APPLICATION NOTE 38

Automated Control of Amplified Pulse Duration Using the Dazzler™ / DazScope™ Solution

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Introduction

Pulse shaping systems are now widely used by the ultrafast laser community for applications ranging from coherent control to multi-photon microscopy. Of particular interest is the ability to directly drive the pulse shaper using the output signal of an experiment, for instance, favoring a given quantum path, intensifying fluorescence, or minimizing pulse duration. The Dazzler™ pulse shaping systems are particularly well suited to these types of control experiments.

In this application note, the basic principle of the DazScope is described and its performance is demonstrated. It is used in conjunction with the Dazzler acousto-optic pulse shaper, which provides accurate amplitude and phase control of ultrafast pulses. When the DazScope and Dazzler are used together the pulse shaping conditions can be automatically driven by the experimental results.

In collaboration with Fastlite™, France, we were able to automatically minimize and stabilize the pulse duration (<30fs) at the output of a Spectra-Physics Spitfire® Pro XP amplifier using this method.

The Effect of Dispersion on Ultrashort Pulses

For a short pulse characterized by a mean angular frequency ω_0, and a Gaussian intensity spectrum of bandwidth $\Delta\omega$ (FWHM), the minimum pulse duration (FWHM) accessible is $\Delta t=(4\ln 2)\Delta\omega$. In this case, the spectral phase of the electric field is a linear function of frequency, and the optical pulse is said to be "transform-limited".

Expanding the spectral phase $\phi(\omega)$ around the frequency ω_0, one gets:

$$\phi(\omega)= \phi_0+\phi_1.(\omega-\omega_0)+\phi_2.(\omega-\omega_0)^2/2+\phi_3.(\omega-\omega_0)^3/6+\phi_4.(\omega-\omega_0)^4/24+\ldots$$

The first and second terms have no effect on the shape of the pulse. Conversely, the second and higher order phase terms generate a chromatic delay that affects the pulse shape and duration. Figure 1 shows the effect of second order phase on the duration of a Gaussian pulse of 30 nm bandwidth (FWHM) centered at 800 nm. According to the graph, a 35 fs pulse corresponding to 30 nm transform-limited Gaussian pulse after experiencing 2500 fs^2 group delay dispersion will broaden by factor of 6. It can be shown that the same pulse will undergo similar broadening due to $2.5 \bullet 10^5 fs^3$ of third order or $3.7 \bullet 10^7 fs^4$ of fourth order phase. Higher order residual phase errors are commonly found after amplification and can limit the ability to generate transform-limited pulses. As a result, these errors need to be accurately corrected in order to access the shortest possible pulse at a given spectral bandwidth.

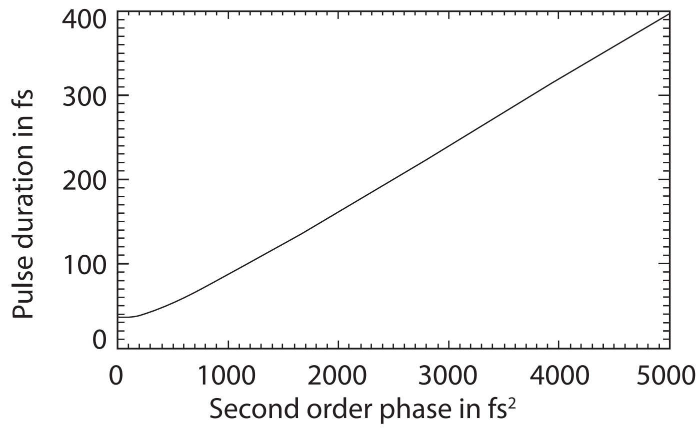

Figure 1: Effect of group delay dispersion on a 35 fs transform limited pulse.

The Dazzler Pulse Shaper

Dazzler System Description

Dazzler systems are turn-key proprietary ultrafast pulse shaping devices providing simultaneous and independent programming of the phase and amplitude of the optical pulse. The Dazzler systems (as depicted in Figure 2) include an acousto-optic crystal module, a dedicated RF arbitrary waveform generator, which delivers RF signals to the crystal modules, and the associated Dazzler software. This user friendly software allows for easy programming of the RF waveforms used to produce specific pulse shapes. The pulse shaping process is described in a later section.

Figure 2: Dazzler pulse shaper system, including RF generator, acousto-optic birefringent crystal (detailed on the right), and dedicated software.

Conventional Pulse Shapers

Pulse shapers based on spatial light modulators (SLM) use dispersive elements such as gratings or prisms to separate the various frequency components in space, some additional collimating optics, and an SLM matrix located in the Fourier plane of a 4F line arrangement[1].

These pulse shapers, although widely used in the ultrafast scientific community, feature drawbacks such as pixelisation, calibration issues, space-to-time coupling effects and a lack of flexibility.

Complications Introduced by Conventional Pulse Shapers are:

-Pixelisation introduces parasitic pulse replicas in the time domain, as evidenced by Nelson et al[2].

-Shaping performances are derived from calibration data. This method assumes a homogeneous pixel behavior which neglects manufacturing heterogeneity effects and differential pixel aging characteristics.

-Temporal manipulation of the phase causes spatial profile variations of the output beam. This is caused by the diffraction at the pixel array which produces a complicated, shaping dependent, spatio-temporal profile. The profile complicates the interpretation of results obtained with shaped ultrafast pulses[3].

-The input pulse spectrum sets the 4F line design, geometry and dimensions. Once this design is fixed, any change in the input spectrum leads to severe performance degradation of the pulse shaper characteristics (such as spectral resolution and maximum chirp).

-Simultaneous amplitude and phase shaping requires cross liquid crystal matrices, increasing the complexity of the pulse shaper.

Dazzler Principle of Operation

Introduced in 1997[4], the first commercial Dazzler (also known as AOPDF, Acousto-Optic Programmable Dispersive Filter) device was delivered in the field in 2000 by Fastlite[5]. Dazzler pulse shapers are based on a patented collinear acousto-optic interaction (Figure 3).

In this interaction, a broadband acoustic pulse is sent to a TeO_2 crystal. Each frequency contained in the incident optical pulse is diffracted by a single phase matched acoustic frequency[6] within the broad-band acoustic pulse. The phase and amplitude at this acoustic frequency are transferred to the phase and amplitude of the diffracted optical beam. This allows complete control of the phase and amplitude of the diffracted pulse by controlling the acoustic phase and power spectra. This process results in two beams at the Dazzler output: the diffracted beam which is shaped both in amplitude and phase, and the direct (non-diffracted) beam for which there is no phase control since it propagates only along the ordinary axis. The two beams are angularly separated through a purposely designed output face of the crystal.

Dazzler Advantages

-Ultra-compact set up: The Dazzler crystal module, as small as 50 x 100 x 20 mm^3, is the only component added on the optical table in order to obtain efficient pulse shaping. Extreme stability is thus inherent to the interaction achieved in the bulk of the birefringent crystal.

-In line geometry: There is no need for dispersing wavelengths spatially which eliminates space-to-time coupling effect observed when using conventional pulse shapers.

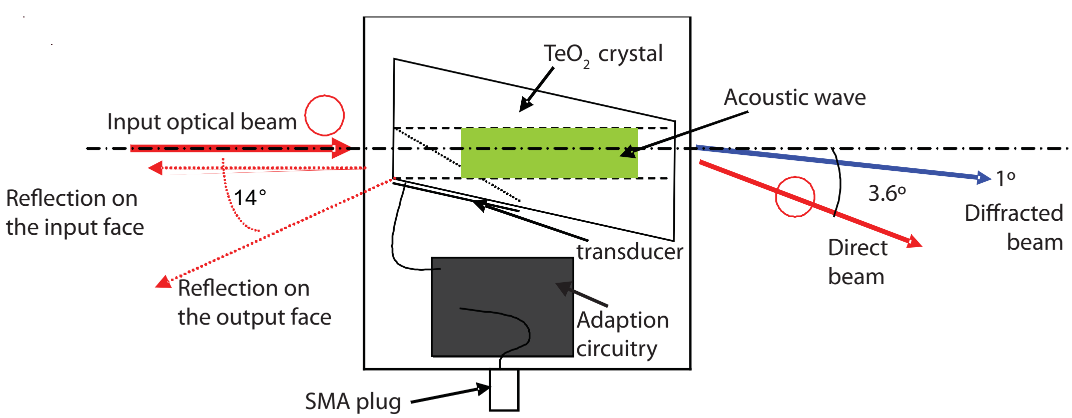

Figure 3: Dazzler beam geometry, showing the unshaped direct beam, and the diffracted beam shaped by acoustic interaction

-No calibration required: The shaping accuracy is linked to the material characteristics. The material used for the Dazzler crystal is Tellurium Dioxide, which has been the material of choice for most acousto-optic devices for thirty years and is very accurately characterized.

-No pixelisation: Since there are no discontinuities in the acousto-optic interaction process, contrast degradation and pulse replicas inherent to pixelated devices are eliminated.

-Quantitative shaping: The spectral control is defined by the material characteristics. Since these are well controlled, accurate results are attained without introducing any assumptions.

-Simultaneous amplitude and phase shaping: Available in a single device.

Dazzler Shaping Accuracy

In addition to compactness, extreme stability and flexibility, Dazzlers provide quantitative shaping of both phase and amplitude. The Dazzler was programmed to introduce 2nd and 3rd order phases in the laser pulse, which was characterized independently with SPIDER set-up[7]. The results are illustrated in Figure 4. Excellent agreement between expected and measured values is evident.

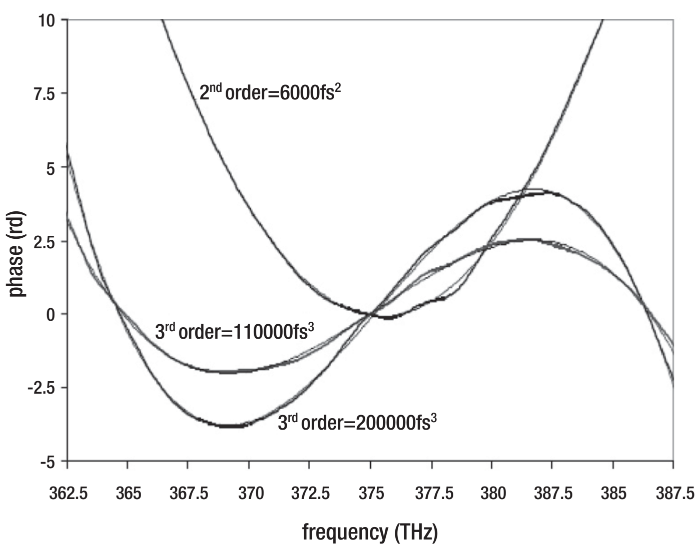

Figure 4: Comparison of theoretical polynomial phase programmed in the Dazzler (smooth curves), and spectral phase measured using a SPIDER set-up.

Automated Dispersion Compensation Using a Dazzler / DazScope System

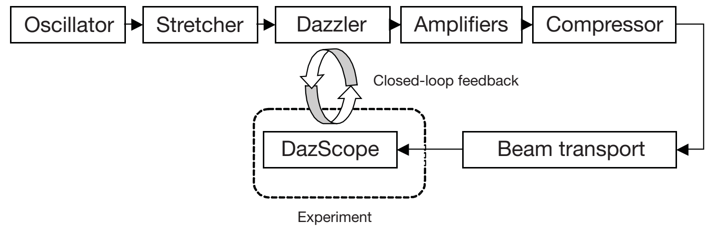

Figure 5: Typical set-up of DazScope pulse optimization system used in a laser amplifier. It could also be used on an oscillator output.

Since a significant number of chirped pulse amplification (CPA) systems now include a pulse shaper in their front-end (*oscillator*), it is highly convenient to use such a device not only to *correct* but also to *characterize* the amplified pulses by adding at the back-end (regen cavity) a non-linear element and a spectral detector. Most techniques for characterizing the phase of short pulses can be divided into three successive steps: a linear filter, a non linear interaction (e.g. SHG) and a spectral measurement of the output. In the case of Frequency Resolved Optical Gating (FROG), the linear filtering consists of generating two time-shifted replicas of the original pulse.

The results from this measurement can be easily reproduced using the Dazzler. However, when pre-shaping is performed in front of a CPA laser chain, methods that rely on pulse replicas are not favored. Indeed, the corresponding pulse structure will, in general, not propagate in the amplifier without being strongly distorted (e.g. a train of pulses will be obtained instead of two pulses) and may even cause major damage to the amplifier. Conversely, in the DazScope approach, *phase-only shaping* is used, producing negligible non linear effects in a strongly chirped CPA amplifier.

The DazScope is designed to minimize the pulse duration of ultra-short laser systems producing transform-limited pulse durations ranging from 20 fs to100 fs. The DazScope / Dazzler solution consists of a Dazzler pulse shaper located upstream of the amplifier, and a compact optical head (non linear crystal, focusing optics and spectrometer (see figure 6) after the amplifier, which measures the second harmonic spectrum (SHG spectrum) of the laser. In the pulse measurement step, the Dazzler adds a pure second order phase correction to the pulse under study. The amount of chirp generated in the

Dazzler is varied according to a well-defined sequence, and the corresponding SHG spectra are recorded. The DazScope software generates the chirp sequence and uses the observed SHG spectra to retrieve the pulse spectral phase. In particular, second, third and fourth order phase terms are precisely determined within a few seconds, and this measurement is fed back to the Dazzler for proper flattening of the pulse spectral phase. The key factor in retrieving high fidelity high spectral resolution phase measurements with the DazScope / Dazzler integrated solution is the Dazzler ability to produce large and accurate chirps.

Automated Dispersion Control of Spectra-Physics Spitfire XP Amplifier Using the Dazzler / DazScope Solution

The Dazzler pulse shaping system was used in conjunction with the DazScope in order to optimize and control the pulse duration at the output of a Spectra-Physics Spitfire Pro XP amplifier. The set-up was analogous to the scheme depicted in Figure 5. However, for these experiments the Dazzler pulse shaper was inserted between the Tsunami® oscillator and the amplifier stretcher. (The Dazzler acting as a linear filter, it is equivalent to insert it before or after the stretcher.)

The Dazzler spectral amplitude settings were first tuned to compensate for the gain narrowing of the amplifier's cavity, providing a wide amplified spectrum (Figure 7, left). The DazScope algorithm was then used to measure second, third and fourth orders spectral phase. This measurement was fed back to the Dazzler in order to flatten the phase of the amplified pulse. The resulting autocorrelation trace FWHM was 42.7fs (Figure 7, right), corresponding to a pulse duration of 27 to 30 fs, depending on the exact temporal profile.

The pulse duration was then purposely degraded to ~300fs in several ways:

Figure 6: DazScope Optical head: focusing lens, non linear crystal for SHG, and high resolution spectrometer.

1. Introducing additional dispersion with the Dazzler
2. Translating the compressor gratings
3. Rotating the compressor gratings (up to 1 degree)
4. Adding one round trip inside the amplifier

In all cases, the DazScope system was successful at deriving the proper second, third and fourth order corrections, and was able to recover the initial optimum autocorrelation curve and pulse duration in a few seconds. Figure 8 shows the 2D traces obtained when misaligning the compressor (10 arcmin rotation, measured autocorrelation FWHM of 300 fs), and after correction by the DazScope (measured autocorrelation FWHM back to 42.7 fs). The DazScope trace shows the SHG (blue) spectrum detected as a function of the second order introduced in the Dazzler pulse shaper. After DazScope correction, the resulting trace exhibits a symmetry versus chirp, as expected in flat phase conditions.

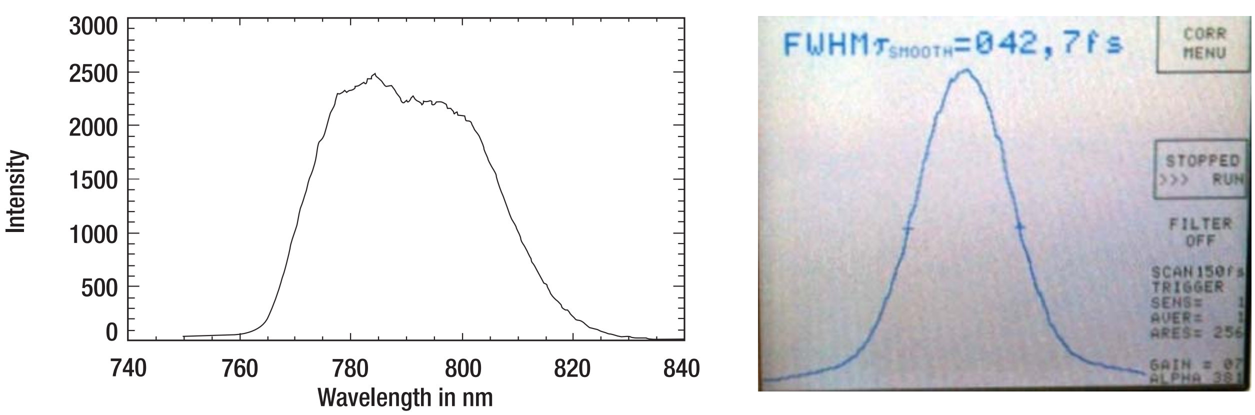

Figure 7: Left: Spectrum measured at the output of Spitfire Amplifier (FWHM= 37nm). Right: Autocorrelation trace obtained after Dazzler/ DazScope optimization

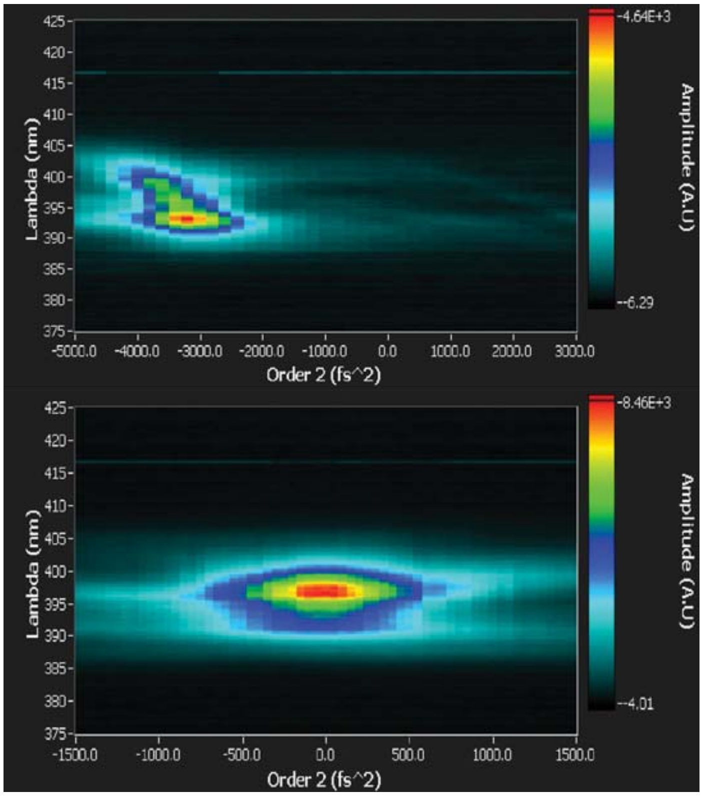

Figure 8: DazScope traces showing frequency doubled (SHG) spectrum as a function of the second order distortion pre-added in the Dazzler pulse shaper. Top: trace obtained after misalignment of the compressor (rotation by 10'). The measured pulse autocorrelation FWHM is 310 fs, strong second order (~ -3500fs^2) and higher order distortions are visible. Bottom: trace obtained after DazScope optimization. The measured pulse autocorrelation FWHM is 43 fs. The measured spectral phase is essentially flat, as illustrated by the symmetry of the trace. The derived residual polynomial phase orders are: ϕ_2=-21fs^2, $\Delta\phi_3$=-1600fs^3, and ϕ_4=90000fs^4, all within the noise limit set by pulse stability.

Conclusions

The correction of gain narrowing and optical dispersion effects is essential for achieving the minimum pulse duration in CPA systems. The advantages of using a Dazzler/ DazScope system to optimize the pulse duration of a Spectra-Physics Spitfire amplifier were demonstrated. The Dazzler pulse shaper, located in front of the amplifier, was first used to control the spectral amplitude and compensate for gain narrowing. In the DazScope mode, the pulse shaper was then used as a phase-only control device. It provides accurate, high resolution characterization and automated correction of the amplified laser spectral phase. Various misalignment and severe offset tests were also carried out, showing the robustness of the system, and its ability to quickly recover from large phase distortions.

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