Spectral Characteristics of Nonlinear-Dispersive Similariton Generated in Single-Mode Fiber without Gain

H. Toneyan[1,2], K. Manoukyan[1], M. Sukiasyan[1,2], A. Kutuzyan[1]
and L. Mouradian[1,2]

[1] *Ultrafast Optics Laboratory, Faculty of Physics, Yerevan State University, Armenia*
[2] *CANDLE Synchrotron Research Institute, Yerevan, Armenia*

E-mail: h.toneyan@gmail.com

Abstract. We report the studies of the spectral features of nonlinear-dispersive similariton generated in a passive single-mode fiber (without gain) with the aim of development-processing of similaritonic technique for pulse duration measurement in femtosecond time scale. Particularly, the dependence of the similariton spectral bandwidth from the input pulse energy and duration is studied in details both numerically and experimentally, to determine the input pulse duration alternatively to the autocorrelation technique.

1. Introduction

Similaritons are pulses that maintain their temporal profiles during the propagation. The generation of similariton pulses with parabolic temporal, spectral and phase profiles was initially predicted by Anderson et al [1]. Later, such parabolic pulses were generated in fibers with gain or distributed dispersion [2-4]. The nonlinear-dispersive (NL-D) similariton of passive fiber (without gain) was generated under the combined impact of Kerr nonlinearity and second order dispersion [5]. The NL-D similariton has the bell-shape spectral and temporal profiles and a parabolic phase (linear chirp) independent of the input pulse parameters.

In this work, we study the spectral peculiarities of NL-D similariton. It was experimentally checked that the spectral bandwidth of the NL-D similariton generated from pulses with near-Gaussian shape is inversely proportional to the square root of the input pulse duration [6]. In our study, we further investigated this property of the NL-D similariton by testing it for various input pulse forms. This study is of special interest for the similaritonic technique of pulse duration determination [7].

2. Numerical study

During our numerical investigations we first numerically modeled the generation of NL-D similariton in passive (without gain) optical fiber. For this we use the nonlinear Schrodinger equation and Fourier split-step method to numerically model the pulse propagation through the fiber. We use dimensionless parameters to describe the pulse properties: $\zeta = z / L_D$ - dimensionless length, where z is the fiber length, $L_D = \Delta t_0^2 / k_2$ is the dispersion length, Δt_0 is the duration of the input pulse, $k_2 = \partial^2 k / \partial \omega^2 \big|_{\omega_0}$ is the parameter of the second order of dispersion, $R = L_D / L_{NL}$ nonlinearity parameter, where $L_{NL} = (k_0 n_2 I_0)^{-1}$ is the nonlinear length, k_0 is the wave number, n_2 is the fiber nonlinearity coefficient, I_0 is the peak intensity. After the generation of NL-D similariton, we checked the dependence of similariton bandwidth from the input pulse duration. First, we examined input pulses without initial chirp. For Gaussian input pulses the similariton bandwidth is inversely proportional to the square root of the input pulse duration in accordance with [5-7]. We compared the coefficients of these dependences for pulses of various shapes.

2.1. Bell-shape pulses. The numerical simulations showed that although the similariton bandwidth is proportional to the square root of the parameter R, the curve coefficients differ for the pulses with different shapes. Our further detailed simulations showed that these coefficients linearly depend on the parameter $\tau_{TL}\Delta\omega_0$ of initial pulse, were $\Delta\omega_0$ is the initial pulse spectral width and τ_{TL} is the duration of the transform limited (TL) input pulse. Taking into account this correction, we normalized the dependence of similariton bandwidth from the square root of R, to get a relation independent from the input pulse shape:

$$\Delta\omega \sim \sqrt{\tau_{TL}\Delta\omega_0}\sqrt{E/\tau}, \tag{1}$$

where τ is the FWHM duration and E is the energy of the input pulse.

In Figure 1 the axis of $\sqrt{R}$ is divided by $\sqrt{\Delta\omega_0}$, as for transform-limited pulses $\tau_{TL} = \tau$. In the left column are shown examples of pulses with asymmetrical temporal shapes, for which the simulations were carried out.
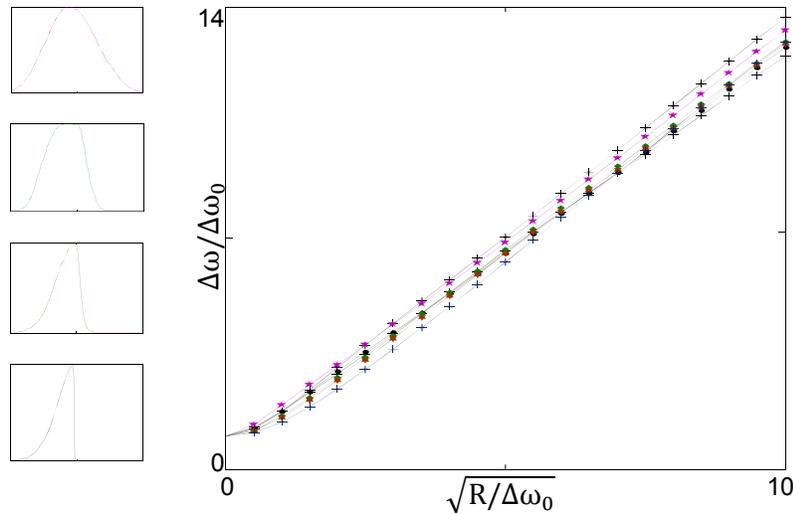
Figure 1. Dependence of the similariton spectral width from the nonlinear parameter R, normalized on $\Delta\omega_0$ input pulse bandwidth. Examples of input pulse shapes (left column).

The relation (1) works only for transform-limited pulses. The duration of bell-shape pulses with spectral phase can also be measured independently of their shape. For this, the similariton spectral bandwidth has to be measured at the base instead of its half maximum. In that case, the relation (1) obtains more simple form:

$$\Delta\omega_{base} \sim \sqrt{E/\tau}, \tag{2}$$

independently from the measured pulse shape. This gives us an opportunity to easily retrieve the input pulse FWHM duration by measuring the base bandwidth of the generated similariton spectrum.

Figure 2 shows the dependence of the similariton spectral width $\Delta\omega_{base}$ from the input pulse duration τ. The $\Delta\omega_{base}$ can be measured anyway below 1/10 of the spectrum peak, but the results are better when this level is chosen lower. Here the $\Delta\omega_{base}$ is measured at 1/100 of the peak intensity of the spectrum. The blue, red and green squares correspond to the chirped Gaussian, super-Gaussian and sech[2] input pulses, respectively. The orange and brown squares have triangle-like asymmetrical spectra. The dashed part of the linear approximation line stands for the peak powers, for which similariton generation isn't taking place. We change the durations of test pulses

by giving them linear chirp, stretching them up to around 4-5 times in temporal domain, which also results in change of the pulse shape.
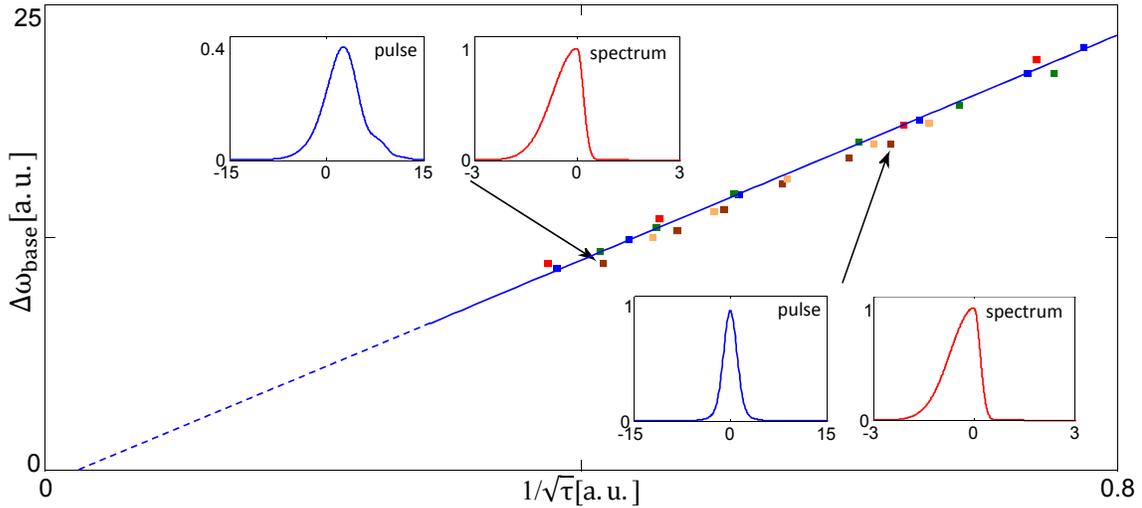
Figure 2. The dependence of similariton spectral width from the duration of the input pulse (numerical study). Similariton spectral width is measured at the base. The different color squares correspond to various initial temporal and spectral shapes and chirps.

2.2. Two-peak pulses. Afterwards, we examined complex pulse shapes, such as two-peak pulses. For regular pulse shapes, durations and spectral widths are determined by means of FWHM. For complex waveforms we use standard deviation (SD) to give the duration and spectral width. To calculate the SD of the parameter a, we used the formula:

$$\sigma_a = \sqrt{\overline{a^2} - \overline{a}^2}. \tag{3}$$
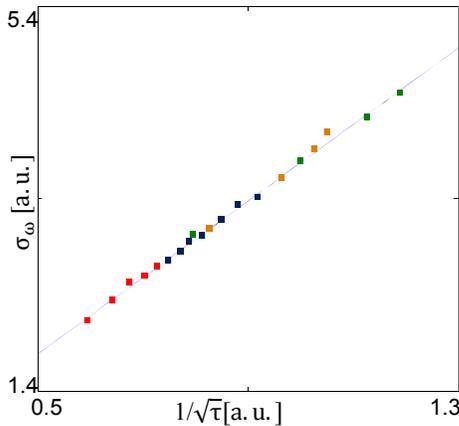
Figure 3. The dependence of the similariton spectral width from the SD-duration for bell-shape (orange, green), two-peak (blue) and three-peak (red) input pulses.

In the case of complex pulses, as for the regular pulses, the numerical simulations show that the bandwidth of the similariton is proportional to the square root of R (Fig. 3). If measured by the means of SD, for all pulse forms, the SD of similariton spectrum is inverse proportional to the square root of input pulse SD duration, with the coefficient independent from the pulse shape:

$$\sigma_\omega \sim \sqrt{E / \sigma_\tau}. \tag{4}$$

We also checked that this relation works for regular pulses as well. Thus, for measurements by means of SD, there is a simple relation between the similariton bandwidth and the input pulse duration for both regular and complex pulses (Fig. 3). The blue and red points of Figure 3 correspond to similaritons generated from two-peak and three-peak pulses respectively, with various shapes and initial chirps. Green and red points correspond to pulses with Gaussian and sech[2] temporal shapes and various initial chirps.

3. Experimental study

In the experiment (Fig. 4), we used laser with 100-fs duration pulses at 800nm central

wavelength and 76 MHz repetition rate. After pulse shaping, we measured the pulse duration by an autocorrelator (AC). The NL-D similariton was generated in a ~1m long Thorlabs 780HP single-mode fiber (SMF). The $\Delta\lambda_{sim}$ bandwidth of the NL-D similariton was measured using an Ando AQ-6515A optical spectrum analyzer (OSA) or, to provide the real-time performance of spectral measurements by applying DFT method [8-10], using a $600\,m$-long telecom fiber with a standard nanosecond oscilloscope.

3.1. Bell-shaped pulses. First we tested the results of numerical study for bell-shaped pulses. We shaped initial pulses with different durations by passing them through different pieces of glass. Also, we dispersively stretched and chirped the laser pulses, both positively and negatively, in an SF11-prism pair-based dispersive delay line (DDL). Studies were carried out for initial pulses with AC durations of $\Delta t_0 \sim 150 - 550$ fs, and similariton spectra of 50-75 nm, in the range of radiation average powers of $\overline{p} \sim 50 - 500 mW$.
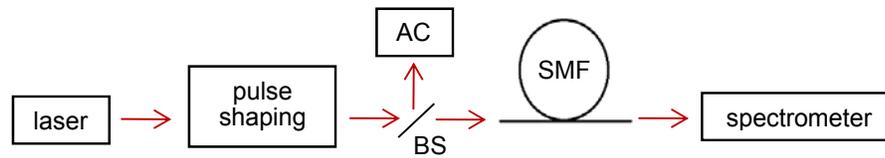
Figure 4. Experimental setup: AC – autocorrelator; BS – beam splitter; SMF – single-mode fiber.

Then, we compared the similariton spectral bandwidths with the input pulse AC durations. We used the input pulse AC duration at FWHM as an equivalent to the pulse duration, as the pulses in this experiment had similar shapes for different chirp values. Taking into account the coupled power by Eq. (2), we resulted in linear curve of Figure 5, in accordance with numerical results.
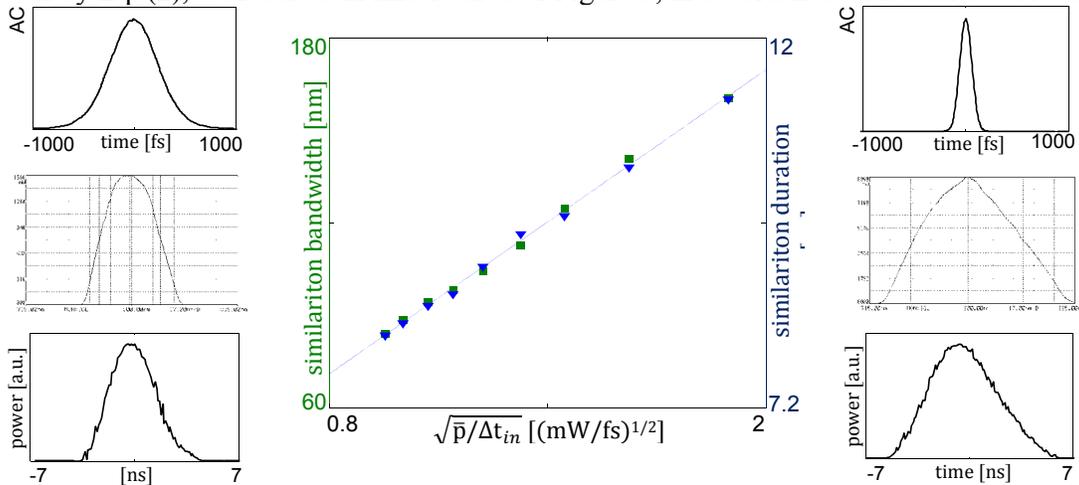
Figure 5. Experimental results for bell-shape input pulses: input pulse duration (central chart) versus $\sqrt{\overline{p}/\Delta t_{in}} \sim P$ power; green squares and blue triangles are the similariton OSA- and oscilloscope-(applying DFT) measured bandwidths, respectively; blue line is for linear approximation. Left and right columns are for initial pulses with 550-fs and 150-fs AC durations. From top to bottom: input pulse AC, OSA-and oscilloscope-measured similariton spectra.

The left and right columns in Figure 5 are for the longest and shortest input pulses (with 146 fs and 550 fs AC-durations), respectively. On the top are the AC traces, and lower are similariton spectra. The similariton spectral bandwidths and input pulse duration are determined at the base, and FWHM, respectively.

3.2. Bell-shaped pulses. To examine the results of numerical analysis for more complex pulse forms, we have shaped two-peak test pulses by inserting a thin microscope glass in a part of laser beam. The difference of refractive indexes caused a spatial delay on part of laser radiation, resulting in formation of two-peak pulses. Then, we dispersively chirped these two-peak pulses in the glasses with different lengths. Thereafter, we generated the NL-D similaritons from these pulses in SMF, and measured their spectra (Fig. 6). SD durations of pulses were ~180-250fs.
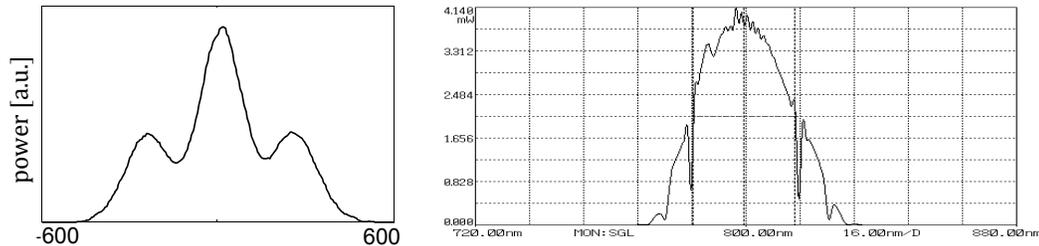
Figure 6. Experiment for similaritons generated from two-peak pulses: input pulse AC (left), and similariton spectrum (right) measured.

We measure the input pulse AC, and calculate the pulse SD-duration, since it is equal to the pulse SD, with a $\sqrt{2}$ coefficient. We also calculated the similariton spectrum SD. It demonstrates a linear dependence (Eq. 4) from the inverse of the square root of the tested pulse SD duration (Fig. 7). The red points in Figure 7 are for dispersively chirped two-peak pulses. Dispersion is applied to the pulses in order to change the pulse shape. We compared these measurements with the ones of chirped laser pulses (green points). The blue line is the linear approximation.
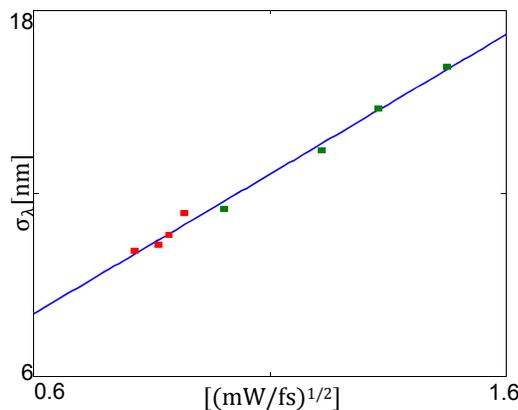
Figure 7. Experimental results for similaritons generated from chirped two-peak pulses (red) and chirped laser pulses (green).

4. Studies of compressed pulses

Above the experiments with pulses of 150-550 fs AC durations and positive or negative chirps are described. We studied also the similariton spectral properties for the compressed pulses, both numerically and experimentally. In our numerical study, we modeled the laser pulse compression and the similariton generation from this compressed pulse. Figure 8 shows the results of simulation. The blues curves show input Gaussian pulse (a) and spectrum (b), and the green ones are for the compressed pulses. The red spectrum in Figure 8(b) is the similariton generated from compressed pulse. The side lobes of the compressed pulse motivate the use of the SD formula (Eq. 3) for pulse duration and spectral width calculations. Results of our simulations, shown on Figure 9, state that the dependence (Eq. 4) of the similariton spectral width from the input pulse SD-duration also works for compressed pulses.
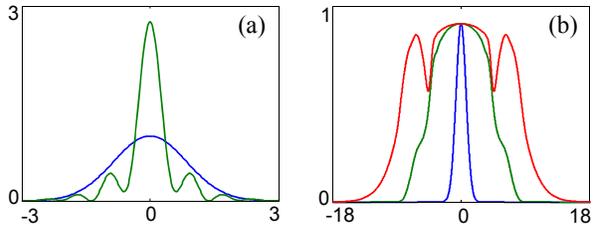
Figure 8. Spectrum of NL-D similariton generated from compressed input pulse. (a) Pulses and (b) spectra of input Gaussian pulse (blue), compressed pulse (green) and similariton (red).

Figure 9. Numerical study for compressed pulses: the similariton spectral width versus the input pulse

Experimentally, our pulse compressor consisted of a short piece (~38 cm) of SMF (Thorlabs-780HP), and a grating pair (groove density: 300 mm⁻¹) based DDL. In this arrangement we compressed the pulses down to ~64 fs AC durations. By changing the amount of dispersion of the DDL, we chirped the compressed pulses positively and negatively, obtaining pulses of ~64-160 fs AC durations with various pulse shapes. Afterwards, we coupled the compressed pulses into an LMA-5 large mode area fiber (~3 m) to generate NL-D similariton (Fig. 10). The fiber core diameter was 5 μm, which is ~2 time smaller than the core size of standard SMF, resulting in stronger nonlinearity. This was done because of the drastic drop of the average power of the radiation after the pulse compressor.

Figure 10. Experiment for compressed input pulses: (left) input pulse AC, and (right) similariton spectrum.

Afterwards, we calculated the compressed pulse SD-durations having the spectra and average power measurements, by using the formula of Eq. 4. Then we compared them with SD of the pulse AC. Figure 11 shows the dependence of the NL-D similariton spectrum SD from the radiation average power and the SD-duration. The purple points are the measurements and the blue line is the linear approximation. The pulses after the compressor, i.e. the initial pulses for similariton generation, had different shapes, spectra and positive or negative chirp. This shows large application range of the similaritonic technique.

We also checked if the results for compressed pulses match with the results for the bell-shaped pulses. We compared the SD of similariton spectra for the chirped laser pulses (~ 500*mW* average power) and compressed pulses (~ 50*mW* average power). The experimental measurements in those two cases are in good agreement with each other (Fig. 12). The blue line is the linear approximation, the green squares are measurements for laser pulses with AC durations of ~150-550 fs and ~10 nm initial spectra, and the purple triangles are for compressed input pulses with AC durations of ~70-100 fs and ~40 nm initial spectra.

5. Conclusion

Thus, in our detailed studies of the spectral characteristics of nonlinear-dispersive similariton generated in a passive single-mode fiber, we generalize the feature of the similariton spectral bandwidth depending from the input pulse energy and duration, which is important for processing of similaritonic technique for pulse duration measurement in femtosecond time scale, alternatively to autocorrelation technique.
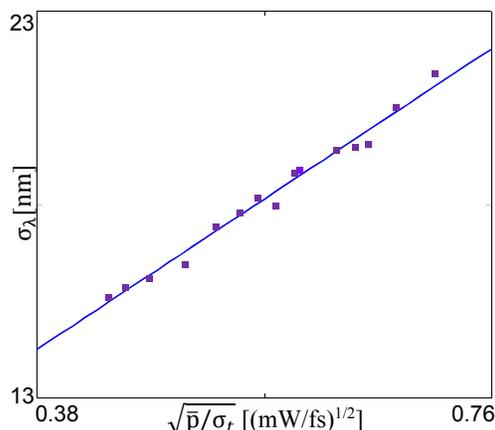
Figure 11. Experimental results for compressed pulses: dependence of the similariton spectrum SD from the coupled power and input pulse SD.
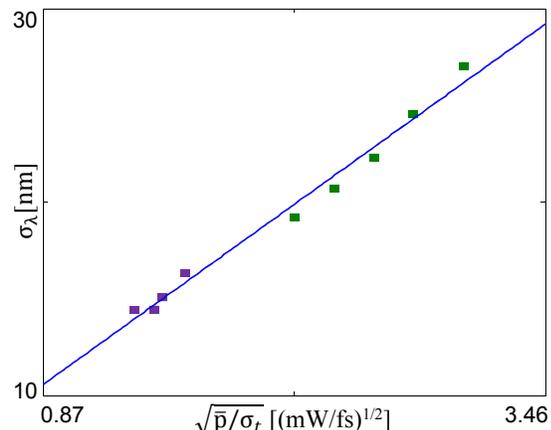
Figure 12. Results for bell-shape and compressed pulses: the similariton spectrum SD vs average power and SD-duration of compressed pulses (purple) and chirped laser pulses (green).

The studies showed that in general, the bandwidth of the generated similariton is proportional to the reverse of square root of test pulse duration, given that the average power of radiation is constant. This general rule for bell-shape near-Gaussian pulses can be applied for determination of duration of complex shape pulses, with some corrections. Particularly, for determination of FWHM duration of any bell-shaped pulse, the spectrum of the similariton can be measured at the peak 1/10 value (or lower). For more complex shapes, such as two-peak pulses and compressed pulses, the SD duration of the pulse can be determined by measuring the similariton spectrum SD.

References

[1] Anderson D., Desaix M., Karlson M., Lisak M., Quiroga-Teixeiro M.L., J. Opt. Soc. Am. B 10, pp 1185-1190 (1993).

[2] Finot C., Millot G., Billet C., Dudley J.M., Opt. Express, Vol. 11, pp. 1547-1552 (2003).

[3] Kruglov V.I., Peacock A.C., Harvey J.D., Dudley J.M., J. Opt. Soc. Am. B 19, pp. 461-469 (2002).

[4] Hirooka T., Nakazawa M., Opt. Lett., Vol.29, pp. 498-500 (2004).

[5] Zeytunyan A., Yesayan G., Mouradian L., Kockaert P., Emplit P., Louradour F., Barthelemy A., J. Europ. Opt. Soc. Rap. Public. 09009, Vol. 4 (2009).

[6] Zeytunyan A.S., Proc. of Yerevan State Univ. Phys. and Mathem. Sci., N 1, pp. 54-57 (2010).

[7] Mouradian L. and Barthelemy A. "Nonlinear-Dispersive Similaritons of Passive Fibers: Applications in Ultra-fast Optics" Chapter 6 in *"Shaping Light in Nonlinear Optical Fibers" Ed. S. Boscolo and Ch. Finot ©2017 John Wiley & Sons Ltd.*

[8] Solli D. R., Chou J., Jalali B., Nature Photon. **2,** 48–51(2008).

[9] Azana J., Muriel M. A., IEEE J. Quant. Electron. **36,** 517–526(2000).

[10] Goda K., Jalali B., Nature Photon. **7,** 102–112(2013).