Development of a Variable Optical Attenuator

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ABSTRACT In response to higher levels of traffic on optical communications networks, wavelength-division multiplexing or WDM--the mainstream system now in use--is developing in two directions: higher data rates and a larger number of channels. The erbium-doped amplifier (EDFA) is an indispensable component of WDM systems, and, in order to provide dynamically flexible gain level adjustment, is often used in combination with variable optical attenuators (VOAs), which have flat wavelength characteristics over a wide band range. This paper reports the development of a VOA able to withstand the 200-mW power produced by high-output EDFAs.

1. INTRODUCTION

To respond to the recent rapid growth in demand for telecommunications services, networks are being implemented using wavelength-division multiplexing (WDM) technology, in which multiple wavelengths are multiplexed on a single optical fiber. Erbium-doped fiber amplifiers (EDFAs) are indispensable to these WDM transmission systems: their gain spectrum corresponds to the bands used for WDM communications, enabling batch amplification of the many signals in the transmission band.

The EDFA makes use of the input signal amplification effect due to stimulated emission of erbium ions, and its gain profile is wavelength dependent. In most designs, therefore, a gain equalizer (GEQ) having a reverse profile to the EDFA gain spectra is used with the EDFA to flatten the gain characteristics across the transmission band and thereby maintain a constant level of reception for the signals of each wavelength [1)].

The GEQ however has a fixed profile, so that when there is a change in span loss during transmission or when the signals are added or dropped (optical add-drop multiplexing or OADM) the signal power to the EDFA changes, altering the wavelength-dependence of its gain profile and causing a deviation in the gain-flatteness provided by the GEQ. This makes it necessary to use an optical component known as a variable optical attenuator (VOA) to flatten the gain profile by applying to the EDFA and GEQ a signal-adjusting function that is substantially independent of wavelength [2)].

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VOAs now on the market may be divided into two types: mechanical, having moving parts, and non-mechanical with no moving parts [3)]. Among non-mechanical VOAs are types that make use of the magneto-optic effect and those that use the thermo-optic effect of the waveguide. But in these non-mechanical types of VOA the settings for attenuation are wavelength-dependent. Mechanical VOAs, on the other hand, use a motor or similar means to move an optical filter having an optical attenuation gradient making it possible to realize a VOA with outstanding wavelength flatness by selecting an optical filter with a low wavelength dependence.

The factors described above have led to a burgeoning demand for VOAs in recent years. This paper reports on the development of a mechanical VOA, a type selected because of its superior wavelength flatness and because it has a proven record in installations with EDFAs.

2. DEVELOPMENTAL TARGET

Table 1 shows the target specifications for the variable optical attenuator. In consideration of the fact that the wavelength range of EDFAs extends from the C-band (1525-1560 nm) to the L-band (1575-1610 nm), it was decided to make the VOA applicable to both.

In setting the specifications as shown in Table 1 we took account of the needs of EDFA designers and developers, specifically as related to the points detailed below. Among existing VOAs, one non-mechanical type was outstanding in terms of optical input power, but somewhat inferior as to wavelength flatness, whereas a mechanical VOA was good in terms of flatness but had an optical input power of only about 50 mW. The target therefore was to realize a VOA that would combine good flatness with an optical input power of 200 mW.

The term "repeatability" in Table 1 denotes the setting accuracy for attenuation when resetting the voltage detected by the potentiometer or the number of pulses applied to the stepping motor, and "backlash" denotes the attenuation setting accuracy under the above conditions when settings have been made including reversing the direction of motor operation.

3. STRUCTURE OF THE VOA

Let us describe the structure of the VOA that was developed through this research by following along the light path. The input and output fibers are single-mode fibers (SMFs). The ferrules at the fiber ends are angled-polished at 6° and an anti-reflection (AR) coating is applied. Beam diameter is expanded by a lens and the distance between the lens and the ferrule is adjusted so that the coupling efficiency is maximized at the operating distance. No adhesive was used in the light path of the VOA, and this was essential to improving optical input power performance. The light beam from the input lens was reflected 180° by a prism, in order that the input and output fibers would be arranged on the same side of the VOA module, with consequent savings of space. From the prism the light beam passes through an optical filter (attenuator element) having an optical density gradient in the direction of filter travel, and is then focused by a lens at the output SMF.

Among attenuator elements, filters with a low level of wavelength dependence are referred to as neutral density (ND) filters. The ND filter is connected by means of a plastic nut to the stepping motor, and regulates attenuation by a reciprocating movement in the direction of the density gradient, driven by a tap formed on the nut and by a screw rotated by the stepping motor. To suppress return loss, it is mounted at an angle to the light path.

A potentiometer is provided to detect attenuation. A brush mounted on the nut detects resistance values by establishing contact with a resistance film. These values yield the filter position and thereby the corresponding attenuation. Settings for the attenuation of the VOA installed in the EDFA are controlled by feedback from EDFA output based on the pre-measured relationship between potentiometer resistance and attenuation.

External interfaces for power supply to the stepping motor and potentiometer, and for reading of the resistance values are provided via a flexible circuit board by means of pin electrodes formed on the bottom panel of the VOA.

To maintain the performance of moving components such as the stepping motor and brush of the potentiometer and electrical contacts on the circuit board, the VOA module package is filled with nitrogen gas and hermetically sealed by welding.

4. PROTOTYPE

Photo 1 shows the VOA developed in this work. The target dimensions of 30 mm width, 50 mm length (30 mm length for the fiber-protective sleeve) and 11 mm height were achieved.

4.1 Optical Characteristics

4.1.1 Insertion loss

Figure 1 is a histogram of VOA insertion loss. Using a 1.55-µm light source, average insertion loss is 0.28 dB with a standard deviation of 0.09 dB. This corresponds to

Table 1 VOA target specifications

Optical characteristics	
Wavelength range	1525-1610 nm
Insertion loss	<0.6 dB
Return loss	>45 dB
Wavelength flatness	0.2 dB or 1% of attenuation, whichever is greater
Polarization-dependent loss (PDL)	<0.15 dB
Temperature dependence	<0.15 dB
Optical input power	200 mW
Drive characteristics	
Motor type	2-phase stepping motor
Motor operating voltage	3.3 V
Attenuation detector	Potentiometer
Resolution of attenuation	<0.1 dB/step
Repeatability	<0.1 dB
Backlash	<0.2 dB
Size (W x L x T)	30 x 50 x 11 mm
Package	Hermetically sealed

Photo 1 Appearance of the VOA

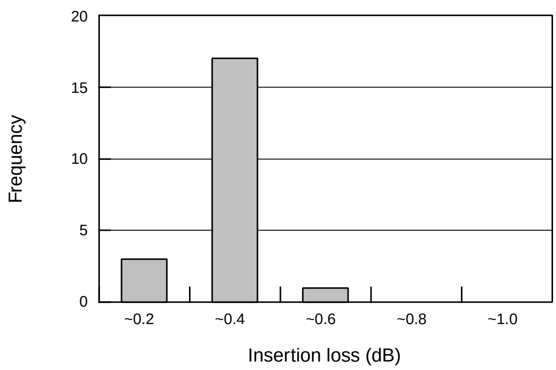

Figure 1 Histogram of VOA insertion loss

the loss between collimators, and the loss in the prism (including AR coating) and that part of the ND filter that is not coated with metallic film. It can be seen that the results obtained from the prototype fully satisfy the developmental target of 0.6 dB.

4.1.2 Return loss
Figure 2 shows the dependence of return loss on motor stepping count at the input and output ports measured for a 1.55-µm light source. This result shows the return loss measured for the entire attenuation range--that is to say for attenuation loss measured while changing motor stepping count. It can be seen that the developmental target of 45 dB or more was attained for the whole of the attenuation range.

Figure 3 shows a histogram of VOA return loss for the input and output ports. In Figure 3 the values taken for return loss for the VOA module are the worst values in the whole attenuation range. The values obtained for average return loss were 48.3 dB at the input port with a standard deviation of 2.2 dB, and 49.1 dB at the output port with a standard deviation of 1.8 dB.

4.1.3 Wavelength characteristics
Figure 4 shows the wavelength dependence of the attenuation spectra. This represents the developmental target. It was confirmed that flatness (maximum attenuation minus minimum) was held to 0.2 dB or less for all ranges of attenuation in the C or L bands, and to 0.3 dB or less for the range covering both C and L bands. Neither were any periodic ripples observed in these spectra, clearly showing that no multiple interference occurred within the ND filter or other optical components. Specifically, defining a ripple as the difference between maximum and minimum attenuation in any 2-nm band at wavelengths of from 1520 to 1620 nm, the average ripple value was 0.032 dB.

4.1.4 Polarization-dependent loss
Figure 5 shows the dependence of polarization-dependent loss (PDL) on motor stepping count. It can be seen that the developmental target of 0.15 dB or less was achieved for the whole of the attenuation range (corresponding to motor stepping count). The wavelength-dependence of PDL was also measured for the C and L bands (no graph shown), and it was confirmed that there was no significant wavelength dependence, and the target value of 0.15 dB was satisfied.

4.1.5 Temperature dependence
Figure 6 is a histogram of the temperature dependence of insertion loss from -5 to +70°C. The average value was 0.10 dB with a standard deviation of 0.05 dB. It can be seen that the target of 0.15 dB or less was comfortably achieved. Temperature dependence is believed to be impacted by the method by which the prism is immobilized, and the good results obtained are attributed to the care taken regarding the amount of epoxy adhesive used, and the position and area to which the adhesive was applied.

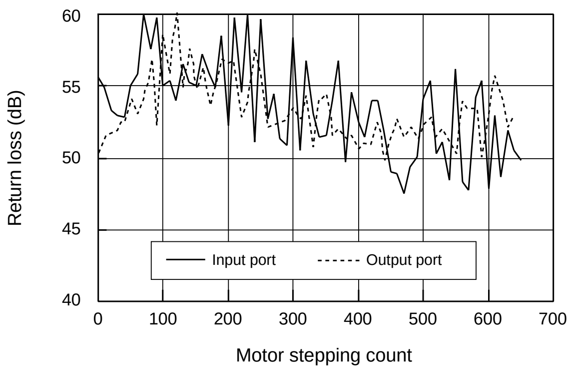

Figure 2 Dependence of return loss on motor stepping count

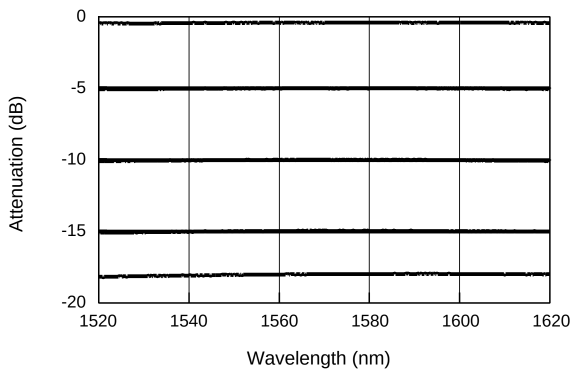

Figure 4 Wavelength dependence of attenuation spectra

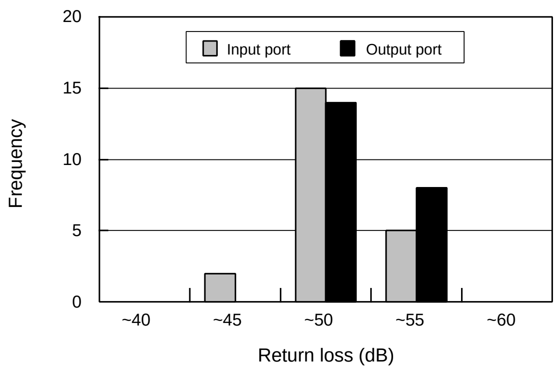

Figure 3 Histogram of VOA return loss

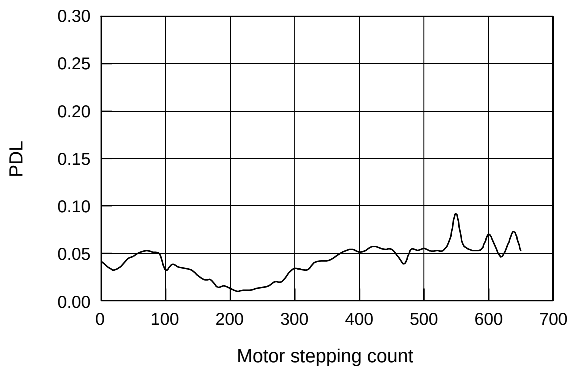

Figure 5 Dependence of PDL on motor stepping count

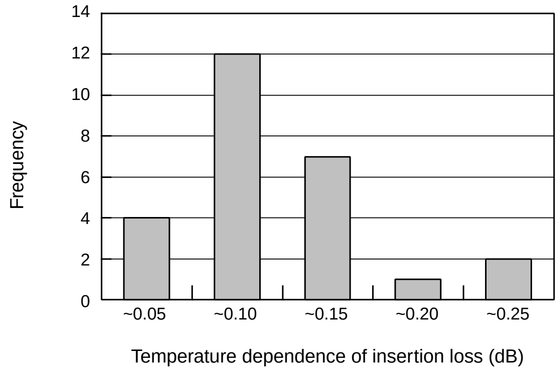

Figure 6 Histogram of temperature dependence of insertion loss

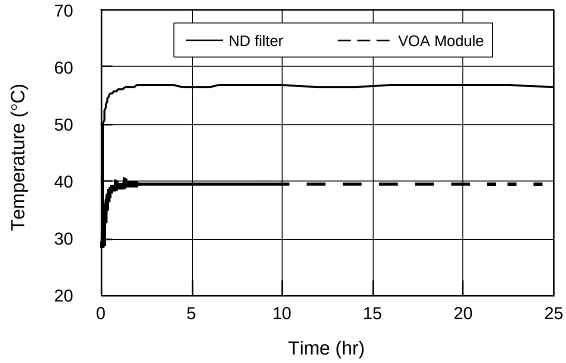

Figure 8 Temperature of ND filter and VOA module

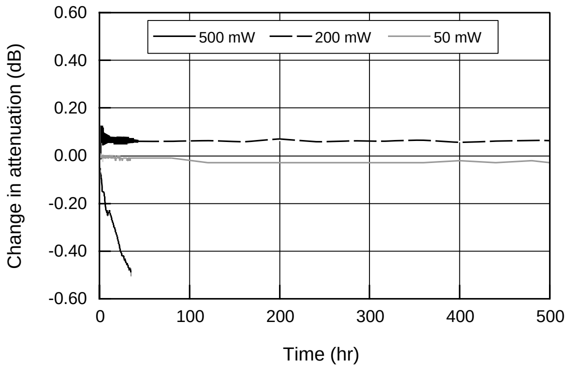

Figure 7 Results of high-power optical input power test of VOA

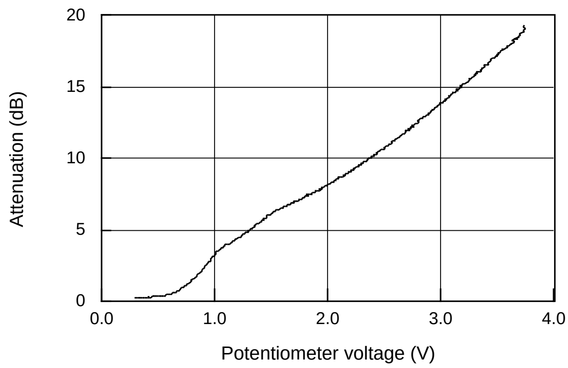

Figure 9 Relationship between potentiometer voltage and attenuation

4.1.6 Input power

Figure 7 shows the results of a high-power optical input power test, in which changes in the attenuation of the VOA were measured as input power changed. As the figure shows, a steady drop in attenuation is seen when optical input power is 500 mW. This is thought to be due to the ND filter's losing its attenuation film function as a result of oxidation of the metals of which it is composed. The reason that the ND filter film becomes oxidized is thought to be absorption of the optical input power by the ND filter film resulting in a rise in film temperature. Thus to guarantee use at the target of 200 mW, we present in Figure 8 the results of measurements of ND filter and VOA module temperature at an optical input power of 300 mW. It can be seen that ND filter temperature was approximately 60°C and module temperature was about 40°C. It is therefore hypothesized that ND filter film oxidation at 500 mW input is promoted by the rise in temperature due to the absorption of the optical input power by the ND filter film and its conversion into heat. From Figure 7, however, it can be seen that, despite the fact that at the target input of 200 mW there was some small increase in attenuation at the early stages of irradiation, which may be attributable to the temperature characteristics of the module itself, the oxidation of the ND filter film progressed extremely slowly so that no change over time in attenuation was measured. Further the temperature of the VOA module only rose to somewhat less than 40°C, confirming that operation under conditions of actual installation would present no problem.

4.2 Operating Characteristics

4.2.1 Attenuation setting accuracy

Figure 9 shows the relationship between potentiometer voltage and attenuation (Note that the attenuation range for the ND filter installed in this VOA was 0 - 20 dB.) Attenuation does show some degree of departure from linearity in the vicinity of 5 dB, but when a single pulse was applied to the stepping motor in a direction such that attenuation was increased or decreased, the direction of increase or decrease in the attenuation and the potentiometer voltage detected were in agreement, confirming that the VOA was functioning normally. The amount of change in attenuation for each pulse applied to the stepping motor averaged 0.040 dB/step, comfortably realizing the target value of 0.1 dB/step.

4.2.2 Repeatability and backlash

The next item evaluated was the repeatability and backlash when a series of 100 pulses was applied to the stepping motor in both directions. The histogram in Figure 10 shows the results. Repeatability was 0.011 dB with a standard deviation of 0.010 dB, and backlash was 0.041 dB with a standard deviation of 0.021 dB, achieving the target values in both cases.

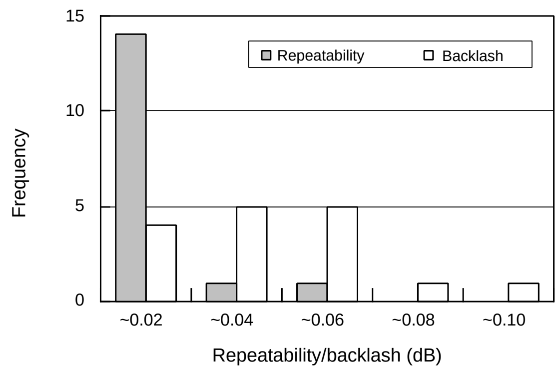

Figure 10 Histogram of repeatability and backlash

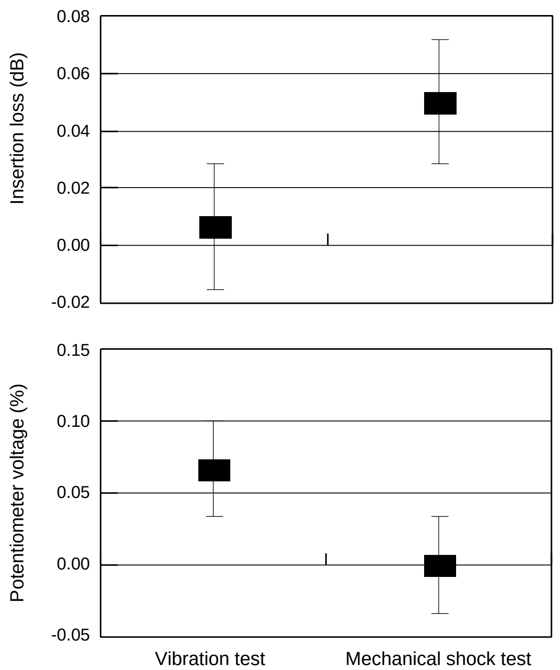

Figure 11 Results of Bellcore mechanical tests

5. RELIABILITY TESTING

5.1 Bellcore Test

The following presents the results of Bellcore tests (GR-1209 and 1221) conducted to test the reliability of the VOA module developed in this report.

5.1.1 Mechanical tests

Figure 11 shows the results of mechanical tests carried out on three modules each--for vibration (Bellcore 1209: 10-55 Hz, amplitude 1.52 mm, 2 hours); and for mechanical shock (Bellcore 1221: 6-ft drop, 8 cycles x 5 times)--in terms of before-and-after change in insertion loss and change in voltage detected by the potentiometer (as a percentage of maximum voltage) when attenuation was set to insertion loss and maximum attenuation.

After each of these mechanical tests there was virtually no change, either in insertion loss or potentiometer voltage, and the units tested were considered to have passed the Bellcore tests.

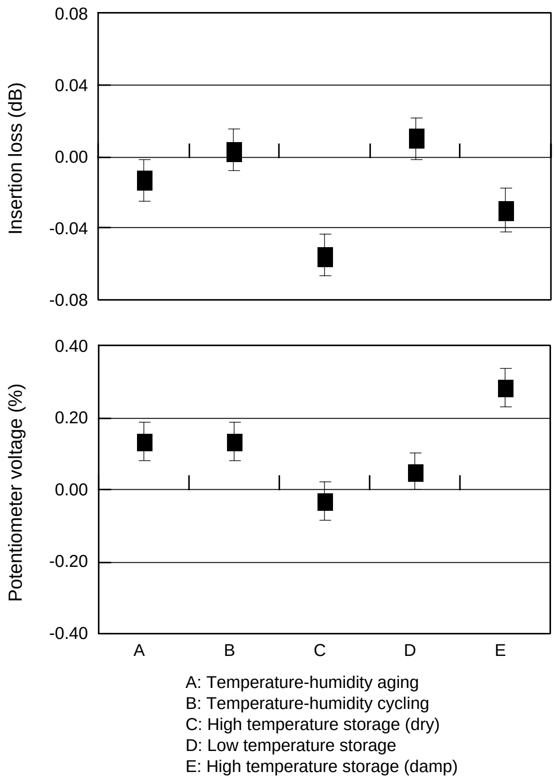

Figure 12 Results of Bellcore environmental tests

5.1.2 Environmental tests

Figure 12 shows the results of tests for environmental temperature and humidity that were carried out on three modules each--for temperature-humidity aging (Bellcore 1209: 85°C, 85% RH, 14 days); for temperature-humidity cycling (Bellcore 1209: -40 to +75°C, 10-80% RH, 42 cycles, 14 days); for high temperature storage (damp) (85°C, 85% RH, 2000 hours); for high temperature storage (dry) (85°C, 2000 hours); and for low temperature storage (-40°C, 2000 hours) (two modules only)--in terms of before-and-after change in insertion loss and change in voltage detected by the potentiometer (as a percentage of maximum voltage) when attenuation was set to insertion loss and maximum attenuation. The results given for the high-temperature storage test and low-temperature storage tests are interim results at the 1000-hour stage, and the tests continue.

After each of these environmental tests there was virtually no change, either in insertion loss or potentiometer voltage, and the units tested were considered to have passed the Bellcore tests.

6. CONCLUSION

A variable optical attenuator (VOA) has been developed that is primarily installed within an optical amplifier and is capable of controlling attenuation by means of external electrical signals that adjust dynamic variations in optical transmission path loss, offers superior wavelength flatness and is capable of accepting high levels of power. It was confirmed that the following target values were satisfied:

Wavelength range	1525-1610 nm
Insertion loss	<0.6 dB
Return loss	>45 dB
Wavelength flatness	<0.2 dB (C-band, L-band)
	<0.3 dB (C+L bands)
PDL	<0.15 dB
Temperature dependence	<0.15 dB
Optical input power	200 mW
Resolution of attenuation	<0.1 dB/step
Repeatability	<0.1 dB
Backlash	<0.2 dB
Size (W x L x T)	30 x 50 x 11 mm

Bellcore tests were carried out to evaluate VOA module reliability, and satisfactory results were confirmed. Tests for high-temperature storage and low-temperature storage are continuing on the way to the 2000-hr mark.

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