Generating quiet continua: noise limitations to supercontinuum generation in photonic crystal fiber*

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Abstract: SC generation in photonic crystal fiber can be associated with intensity fluctuations arising from the nonlinear amplification of input pulse noise. Experiments and simulations are used to identify system parameters that minimize these fluctuations.

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1. Introduction

Since the experimental discovery of supercontinuum (SC) generation in photonic crystal fiber (PCF) by Ranka et al. in 2000 [1], an extensive amount of experimental and theoretical work has been carried out in order to better understand this phenomenon. Although the original experiments used femtosecond pump pulses, SC generation in PCF was subsequently demonstrated under a variety of experimental conditions, including using picosecond and nanosecond pulse sources [2,3]. These SC have already found important applications, particularly in optical frequency metrology where they have led to the development of a new generation of optical clocks with short-term stability exceeding the performance of the world's best microwave-based atomic clocks [4, 5].

All these applications exploit the broad spectral width and high brightness of the SC, but they also demand low noise properties, since intensity fluctuations will ultimately limit the precision and sensitivity of any measurement. Unfortunately, recent experiments have reported that the SC can possess significant broadband amplitude noise that can attain levels corresponding to 50% temporal intensity fluctuations for certain ranges of input parameters [6]. This noise extends well beyond the frequency roll-off of any laser technical noise; it thus appears as a fundamental limit to the SC stability. While in some experiments empirical steps have been taken to reduce the noise, it is clear that a more complete understanding of its physical origin and scaling properties is essential if the SC is to be exploited to its full potential.

The purpose of this paper is to describe a systematic experimental and numerical study of this broadband amplitude noise on the SC with the objectives of identifying its physical origin and developing practical guidelines for its minimization. We show that the origin of the noise is the amplification of quantum fluctuations to macroscopic levels. This noise amplification is closely related to earlier work on the amplification of amplified spontaneous emission during continuum broadening of short 1.5 micron pulses in conventional fiber [7]. Although this noise cannot be eliminated in our case because of its fundamental origins, we nonetheless identify methods of reducing its amplification through a judicious choice of input pulse parameters. Aside from the direct practical relevance of these results to applications of the SC, this work represents a significant advance in the modeling of SC generation by extending the modeling capabilities to include prediction of noise properties. Here, we present a detailed comparison between the measured noise on the SC and that predicted from numerical simulations based on a generalized nonlinear Schrödinger equation (NLSE) that rigorously includes the effects of both noise on the input pulse as well as noise due to spontaneous Raman scattering.

2. Experimental setup

Figure 1 shows the experimental setup that was used to measure the amplitude noise across the SC. A mode-locked Ti:Sapphire laser provides pulses with a bandwidth of ~45 nm FWHM centered at 810 nm. A double-pass prism pair was used to introduce a variable chirp on the laser pulses before injection into a microstructure fiber 15 cm long with zero group-velocity-dispersion at 770 nm. The input pulses were characterized using interferometric autocorrelation measurements. The injected pulse energy was 0.9 nJ. The resulting SC is spectrally filtered by a monochromator (8 nm bandwidth) before photodetection. To study the broadband noise properties of the supercontinnum, the resulting RF noise power (about the first harmonic) is measured at 3 MHz where technical noise is negligible and the Ti:Sapphire laser is shot noise limited. The broadband noise component is quantified directly in terms of the measured relative intensity noise (RIN), calculated as the total noise power in a 1 Hz bandwidth divided by the total detected power.

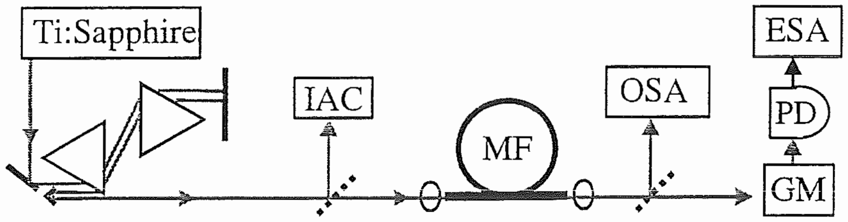

Figure 1: Experimental setup. IAC, interferometric autocorrelator; MF, microstructure fiber; GM, grating-based monochromator; PD, photodiode; ESA, electrical spectrum analyzer; OSA, optical spectrum analyzer.

3. Results and comparison with simulation

The solid lines in Figure 2 show typical results obtained for the experimentally measured spectrum and the associated RIN with near-transform-limited 22 fs input pulses. As noted by other groups, we see complicated spectral structure on the SC, but the RIN measurements here also reveal the dramatic and complicated wavelength-dependent structure of the SC noise, where fluctuations as high as 20 dB are common. Although these RIN measurements were made at an RF frequency of 3 MHz, experiments revealed that the magnitude of the RIN at any particular wavelength was independent of RF frequency; in other words it is clearly white noise. Additional experiments showed that, under a wide variety of input pulse conditions, the measured SC exhibited a consistent dip in the RIN at the input laser wavelengths (λ_p~810 nm) and also across the Raman soliton on the infrared side of the spectrum (λ_s~1300 nm). Otherwise, no universal correlation between the RIN and the optical spectrum was observed.

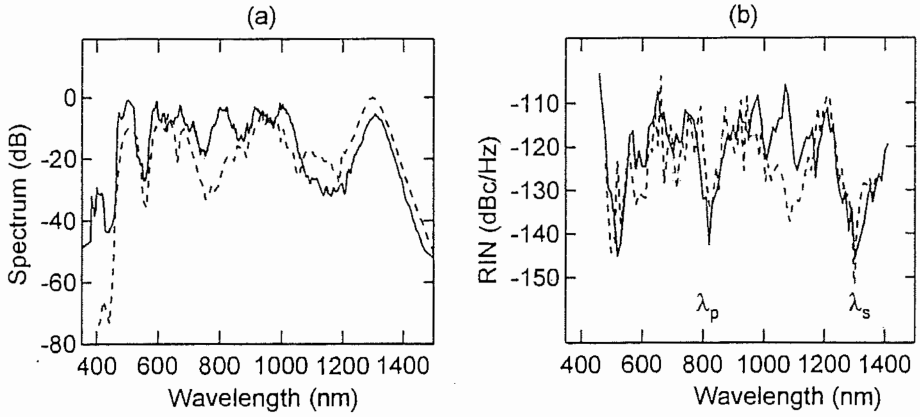

Figure 2: (a) Spectrum and (b) RIN as a function of wavelength across the SC for experiment (solid lines) and from simulations (dashed lines). λ_p and λ_s respectively indicate the input pulse and Raman soliton wavelengths.

The experimental spectral and noise characteristics of the SC were compared with the results of a generalized NLSE extended to include both shot noise on the input pulse and the effect of spontaneous Raman scattering in the fiber [8]. Multiple simulations of SC generation with different noise seeds were used to calculate the expected RIN for direct comparison with the values experimentally measured. For the experimental parameters in Figure 2, the corresponding simulation results are shown as the dashed lines, and we note good agreement between both the overall structure of the SC simulated spectra and the wavelength-dependent RIN.

Both the SC spectrum and its noise were found to depend strongly on the input pulse parameters. Although the RIN always exhibits a complicated wavelength dependence as in Fig. 2, the SC noise properties for a particular choice of input parameters can be conveniently quantified in terms of the median RIN calculated across all wavelengths for which there is sufficient optical power. For example, the triangles in Figure 3 shows experimental results measuring (a) the SC spectral width and (b) the median RIN as a function of the input pulse chirp. Note that a chirp range of 0 to ±400 fs^2 corresponds to a range of input pulse durations of 22-62 fs. We see that while the spectral width increases with decreasing pulse duration, the broadband noise increases dramatically with increasing pulse duration. With minimal chirp and the lowest pulse duration of 22 fs, the broadband noise is near-shot-noise-limited at around -130 dBc/Hz, but it increases by 30 dB as the pulse duration increases by a factor of three. These experimental results agree very well with the results of numerical simulations (shown as the circles) over the same parameter range, confirming the validity of our stochastic NLSE model of the SC generation process. Additional simulations have also revealed that the primary physical origin of the broadband noise on the spectrum is the amplification of input pulse shot noise through modulation-instability-like effects during propagation. Spontaneous Raman scattering makes a relatively minor contribution.

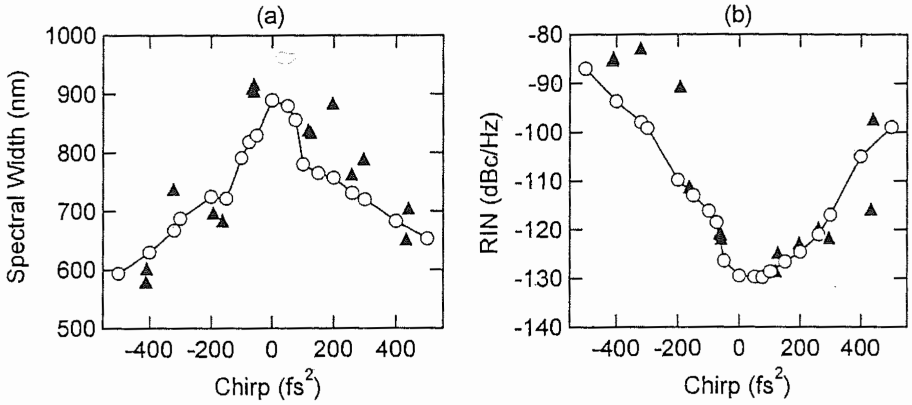

Figure 3: (a) Spectral width and (b) RIN as a function of chirp comparing experiment (triangles) and simulation (circles).

4. Conclusions

The results of the experimental and numerical study described here allow us to conclude that the measured broadband noise on the SC spectrum has its physical origin in the amplification of shot noise on the input pulse. Using chirp-free pulses of around 20 fs duration allows the generation of near-shot-noise-limited SC spanning more than an octave.

5. References

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