Wavelength Remodulation Using DPSK Down-and-Upstream With High Extinction Ratio for 10-Gb/s DWDM-Passive Optical Networks

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***Abstract*—We propose and demonstrate a novel wavelength remodulation scheme using differential phase-shift keying (DPSK) modulation format in both downstream and upstream signals for "colorless" dense wavelength-division-multiplexed (DWDM) passive optical networks (PONs). The scheme enables high extinction ratio in both downstream and upstream remodulated signals. Error-free operation was achieved in a 20-km-reach 10-Gb/s DWDM-PON without dispersion compensation. Timing misalignment tolerance between downstream and upstream remodulated signals and maximum launched optical power for the proposed scheme are studied. Comparison with other wavelength remodulation schemes for DWDM-PONs is also performed, showing the proposed scheme can be a potential candidate for next-generation wavelength reuse DWDM-PONs.**

***Index Terms*—Differential phase-shift keying (DPSK), passive optical networks (PONs), wavelength remodulation.**

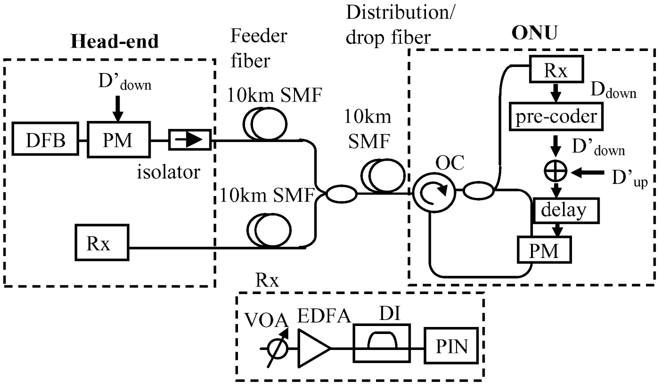

Fig. 1. Experimental setup of DWDM-PON using DPSK in downstream and upstream signals. VOA: variable optical attenuator; EDFA: erbium-doped fiber amplifier; DI: delayed interferometer. Inset: optical preamplified Rx.

I. INTRODUCTION

DENSE wavelength-division-multiplexed (DWDM) passive optical networks (PONs) offer a potentially cost-effective way of increasing individual customer bandwidths through increased use of the wavelength domain [1]. One great challenge in these DWDM-PONs is the transmitter at the optical networking units (ONUs), located in the customer premises, which must have a wavelength that is precisely aligned with a specifically allocated DWDM grid wavelength. A cost-effective solution would ideally employ the same components in each ONU, which should thus be independent of the wavelength ("colorless") assigned by the network. Optical carriers are distributed from head-end office to different ONUs to produce the upstream signals. Remodulation of downstream signal to generate upstream signal further reduces the cost by wavelength reuse. Several remodulation schemes have been proposed, including using both downstream and upstream on-off keying (OOK) [2]; downstream differential phase-shift keying (DPSK) and upstream OOK [3]; downstream inverse return-to-zero (IRZ) and upstream OOK [4]; downstream low extinction-ratio (ER) OOK and upstream DPSK [5]. However, these approaches are limited by various combinations of high chirp [2], [3], limited speed [2]–[4], and reduced ER [5]. DPSK erasure and orthogonal DPSK/intensity modulation (IM) scheme for virtual private network has also been proposed [6]; however, analysis of downstream DPSK to solely upstream DPSK (without IM) remodulation has not been performed. Also, the performance of this wavelength reuse scheme under typical PON conditions, such as transmission ($\sim$20 km), remodulation misalignment tolerance, and maximum launched optical power have not been studied [6].

Here, we propose and demonstrate a novel wavelength remodulation scheme using DPSK in both upstream and downstream signals for 10-Gb/s DWDM-PONs. The remodulation enables high ER signals in both directions. A 20-km-reach colorless DWDM-PON without dispersion compensation was demonstrated and 0.6-dB power penalty was added during the remodulation process. Timing misalignment tolerance and maximum launched power for the proposed scheme were also studied. Comparison with other wavelength remodulation schemes was performed, showing the proposed scheme can be a potential candidate for next-generation wavelength reuse DWDM-PONs.

II. EXPERIMENTAL SETUP

Fig. 1 shows the experimental setup for the proposed DPSK downstream and upstream remodulation scheme. The downstream 10-Gb/s DPSK signal was generated by encoding a continuous-wave (CW) (1548 nm) with a differentially precoded nonreturn-to-zero (NRZ) data (D'_{down}, where "prime" denotes

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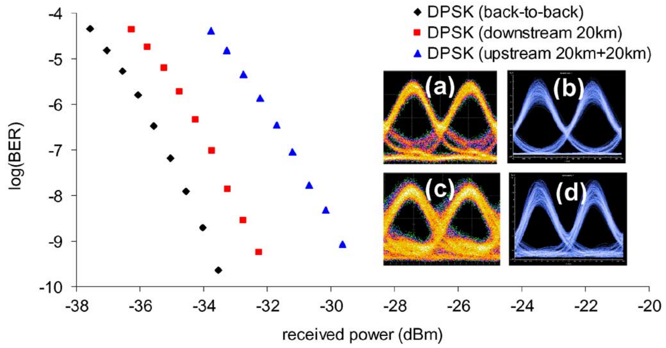

Fig. 2. The 10-Gb/s BER measurements of DPSK. Demodulated DPSK (a) experimental, (b) simulated downstream eyes; and (c) experimental, (d) simulated upstream eyes.

differentially precoded) through a LiNbO$_3$ phase modulation (PM). The downstream signal was transmitted through a 10-km feeder single-mode fiber (SMF) and 10-km distribution/drop fiber. The optical fiber cannot be fully dispersion-compensated in practice because the distance varies for different ONUs, hence no dispersion compensation was used in the experiment. Dual-feeder fiber architecture [1] was employed to reduce Rayleigh backscattering reflecting towards the head-end receiver (Rx) [7], while maintaining the merits of using single distribution/drop fiber to the ONU. A detail theoretical and experimental analysis of the dual-feeder fiber architecture has been discussed in [1]. The downstream DPSK signal was launched into the ONU via an optical circulator (OC), and 10% of optical power was received by an optically preamplified Rx, which consisted of a variable optical attenuator, erbium-doped fiber amplifier, a delayed interferometer for DPSK demodulation, and a 10-Gb/s PIN. The rest of the optical power was launched into a PM to generate the upstream signal. To rewrite the phase information onto the downstream optical signal, $D'_{\text{down}} \oplus D'_{\text{up}}$ was applied to the PM, where $\oplus$ is the exclusive-OR (XOR) logic operation. Using the fact that $D'_{\text{down}} \oplus D'_{\text{down}} = 0$, and $0 \oplus D'_{\text{up}} = D'_{\text{up}}$, the phase information was rewritten and only D'_{up} remained in the phase, producing the upstream signal. It should be noted that the alignment between the downstream and the applied electrical signals to the PM is crucial (will be discussed in Section III), and this can be controlled using the electrical delay line and electrical buffers.

III. RESULTS AND DISCUSSION

Numerical analysis using VPI TransmissionMakerV7.1 was performed to confirm the experimental results. Fig. 2 shows the 10-Gb/s experimental bit-error-rate (BER) measurements of the proposed scheme, with the experimental and simulated DPSK eye diagrams of downstream and upstream signals in the insets. Power penalty of 1.2 dB at BER of 10^{-9} was measured for the demodulated DPSK downstream signal at the ONU after the transmission of 20-km SMF without dispersion compensation. Power penalty of 4.4 dB (compared with back-to-back) was measured for the remodulated upstream DPSK signal at the head-end Rx, due to the accumulated dispersion of 40-km SMF and the remodulation process at the ONU.

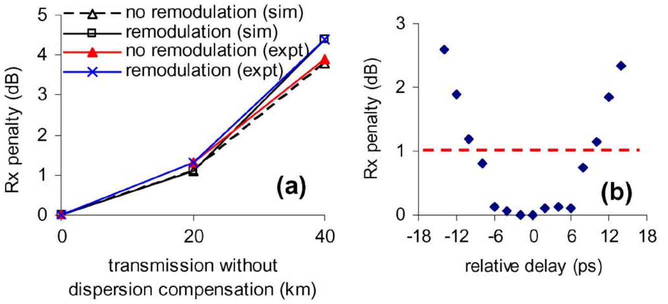

Fig. 3. (a) Comparison of transmission of DPSK signal through 40-km SMF; and the downstream–upstream transmission and remodulation of the DPSK. (b) Rx sensitivity penalty of remodulated upstream DPSK versus timing misalignment in ONU.

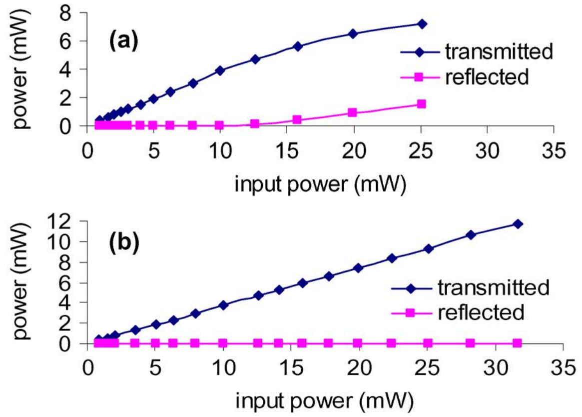

Fig. 4. SBS tolerance of (a) NRZ and (b) DPSK signals.

To estimate the power penalty introduced during the remodulation process, transmission of the DPSK signal without remodulation was performed. Fig. 3(a) compares the Rx sensitivity penalty at a BER of 10^{-9} between the transmission of DPSK signal through 40-km SMF; and the downstream and upstream transmission and remodulation of the DPSK, showing that the remodulation introduced an additional 0.6-dB power penalty. There is a good match between the experiment and simulation in terms of Rx sensitivity penalties and eye shapes, as shown in Figs. 2 and 3(a). The ER of the back-to-back demodulated DPSK signal is 11.7 dB, while the ER of downstream and remodulated upstream DPSK signals can maintain a quite high ER of 8 and 7.2 dB, respectively. The degradation of the ER is due to chromatic dispersion, and the low ER downstream signal is not required for the upstream remodulation, when compared with other remodulation schemes [5]. Fig. 3(b) shows the Rx sensitivity penalty at a BER of 10^{-9} induced to the DPSK upstream signal by timing misalignment between the downstream DPSK signal and the applied electrical signal to the PM in ONU. We adjusted their relative delay by an electrical delay line and measured the corresponding Rx penalty. The tolerance for 1-dB penalty is about 20 ps, which is similar to other reported remodulation schemes [5].

It is worth mentioning that launching higher optical power is desirable for PON to increase the maximum reach and the split ratio of PON. Fig. 4 compares the experimental transmitted and back-reflected average power of NRZ (as a reference) and

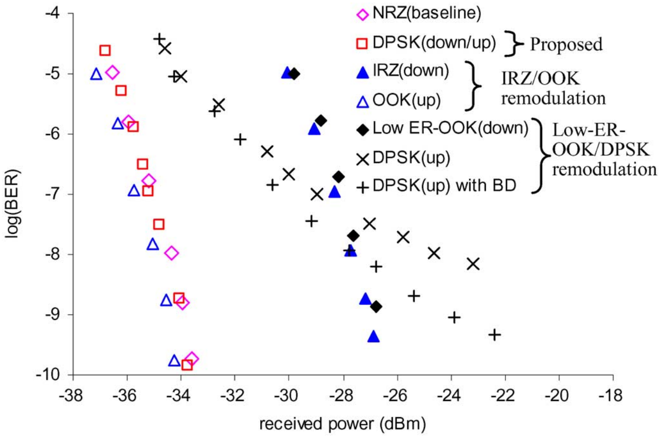

Fig. 5. Simulated BER curves for comparing different remodulation schemes at back-to-back Rx penalty with NRZ signal.

DPSK signals through a 20-km SMF, showing that the reflected power starts to increase, while the transmitted power starts to become saturated [Fig. 4(a)] at 10-mW NRZ input power, due to stimulated Brillouin scattering (SBS). Fig. 4(b) shows that DPSK allows at least 5 dB higher input power than that of NRZ. This is because the absence of the carrier component and wider spectrum of DPSK format is more tolerance to SBS. Hence, a longer reach or higher split ratio PON may be achieved for the proposed scheme. Considering the Rxs are preamplified (Rx sensitivity -30 dBm), no amplification at the ONU, insertion losses of the OC, PM, and arrayed waveguide grating (not shown in Fig. 1) are 1, 3, and 3 dB respectively, fiber loss is 0.2 dB/km and the splice loss per connection is 0.1 dB, eight ONUs (splitting loss 9 dB) could be supported, in principle, if the launch power is 15 dBm. The amplification stage in ONU is necessary if more ONUs have to be supported.

IV. COMPARISON OF DIFFERENT REMODULATIONS

To further show the advantages of the proposed scheme, we compared it [with and without balance detection (BD)] with the previously proposed remodulation schemes, including downstream IRZ and upstream OOK [4]; downstream low ER-OOK and upstream DPSK [5]. Since the reported schemes were operated at different data rates, simulations were performed at 10 Gb/s for all cases in both upstream and downstream signals during the comparison to evaluate the back-to-back Rx sensitivity penalty of different remodulation schemes when compared with the NRZ modulation (Fig. 5). For the proposed DPSK downstream and upstream scheme (at back-to-back), no power penalty was observed when compared with the NRZ signal, and in principle, Rx sensitivity improvement of 3 dB can be observed if BD was used. For the IRZ downstream and OOK upstream remodulation schemes, a power penalty of 6.8 dB was observed in the IRZ signal at a BER of 10^{-9} due to its high residual CW background to provide enough optical power for the remodulation of upstream OOK. However, the upstream OOK showed a negative power penalty of 0.5 dB because the upstream OOK was remodulated onto the residual CW background of the downstream IRZ, generating a return-to-zero-like upstream signal. Hence, this enhanced the Rx sensitivity. For the low-ER OOK downstream and DPSK upstream case, a low-ER OOK downstream signal was required to provide enough residual optical power for the upstream remodulation. Hence, a high power penalty of 7.2 dB was observed due to the reduced ER (using the ER $= 4.9$ dB as described in [5]). BER 10^{-9} DPSK upstream detection was not possible unless BD (power penalty of 10 dB) was used. The power penalty was due to the conversion of the low-ER OOK downstream signal to amplitude fluctuation in the upstream DPSK signal. The slopes of the DPSK upstream signals are less steep due to the noise introduced by the amplitude fluctuation.

V. CONCLUSION

We proposed and demonstrated a novel wavelength remodulation scheme using DPSK in both upstream and downstream for 10-Gb/s DWDM-PONs, with high ER for signals in both directions. A 20-km-reach PON without dispersion compensation was demonstrated and a 0.6-dB power penalty was added during the remodulation process. Timing misalignment tolerance of 20 ps (1-dB penalty) and a maximum launch power of at least 15 dBm was achieved. A comparison with other wavelength remodulation schemes was performed, showing that the proposed scheme can be a potential candidate for next-generation wavelength reuse DWDM-PONs.

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