Measurements and simulations of noise imposed on supercontinuum generated in microstructure fiber

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Abstract: We present experimental and theoretical investigations of the highly nonlinear and broadband noise that exists on supercontinuum spectra generated from launching femtosecond Ti:Sapphire pulses into microstructure fiber.
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Extremely broad spectra, or supercontinua, are generated by launching femtosecond pulses from a Ti:Sapphire laser into highly nonlinear microstructure and tapered silica fibers [1,2]. The combination of the small effective area of the fiber and the proximity of the fiber zero-dispersion wavelength to the Ti:Sapphire wavelength leads to extreme broadening of an injected Ti:Sapphire laser pulse from an initial spectral width of 50 nm to over 1100 nm. The resulting supercontinuum yields a broadband bright light source that can be exploited for a number of applications, including optical coherence tomography [3] and frequency metrology [4]. In these applications, the signal-to-noise ratio of the supercontinuum is an important parameter but, unfortunately, noise on the generated supercontinuum can be quite high even at frequencies well beyond those associated with the technical laser noise [5, 6,7]. Similar noise has been studied in supercontinuum generation in conventional fibers, and has been attributed to the amplification of input pulse noise due to dispersive and nonlinear effects such as modulational instability [8]. In this paper we describe an experimental study of this noise superimposed on supercontinuum generation in microstructure fibers, and describe simulations using an extended stochastic nonlinear Schrödinger equation (NLSE) that are in good agreement with experiment.

Experimentally, the output of a 100 MHz Kerr-lens mode-locked Ti:Sapphire laser was first directed through a pair of double-passed fused-silica compensating prisms in order to control the laser chirp, and then focused into a microstructure fiber 15 cm long with a core diameter of 1.7 μm and zero-dispersion wavelength near 760 nm [1]. A small amount of light was split off after the compensating prisms and directed to an interferometric autocorrelator, which yielded the pulse chirp and duration. The supercontinuum output from the fiber was filtered by a grating monochromator with a passband of 8 nm and detected by a low-noise Si or InGaAs receiver, depending on the wavelength. As the grating monochromator was tuned across the supercontinuum, a RF spectrum analyzer recorded the noise at a Fourier frequency of 3 MHz. (Previous measurements showed the noise to be independent of Fourier frequency provided that it exceeds the low-frequency amplitude noise present on the laser output [6].) The top curves in Figure 1 show the measured supercontinuum spectrum and the associated relative intensity noise (RIN) as a function of wavelength for two different pulse durations, corresponding to different values of chirp imposed by the group-velocity disperison (GVD) of the prism pair. Both the supercontinuum spectral width and the RIN are seen to depend very strongly on the pulse duration and chirp; the maximum spectral broadening and minimum RIN are simultaneously observed when the chirp and pulse duration are minimized.

We also studied the spectral and noise characteristics using numerical simulations based on a stochastic NLSE that included the global dispersion from 300 to 1700 nm, higher order nonlinearity, and stimulated Raman scattering. Two noise terms were included: shot noise and spontaneous Raman noise. The spontaneous Raman noise was modeled via a stochastic Langevin source term including both intensity-dependent and spontaneous components [9]. The input pulses were assumed to have hyperbolic secant intensity profiles with a chirp appropriate to the prism compressor used in the experiment. The simulation results are shown as the bottom curves in Figure 1, and are in good agreement with experiment.

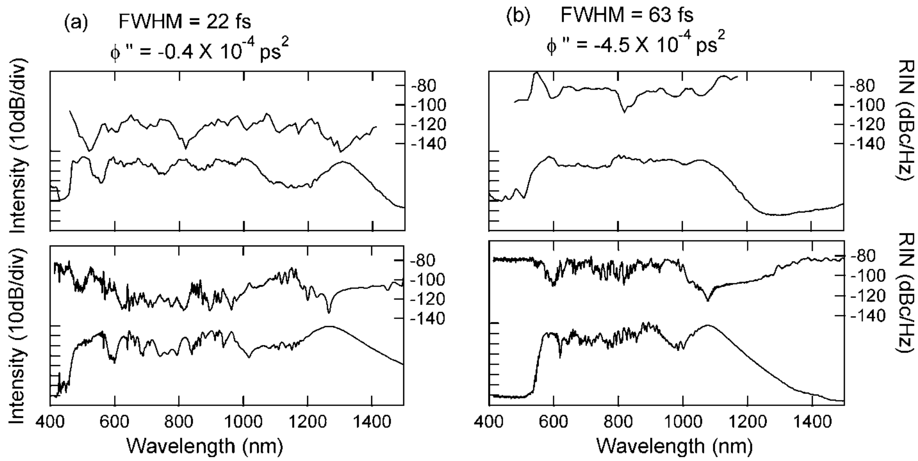

Figure 1: Top: experimental, and bottom: simulated spectra and RIN versus wavelength for two pulses with different quadratic phase shifts (φ'') and corresponding full-width half-maximum (FWHM) pulse durations.

The variation in the median RIN over a wide range of pulse chirp is shown in Figure 2, where the median RIN was calculated from the data in Figure 1 and similar data sets at other values of pulse chirp. The experimental results (open circles) are in good agreement with the results of simulations (closed circles) over this range of pulse durations. The discrepancies between simulation and experiment are attributed mainly to uncertainties in the fiber dispersion and nonlinearity parameters, which play an important role in the amplification of the noise.

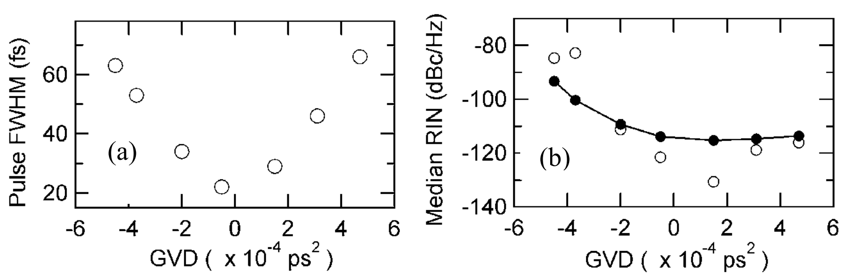

Figure 2: (a) Pulse duration and (b) RIN versus group velocity dispersion (GVD) (*i.e.* quadratic phase shift) from experiment (open circles) and simulation (closed circles).

Since the initial shot noise on the 0.8 nJ laser pulse was -172 dB/Hz, these results indicate that this noise seed has been amplified by a factor of 40 to 70 dB. Moreover, although this study has been carried out at Fourier frequencies for which the laser was shot-noise limited, the presence of any technical noise on the laser will also couple into the supercontinuum noise and will further substantially degrade the RIN. The increased understanding of the RIN gained in this work will aid in reducing noise that could limit applications of fiber-generated supercontinuum.

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