APPLICATION NOTE

Pulse Stretching Using High Accuracy Chirped Fiber Bragg Grating

By Rene Dionne and Michel Morin, Ph.D.

TeraXion PowerSpectrum^{TM} HPSR High Accuracy Pulse Stretcher

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Introduction

Advanced material processing requires industrial ultrafast lasers to generate pedestal-free picosecond or even femtosecond pulses with high energy and average power, while being environmentally stable and at low cost. A good way to achieve this and minimize cost is to use a Chirped Fiber Bragg Grating (CFBG) as a pulse stretcher, but it is critical to use the right one.

Ultrafast Laser Architecture

High-power ultrafast lasers are built using a low power, high repetition rate ultrafast oscillator generating short pulses with nJ energy level. These low energy pulses are then amplified by a bulk or a fiber amplifier to hundreds of mJ of energy per pulse.

In order to avoid optical damage to the amplifier and nonlinearities that distort the pulse and reduce its peak power, Chirped Pulse Amplification (CPA) is required. This technique consists in strongly stretching the pulse prior to amplification and recompressing it afterwards, hence avoiding detrimental high peak powers in the amplifier stage.

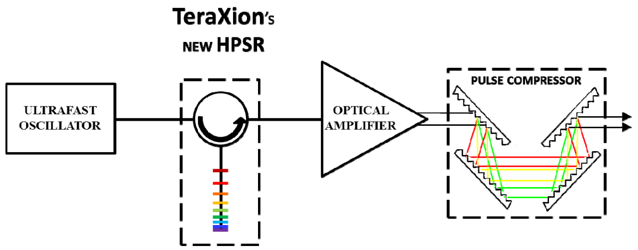

Figure 1: CPA laser system architecture

This technique has been implemented for years with bulk optics for both stretching and compression. Nowadays, the laser industry relies more and more on fiber components to improve the system stability, reduce costs and get a turnkey solution. Most commercial ultrafast lasers are built with a combination of bulk and fiber components, bulk components being still required at the compression stage and sometimes at the amplification stage depending on the peak power involved.

Pulse Stretchers Requirements

The most important application of pulses produced by ultrafast lasers is the well localized and sudden deposition of energy within a material. This allows material ablation to take place before heat has time to propagate in the surrounding area. Detrimental thermal effects are thus minimized and a spatially sharp processing is allowed. To this end, the laser should produce ultrashort, powerful and clean pulses, without satellites or a low-intensity pedestal. Dispersion control and passband optimization are of paramount importance in achieving this goal.

A CPA system relies heavily on dispersion management, whereby the pulse duration is increased by up to three orders of magnitude prior to amplification and then reduced back to its original value afterwards. This should be accomplished while maintaining the temporal pulse quality. The dispersions of the stretcher, the compressor and the amplifier should be well matched, their group delay spectral variations compensating one another to a fraction of the target output pulse duration. The CPA of pulses with duration of tens of picoseconds and beyond can be performed with a linear dispersion stretcher, even if the compressor (typically a Treacy compressor built from bulk diffraction gratings) is nonlinear. The compressor nonlinear dispersion then has little effect on the group delay over the limited bandwidth of the pulse (for e.g. 150 pm FWHM for a Fourier Transform limited pulse of 10 ps at 1 µm). The use of a linearly chirped CFBG or dispersion compensating fiber (DCF) is then appropriate. As the target output pulses get shorter, dispersion control becomes more critical: the tolerable group delay distortions are reduced while the distortions resulting from the dispersion acting over an increasing pulse bandwidth get larger. At transform limited pulse durations below 5 ps, it becomes necessary to take higher-order nonlinear dispersion into account. Preferably, the pulse stretcher should compensate as well for the dispersion of optical components other than the pulse compressor (for e.g. the dispersion of the amplifying optical fiber) within the ultrafast laser system and for nonlinearities when present.

The achievable pulse shortness is limited by the overall laser system bandwidth. The CPA chain should provide enough passband not to degrade the pulse quality. Spectral clipping by the stretcher or compressor results in longer pulses with stronger sidelobes. A clear passband of about 2 to 3 times the pulse FWHM bandwidth should be afforded by the CPA system.

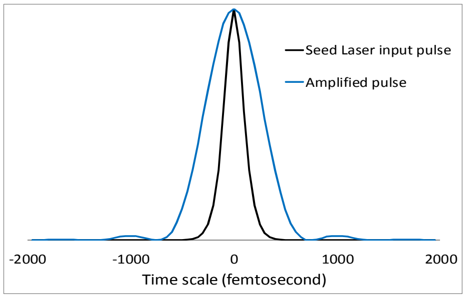

Figure 2: Spectral clipping of the seed spectrum

Depending on the gain medium and the amplification level, most amplifiers reduce the effective spectral bandwidth of the pulse, thus limiting the achievable pulse shortness. Even fiber amplifiers, known for their large amplification band, produce gain narrowing with pulses shorter than 300 fs. This limit can be on the order of a picosecond for some bulk amplifiers. Gain narrowing can be counteracted by spectrally shaping the pulse prior to amplification, this precompensation being designed to equalize the spectrum of the amplified pulse. As a result, shorter pulses with a larger bandwidth are obtained at the output of the amplifier.

Chirped Fiber Bragg Grating (CFBG) Stretchers

The compactness, low cost and design flexibility of Chirped Fiber Bragg Grating (CFBG) stretchers make them the ideal solution for high energy ultrafast lasers. The CFBG consists in a quasi-periodic modulation of the index of refraction along an optical fiber that is created by exposing the fiber to UV light interference fringes. This modulation acts as a grating that reflects light at a wavelength that depends on the period of the modulation. This period can be varied along the length of the fiber, hence allowing full control of the position along the grating at which light gets reflected as a function of wavelength. Accordingly, the variation of the group delay as a function of wavelength can be tailored at will. This unmatched flexibility allows designing a CFBG to compensate for the dispersion of any compressor and other optical components within the laser system. Nonlinear effects can also be taken into account when designing a CFBG pulse stretcher. The reflectivity of the grating as a function of wavelength can be tailored as well by adjusting the strength of the modulation along the fiber. The CFBG pulse stretcher can thus perform spectral shaping as well, to precompensate for gain narrowing for example.

Specifying a CFBG Pulse Stretcher

The design of a CFBG pulse stretcher affords great flexibility with regards to the target group delay spectral response. A pulse stretcher can thus be specified that compensates for the dispersion of a pulse compressor but also of other optical components within the ultrafast laser system such as optical fiber paths. Nonlinear effects can also be taken into account if required.

The dispersion of the pulse stretcher can be specified in terms of the Taylor expansion coefficients of its optical phase, i.e.

$$\phi(\omega) = \sum_{n=0}^{\infty} \frac{\beta_n}{n!}(\omega - \omega_c)^n$$

where ω is the radial optical frequency and coefficients

$$\beta_n = \left. \frac{d^n \phi}{d\omega^n} \right|_{\omega=\omega_c}$$

typically expressed in ps^n, are the derivatives of the phase at center frequency ω_c. The accuracy required when specifying the optical phase, i.e. the number and precision of coefficients β_n, increases with the shortness of the output laser pulses.

When the CFBG stretcher is required to compensate only for the dispersion of a pulse compressor, a geometrical description of the compressor (angle of incidence, separation between the gratings and line density of the gratings) can be provided instead. The target dispersion of the pulse stretcher is determined by TeraXion from these parameters taking into account the complete group delay response of the compressor.

As aforementioned, the spectral dependence of the CFBG pulse stretcher reflectivity can also be tailored to optimize the performance of an ultrafast laser system. The passband of the stretcher should be wide enough to avoid spectral clipping of the pulses. The spectral dependence of the reflectivity can be specified to counteract gain narrowing.

In conclusion, the spectral dependence of the optical phase and reflectance of a CFBG pulse stretcher can both be specified to optimize the performance of a CPA system.

CFBG Pulse Stretcher Performance and Impact on Laser Performances

The performance of a CFBG pulse stretcher, even when ideally designed, is ultimately limited by manufacturing errors resulting from instabilities while inscribing the FBG, particles on the fiber, heterogeneity of the fiber, etc. These manufacturing errors result in the presence of Group Delay (GD) ripples across the spectrum of the stretcher. These ripples translate into a pedestal or side pulses accompanying the main recompressed pulse. This reduces the pulse peak power and its efficiency of interaction with a material.

The period of the spectral group delay ripples determines the nature of the pulse degradation. Long period ripples have a strong impact and redistribute energy close to the main pulse, while high frequency ripples create very weak side pulses that are far away from the main pulse.

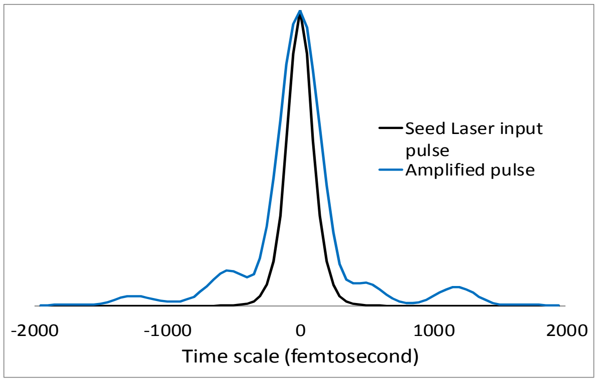

Figure 3: Laser pulse using un-optimized CFBG stretcher

TeraXion has put into place the capabilities required for the group delay characterization of CFBG pulse stretchers used within industrial ultrafast lasers. Furthermore, simulation tools have been developed to determine the effect of the CFBG spectral response, including group delay ripples, on recompressed pulses.

TeraXion High Accuracy Pulse Stretcher (HPSR) Performance

Since 2000, TeraXion has been a leading manufacturer of FBGs for the telecommunications industry, a main application being the compensation of chromatic dispersion on high speed communication links. In order to meet this industry's exacting requirements, TeraXion has developed the expertise and proprietary processes allowing an exceptional control over the temporal response of CFBGs. Recognizing ultrafast industrial fiber lasers as an emerging market of importance, TeraXion has adapted this technology to the wavelength of operation and to the time scales typical of these lasers.

The minute group delay errors found in TeraXion's new PWS-HPSR allow the faithful recompression into clean pulses at the hundreds of femtoseconds level. The end result is an incredible CPA performance enabled by the industry's top of the line pulse stretcher.

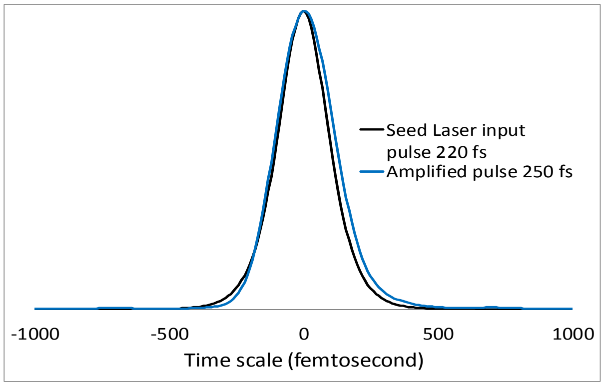

Figure 4: Laser pulse using a TeraXion's PWS-HPSR

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TeraXion Tunable Pulse Stretcher (TPSR)

Flagship telecommunication products for TeraXion have been tunable dispersion compensators, in which the dispersion of a CFBG is adjusted by applying more or less complex thermal gradients along the grating. This technology has now been adapted to produce a Tunable Pulse Stretcher (TPSR), in which dispersion is adapted to compensate for environmental fluctuations altering the ultrafast laser output pulses. Compensating at the pulse stretcher level will prove easier, more accurate, more robust and much cheaper than performing the same task with a bulk optics compressor equipped with expensive high-precision optical mounts.

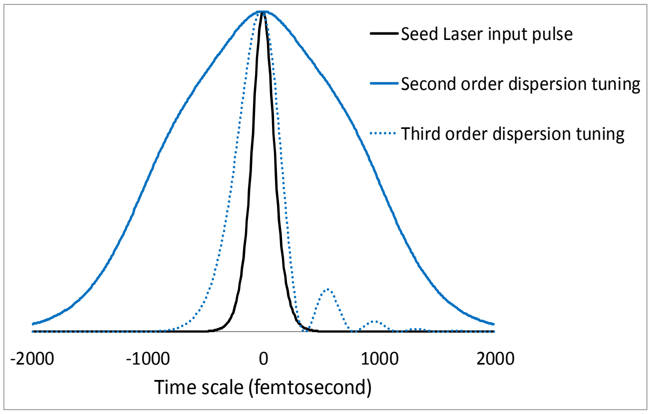

Figure 5: Second Order Dispersion (SOD) and Third Order Dispersion (TOD) tuning using TeraXion's PWS-TPSR

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About TeraXion

TeraXion designs, manufactures and markets best in class photonic products to selected emerging markets including high-speed fiber-optic transmission networks as well as fiber lasers and optical sensing applications. Over the years, TeraXion's abilities to transform complex technologies into manufacturable high-technology products have been applied to Silicon Photonics (SiP) and Indium Phosphide (InP) for next-generation 100 Gb/s and above modulators and receivers.

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