Functional integrated modulators and receivers utilizing PLC hybrid integration technology for coherent transmission

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Abstract: We review our recent progress toward transmission speeds per channel of 100 Gbit/s and beyond, focusing on optical modulators and receivers for coherent transmission using PLC integration technology. We have used PLC-LiNbO₃ hybrid integration technology to develop optical multilevel modulators, including a DP-QPSK modulator and a 64 QAM modulator for 100 Gbit/s and post 100 Gbit/s. This technology provides practical performance and scalability for various advanced modulations. We have also developed flexible-format modulators for future elastic networks, which will enable the efficient use of the spectral resource. This modulator can select an optimum carrier number and modulation level according to the transmission conditions. In terms of receivers, we have developed integrated optical receiver front-ends for 100 Gbit/s DP-QPSK based on hermetically sealed O/E converters. PLC hybrid-integration technologies are promising for compact, practical, cost-effective, and highly reliable coherent optical modulators and receivers.

Keywords: Coherent, PLC, lithium niobate, modulator, receiver, integration

Classification: Optoelectronics, Lasers and quantum electronics, Ultrafast optics, Silicon photonics, Planar lightwave circuits

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1 Introduction

The rapid increase in data and video traffic has led to a strong demand for speeds of 100 Gbit/s per channel and beyond in the transport network. Digital coherent detection utilizing polarization division multiplexing such as dual-polarization quadrature-phase-shift keying (DP-QPSK) [1] has recently attracted great attention due to its ability to receive high spectral efficiency signals with high receiver sensitivity, and to compensate digitally for transmission impairments such as chromatic dispersion and polarization mode dispersion. Thus the research and development of coherent transmission systems has been extensively pursued throughout the world to realize a large capacity of 100 Gbit/s and more than 100 Gbit/s per channel.

Figure 1 (a) and (b), respectively, show typical block diagrams of a transmitter and a receiver for digital coherent transmission systems [2]. Compared with direct detection transmission systems including on-off-keying (OOK) and differential phase shift keying (DPSK), coherent transmission systems require highly-functional complicated optics on both the transmitter and receiver sides. As these devices will be installed along with digital signal processors (DSPs) in conventional 5x7-inch transponder modules, they must be compact. Moreover, the optical skew in both modulators and receivers

Fig. 1. Basic configurations of (a) transmitter and (b) receiver for 100 Gbit/s digital coherent transmission system.

must be precisely controlled to handle four parallel transmission signals (XI, XQ, YI, and YQ). Integrated modulators and receiver front-ends are of great interest as regards meeting these requirements. The Optical Internetworking Forum (OIF) has standardized the components indicated by dotted boxes in Fig. 1 (a) and (b). Furthermore, various advanced multilevel formats such as quadrature amplitude modulation (QAM) and orthogonal frequency-division multiplexing (OFDM) can also be used in digital coherent transmission systems.

As for the modulator, to achieve these advanced modulations, multilevel electronics such as arbitrary waveform generators (AWGs) or digital-to-analogue converters (DACs) have been used in many transmission experiments [3, 4]. By using them, we can cover various modulation formats with a simple optical setup. On the other hand, optical multilevel-signal syntheses, in which only binary electronics is used, have also been studied extensively [5, 6, 7, 8, 9, 10, 11]. These schemes are promising for high-speed multilevel modulation because binary electronics poses fewer challenges for high-speed operation than multilevel electronics [8, 11].

Several integrated optical modulators for the optical syntheses have been reported. Modulators for 16 QAM [7] and 64 QAM [12] with parallel (Mach-Zehnder modulator) MZM configurations have been demonstrated; both employ planar lightwave circuit (PLC)-LiNbO₃ (LN) integration. Other configurations for 16 QAM have also been reported, such as a tandem/parallel MZM with LN monolithic integration [9], and a parallel electro-absorption modulator (EAM) with InP monolithic integration [8]. Flexible-format modulators utilizing PLC-LN integration have been developed for flexible optical networks, which enables efficient use of optical spectral resources [13, 14].

At the same time, integrated receiver front-ends for coherent detection have also been studied extensively using a number of approaches as summarized in Table I [15, 16, 17, 18, 19, 20, 21, 25]. Various types of monolithic InP integrated receiver front-ends have been reported in a photonic integrated circuit (PIC) and module.

The monolithic approaches with InP can integrate the various devices including local oscillators (LOs), 90-degree optical hybrids (OHs), photodiodes (PD), and trans-impedance amplifiers (TIAs). The size and the elimination

Table I. Reported integrated coherent receiver front-ends.

Ref.)	WDM demux.	LO	PBS	BS	OH	PD	TIA	ADC	Note
[15]	-	InP	-	-	InP	InP	-	-	PIC
[16]	-	-	-	-	-	InP	InP	-	PIC
[17]	-	-	Si	Si	Si	Ge	-	-	PIC
[18]	InP	-	InP	InP	InP	InP	-	-	PIC
[19]	-	-	-	InP	InP	InP	-	-	PIC
[20]	-	-	-	-	InP	InP	?	-	Module
[21]	-	-	Bulk	Bulk	InP	InP	?	-	Module
[25]	-	-	Silica	Silica	Silica	InP	InP	-	Module

LO: Local oscillator
ADC: Analog-digital converter

of optical alignment of these approaches are attractive. However, a practical polarization beam splitter has not yet been achieved with InP waveguides. Monolithic approaches with silicon photonics are also attractive [17]. The coupling loss between optical fiber and silicon waveguides and dark current at photodiode seem to have room for improvement. We believe that PLC hybrid integration is a practical approach that exploits the most suitable devices and integrates them.

We have worked on integrated modulators and receivers utilizing PLC hybrid integration technology. This paper introduces our activities in relation to integrated devices for digital coherent transmission systems including PLC-LN hybrid modulators for advanced modulation formats, and integrated coherent receivers utilizing PLC hybrid integration with hermetically sealed O/E converters.

2 PLC-lithium niobate hybrid modulators

2.1 Basic concept

Figure 2 shows the basic structure of a PLC-LN hybrid integrated modulator. We use an LN chip with an array of simple straight phase modulators and PLCs that incorporate all the other circuit components, such as couplers and filters. This structure combines the large electro-optic bandwidth of LN and the excellent transparency and design flexibility of PLCs. Another merit is that this configuration is highly scalable because we can increase the level of integration by increasing the number of phase modulators in the LN chip and devising PLCs with corresponding complexity. As shown in Fig. 3, we

Fig. 2. Basic PLC-LN hybrid-integrated structure.

Fig. 3. PLC-LN hybrid modulators.

have developed various modulators with increasing levels of integration.

2.2 DP-QPSK modulator

The DP-QPSK modulator has the configuration shown in Fig. 4. Eight straight phase modulators with four high-speed signal electrodes in a Z-cut LN chip and thirteen couplers in PLCs make up two QPSK modulator circuits connected in parallel. In addition, a polarization multiplexing circuit, consisting of a polarization rotator with a half-wavelength plate (HWP), and a waveguide polarization beam combiner (PBC) are connected to their output. Figure 5 shows a photograph of this module. The module package is $118 \times 13.5 \times 7$ mm, and 131 mm long when including both side fiber boots, which approaches the smallest size ever reported.

Typical characteristics of a 100 Gbit/s DP-QPSK modulator are listed in Table II. The overall optical insertion loss is less than 9 dB at a wavelength of $1.55 \mu\text{m}$ including a polarization division intrinsic loss of 3 dB.

Fig. 4. Configuration of PLC-LN DP-QPSK modulator.

Fig. 5. Photograph of PLC-LN DP-QPSK modulator ($118 \times 16 \times 7$ mm)

Table II. Typical properties and target specifications of a 100 G PDM-QPSK modulator.

Parameter	Properties	Targets spec.
Insertion loss	8.7 dB	< 14 dB
PDL	0.1 dB	< 1.5 dB
Optical return loss	> 35 dB	> 30 dB
Extinction ratio; Parent MZI	> 46 dB	> 22 dB
Child MZI	> 25 dB	> 20 dB
Polarization extinction ratio	31 dB	> 20 dB
EO bandwidth	> 27 GHz	> 23 GHz
RF port $V\pi$ @ 32Gbaud	< 3.5 V	< 3.5 V

Fig. 6. Measured eye pattern.

The modulator has an electro-optic 3-dB bandwidth of > 27 GHz. The RF driving voltage was less than 3.5 V at 32 Gbit/s. Figure 6 shows the measured eye pattern for a driving voltage of 3.0 V. The modulator was driven with 32-Gbit/s non-return-zero $2^{31}-1$ pseudo-random bit sequences (PRBSs) in a back-to-back setup. Clear eye opening was obtained in this experiment. The OIF standardized a 100-Gbit/s integrated modulator in April 2010 [2]. Our DP-QPSK modulator complies with the target specifications suggested by the OIF.

2.3 64 QAM modulator

Figure 7 shows the configuration of a 64 QAM modulator [12, 22]. Three QPSK modulation circuits, each consisting of dual-parallel Mach-Zehnder modulators (MZMs), are connected in parallel by a pair of PLC asymmetric $1 \times 3/3 \times 1$ splitter/combiners, each with a power splitting/combining ratio

Fig. 7. Configuration of 64 QAM modulator.

Fig. 8. Constellations of 240 Gbit/s.

of 4:2:1. These asymmetric circuits are designed by using the wavefront matching method (WFM), with which we can optimize the waveguide pattern on the basis of the desired splitting/combining ratio. PLC variable optical attenuators (VOAs) enable us to fine tune the power ratio. The 64 QAM signal is synthesized by coupling three QPSK signals with a field-amplitude ratio of 4:2:1 (power ratio of 16:4:1). The module has a small overall optical insertion loss of 5.5 dB, as well as a broad electro-optic bandwidth of > 25 GHz.

By driving the modulator with six 20-Gbaud binary data signals and using an external DP circuit, we generated a 240-Gbit/s DP-64 QAM signal. The signal was received with a coherent receiver using a pilotless demodulation algorithm in an offline digital signal processor (DSP). Figure 8 shows constellations obtained with a back-to-back intradyne setup. The 64 signal points are clearly distinguished. The bit error rate was better than 1.3×10^{-2} .

2.4 Flexible-format modulator

The concept of a flexible optical network, in which various modulation formats are used flexibly to exploit spectral resources efficiently, has been the focus of attention in recent years [24]. We devised a flexible-format optical modulator with which we can select the optimum combinations of carrier number and modulation level according to the transmission conditions [14].

Figure 9 shows the configuration of a flexible-format optical modulator. The modulator circuit includes three tunable interleave filters (TILFs), eight parallel MZMs, two variable couplers (VCs), a polarization rotator with a HWP, and a waveguide PBC as shown in Fig. 9. TILFs and VCs are controlled with a PLC thermo-optic phase shifters. By tuning these TILFs and

Fig. 9. Configuration of a flexible-format optical modulator [14].

Fig. 10. Measured optical output spectra and constellations for 200-Gpbs operation in 4-carrier BPSK, 2-carrier QPSK, and 1-carrier 16-QAM modes.

VCs, we can flexibly change the combination of carrier number and modulation level according to the transmission conditions, such as the required transmission distance. Detailed principle is described in [14].

Figure 10 shows the measured optical output spectra and constellations of X-polarization signals. We also obtained the same clear constellation in Y-polarization signals. We demonstrated 4-carrier BPSK, 2-carrier QPSK, and 1-carrier 16-QAM operations, all with a bit rate of 200 Gbit/s and a symbol rate of 25 Gbaud, in total.

3 Integrated coherent receiver front-ends [25]

We have also worked on PLC hybrid integration technology to realize a coherent receiver front-end in a practical method. Figure 11 shows a schematic of our proposed configuration for an all-in-one DP-QPSK coherent receiver front-end. The receiver front-end consists of a PLC-based DPOH and a chip-scale packaged O/E converter (CSP-O/E) [26] with InP-based PDs and

Fig. 11. DP-QPSK coherent receiver configuration using one-chip DPOH with PBSs and 90°OHs, local hermetically sealed CSP-O/E with PDs and TIAs, and multi-channel micro collimator optics.

Fig. 12. (a) Temperature dependence and (b) wavelength dependence of PLC-based DPOH.

InP-based TIAs. Novel micro collimator optics was introduced to connect them optically.

The PLC-based DPOH is suitable for realizing stable and compact optical circuits for the coherent receiver. We modified the design of the DPOH for hybrid integration. The input signal is split into two orthogonal polarization components at a PBS, which consists of a symmetrical Mach Zehnder interferometer with polyimide quarter waveplates tilted at 0 and 90 degrees, respectively, inserted in the two arms. This configuration is highly symmetric and thus can suppress the temperature dependence of the polarization extinction ratio (PER). A polyimide half waveplate is inserted after one output port of the PBS to rotate the polarization. Figure 12 shows an example of the reported optical performance of the PLC-based DPOH for the coherent receiver. This DPOH exhibits a low phase deviation from 90 degrees of less than 3 degrees taking account of the temperature and wavelength dependence [27]. Furthermore, the high PER is better than 25 dB over the C-band. This PLC-based DPOH was fabricated with a refractive index difference of 1.5% and a core size of $4.5 \times 4.5 \mu\text{m}$ [27, 28]. The chip size is $22 \times 16 \text{ mm}$.

We developed a new compact O/E assembly structure suitable for micro collimator optics. To maintain the reliability of the PD and TIA, we developed the CSP-O/E shown in Fig. 13. The CSP-O/E consists of a very small ceramic package with heatsink and a window in which the PD array chip [29] and the TIA array chip [30] are hermetically sealed. The signal output of the ceramic package has a 3-dB bandwidth of over 40 GHz, which is wide enough to handle 32-Gbaud electrical signals from the TIA. The CSP-O/E size is $9.2 \times 8.2 \times 1.4 \text{ mm}$. A flexible print circuit (FPC) with DC block capacitors is attached to the CSP-O/E. In the -5 to 80°C temperature range, we expect the relative positions of the DPOH and the PDs in CSP-O/E to vary by around $\pm 5 \mu\text{m}$ in the X and Y directions. This variation may cause an optical coupling variation, which will result in a PD responsivity imbalance. Therefore, the optical connection between the DPOH and the CSP-O/E requires microminiaturized optics with a low loss and a wide coupling tolerance.

For this purpose, we introduced multi-channel micro collimator optics as shown in Fig. 13. The collimator optics with 45° mirrors consists of a 1st

Fig. 13. Cross-sectional view of integration structure.

Fig. 14. Photograph of fabricated all-in-one DP-QPSK coherent receiver. Module size is $50 \times 27 \times 6$ mm.

lens array attached to a PLC and a 2nd lens array attached to the window of the CSP-O/E. We designed the collimation path via the mirror to be 2.5 mm long. The lens array is composed of graded index (GRIN) optical fibers. We measured the coupling tolerance between the PLC waveguide and a PD with a diameter of $19 \mu\text{m}$, and confirmed that the micro collimator optics had a very wide tolerance of over $\pm 10 \mu\text{m}$ at a 0.2-dB down width. This result shows that the micro optics has sufficient tolerance to allow a coupling deviation caused by a temperature change. The photograph in Fig. 14 shows a fabricated DP-QPSK coherent receiver front-end. Two CSP-O/Es are optically aligned with the PLC through the micro collimator optics. The module size is $27 \text{ mm} \times 50 \text{ mm} \times 6 \text{ mm}$.

Figure 15 shows the responsivity of the receiver. The responsivity includes the DPOH insertion loss of 10.8 dB of which the inherent splitting loss is 9 dB. The excess loss of the micro collimator optics is around 0.4 dB, and the responsivity imbalance between adjacent PDs is less than 0.4 dB. Figure 15 (b) shows the responsivity variation in an environmental temperature range of -5 to 80°C . We confirmed a variation of less than $\pm 0.25 \text{ dB}$ for all PD

Fig. 15. Optical characteristics of receiver module (a) PD responsivity including the PLC-based DPOH. (b) PD responsivity deviation against temperature change of -5°C to 80°C . The deviation is within ± 0.25 dB.

Fig. 16. Measured constellation diagrams at 112-Gbit/s DP-QPSK back-to-back detection.

channels. These results show that the micro optics have a stable structure in practical use, because a responsivity variation of less than 0.8 dB between PDs is required for 100-Gbit/s DP-QPSK signal detection when we assume a skew of ± 1 ps.

We evaluated the performance of the receiver with 112 Gbit/s DP-QPSK (28-Gbaud $\times$ 2-digit $\times$ 2-polarizations) signals. Figure 16 shows the resulting constellation diagrams under a back-to-back condition at a signal light power of -10 dBm and a local light power of 4 dBm. A good separated constellation was observed for both polarization channels.

4 Conclusion

We have developed highly functional modulators and a compact integrated optical front-end utilizing PLC hybrid integration technology for 100 Gbit/s and post-100 Gbit/s coherent transmission systems. We have successfully demonstrated a DP-QPSK modulator by using PLC-LN integration technology. This technology is also scalable toward beyond 100 Gbit/s, including 64 QAM modulators and OFDM modulator. Furthermore we have successfully demonstrated flexible modulators with which we can select the optimum

combination of carrier number and modulation level for future efficient flexible networks. In terms of receivers, we have successfully demonstrated an integrated optical front-end for 100 Gbit/s DP-QPSK by using our newly developed silica-based PLC hybrid integration technologies with multi-channel micro collimator optics and hermetically sealed O/E converters. PLC integration technologies can be applied to compact, cost-effective, and highly reliable coherent optical modulators and receivers.

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