Silica-Based PLC with Heterogeneously-Integrated PDs for One-Chip DP-QPSK Receiver

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Abstract We fabricated a DP-QPSK receiver PLC by the heterogeneous integration of eight high-speed PDs on a compact silica-based PLC platform with a PBS, 90-degree optical hybrids and a VOA. 32 Gbaud DP-QPSK signal demodulation was successfully demonstrated.

Introduction

With advanced formats such as dual polarization quadrature phase shift keying (DP-QPSK) and quadrature amplitude modulation (QAM) there is a strong need for an integrated coherent receiver. This is because the receiver is composed of plural optical passive circuits that control polarization and phase, such as a polarization beam splitter (PBS) and a 90-degree optical hybrid (OH), and a high-speed photodiode (PD) array to detect the signal. Compact integrated receivers based on InP- and Si-based photonic integrated circuits (PICs) have already been reported\(^1\),\(^2\). However, the PIC performance including the passive/active components should be further improved for practical applications.

We recently demonstrated the heterogeneous integration of a silica-based planar lightwave circuit (PLC) and a high-speed InP PD\(^3\). Unlike the widely used hybrid integration approach\(^4\), these PDs were monolithically fabricated on a PLC using a photolithographic process. Micro mirrors were also integrated on the PLC to provide optical coupling between the waveguides and the PDs. Thus low-loss optical coupling is easily realized without any complicated optical alignment or micro lenses. However, in the previous study we demonstrated the integration of only four PDs with a single OH. And so, heterogeneous integration on a silica-based PLC has the potential to realize a more integrated receiver.

Here, we demonstrate the integration of a PBS, two OHs, a VOA, eight PDs and a monitor PD in 1-chip for DP-QPSK demodulation. The nine PDs and the micro mirrors are fabricated by using the heterogeneous integration technique. To achieve a small integrated PLC, we employ a PLC based on 2.5%-\(\Delta\) waveguides with a minimum bending radius of 1 mm. The PLC chip is 11 mm x 11 mm, which is half the size of a conventional PLC-type PBS-integrated OH\(^5\). We employ the VOA to expand the input power dynamic range of the receiver PLC. We demonstrate 32 Gbaud QPSK signal demodulation at various input optical powers and the attenuation level of the integrated VOA.

Concept of a heterogeneously integrated DP-QPSK receiver PLC and its characterization

Figure 1 shows the schematic configuration of a heterogeneous integrated DP-QPSK receiver PLC. The VOA driven by the thermo optic effect is composed of a Mach-Zehnder interferometer (MZI) and thin film heaters. The PBS is also composed of an MZI and two polyimide quarter waveplates. The waveplates were tilted at 0 degrees and 90 degrees and inserted in both arms of the MZI\(^5\). The signal and local lights are mixed at the 90-degree OHs. The interference signals from the OHs are reflected into the PDs by the micro mirrors. The attenuation of the VOA is controlled by monitoring the input power with the monitor PD, which was fabricated at the same time as the other eight PDs. The optical tap ratio to the monitor port is 10%.

Figure 2(a) shows an integrated receiver chip based on a PLC. Using a PLC technology based on 2.5%-\(\Delta\) waveguides, a PBS, two OHs, and a VOA are integrated into a compact chip with a size of 11 mm x 11 mm. In addition, eight PDs...
and a monitor PD are also fabricated on the PLC without any increase in the chip size owing to the heterogeneous integration. Figure 2(b) shows the PD integration area. The PDs located at the chip edge are uniformly fabricated using a photolithographic process. The PD pitch is set at 300 μm corresponding to the electrode pitch of a transimpedance amplifier (TIA). The PD chip edge location enables us to connect PDs and TIA within a short distance, which is necessary for high-speed signal transmission. The mirror angle is set at 58 degrees to increase return loss. The diameter of the reflected beam expands to only 10 μm at the PD detection region with a diameter of 19 μm. Therefore, highly efficient and compact optical coupling can be obtained without any optical lenses.

Figure 3 shows the polarization extinction ratio (PER) of the PBS. A PER of >20 dB over the C-band for the TE and TM ports is confirmed. Figure 4 shows the phase differences between the I and Q channels of the positive and negative outputs. To measure the phase error, we attached an extra delay line circuit and a Y-branch splitter in front of the input ports, and estimated the phase error from the transmission spectra. The estimated phase deviations from 90 degrees were less than 3 degrees. Figure 5 shows the VOA attenuation characteristics and the polarization dependent loss (PDL). These results were obtained with a test sample to estimate characteristics of the VOA integrated in the receiver PLC. 10 dB attenuation was obtained at 420 mW, while the PDL was less than 2 dB.

Next, we measured the responsivities of PDs integrated on a PLC at a wavelength of 1.55 μm (Fig. 6). The measured fiber-to-PD responsivities were around 0.015 A/W for the signal input. The relatively small responsivities compared with the PD responsivity of 0.9 A/W were due to the large insertion loss of 17.8 dB. This comprises a splitting loss of 6 dB, a fiber-to-PLC coupling loss of 0.5 dB, a PLC-to-PD coupling loss of 0.9 dB and an excess loss of 10.4 dB. This excess loss is larger than a designed value of 6 dB, mainly due to the imperfect design parameters of the 2.5%−Δ PLC, so there is the potential for improvement. A PER of about 20 dB was confirmed for both polarizations, which indicates good PBS performance. We also measured the frequency response of the PD integrated on the PLC at a bias voltage of 3.5 V. We obtained a high-speed...
OE response with a 3 dB bandwidth of over 25 GHz resulting from the Mic-PD design.

**Demonstration of 32 Gbaud DP-QPSK signal demodulation using the integrated receiver PLC**

Figure 7 shows the measurement setup we used to demonstrate 32 Gbaud DP-QPSK signal demodulation. Two tunable laser arrays (TLAs) are used as a signal and a local oscillator. The signal was modulated with a pseudorandom binary sequence (PRBS) of $2^{15}-1$. The local oscillator power was set at +16 dBm. A clear constellation was confirmed by off-line digital signal processing, as shown in Fig. 8(a). To evaluate the advantage of VOA operation, we measured the Q values at an input power of over -3 dBm. As the input power increased from -3 to +7 dBm, we adjusted the attenuation level from 0 to 10 dB, so that the effective signal input power maintained a constant value of -3 dBm. Figure 8(b) shows the OSNR dependence of the Q value. A Q value of around 9.1 dB was successfully obtained at an OSNR of 16 dB. Moreover, the change in the Q value was small irrespective of the VOA attenuation level. This result proves that VOA integration on a small-sized PLC has the potential to improve the input power dynamic range of an integrated receiver for future photonic networks.

**Conclusions**

We demonstrated the 1-chip DP-QPSK receiver PLC integrated with a PBS, two OHs, a VOA, eight PDs and a monitor PD on a silica-based PLC platform. Using heterogeneous integration technology, high-speed InP PDs were integrated without using a lens, and uniform responsivities were obtained. Thanks to a polarization extinction ratio of over 20 dB at the PBS and phase deviations of less than 3 degrees from 90 degrees at the OHs, 32 Gbaud DP-QPSK signal demodulation was successfully demonstrated.

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**References**

[1] R. Kunkel et al., Proc. IPRM’2009, TuB2.2.
[2] C. R. Doerr et al., Proc. OFC’2009, PDPB2.
[3] Y. Kurata et al., Proc. ECOC’2011, Th.12.LeSaleve.5.
[4] T. Ohyama et al., Proc. OECC’2010, PD6.
[5] Y. Nasu et al., Proc. ECOC’2011, Tu.3.LaSaleve.4.
[6] T. Yoshimatsu et al., Electron. Lett. 46(13), 941–943 (2010).