Predicting supercontinuum pulse collisions with simulations exhibiting temporal aliasing

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Interactions between supercontinuum (SC) light pulses, produced by the propagation of rapidly sequenced picosecond pump laser pulses along a photonic crystal fiber, result in spectral broadening, which we attribute to interpulse soliton collisions. This phenomenon was measured experimentally, following our observation of spectral broadening in numerical simulations that exhibit so-called "pulse wraparound" or "temporal aliasing." This occurs in simulations with narrow time grids: as early parts of the SC pulse leave the computational time domain, they "reenter" at the beginning and so interact with later parts of the evolving SC pulse. We show that this provides an effective model to predict the experimentally observed spectral changes.

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Computer simulations based on the generalized nonlinear Schrödinger equation predict the generation of supercontinuum (SC) light in photonic crystal fiber (PCF) with remarkable accuracy [1–4]. In general, one begins by defining a laser pulse within a numerical grid and then iteratively adjusts the pulse to simulate stepwise propagation along the PCF. At least two fiber parameters must be specified in the model: group velocity dispersion (evaluated in the frequency domain) and nonlinearity (evaluated in the time domain). The algorithm thus requires Fourier transformation of the model pulse at each step [3]. Problems occur when pulses reach the edge of the transform grid. Too narrow a time grid results in overflow, that is, the modeled pulse "wraps around" itself, as shown in Fig. 1. In general, this manifestation of temporal aliasing is undesirable and is prevented by techniques such as windowing (attenuating signals near the grid edge) or zero padding (employing a wider time grid) [5]. We show in this Letter, however, that temporal aliasing can be exploited to simulate SC generation from closely spaced pump laser pulses. In simulations, interpulse soliton collisions ensuing from injection of rapidly sequenced laser pulses into PCF broaden the SC spectra. The spectral broadening is attributed to turbulent collisions of solitons and trapped dispersive waves produced by the breakup of the pump pulse [6]. A model pulse that wraps around itself (or, in practice, a pulse that collides with a second pulse in fiber) experiences a second regime of these interactions, resulting in a broader SC than if its breakup products were to propagate unperturbed. Experimental observations of closely spaced pulses reveal broadening equivalent to that of temporally aliased models.

To model SC pulse collisions, we generated sets of SC simulations using an established algorithm [4], with fiber parameters set to match a commercial PCF [7] of 20 m length, and pump laser parameters appropriate to an experimental double-pulse arrangement (Fig. 2): 1064 nm center wavelength, 500 W peak power, 5 ps pulse duration, plus noise of one random-phase photon per frequency bin. The time grid resolution was 1.2 fs. A time grid width of 320 ps contained all simulated pulses without wraparound. The histogram of the maximal soliton delay in 150 such isolated SC pulses is shown in Fig. 1(d). It is apparent that a 160 ps grid width would lead to about half of the pulse simulations exhibiting wraparound effects, whereas all pulses would do so for grid widths of 80 ps or less. Sets of 150 simulations were performed for grid widths of 80, 160, and 320 ps. The 320 ps grid predicts the spectra of isolated SC pulses. The 160 and 80 ps grids are models for the SC produced when pumping the fiber with periodic input pulses—corresponding to effective pump laser repetition rates of 6.25 or 12.5 GHz, respectively.

Experimentally, SC pulse collisions can be studied with the double pulse setup [8] shown in Fig. 2. We model the twin pulse as the sum of one isolated pulse (such as the one shown in Fig. 1(a), where the pulses do not overlap) plus one aliased pulse (such as the one shown in Fig. 1(b), where the self-interactions mimic the collisions arising from overlap with the preceding pulses). Hence, we predict the measured double-pulse SC spectrum as the sum of the mean aliased pulse spectrum (modeled with a time grid width equal to the twin pulse separation, to model interpulse interactions) and the mean isolated pulse spectrum (to account for the noninteracting edges of the pulse pair). This simple method closely predicts the spectral broadening measured in the double pulse experiments (Fig. 3).

The experimental arrangement in Fig. 2 was used to study SC spectra generated by pairs of ps pump pulses separated by between 80 and 320 ps. Laser and fiber parameters matched those used in simulations. A beam splitter and delay lines convert the 1 MHz fiber

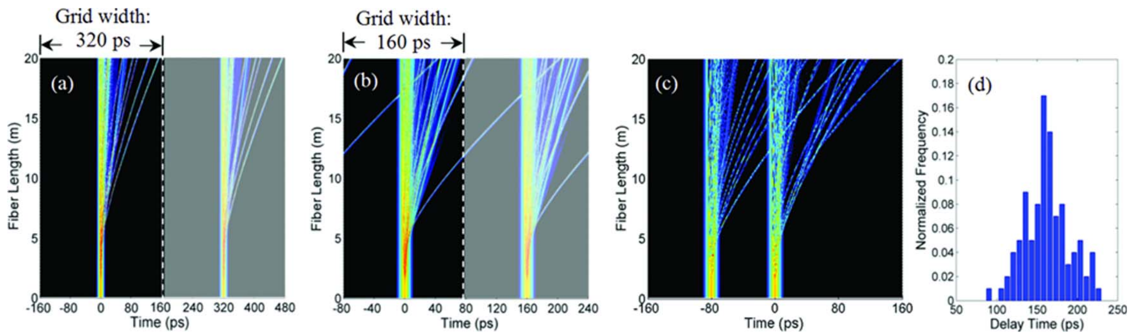

Fig. 1. (Color online) SC simulations using (a) a 320 ps time grid and (b) a 160 ps time grid, resulting in pulse wraparound and associated extrasoliton collisions after 17 m. Copies of the simulation grid (gray area) illustrate the physical interpretation of time-aliased simulations. (c) A full simulation of a pair of pulses. (d) Histogram of maximal soliton delays in 150 simulations using 320 ps grids, as depicted in (a).

laser (Fianium FemtoPower 1060) output into a source of twin pulses, which were coupled into the PCF. Similar systems have been employed to investigate soliton collisions and dispersive waves emitted during SC generation from femtosecond pulses [8,9]. The polarizer was set to allocate equal power to each arm of the beam splitter. Polarization effects were neglected in the SC simulations because the PCF is not polarization maintaining. The mean power of the fiber laser was monitored, and the standard deviation of the laser power was $<0.5\%$ throughout the experiments. Variation of pump power is thus excluded as a main source of the observed spectral changes.

Experimental double-pulse SC spectra are presented in Fig. 3(a). With 320 ps pump–pulse separation, the SC pulses were found not to interact. Blocking the light path in one delay line halved the output power without affecting the observed spectral shape. However, at 80 ps separation, there is a pronounced spectral broadening at both spectral edges, with a total broadening of about 25 nm compared with the noninteracting case. The aliased simulations shown in Figs. 3(b) and 3(c) predict this amount of broadening and also match closely with the observed changes in spectral shape. The explanation

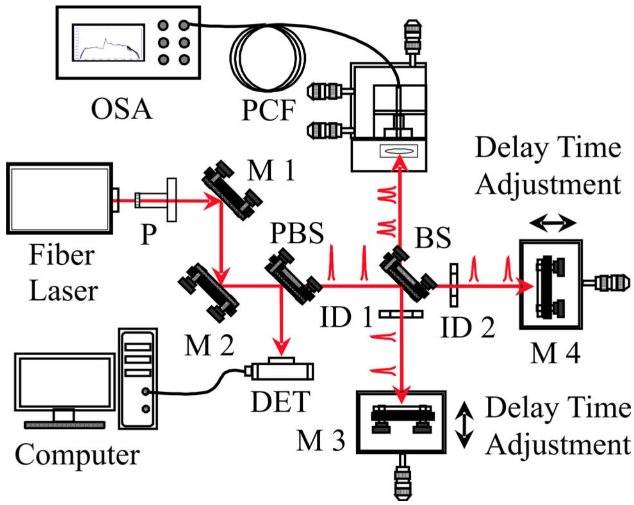

Fig. 2. (Color online) Experimental setup for double pump-pulse SC generation: P, polarizer; M, mirror; ID, iris diaphragm; BS, 50% beam splitter; PBS, 8% pellicle beam splitter; DET, light detector; and OSA, optical spectrum analyzer.

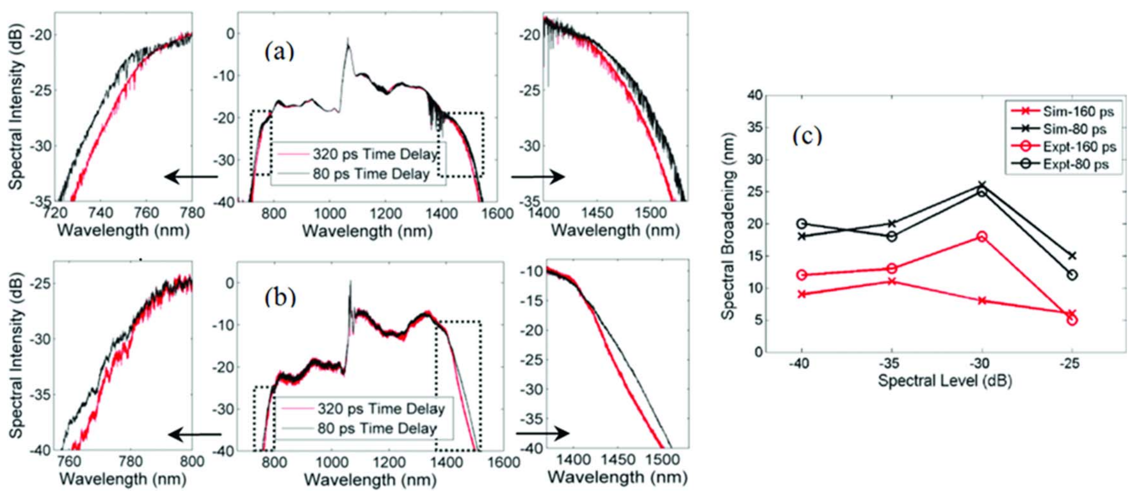

Fig. 3. (Color online) (a) Experimental and (b) simulated double input pulse SC spectra. (c) The spectral broadening of pulse pairs at initial separations of 160 and 80 ps is compared with effectively independent pulses at 320 ps separation, for experimental measurements and time-aliased predictions. The experimental spectral features around 1350 to 1400 nm are due to ambient water vapor absorption.

for the broadening is that additional redshift accrues to those maximally time-lagging solitons that collide with the body of a second SC pulse, and dispersive waves trapped by these solitons are then also shifted to shorter wavelengths. Enhancing this process might be of interest in the production of novel blue light sources for spectroscopic use [10–13].

The simulations presented encapsulate the physics of SC pulse collisions, within some limits, as follows. The time-aliased simulations assume identical random noise (which models spontaneous effects) in each of the paired pulses. This is a physically unrealistic assumption, but, as evident from Fig. 3, it does not detract from producing accurate spectral predictions. In fact, the noise on the experimental pulse pairs is probably dominated by technical noise from the laser, which should be identical for each twin, leading to experimental behavior close to the case of aliased simulations. A set of 30 simulations containing pulse pairs with nonidentical noise and 80 ps separation were performed using a wide time grid: this method also predicts spectral broadening in the range of 10–50 nm and supports the notion of interpulse soliton collisions leading to broader SC spectra. However, it is computationally intractable to generate large sets of simulations and thus to obtain an accurate average when both wide time grids are required to contain the pair, and fine time resolution is required for physical accuracy. The interesting topic of modeling ultra-high-repetition-rate SC sources will benefit from increasing computer capabilities. Another limit of numerical SC simulations is that, from Fig. 3, one recognizes a discrepancy between the absolute width of the predicted SC spectra compared with experimental spectra, while the relative broadening is accurately predicted. The former (absolute width) arises from a sensitive dependence on parameters such as fiber dispersion and input pulse shape [14], which were not available to sufficient accuracy. The latter (relative broadening), however, is precisely accounted for by the time-aliased model.

In conclusion, temporal aliasing in SC pulse simulations can be used for predictions of colliding SC pulse envelopes. Twin-pulse SC generation with short time delays exhibit broadening at both spectral edges compared with isolated SC pulses, attributed to collisions between time-lagging solitons and the delayed pulse. The amount of spectral broadening (about 25 nm in this case) was accurately predicted to within a few nanometers by time-aliased models. The predictions can also be extended to multiple pulse sequences, offering significant reductions in computational cost.

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