Optics and Laser Technology 131 (2020) 106422

Contents lists available at ScienceDirect

Optics and Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

Full length article

Single- and multi-soliton generation in figure-eight mode-locked fibre laser with two active media

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HIGHLIGHTS

- F8 dual-pump mode-locked fibre laser is flexible source of soliton singlets/molecules.
- Generation of electronically controlled ps pulse bursts with ns inter-pulse delays.
- Number of generated solitons count round-trip is controllably varied from 1 to 7.
- Possibility of twofold variation of soliton energy within a specified state.
- Identified are features of transitions between different soliton patterns/bursts.

ARTICLE INFO

Keywords:
Mode-locked fibre laser
Source of soliton singlets and molecules
Bursts of picosecond solitons

ABSTRACT

We present a study of generation of a figure-eight mode-locked all-PM fibre laser having two independently pumped active media in each loop of the cavity under varied power level of both pump sources. Controllable and reproducible generation of 1- to 7-picosecond solitons per cavity round trip is demonstrated, as well as the possibility of soliton peak power and energy adjustment in a pre-determined passively mode-locked regime. Salient features are identified of transition among regimes with different soliton count, including those generating Raman solitons. The studied all-fibre laser system makes it possible to reproducibly generate pre-determined soliton molecules with variable energy. Such a fibre-optical system may be widely used as a seed generator of electronically controlled bursts of picosecond solitons with nanosecond inter-pulse delays.

1. Introduction

The broad diversity of generation regimes exhibited by mode-locked fibre lasers results both from the possibility of adjusting the optical media nonlinearity within a relatively wide range and from the available variety of combinations of dispersion, polarisation, and other laser cavity parameters. The figure-eight laser is one of the platforms supporting controllable realisation of various mode-locked regimes. In such a laser, one of the loop mirrors has nonlinearity while the other one only has gain and supports uni-directional generation [1–5]. We will henceforth refer to this configuration as NALM-ALM. Fibre lasers with an all-PM (polarisation-maintaining) NALM-ALM configuration provide extended possibilities of fully electronic reproducible and precise control within a two-dimensional pump power space over various generation regimes of the laser, as well as highly accurate adjustment of pulse duration and energy parameters (pulse energy, peak radiation power), which may be quite high in this type of laser. As such extended modes of control over the pulse parameters in these lasers are implemented, new effects spring to action, which require further investigation.

It should be noted that the NALM technology [6] and its modifications [7,8] employed in a functional analogue of a saturable absorber are superior to technologies based on natural saturable absorbers [9,10], in particular for soliton operation. The major advantage of technologies based on artificial saturable absorbers is their ability to provide, as a rule, higher energy parameters of output pulses.

The accessibility of comparatively high energy parameters of the generated dissipative solitons (DS) [11–15] may lead to their decomposition into several solitons with lesser energy, — which effect is traditionally interpreted as energy quantisation of DS [16–24], — and to formation of relatively low-energy bound solitons with discrete and fixed separation [18–20]. In order to control the process of formation of a given soliton pattern (or a desired bound state), various methods are employed [25–30]. These methods, however, suffer either from limited latitude of control because only one degree of freedom, — the pump power, — is accessible [23,25,26] or from lack of reproducibility since

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https://doi.org/10.1016/j.optlastec.2020.106422
Received 11 April 2020; Received in revised form 20 May 2020; Accepted 12 June 2020

polarisation controllers must be used [5,27–37], which have rather too many degrees of freedom. Moreover, polarisation controller settings are even more difficult to reproduce if mechanical controllers are used.

In [4], the properties of single- and multi-soliton generation regimes in a fibre laser with an all-PM NALM-ALM configuration were explored. In that experiment, however, only one parameter was measured, the pump power of the NALM loop of the laser cavity, whereas the pump power of the second cavity loop (ALM) was fixed. There is significant interest in more complete exploration of the generation properties of this convenient all-PM-fibre electronically controlled configuration where generation properties may be dynamically adjusted by means of two variables, *i.e.* the power levels of two independent pump sources in each of the loops of the figure-eight NALM-ALM mode-locked fibre laser.

The present work reports for the first time on study of the generation properties of a figure-eight NALM-ALM mode-locked all-PM fibre laser under varied power levels of the pump sources of both cavity loops. We present a detailed map of generation regimes of this laser that demonstrates the possibilities of reproducible electronic control over single- and multi-soliton generation, as well as the variability ranges of pulse energy and peak power of DS in various regimes.

2. Experimental set-up

The experimental set-up of the studied figure-eight NALM-ALM passively mode-locked fibre laser is schematically shown in Fig. 1.

The experimental installation was created on the basis of a figure-eight mode-locked fibre laser whose each loop contained an independently pumped active medium. Besides the active media, in one of the loops there is an optical isolator that ensures uni-directional generation in this loop and laser radiation output in one direction through a 30/70 output coupler. This loop is connected to the other one through a 50/50 fibre coupler. The other loop only has a gain medium and passive fibre, thereby constituting a nonlinear amplifying loop mirror (NALM). As it was already mentioned earlier, this combination of a NALM and an amplifying loop mirror (ALM, the first cavity loop) gives rise to the term NALM-ALM adopted here. The active media parameters are as follows: ALM – 2.5-m Yb-doped fibre (nLIGHT Liekki Yb1200-6/125), NALM – 2.5-m Yb-doped fibre (nLIGHT Liekki Yb1200-6/125). These gain fibres were pumped with two laser diodes LD1 and LD2 through two 975/1080-nm combiners, each diode delivering up to 5 W at 975 nm. The cavity's passive fibre was of PM-980 type (Nufern/Coherent) and the total cavity length was equal to 13.47 m. The output intensity was detected with a high-speed photodetector (NewPort 818-BB-35F 12.5 GHz) and visualised with a fast oscilloscope (Tektronix, DPO71604C 16 GHz). The output radiation spectrum was registered with an optical spectrum analyser Yokogawa AQ6375. An A.P.E. pulseCheck auto-correlator was used for measurement of pulse duration.

3. Results

Raising the power of pump sources LD1 and LD2, as well as adjustment of their ratio results in realisation of various mode-locked generation regimes differing in pulse count per round trip. As the LD1 and LD2 power was raised within the 5-W range, consecutive growth of pulses per round trip was observed from 1 to 7. Fig. 2 presents time traces corresponding to generation of 1–6 pulses per round-trip at the fundamental repetition rate of 15.15 MHz. The oscilloscope traces of Fig. 2 were normalised, however the actual peak height in these traces does not differ much from the normalised values (within 10–20%). It can be seen from Fig. 2 that the temporal position of pulses within a bunch is not equidistant when there are 3 or more of them. For example, in the case of six pulses, the inter-pulse distance (or delay) drops from 0.7 to 0.3 ns.

To study all possible pulsed regimes of our laser cavity, we consistently changed the powers of both pumping diodes in the range from 5 to 0.5 W in the following order. At a fixed power of the LD1, we gradually reduced the power of the LD2 from 5 to 0.5 W with a step of 0.03 W and measured the parameters of the output radiation at each power step. Then the power of LD1 was reduced by 0.03 W, and the procedure was repeated until LD1 power became equal to 0.5 W. The resulting map is presented in Fig. 3. As it is seen from Fig. 3, the map of mode-locked generation regimes of the figure-eight NALM-ALM fibre laser is divided into 7 regions marked with different colours and corresponding to generation of different number of solitons per round trip. Black areas of Fig. 3 represent transition regimes where Raman generation at 1120 nm (first Stokes component) was observed.

White areas of Fig. 3 correspond to CW and unstable regimes, as well as to regimes producing noise-like (double-scale) pulses [38,39], which latter were identified by the shape of their measured auto-correlation function. Therefore, coloured and black areas of Fig. 3 represent generation of coherent pulses.

The measured map (Fig. 3) leads to the following conclusions:

1. Areas corresponding to generation of different pulse counts per round trip have different size, the one with 2 solitons per round trip being the largest.
2. Starting with the area related to generation of 3 solitons per round trip, the areas with higher number of solitons per round trip become progressively smaller.
3. Within each of the indicated areas corresponding to generation of specified number of solitons per round trip, it is possible to adjust the soliton parameters by variation of powers of the pump sources LD1 and LD2.
4. Transition among the areas corresponding to generation of 1–5

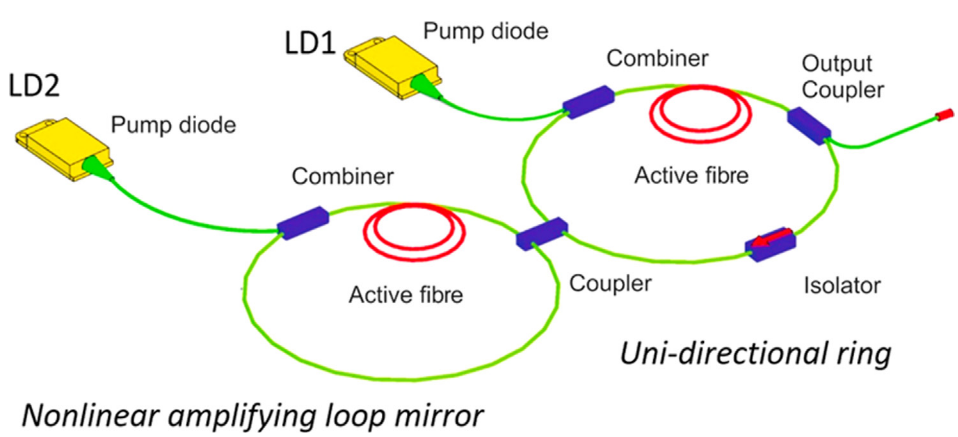

Fig. 1. Experimental set-up of the figure-eight NALM-ALM mode-locked fibre laser.

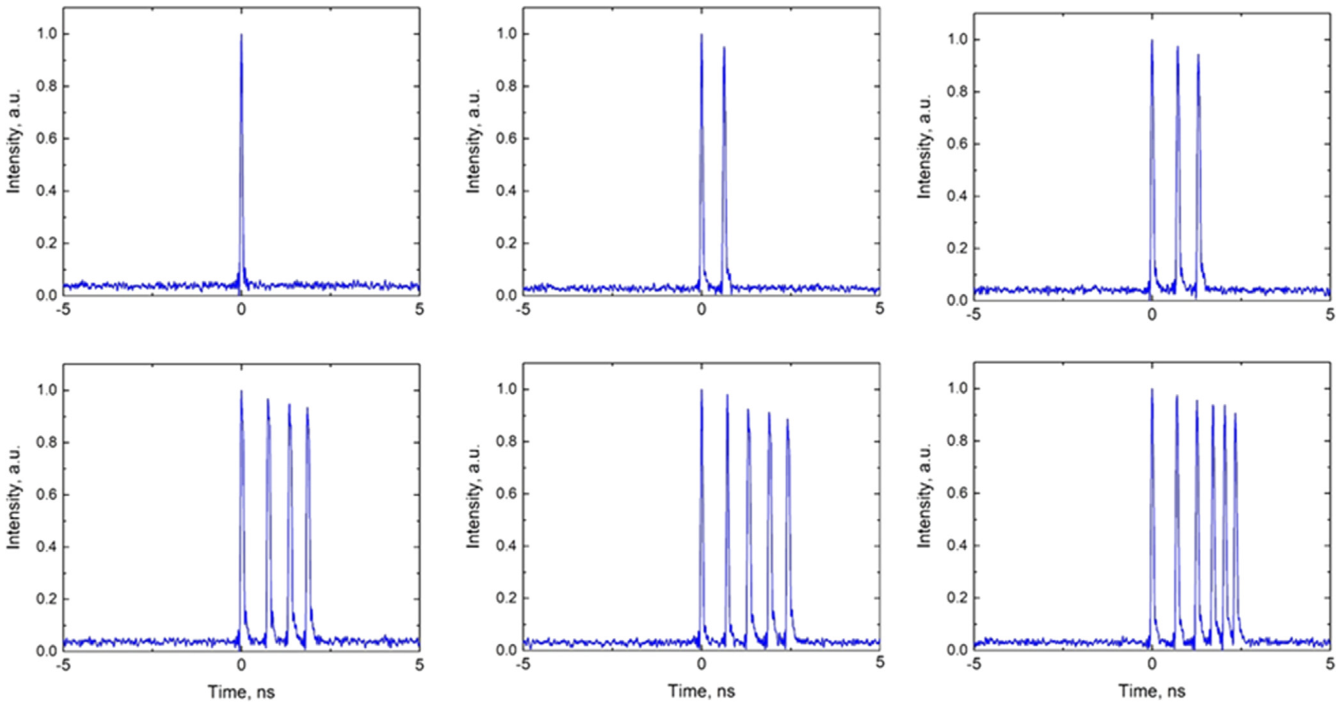

Fig. 2. Oscilloscope traces of mode-locked single- and multi-soliton generation.

solitons per round trip are possible both through areas of Raman generation and directly without it. The transition between the areas with 6 and 7 solitons per round trip is only possible through an area of Raman generation.

The observed generation regimes were stable within the areas of Fig. 3. Moreover, the pulse positions were also stable. Nevertheless, in multi-pulsed regimes we observed small movement of subsequent solitons with respect to the first one of the bunch close to the regime boundary in transition from one multi-pulsed regime to another.

It is important to mention the presence of hysteresis phenomena and dependence of the map of Fig. 3 upon the direction (increasing or decreasing) of pump power adjustment. In case of direction reversal, the general structure of the map will remain, but quantitative parameters (pump radiation powers) may change by 20–30%.

The possibility of fine adjustment of the soliton energy and peak power by variation of the power delivered by pump sources LD1 and LD2 within a specified area of Fig. 3 constitutes an advantage of the studied laser platform over many others, in which control is limited to setting the number of solitons without a way to control their parameters. Fig. 4 illustrates the range of fine adjustment of the soliton energy and duration in the regimes producing 1–6 solitons per round trip.

It can be seen that in the regimes featuring 1 and 2 solitons, their energy and duration can be adjusted more than by a factor of 3, that is from ~6 up to ~20 nJ and from ~50 to ~160 ps respectively. As the number of solitons per round trip grows, the areas of parameter variation shrink down, as it is reflected in progressively smaller generation areas of Fig. 3. Broad possibilities of soliton parameter variation in regimes generating 1 and 2 solitons per round trip are also presented in Figs. 5 and 6.

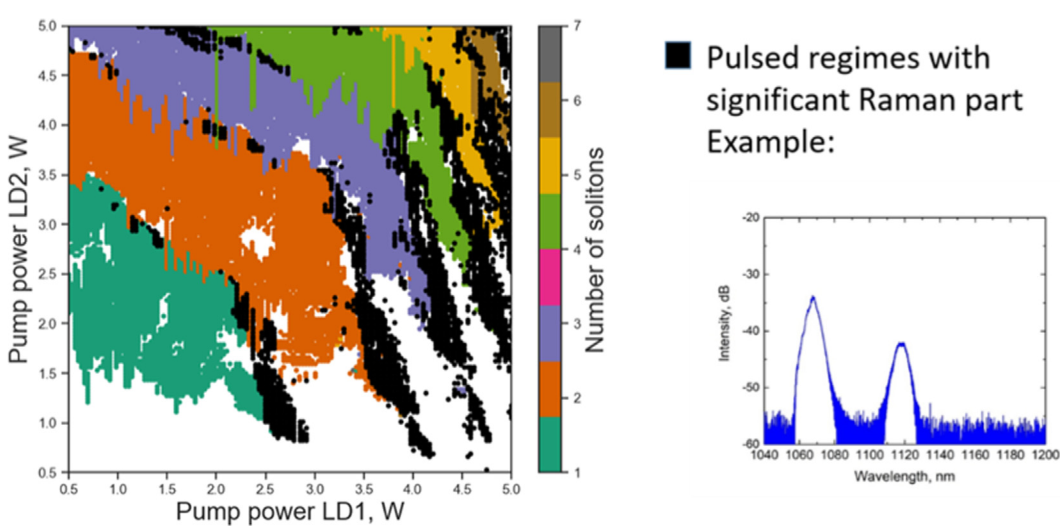

Fig. 3. Map of mode-locked generation regimes of the figure-eight NALM-ALM fibre laser (left); laser output spectrum in transition regimes producing Raman radiation.

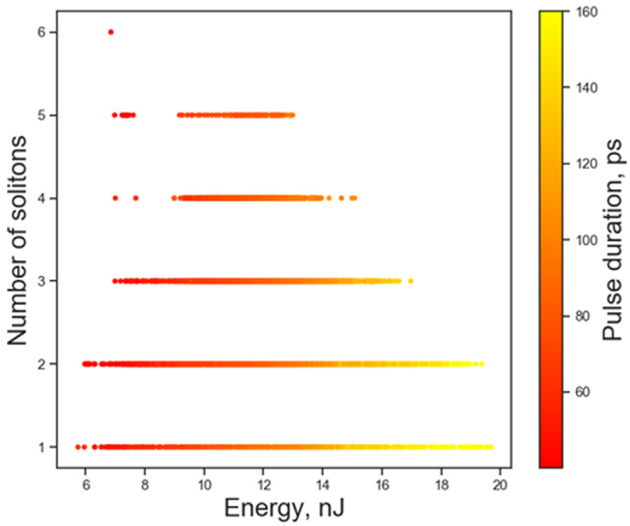

Fig. 4. Variability of soliton energy and duration in the generation regimes with different number of solitons per round trip (1–6).

4. Discussion of results

The two-dimensional pump power space of the studied F8 mode-locked fibre laser with independently pumped active media in each loop of the cavity offers advanced possibilities of flexible electronic control over single- and multi-soliton generation and allows substantially broader utilisation of the fibre technology advantages. To the absence of the need to align and service the laser are added the possibilities of electronic control over the generated radiation parameters via relatively simple algorithms that ensure reproducible output parameters and do not require more complicated methods relying on machine learning [40,41]. NALM-based [42] technology of F8 mode-locked fibre lasers with two active media enables characterisation of generation properties within a two-dimensional pump power space, the reliability and unambiguity of this characterisation being only possibly limited by hysteresis phenomena [38]. Nevertheless, if these phenomena are taken into consideration the proposed technology leads to relatively accurate reproduction of generation properties of mode-locked fibre lasers by means of electronic control.

The presence of soliton properties analogous to quantised states, — a discrete set of energy states, — was pointed out in many publications [see, for example, 43, 44]. However, as the results of the present work demonstrate, energy states of dissipative solitons and soliton molecules are not strictly deterministic. Energy "levels" of such solitons and molecules have certain width, within which it is possible to continuously vary their energy. The width of these "levels" becomes narrower at larger soliton counts within a molecule. Nonetheless, for relatively small number of generated solitons per round trip (1–5), their energy may be varied by a factor exceeding 2 without modification or collapse of the specified mode-locked regime. It is necessary to mention that the studied laser platform allows generation of specified patterns of solitons with similar energies, as opposed to soliton rain [45–50], which is a set of solitons with widely different energies and usually with chaotic pulse separation.

Soliton patterns generated in the proposed laser system essentially represent bursts of picosecond pulses with nanosecond inter-pulse delays. Burst generation modes find a host of applications in industry (laser high-precision micromachining technologies [51–55], material modification [56]), research (laser ablation as a sampling tool for analytical purposes [57], diagnostics [58], and measurements [59,60]), and bio-medical field (laser ablation of biomaterials [61] and imaging [62]). The proposed laser offers fine and reproducible electronic control over the number of picosecond pulses inside a burst and may be used as an advanced flexible seed oscillator for the leading-edge pulse-burst laser systems.

It is important that the generated soliton bunch states are highly stable over long periods of time (hours, days) on condition of stable pump radiation power (requirements are relatively moderate: < 1% pump power fluctuations) and comparatively stable environment (ambient temperature excursion within ± 5 °C). NALM-based mode locking technologies ensure much weaker dependence of generation properties on the ambient conditions as compared, for example, to those based on nonlinear polarisation evolution [63] that lead to significant changes caused by strain and temperature drift of fibre.

5. Conclusion

The presented laser platform relying on a figure-eight NALM-ALM mode-locked fibre laser allows not only electronic control over the number of solitons per round trip in mode-locked operation, but also fine variation of soliton energy and duration within a specified mode-locked regime. Controllable and reproducible generation of 1 to 7 picosecond solitons per round trip was demonstrated. In regimes with 1–5 solitons per round-trip, their energy may be continuously varied by a factor exceeding 2 without change or collapse of the specified mode-locked regime. Therefore, the studied all-fibre laser system enables generation of pre-determined soliton molecules with variable energy and corroborates the statement that quantisation of dissipative solitons in a non-conservative system (such as a laser) is not strictly

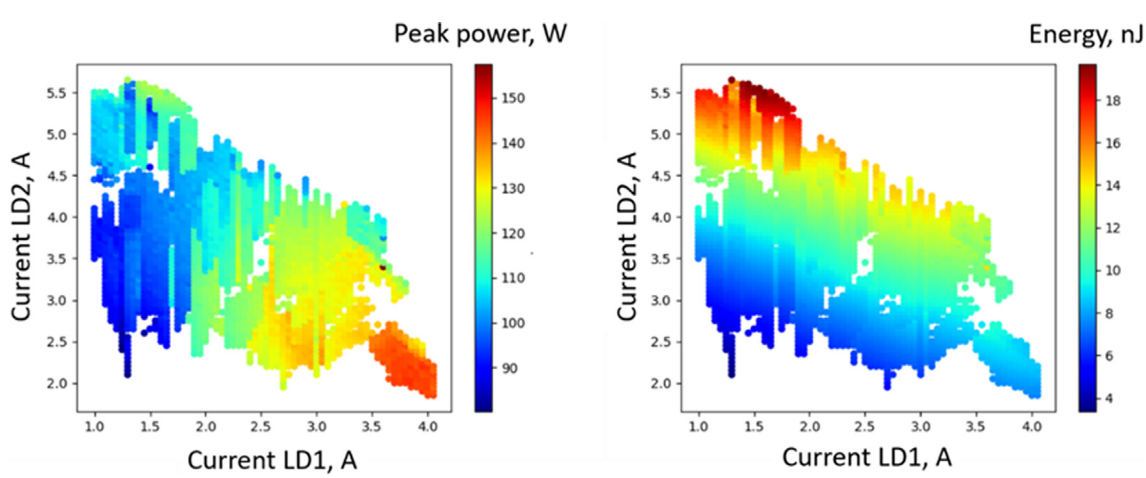

Fig. 5. Distribution maps of peak power and energy of solitons as functions of powers of pump sources LD1 and LD2 in the regime producing a single soliton per round trip.

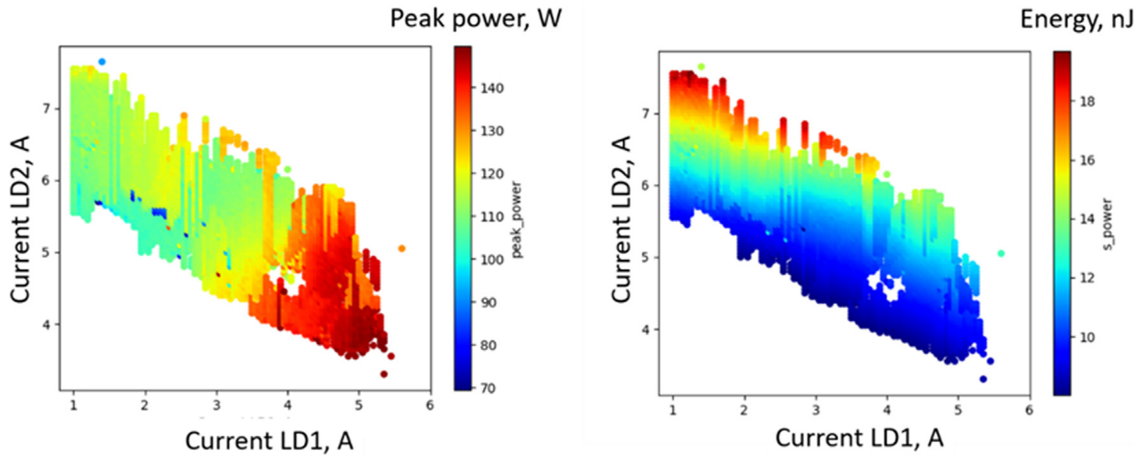

Fig. 6. Distribution maps of peak power and energy of solitons as functions of powers of pump sources LD1 and LD2 in the regime producing two solitons per round trip.

deterministic with respect to energy. The presented laser platform will find numerous applications as a convenient master oscillator of picosecond burst-trains with electronically tuneable number of pulses in each burst featuring the intra-burst repetition frequency of ~GHz.

CRediT authorship contribution statement

Alexey Kokhanovskiy: Resources, Software. **Evgeniy Kuprikov:** Data curation, Investigation. **Sergey Kobtsev:** Validation, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The work was supported by the grant of the Russian Science Foundation (project 17-12-01281).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.optlastec.2020.106422.

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