Light without Limits: Taming Dispersion in Tomorrow's High-Speed Networks

Definition

Dispersion, or the degradation of optical signals over distance, presents a formidable technical challenge in high-speed network environments such as optical carrier (OC).192 and OC.768. There are three types of dispersion: chromatic; its subset, slope mismatch; and polarization mode.

Overview

On the horizon of the telecommunications industry lies great promise, as ultra high-speed, 40 Gbps OC.768 networks lie within reach. But alongside that promise is a formidable technical challenge called *dispersion*. Numerous solutions exist today, or are in development, to address chromatic and polarization mode dispersion, phenomena that become problematic at OC.192 and severe at OC.768 network speeds.

This tutorial examines the market forces causing the push toward ultra high-speed OC.768 networks and provides an overview of chromatic, slope mismatch, and polarization mode dispersion. It also reviews the key criteria for dispersion compensation solutions.most important, tunability and multichannel capabilities.

Topics

1. Introduction

> The market for DCMs [(chromatic) dispersion compensation modules] is going to grow rapidly in the near future, driven by the advent of ultra long-haul and 40 Gbps systems. Both applications require greater numbers of DCMs per link and higher priced, higher performance devices having 100 percent slope compensation, and in some cases, dynamically tunable slope compensation. Overall, we are forecasting a 47 percent compound annual growth rate for this market through 2004.[1]
> —**John Lively**, Senior Analyst of Optical Components, RHK

> It's really 40 Gbps [OC-768] where the entire market believes that PMD [polarization mode dispersion] will be an inescapable issue.[2]
> —**Dana Cooperson**, Director of Optical Transport, RHK

These comments capture the essence of what is perhaps the telecommunications industry's most formidable technical challenge, looming on the horizon alongside the promise of ultra high-speed 40 Gbps OC–768 networks. The challenge is a phenomenon called *dispersion*, which is the degradation of optical signals over distance.

In optical fibers, waveforms broaden over long distances, making these signals difficult to interpret by the time they reach the receiving end. The result is distorted data signals that result in transmission errors at the intended receiver. As network speeds and span lengths increase, dispersion becomes more severe. This applies to *chromatic dispersion* (CD)—which occurs because different wavelengths of light travel at different speeds—its subset, *slope mismatch dispersion*, and *polarization mode dispersion* (PMD), which is caused by light traveling faster in one polarization plane than another.

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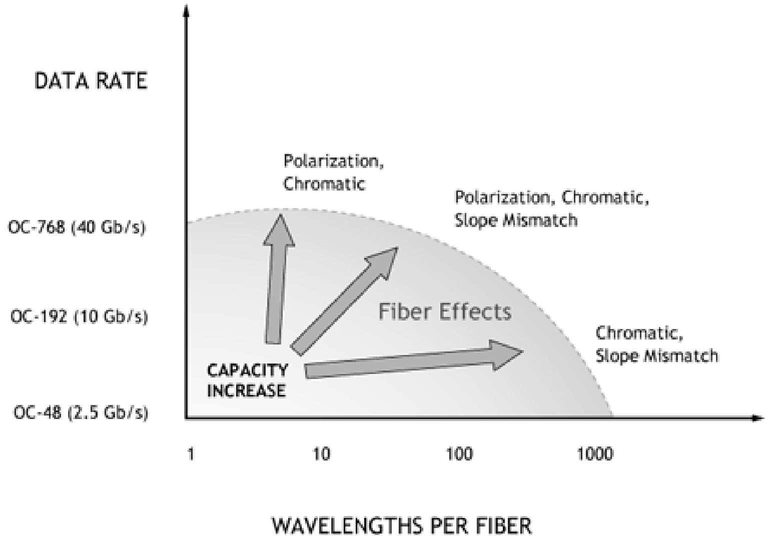
[1] "Defeating Dispersion, Part 2," by Annie Lindstrom, *Telephony Magazine*, December 4, 2000
[2] "Defeating Dispersion, Part 1," by Annie Lindstrom, *Telephony Magazine*, November 27, 2000

Figure 1. Dispersion challenges intensify significantly with increases in network speed and channel capacity.



Dispersion presents a major challenge because not all fiber is created equal. Approximately 20 percent to 30 percent of the single-mode fiber manufactured before the mid 1990s is deficient because the core of this fiber is not perfectly round.[3] This imperfection becomes problematic as bit rates and span lengths increase. Verizon Communications and SBC Communications believe that 60 percent to 70 percent of their fiber will not cost-effectively support OC–192 systems.[4] (It should be noted that these problems are not totally PMD–related; they also encompass splices and connectors, which exacerbate polarization mode dispersion.)

Numerous solutions exist today, or are in development, to address CD and PMD, phenomena that become problematic at OC–192 and severe at OC–768 network speeds. These solutions range from improving the quality of the fiber used to build networks, to employing dispersion compensating fiber, to developing sophisticated new dispersion compensation modules. The market for dispersion compensation solutions is expected to grow meteorically as OC–768 gains traction; RHK sizes the worldwide market for chromatic dispersion compensation devices, alone, at $341 million in 2001, rising to $837 million in 2004.[5]

This tutorial examines the market forces causing the push toward ultra high-speed OC–768 networks and provides an overview of chromatic, slope mismatch, and polarization mode dispersion. It also reviews the key criteria for dispersion compensation solutions—most important, tunability and multichannel capabilities.

[3] “Defeating Dispersion, Part 1,” by Annie Lindstrom, *Telephony Magazine*, November 27, 2000
[4] *Ibid*
[5] *Ibid*

2. Poised to Take a Quantum Leap: Network Evolution and OC–768

The Internet has forever changed the way companies function and the way people live, work, and play. As though fulfilling unwritten laws of physics and economics, bandwidth demand has expanded to constantly "push the edge of the envelope" of network capacity, with useful, novel applications springing up that immediately test the limits of ever-improving networks. These include peer-to-peer computing—most famously, Napster—Webcasting, storage area networks, and the coming growth of video-on-demand that will deliver VHS–quality movies into the home via a broadband Internet connection. Bandwidth-hungry applications are driving usage growth rates to more than 100 percent per year; as a result, many trunks that were lit only 30 percent in 1997 have now reached the point of fiber exhaust.

Investing in the "Network of the Future"

As businesses and individuals continue to exhibit an insatiable demand for bandwidth, the telecommunications industry and its suppliers have become highly motivated to build networks that deliver data farther, and faster, than ever before. Cost-effective bandwidth growth requires the upgrade of existing fiber links—an installed base that's growing at more than 10 percent per year—in addition to laying new fiber, which carries an installation investment of up to $.5 million per kilometer.

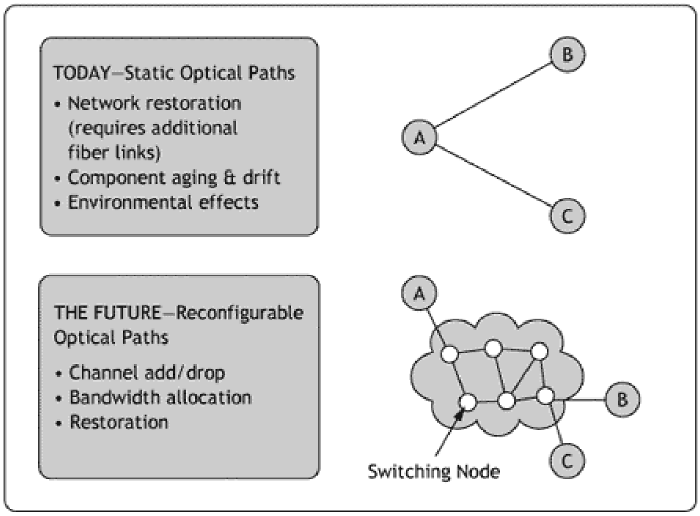
So although 2.5 Gbps OC–48 networks were widely perceived as "ultra high speed" just a few years ago, telecommunications companies are now rapidly ramping up capacity on many links to 10 Gbps OC–192, and the industry has set its sights on 40 Gbps OC–768. Many industry observers believe that OC–768 networks will become a reality within the next 12 to 24 months.

The Need for Tunable, Multichannel Solutions

Managing dispersion in high-speed optical networks is just one component of the overall challenge designers are contemplating as they start to plot OC–768 "networks of the future."

As the industry moves toward full-mesh, all-optical networks, unprecedented new levels of flexibility and manageability will be within reach. In this OC–768 environment, network traffic will flow over many dozens of channels and be dynamically routed around network faults. Today's tedious provisioning process, which can take days or weeks, will be replaced by a far more dynamic management environment in which customers themselves can secure a specific bandwidth allocation for a fixed length of time—to handle a global Webcast, for example, peer-to-peer traffic, or myriad other applications.

Figure 2. In the dynamic, highly reconfigurable networks of the future, tunable, multichannel dispersion compensation modules are required to adapt to variable path characteristics.



The easily reconfigured "network of the future"—based on dense wavelength division multiplexing (DWDM) technology and characterized by streamlined channel switching, channel add/drop, as well as dynamic path reconfiguration for bandwidth allocation and restoration—requires its components to be similarly flexible. As it pertains to dispersion compensation modules, specifically, *tunability* and inherent *multichannel capabilities* become issues of paramount concern.

Tunability is the ability to optimize the amount of compensation delivered by a dispersion compensation module (DCM) to precisely match network requirements. A DCM can be tuned manually, remotely, or adaptively or through a combination of techniques. Manual tuning is performed by a network technician who adjusts DCMs prior to or after their installation on telecommunications racks. Remote tuning is done from a central console, using network management software. Adaptive tuning, as the term suggests, is a dynamic, intelligent process executed within the DCM, without any human intervention. From a dispersion compensation perspective, adaptive tunability is essential in allowing "networks of the future" to manage change as they adapt to variable path characteristics, environmental fluctuations, and configurations that are themselves in a constant state of change.

Within DCM units, native multichannel capability is similarly essential; it eliminates the current "one channel, one box" ratio required by rudimentary first-generation dispersion compensation devices. In many current solutions, one DCM must be provided for each channel. In DWDM environments with just a few channels, this situation is manageable. However, in complex OC–192 and OC–768 environments, space and cost constraints demand that DCMs have multichannel functionality.

DCMs with multichannel capability are also a vast improvement over the most common solution used today, spooled dispersion compensating fiber (see *Topic 3*). DCF, as it is commonly called, is a chromatic dispersion solution optimized for a specific wavelength within a network link. Although DCF produces acceptable results in today's networks, as network fiber becomes upgraded and loaded with more channels, its performance becomes sub-optimal. In addition, DCF only partially addresses slope mismatch and does not compensate for polarization mode dispersion.

3. Dispersion: Shedding New Light on Network Potential

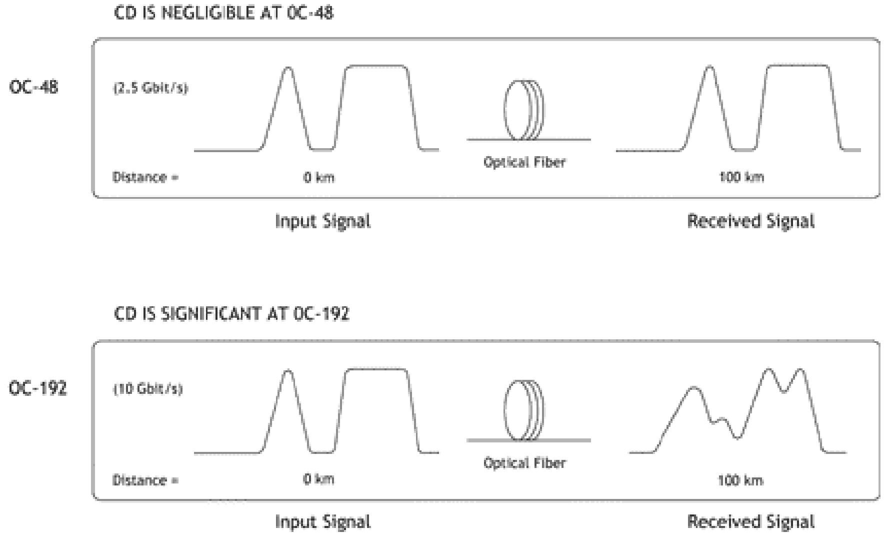
Before any "network of the future" can be considered, the "network of today" must be dealt with. This includes legacy fiber, its ability to handle OC–192 and OC–768 speeds, and the physics of dispersion.

Dispersion Defined

As described in *Topic 1*, CD, slope dispersion, and PMD cause waveforms within optical fibers to spread out, lose their shape, and become difficult to detect by receivers at the end of a fiber span. Unchecked, dispersion causes bit error rates to increase to unacceptable levels.

- **Chromatic dispersion** is based on the principal that different-colored pulses of light travel at different speeds. More technically, CD is the sum of material dispersion and waveguide dispersion. "Material dispersion" is caused by the variation in refractive index of the glass in the fiber as a function of the optical frequency. "Waveguide dispersion" is due to changes in the distribution of light between the core and the cladding[6] of single-mode fiber.

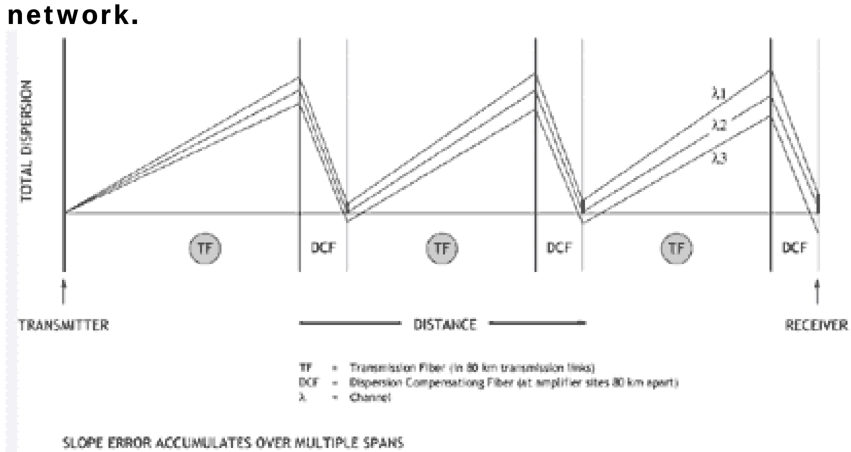
Figure 3. Chromatic dispersion becomes a significant problem at network speeds of OC–192 and higher.



In today's 2.5 Gbps OC–48 networks, the impact of chromatic dispersion is minimal. Unfortunately, dispersion effects do not increase linearly; the growth is at a rate of the square of the increased speed of the transmission. Therefore, at 10 Gbps (OC–192), CD has a major impact on network performance because it is 16 times worse than at 2.5 Gbps (see Figure 3). Similarly, at 40 Gbps, dispersion levels are 256 times higher than at OC–48.

- Slope mismatch dispersion is a subset of chromatic dispersion. It occurs in single-mode fibers because dispersion varies with wavelength. This can result in a significant buildup of dispersion, especially at the extremes of a band of wavelength channels (see Figure 4). Full compensation of this type of dispersion requires slope matching or tunable compensation at the receiver.

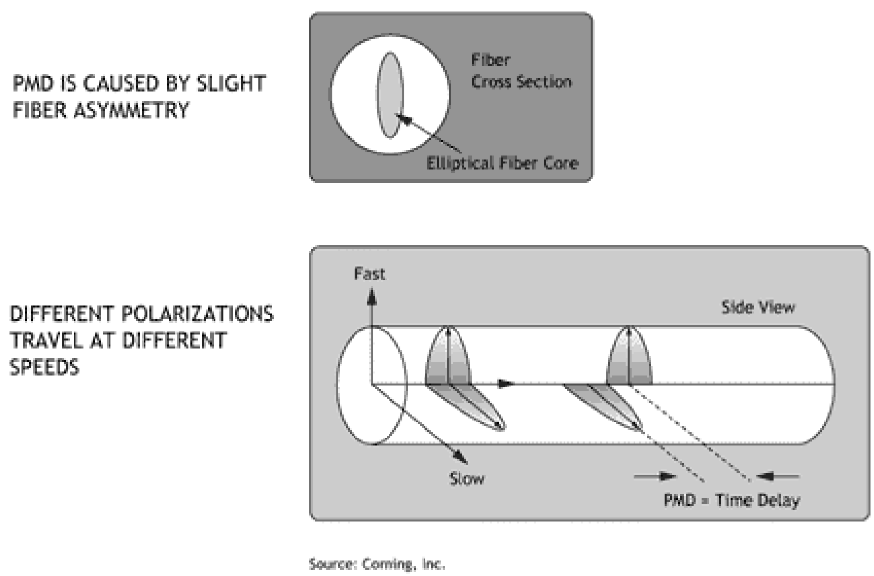
Figure 4. In conventional solutions, slope mismatch dispersion must be addressed individually on each channel of a DWDM network.



As indicated in *Figure 4*, uncorrected “slope” dispersion at channels away from the center channel (λ_2) accumulates over successive transmission links and can reach unacceptable levels.

- **Polarization mode dispersion** occurs as light travels down single-mode fibers, in two polarization modes. When the core of the fiber is asymmetric, the light traveling along one polarization moves slower or faster than the light traveling along the other polarization. This can cause the pulse to spread enough to make it overlap with others or distort the shape of the pulse enough to make it undetectable by the receiver (see *Figure 5*).

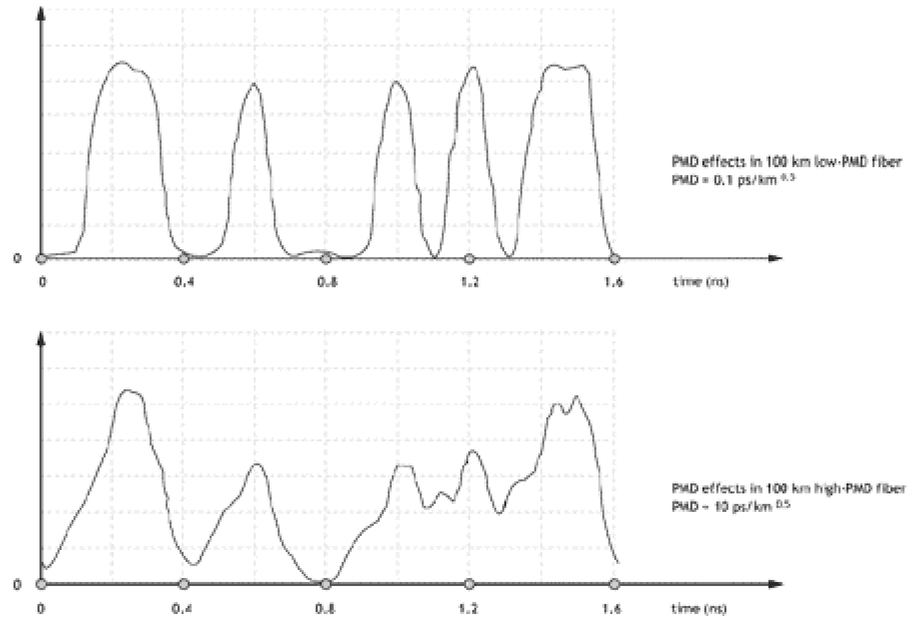
Figure 5. PMD changes randomly with environmental effects such as temperature and imperfections in fiber cores.



PMD levels rise directly with network speeds (i.e., PMD is four times as severe at 40 Gbps OC–768 as it is at 10 Gbps OC–192) and also increase proportionally to the square root of the distance. For example, if the span length is doubled, PMD increases by a factor of 1.4.

In addition, PMD is a dynamic phenomenon, changing randomly with environmental effects such as temperature and infinitesimal asymmetries in the fiber core (see *Figure 6*). For this reason, PMD requires adaptive compensation from adaptively tunable DCMs.

Figure 6. PMD levels can range from mild to severe on OC–192 networks, influenced by a range of factors.



PMD CHANGES RANDOMLY WITH ENVIRONMENTAILCONDITIONS, REQUIRING ADAPTIVE COMPENSATION.

Overcoming Dispersion: A Unified Approach

Given the complexity of the dispersion challenge and the fact that its real-world impact is only beginning to be experienced and understood, three principles are emerging that promise to help companies address dispersion globally, throughout the network.

The first principle involves *tackling the trio of dispersions*—CD, slope mismatch and PMD—on the network level as a group, rather than individually. By taking a global view of the dispersion challenge, companies can best understand the interaction between CD, slope mismatch, and PMD and explore synergies between the various dispersion compensation solutions. This approach also best leverages the time and resources committed to exploring dispersion and helps ensure that chosen solutions will work together seamlessly, in a synergistic manner.

The second overarching principle that can be effectively employed in assessing dispersion compensation solutions is *tunability*, which allows the chosen DCMs to adapt to changes in the network environment. As discussed in *Topic 2*, adaptive tunability is essential in enabling networks of the future to manage change as they adapt to variable path characteristics, environmental fluctuations, and configurations that are themselves in a constant state of change. Tunability is especially critical for polarization mode dispersion solutions, which must adapt to random environmental fluctuations.

Finally, *multichannel capability* is critical simply because “one channel, one box” solutions are highly inefficient at OC–192 and OC–768 levels. This is due to physical space constraints on network racks, as well as power consumption considerations.

Current Approaches Fall Short

Although today’s networks have an OC–192 ceiling, several solutions exist that partially address the dispersion challenge. These include the following:

- **Non-zero dispersion shifted fiber (NZDSF)**—A new approach to manufacturing fiber has produced NZDSF, which is superior to traditional single-mode fiber because it utilizes a different design—a more complex refractive index profile—that results in less dispersion. NZDSF is also manufactured to higher standards, which produce a more perfectly circular core. This creates less dispersion-creating variability in the fiber, thereby allowing signals to be transmitted longer distances. However, dispersion still accumulates with distance but at a lower rate.

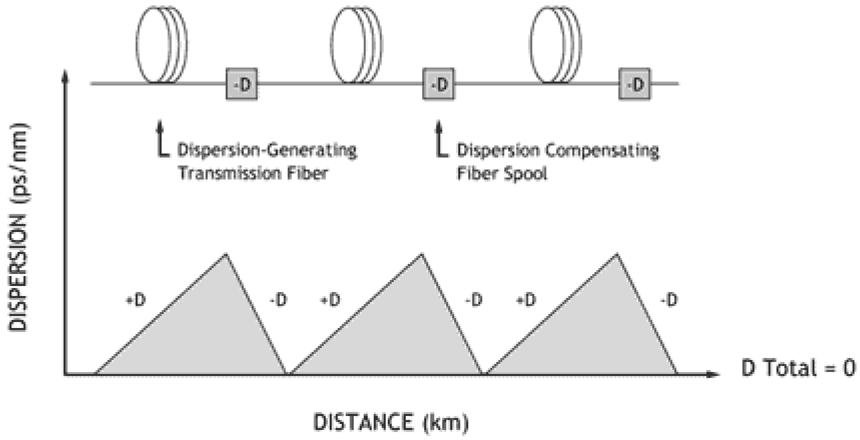
  Although NZDSF partially addresses PMD at OC–192, it still requires chromatic dispersion correction; in addition, the slope mismatch problem is more severe in NZDSF fiber than in single-mode fiber.

  Finally, NZDSF is a limited solution in that, like all fiber, it is costly to install and will only comprise a small portion of the global fiber-optic network for the foreseeable future. As previously noted, the majority of installed fiber is single-mode.

- **Dispersion compensating fiber (DCF)**—is the traditional solution for handling chromatic dispersion. Spools of DCF are placed at intervals along the network—approximately 15 kilometers of DCF for every 80 kilometers of network fiber—and are typically stacked atop telecommunications racks (see *Figure 7*).

  While each spool of DCF adequately solves chromatic dispersion, if it is used on fiber carrying multiple wavelengths, it is usually set to correct CD most accurately on the center wavelength. However, dispersion still accumulates at other wavelengths and can be a significant problem at the edge of a band of wavelength channels. DCF also does not address PMD.

Figure 7. Chromatic dispersion has traditionally been addressed with spools of dispersion compensating fiber placed at intervals along the network.



Exciting New Developments: DCMs

The newest approach to taming CD, slope mismatch, and PMD is with dispersion compensation modules (devices), a development hotbed within today's optical networking industry. DCMs are placed in front of receivers on the network and make continual adjustments to the signal, based on information derived from analyzing a sample of the optical pulse as it travels through the module. The degree to which a pulse is corrected is based on its state, read by the DCM's detector as pulses pass through it. DCMs offer the most promise in the race to beat dispersion, for several reasons:

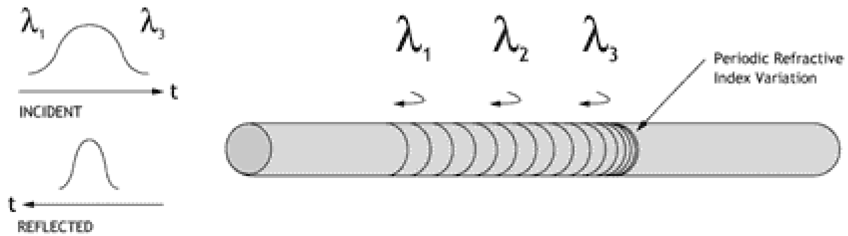
- A wide range of tunability options, including remote and adaptive
- Low cost and ease of replacement (relative to alternatives such as laying new fiber)
- Small form factor (several inches, as opposed to cumbersome DCF spools)
- High levels of innovation

Fiber Bragg Gratings: Maximum Efficiency

One of the most advanced technologies being incorporated into DCMs is *fiber Bragg gratings*, short lengths of optical fiber that reflect a particular wavelength. Fiber Bragg gratings feature periodically spaced zones in the fiber core that have been altered to have different refractive indexes slightly higher than the core.

This structure selectively reflects a very narrow range of wavelengths while transmitting others (see *Figure 8*).

Figure 8. In fiber Bragg gratings, a periodic refractive index variation along the axis of the fiber causes narrowband refraction.



The name comes from Bragg's Law, which describes the optimal spacing of the changes. Sir William Lawrence Bragg, noted British physicist (1890–1971) made this discovery in his study of X-rays and crystal structures. [7]

Fiber Bragg gratings are typically between one millimeter and 25 millimeters long. To create the appropriate stack of high- and low-refractive-index regions along a piece of optical fiber, its refractive index must be permanently modified via a photosensitive effect. This is accomplished by exposing the optical fiber to ultraviolet (UV) light.

Compared to most other fiber-optic components, fiber Bragg gratings are simple to manufacture. And unlike micro-optic devices such as thin films and isolators, they do not require complex and precise alignment. Perhaps the biggest advantage of fiber Bragg gratings is their low insertion loss when placed onto the network. This is because the alteration (grating) is made to the fiber itself, allowing the light wave to continuously remain within the fiber.[8]

[6]Cladding is the plastic or glass sheath that is fused to, and surrounds, the core of an optical fiber. Its mirror-like coating keeps the light waves reflected inside the core. The cladding is covered with a protective outer jacket. *Definition from Computer Desktop Encyclopedia.*

7 Definition from *Computer Desktop Encyclopedia*

8 Excerpted from "Fiber Bragg Gratings," SPIE's *OE Magazine*, January 2001

4. A Dispersion Compensation Checklist

Although the market for advanced dispersion compensation management solutions is nascent, many choices abound, and the number is growing quickly. To help ensure maximum return on investment in both the short- and long-term, companies contemplating the purchase of DCMs should consider the following "checklist" of attributes. The top three attributes include the following:

- **One-stop shopping**—The rapid emergence of high-speed networks gives equally rapid rise to not one, but three new technical challenges: chromatic, slope mismatch, and polarization mode dispersion. Most companies developing dispersion compensation solutions address only one of the three. The risk in this approach is that, once combined on a single network, DCMs from multiple vendors will not work together optimally. This creates the potential for purchasers to divert significant resources to tune the combined performance of the collection of DCMs, in order to assure peak performance.

  Instead, choosing a single provider from which to procure a full suite of dispersion compensation solutions can dramatically mitigate integration and optimization risk and maximize network performance. A provider with a range of complementary dispersion compensation solutions—CD, slope mismatch, and PMD—can eliminate much potential delay and expense in ramping up high-performance networks to OC–192 speeds and beyond.

- **Tunability**—Again, the importance of tunable dispersion compensation solutions cannot be underestimated, particularly in solving chromatic dispersion in quickly growing OC–192 networks and the emerging area of polarization mode dispersion. Adaptive tunability is essential in allowing networks of the future to manage change as they adapt to variable path characteristics, environmental fluctuations, and configurations that are themselves in a constant state of change.

- **Multichannel capability**—Likewise, to realize the potential of OC–192 and OC–768 DWDM networks, DCM solutions featuring multichannel capability are an absolute must. Because OC–192 and OC–768 can have up to multiple dozens of channels, an ever-dwindling amount of space on telecommunications racks necessitates multichannel capability in dispersion compensation solutions.

Also highly important, any potential dispersion compensation solution should offer the following:

- **High reliability**—The highest-quality DCMs offer carrier-grade reliability, typically 99.999 percent uptime. As more and more components are introduced into a network, the number of potential points of failure rises directly. To proactively ensure as little network downtime as possible, DCMs must offer the highest levels of reliability.

- **Fail-safe/one moving part**—A key component of uptime is fail-safe design, with a minimum number of moving parts. Complex, sensitive optical networking devices with components such as thin films, isolators, and mirrors introduce a significant amount of operational risk into network operations.

- **Ease of operation**—Because they will be deployed at hundreds, or even thousands, of locations, the chosen DCMs must be easy to install and operate. Adaptive tunability—as opposed to manual tuning, which requires human intervention—plays a large role in streamlining ongoing operations and maintenance of DCMs.

- **Compliance**—"Future proofing" the network is a major concern of every carrier, in order to attain maximum ROI. Any dispersion compensation solution should ensure compatibility with the myriad components from disparate providers that compose networks both today and tomorrow.

- **Low insertion loss**—Because networks transmit at only nine dBm (decibels relative to milliwatt) of power, any device inserted into the network must have minimal loss. Some early-stage DCMs incur as much as eight dB of loss, which means that almost 85 percent of the light is lost; next-generation technology promises to deliver low insertion loss of only two to four dB.

5. Conclusion

An intense, global effort is underway to build and operate broadband networks that will cost-effectively deliver greater network capacity at faster speeds and over longer distances. New data-intensive applications—ranging from peer-to-peer computing to storage area networks, and beyond—are driving seemingly insatiable demand for more bandwidth.

Optical networks are key to this vision. They offer massive scalable bandwidth, protocol and bit-rate independence, and the ability to launch and scale new services on demand. To deliver high-speed, wide-channel–count optical networks that meet escalating bandwidth requirements, communications network providers are looking for efficient new ways to overcome the problem of dispersion. This optics phenomenon, which becomes more severe as span lengths and bit rates increase, causes degradation of signals and transmission errors. Dispersion challenges, which include chromatic, slope mismatch, and polarization mode, must be solved in order to usher in the next generation of all-optical, fully meshed networks operating at OC–192, OC–768, and beyond.

In the quest for dispersion compensation solutions, DCMs hold significant promise in addressing the formidable challenges associated with multichannel, high-speed networks. Recent innovations with components such as fiber Bragg gratings, coupled with breakthrough developments in tunability and multichannel capabilities, are shining stars on the industry's horizon.

Self-Test

1. ____________________ is the degradation of optical signals over distance.

    a. Distortion

    b. Capacity

    c. Dispersion

    d. Polarization

2. In optical fibers, waveforms broaden over long distances, making these signals easy to interpret by the time they reach the receiving end.

    a. true

    b. false

3. Approximately 20 percent to 30 percent of the single-mode fiber manufactured before the mid 1990s is deficient because the core of this fiber is not perfectly ____________.

    a. formed

    b. round

    c. hollow

    d. clear

4. Napster is an example of __________________________.

    a. video-on-demand

    b. Webcasting

    c. ISP

    d. peer-to-peer computing

5. ____________ is the ability to optimize the amount of compensation delivered by a dispersion compensation module (DCM) to precisely match network requirements.

   a. Tunability

   b. Dispersion

   c. Polarization

   d. Multichannel capability

6. _________________ eliminates the current "one channel, one box" ratio required by rudimentary first-generation dispersion compensation devices. In many current solutions, one DCM must be provided for each channel.

   a. Compensation

   b. Tunability

   c. Multichannel capability

   d. Dispersion

7. Slope dispersion and PMD cause waveforms within optical fibers to spread out, lose their shape, and become difficult to detect by receivers at the end of a fiber span.

   a. true

   b. false

8. ________________ is based on the principal that different-colored pulses of light travel at different speeds.

   a. Slope mismatch dispersion

   b. Polarization mode dispersion

   c. Chromatic dispersion

9. ___________________ occurs as light travels down single-mode fibers, and when the core of the fiber is asymmetric, the light traveling along one side moves slower or faster than the light traveling along the other side.

   a. Slope mismatch dispersion

   b. Polarization mode dispersion

c. Chromatic dispersion

10. ___________________ occurs in single-mode fibers because dispersion varies with wavelength. This can result in a significant buildup of dispersion, especially at the extremes of a band of wavelength channels.

a. Slope mismatch dispersion

b. Polarization mode dispersion

c. Chromatic dispersion

Correct Answers

1. ____________________ is the degradation of optical signals over distance.

a. Distortion

b. Capacity

c. Dispersion

d. Polarization

See Topic 1.

2. In optical fibers, waveforms broaden over long distances, making these signals easy to interpret by the time they reach the receiving end.

a. true

b. false

See Topic 1.

3. Approximately 20 percent to 30 percent of the single-mode fiber manufactured before the mid 1990s is deficient because the core of this fiber is not perfectly ____________.

a. formed

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c. hollow

d. clear

See Topic 1.

4. Napster is an example of __________________________.

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   b. Webcasting

   c. ISP

   d. peer-to-peer computing

   See Topic 2.

5. _____________ is the ability to optimize the amount of compensation delivered by a dispersion compensation module (DCM) to precisely match network requirements.

   a. Tunability

   b. Dispersion

   c. Polarization

   d. Multichannel capability

   See Topic 2.

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   a. Compensation

   b. Tunability

   c. Multichannel capability

   d. Dispersion

   See Topic 2.

7. Slope dispersion and PMD cause waveforms within optical fibers to spread out, lose their shape, and become difficult to detect by receivers at the end of a fiber span.

   a. true

b. false

See Topic 3.

8. ________________ is based on the principal that different-colored pulses of light travel at different speeds.

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   b. Polarization mode dispersion

   c. Chromatic dispersion

   See Topic 3.

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    a. Slope mismatch dispersion

    b. Polarization mode dispersion

    c. Chromatic dispersion

    See Topic 3.

Glossary

CD
chromatic dispersion

dB
decibel

dBm
decibels relative to milliwatt

DCF
dispersion compensating fiber

DCM
dispersion compensation module

DWDM
dense wavelength division multiplexing

Gbps
gigabits per second

NZDSF
non-zero dispersion shifted fiber

OC
optical carrier

PMD
polarization mode dispersion

UV
ultraviolet