Multi-functional Optical Module Using Multi-chip PLC Integration Technology for Next-generation Optical Networks

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Abstract

The next generation of optical networking requires optical parts with complex functionality that are smaller and cheaper than ever before. The silica-based planar lightwave circuit (PLC) technology developed at NTT Photonics Laboratories is expected to satisfy the market demands as the predominant technology due to its smallness and its suitability for mass production. This article reviews recent progress achieved by complex function-integrated optical modules in which silica-based PLCs with various functions are integrated using multi-chip PLC integration technology.

1. Multi-chip PLC integration technology

NTT Photonics Laboratories has proposed and enhanced the multi-chip PLC integration technology that directly connects multiple planar lightwave circuits (PLCs) as a platform technology that enables smaller advanced optical modules for dense wavelength division multiplexing (DWDM) at lower cost [1]. This technology easily eliminates or overcomes the major barriers such as poor yields and insufficient versatility that exist with monolithically integrated optical circuits. In addition, high-performance modules can be implemented since this technology makes it possible to manufacture individual optical circuits with optimal designs and manufacturing conditions.

The V-AWG, which is a combination of a variable optical attenuator (VOA) and an arrayed-waveguide grating (AWG) wavelength division multiplexer, is the first complex function-integrated PLC module for practical applications (**Fig. 1**). This module consists of a VOA achieved using a Mach-Zehnder interferometer (MZI) using the thermo-optic effect, a power tap circuit utilizing a wavelength insensitive coupler (WINC), a monitor photodiode (PD), an AWG wavelength division multiplexer, and an electronic control board that provides intelligent control of these optical parts.

We have focused on the research and development of the V-AWG as the first application of multi-chip PLC integration technology [2]. This technology succeeds in drastically reducing the size of the module because the space previously needed for fiber routing, optical connectors, and fusion splice joints is no longer required. Moreover, the decreased number of connection points with single-mode fiber yields a major improvement in insertion loss if the optical waveguides have a high refractive index difference (Δ).

A photograph of the interior of a manufactured ultrasmall 8-channel V-AWG module is shown in

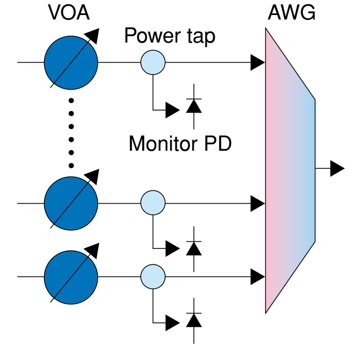

Fig. 1. AWG multiplexer with variable optical attenuator (V-AWG).

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Fig. 2 and the module's transmission spectrum characteristics are shown in **Fig. 3** [3]. We succeeded in fabricating the module as small as 70 mm × 45 mm × 14 mm, which is 1/20 of the volume specified in the industrial standard MSA (multisource agreement), but it still has all the required functions.

Moreover, by using an athermal AWG, which does not require a temperature controlling circuit, and a low-power-consumption VOA implemented by optimizing its thermal insulation groove, we have succeeded in reducing the maximum power consumption, including the power consumption of the control board, to less than 0.8 W. Furthermore, we have achieved excellent optical characteristics: insertion loss of 5 dB and polarization-dependent loss of less than 0.4 dB at 15-dB attenuation. As a result, this ultrasmall 8-ch V-AWG module is expected to be widely applied, not only in backbone networks, which are now using standard V-AWGs, but also in metropolitan area networks which require lower power consumption and smaller multifunction integrated modules.

Next, we introduce the results of a study in which the multi-chip PLC integration technology was applied to a 32-ch dynamic wavelength channel selector (DWCS) consisting of a 32 × 1 optical switch and an AWG [4]. The DWCS provides a multiple-channel optical monitor with a small size and low cost, both of which are essential for practical network quality control. It can selectively transmit one designated wavelength out of all the DWDM signals. **Figure 4** shows the compact PCI-based*1 DWCS board and its internal structure, which incorporates a temperature controlling circuit for the AWG and the current driving circuit that can control the optical switch within 0.5 ms.

To make the DWCS small, we designed the AWG and the optical switch using 1.5% Δ waveguides whose minimum bending radius is 2 mm and used a flat-top AWG to suppress the spectrum distortion generated by filtering. To improve the extinction ratio

*1 PCI: peripheral component interconnect. An interconnection system between a microprocessor and attached devices.

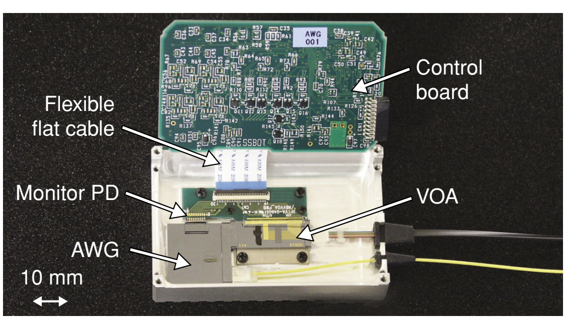


Fig. 2. Internal structure of ultrasmall 8-ch V-AWG module.

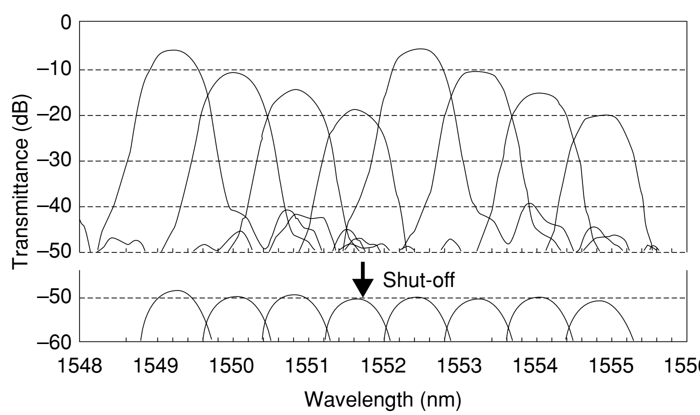
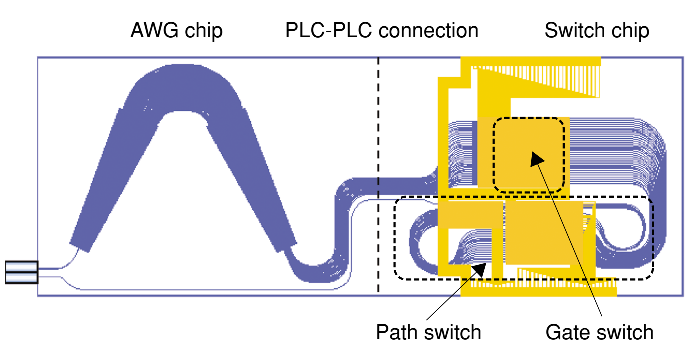
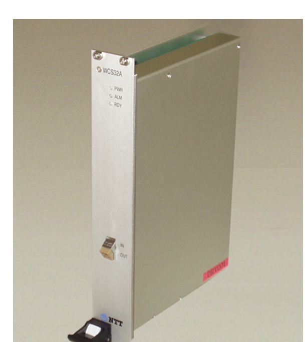


Fig. 3. Transmission spectrum of ultrasmall 8-ch V-AWG module.



(a) Internal structure



(b) Photograph of the compact PCI-based DWCS board

Fig. 4. 32-ch dynamic wavelength channel selector (DWCS).

of the switch, we used a five-stage tree structure with a gate switch to each input port. We succeeded in keeping the size small: the optical module part is extremely small, only 24 mm × 64 mm, and is mounted on a relatively small board, 235 mm × 160 mm × 40 mm (6U, which takes up the width of two slots) including the control board. We achieved an average insertion loss of 6.5 dB and adjacent channel crosstalk of less than –35 dB, which have been proved to be sufficient for practical use. If we increase the number of stages for the gate switch, we should be able to suppress the crosstalk further. In addition, the switching time of the DWCS is less than 2 ms.

2. Hybrid multi-chip PLC integration technology

The multi-chip PLC integration technology can not only combine multiple silica-based PLCs, but also integrate silica-based PLCs and waveguides based on different materials providing the many sophisticated functions necessary for an optical network. First, we introduce a 4-ch 10-Gbit/s WDM transmitter/receiver module, which was developed for the VSR (very short reach) optical interface by using the multi-chip PLC integration technology [5].

In recent years, with the rapid development of the access network, we have started to see an increase in demand for optical transmission equipment with the high throughput of 40 Gbit/s for high-speed VSR connections between routers. The 10-Gbit/s × 4-ch VSR standardized by the Optical Internetworking Forum (OIF) is considered to be a promising candidate to satisfy this demand. This standard established a transceiver (Tx) and receiver (Rx) by using 4-ch coarse WDM (CWDM) with a wavelength spacing of 24.5 nm in the 1300-nm band. The structure of our module is shown in **Fig. 5**. First, we attached the AWG multiplexer/demultiplexer and the PLC platform with laser diodes (LDs) and PDs mounted on it using the multi-chip PLC arrangement. The input and output electric signals pass through a printed circuit board that incorporates the LD driver and PD preamplifier IC (integrated circuit).

The shape of the AWG transmission spectrum is optimized separately for the multiplexer and for the demultiplexer. In particular, we use multimode output waveguides for the Rx demultiplexer to achieve a very flat transmission spectrum at low cost. Furthermore, we mounted a distributed feedback LD (DFB-LD) for the Tx and a refracting-facet photodiode (RFPD) for the Rx on the PLC by the passive alignment technique*2 and introduced a fan-out waveguide configuration*3 to suppress optical and electrical crosstalk between channels.

We achieved an optical output of more than –3 dBm with 10-Gbit/s direct modulation for the Tx and high and flat optical sensitivity of about 0.4 A/W for the Rx. These characteristics satisfy the typical required specifications. Moreover, we obtained 3-dB receiver bandwidth of 9 GHz and adjacent channel crosstalk of less than –21 dB. **Figure 6** shows the results of a

*2 Passive alignment technique: precise alignment method for LD and PD by visual recognition with position markers.

*3 Fan-out waveguide configuration: waveguide configuration that separates waveguides by a sufficient distance to ensure that they do not interfere with each other.

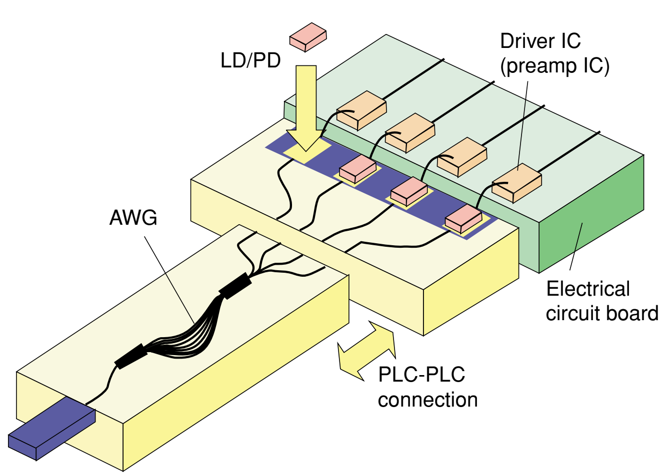


Fig. 5. Structure of 4-ch 10-Gbit/s module for VSR applications.

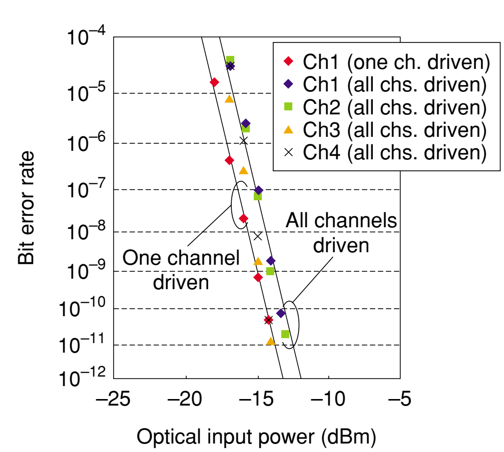


Fig. 6. Results of 10-Gbit/s × 4-ch bidirectional transmission experiment.

10-Gbit/s × 4-ch module bidirectional transmission experiment in 5-km-long fiber. We obtained error-free operation (bit error rate: 10^{-12}) with all channels simultaneously active. The minimum optical reception sensitivity was –12 dBm, which satisfies the VSR specifications.

Next, let us move on to the periodically poled lithium niobate (PPLN) waveguide module, which integrates silica-based 1 × 4 couplers and delay line circuits for ultrahigh-speed optical time division multiplexing (OTDM) [6]. The module structure is shown in **Fig. 7**. The two silica-based PLC waveguides and the PPLN waveguide are connected to each other. The 40-GHz clock light is split by 1 × 4 couplers and then each clock light is multiplexed with a 40-Gbit/s NRZ (non return to zero) signal light and then coupled into the PPLN waveguide. The wavelength-converted lights generated in the PPLN waveguide pass through the delay line circuits and are then multiplexed by the 4 × 1 couplers to produce OTDM output light.

Since it is essential to minimize the connection loss between the silica-based PLC and the PPLN waveguide to generate wavelength-converted light efficiently, we used a 1.5% Δ waveguide with a horizontally tapered spot size converter to match the flat electrical field of the PPLN waveguide. As a result, this waveguide achieved the low connection loss of 0.3 dB, whereas ordinary 0.75% Δ waveguides exhibit connection loss of 1 dB. Furthermore, by applying this 1.5% Δ waveguide, we were able to reduce the size of the entire module to 85 mm × 10 mm and halve the insertion loss. Wavelength conversion efficiency was about 300 %/W, of which about 100 %/W was due to the improvement in PLC-PPLN connection loss and propagation loss, so it turns out that the wavelength conversion efficiency was improved by about 1.5 times due to our efforts. The 160-Gbit/s OTDM output waveform is shown in **Fig. 8.** We confirmed good eye opening without any variation in the signal interval, proving that the multi-chip PLC integration technology is very useful for future ultrahigh-speed optical communications.

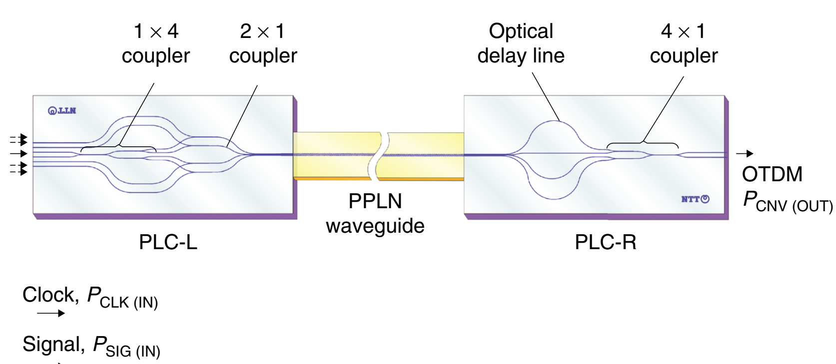


Fig. 7. OTDM multiplexer module structure.

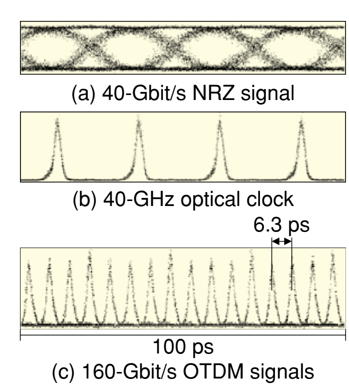


Fig. 8. 160-Gbit/s OTDM output waveform.

3. Future of the multi-chip PLC integration technology

The ROADM (reconfigurable optical add/drop multiplexing) ring network, which is expected to be used in metro-networks, requires a wavelength selective switch (WSS) module that can output any designated wavelength to any designated output port to connect multiple ROADM ring networks. We expect the multi-chip PLC integration technology to be very effective for making a high-performance optical module such as the WSS quickly and at a low cost. For this reason, we plan to strengthen our research and development activities in this area.

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