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Spectral modification of supercontinuum light by means of fs-light pulses optimized in a closed learning loop

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First closed loop optimization experiments on the spectral envelope of white light produced by shaped fs pulses irradiated on a thin (2 mm) sapphire plate are presented. Thereby, the spectral position of the maximal white light intensity could overall be shifted by about 80 nm. The modification of this spectral characteristic due to non-linear effects in optimal control is discussed with regard to novel applications in laser development.

Keywords: supercontinuum generation, optimal control.

1. Introduction

The phenomenon of white light radiation is observed in gases, liquids, and solids. White light radiation is generated by means of a complex interaction of many processes stemming from the third-order nonlinear susceptibility, as well as from ionization and plasma generation [1]–[6]. Because of the strongly coupled time and space variation, this process is complex and therefore still a subject of current study [7]. White light is also an easy source of tunable short pulse radiation already realized in several laboratories [8]–[10]. The potential for applications would be greatly enhanced if the spectrum of the white light could be modified.

Several studies regarding the white light generation show that in the simplest approach the intensity-dependent index of refraction results in an instantaneous frequency at a distance L within the medium, $\omega = \omega_0 - k_0 n_2 L \mathrm{d}I/\mathrm{d}t$ [7]. Due to the second term, pulse shaping could be used to influence the spectral components of the white light. A first study in this regard showed considerably different white light spectra for different particular pulse shapes [7]. This observation gives rise to the question whether the spectrum of the white light could be influenced in a controlled way. As a well suited method to achieve this goal closed loop optimization can be applied. In 1992, Judson and Rabitz [11] proposed closed loop experiments for controlling experimental observables. Since then several teams have successfully performed various optimization experiments [12]–[15]. To date the optimization objectives included such processes as population transfer, fragmentation, ionization, and impulsive stimulated Raman scattering (ISRS). The method enables one to find an optimal pulse form by using an iterative process. Programmable pulse shapers were combined with optimization algorithms, which are capable of solving large dimensional search problems. Feedback loop optimization is well suited for this problem since the process has a high level of complexity. One can imagine that even for simple pulses there could be several regions of the same LdI/dt. This would correspond to the same white light frequency, which could give rise to interferences and hence oscillations in the white light spectrum. The temporal phase of the excitation pulse may affect the spectral shape of the white light, as well. Moreover, considering the relatively high pulse intensities used other nonlinear processes may also contribute to the white light generation and may be influenced by the pulse shape. Thus, a new challenge arises in learning about these effects.

In the next section the functioning of the experimental setup is explained. The experimental results of the modification of the white light spectrum by optimal control are presented in Sec. 3. The article ends with conclusions.

2. Experimental setup

A femtosecond laser beam is focused by a plane-convex lens (50 mm focal length) onto a 2 mm thick sapphire plate. The emitted white light is collected in a glass fiber via a second lens located on the beam axis. This fiber is connected to a spectrometer (Ocean Optics) within the computer, which allows a fast monitoring and therefore on line modification of the observed spectrum. In order to strongly diminish the fundamental laser light at 790 nm a BG 39 filter (Coherent) is located in front of the fiber. This is necessary to prevent the CCD array of the spectrometer from overload by the laser light.

The light of a fs Ti:Sapphire oscillator (Tsunami; Spectra Physics) is amplified in a chirped pulse regenerative/multipass amplifier (Quantronix). It provides pulses of 1.5 mJ energy and about 150 fs time duration. In order to have a diminished light intensity for the experiment, a grey filter was placed before the shaper (2–5 μJ pulse energy at the sapphire plate). This also prevents the shaper from destruction by too high pulse energies. The low pulse-to-pulse deviation of about 1% assures a good stability of the white light obtained, which is necessary for the optimization. Averaging over 150 ms improves the signal stability. The experiments are carried out at a central wavelength of $\lambda_0 = 790$ nm. The corresponding width of the laser spectrum is about $\Delta\lambda \approx 8$ nm at FWHM.

The pulse shaper consists of a liquid crystal modulator mask (CRI-SLM-256) [16]. It is placed in the Fourier plane of a zero dispersion compressor [17] – see Fig. 1. The

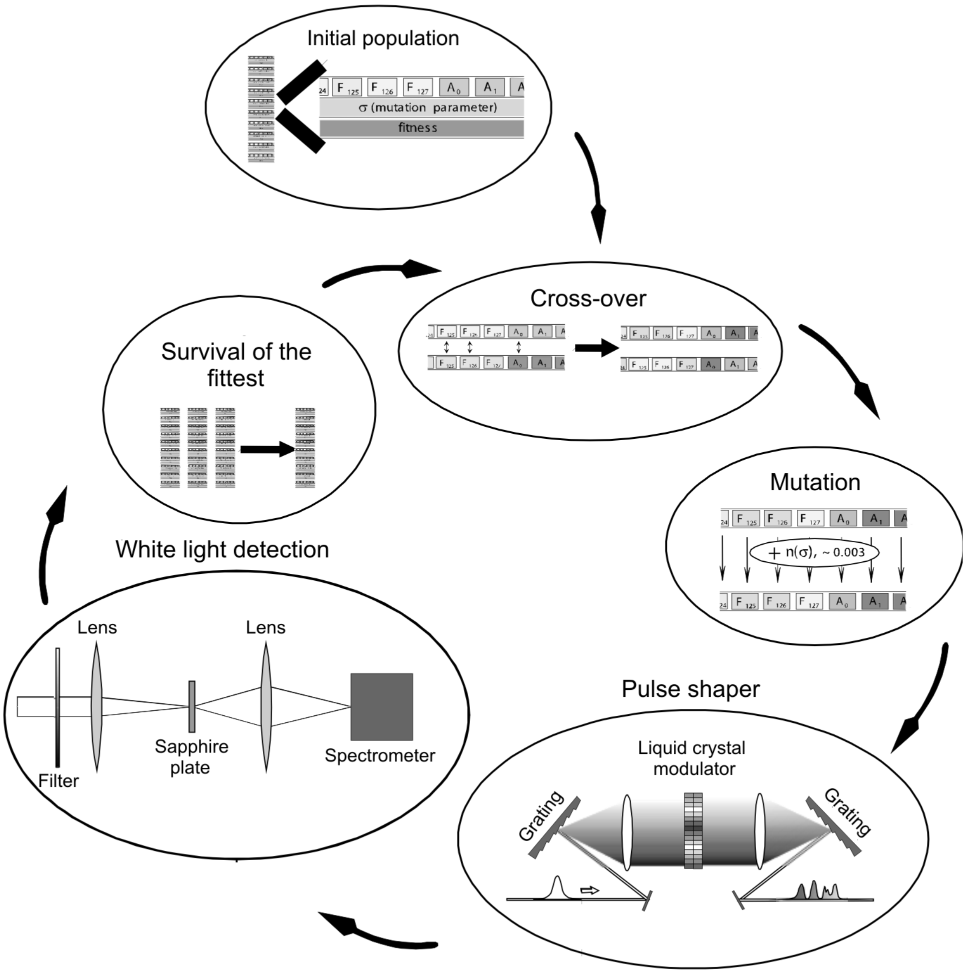

Fig. 1. Scheme of the closed loop experiment. Arbitrary pulse form patterns altered by cross over and mutation operators are sent to a pulse shaper. The created pulse forms are tested by the desired fitness function chosen from the white light spectrum. The spectral features obtained provide a measure for the quality (fitness) of the applied pulse forms.

two liquid crystal arrays of the modulator mask allow independent spectral phase and amplitude modulation [18] with a discretization of 128 pixels. As the most general case all values are optimized (free optimization). Here only phase optimization is applied in order to keep the pulse energy constant.

The implemented closed loop experiment combines the spectral detection with a programmable pulse shaper, which is driven by a self-learning optimization algorithm based on evolutionary strategies (see Fig. 1). According to the experimental feedback signal, the algorithm iteratively creates and selects pulse forms. Convergence is reached when there is no further progress in optimizing the signal, whereby the optimal pulse shape is found. In our case the desired spectral features determine the quality (fitness) of the pulse forms.

Each pulse form is determined by an array of 128 numbers (individual), representing the phase values. At the beginning individuals consisting of random numbers are created. Groups of individuals are called populations. The array values are modified by two operators called cross-over and mutation. After being written on the modulator, each pulse form of the first population creates a signal which represents its fitness. In the last step of the cycle, the best individuals are selected and serve as parent individuals for the next iteration. Details of the algorithm have been published elsewhere [19].

3. Experimental results

A typical learning curve of the optimization measurement (here for the spectral range 400–700 nm) is shown in Fig. 2. A significant rise in the integral spectral signal with increasing iteration (generation) number is clearly visible. The three values for each generation show the best, the mean and the worst of all values in one generation. At the beginning the white light intensity is very small because the phase values of the first generation are randomly chosen. This leads to complex pulse trains spread in time over several ps, which yields low white light signals. With successive iterations the signal exceeds the outcome of the initial pulse and converges after about 40 generations.

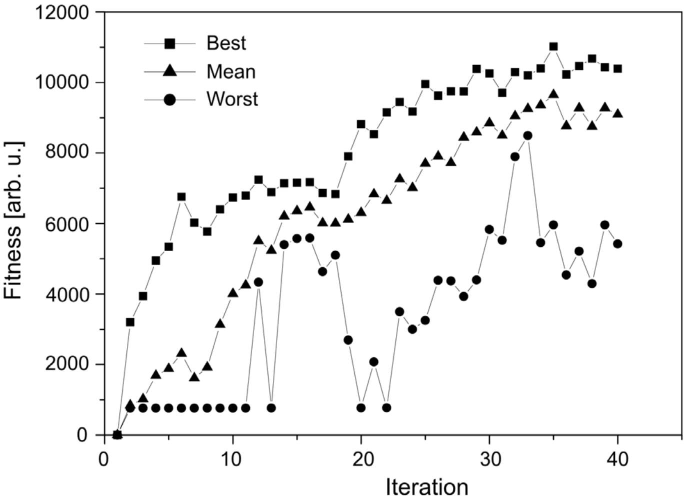

Fig. 2. Progression of the white light signal for the frequency range 400–700 nm during optimization. At the beginning the yield is small since the initial pulses are randomly formed. After approximately 40 generations the algorithm reaches a maximum.

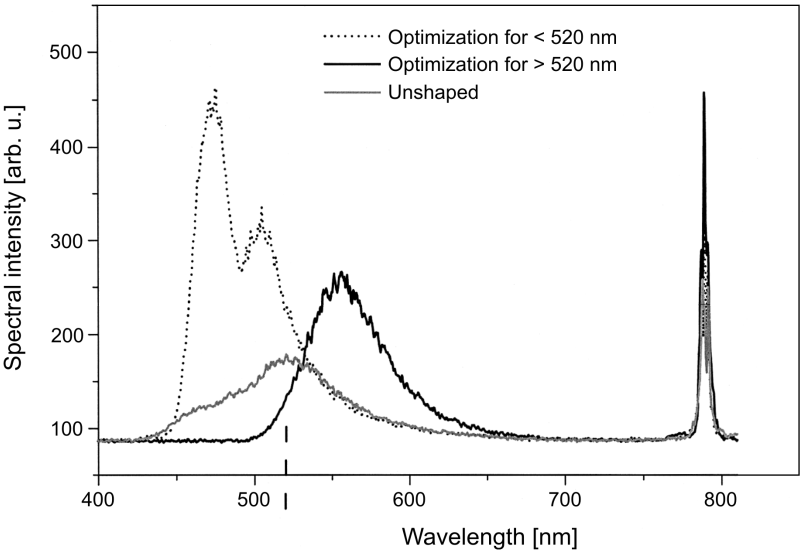

Fig. 3. White light spectra recorded by the implemented spectrometer. The dotted line shows the spectrum for the optimization of the maximal ratio 400–520 nm *vs.* 520–700 nm. The white light spectrum for minimization of the above ratio is represented by a solid line and the white light spectrum for an unshaped pulse is shown by a grey line. The dashed vertical line marks the limit between both ranges at 520 nm.

The noise in the optimization curve presented is due to the fluctuation in the laser beam, whereby the nonlinear effects in white light creation amplify the fluctuations considerably. Theoretically, a smooth monotonous rise should be expected, since the optimization algorithm leaves the best individual of each generation unchanged. Nevertheless due to beam fluctuations, the best individual in one generation can provide a weaker signal in the following one. This will lead to a decrease in signal intensity, if additionally all other individuals are weaker than the previous best one. Therefore the slight negative variations in the curve of the best values can be understood.

In order to achieve a shift of the white light spectrum, the ratio of the spectral range 400–520 nm *vs.* 520–700 nm is optimized. Thereby, the ratio of the integral signals (fitness) is either minimized or maximized. The integral value for each spectral range is gained by integrating and subtracting the baseline signal. The 520 nm is chosen for the separation of the two spectral ranges since at this wavelength the area under the initial white light spectrum is divided into two almost equal parts. This allows both minimization and maximization at equally good starting conditions.

Figure 3 shows the white light spectrum recorded by the implemented spectrometer. The dotted line indicates the spectrum for the maximization of the ratio 400–520 nm *vs.* 520–700 nm. It starts at shorter wavelengths than the initial spectrum, shows a global maximum at 480 nm and declines smoothly to the long wavelength side. The white light spectrum for minimization of the above ratio is represented by a solid line. The curve rises at longer wavelengths and has its maximum at 560 nm. The widths of the two spectra do not differ considerably. An auxiliary feature visible in Fig. 3 is the observation that the intensity at the laser wavelength of 790 nm is lower when the total white light intensity is higher. This might indicate the transformation of the laser light into the fundamental white light component, but other origins cannot be excluded.

The substantial difference of 80 nm between the two maximal white light intensities is surprising and not understood entirely up to now. Simple explanations like intensity and pulse duration dependences are not valid according to our additional preliminary studies. The intensity pulse form in time probably plays a major role for the spectral shift (claimed in [7]) but this needs further verification. A detailed investigation of the acquired optimized laser pulse forms was not possible with the experimental setup. SCHUMACHER [7] observed that a fast-rise-time pulse generates a red shifted white light spectrum whereas a fast-fall-time pulse creates a blue shifted spectrum, which can be understood qualitatively by self-phase modulation. Yet, he has not achieved a quantitative agreement with model calculations, which indicates a more complex origin of white light generation. Other contributing nonlinear effects [1] (*i.e.*, self -steepening, self-focusing, stimulated Raman scattering, four-photon parametric generation) may also be influenced by the pulse shape, presumably leading to amplification of particular white light frequency components. This assumption certainly requires further investigation in the future.

4. Conclusions

We investigated the closed loop optimization of the spectral shape of white light induced by focusing fs pulses in a thin sapphire plate. In particular, a shift of the white light peak in both spectral directions could be enforced. The amount of the total spectral shift achieved was measured to be 80 nm. Extensive theoretical simulations should be undertaken in order to understand the observed features and the modification of the spectral components due to the optimal control process. The reported ability of tuning the white light maximum frequency could create great potential for new short pulse laser applications. For example, the process of seeding optical parametric generators for producing tunable radiation (OPO, NOPA) could be made considerably more efficient. Even the design of particularly shaped white light pulses in time and frequency may be achieved with the method presented. This could enable further potential applications in short pulse laser technique.

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