Recent Progress in Silica-based Planar Lightwave Circuits (PLCs)

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Abstract

Photonic components, such as optical splitters, multi/demultiplexers, and switches, are key factors in creating a ubiquitous society supported by photonic networks. Silica-based planar lightwave circuits (PLCs) are promising technologies and have provided several photonic components for practical networks because of their compactness, mass-producibility, and high reliability. This article reviews core technologies related to silica-based PLCs and their recent progress.

1. Silica-based PLC devices for photonic networks

The revolution in information technology typified by the explosive expansion of Internet services has led to a paradigm shift in telecommunication. Email and video distribution services are replacing legacy telephone and facsimile, and digital data traffic has been doubling every half-year. To support this qualitative and quantitative revolution in telecommunication, fiber-optic technologies have been developed aggressively because of their high speed and large capacity. In addition, photonic networks based on reconfigurable optical add/drop multiplexing (ROADM) and optical cross connect (OXC) systems have recently been investigated with a view to improving system flexibility and scalability.

Such photonic networks require functional photonic components, namely optical splitters, multi/demultiplexers, and switches, and several types of photonic components based on bulk-optics, MEMS (microelectromechanical systems), and planar waveguide technologies have been developed. Of these, silica-based planar lightwave circuits (PLCs), which were originally researched and developed by NTT Photonics Laboratories, have advantages of compactness, mass-producibility, and high reliability and provide various functional components because of their high design flexibility and precise fabrication technology [1]. **Figure 1** shows typical PLC components developed in our laboratory. Arrayed-waveguide gratings (AWGs) are used as *de facto* standard filters for wavelength division multiplexing (WDM) in long-haul systems, and optical splitters and monitoring couplers have been put into practical use for fiber-to-the-home (FTTH) systems. Optical matrix switches and integrated variable optical attenuator multiplexers (V-AWGs) are promising for use in next-generation photonic networks.

In this feature article, we review PLC technologies and recent progress in functional PLC components, which have been actively developed at NTT Photonics Laboratories. The detailed technologies of specific PLC components are described in the following featured technical articles: “PLC Optical Switch that Enhances the Optical Communication Network”, “PLC Components Used in FTTH Access Networks”, and “Multi-functional Optical Module Using Multichip PLC Integration Technology for Next-generation Optical Networks”. In addition, future PLC technologies are introduced in two articles entitled “PLC Optical Signal Processing Devices for Developing Highly Functional Optical Networks” and “New Waveguide Fabrication Techniques for Next-generation PLCs”.

2. Photonic components based on silica-based PLCs

We have been investigating PLC fabrication tech-

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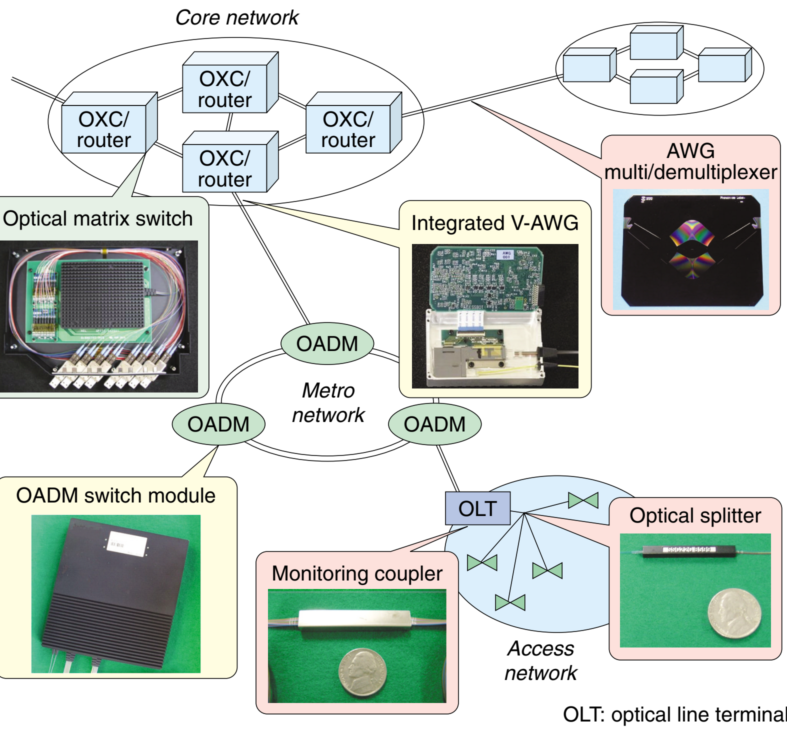

Fig. 1. Silica-based PLC components used in fiber-optic networks.

nologies related to 1) low-loss silica-based glass deposition and precise microstructure formation and 2) PLC design technologies for controlling optical power and phase interference in order to make functional components. PLCs are fabricated on silicon or quartz substrates by a combination of flame hydrolysis deposition (FHD) and reactive ion etching (RIE). Because FHD is based on an optical fiber fabrication method and RIE is used to fabricate LSI chips, PLCs have the potential to allow mass-production and provide cost-effectiveness, high reliability, and high-density integration. For various kinds of photonic component applications, we can make waveguides with a low loss of 0.017 dB/cm for small-scale PLCs and bent waveguides with a small radius of curvature of less than 2 mm for high-density integrated PLCs by adjusting the refractive index difference (Δ).

Silica-based PLC components are categorized as optical power control or optical interferometer types based on their operating principles as shown in **Fig. 2**.

Optical splitters in which the optical power is divided at a Y-branch are typical optical power control type PLC components. Several types of optical splitters such as 1×4, 1×8, and 1×32 can be made compactly on a chip by connecting multistage Y-branches in a tree structure. This makes them superior to conventional fused-fiber type splitters in terms of cost and mass-producibility. PLC type splitters have already been put into practical use in access networks, namely FTTH systems, and their long-term reliability for telecommunication use has already been established.

For the optical interferometer type PLC, very precise optical phase control is required to obtain a desired component performance. From this viewpoint, silica-based PLCs are very suitable technologies for such interferometer type PLCs because of their sub-micrometer-accuracy waveguide formation. Mach-Zehnder interferometers (MZIs) with two-waveguide beam interference are basic interferometer type PLCs and have provided several functional PLCs. The wavelength insensitive coupler (WINC) with a non-wavelength selective coupling ratio is one such MZI-PLC and it has been employed in systems for monitoring installed optical fiber cables. A lattice-type waveguide filter, composed of cascaded MZIs, is very interesting because arbitrary filter characteristics can be synthesized by designing the MZI parameters. Several lattice filter PLCs have been developed including an interleave filter [2] with a rectangular wavelength response and a chromatic dispersion compensator [3]. The PLC type splitter and WINC are described in detail in the third article.

An optical switch [4], [5] and a variable optical

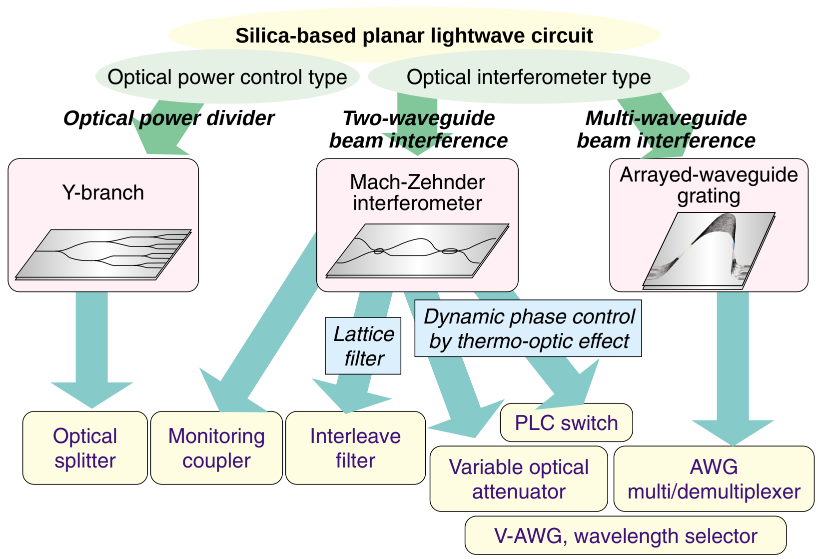

Fig. 2. Functional optical components based on silica-based PLC technology.

attenuator (VOA) [6] are key components for the ROADM and OXC systems of photonic networks. Thin-film heaters placed on the arm waveguides of an MZI let us control the operation of an optical switch and its optical power level based on the thermo-optic effect with a response time of 1–3 ms. The PLC switch and VOA offer good reliability and integration because they are solid-state switches with no moving elements. A 1 × 128 optical switch and a 16 × 16 matrix switch with 512 switch elements have already been investigated. These technologies are described in the second article.

Of the interferometer type PLCs, an AWG filter based on multi-waveguide beam interference is the most noteworthy. The AWG multiplexes/demultiplexes several tens of WDM signals simultaneously in one circuit and has been used in practical dense WDM systems worldwide. The number of AWG channels has reached 64 for commercialized devices and 400 in our laboratory. Recently, multi-functional integrated PLCs such as the V-AWG or a wavelength selector consisting of an AWG, switches, and VOAs have been investigated to meet the requirements of advanced networks.

3. PLC technologies for multi-functional integrated PLCs

We have been investigating the PLC technologies of pure silica-based glass deposition, fine waveguide formation, and optical phase control by the thermo-optic effect. This has enabled us to develop several functional PLCs including optical splitters, switches, and AWGs. In addition, we have been studying differentiation technologies such as a UV trimming technique for precise phase adjustment and ultrahigh-Δ waveguides for ultrahigh-density compact PLCs. **Figure 3** shows the relationship between the fabrication process technologies such as the PLC platform and various kinds of PLC devices based on them.

Recently, photonic network innovation as typified by the ROADM system has been driving the requirements for multi-functional optical modules in which several different functional PLC devices are assembled or integrated. These modules are usually fabricated using individual packaged optical components, which are connected using patching fibers. This conventional approach results in a large module size and a high assembly cost due to the need to handle a jumble of fibers. In contrast, although monolithic integration techniques have been investigated, it is difficult to achieve a high level of performance with a high yield because the circuits for the functions require different optimum parameters and process conditions. To solve these problems, we have proposed and developed PLC integration technologies such as multi-chip PLC integration and the hybrid integration of active semiconductor devices [7].

An intelligent optical module that can control dynamic PLCs, namely optical switches and VOAs, which uses a built-in electrical controller, is a particularly promising multi-functional optical module. We are therefore investigating such an intelligent PLC module and system PLCs, such as a 32-channel

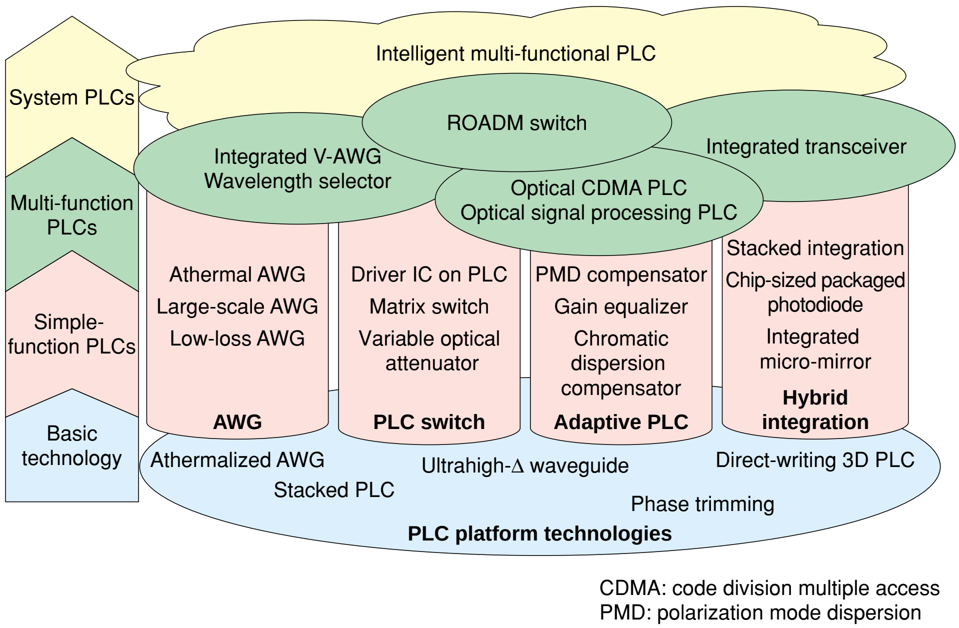

Fig. 3. PLC platform technologies and associated functional PLC devices.

wavelength selector with an AWG and optical selective switches and an 8-channel V-AWG module [8] with power monitors, arrayed VOAs, and an AWG. The technologies are described in the fourth article. These intelligent multi-functional PLCs are expected to become key technologies for the ROADM and OXC systems in the next-generation photonic networks.

4. Evolution of silica-based PLC technologies

To sum up, we described the evolution of silica-based PLC technologies from the perspective of our PLC R&D activities, as shown in **Fig. 4**. We were the

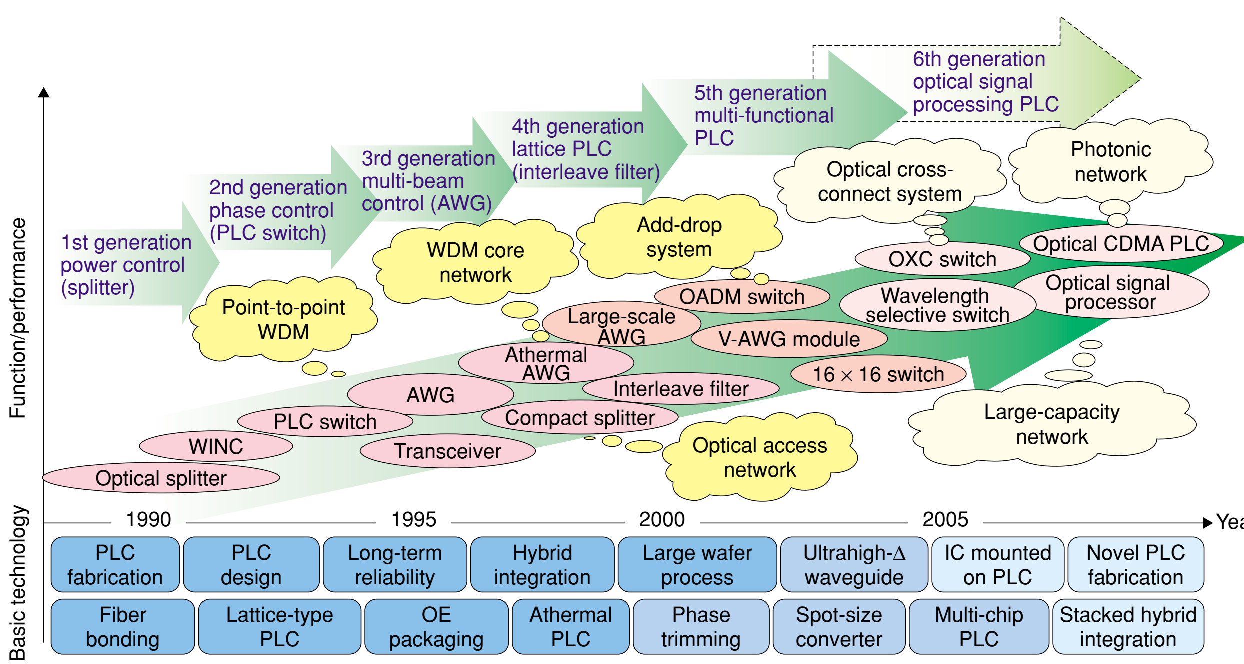

Fig. 4. Evolution of silica-based PLC technologies.

first to investigate optical power control PLCs such as optical splitters. Next we studied phase control PLCs and developed PLC switches based on MZIs. We then developed multi-beam interferometer PLCs, namely AWG filters, and proposed a novel optical design based on a lattice-type PLC. These notable PLC components were made by using our PLC design and fabrication technologies to achieve low loss and precise phase control and using our assembly technologies to provide good optical and electrical (OE) packaging. We are currently developing multi-functional fifth-generation PLCs and concurrently investigating basic technologies related to an ultrahigh-Δ waveguide for high-density integration and highly reliable hybrid integration for semiconductor devices. The comprehensive development of PLC design, fabrication, and packaging technologies will assist the improvement of PLC functionality, thus helping us to make next-generation signal processing PLCs for novel photonic networks.

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