Noise in supercontinuum generated using PM and non-PM tellurite-glass all-normal dispersion fibers

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Intensity fluctuations in supercontinuum generation are studied in polarisation-maintaining (PM) and non-PM all-normal dispersion tellurite photonic crystal fibers. Dispersive Fourier transformation was used to resolve shot-to-shot spectra generated using 225 fs pump pulses at 1.55 µm, with experimental results well reproduced by vector and scalar numerical simulations. By comparing the relative intensity noise for the PM and non-PM cases, supported by simulations, we demonstrate the advantage of the polarisation-maintaining property of the PM fibers in preserving low-noise dynamics. We associate the low-noise in the PM case with the suppression of polarisation modulation instability. © 2022 The authors

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Motivated by important applications that require low-noise broadband light sources, there has been a recent interest in supercontinuum (SC) generation in all-normal dispersion (ANDi) fiber [1–4]. In addition to providing a flat-top and broadband spectrum, SC generated in ANDi fibers can yield high shot-to-shot coherence due to the relative insensitivity to input noise of self-phase modulation and optical wave breaking dynamics in the normal dispersion regime. The superior noise properties of ANDi SC over SC generated by pumping in the anomalous dispersion have been verified by measurements of spectral fluctuations using unequal path Michelson interferometers, RF beating with stabilised laser diodes, relative intensity noise (RIN), and dispersive Fourier transformation (DFT) [5–8]. However, it has also been established that SC coherence in ANDi fibers can degrade with increased pulse duration and fiber length due to parametric interaction between coherent and incoherent components [9], as well as polarisation modulation instability (PMI) [10].

Experiments have used both polarisation-maintaining (PM) and weakly birefringent (non-PM) ANDi fibers to demonstrate low-noise SC generation. With PM-ANDi fiber, low-noise SC can be obtained by matching the linear pump polarisation to one of the principal axes of the fiber [8, 11, 12]. With non-PM-ANDi fiber, the onset of PMI depends on the pump pulse duration, fiber length, and peak power (Pp) [10]. As a result, very specific pump parameters and fiber lengths need to be chosen to avoid PMI-induced noise, limiting the spectral broadening that can be achieved [7].

A difficulty with these previous studies, however, is that the range of experimental parameters used makes it difficult to quantitatively compare the SC properties obtained using PM and non-PM ANDi fiber. In this Letter, we address this problem directly through a combined experimental and numerical study of SC noise in PM and non-PM ANDi fibers under controlled conditions. Specifically, we use two variants of a highly nonlinear ANDi tellurite glass photonic crystal fiber (PCF); one fabricated with polarisation-maintaining functionality, the other without. Both variants share a hexagonal air-hole lattice structure. The DFT technique is used to quantify the RIN of SC generated in both fibers, and we explicitly show the superior noise properties of the SC when the PM-ANDi fiber variant is used. These experimental results are supported by numerical simulations using both scalar and coupled generalized nonlinear Schrödinger equation (GNLSE) models.

The non-PM fiber (labelled NL47A4) was previously studied for its SC performance in Ref. [13]. This fiber was used as the starting point to develop the PM variant, (labelled NL51A3.2). Scanning electron microscope (SEM) images of both fibers are shown in Fig. 1(a-b). The measured group velocity dispersion (GVD) of the non-PM, and the two degenerate modes of the PM fibers are plotted on the left axis of Fig. 1(c). The right axis of Fig. 1(c) plots the measured group birefringence of the PM fiber.

Pulses with a full width half maximum, TFWHM = 225 fs from an optical parametric oscillator (Coherent Chameleon compact) at 1.55 µm and a repetition rate of 80.15 MHz were used to generate SC in both fibers. A 40× microscope objective was
used for coupling, and a half-wave plate (Thorlabs AQWP10M-1600) was used to control the polarisation orientation.

The SC output was coupled into a 170 m long dispersion-shifted fiber (DSF) for shot-to-shot spectral measurements using DFT [14–16]. The input to the DSF was attenuated to ensure linear propagation. The DSF had a normal GVD of $\beta_2 = 107$ ps$^2$/km, and a dispersion slope $\beta_3 = 0.082$ ps$^3$/km at 1.55 $\mu$m. The DFT setup used a 50 GHz InGaAs detector ($\Delta t$: XPDV2120R) and a 12 GHz, 40 G S/s oscilloscope (Agilent DSA91204A). The pulse train was recorded for 5 $\mu$s, corresponding to 400 consecutive SC pulses. The 5.8 nm spectral resolution of the DFT was limited by the system bandwidth.

The spectrum obtained from the CGNLSE simulations (green) was varied. At the powers used in the experiments, the axis at which the broadest SC was generated is denoted as the fast axis, as the dispersion for the pump pulse when coupled to this axis is lower than the dispersion when coupled to the slow axis.

CGNLSE [17] was used to numerically simulate the SC and the noise properties of the SC in the non-PM ANDi fiber. The effective refractive index of the fiber was numerically calculated using the fiber parameters, and the full dispersion profile of the fiber was used in the simulations. The mode profile dispersion is included in the simulation such that the photon number is conserved when the net loss is zero [18]. The total loss of the fiber was included in the simulation and was calculated as the numerically obtained confinement loss and the fiber material loss measured in Ref. [13]. The weak birefringence between the two fundamental modes was accounted for by their phase mismatch, $\Delta \beta = \Delta n \omega_0 c$, where $\omega_0$ is the angular frequency of the pump. The implementation of the CGNLSE is similar to that in Ref. [10]. Nonlinear index, $n_2 = 4.88 \times 10^{-19}$ m$^2$/W, birefringence, $\Delta n = 10^{-7}$, and the Raman response curve with single Lorentzian profile with damping time of vibrations, $\tau_1 = 5.5$ fs, $\tau_2 = 32$ fs, and fractional contribution of the delayed Raman response, $f_R = 0.2$ were used in the simulations. The input pulse was Gaussian with $T_{\text{FWHM}} = 225$ fs. Quantum noise in the pump was included by adding independent and normally distributed real and imaginary parts in each time bin with the width $\Delta t$ of the input envelope function in the Wigner representation. The quantum noise has a variance of $\hbar \omega_0/2\Delta t$ [19, 20]. The pump was measured to have a RIN = 0.6%, using the DFT technique. This technical laser noise was added to the $P_0$ of the input pulse such that the energy $P_0 T_{\text{FWHM}}$ was constant [7, 21]. All RIN computations were done with an ensemble of twenty independent simulations with different noise seeds, and all simulated spectra presented in the figures were averaged over those twenty individual simulations.

The spectrum obtained from the CGNLSE simulations (green) when coupled into the slow axis of the non-PM fiber with $P_0 = 2.1$ kW is plotted in Fig. 2(a), along with the experimentally measured spectrum (blue) and the measured DFT average (red). The CGNLSE simulation reproduces the measured spectrum very well. The spectrum obtained from the CGNLSE simulations (green) for the slow axis with $P_0 = 2.1$ kW is plotted in Fig. 3(d), as well, along with the 400 individual shots in grey and the measured DFT average, for reference. Fig. 3(b) shows the corresponding RIN plot. The blue curve is the RIN calculated from the experimental DFT data, and the magenta curve is the RIN calculated from the CGNLSE simulations. The RIN obtained from the experimental DFT data exceeds 5% [indicated
mixed parametric Raman (MPR) noise alone are low for all of the \( P_0 \) in the plot, indicating that the high RIN observed in Fig. 3(f) is indeed caused by PMI.

Next, we investigated the noise characteristics of the SC using the PM variant of the fiber. The pump polarisation was first aligned to the fast axis of the PM ANDi fiber. The measured DFT average (red) is plotted in Fig. 5(c). The grey traces are the overlaying spectra of the 400 SC shots resolved using the DFT. The polarisation of the pump was then rotated by 90° to couple into slow axis of the fiber. Figure 5(d) shows the measured DFT average (red) and the 400 individual spectra (grey) for this case. The SC and the RIN out of the fiber were simulated using scalar-GNLSE. The spectrum obtained from the scalar-GNLSE simulations (green) with \( P_0 =0.5 \text{ kW} \) is plotted in Fig. 5(d). The spectrum obtained from the scalar-GNLSE simulations (green) for the slow axis with \( P_0 =0.5 \text{ kW} \) is plotted in Fig. 2(b), along with the experimentally measured spectrum (blue) and the measured DFT average (red), for reference. We see that the scalar-GNLSE simulation agrees very well with the measured spectrum. Figure 5(b) shows the corresponding RIN plots. The blue curve is the experimental RIN calculated using the DFT spectra. The measured RIN is low and is around 1% [indicated by dashed lines in Figs. 5(a-b)] across the entire SC width where our DFT measurements are accurate. The magenta curve is the RIN numerically calculated from the simulations. The measured shot-to-shot fluctuations, characterised in terms of RIN, agree very well with the RIN obtained from the simulations. Specifically, the simulation follows well the slope at wavelengths where the RIN begins to rise, at the shorter wavelength side. Similarly, Fig. 5(c) shows the measured and simulated spectra for the fast axis, while Fig. 5(a) shows the corresponding RIN curves. Figure 5(e) shows SC from forty sets of CGNLSE simulations with \( P_0 \) varied from 0.1 kW to 3 kW for the slow axis. The dotted horizontal line marks the spectrum generated with \( P_0 =2.1 \text{ kW} \), corresponding to the \( P_0 \) used in the experiment. The corresponding RIN plotted in Fig. 3(f) demonstrates that an input \( P_0 \) greater than 1.5 kW causes large pulse-to-pulse fluctuations in the output SC. Figures 5(a-f) show that when a weakly birefringent ANDi fiber is used along with a relatively long pump pulse and a large absolute value of dispersion, the SC generation dynamics exhibit large pulse-to-pulse fluctuations, in most of the cases due to PMI, as shown in Ref. [10]. To verify the origin of the large pulse-to-pulse fluctuations observed in the non-PM fiber, we implemented a separate scalar-GNLSE simulation in the interaction picture [22] with all the input parameters the same as in the CGNLSE simulations. The implementation of the scalar-GNLSE is similar to that in Ref. [7], and further details on the implementation can be found there. We carried out forty sets of scalar-GNLSE simulations with \( P_0 \) varied from 0.1 kW to 3 kW for the non-PM fiber. The spectrum at the end of the fiber is plotted in Fig. 4(a) and the corresponding RIN plots are shown in Fig. 4(b). The dotted horizontal lines in Figs. 4(a-b) mark the \( P_0 =2.1 \text{ kW} \) used in the experiments. The RIN plots in Fig. 4(b) show that the pulse-to-pulse fluctuations in the SC caused by
Therefore, we have studied the noise properties of the SC for This is attributed to the presence of the large holes introduced to its fundamental axis. 

Despite the difference in $P_0$ coupled into the PM and non-PM ANDi fibers, the noise properties of the two can be directly compared because all other experimental parameters were the same. 

A DFT noise study in Ref. [5] used a weakly birefringent all-solid soft glass ANDi fiber, pumped by a 390 fs laser pulse at 1.55 $\mu$m. Unlike in our case, the noise observed was attributed to MPR noise and PMI was not associated with the observed pulse-to-pulse fluctuations. The SC out of a germanium doped PM ANDi fiber, pumped by a 25 fs laser pulse at 1.55 $\mu$m was studied in Ref. [8]. Even though the individual DFT spectra seemed relatively stable, the pulse-to-pulse noise quantified as SNR (which is the inverse of RIN) shows large variations across the SC spectrum. These results individually do not provide a clear picture of the conditions needed to obtain a low-noise SC. Therefore, we have studied the noise properties of the SC for both the PM and the non-PM ANDi fibers, and we have experimentally verified them in the relatively long fs pulse regime. The RIN plot for the SC from the non-PM fiber [see Fig. 3(f)] shows that for a low pump $P_0$, the RIN remains low, but then rises due to PM as $P_0$ increases. However, for the same pulse duration and the set of $P_0$ value, the SC out of the PM fiber always remains low-noise [see Fig. 5(f)], when pumped along its fundamental axis.

In conclusion, we have experimentally characterised spectral fluctuations in SC generation from a weakly birefringent non-PM ANDi fiber and its PM version when pumped by 225 fs pulses at 1.55 $\mu$m. The experimentally measured RIN was reproduced very well using CGNLSE simulations for the non-PM fiber and using scalar-GNLSE simulations for the PM fiber. We show that for the non-PM fiber, PMI plays a detrimental role while attempting to maintain low-noise, and for the fiber and pump parameters used in our case, MPR noise has a negligible effect. Finally, using the same pump conditions, we have demonstrated that it is indeed possible to obtain ultra-low-noise (RIN<1%) SC when pumping along the fundamental axis of the PM version of the ANDi fiber.

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**Data availability.** Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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