Dealing with the critical problem of chromatic dispersion

As transmission speeds move from 2.5 to 10 Gbits/sec, chromatic dispersion becomes a serious problem. Here's a look at when and where dispersion becomes a concern, and the best ways to control it.

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Throughout the world, system operators are moving toward 10-Gbit/sec transmission speeds to meet an ever-growing demand for network capacity. In most cases, their upgrade plans involve installing optically amplified multiwavelength transmission systems such as the Nortel Multiwavelength Optical Repeater or the Lucent WaveStar on standard singlemode fiber. In this situation, chromatic dispersion becomes a serious concern because conventional fiber is optimized for single-wavelength transmission at 1310 nm. With more than 15 million fiber-km of conventional singlemode fiber installed in telecommunications networks today, controlling chromatic dispersion is one of the most important issues facing the industry.

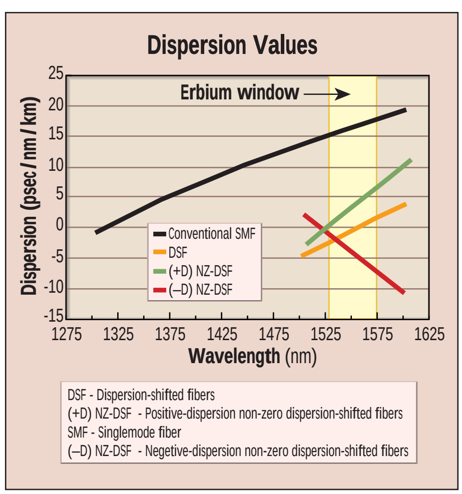
Dispersion-compensating fiber is the tried-and-true solution to the dispersion problem. However, other recently introduced technologies—notably dispersion-compensating gratings—could play a role in the future.

Chromatic dispersion

Chromatic dispersion is caused by a variation in the group velocity of light traveling within a fiber with changes in optical frequency. A data pulse always contains a spectrum of wavelengths. As the pulse travels along the fiber, the shorter-wavelength components travel faster than the longer-wavelength components. This effect broadens the pulse and causes it to interfere with neighboring pulses and distort the transmission signal.

Where is dispersion a problem? Different telecommunications fibers are optimized for operation at different wavelengths (see figure). The figure shows the dispersion values of common fibers at wavelengths used in optically amplified multiwavelength systems (the so-called erbium window). It is apparent that different fibers not only have different dispersion values in that window but different dispersion slopes (i.e., change with wavelength) as well.

Conventional standard singlemode fibers such as SMF-28 were designed originally for single-channel operation at 1310 nm, the then-prevailing transmission wavelength in long-haul optical-fiber telecommunications systems. Consequently, they have dispersions of 15-18 psec/nm/km in the 1550-nm erbium window. The result is that a signal pulse traveling over an 80-km link of conventional singlemode fiber accumulates roughly 17 × 80, or 1360 psec/nm of dispersion.



In the erbium window, different fibers have different dispersion values and slopes, which heightens the dispersion-compensation challenge.

The combined effects of fiber dispersion and the finite signal linewidth of the modulated transmission lasers result in intersymbol interference that will introduce errors in the data stream if left unchecked. Dispersion compensation is necessary above some threshold value of negative dispersion (proportional to link length) to reduce the error rate to acceptable levels. At a rate of 10 Gbits/sec, this threshold is generally about 1000 psec/nm, corresponding to 60 km of SMF-28 fiber; at higher data rates, the threshold is reduced. Hence, the most common application for dispersion compensation today is on SMF-28-type fiber links operating in the 1550-nm window at speeds of 10

Gbits/sec with span lengths of greater than 60 km.

Dispersion-compensation fiber

Recognizing that chromatic dispersion would eventually become a problem with the widescale deployment of optical amplifiers, Corning scientists in the early 1990s invented a solution, and in 1992 received a patent for it. The solution was a new type of optical fiber called dispersion-compensation fiber. This special fiber introduces high levels of negative dispersion over relatively short lengths, which offsets or cancels the positive dispersion accumulated by a pulse traveling through optically amplified systems on standard singlemode fiber.

Compensation is provided on a link by installing a specified length of dispersion-compensation fiber somewhere in the system (typically at the receive end) in the form of a small spool designed to minimize space within equipment racks. Signal light passes through the span, then through the dispersion-compensation fiber, and on to the receiver. Since the first commercial deployment in 1994, dispersion-compensation fiber has been widely used in high-speed network upgrades around the world by major operators like MCI and WorldCom.

Dispersion-compensating gratings

Dispersion-compensation fiber is an attractive solution because it is broadband, fully passive, commercially available, and compatible with all-optical transparent network concepts.

Another potential method of compensating for dispersion is through the use of dispersion-compensating gratings, basically wavelength-selective mirrors written into the core of a singlemode fiber. The application of gratings to dispersion management was invented and patented by Richard Epworth of Nortel in 1990. Unlike dispersion-compensation fiber, however, this technology remained in the laboratory for several years. Only recently have working prototypes reached the marketplace for evaluation.

Dispersion-compensating gratings have long held the promise of being compact, low-loss, and polarization-insensitive devices. But for broadband compensation applications (i.e., to compensate for large portions of the erbium window), there are several drawbacks that have impeded the commercialization of dispersion-compensation gratings. The first and perhaps most important is *group delay ripple*, which is a phenomenon caused by high-frequency deviations from the mean dispersion slope of the grating over wavelength.

Light signals at wavelengths aligned with these slope defects may see dispersion values considerably higher or lower than the mean and may fail to transmit properly. Given a group delay ripple of 100 psec in today's commercially available dispersion-compensating grating products, a transmitter laser center-wavelength drift of 10-20 psec can cause system failure. To avoid this problem, operators would need lasers with a drift of 2 psec or less. Unfortunately, the state of the art today is still too high—around 10 psec.

> **The best solutions will come from suppliers that have capabilities in both dispersion-compensation fiber and gratings and can leverage the strengths of both technologies.**

The second drawback is manufacturability. While optical fiber manufacture is a very mature, well understood, and low-cost process, gratings manufacturing is in its infancy. Since the range of wavelengths compensated by a dispersion-compensating grating depends upon grating length, full erbium-window broadband dispersion-compensating gratings must by necessity be several meters long. A robust process for high-volume, low-cost, reliable manufacture of such broadband gratings has yet to be demonstrated.

Another approach is to make several smaller gratings covering adjoining segments of the operating window. However, concatenation of the gratings necessitates the use of one or more circulators, which then increases the insertion loss.

A third problem comes from the different dispersion values requiring gratings of different lengths. Since long-haul links vary in length and require different compensation levels, dispersion-compensating gratings will have to be made in varying lengths. This can involve a semi-custom manufacturing environment for the gratings. Fiber, on the other hand, is made using a high-speed continuous manufacturing process and is simply cut to a length to yield the desired dispersion value.

Due to the maturity of the fiber-based solution and the unresolved technical and manufacturing issues associated with dispersion-compensating gratings, fiber-based compensation remains the preferred solution for dispersion compensation today (see table).

Dispersion in NZ-DSF systems

The original dispersion-shifted fibers, such as Corning SMF/DS, have zero dispersion at 1550 nm and thus are optimized for single-wavelength operation at that window. More recent fiber designs such as Corning's LEAF fiber or Lucent's Truewave fiber are optimized for multiwavelength transmission in the 1550-nm band. Consequently, these fibers have a carefully planned dispersion slope (i.e., change in dispersion value over the operating window) and non-zero dispersion in the erbium window—they generally are called non-zero dispersion-shifted fibers (NZ-DSF). Those with a positive dispersion in the erbium window are called +D fibers and those with negative dispersion, -D fibers. Referring again to the figure, with signals experiencing up to 6 psec/nm/km of dispersion as they travel down these fibers, the fibers may accumulate up to 450 psec/nm of dispersion over the course of an 80-km link.

The potential need for dispersion compensation in NZ-DSF systems is easily addressed with existing dispersion-compensated fiber by simply providing modules with less fiber and hence appropriately less dispersion. Standard single-mode fiber can be used to create modules with positive dispersion for compensating -D fiber systems.

Comparison of Commercially Available Dispersion-compensating Devices

Specifications	DC fiber*	DC grating**
Chromatic dispersion	1317 psec/nm	1360 psec/nm
Polarization mode dispersion	1.5 psec	5.0 psec
Passband	1528 to 1560 nm	1528 to 1561 nm
Insertion loss	8.6 dB	13.0 dB
Delay ripple	Not applicable	100 ps
Package dimensions	200 × 200 × 41 mm	178 × 178 × 50 mm

*Corning Product Information Sheet PI 739, February 1998
**Nortel Product Information Sheet PB0031 Issue 2, March 1998

What's next?

Emerging optical add-drop multiplexers present a new dispersion-compensation application. They can remove individual wavelengths at an intermediate point in the network, and these wavelengths then require dispersion compensation before being sent to the detector. While a broadband fiber-based solution would do the job here, a narrowband dispersion-compensation grating would be a more elegant solution, assuming group delay ripple can be managed over a short wavelength range. In fact, 50-GHz wavelength-filtering gratings with built-in compensation for wavelength add-drop multiplexing applications are now under development by Corning and others. These devices are expected to hit the market within the next 12 months.

Finally, despite being commercially available for four years, dispersion-compensation fiber itself has plenty of opportunity for enhanced performance in the future. Increasing the fiber's effective area and dispersion—hence shortening the fiber required for a given dispersion value—is one solution to fiber nonlinearities, which may become a problem in advanced networks at very high speeds. Increasing volume deployment will continue to drive costs down. Smaller and smaller package sizes are desired and may be possible through reduced coating or cladding diameter, improved winding algorithms, and new fiber designs.

In summary, dispersion problems of different types arise in many different fibers as a function of transmission speed, channel count, and span length.

The best solutions to future dispersion problems will come from suppliers that have capabilities in both dispersion-compensation fiber and gratings and can leverage the strengths of both technologies. Indeed, an industry consensus appears to be forming around an approach for NZ-DSF systems based on using fiber for broadband compensation and dispersion-compensating gratings for narrowband applications. ◆

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