Spectral interference measurement of nonlinear pulse propagation dynamics in optical fibers

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Ultrafast pulse shaping and ultrafast pulse spectral phase-retrieval techniques are used in the spectral interference measurement of nonlinear pulse propagation dynamics in dispersion-shifted optical fiber. Nonlinear responses in both amplitude profile and phase profile of the pulses at zero-dispersion wavelength as well as at nonzero-dispersion wavelength are directly measured. A numerical simulation that uses a third-oder-dispersion-included nonlinear Schrödinger equation gives excellent agreement with the experimental data. © 2000 Optical Society of America

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Nonlinear pulse propagation effects are important in many communications architectures. The onset of nonlinearity generally induces undesirable effects such as four-wave mixing, but at somewhat higher powers nonlinearity can provide pulse stabilization in the form of soliton generation.[1] Whereas amplitude changes that result from nonlinear interactions are routinely measured, the phase changes that are induced by nonlinear effects also contain important information, and in many cases the phase profile would provide a more sensitive measure of the dynamics. However, this profile is usually not attainable experimentally because of difficulties in measuring the phase of an optical field. Spectral interference[2] has been used to measure the accumulated (overall) nonlinear phase shift by propagation of both the reference and the signal through the fiber and attenuation of the reference.[3] The power dependence of the nonlinear phase shift has been studied at two different wavelengths near the zero-dispersion wavelength of a dispersion-shifted fiber.[3] However, recent developments in ultrafast pulse shaping and detection technologies,[4–9] particularly spectral phase-profile-retrieval methods, which work with weak pulses,[6–9] suggest that a more detailed characterization is now possible.

We use our ultrafast laser pulse shaping technology at 1550 nm (Ref. 4) to prepare ~1-ps pulses, which are subsequently transmitted through 4 km of dispersion-shifted optical fiber (DS fiber; SMF/DS from Corning, Inc.) with launch power just above the level that will induce significant nonlinear distortions. Pulses centered at several wavelengths around the zero-dispersion wavelength of the DS fiber are studied, and the nonlinear response in both amplitude profile and phase profile is observed. In particular, the nonlinear behavior of the pulse propagation at the zero-dispersion wavelength is studied both experimentally and by numerical simulation. The amplitude response is also consistent with previous results by other authors[1]; here the nonlinear phase profile is retrieved directly for the first time to our knowledge.

Experimentally, as shown in the inset in Fig. 1, a phase-coherent delay is generated between a strong pulse and a weak pulse simply by use of a nonwedged beam splitter. The idea is to have the strong pulse experience nonlinear response, while the weak pulse experiences essentially only linear response. Spectral interference[2,3,9] between these two pulses therefore contains the information about the nonlinear response in both amplitude and phase. In our case, the weak pulse trails the strong pulse, but the delay between the two pulses is large enough (16 ps) to prevent any temporal overlap (so the nonlinear effects induced by the strong pulse will not affect the weak pulse). In a material or system that has a slow recovery time (such as a semiconductor optical amplifier), one can choose the weak pulse to lead the strong pulse by positioning the beam splitter in either a front surface reflection or a back surface reflection configuration.

The weak pulse sees only linear response; consequently, no new optical frequencies are generated, and

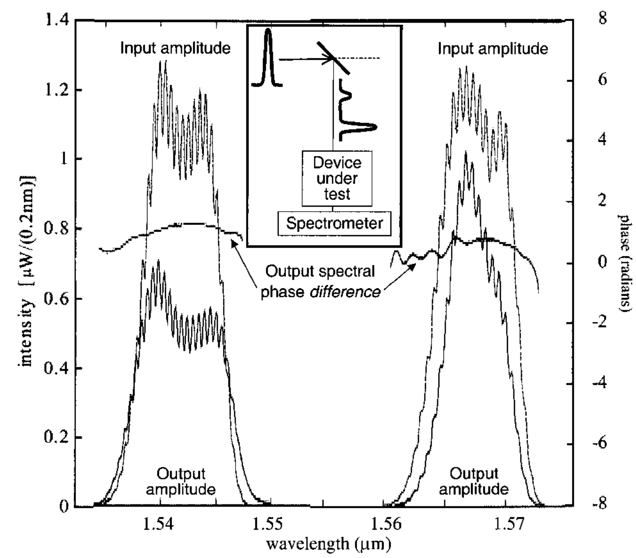

Fig. 1. Pulse spectra before and after the 4-km DS fiber transmission and retrieved nonlinear phase responses. The pulses are centered at wavelengths of 1542 and 1567 nm (two separate experiments are shown), on either side of the zero-dispersion wavelength of 1550 nm. Inset, a phase-coherently delayed pair of a strong pulse and a weak pulse can be generated simply by use of a nonwedged beam splitter.

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the pulse has essentially the same intensity spectrum as the input pulse. The phase difference between the weak pulse and the strong pulse as a result of the nonlinear dynamics (in a 4-km DS fiber here) can be retrieved by a phase-retrieving method similar to that which is detailed in Ref. 9. Essentially, the collected intensity spectrum is first Fourier transformed. Because two pulses are displaced in time by ~16 ps, the intensity spectrum after Fourier transformation becomes a time series with one zero-delayed component and two nonzero-delayed components. Either the positive or the negative nonzero-delayed component can be used to retrieve the phase difference between the interfering pulses, as follows. One of the nonzero-delayed components is numerically filtered out and then inversely Fourier transformed, and finally the phase argument is retrieved. According to Ref. 9, this phase argument is the phase difference between those two interfering pulses. The result is thus the phase difference between the weak and the strong pulses, which is induced only by the nonlinear dynamics. The retrieved phase is meaningful only in the spectral range of the input pulse, because only in this spectral range does interference between the unchanged weak pulse and the distorted strong pulse occur.

The input pulse is originally generated from a fiber-ring mode-locked laser (ErF, from CLARK-MXR, Inc.) and is subsequently shaped by an ultrafast acousto-optic pulse shaper.[4] The pulse shaper essentially imposes a narrow (~8-nm FWHM) bandpass filter that transmits optical frequencies in a selected range; therefore a wide tuning range for the center wavelength is attainable with a single source. Only amplitude modulation is imposed on the original chirp-free pulses, generating pulses that are also chirp free and ~1 ps long in time. The input signal level is ~30-dBm (1-μW) average power. The sensitivity used in the measurements shown here is 73-pW (−71.4-dBm) average power. The resolution bandwidth is 0.2 nm, and the duty cycle ratio of the pulse train is $\sim 2.7 \times 10^4$. This gives a pulse peak power of ~1-W and a signal-to-noise ratio of ~41-dB. The weak pulse intensity is ~2% of the strong pulse intensity (−17 dB). Thus the interference fringes should have a signal-to-noise ratio of roughly (41−17) = −24 dB for both spectra.

Figure 1 shows pulse spectra before and after the 4-km DS fiber transmission, including the retrieved nonlinear phase responses across the spectrum. The pulses are centered at wavelengths of 1542 and 1567 nm (two separate experiments are shown), on either side of the zero-dispersion wavelength of 1550 nm (where the group-velocity dispersion parameter D is approximately zero). For the DS fiber that we used here, the dispersion slope S is estimated to be 0.085 (ps/nm^2)/km. The longer-wavelength region has positive D [D is ~+1.45 (ps/nm)/km at 1567 nm] and is therefore the negative dispersion region where soliton action may occur. The lower wavelength region has negative D [D is ~−0.68 (ps/nm)/km at 1542 nm] and is therefore the positive dispersion region, for which coupling between self-phase modulation (SPM) and dispersion can broaden the pulse quickly.[1] The oscillations on the input and output spectra simply reflect the spectral interference between the weak and the strong pulses. Note that a small, fairly uniform positive phase shift is observed in both cases (the maxima of the input spectral oscillations do not exactly coincide with the maxima of the output spectral oscillations). With either negative or positive dispersion, the pulse rapidly becomes chirped as it propagates through the fiber, so the amplitude decreases rapidly. The main effect of the nonlinearity is a nearly wavelength-independent shift for the pulse.

Near the zero-dispersion wavelength of 1550 nm (Figs. 2 and 3) we see splitting of the pulse spectrum. This nonlinear behavior characteristic is typical when β_2 equals zero and β_3 dominates the dispersion.[1] The retrieved spectral nonlinear phase profile for this 1550-nm pulse also shows the effect of the nonlinear dynamics that results from coupling between SPM and dispersion. This nonlinear phase profile

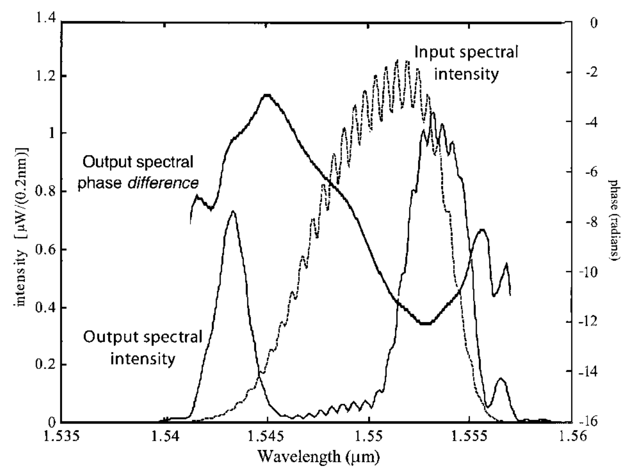

Fig. 2. Pulse spectra before and after the 4-km DS fiber transmission and the retrieved nonlinear phase profile for pulses centered at the zero-dispersion wavelength of 1550 nm (where the group-velocity dispersion parameter D is approximately zero). The splitting of the pulse spectrum is the characteristic response to the coupling between the third-order dispersion and the SPM in the fiber.

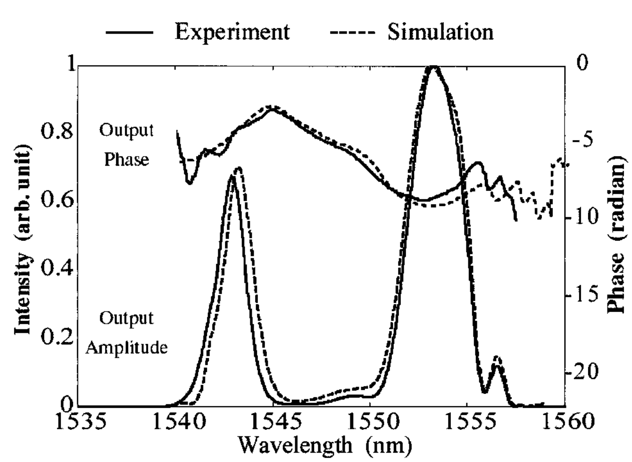

Fig. 3. Pulse propagation simulation at the zero-dispersion wavelength of the fiber. The simulation results are shown along with the experimental results for comparison. The beats in the spectra are removed by gating away of the weak pulse numerically. The agreement is excellent.

contains much more information than the mere overall nonlinear phase shift that was measured previously.[3] For example, the cubic and parabolic phase structures with opposite signs for the central and two wing portions (respectively) of the pulse spectrum are evident in Fig. 2.

Spectra centered at other wavelengths are also recorded, and nonlinear phase profiles are retrieved. It was found that approximately 5 nm away from the zero-dispersion wavelength (1550 nm here) one starts to see a wavelength-dependent nonlinear phase shift.

The effects of both SPM and dispersion can be taken into account by the standard split-step fast Fourier transform method for the nonlinear Schrödinger equation in the optical fiber.[1] The third-order dispersion effect has to be included in the nonlinear Schrödinger equation for this 1550-nm pulse because the center wavelength of the pulse is almost at the zero-dispersion wavelength. Higher-order dispersions and other nonlinear effects, such as the intrapulse stimulated Raman effect, can be neglected here because of the moderate bandwidth associated with the shaped pulses that are launched into the optical fiber. The simulation results are shown in Fig. 3, along with the experimental results for comparison. Here we remove beats in the spectra by gating away the weak pulse numerically. The agreement is excellent when one takes into account that exact values for the fiber parameters is not available. Using interation algorithms to fit experimental results by tuning fiber parameters should promise a better fit and measurement of fiber parameters with greater precision.

In summary, this study demonstrates a new powerful and easy-to-apply technique with which to study nonlinear response in both amplitude and phase. The technique is also applicable to other nonlinear systems, such as semiconductor and wavelguide devices. In general, if the input pulse has a known amplitude and phase profile, nonlinear as well as linear characteristics of the system under test can be retrieved. On the other hand, if the nonlinear system has a known response, a full characterization of the input pulse—in both amplitude and phase—is achievable with the help of similar interative algorithms that are used in the frequency-resolved optical gating pulse characterization method.[5]

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