

# Classic, all-fiber, and similaritonic techniques of spectral compression

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**Abstract.** A comparative experimental study of five techniques of spectral compression based on the self-phase modulation and phase addition processes, similariton generation and soliton effect is reported. In view of all-fiber configuration, the hollow-core fiber was used in experiments along with the standard single-mode one. The nonlinear process of spectral self-compression, a spectral analogue of soliton effect compression, in a hollow core fiber with anomalous dispersion is observed experimentally. To reveal the nature and origin of aberrations of spectro-temporal lenses induced by the phase modulation and phase addition process, the experiments are conjugated with numerical studies. An up to 23x aberration free spectral focusing in the time lens induced by similariton through sum-frequency generation is demonstrated experimentally.

## 1. Introduction

The interest to the nonlinear process of spectral compression in a dispersive delay line followed by a single-mode fiber, revealed over two decades ago [1-4], is motivated by the numerous prospective applications in ultrafast optics and photonics, often based on the spatiotemporal analogy and the concept of time lens [5,6]. Spectral compression is a temporal analogue of diffracted beam collimation in a light-induced lens. In the dispersive delay line, pulses are stretching and phase-modulating (frequency-chirping). Further compensation of the dispersively accumulated phase-shift by means of self-phase modulation in a nonlinear fiber leads to the spectral narrowing: the temporal phase-shift induced by the Kerr effect in the fiber, like a time lens, “collimates” the radiation in time, and “focuses” the spectrum. The time lens, like the spatial one, has a more general feature of Fourier transformation, leading to the conversion of temporal information to the spectral domain, and thus to the applications to the signal analysis and synthesis problems in ultrafast optics: spectral imaging of the pulse temporal profile for direct femtosecond pulse measurements [7,8] and fine frequency tuning of radiation along with spectral compression [8] for resonant spectroscopy, generation of dark solitons [5], and the femtosecond pulse undistorted delivery [9]. Spectral compression was recently proposed also for similariton fiber laser architecture instead of highly dissipative spectral filtering [10]. Spectral compression is of interest in the context of nonlinear vibrational microscopy where high spectral brightness is required, such as in coherent anti-Stokes Raman scattering (CARS) or stimulated Raman scattering microscopy. 8.7x spectral compression through the generation of negatively chirped parabolic pulses was demonstrated in [11], showing aberration-free spectral focusing due to the



optimal parabolic pulse shape. Further development resulted in 12x compression in an all-fiber configuration for telecommunication wavelengths, utilizing kilometre-long fiber [12].

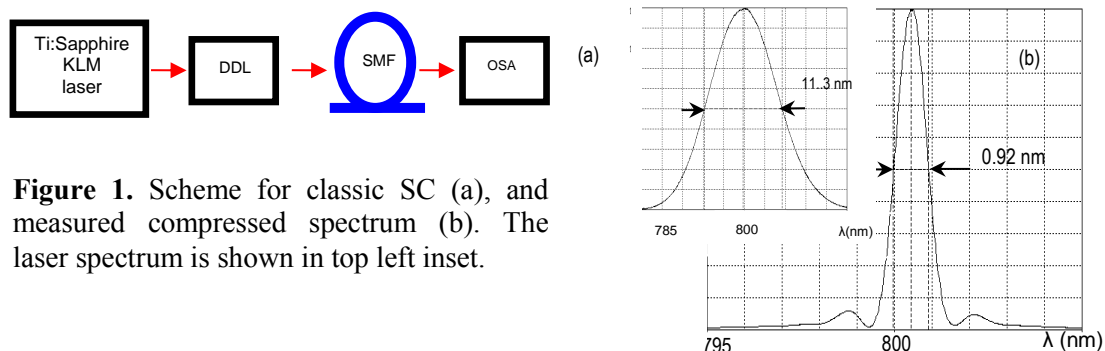
Current problems of ultrafast optics and photonics, particularly femtosecond signal generation, manipulation, delivery and characterization, stimulate a detailed study of the spectral compression process and the variety of the its modern techniques. We comparatively studied three spectral compression schemes in our initial experiments [13]. In this work, we complete this study and present five spectral compression techniques, together with numerical simulations. We pay special attention to aberration of spectral focusing in view of achievement aberration-free process, as well as to all-fiber configuration of the process implementation.

## 2. Experiment

We report on a comparative study of spectral compression (SC) techniques based on the self-phase modulation (SPM) and sum-frequency generation (SFG) processes, similariton generation and soliton effect. In our experiments, we use the radiation of a standard Coherent Verdi 10 + Mira 900F femtosecond laser system with the following parameters: 100 fs FWHM pulse duration,  $\sim 11$  nm spectral bandwidth, 800 nm central wavelength, 1.5 W average power at the 76 MHz repetition rate.

### 2.1. Classic technique of spectral compression

First, we experiment the SC in the classic scheme, i.e. in a system consisting of prism compressor as a dispersive delay line (DDL) with negative dispersion, and a single-mode fiber (SMF) as a nonlinear medium for SPM. Our DDL consisted of a 3.75 m separated SF11 prism pair with the reverse mirror. A 92 cm-long Newport F-SE 780 nm SMF was used for nonlinear SFM (figure 1a).



**Figure 1.** Scheme for classic SC (a), and measured compressed spectrum (b). The laser spectrum is shown in top left inset.

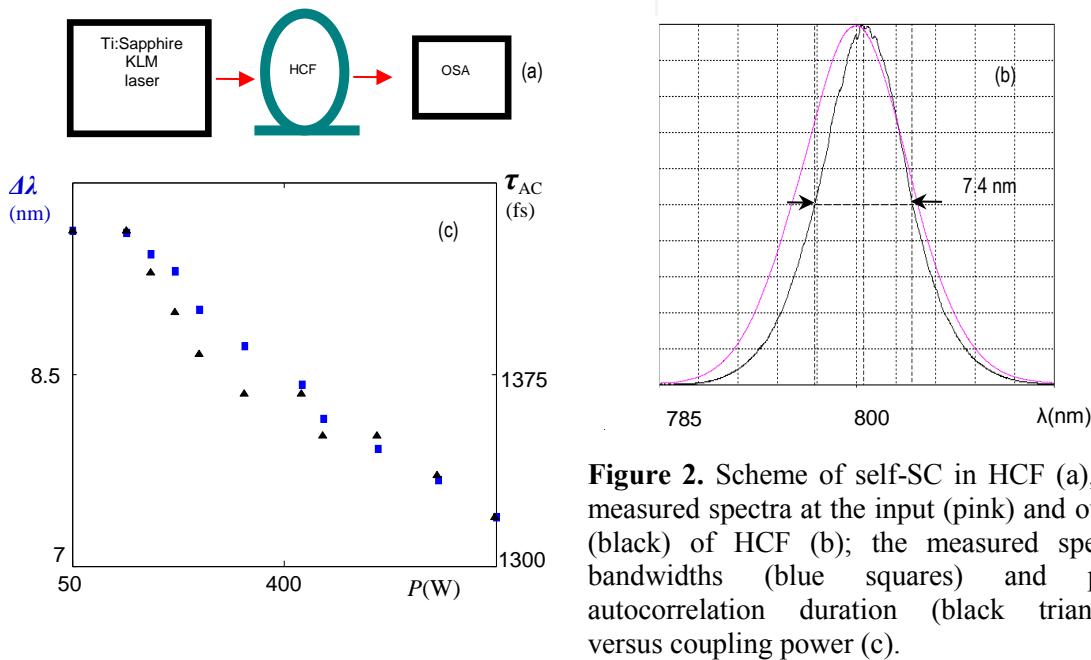
Starting from the 11.3 nm-bandwidth pulses, 12.3x spectrally compressed pulses with 0.92 nm bandwidth are obtained at the output (figure 1b), with  $\sim 2$  ps autocorrelation duration and 0.42 W average power. Such spectrally compressed pulses can be useful for the CARS techniques.

### 2.2. Spectral self-compression

Thereafter, we have experimented hollow core fiber (HCF, ThorLabs HCF-800, 2 m) with anomalous dispersion at 800 nm wavelength. First, we simply coupled the radiation into HCF and measured the output spectrum depending on radiation power in the fiber (figure 2a).

Figures 2b and 2c demonstrate up to 1.3x spectral narrowing in HCF as a result of combined impact of weak nonlinearity and anomalous dispersion, evidencing the process of self-SC, which is the spectral analogue of soliton compression [14]. Detailed numerical studies of the process based on the solution of nonlinear Schrödinger equation, with the factors of Kerr-nonlinearity and anomalous dispersion, show few-tens of ratios of spectral self-compression [15]. Figure 2c shows nonlinear character of the process: both the spectral bandwidth and pulse autocorrelation duration at the output of HCF are decreasing monotonically with the increase of coupled radiation power. The spectral shift of SC radiation visible in figure 2b is caused by high-order dispersive effects, in accordance with our

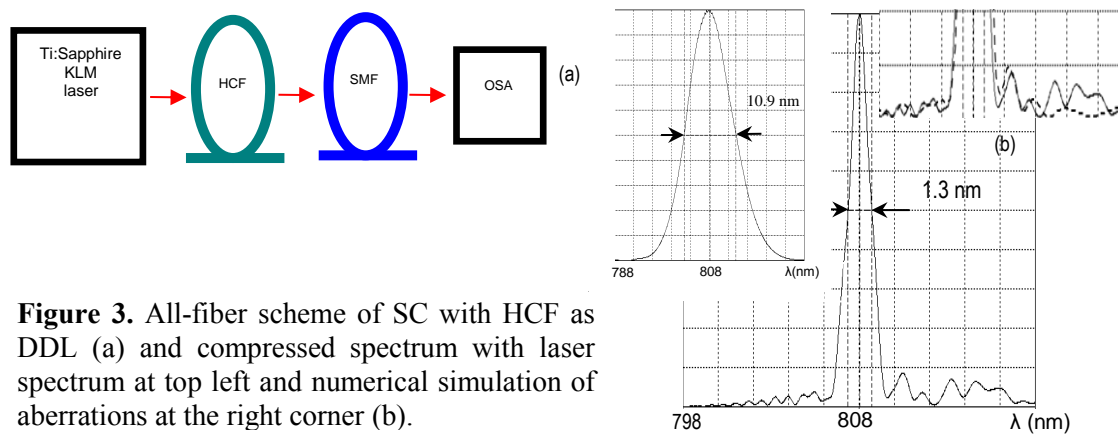
numerical analysis. Thus, due to the combined impact of low nonlinearity and anomalous dispersion, we have experimentally observed spectral self-compression in a hollow-core fiber.



**Figure 2.** Scheme of self-SC in HCF (a), and measured spectra at the input (pink) and output (black) of HCF (b); the measured spectral bandwidths (blue squares) and pulse autocorrelation duration (black triangles) versus coupling power (c).

### 2.3. All-fiber spectral compression

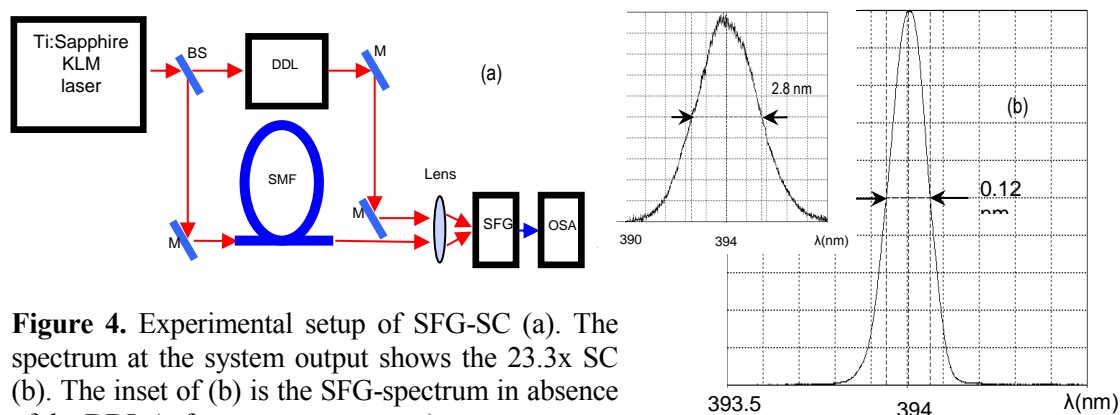
Afterwards, the output pulse from the HCF was coupled into a conventional SMF (Newport F-SE @ 780 nm, 80 cm) (figure 3a). We have obtained compression of the initial 10.9 nm spectrum down to 1.3 nm (figure 3b), corresponding to 8.4x SC, with 0.4 W average output power. The strong side lobes of the compressed spectrum observed in figure 3b, are caused, according to our numerical simulations, by the high-order dispersion of HCF, measured via spectral interferometry. In this experiment, the HCF dispersion was tuned and SC was optimized by setting the laser wavelength to 808 nm. Further development in this direction is anticipated by using the HCFs with flattened dispersion, as well as by splicing the HCF and SMF.



**Figure 3.** All-fiber scheme of SC with HCF as DDL (a) and compressed spectrum with laser spectrum at top left and numerical simulation of aberrations at the right corner (b).

#### 2.4. Similaritonic spectral compression

Thereafter, we implemented SC through a phase addition process, particularly through the SFG [8]. Figure 4 illustrates these studies. In this experiment, we have split the initial laser radiation into high- and low-power beams (80% and 20%). We coupled the high-power beam to standard SMF (1.65 m Newport F-SPF PP@ 820 nm), and generated a 100 nm bandwidth nonlinear-dispersive similariton [16]. The low-power beam was directed to DDL consisting of a 3.5 m separated SF11 prism pair with a reverse mirror. Then, the beams were focused in a BBO crystal for SFG, resulting in 23.3x SC for frequency, and more than 90x SC for wavelength, down to 0.12 nm bandwidth (figure 4b). The SFG-SC ratio  $\Delta\omega_{in}/\Delta\omega_{out}$  corresponds to the  $\Delta\lambda_{in}(400nm) = \Delta\lambda_{in}(800nm)/4$  bandwidth of the SFG spectrum measured in the absence of DDL. An important benefit of similaritonic technique is the opportunity of frequency tuning of signal radiation in a range given by the similariton spectrum. The latter is caused by the chirp of similariton, which allows shifting the SFG spectrum controlling the delay between similariton reference and signal pulses.



**Figure 4.** Experimental setup of SFG-SC (a). The spectrum at the system output shows the 23.3x SC (b). The inset of (b) is the SFG-spectrum in absence of the DDL (reference measurement).

#### 2.5. SFG-spectral compression with HCF

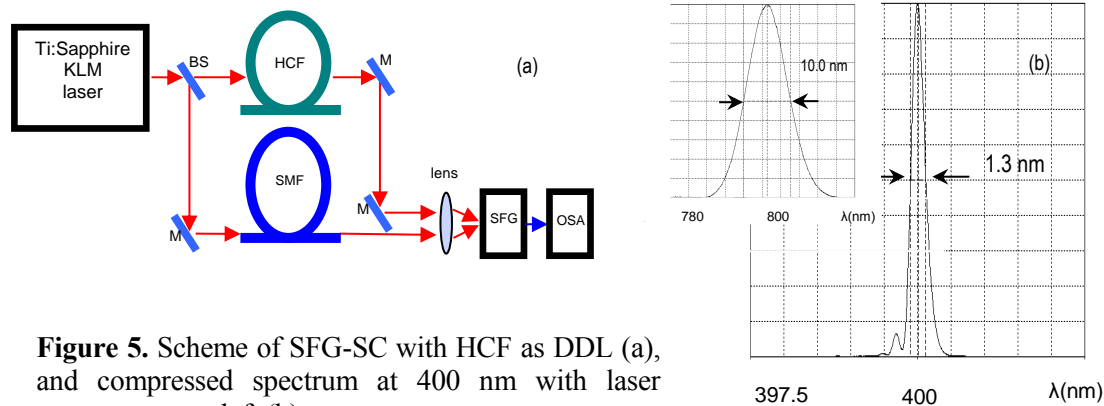
We have also carried out experiments with HCF in the SFG scheme, replacing the prism DDL of similaritonic technique by a 2 m-long HCF (figure 5a). As a result we had compression from 10 nm at 800 nm central wavelength down to 0.2 nm on second harmonic wavelength, which corresponds to 11x SC for frequencies, and 44x SC for wavelengths (figure 5b). Although the original similaritonic technique of Section 2.4 is aberration free, there are side lobes for compressed spectrum (figure 5b) in this configuration, caused by uncompensated higher order dispersion of HCF.

### 3. Simulations

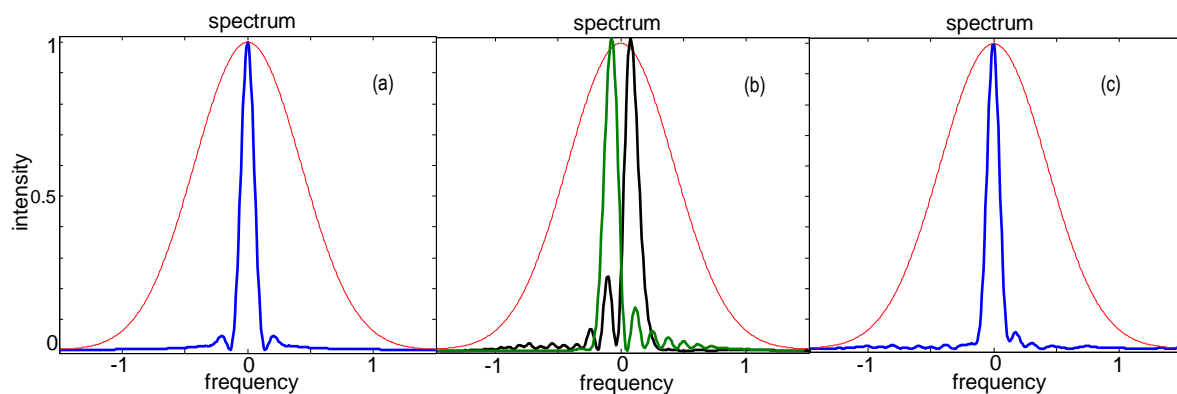
To understand the nature and origins of the side lobes in SC configurations with HCF, we have done numerical studies towards SC with uncompensated higher orders of dispersion (figure 3b). For the pulse propagation in the SMF, a standard nonlinear Schrödinger equation with the terms of Kerr nonlinearity and GVD is solved by the use of split-step Fourier method [16-18].

First, we tested DDL with only second order of dispersion, which resulted in spectral compression represented in fig.6a (red curve stands for initial spectrum, blue curve for compressed spectrum). Thereafter we changed the DDL in the program to have second, third and fifth orders of dispersion and modelled spectral compression (figure 6c). We tested third and fifth orders of dispersion which resulted in SC represented in green and brown curves (figure 6b) respectively. Thereafter we have tested the combined impact of both effects (figure 6c). We found out that side lobes similar to lobes in spectral compression scheme with use of HCF (figure 3b) occur when we put considerable values of

third and fifth orders of dispersion, which are not compressed in self-phase modulation process. We assume, based on this numerical studies, that side lobes are caused by third and fifth orders of dispersion. Forth order of dispersion was also tested but had no considerable impact on spectrum deformations.



**Figure 5.** Scheme of SFG-SC with HCF as DDL (a), and compressed spectrum at 400 nm with laser spectrum at top left (b).



**Figure 6.** Results of numerical simulations for SC. Red curves are for initia spectrum. (a) Blue curve is compressed spectrum considering 2<sup>nd</sup> order dispersion only corresponding to classic scheme of Sec. 2.1. (b) SC with 2<sup>nd</sup> + 3<sup>rd</sup> order dispersion (green), and 2<sup>nd</sup> + 5<sup>th</sup> order dispersion (black). (c) SC with the combined impact of 2<sup>nd</sup> + 3<sup>rd</sup> + 5<sup>th</sup> order dispersion corresponding to all fiber scheme with HCF of Sec. 2.3.

Concluding, we have implemented femtosecond pulse SC through five different techniques: classic and all-fiber through SPM, similaritonic and all-fiber similaritonic through SFG. Spectral compression with the ratios 12.3x, 8.4x, and 11x for the classic, all-fiber, and all-fiber similaritonic techniques, correspondingly, are achieved. Spectral focusing in all this cases require compensation of high-order dispersion to avoid side lobes in compressed spectra.

We demonstrated a 23.3x aberration-free SC for the similaritonic SFG-method.

Finally, we have experimentally observed 1.3x spectral narrowing in HCF as a result of combined impact of weak nonlinearity and anomalous dispersion, proving the process of self-SC, which is the spectral analogue of soliton effect compression.

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