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Rapid communication

Femtosecond pulse shaping by an evolutionary algorithm with feedback

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Abstract. We report on computer controlled compression of femtosecond laser pulses using a programmable liquid crystal spatial light modulator which is feedback-controlled by an evolutionary algorithm. This algorithm generates the optimal laser field on the basis of feedback from the experiment by optimizing the laser pulse iteratively. Without knowledge of the (chirped) input pulses, the experimental signal (second harmonic light/SHG) is maximized by the algorithm, thus resulting in fully compressed pulses. This method only makes use of the experiment's response (SHG signal) on the formed pulses. No other parameters need to be considered. This approach leads to many experimental applications in all fields of optics and ultrafast spectroscopy where particularly shaped pulses are advantageous.

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With the onset of femtosecond laser technology a fascinating field of applications opened up. Femtochemistry, as well as medical surgery, two-photon microscopy, micromachining, opto-communications, and other fields, already benefit from the feasibility of controlling both the intensity profile $I(t)$ and the phase $\phi(t)$ of spectrally broad pulses. There is rapid progress in the development of optical devices which help to form the temporal and spectral shape of ultrashort pulses. Pioneering work in tailoring femtosecond laser pulses was done by Weiner and coworkers [1, 2]. The programmable pulse shaper is based on a Fourier transform technique where a liquid crystal spatial light modulator (LC-SLM) linearly filters the spectral components of the laser pulses in the frequency domain [3–5]. Other methods, using an acousto-optic modulator (AOM) instead of a liquid crystal display (LCD) but implying a lower energy throughput, are also employed [6, 7].

Particularly, the quantum control of chemical reactions [8, 9] benefits from these pulse shaping techniques [10]. Initial ideas involving tailored pulses focused on the prediction of special electric fields necessary to produce a specific experimental output. But on the one hand, these calculations can be done for simple systems only, and on the other hand, the subsequent generation of the calculated pulse shapes is still an experimental challenge. For complex molecules, for instance, this approach fails completely because often molecular potential energy surfaces are not known accurately enough. Therefore Rabitz and coworkers suggested to use an evolutionary algorithm directly including an experimental parameter as a feedback [11, 12]. With this method the system itself should find the optimized laser field by varying and improving the laser pulse iteratively.

We have realized this kind of feedback optimization experimentally using the example of chirped femtosecond laser pulses. In principle, without any prior knowledge of their intensity or phase profile, temporally broadened input pulses are recompressed with a pulse shaping apparatus. As a feedback, we record the non-resonant second harmonic generation (SHG) efficiency of the output pulse. An automation is achieved in the sense that an evolutionary computer algorithm addresses the pulse shaper, monitors the response of the system, and subsequently selects the optimized laser pulses.

Another approach, using a genetic algorithm and an AOM with feedback, was recently reported by the Wilson group [13]. They optimized the electronic population transfer in a dye molecule.

1 Experimental setup

We use a home-built Ti:Sapphire oscillator to generate 60 fs pulses at a center wavelength of 800 nm with an averaged output power of 300 mW and a repetition rate of 80 MHz. The beam is directed through a 150 mm SF10-rod (see Fig. 1), which results in dominant second order group velocity dispersion (GVD) and therefore in temporally broadened pulses of about 1.2 ps duration. A pulse shaper is used to recompress the pulses with the aid of an evolutionary algorithm. We take the SHG signal produced in a 100 μm BBO crystal as feedback for the controlling computer program. The shorter the pulses are, the higher is the SHG efficiency and hence the detected signal.

The pulse shaper works with a Fourier transform technique on the frequency components of the input pulse. It is set up as a zero dispersion compressor [14] using two holograph-

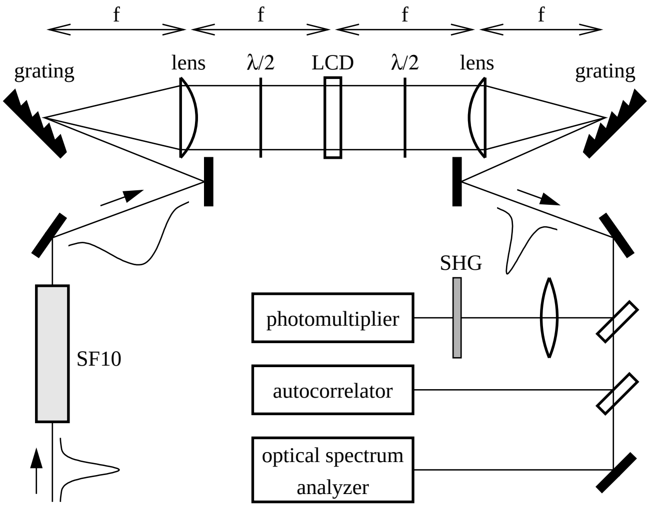

Fig. 1. Schematic experimental setup. A femtosecond laser pulse is temporally broadened by a SF10-rod, and recompressed by a pulse shaper

ic gratings (1800 lines/mm) in the focal planes of 80 mm plano-convex lenses. Striking the first grating, the different wavelengths emerge at different angles and are focused to separate spots in the back focal plane of the first lens (the Fourier plane of the system), where a commercial LCD is placed. The spectrum is then recombined to form a collimated output beam by the symmetrically arranged second lens and grating. The energy throughput lies between 20% and 40%, depending on the experimental setup.

The liquid crystal spatial light modulator consists of 128 rectangular pixels with an active width of 97 μm, separated by 3 μm gaps. The liquid crystal molecules are oriented parallel to the lines of the LCD in order to improve the optical modulation quality [3]. If a voltage is applied they tilt backwards, and therefore the refractive index for vertically polarized light changes. An additional optical path length can thus be introduced to each spectral component separately. Since the LCD requires vertical polarization, and the gratings need horizontal polarization for efficient diffraction, a pair of half wave plates is inserted in front of and behind the LC-SLM.

In the data acquisition process 12-bit voltage encodings are calculated for each pixel and sent to the display. The SHG signal is recorded after a delay of 500 ms, which is the response time of this specific LCD.

2 The algorithm

An evolutionary algorithm is a global optimization method which mimics processes actually taking place in the biological evolution. Genetic qualities influence the chance of an individual's survival, the struggle for live leads to a natural selection (the "survival of the fittest"), and genetic variants that have proven to be well adapted to the environmental conditions appear preferably in the next generations.

Two main concepts of evolutionary algorithms are discussed in the literature: the genetic algorithms [15] and the evolution strategies [16]. Both are global in their search and employ similar working schemes, but there are some differences. The genetic algorithms use binary encodings for the genetic information and rely heavily on the crossover procedure, whereas the evolution strategies prefer floating point representations and take mutations with an automatic mutation leap adaptation as method to increase the fitness. The evolution strategies select only the fittest individuals for reproduction whereas the genetic algorithms take all individuals into account, weighted by their fitness. Although for complex topologies of the search field the risk of ending up in a local minimum is slightly greater for evolution strategies than it is for genetic algorithms, the use of evolution strategies very much increases the efficiency and robustness of the optimum seeking process. For a further comparison of the different types of evolutionary algorithms see [17].

Our realization of an evolutionary algorithm follows mainly the evolution strategy approach, but with additional crossover procedures. It works with a population consisting of individuals all carrying the LCD pixel voltage values as their genes. The algorithm always starts with completely random gene configurations. By measuring the corresponding SHG signal a certain fitness value is assigned to each individual. After that, a selection step is performed: only the fittest individuals of the population are allowed to survive whereas all others are killed. The survivors, together with their offspring produced by mutation and crossover, form a new generation of the original population size. Then a new cycle of the evolution process starts (see also Fig. 2). Again the fitness of the individuals is recorded, a selection is performed, and offspring is produced. Generation after generation the fitness of the surviving individuals increases until finally the optimum is reached, and, in our experiment, the display pattern for maximal SHG signal and shortest laser pulse is found.

The mutation works as follows: the voltage value in each gene is changed by a certain amount. It is calculated by a random number generator, using a Gaussian probability distribution centered around zero and having a width proportional to

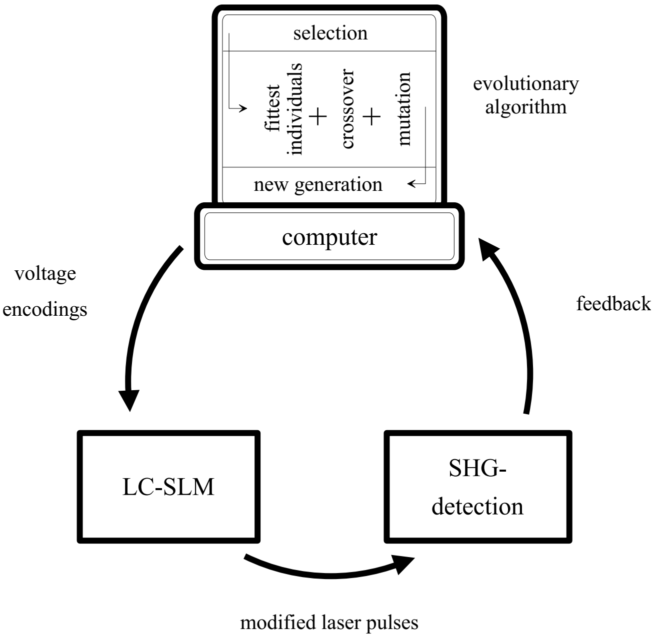

Fig. 2. Feedback loop. Given voltage encodings generate specific second harmonic signals. The best patterns are selected and allowed to produce their offspring by mutation and crossover. The new generation is then tested, and so forth

the last mutation jump. This has the effect of self-optimizing mutation leaps. In the crossover procedure, pairs of individuals interchange randomly chosen genes. Thereby two complementary children are created.

We have typically worked with a population size of 60. There are 10 survivors, each of which has 4 children by mutation and 1 child by crossover, yielding again 60 individuals for the next generation. Variations of these parameters are also possible, of course.

It should be pointed out that first, no a priori knowledge of the input pulse is needed in the algorithm; second, the optimization works with any feedback signal, not only with SHG; and last, no display calibration is needed because the algorithm works directly with the voltage encodings.

3 Results and discussion

Typical developments of the SHG signal with respect to the generation number are shown in Fig. 3. The signal increase takes different ways in each measurement, but the maximum is always reached. This can be verified by comparison with the signal intensity from the "chirp scan method" (explained below).

Figure 4 shows autocorrelations of the chirped input pulse (a) with $\tau_{\text{chirped}} = 1.2$ ps, and of the output pulse compressed by the evolutionary algorithm (b).

A proof for the total recompression of the pulse and the SHG maximum is given in Fig. 5 (note the different time scale as compared to Fig. 4). We start with an unchirped pulse by taking the SF10-rod out of the beam and switching the display controller off (curve a, $\tau_{\text{unchirped}} = (86 \pm 3)$ fs). The bandwidth limit is almost reached, the deviation probably being due to imperfections in the optical setup. Nevertheless, we would expect the algorithm to find back to this pulse length if all works well. Curve b shows the autocorrelation of the recompressed pulse. The pulse duration is $\tau_{\text{compressed}} = (88 \pm 3)$ fs, which means that the optimum was indeed found automatically by the computer.

As a means to double-check the result, a "chirp scan method" can also be used. The values of different chirp orders are varied continuously within a given interval (only the second order was found to be significant), and sent as a LCD-pattern. Only in this procedure calibrations of phase with respect to voltage and wavelength with respect to pixel number are needed. The autocorrelation (Fig. 5c), taken at SHG maximum with an introduced second order chirp of $\partial^2\phi/\partial\omega^2 = -2.59 \times 10^4\,\text{fs}^2$, exhibits the pulse length $\tau_{\text{scanned}} = (86 \pm 3)$ fs, as it was found by the evolutionary algorithm. Optimal compression therefore does not require any knowledge of the input pulse.

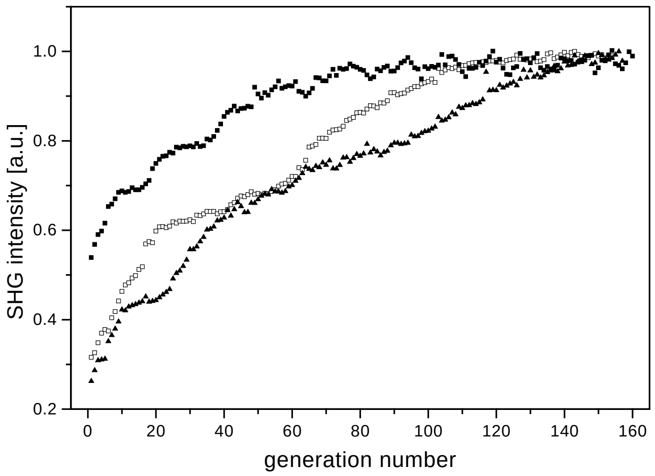

Fig. 3. SHG signal intensity vs. generation number. Although the three curves take different ways, they all reach the maximum possible value

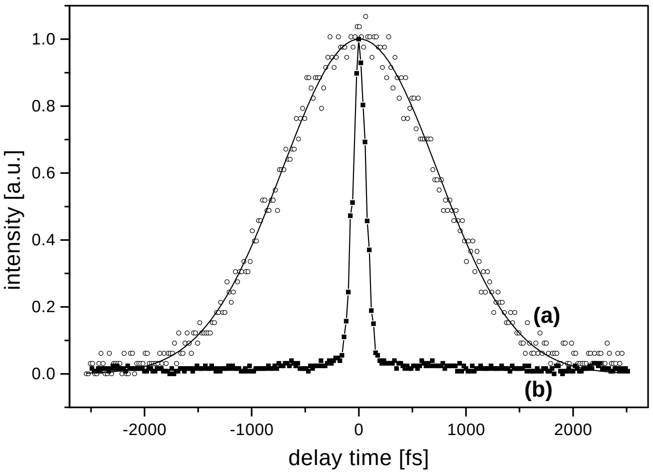

Fig. 4. Autocorrelations of broadened input pulse (a), and of recompressed output pulse (b). The evolutionary algorithm automatically finds a display configuration capable of compensating for the chirp introduced by the SF10-rod

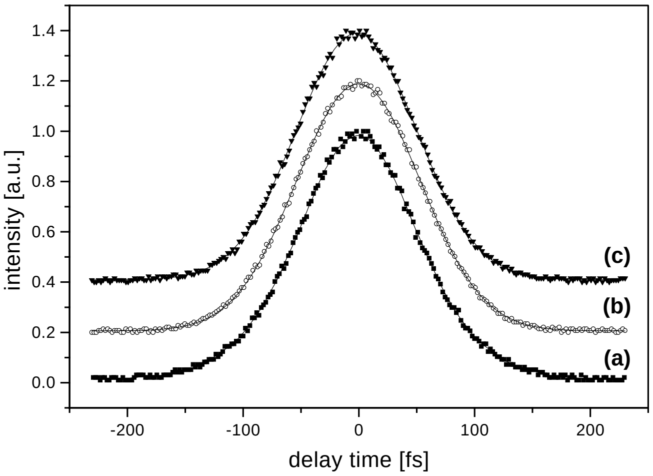

Fig. 5. Autocorrelations of unchirped start pulse (a), pulse recompressed by evolutionary algorithm (b), and by "chirp scan method" (c). No difference in pulse length is detectable, which is a sign for the high fidelity of the algorithm-conducted reconstruction

Applying evolutionary algorithms may even be useful for the characterization of pulse shapes. If the algorithm has successfully compressed an unknown pulse, the corresponding display chirp adjustment is equal and opposite to the chirp of the pulse being analyzed. This is illustrated (on the example of our SF10-rod) in Fig. 6 where the display introduced phase is plotted with respect to the wavelength (solid curve). The $\partial^2\phi/\partial\omega^2$ from the "chirp scan method" corresponds to the

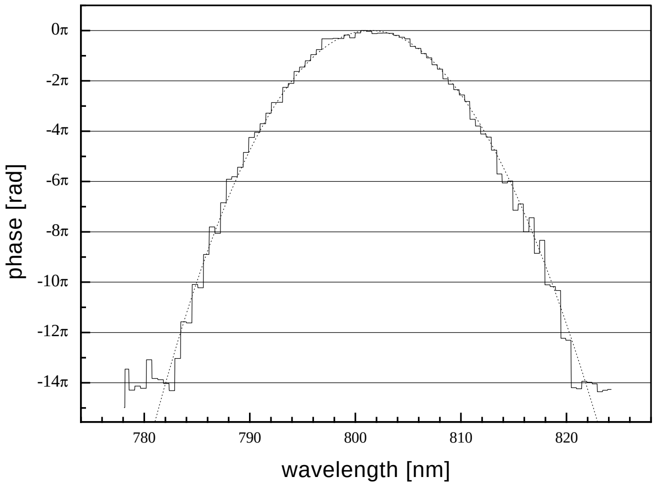

Fig. 6. Display introduced phase vs. wavelength (*solid curve*). The discretization is due to the finite pixel size. The quadratic dependence is characteristic for the second order GVD resulting from propagation in SF10. It is extraordinarily well compensated for by the algorithm, as can be seen by a comparison with the chirp $-2.59 \times 10^4\ \mathrm{fs}^2$ (*dotted curve*) obtained from the "chirp scan method"

parabolic phase indicated by the dotted curve. A comparison reveals that the algorithm's result perfectly agrees.

With the LCD we have used, one experiment takes about 2 h. This is not an effect of the algorithm (which calculates the new patterns very quickly) but of the slow liquid crystals. If faster LCD technology is applied (say, 10 ms response time instead of 500 ms), the optimum can be found in 2 min.

Immediate applications of this computer controlled optimized pulse shaping are found in femtosecond experiments, such as two photon microscopy, ultrafast soft X-ray generation, frequency conversion, control of wavepacket motion, and population transfer etc. where the nonlinear response can serve as feedback. Of course any other system response, besides SHG for instance, could be used as feedback.

In optics and ultrafast laser physics this new tool also tremendously reduces the effort to find the optimal laser pulse either bandwidth limited or arbitrarily shaped.

4 Conclusion

We have demonstrated experimentally that chirped femtosecond pulses can be recompressed by a computer controlled pulse shaping apparatus using an evolutionary algorithm with feedback. Without any knowledge of the input pulses nearly transform limited output pulses are obtained. The experiment is performed using 800 nm pulses from a 80 MHz Ti:Sapphire laser. The pulses are formed with a programmable liquid crystal spatial light modulator based on the design of Weiner *et al.* [3]. The shaped pulses generate a SHG signal in a thin BBO-crystal which serves as feedback for the controlling computer program. The optimal pulse shape resulting in maximized SHG signal is found by an evolutionary algorithm. The generation process is very efficient and robust.

With this tool novel experiments can be realized simply by choosing the appropriate feedback. The technique is extremely useful in a wide range of fields and applications where specific temporal and spectral ultrashort laser pulses are required. Not only in ultrafast spectroscopy, e.g. quantum control of chemical reactions, this technique will open up new directions, but also in applied optics, e.g. short pulse microscopy, this will have a fundamental impact on applications.

Note added in proof

In an additional experiment a complex phase modulated laser pulse, generated by a regeneratively amplified Ti:Sapphire laser, was compressed to a pulse duration corresponding to 1.07 times the bandwidth limit. This result could not be obtained by simply introducing second and third order chirp. With this we have explicitely demonstrated that even very complicated phase functions are found by the new technique.

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