Advances in technology have resulted in new types of variable optical attenuators for DWDM systems specifically adapted to a wide range of applications.

Novel VOAs provide more speed and utility

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As the dense-wavelength-division-multiplexing (DWDM) revolution proceeds, demand has grown enormously for active optoelectronic components that enable full network control in the optical domain. These components contribute dramatically to improvements in network speed, capacity, and reliability. Electronically controllable variable optical attenuators (VOAs) play a crucial role in controlling optical signal levels throughout the network.

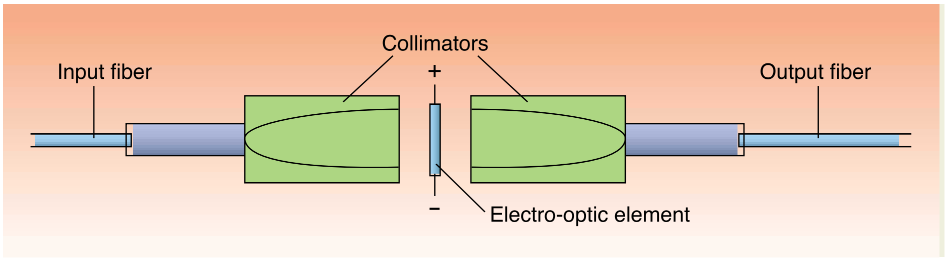

FIGURE 1. In the configuration of a VOA based on a high electro-optic (EO) material, light introduced via an input collimator passes through an EO element and exits by way of an output collimator. Attenuation control is affected by adjusting the electric field across the EO element.

What drives VOA demand

In the last several years, designers have begun to use VOAs extensively. Three main network applications for the devices have surfaced to date. The first is termed pre-emphasis and is performed because head-end DWDM transmission systems require that the optical power between all channels be equalized before they are combined into a single optical fiber. Direct control of a laser's drive current is not desirable because changes to the current cause an unacceptable wavelength shift. Using VOAs to adjust WDM channel power enables the lasers to maintain optimum wavelength stability.

A second application is channel balancing. At add/drop network nodes, channel equalization is imperative because optical signals arrive independently from different points in a network, making pre-emphasis impractical. The third application, optical automatic gain control—simultaneous attenuation of multiple wavelengths between stages in erbium-doped fiber amplifiers (EDFAs)—enables tuning of amplifier gain for specific span lengths. This capability optimizes power levels throughout the transmission line and reduces spectral gain tilt induced in EDFAs by changing optical power—for example, adding or dropping channels. Finally, VOAs can be combined with other functionalities for new uses (see "Combination VOA/modulator enhances network control," p. 140).

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Beyond network use, VOA demand by instrumentation manufacturers has dramatically increased. For example, VOAs contribute to tunable laser instrumentation by maintaining constant output power during a sweep across a range of wavelengths.

Performance requirements

In the area of optical performance, the most important specifications of a VOA are insertion loss (in most applications less than 1 dB is required) and dynamic range of attenuation (typically 15 to 25 dB). In addition, a VOA must provide constant attenuation at all wavelengths and with respect to temperature. Also important is polarization-dependent loss (PDL) and polarization-mode dispersion. Because the polarization-related parameters are additive and cannot be compensated for, their values have become critical as distances between electronic regeneration stations increase. For example, the total loss induced by a VOA with a 0.3-dB PDL in a ten-EDFA span would be 3 dB, a sizable impact to the system's total budget.

The increasing number of DWDM wavelengths is putting pressure on designers to find ways to reduce the printed-circuit-board footprint required by all optical components. Manufacturers of VOAs have found a variety of different approaches to address this need, such as more-compact components. Variable optical attenuators, such as a series developed by Corning Applied Technologies (Woburn, MA), use micro-optic subcomponents to provide the VOA function in a footprint as small as 260 mm^2.

Additional functions are being incorporated: VOAs can be combined with an integrated optical tap to eliminate the space required for an external tap coupler. Alternatively, the VOA function can be incorporated inside an add/drop multiplexer for power balancing of incoming wavelengths.

Requirements for VOA speed vary substantially, depending on the application. In long-haul EDFA designs, attenuators need to respond to gradual changes in signal level caused by environmental conditions; for instance, changes in temperature put varying amounts of strain on the optical cabling, causing slight variations in its attenuation. However, in dynamic network nodes there is a strong need to effect the add/drop of optical channels in the time specified by SONET or other standards. In these situations a VOA response time of one millisecond or less is very desirable.

Combination VOA/modulator enhances network control

With the advent of high-speed variable-optical-attenuator (VOA) technology, network designers are now able to increase the flow of control information between network nodes without requiring the expense and high insertion loss involved in optical-signal de-multiplexing (see figure). By using a VOA that has an intrinsically fast material response speed of approximately 1 µs, both signal level and modulation functionalities can be implemented without increasing component count.

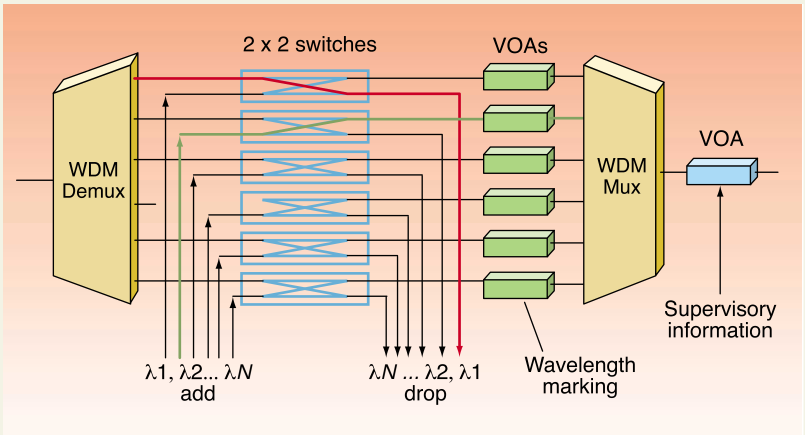
The key to successful operation is to first select a device that can be modulated at a rate many times the fundamental VOA response time, eliminating the possibility of the modulation effecting the underlying optical power setting. Then choose a small depth of modulation (for example, a few tenths of a decibel) so that there is no interference with the fundamental optical signal.

Network applications

Two network applications have emerged for this combination of functionalities.

One is frequency tagging of wavelengths, in which each wavelength is tagged by modulating it at a slightly different frequency in the kilohertz range. Downstream, wavelengths can be electronically separated out by optically tapping the signal path and filtering the detected signal based on modulation frequency. This enables identification of active wavelengths as well as their relative power levels.

Another application is communication of supervisory information between nodes; in this application the output of a node is modulated to impress network-level information on the data stream. Here, data rates in the 100- to 500-kHz range are desirable. At the next network node, information can be extracted without the need to demultiplex the fundamental signal. ❑



Combined VOA and modulation capabilities are possible in an optical-network node when the VOA is extremely fast. Without disturbing the underlying optical signal, modulation to the depth of a few tenths of a decibel enables frequency tagging of wavelengths or addition of supervisory information.

Approaches to variable optical attenuation

There are many different ways to achieve variable optical attenuation (see table). In one method, an electro-optic (EO) based VOA controls the level of attenuation by changing the index of refraction in an EO material through application of an electric field. It offers excellent optical specifications and high-speed operation.

One of the most popular VOA technologies in production today uses a mechanical means to effect attenuation. This is accomplished either by the mechanical interference of the light beam by a stepper-motor-driven blade or filter, or by fiber deflection. These designs offer excellent optical performance at the cost of slower speeds (typical settling times for a 10-dB shift in attenuation are 100 to 500 ms) and larger physical size.

Thermo-optic devices take advantage of the relationship between the index of refraction and temperature of certain materials. One approach is a side-polished fiber in which a polymer in close proximity to the fiber core changes its index with temperature, affecting the amount of light coupled out of the fiber core and dissipated in the cladding. While this approach lends itself to compact devices with low insertion, the response time is very slow.

In another thermo-optic device based on a Mach-Zehnder interferometer, one arm of the interferometer is heated to create an optical-path-length difference with respect to the second arm; thus, the output optical power depends on the temperature difference between these two paths. Several companies have produced this type of device with good results—excepting a high (greater than 1.5 dB) insertion loss caused by the fiber/substrate junction and the waveguide structure.

Other technologies include liquid-crystal and MEMS-based VOAs, both

VOA technology comparison

TECHNOLOGY	ELECTRO-OPTIC	MECHANICAL (BEAM INTERFERENCE)	MECHANICAL (FIBER DEFLECTION)	THERMO-OPTIC (FIBER)	THERMO-OPTIC (PLANAR WAVEGUIDE)	MEMS
Insertion Loss (dB)	0.8	0.6	0.3	0.2	2	1
Dynamic Range (dB)	25	30	15	20	20	60
Speed for 3-dB attenuation (ms)	0.1	100	500	1000	2	20

newcomers to the market place. They offer the potential of very compact VOA arrays. Several companies have exhibited prototype devices.

Two VOA solutions

Recent technological developments have resulted in VOAs with improved qualities. One of these new devices finds use for pre-emphasis and channel balancing, where speed and size are critical. During the past five years, advances in materials technology at Corning Applied Technologies have enabled the development of VOAs that combine desirable optical properties with all-solid-state reliability and speed. These devices are built around the use of an EO material as the control mechanism. The use of EO materials in optical networks is not new. Highly reliable lithium niobate ($LiNbO_3$) modulators are significant contributors to optical network operation.

Variable optical attenuators can be manufactured using materials with substantially higher EO coefficients than $LiNbO_3$. This approach allows a nonguided, free-space design (see Fig. 1). Light travels perpendicular to the EO material's surface, enabling low insertion loss and polarization-insensitive operation. Adjusting the electric field applied to the EO element changes the material's index of refraction and thereby the level of light output.

The results to date have been significant. Variable optical attenuators occupying only 260 mm^2 (0.4 in.^{2}) offer a 25-dB dynamic range with insertion loss of less than 1 dB. This small size enables future integration of several optical functions (VOA arrays, attenuator/ filter combinations, and so on) in a very compact package. In addition, optical characteristics are excellent.

The fundamental response time of these VOAs is well under 1 µs. The high speed permits the implementation of a real-time closed-loop control system (see Fig. 2). This approach brings the clear benefits of precise attenuation setting based on real-time light intensities and very low temperature dependence.

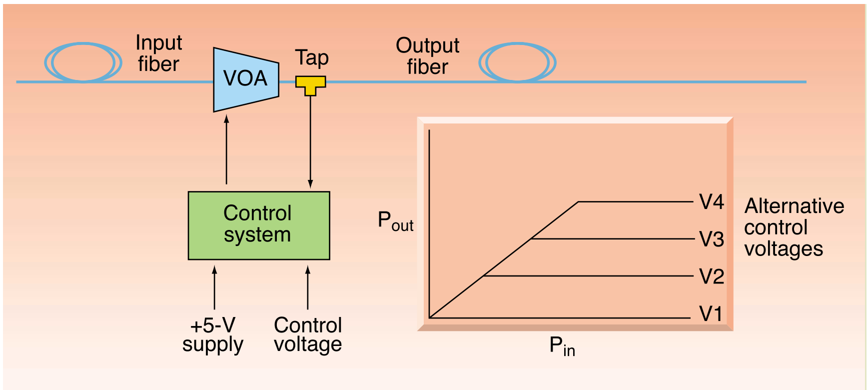


FIGURE 2. A variable optical attenuator becomes part of a closed-loop control system. The output tap coupler provides real-time information to the control system, which compares its value to the desired level specified by the user through the control voltage setting. The system then automatically provides the correct voltage setting to the VOA.

Closed-loop control systems have been built that have a 10% to 90% system response time of less than 500 µs. Setting repeatability is outstanding. After 20 million cycles from minimum insertion loss to 20 dB, the control voltage versus attenuation curve remained accurate to within 0.01 dB. Temperature dependence for the entire system from 0°C to +70°C is only 0.1 dB.

A second VOA with improved qualities is used for automatic optical gain control, where optical performance is critical. Multiclad coupler-based VOA technology developed at Corning optimizes optical performance by using a continuous fiber throughout the VOA. The design is based on the controlled displacement of a fused coupler by a precision stepper motor. As the coupler is bent, a fraction of the input power is diverted to its tap leg. Optical performance is close to ideal: less than or equal to 0.3-dB insertion loss, less than or equal to 0.2-dB wavelength flatness and PDL combined, and temperature stability over a 0°C to 70°C range of 0.4 dB.

Latching—the ability to hold the attenuation level with or without electrical power to the attenuator—is important. Many designers demand that the control of the optical signal be stable even during power outages. Latching in the Multiclad VOA is accomplished by magnetically stabilizing the stepper motor when the power is eliminated, holding the position of the coupler constant and thus its value of attenuation as well.

The growth in optical networks has spawned a range of VOA alternatives. While the more-mature mechanically based devices provide excellent optical performance, newer technologies offer designers trade-offs in speed, size, and integration of other network functionality. ❏