Ultra-Low-Loss Athermal AWG Module with a Large Number of Channels

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ABSTRACT There is an urgent need for an arrayed waveguide grating (AWG), the device that handles the function of wavelength multiplexer/demultiplexer, that is unaffected by temperature, i.e., athermal. To satisfy this requirement we have applied proprietary athermalizing technique, resulting in development of a multi-channel athermal AWG, which had not been achieved previously. Also, by design of the circuit pattern it has been possible to achieve a 100-GHz 48-channel athermal AWG module that has an insertion loss of less than 2.8 dB. For all channels, temperature dependence is less than ±0.015 nm for center wavelength and ±0.1 dB for insertion loss.

1. INTRODUCTION

With the increasing diversity of D-WDM systems in recent years, one of the needs facing the AWG, which handles the function of wavelength multiplexer/demultiplexer, is for athermalization (temperature-independence) requiring no power supply. The advantages of athermalization are, most obviously, elimination of the need for a power supply, plus the fact that there is no need to monitor the temperature of the AWG module. This would make it possible for the AWG module to be isolated from transmission devices inside an office and to be installed in a variety of locations having no power supply, making them able to satisfy the needs of the increasingly diversified optical communications networks of the future.

Another point that may be mentioned is improving module reliability. In conventional AWGs, where heat is regulated using a heater, etc., it is necessary, in order to maintain the AWG center wavelength constant, to keep the AWG chip at a temperature of 70°C or above, raising problems of thermal degradation of the adhesives used in module construction. Thus if an athermal device can be fabricated, temperature maintenance will be rendered superfluous and reliability improved.

Various approaches to athermalizing AWGs have been reported [1)~4)], but to allow their use in actual D-WDM systems there is a need for greater freedom in terms of number of channels, and a further reduction in temperature dependence.

The authors therefore have proposed a unique principle of athermalization, and using it have developed a 100-GHz 48-ch athermal AWG module with a semi-flat spectrum profile that is mid-way between Gaussian and flat-top [5), 6)]. We therefore report here an ultra-low-loss 100-GHz 48-ch AWG module, which thanks to loss-reduction technique, achieves an insertion loss of 2.8 dB or less. We also report the establishment of a proprietary technique for center wavelength adjustment, which can lead to lower module cost.

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2. ATHERMALIZING TECHNIQUE

2.1 Principle of AWG Multiplexing/Demultiplexing

The arrayed waveguide grating (AWG) is a planar lightwave circuit (PLC) in which the optical waveguide is formed by deposition of clad and core layers of silica glass onto a silicon substrate. Figure 1 is a simplified representation of AWG circuitry, comprising input waveguides, input slab waveguide, arrayed waveguide, output slab waveguide and output waveguides. The following description relates to the function of an AWG when used as a wavelength demultiplexer.

When multiplexed optical signals are input to the input waveguides, they are spread by diffraction in the slab waveguide to transmit to the arrayed waveguide. Since adjacent waveguides of the array differ in length by a fixed amount ΔL, passage through the arrayed waveguide imparts a phase difference, so that focusing occurs at differing points at the end of the output slab waveguide depending on the wavelength. Thus signals of differing wavelength can be extracted by disposing the output waveguides at their respective focus points.

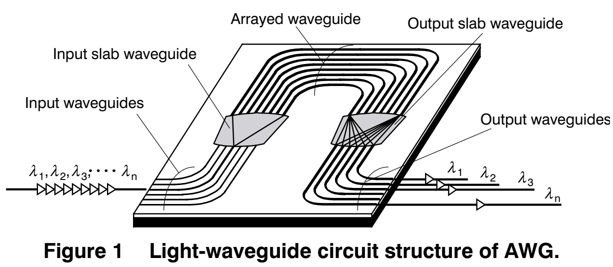

Figure 1 Light-waveguide circuit structure of AWG.

An AWG can also function as a wavelength multiplexer. In the reverse of the case described above: when optical signals of various wavelengths are input from the output slab waveguide, they are multiplexed and output from the input waveguides.

2.2 Temperature Dependence of the AWG

The index of refraction for the silica glass from which the optical waveguides are made is temperature dependent, causing the center wavelength of the AWG to be temperature-dependent as well. Figure 2 illustrates the principle of temperature dependence. Let us suppose that at room temperature (R.T.), the phase front of the optical signals propagated in the arrayed waveguide forms an arc at the end of the slab waveguide, focusing the light at the center output waveguide. When temperature rises above R.T., the effective index of refraction n_{eff} increases, resulting in an increase in the arrayed waveguide phase difference $(2\pi/\lambda)(\Delta L)\ n_{eff}$, where λ is the center wavelength and ΔL is the difference in signal wavelength between adjacent arrayed waveguides. When the phase difference in the arrayed waveguide increases, the phase front becomes tilts, as can be seen in Figure 2, and since light has the property of advancing perpendicular to the phase front, its focus point will shift. That is to say light of differing wavelength will be output from the center output waveguide, and a wavelength shift will occur.

The temperature dependence of the center wavelength of an AWG made of silica glass is 0.011 nm/°C, a value too large to be neglected for applications to D-WDM systems. Thus conventionally AWG modules have had to be provided with Peltier effect devices or heaters to maintain constant chip temperature.

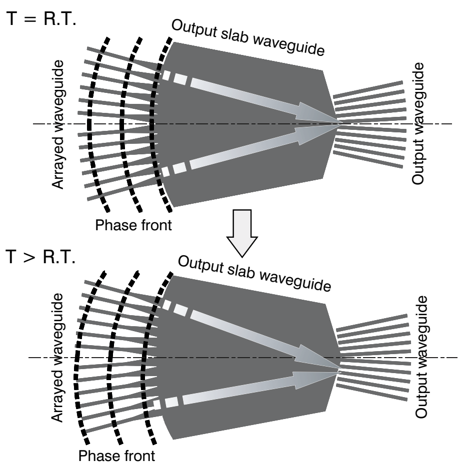

Figure 2 Principle of temperature dependence.

2.3 Principle of Athermalization

In order to compensate for temperature dependence of the AWG center wavelength without the use of Peltier effect devices or heaters, the authors proposed the athermalizing principle described below. Figure 3a is a simplified structural diagram of the athermal AWG. Each of the AWG circuits is cut at one of the slab waveguides into two pieces--one larger and one smaller, and these chips are connected by a compensating plate made of copper. As temperature fluctuates the copper plate expands and contracts, causing the small piece to slide. Figure 3b is a cross-sectional representation of the mechanism of temperature compensation, with each frame showing an output slab waveguide in cross-section.

As shown by the arrows in Figure 3a, we may examine a case in which an optical signal is input at point (1) and output at point (2). In a conventional temperature-dependent AWG, the focus point will shift as the temperature fluctuates; that is to say, from the same output waveguide light of a different wavelength will be output. In an athermal AWG, on the other hand, the focus point changes as the temperature fluctuates, but the expansion or contraction of the copper plate moves the output waveguide to the new focus point, so that from the same output waveguide light of the same wavelength can be extracted.

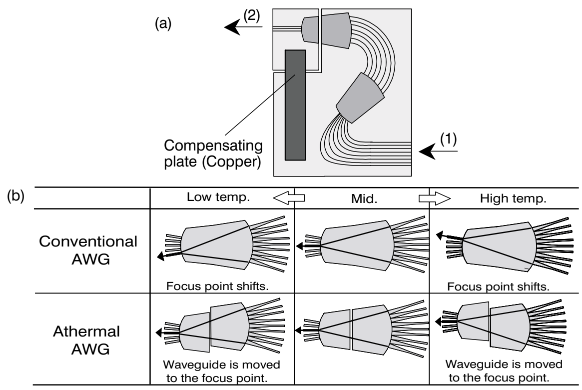

Figure 3 Outline of athermal AWG.

2.4 Designing an Athermal AWG

To achieve precise compensation for the temperature dependence of the center wavelength using the athermalizing principle described above, it is necessary to adjust the length of the copper compensating plate. The relationship between the center wavelength shift due to temperature fluctuation dλ and the amount of positional adjustment dx may be represented by

$$dx = \frac{L_f \Delta L}{n_s d \lambda_0} n_g \frac{d\lambda}{dT} \Delta T \qquad (1)$$

where:
L_f is the focal length of slab waveguide,
ΔL is the difference in optical path length between adjacent arrayed waveguides,
n_s is the effective index of refraction of the slab waveguide,
n_g is the grouped index of refraction of the arrayed waveguide,
d is the pitch of adjacent arrayed waveguides,
λ_0 is the center wavelength, and
ΔT is the amount of temperature fluctuation.

Substituting the circuit parameters from Table 1 into Eq. (1) yields

$$dx = 0.275 \Delta T \quad (2)$$

indicating that shifting the focus point by 0.275 mm for each 1°C will compensate for the temperature dependence of the center wavelength. We may then calculate that since the coefficient of linear thermal expansion for the copper plate is 1.7 x 10^{-5}, the plate should be 16.2 mm in length.

Table 1 Circuit parameters for the AWG.

Parameters	Values
Channel spacing	100 GHz
Number of channels	48
Relative refractive index difference	0.8 %
Focal length of slab waveguide: Lf	17.2 mm
Length difference of arrayed waveguide: ΔL	31.0 μm
Pitch of adjacent channel waveguides: d	13.75 μm
Diffraction order: m	29

2.5 Techniques for Center Wavelength Adjustment

Generally speaking, for an AWG to be used in a D-WDM system, the center wavelength of the AWG must be matched to the grid wavelength, and in the fabrication process for athermalization we have also developed a proprietary technique for matching center wavelength to grid wavelength [6]. This is a method in which the center wavelength can be easily changed by varying the curing temperature of the adhesive used to connect the copper plate to the chip. Figure 4 shows a flowchart for center wavelength adjustment and the fabrication process. The following description of the procedure for center wavelength adjustment is in accordance with this flowchart.

First of all, before cutting the AWG chip, the center wavelength of the chip is measured. From the value thus obtained the shift from the grid wavelength is calculated and the curing temperature is determined. We may then proceed to fabrication, which comprises four processes.

Process 1: The AWG chip is temporarily attached to the base plate and the chip is then cut into two at the slab waveguide.
Process 2: Adhesive is applied to the copper plate, which is connected to a specified position on the chip.
Process 3: The chip as a whole is kept uniformly at each curing temperatures that have been calculated while the adhesive cures. The plate will undergo thermal expansion and it is connected to the chip so that this length is maintained.
Process 4: The chip is returned to room temperature, at which time contraction of the copper plate will cause a change in the relative positions of the large and small pieces. That is to say, the relative position of the waveguides changes making it possible to shift the center wavelength. The chip is then removed from the base plate.

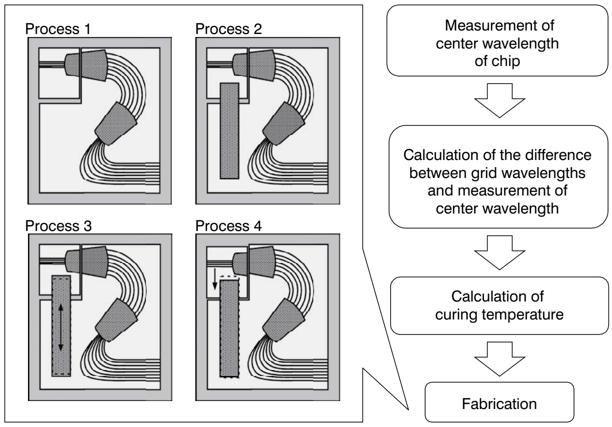

Figure 4 Flowchart for adjustment of the center wavelength and fabrication.

Let us now describe the method for calculating the curing temperature, which relies on its relationship to center wavelength shift, as shown in Figure 5. This relationship can be approximated by a straight line, the slope of which is virtually the same as the temperature dependence of the AWG (0.011 nm/°C), and theoretically agrees with it. In the case, for example, that the difference measured at 25°C between the center wavelength before cutting and the grid wavelength was 0.4 nm, a curing temperature of 63°C will result in matching with the grid wavelength, and matching was achieved with a precision of ±20 pm or better.

What is more, the range of center wavelength matching is approximately 0.8 nm (far greater than the value of 0.15 nm for conventional temperature-controlled AWGs), making it possible to achieve a significant improvement in center wavelength yield during AWG chip fabrication. For this reason the wavelength adjustment technique described here offers a major advantage in cost reduction.

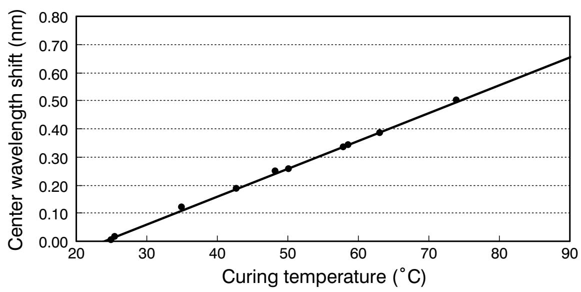

Figure 5 Relationship between center wavelength shift and curing temperature.

3. LOSS-REDUCTION TECHNIQUE

To extend the areas in which AWGs can be used in metro/access systems, etc., the loss in the AWG itself must be reduced. We have therefore examined techniques for obtaining lower-loss AWGs.

3.1 Causes of AWG Losses and Methods of Reduction

In addition to propagation loss and the connection loss between the input and output waveguides and optical fibers, AWG loss also includes the mode-field mismatch losses inherent in the circuits. To realize lower AWG losses we decided to focus on reducing this mode-field mismatch loss.

Figure 6a shows the mechanism for generation of mode-field mismatch loss. In the AWG when the arrayed waveguide is excited from the slab waveguide, the photoelectric field distribution at the end of the slab waveguide is continuous, but, on entering the arrayed waveguide, instantaneously converts to a discrete field distribution. This is the point at which mode-field mismatch loss is generated, and the loss that is generated turns into emission loss and is observed as AWG loss. That is to say, loss can be reduced if the emission loss can be suppressed. Accordingly we laid out a low-loss pattern, as shown in Figure 6b [7], in which band-shaped waveguides are arranged so as to cross the part of the arrayed waveguide that is connected to the slab waveguide. These band waveguides are disposed at a constant pitch with waveguide width W_B gradually diminishing with increasing distance from the slab waveguide. These parameters were optimized using the beam propagation method (BPM).

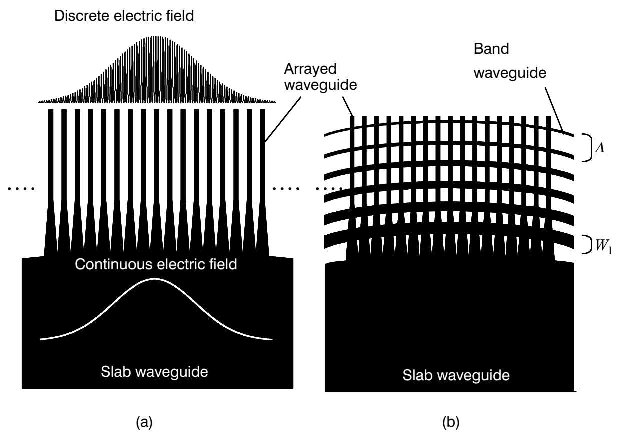

Figure 6 Mechanism of loss generation and a low-loss pattern.

3.2 Result of BPM Simulation

Figure 7 compares the results of simulation for a conventional circuit without a low-loss pattern (7a) and for a circuit incorporating a low-loss pattern after parameter optimization (7b). It can be seen that in the conventional circuit, the light emerging from the slab waveguide does not connect smoothly to the arrayed waveguide, and considerable emission loss is generated. In the circuit incorporating a low-loss pattern, on the other hand, no significant emission loss is seen. Estimates of the emission loss in the two circuits come to 0.70 dB for (a) and 0.17 dB for (b). Thus it is seen that use of the low-loss pattern effected a loss reduction of more than 0.5 dB. Since in an AWG there are two areas of connection between the arrayed waveguide and the slab waveguides, we can expect a reduction of better than 1.0 dB.

To achieve a further reduction in loss, identical linear taper waveguides, as shown in Figure 8, were disposed at the input and output waveguide patterns.

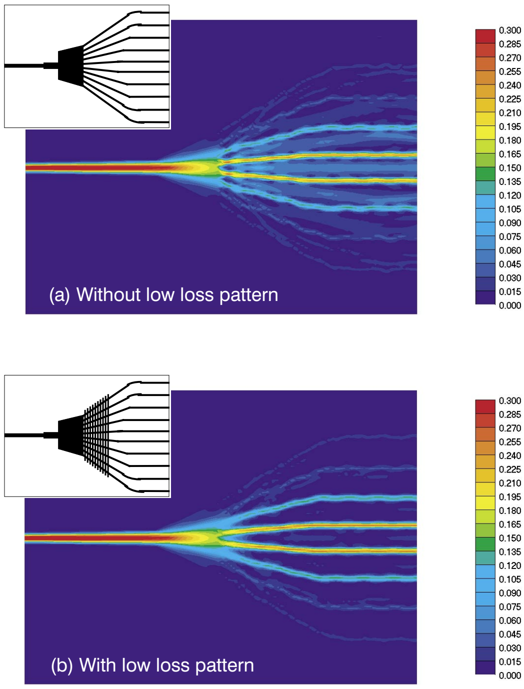

Figure 7 Results of simulation by BPM.

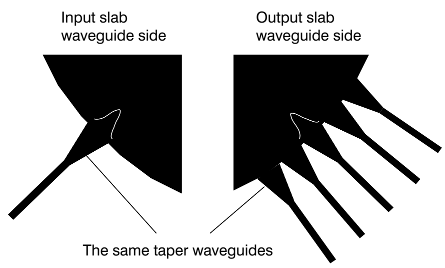

Figure 8 Patterns at the input and output slab waveguides.

4. FABRICATION

Incorporating the low-loss pattern described above, we fabricated a 100-GHz 48-ch AWG using PLC fabrication technology combining flame hydrolysis deposition (FHD), photolithography, and reactive ion etching (RIE). The chip was then cut at the slab waveguide and its center wavelength was matched to the grid wavelength using the proprietary technique for center wavelength adjustment described above. Optical fibers were then connected to the AWG chip, which was then packaged. Figure 9 shows the appearance of the athermal AWG module that was fabricated. The package was slim in profile, measuring 130 x 80 x 8.5 mm.

Figure 9 Appearance of athermal AWG module.

Figure 10 shows the spectrum of the ultra-low-loss 100-GHz 48-ch athermal AWG. Excellent optical characteristics were obtained, with insertion loss of less than 2.8 dB (1.8~2.8 dB), adjacent crosstalk less than –30 dB, non-adjacent crosstalk less than –30 dB, and total crosstalk less than –22 dB. There was no degradation of optical characteristics due to athermalization.

Figure 11 shows the temperature-dependence of center wavelength. In all channels the center wavelength shift over a temperature range of –5 to 70°C was ±0.015 nm, indicating that the temperature dependence of center wavelength was compensated for almost completely. The change in insertion loss was ±0.1 dB. Figure 12 shows the temperature-dependence of the spectrum. No spectrum degradation was observed at any of the temperatures, confirming that other optical characteristics were also stable.

Reliability has been confirmed using a 100-GHz 32-ch athermal AWG module of identical structure.

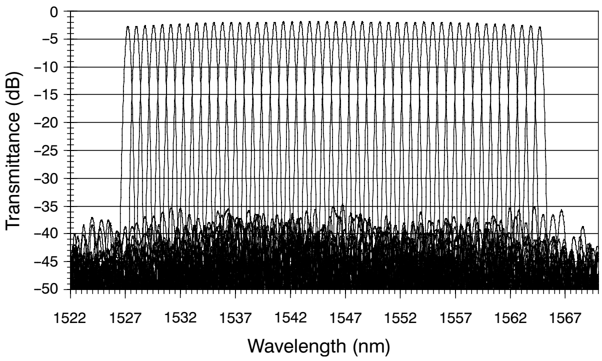

Figure 10 Spectrum of ultra-low-loss 100-GHz 48-ch athermal AWG.

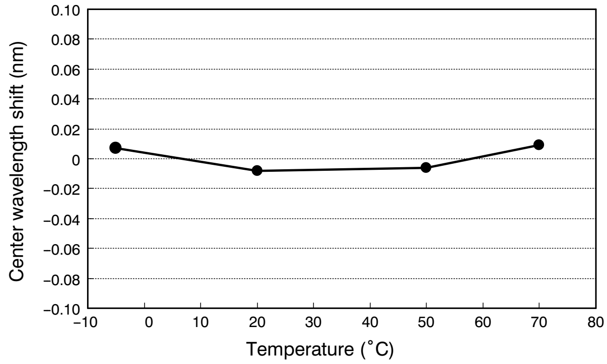

Figure 11 Temperature dependence of center wavelength.

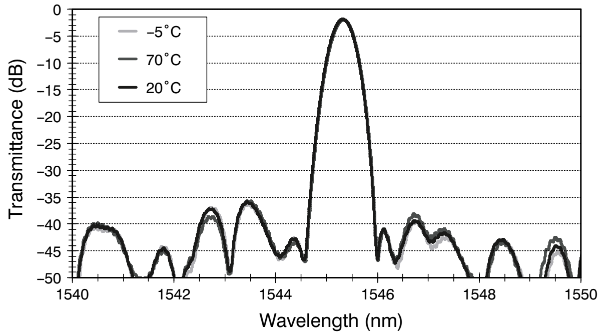

Figure 12 Temperature dependence of transmission spectrum.

5. CONCLUSION

We have developed a 100-GHz 48-ch AWG module with insertion loss of less than 2.8 dB using techniques of athermalization and loss reduction. On all channels, the AWG module had a center wavelength shift of less than ±0.015 nm and an insertion loss change of ±0.1 dB over temperatures ranging from –5 to 70°C.

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