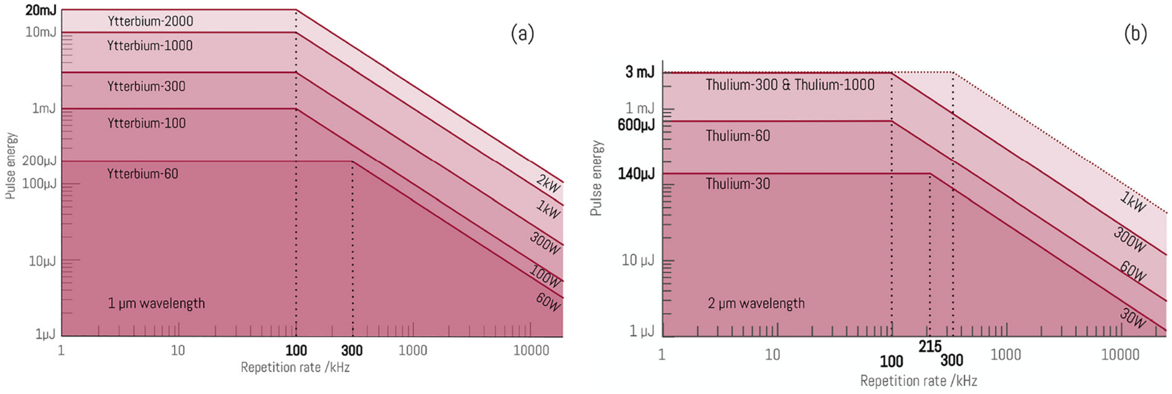

Figure 1: Pulse energy versus repetition rate of various commercialized ultrafast (<300 fs pulse duration) fiber lasers, (a) ytterbium-doped (1 μm emission wavelength) and (b) thulium-doped (2 μm emission wavelength). The term ytterbium or thulium followed by a number indicates the particular platform and its maximum accessible average power in Watt.

3 Coherent beam combination

The approach of laser-amplifier parallelization has already been used for decades for power scaling of both continuous wave and pulsed laser systems [23]. The different techniques can be classified either as tiled aperture, i.e. overlapping the beams only in the far field, or as filled aperture, i.e. overlapping the beams both in the near field and in the far field. Such a geometric combination can be realized incoherently in the most simple approach, i.e. the beams to be combined are either not coherent or at least the phase difference between them is not controlled in an active manner. Prominent examples are depicted in the upper part of Figure 2 such as a geometric, wavelength, or polarization combination. While for the first example the laser beams are just arranged next to each other, the combination takes place for the other two cases by using a diffraction grating exploiting the difference in wavelength or by using a polarizing element exploiting the different states of polarization. All these approaches allow increasing the achievable laser output power. However, for the three examples in the figure, this power scaling comes at the cost of spatial beam quality, wavelength, or polarization purity. Power scaling while maintaining all other beam properties can only be achieved by additionally controlling and stabilizing the phase difference, which is illustrated by the lower part of Figure 2.

One of the most common techniques for high-power ultrashort-pulse coherent beam combination is the filled-aperture approach based on polarization beam combination as shown in Figure 3a. In a corresponding laser system, femtosecond pulses from a front-end oscillator are stretched in time, reduced in repetition rate, and preamplified in several low-power amplifier stages. Before the main-amplifier stage, they are divided into N copies which are then amplified in N parallel channels. This beam division can be realized by using polarization beam splitters that divide an incident linearly polarized laser beam into two linearly polarized beams with perpendicular polarization orientation. Separation into $N > 2$ channels can be achieved by cascading these 1:2 splitters. After amplification, the parallel laser beams are recombined in a coherent manner exploiting again similar cascaded polarization beam splitters in reversed geometry. Due to the active control of the phase difference between the different channels, each two perpendicular linearly polarized beams are again combined into a single linearly polarized beam. At each combination step, the polarization state can be used as an error detection mechanism for the phase difference between the two channels, since any phase difference results in a deviation from the linear polarization state. Therefore, $N - 1$ amplifier channels are equipped with delay lines to match the individual path lengths for efficient recombination after the main amplifiers. The individual delay lines contain piezo-driven mirrors for active phase control and stabilization of any path-length differences. After every combination step of two beams, a small fraction of the combined beam is directed toward a Hänsch-Couillaud detector [24] to determine the polarization state. This information is processed with a PID controller that acts on the corresponding delay line to optimize the beam for linear polarization. Finally, after the last combination step, the beam is sent into a grating-based compressor to recompress the stretched pulses down to few-hundred-fs

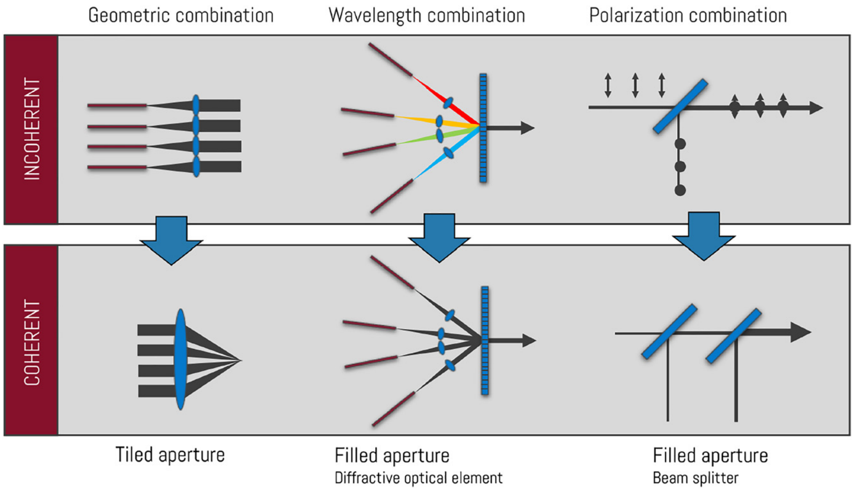

Figure 2: Overview of various approaches for a coherent and incoherent combination of light beams.

pulse duration. With such a setup, the combination of up to 16 parallel channels (Figure 3b) has been already reported delivering outstanding parameter combinations of up to 10 mJ pulse energy at 1 kW of average power and <120 fs pulse duration [25]. By using a similar geometry but with dielectric intensity beam splitters and combiners that allow for even higher average powers due to the simpler and less-absorbing multilayer coatings, a record value of 10 kW of average power in the ultrafast regime has recently been demonstrated showing simultaneously an excellent beam quality [4]. However, when using intensity beam splitters instead of polarization beam splitters, the state of polarization cannot be used anymore to measure the phase difference and alternative stabilization approaches such as LOCSET or SPDG have to be employed [4].

The geometry of parallel amplification brings further advantages regarding the use of external optical components that typically have to be placed in the high-power output beam. Optical isolation, for example, an imperative necessity for the use of ultrafast fiber lasers for materials processing, becomes extremely challenging for kW-level average powers. However, in systems with parallel amplification, each amplifier channel can be equipped with an individual optical Faraday isolator reducing the power-handling requirements accordingly. Moreover, external modulation can be similarly challenging at the highest power levels. Also, in this case, coherent-combination technology offers unique possibilities to circumvent existing limitations that will be discussed in the following.

4 High-speed amplitude modulation – fast switch

Many materials-processing technologies employing high-power laser systems require fast control of the amplitude of the laser output [3, 26]. Although state-of-the-art laser technology can deliver femtosecond pulses with average powers even beyond the kilowatt level, pulse-to-pulse amplitude control at multi-MHz, or even GHz-level is impossible by employing classical approaches such as acousto-optic modulators (AOMs) or Pockel's cells. These modulators are either too slow or they cannot handle high average powers and/or peak powers due to the propagation of the high-power output beam through a considerable amount of optical medium. An alternative approach to control the amplitude of a high-power laser system is to use coherent-combination technology. As described in the previous section, in order to maintain a coherent combination, i.e. constructive interference at the output port of the laser, one has to actively control the phase difference of the channels to be combined. Thus, from another point of view, the output of the laser can be arbitrarily modulated by modulating this phase difference. Figure 4a shows the basic principle of this switching mechanism. Depending on the imprinted phase difference, the pulses either constructively or destructively interfere with the laser output. The other output of this interferometer is typically dumped, but can also be used as a second laser output. By using more sophisticated geometries, even more laser outputs each controllable on a pulse-to-pulse time scale can be realized. Additionally, the chosen phase difference allows not only to switch the laser output on and off but also to generate intermediate values to arbitrarily modulate the system output. This brings a huge advantage for power scaling of an externally modulated ultrafast laser system, since contrary to the classical approaches such as AOMs or Pockel's cells, this modulation can be imprinted on the laser pulses at a low-power stage at the beginning of the amplification chain. Therefore, low-power fiber-coupled phase modulators with GHz-modulation speeds can be employed allowing for a pulse-to-pulse modulation even for high-repetition-rate systems in the multi-MHz or even GHz

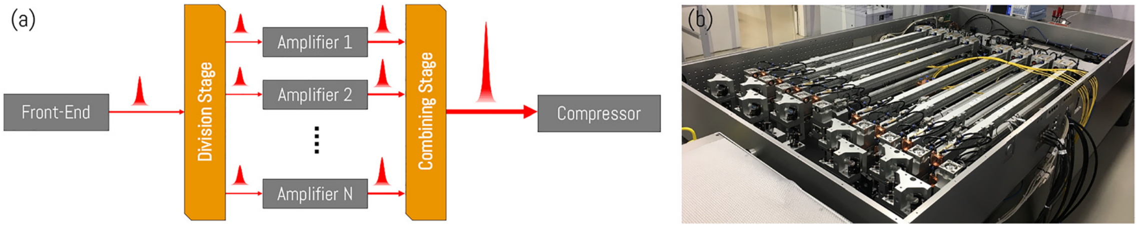

Figure 3: (a) Schematic view of the coherent-combination technique used to amplify the seed laser pulse in *N* parallel amplifier channels. (b) Photograph of a 16-channel coherent-combination amplifier installed in a customer's laboratory.

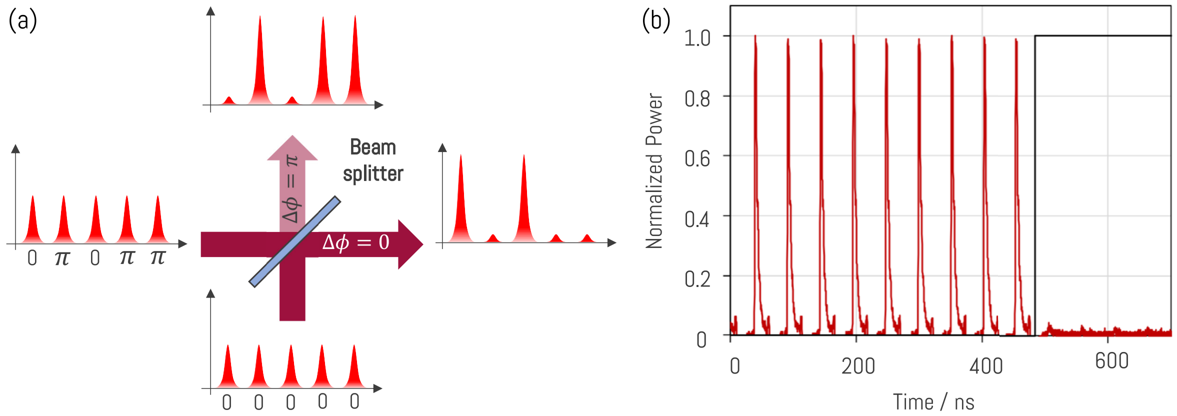

Figure 4: (a) Working principle of the “Fast Switch” amplitude-modulation technique. The exemplary phases given below both incoming pulse trains (left and bottom of the beam splitter) result in constructive or destructive interference at the two possible output ports (right and top of the beam splitter). (b) Exemplary photo-diode trace of the amplitude-modulated output. The onset of the modulation signal is shown as the black line.

regime. Figure 4b shows exemplarily the measured output pulses of a 20 MHz ultrafast laser system operating at 500 W of average power. Between two subsequent pulses, the output amplitude of the emitted laser pulses is completely modulated.

Besides the virtually arbitrary modulation speed, the power limit of this novel type of external modulation is determined by the final combining element that coherently adds the laser pulses. At this point in the laser system, the pulses are typically still stretched to the ns-pulse duration within the CPA regime. Thus, peak-power effects can be avoided by using sufficient beam diameters. Regarding the average-power capability, optimized combining elements such as large-aperture thin-film polarizers or dielectric intensity beam splitters have already proven their usability in multi-kW operation [4].

5 Burst modules for repetition rates beyond the GHz level

Coherent combination of femtosecond pulses allows for both peak- and average-power scaling and, as shown in the previous section, pulse-to-pulse modulation even at the highest repetition rates. However, the maximum available repetition rate is typically limited by the employed femtosecond oscillator. State-of-the-art oscillators typically emit in the range between a few 10 MHz and a few hundred MHz. However, novel material-ablation schemes require pulse bursts with even higher fundamental repetition rates at or even beyond the GHz level for ideal operation [27–29].

A standard approach to generate GHz-pulse bursts [5, 6] is to use a seed oscillator with a GHz repetition rate emitting a continuous pulse train and to employ a pulse picker to generate the bursts afterward. While being easy to implement, this approach is relatively inflexible and imposes strong requirements on the pulse picker.

The setup presented herein employs a state-of-the-art MHz-level oscillator followed by a standard pulse picker. The pulse burst is generated by cascaded fiber-based delay lines [30] as schematically shown in Figure 5. This method allows for intra-burst repetition rates >10 GHz with variable pulse numbers at flexible repetition rates. Such a burst module can be integrated into the early stages of the amplifier chain and employs a sequence of all-fiber 1-to-2 splitters each of them producing two replicas of the input pulse. One of the replicas is delayed in a dispersion-compensated fiber-based delay line. The resulting double pulse is split again at the subsequent all-fiber 1-to-2 splitter generating four pulses after the second delay line. By using N of these stages, a pulse train consisting of 2^N pulses can be generated with an intra-burst repetition rate >10 GHz. The repetition rate can be varied by adapting the fiber-length difference allowing for a minimal pulse separation of a few ps. Via active control of the losses in each delay line, the number of pulses in the burst and the relative amplitude can be modified. This amplitude can be used, in addition to the external modulation discussed above, to adapt to the specific demand of the application and, additionally, to pre-compensate the temporal shaping due to gain saturation in the subsequent amplifier chain. Figure 6 depicts pulse bursts with repetition rates between 400 MHz and 3.6 GHz measured with a fast photodiode at the output of a 300 μJ fs fiber CPA system operating at 100 W of average power. The burst module has been retroactively integrated into an existing laser system, a further advantage of the described technology.

6 Summary and outlook

Today, ultrafast fiber lasers and amplifiers employing coherent-combination technology are able to generate output parameters that have been inaccessible for any state-of-the-art laser architecture only a few years ago. Regarding the ultrafast materials-processing market, these novel laser systems will allow for unprecedented processing speeds, throughput and, therewith, cost efficiency. Together with an external pulse-to-pulse modulation based on coherent phase control and, if necessary, the use of additional GHz-burst modules, even wider parameter spaces will become available. Already today, these high-power systems are comparable to single-emitter systems in terms of stability and reliability. The open point to be addressed in the near future is the reduction of complexity, size, and cost. A dominant cost driver is the component count resulting from the *N* parallel fiber-amplifier channels each possessing its own beam steering optics, pump diode, and pump-light coupling, fiber cooling, etc. The straightforward approach to significantly reduce complexity is the development of multicore fibers. These fibers will be a key component for next-generation coherent-combination technology. In a multicore fiber, parallelization of all *N* amplifier channels is realized in a single fiber with *N* signal cores but only one surrounding pump core, one pump diode, one amplifier module, and one set of coupling optics. By using a 4×4 multicore fiber for ultrafast pulse amplification, promising results have been achieved recently [31, 32] giving a first glimpse of the disruptive potential of this technology.

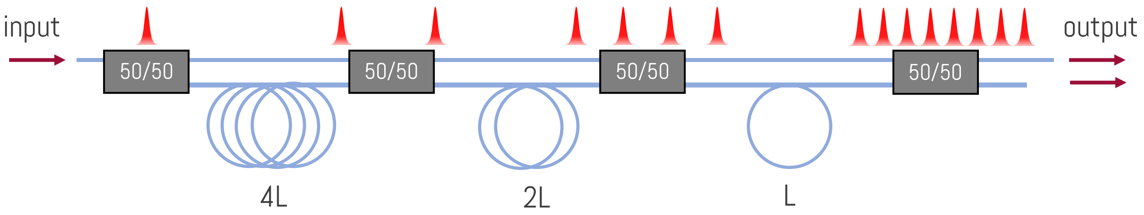

Figure 5: Schematic setup of an all-fiber burst module using fiber-based dispersion-optimized delay lines.

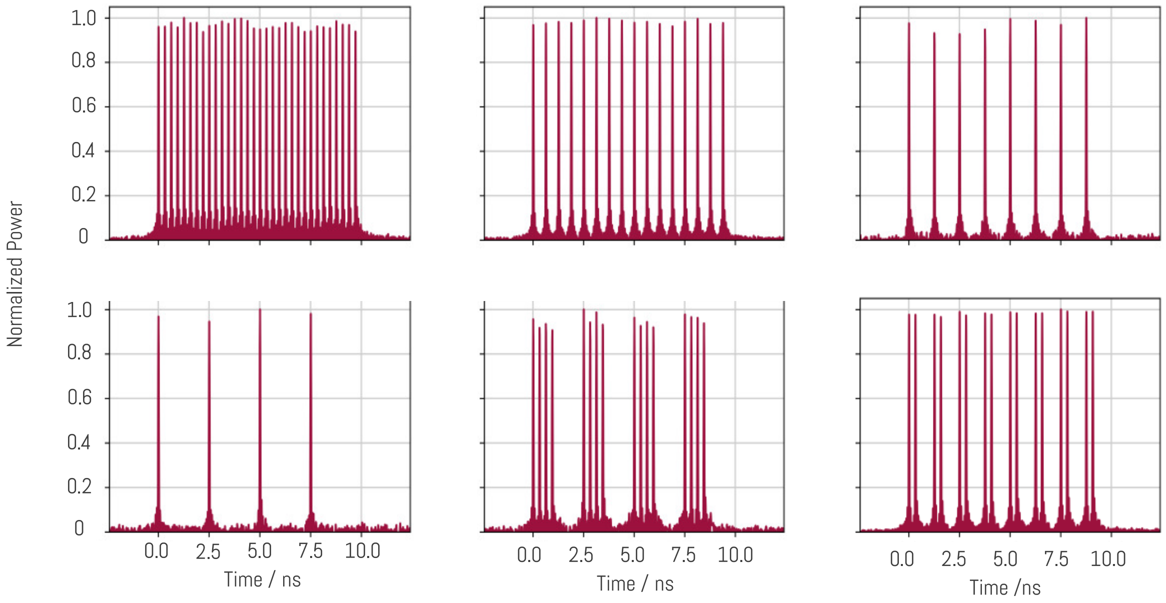

Figure 6: Different 300 fs pulses trains derived from the burst module of a 100-W system at 300 μJ pulse energy. Six exemplary burst distributions are depicted resulting from loss modulation at different positions in the chain of delay lines.

Author contributions: All the authors have accepted responsibility for the entire content of this submitted manuscript and approved submission.

Research funding: German Federal Ministry of Education and Research (project "PINT", 13N15244, funding program Photonics Research Germany); Free State of Thuringia/EFRE (project "Ultraflex", 2018FE0072), Free State of Thuringia/ EFRE (project "Parallas", 2015FE9157).

Conflict of interest statement: The authors declare no conflicts of interest regarding this article.

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