Broadband noise on supercontinuum generated in microstructure fiber*

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Abstract: The broad supercontinuum generated by pumping highly nonlinear microstructure fiber with a femtosecond laser exhibits broadband amplitude noise. We experimentally investigate this amplitude noise as a function of wavelength, input pump power, and chirp.

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1. Introduction

Extremely broad spectra, or supercontinua, can be generated by launching femtosecond pulses from a Ti:Sapphire laser into the recently developed, highly nonlinear microstructure and tapered silica fibers [1,2]. The combination of the small effective area of the fiber and the coincidence of the zero-dispersion wavelength of the fiber with the Ti:Sapphire wavelength leads to broadening of the initial ~50 nm wide Ti:Sapphire laser pulse to spectral widths of over 1100 nm. The resulting supercontinuum provides a broad, spectrally bright, short-pulse source of light that can be exploited for a number of applications, including optical coherence tomography [3] and wavelength or frequency metrology [4].

The use of the supercontinuum for frequency metrology relies on the fact that the generated spectrum is actually comprised of a series of discrete spectral lines spaced at the repetition rate of the pulsed mode-locked Ti:Sapphire laser. By locking the repetition rate of the laser to a known microwave frequency, the spacing of these spectral lines is fixed. Furthermore, by using a self-referencing technique that compares the lower-frequency component of the supercontinuum to components an octave higher in frequency, the offset of the frequency comb with respect to zero frequency can also be fixed. The end result is a stable, known frequency comb at optical wavelengths. One of the limits to the stability of this optical comb is any amplitude noise on the generated supercontinuum [5]. When the laser light that exits the fiber illuminates a photodiode, this amplitude noise appears as a noise floor below the coherent peaks of the frequency comb. The amplitude noise therefore limits the ability of the system to phase-lock the femtosecond optical comb to an optical frequency reference and to stabilize the comb offset frequency. Frequency metrologists have taken steps to avoid this noise, including running 100 MHz repetition-rate systems substantially below their maximum power levels and therefore sacrificing possible signal-to-noise ratios.

Recent work has shown that the supercontinuum spectrum is highly sensitive to the input pulse power; pulse energy changes of 1 % can dramatically alter the intensity of the spectrum [6] and lead to correspondingly large amplitude noise. One would expect this amplitude noise to be correlated with the amplitude noise spectrum of the Ti:Sapphire laser, which in turn is largely governed by the amplitude noise spectrum of the pump laser [7]. This noise falls off strongly with frequencies above a few hundred kilohertz. Below, we present measurements of a second type of amplitude noise. This amplitude noise, which has been observed previously [5], is extremely broadband in frequency, highly nonlinear in the input pump power, strongly dependent on the input pulse length or chirp, and even shows some structure as a function of wavelength.

2. Experimental Measurements

The experimental setup is shown in Figure 1. A 100 MHz Kerr-lens mode-locked Ti:Sapphire laser generates pulses centered at about 820 nm with a FWHM of 43 nm and an average power of approximately 600 mW. A pair of double-passed fused silica compensating prisms at a 120 cm spacing are used at the laser output to control the laser chirp. A small amount of light is split off after the double-passed prisms and directed to an interferometric autocorrelator, which yields the pulse chirp and duration [8,9]. The laser pulse, with adjustable chirp, is then launched into a 14 cm long microstructure fiber [1] with a core diameter of 1.7 μm and zero-dispersion wavelength near 760 nm. The output from the fiber is fiber-coupled to a grating monochromator with a passband of 10 nm. The filtered supercontinuum light is then detected by a low-noise Si or InGaAs receiver, depending on the wavelength. As the grating monochromator is tuned across the supercontinuum, the RF spectrum analyzer records both the spectrum near the 100 MHz laser repetition rate and the noise at a series of Fourier frequencies from 1 to 50 MHz, averaged over a 0.5 MHz bandwidth. In addition, a small amount of output power from the fiber is coupled into an optical spectrum analyzer to monitor the width and shape of the supercontinuum spectrum.

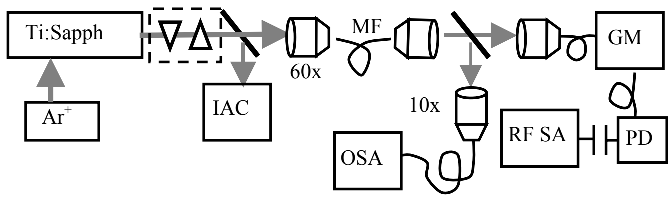

Figure 1: Schematic of experimental setup to measure spectrally resolved broadband amplitude noise on the supercontinuum. Shown are the Argon ion laser (Ar+) pumping a Kerr lens mode-locked Titanium:Sapphire laser, a double-passed prism pair, an interferometric autocorrelator (IAC), microscope objectives with x60 and x10 magnifications, microstructure fiber (MF), a grating monochromator (GM), a photodetector (PD), a RF Spectrum analyzer (RF SA), and an optical spectrum analyzer (OSA).

By adjusting the compensating prisms, we acquired data at three different pulse durations: 36 fs, 50 fs with a negative chirp, and 112 fs with a positive chirp. The spectral width of the input pulse supports a bandwidth-limited pulse of 16 fs duration, assuming an hyperbolic secant pulse envelope [10]. An example of the supercontinuum and the measured rf noise for the three different input pulse chirps is shown in Figures 2 and 3. Figure 2 demonstrates that the resulting supercontinuum changes both its width and structure with chirp. Figure 3 shows the relative intensity noise (RIN) as a function of wavelength and Fourier frequency. From these data, it is evident that the noise is broadband and largely independent of Fourier frequency. (Although at very high input powers we have observed a peak in the noise at a discrete frequency in addition to the broadband component). For comparison, the average shot noise is ~ -130 dBc/Hz. Note that there is some variation of the RIN with wavelength.

To illustrate the general dependence of the noise on input power and chirp, we have plotted the mean RIN versus the power exiting the fiber in Figure 4, calculated by averaging the RIN at each wavelength directly. The noise increases nonlinearly with laser power for a given input pulse shape. This is consistent with our observation that high-repetition-rate lasers in similar experiments exhibit much lower noise, and indicates that the peak energy of the pulse determines the RIN. However, peak pulse energy is not the only factor that contributes to the noise; interestingly, the RIN is at a minimum for the minimum input pulse duration – the same condition that gives a maximum in the spectral width. Also, the sign of the chirp appears to be important, since the 50 fs negatively chirped pulse shows more noise than the 112 fs positively chirped pulse.

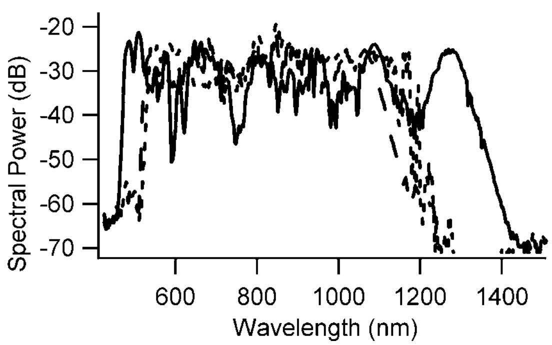

Figure 2: Supercontinuum spectra at ~95 mW output power for three different input pulse durations: 36fs (solid line), 50 fs (dotted line), and 112 fs (dashed line).

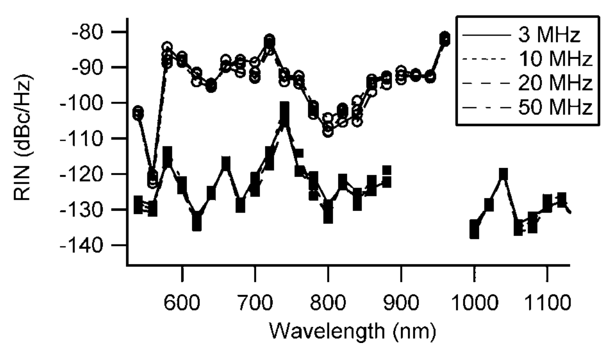

Figure 3: Corresponding RF noise for pulse durations 36 fs (squares) and 50 fs (circles).

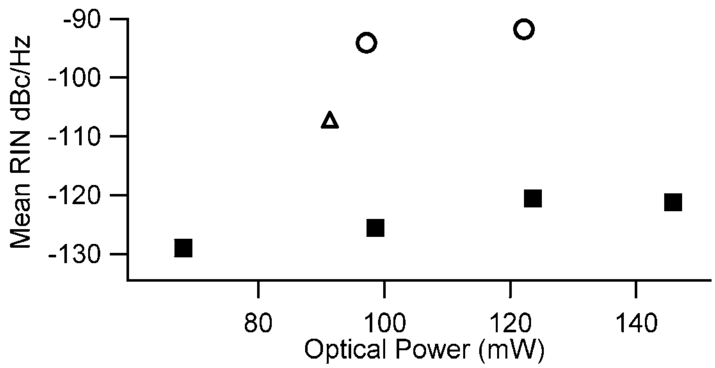

Figure 4: Mean RIN versus laser input power for 36 fs pulse duration (squares), 50 pulse duration (circles), and 112 fs pulse duration (triangles).

3. Discussion and Conclusions

The data above demonstrate the dependence of the broadband noise on power and pulse chirp; this noise can also depend on polarization and other experimental parameters that were held fixed during this experiment. Nonlinear noise has been observed previously in supercontinua of widths of a few hundred nanometers generated in conventional optical fiber and has been attributed to amplified spontaneous emission (ASE) from the source that causes a random evolution of higher-order solitons [11]; the same mechanism may be responsible for the noise observed here. The nonlinear dependence on power suggests that the peak pulse intensity determines the noise. However, the scaling of the noise with pulse duration is not consistent with this concept. In addition, while nearly unchirped pulses provide less noise than chirped pulses, unchirped pulses provide broader spectra. This can be exploited to minimize the broadband noise in metrology applications.

Acknowledgements

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