Photonic Integration Technologies for Large-Capacity Telecommunication Networks

Yoshinori Hibino

(Invited Paper)

NTT Photonics Laboratories, NTT Corporation, Atsugi 243-0198, Japan

DOI: 10.1109/JPHOT.2010.2047387
1943-0655/$26.00 ©2010 IEEE

Manuscript received February 14, 2010; revised March 4, 2010. Current version published April 23, 2010. Corresponding author: Y. Hibino (e-mail: hibino.yoshinori@lab.ntt.co.jp).

Abstract: Photonic integration technologies, which have been developed since the deployment of optical communications, are essential for increasing the network capacity at a low cost and with efficient power consumption. This paper reviews recent progress on photonic integrated devices for higher bit-rate and long-distance transmission technologies with advanced modulation formats.

Internet protocol (IP) data traffic has increased hugely with the increased access to such broadband access environments as fiber to the home (FTTH) and asynchronous digital subscriber lines (ADSLs), which have enabled the provision of video on demand, video chat, and other similar services. In Japan, IP data traffic doubles annually, and if this trend continues, in 10 years, the traffic will be 100 to 1000 times that of today.

A very-large-capacity backbone network is needed to support the huge traffic volume generated by access networks. For this purpose, various technologies, including time-division multiplexing (TDM) up to 40 Gb/s per channel, wavelength-division multiplexing (WDM), and a phase-shift keying (PSK) modulation method, have been developed and installed to support the existing IP traffic demand. In the near future, we will require WDM transmission systems with even greater transmission capacity. Recently, optical transmission technologies combined with coherent detection and digital signal processing technologies (digital coherent technologies) have been attracting a great deal of attention with a view to improving optical transmission performance.

Various optical components have been developed to construct telecommunication systems with large capacities and a variety of functions including WDM, FTTH, and ROADM using silica-based planar lightwave circuits (PLCs) [1], InP-based active components [2], and micro-optics technologies. PLC-based integrated devices have the advantages of high stability, reliability, and excellent optical performance, and we have recently been developing PLC-based components for high-bit-rate and large-capacity transmission systems [1]. InP-based active devices such as laser diodes and photodiodes are essential for optical telecommunications. Integration technologies based on InP active components have progressed greatly and can be used to construct highly functional devices. Micro-optics devices have continued to provide high levels of performance over many years. Photonic network systems are becoming more complicated, thus making it necessary to integrate more passive and active optical components on PLC platforms to achieve low cost and high flexibility. This paper reviews recent progress on such integrated components for large-capacity transmission technologies with advanced modulation formats.

Non-return-to-zero (NRZ) modulation formats have generally been used for systems operating at up to 10 Gb/s. However, advanced modulation formats are needed if we are to increase the capacity of transmission systems with high-bit-rate technologies of 40 Gb/s or more in WDM systems. Especially, the combination of advanced modulation formats and digital coherent detection techniques is emerging as one of the most promising solutions for these high-bit-rate transmission systems, because of the high tolerance to fiber dispersion and band filtering in the add/drop nodes [3]. With regard to advanced modulation formats, there have been reports on polarization-division multiplexing (PDM) and spectrally efficient modulation formats such as quadrature PSK (QPSK), orthogonal frequency-division multiplexing (OFDM), and multilevel quadrature amplitude multiplexing (QAM). By employing digital coherent detection techniques, the transmission performance, namely the product of transmission capacity and fiber length, has been greatly improved compared with direct detection methods such as RZ-DQPSK. The top data was currently obtained as about 112 Pb/s $\times$ km (15.5 Tb/s $\times$ 7200 km) [4].

Recently, transmission technologies with a PDM-QPSK modulation format and digital coherent detection have been extensively developed for 100-Gb/s-class WDM systems [5]–[7]. A transceiver for the 100G-level PDM-QPSK format consists of a digital signal processor (DSP), analog–digital converters (ADCs), and optical components. The role of digital signal processing in digital coherent technology is to recover the received signal data, which are degraded owing to such factors as chromatic dispersion and PMD during signal propagation through optical fibers. At the receiver, the data are digitally sampled by the ADCs. The ADC requires at least two samples per symbol. For instance, the ADC sampling speed for the PDM-QPSK modulation format with 112 Gb/s (28 GBd) is more than 56 GS/s. The digitized signal data are transported to the DSP and processed to compensate for the chromatic dispersion, polarization-mode dispersion (PMD), frequency offsets, and phase offsets. The digital coherent techniques have the advantages of being able to extract phase-modulation formats, utilize polarization modes, and increase sensitivity with a high power local oscillator.

It will become essential to integrate modulators and PDM components in the transmitter part in the transceiver for the PDM-QPSK schemes. To integrate two QPSK modulators and a PDM circuit with practical performance levels, we have developed a hybrid assembly technique with silica-based planar PLCs and $LiNbO_3$ (LN) phase modulators [8], in which we use a simple straight-line phase modulator array with LN, and butt joint it with PLCs on either side. Thus, we can achieve interferometer-type high-speed modulators with low losses and various circuit designs. We constructed the PDM-QPSK modulator using the PLC and LN hybrid-integration technique. The modulator consists of three chips: two 1.5%-δ PLCs, PLC-L and PLC-R, and an eight-channel array of LN phase modulators. This multichip circuit integrates two QPSK modulators (QPSK1 and 2) with two sub-MZMs (I and Q) nested in each, a polarization rotator using a half-wavelength plate (HWP), and a polarization beam combiner (PBC). The performance of the module is acceptable for the 100G-level PDM-QPSK. Using the modulator, we obtained the transmission data of 84 Pb/s $\times$ km (13.5 Tb/s $\times$ 6200 km) [9].

Higher order multilevel modulation formats are indispensable if we are to achieve systems with higher bit rates of more than 100 Gb/s and large capacities of over 10 Tb/s [10]–[15]. We have demonstrated the signal modulation and detection of a 240-Gb/s PDM 64-QAM signal [16]. A 20-GBd PDM 64-QAM signal was successfully generated by employing the optical synthesis technique with the PLC-LN hybrid modulator, in which six MZMs and low-loss asymmetric couplers are integrated with the PLC-LN hybrid configuration. The modulator generates a 64QAM signal through an optical signal synthesis with QPSK signals [28]–[30]. Fig. 1(a) shows the circuit configuration of the 64-QAM modulator. The modulator consists of two 1.5%-Δ PLCs, PLC-L and PLC-R, and a X-cutLN chip with an array of 12 high-speed phase modulators and six signal electrodes (coplanar waveguides). The asymmetric 1 $\times$ 3 splitter and 3 $\times$ 1 combiner (cascaded 4 : 3 and 2 : 1 Y-branches) were fabricated in PLC-L and PLC-R, respectively.

In the transmission experiment, the 64-QAM signal was generated by superposing three QPSK signals with an amplitude ratio of 4 : 2 : 1. The 20-GBd 64-QAM signals were then polarization multiplexed to form a 240-Gb/s PDM 64-QAM signal and were detected with a digital storage oscilloscope at 50 GS/s and postprocessed offline. Fig. 1(b) shows the constellation diagrams after equalization when the independent LO was used. The 64 signal points are clearly distinguished in

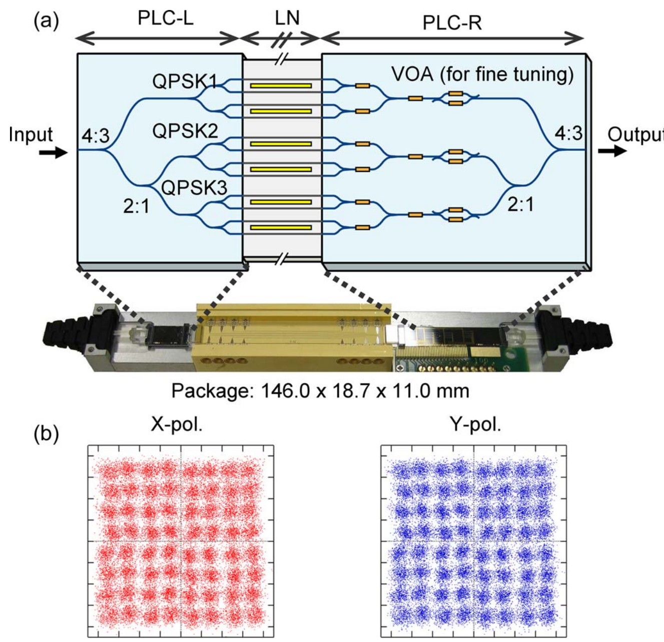

Fig. 1. (a) Configuration of 64-QAM modulator. (b) Constellation diagrams of 64-QAM modulation.

both polarizations, confirming that we achieved successful polarization demultiplexing and equalization. The spectral width of the main lobe of this modulation format was 40 GHz, which was one sixth of the line rate. Because of this narrow spectral width, an SE of 8 b/s/Hz, which is the highest so far, can be expected for WDM transmission with a spacing of 25 GHz.

This review described photonics-integrated devices for the high-bit-rate transmission technologies with advanced modulation formats such as 100G-class PDM-QPSK and 64-QAM. The devices exhibited sufficiently high levels of performance for practical use. Since they provide the advantages of mass producibility, dense integration, and high stability, photonics-integrated devices will contribute to further advances in high-bit-rate transmission.

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