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High-Efficiency In-Fiber Nonlinear Conversion of Nanosecond Optical Pulses into Structured Packets of High-Peak-Power Ultrashort Pulses

Igor I. Korel[1], Boris N. Nyushkov[1,2], Anastasia Yu. Kutishcheva[1], Sergey M. Kobtsev[2]
[1]Novosibirsk State Technical University, Novosibirsk 630073, Russia
[2]Novosibirsk State University, Novosibirsk 630090, Russia

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INTRODUCTION

Reported is an energy-efficient method for conversion of relatively long (nanosecond) optical pulses into an extraordinary light structure – a packet of ordered picosecond pulses which differs from the known types of ordered ultrashort pulse patterns. The method relies on revealed peculiarities of nonlinear evolution of a dark pulse with finite background in anomalous-dispersion fibers.

Under certain conditions, energy of the background nanosecond pulse can be mostly (in excess of 50%) converted into a structured burst of ultrashort bright pulses. This burst can feature relatively high (manifold of the initial value) peak power and ultrahigh (sub-THz) intraburst pulse repetition rate.

The revealed effect is assumed to be related to modulation instability induced by self-phase modulation. It develops in conventional telecom single-mode fibers at moderate propagation distances (of the order of 1 km) which ensure relatively low net linear losses (<1 dB). Thus, it features high conversion efficiency.

METHODS

Propagation of the above introduced waveform in telecom optical fibers was modeled by solving numerically the Nonlinear Schrödinger Equation (NLSE) which takes into account the Kerr nonlinearity, second- and third-order dispersion, and linear losses:

$$\frac{\partial A}{\partial z} = -\frac{i\beta_2}{2}\frac{\partial^2 A}{\partial t^2} + \frac{\beta_3}{6}\frac{\partial^3 A}{\partial t^3} + i\gamma\left|A\right|^2 A - \frac{\alpha}{2}A,$$

The used parameters of dispersion, nonlinearity and loss had values corresponding to conventional single-mode telecom fibers compliant with the ITU-T G.652.D standard (fibers like Corning SMF-28e+):

β_2 = -21.4 ps^2/km, β_3 = 0.12 ps^3/km, γ = 2 km^{-1}W^{-1}, $\alpha \equiv$ 0.2 dB/km.

Radiation power and fiber lengths were limited to below the threshold of stimulated Raman scattering. Two different numerical methods were used to verify the results (namely, the symmetrized split-step Fourier method, and the finite difference method).

Figure 1 shows a general view of the initial temporal profile of the studied waveform which can be generated at 1.55 µm by using our early reported technique of arbitrary optical waveform synthesis [1].

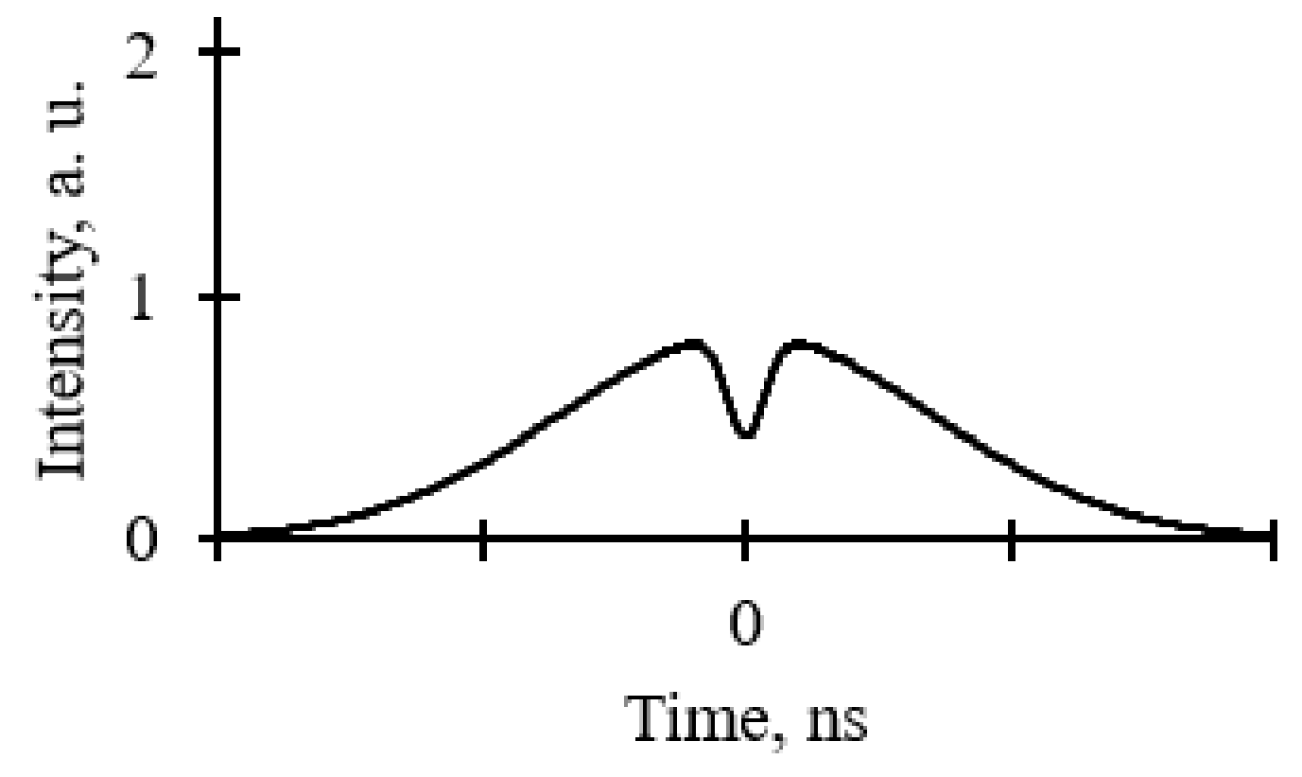

Fig. 1. General view of the initial temporal profile of the light structure whose nonlinear in-fiber evolution was investigated. The dark and background pulses fit Gaussian profiles.

RESULTS and DISCUSSION

Figures 2 and 3 demonstrate frame-by-frame nonlinear in-fiber evolution of the above introduced waveforms with different initial durations as derived from the simulation. The evolving temporal profiles were derived at different propagation distances (denoted in terms of the nonlinear length L_{NL}). Herein the nonlinear length is ~50 m. Figure 2 allows comparison of the evolution rates achieved with the different initial background pulse durations (100 ns versus 10 ns). Figure 3 allows comparison of the evolutions rate achieved with the different initial dark pulse durations (1 ns versus 0.1 ns). The enlarged view (Fig. 4) of the obtained bursts of bright pulses reveals quite regular intraburst structure with the picosecond-scale characteristic time.

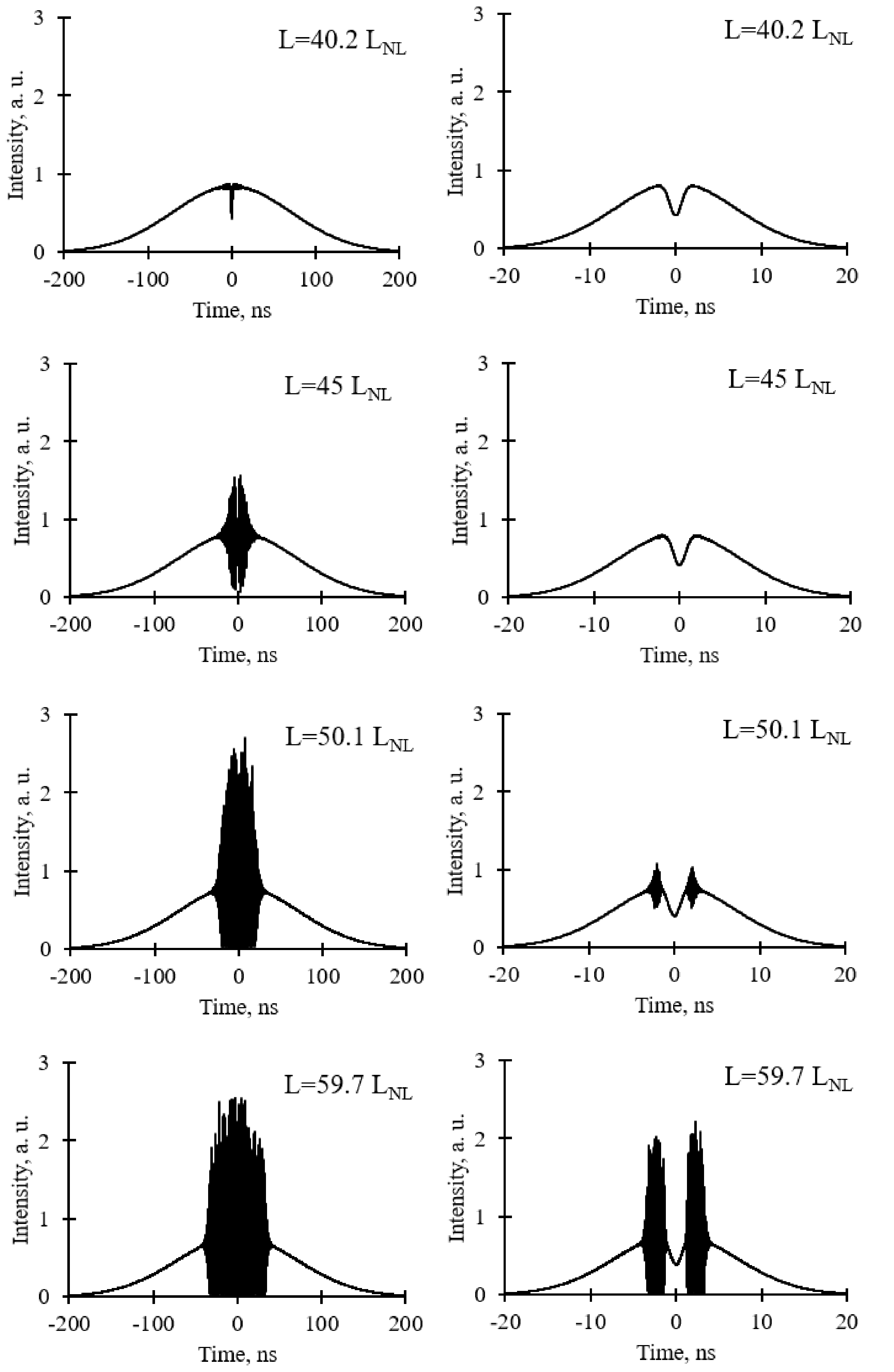

Fig. 2 Temporal profiles of the light structures evolving from the 1-ns dark pulse at different propagation distances in the anomalous-dispersion telecom fiber. The left-hand column shows evolution beginning from a 1-ns dark pulse with the 100-ns background pulse; the right-hand column – from the same 1-ns dark pulse but with the 10-ns background pulse.

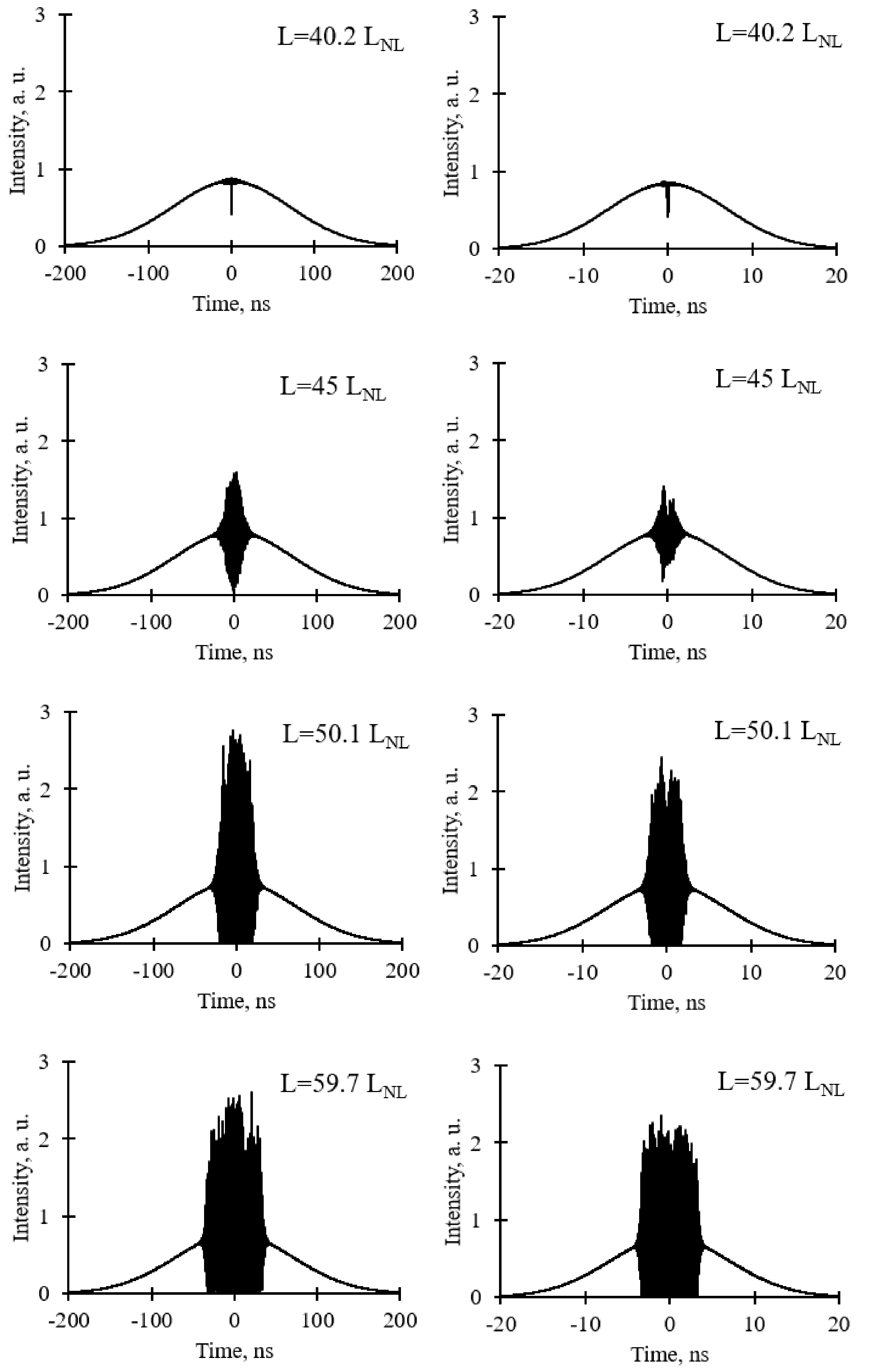

Fig. 3 Temporal profiles of the light structures evolving from the 0.1-ns dark pulse at different propagation distances in the anomalous-dispersion telecom fiber. The left-hand column shows evolution beginning from a 0.1-ns dark pulse with the 100-ns background pulse; the right-hand column – from the same 0.1-ns dark pulse but with the 10-ns background pulse.

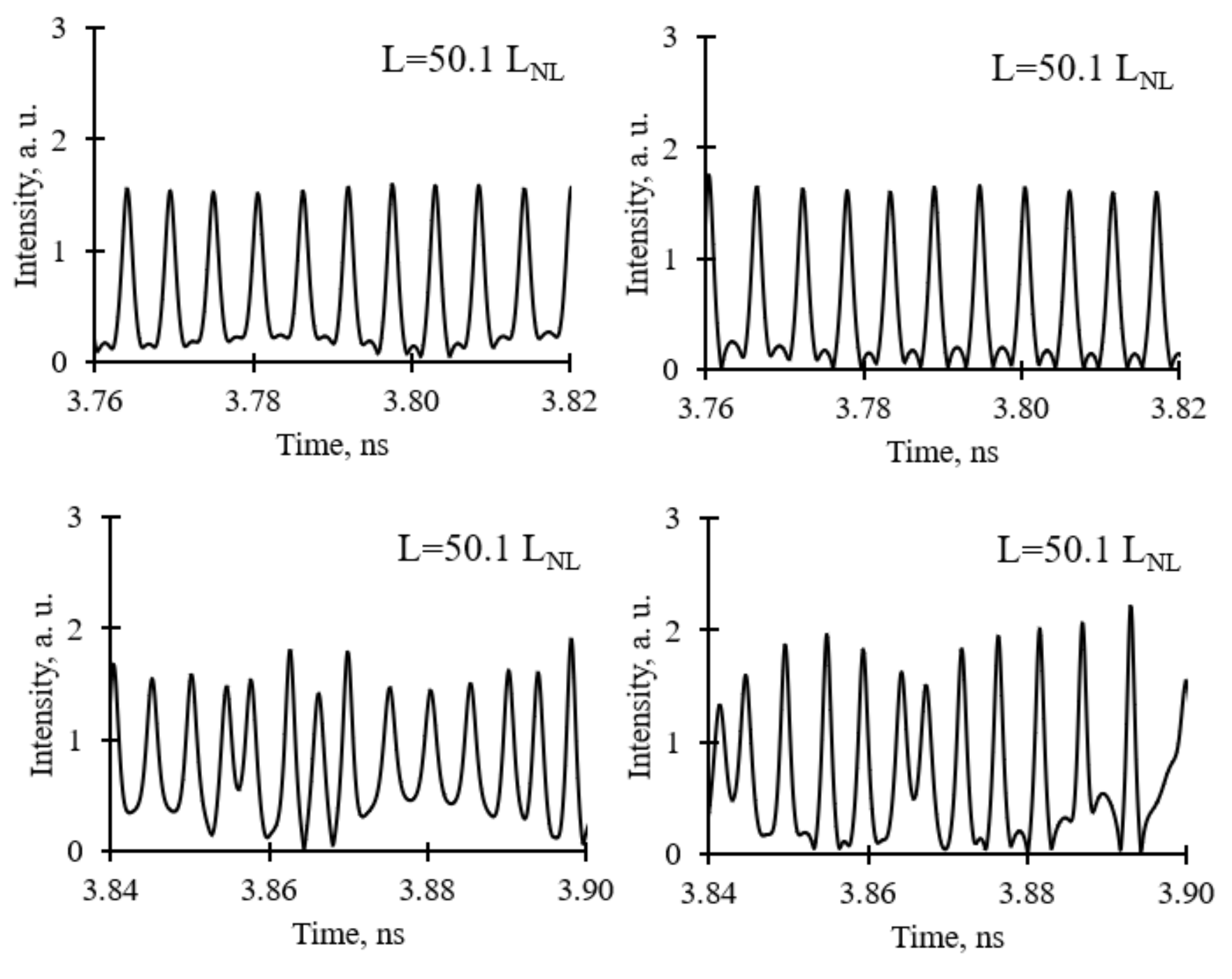

Fig. 4. Enlarged view of the intraburst structures evolving from the different initial dark pulses: the upper panel – structure evolved from the 1-ns dark pulse with the 100-ns background pulse (left trace) and, alternatively, 10-ns background pulse (right trace); the lower panel - from the 0.1-ns dark pulse with the 100-ns background pulse (left trace) and, alternatively, 10-ns background pulse (right trace).

CONCLUSIONS

Nonlinear in-fiber conversion of a dark pulse with finite (nanosecond-scale) background into a burst of ordered picosecond bright pulses was examined numerically with reliably feasible parameters. The demonstrated conversion takes place in low-loss telecom fibers with a length limited to few kilometers, and thus features high energy efficiency. The obtained light structure can feature relatively high (manifold of the initial value) peak power and ultrahigh (sub-THz) intraburst pulse repetition rate. We believe that controllable generation of such bursts can find many applications.

E-mail: b.nyushkov@nsu.ru

References: [1] Nyushkov, B., Kobtsev, S., Ivanenko, A. and Smirnov, S., "Synthesis of periodic and aperiodic arbitrary waveforms in a SOA-fibre laser," Proc. SPIE 11547, 115471C (2020).