Pulse Shaping with the MIIPS-Process

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The full potential offered by ultra-short laser pulses can only be effectively used when the pulses can be manipulated. This is achieved by analysing them and optimising their phase and amplitude through a closed loop. Until recently, the setup and algorithms were still at an experimental stage, but now a stable process is available that enables applications with a commercial system.

The manipulation of the phase and intensity of ultra-short laser pulses (pulse shaping) is becoming increasingly important in various fields of ultra-short pulse spectroscopy as well as material processing, for example, in order to produce higher harmonics or to further increase the peak power, respectively. At the same time, the control of molecular reaction kinetics has become a widespread process in biophysics and biochemistry. With this technique, the phase-corrected laser pulses are used to drive molecules into defined target conditions. As the required quantum-mechanical descriptions are generally either very complex or are unknown for the individual process, the signal gained from the experiment is used in a feedback loop that optimises the pulse shape in accordance with the result [1,2].

Pulse shaping

Ultra-short pulses can reach extremely high peak intensities (amplified >10^18 W/cm^2) and thus provide the opportunity to tread completely new paths in scientific and commercial applications. Nevertheless, the shorter the pulse, the more difficult it is to handle. Due to dispersion effects, broadband laser pulses generally lose their shape when they pass through optical components so that they are often already temporally dilated when they reach the sample under investigation [3]. As time periods in the fs-range cannot be directly modulated, the Fourier Transform is used to represent the relationship between the time and the frequency domain; the temporal shape of a pulse can be manipulated by changing the phase function and the amplitude of the frequency components. A pulse is considered to be Fourier limited when the phases of the spectral components are constant across the complete spectral range. At the same time, this means that the pulse is temporally as short as can be permitted by the given bandwidth.

To fully utilise the complete potential of a pulse, it is thus necessary to exactly measure and, where necessary, correct the phases of the spectral pulse components. Pulse forming is usually achieved through the use of prisms, gratings and negative dispersion mirrors, but also active elements such as acousto-optic modulators or liquid crystal arrays (e.g. [4]). The latter permit the systematic manipulation of the phases and, consequently, the generation of special pulse forms (figure 1). When amplified pulses are the objects of manipulation, the high intensities can quickly damage the pulse shaping components when the amplifier output is used directly. In addition, in most cases, power is lost through the limited transmission (usually <50%) of the optical setups that are necessary. These problems can be avoided by placing the pulse shaping in front of the amplifier stage. As long as the downstream amplifier is operated at saturation, the losses will not affect the output power of the amplifier [5].

In conventional pulse shaping setups, measuring devices such as FROG [6] or SPIDER [7] are used for spectral analysis. These provide the feedback that sets the active pulse shaping components. These are complex measuring processes that usually require two copies of the same pulse to be generated – and at least an interferometer and a doubling unit have to be used. Genetic algorithms determine from the measurement data the direction and order of magnitude of the correction that is then transposed by the pulse shaping elements. Existing concepts, consequently, require at least two sophisticated optical components, a phase analyzer and a pulse shaper, to perform the measurement procedure and shape the pulse. The optical components that form and detect the pulses have, until now, usually been developed or put together by the researchers themselves. An alternative is provided by a technology called “Multi-photon Intrapulse Interference Phase Scan”, in short MIIPS,
developed by Prof. Marcos Dantus and his team at the Michigan State University [8].

The MIIPS process

MIIPS is based on a direct measurement at a single beam, making it insensitive to interferences. The phase information is directly taken from the frequency doubled spectrum (SHG spectrum) of the pulse being investigated. For analysis, a pulse shaping unit is used to impress a known reference function $f(\omega)$ onto the spectral phase of a pulse to at least compensate for local interferences of the phase through the unknown phase function of the pulse $\Phi(\omega)$. The sum of the reference function and the original phase function of the pulse is indicated through:

$$\phi(\omega) = \Phi(\omega) + f(\omega)$$  \hspace{1cm} (1)

The local intensity of the signal at the doubled frequency $2\omega$ is the outcome of the square of an integral of all the possible frequency combinations that occur in the pulse between the frequencies $\omega + \Omega$ and $\omega - \Omega$ with the respective positive and negative deviation $\Omega$ from the frequency being considered as $\omega$:

$$S^{(2)}(2\omega) \propto \int \left| E(\omega + \Omega)E(\omega - \Omega) e^{i(\omega+\Omega)f(\omega-\Omega)}\right|^2 d\Omega$$  \hspace{1cm} (2)

The phase exponent of the mixed signal within the pulse is consequently $\phi(\omega + \Omega) + \phi(\omega - \Omega)$. The SHG signal is at its strongest the nearer that this phase exponent tends towards 0 (Fourier limited pulse). In this case, the oscillating part of the integral above $\Omega$ ceases. As the phase function is continuous, the composite term can be written as a Taylor series:

$$\phi(\omega + \Omega) + \phi(\omega - \Omega) = 2\phi(\omega) + \phi''(\omega)\Omega^2 + \ldots + \frac{2}{n!}\phi^{(n)}(\omega)\Omega^n$$  \hspace{1cm} (3)

for which, at first approximation, the higher order terms can be disregarded. The SHG signal consequently reaches a local maximum, when $\phi'(\omega)$ tends towards 0. From (1) the following results for this case:

$$\phi'(\omega) = -f'(\omega)$$  \hspace{1cm} (4)

To determine the phase deviation across the complete spectrum, the reference function is extended by a variable parameter $\delta$ that is continuously scanned. In this way, for each frequency $\omega$ a $\delta_{\omega}(\omega)$ can be determined with which the SHG signal can reach its maximum. The original phase position within the pulse can, therefore, be determined for the complete spectrum through the two-time integration of $-f'(\omega)\delta_{\omega}(\omega)$.

As reference a sinus function of the form $\sin(2\pi \omega/\alpha - \delta)$ is usually used, whereby the phase variable $\delta$ is scanned across $4\pi$. The sinus function is particularly suitable for this as it limits the phase shift applied by the pulse shaper, however, in principle other functions can also be used. For each $\delta$ a SHG spectrum is taken. The three-dimensional representation of the SHG-intensity in accordance with the pulse frequency and the scan parameter $\delta$ in figure 3 shows a number of so-called MIIPS-traces. The parameters of the maximum SHG intensity can be read from these traces. The $\delta_{\omega}(\omega)$ of two neighbouring MIIPS-traces is used for the analysis and calculation of the phase correction, which increases the accuracy. In the same way, the accuracy of the process increases as the phase deviation to be corrected decreases [9]. For this reason, the process is frequently repeated, whereby the sum of the previously determined correction functions is used as the starting point of the next run or for the final correction through the pulse shaper. This in general lowers the phase deviation across the complete area of the spectrum used to less than 0.1 rad.

The MIIPS system

In the commercial MIIPS implementation “Silhouette”, the pulse shaper box consists of a zero-dispersion pulse stretcher (4f-setup), a liquid crystal spatial light modulator (SLM) as well as a spectrometer. This is fiber coupled to the sampling head that is continuously scanned. In this case the phase shift applied by the pulse shaper, however, in principle other functions can also be used. For each $\delta$ a SHG spectrum is taken. The three-dimensional representation of the SHG-intensity in accordance with the pulse frequency and the scan parameter $\delta$ in figure 3 shows a number of so-called MIIPS-traces. The parameters of the maximum SHG intensity can be read from these traces. The $\delta_{\omega}(\omega)$ of two neighbouring MIIPS-traces is used for the analysis and calculation of the phase correction, which increases the accuracy. In the same way, the accuracy of the process increases as the phase deviation to be corrected decreases [9]. For this reason, the process is frequently repeated, whereby the sum of the previously determined correction functions is used as the starting point of the next run or for the final correction through the pulse shaper. This in general lowers the phase deviation across the complete area of the spectrum used to less than 0.1 rad.

Figure 2: Actual implementation: The Silhouette MIIPS system

that enables broadband phase matching. The measured signals are transmitted through the fiber to the spectrometer in the pulse shaper box. A USB port is provided to enable the connection of a laptop computer for the evaluation of the spectrum, control of the liquid crystal SLM and output of the pulse data. An additional liquid crystal array enables the amplitude of the individual frequency components to be directly manipulated. The shaper box is generally installed directly after the oscillator whereas the small flexible sampling head can be installed at any point within an experimental setup. This is the position at which the phase components are to be compensated, for example at the exact position of the sample being examined. As standard, the system can be adjusted for two different bandwidths. The 128 pixel liquid crystal arrays can modulate spectral regions of 100 nm or 200 nm. The total loss in average power is less than 30%.

Pulse shaping behind the ultra-short pulse oscillator

The first example is the direct shaping of pulses behind an ultra-short pulse oscillator. The oscillator (in this case a Micra-5) has a variable bandwidth between 30 nm and 100 nm and an average power of approx. 400 mW. The repetition rate can be varied between 76 MHz and 82 MHz. The use of pulse shaping and prism compensation enables a pulse duration of

Figure 3: MIIPS trace of an uncompensated pulse (left). The trace of a perfectly compensated pulse shows, with a sinus reference function, straight parallel lines at the distance $\pi$ (right). Linear chirp changes the distance of the lines to each other, square chirp portions change the angle, and high order interference causes curvatures to be introduced. Fundamental information about the characteristics of the phase within a pulse can be immediately read from the MIIPS trace
Pulse shaping in an amplifier system

In the second example, the Silhouette is inserted between the oscillator and amplifier in a short pulse system similar to that shown in figure 6. The oscillator in this setup is, once again, the Micra system described above. The amplifier used in this case is a Legend USP HE, a purely regenerative amplifier with more than 3 mJ output energy. The MIIPS-process enables the performance of almost any commercially available or purpose-built laser system with a pulse duration of less than 60 fs to be improved or optimised. Particularly important for the user is that the commercial implementation of the system guarantees constant pulse duration and bandwidth limited pulses at the push of a button – reproducible every time, without consuming procedures to optimise the dispersion compensation within the individual components of the laser system.

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Literature


Figure 4: Compressed pulse from a Micra-5 fs oscillator near to the transform limit. The pulse duration measured here is 10.4 fs

Figure 5: Pulse manipulation of a Micra oscillator for CARS – spectroscopy. The results are two coherent pulses with almost identical bandwidth and intensity, but a spectral separation of approx. 88 nm

10.4 fs to be reached, instead of 16 fs if only prism compensation is used (figure 4). In addition, the system enables (any) two components to be selected from the spectrum of the laser, as shown in figure 5. In this way an oscillator is simulated that emits two colours at the same time, in this case 770 nm and 855 nm. Spectral behaviour of this kind is required for a variety of applications, for example in CARS (Coherent Anti-Stokes Raman Scattering) spectroscopy.

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Figure 7: Pulse manipulation enables the pulse duration to be shortened by approx. 25%, almost at the transform limit and with minimum phase error

Figure 6: Setup for phase manipulation. The Silhouette pulse shaper is placed between the seed laser (Micra) and amplifier (Legend-Elite). The pulse length can be optimised either directly behind the amplifier or behind the optical setup directly at the experiment

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