Low-Cost Coherent UDWDM-PON by Hybrid DBPSK/ASK-2 Modulation

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Abstract—The coherent ultra-dense wavelength division multiplexed passive optical network (UDWDM-PON) has been widely studied recently, in which the envelop detection based coherent reception of on-off keying (OOK) signal has been shown to possess both high receiver sensitivity and tolerance against laser linewidth/chirp. In order to increase the spectral efficiency (SE) to 2 bit/s/Hz, researchers formulated a hybrid DBPSK/ASK-2 modulation using the silicon Mach-Zehnder modulator (MZM), where both amplitude and phase modulation are employed. The experimental result shows that the proposed DBPSK/ASK-2 modulation is of better performance than PAM-4 at the same SE of 2 bit/s/Hz. When the low-cost silicon MZM and DFB laser of 4-MHz linewidth are employed, the receiver sensitivity of DBPSK/ASK-2 exceeds that of the PAM-4 by about 5.7dB. We can achieve about -46dBm receiver sensitivity at 2.5 GBaud after transmission over 80-km standard single mode fiber (SSMF). The proposed DBPSK/ASK-2 modulation using low-cost silicon MZM and DFB laser is considered as a practical and reliable method for the future UDWDM-PON at the SE of 2 bit/s/Hz.

Index Terms—UDWDM-PON, Coherent Detection, DBPSK, ASK.

I. INTRODUCTION

THE coherent ultra-dense wavelength division multiplexed passive optical network (UDWDM-PON) has been extensively investigated due to the fact that coherent detection of the system may be deployed to avoid using costly AWGs within the network. This merit can be achieved by providing wavelength selectivity and enhanced power budget [1-2]. The question of how to reduce the cost of the coherent optical network units (ONUs) has been a critical issue in the study of UDWDM-PON. Ivan N. Cano et al. have demonstrated the feasibility of 1.25-Gb/s coherent UDWDM-PON with cost-effective direct phase-modulated DFB laser and DBPSK modulation. About -49dBm receiver sensitivity is achieved using balanced heterodyne receiver [3]. M. Presi et al. also demonstrated the feasibility of an ultra low-cost coherent UDWDM-PON using the 3x3 optical hybrids and DFB laser as local oscillator (LO), where -48dBm receiver sensitivity is achieved with 1.25-Gb/s OOK signal [4]. Both DBPSK and OOK modulation show high tolerance against laser linewidth and high receiver sensitivity for coherent UDWDM-PON based on simplified coherent structure.

In order to increase the accessing speed in each UDWDM channel to a greater extent, spectral efficiency (SE) of 2bit/s/Hz is required. Other researchers have considered and demonstrated the merits of PAM-4 format using both direct-modulated VCSELs [5] and external modulation based on Mach-Zehnder modulator (MZM) as one of the solutions [6]. However, when taking the advantages of silicon photonics technology into consideration, the external modulation based on silicon MZM is thought to be promising due to its nature of low-cost, high reliability, and high density integration by CMOS fabrication processes [7]. In this paper, we propose a hybrid DBPSK/ASK-2 modulation based on the silicon MZM. At the SE of 2bit/s/Hz, experimental results have shown that the proposed DBPSK/ASK-2 modulation can obtain a better performance than the PAM-4 modulation in both optical signal to noise ratio (OSNR) and receiver sensitivity. We also demonstrate an ultra low-cost UDWDM-PON using the silicon MZM and DFB laser of 4-MHz line width in experiments. We have achieved a receiver sensitivity of about -46 dBm at the BER threshold of 3.8×10^{-3} when a 2.5-GBaud and (5-Gb/s) upstream was transmitted over 80-km SSMF.

II. HYBRID DBPSK/ASK-2 MODULATION

Fig. 1 Modulation principle of PAM-4 based on external intensity modulation using MZM and digital signal processing for the recovery of signal

Figure 1 illustrates the modulation principle of PAM-4 signal based on external intensity modulation using MZM and the digital signal processing (DSP) for the recovery of PAM-4 signal. The spectral efficiency of PAM-4 signal is 2bit/s/Hz, while the constellation takes only intensity domain in the I-branch. The bias of MZM should be set to the linear region. For the receiver DSP, the envelop detection is applied before a FIR filter with cascaded multiple modulus algorithm (CMMMA) [8]. In the last step, the recovered PAM-4 signal is de-mapped and the BER is calculated.

Fig. 2 Principle of encoding, modulation and recovery for the proposed DBPSK/ASK-2 signal using MZM.

As demonstrated in Fig. 2, the proposed DBPSK/ASK-2 modulation includes both amplitude and phase modulation. There are 2 bits encoded in each symbol: one for DBPSK encoding, while the other for ASK-2 encoding. The best alternative amplitudes for ASK-2 should be conformed to $A_1 = 3 \cdot A_2$. The bias of MZM is set at the null point. Firstly, the received complex signal ($I+j \cdot Q$) is equalized by a FIR filter with CMMMA. Then, the phase and amplitude are extracted respectively for DBPSK and ASK-2 decoding. Please be aware that the polarization division multiplexing (PDM) can also be supported by extending the FIR filter to 2×2 MIMO [9]. The ASK modulation with coherent envelop detection has been shown extremely robust to laser linewidth [4-6]. DBPSK format has also been demonstrated by a low cost DFB laser [3]. Due to the own characteristics of MZM, both DBPSK and ASK can be done at the same time. On the other side, thanks to the introducing of DBPSK modulation, the optical carrier can be extremely suppressed. Thus, the OSNR/sensitivity performance can be greatly improved due to the lower optical carrier power, which has also been demonstrated in [11].

III. EXPERIMENTAL SETUP

Fig. 3 shows the experimental setup for the upstream transmission of 2.5-GBaud hybrid DBPSK/ASK-2 signal over 80-km SSMF. At the optical network unit (ONU), a DFB laser with 10-dBm output power of 4-MHz linewidth was used as the optical source. An arbitrary waveform generator (AWG) of 2.5-GS/s sampling rate generated the proposed hybrid DBPSK/ASK-2 signal. We used a low-cost single push-pull silicon MZM as the optical modulator, whose PN junction position and doping concentration was carefully optimized. The on-chip insert loss of silicon MZM was 4 dB. This value can increase up to 5.7-dB extinction ratio (ER), when driven directly by the AWG with 1-V peak-to-peak voltage (VPP). The inset of Fig. 3 shows the diagram of the silicon MZM with corresponding eye diagram driven at 1-V VPP. In order to compare the value, we also conducted a 2.5-GBaud transmission of PAM-4 signal in the upstream direction. Fig. 3(a) and Fig. 3(b) demonstrate the received spectrum of proposed DBPSK/ASK-2 and PAM-4 respectively.

Fig. 3. Experimental setup for the upstream transmission of 2.5-GBaud hybrid DBPSK/ASK-2 signal over 80-km SSMF, (a) received spectrum of the proposed DBPSK/ASK-2 signal, (b) received spectrum of the PAM-4 signal, both at 10dB/div in the vertical coordinate.

After the transmission over 80-km SSMF, a variable optical attenuator (VOA) was used to emulate the power splitter, which can also dynamically adjust the link power budget. A polarization controller (PC) was used before the integrated coherent receiver (ICR) in order to align the input polarization states. Other researches have demonstrated that the PC can be removed by introducing polarization diversity technology [6,10]. The output of the ICR was digitally sampled by an oscilloscope at 50-GS/s sampling rate, before being processed in a MATLAB program offline. The offline processing includes frequency down conversion, digital low pass filtering, resampling to 2 samples per symbol, channel equalization, DBPSK/ASK-2 signal decoding and BER calculation.

IV. RESULTS AND DISCUSSIONS

Fig. 4 OSNR versus BER performance for the proposed DBPSK/ASK-2 modulation, using both ECL and DFB, respectively

In order to evaluate the performance of proposed DBPSK/ASK-2 modulation, especially the tolerance against laser's linewidth, we conducted a contrast experiment by replacing the DFB laser with an ECL of 100-kHz linewidth. Fig. 4 illustrates the OSNR versus BER performance for the proposed DBPSK/ASK-2 modulation, using both ECL and DFB. At the 7% FEC threshold ($BER=3.8 \times 10^{-3}$), only 0.2-dB OSNR penalty was observed for the DFB laser (compared to ECL), which shows the robustness of DBPSK/ASK-2 modulation against laser's linewidth.

Fig. 5 OSNR versus BER performance for both DBPSK/ASK-2 and PAM-4 modulation based on silicon MZM.

We also conduct a 2.5-Gbaud transmission of PAM-4 signal in the upstream based on the same MZM for comparison. Fig. 5 shows the OSNR performance for both modulation formats. At the 7% FEC threshold, the required OSNR was 3.7 dB and 8.7 dB for 2.5-Gbaud DBPSK/ASK-2 and 2.5-Gbaud PAM-4 respectively. At the same SE of 2-b/s/Hz, the proposed hybrid DBPSK/ASK-2 modulation shows an improvement of 5-dB OSNR over PAM-4 for the BER threshold of 3.8×10^{-3} .

Fig. 6 Receiver sensitivity for both hybrid DBPSK/ASK-2 and PAM-4, measured at back to back

We also investigated the receiver sensitivity for both hybrid DBPSK/ASK-2 and PAM-4, as shown in Fig. 6. The receiver sensitivity of hybrid DBPSK/ASK-2 modulation was about -46.2 dBm, while that of PAM-4 modulation was -40.5 dBm after we set the 7% FEC threshold. About 5.7-dB improvement of receiver sensitivity could be achieved by the proposed method. Since the optical components used in OLT and ONU may be different due to the cost issue, the loss budget may differ slightly. There is no optical amplifier used in ONU, the maximum launch power is supposed to be 0 dBm, so the loss budget should be around 46dB.

In the last step, we would like to demonstrate the feasibility of proposed method for long reach PON (LR-PON) with the transmission of signals over 80-km SSMF. As shown in Fig. 7, the receiver sensitivity penalty of 80-km SSMF was lower than that of back to back, with only 0.4-dB was found for 80-km SSMF.

Fig. 7 Receiver sensitivity of DBPSK/ASK-2 for both back to back (B2B) and transmission over 80-km SSMF

V. CONCLUSIONS

We devise and develop an ultra low-cost UDWDM-PON using silicon MZM based DBPSK/ASK-2 modulation. It can be seen clearly from the experimental results that proposed DBPSK/ASK-2 modulation performs considerably better than PAM-4 at the same spectral efficiency of 2bit/s/Hz. Using the low cost silicon MZM and DFB lasers of 4-MHz linewidth, the receiver sensitivity of DBPSK/ASK-2 leads the PAM-4 format by about 5.7 dB. About -46 dBm receiver sensitivity is gained at 2.5 GBaud after transmission over 80-km SSMF. We believe that this character shows considerable potential for the future ultra low-cost UDWDM-PON at a spectral efficiency of 2 bit/s/Hz.

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