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Signal remodulation without power sacrifice for carrier distributed hybrid WDM-TDM PONs using PolSK

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ABSTRACT

Signal remodulation is considered to lower the cost of future WDM-PON by wavelength reuse. We propose and demonstrate a signal remodulation scheme using PolSK modulation in both downstream and upstream signals for "colorless" WDM-PON. High extinction-ratio can be achieved in both downstream and remodulated upstream signals; hence power sacrifice of using residual optical power in downstream signal for the upstream remodulation is eliminated. Split-ratio analysis is performed for the hybrid WDM-TDM architecture. Results show that the proposed scheme could be a potential candidate for next generation wavelength reuse WDM-TDM PON.

1. Introduction

It is generally agreed that fiber-to-the-home (FTTH) provides the ultimate in bandwidth and flexibility in upgrades when considering high-speed broadband access, especially with data rate of 1 Gb/s or above. Traditional time division multiplexed (TDM) based passive optical network (PON) is considered as an attractive FTTH. Recently, research attention has turned to wavelength division multiplexed (WDM) PONs, and also hybrid WDM-TDM PONs [1] in order to fully utilize the advantages generated by the WDM and TDM technologies. To lower the cost, network operators would like to use "colorless" optical networking units (ONUs) at end users [1]. Remodulation of downstream to generate upstream signal can further reduce cost by wavelength reuse. Remodulation schemes of using on–off keying (OOK) in both downstream and upstream [2]; differential phase shift keying (DPSK) downstream and OOK upstream [3] have been proposed. However, they are limited by high chirp and speed of the Fabry–Perot laser diode (FP-LD) used in the ONUs [4–6]. Low extinction-ratio (ER) OOK downstream and DPSK upstream [7]; and inverse return-to-zero (IRZ) downstream and OOK upstream [8] remodulation have also been demonstrated, however, the residual continuous wave (CW) background in the low ER OOK and between IRZ pulses are required respectively to provide high enough optical power for the upstream remodulation. These greatly reduce the receiver (Rx) sensitivity by saturating the upstream Rx, and limit the maximum reach and split ratio of the WDM-PONs.

Here, we propose and demonstrate a 10 Gb/s signal remodulated WDM-TDM PONs. Polarization shift keying (PolSK) is employed in both upstream and downstream directions. PolSK is considered as one of the promising modulation formats for future optical networks [9–13]. PolSK transceiver [11] has been demonstrated; and 40 Gb/s PolSK modulator [12] has been commercially available recently. Pre-coding and decoding are not required when compared with DPSK [14]. Polarization multiplexing can also be a good solution in long haul networks [15], and PolSK also offers several advantages [16]; however its use in access networks requires complicate operation. The proposed architecture enables high ER signals (downstream and upstream) in a 20-km-reach colorless hybrid WDM-TDM. Studies of timing and polarization misalignment tolerances and maximum launching power are carried out. Split-ratio analysis is performed.

2. Experiment

Fig. 1 shows the experimental setup for the proposed PolSK signal remodulated WDM-TDM PON. The downstream 10 Gb/s PolSK signal was generated by launching a CW (wavelength at 1548 nm) at 45° into a $LiNbO_3$ phase modulation (PM) which was electrically driven by a non-return-to-zero (NRZ) data (D_{down}) in the optical line terminal (OLT). The anisotropy of the electro-optic coefficient of $LiNbO_3$ crystal allows the relative phase shift between the two optical axes to change as a function of applied voltage. Hence, the phase shift between the two axes allows the output polarization to be modulated. Dual-feeder fiber architecture [1] was employed to reduce Rayleigh backscattering reflecting towards the head-end Rx, while maintaining the merits of using single distribution/drop fiber

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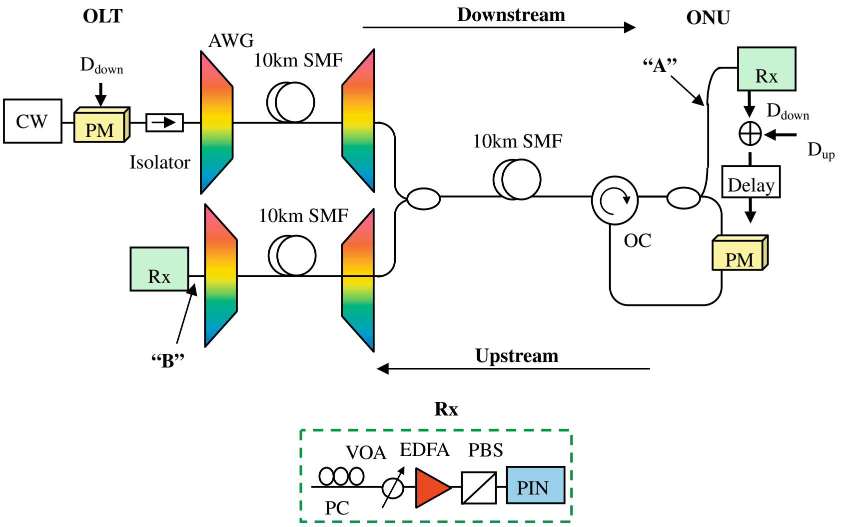

Fig. 1. Experimental setup of PON using PolSK in downstream and upstream signals. PM: phase modulator, AWG: arrayed waveguide grating, SMF: single-mode fiber, OC: optical circulator, PC: polarization controller, VOA: variable optical attenuator, EDFA: erbium-doped fiber amplifier and PBS: polarization beam splitter. Inset: optical pre-amplified receiver (Rx).

to the customer. The downstream signal was traveling in a 10-km single-mode fiber (SMF) in the feeder section via a pair of arrayed waveguide grating (AWG) (Gaussian shaped, 3-dB width of 50 GHz) and then 10-km in the distribution/drop section. No dispersion compensated was used. At the ONU, 10% of optical power was received by an optically pre-amplified Rx. As shown in the inset, a variable optical attenuator (VOA), erbium-doped fiber amplifier (EDFA), a polarization beam splitter (PBS) for PolSK demodulation, and a 10-Gb/s p-i-n photodiode (PD) were used in the Rx. The use of EDFA in the optically pre-amplified Rx can increase the cost of the ONU, and using semiconductor optical amplifier (SOA) in the ONU is also considered for some PON architecture operating at 10 Gb/s [17]. Besides, PBS can be replaced by a polarizer to reduce the cost.

Ninety percent of the optical power was launched into a PM for signal remodulation. Since $D_{\text{down}} \oplus D_{\text{down}} = 0$; $0 \oplus D_{\text{up}} = D_{\text{up}}$; and the downstream signal is launched at the appropriate angle to the PM (by the polarization controller (PC)), the phase information was rewritten when we applied the electrical data of $D_{\text{down}} \oplus D_{\text{up}}$ to the PM (where $\oplus$ is the XOR logic operation). Thus only D_{up} remained in the upstream optical signal. Electrical buffer and polarization tracking [18] can be used in practice.

3. Results and discussion

Fig. 2 shows the 10 Gb/s experimental bit-error rate (BER) measurements of the proposed scheme. The experimental and simulated (using VPI TransmissionMakerV7.1) PolSK eye-diagrams of downstream and upstream signals were also shown in the insets. Power penalty of 1.7 dB and 4.7 dB at BER of 10^{-9} was measured for the demodulated PolSK downstream signal after the 20-km SMF transmission and the remodulated upstream PolSK signal at the upstream Rx, respectively. The ERs of the downstream and upstream signals are 10.8 dB and 7.7 dB, respectively. The power penalties could be due to the polarization misalignment and the crosstalk induced during the remodulation of the upstream data on top of the existing downstream data.

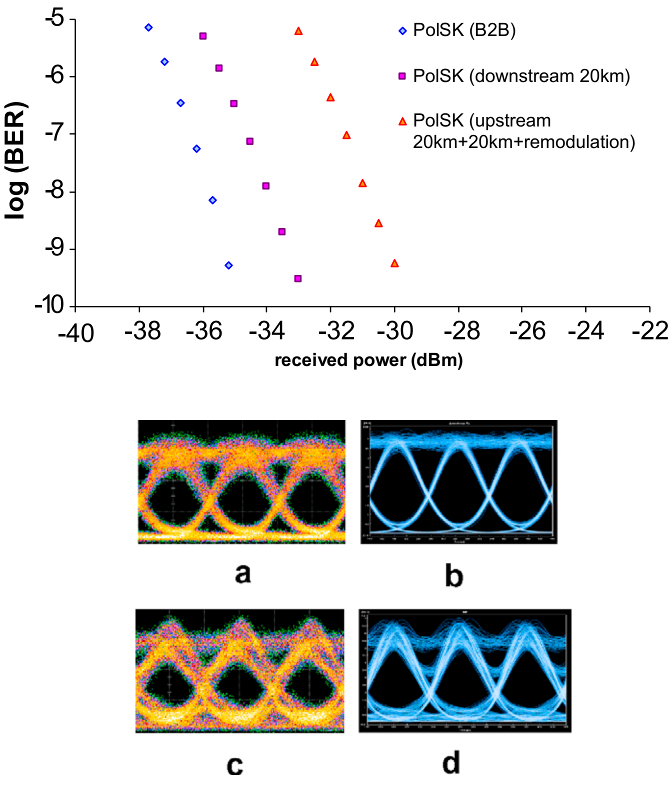

Fig. 2. BER measurements. Inset: Demodulated (a) experimental, (b) simulated downstream observed at "A" in Fig. 1; and (c) experimental, (d) simulated upstream eyes observed at "B" in Fig. 1.

The Rx sensitivity penalty at BER of 10^{-9} induced by timing misalignment between the downstream PolSK and the applied electrical signal to the PM, and the polarization misalignment between the downstream PolSK and the principal axis of PM are shown in Fig. 3a and b, respectively. The relative delay and polarization was adjusted by an electrical delay line and an electrical PC respectively. The tolerance for 1-dB penalty is ~20 ps (which is similar to other reported remodulation scheme [7]) for the timing misalignment and ~16° for the polarization misalignment. In both cases, the tolerances start to increase exponentially when moving away from the center positions; and this requires tighter system requirements. Since the random birefringence of buried optical fiber networks typically causes only 2–10° fluctuations in the polarization angles of the propagating signals [19], a slow dynamic polarization control may be used to compensate the polarization fluctuation [20].

4. Split-ratio analysis in hybrid DWDM-TDM PON

Higher launching optical power is desirable for PON to increase the maximum reach and the split-ratio. Here, we compared the transmitted and back-reflected average power of NRZ (as a reference) and the PolSK signals through a 20-km SMF. Each signal was launched into a 20-km SMF via an optical circulator (OC). The transmitted and the back-reflected powers were measured by a power meter at the other end of the 20-km SMF and the output port of the OC respectively. The laser linewidth is about 10 MHz and the fiber loss is 0.2 dB/km. We can observe that the reflected power starts to increase at 10-mW NRZ input power (Fig. 4a), due to stimulated Brillouin scattering (SBS). Fig. 4b shows that PolSK allows ~3 dB higher input power than that of NRZ, due to a wider spectrum of PolSK signal. Then, by considering the Rxs are pre-amplified (upstream Rx sensitivity is about −30 dBm), no amplification at the ONU, insertion losses of the OC, PM and AWG are 1 dB, 4 dB and 4 dB, respectively, fiber loss is 0.2 dB/km, and the splicing loss per connection is 0.1 dB, by means of theoretical estimation, 4 ONUs could be supported, if the launch power is 13 dBm into the first section of the fiber (feeder fiber). Fig. 5 shows the schematic of the split-ratio analysis of the hybrid DWDM-TDM PON with signal power indication. Thirty-two ONUs could be supported if a 15 dB amplification stage can be included in the ONU.

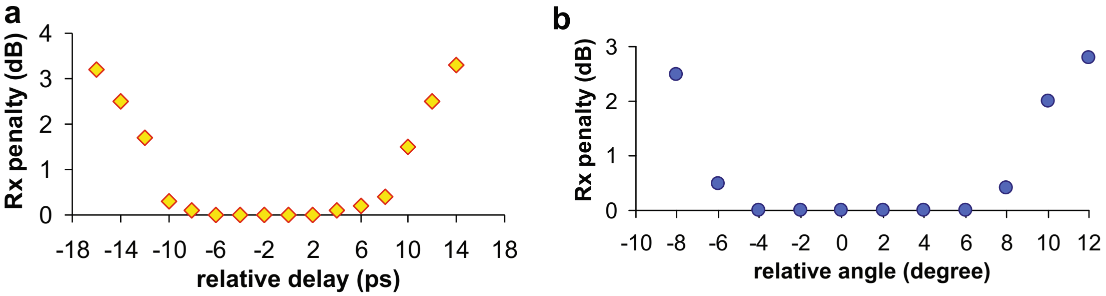

Fig. 3. Rx sensitivity penalty of remodulated PolSK versus (a) timing and (b) polarization misalignment in ONU.

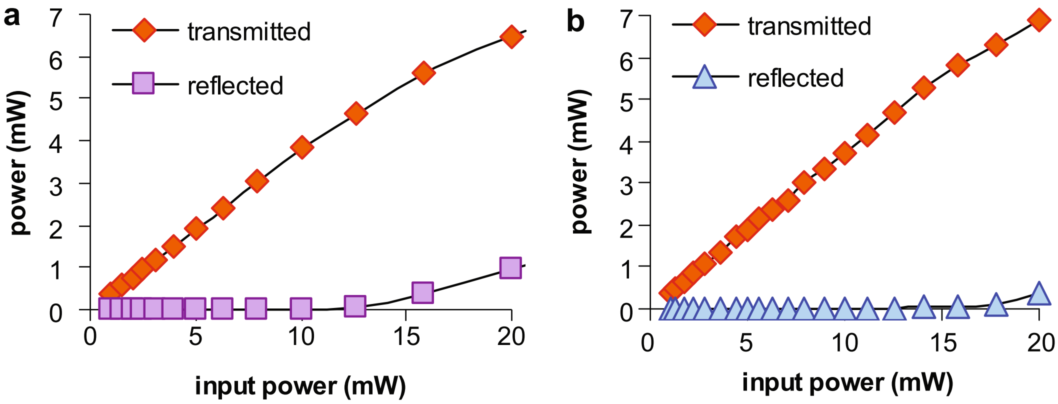

Fig. 4. SBS tolerance of (a) NRZ and (b) PolSK signals.

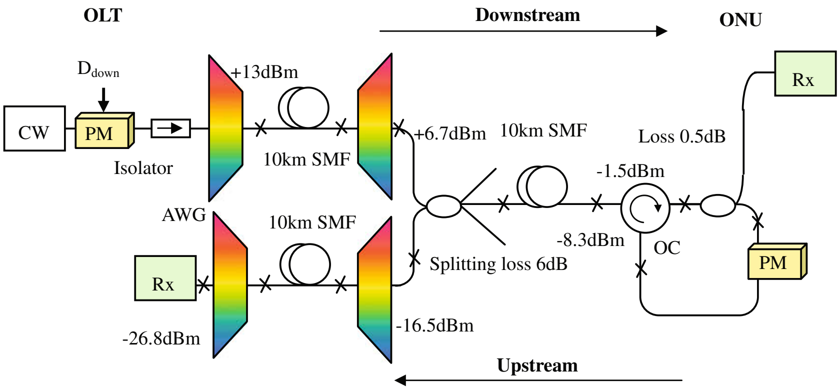

Fig. 5. Schematic of split-ratio analysis of the hybrid WDM-TDM PON with signal power indication. PM: phase modulator, SMF: single-mode fiber and OC: optical circulator.

5. Conclusion

A signal remodulation 10 Gb/s WDM-TDM PON architecture using PolSK format in both upstream and downstream signals was proposed and demonstrated. Timing misalignment tolerance of 20 ps and polarization misalignment tolerance of 16° were measured at 1-dB penalty window. Split-ratio analysis by theoretical estimation was performed showing that 4 ONUs could be supported without any amplification, and 32 ONUs could be supported if a 15 dB amplification stage is included in the ONU.

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