40-Gb/s downstream DPSK and 40-Gb/s upstream OOK signal remodulation PON using reduced modulation index

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Abstract: As different high speed signal-remodulation wavelength division multiplexed – passive optical network (WDM-PON) solutions up to 10 Gb/s have been proposed, researchers are going to further increase the data rate of PON towards 40 Gb/s or higher. However, scaling up from 10 Gb/s/wavelength to 40 Gb/s/wavelength PON is very challenging. Although many studies have been performed on upgrading the exiting 10 Gb/s network to 40 Gb/s, the study of the 40 Gb/s signal-remodulation network is very little. In this work, we will first study the chromatic dispersion effect on the signal-remodulation PON. Then, we will propose and demonstrate a signal-remodulation PON using 40-Gb/s downstream differential-phase shift keying (DPSK) and 40-Gb/s upstream on-off keying (OOK) signals. By using the reduced modulation index (RMI) of the downstream DPSK signal, the tolerance to the residual chromatic dispersion of the whole system can be greatly enhanced. Due to the reduced impact of the accumulated chromatic dispersion, the quality of the upstream remodulated OOK signal can be significantly improved. Besides, by detecting the downstream demodulated DPSK signal at the destructive output port of the demodulator, good quality of the demodulated DPSK signal can still be achieved.

OCIS codes: (060.2330) Fiber optics communications; (060.4510) Optical communications.

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1. Introduction

Wavelength division multiplexed – passive optical network (WDM-PON) is considered as a promising next generation access network architecture. WDM-PON using "colorless" or wavelength-insensitive optical networking unit (ONU) is attractive since this can reduce the

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inventory cost. Carrier-distribution PONs [1,2] have been proposed for the colorless WDM-PONs. In these PONs, the laser sources used to generate the upstream signal are located at the central office (CO). Wavelength-insensitive reflective optical modulator (R-MOD) is used in each ONU. The centrally located laser sources provide the optical carrier for each R-MOD inside the ONU to generate the upstream signal.

In the carrier-distribution WDM-PONs, usually a pair of wavelengths is needed for each ONU. One wavelength is distributed towards the ONU as a distributed carrier, which will then be modulated as the upstream signal. The other wavelength is used to carry the downstream signal. Signal remodulation can be used to greatly enhance the bandwidth utilization of the fiber. In the signal-remodulation PON, the downstream signal will be remodulated at the ONU to produce the upstream signal, thus, only one wavelength is required for each ONU (carrying both downstream and upstream signals). Different signal-remodulation PONs of up to 10 Gb/s have been reported, such as using asymmetric downstream and upstream on-off keying (OOK) [3] signals, using both downstream and upstream differential phase shift keying (DPSK) signals [4], and using downstream DPSK and upstream OOK signals [5]. Intuitively thinking, using downstream DPSK and upstream OOK signals could be one of the best solutions since the downstream DPSK signal has a constant amplitude and the intensity-remodulated upstream signal can be directly modulating onto the downstream carrier without the need of synchronization (as reported in case [4]) and without using gain-saturation to suppress the downstream OOK signal (as reported in case [3]).

As different high speed PON solutions up to 10 Gb/s have been proposed, researchers are going to further increase the data rate of PON towards 40 Gb/s or higher [6,7]. However, scaling up from 10 Gb/s/wavelength to 40 Gb/s/wavelength PON is very challenging, since much higher optical bandwidth and optical signal to noise ratio (OSNR) are required, and at the same time, the chromatic dispersion tolerance is greatly reduced. Although many studies have been performed on upgrading the exiting 10 Gb/s network to 40 Gb/s [8], the study of the 40 Gb/s signal-remodulation network is very little. In this work, we will first study the chromatic dispersion effect on the signal-remodulation PON. Then, we will propose and demonstration a 40 Gb/s downstream DPSK and 40-Gb/s upstream OOK signal-remodulation PON. By using the reduced modulation index (RMI) of the downstream DPSK signal, the tolerance to the residual chromatic dispersion can be greatly enhanced. Due to the reduced impact of the accumulated chromatic dispersion, the quality of the upstream remodulated OOK signal can be improved. Besides, by detecting the downstream demodulated DPSK signal at the destructive output port of the Mach-Zehnder Interferometer (MZI)-based DPSK demodulator, good quality of the demodulated DPSK signal can be achieved.

2. Residual chromatic dispersion studies for signal-remodulation PON

Figure 1 shows the schematic of a signal-remodulation WDM-PON. DPSK signal was used as the downstream signal, which was distributed from the CO and remodulated at the ONU to generate the upstream OOK signal. Numerical analysis using commercial software VPI Transmission Maker V7.5 was used. A precoded non-return-to-zero (NRZ) data at pseudorandom binary sequence (PRBS) of 2^7-1 was applied to an optical phase modulator (PM) to produce the downstream DPSK signal. The downstream signal was then launched to the ONU via 20 km single mode fiber (SMF) which was fully dispersion compensated by dispersion compensating fiber (DCF). Residual dispersion was introduced by using additional lengths of SMF. In the simulation, a pair of Gaussian shaped AWG with the 3-dB bandwidth of 200 GHz was used. At the ONU, a MZI with delay of 25 ps was used to demodulate the DPSK signal. An optically pre-amplified receiver (Rx), consisting of an EDFA (noise figure = 5 dB), optical bandpass filter (3-dB bandwidth of 200 GHz) and a 40 GHz PIN photodiode, was used to receive the downstream signal. The rest of the downstream signal was then remodulated by the Mach-Zehnder modulator (MZM), which was electrically driven by the NRZ data. The remodulated OOK signal was then sent back to the optically pre-amplified Rx at the CO.

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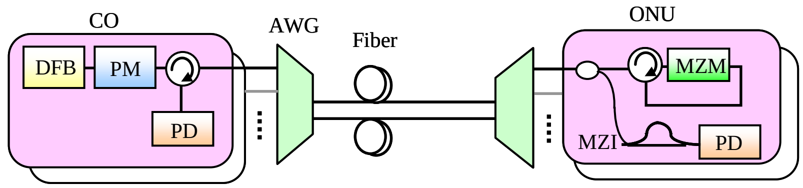

Fig. 1. Schematic of a signal-remodulation WDM-PON. DFB: distributed feedback laser, PM: phase modulator, PD: photodiode, AWG: arrayed waveguide grating, MZM, Mach-Zehnder modulator, MZI: Mach-Zehnder interferometer.

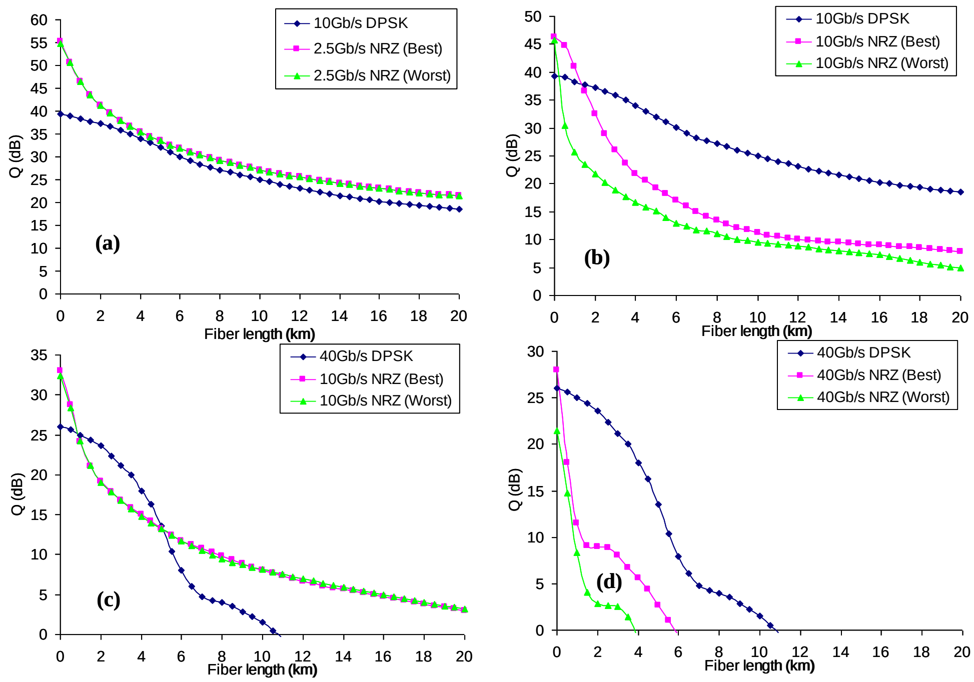

Fig. 2. Simulated performances of the DPSK-OOK signal-remodulation PON.

The performances of the DPSK-OOK signal-remodulation PON were studied. Figure 2(a) and (b) shows the Q (dB) of the downstream DPSK and upstream OOK signal at 10 Gb/s (downstream) with 2.5 Gb/s (upstream), and symmetric 10 Gb/s respectively. We can see that in the case of 10 Gb/s (downstream) and 2.5 Gb/s (upstream), error-free (Q > 15 dB) transmission can be achieved in both direction under typical access fiber length of 20 km (i.e. dispersion compensation is not required). However, when using the symmetric 10 Gb/s signals, the upstream OOK signal is degraded by the accumulated chromatic dispersion. We also adjusted the time delay between the downstream DPSK and the upstream OOK signals. We found that the performance of the upstream OOK signal depends on the time-delay. For the optimum delay, we can obtain good performance (the best case), for the most non-optimum delay, we obtain poor performance (the worst case). In the symmetric bit-rate operation, the residual dispersion tolerance (i.e. the maximum dispersion value the system can obtain a Q of 15 dB) is only equivalent to ~5 km of SMF in the worst time-delay. By increasing the bit-rate to 40 Gbs/ (downstream) and 10 Gb/s (upstream), the effect of chromatic dispersion increases rapidly. The residual dispersion tolerance of the downstream and upstream signals is only equivalent to ~5 km and ~3 km of SMF respectively, as shown in Fig. 2(c). When comparing the upstream 10 Gb/s NRZ in Fig. 2(b) and (c), the performance degradation of the upstream 10 Gb/s NRZ in Fig. 2(c) is due to the phase-to-intensity noise introduced by the AWG filtering of the 40 Gb/s downstream DPSK signal. The situation is even worst when symmetric 40 Gb/s is operated (Fig. 2(d)). In this case, the upstream OOK signal can only have chromatic dispersion tolerance of ~1 km.

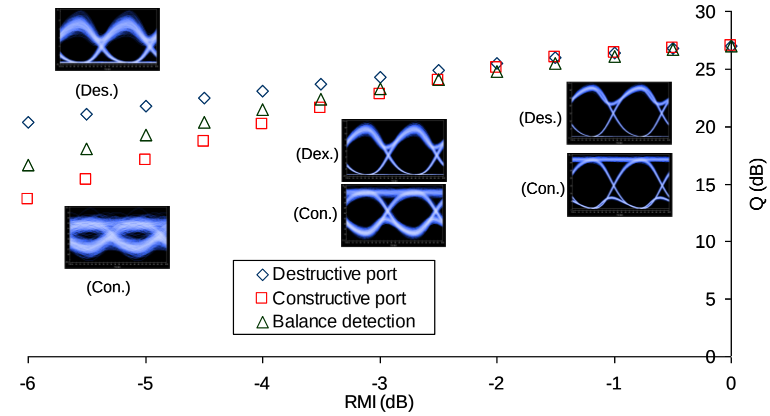

Fig. 3. Simulated signal qualities of the demodulated DPSK signal at the destructive, constructive output ports of the MZI and at balanced detection under different reduced modulation index (RMI). Corresponding eye-diagrams at RMI of 0, –3 and –6 dB.

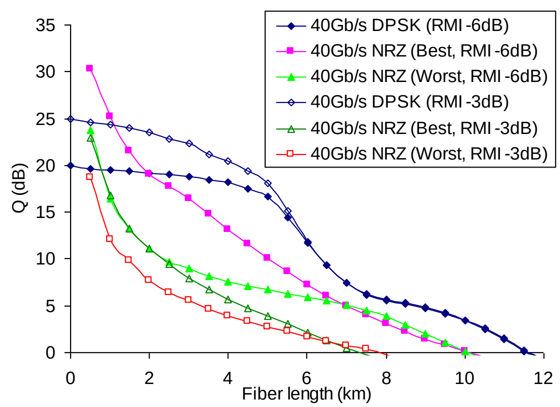

Fig. 4. Simulated performances of the DPSK-OOK signal-remodulation PON using RMI.

We then propose using RMI to the downstream DPSK signal to decrease the impact of the accumulated chromatic dispersion of the upstream OOK signal, thus, the reach and signal performance of the upstream signal can be greatly enhanced. Here, the RMI is defined as reducing the applied driving voltage to the PM, for example, if applied voltage V_π is needed for a π phase change to the optical signal, –6 dB RMI means reducing the V_π by 6 dB. By reducing the modulation index of the DPSK signal, it raises a question of how much degradation will be introduced to the downstream DPSK signal. Fortunately, in the demodulation of the DPSK signal using the MZI, reducing the modulation index mainly affect the signal at the constructive output port of the MZI, while the signal at the destructive output port is slightly affected. The demodulation principle of DPSK using MZI is to compare the phase shift of the signal with the adjacent bit. At the destructive output port, for consecutive logic "0" or logic "1", although the phase shift in the DPSK signal is less than π due to the reduced modulation index, high extinction ratio of demodulated DPSK signal can still be achieved since the phase shift between adjacent bits are the same. On the other hand, the demodulated DPSK signal at the constructive port will have a poor extinction ratio. Figure 3 shows the simulated demodulated DPSK signal at the destructive and constructive output ports of the MZI. When the RMI is reduced to –6 dB, good quality of demodulated DPSK can still be observed at the destructive port. Simulation results of using balance detection have been included for comparison.

Based on the simulation results in Fig. 3, a simulation using symmetric 40 Gb/s signal-remodulation PON described in Fig. 1 was performed. Figure 4 shows that by using RMI of –6 dB, the residual chromatic dispersion tolerance of the downstream DPSK signal is still equivalent to ~5 km of SMF and the back-to-back DPSK signal quality is slightly degraded. However the residual chromatic dispersion tolerance of the remodulated OOK signal is greatly increased from ~1 km to ~4 km SMF.

3. Experiment, results and discussion

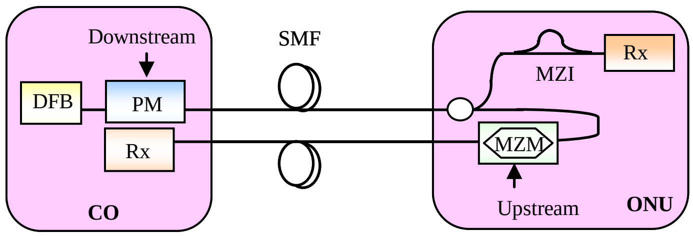

Fig. 5. Experimental setup of the signal-remodulation PON. DFB: distributed feedback laser, PM: phase modulator, Rx: receiver, SMF: single mode fiber, MZM: Mach-Zehnder modulator, MZI: Mach-Zehnder interferometer.

The proposed signal-remodulation PON using RMI was evaluated using experiment. Figure 5 shows the experimental setup. A distributed feedback (DFB) laser with output power of 5 dBm was launched into a PM to produce the 40 Gb/s DPSK downstream signal. Different RMI was generated by controlling the electrical input signal to the PM. The signal was then launched to the colorless ONU via 3 km of SMF. At the ONU, 20% of the downstream signal was first demodulated by a MZI with delay of 25 ps and detected by an optically pre-amplified Rx, consisting of an EDFA (gain = 30 dB, noise figure = 5 dB), an optical bandpass filter and a 40 GHz PIN. The rest of the downstream power was remodulated by a 40 GHz MZM at the ONU to generate the upstream OOK signal, which was then sent back to the optically pre-amplified Rx at the CO. In the 40 Gb/s WDM-PON, feeder fiber (~20 km) must be compensated by DCF, and the distribution fiber is difficult to compensate but is usually short, and this method can tolerate these uncompensated distribution fibers.

Figure 6 shows the BER performance of the downstream DPSK and upstream OOK signals. By using RMI, the power penalty of the DPSK increases to 4.5 dB, however, the remodulated upstream OOK signal is significantly enhanced from having an error-floor at 10^{-5} to error-free, and the performance is obtained under optimized time delay. The corresponding experimental and simulated 40 Gb/s eye-diagrams are shown in the insets. Clear open eye of the remodulated upstream OOK signal can be observed showing the proposed RMI and MZI-destructive port detection scheme is successful. The experimental eye-shapes also match with the simulation.

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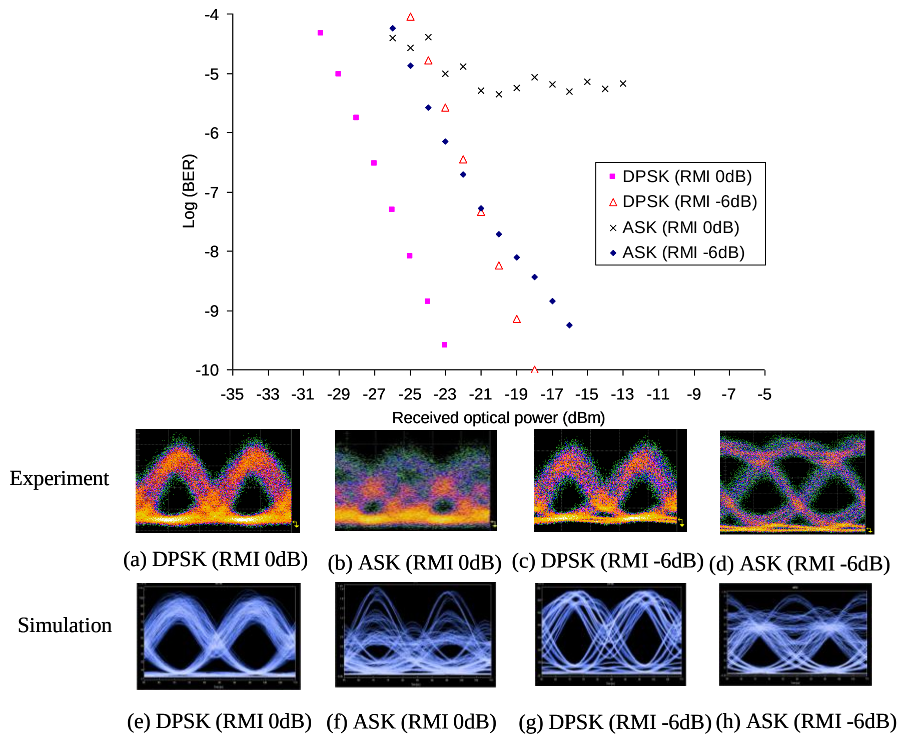

Fig. 6. Measured BER of the downstream DPSK and upstream OOK signal without and with using RMI. Insets: corresponding experimental and simulated eye-diagrams of the downstream and upstream signals.

4. Conclusion

Higher data rate WDM PONs towards 40 Gb/s are needed in the future. However, scaling up from 10 Gb/s/wavelength to 40 Gb/s/wavelength PON is very challenging, particularly in the signal-remodulation PON. In this work, we studied the chromatic dispersion effect on the signal-remodulation PON using downstream DPSK and upstream OOK signals. Simulation and experimental results show that due to the accumulated chromatic dispersion, the upstream remodulated OOK signal is greatly affected. Here, we proposed and demonstrated using RMI and MZI-destructive port detection scheme can greatly increase the chromatic dispersion tolerance and significantly enhance the quality of the remodulated upstream OOK signal, while good quality of the demodulated DPSK signal can be maintained. Although the present architecture may be expensive, we believe that cost can be saved by using signal remodulation, in which only one wavelength is needed for both upstream and downstream signals.

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