RECENT ADVANCES IN ULTRA-LOW NOISE COHERENT SUPERCONTINUUM GENERATION

E. Genier[1,2], P. Bowen[1], P. M. Moselund[1], O. Bang[3], J. M. Dudley[2], and T. Sylvestre[2]

1. NKT Photonics A/S, Blokken 84, DK-3460, Birkerød, Denmark

2. Institut FEMTO-ST, UMR 6174 CNRS-Université Bourgogne Franche-Comté, Besançon, France

3. DTU Fotonik, Department of Photonics Engineering, Technical University of Denmark, Lyngby

Email: etienne.genier@univ-lille.fr (Now at PHLAM/IRCICA, Univ. Lille)

ABSTRACT

We review our recent works on coherent supercontinuum generation in all-normal dispersion photonic crystal fibers and demonstrate ultra-flat octave-spanning coherent spectra with excellent noise and polarization properties. These new broadband fiber sources could find important applications in biomedical imaging, optical spectroscopy and metrology, where the signal-to-noise ratio is essential.

KEYWORDS : Optical fibers, supercontinuum generation, coherence, noise

Supercontinuum (SC) generation in all-normal dispersion (ANDi) photonic crystal fibers (PCFs) has recently been investigated due to its ability to generate a low-noise broadband coherent spectrum, with a noise level much lower than typical soliton-based SC sources based on anomalous dispersion fibers [1,2]. ANDi SC generation, which is essentially based on nonlinear coherent effects such as self-phase modulation (SPM) and subsequently optical wave breaking (OWB), has a high degree of coherence and high pulse to pulse stability [2].

Here we review our recent results towards ultra-stable and flat SC generation using ANDi fibers. We report an ultra-flat octave-spanning (670 nm-1390 nm) coherent SC with excellent low noise (RIN<0.54 %) and polarization (PER>17 dB) properties. This was achieved using a polarization-maintaining (PM) ANDi PCF pumped by a compact ytterbium-doped femtosecond laser at 1049 nm. We further report the observation of cross-phase modulation instability (XPMI) in PM ANDi fibers [3] and we describe an improved numerical modelling based on the nonlinear Schrödinger equation (NLSE) for coherent SC generation [4].

Figure 1(a) shows the experimental setup for coherent SC generation in ANDi Fibers. As a pump laser, we used a femtosecond ytterbium solid-state mode-locked laser (Origami 10 HP, NKT Photonics) centered at 1049 nm, delivering a 180 fs pulse train at an 80 MHz repetition rate with a maximum average power of 4 W, a low RIN of 0.5%, and a PER of 31 dB. The fiber is a PM ANDi PCF from NKT Photonics (Model NL-1050-NEG-PM). This fiber has a core diameter of 2.4 µm, a small hole-to-hole pitch of 1.44 µm, and a nonlinear coefficient of 26.8 $W^{-1}km^{-1}$. The fiber's dispersion and loss profiles are shown as an inset in Fig. 1. The dispersion has an all-normal parabolic profile with a peak at -13 ps/nm/km at 1040 nm. The PM property of the PCF is mainly stress-rod induced and it has a slightly elliptic core, which together gives it a high birefringence of 4.7 10^{-4} at the pump wavelength. Figure 1(b) shows the spectral intensity profile for 3 selected polarizations and an average output power from the fiber of 720 mW. We obtain the broadest and flat bandwidth while pumping along the fiber slow axis (red curve), with a spectrum going from 685 nm to 1395 nm at -3 dB. We find the spectrum becomes more noticeably modulated as we move closer to the center of the spectrum. Furthermore, the modulations appear together with the observation of an XPMI peak [3] near 1400 nm when pumping along the slow axis.

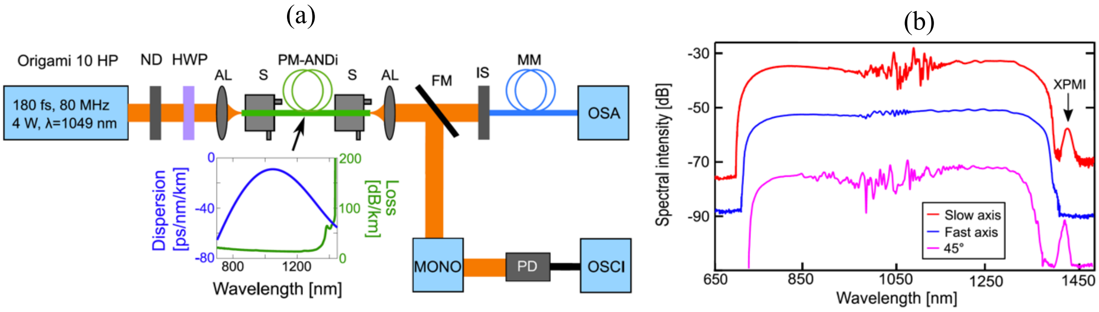

Fig. 1 (a) Schematic of the setup, including ytterbium femtosecond mode-locked laser (ORIGAMI 10 HP), variable neutral density filter (ND), half wave plate (HWP), aspheric lenses (AL), 3D translation stages (S), 2 m of PM-ANDi PCF, flip-mirror (FM), integrating sphere (IS), 2 m of multimode pick-up fiber (MM), optical spectrum analyzer (OSA), monochromator (MONO), photodiode (PD), and oscilloscope (OSCI). (b) Experimental SC spectra at the output of the PM-ANDi PCF for output average power of 720 mW with an input pulse duration of 180 fs while pumping along the slow axis (red curve), fast axis (blue curve) and at 45° from the axes (pink curve).

Figure 2 (a) shows the experimental SC spectra for an increasing power from 1 mW to 720 mW when pumping along the fiber's fast axis. The SC bandwidth goes from 9 nm (in the linear regime) to 720 nm (from 670 nm to 1390 nm) at -3 dB, which is more than one octave with a power spectral density higher than 0.4 mW/nm (-4 dBm/nm). The relative intensity noise (RIN) was further measured across the full SC bandwidth using a monochromator as a tunable spectral filter, two photodetectors (Silicon and InGaAs) and a fast oscilloscope. Fig. 1(b) depicts the spectrally-resolved RIN as red dots (silicon) and as green dots (InGaAs), while the blue curve shows the related SC spectrum while pumping the fiber at 45° off the axes. We measured an average RIN down to 0.54 % from 700 nm to 1100 nm, which is very close to that of the pump laser (0.5 %). The results also show that the RIN increases drastically on the SC edges due to both the reduction of the SC power and the strong effect of laser peak power fluctuations on the SC bandwidth [4]. We also find good agreement (see brown dashed and black doted curves) with numerical simulations of the nonlinear Schrödinger equations.

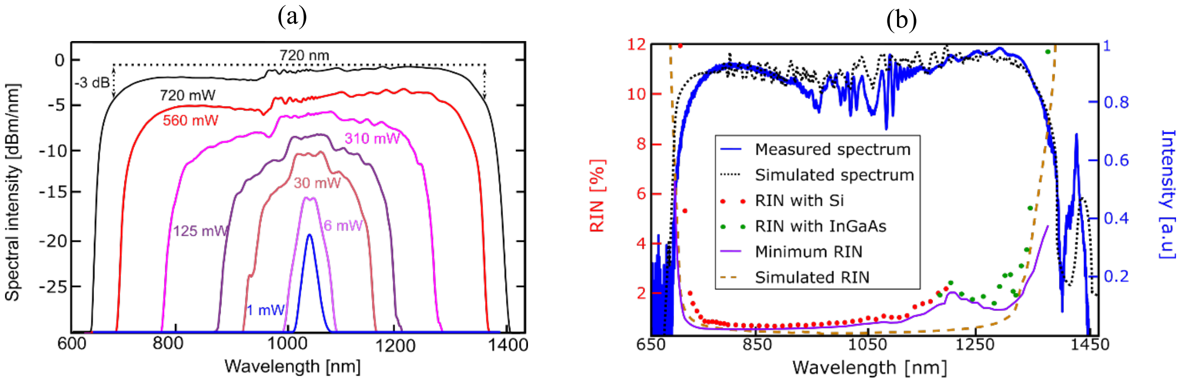

Fig. 2 (a) Experimental SC spectra at the output of the PM-ANDi PCF for an output average power from 1 mW to 720 mW with an input pulse duration of 180 fs and an input beam polarized along the fast axis. (b) RIN measurements using a silicon (red dots) and an InGaAs (green dots) photodetector and an oscilloscope, and corresponding average normalized SC spectrum (solid blue), pumping at 45° from the fiber principal axes at maximum power. Simulated SC (black dots) and RIN spectra (dashed brown). The pink curve shows the estimated minimum RIN values from our measurement system.

In conclusion, using a compact ytterbium mode-locked laser producing 180 fs pulses and a highly-nonlinear polarizationmaintaining ANDi PCF, we were able to generate an ultra-flat octave-spanning SC spectrum with a bandwidth up to 720 nm (from 670 nm to 1390 nm) and associated PSD higher than 0.4 mW/nm. We have shown that the SC is linearly polarized with a PER of 17 dB across the whole spectrum bandwidth and with a spectrally-resolved RIN below 0.54 % from 700 nm to 1100 nm, which is, to the best of our knowledge, the lowest average SC ANDi RIN value ever reported with this measurement method. This system could find many applications in OCT, metrology, or as a wavelength-tunable fs laser source thanks to its octave-spanning bandwidth, flatness, low-noise, high coherence, polarization and near-linear chirp properties.

References

[1] L. E. Hooper, P. J. Mosley, A. C. Muir, W. J. Wadsworth, and J. C. Knight, Opt. Express 19, 4902 (2011).

[2] A. M. Heidt, J. S. Feehan, J. H. V. Price, and T. Feurer, "Limits of coherent supercontinuum generation in normal dispersion fibers," J. Opt. Soc. Am. B 34, 764-775 (2017).

[3] E. Genier, A. N. Ghosh, S. Bobba, P. Bowen, P. M. Moselund, O. Bang, J. M. Dudley, and T.t Sylvestre, "Cross-phase modulation instability in PM ANDi fiber-based supercontinuum generation," Opt. Lett. **45**, 3545-3548 (2020).

[4] E. Genier, P. Bowen, T. Sylvestre, J. M. Dudley, P. Moselund, and O. Bang, "Amplitude noise and coherence degradation of femtosecond supercontinuum generation in all-normal-dispersion fibers," J. Opt. Soc. Am. B 36, A161-A167 (2019).