16-ch Arrayed Waveguide Grating Module with 100-GHz Spacing

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ABSTRACT Dense wavelength-division multiplexing is well on its way to dominating the field of fiber-optic communications, and creating the need for higher-capacity multiplexer/demultiplexers for the optical signals. The authors have developed an arrayed waveguide grating (AWG) module that is capable of handling multiple wavelengths and based on planar lightwave circuit (PLC) technology suitable for mass production. Modules are only 8.5 mm thick and come in a sealed package. A 100-GHz 16-ch AWG module has been fabricated and has been confirmed to have outstanding optical characteristics and reliability.

1. INTRODUCTION

Explosive growth in the Internet and other multimedia applications has created a need for larger communications capacity. Dense wavelength-division multiplexing (DWDM) represents a breakthrough in this area. DWDM mainly uses the 1550-nm band, the gain window of erbium-doped fiber amplifiers (EDFA), effecting simultaneous transmission of a number of different wavelengths on a single fiber. This provides a quantum increase in network capacity without the need for laying new lines. 1), 2)

Figure 1 is a schematic that shows a typical DWDM communications system. Signals having wavelengths λ_1 through λ_n from a plurality of transmitters (Tx) are passed through a multiplexer and are aggregated on a single optical fiber. EDFAs (marked Amp) are provided according to the length of the transmission path to amplify the power of the attenuated signal. The path may also be provided with an add/drop multiplexer (ADM), which can add or drop signals of any desired wavelength, or an optical cross-connect (OXC). The multiple signals transmitted on the single optical fiber are then demultiplexed into signals of the original wavelength. As Figure 1 makes clear, DWDM transmission requires a multiplexer/demultiplexer for the various signal wavelengths. A device used for this purpose of a type using a dielectric filter has been developed, 3) and has been applied in DWDM systems with 4 to 8 channels with 200-GHz (approximately 1.6 nm) spacing or wider, but when the number of channels is increased, devices using a dielectric filter are too bulky and expensive, and their reliability drops. Thus for systems having a larger number of channels, there is a need for a practical multiplexer/demultiplexer of the AWG type.

The AWG is a type of PLC in which optical waveguides consisting of a silica-based cladding and core are fabricated on a substrate of silicon. 4), 5) AWGs have design flexibility with respect to number of channels and wavelength spacing, and are superior in mass productivity, compactness and reliability. Accordingly they are expected to have a major role to play in DWDM systems. The authors have developed a compact and highly reliable AWG module for the multiplexer/demultiplexer of the 100-GHz 16-channel DWDM system that is currently on the verge of commercial applicability.

2. PRINCIPLE OF THE AWG

2.1 Multiplexing and Demultiplexing

Figure 2 shows the circuit structure of an AWG, in which input waveguides, input slab waveguides, array waveguides, output slab waveguides and output waveguides are fabricated on a substrate. The following description relates to operation when used as a wavelength division demultiplexer.

When a multiplexed signal consisting of a plurality of wavelengths λ_1 through λ_n is applied to an input waveguide, it is spread by diffraction at the input slab waveguide and input to the arrayed waveguides. The arrayed waveguides consist of a plurality of optical waveguides

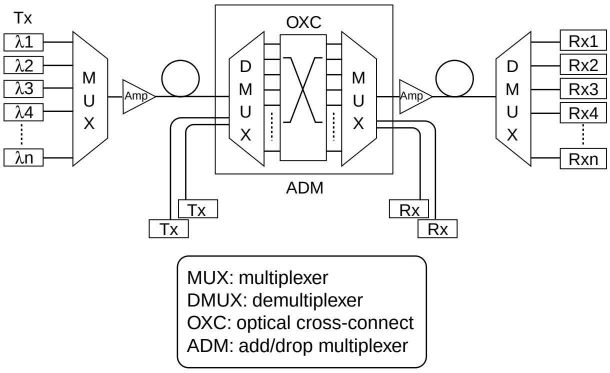

Figure 1 Schematic of DWDM system

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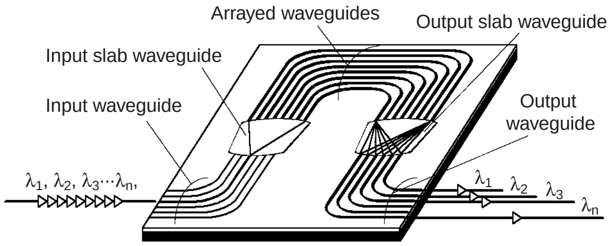


Figure 2 Optical waveguide circuit structure of AWG

that propagate the signals from the input slab waveguide, and which are arranged so that adjacent waveguides have a specific length difference ΔL. This means that at the output port of the arrayed waveguides, a phase offset corresponding to ΔL will be imposed on the signal propagated in each waveguide. After passing through the arrayed waveguides the signals reach the output slab waveguides and are spread by diffraction, but due to the mutual interference between the signals from each waveguide, all the wave fronts are diffracted, at a specified wavelength, in a uniform direction.

Accordingly the signals of differing wavelength are focused at different positions on the output side of the output slab waveguides, so that by positioning an output waveguide at each of these positions, each of the signals is sent to a different output waveguide, thereby extracting the signals λ_1 through λ_n.

Note, however, the signals passing through the input and output waveguides propagate with spatial field. Thus the transmission spectrum of the signals from the output waveguides is generally Gaussian, as shown in Figure 3. Recently it has been possible, by tinkering with the shape of the input and output waveguides, to develop AWGs with a flat-top transmission spectrum. 6)

2.2 Temperature Dependence of the Center Wavelength

Since the AWG acts as a diffracting device, making use of the length and length difference of the arrayed waveguide transmission paths, precise control must be exerted over the difference ΔL between the lengths of adjacent waveguides. In actual practice, however, the changes in the refractive index of the waveguide material caused by changes in temperature, together with the thermal expansion and contraction of the substrate and waveguides, result in changes in both the length and the ΔL of the transmission path. This changes the focal point at the output side of the output slab waveguides as well as the wavelength of the light entering the output waveguides. This change in center wavelength in the 1550-nm band amounts to approximately 0.011 nm/°C.

Furthermore, there might be, say, 100 waveguides in the array, core shape and refractive index are bound to diverge from the designed values. Also even a minor discrepancy in the position of an output waveguide will mean that the signal it produces will vary from the desired wavelength.

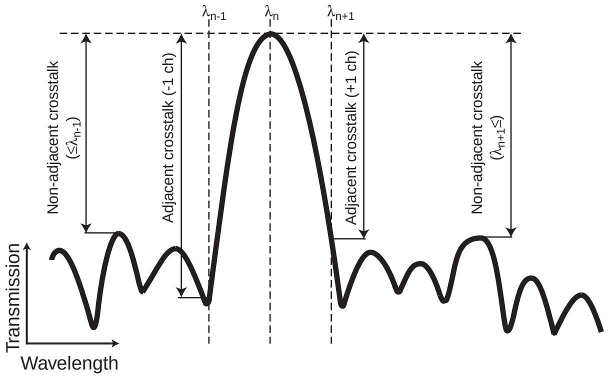


Figure 3 AWG transmission spectrum and crosstalk definitions

DWDM transmissions, however, use an international standard wavelength--called grid wavelength (represented by λ_n in this paper), so that the center wavelength of the AWG must be accurately matched to this grid wavelength. Thus the initial temperature of the AWG is generally regulated so that the center wavelength matches the grid wavelength, and some structure is required to assure that this temperature is maintained despite changes in ambient temperature.

3. REQUIRED OPTICAL CHARACTERISTICS

In general, multiplexer/demultiplexers for DWDM are required to have the following optical characteristics:

- Small center wavelength offset from grid wavelength;
- Low insertion loss;
- Low channel crosstalk.

Since in DWDM the wavelength spacing between adjacent channels is extremely small, the optical line width used in communication must be finer. Even a small offset between the AWG center wavelength and the grid wavelength results in optical loss increase at the grid wavelength. This offset in center wavelength facilitates the passage of light from other channels, degrading propagation characteristics. The permissible center wavelength offset depends on the transmission spectrum of the AWG and the transmission bit rate of the system, but is normally not more than 0.05 nm.

As in the case of other fiber-optic transmission devices, insertion loss should ideally be as low as possible, but here the target was set as 5 dB or better.

Channel crosstalk in terms of a specific AWG channel n is expressed as the difference between the insertion loss at the grid wavelength λ_n of channel n and the insertion loss at the grid wavelength of the respective channel. Crosstalk with respect to the wavelengths of channels n±1 (λ_{n-1} and λ_{n+1}) is termed "adjacent crosstalk" (Figure 3). "Non-adjacent crosstalk" is defined as the difference between insertion loss when $\lambda = \lambda_n$ and the maximum value of insertion loss in the wavelength range $\lambda \leq \lambda_{n-1}$ and $\lambda \geq \lambda_{n+1}$. Channel crosstalk should be as low as possible, but here a target of -25 dB or better was set.

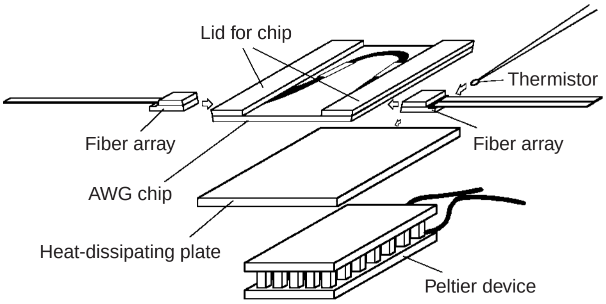


Figure 4 Structure of AWG module

4. STRUCTURE OF THE AWG MODULE

4.1 Structure and Fabrication Procedures

Furukawa Electric has amassed broad experience in the fabrication of a wide variety of PLC modules, including 1 x n star couplers, multi-channel wavelength-insensitive couplers (WINCs), and the like, and this expertise was applied in AWG module fabrication as well. Figure 4 shows AWG module structure.

In fabricating the AWG module, a chip is cut according to the dimensions of the waveguide circuits formed on the substrate. A lid is affixed over the input and output ports, and the end-faces of the chip are polished to an angle of 8° to reduce reflection. The optical fibers for input and output are connected using fiber arrays, in which the fibers are laid out accurately on the V-groove of a glass substrate and bonded in place. The end-faces of fiber arrays are also polished to an angle of 8°. The arrays are then aligned to the AWG chip while monitoring the optical power, and the facets are bonded in place. The use of an automated alignment unit having a precision traveling stage in aligning the light axes achieves low connection loss in a short time.

4.2 Controlling AWG Module Temperature

As has been mentioned above, accurate control of the temperature of the PLC chip is essential, and this is accomplished by a Peltier device and a thermistor (see Figure 4). The Peltier device acts as a heater or cooler depending on the direction of current flow. Temperature signals from the thermistor are fed to an external controller which controls the current to the Peltier device, providing precise temperature control. The module is also provided with a heat-dissipating plate. The temperature control system was designed to maintain AWG chip temperature at 40 to 50°C, and is effective at ambient temperatures of 0 to 70°C.

Normally, of course, when a Peltier device is used for cooling, heat is produced on the opposite surface, so that, in addition to providing accurate control of AWG chip temperature, it was necessary to provide for the effective dissipation of the heat thus generated. By paying careful attention to Peltier device selection, package design and optimization of the package cover material, it was possible to design an AWG module with a thickness of only 8.5 mm. As can be seen in Photo 1, the package of the slimline AWG module is provided with heat-dissipating fins. It is extremely power-efficient, with a consumption of not more than 5 W at ambient temperatures of 0 to 70°C.

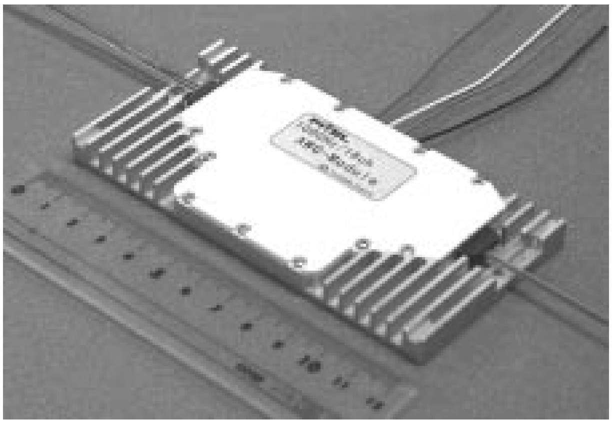


Photo 1 100-GHz 16-ch AWG module

4.3 Sealed Package

When a temperature-controlled AWG is operated in a high-temperature, high-humidity environment, moisture will condense on the AWG chip because it is at a lower temperature. Not only is the heat capacity of the chip increased but accurate temperature control is impossible, and as moisture builds up, heat dissipation cannot keep up with the heat produced by the Peltier device, and temperature control failure occurs. The authors therefore decided to eliminate this problem by using a sealed package arrangement with an O-ring gasket between the package and the cover and sealing compound at the outlet for the optical fibers and power cord, thereby improving performance with respect to high temperature and high humidity.

5. 100-GHZ 16-CH AWG MODULE

Using the sealed package structure described above, an AWG module was fabricated, based on an AWG chip providing 16-channel WDM with a channel spacing of approximately 0.8 nm. Single-mode fibers were used to connect to the AWG chip. The module was extremely compact, measuring only 120 x 60 x 8.5 mm, including the heat-dissipating fins. The results of optical measurements are described below.

5.1 Optical Characteristics

5.1.1 Establishing Operating Temperature and Measuring Center Wavelength

To measure the optical characteristics of the AWG module, it was first necessary to establish the operating temperature. This was accomplished by a technique that involved: 1) measuring the center wavelength at each port at a given temperature; 2) calculating the temperature at which the average center wavelength offset was smallest; and 3) repeating measurements of center wavelength at the calculated temperature. The optical characteristics are

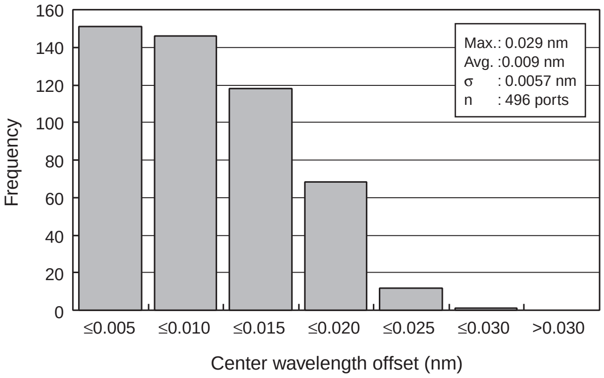


Figure 5 **Histogram for center wavelength offset of AWG module**

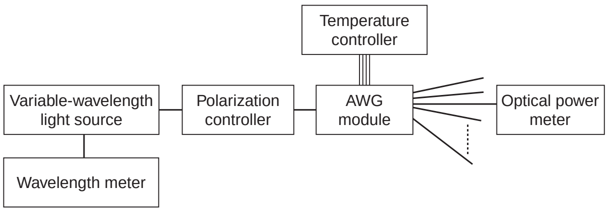


Figure 6 **Setup for insertion loss measurement**

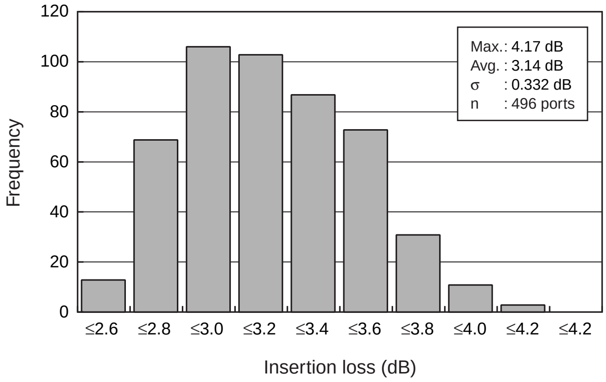


Figure 7 **Histogram for insertion loss of AWG module**

the results of measurements made at room temperature when set to the operating temperature established in this way.

Figure 5 is a histogram of the absolute values measured for center wavelength offset of 31 AWG modules (496 ports). The maximum was 0.029 nm, and the average was 0.009 nm--fully satisfactory for a DWDM multiplexer/demultiplexer.

5.1.2 Insertion Loss

Figure 6 shows the setup for measuring insertion loss, using a variable-wavelength light source accurately controlled by a wavelength meter. The use of a polarization controller allows simultaneous measurement of the polarization dependent loss of the module. Figure 7 is a histogram showing insertion loss at each grid wavelength. The measured value includes polarization dependent loss.

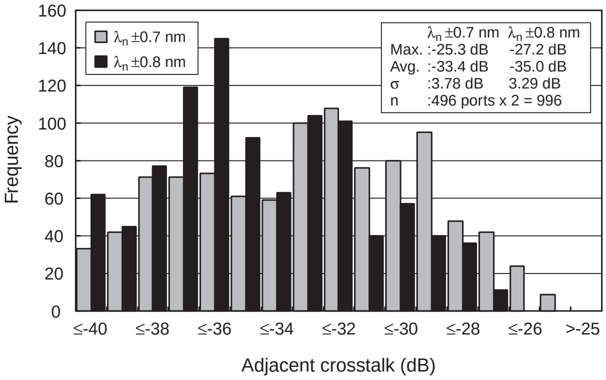


Figure 8 **Histogram for adjacent crosstalk of AWG module**

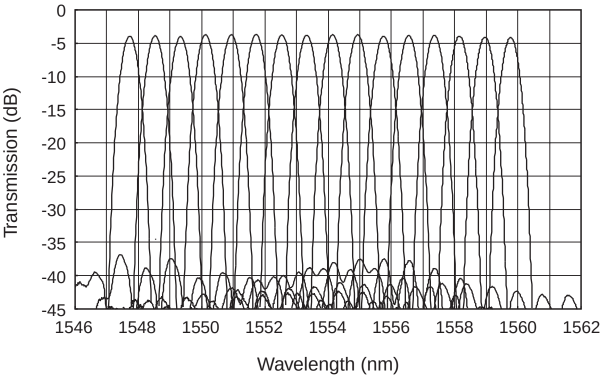


Figure 9 **Typical transmission spectrum of AWG module**

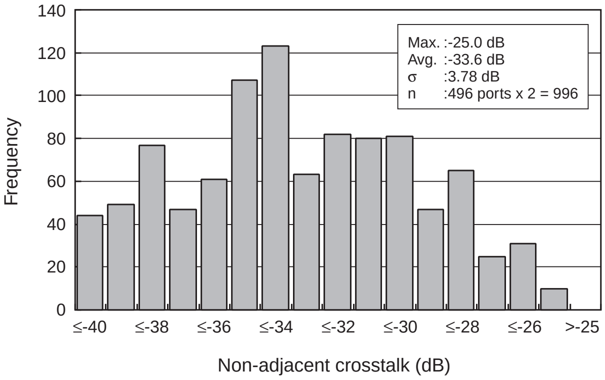


Figure 10 **Histogram for non-adjacent crosstalk of AWG module**

Insertion loss results are excellent, with a maximum of 4.14 dB, an average of 3.14 dB, and a standard deviation of 0.33 dB.

5.1.3 Crosstalk

Adjacent crosstalk was measured at grid wavelength ± 0.7 nm and grid wavelength ± 0.8 nm. Figure 8 is a histogram of the results. Crosstalk at grid wavelength ± 0.7 nm was -25.3 dB maximum and -33.4 dB average, and at grid wavelength ± 0.8 nm was -27.2 dB maximum and 35.0 dB average.

Non-adjacent crosstalk was measured using an ampli-

Table 1 Optical characteristics of 31 AWG modules

Item		Result			n
		Max.	Avg.	σ	
Center wavelength offset (nm)		0.029	0.009	0.0057	496
Insertion loss at λ_n (dB)		4.17	3.14	0.332	496
Ripple at $\lambda_n \pm 0.1$ nm (dB)		1.23	0.82	0.093	496
PDL at λ_n (dB)		0.34	0.06	0.036	496
Adjacent crosstalk (dB)	$\lambda_n \pm 0.7$ nm	-25.3	-33.4	3.78	496 x 2=992
	$\lambda_n \pm 0.8$ nm	-27.2	-35.0	3.29	496 x 2=992
Non-adjacent crosstalk at λ_n - 0.8 nm≤λ≤λ_n + 0.8 nm (dB)		-25.0	-33.8	3.78	496 x 2=992
Return loss at λ_n (dB)	In	42.4	51.6	2.06	31 x 16=496
	Out	42.4	51.6	2.05	496

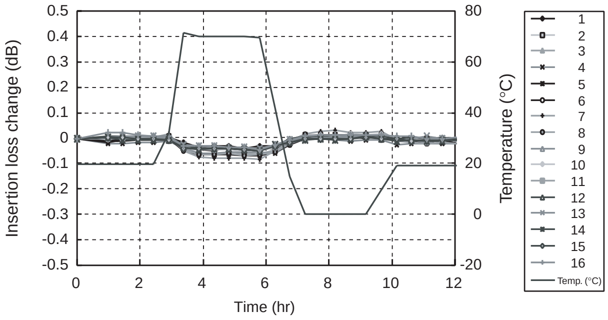
fied spontaneous emission (ASE) light source and optical spectrum analyzer (OSA). Values were calculated based on the measurement results (Figure 9) as the difference between the insertion loss when $\lambda = \lambda_n$, and the minimum insertion loss when $\lambda = \lambda_n$-0.8 nm and the minimum insertion loss when $\lambda = \lambda_n$+0.8 nm. The range measured was the range of grid wavelengths for the 16 channels ± 0.8 nm (λ_1-0.8 nm ≤λ ≤ λ_{16}+0.8 nm). Figure 10 shows the results: -25.1 dB maximum and -33.7 dB average.

5.1.4 Summary of Optical Characteristics

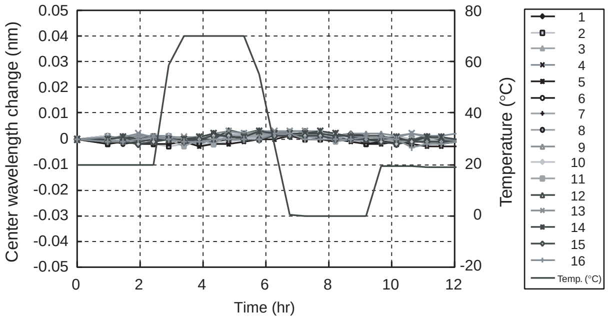
Table 1 summarizes the optical characteristics of the AWG modules. Ripple (λ_n±0.1 nm) signifies the deviation in insertion loss in the range of grid wavelength + 0.1 nm. Return loss was measured at input and output ports for each grid wavelength.

5.2 Temperature Dependence

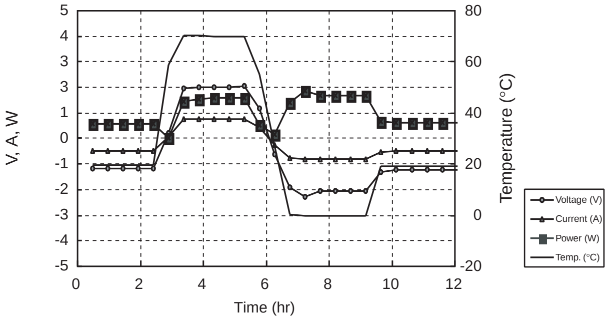
It was confirmed that the AWG modules can operate at ambient temperatures of 0 through 70°C, and Figure 11 shows the changes in insertion loss, center wavelength and power consumption during ambient temperature cycling of 20°C→70°C→0°C→20°C. The AWG module tested had an operating temperature of 44.4°C. The variation in insertion loss was less than 0.1 dB and that in center wavelength less than 0.01 nm; power consumption also showed normal variation. This confirmed that the AWG module is stable with respect to fluctuations in ambient temperature.



a) Insertion loss (dB)



b) Center wavelength (nm)



c) Voltage, current and power consumption

Figure 11 Temperature dependence of AWG module characteristics

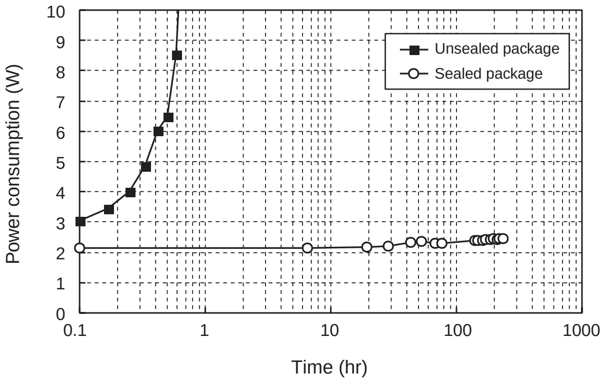


Figure 12 Damp heat performance of AWG in sealed and unsealed packages

6. SEALED PACKAGE

As stated above the AWG modules have a sealed package structure allowing them to operate even under conditions of high temperature and humidity. To confirm the effectiveness of the seal, temperature control of the modules was carried out at an ambient temperature of 70°C and relative humidity of 90%, and power consumption was monitored. Figure 12 plots the power consumption for AWG modules in sealed and unsealed packages. In the case of unsealed modules, power consumption began to rise immediately after the start of the test, and control failure occurred in less than an hour. AWGs in sealed packages, on the other hand, were found to be stable even after 200 hours of operation.

Table 2 Results of reliability tests

Item	Conditions	n	Changes in					
			Insertion loss (dB)			Center wavelength (nm)		
			Avg.	Worst	σ	Avg.	Worst	σ
Vibration	10~55 Hz, 1.52 $\mathrm{mm}_{p\text{-}p}$ 3 axes, 2 hours/axes	3	0.03	0.20	0.06	-0.001	-0.004	0.002
Thermal shock	-15~85°C, Slope :2 mins Keep :30 mins	3	0.01	0.24	0.12	0.001	0.004	0.002
Low temperatures	-40°C, 336 hours	3	-0.04	-0.24	0.09	-0.002	-0.007	0.003
Temperature cycling	-40~75°C, 1000 cycles	4	-0.02	-0.18	0.06	-0.004	-0.007	0.002
Damp heat	85°C, 90% RH, 5000 hours	4	0.43	0.60	0.09	-0.004	-0.030	0.016

7. RELIABILITY TESTS

Reliability tests were carried out in accordance with Bellcore standards GR-1209 and GR-1221, covering vibration, thermal shock, low temperatures, temperature cycling and damp heat. Table 2 shows the test conditions and results obtained in each of the tests. To verify AWG module reliability, fluctuations in insertion loss and center wavelength were measured. To accelerate the damp heat test, a temperature of 85°C was used--10°C higher than the temperature specified. AWG module temperature control was not activated during the tests, and optical characteristics before and after the test were measured with AWG module temperature control at room temperature. The variation in insertion loss was 0.6 dB maximum, and no failures were observed. This confirmed the high reliability of these AWG modules.

8. CONCLUSIONS

An AWG module with 16 channels at 100-GHz spacing capable of being used in DWDM systems has been developed and fabricated. The AWG module has the following characteristics:

a) Superior optical characteristics
  - Center wavelength offset: ≤0.03 nm
  - Insertion loss: ≤4.5 dB
  - Crosstalk: ≤-25 dB
  - PDL: ≤0.4 dB
  - Return loss: ≥40 dB

b) Slim-line profile, only 8.5 mm thick

c) Equipped with heat-dissipating fins, and consumes no more than 5 W at ambient temperatures of 0 to 70°C

d) Sealed package structure for improved performance under high temperatures and humidity

e) Reliability demonstrated under Bellcore standards GR-1209 and GR-1221.

From these results, we are confident that the AWG modules developed here will have a role to play as high-performance multiplexer/demultiplexers in DWDM systems.

In addition to the AWG modules described in this paper, development work is going forward on AWG modules for up to 42 channels, and flat-top broadband transmission characteristics. Furukawa Electric is also able to provide temperature controllers, optical power monitors for AWG modules, as well as MUX/DEMUX modules with alarm functions.

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