designfeature *By Joshua Israelsohn, Technical Editor*

The alchemy of GLASS

YOU DON'T HAVE TO BE A RUMPLESTILTSKIN TO SPIN A BIT OF GOLD FROM FIBER STRANDS. BUT AT 10 GBPS AND FASTER, ON METRO RUNS OR LONGER, YOU DO NEED A DISPERSION COMPENSATOR IN YOUR BAG OF TRICKS IF YOU'RE GOING TO DABBLE IN...

THE GOAL of those who develop fiber-optic communications technologies is to extract the greatest value from each strand of glass. Span, signaling rate, deployment agility, and fiber installation and operating costs all play into the models network operators must balance (the current market downturn notwithstanding) to operate profitably. Advances in dispersion-compensation technologies favorably affect all of these parameters and are becoming critical as metro loops reach spans of 40 to 120 km.

Among the physical media used for high-speed communication, fiber-optic cable has a lot going for it. Obvious are its advantages over copper when comparing cable size, weight, and immunity to EMI and crosstalk. But the economics of fiber are compelling due to its comparatively low attenuation. Attenuation in highly purified glass is on the order of 0.15 dB/km at 1550 nm compared with something closer to 1 dB/*cm* for window glass or, perhaps more directly useful, 10 dB/km for copper coax at 50 MHz (**Reference 1**). Unfortunately, attenuation is not the cable's only cumulatively degrading effect on a data stream. Dispersion terms—properties of the physical media and of the transmitted light spectra—spread the pulse widths, blurring the pulse stream and limiting maximum spans and signaling rates. Pulse spreading not only results in poor edge fidelity and increased jitter, but also, by redistributing a pulse's energy over a larger width, reduces the pulse amplitude. In sufficiently severe cases, dispersion causes *ISI* (intersymbol interference) and pattern-dependent errors.

Intermodal dispersion, also known as *mode dispersion* (an unfortunate overuse of the word *mode*), is the simplest to envision of the dispersion terms. It occurs in multimode fibers and explains why this type of cable is suitable only for moderate-run lengths at less than aggressive signaling rates. Each of the multiple propagation paths along a multimode fiber has a different length (**Figure 1**). The shortest corresponds to the lowest order or axial ray, m_0. The longest corresponds to the highest order meridional ray, m_n, which reflects at the critical angle

$$\theta_c = \arcsin\frac{n_{cl}}{n_{co}},$$

where n_{co} and n_{cl} are the refraction indices of the core and cladding, respectively. You can calculate the difference in propagation times for a given length of fiber as:

$$\Delta_t = \frac{n_{co}d}{c}\left(1-\frac{1}{\sin\theta_c}\right),$$

where d is the run length.

One way that fiber manufacturers reduce intermodal dispersion is by making cable with a graded refractive index profile rather than a step index profile. In a graded-index cable, the propagation velocity increases as a ray moves away from the core center (**Figure 2**). The velocity increase compensates for the longer paths the meridional rays traverse. Graded-index fiber can significantly increase the maximum signaling rate for ultrashort-haul service—a nearly three-orders-of-magnitude improvement in a 1-km span.

Beyond the ultra-short haul, multimode fiber offers insufficient bandwidth and span (**Reference 2**). Longer feeds, commonly at 2.5 Gbps and moving into 10 Gbps with 40-Gbps technologies threatening should market conditions sufficiently improve, operate on single-mode fiber, which does not exhibit intermode dispersion. Single-mode strands do, however, exhibit *PMD* (polarization-mode dispersion), which derives from irregularities in the cable due to manufacturing tolerances that lead to cross-sectional asymmetry, core misalignment, doping impurities, and bubbles (**Reference 3**). Installation-related stresses also induce localized asymmetries. PMD is a dominant error term that affects WDM metro/regional-transport spans longer than about 300 km and long-haul and ultra-long-haul DWDM runs that extend to 4000 km and beyond.

Contrary to what you might infer from the name "single-mode fiber," the wave equations that describe a transverse electromagnetic wave propagating along the strand in the z direction have two orthogonal linearly independent solutions, polarized in the x and the y directions, respectively. Because the wave equation solutions are orthogonal, any linear combination of the two is also a solution (**Reference 4**). In an ideal fiber with constant refractive indices for core and cladding along its length and cross-sectional circular symmetry, the two orthogonal polarization modes enjoy equal propagation constants. In real fiber-optic cable, however, cross-sectional asymmetries exist along the fiber's length. In such cases, the propagation velocities for the two polarization modes differ, giving rise to PMD (**Figure 3**).

The sources of PMD include the manufacturing tolerance of fiber cross-sectional symmetry and stress-induced asymmetries introduced after manufacturing. The asymmetries include static stresses due largely to installation-related bending and loading and dynamic stresses due to environmental vibration and thermal gradients. The statistical distribution of cross-sectional asymmetries gives some relief from PMD. One local asymmetry can cancel another orthogonal one elsewhere along the cable's length. The overall PMD, expressed in units of psec/$\sqrt{\text{km}}$, is essentially bit-rate-independent.

About 15 billion meters of fiber in the ground comprises the large amount of legacy cable made before 1995 as well as some newer cable. The center of the PMD distribution in older fiber can be as large as 10 psec/$\sqrt{\text{km}}$ (**Reference 5**). This amount of PMD is a concern even in metro links due to the expansion into suburban areas, which has created pressure for lengthening spans from 40 to 120 km. Newer fiber brings improved performance with PMD on the order of 0.1 psec /$\sqrt{\text{km}}$—still a concern for long-haul and ultra-long-haul runs that can range from 4000 to 8000 km.

A PALETTE IN A PULSE

If light pulses in fiber-optic strands were precisely monochromatic, then you could measure intermodal and polarization-mode dispersion terms in multimode and single-mode fibers, respectively, and that would be the end of it. But the signal from a pulse-modulated monochromatic source occupies a spectrum related to the modulation rate, so a third component—*CD* (chromatic dispersion)—occurs. The chromatic term is common to all fiber-optic systems and has two sources.

AT A GLANCE

▷ The several optical-dispersion terms derive from characteristics of a fiber-optic cable. They combine to smear the pulse stream and cause intersymbol interference.

▷ The current infrastructure includes about 15 billion meters of buried fiber. Much of it is legacy fiber, which exhibits less-than-stellar dispersion performance.

▷ A large variety of compensation technologies exists. Many that operate in the optical domain are large, comparatively expensive, and unable to track out dynamic dispersion components. Recently developed dispersion compensators operating in the electronic domain are by contrast well-integrated into I/O functions, agile, and poised to offer network operators substantial savings.

▷ Compensators operating in the optical domain may still have advantages in WDM and DWDM feeds, particularly as photonic designers develop and commercialize small and efficient technologies, such as the Etalon.

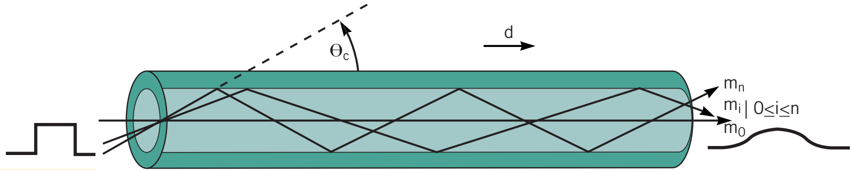

Figure 1 Intermode dispersion derives from the multiple path lengths taken for the various rays in a multimode cable.

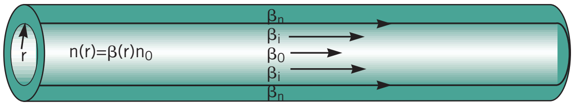

Figure 2

Intermode dispersion is significantly reduced in graded-index fiber, which accelerates rays nearer the cladding.

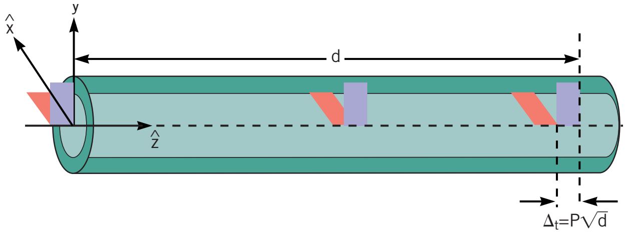

Figure 3

Polarization-mode dispersion includes dynamic components induced by thermal and mechanical stress. It is the dominant dispersion term in long-haul and ultra-long-haul spans.

First, the fiber's refractive index is not a fixed constant but rather a function of wavelength. As a result, the pulse's spectral components travel at different rates (**Figure 4**). The literature refers to this form of chromatic dispersion as *group velocity dispersion* or *material dispersion.*

A second chromatic dispersion mechanism—*waveguide dispersion*—derives from the fact that a fraction of the transmitted light couples through the core, while the remainder propagates through the cladding. The two have, by definition, different refractive indices and, thus, different group velocities. The different propagation velocities give rise to a pair of time-skewed waveforms whose amplitude ratio is a function of the energy distribution between the core and the cladding (**Figure 5**). Both refractive indices have a wavelength dependence, and the time skew tends to be smaller than the chromatic pulse spreading, so waveguide dispersion is not considered with the other achromatic errors but lumped in with the group velocity dispersion as a chromatic term. You express CD in picoseconds per nanometer-kilometer: the spread in pulse arrival time per unit spectrum and unit span. For this reason, you'll see references to CD compensation as *slope compensation* or *slope correction*.

CD increases as the square of the bit rate—one of the challenges facing engineers moving systems from OC-48 to OC-192 and a particular challenge for those who are trying to make practical systems at OC-768. As was the case with PMD, the CD in old fiber is about four times worse than in new fiber—17 versus 4.4 psec/nm-km. Though a fourfold improvement is helpful, it leaves another factor-of-four improvement for engineers to make with some combination of CD tolerance and CD compensation.

WHAT CHIRPS BUT DOESN'T HAVE WINGS?

Unlike other dispersion terms that depend solely on the properties of the fiber, the laser diode's output exhibits a similar effect due to the diode's propensity to modulate its center wavelength during the pulse interval. The wavelength modulation follows the pulse envelope with the longer wavelength components launching before the shorter wavelengths (**Figure 6**). This temporal-wavelength relationship, called *chirp* (or more specifically in this case, *negative* chirp, indicating that the shorter wavelengths follow the longer ones), can fortuitously cancel the chromatic dispersion in a length of standard fiber (**Figure 4**). Given the sign of the diode's chirp, it follows that the standard fiber's chromatic dispersion at, say, 1550 nm, causes positive chirp. When the fiber's chromatic dispersion and length ideally suit the laser's chirp, you can observe a compressed pulse shape with sharpened edges (**Reference 6**). The laser's negative chirp preconditions the pulse, allowing longer spans at a given signaling rate than would a zero-chirp pulse.

Lasers are not the only mechanisms that can induce chirp. Indeed, one common mechanism for compensating chromatic dispersion is a *chirped fiber Bragg grating*—a length of fiber manufactured with a chirped refractive-index pattern. Another passive CD-compensation technology, *DCF* (dispersion control fiber), uses a glass formulation that exhibits negative chromatic dispersion. These purely optical compensation methods suffer from several limitations. The Bragg gratings work well for narrowband channels, but tolerance in the manufacturing process make them less attractive for wideband applications, such as WDM. DCF is expensive and also cannot fully compensate 40-nm DWDM.

Passive optical compensators enjoy advantages over compensation methods. They operate entirely in the optical domain avoiding the cost and complexity of OEO (optical-electronic-optical) conversions. They require no energy input other than the uncompensated signal. Beyond their limitations in WDM and DWDM service, their disadvantages include the introduction of significant insertion loss and the lack of a ready means of adjustment. Their insertion loss is a

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significant detraction. Optical amplifiers can make up the gain, but they add noise and significant capital and operating expense, which adds to the already-large cost of the passive compensators. DCF is also large, requiring a length of compensating fiber nearly one-fifth of the length of the compensated span.

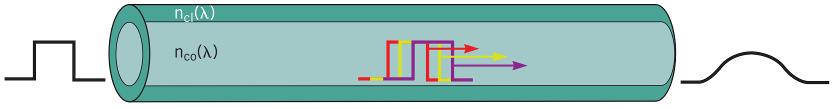

Figure 4

Chromatic dispersion is caused by a pulse's finite spectral width interacting with the fiber's refractive index, which is a function of wavelength.

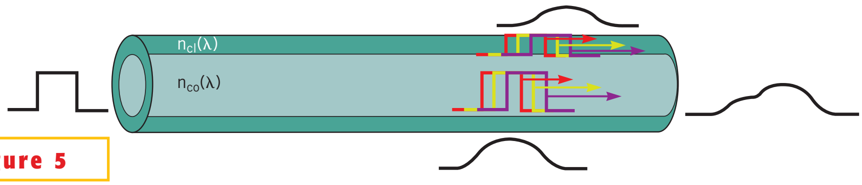

Figure 5

The waveguide dispersion term accounts for the energy that propagates through the cladding.

BEYOND THE ROPE

Until a couple of years ago, electronic-signal-processing components offered little to mitigate the dispersion effects of optical media. *FEC* (forward-error-control) coding, which provides an error-recovery mechanism that operates at the expense of a small bandwidth overhead, was among the most effective techniques.

As beneficial as FEC coding has been, it, too, has limitations. FEC is an encoding/decoding technology and, therefore, requires processing on both ends of the rope. In an enterprise or campus environment, in which a single organization can choose the equipment for both ends of the fiber, coordinating the facilities on both ends needn't cause a problem, though it can. But outside those environments, interoperability requirements demand a standards-based approach. The UTI G.709 digital wrapper is an example of such a standard. The G.709 implements a Reed-Solomon FEC to provide 6 dB of coding gain at a bit-error rate of 10^{-15} in OC-192 lines with only a 7% coding overhead.

As beneficial as FEC processing can be, it can act on errors only once they are made. It can't change the receiver's perception of the incoming signal quality; allow reliable links over greater spans, particularly in the face of dynamic line conditions; or facilitate higher speed feeds on legacy fiber.

Products such as Vitesse's VCS8123 adaptive CDR (clock-and-data-recovery) chip, an *EDN* Innovation 2000 winner, exemplify important steps toward *reducing* transmission errors in the electrical domain. The VCS8123 brings local intelligence to bear on physical-layer signal processing and optimization in the analog domain—still a rare attribute but one that is gaining currency. At the time of its announcement, the 8123's ability to dynamically adjust its operation to accommodate changing signal conditions set it apart from competing CDRs (**Reference 7**). But, more important (and less well-appreciated at the time), it indicated a shift in the ways I/O architects and component designers were thinking about physical-layer functions. This approach represents a clear move away from a "dumb-PHY" model that blindly provides the means for a change of signal domain—from optical to electrical and from analog to digital—toward a "smart-PHY" model that adapts to signal quality and reduces the occurrence of errors on marginal feeds.

WELL-FOCUSED TECHNOLOGIES

AMCC's Eyemax chip set for OC-192 and equivalent FEC rates also uses an adaptive CDR for dispersion compensation in the S3094 CDR/demultiplexer and G.709-compliant algorithms in the S19208 FEC postprocessor. The S3094 reduces the effects of ISI that CD and PMD cause. The chip provides threshold adjustment and gain control. An external phase adjustment covers ±0.25 UI (unit interval), and the phase stability is ±4 psec.

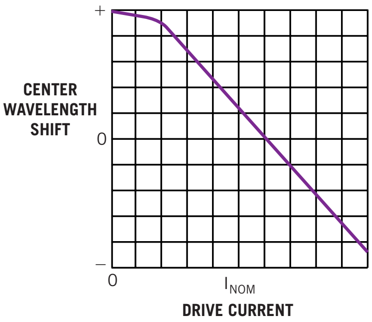

Figure 6

A laser-diode's propensity to modulate its center wavelength with its pulse envelope is called chirp. It causes long- and short-wavelength spectral components to launch at slightly different points along the envelope, causing a dispersion effect similar to chromatic dispersion.

The 3094 receiver and its companion transmitter chip, the S3193, can operate with RZ or NRZ modulation over the 9.953- to 12.66-Gbps range. The RZ modulation option makes the chip set attractive for longer haul services, in which the shorter pulses reduce ISI and make the channel more robust, particularly in the face of PMD.

The S19208 is a bidirectional, enhanced FEC. It uses the ITU G.709 frame and overhead structures and supports the standard G.975 6.2-dB gain rate and a proprietary EFEC code that offers 8 dB or more of coding gain. The 16-bit system-side interface operates at 622 Mbps through OIF MSA (Optical Internetworking Forum Multisource Agreement)-compliant ports. The FEC Framer offers a host of monitoring and diagnostic facilities, including 8B/10B monitoring, 10-GbE Ethernet monitoring, SONET/SDH performance-monitoring supporting OC3 through OC192, and SDH1 through SDH64. The chip can synthesize SONET frames and pseudorandom sequences and inject errors to verify remote error reporting. The $1200 (1000) S3094/S19208 chipset complies with Telcordia, ITU-T, and OIF specifications.

Provided that the fiber-optic link's nonlinearities are small enough to ignore, the dispersion-induced waveform distortion and ISI are, from a signal-processing perspective, linear effects caused by pulse stretching. As a result, you can

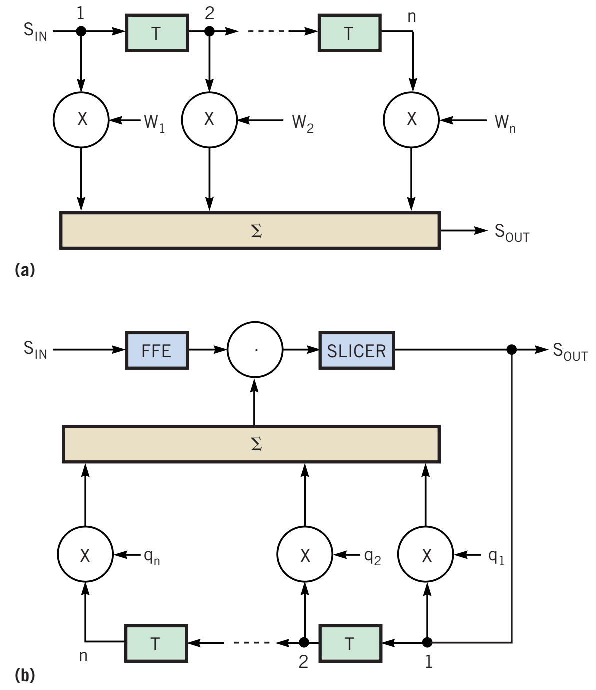

Figure 7 Santel Networks' DSP-based dispersion-compensating PHY chip set implements a feed forward-equalizer (a) and a decision-feedback equalizer (b) to reduce intersymbol interference.

model the channel as a filter with a transfer function, $H_D(f)$. A conceptually simple compensation scheme involves concatenating an equalizer with the inverse transfer function, $H_D^{-1}(f)$—essentially what DCF does in the optical domain (**Reference 8**).

You can compensate the nominal and the dynamic PMD that thermal stress induces with a thermally based compensation method, such as Mitsubishi's FQ-40 series tunable compensators, which use chirped-fiber Bragg gratings mounted over multiple thin-film heaters. The heaters change the local refractive index of their associated grating segment.

The FQ-40 includes a Peltier cell that keeps the center of the grating at constant temperature to lock the center wavelength. The device is tunable across the C and L bands. The compensator's center dispersion is −250 psec/nm, tunable over a minimum ±50-psec/nm range.

Response time is an important limitation for thermally tuned Bragg gratings. Typical responses are in the tens of seconds, much too slow to compensate for the dynamic components of PMD induced by environmental vibration. Additionally, networks that implement dynamic-λ-allocation strategies need compensation technologies with quick response.

Santel Networks solves the problem in the electronic domain by making fast-tunable equalizing compensators that incorporate a DSP in the PHY. The design improves the compensation-tuning response time, requires much less space, and offers substantial cost savings.

Santel forms two filter structures—an FFE (feed-forward equalizer) and a DFE (decision-feedback equalizer)—and integrates them with a CDR and demultiplexer in the two-chip S44501/S44003. Both filters are FIR (finite-impulse-response) types (**Figure 7**). The number of filter taps determines the amount of pulse stretching for which the equalizer can compensate.

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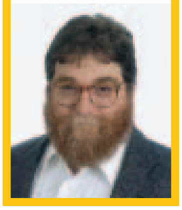

The FFE samples the incoming signal and sums delayed samples weighted by the filter coefficient (**Reference 9**). The second stage equalizer, the DFE, cancels from the current sample those ISI components that are generated by previously detected symbols. The $500 (production volumes) chip set yields a 3- and 2.5-dB reduction, respectively, in CD and PMD-induced OSNR (optical signal-to-noise ratio) penalty.

The CDR features an automatic threshold adjustment and meets the GR-1377-CORE jitter-tolerance requirements. The LVDS demultiplexer outputs match FEC and multiplexer interfaces. The chip set provides first- and second-order PMD compensations of 65 psec and 2000 psec^2; the CD compensation range is ±1700 psec/nm. The Santel chip set's input line-rate range is 9.952 to 12.5 Gbps—sufficient to accommodate OC-192 or 10-GbE Ethernet signals either with or without the bandwidth overheads required for FEC or Digital Wrapper. Of the two, the signal conditioner comes in a 196-pin BGA with a 15×15-mm footprint. The controller fits into a 256-pin, 17×17-mm BGA.

Two recent start-ups—Big Bear Networks, launched in June 2000, and Accumux Technologies, founded in 2001—appear poised to enter the dispersion-compensation market with their first products early next year. Big Bear is taking a direction similar to that of Santel with a two-chip DSP-based compensating CDR/demultiplexer. Accumux bases its compensation technology on an Etalon structure—an optical resonator that could provide compensation for DWDM beams without demultiplexing the individual wavelengths. Accumux's Etalon can perform slope compensation across 80 DWDM channels (100-GHz spacing) in the C and L bands. Other specifications for these products were unavailable at press time, but progress thus far suggests that dispersion compensation is heating up as more vendors seek their gold in the glass.□

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