3.1 Principle

An AWG MUX/DeMUX is a planar device with both imaging and dispersive properties. It consists of I/O waveguides, the number of which usually equals the number of transmitting channels; an array of waveguides (also called phased array, PA); and two star couplers [also called a free-propagation region (FPR)], as shown in Fig. 5. The waveguides in the PA are spaced at regular intervals, with a constant path-length increment ΔL from one to the next, and join the star couplers at each end.

AWGs can function both as wavelength division MUX and DeMUX. An example of the operating principle of an AWG configured for spectral demultiplexing can be seen in Fig. 5. In this configuration, the input star coupler is an expanding free-propagation region where the light beam becomes divergent, while the output star coupler functions as a focusing FPR where each spectrally separated light beam is focused at one well-defined point on the focal line. Operation of the AWG DeMUX can be explained as follows: one of the input waveguides (usually the waveguide positioned at the center of the object plane of the input star coupler) carries an optical signal consisting of multiple wavelengths, $\lambda_1 - \lambda_n$ into the coupler. Once in the coupler, the light beam is no longer confined laterally and thus expands. The array waveguides capture this diverging light, which then propagates toward the input aperture of the output star coupler. The length of array waveguides is selected so that the optical path length difference between adjacent waveguides, ΔL, equals an integer multiple of the central wavelength, λ_c, of the DeMUX. For this wavelength, the fields in the individual arrayed waveguides will arrive at the input aperture of the output coupler with equal phases, and the field distribution at the output aperture of the input coupler will be reproduced at the input aperture of the output coupler. In the output star coupler, the light beam interferes constructively and converges at one single focal point on the focal line. In this way, for the central wavelength λ_c, the input field at

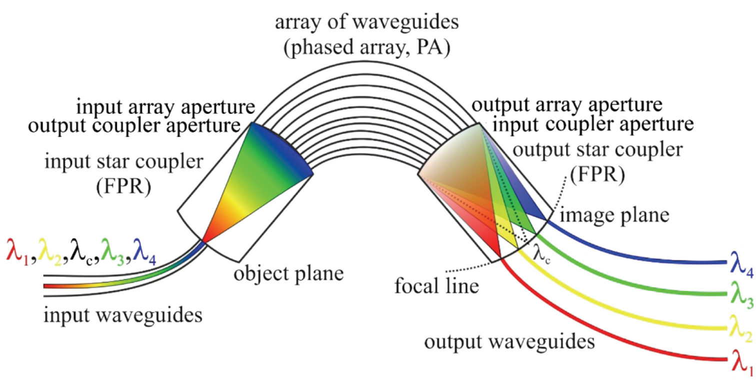

Figure 5 Principle of an AWG optical DeMUX.

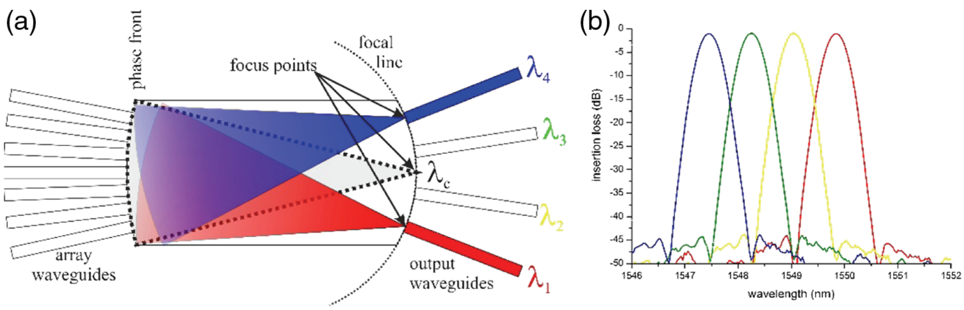

Figure 6 (a) Focusing the wavelengths on different positions of the focal line with four demultiplexed wavelengths. (b) The result is called an AWG spectral response.

the object plane of the input star coupler is transferred to the center of the image plane of the output star coupler.

If the wavelength is shifted to $\lambda_c \pm \Delta\lambda$ (i.e., λ_1, λ_2, ...), there will be a phase change in the individual PA waveguides that increases linearly from the lower to the upper channel. As a result, the phase front at the input aperture of the output star coupler will be slightly tilted, causing the beam to be focused on a different position of the focal line in the image plane (Fig. 6). By placing a waveguide in the correct position, the field for each wavelength can be coupled into the respective output waveguide (also called the transmitting channel).[27,28]

3.2 Different AWG types

Various AWGs are available on the market today and their optical characteristics depend largely on the optical properties of the waveguide materials used. AWGs can be fabricated on various material platforms such as silica-on-silicon (SoS) buried waveguides,[29–33] silicon-on-insulator (SOI) ridge waveguides,[34] SOI-nanowires,[35–37] buried InP/InGaAsP ridge waveguides,[38–41] polymer waveguides,[42–44] or Si_3N_4 waveguides.[45–47] In terms of material, they can all be divided into two main groups, the so-called low-index-contrast and high-index-contrast AWGs.

Low-index-contrast AWGs (SoS-based waveguide devices) were introduced to the market in 1994.[48] For the most part, they use SiO_2-buried rectangular waveguides, usually with a cross-section of (6×6) μm^2 and a low refractive-index contrast between the core (waveguide) and the cladding, $\Delta n \sim 0.011$ [where the refractive index of the core $n_c \sim 1.456$ and the refractive index of the cladding $n_{cl} \sim 1.445$, as shown in Fig. 7(a)]. This parameter is also often expressed in percent as $\Delta n \sim 0.75\%$, from $(n_c - n_{cl})\cdot 100/n_c$. Low-index-contrast AWGs still hold a large share of the AWG market because of their many advantages. First, their modal field matches well with that of single-mode optical fibers, making it relatively easy to couple them to fibers [Fig. 7(c)]. Second, they combine low propagation loss (<0.05 dB/cm, because there is little absorption and scattering in the

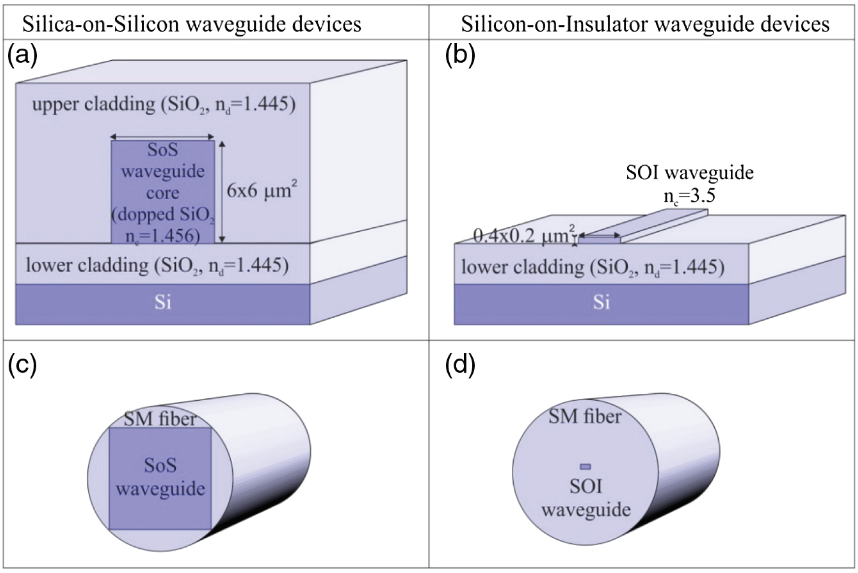

Figure 7 (a) and (b) Cross-sections of SoS and SOI waveguides with typical dimensions and refractive indices. (c) and (d) Comparison of the waveguide dimensions with the standard SM fibers.

waveguides) with a high fiber-coupling efficiency (low losses on the order of 0.1 dB).[48] However, the very low refractive-index contrast means the bending radius of the waveguides needs to be very large (on the order of several millimeters) and may not fall below a particular, critical value. As a result, silica-based AWGs usually have a very large size of several square centimeters that limits the integration density of SiO_2-based photonic integrated devices.

High-index-contrast AWGs, such as SOI-based waveguide devices, use a high refractive-index difference $\Delta n \sim 2.055$ for Si/SiO_2 (~2.5 for Si/air) between the refractive indices of the core (Si, $n_c \sim 3.5$) and the cladding (SiO_2, $n_{cl} \sim 1.445$, or air, $n_{cl} = 1.0$), as shown in Fig. 7(b) (in percent, $\Delta n \sim 58\%$). This is approximately 100 times higher than that of typical SoS waveguides. Due to the fact that a waveguide's size decreases proportionally to the increase in refractive index contrast, the waveguide size for this material composition shrinks into the nanometer scale [Fig. 7(b)]. Such high-index contrast makes it possible to guide light in waveguides with a far smaller bending radius (bending on the scale of several tens of microns), which leads to a significant reduction in the size of AWGs by more than two orders of magnitude when compared to AWGs based on silica materials.[49–51] Such compact devices can easily be implemented on-chip and have already found applications in WDM systems as add-drop filters, channel monitors, routers, cross-connects, and wavelength converters for complex optical metropolitan and local area networks (LAN). Typically, the spectral resolution of an

AWG can be raised by increasing the interference order of the grating or the number of arrayed waveguides. As a result, SOI-AWGs have been used not only for WDM but also for other emerging applications, such as optical sensors, particularly optical chemical and biosensors, silicon devices for DNA diagnostics, and optical spectrometers for infrared spectroscopy.[52–54]

The main problem arising from the reduced size of waveguides is the coupling of the optical signal from the fiber into such small input waveguides [Fig. 7(d)], which causes much higher coupling losses, on the order of 10 dB, than in silica AWGs. The second drawback of high-index-contrast waveguides is the sensitivity of the mode index to the dimensional fluctuation of the waveguide core, which leads to a rapid increase in random phase errors in the fabricated array grating arms. These technological imperfections affect the AWG's performance by causing a marked increase in the crosstalk (measured crosstalk is normally >15 dB[55]). In addition, in Si-nanowire waveguides, the scattering loss (per unit of length) is much larger than the loss for conventional low-index-contrast waveguides due to the light scattering on imperfections of the fabricated waveguide sidewalls.[56] In order to reduce the roughness of these sidewalls and thus minimize such high-dimensional fluctuations, the SOI-nanowire AWGs require very-high-resolution fabrication technology that still presents a considerable challenge today. An alternative to high-index-contrast and low-index-contrast AWGs is the Si_3N_4 material platform, which has a moderate index contrast lying between both main groups.[45,46,57,58]

Based on the applications, AWGs can be categorized according to the number of transmitting channels, channel spacing, and the spectral response.

Number of channels: As the number of transmitting channels (wavelengths) used to carry the information in WDM systems is generally a power of 2, the AWGs are designed to separate two different wavelengths (or 4, 8, 16, 32, 64, and so on). In addition, AWGs with 40 and 80 channels are also available.

Channel spacing: The wavelengths being used in transmitting channels are usually around the 1550-nm region, the wavelength region in which optical fiber performs best due to very low losses. Each wavelength is separated from the previous one by a multiple of 0.8 nm (also referred to as 100-GHz spacing, which is the frequency separation, Fig. 2). Thus, wavelengths can also be separated by 1.6 nm (i.e., 200 GHz) or any other channel spacing that represents a multiple of 100 GHz (0.8 nm). Systems with channel spacings of 100 GHz or higher are classified as WDM systems. However, as increasing capacity demands make it desirable to squeeze even more wavelengths into an even tighter space, systems are being designed with as little as half the regular spacing, i.e., 0.4 nm = 50 GHz, or even a quarter, i.e., 0.2 nm = 25 GHz. Systems with these narrow channel spacings are classified as DWDM systems. As the demand for higher capacity continues to grow, it will be necessary to keep raising the channel counts of AWGs as far as possible, thereby decreasing their channel spacing down to 12.5 GHz (=0.1 nm), 10 GHz (=0.08 nm), or less.