

# Variable Optical Attenuators Combined with an Arrayed Waveguide Grating Filter for Next-generation WDM System

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*ABSTRACT: An ever-increasing demand for transmission capacity has been pushing the bandwidth per fiber into the multi-terabit regime. Moreover, the transmission distances of terrestrial systems have been increased to thousands of kilometers, without the need for electrical regeneration. Such ultra-long haul and ultra-high capacity systems require new devices like the one described in this paper. It combines variable optical attenuators (VOAs) with an arrayed waveguide grating (AWG) and has a low loss, low PDL and high stability. It is expected to play an important role in next-generation WDM systems.*

## [1] INTRODUCTION

An ever-increasing demand for transmission capacity has pushed the bandwidth per fiber into the terabit regime. Intense research efforts have been concentrated on achieving a multi-terabit capacity per fiber<sup>(1)</sup>. In addition to this huge increase in capacity, the transmission distance of current terrestrial systems is expected to increase to thousands of kilometers, without the need for electrical regeneration. These ultra-long haul and ultra-high capacity systems require new optical amplifier technology such as the simultaneous use of Raman amplifiers and erbium-doped amplifiers, which are well controlled over the whole gain bandwidth<sup>(2)</sup>. In such systems, the gain variation over the bandwidth introduces a huge transmission penalty, due to effects such as detector saturation or interchannel crosstalk, which is enhanced in wavelength division multiplexing (WDM) systems with many concatenating fiber amplifiers<sup>(3)</sup>. To overcome this problem, new optical devices such as variable optical attenuators (VOAs) and dynamic gain equalizers become very attractive; however, no such devices have been available until now. In this paper, a novel device combining VOAs with an arrayed waveguide grating (AWG) is described. This device is expected to play an important role in the next generation of wavelength division multiplexing systems.

## [2] NEXT-GENERATION WDM SYSTEM

**Figure 1** shows an example of a next-generation WDM system. In this system, two offices are connected with each other via single optical fiber. At the transmitter side, densely packed optical signals are launched into the optical fiber via variable optical attenuators combined with a wavelength multiplexer (VOA-MUX). At the receiver side, these optical signals are demultiplexed into individual signals by wavelength demultiplexers. At some of the nodes between the offices, specific optical signals are dropped or added depending on the traffic demand. Raman amplifiers, which make the system

robust against optical nonlinearity phenomena such as four wave mixing, are used to increase the transmission distance. In this example, the optical signals pass through many amplifiers, which exaggerates the nonuniformity of the gain spectrum of individual amplifiers. Furthermore the optical signals dynamically change in the intermediate nodes, which affect the whole gain spectrum. The optical signal level varies greatly because of these effects, and this considerably deteriorates transmission performance.

To resolve the above problems, VOA-MUXs can play a central role, because their individual signal levels can be set dynamically to the appropriate values to get uniform signal levels at the receiver side.

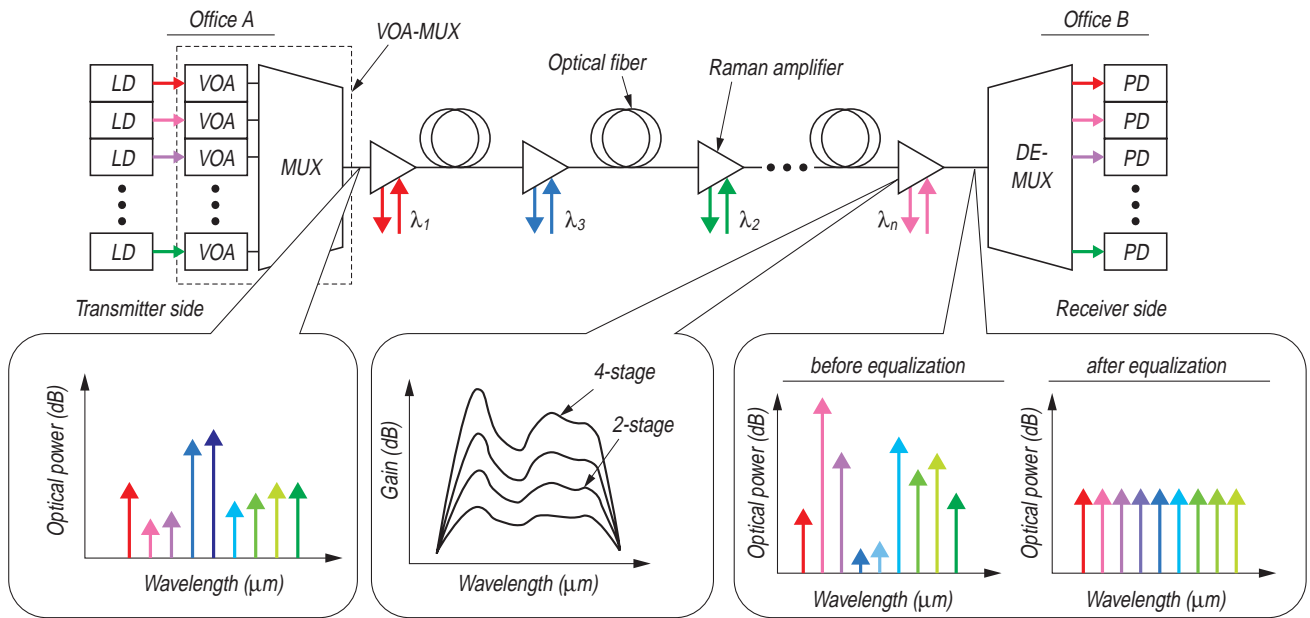
## [3] VOA-MUX MODULE STRUCTURE AND FUNCTION

**Figure 2** shows the schematic diagram of the VOA-MUX module. It consists of one arrayed waveguide grating (AWG), several VOAs and electric control circuits, all of which are packed into an all-in-one module. The AWG and VOAs are formed as planar lightwave circuits (PLC) and are mounted on the same circuit board. Four VOA elements are integrated onto one PLC chip, which reduces the cost of the device. VOA outputs and AWG inputs are connected by ribbon fibers to simplify assembly. The AWG has built-in electrical circuits that automatically control the temperature so as to maintain steady center wavelengths for each channel regardless the ambient temperature. This module also has a built-in electrical communication interface that allows the customer to set the attenuation channel number, attenuation level, error conditions, etc.

### VOA structure and characteristics

**Figure 3** shows the structure of a VOA element. Each VOA element is based on a Mach-Zender Interferometer (MZI) optical circuit. The thin film heater is formed on the MZI arms, which shifts phase via the thermo-optic (TO) effect. The optical signal from the input port is divided into two equal parts at the first Y-branch. When no current is applied to both heaters, the optical signals pass through the second Y-branch without

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LD:Laser Diode VOA:Variable Optical Attenuator PD:Photo-Detector

Fig. 1—Example of a next-generation WDM system

Two central offices are connected with each other via single optical fiber. At some nodes between two central offices, the specific optical signals are dropped or added depending on the traffic situation.

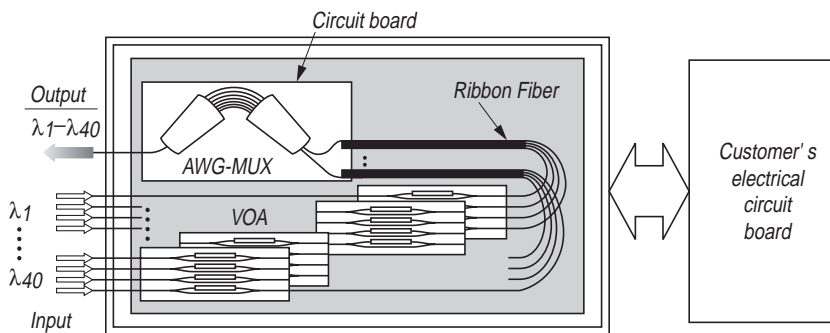


Fig. 2—VOA-MUX module  
VOA-MUX module consists of arrayed waveguide grating (AWG), VOAs and control circuits, all of which are mounted on the same circuit board.

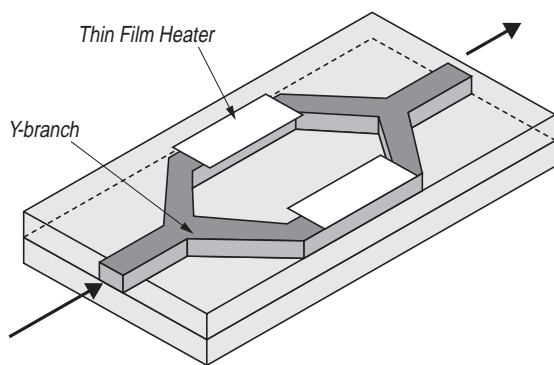


Fig. 3—VOA element

Each VOA element is based on a Mach-Zender Interferometer (MZI) optical circuit. The thin film heaters are formed on MZI arms, which is dedicated to phase shift via Thermo-Optic (TO) effect.

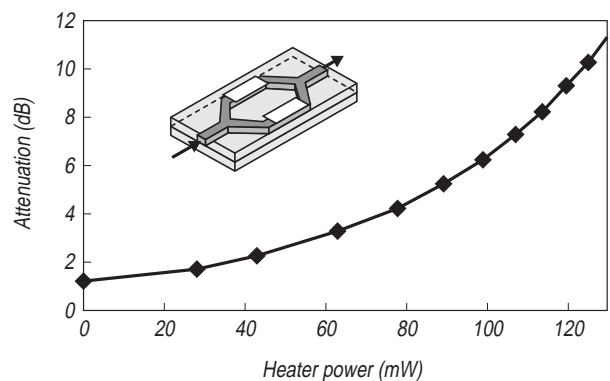


Fig. 4—Attenuation as a function of heater power

The attenuation increases monotonously as the heater power increase. The heater power is around 120 mW for 10 dB-attenuation.

any radiation loss because the confluent optical signals are in phase. However, when only one of the heaters is activated, the optical signal is phase-shifted via TO effect only in the heated

MZI arm. This phase shift generates the radiation mode at the second Y-branch, which results in optical attenuation.

The attenuation level thus depends on the amount of phase shift, which is a function of heater power, as shown in Fig. 4.

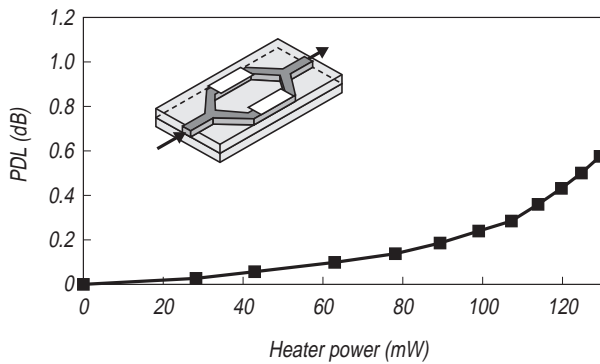


Fig. 5—PDL as a function of heater power  
The PDL increases according to heater power. However, even for a high attenuation level of around 10 dB (heater power is around 120 mW, the PDL is still within the acceptable level of 0.4 dB.

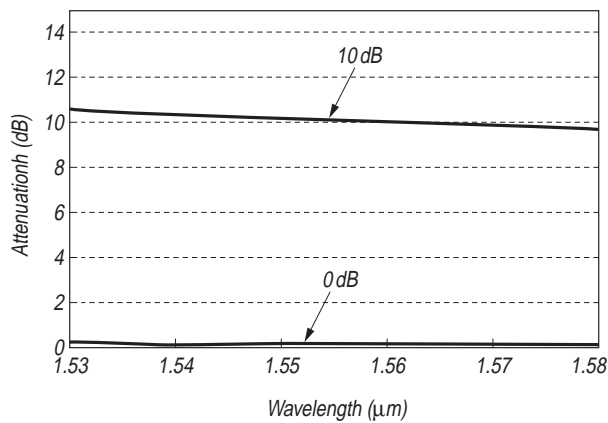


Fig. 6—Attenuation wavelength dependence  
Although there is a small dependence over the 1.55-um region, which is the useful wavelength band for a WDM system, the variation is still within an acceptable level.

The attenuation increases monotonically as the heater power increases. The required heater power to achieve a 10-dB attenuation is around 120 mW.

It is well known that even in a single mode waveguide, there are two orthogonal polarization modes: x-polarization and y-polarization. Generally, optical devices have polarization-dependent characteristics, such as, polarization dependent loss (PDL). **Figure 5** shows the PDL of a VOA element as a function of heater power. Although the PDL increases with heater power, it is still within the acceptable level of 0.4 dB for a 10-dB attenuation.

It is desirable that VOAs have wavelength-independent characteristics. **Figure 6** shows an example of the attenuation wavelength dependence on a VOA element. There is a slight dependence over the C-band region (1.53 um to 1.565 um), which is within the acceptable level.

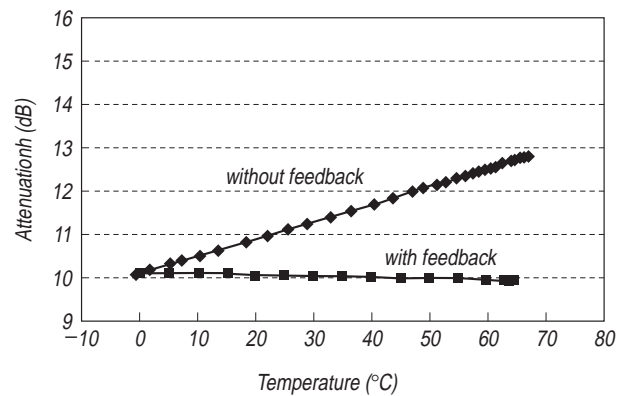


Fig. 7—Attenuation as a function of heater power  
The attenuation changes by about 3 dB without feedback (heater power control).  
On the other hand, with feedback, the attenuation is almost constant over the temperature range.

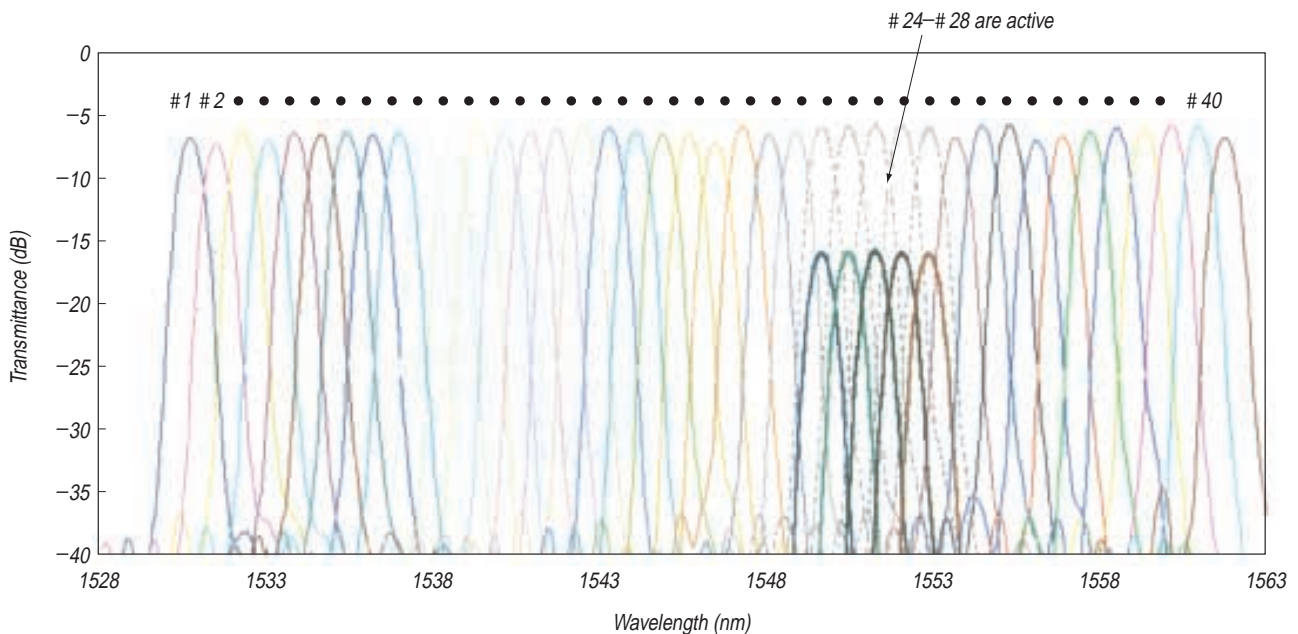


Fig. 8—Spectral response of 40-channel VOA-MUX  
Five channels (#24-#28) are activated to get a 10-dB attenuation. No spectral degradation is visible in this figure.

When VOAs operate in the high attenuation range, the attenuation value becomes sensitive to small perturbations such as slight stress changes or small temperature distribution variations in the MZI elements. Therefore, the heater power is automatically controlled according to the ambient temperature, which is monitored by a sensor in the module. **Figure 7** shows the temperature dependence. During this measurement, the attenuation level was set to 10 dB. Without heater power control feed back, an attenuation change of about 3 dB over 0°C to 65°C was obtained. With feedback, on the other hand, the attenuation was almost constant over the same temperature range.

#### VOA-MUX characteristics

The spectral response of a 40-channel VOA-MUX is shown in **Fig. 8**. Five channels (#24-#28) are activated to get a 10-dB attenuation. No spectral degradation occurs in any of the channels, either activated or non-activated. The device is stable versus changes in ambient temperature as well as the on-off condition of the VOA elements. **Figure 9** is a photograph of the VOA-MUX module in which the optics are compactly mounted on the electrical circuit board. **Table 1** shows the VOA-MUX specifications. Various channel spacings and channel numbers are available.

#### [4] CONCLUSION

Hitachi Cable's VOA-MUX module consists of VOAs, AWG and control circuits, all of which are packed inside an all-in-one module. It also has a built-in communication interface for the customer's electrical circuit board that allows the customer to choose attenuated channel number, attenuation level, error conditions and so on. It has a low loss, low PDL and high stability. It is expected to play an important role in next-generation WDM systems.



Fig. 9—Photograph of VOA-MUX module  
All optics are compactly mounted on the electrical circuits board.

TABLE 1 VOA-MUX SPECIFICATIONS

Various channel spacings and channel numbers are supported.

Item	Specification
Channel Spacing:	100, 200 GHz
Insertion Loss:	<10 dB (VOA off)
PDL (@10 dB attenuation):	<0.5 dB
Dynamic Range:	>10 dB
Power Consumption:	<150 mW/each VOA

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