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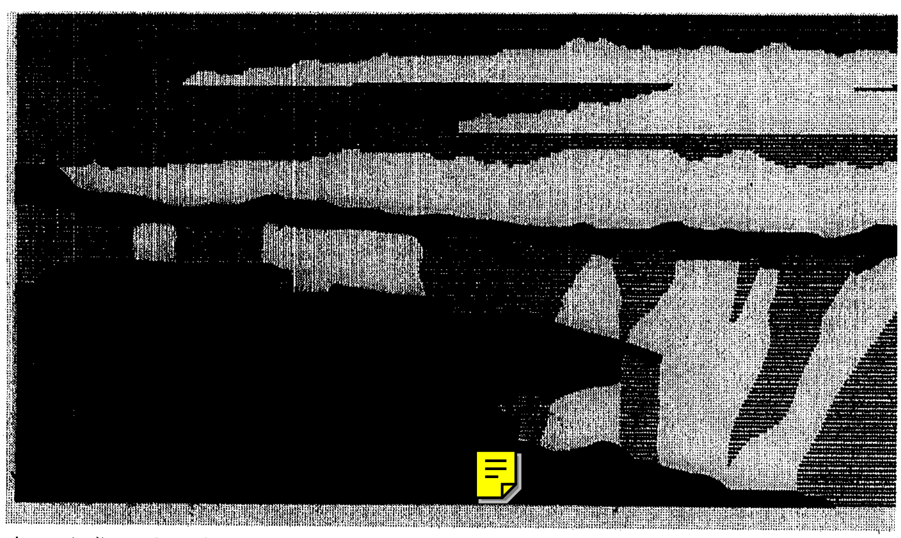

Modeling Femtosecond Pulse Propagation in Optical Fibers

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Abstract:

Femtosecond pulse propagation in optical fibers requires consideration of higher-order nonlinear effects when implementing the non-linear Schroedinger equation. We show excellent agreement of our model with experimental results both for the temporal and phase features of the pulses.

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Ultrafast pulse propagation in optical fibers presents a number of challenges given the effect of nonlinearities which become important on such a short time scale. The modeling of femtosecond pulse propagation becomes, consequently, a harder task which has to account for all these effects. In this work, we have included higher order corrections in the non-linear Schroedinger equation and compared the numerical simulation results with experimental data. Our work, besides taking into account the temporal evolution of the pulse, keeps into account also the phase behavior of the electric field, which we compare with experimental results obtained with Frequency Resolved Optical Gating [1]. We also account for self-frequency shift of the pulse and obtain excellent agreement with the experimental results on the Raman shift.

We consider a model based on the lossless Nonlinear Schroedinger Equation (NLSE)

$$\partial A/\partial Z + i/2\, \beta_2\, \partial^2 A/\partial T^2 = i\, \gamma |A|^2 A \qquad (1)$$

to describe the pulse propagation. Given the distinctively short pulse width, we must take into account intensity dependent terms such as the third order dispersion and the delayed Raman response. With the addition of fiber loss the equation becomes:

$$\partial A/\partial Z + \alpha/2\, A + i/2\, \beta_2\, \partial^2 A/\partial T^2 - 1/6\, \beta_3\, \partial^3 A/\partial T^3 = i\, \gamma \left(|A|^2 A - T_R\, A\, \partial |A|^2/\partial T\right) \qquad (2)$$

where A represents the pulse envelope, Z is the distance in Km, T is time in femtoseconds, α is the loss coefficient, β_2 represents the second order dispersion, β_3 represents the third-order dipersion, γ represents the nonlinear term and T_R is the delayed Raman response.

To evaluate the derived equation to the physical conditions of the experiment, we further transform equation (2) to a dimensionless equation by using as input parameters the values obtained experimentally from the reconstructed FROG traces. By transforming (2) $\tilde{A}=A/(P_{peak})^{1/2}$, $t = T/T_{FWHM}$, $z = Z/Z_0$.

The characteristic distances for dispersion, nonlinear effects Raman and losses give a measure of the time it takes for these effects to influence pulse propagation. These quantities are defined as [2]

$$Z_{Disp2}=2T^2_{FWHM}/\beta_2, \quad Z_{Disp3} = 6T^3_{FWHM}/\beta_3, \quad Z_{NL} = 1/(\gamma P_{peak}),$$
$$Z_{Raman}= (T_{FWHM}/T_R)\, 1/(\gamma P_{peak}), \quad Z_{Loss}=2/\alpha.$$

Typically, for an initial pulse having a duration of 170 fs, and an average power of 45 mW, the characteristic parameters are Z_{Disp2}=2.83 $\cdot 10^{-3}$ Km, Z_{Disp3} = 2.86 $\cdot 10^{-2}$ Km, Z_{NL} = 2.95 $\cdot 10^{-4}$ Km, Z_{Raman}= 3.35 $\cdot 10^{-2}$ Km, Z_{Loss}=22.86 Km.

The experimental approach is briefly outlined as follows: pulses having duration τ~170 fs generated by an OPO tuned to λ= 1.55 μm (E=3.5 nJ at 80 MHz) are attenuated and coupled into a link of single-mode optical fiber (Corning SMF-28). These pulses exhibit a slight linear chirp. The output from the fiber is sent to a single-shot SHG-FROG arrangement [3]. The pulse propagation can be examined and followed with the cutback method. The pulse energies are carefully varied before being launched into a fixed-length segment of fiber and FROG traces are correspondingly detected. The fiber is then cut (10 m per slice for the present experiments) and the process repeated. This procedure allows (1) an energy-dependent analysis of the propagation at fixed fiber lengths and (2) the characterization of the propagation of the pulse for a fixed energy through the length of the fiber.

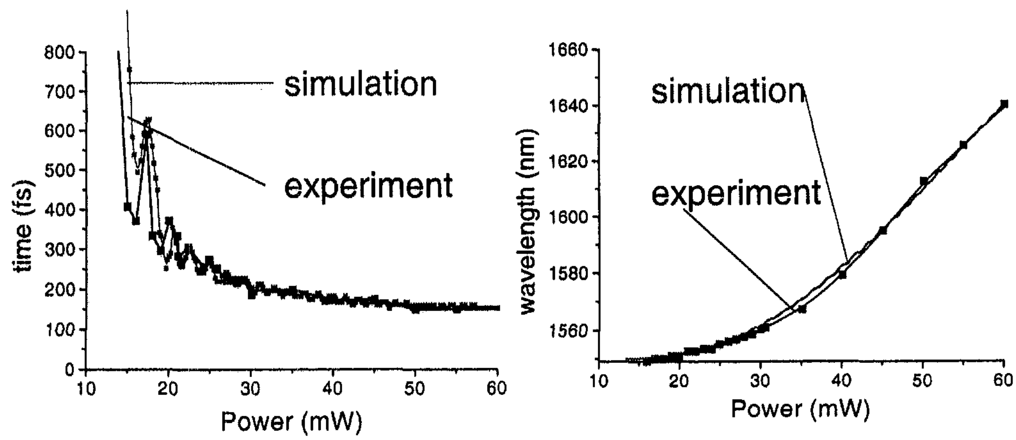

Figure1- Pulsewidth variation as a function of power (left) and Raman self-frequency shift (right) for a t=170 fs pulse propagating through Z=40 m of single mode fiber. The simulation results track the experimental data in both cases.

The results of the characterization of the propagation of the pulse and the comparison with the NLSE calculations are illustrated in figures 1 and 2. Figure 1 shows the evolution of the pulse duration for increasing power and the Raman shift in a fixed segment of fiber having a length of Z=40 meters. The agreement between simulation and the experimental results is excellent, especially for the pulse duration evolution, where the model closely tracks the pulsewidth oscillations that are typically observed when a chirped pulse is evolving towards a near-solitonic state [4,5]. Further attention is dedicated to the electric field behavior of the pulses, given the phase sensitive detection capacity of FROG. The results of these simulations are illustrated in figure 2. In this case, a comparison is performed between the experimentally observed phases and the calculated ones for increasing pulse power values in the Z=40m case. Again, the experimental results and the calculated ones are in good agreement. This is especially notable, given that the pulse is undergoing a spectral shift on top of experiencing temporal oscillations. The modified NLSE is capable of tracking the phase variation while the Raman effect is causing the pulse to self-frequency shift.

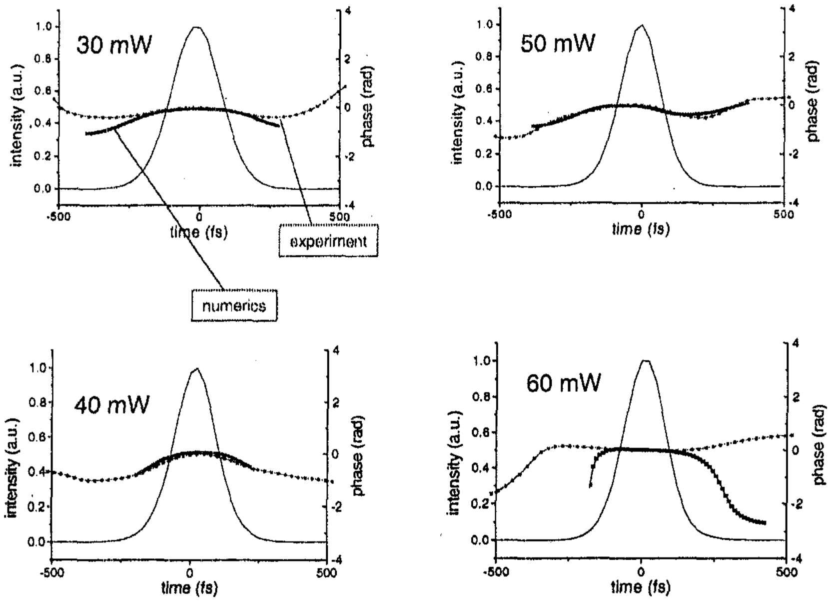

Figure 2- Experimentally recovered FROG traces at the output of a Z=40 meter segment of single mode fiber for increasing power and calculated phase behavior from the NLSE. The calculated phase follows the experimentally observed one over the central portion of the pulse. The flat phase observed for the P=60 mW case is indicative of a self-frequency shifted soliton.

In conclusion, we have shown that a perturbed NLSE approach describes very efficiently the behavior of femtosecond pulse propagation in optical fibers. Extension of this model to cover a wider spectral range promises to be of great utility for the simulation of structures presenting higher nonlinear properties such as photonic crystal fibers.

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