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OPTICAL PHYSICS

Programmable optical waveform generation in a mode-locked gain-modulated SOA-fiber laser

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In this work, we demonstrate for the first time, to the best of our knowledge, programmable generation of arbitrarily complex optical waveforms in a hybrid synchronously pumped fiber-semiconductor laser. We show that in the mode-locked operation, the temporal profile of the generated pulses may follow that of electrical pulses pumping a semiconductor optical amplifier. Controlling the temporal profile of the electrical pump pulses enables the formation of a desired amplitude–time pattern of laser pulses reproduced over each cavity round trip. The identified availability of stable periodic optical waveforms with a pre-set shape and structure opens up prospects for a new generation of laser radiation sources with a widely controllable pulse shape for research and practical applications.

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1. INTRODUCTION

Formation of laser pulses with an arbitrary pre-set shape and structure is one of the most pressing problems in laser physics. The most desirable solutions should provide direct control of laser pulses when their shape and structure follow that of a controlling electrical signal. Arbitrary waveform synthesizers in the optical domain are a novel type of modern equipment [1]. The simplest implementation of such devices is the modulation of continuous or pulsed laser radiation with an external programmable intensity modulator [2–5] or a special shaper [6,7]. This approach allows creation of almost any pulse shape, but there is a substantial drawback inherent in all extra-cavity methods of control over parameters of laser pulses: an external modulator must be used, and it must be synchronized with the laser output. In addition, they incur significant intensity losses in the process of profiling.

The methods of intra-cavity radiation pulse formation (mode locking, *Q*-switching, pulsed pumping/gain switching) ensure significantly higher generation efficiency; however, they only provide limited options of the pulse shape control. It would be convenient to control the pulse shape directly with electrical pulses, i.e., if the shape of output light pulses was identical to that of the electrical driving pulses. Traditionally, active mode locking was considered to generate relatively short pulses synchronized with controlling electrical pulses in phase/time, but its potential for laser pulses generation with a pre-determined shape and structure has hitherto remained virtually untapped. Until now, the relationship between the parameters of electrical control pulses and the generated light pulses was only limited to phase locking of the electrical and light pulses [8], and synchronization of their duration and repetition rate [9,10] (on condition of the repetition rate being a multiple of the cavity resonance frequency).

The dependence of generated light pulse parameters on those of electrical control pulses is important in the case of active mode locking because the active mode locking not only allows the synchronization of optical and electrical pulses, but also provides the means for high-precision control of the main frequency and temporal parameters of pulsed generation (in particular, the repetition rate and duration), and also features a low level of amplitude and phase noise. The advantages of mode-locked lasers promoted them to a very prominent role in modern time-frequency metrology [11,12].

It is necessary to note that the recent progress in methods of passive mode locking has also allowed a certain degree of influence over the parameters of generated light pulses through parameters of electrically controlled artificial saturable absorbers (technologies NOLM/NALM [13] and NALM2 [14]), including methods relying on machine learning [15,16]. Spectral pulse shaping [17,18] was also demonstrated with electronic control [19]. However, the proposed methods of control so far fall short by a wide margin of achieving control over the laser pulse profile by shaping of driving electrical pulses.

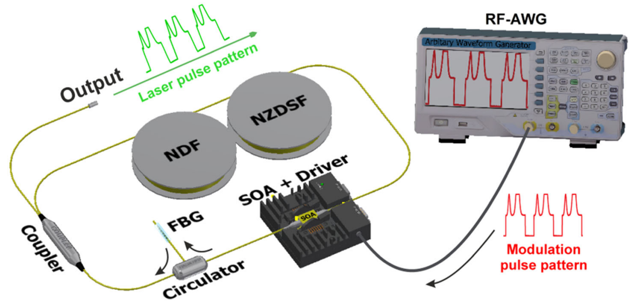

Fig. 1. Experimental setup: SOA, semiconductor optical amplifier; NDF, normal-dispersion fiber; NZDSF, non-zero dispersion shifted fiber; FBG, fiber Bragg grating; RF-AWG, radio-frequency arbitrary waveform generator.

To the best of our knowledge, the present work for the first time proposes and studies a method of generation of arbitrary desired optical waveforms within the limits of the repetition rate in an actively mode-locked laser. Established are the conditions of the electrical-to-optical conversion under which the shape and structure of light pulses follow those of controlling electrical pulses, thus allowing the generation of user-specified periodic amplitude–time patterns of laser pulses.

2. EXPERIMENT

The experimental installation is schematically shown in Fig. 1. As the basis for the proposed mode-locked optical waveform generator, we used a semi-fiber laser, similar to the one specified in [20] with a semiconductor optical amplifier (SOA) serving as the active medium. We used a polarization-independent SOA Covega SOA1013 with ~1 ns response time.

This laser has an all-fiber ring cavity, in which the wavelength selection and stabilization of the output spectrum is performed with a fiber Bragg grating (FBG) coupled to the cavity through a circulator, the latter component being also used to create a unidirectional generation in the circular cavity. The FBG we used had a 1 nm reflection bandwidth, centered at ~1540 nm with a reflection coefficient of 0.95.

The experimental laser is mode-locked through synchronous pumping of the SOA by current pulses at the repetition rate equal to the inter-mode frequency of the cavity. Essentially, the SOA serves two purposes, those of the active medium and gain modulator. Modulation bandwidth of the current driver we used was ~0.7 MHz, while the high-frequency limit of the current driver corresponded to the inter-mode frequency of a ~290 m-long fiber cavity. To lower the working frequency of the current driver that determines the pulse repetition rate, and to allow profiling of the temporal envelope of optical laser pulses at frequencies exceeding the working one, the fiber cavity was lengthened to 4.8 km. This led to a drop in the working frequency of the current driver to 43.35 kHz and consequently enabled profiling of the temporal envelope of optical pulses within the cavity round-trip time of 23 μs with a nearly 1 μs resolution.

Initially, we assumed the possibility of relatively short (for example, sub-nanosecond) pulses and therefore extended the laser cavity with two stretches of fiber, each 2.4 km long, having the opposite dispersion sign for minimization of the total dispersion of the long cavity. One of these fibers had dispersion of -8.8 ps/(nm · km) (NDF, Corning MetroCor), and the other one, $+1.8$ ps/(nm · km) (NZDSF, True-Wave Classic) at the wavelength of 1,540 nm. In our subsequent studies, we discovered that the output pulses were comparatively long (in the microsecond range), and intracavity dispersion compensation was not necessary. A conventional single-mode fiber (e.g., SMF-28) could have been used just as well for cavity extension in case of microsecond or even nanosecond pulses. It should be noted that the lowered inter-mode frequency of the cavity also extends the temporal distance between the successive pulses and affords broader possibilities of generation of periodic optical waveforms with a preset shape and structure.

The laser output was extracted through a 50% coupler, and the average output radiation power did not exceed 8 mW.

To control the amplitude–time profile of the electric pulses driving the SOA, we used a programmable radio frequency (RF) arbitrary waveform generator (RF-AWG, Rigol DG4162).

3. RESULTS AND DISCUSSION

First, we studied the dependence of the laser output power in continuous-wave (CW) operation on the SOA current. The measured data are presented in Fig. 2(a) in the range from 247 mA (the threshold current, at which the generation emerges) to 500 mA (the maximum allowable SOA current). From this figure, it is seen that the dependence is close to linear. This, along with a relatively fast SOA response [21], is a good basis for transfer of the shape of driving electrical pulse onto the laser pulse. Figure 2(b) provides spectra of the laser output at different SOA current values. The widths of these spectra are

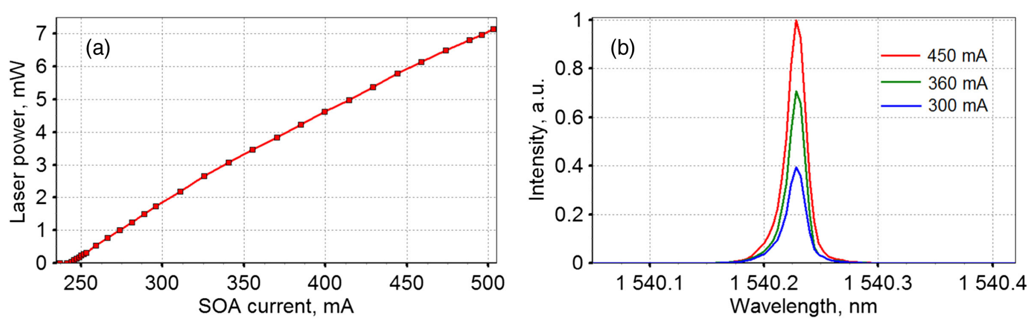

Fig. 2. (a) Dependence of the laser output power in CW operation upon the SOA current; (b) spectra of the laser output at different SOA current levels.

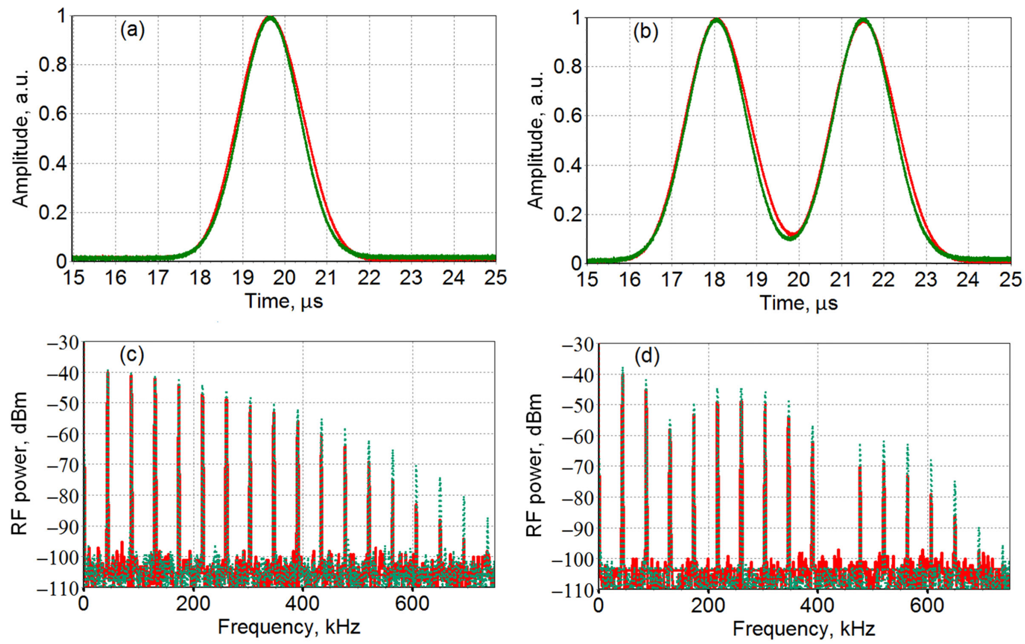

Fig. 3. (a), (b) Time traces of driving electrical pulses (green curves) and generated laser pulses (red curves); (c), (d) corresponding RF spectra (resolution bandwidth, 1 kHz).

defined by the spectral resolution (0.02 nm) of the spectrum analyzer we used.

For pulsing the semi-fiber laser, we used gain modulation with the SOA current swing between 253 mA and 445 mA, that is, above the generation threshold with the 97% modulation depth (considering the lasing range of the current). This regime was different from gain switching [22], where the amplitude modulation is 100% deep, and the generation threshold is reached at each switching and is accompanied by nonlinear distortion of the correlation of the laser pulse shape with the shape of driving electrical pulse.

When driving SOA with pulses of a different shape in the microsecond duration range at the repetition rate of 43.35 kHz (the reciprocal to the cavity round-trip time), the generated laser pulses followed the shape of the electrical ones, so much so that it was difficult to distinguish between them in direct comparison. The temporal profile of the generated laser pulses was registered with a fast photo detector and an oscilloscope. Figures 3(a) and 3(b) compare temporal profiles of the control electrical pulses and the corresponding laser output for the cases of programming a single and two overlapping Gaussian pulses, respectively. It can be seen that these profiles closely resemble each other. To better identify differences between them, we measured the RF spectra of these electrical and laser pulse trains. The measured RF spectra are given in Figs. 3(c) and 3(d). The difference in RF spectra is more visible, although not very significant, indicating a high-quality transfer of the shape from the driving electrical pulses onto the laser pulses. This difference is caused mainly by a slight stretching (by few percent) of the generated laser pulses as compared with the original electric pulses. At the fundamental pulse repetition frequency, the laser radiation RF spectra feature nearly the same S/N ratio as the driving electrical pulse train (about 60 dB). This is an important indication of high quality of both mode locking and pulse shape transferring.

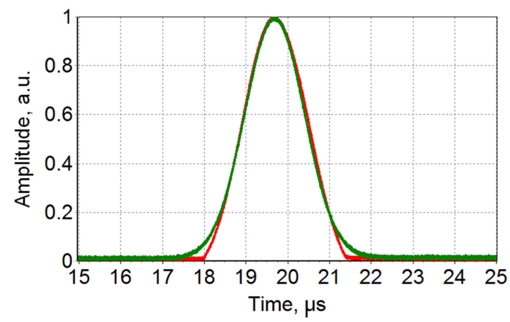

Fig. 4. Oscillograms of driving electrical pulses (green curve) and the generated laser pulse (red curve) in the gain-switching mode.

It is necessary to emphasize that such accurate transferring of electrical pulse shapes onto the laser pulses was possible only in the regime in which the SOA injection current was modulated above the generation threshold. In this mode, the shape of the generated pulses followed exactly that of the modulation pulses, including the low-intensity wings close to the generation threshold. Figure 4 demonstrates a pumping pulse (green) and the corresponding generated pulse (red) in the gain-switching mode (i.e., when the SOA current was modulated down to below the threshold). It can be seen that the generated pulse shape differs from that of the pumping pulse at low intensities close to the threshold (the wings are not reproduced). Thus, the gain modulation above the lasing threshold is preferable to the gain-switching mode (i.e., to gain modulation below the threshold) in the context of the present study.

The next logical question about continued studies was whether the proposed approach allows transferring diverse, more complicated, and ultimately, arbitrary shapes of driving electrical pulse onto the laser pulse. To find this out, we studied

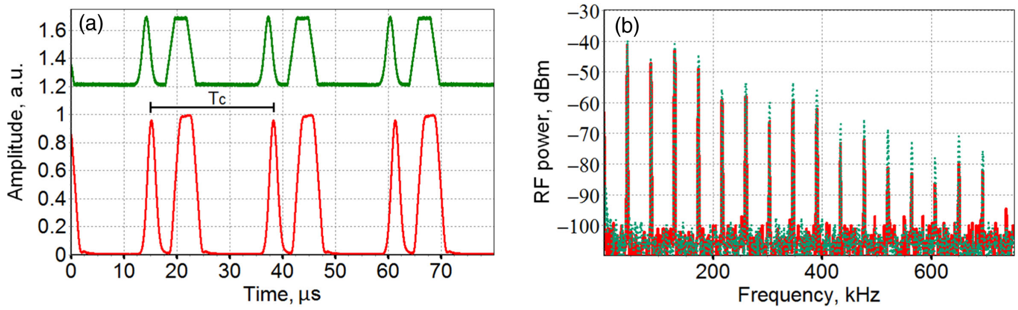

Fig. 5. (a) Oscillograms of the driving electrical signal (green curves) and generated train of the laser pulse patterns (red curves); (b) corresponding RF spectra (resolution bandwidth, 1 kHz).

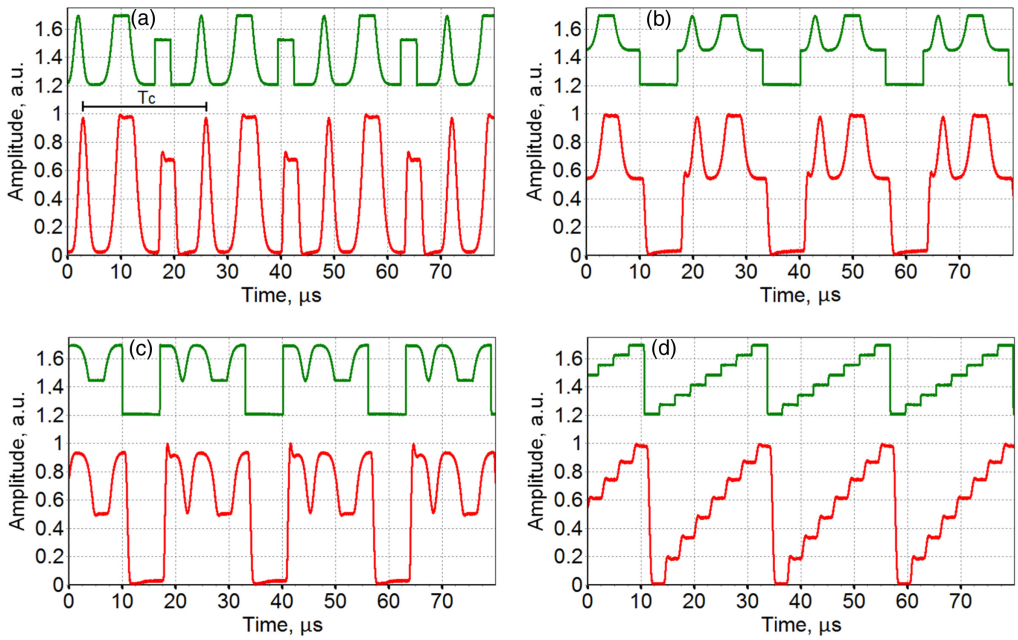

Fig. 6. Oscillograms of complicated forms of driving electrical signal (green curves) and resulting laser pulse patterns/waveforms (red curves).

the generation properties of the laser when SOA was controlled with complex pulse patterns and waveforms. First, the SOA was driven with a discrete pulse pattern composed of a Gaussian and a trapezoid within the time frame of the cavity round trip ($\mathbf{T_c} = 23$ µs). Figure 5 presents the resulting oscillograms and RF spectra of the driving electric signal and the generated regular train of the laser pulse pattern. These measurements proved high-quality reassembling the given pulse pattern in the optical frequency range. It is remarkable that not only smooth shapes like Gaussian pulses, but also broken-line functions with nearly the same noise figure, can be faithfully transferred. On this basis, we moved to more complicated pulse patterns and waveforms.

Presented in Figs. 6(a)–6(d) are oscillograms of more complicated driving electrical pulses and corresponding generated laser output. It can be seen from Fig. 6 that, effectively, the proposed approach allows a transfer of arbitrary pulse shapes and patterns from the driving electric signal onto the generated laser pulses. Therefore, the proposed mode-locked laser system is capable of producing microsecond-scale periodic optical waveforms following the temporal profile of electrical pulses used for synchronous pumping of the SOA. The temporal scale of optical waveforms in this method cannot exceed the cavity round-trip time.

It should be noted that only square edges of generated optical waveforms were affected by the moderate modulation bandwidth of the employed current driver, which is the electronic bottleneck of the system. To clarify this, we present in Fig. 7 time traces of pulses with the steepest leading and trailing edges possible in the studied system.

Figure 7(a) shows the laser response (red curve) to synchronous pumping by rectangular pulses (green curve). Visible are slower leading and trailing edges of the laser pulse with a rise time of ~0.5 µs (measured between 10% and 90% amplitude levels). Figure 7(b) presents the pumping pulse pattern (green curve) consisting of 0.7-µs-long rectangular sub-pulses and the respective generated laser pulse pattern (red curve). It can be observed that the structure and profile of the generated pulse pattern tend to copy that of the pumping pulse pattern having temporal features close to the ultimate time resolution of the system.

An important feature of the proposed approach for the generation of programmable optical waveforms is that the laser

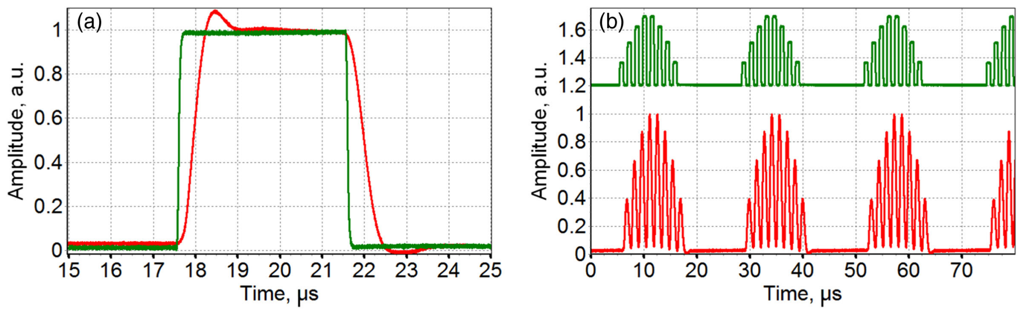

Fig. 7. Oscillograms of pulses with the steepest leading and trailing edges generated in the laser under study.

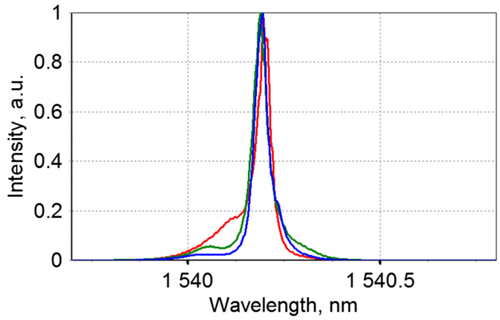

Fig. 8. Laser output spectra: the blue curve corresponds to the pulses of Fig. 6(b), the green curve to the pulses of Fig. 6(c), and the red curve to the pulses of Fig. 6(d).

output spectrum is not strongly affected by the shape and power of the generated pulses. Figure 8 demonstrates the laser output spectra corresponding to the pulses shown in Figs. 6(b)–6(d). The spectral width and position of the maximum do not change significantly, even if the waveform is dramatically modified.

Revealed stability of the lasing wavelength and spectrum width presents an advantage of the proposed method over some other ways of generating programmable optical waveforms. For instance, it is possible to form different pulses by driving the injection current of a diode laser [23]. However, deep modulation of the current in conventional laser diodes also swings its lasing wavelength, which is not acceptable for a number of applications.

We have demonstrated above the feasibility of the proposed method of programmable optical waveform generation on a microsecond time scale. We believe that this approach may be extended at least into the nanosecond pulse range if a faster current driver is used. Implementation of faster pulse trains is also possible, although it must obviously be different for the MHz and GHz ranges. The speed of the Covega SOA1013 component allows the modulation at frequencies up to ~1 GHz (when an appropriately fast current driver is used). This will not only raise the pump pulse repetition rate into the MHz domain, but also allow the profiling of their temporal envelope. Peculiarities of this implementation will be identified after studying the gain modulation mode in the MHz frequency domain. The GHz modulation seems very difficult both from the electronics viewpoint (SOA and the current driver need modulation bandwidth > 1 GHz) and from the optics viewpoint, because the laser cavity must be shorter than ~0.3 m. This poses a special problem for fiber lasers.

An important question about the proposed method of optical waveform generation is how precisely the synchronous pumping must be matching the inter-mode frequency of the cavity. In the studied laser, a noticeable modification of an initial laser pulse shape occurred when the pump pulse repetition rate was detuned from the inter-mode cavity frequency by more than 20 Hz. Such close matching of the repetition rate of the pumping pulses to the inter-mode cavity frequency can tolerate their relative instability if it is below $5 \cdot 10^{-4}$, which is not a technical hurdle. For instance, the inter-mode cavity frequency may drift due to changes in the fiber optical length caused by thermal expansion. However, for a quartz fiber, a 0.05% change in its optical length requires a temperature excursion in excess of 100°C. Therefore, thermal fluctuations of the inter-mode cavity frequency may be ignored in this case.

4. SUMMARY

To the best of our knowledge, this work for the first time presents the results on a programmable optical waveform generator based on an actively mode-locked SOA-fiber laser. It was demonstrated that over the microsecond duration scale, it is possible to implement the electrical-to-optical conversion, where the shape and the structure of generated light pulses follow precisely those of the controlling electrical pulses used to synchronously pump the SOA. The key factors enabling such electrical-to-optical waveform transferring are synchronous pumping of SOA in the gain-modulation regime, a relatively low-peak power, and a narrow optical spectrum of the laser radiation. Due to these factors, the generated optical waveforms are not noticeably affected by optical nonlinearity and dispersion of the laser cavity. A rather fast (nano- or even picosecond) SOA response allows using this method in the sub-microsecond range of durations as well. The advantages of the proposed method for the generation of nearly arbitrary optical waveforms are a comparatively high-energy efficiency (compared to methods based on amplitude modulators), a stable and relatively narrow optical spectrum (in comparison with approaches based on direct modulation of the diode laser current), and a high S/N ratio, typical of a mode-locked operation. The discussed approach may serve as the base of next-generation laser radiation sources with a broadly controllable pulse shape for scientific and industrial applications.

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