The Power of Dispersion Management for 10-Gb/s and 40-Gb/s Systems

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Abstract: We review applications and requirements of dispersion compensation that enable high-capacity, long-haul, and ultra-long-haul 10-Gb/s and 40-Gb/s DWDM transmission. We briefly describe their impact on system performance and present some future perspectives.

The introduction of 10 Gb/s transmission in the mid 1990s required the implementation of chromatic dispersion compensation in order to transmit information beyond a few tens of kilometers. Since these early compensated systems, transmission has pushed toward higher data rates (namely, 40 Gb/s), longer distances (beyond 2000 km), and more WDM channels. This evolution in capacity and reach has been accompanied by changing requirements for dispersion compensation.

By the end of the 1990s, the introduction of ultra-long-haul (ULH) 10-Gb/s DWDM systems, capable of carrying signals in optical form for distances longer than 3000 km, required the implementation of dispersion maps where precise amounts of chromatic dispersion are provided at end terminals (pre- and post- compensation) and along the signal path (in-line compensation.) Since longer transmission distances are accompanied by an increase in accumulated nonlinear effects, these dispersion maps seek to balance the spectral-energy redistribution of self-phase modulation (SPM) with the temporal pulse-shaping effects of dispersion, while at the same time preventing the onset of deleterious cross-nonlinear interactions (mainly cross-phase modulation, XPM).

While systems operating at 10 Gb/s per channel generally employ fixed dispersion compensation, the introduction of 40-Gb/s transmission systems (commercially available since 2002) with a typical 16-fold reduction in dispersion tolerance, impose stringent dispersion requirements that often necessitate Tunable Dispersion Compensation (TDC), most often employed as post-compensation before the receiver. Currently, TDC devices for 40 Gb/s applications exhibit a tuning range of 400 ps/nm which approximately coincides with the dispersion tolerance of 500 ps/nm (corresponding to 1-dB penalty) of the most common On-Off-Keying formats encountered in 10 Gb/ systems (mainly NRZ for long-haul and RZ for ultra-long-haul applications). In some cases, a limited TDC range may become the main constraint on the achievable reach of a 40 Gb/s sytem.

Transmission systems that need to employ TDC are generally very sensitive to dispersion variations, such as those produced by temperature fluctuations in optical fibers, and require performance monitoring to achieve an efficient implementation. In recent years, state-of-the-art optical transport systems started to incorporate Forward Error Correction (FEC). FEC provides a convenient feedback on the Bit Error Rate (BER) performance that can be used to control TDC parameters.

When comparing dispersion-compensation requirements for 10 and 40 Gb/s, an important aspect to be considered is that optimal dispersion maps for 40 Gb/s are generally sub-optimal for 10 Gb/s transmission (and vice versa), as they now need to cope with nonlinearities arising from different nonlinear effects, such as Intra-channel XPM (IXPM) and Intra-channel Four-Wave Mixing (IFWM), with different scaling rules and impact on system performance [1]. For instance, 40 Gb/s

channels can operate under full dispersion per-span dispersion compensation, whereas such a dispersion map would lead to very poor performance in the case of 10 Gb/s WDM transmission due to XPM [2].

A gradual upgrade from 10 to 40 Gb/s systems will most likely bring scenarios of both data rates present in the same optical fiber. Furthermore, information carried at different rates may be imprinted by means of different modulation schemes (such as DPSK for 40 Gb/s co-existing with 10 Gb/s NRZ or RZ) with different intrinsic tolerances to residual dispersion (and nonlinearity) [3].

State-of-the-art ULH terrestrial systems also incorporate Optical Add/Drop Modules (OADMs) that optically route signals [4], allowing individual or group-of-channels to be dropped, added, or passed-through in between end-terminals. Ideally, these OADMs should implement dispersion maps able to handle hybrid data traffic with different dispersion tolerances, providing the desired amount of pre-, in-line, and post-compensation, depending on channel-routing conditions. Also, OADM applications may need a larger TDC dynamic-range than currently available to successfully handle 40 Gb/s traffic, especially in the common case of systems employing singly periodic dispersion maps.

In general, new dispersion maps are required in order to cope with new demands imposed by higher data rates, hybrid data traffic, and added system functionalities. As an example, one way to reduce the required TDC range for the aforementioned applications, and thus allowing a longer reach for 40 Gb/s traffic, is to implement a doubly-periodic dispersion map [5], where the residual dispersion is reset to the original pre-compensation value (at the system input-end) at OADM sites and end terminals. However, achieving such a map over a large WDM channel-spectrum (> 100 WDM channels) may impose strict requirements on Dispersion Compensation Modules' (DCMs) specifications, thus potentially impacting engineering rules and cost, and may also lead to increased XPM penalties for 10 Gb/s traffic.

Virtually all systems requiring fixed dispersion compensation are based on dispersion-compensating fibers (DCFs). However, depending on the application, dispersion compensation can be implemented by devices not based on DCFs. In recent years, alternatives to DCF-based dispersion compensation have emerged and some technologies have matured and became commercially available. These technologies include devices based on Fiber Bragg Gratings (FBGs) [6] and on Gires-Tournois Etalons (GTEs) [7].

Current commercial technologies employed for 40-Gb/s TDC are based on FBGs. FBGs, being fiber-based devices, are fully compatible with optical fibers, exhibit low insertion loss, low PMD, and low cost. Drawbacks of FBGs include a potentially large Group-Delay Ripple (GDR) and a limited tuning range. With the advent of ULH systems (reach > 1,500 km) this limited tuning range can become a performance-limiting factor.

In the case of 10 Gb/s systems, GTE-based DCMs have recently started to make their way into metro and LH systems as an alternative to DCF due to their large tuning range (2800 ps/nm), small form factor, low cost, and, in some cases, better Figure of Merit (FOM). Note that TDC also finds applications where tunable DCMs can be set to the required value for use as pre-, in-line, and post-compensation, thus helping reduce inventory overheads.

In general, advantages of non-DCF devices include immunity to Kerr nonlinearities, a small form factor, and the possibility of engineering arbitrary dispersion profiles. High FOMs and small form factors make these devices very attractive candidates for use in OADMs. One disadvantage lies in their lack of Raman gain, a desirable feature in ULH systems where high signal-to-noise levels are required, and large discrete-losses need to be avoided. Another potential disadvantage comes from these devices exhibiting dispersion passbands than can lead to cascading effects. To address this issue, recent system experiments have been performed on the feasibility of employing GTE-based DCMs for LH and ULH 10-Gb/s transmission showed no degradation attributable to group-delay and/or insertion-loss ripple, even under cascaded evaluation and detuning of the transmitter wavelength [8,9].

Summary

With the introduction of 10 Gb/s transmission, dispersion compensation became a necessity in order to achieve optical reaches beyond a few tens of kilometers. Further increase in the capacity and reach of these systems has been accompanied with changing demands on dispersion compensation. In the late 1990s, the introduction of ultra-long-haul 10-Gb/s systems, capable of carrying signals in optical form for distances in excess of 3,000 km, accentuated the need of dispersion maps able to cope with the increased impact of nonlinearities. For such long reaches, in turn, there is a need to be able to address channels in between end terminals, thus requiring the implementation of optical add/drop points where signals can be accessed and routed, imposing new constraints in the design of dispersion maps.

The advent of 40 Gb/s transmission has ushered in the use of tunable dispersion compensation, provided by non-DCF devices. Technologies based on FBGs and GTEs are now commercially available for TDC applications. In particular, GTE-based devices are becoming attractive candidates for multi-channel dispersion compensation in LH 10-Gb/s systems due to their small footprint, immunity to Kerr nonlinearities, and low cost. On the other hand, current non-DCF devices cannot be Raman-pumped.

Recent system experiments on the feasibility of employing GTE-based DCMs for long-haul and ultra-long-haul 10 Gb/s transmission showed no degradation attributable to group-delay and/or insertion-loss ripple, even under cascaded evaluation.

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