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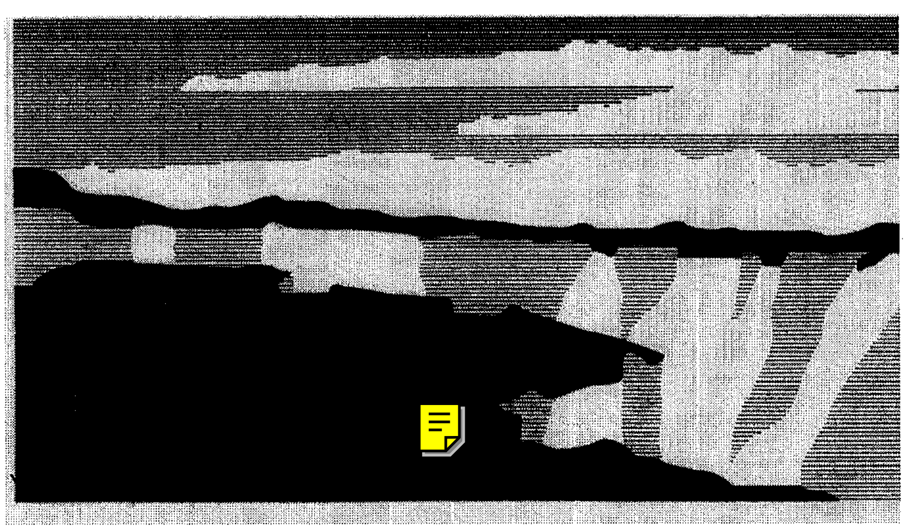

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Abstract:

We present an adaptive control loop that synthesizes fs-pulses that are self-correcting for higher order nonlinear effects when launched in a conventional single-mode fiber, nearly preserving the initial (t~200 fs) pulse duration.

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Nonlinear optical effects are among the dominant factors in determining the limits of information carrying capacity of fiber transmission systems [1]. Moving away from the more traditional picosecond (10-20 ps) pulse regime, these effects become extremely hard to defeat or even predict, and present fundamental obstacles for the propagation of femtosecond pulses of detectable energy in single-mode optical fibers, inducing severe pulse distortion even after a very short propagation distance. We show here that adaptive pulse preshaping could overcome these limitations by synthesizing pulses that are self-correcting for higher order nonlinear effects when launched in the fiber. In the traditional low-power picosecond regime, chromatic dispersion (or group velocity dispersion) causes the optical pulse to broaden in time as it propagates through the fiber. In the anomalous dispersion region (for wavelengths λ>1.3 μm in standard fibers) suitable powers of the optical pulses provide a balance between nonlinear self phase modulation and chromatic dispersion, leading to the formation of optical solitons [2,3]. Femtosecond pulses, however, have sufficient intensity to excite the fiber material well beyond the linear regime. Effects such as the random variation of the fiber dispersion along the fiber, polarization-mode dispersion, third-order dispersion, Raman and high-order nonlinear effects, in addition to linear dispersion and the intensity dependence of the index of refraction all contribute to the temporal distortion of the original pulse as it propagates through the fiber.

In our experiment, these effects are defeated through the use of an adaptive control feedback loop that acts on the spectral phase of the femtosecond optical pulses launched in the fiber. The adaptive approach, first proposed by Rabitz [4], involves the design of light fields, through feedback control, with femtosecond temporal features, guided by a parameter of interest generated by the experiment at hand. The first demonstrations of this method have shown efficiency and power [5]. Pulse shapers in conjunction with dispersion compensation has been successfully employed to compensate for higher order dispersion terms for linear pulse propagation over long lengths of fiber [6,7]. In the present case, we operate in a strongly nonlinear regime relying uniquely on the adaptive control loop to find an optimized ultrashort pulse shape which, once launched, will compensate for the pulse distortion that takes place as the pulses propagate through the optical fiber. In the experiment, ultrashort pulses generated by an optical parametric oscillator (λ=1.55 μm, 80 MHz) are shaped in a zero-dispersion stretcher [8] by a computer controlled Spatial-Light Modulator. This device provides phase-only filtering on the pulses. Of the 128 pixels only the central 60 are used due to the spatial extent of the dispersed spectrum in the pulse shaper. After being shaped, the pulses are coupled into an optical fiber link . The output pulse after propagation in the fiber is then sent to a second harmonic (SH) crystal, and the SH-radiation generated by the pulse acts as the control parameter for the adaptive feedback loop. As shorter pulses exit the fiber, their peak intensity will increase, leading to the generation of a stronger SH signal. The latter is sent to a computer algorithm which modifies the spectral phase in the pulse shaper until a maximum value for the SH signal is obtained indicating that the pulse propagation has been optimized. The feedback loop relies on a Genetic Algorithm (GA) search that, after acquiring data from the output of the fiber, updates the pulse shaper at the fiber input to maximize the SH-signal. Practically, the computer-controlled algorithm generates a *random* initial "population" of spectral phase filters and no particular pulse shape is assumed. These filters are sent to the SLM and the shaped pulses, resulting from each filter, are propagated through the fiber. The corresponding output pulses are evaluated according to a "fitness" function -the magnitude of the SH-signal. The pulses which have the highest peak intensity (i.e. shortest duration) at the fiber output will generate the highest SH-signal and are considered the "fittest". The latter are selected, thereby extracting from the initial filter "population" a new group of filters. This selected group is used as a seed to generate a new "population" of filters through crossover and mutation operators, and the process is iterated until the pulse propagation has been optimized. For the detection and characterization of the input and output from the fiber, we employ a single-shot Frequency-Resolved Optical Gating (FROG) arrangement[8,9].

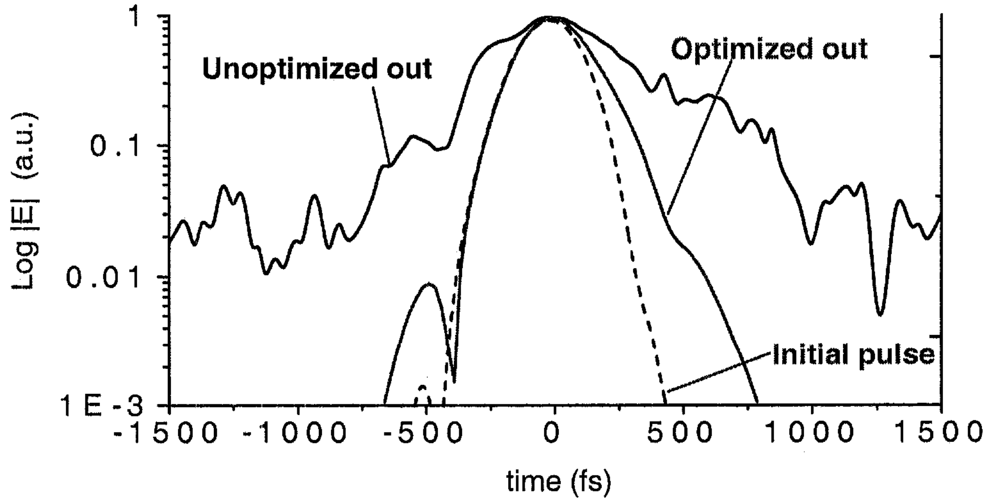

Figure 1 - Comparison of the initial unshaped pulse (dashed line), output from the unshaped pulse and output from the optimally shaped pulse propagation, plotted on a logarithmic scale covering of the dynamic range of the measurement. Suppression of the wing structure is particularly evident in this case.

An initially unshaped pulse of average power P=25 mW and duration of 204 fs (i.e. peak power in excess of 1 kW) is coupled into a conventional (Corning SMF-28) 10-meter single-mode optical fiber segment. Typically, two parameters, the dispersion length L_D and the nonlinear length L_{NL}, provide the scales over which dispersive and nonlinear effects become important for pulse evolution in fibers [3,10]. For the pulse and fiber parameters employed, the dispersion length $L_D = \tau_0^2/|\beta_2|$ is equal to ~2 m, whereas the nonlinear length $L_{NL}=1/(\gamma P_0)$ is ~20 cm, where τ_0 and P_0 are the initial pulsewidth and peak power, β_2 is the group velocity dispersion parameter and γ is the nonlinearity coefficient ($n_2\omega_0/cA_{eff}$). The ratio $L_D/L_{NL}=10$ insures that the pulse distortion is governed mostly by nonlinear effects. The output resulting from the unshaped pulse propagation is temporally broadened (τ = 352 fs FWHM in the central peak, with features extending out to nearly 1 ps) and has become distorted compared to the initial pulse. The effect of higher-order nonlinearities are evidenced both in the asymmetric broadening of the pulse and in the structure present in the wings of the pulse.

The output pulse resulting from the launch of the optimized input shape found by the control loop, has a time duration of 213 fs, with a noticeably smoother phase structure. The comparison is shown in figure 1. The structure of the unoptimized pulse is substantial throughout its temporal profile. The optimized output pulse reveals, in contrast, no detectable wing structure over the same range, and a pulse shape approaching that of the original unshaped input pulse, especially on the leading edge.

Analysis of the temporal phase functions of the shaped and unshaped pulses reveals a strong compensation effect on the cubic and quartic phase terms, identifying these nonlinearities as the dominant contributions to the distortion of the propagating pulse.

These results demonstrate the feasibility of fiber delivery of energetic ultrashort pulses defeating the nonlinear propagation effects by appropriate preshaping of the input pulse through linear filtering combined with adaptive control. The system is quite robust and is independent of the initial pulse shape and its energy, although still limited by the update time and reorientation of the liquid crystals in the SLM, which hinders real-time operation. Also, as the fiber distances grow, the overall precompensation required will become more challenging, although theoretical demonstration of compensation with pulse shaping has been shown over 0.1 Km [11]. From an applied point of view, the concept of precompensation promises to be a powerful approach for future incarnations of photonic networks. The technique provides a solution that advantageously harnesses the same nonlinearities that are regarded as a serious limiting factor in the overall network capacity, enabling the possibility of using much shorter and powerful pulses as carriers of data.

More generally, extensions of the method to various fiber types and lengths in conjunction with different pulses and wavelengths can be foreseen as an important development for the delivery of ultrashort pulses for various applications in the sciences where remote delivery of reasonably powerful ultrashort pulses is needed. The choice of more refined decision criteria that are not focused on the delivery of the shortest pulse possible, can provide the delivery of shaped ultrafast pulses, further extending the ability to control physical processes on the ultrafast time scale.

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