A New Remodulation Scheme for WDM-PONs With Enhanced Tolerance to Chromatic Dispersion and Remodulation Misalignment

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***Abstract*—We investigate the use of differential phase-shift keying (DPSK) with a reduced modulation depth (RMD) as the downstream modulation format to enhance the tolerance to both chromatic dispersion and remodulation timing misalignment. Despite the RMD, in each optical network unit the demodulated DPSK signal from the destructive port of the delay-interferometer still maintains a high extinction ratio (ER), whereas the signal from the constructive port has a very low ER and can be readily remodulated by the upstream signal. Error-free operation at 10 Gb/s was achieved in a 20-km-reach experiment without dispersion compensation and remodulation synchronization.**

***Index Terms*—Differential phase-shift keying (DPSK), modulation depth, wavelength-division-multiplexed passive optical network (WDM-PON).**

I. Introduction

THE wavelength-division-multiplexed passive optical network (WDM-PON) is a promising technology for the next-generation access networks, due to its large bandwidth and upgrade flexibility [1]. Centralized light source (CLS) at the central office (CO) is an attractive solution for low-cost implementation of WDM-PON, as it eliminates the need of wavelength-specific transmitters and wavelength management at the optical network units (ONUs). In the existing CLS schemes, one straightforward approach is to distribute the upstream optical carriers from hithe CO to ONUs. Remodulation of downstream signal to generate the upstream signal can further save the wavelengths and light sources by wavelength reuse. Several remodulation schemes that support 10-Gb/s operation have been proposed, including downstream differential phase-shift keying (DPSK) and upstream on–off keying (OOK), downstream frequency shift keying and upstream OOK, downstream inverse return-to-zero and upstream OOK, and downstream DPSK and upstream DPSK [2]–[5]. However, these schemes have the disadvantages of either poor chromatic dispersion (CD) tolerance for 10-Gb/s upstream transmission or the need of synchronization for remodulation. In practice, it is highly desirable to operate a robust WDM-PON without CD compensation and remodulation synchronization at each ONU, thus reducing the implementation complexity and system cost. For this purpose, one scheme using low-extinction-ratio (ER) OOK downstream and DPSK upstream has been proposed [6]. However, expensive balanced detectors are required at the optical line terminal (OLT).

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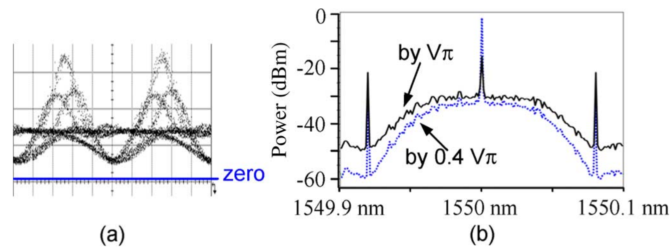

Fig. 1. (a) Eye diagram of the 10-Gb/s FMD-DPSK signal after transmission in 20-km SMF without demodulation by DI. Time scale: 20 ps/div. (b) Spectrum comparison between two DPSK signals with different driving voltages (raised-cosine driving signal is assumed).

In this letter, we propose a novel remodulation scheme using downstream DPSK, with a reduced modulation depth (RMD), and upstream OOK to enhance the tolerance to CD for upstream signal and the tolerance to remodulation timing misalignment. Despite the use of RMD-DPSK for downstream transmission, in each ONU the demodulated RMD-DPSK signal from the destructive port of the delay-interferometer (DI) can still achieve a high ER, whereas the constructive port output has a very low ER and can be employed as the source for upstream remodulation. Compared to prior remodulation schemes, the ONU structure is further simplified, as the power splitter is eliminated and the DI is used for both downstream signal demodulation and the separation of the downstream/upstream signals. As RMD-DPSK requires a smaller driving voltage, a lower cost driver for the phase modulation can be used.

II. Principle and System Architecture

For the conventional scheme using downstream DPSK with full modulation depth (FMD) and upstream OOK, the inferior tolerance to CD and remodulation misalignment might not be intuitive. The constant-intensity nature of the DPSK modulation format reduces various nonlinear phenomena during transmission and greatly facilitates the remodulation by the upstream OOK signal. However, such constant intensity is distorted during transmission due to CD. Fig. 1(a) shows the severe intensity fluctuation of a traditional 10-Gb/s DPSK signal with FMD after 20-km transmission in single-mode fiber (SMF) without demodulation by DI. Due to such periodic intensity variation, rigorous timing alignment at the ONU is

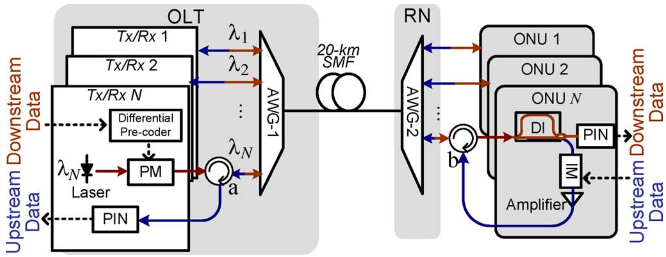

Fig. 2. Proposed remodulation architecture using downstream RMD-DPSK and upstream OOK. Tx/R: transceiver.

required for OOK remodulation. The upstream OOK signal also suffers substantial power penalty [6]. By reducing the modulation depth of the downstream DPSK signal, the optical power will be shifted from sidebands to the central carrier tone, as shown in Fig. 1(b) by simulation. Here we propose to use the DI's destructive port to demodulate the downstream RMD-DPSK signal, whereas the DI's constructive port is used to filter out the carrier tone as the source for remodulation. Thus, the tolerance to CD and remodulation misalignment for upstream signal can be significantly enhanced, compared with prior schemes using part of the FMD-DPSK signal, with relatively wide spectrum, as the source for remodulation [6].

One issue is the possible ER degradation of the demodulated signal caused by the modulation depth reduction. The ER degradation actually depends on which port of the DI is used for the DPSK demodulation. For the destructive port, the demodulated “0” is the same as that in the case of FMD, as “0” denotes that the adjacent bits have the same phase, disregarding the specific phase values of the adjacent bits. Thus, the ER of the demodulated RMD-DPSK signal from the destructive port, theoretically, is independent of the phase modulation depth and is always infinite, as the demodulated “0” of the RMD-DPSK signal is perfectly null. On the contrary, the ER of the output signal from the constructive port is substantially reduced, which greatly facilitates upstream remodulation.

Fig. 2 illustrates the proposed remodulation architecture for a WDM-PON using downstream RMD-DPSK and upstream OOK. For each downstream wavelength at the OLT, differentially precoded data with low driving voltage is used to drive an optical phase modulator (PM) to generate the downstream RMD-DPSK signal. After transmission, at the ONU the downstream RMD-DPSK signal is demodulated from the destructive port of the DI before direct detection, while light from the constructive port is fed into an optical intensity modulator (IM) for upstream data remodulation.

III. Experiment Demonstration

We have experimentally demonstrated the proposed remodulation scheme based on the setup shown in Fig. 2. At the OLT, continuous-wave (CW) lights at 1549.3 and 1550.1 nm were coupled into a PM driven by a 10-Gb/s $2^{31}-1$ pseudorandom binary sequence (PRBS) with the driving voltage of $\sim$0.4 $V\pi$. The partially phase-modulated output was then amplified to 6 dBm per channel and was coupled into a 20-km SMF. At the remote node (RN), an arrayed waveguide grating (AWG) with a channel spacing of 0.8 nm and a 3-dB bandwidth of 0.35 nm was used to separate the two channels. The 1549.3-nm channel was input into a DI with 94-ps relative delay. The demodulated downstream data from the destructive port of the DI was then directly detected by a 10-Gb/s p-i-n receiver. Light from the constructive port was combined with the 1550.1-nm channel from the AWG via a 3-dB coupler and then fed into an optical IM, driven by a 10-Gb/s $2^{31}-1$ PRBS as the upstream data. The two channels were modulated by the same IM at the ONU and the same PM at the OLT due to equipment availability. To investigate the enhanced tolerance of the proposed remodulation scheme to CD and remodulation timing misalignment, first the effect from Rayleigh backscattering was isolated by using another piece of 20-km SMF for upstream transmission. At the OLT, another AWG with the same parameter was used to route the upstream channel at 1549.3 nm to a 10-Gb/s p-intrinsic-n (PIN) receiver for direct detection and performance measurement. Then the 1550.1-nm channel was evaluated similarly.

As the two WDM channels had very similar performance, only the eye diagrams and bit-error-rate (BER) measurements for the 1549.3-nm channel are shown. Although the driving voltage of the PM was as low as 0.4 $V\pi$, the eye of the demodulated DPSK signal from the destructive port of the DI was still wide-open, with a measured ER of 13.6 dB, as shown in the inset of Fig. 3(a). Meanwhile, the constructive port output had an ER as low as 1.9 dB, ready for upstream remodulation with enhanced tolerance to remodulation timing misalignment.

The BER measurement results for both down- and up-stream signals (with optimal remodulation synchronization) are shown in Fig. 3(a). After 20-km SMF transmission, the CD caused power penalty was $\sim$0.4 and $\sim$1 dB for the downstream RMD-DPSK signal and the upstream OOK signal, respectively. The BER curve for FMD-DPSK signals is also shown in Fig. 3(a). In the back-to-back (B2B) case, compared with the FMD-DPSK signal, the modulation depth reduction impaired the receiver sensitivity (at BER of 10^{-9}) by only around 1 dB, due to the high ER of the demodulated RMD-DPSK signal. After 20-km SMF transmission, the sensitivity difference between the RMD-DPSK and FMD-DPSK signals was further reduced to 0.2 dB. We should mention that compared to FMD-DPSK, the RMD-DPSK signal can tolerate less phase error in the DI, because the phase shift between different symbols is 0.4π instead of π. We measured the tolerance (for 1-dB power penalty at BER of 10^{-9}) of both FMD-DPSK and RMD-DPSK signals to the frequency offset between the laser source and the DI. Compared to the FMD-DPSK signal, the RMD-DPSK signal was more sensitive to frequency offset by a factor of 3.5. To investigate the tolerance to remodulation timing misalignment, we have deliberately adjusted the remodulation synchronization through an electronic delay within one bit period. Less than 1-dB power penalty was observed. The eye diagram corresponding to the worst remodulation synchronization (50-ps misalignment) is also shown in the inset of Fig. 3(a), with only slight distortion compared with the eye with optimal remodulation synchronization.

We then demonstrated the proposed remodulation scheme based on the setup in Fig. 2, using more practical, single-fiber configuration. At the OLT, CW light at 1547.8 nm was fed into a PM driven by a 10-Gb/s $2^{31}-1$ PRBS with the driving voltage of $\sim$0.4 $V\pi$. The RMD-DPSK signal was fed into AWG-1 ($\sim$4-dB loss) at the OLT through circulator-a. The output from AWG-1 was amplified to 5 dBm before feeding

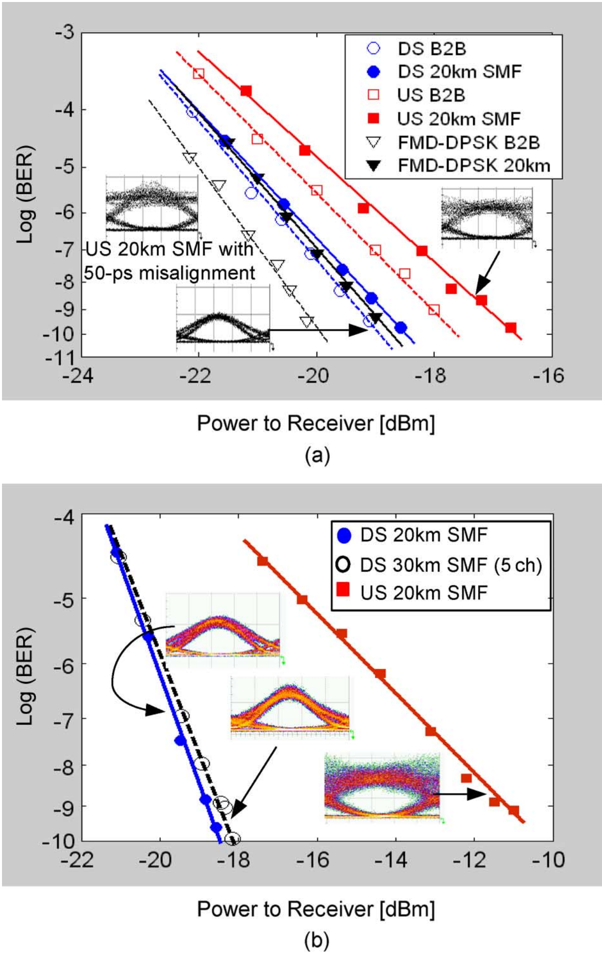

Fig. 3. BER measurements of both downstream (DS) and upstream (US) signals (a) using dual-fiber configuration, (b) using single-fiber configuration. Inset: corresponding eye diagrams for different cases. Time scale: 20 ps/div; ch: channel.

into a 20-km SMF (∼4-dB loss). After propagating through AWG-2 (∼4-dB loss) at the RN and circulator-b (∼0.6-dB loss), −3.6-dBm optical power was fed into the DI at ONU. The output power from the destructive port of the DI was −13.9 dBm and was detected for downstream signal. Optical power of −4.9-dBm from the constructive port of the DI was fed into a Mach–Zehnder IM driven by a 10-Gb/s $2^{31}-1$ PRBS as the upstream data. The signal with a power of −13.3 dBm from the IM was amplified to 5.2 dBm, and then transmitted back to the OLT with −8-dBm received power by the receiver. The amplification increased the power ratio of the upstream signal to the Rayleigh backscattered signal [7]. For practical implementation, the Mach–Zehnder IM and the optical amplifier in this proof of concept experiment can be replaced by an electro-absorption modulator integrated with a semiconductor optical amplifier for 10-Gb/s polarization-insensitive operation [8]. The BER measurement results and the corresponding eye diagrams for single-fiber configuration are shown in Fig. 3(b). Rayleigh backscattering induced around 5-dB power penalty for the upstream signal. The receiver sensitivity at BER of 10^{-9} for the upstream signal was −11.3 dBm, implying a 2.4-dB margin even for the worst remodulation synchronization (0.9-dB power penalty at BER of 10^{-9}). Negligible power penalty induced by Rayleigh backscattering was observed for the downstream signal. The receiver sensitivity at BER of 10^{-9} for the downstream signal was −18.8 dBm, implying a 4.9-dB margin.

It is worth mentioning that using downstream RMD-DPSK makes it possible to launch higher optical power to increase the maximum reach of PON, thanks to its nearly constant power [5]. To investigate the tolerance of the proposed scheme to nonlinear distortion, five downstream RMD-DPSK channels at the wavelength from 1546.2 to 1549.4 nm, spaced by 0.8 nm, were first multiplexed by AWG-1 into 10-km SMF to decorrelate each channel. Then after being amplified to 13 dBm (around 6 dBm per channel), the decorrelated signals are fed into 20-km SMF. Negligible nonlinear distortion was observed for all the five demodulated channels at the ONU. For the middle channel at 1547.8 nm, the BER measurement result as well as its eye diagram is shown in Fig. 3(b). Simulation investigation for 16 downstream RMD-DPSK channels was also conducted, showing the same results.

IV. Conclusion

We have proposed a novel remodulation scheme for WDM-PONs using downstream DPSK with an RMD and upstream OOK to enhance system tolerance to CD and remodulation misalignment. Error-free operation of both down- and up-stream signals, at 10 Gb/s without remodulation synchronization, are achieved after the transmission of 20-km SMF. In addition to the robustness to CD and remodulation misalignment, the proposed scheme also features simple ONU structure and lower driving voltage for phase modulation.

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