Development of a Heater-Control AWG Module

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ABSTRACT Arrayed waveguide gratings (AWGs) have an important role in the dense-wavelength division multiplexing (DWDM) systems that are coming into wider use both in North America and elsewhere around the world. The authors have accordingly developed a heater-control AWG module that is only 12 mm thick and consumes less than 5 W of power. It also achieves optical characteristics that are stable with respect to changes in ambient temperature and tension on optical fibers. Optical characteristics and reliability were confirmed with the fabrication of prototype 100-GHz, 40-channel AWG modules.

1. INTRODUCTION

In response to the need for fiber-optic systems of greater capacity and higher bit rate, dense-wavelength division multiplexing (DWDM) systems, in which multiple optical signals of differing wavelengths are aggregated, are in actual service in North America and coming into wider use elsewhere in the world.

Figure 1 is a schematic showing the structure of an optical communication network based on DWDM technology. This has, until recently, been used mainly in long-haul systems connecting large cities and ultralong-haul systems spanning oceans [1), 2)]. But it is expected to be introduced in medium-haul applications between smaller centers and in big-city metro rings. And with the growing need for greater capacity, existing DWDM networks are expected to be given more channels and enhanced functions. Wavelength-division multiplexer/demultiplexer will be key in achieving this type of architecture for fiber-optic networks.

Multiplexers/Demultiplexers are devices that are capable of multiplexing optical signals of different wavelengths, or demultiplexing a multiplexed signal. They come in a variety of designs--arrayed waveguide gratings (AWG), fiber Bragg gratings (FBG), and thin-film filters (TFM).

AWGs are planar lightwave circuits in which optical waveguides are integrated on a substrate of silicon, silica, or the like, and they are fabricated by a glass deposition and patterning process involving photolithography and etching [3), 4)]. The AWG offers a high degree of design freedom in terms of number of channels and wavelength spacing, so that more channels can be easily provided, and accommodated in a smaller space. And even when there are more channels there is minimal change in module cost, so that costs per channel are lowered. Furthermore in AWGs wavelength dispersion is very low making it suitable for bit rates as high as 40-Gbps and holding great promise for an expanding role in DWDM systems.

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2. PRINCIPLE OF THE ARRAYED WAVEGUIDE GRATING (AWG)

2.1 Multiplexing/Demultiplexing

Figure 2 shows the waveguide circuit structure of an AWG, with the input waveguide, input slab waveguide, arrayed waveguide, output slab waveguide and output waveguide formed on the substrate.

Following is a description of operation as an optical demultiplexer. When a WDM signal comprising a number of optical signals having wavelengths λ_1 through λ_n enters the input waveguides it is diffracted and spread by the input slab waveguides and is transmitted to the arrayed waveguides. These are waveguides placed side-by-side in which each of the signals emitted by the input slab waveguides is propagated, and adjacent waveguides are dis-

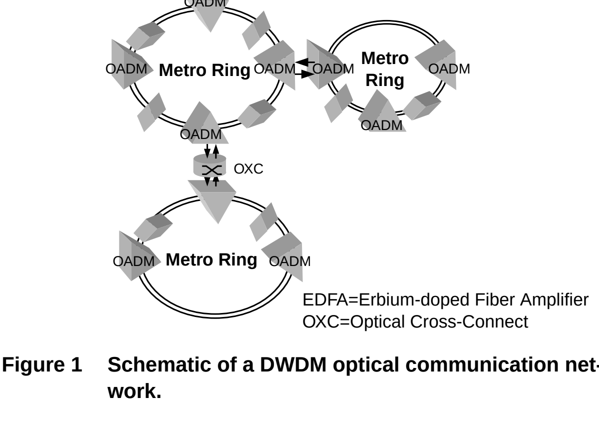


Figure 1 Schematic of a DWDM optical communication network.

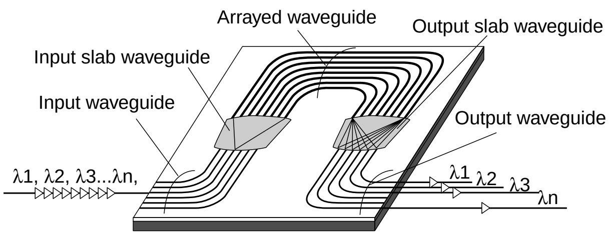


Figure 2 Waveguide circuit structure of AWG.

posed at a fixed optical path length difference. For this reason a phase difference appears in the signal propagated in each waveguide corresponding to $n_c\lambda L$. The signal passing through the arrayed waveguides then enters the output slab waveguides and is diffracted and spread, but the signals passing though the respective waveguides interfere with each other so that in effect they are all diffracted in a direction such that their wave fronts are aligned. When the effective index of refraction for the arrayed waveguides and slab waveguides are n_c and n_s, the angle of diffraction is θ, the distance between arrayed waveguides is d and the wavelength is λ, the in-phase conditions in which the wave fronts are aligned may be represented by

$$n_s d\theta + n_c \Delta L = \mathrm{m}\lambda \tag{1}$$

where m is an arbitrary integer and the order of diffraction. Since the angle of diffraction that gives the direction in which the wave fronts are aligned is dependent on wavelength, signals of differing wavelengths are each diffracted in a different direction. Accordingly the points at which signals of differing wavelength converge at the output ports of the output slab waveguides differ, and by positioning an output waveguide at each of these points, signals of differing wavelength can be sent to a different waveguide, thereby extracting signals of wavelength λ_1 through λ_n.

The above description relates to the operation of an AWG as a wavelength-division demultiplexer, but the same AWG can also be used as a multiplexer. That is to say, when a signal of each wavelength from the output waveguide (when used as a wavelength-division multiplexer) is input, the signals from the input waveguides (when used as a wavelength-division multiplexer) are all output together.

2.2 Temperature-Dependence of Center Wavelength

As has been described, an AWG can be used to multiplex and demultiplex signals of a set wavelength, but this wavelength (the center wavelength) is temperature dependent.

When there is a change in temperature, there is a change in the index of refraction of the waveguide material and an expansion or contraction of the substrate and waveguides, resulting in a difference in the length of the optical path. This results in a shift in the position of the focal point at the output side of the output slab waveguides, and a change in the wavelength of the signals entering the output waveguides. By taking θ in Equation (1) as 0 and differentiating an equation solved for λ by temperature T, it becomes possible to represent the magnitude of the temperature dependence of wavelength by

$$\frac{d\lambda}{dT} = \frac{\lambda}{n_c} \cdot \frac{dn_c}{dT} + \frac{\lambda}{L} \cdot \frac{dL}{dT} \tag{2}$$

where the first term on the right side of the equation represents the temperature dependence of the index of refraction and the second term the change in the index of refraction caused by stress on the waveguide due to the change in the length of the waveguide path accompanying expansion or contraction of the substrate. Since the temperature dependence of the index of refraction of silica glass is 8×10^{-6}/°C and the coefficient of expansion of the substrate is 3×10^{-6}/°C (in the case of silicon), we obtain a change in center wavelength of approximately 0.011 nm/°C.

To make up for the temperature dependence of the center wavelength requires a means of keeping the AWG at a constant temperature irrespective of changes in ambient temperature. Generally this control is accomplished using a Peltier device or a heater, and Furukawa Electric has already developed an AWG module using a Peltier device[5]. In the present work, the authors have developed a heater-cotrol AWG module.

3. PERFORMANCE REQUIREMENTS FOR AWG MODULES

In addition to its fundamental optical characteristics, an AWG module must meet requirements with respect to:

- low power consumption,
- a compact package
- stability with respect to changes in ambient temperature, and
- high reliability.

Recently there has been a trend toward greater total system power consumption, driven by the higher power of erbium-doped fiber amplifiers (EDFAs), the introduction of Raman amplifiers, and the adoption of new types of optical modules due to the enhanced performance and functionality of DWDM systems. The systems as a whole must also be larger to provide enough space to accommodate these devices. This has resulted in an urgent need for individual modules that are more compact and use less power.

There is, however, a trade-off between the size and power consumption of optical modules. Figure 3 is a generic representation (omitting the temperature control mechanism) of an AWG module, which is an example of an optical module with temperature control. Increasing distance g between the AWG chip and the upper and lower extremities of the inside of the package improves the heat insulating properties of the air and decreases power consumption, but results in greater thickness t of the package itself. If, on the other hand, distance g is

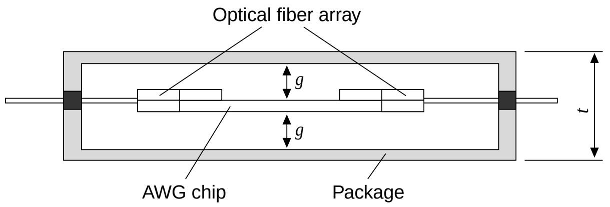


Figure 3 Cross-sectional view of AWG module.

decreased, package thickness is reduced but the thermal conductivity of the AWG chip and package becomes greater, and power consumption is increased.

It is therefore no easy matter to design an AWG module that is both small and low in power consumption. The authors set targets of a package thickness of 12 mm or less and a power consumption, when used at ambient temperatures of 0~70°C, of not more than 5 W, and proceeded to optimize AWG module package design, package materials, and the method of holding the AWG chip.

4. STRUCTURE OF HEATER-CONTROL AWG MODULE

Following is a description of the structure of a heater-control type AWG module. Optical fiber arrays were connected to the AWG chip, and a heater and resistance temperature device (RTD) were mounted within the package. Photo 1 shows a 100-GHz, 40-ch heater-control AWG module. As can be seen in Figure 4 the package has a footprint of only 119.6 × 65.5 mm, and is only 12 mm thick. This package can also accommodate other types of AWGs (50-GHz, 40-ch, etc.).

To keep down the power consumption of this module the package was made using a plastic of low thermal conductivity, and measures were taken to minimize the area of contact between the AWG chip and the package.

The decision to use a plastic package, however, raised a number of problems. Plastics normally have a large coefficient of thermal expansion making the package highly responsive to changes in ambient temperature, so that if the optical fibers are attached to the package they are subjected to tension. This applies stress to the joint interface between the chip and the optical fiber array, resulting in an increase in insertion loss and even in breakage of the module. For this reason when plastic is used for the package the normal practice is either to leave the optical fibers unattached, or to use an adhesive that is resilient. This means, however, that if tension is applied to the optical fibers it is transmitted to the joint interface between the optical fiber array and the AWG chip, resulting in a major increase in insertion loss. In the heater-control AWG module described here, a structure was adopted that overcomes this problem, modifying the point of fiber attachment so that even when ambient temperature changes or tension is applied to the fiber, the stress is not transmitted to the chip-optical fiber array joint.

Photo 1 Appearance of 100-GHz, 40-ch heater-control AWG module.

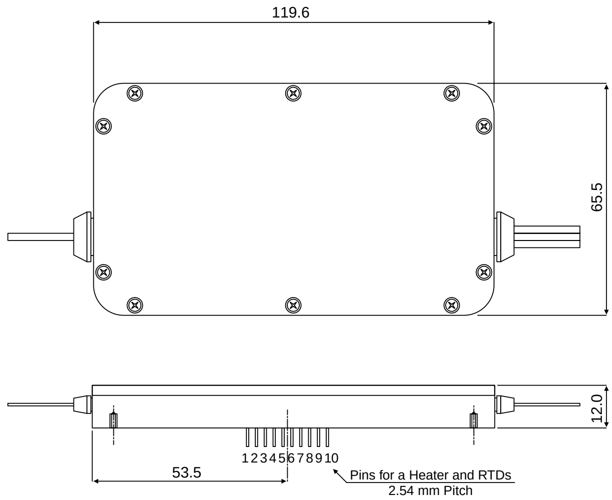


Figure 4 Dimensions of 100-GHz, 40-ch heater-control AWG module.

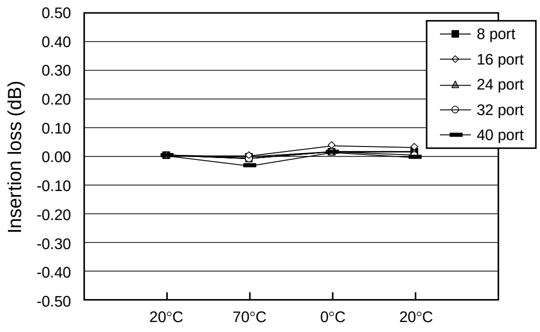
5. PROTOTYPE 100-GHz, 40-ch HEATER-CONTROL AWG MODULES

Using the structure described above, seven prototype 100-GHz, 40-ch heater-control AWG modules were fabricated, and evaluated for the desired characteristics.

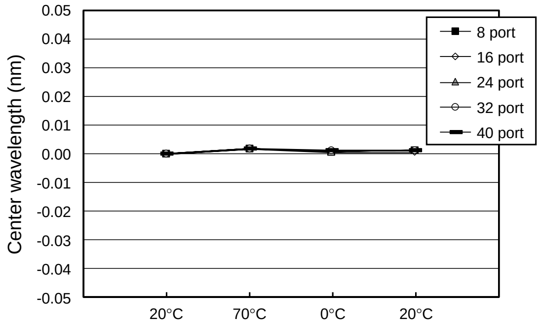
Generally speaking the center wavelength of an AWG will vary as a result of fabrication error, and to make sure that the center wavelength agrees with the grid wavelength, the control temperature must be set separately for each device. In the case of a heater-control type AWG module this control temperature must be set higher than the operating temperature range (0~70°C), and here a temperature of 70 to 80°C was adopted. In order to evaluate the suitability of the module structure adopted, the control temperature was set at 80°C for these prototypes.

5.1 Temperature Dependence

The operation of the prototype heater-control AWG modules was confirmed at ambient temperatures of from 0 to 70°C. Figure 5 shows the temperature dependence of insertion loss and center wavelength during ambient temperature cycling of 20°→70°C→0°C→20°C. Fluctuations are represented as a change from the value at the initial setting of 20°C. It can be seen that fluctuation was extremely small for both insertion loss and center wavelength.



a) Insertion loss



b) Center wavelength

Figure 5 Temperature dependence of selected characteristics.

Table 1 summarizes the change in insertion loss and center wavelength at 70 and 0°C referenced to the value at 20°C. The maximum fluctuation in insertion loss was only 0.05 dB, confirming that the fiber anchoring structure was satisfactory. Similarly the maximum fluctuation in center wavelength was only 0.006 nm, demonstrating that despite changes in ambient temperature, the optical characteristics showed excellent stability.

Figure 6 shows a typical transmission spectrum of a prototype module. With an insertion loss of 5 dB or below and crosstalk of -26 dB or below, it was confirmed that optical characteristics were equivalent to those of Furukawa Electric's Peltier-control type AWG modules.

Table 1 Summary of temperature dependence of selected characteristics.

Ambient temperature (°C)	Change from value at 20°C	
	Insertion loss (dB)	Center wavelength (nm)
70	Ave : 0.01 Worst : 0.05 σ : 0.023 n = 4	Ave : 0.001 Worst : 0.006 σ : 0.0030 n = 7
0	Ave : 0.01 Worst : 0.05 σ : 0.020 n = 4	Ave : 0.001 Worst : 0.003 σ : 0.0011 n = 7

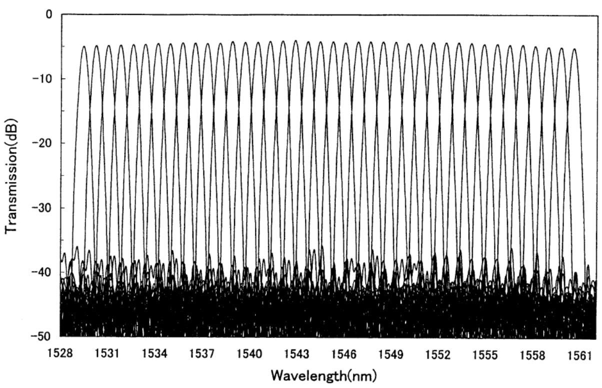


Figure 6 Typical transmission spectrum of 100-GHz, 40-ch heater-control AWG module.

5.2 Power Consumption

The power consumption of the prototype heater-control AWG modules was measured at ambient temperatures of 0, 20 and 70°C. The control temperature was 80°C for all modules. Figure 7 shows typical results for measurement of power consumption, which varied in linear proportion to temperature with maximum consumption at 0°C. Table 2 summarizes the results of measurements for the seven prototype modules. The maximum value of power consumption was 4.38 W, comfortably lower than the target value of 5 W.

5.3 Optical Fiber Retention (Tension) Tests

The prototype heater-control AWG modules were subjected to optical fiber retention (tension) tests in conformity

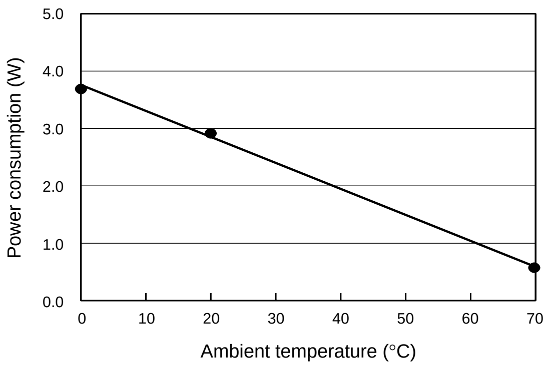


Figure 7 Typical power consumption.

Table 2 Summary of power consumption. (n=7)

Ambient temperature (°C)	Change in power consumption (W)
0	Ave : 4.01 Worst : 4.38 σ : 0.228
20	Ave : 3.11 Worst : 3.37 σ : 0.145
70	Ave : 0.57 Worst : 0.62 σ : 0.024

with Telcordia GR-1209. Tests were carried out on the input- and output-side fibers independently, with the module held fast, using a tensile load of 15 N on the input side and both 15 N and 30 N on the output-side, applied for periods of 1 minute. Table 3 shows typical results for changes in insertion loss, measured immediately before and 1 minute after release of the load at three ports--1, 20 and 40, shown in terms of change from the value before testing. As can be seen, the tensile stress produced no change whatever in insertion loss confirming that these modules offer excellent stability with respect to tension on the optical fibers.

6. RELIABILITY TESTS

Reliability tests, comprising vibration, impact, temperature cycling and damp heat tests were carried out in conformity with Telcordia GR-1209 and 1221. During the tests temperature control of the AWG modules was not carried out. Further, the respective optical characteristics were measured at an ambient temperature of 20°C, with module temperatures controlled at 80°C. Table 4 summarizes the various test conditions and the results that were obtained (for insertion loss and center wavelength). Results are shown in terms of the change from the value before testing. As can be seen, the maximum value of change in insertion loss was 0.13 dB and the maximum change in center wavelength was 0.005 nm. Degradation of performance did not occur in either test, confirming that the heater-control AWG modules developed here had a high level of reliability.

Table 3 Typical results for change in insertion loss under optical fiber retention (tension) tests.

	Load (N)	Port measured	Immediately before release of load (dB)	1 min after release of load (dB)
Input side	15	1	0.00	0.00
		20	0.00	0.00
		40	0.00	0.00
Output side	15	1	0.00	0.00
		20	0.00	0.00
		40	0.00	0.00
	30	1	0.00	0.00
		20	0.00	0.00
		40	0.00	0.00

7. CONCLUSIONS

The authors have developed a heater-control type AWG module that can be used in DWDM systems. This module has the following features:

- Slim-line package only 12 mm thick;
- Maximum power consumption of not more than 5 W (at ambient temperatures of 0~70°C);
- Fluctuation in center wavelength of ±0.01 nm or less (at ambient temperatures of 0~70°C);
- Fluctuation in insertion loss of 0.1 dB or less (at ambient temperatures of 0~70°C);
- A structure that withstands tension on the optical fibers;
- Optical characteristics equivalent to those of Peltier-control AWG modules manufactured by Furukawa Electric; and
- High reliability (conforming to Telcordia GR-1209 and 1221).

The heater-control design developed in this work can, in addition to the 100-GHz, 40-ch modules described in this paper, also be applied to 50-GHz, 40-ch modules.

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Table 4 Results of reliability tests. (n=3)

Type of test	Conditions	Change in characteristic	
		Insertion loss (dB)	Center wave-length (nm)
Vibration	20 G, 20~2000 Hz 4 min/cycles 4 cycles/axis	Ave : 0.00 Worst : 0.06 σ : 0.018	Ave : -0.001 Worst : 0.004 σ : 0.0016
Impact	500 G 5 times/direction 6 directions	Ave : 0.00 Worst : 0.05 σ : 0.023	Ave : 0.000 Worst : -0.002 σ : 0.0009
Temperature cycling	-40°C~85°C 49 cycles	Ave : 0.02 Worst : 0.06 σ : 0.015	Ave : 0.000 Worst : -0.002 σ : 0.0005
Damp heat	85°C・85 %RH 336 hr	Ave : 0.05 Worst : 0.13 σ : 0.049	Ave : 0.001 Worst : 0.005 σ : 0.0023