

OPTICAL NETWORKING

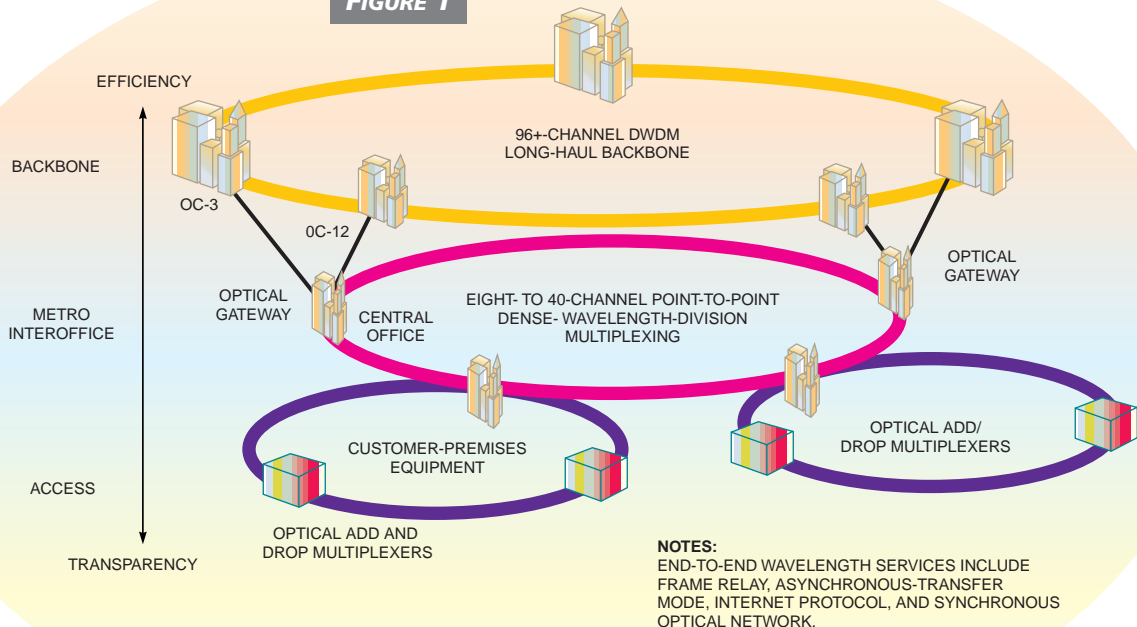
lightens carrier-backbone burden

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The long-haul fiber-optic links for voice traffic—considered limitless 10 years ago—are now flooding with data. With Internet traffic doubling every six months and voice-circuit overloads occurring regularly, carriers want to expand their capacity. Increasingly, they are resorting to the misleadingly named “wavelength-division multiplexing” (WDM). “Wavelength-data multiplexing” might be a better name because this technology does not divide wavelengths. Instead, the technique adds parallel wavelengths to the optical fiber. Besides increasing capacity, these independent optical channels allow carriers to mix protocols and data rates on the fiber links, enabling a more direct connection between end-user applications and the optical layer. However, moving the optical layer closer to users requires switching and routing payloads with devices that manipulate photons rather

More and more users are finding faster ways to send data and are thus overburdening long-haul communications backbones. Optical networking is poised to ease that overload with mixed protocols and data rates and newly emerging photonics.

FIGURE 1



The optical network will provide bandwidth capacity and multiple service offerings from the access network through the backbone network.

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than electrons. This evolution toward optical networking depends on the interplay of these devices with electronic networks.

Optical networking implies that data entering the network at any node traverses the network in the optical domain and exits at any other node. An optical network converts data bits from digital-electronic to digital-photonic format at the source. Practically, however, the source, such as a computer, fax, or digital-TV feed, as well as the links to the access networks, will be electronic for the foreseeable future, meaning that the optical layer will terminate in the access network (**Figure 1**). The data remains in the photonic format until its conversion to electronic format at the access-network node closest to the destination.

This vision of the optical network requires it to transmit, route, and manage data and to perform survivability functions, which keep a network alive while allowing diagnosis of the faults. Fiber-optic long-haul networks rely on electronic devices and standard protocols, such as the synchronous optical network (SONET) in North America and the synchronous digital hierarchy (SDH) in Europe, to perform the critical functions of a carrier's business. The carriers' investments in the electronic infrastructure are substantial and prohibit a sudden change to optical networks until the technology is sufficiently mature and dependable.

However, a slow evolution from SONET/SDH-based networks toward optical-layer networks is occurring because of optical's increased capacity and greater mix of services. Further, optical networks offer higher reliability because of immunity to EMI and RFI; this immunity, in turn, decreases bit-error rates. Also, optical networks can cover greater distances and use thinner cables than electrical networks. These advantages mean that optical networks are evolving and migrating to regional networks and will eventually take over metro and telephony-access-area networks. However, this admittedly simplified evolutionary scheme to optical networking requires significant photonic technological advances to become a reality.

@a glance

- Optical networking means that photonic data enters the network at any node and can exit the network at any other node before being converted back to electronic format.
- Optical-fiber amplifiers regenerate optical signals across the spectrum without concern for protocols or data rates.
- Wavelength-division multiplexing allows sending multiple colors, or wavelengths, on a single fiber connection.
- Optical add/drop multiplexers, cross-connections, and switches need further development for a complete optical network.

Since the mid-1980s, fiber-optic point-to-point links have provided the telecommunications backbone. The capacity planners calculated their requirements based on the assumption that a typical user would make only one six-minute phone connection per hour. However, by the mid-1990s, the Internet, cell phones, teleconferencing, faxes, digital video, and corporate intranets dramatically changed that assumption. By some estimates, many users now consume as much as 180 minutes per hour of equivalent bandwidth. Add to that the high-speed cable modems, digital-subscriber-line modems, and wireless broadband-access systems that are available to consumers, and the bandwidth

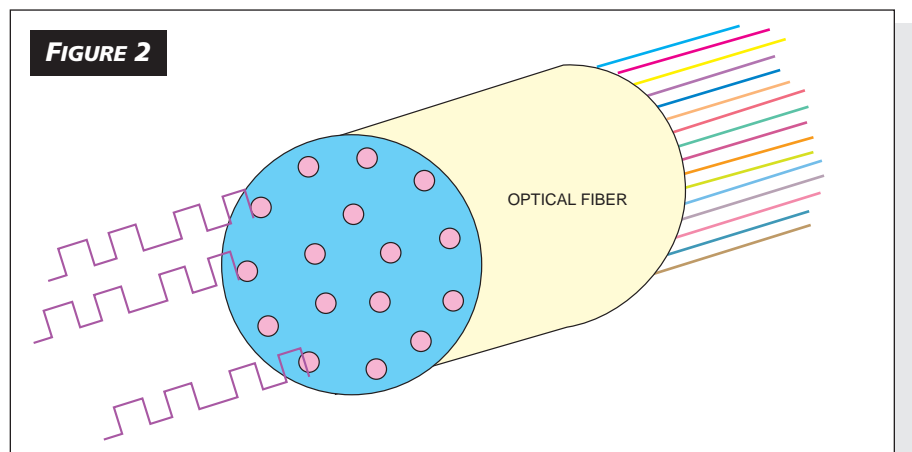
requirements continue to increase.

Users are demanding not only increased bandwidth, but also quality of service (QoS) and bandwidth management. Better QoS for such applications as multimedia translates to carriers' guarantees of low latency and little jitter from the network. Moreover, corporate intranets are demanding privacy and security from public and leased lines. The QoS and security issues motivate the carriers to lease dedicated gigabit channels that provide multiple-gigabit/sec data rates. As a result, carriers need more bandwidth, the ability to allocate bandwidth by request or reservation, and more channels to meet their customer's demands.

Expanding bandwidth

To satisfy customers' bandwidth demands, the datacomm and telecomm carriers have three choices: Lay more fiber, increase the bit rate on the fiber, or employ WDM. Laying more fiber is the economical choice when the distance is short and the conduit and rights-of-way are available. Laying more fiber is a poor option in densely occupied cities in which digging trenches in streets has high ancillary costs. Also, laying more fiber does not enable the carrier to offer new services, dedicated channels, or bandwidth management in the optical layer.

Increasing the time-division-multiplexing (TDM) bit rate that the fiber carries means increasing bit rates from SONET's 155-Mbps optical carrier (OC)-



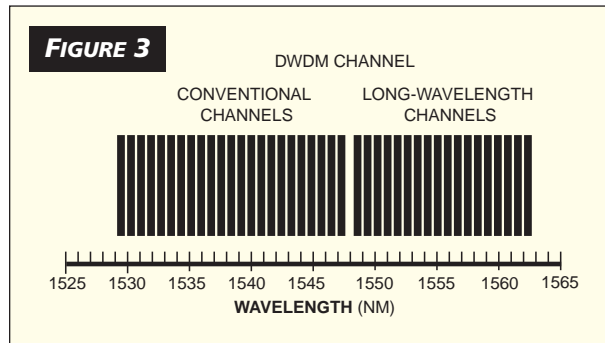
Wavelength-division multiplexing enables multiple wavelengths, or colors, to simultaneously carry independent channels through a single optical-fiber link.

3 and SDH's 155-Mbps synchronous-transport module (STM)-1 to the 622-Mbps OC-12/STM-4, the 2.5-Gbps OC-48/STM16, or the 10-Gbps OC-192/STM-64. The electronics to implement these options becomes increasingly expensive, especially at the OC-192 level, because of the relative immaturity and need for special processes, such as GaAs transceivers and switches. In addition, as the bit rates increase, the reach shortens, requiring more regeneration equipment to boost the signal strength in long-haul routes. After OC-192, the 40-Gbps OC-768 is a quantum leap for electronic components and prohibitively expensive. Even if cost were not a consideration, increasing the bit rate for the TDM protocols offers little improvement in the bandwidth granularity and services that customers want.

WDM transmission to the rescue

The other option, implementing WDM, adds parallel wavelengths, or colors, of light that each carries its own channel (Figure 2). With WDM, carriers can quickly increase capacity and avoid the hassles of laying new fiber. Also, the carriers can use the lower cost OC-3, OC-12, and OC-48 data rates on multiple channels to achieve aggregate bandwidths greater than the 10- and 40-Gbps rates they would achieve by increasing the TDM bit rates. Besides increased capacity, the carriers can also provide each channel with the services and data rates their customers require.

The first WDM systems doubled the capacity in the installed fiber by assigning incoming optical signals to the two wavelength windows in which the losses in the fiber hit a minimum—1310 and 1550 nm. Then, in the early 1990s, new techniques for tuning lasers and filtering wavelengths allowed putting more channels around the 1550 band. These techniques led to dense-wavelength-division

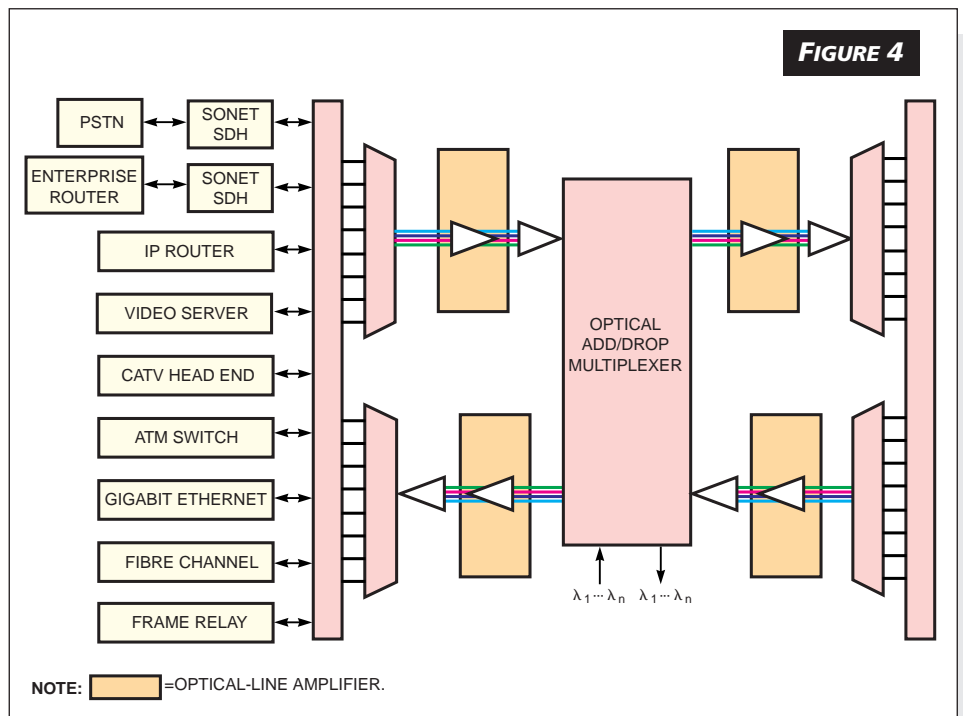


The 1530- to 1565-nm dense-WDM window accommodates 43 channels with 100-GHz spacings that can each carry 10-Gbps signals.

multiplexing (DWDM): packing more than eight—and, sometimes, as many as 100—wavelengths into a fiber. However, the International Telecommunications Union (ITU)-T G.692 recommendation for DWDM standard-wavelength spacing divides the 1530- to 1565-nm wavelength window into 43 wavelength channels with 100-GHz spacing (Figure 3). Each channel can carry an OC-192 signal for a 430-Gbps total bandwidth. Some vendors are going beyond the standard and offering DWDM systems

with 50-GHz channel spacing for a total of 96 channels, but this channel spacing can accommodate only OC-48 signals, resulting in 240 Gbps of total bandwidth.

The WDM option for increasing capacity was prohibitively expensive until the commercialization of the erbium-doped fiber amplifier (EDFA) (Reference 1). Before EDFAs, WDM transmission required regenerators every few hundred meters to convert each wavelength to electronic format, amplify the signal, and then reconvert the wavelengths to optical format. EDFAs eliminate the optical-electrical conversions and regenerate the signal by multiplying the volume of photons without regard to the wavelength characteristics. A single EDFA regenerates the entire spectrum of wavelengths as a group and without any regard to bit rate or protocol on individual wavelengths. Although an EDFA may cost 50% more than a single-channel electronic amplifier, the EDFA scales to any number of channels or



The DWDM multiplexer accepts any optical signal, independent of the protocol or the bit rate.

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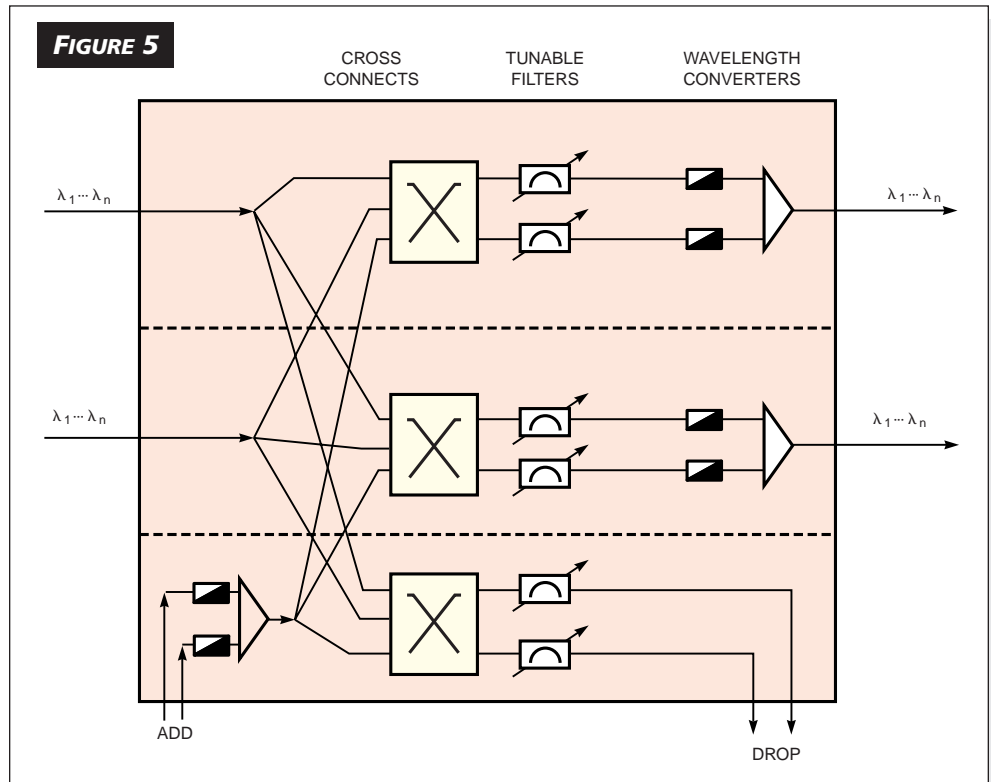
bandwidths without modification.

DWDM and all-optical amplifiers are the cornerstone technologies of optical networking. All-optical amplifiers enable cost-effective DWDM, which, in turn, enables high-bandwidth channel delivery through complex networks. By allowing the introduction of multiple protocols and data rates into the optical layer, DWDM systems can interconnect networks across wide areas. Fiber optics connect ATM, frame-relay, Ethernet, and other high-speed switch-output networks (Figure 4). Because these networks have switches, routers, or multiplexers that can output data streams at optical channel speeds, such as OC-3, OC-12, and OC-48, they feed data streams directly to the optical layer. Furthermore, DWDM systems simply integrate the SONET and SDH data streams as any other data stream. This ability leads some optical-network fans to proclaim the demise of SONET/SDH networks.

With DWDM's ability to directly accept multiple protocols and data rates, some optical enthusiasts claim that the SONET/SDH protocols are unnecessary because SONET's main purpose is to multiplex many 64-kbps DS0 voice channels into 55.84-Mbps OC-1 and OC-3 and optical channels. However, SONET/SDH benefits extend beyond multiplexing. The protocols provide intelligent network elements that enable remote provisioning, testing, inventory, customization, and reconfiguration. SONET/SDH also provides survivability in networks that experience single-node and multiple-link failures and compatibility with legacy and future networks. Again, carriers won't readily abandon the investment they have in the SONET/SDH architecture for an untested optical network.

Optical-network components

The all-optical network will rely on technical developments to fulfill the



Alcatel's generic architecture for an optical cross-connection with add/drop ports provides for broadcast, multicast, or select channel routing from inputs to outputs.

hype that preceded it. First, recent fiber-optic cable designs improve the transportation of DWDM by controlling multichannel interference, but widespread deployment is only beginning. Next, all-optical amplifiers are approaching full wavelength-window coverage and gain flatness across the usable spectrum. Programmable add/drop multiplexers for which first-generation equipment is just entering the commercial market improves optical networks' flexibility. High-port-count switches and routers further improve this flexibility, but cost reduction and switching response time while accommodating more wavelengths are technical hurdles. Even when these technologies mature, optical-system reliability will depend on inline wavelength monitoring and integrating the photonics and electronics.

With the introduction of photonic amplifiers, the focus on new fiber development shifts from optical attenuation and dispersion to optical nonlinearity. These nonlinearities cause wavelength

channels to have different velocities because of zero-dispersion factors. On the other hand, too much dispersion causes intersymbol interference within a channel. Newer, nonzero-dispersion fiber incorporates a bit of dispersion at the signal wavelength to counteract the nonlinearity and allow for longer reach of multiple wavelengths.

Examples of the new dispersion-managed cables come from Amp, Bookham, Furukawa, and Lucent. Lucent optimized the TrueWave fiber for WDM long-haul applications without using dispersion compensation. TrueWave performs well on wavelengths of approximately 1550 nm. The fiber permits wavelengths to carry OC-192 bit rates for distances of 400 km, which reduces the requirement to regenerate signals with electronic or optical amplifiers to reach these distances.

For metropolitan networks, Lucent developed AllWave fiber to increase wavelength density. Increased density gives service providers more channels

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per fiber to lease but at the expense of lower bit rates and distances. The trade-off between number of channels and bit rate/distance fits into metro and access-network applications. AllWave provides 50% more usable-wavelength channels than today's conventional fiber by using a new purifying process during manufacturing that virtually eliminates water molecules, which make some wavelength windows unusable.

Optical amplifiers

Advances in optical amplifiers complement the fiber developments. The first-generation EDFAs had wavelength-dependent gain profiles. This technology resulted in large gain variations between wavelengths at the receiving

end of long-haul transmissions that employed many cascaded EDFAs. To counter this affect, EDFA vendors developed gain-flattened amplifiers by using fiber-grating filters (see sidebar "Fiber gratings are key to optical networks"). The filters equalize the gain across the spectrum and, therefore, achieve maximum bandwidth.

In addition to the commercialization of gain-flattened EDFA, new amplifier designs can support 100 wavelength channels at 100-GHz spacing. These amplifiers have an 80-nm bandwidth that spans conventional 1525- to 1565-nm channels and the long-wavelength channels beyond 1565 nm (L-band). The gain spectrum in the L-band varies by several decibels from the C-band

requiring a second gain-equalizing fiber grating. The result is a uniform gain over the entire 80-nm spectrum.

However, beyond gain-flattened amplifiers and the ITU-T Recommendation G.692 for wavelength-centering specifications, little standardization of EDFA devices exists (**Reference 1**). To promote standardization and second-sourcing of EDFAs, Ericsson and Nortel Optoelectronics recently announced a common footprint design and package interface. The devices use the EDFA gain-flattened design in a sardine-can-sized package for efficient fiber management and reduced board space. The cooperation includes a standard pc-board layout for preamps, booster amps, and midstage access-line amplifiers.

OPTICAL NETWORKING VENDORS AND ORGANIZATIONS

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Much optical network innovation is occurring in optical add/drop multiplexers (OADMs) and optical cross-connect switches (OCCSs). Although companies such as Alcatel, Lucent, Osicom, and SCI offer OADM products, many improvements are necessary for widespread adoption. OADMs will primarily serve metropolitan-area networks and will need to be remotely software-configurable to serve carriers' customer

needs for bandwidth and services.

The generic architecture for an OADM and OCCS system is similar to that of an electronic system (Figure 5). Both OADMs and OCCSs require optical filtering for wavelength selection and an optical switch to dynamically connect input to output ports. One of the hurdles for all-optical switching is the discrepancy between switch-response time and optical-carrier data

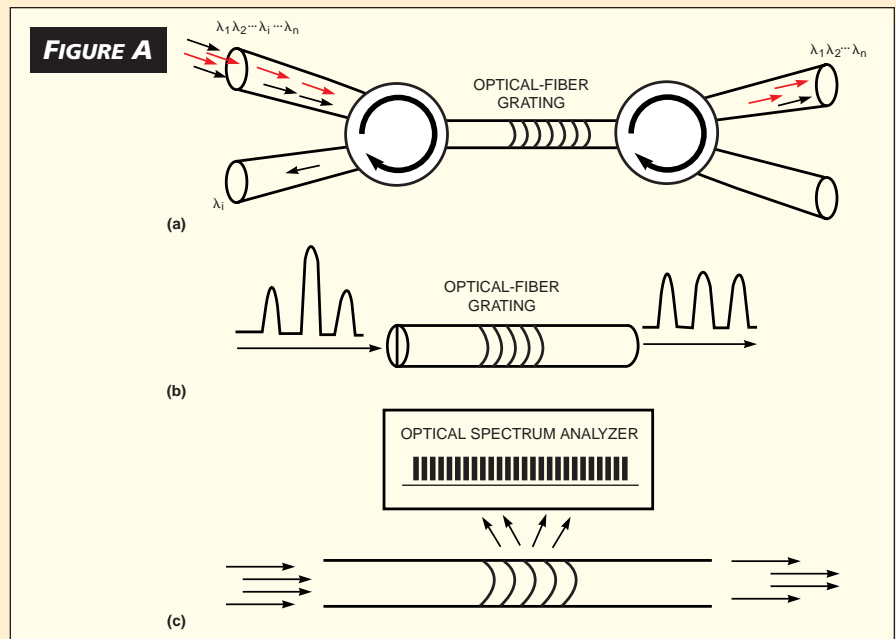
rates. Mechanical and thermo-optic switches are available but take as long as 1 msec to switch wavelengths. New large-scale switch designs with submicrosecond response times use a manufacturing technique similar to that used for high-speed optical modulators: a constant laser with external modulation. An array of lithium-niobate based electro-optic switches direct input fibers to output fibers.

FIBER GRATINGS ARE KEY TO OPTICAL NETWORKS

Optical networks rely on passive optical filtering for several key functions. Many optical equipment vendors use UV-induced optical-fiber gratings, or "fiber Bragg gratings" (FBG). However, FBG is only the most popular of several technologies, such as thin dielectric films, Fabry Perot devices, and bulk optic gratings, that photonic designers use in wavelength-division-multiplexed (WDM) systems. The eventual use of one technology over the others will depend on how the devices scale in cost and functions as the number of wavelengths increases.

The fiber-optic gratings are permanent, temperature-independent reflection filters (Figure Aa). The fabrication process uses intense UV light to holographically imprint diffraction gratings to the core of an optical fiber. The result is control of wavelengths with precision accuracy of ± 0.02 nm. True mass production of fiber-grating-based WDM filters is only occurring now, and future developments will include modular grating subsystems for adding, dropping, and routing wavelength channels.

The UV-induced fiber-optic gratings find uses in controlling, combining, routing, and monitoring wavelengths in all optical-network functions except receivers. The passive filtering components control wavelengths as gain-equalizing filters, adjustable filters, and dispersion compensation devices (Figure Ab). To flatten the gain slope of individual amplifiers, erbium-doped fiber amplifiers incorporate fiber-grating filters with finely tuned transmission profiles to equalize the gain variation to ± 1 dB. Dispersion compensation is important for upgrading legacy fiber with high dispersion at wavelengths near 1550 nm at which level low loss and long reach make WDM most attractive.



Optical fiber gratings reflect (a), filter (b), or tap (c) finely tuned wavelengths in optical fiber.

The FBG combining and routing properties are instrumental for WDM multiplexing and demultiplexing, add/drop filtering, and switching. Photonic designers are exploring several techniques for combining and routing fiber-optic gratings. For example, FBGs integrated into planar silica-on-silicon technology form the basis for a type of programmable optical router. This technology allows low-cost integration of active and passive photonic devices with electronic chips on a silicon substrate.

The tapping properties of fiber-optic gratings are desirable to augment network-management and control systems (Figure Ac). An inline optical-spectrum analyzer provides inline monitoring of multiple wavelengths. An FBG taps a small fraction of the signal out of the fiber and directs it to a detector array for real-time analysis.

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Alcatel's offerings provide a glimpse of the state of the art in OADMs and OCCSs. Alcatel's Optinex 1640 OADM for high-capacity, long-haul applications delivers 40 channels on ITU 100-GHz spacing, and you can configure any eight of those channels through software for add, drop, or pass-through capability. The 1640 OADM accepts any mix of optical signals from 100 Mbps to OC-192 and uses an integrated transponder to translate incoming wavelengths to ITU compliance for output. Each of the 40 channels can carry a 10-Gbps signal, making this OADM able to carry 400-Gbps data.

Targeting the SONET-to-optical-layer-boundary applications is the Optinex 1680 OGX optical gateway cross-connect. It functions as a gateway between the SONET transport layer and the emerging optical layer. The 1680 OGX accepts SONET OC-3, DS3, or STS-1 rates and then internally aggregates and grooms these signals for DWDM output. Because the complex grooming functions are more efficiently performed electrically, the internal workings of the 1680 are electronic rather than optical.

Managing the optical network

Combining the SONET, ATM, and other protocols for variable-bit-rate DWDM transportation is a complex task for network-management software. OADM vendors would like to protect their users from this complexity and are, therefore, providing management software with their products. However, this software remains extremely complex because direct optical monitoring of the fiber is unavailable but necessary for systemwide management and control. A network operator needs to know real-time details, such as the number of wavelength channels present and their signal levels at each node in the system, for full control and to simplify the software.

Using a fiber grating that taps off a small fraction of the signal in a fiber is one way to simplify the software. The signal fraction supplies real-time inline data monitoring at a central management station over a dedicated manage-

ment channel. The tapped information allows the network manager to control gain, throughput, channel rerouting, and other such management tasks from remote locations for every network element in the system.

The eventual architecture of the optical-network evolution will depend on the cost of the components and the software complexity required to manage those components. One thing is for sure, though: Local and long-haul carriers will install more fiber and increase the capacity of the installed fiber with DWDM technology. The fiber will move closer to the applications and, therefore, will further pressure carriers to evolve to optical networks. It remains to be seen how carriers will integrate electronics, photonics, and management software into one backward- and forward-compatible system offering the reliability, capacity, and services that customers demand. **EDN**

References

1. Schweber, Bill, "How it works: Optical amplifiers literally pump up the (photon) volume," *EDN*, July 16, 1998, pg 40.

Acknowledgments

Thanks to Deepak Rana of Transwitch and Daryl Chaires of Alcatel for information on SONET/SDH and optical networking.



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