Few-cycle all-fiber temporally coherent supercontinuum sources

Azahara Almagro-Ruiz ^{*a}, Salvador Torres-Peiró^a, Héctor Muñoz-Marco^a, Romain Dauliat^b, Raphael Jamier^b, Rosa Romero^c, Paulo T. Guerreiro^c, Marina Cunquero^d, Gustavo Castro^d, Pablo Loza-Álvarez^d, Helder Crespo^c, Philippe Roy^b, Pere Pérez-Millán^a

^aFYLA LASER S.L., Ronda Guglielmo Marconi 12, 46980, Paterna, Valencia, Spain;

^bUniversité Limoges, XLIM, UMR CNRS 7252, F-87000 Limoges, France;

^cSphere Ultrafast Photonics, S.A., R. do Campo Alegre 1021, Edifício FC6, 4169-007, Porto, Portugal;

^dICFO-Institut de Ciències Fotòniques, The Barcelona Institute of Science and Technology, Av. Carl Friedrich Gauss 3, 08860 Castelldefels, Spain

ABSTRACT

We present a monolithic fiber optic configuration for generating temporally coherent supercontinuum (SC) pulsed emission with the shortest pulse duration presented to date, to our knowledge, by an all-fiber source. Few-cycle pulses as short as 14.8 fs are obtained, with central emission wavelength of 1060 nm, repetition rate of 75 MHz and average power of 250 mW. The SC generation is obtained by pumping an all-normal dispersion (ANDi) photonic crystal fiber (PCF) with a mode-locked Yb fiber laser. Spectral broadening by self-phase modulation preserves compressible pulses in the temporal domain. Compared to previously reported configurations exploiting ANDi PCFs, all stages of our source are fiber based and fiber coupled between them. Avoidance of free-space propagation between stages confers unequalled robustness, efficiency and cost-effectiveness to this novel configuration. The ANDi PCF was designed and produced to provide a convex, flat-top dispersion curve with group velocity dispersion lower than 0 and higher than -20 ps/nm/km, ~~in the range~~ from 900 to 1200 nm. A d-scan system was designed and built to compress and characterize the pulses. The spectrum, wider than 150 nm, supports a Fourier limit pulse duration of 13.7 fs, and pulses have been actually compressed down to 14.8 fs, which demonstrates a high level of temporal coherence in the achieved supercontinuum; second- and third-order dispersion of the pulses are measured as low as -145 fs² and 875 fs³, respectively. The source has been integrated in a two-photon fluorescence and second-harmonic generation microscopy setup, where 3D images of biological samples were successfully obtained

Keywords: Fiber laser, Supercontinuum, Temporal coherence, Ultrashort pulses, Nonlinear Microscopy, All-Normal Dispersion Photonic Crystal Fiber, Dispersion-scan, Few-cycle lasers

1. INTRODUCTION

Supercontinuum (SC) sources emit ultra-broadband spectra in short pulses, usually at high repetition rates. The broadest SC spectra (up to 400 to 2500 nm using SiO₂ fibers) are generated by pumping highly nonlinear photonic crystal fibers (PCFs) with femtosecond or picosecond pulses with wavelengths in the anomalous group velocity dispersion (GVD) regime of the PCF, and close to its zero-dispersion wavelength (ZDW). In these conditions, spectral broadening is dominated by soliton effects where higher order solitons break down into redshifted fundamental solitons, which are Raman shifted to longer wavelengths while blue-shifted radiation is generated by dispersive waves^{1,2}. This broadening mechanism leads to a complex temporal pulse profile, lack of spectral flatness, increase of noise, and low temporal coherence across the bandwidth due to shot-to-shot fluctuations in relative phase and intensity. Nevertheless, in the last years, research on SC generation has demonstrated a successful approach to overcome the lack of temporal coherence of supercontinuum pulses, allowing to obtain very high-quality few-cycle pulses: pumping near the flattened top of the convex dispersion curves of all-normal dispersion (ANDi) PCFs (for which dispersion lies completely in the normal dispersion region), spectral broadening appears due to the action of self-phase modulation (SPM) and optical wave breaking (OWB)³. In this way, highly coherent, flat-top, SC emission can be generated, preserving compressible pulses in the temporal domain.

*aalmagro@fyla.com; phone +34 607 971 021; FYLA.com

Different approaches to generate temporally coherent SC using ANDi PCFs have been proposed. In some configurations^{4,5,6,7,8,9,10} the seed stage (or pump stage) of the coherent SC source is built with free-space optics technology: e.g. Ti:Sapphire lasers, optical parametric oscillators (OPOs) or master oscillator power amplifiers (MOPAs). In other configurations^{11,12,13} the seed stage is a fiber laser but light coupling to the ANDi PCF is performed with free-space optics. Chow et al.¹⁴ proposed an all-fiber configuration based on ANDi PCFs for the 1.55 μm band, but a demonstration of transform limited or near-to-transform-limited compression of the generated SC is still lacking. To the best of our knowledge, none of the current state-of-the-art configurations that demonstrate transform limited or near-transform-limited generation of few-cycle temporally coherent supercontinua using ANDi PCFs is an all-fiber configuration (said all-fiber configuration understood as a monolithic fiber optic configuration where all its stages are fiber based and coupled to each other by a fiber splice or a fiber-based transition). In the present work we present a monolithic fiber optic configuration for generating temporally coherent supercontinuum pulsed emission with the shortest pulse duration presented to date, to our knowledge, by an all-fiber source. Few-cycle pulses as short as 14.8 fs are obtained, with central emission wavelength of 1060 nm, repetition rate of 75 MHz and average power of 250 mW. Being all-fiber, the source is more simple, robust, efficient and cost-effective than previously reported few-cycle temporally coherent SC sources.

A straightforward consequence of the ability of this source to deliver pulses of such extremely short duration is that pulse peak powers are extremely high (>100 kW) at low average powers (<250 mW). We anticipate that applications like nonlinear microscopy, where imaging efficiency increases exponentially with pulse peak power, but low average power is desirable to maintain integrity of samples, will benefit from this type of illumination source. Besides, the ultrabroadband emission of the few-cycle source offers the advantage of simultaneous excitation of different fluorophores (sensible to different wavelengths) for multichannel imaging, in contrast to the sequential excitation required by standard illumination with several or with tunable femtosecond lasers. The first demonstrations of these advantages using an all-fiber laser source are presented in this work, where we successfully obtained high resolution images of biological samples in a two-photon fluorescence and second-harmonic generation microscopy setup.

2. FEW-CYCLE ALL-FIBER TEMPORALLY COHERENT SUPERCONTINUUM

2.1 Monolithic Fiber Optic Configuration

Figure 1 illustrates our approach to obtain a few-cycle temporally coherent supercontinuum source. It is configured as a sequential structure of fiber-based stages, each of them connected to the next by a fused fiber splice. We use a chirped pulse amplification (CPA) configuration¹⁵, fully all-fiber, where the temporal compression stage is built with a hollow core photonic bandgap fiber (HC PBGF). Maintaining the temporal coherence throughout its stages, such configuration delivers pulses of >15 kW peak power and <250 fs duration at the input of an ANDi PCF, where temporally coherent spectral broadening is generated by SPM. The collimated output from the ANDi PCF is launched into a d-scan unit to measure the amplitude and phase properties of the pulses¹⁶.

Figure 1. All-fiber configuration of the few-cycle temporally coherent SC source.

The seed of the system is a passively mode-locked all-fiber laser that delivers linearly polarized pulses with the following characteristics: spectral bandwidth at full width at half maximum (FWHM), $\Delta\lambda_{\text{FWHM}} = 13.6$ nm; temporal pulse width (at FWHM), $\Delta\tau_{\text{FWHM}} = 3.1$ ps; peak power, $P_p = 86$ W; central wavelength, $\lambda_c = 1060$ nm; pulse repetition rate, PRR = 75 MHz. The central wavelength and the pulse repetition rate remain unchanged throughout all the stages of the system. The output fiber of the seed laser is fusion spliced to a polarization maintaining (PM) fiber, Nufern PM-980XP, of 20 m length and normal group velocity dispersion (GVD) at the seed wavelength, where the pulses are stretched temporally. At the fiber output of the fused fiber combiner used to couple light from a 976 nm pump diode to the next amplifying stage, the optical

characteristics of the pulsed signal are: $\Delta\lambda_{FWHM} = 13.6$ nm; $\Delta\tau_{FWHM} = 9.6$ ps; $P_p = 27.8$ W; peak intensity, $I_p = 92$ MW/cm². The amplifier is composed of a double clad PM Yb-doped active fiber, Nufern PM-YDF-5/130-VIII, of 4.5 m length and normal GVD. At the output of the amplifier stage, at a pump diode current $I_{pump} = 4$ A (pump diode average power of 3 W), the optical characteristics of the pulsed signal are $\Delta\lambda_{FWHM} = 14.5$ nm; $\Delta\tau_{FWHM} = 15$ ps; average power $P_{avg} = 0.85$ W; $P_p = 756$ W; $I_p = 2.50$ GW/cm². The fiber end of the amplifier is fusion spliced to a HC PBGF of 7.2 μ m mode field diameter (MFD), 10 m length and anomalous GVD of -72×10^3 fs²/m at 1060 nm. The function of this fiber is to compress the pulses to achieve the peak power required at the input of the ANDi-PCF to efficiently generate temporally coherent spectral broadening by SPM. Also, its length is designed so that the net group delay dispersion (GDD) experienced by the pulses from the oscillator output is slightly anomalous: -0.015 ps². Doing so, the pulse still undergoes compression in the first segment of the ANDi PCF and SPM efficiency is optimized by having the maximum peak power achievable inside the ANDi PCF. Since the material of the core is air, nonlinear effects due to high peak power are avoided, hence the pulse does not experience spectral broadening. At the fiber output of the HC PBGF the optical characteristics of the pulsed signal are: $\Delta\lambda_{FWHM} = 14.5$ nm; $\Delta\tau_{FWHM} = 200$ fs; $P_{avg} = 0.65$ W; $P_p = 43.3$ kW; $I_p = 106.3$ GW/cm². The end of the HC PBGF was fusion spliced to the ANDi PCF. To maintain the integrity of the structure of both fibers, the arc discharge parameters were set for a weak splice that was afterwards protected by a thermoretractable splice protector. A coupling efficiency of 0.4 is obtained with this procedure.

The last stage of the all-fiber system is composed of a highly nonlinear ANDi PCF of a total length of 20 cm and MFD of 2.6 μ m. GVD in this fiber is normal within a very broad spectral bandwidth (broader than 300 nm, centered at 1060 nm), with a quasi-flat and symmetric shape (see figure 4) and very close to 0 in order to limit pulse stretching as much as possible. The function of this stage is to spectrally broaden the spectrum of the pulsed signal by the SPM nonlinear effect under near-zero-dispersion conditions, which preserves the temporal coherence of the pulses so that they can be compressible down to pulse widths corresponding to the Fourier limit of their spectrum. The output signal from the ANDi PCF is delivered to free-space and collimated. At this point the optical properties of the pulsed signal are as follows: $\Delta\lambda_{FWHM} = 150$ nm; $\Delta\tau_{FWHM} = 80$ fs; $P_{avg} = 0.25$ W; $P_p = 41.7$ kW; $I_p = 784.8$ GW/cm².

Figure 2. Optical spectra of the pulsed signal at the output of the HC PBGF (dashed line) and at the output of the ANDi PCF (continuous line), both at the same pump diode current, $I_{pump} = 4$ A.

Figure 2 shows the optical spectrum of the pulsed signal at the output of the ANDi PCF, compared to the optical spectrum at the output of the HC PBGF, both at the same pump diode current, $I_{pump} = 4$ A. Due to the nonlinear effect of SPM experienced by the pulsed signal, its optical spectrum is broadened from 14.5 nm to 150 nm (FWHM). Said pump current is slightly above the current limit below which spectral broadening is due to SPM only. The shoulder peak at 950 nm in the short-wavelength edge of the spectrum indicates the beginning of the appearance of OWB effects, which are to be avoided to maintain “pure” temporally coherent spectral broadening by SPM³.

Finally, a free-space temporal compressor of fixed anomalous GDD and variable normal GDD is used to compress the pulses from the output of the ANDi PCF. The variable compression is introduced by a glass wedge pair placed in the path of the optical signal. Dispersion is varied by changing their relative position (insertion length), therefore changing the amount of glass material effectively traversed by the optical signal. Figure 3 shows the results of the technique that we have used to measure the properties of the compressed pulses. Known as the d-scan technique, it is based on performing a dispersion scan to the pulses with a pulse compressor while measuring the spectrum of the resulting second-harmonic (SH) signal¹⁶. The compressor is designed to provide a range of net GDD to the pulse from - 1000 fs² (0 mm insertion length, figure 3) to +1500 fs² (17 mm insertion length, figure 3). From this measurement, the phase and the amplitude properties of the electric field of the pulses are retrieved. The pulses present very low GDD and TOD values (-145 fs² and 875 fs³, respectively) with 68.4% of the energy in the main peak. The measured pulse width of the compressed pulse is 14.8 fs (4.23 optical cycles). This result demonstrates the high degree of temporal coherence of the pulsed signal, since it is very close to the Fourier limited duration supported by its optical spectrum (13.8 fs). Average and peak power at the output of the compressor are $P_{\text{avg}} = 160$ mW and $P_p = 144.1$ kW, respectively.

To the best of our knowledge, with the measurement of a temporal pulse width of 14.8 fs we report the shortest pulses obtained to date from an all-fiber source.

Figure 3. SHG d-scan retrieval results and resulting pulse in the spectral and time domain. (Top left) Measured, calibrated d-scan trace. (Top-right) Retrieved d-scan trace. (Bottom-left) Red line: Measured linear spectrum. Blue line: Retrieved spectral phase. Black line: 4th order polynomial fit of the spectral phase. (Bottom-right) Dashed green: Temporal intensity profile of the transform limited pulse. Light green: Temporal intensity profile of the measured pulse.

2.2 All-Normal Dispersion Photonic Crystal Fiber

The ANDi PCF used in this work has been manufactured using the standard stack and draw method. It is made of F300 silica and exhibits a PCF solid core design. In other words, the solid-core results from a missing hole that is surrounded by N arrays of holes running along the fiber longitudinal axis. Holes are displayed in a periodic manner with a triangular lattice. The air holes have a diameter d . The distance between hole centers, called pitch, is Λ . The microstructure of air holes is surrounded by a jacket of uniform silica that confers the fiber a typical diameter of 125 μm . It is well known that the parameters Λ and d strongly influence the propagation of light in the core and for the targeted application. These parameters have been chosen to get a single-transverse mode propagation, low confinement losses, a small effective area and the most relevant, a well-controlled chromatic dispersion over the whole spectral wavelength band of interest. Indeed, in order to limit nonlinear effects to SPM, the chromatic dispersion of this microstructured fiber has to be normal within a very broad spectral bandwidth (> 150 nm centered around the central wavelength of the exciting optical signal) and very

close to 0 to limit pulse temporal stretching as much as possible. Besides, this dispersion curve has to present a quasi-flat, convex and symmetric shape in order to generate symmetric spectral broadening. Considering a central wavelength of 1060 nm, such properties of the dispersion curve are obtained combining the values of Λ and d within the following ranges: $d = [0.55; 0.65] \mu\text{m}$; $\Lambda = [1.5; 1.70] \mu\text{m}$. Efficient confinement of the light inside the core is obtained by values of N equal to 7 or higher.

Figure 4 A shows an electron microscope image of the cross section of the manufactured ANDi PCF used to obtain the results detailed above. It presents an average hole diameter $d = 0.61 \mu\text{m}$ and an average pitch $\Lambda = 1.67 \mu\text{m}$. Figure 4 B illustrates the theoretical and measured dispersion curve of the fiber. In the whole range of wavelengths of $1060 \pm 150 \text{ nm}$, the dispersion parameter D of the fiber is negative, lower than 0 ps/nm/km and higher than -30 ps/nm/km (which is equivalent to say that its GVD is normal, higher than $0 \text{ fs}^2/\text{m}$ and lower than $17.9 \times 10^3 \text{ fs}^2/\text{m}$).

Figure 4. Properties of an example of ANDi PCF manufactured in this work. (A) Electron microscope image of the cross section of the ANDi PCF, with average hole diameter $d = 0.61 \mu\text{m}$ and average pitch $\Lambda = 1.67 \mu\text{m}$. (B) Theoretical and measured dispersion curve of the fiber.

3. BROADBAND NONLINEAR MICROSCOPY

We have tested the applicability of the new few-cycle all-fiber SC source for broadband nonlinear microscopy. Particularly, we present the first experiments demonstrating broadband simultaneous multichannel imaging using such a source, based in two-photon excitation (TPE)¹⁷ and in second-harmonic generation (SHG)¹⁸.

The output pulses from the temporally coherent SC source are launched into an adapted inverted microscope (Eclipse TE2000-U, Nikon) (figure 5 A). The dispersion experienced by the pulses through the optical components of the microscope are previously pre-compensated by the pulse compressor referred above, so that pulse duration at the sample plane is minimum. The images presented here have been obtained with a pulse duration of $\sim 17 \text{ fs}$ and an average power of $\sim 4 \text{ mW}$ at the sample plane. The coupling system of the external illumination source included two galvanometric mirrors (Cambridge Technology, UK) and a telescope arrangement. We used a dichroic mirror (FF825-SDi01, Semrock) for sending the laser to the illumination objective. The generated fluorescent light captured using this objective was collimated and sent through the same dichroic mirror to a PMT detector (H9305-04, Hamamatsu). Three different microscope objectives, with different refractive index immersion media (air, water, oil), numerical apertures (NA 0.75, 1.05, 1.4) and magnifications (20x, 25x, 60x) were used. Any possible leakage of the laser light was filtered with a BG40 filter (FGB37-A, Thorlabs). The two-photon emission fluorescence (TPEF) signal was filtered with fluorescence filter cubes (Standard series, Nikon) and collected in the backward direction. We used a 25x NA1.10 water objective (Apo LWD, Nikon) for SHG signal collection in the forward direction. The SHG signal was filtered with a bandpass filter (FF01-542/27-25, Semrock).

Figure 5. (A) Setup diagram. The excitation laser (red) is focused on the sample with a microscope objective. The TPEF signal (green) is collected in the backward direction. In the forward direction, the excitation laser and the SHG signal (blue) are collected with a microscope objective. A dichroic mirror is used to separate the laser light from the nonlinear signals. The TPEF signal is filtered from the SHG with a narrow bandpass filter. The TPEF and SHG signals are detected using PMT detectors: the transmitted light from the excitation laser is detected with a photodiode. (B) MAX projection of a Z-stack of TPEF images of a rhizome of *Convallaria majalis*. Chloroplasts (green) and cell walls (red) are clearly shown. Scalebar: 5 μm . (C) SUM projection of a Z-stack corresponding to 56 images (0.65 μm step spacing) of SHG signal of the muscle and pharynx (gray) and TPEF from the neurons (red) of a living *C. elegans* (OH15500 strain). Scalebar: 25 μm .

To test the capability of the temporally coherent SC to nonlinearly excite multiple markers we proceeded to acquire TPEF images of multiple fluorophores. We also proceeded to capture SHG images. In such case the TPEF signal was properly filtered, as indicated. Representative examples are shown in figure 5. Figure 5 B shows the rhizome of *Convallaria majalis* stained with Fast Green and Safranin. Chloroplasts are shown in green (FITC filter) and cell walls are shown in red (TRITC filter). We have also been able to image in vivo samples with cellular resolution. In particular, paralysed *C. elegans* specimens. In figure 5 C, we can see a *C. elegans* OH15500 strain expressing tagRFP in all neurons. The SHG signal revealed all the different structures of the pharynx of the animal: corpus, isthmus and posterior bulb. Moreover, we can see the muscle fibers and their contraction during swallowing over time. These structures are a high-priced reference while imaging neurons with TPEF. To summarize this section, by using different emission filters, we have been able to split the fluorescence from the different fluorophores to visualize multiple structures with a single illumination source.

REFERENCES

- [1] Husakou, A. V. and Herrmann, J., "Supercontinuum Generation of Higher-Order Solitons by Fission in Photonic Crystal Fibers," *Phys. Rev. Lett.* 87, 203901 (2001).
- [2] Dudley, J. M., Genty, G. and Coen, S., "Supercontinuum generation in photonic crystal fiber," *Rev. Mod. Phys.* 78, 1135-1184 (2006).
- [3] Heidt, A. M., Feehan, J. S., Price, H. V. and Feurer, T., "Limits of coherent supercontinuum generation in normal dispersion fibers," *J. Opt. Soc. Am. B* 34, 764-775 (2017).
- [4] Demmler, S. et al., "Generation of high quality, 1.3 cycle pulses by active phase control of an octave spanning supercontinuum," *Optics Express* 19, 20151-20158 (2011).
- [5] Heidt, A. M. et al., "High quality sub-two cycle pulses from compression of supercontinuum generated in all normal dispersion photonic crystal fiber," *Optics Express* 19, 3775-3787 (2011).
- [6] Liu, L. et al., "Coherent mid-infrared supercontinuum generation in all-solid chalcogenide microstructured fibers with all-normal dispersion," *Optics Letters* 41, 392-395 (2016).
- [7] Kedenburg, S., Steinle, T., Mörz, F., Steinman, A. and Giessen, H., "High-power mid-infrared high repetition-rate supercontinuum source based on a chalcogenide step-index fiber," *Optics Letters* 40, 2668-2671 (2015).
- [8] Liu, Y. et al., "Suppressing Short-Term Polarization Noise and Related Spectral Decoherence in All-Normal Dispersion Fiber Supercontinuum Generation," *J. Lightwave Technol.* 33, 1814-1820 (2015).

- [9] Klimczak, M. et al., "Coherent supercontinuum generation up to 2.3 μm in all-solid soft-glass photonic crystal fibers," *Optics Express* 22, 18824-18832 (2014).
- [10] Hartung, A., Heidt, A. M. and Bartelt, H., "Pulse-preserving broadband visible supercontinuum generation in all-normal dispersion tapered suspended-core optical fibers," *Optics Express* 19, 12275-12283 (2011).
- [11] Hooper, L. E., Mosley, P. J., Muir, A. C., Wadsworth, W. J. and Knight, J. C., "Coherent supercontinuum generation in photonic crystal fibre with all-normal group velocity dispersion," *Optics Express* 19, 4902-4907 (2011).
- [12] Tarnowski, K. et al., "Coherent supercontinuum generation up to 2.2 μm in an all-normal dispersion microstructured silica fiber," *Optics Express* 24, 30523-30536 (2016).
- [13] Nishizawa, N. and Takayanagi, J., "Octave spanning high-quality supercontinuum generation in all-fiber system," *J. Opt. Soc. Am. B.* 24, 1786-1792 (2007).
- [14] Chow, K. K., Takushima, Y., Lin, C., Shu, C. and Bjarklev, A., "Flat super-continuum generation based on normal dispersion nonlinear photonic crystal fibre," *Electron. Lett.* 42, 989-991 (2006).
- [15] Strickland, D. and Mourou, G., "Compression of amplified chirped optical pulses," *Opt. Commun.* 56, 219-221 (1985).
- [16] M. Miranda et al., "Characterization of broadband few-cycle laser pulses with the d-scan technique," *Opt. Express* 20, 18732-18743 (2012).
- [17] Gannaway, J. N. and Sheppard, C. J. R., "Second-harmonic imaging in the scanning optical microscope," *Opt. Quant. Electron.* 10, 435-439 (1978).
- [18] Denk, W., Strickler, J. H. and Webb, W. W., "Two-photon laser scanning fluorescence microscopy," *Science* 248, 73-76 (1990).