WHITE PAPER

Dispersion Control for Ultrafast Optics

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Executive Summary

Intense, ultrashort optical pulses, with durations of a few picoseconds or less, are of interest for numerous scientific applications, such as nonlinear optics and optical sampling of ultrafast phenomena. They also allow material processing with minimum detrimental thermal effects. Ultrashort optical pulses are mainly produced by mode-locked lasers, either in a bulk or fiber format.

Chromatic dispersion in an optical fiber is first discussed, in order to define terms. The dispersive capabilities of chirped fiber Bragg gratings (CFBG) are then presented. Finally, their application to dispersion management in mode-locked fiber lasers and CPA systems are reviewed.

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Introduction

Intense, ultrashort optical pulses, with durations of a few picoseconds or less, are of interest for numerous scientific applications, such as nonlinear optics and optical sampling of ultrafast phenomena. They also allow material processing with minimum detrimental thermal effects. Ultrashort optical pulses are mainly produced by mode-locked lasers, either in a bulk or fiber format. Bulk mode-locked lasers, using for example a Ti:sapphire crystal or a thin disk of Yb:YAG as gain medium, are complex and expensive systems. They can produce higher energy pulses, but with a beam quality typically dependent on the average output power. Mode-locked fiber lasers have grown into reliable and compact sources making ultrashort optical pulses readily available for scientific, medical and industrial applications (micromachining, marking, wafer cutting, etc.). Guidance by a single mode fiber limits the available energy per pulse but eases beam handling and ensures a near-diffraction limited output irrespective of the average power. The energy per pulse can be increased by amplification, usually implemented as chirped pulse amplification (CPA). A recent review of ultrafast fiber laser sources is presented in reference [1].

Propagation in a single mode fiber, on which rely fiber lasers and amplifiers, exacerbates the effects of nonlinear distortion and chromatic dispersion. Pulses intense enough to generate nonlinear self-phase modulation (SPM) become chirped with a concomitant increase in spectral bandwidth. The spectrally dependent group delay of a standard optical fiber can lead to a sizable lengthening of sub-picosecond pulses after propagation over less than one meter of fiber. The simultaneous action of SPM and chromatic dispersion can generate a variety of behaviors, from the formation of stable soliton pulses to distortions and pulse break-up [2]. Proper dispersion management in ultrafast fiber lasers and amplifiers is thus essential for the production of ultrashort and clean pulses. This paper discusses how this can be achieved with compact, fiberbased dispersive components.

Chromatic dispersion in an optical fiber is first discussed, in order to define terms. The dispersive capabilities of chirped fiber Bragg gratings (CFBG) are then presented. Finally, their application to dispersion management in mode-locked fiber lasers and CPA systems are reviewed.

Chromatic dispersion in a single mode optical fiber

Chromatic dispersion in an optical fiber can be discussed in terms of the frequency dependence of the effective constant of propagation β around an optical carrier angular frequency ω_0, i.e.

$$\beta(\omega) = n(\omega)\frac{\omega}{c} = \frac{\beta_0}{0!} + \frac{\beta_1}{1!}(\omega-\omega_0) + \frac{\beta_2}{2!}(\omega-\omega_0)^2 + \ldots, \quad (1)$$

where c is the speed of light in vacuum, n is the effective refractive index and

$$\beta_m = \left[\frac{d^m\beta}{d\omega^m}\right]_{\omega=\omega_0}. \quad (2)$$

More specifically, one has

$$\beta_1 = \frac{1}{c}\left[n + \omega\frac{dn}{d\omega}\right] = \frac{n_g}{c} = \frac{1}{v_g} \quad (3)$$

and

$$\beta_2 = \frac{d\beta_1}{d\omega} = \frac{d}{d\omega}\left[\frac{1}{v_g}\right] = \frac{1}{c}\left[2\frac{dn}{d\omega} + \omega\frac{d^2n}{d\omega^2}\right], \quad (4)$$

where n_g is the group index and v_g is the group velocity. Parameter β_1 represents the group delay per unit length of fiber and has units of ps/km.

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Parameter β_2 is responsible for pulse broadening and is referred to as the group velocity dispersion (GVD): it represents the rate of variation of the group delay per unit length as a function of the radial frequency and is expressed in ps^2/km (= ps/THz•km). Higher order dispersion terms (β_3, β_4, …) produce pulse distortion and are expressed in ps^3/km, ps^4/km, etc.. Figure 1 presents the group velocity dispersion in a standard silica single mode fiber as a function of wavelength, where it is seen to vanish near 1.32 µm. Dispersion is said to be normal when $\beta_2 > 0$ and anomalous otherwise ($\beta_2 < 0$). Dispersion in standard silica fibers is anomalous at wavelengths larger than 1.32 µm.

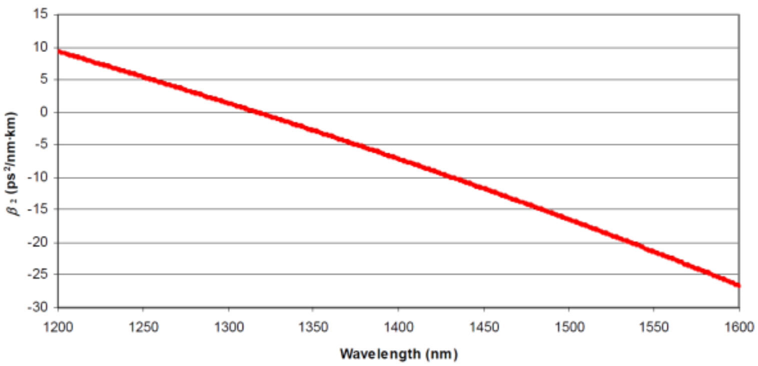

Figure 1: Group velocity dispersion in a standard silica single mode fiber

The differential group delay $\Delta\tau_{CD}$, defined as the variation in group delay resulting from chromatic dispersion over a spectral bandwidth $\Delta\nu$, is equal to

$$\Delta\tau_{CD} \sim 2\pi|\beta_2|\Delta\nu \quad . \tag{5}$$

In the case of a bandwidth-limited pulse of duration this becomes

$$\Delta\tau_{CD} \sim \frac{2\pi|\beta_2|}{\Delta\tau} \quad . \tag{6}$$

A group velocity dispersion typical of standard single mode fiber at 1.55 µm (-22 ps2/km) and a pulse duration of 100 fs leads to a differential delay of 1.4 ps per meter of fiber, much larger than the initial pulse duration. Intra-cavity chromatic dispersion is instrumental in determining the regime of operation and the pulse duration in ultrafast mode-locked fiber lasers. It is customary to specify this dispersion taking into account the actual optical fiber length and to express the different dispersion orders in ps^2, ps^3, etc.

Chromatic dispersion in chirped fiber Bragg gratings

A fiber Bragg grating (FBG) consists in a strand of optical fiber containing a quasi periodical modulation of the core refractive index over a certain length [3,4]. This modulation is created by exposure to an ultraviolet light interference pattern incident transversely along the fiber. Exposure to UV light increases the refractive index proportionately to the local intensity. The periodic intensity of the interference pattern is thus transferred into a similar modulation of the refractive index. Proper thermal annealing after UV inscription ensures long term stability of the grating.

The periodic nature of the index modulation translates into a resonant response, the FBG reflecting light preferentially at the Bragg wavelength defined by

$$\lambda_B = 2n_{eff}\Lambda \quad , \tag{7}$$

where n_{eff} is the average effective index of the fiber and Λ is the period of the grating. On the other hand, the grating reflectivity depends on the amplitude of the index modulation. State-of-the-art manufacturing techniques allow controlling independently the longitudinal profiles of both the modulation amplitude and period, granting the FBG technology an unmatched flexibility for shaping complex spectral responses in intensity and group delay.

A grating with a modulation period that varies along the fiber axis reflects light of different wavelengths at different positions. For example, a chirped fiber Bragg grating (CFBG) with a linear period profile generates a group delay that varies linearly with wavelength. Figure 2 illustrates pulse stretching by a chirped grating with a period that decreases away from the entrance point. Longer wavelengths are reflected early along the grating while shorter wavelengths are reflected later near the back. The spectrum of the pulse is dispersed temporally, resulting in a stretched output pulse. More elaborate period profiles can be realized to generate complex spectral dispersions. The modulation amplitude of the CFBG can be tailored longitudinally as well, in order to shape spectrally the grating reflectance.

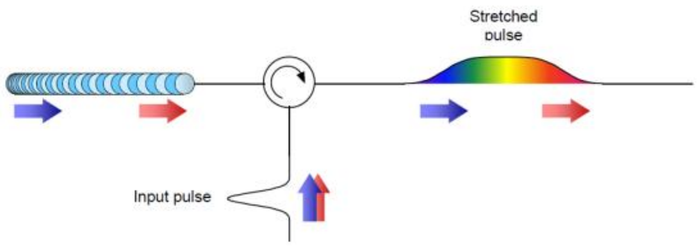

Figure 2: Pulse stretching by a chirped fiber Bragg grating

TeraXion CFBGs are available for Yb-doped and Er-doped fiber lasers. They can provide normal or anomalous dispersions ranging from ±0.015 to ±1200 ps2. The dispersion can be tuned thermally by applying a thermal gradient along the grating [5]. The maximum differential delay is limited by the grating length and amounts to nearly 1 ns for 14 cm long gratings. Reflectivity can be as high as 99% and the FWHM bandwidth can reach 100 nm. Chirped FBGs are thus compact, lowloss devices. Operating in reflection, they are used with an optical circulator as illustrated in Figure 2. If required, they can be cascaded to increase the dispersion levels. For example, two CFBGs can be readily cascaded with a four-port circulator. These gratings can be fabricated in standard or polarization-maintaining fiber if polarization control is required. Group delay and amplitude ripples in a filter spectral response can distort an incoming pulse or create echoes that contaminate the pulse background [6]. Chirped FBGs for ultrafast optics applications are now available with minimal group delay and insertion loss ripples.

Ultrafast optics applications of CFBGs

Mode-locked fiber lasers

Mode-locked lasers emit a periodical train of ultrashort optical pulses, the interval between successive pulses being equal to the round trip time within the laser cavity. The periodically pulsed output results from partial transmission by the output coupler of a single pulse making round trips inside the laser cavity. This solitary pulse owes its emergence from spontaneous emission at the laser turn-on from a preferential loss mechanism that favors oscillation during a limited time slot or at high intensity.

In actively mode-locked lasers, an intra-cavity modulator creates a time-varying loss with a period equal to the cavity round trip time. Photons propagating through the modulator at minimum loss get amplified preferentially at each round trip, while others traversing the modulator at less favorable times are discriminated against. The end-result is a single opticalpulse making round trips inside the cavity that goes through the modulator at minimum loss. Operation of such a laser hinges on an accurate match between the modulation period and the cavity round trip time. The achievable pulse duration depends on the modulation period and thus on the cavity length, shorter cavities leading to shorter pulses. Implicit in this description is the existence of a dynamical equilibrium that ensures stability of the intra-cavity pulse.

Since the pulse gets slightly compressed every time it goes through the loss modulator, it must be stretched on each round trip by the rest of the cavity, either as a result of dispersion or limited gain bandwidth. Not only the loss modulator, but the whole of the laser cavity shapes the intracavity pulse.

Passive mode-locking relies on an intensity-dependent loss such as provided, for example, by a saturable absorber. The emergence of a pulse is favored by an intra-cavity loss being quenched by the optical intensity. The loss modulation is driven by the optical pulse itself and gets stronger and faster as the pulse gets more intense and shorter. For this reason, passive mode-locking typically produces shorter pulses than active mode-locking. Ultrafast fiber lasers are mode-locked passively. The intensity-dependent loss can be provided by a saturable absorber: fiber lasers have been mode-locked with semiconductor and carbon nanotubes saturable absorbers. It can also result from self-phase modulation, whereby the optical intensity produces an increase in the refractive index of the optical fiber. Self-phase modulation is translated into an intensitydependent loss when it takes place in a Sagnac interferometer built as a fiber loop, in which case reflection and transmission by the interferometer become intensity-dependent. Nonlinear polarization evolution coupled to a polarization-dependent loss element can also serve as the basis of passive mode-locking in fiber lasers. This type of mode– locking is susceptible, however, to the optical fiber birefringence, which can vary with temperature.

Nonlinear self-phase modulation resulting from power concentration in the single mode fiber core and chromatic dispersion by the optical fiber are instrumental in determining the behavior of mode-locked fiber lasers. As aforementioned, their combined action can have various impacts, beneficial or detrimental, on optical pulses. All elements present in the laser cavity must be considered when assessing the behavior of the laser. Various laser designs have been developed to obtain stable mode-locked pulses, which can be classified according to their cavity dispersion [1].

A soliton laser has a cavity with anomalous dispersion (β_2<0). It produces bandwidth-limited pulses with a hyperbolic-secant temporal profile that propagate undistorted in a nonlinear fiber with anomalous dispersion. Perturbations resulting from self-phase modulation and dispersion must be balanced in order for such pulses to survive. As a result, the soliton energy and duration are linked, their product being a constant dependant on the fiber chromatic dispersion and nonlinearity. The energy and duration of pulses produced by a soliton laser both scale with the square root of the cavity dispersion [1]. Large values of negative dispersions can be obtained without a concomitant increase in nonlinearity by inserting a CFBG inside the cavity, allowing the production of more energetic, albeit longer output pulses [7]. Chirped FBGs can also extend the spectral domain over which soliton lasers are operated. As aforementioned, typical single mode silica fiber displays anomalous dispersion at wavelengths larger than 1.3 µm, which limited early demonstrations of soliton oscillation to Er-doped fiber lasers. Chirped FBGs were used to achieve soliton oscillation of a Nd-doped fiber laser at 1066 nm [8].

The output pulses from soliton lasers have long temporal wings and spectral sidebands resulting from a weak background accompanying their generation. Dispersion-managed fiber lasers, which operate near zero dispersion, typically produce shorter Gaussian pulses with greatly suppressed temporal wings and no spectral sidebands [1]. These lasers are usually built from fibers with dispersions of opposite signs. The fiber with normal dispersion cannot support solitons and produces a marked lengthening of the propagating pulse. This reduces nonlinear effects and allows the production of more energetic pulses. The pulse duration changes sizably during the course of a round trip inside the cavity. Chirped FBGs have been used to adjust the total dispersion in dispersion-managed lasers both at 1 µm (Yb-doped) and 1.5 µm (Er-doped) [9].

The laser configuration is illustrated in Figure 3. The grating was written in a polarization maintaining fiber, thus allowing truly single-polarization oscillation.

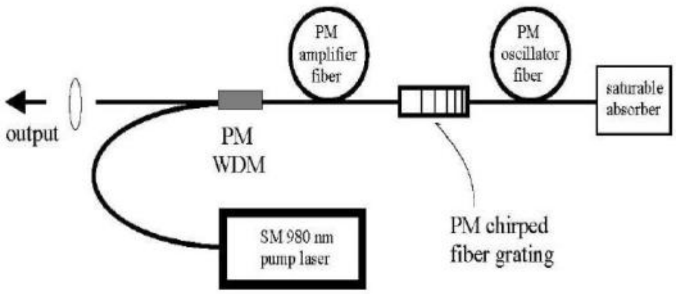

Figure 3: Dispersion-managed MOPA using a CFBG as output coupler

Mode-locked fiber lasers having a gain medium with normal dispersion and slightly positive overall cavity dispersion can be designed to produce chirped pulses of parabolic shape known as similaritons [1]. These are resistant to wave breaking and can withstand larger nonlinearities than solitons and Gaussian pulses: the pulse duration and chirp vary along the cavity, but the parabolic shape is maintained. Similariton lasers can produce more energetic pulses than soliton and dispersion-managed lasers. A similariton laser based on a Yb-doped fiber gain medium and a chirped fiber grating for dispersion adjustment was demonstrated in [10]: the overall dispersion cavity amounted to only 3000 fs^2.

Chirped FBGs used to adjust the cavity dispersion of mode-locked fiber lasers must have a bandwidth of many nanometers accommodating the mode-locked pulse spectrum and a small dispersion associated to a few meters of optical fiber or even less. For example, a 12-mm long grating used to demonstrate soliton oscillation in an Nd-doped fiber laser had a bandwidth of 7 nm centered around 1066.5 nm and provided a dispersion of 9.27 ps^2 [8]. The grating used to control the dispersion of a soliton Er-doped fiber laser had a bandwidth of 13 nm centered near 1555 nm, was 5-mm long and provided a dispersion at 1580 nm of 3.4 ps^2 [7]. Gratings used to adjust the dispersion in dispersion-managed lasers are required to provide dispersions representing a fraction of a ps^2, which is achieved with grating chirps of hundreds or even thousands of nm/cm [9].

Chirped pulse amplification (CPA)

The energy of ultrashort pulses can be increased through amplification. In doing so, care must be exercised that high peak intensities sufficient to trigger nonlinear distortion of the pulse or optical damage to the amplifier are not reached. This is especially true when fiber amplifiers are used, given the strong transversal confinement of the propagating pulse. To overcome these limitations, chirped pulse amplification can be used. The highest energies with femtosecond pulses are obtained via this technique. It consists in stretching the incoming pulse to a considerably longer duration with a strongly dispersive element prior to amplification. The pulse intensity is thus reduced to a level that avoids the aforementioned detrimental effects. In fiber amplifier systems, pulses are typically stretched to 1 ns or more in order to minimize nonlinear effects [11]. After amplification, the pulse is recompressed to its initial duration by an element of opposite dispersion. Chirped pulse amplification can also be used to offset the small energy storage capacity of semiconductor optical amplifiers (SOA) [12]. These amplifiers cannot hold much energy at any given time but can be replenished quickly. Stretching very strongly a pulse prior to amplification allows repumping of the gain medium during passage of the pulse, in essence recycling carriers that can each contribute multiple photons to the amplified pulse.

A CPA system is illustrated in Figure 4, where both stretching and recompression are performed by CFBGs with opposite dispersions. A fiber-based CPA relying on two CFBGs was demonstrated by Galvanauskas et al. [13]. Since the full peak power of the pulse is recovered within the compressor, achievable energies with such systems are well below a microjoule. In general, a bulk compressor is used, in which the transversal spatial extent of the pulse can be increased sizably to avoid optical damage or nonlinear effects.

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This is often realized with a pair of diffraction gratings as illustrated in Figure 5. The achievable dispersion for a given distance between the gratings can be increased by operating at grazing incidence, but this also increases higher order dispersion [2]. On the other hand, the quality of recompression depends on the match between the stretcher and compressor dispersions. Use of a nonlinearly chirped FBG to address the higher order dispersion of a grating compressor is definitely advantageous, as demonstrated by Imeshev et al. who compared grating recompression of pulses stretched with linearly and nonlinearly chirped FBGs [15]. Ultrashort 400-fs, 60-pJ pulses from an Er-doped fiber laser were stretched to over 700 ps by a nonlinearly chirped FBG ($\beta_2 L$ ~ 124 ps^2, $\beta_3 L$ ~ 4.72 ps^3, length ~ 12.6 cm, bandwidth ~ 9.8 nm, group delay ripple < 2 ps) and a linearly chirped FBG with the same GVD. Recompression of nonlinearly dispersed pulses produced near bandwidth-limited pulses with a contrast ratio better than 30 dB. On the other hand, when the linearly chirped stretcher was used, uncompensated higher order dispersion of the compressor lead to sizable temporal wings. A CFBG-based pulse stretcher can be designed to match not only the dispersion of the compressor, but also that of all other elements of the CPA system (e.g. transport fibers and fiber amplifier). This pulse shaping control afforded by CFBGs is especially of interest for applications requiring clean pulses with energy-free background.

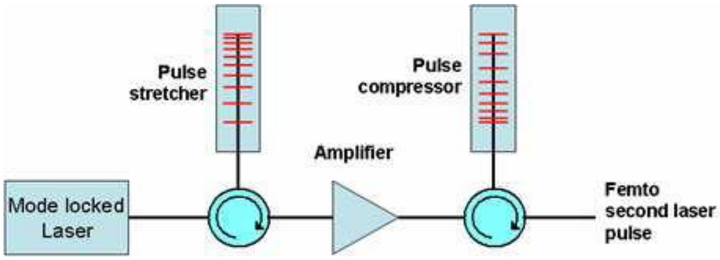

Figure 4: Chirped pulse amplification

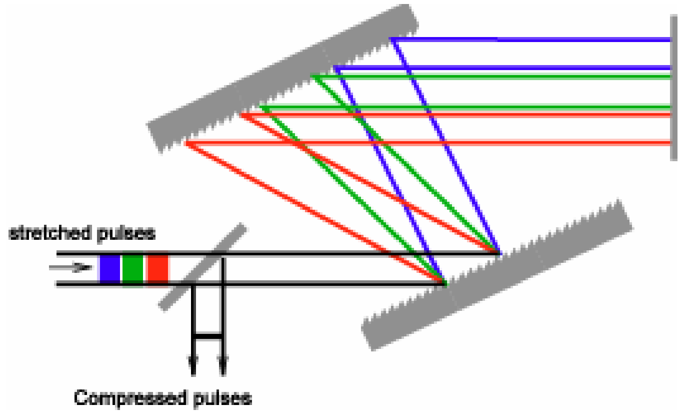

Figure 5: Compression of a stretched pulse with a grating pair [14]

CFBG pulse stretchers can bring another benefit to chirped pulse amplification. As shown by Barty et al., spectral shaping of the stretched pulse can be used to offset bandwidth limiting by the amplification process, thus allowing the production of shorter pulses [16]. This task could be accomplished by chirped FBGs with a properly shape reflectivity spectrum.

Like intra-cavity dispersion compensators, FBG pulse stretchers must accommodate the bandwidth of ultrashort pulses. Contrary to these, however, they must provide a differential group delay as large as possible. The maximum grating length achievable with phase mask writing is compatible with stretching to the nanosecond-level.

Conclusion

TeraXion developed CFBGs initially to address dispersion compensation needs in optical telecommunications links. Having met the exacting reliability requirements of this industry, CFBGs have gained wide acceptance as dispersion compensators for high speed links. The methods and principle of these highly reliable and well understood components are now applied to the benefit of ultrafast optics:

- They can be spliced to other fibers, allowing construction of truly fiber-based lasers;
- They are more compact than other dispersion compensators;
- They represent the most flexible dispersion compensation technology. They can provide normal or anomalous dispersion at wavelengths of current interest in fiber lasers. Nonlinearly chirped FBGs can be designed to correct for dispersions of all orders, which is especially interesting in CPA systems. They can also provide spectral shaping;
- They can be written in PM fibers, thus allowing the construction of environmentally stable cavities;
- Their shortness and the size of the fiber core in which they are written limit their nonlinearity;
- Their dispersion can be tuned.

References

[1] M. E. Fermann and I. Hartl, *Ultrafast Fiber Laser Technology*, IEEE J. Select. Topics Quantum Electron. **15**, 191-206 (2009).

[2] G. P. Agrawal, *Nonlinear Fiber Optics 2nd edition*, Academic Press (1995).

[3] A. Othonos and K. Kalli, *Fiber Bragg Gratings. Fundamentals, Applications in Telecommunications and Sensing,* Artech House (1999).

[4] R. Kashyap, *Fiber Bragg Gratings*, Academic Press (1999).

[5] Y. Painchaud, C. Paquet and M. Guy, *Optical Tunable Dispersion Compensators Based on Thermally Tuned Fiber Bragg Gratings*, Opt. Photon. News **18** (9), 48-53, September 2007.

[6] C. Scheerer et al., Influence *of filter group delay ripples on system performance*, European Conference on Optical Communications (ECOC), Vol. **1**, 410-411 (1999).

[7] M. E. Fermann, K. Sugden, and I. Bennion, *High-power soliton fiber laser based on pulse width control with chirped fiber Bragg gratings*. Opt. Lett. **20**, 172-174 (1995).

[8] M. Hofer et al., *High-power neodymium soliton fiber laser that uses a chirped fiber grating*, Opt. Lett. **20**, 1701-1703 (1995).

[9] I. Hartl et al., *Ultra-compact dispersion compensated femtosecond fiber oscillators and amplifiers*, Conference on Lasers and Electro-Optics (CLEO), paper CThG1 (2005).

[10] I. Hartl et al., *Self-referenced fCEO stabilization of a low noise femtosecond fiber oscillator*, Conference on Lasers and Electro-Optics (CLEO), paper CTuU (2008).

[11] R. Paschotta, http://www.rp-photonics.com/encyclopedia.html.

[12] K. Kim, S. Lee, and P.J. Delfyett, *All-semiconductor high-power eXtreme chirped pulse amplification system*, Proc. SPIE **6243**, paper 62430T (2006).

[13] A. Galvanauskas et al., *All-fiber femtosecond pulse amplification circuit using chirped Bragg gratings*, Appl. Phys. Lett. **66**, 1053-1055 (1995).

[14] http://en.wikipedia.org/wiki/Chirped_pulse_amplification

[15] G. Imeshev, I. Hartl, and M.E. Fermann, *Chirped pulse amplification with a nonlinearly chirped fiber Bragg grating matched to the Treacy compressor*, Opt. Lett. **29**, 679-681 (2004).

[16] C. P. J. Barty, C.L. Gordon, and B.E. Lemoff, *Multiterawatt 30-fs Ti:sapphire laser system*, Opt. Lett. **19**, 1442-1444 (1994).

About TeraXion

TeraXion is a leading-edge photonic solutions provider for high-end applications of the optical communications, industrial lasers and optical sensing markets. Its line of OEM chromatic dispersion management solutions includes Telcordia-qualified low-loss static and tunable dispersion compensators for terrestrial and submarine networks. TeraXion offers customized filtering solutions based on advanced FBG technology and narrow linewidth semiconductor laser sources for RF photonic and coherent detection systems.

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