This article introduces the principles, fabrication techniques, and recent progress of planar-type arrayed-waveguide-grating (AWG) multi/demultiplexers, which have been developed for wavelength division multiplexing (WDM)-based photonic networks. The AWG has already been used in point-to-point WDM systems and is a key component in the construction of flexible and large-capacity WDM networks. This is because, compared with conventional filters consisting of thin-film interference filters and micro-optics, the AWG offers the advantages of low loss, high port counts, and mass productivity. Further progress on the AWG is expected to contribute greatly to the construction of future photonic networks including optical add/drop multiplexing systems and optical crossconnect systems.

**WDM Filters and Photonic Networks**

The rapid and global spread of the Internet is accelerating the growth of optical communications networks. Photonic networks based on WDM systems [1,2] have played a key role in increasing the capacity and flexibility of these communications networks. Figure 1 is a schematic showing a typical photonic configuration. The first networks were point-to-point WDM transmission systems. Today, ring networks are evolving that require optical
add/drop multiplexing and optical crossconnect systems. Various optical devices have been developed for WDM-based photonic networks, and some of them have already been installed in commercial communication systems. Of these devices, the WDM filter is one of the most important passive devices used in the networks. Filters are needed wherever signals with different wavelengths propagating in a fiber must be multiplexed or demultiplexed in a WDM network.

A typical spectrum of a WDM filter used in a system with a channel spacing of 100 GHz (0.8 nm) is shown in Fig. 2. Since the signal wavelengths are densely set at frequencies standardized by the International Telecommunication Union (ITU), the filters must have a narrow transmission band, and the wavelength of the passband must precisely match the ITU grid frequencies. In addition to wavelength accuracy, we must achieve high levels of performance including low loss, low crosstalk, and a wide passband. While various kinds of filters have been developed in response to this demand, there are two major types used in practical systems: bulk-type thin-film interference filters and planar-lightwave-circuit (PLC) filters.

Thin-film multilayer interference filters, whose principle has been long understood, have been developed for use as narrow-band WDM filters. The structure of the thin-film filter is based on that of the Fabry-Perot (F-P) etalon, which is composed of a cavity and mirrors and which acts as a bandpass filter. The center wavelength of the passband is determined by the cavity length. A narrow thin-film interference filter for WDM consists of more than two F-P cavities separated by dielectric reflection layers, and each cavity contains a multilayer structure with more than 50 layers [3]. The two kinds of layers are deposited alternately on a glass substrate with a unit thickness of half the target wavelength, and the materials used for the layers are usually SiO2 and TiO2 because of the large difference between their refractive indices. The passband shape of a WDM filter improves as the number of cavities increases. It has thus become possible to obtain filters with a loss of less than 0.5 dB, a wide band, and a low crosstalk. A WDM multi/demultiplexer can be formed by cascading thin-film filters with different wavelengths in series. However, it is rather difficult to reduce the wavelength spacing and increase the port count of this type of multi/demultiplexer because making a thin-film filter with a narrow passband becomes more difficult, the assembly cost increases, and the insertion loss accumulates at each stage.

Recently, the rapid progress made in networks has led to the demand for more channels at a reduced cost. These trends are accentuating the need to fabricate filters with even narrower passbands and large port counts. PLC-type devices consisting of fiber-matched silica-based waveguides on Si [4] can meet this demand because they can provide various large-scale key devices for photonic networks. PLC-type devices can also offer long-term stability and be mass produced. These PLC devices include wavelength N × N multi/demultiplexers, optical add/drop or cross-connect switches, multwavelength light sources for WDM transport networks, programmable filters for high-speed transmission systems, 1/N optical power splitters, optical couplers, and 1.3/1.55 μm WDM optical modules for access networks. Of these devices, the AWG multi/demultiplexer is one of the most successful optical filters, and it is a key component of photonic networks.
AWG Principles

Silica-based waveguides have been employed to develop AWGs for use as dense WDM filters [5, 6]. The configuration of an $N \times N$ AWG multiplexer is shown in Fig. 3(a). The multiplexer consists of $N$ input/output waveguides, two focusing slab waveguides, and arrayed waveguides with a constant path length difference $\Delta L$ between neighboring waveguides. The input light is launched into the first slab waveguide and then excites the arrayed waveguides. After traveling through the arrayed waveguides, the light beam interferes constructively at one focal point in the second slab. The location of the focal point depends on the signal wavelength $\lambda$ because the relative phase delay in each arrayed waveguide is given by $\Delta L / \lambda$. The slab and array waveguides act as a lens and grating, respectively, as shown in Fig. 3(b).

Here we consider the principle of the AWG in more detail. In the first slab region, input waveguide separation is $D_1$, the arrayed waveguide separation is $d_1$, and the curvature radius is $f_1$. The waveguide parameters in the first and the second slab regions may differ. Therefore, in the second slab region the output waveguide separation is $D$, the arrayed waveguide separation is $d$, and the curvature radius is $f$. The input light at position $x_1$ ($x_1$ is measured in a counter-clockwise direction from the center of the input waveguides) is radiated to the first slab and then excites the arrayed waveguides. The amplitude profile in each arrayed waveguide usually has a Gaussian distribution. After traveling through the arrayed waveguides, the light beams constructively interfere at one focal point $x$ ($x$ is measured in a counter-clockwise direction from the center of the output waveguides) in the second slab. Let us consider the phase retardation for the two light beams passing through the $(i-1)$th and $i$th arrayed waveguides. The difference between the total phase retardations for the two light beams passing through the $(i-1)$th and $i$th arrayed waveguides must be an integer multiple of $2\pi$ in order that the two beams constructively interfere at focal point $x$. Therefore, we have the interference condition as

$$\beta_i(\lambda_o) \frac{d_1 x_1}{f_1} - \beta_i(\lambda_o) \frac{dx}{f} + \beta_i(\lambda_o) \Delta L = 2m\pi$$

(1)

where $\beta_i$ and $\beta_c$ denote the propagation constants in a slab region and an arrayed waveguide, $m$ is an integer, and $\lambda_o$ is the center wavelength of the WDM system. When the condition $\beta_i(\lambda_o) \Delta L = 2m\pi$ or

$$\lambda_o = \frac{n_c \Delta L}{m}$$

(2)

is satisfied for $\lambda_o$, the light input position $x_1$ and the output position $x$ should satisfy the condition

$$\frac{d_1 x_1}{f_1} = \frac{dx}{f}$$

(3)

In Eq. (2), $n_c$ is the effective index of the arrayed waveguide ($n_c = \beta_c/k$; $k$: wavenumber in a vacuum) and $m$ is the diffraction order. The above equation means that light is coupled into the input position...
x1 and the output position x is determined by Eq. (3). Usually the waveguide parameters in the first and the second slab regions are the same; they are \( d_1 = d \) and \( f_1 = f \). Therefore, input and output distances are the same as \( x_1 = x \). The dispersion of the focal position \( x \) with respect to the wavelength \( \lambda \) for the fixed light input position \( x_1 \) is given by differentiating Eq. (1) with respect to \( \lambda \) as

\[
\frac{\Delta x}{\Delta \lambda} = \frac{N_c \beta}{n_d \alpha_0} \tag{4}
\]

where \( n_d \) is the effective index in the slab region, and \( N_c \) is the group index of the effective index \( n_c \) of the arrayed waveguide (Nc).

These results indicate that SH-\( \Delta \) waveguides can help to create a new generation of PLC devices.
us to design complicated circuits by using various numerical simulation techniques. Moreover, the reliability of the PLC devices has been confirmed with reference to the Bellcore reliability requirements [9].

We have fabricated various kinds of AWG multiplexers ranging from a 15-nm spacing 8-channel AWG to a 25-GHz spacing 256-channel AWG. The grating parameters and achieved performance of the fabricated AWGs are listed in Table 1. All the AWGs, except the 25-GHz spacing 256-channel AWG, were fabricated using Η∆ waveguides. The characteristics of a 256-channel 25-GHz-spacing AWG are detailed later. Every other AWG had a crosstalk of better than $-30$ dB. The 3-dB bandwidths obtained experimentally agree very well with theoretical values calculated by using the beam propagation method (BPM). Transmission spectra of the 25-GHz spacing 128-channel AWG are shown in Fig. 5. The on-chip loss at the center port of the AWGs ranges from 2.1 to 3.5 dB.

The spectral shape of normal AWGs, such as those listed in Table 1, are Gaussian since the spectra reflect the beam intensity distribution in the waveguide because the wavelength accuracy of the light source in the WDM system is relaxed. However, flat-top spectra are required for WDM applications. A flat passband has been realized by using parabolic waveguide horns in the input waveguides [10]. The transmission spectra of a 16-channel flat-passband AWG with a 100 GHz spacing are shown in Fig. 6. A 3-dB bandwidth of about 80 GHz was achieved. Moreover, the insertion loss ranged from 8 to 8.5 dB and the worst crosstalk was about $-37$ dB.

The center wavelength of a conventional AWG shifts to a longer wavelength by about 0.1 nm/oC. This is because the refractive index of a silica-based waveguide depends on temperature. The AWG temperature must therefore be controlled with a heater or a Peltier device to stabilize the center wavelength. By contrast, an athermal AWG has also been shown to expand the application area

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### Table 1. Experimental Performance of Fabricated Multiplexers.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Experimental Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel Spacing</td>
<td>15 nm 2 nm 0.8 nm (100 GHz) 0.4 nm (50 GHz) 0.2 nm (25 GHz) 0.2 nm (25 GHz)</td>
</tr>
<tr>
<td>Number of Channels</td>
<td>8 8 32 64 128 256</td>
</tr>
<tr>
<td>Center Wavelength</td>
<td>1.55 µm</td>
</tr>
<tr>
<td>Path Difference</td>
<td>12.8 µm 50.3 µm 63.0 µm 63.0 µm 63.0 µm 27.7 µm</td>
</tr>
<tr>
<td>Focal Length</td>
<td>2.38 mm 5.68 mm 11.35 mm 24.2 mm 36.3 mm 41.1 mm</td>
</tr>
<tr>
<td>Diffraction Order</td>
<td>12 47 59 59 59 26</td>
</tr>
<tr>
<td>On-Chip Loss</td>
<td>2.4 dB 6.1 dB 2.1 dB 2.8 dB 3.5 dB 2.7 dB</td>
</tr>
<tr>
<td>3-dB Bandwidth (BPM Simulation)</td>
<td>6.3 nm (6.3 nm) 0.74 nm (0.75 nm) 49 GHz (37 GHz) 19 GHz (21 GHz) 11 GHz (9.5 GHz) 14.4 GHz (12.5 GHz)</td>
</tr>
<tr>
<td>Channel Crosstalk</td>
<td>$&lt;-28$ dB $&lt;-29$ dB $&lt;-28$ dB $&lt;-27$ dB $&lt;-16$ dB $&lt;-33$ dB</td>
</tr>
</tbody>
</table>

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6. Transmission spectra of flat-passband low-crosstalk AWG.

7. Photo of 16-channel SH-Δ AWG chip with 100-GHz channel spacing.
and reduce the cost [11]. The temperature-dependent optical path difference in silica-based waveguides is compensated for by employing a triangular groove filled with silicone adhesive, which has a negative thermal coefficient. Since the negative optical path change in the silicone is several tens of times larger than in silica-based waveguides, the negative optical path change in the silicone can compensate for the positive optical path change in the silica, thereby achieving temperature insensitive operation with small silicone gaps that cause only a slight loss increment. Although the wavelength shift observed over a 0 to 85°C temperature range was 0.95 nm for a conventional AWG, it is only 0.05 nm for the athermal AWG. This result confirms that the athermal AWG is sufficiently stable for practical use.

**The AWG is superior to conventional filters in that it offers low loss, a high port count, and can be mass produced.**

### Recent Progress

As described above, we have already developed various AWGs using silica waveguides with a Δ of around 0.7%, which has a minimum bending radius rmin of about 5 mm. An effective way to integrate circuits more densely and to reduce the cost of PLC devices is to increase the Δ. However, it is well known that an increase in Δ causes a great increase in waveguide loss, phase error, and fiber-waveguide coupling loss. To avoid these problems, we have improved techniques for fabricating GeO2-doped silica waveguides on Si with a higher Δ and for connecting them with optical fibers. We have thus realized high-density PLCs with an rmin of 2 mm using a GeO2-doped silica waveguide with a Δ of 1.5% [12]. We used this super-high (SH)-Δ waveguide to fabricate two kinds of AWGs with low loss and low crosstalk: a 16-channel 100-GHz spacing AWG and the first 256-channel 25-GHz spacing AWG [13]. Here we describe the characteristics of these AWGs and techniques for obtaining low-loss fiber connection with waveguides using a high numerical aperture (H-NA) fiber and the thermally-expanded-core (TEC) technique. These results indicate that SH-Δ waveguides can help to create a new generation of PLC devices.

We fabricated GeO2-doped silica waveguides on Si with a Δ of ~1.5% and a core size of ~4.5 × 4.5 µm². We improved the conventional fabrication method, which consists of FHD and RIE, at every stage including the core deposition process. We estimated the bending loss from waveguides with 16 45-degree bends. We confirmed that the bending loss of the waveguide was less than 0.1 dB/90 degrees for the TE and TM modes up to a radius of 2 mm. We obtained a propagation loss of 0.05 dB/cm from a 40-cm-long waveguide, and this value is almost the same as that of the 0.7% Δ waveguide.

One of our most important goals for the SH-Δ waveguide is the realization of low-loss fiber connection. To reduce the coupling loss, we prepared an H-NA fiber with a mode field diameter of about 5.7 µm at 1.55 µm. We estimated the coupling loss between the SH-Δ waveguide and the H-NA fiber to be less than 0.1 dB/point. This value is much lower than that of about 2.0 dB/point between a single-mode fiber (SMF) and the waveguide. Moreover, to avoid a high connection loss between the H-NA fiber and the SMF, we used a splicing technique in which additional arc fusion induces the TEC effect. We found that we could obtain a splicing loss of less than 0.3 dB by controlling the additional arc fusion times. This indicates the possibility of constructing SH-Δ PLC devices with a low loss using this SMF-H-NA-fiber pigtailing.

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8. Transmission spectra of 16-channel 100-GHz spacing SH-Δ AWG.

9. Transmission spectra of 256-channel 25-GHz spacing SH-Δ AWG.
We used a waveguide with an $r_{\text{min}}$ of 2 mm to fabricate AWGs. It should be noted that the AWG chip size can be greatly reduced by using the SH-\(\Delta\) waveguide. In fact, we were able to design 26 AWG chips (13 $\times$ 16 mm) with 16 channels and a 100-GHz spacing on a 4-inch wafer using the SH-\(\Delta\) waveguide. This is four times the number of chips possible with a conventional AWG. The path length difference and the FSR were set at 63 $\mu$m and 3.2 THz, respectively. Figure 7 is a photograph of the AWG chip, which is almost the same as a penny in size. The transmission spectra of the 16-channel SH-\(\Delta\)THz, respectively. Figure 8 is a photograph of the AWG chip, which we measured with the SMF-H-NA fibers, are shown in Fig. 8. The on-chip loss of the SH-\(\Delta\) AWG was 2.4 dB at the center port and less than 3.3 dB at the outer port, as shown in Fig. 8. The 3-dB bandwidth and the background crosstalk were 0.47 nm and less than –33 dB, respectively. The characteristics of this AWG are comparable to those of a conventional AWG.

We were also able to incorporate a 256-channel AWG with a 25-GHz spacing on a 4-inch wafer and fabricate it successfully. The TE mode spectra of the AWG measured with the SMF-H-NA fibers are shown in Fig. 9. We obtained a surprisingly low on-chip loss ranging from 4.4 to 6.4 dB for the central and peripheral output ports and the loss uniformity of the channels was good. The 3-dB bandwidth and crosstalk were 0.12 nm and –33 dB, respectively. These characteristics are better than those of a 128-channel 25-GHz AWG made with a conventional waveguide on a 5-inch wafer, and the SH-\(\Delta\) AWG chip was also smaller.

**Conclusion**

This article reviewed the principles, fabrication techniques, and recent progress of planar-type AWG multi/demultiplexers developed for WDM-based photonic networks. The AWG is one of the key components for constructing flexible and large-capacity WDM networks. The AWG is superior to conventional filters consisting of thin-film interference filters and micro-optics in that it offers low loss, a high port count, and can be mass produced. Moreover, we have been developing SH-\(\Delta\)AWGs with an $r_{\text{min}}$ of 2 mm. These include a small 16-channel AWG and the first 256-channel 25-GHz spacing AWG with a low loss of 4.4 dB and a low crosstalk of –33 dB. This wide variety of AWG-type multi/demultiplexers has been used in point-to-point WDM, optical add/drop multiplexing systems, and optical crossconnect systems. The fact that PLC technologies allow us to construct various optical devices with high levels of performance as well as AWG-type demulti/multiplexers means that PLC-type devices will undoubtedly lead to innovations in photonic networks.

**Acknowledgments**

The author thanks Dr. Katsunari Okamoto, Dr. Tetsuo Miya, Dr. Tohru Maruno, Dr. Yasuji Ohmori, and Dr. Akira Himeno for useful discussions and encouragement.

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