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Fiber Bragg Gratings: The Dispersion Compensation Technology For 40G And 100G Optical Transport

Fiber Bragg Grating technology bests conventional dispersion compensation fiber in terms of attenuation and bandwidth in the new 40- and 100-Gbit/s optical networks.

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The pursuit of faster and more cost-effective optical transport networks is a never-ending quest for both optical-system vendors and network operators in the telecommunications industry. In much the same manner as the transition from 2.5G (gigabits) to 10G in the late 1990s, the industry is now experiencing similar challenges with the next capacity-quadrupling technology step from 10G to 40G.

The pace at which this transition will occur is largely governed by the access to suitable technology at a reasonable cost. This article explains how dispersion compensation based on Fiber Bragg Gratings (FBGs) can deliver cost savings as well as meet the technical requirement needed to facilitate higher-bit-rate optical transport networks.

During the past couple of years, FBG-based dispersion compensators have become a real alternative to the incumbent technology of dispersion compensating fibers (DCFs). With DCF technology maturing to the point where changes can only be evolutionary rather than revolutionary, the field has now opened up to the disruptive and cost-effective technology of FBGs.

Initially faced with the skepticism received by any disruptive technology, the advantages of utilizing FBGs for dispersion management have eventually become too obvious to ignore. This is evident from the thousands of FBG-DCMs deployed in various systems worldwide over the past several years.

FBG-based dispersion compensation

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 that eventually results in data loss and/or traffic interruption.

The traditional means of overcoming the issue of dispersion has been to incorporate 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. This, 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 “nonlinear” effects.

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

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 a FBG with a standard optical circulator, a highly effective dispersion compensation module (DCM) can be realized.

A graphical illustration of a FBG and the dispersion compensating principle is shown in Figures 1 and 2.

The re-compression of a dispersion-broadened pulse is accomplished by letting the “fast” wavelengths of the pulse reflect farther away in the FBG than the “slow” wavelengths reflected closer to the circulator. The exact reflection position for each wavelength is governed by the precise, photo-induced, refractive index changes within the fiber, which are controlled, down to single nanometers, by a highly sophisticated manufacturing method.

Accurate control over the FBG chirp is the key for precise dispersion compensation. By utilizing state-of-the art direct-write FBG manufacturing techniques, dispersion characteristics can be made to precisely mimic the dispersion properties of the fiber or span intended for compensation.

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. The continuous type provides, in much the same manner as a DCF, continuous compensation throughout the C or L band. The continuous type thereby offers total channel plan independence, a feature especially interesting when considering higher bit rates, dense channel spacing, and future upgradeability.

FBGs vs. DCFs
As mentioned earlier, insertion loss is one of the largest drawbacks when it comes to utilizing DCFs for dispersion compensation. For example, commercial DCFs for 100- to 120-km standard single-mode fiber compensation have about 10 dB of insertion loss, whereas a continuous FBG-DCM compensating the same span length would only have between 3 to 4 dB (and below 3 dB for a channelized FBG solution).

Furthermore, the DCF has a loss that's approximately linear with the compensated length, whereas loss is more or less constant in FBGs (Fig. 3).

Insertion loss is a major cost driver in optical networks, because it directly affects the amount of amplification needed. Keeping down the numbers of amplifiers isn't just a key issue in terms of cost, though. It's also a fact that erbium-doped fiber amplifiers (EDFAs) actually add strongly wavelength-dependent dispersion—negatively affecting system performance as their numbers increase.

Another benefit of the FBG-DCM is its resilience to withstand high optical power. In contrast to DCFs, which display severe nonlinearity issues at quite moderate optical powers, the FBG-DCM can tolerate the highest optical power commonly found in any optical network without inducing any such effects.

Accurate dispersion compensation becomes more stringent when increasing the bit rate. Slightly depending on modulation format, the dispersion tolerance is proportional to the square of the bit rate. Typically, the chromatic dispersion tolerance for a 10G transmission line is above 1000 picoseconds per nanometer (ps/nm). But when considering optical transport at 40G, this tolerance typically falls well below 100 ps/nm.

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

Low residual chromatic dispersion is an important requirement, particularly in high-bit-rate applications and where full-wavelength-band dispersion compensation is desirable. Thus, the ability of FBG technology to tailor the FBG's compensation behavior to fit virtually any dispersion and dispersion slope characteristic becomes a key advantage.

Figure 4 illustrates a comparison between a typical DCF and FBG compensation of NZ-DSF. It can clearly be seen that a significant wavelength-dependent dispersion variation exists for the DCF. In practice, this means that the different channels being transmitted throughout the C-band would experience different compensations, and worst-case, some channels may not work properly.

To overcome the severe dispersion requirements imposed by high-bit-rate transport, a number of strategies were developed. One way to increase 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).

Utilizing new modulation schemes will certainly increase the tolerance to chromatic dispersion. Consequently, many system vendors and operators are turning to tunable dispersion compensators (T-DCMs) for future systems.

T-DCMs allow the system vendor to basically use 10G design rules for 40G networks, since it has the potential to increase the dispersion tolerance tenfold. As such, the original 10G link can remain largely intact. In addition, the T-DCM will also handle time-varying dispersion changes induced by normal temperature variations along the fiber.

FBG-based technology has proven very suitable for T-DCM. 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 being developed.

Low-cost architectural strategies
The specific cost savings achievable by introducing FBG-based dispersion compensation is closely related to the specific topology of an optical transport link. However, some general and straightforward examples immediately stand out.

By making good use of the low insertion loss, the equivalent of hundreds of kilometers of SMF dispersion compensation can be concentrated in single nodes. This is especially interesting to achieve cost-effective point-to-point networks that don't require distributed dispersion compensation.

The low loss and high-power tolerance further provide network designers with the possibility of placing the compensation either directly after the multiplexer on the transmitter side or after the booster (placing the DCM will be governed by optical signal-to-noise ratio (OSNR) requirements and/or terminal equipment layout). In the case of DCF-DCM, issues normally arise either from high loss limiting the amount of dispersion compensation close to the transmitter, or the introduction of high nonlinearity penalties if placed directly after the booster.

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

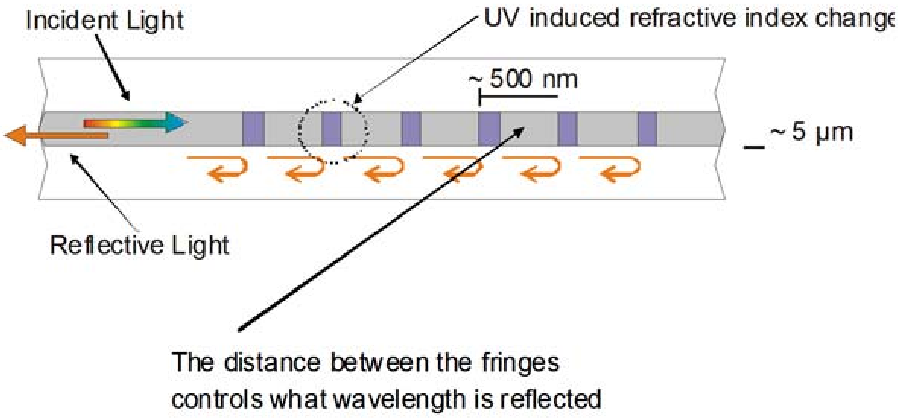
In some cases, drawing on the low insertion loss of the FBG-DCM, which in turn enables a simple in-line approach, can actually eliminate the need for mid-stage access amplifiers in these networks. If such a strategy is fully implemented in a network, the amplifier-related cost saving per span may reach as high as 40% (Fig. 5).

Even in networks that normally don't use mid-stage access amplifiers, insertion-loss-related cost saving could still be significant. By simply utilizing amplifiers with less available output power, the savings on amplifications can be in the area of 20% for a standard 80-km span.

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. A FBG-DCM would support full dispersion compensation of a 25% longer span than an equivalent DCF-based solution (Fig. 6), leading to significant savings when it comes to both CAPEX and OPEX.

FBG-based chromatic dispersion management provides the telecom industry with unparalleled possibilities when in comes to cost and performance network optimization. The increased focus on cost, especially considering the future of 40 and 100G networks, is effectively addressed by this unique and, in many aspects, disruptive technology.

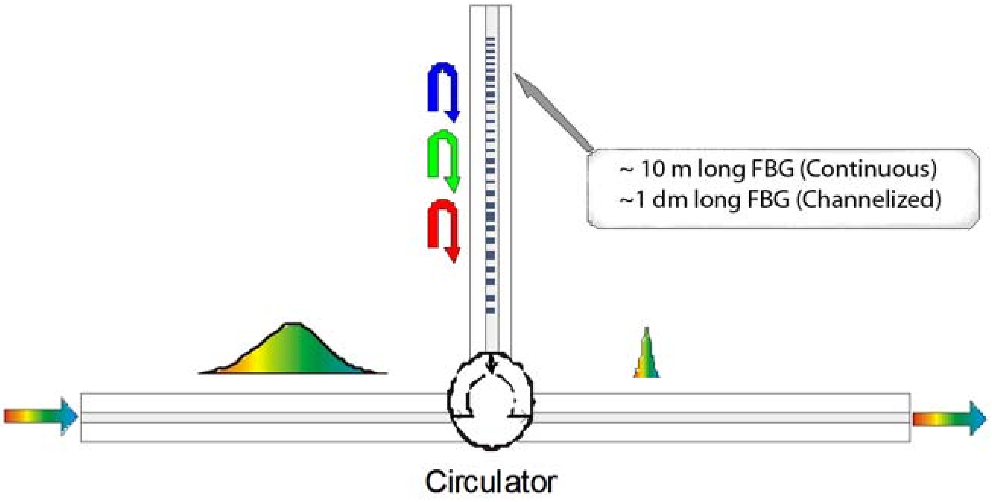
Fig1 WEB



The distance between the fringes controls what wavelength is reflected

1. Shown is a reflective Fiber Bragg Grating.

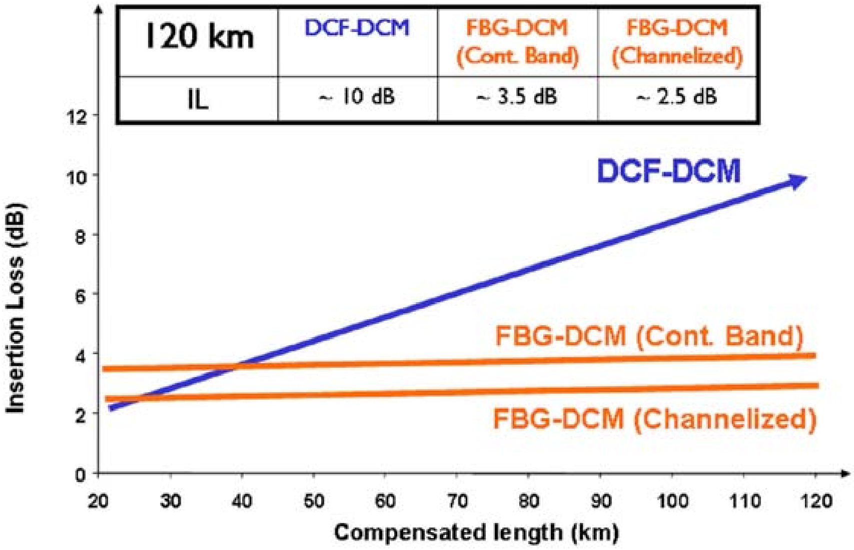
Fig2 WEB



~ 10 m long FBG (Continuous)
~1 dm long FBG (Channelized)

2. This illustrates the principle of FBG-based dispersion compensation.

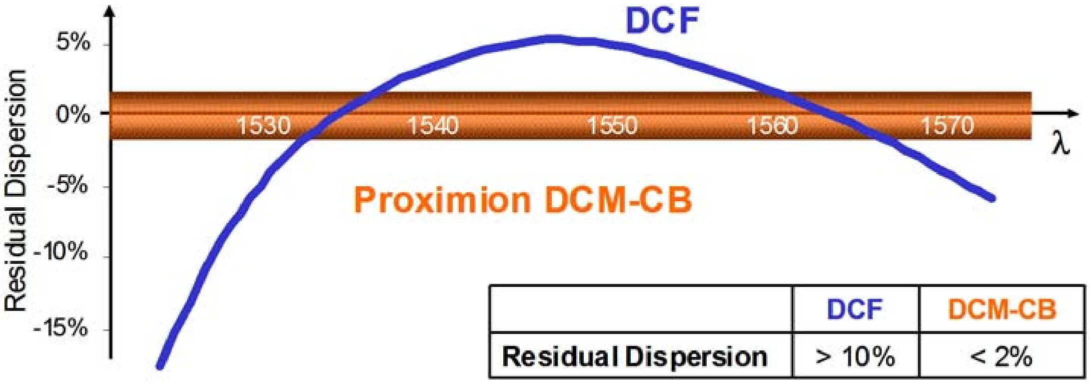
Fig3 WEB



120 km	DCF-DCM	FBG-DCM (Cont. Band)	FBG-DCM (Channelized)
IL	~ 10 dB	~ 3.5 dB	~ 2.5 dB

3. When comparing insertion loss between a DCF-DCM and FBG-DCM, the loss is generally constant in FBGs while the DCF loss tends to be linear with the compensated length.

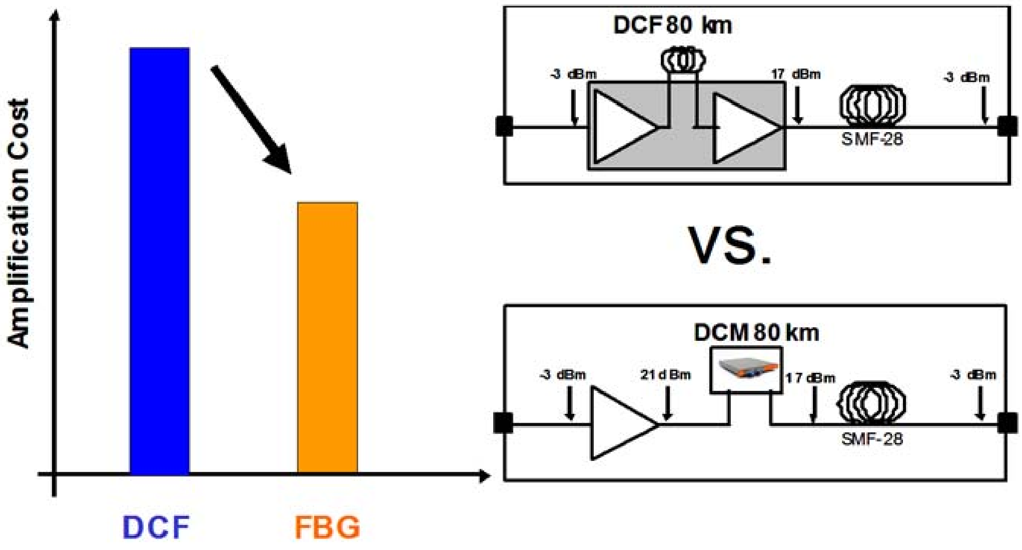
Fig4 WEB



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

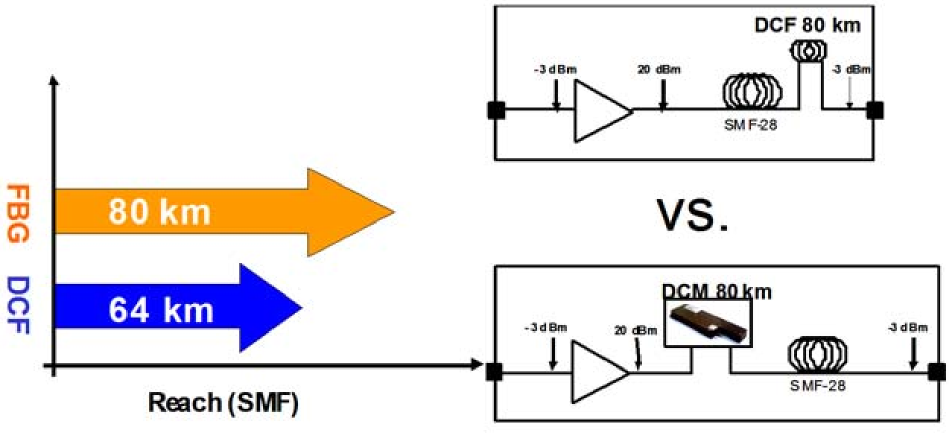
4. Shown is the typical residual dispersion for a DCF versus FBG-DCM over the C-band for a NZ-DSF compensation.

Fig5 WEB



5. Using a FBG-DCM can save up to 40% in amplication cost.

Fig6 WEB



6. A FBG-DCM has a 25% longer reach advantage over a DCF-DCM.

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