Silica-based waveguide devices for photonic networks

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Silica-based waveguide devices as represented by planar lightwave circuits (PLCs) are key devices for constructing photonic networks with huge data transmission capacity and flexibility. As a result of recent progress on optical communication networks, dynamically controlled silica-based optical devices have become both significant and practical. The thermo-optic (TO) effect is employed to control optical signals. The devices that have been developed include TO switches, variable optical attenuators (VOAs), and devices in which they are integrated. The silica-based waveguide phase shifters that employ the TO effect in these devices are compact, highly reliable, and suitable for large-scale integration. This paper reviews the large scale matrix switches including an 8 × 8 TO switch and a 32 × 32 TO switch. And a 40-ch VOA integrated AWG multiplexer with tap couplers, micromirrors, and monitor photodiodes is also demonstrated.

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1. Introduction

Silica-based materials have contributed greatly to optical communication systems and, of these materials, optical silica fiber is particularly well known. The introduction of optical communication systems into subscriber systems and of wavelength division multiplexing (WDM) transmission systems into trunk line and metro network systems has led to the use of many kinds of planar type silica-based optical devices, including power splitters, couplers, filters, wavelength multi/demultiplexers, and optical switches. These devices are mainly constructed by using silica-based planar lightwave circuit (PLC) technologies including glass deposition techniques such as flame hydrolysis deposition (FHD) based on silica fiber fabrication technologies, photolithographic techniques, and reactive ion etching (RIE) (Fig. 1). The recent progress achieved with optical communication networks has made dynamically controlled silica-based devices both significant and attractive.

Figure 2 is a schematic diagram of a photonic network. Although most copper transmission lines are now being replaced with optical technology, network nodes, such as switching and cross-connect nodes, still depend on electrical technology, that is, the signals are processed in the nodes after optical-electrical (O-E) conversion. Therefore, network throughput depends on the limitations of electrical circuits. Optical nodes are being used to reduce the load on electrical circuits, and this includes the introduction of fixed optical add/drop multiplexing (OADM) systems. More recently, the need has arisen for flexible and dynamically controlled optical networks with a large capacity. As a result, reconfigurable optical add/drop multiplexing (ROADM) systems have been installed and Er-doped fiber amplifier (EDFA) systems have been provided with rapid transient suppression and variable gain functions to cope with changes in the number of incoming wavelengths. Switching and variable optical devices are now being installed in mainstream optical communication networks, and these devices have become increasingly significant as the demand for these functions has increased.

The electro-optic (EO) and thermo-optic (TO) effects are often used to control optical signals dynamically. The fast optical response of the EO effect is particularly attractive, and the typical switching response of an EO switch is less than 1 ns. Many EO switches have been developed that employ various kinds of materials, for example certain ferroelectric materials including LiNbO3 (LN) and PLZT, liquid crystal, semiconductor, and organic nonlinear optical materials.

Silica-based materials generally have an extremely low EO
effect compared with LN or other ferroelectric crystals. Therefore, there have been many attempts to increase the EO efficiency of silica-based materials because of the attractiveness of EO devices that are monolithically integrated with silica-based waveguide devices, and the possibility of creating novel optical devices. A primitive silica-based waveguide EO switch has been demonstrated, but a long phase shifter and a high switching voltage were needed to realize a switching response, because of the low EO efficiency. Improved EO coefficients have also been reported and are almost same as that of LN. However, this research and development is still under way.

Thermo-optic optical devices are also very attractive as integrated silica-based waveguide devices. Silica-based materials have a $1 \times 10^{-5}$ of $dn/dT$, thermo-optic coefficient. This means that optical signals can be controlled using the TO effect. Although the response of the TO effect is relatively slow compared with that of the EO effect and TO devices have a switching speed of a few milliseconds, this is sufficient for applications provisioning light paths, such as optical crossconnects and ROADMs. Moreover, silica-based TO switches have little polarization dependence, a low loss, and are compact. The TO phase shifters used in our conventional TO switches are a few millimeters long. Such a compact switching unit is suitable for constructing large-scale integrated matrix switches, switch arrays, and integrated PLCs. Therefore, various kinds of large-scale integrated $N \times N$ matrix TO switches, TO switch arrays, and TO VOAs integrated with AWG multiplexers have been developed and demonstrated.

This paper reviews integrated silica-based waveguide devices including optical switches, variable optical attenuators (VOAs), and VOAs integrated with wavelength multiplexers. These devices are fabricated by using silica-based PLC technologies and make it possible to control optical networks dynamically with flexibility.

2. Planar lightwave circuit (PLC) technologies

PLC technologies enable us to meet current demand, and integrated silica-based waveguide devices are promising for use in photonic networks with huge transmission capacity and flexibility based on WDM systems. This is because silica-based waveguide devices have low loss, superior chemical stability, and high reliability, as well as the advantages of a single-mode fiber matched structure and mass producibility.

The reported lowest loss for a silica-based waveguide is 0.3 dB/m, which was measured for a 2.5 m long waveguide on a Si substrate. Silica-based PLC devices are suitable for attaching to silica fibers because they are made of almost the same material in terms of chemical properties and thermal expansion. And the spot size of the output light from these devices is similar to that of silica fiber, and so they can be attached to silica fiber with a low coupling loss.

Moreover, the combination of lightwave circuit design technologies, highly uniform glass film deposition, and precise waveguide process techniques enables us to fabricate high precision wavelength multi/demultiplexers such as arrayed waveguide gratings (AWG) multi/demultiplexers. The AWG multi/demultiplexer consists of input/output waveguides, two focusing slab waveguides, and arrayed waveguides with a constant path length difference $L_1$ between neighboring waveguides. The input light is launched into the first slab waveguide and then coupled with the arrayed waveguides. After traveling through the arrayed waveguides, the light beam interferes constructively at one focal point in the second slab waveguide. The location of the focal point depends on the signal wavelength $\lambda$ because the relative phase delay in each arrayed waveguide is given by $n_1 L_1/\lambda$. The slab and arrayed waveguides act as a lens and a relief grating, respectively. The AWG multi/demultiplexer is currently a key device in WDM systems. The integration of silica-based TO switches and AWG multi/demultiplexers makes them even more attractive.

Various kinds of dynamically controlled silica-based devices that include TO switches and VOAs are fabricated by using silica-based PLC fabrication technologies, including FHD, a photolithographic technique, and RIE. Figure 3 schematically shows the fabrication process. The first step involves the deposition of two successive glass particle layers on a silicon substrate by using FHD. These layers serve as the undercladding and the core. After deposition, the Si substrate with these porous glass layers is heated in an electric furnace for consolidation. The designed core ridges are patterned by photolithographic and RIE techniques based on LSI fabrication technologies. Finally, FHD is used again to cover the core ridges with an overcladding glass layer. After the channel waveguides have been fabricated, thin film heaters and evaporated Au electrodes are patterned on top of the overcladding. Furthermore, grooves are formed beside the cores with heaters to reduce the power consumption needed for shifting the phase to switch the optical signal or control the intensity level.

![Silica-based planar lightwave circuit fabrication process](image-url)
3. Switch/VOA basic configuration and characteristics

Various types of waveguide-based optical switches have been developed and reported, and they can be classified according to their switch unit structure. A typical example is the interferometer switch, or Mach–Zehnder interferometer (MZI) switch, and we employ this type as a $2 \times 2$ switching unit using silica-based waveguides. Another type is a digital optical switch (DOS) based on an X- or a Y-junction. DOSs are often employed with polymer-based waveguides, semiconductor waveguides, or other dielectric crystal waveguides. In addition, a reflection control switch has been reported. This type of switch consists of intersecting optical waveguides with grooves filled with fluid, such as refractive index matched oil, at each waveguide cross-point. And optical signals are controlled by moving the oil or a bubble in the grooves. The MZI-type switch, which has no moving parts, is highly reliable, and its optical characteristics match those of silica-based materials with a positive temperature coefficient.

Figure 4(a) is a schematic of the waveguide MZI-type switch that we employ. The MZI is composed of two 3-dB (50%) directional couplers (DCs) and two arm waveguides. Assuming that the arm waveguides have the same optical path length and both 3-dB couplers have a phase of $\pi/4$, the MZI optical response can be described as follows,

$$
\begin{align*}
A_{\text{out}} &= A_0 \sin^2(\varphi/2) \\
B_{\text{out}} &= A_0 \cos^2(\varphi/2)
\end{align*}
$$

where, $\varphi$ is the additional phase for the MZI. $A_0$ indicates the intensity of the input light from port 1. $A_{\text{out}}$ and $B_{\text{out}}$ represent the intensities of the output lights from ports A and B, respectively.

The output light can be controlled by shifting the phase with the electro-optic (EO) effect or the thermo-optic (TO) effect, and it has a sinusoidal response according to the phase shift. Figure 4(b) shows the theoretical optical output response versus the phase shift. With respect to output port A, it is in the off state as the additional phase equals zero ($\varphi = 0$), and in the on state as the phase is $\pi$, which corresponds to a half-wavelength. This is the switching response. When we adopt any intended phase between 0 and $\pi$, the MZI with the phase shifter functions as a variable optical attenuator.

Silica-based waveguides have a TO coefficient of $1 \times 10^{-5}$. This means the refractive index of a waveguide can be controlled by changing the waveguide temperature. The core temperature is changed by supplying electrical power to the patterned thin film heaters on the overcladding of the MZI, and is approximately proportional to the applied electrical power in the region that we conventionally use for switching optical signals. By varying the refractive index of one waveguide arm using the TO effect, we can change the optical path length ($\Delta nL$) by half a wavelength, and thus change the switch state. With a 4 mm phase shifter, the temperature increase of the core is estimated to be 20°C.

The electric power consumption for switching the state is typically about 0.12 W for a TO phase shifter with thermal insulation grooves. The switching power depends on the thermo capacity and thermal insulation characteristics around the core and the patterned thin film heater. These thermal insulation grooves adjacent to the phase shifters are very effective for reducing electrical power consumption, which is approximately 1/5 that without the grooves. Further improvements have been made as regards reducing the power consumption.

Figure 5 shows the typical time response of a silica-based TO switch. The rise and fall time of the output light were both approximately 1 ms. The time response also depends on the calorific capacity and thermal insulation characteristics. In general, the time response becomes faster with higher thermal conductivity and smaller calorific capacity. A silica-based TO switch using a Si substrate with high thermal conductivity has a faster optical response than a switch using a silica substrate.

The heaters of the TO phase shifters are processed by using photolithographic and etching techniques. And the heaters are a few millimeters long, which is sufficient for switching between the on and off states in conventional use. A compact switching unit is suitable for constructing large-scale integrated matrix switches, switch arrays, and integrated PLCs.

Another advantage of TO switches using PLC technology is...
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their high reliability. The long-term reliability of the switches was examined using eight arrayed 2 × 2 switch modules in accordance with Telecordia standard tests including heat-damp, high-temperature, low-temperature, heat-cycle, vibration, and impact tests. Excellent reliability was confirmed as regards insertion loss, extinction ratio, and heater resistance. Well-established PLC technologies provide us with large-scale and high-density integrated-PLCs with high reliability.

4. Large-scale N × N matrix SW

We have developed various kinds of N × M matrix switch that connect N-inputs and M-outputs in any combination such as 8 × 8, 16 × 16, 1 × 128, and 32 × 32, and improved their characteristics.15)(16)(22)–31) Large-scale switches are made by integrating basic switch units. To improve the extinction ratio to over 40 dB, a tandem two-MZI configuration is employed as a basic 2 × 2 switch unit. An 8 × 8 strictly nonblocking matrix switch (for N = M = 8) is generally configured by connecting 8 × 8 (= 64) sets of 2 × 2 switch units at cross-points in the form of a mesh (Fig. 6), which must be integrated with 128 MZIs on a single PLC chip.

The performance of fabricated switches has been improved. Although the chip size of an early 8 × 8 switch was 68 mm × 68 mm, recently the size has been reduced to 106 mm × 15 mm, which was achieved by employing an improved design for the compressed arrangement.29) Figure 7 shows a photograph of a fabricated compact 8 × 8 switch chip. The switch was fabricated with GeO₂-doped silica-based waveguides and the refractive index of the core was about 0.75% higher than that of the cladding glass layer. The core size was 6 μm × 6 μm.

The optical loss characteristics were measured by using non-polarized light at a wavelength of 1550 nm and standard single-mode fiber. It was confirmed that the average insertion loss was 2.5 dB, and the loss for all 64 paths was almost uniform (Fig. 8). These are fine characteristics, considering the loss value includes a coupling loss of 0.35 dB per facet between the waveguide and single-mode optical fiber. The extinction ratio was higher than 50 dB and the average value was 61 dB. The total electrical power consumption for switching was 3.5 W.

The scale of the developed silica-based matrix switches has been increased to 32 × 32.30) The 32 × 32 switch has a similar structure to the 8 × 8 switch, which is also composed of 2 × 2 switch units using two MZIs in tandem. The 32 × 32 switch has 1024 switching units at each crossing point, that is, the switch consists of 2048 MZIs. The chip is 110 mm × 115 mm and can be designed on a 6-inch wafer. Figure 9 shows the photomask pattern of the 32 × 32 switch. The 32 × 32 switch was also fabricated with GeO₂-doped silica-based waveguides and the refractive index of the core was approximately 0.75% higher than that of the cladding layer. To operate the 32 × 32 switch, we need to control 2048 phase shifters of 2048 MZIs, which must connect with 2048 heaters, and supply them with electrical power. Flexible printed circuits (FPCs) were employed for connecting the patterned heaters with outside electrical driving circuits. This provides design flexibility and reduces the chip size as a result of the reduced wiring space.

We confirmed that all 2048 TO phase shifters of the MZIs...
were successfully controlled. **Figure 10** shows histograms of the on- and off-state insertion losses for all 1024 paths. The average on-state insertion loss was 6.6 dB for passing through 64 MZIs, which were measured with non-polarized light at a wavelength of 1550 nm. The extinction ratio was higher than 45 dB and the average value was 56 dB. The electrical power consumption needed to switch each MZI was about 205 mW, and the total consumption was about 13 W, which corresponds to the operation of 64-MZIs (32 switch units). These results represent practical values for ROADM or cross-connect system applications. Furthermore we confirmed the superiority of our PLC technology for large-scale and high-density integration.

5. **ROADM and single chip integrated V-AWG**

An arrayed waveguide grating (AWG) multiplexer with a variable optical attenuator (V-AWG) using silica-based PLC technology is one of the most significant devices for constructing photonic networks that include reconfigurable optical add-drop multiplexing (ROADM) systems or wavelength selective switch systems. **Figure 11** shows the logical ROADM configuration. One typical ROADM system consists mainly of a demultiplexer, 2 × 2 or 2 × 1 switch arrays, VOAs with tapping and optical power monitors for optical power level equalization, and a multiplexer.

The development of a single-chip integration technique for V-AWGs has attracted a lot of attention, because single-chip integrated PLC technologies can eliminate the fiber-attaching process and the effort needed to arrange fibers in a module. Furthermore, they can make a module more compact. We have already demonstrated single chip integrated 16-ch V-AWGs with tap-couplers, micro mirrors, and monitor photodiodes (PDs). More recently, in order to meet the need for increased
wavelength counts and thus increase transmission capacity, we have developed an integrated 40-channel (40-ch) V-AWG with a monitor-PD on a single chip.

Figures 12(a) and (b), respectively, show the logical configuration and the layout of a single-chip integrated with a 40-ch V-AWG and a 40-ch AWG-demultiplexer with a spacing of 100 GHz (~0.8 nm). An array of 40 variable optical attenuators (VOAs), wavelength insensitive couplers (WINCs), as power taps, following micromirrors, and an AWG-multiplexer were designed in tandem on a single chip. Furthermore, an AWG demultiplexer was also designed in parallel.

We employed an AWG multi/demultiplexer with a flat transmission response and a parabolic horn waveguide in the integrated PLC, and also used athermal AWGs with silicone resin to prevent the thermal effect of the VOAs.

The VOA is composed of a cascaded MZI with thin film heaters on each of the arm-waveguides of the MZIs, which is very nearly the same structure as MZI-type switches. The VOA controls the optical power level by controlling the electrical power applied to the heaters through the thermo-optic (TO) effect.

The chip was fabricated with GeO$_2$-doped silica-based waveguides and the refractive index of the core was 1.5% higher than that of the cladding glass layer. The core size was 4.5 μm × 4.5 μm. The chip size was 25 mm × 75 mm, and the fabrication employed a 6-inch wafer. A photograph of the fabricated integrated V-AWG chip is shown in Fig. 13.

To monitor the optical power level, we employed chip-scale-package (CSP) PDs, which consisted of a hermetically sealed 20-channel PD array with a detection area 80 μm in diameter and a pitch of 250 μm. The size of a CSP-PD is 13 mm × 3 mm × 1.5 mm, and CSP-PDs were mounted on top of the cladding above the micromirrors. As semiconductor device functionalities, such as a photodiode and a laser diode, are introduced into integrated PLC devices, the use of individually sealed devices is superior to in-plane bare semiconductor chip integration because of their reliability and design flexibility.

Parts of each of the 40 introduced lights were divided with the coupler, led to the micromirror and reflected up to a CSP-PD. The micromirrors were fabricated by using resin formed into a slope coated with evaporated Au at the end of the waveguide. A SEM image of the micromirrors is also shown in Fig. 13.

The transmission characteristics of the V-AWG operated with different attenuations are shown in Fig. 14. The insertion loss of the V-AWG was 6.0 to 6.8 dB for 40 ports, and the PDL was less than 0.2 dB at maximum transmission. To maximize the transmission, we applied an electrical power of about 250 mW to the VOA. Figure 15 shows the transmission characteristics of the AWG demultiplexer collocated in parallel. The insertion loss of the demultiplexer was 5.1 to 5.9 dB and the PDL was less than 0.1 dB. The adjacent crosstalk was less than –30 dB. The transmission characteristics were examined by using broadband ASE light from an Er-doped fiber amplifier and a spectrum analyzer.

Figure 16 is a photograph of the integrated PLC module. The integrated PLC chip was mounted in an aluminum case. To supply electrical power to the VOA heaters, patterned electrodes on
the PLC chip were connected to a pin grid array through a flexible printed circuit (FPC). We confirmed that all 160 electrodes patterned beside the phase shifter heaters were connected with FPCs, because a 40-ch VOA consists of two tandem stages of MZIs with two phase shifters for each waveguide arm. And we also confirmed the successful operation of the 40-ch VOA. FPC connection technology provides us with design latitude for the electrical wiring pattern on the integrated PLC.

CSP-PD outputs were also connected to pin grid arrays (PGAs) through FPCs. Figures 17(a) and (b) show the module responsibility and PD crosstalk characteristics of the stacked CSP-PD. The module responsibility was 13 to 19 mA/W. This includes the tap ratio and the coupling loss between the fiber and the PLC. Taking these losses and the reflection loss at the micromirror into account, we estimated the PD responsibility to be approximately 1 A/W. And the PD adjacent crosstalk was less than –25 dB.

We demonstrated the single-chip integration of a 40-ch AWG demultiplexer and a 40-ch AWG multiplexer with a VOA array, taps, micromirrors, and stacked CSP-PDs. And we confirmed their fine characteristics. A stack integration technique combined with micromirrors is very useful and attractive for extending the functionality of PLCs. The fabrication technique used for the integrated V-AWG can be applied to other integrated PLC devices with expanded functionality.

6. Summary

Integrated silica-based waveguide devices including switches/VOAs and VOA integrated multiplexers were reviewed. A compact and low loss 8 × 8 matrix TO switch and a large-scale 32 × 32 matrix TO switch were introduced. The insertion loss of a 32 × 32 switch was 6.6 dB and the extinction ratio was 56 dB. The switching response was about 1 ms and this is sufficient for signal light path provisioning applications. Moreover, a 40-ch VOA integrated AWG multiplexer with tap couplers, micromirrors, and monitor PDs was also demonstrated. It was confirmed that all of the 40-ch VOAs operated successfully and the multi/demultiplexing characteristics were also good. These dynamic devices employ the thermo-optic effect, and are suitable for large-scale, high port count, and high-density integration because of their low loss, compactness, and high reliability. It was also demonstrated that the stack integration technique combined with micromirrors was very useful for introducing functionality into PLCs. Devices fabricated by using silica-based PLC technologies are key components for constructing photonic networks with large transmission capacity and flexibility. Furthermore, PLC technologies provide us with highly integrated silica-based waveguide devices, which are useful for achieving more compact and cost-effective optical modules.

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References

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