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Amplitude noise on supercontinuum generated in microstructure fiber: measurements and simulations

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Abstract: Supercontinua generated in microstructure fiber can exhibit significant excess amplitude noise. We present experimental and numerical studies of the origins of this excess noise and its dependence on the input laser pulse parameters.

Femtosecond pulses from Ti:sapphire lasers can be broadened to over an octave in frequency when launched into microstructure fiber or tapered fiber [1,2]. The supercontinuum has a number of attractive properties; it is a high-power, broad-spectrum, phase-coherent source with a single spatial mode and has led to a revolution in frequency metrology by permitting a simple and direct link between optical and microwave frequencies [3,4]. Unfortunately, it can suffer from significant amplitude noise, well in excess of shot noise. A good understanding of this excess amplitude noise is crucial for minimizing it and thereby optimizing the performance of optical clocks based on the supercontinuum.

In recent work, we have shown that the excess noise is actually comprised of two components: a broadband or white-noise component, and a low-frequency component. The low-frequency component of the amplitude noise is duplicated around each harmonic of the laser repetition rate. It results from amplification of the technical noise (*i.e.,* all noise excluding shot noise) on the input Ti:sapphire pulse, which in turn results primarily from technical noise on the pump laser [5]. In contrast, the substantial white-noise component of the supercontinuum is independent of the laser's low-frequency technical noise. It results from amplification of the quantum shot noise on the input laser pulse, and, to a lesser extent, of spontaneous Raman scattering in the fiber [6,7].

In a given experiment, the dominant source of noise can be either the low-frequency or the high-frequency component, depending on the parameters of the input laser pulse, the experimental configuration, and the choice of pump laser. Under suboptimal conditions, the excess amplitude noise can lead to fluctuations in pulse amplitude in the time-domain approaching 100%. Here, we discuss and contrast the dependencies of the two noise sources on the input laser pulse parameters. As we will show, a "quiet" pump laser and a short femtosecond pulse are critical for producing a supercontinuum with low excess amplitude noise.

We have studied the excess noise generation through both experiment and simulation. Figure 1 shows the experimental setup used to measure the amplitude noise across the supercontinuum. A mode-locked Ti:sapphire laser provides pulses with a bandwidth of ~45 nm FWHM centered at 810 nm. Pulses with variable chirp and 0.9 nJ energies are injected into a microstructure fiber 15 cm long with zero group-velocity-dispersion at 770 nm. The resulting supercontinuum is spectrally filtered by a monochromator (8 nm bandwidth) before photodetection. The resulting RF noise power is measured near the first harmonic to determine the low-frequency component, and is measured at higher frequencies (>3 MHz) to determine the broadband component of the noise. The two noise components are quantified differently. The low-frequency component is an amplified version of the technical noise already present on the input laser pulse; therefore, it is quantified in terms of an amplification factor. 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.

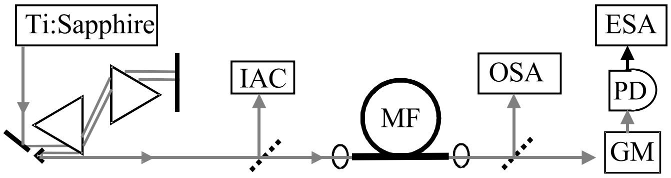

Figure 1: Experimental setup used to measure the excess amplitude noise across the supercontinuum. IAC, interferometric autocorrelator; MF, microstructure fiber; OSA, optical spectrum analyzer; GM, grating-based monochromator; PD, photodiode; ESA, electrical spectrum analyzer.

In order to simulate the noise, we developed a numerically simulation of supercontinuum generation using the generalized nonlinear Schrödinger equation (NLSE). To simulate the amplification of the low-frequency component of the input laser noise, we first determined the sensitivity of the supercontinuum spectrum to the input pulse energy and then related this sensitivity directly to the noise amplification. To simulate the broadband component of the noise, we included both shot noise on the input pulse and an added stochastic term to the NLSE that represented spontaneous Raman scattering in the fiber; multiple simulations of the supercontinuum generation with different noise seeds were then used to calculate the expected RIN.

We found reasonable agreement between experiment and simulation for different input laser pulse parameters. Both measurement and simulations demonstrate that both the low-frequency and broadband components of the noise vary dramatically with wavelength across the supercontinuum. As expected, the spectral width, the amplification of the low-frequency noise, and the broadband noise all increase exponentially with input laser pulse energy. More surprising is the dependence of the noise components on the pulse duration. While the spectral width increases with decreasing pulse duration, the broadband noise increases dramatically with increasing pulse duration. At the lowest pulse duration of ~20 fs, the broadband noise is at a reasonably low level of ~-130 dBc/Hz, but it increases by 30 dB as the pulse duration increases by a factor of three. In contrast, the amplification of the low-frequency noise, which is about 20-30 dB, is roughly independent of the pulse duration. This dramatically different behavior of the broadband and low-frequency noise components is a result of their different underlying origins. The amplification of the low-frequency component is a straightforward consequence of the sensitivity of nonlinear frequency generation to the input pulse intensity. The amplification of the input shot noise is a result of modulation instability gain that amplifies the very high (terahertz) components of shot noise during the initial evolution of the pulse in the fiber.

The low-frequency component of the noise can be reduced by reducing the amplitude noise on the input laser pulse through the use of a quieter pump laser. Unfortunately, the broadband component arises from amplification of the shot noise on the input laser pulse during the supercontinuum generation process and thus represents a fundamental limit to the supercontinuum stability. Nevertheless, this noise can be minimized by using input pulses with the shortest duration, where the spectral width of the supercontinuum is also fortuitously maximized.

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