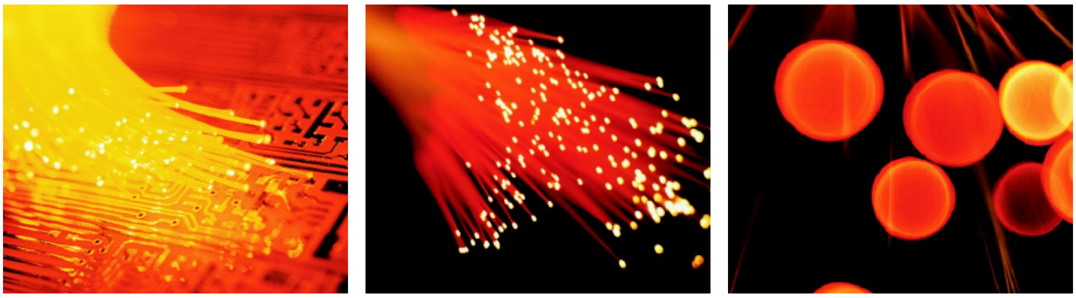
Dispersion Management

White Paper

Fiber Bragg Grating based DCM



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Abstract

This white paper will discuss the underlying technology and cost saving potential provided by Fiber Bragg Grating (FBG) based dispersion compensation.

Unique and enabling FBG features such as low insertion loss, lack of non-linearities, low latency, tunability etc will be explained in detail and a comparison between the incumbent dispersion compensating technology, namely Dispersion Compensating Fibers (DCF), and FBG based Dispersion Compensation Modules (FBG-DCMs) will be done. Important differences between the two technologies in regard to key characteristics and general properties as well as cost efficiency will be discussed.

Furthermore a number of implementing strategies and network architectures for specific optical transport applications will be disclosed.

The dispersion compensators discussed in this paper are commercially available from Proximion Fiber Systems AB.

About Proximion AB

Proximion Fiber Systems AB is a world-class provider of optical modules and sub-systems based on Fiber Bragg Grating (FBG) technology. By combining these unique optical devices with the truly innovative skills of our team, Proximion contributes to our customers' and partners' success in a variety of markets.

FBG based Dispersion Compensating Technology

Chromatic dispersion, i.e. temporal distortion (spreading or smearing) of short optical pulses as they traverse optical fibers, is a fundamental problem in optical transport. The distortions of the signal will, if not properly compensated for, lead to inter-symbol interference which eventually results in data loss and/or traffic interruption.

The traditional means of overcoming the issue of dispersion has been to incorporate space consuming bundles of DCF throughout the optical network. DCF based compensation is a quite straightforward technique, based on optical fibers having a dispersion coefficient with an opposite sign compared to standard single mode fiber used for the actual transport.

Typically, DCFs have a dispersion coefficient four to eight times that of standard single mode fiber. However, this level of dispersion is achieved by reducing the diameter of the fiber core, which in turn increases the fiber transmission loss as well as limits the levels of optical power that can effectively be transmitted through the fiber without inducing other distortions, so called “non-linear” effects.

Chromatic dispersion compensation using highly efficient reflective Fiber Bragg Gratings is significantly different from DCF compensation and proves to have, as later will be described, some obvious benefits with regard to addressing both the technical as well as the cost-related issues of current and future dispersion compensation.

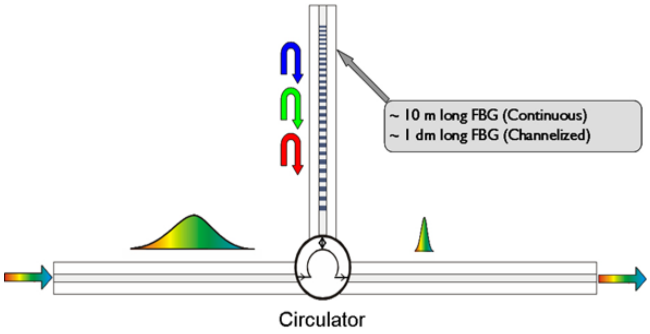


Figure 1 – FBG based dispersion compensation principle

Dispersion compensation utilizing FBGs is based on the introduction of wavelength-specific time delays through the use of a precisely chirped FBG. By combining such an FBG with a standard optical circulator a highly effective Dispersion Compensation Module (DCM) can be realized.

A graphical illustration of the FBG based dispersion compensating principle is shown in Figure 1.

FBG-DCMs are devised by basically assembling an optical circulator and a chirped FBG. The basic principle is to achieve the compression of a dispersion broadened pulse by letting the “fast” wavelengths of the pulse be reflected further away in the FBG than the “slow” wavelengths that are reflected closer to the circulator.

Two main types of FBG based dispersion compensators are commercially available today, multi-channel (or channelized) and continuous. The channelized version provides channel spacing specific, or grid specific, compensation whereas the continuous type provides, in much the same manner as a DCF, continuous compensation throughout the C-band, hence providing total channel plan independency.

Important to realize is the lack of channel partitioning of the bandwidth in the continuous type of FBG-DCM. The device operates truly continuously over the whole C-band. One additional benefit of having a continuous FBG is that no temperature control is required for the component, as there is no need to prevent the DCM operating bandwidth to glide out of the ITU channel. Furthermore, for standard fibers, the derivative of the group delay, i.e. the dispersion, is essentially the same regardless if the grating shifts in wavelength with temperature hence the FBG-DCM is a totally passive optical component with no active components.

Optical Characteristics

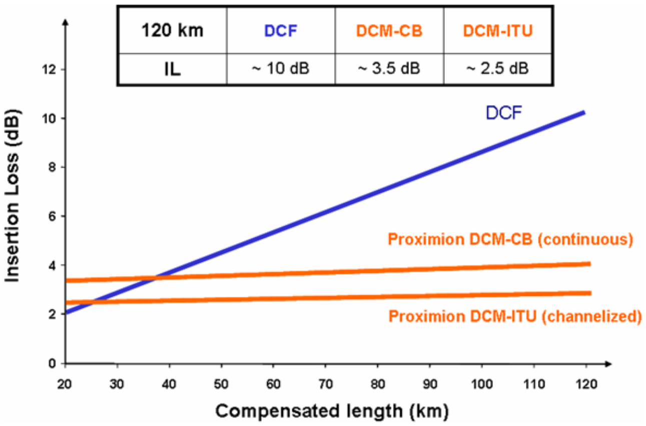
Insertion Loss

The most obvious and commonly known advantage relating to FGB based Dispersion Compensation Modules (FBG-DCMs) is the low insertion loss (IL). Typically, a 120 km FBG-DCM has an insertion loss in the range of 2-4 dB dependent on type while a DCF equivalent represent an IL of approximately 10 dB or even higher.

In the case of DCFs the insertion loss originates from the attenuation in the fiber itself due to the reduction in core diameter needed to achieve sufficient dispersion compensation. This will result in a linear increase of the insertion loss with span length, i.e. the amount of dispersion to be compensated for.

The FBG case is fundamentally different compared to that of a DCF as the length of the fiber gratings used is very short, hence having only a fraction of the total loss. In fact, the IL of an FBG-DCM is mainly governed by the optical components used in the design, e.g. circulator(s) and in some cases tilt filters.

This lack of linear compensation length behavior, i.e. span length independence, is of course a huge cost saver when it comes to compensation of longer spans, since it directly reduces the amount of amplification needed to sustain sufficient optical signal strength. The typical IL characteristics of DCF and FBG based dispersion compensation is illustrated in Figure 2.



120 km	DCF	DCM-CB	DCM-ITU
IL	~ 10 dB	~ 3.5 dB	~ 2.5 dB

Figure 2 – Insertion Loss comparison between DCF-DCM and FBG-DCM

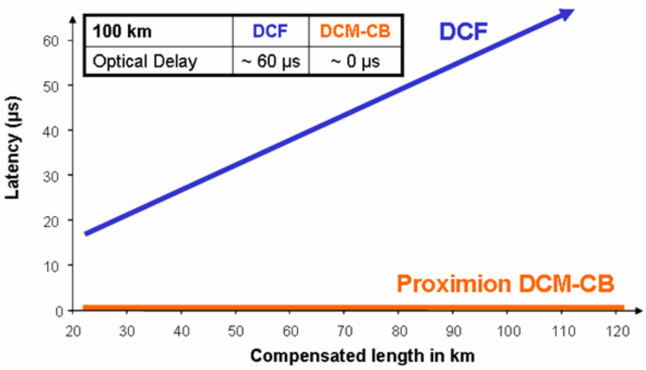
Latency

The typical length of a DCF is about 15%-20% of the length of the span to be compensated. This fact inevitably leads to bulky components since a single DCF-DCM may contain in excess of 20 km of fiber. Long fibers are not an issue in the case of FBG-DCMs, which directly translates to massive terminal space savings due to the favorable form that can be achieved.

Apart from the highly favorable form factor, this length difference also yields one other key advantage of the FBG-DCM compared to the DCF-DCM, namely low latency.

The latency, defined as the time delay of an optical signal imposed by any in-line device, is in the case of passive dispersion compensation directly proportional to the optical path length of said device.

Latency numbers in the range of 50-100 µs is not uncommon for DCF-DCMs. On the other hand, the latency of an FBG-DCM is typically three orders of magnitude smaller and can in most practical cases be considered negligible, see Figure 3.



100 km	DCF	DCM-CB
Optical Delay	~ 60 µs	~ 0 µs

Figure 3 – Latency comparison between DCF-DCM and FBG-DCM

It is commonly known that latency is an issue in Storage Area Networks (SAN) and other applications relying on massive package transfer due to the negative impact on effective throughput and/or reach. Low latency is also a key enabler for the novel cost efficient and high performance amplifier designs currently emerging.

Power management and non-linearities

The ability to tolerate high optical powers without suffering from penalties caused by non-linear effects is also one prominent characteristic separating the FBG-DCM from the DCF-DCM. While a DCF will display non-linearity effects at rather low optical powers, typically limiting the power to -2 dBm per channel, the FBG-DCM will not introduce such effects even at the highest power levels present throughout any traditional optical network.

General Properties and Applications

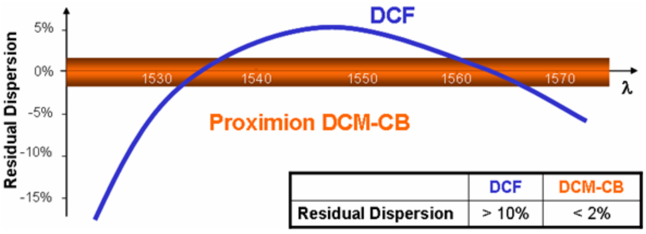
Dispersion Matching

High residual dispersion, i.e. the mismatch between the dispersion compensator characteristic and the optical line dispersion characteristic, inevitably leads to transmission penalties. When considering the ongoing transition from 10G to 40G and above more stringent requirements on dispersion tolerances are expected hence dispersion matching becomes even more important than before.

DCF-based compensation typically displays a high degree of wavelength-dependent residual dispersion due to manufacturing and design issues leading to batch-to-batch variations and inadequate slope matching. This behavior is especially noticeable for DCFs targeting non-zero dispersion-shifted fiber (NZ-DSF), e.g. LEAF fiber compensation, but also exists to some extent for standard single-mode fiber (SMF) optimized DCFs.

In the case of FBG based dispersion compensation the story is quite different. By utilizing advanced fiber exposure techniques the chirp of the FBG can be tailor made. This ability to tailor the compensation behavior of the FBG, to fit virtually any dispersion and dispersion slope characteristic is one of many advantages of FBG technology.

A comparison between a typical DCF and FBG compensation of NZ-DSF is illustrated in Figure 4.



	DCF	DCM-CB
Residual Dispersion	> 10%	< 2%

Figure 4 – Typical residual dispersion for DCF-DCM versus FBG-DCM for a NZ-DS Fiber

Proximion standard products are designed to fit the most commonly deployed standard G.652 or G.655 fibers, i.e. SMF-28 and LEAF, Figure 5.

For traditional optical transport the majority of the dispersion compensation used is negative but some special applications rely on positive dispersion compensation as well. In the FBG case, positive dispersion can easily be produced, since it basically just involves the reversal of the grating chirp.

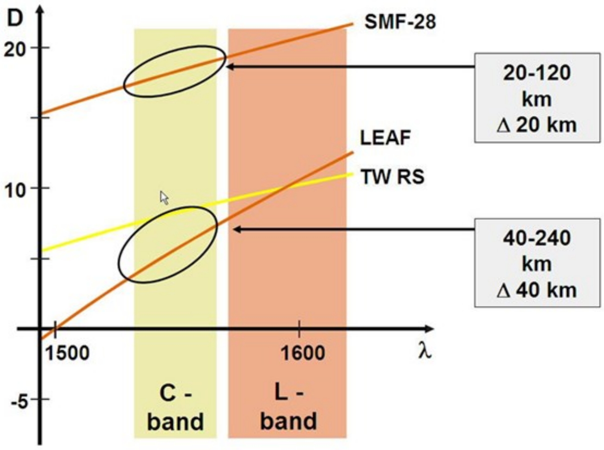


Figure 5 – Standard DCM-CB fiber types and typical span length granularity

Form Factor

The form factor of terminal equipment is also an important property to take into account when designing optical transport networks. Using bundles of DCF, typical in the excess of 10 kilometers each, can not be considered to be an effective use of terminal space. The extremely short fiber used in FBG designs enable an immense space saving hence resulting in substantial OPEX and CAPEX related savings.

In Figure 6, a comparison of the form factor for different dispersion compensation technologies is presented. Simply by exchanging a typical DCF-DCM with a continuous FBG-DCM will result in a direct space saving of about 75%. A channelized FBG-DCM would require less than 5% of the space of a dispersion equivalent DCF.

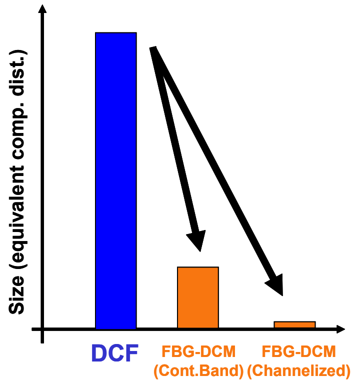


Figure 6 – Form Factor comparison between DCF-DCM and FBG-DCM

FBG-DCM optimized Mid-Stage Access EDFA Amplifiers

Conventional Erbium Doped Fiber Amplifiers (EDFAs) can be optimized in a number of ways if the unique qualities of the FBG-DCM are properly taken advantage of. Significant improvements can be achieved not only regarding performance, such as improving Noise Figure (NF), but also size, cost and robustness of design.

A traditional Mid-Stage access Amplifier (MSA), as shown in Figure 7, is designed to mitigate the high insertion loss of DCF-DCM by, for instance, utilizing a triple-stage, dual-pump approach, i.e. a dual stage pre-amplifier in combination with a booster.

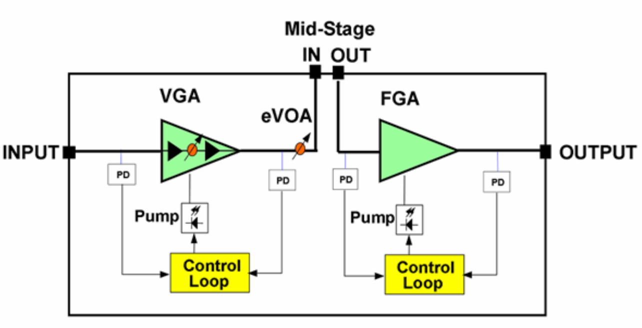


Figure 7 – Conventional mid-stage access amplifier

The main elements of this design are a dual stage variable gain pre-amplifier, and an additional variable optical attenuator (eVOA) placed before the mid-stage access. The variable gain pre-amplifier, which itself includes an eVOA between the two sub-stages, provides for the variable gain operation of the entire MSA. The additional eVOA before the mid-stage access is required to support different DCF losses for different span length.

By simply substituting a DCF-DCM with an equivalent FBG-DCM, the low and virtually span length independent mid-stage loss allows the two eVOA's to be combined without adversely affecting the overall NF performance. In addition, the simplified design requires fewer passive components further improving the NF.

Furthermore the virtually non-existent latency provides the MSA designer with the opportunity to use a single control loop; hence only one pump is necessary to serve the entire amplifier. The lower pump power needed also improves the overall NF.

Figure 8 shows an MSA design optimized for FGB based dispersion management. This design has the advantage of much reduced component count (single pump, single eVOA, fewer detectors, fewer passive components), as well as significantly simplified electronics (single control loop instead of two separate control loops). This results in up to 30% cost reduction, as well as 50% footprint reduction compared to the conventional MSA design.

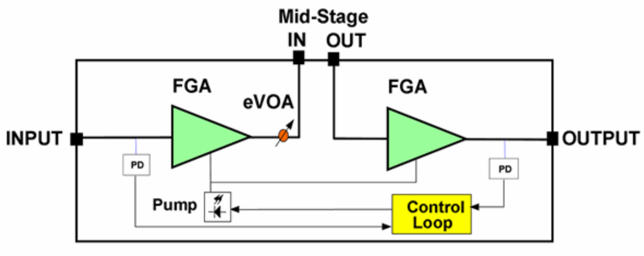


Figure 8 – FBG-DCM optimized mid-stage access amplifier

Even further cost reduction can be achieved by integrating the circulator from the FBG-DCM within the amplifier, as shown in Figure 9.

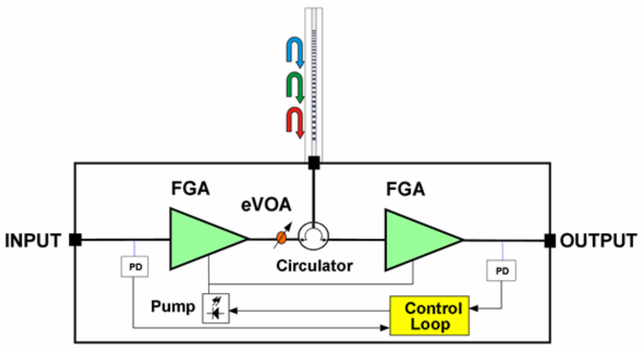


Figure 9 – FBG-DCM optimized mid-stage access amplifier

Network Architectures and Cost Saving Strategies

Point-to-Point Networks

By making good use of the low insertion loss, the equivalent of hundreds of kilometers of single-mode fiber (SMF) dispersion compensation can be concentrated in single nodes. This is especially interesting to achieve cost-effective point-to-point networks, not requiring distributed dispersion compensation.

The low loss and high-power tolerance further provide the network designer with the possibility of placing the compensation either directly after the multiplexer (MUX) on the transmitter side or after the booster. The exact placement of the FBG-DCM will be governed by optical signal-to-noise ratio (OSNR) requirements and/or terminal equipment layout.

In Figure 10 one implementation possibility is illustrated.

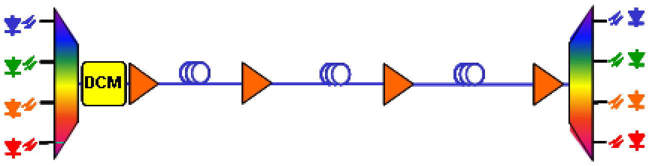


Figure 10 – Point-to-Point optical transport network with pre-booster FBG-DCM placement

In the case of DCF-DCM issues normally arises either from high loss limiting the amount of dispersion compensation close to the transmitter or the introduction of high non-linearity penalties if placed directly after the booster.

Dispersion Distributed Networks

Networks requiring distributed dispersion compensation, typically an architecture used when requirement on signal fidelity at each node is vital, normally relies on the use of mid-stage access amplifiers, or node specific DCMs, to accommodate this.

By utilizing the low insertion loss of the FBG-DCM, the elimination of mid-stage amplifiers is in some networks, an attractive strategy to pursue. If such a strategy is implemented in a network the amplifier related cost saving per span can be as high as 40% (Figure 11).

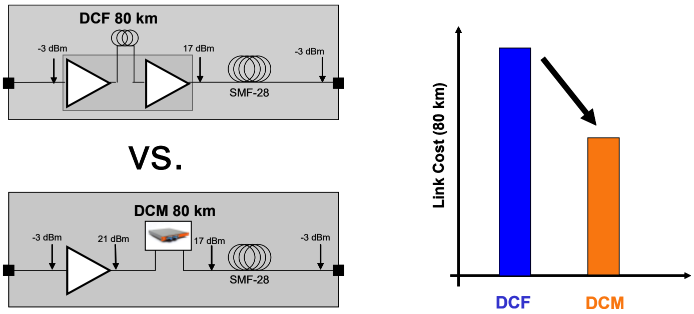


Figure 11 – Amplification cost saving by utilizing in-line FBG-DCM

Even in networks where MSAs are not used the insertion loss related cost saving could still be significant. By simply utilizing amplifiers with less available output power, as illustrated in Figure 12, the savings on amplifications alone can be in the area of 20% for a standard 80 km span.

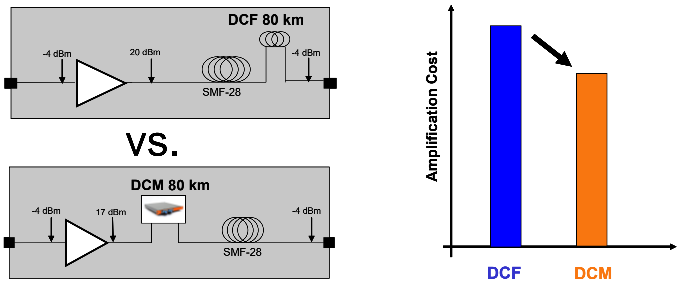


Figure 12 – Cost saving enabled by high loss DCF-DCM to low loss FBG-DCM substitution

Green Field Networks and Hut-skipping

In green field projects or in networks where hut skipping is of interest the low loss of the FBG-DCM can directly be translated to a reach advantage.

As illustrated in Figure 13, a channelized FBG-DCM would support full dispersion compensation of a 25% longer span than an equivalent DCF based solution. In the case of a continuous FBG-DCM the reach advantage over DCF is about 20%.

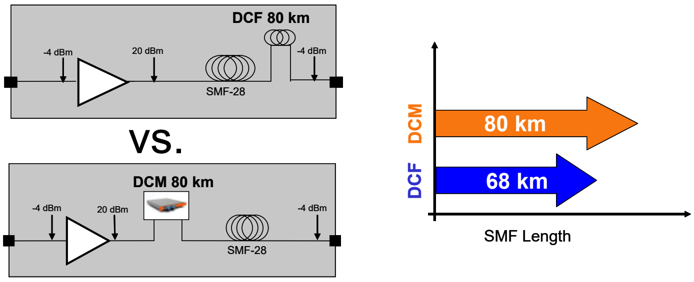


Figure 13 – Reach advantage for an FBG-DCM over a DCF-DCM

When upgrading legacy networks the low insertion loss provided by the FBG-DCM can enable hut-skipping, i.e. every second or third terminal would not require any dispersion compensating elements.

Any reduction in terminal equipment or an increase in reach, meaning less sites to maintain, naturally leads to significant cost savings, not only directly addressing CAPEX but OPEX as well.

Submarine Networks

In ultra long haul applications, i.e. submarine links, where typically fiber mixing is the method of choice for dispersion management, aggregated dispersion becomes an issue. It is in general no problem to optimize the optical transport fiber to have a zero dispersion at the center of the transmitted band, however huge amounts of residual dispersion is usually built up at the edges of said band, as illustrated in Figure 14.

This dispersion build-up is caused by the difference in dispersion versus wavelength characteristics of the fibers used and increases linearly with the transport distance and can reach values of several thousands ps/nm.

There are methods used today where DCF fiber is employed to compensate for the negative dispersion and bundles of SMF fibers are used to compensate for the positive ditto. However this solution, when considering dispersion values in the thousands, is extremely bulky and loss prone.

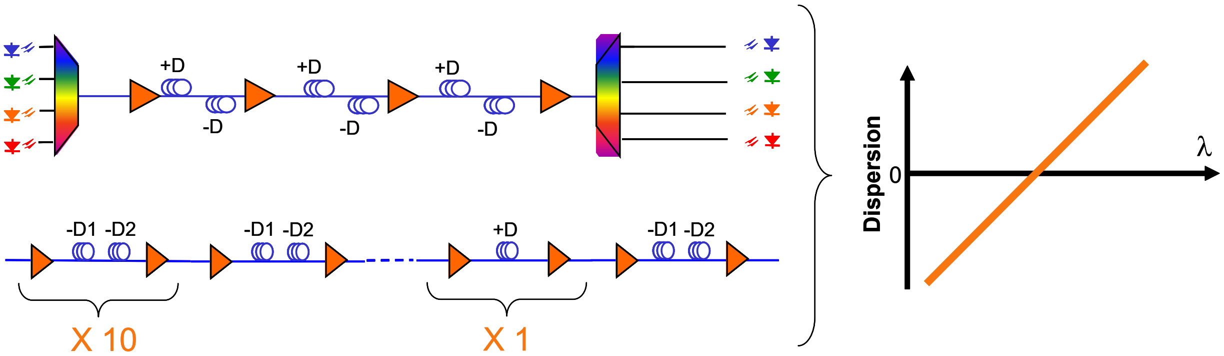


Figure 14 – Residual dispersion build-up in submarine transmission links

For example by utilizing standard SMF fiber to compensate for a residual dispersion of -3500 ps/nm would require about 200 km of SMF hence resulting in a direct loss in the excess of 40 dB. Further considering form factor an equivalent FBG-DCM would require about 20 times less space than the SMF based compensation.

One way of addressing the space and loss issues relating to the residual dispersion is to incorporate channelized FBG devises. These DCM-ITUs would typically be incorporated on a channel by channel basis as illustrated in Figure 15.

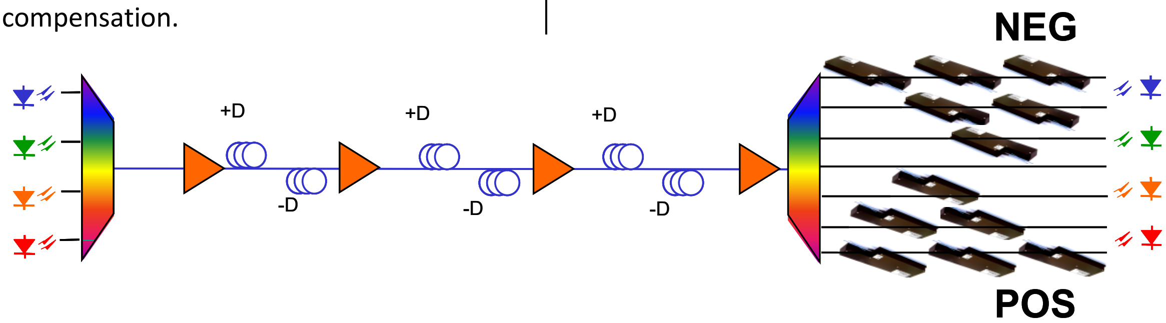


Figure 15 – Channel specific dispersion compensation utilizing FBG-DCMs

Yet another way to address this issue, and probably the most cost effective as well, is to utilize continuous band FBG-DCM technology. By fully taking advantage of the fact that the design chirp governs the dispersion characteristics and the fact that FBGs can effortlessly be combined makes it possible to match basically any residual slope characteristics.

In Figure 16, an FBG based residual slope compensator set-up is presented. In this particular case the effective transmission bandwidth has been divided into three bands. The exact implementation is of course dependent on terminal design, interleaving strategy, C-band utilization and maximum dispersion of a specific optical transport amp chain.

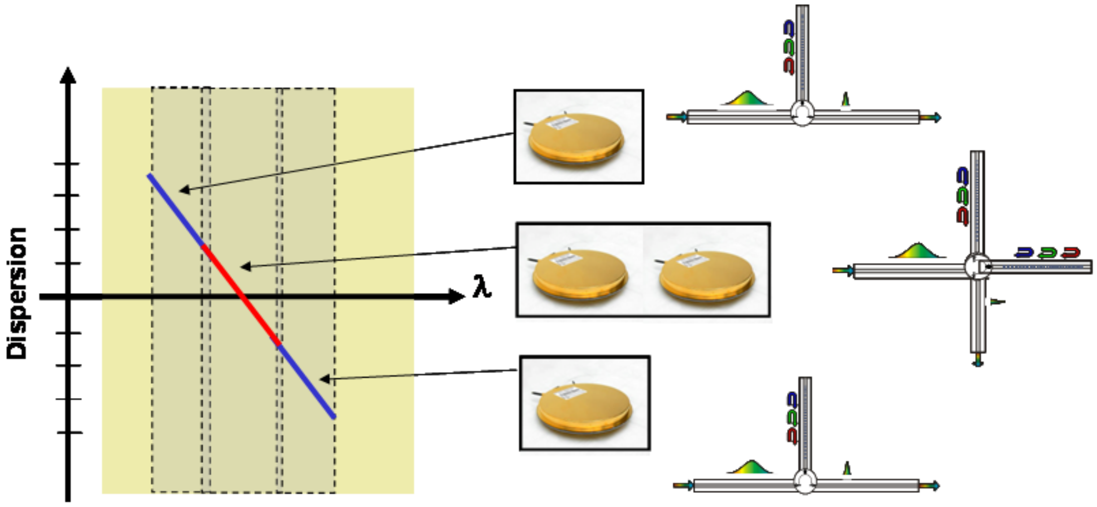


Figure 16 – FBG based Residual Slope Compensator

Pay special attention to the middle band where two FBGs, a positive and a negative, have been combined by the use of a 4-port circulator in order to achieve zero dispersion at a specific wavelength.

High Bit Rate Applications

When it comes to dispersion compensation it indeed becomes more stringent when the bit rate increases. For instance while a 10G network transponder may have a dispersion window in the excess of 1000 ps/nm the 40G equivalent will be below 100 ps/nm.

Different strategies to mitigate this sensitivity to dispersion in high bit rate networks has been pursued. One way of increasing the dispersion tolerance is to move away from simple digital encoding formats, e.g. On-Off Keying (OOK) and start employing more dispersion tolerant formats such as Duobinary and Differential Quadrature Phase Shift Keying (DQPSK).

Although utilizing new modulation schemes for sure will increase the tolerance to chromatic dispersion many system vendors and operators are turning to Tunable Dispersion Compensators (TDCMs) for their future systems.

TDCMs allows the system vendor to basically use 10G design rules for 40G networks since it has the potential to increase the dispersion tolerance tenfold, thus allowing the original 10G link to remain largely intact.

Figure 17 – Proximion's TDCM

In addition, the TDCM will also handle time-varying dispersion changes induced by normal temperature variations along the fiber.

FBG based technology has proven very suitable for TDCMs. FBG based adaptive dispersion compensation is commercially available today and tunable FBGs are being considered as the technology of choice in numerous 40G and 100G optical systems currently being developed.

It is advantageous from a system point of view to be able to compensate for both positive and negative dispersion. This can be done by having two temperature controlled FBGs connected to an optical four-port circulator. See figure 18. In such an implementation the mean temperature can be made to control the wavelength while the temperature gradients control the dispersion.

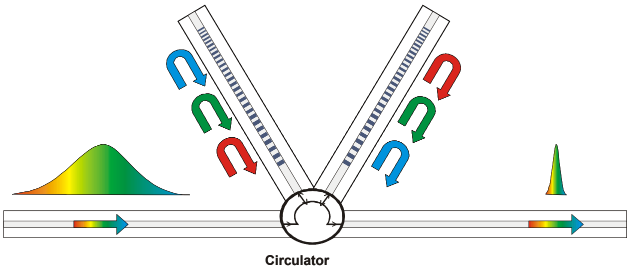


Figure 18 – Basic principle of TDCM

This gives a colorless operation with a wide dispersion tuning range. Due to the colorless operation identical products can be used for all channels across the full C-band spectrum. Furthermore, the FBG technology enables low loss, wide optical bandwidth in combination with a very attractive form factor.

Storage Area Networks (SAN)

When considering SAN or other packet based optical transport networks the negligible latency provided by the FBG-DCM is a key parameter.

As bit rates increases in this type of network architectures the need for dispersion management has become a reality. Since these types of networks usually rely on latency sensitive data transfer protocols, e.g. FibreChannel, the choice of dispersion compensation technology is vital for optimizing the optical transport.

In a typical SAN application an FBG-DCM would support up to 10% longer transport without any reduction in effective bit rate (drooping) compared to a DCF solution, alternatively support a 10% higher bit rate once drooping occurs (Figure 19).

The low insertion loss in combination with the favorable form factor of course adds additional value for SAN applications as well.

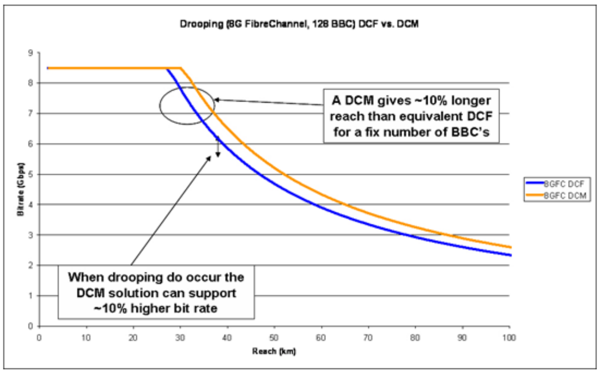


Figure 19 – Effective throughput/reach advantage for FBG-DCM over DCF-DCM

Single Channel Applications

FBG based dispersion has been used for many years to address the specific requirements for single channel applications, such as TDM based SONET/SDH systems.

The DCMs used in these systems has usually been in the form of athermal packaged channelized gratings. However, quite recently, a novel packaging technique has made it possible for these single channel FBG-DCMs to be offered integrated in patch cords.

This new packaging technique enables the use of wider continuous gratings rather than narrow channelized ones. The freedom in grating design and unique form factor offered by this solution makes this a very suitable solution not only for 10G systems but also for 40G/100G systems using wider modulation formats.

The utilization of a wide continuous grating further removes the necessity of costly thermal stabilization of the FBG hence a smaller and more cost effective component can be realized.

Figure 20 – FBG and circulator incorporated in a patch cord

FBG Technology and Manufacturing

A fiber Bragg grating can, in its simplest context, be seen as an optical filter where a part of the incident light is either being transmitted or reflected. Since the grating is written in the actual core of the fiber it interacts with the light being transmitted.

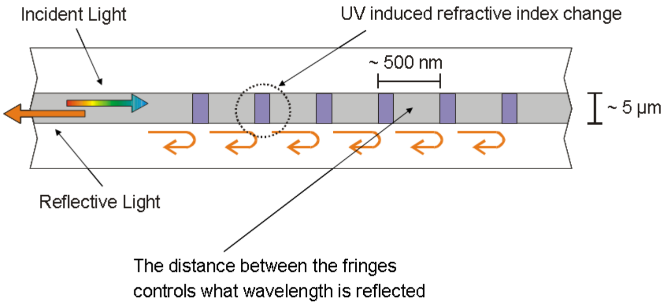


Figure 21 – A view of the ultraviolet fringe pattern induced in the core of the fiber. The distance between the fringes controls what wavelength is reflected, e.g. 500 nm would typically reflect wavelengths close to 1500 nm.

A grating is generated by exposing the core, typically no more than 5 µm in diameter (i.e. a tenth of the diameter of a normal human body-hair) of a specially prepared optical fiber to a fringe pattern of ultraviolet light. The ultraviolet light will locally induce a change in the refractive index of the core. A change in refractive index, even a small change, will be seen as a tiny mirror by the light trying to pass through the grating, and a small portion will be reflected.

By generating many of these local mirrors in sequence at well defined distances, an optically resonant cavity is produced. By tuning the distance and amplitude between the mirror elements, the filter characteristics (e.g. the wavelengths and amount of reflected light) can also be tuned.

Proximion's versatile and proprietary grating writing technology utilizes a two-beam interferometer, as shown in Figure 22, to create a fringe pattern of ultraviolet light used for inducing the change of refractive index to the core of the fiber. A highly accurate motion controller can sequentially add up these fringe patterns with nanometer precision over long distances.

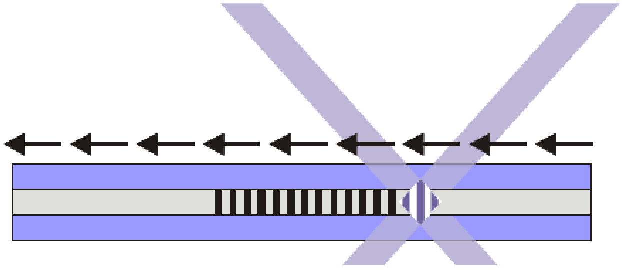


Figure 22 - Two ultraviolet laser beams interfere, resulting in a fringe pattern. By accurately controlling the motion of the fiber many successive fringe patterns can be added into very long gratings

By actively controlling the period of the fringe pattern basically any type of FBG can be generated. Grating characteristics such as wavelength range, reflection and dispersion compensation characteristics are easily controlled via the exposure SW.

Summary

FBG based chromatic dispersion management provides the telecommunication industry with unparalleled possibilities when it comes to cost and performance network optimization. The increased focus on cost, especially considering the future of 40G and 100G networks, is well served by this unique and in many aspects disruptive technology – a conclusion supported by the to date, thousands of units deployed in various networks worldwide.