Phase-Modulation-Based Loopback Scheme for Rayleigh Noise Suppression in 10-Gb/s Carrier-Distributed WDM-PONs

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***Abstract*—We propose a novel scheme to suppress Rayleigh noise in carrier-distributed wavelength-division-multiplexed passive optical networks, by using differential phase-shift keying (DPSK) as the upstream modulation format. Due to the narrow spectrum of the distributed carrier, the Rayleigh noise towards the optical line terminal (OLT) also has narrow spectrum and can be effectively suppressed by the notch filter-like destructive port of the delay-interferometer at the OLT, which is used to demodulate the upstream DPSK signal simultaneously. Experimental demonstration of the 10-Gb/s upstream signal is achieved with less than 0.2-dB power penalty induced by Rayleigh noise after the transmission of 20-km single-mode fiber.**

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

I. Introduction

The wavelength-division-multiplexed passive optical network (WDM-PON) is promising to provide broadband access, offering triple-play services with video, data, and voice [1]. The colorless optical network unit (ONU) is a key technical issue for low-cost implementation of WDM-PON. As all ONUs use identical modules, it greatly facilitates mass production and the operation, administration, and maintenance (OA&M) functions. One promising solution for broadband (10 Gb/s or above) colorless ONU is the optical loopback technique [2], [3]. Using this technique, centralized optical carriers are distributed from the optical line terminal (OLT) to each ONU, modulated, and sent back to the OLT. In single-fiber loopback access networks, the intrinsic Rayleigh backscattering (RBS) of the optical carrier induces severe interferometric crosstalk to the upstream signal, leading to bit-error-rate (BER) degradation at the receivers at the OLT [4]. Dual fibers can be used for upstream and downstream, respectively, to avoid RBS, at the expense of higher system cost [2]. Many studies have been carried out to mitigate this interferometric crosstalk [5]–[8]. Light source scrambling can be used to increase the frequency span of interferometric crosstalk beyond the receiver's bandwidth [5]. However, a broadband modulator and an oscillator, with bandwidth several times larger than the signal bit rate, are needed at each ONU. Another scheme uses an additional phase modulator (PM) at each ONU to spectrally broaden the intensity modulated upstream signal, thus reducing the spectral overlap between the upstream signal and the RBS [6], [7]. To eliminate that additional PM at each ONU and to improve the dispersion tolerance, carrier suppressed subcarrier amplitude modulated phase-shift keying has been proposed as the upstream modulation format, at the expense of more complicated modulation circuit at the ONU [8].

In this letter, we propose and demonstrate a simple scheme to suppress the RBS-induced interferometric crosstalk to the upstream signal in the carrier-distributed WDM-PON. Differential phase-shift keying (DPSK) is used as the upstream modulation format and the destructive port of the DI is employed to demodulate the upstream DPSK signal. As the spectrum of RBS towards the OLT is narrow due to the very narrow spectrum of the distributed carrier, the RBS noise can be considerably rejected by the notch filter-like destructive port of the delay interferometer (DI) at the OLT, which is used simultaneously to demodulate the upstream DPSK signal. It should be noted that optical filtering at the OLT is also required in the previous schemes [6]–[8], which is realized by either narrow notch filters or a wavelength-detuned arrayed waveguide grating (AWG). Compared with the prior schemes for RBS mitigation [6], [7], one intensity modulator can be saved at each ONU. Special electrical signal processing at each ONU as in [8], is not needed in the proposed scheme. Phase-modulation-based upstream transmission has been previously reported in [9], to remodulate the downstream DPSK signal. However, that scheme is less robust to RBS noise and dual-feeder fiber architecture is employed for RBS mitigation. The spectrum of the downstream DPSK signal in [9] is not so narrow as that of the distributed carrier in this scheme, thus its RBS cannot be effectively suppressed by the DI at the OLT.

II. Principle and System Architecture

The DI used for DPSK demodulation is functionally equivalent to a delay-and-subtract or delay-and-add filter, depending on whether the destructive or constructive port is used [10]. For the destructive port, it could act as a notch filter to reject the RBS of the optical carrier, which has a very narrow spectral width. We use DPSK as the upstream modulation format in carrier-distributed WDM-PONs, so that the destructive port of the DI used for upstream DPSK demodulation could simultaneously suppress the RBS of the optical carrier.

Fig. 1 illustrates the proposed loopback architecture. The optical carriers for upstream transmission at different wavelengths

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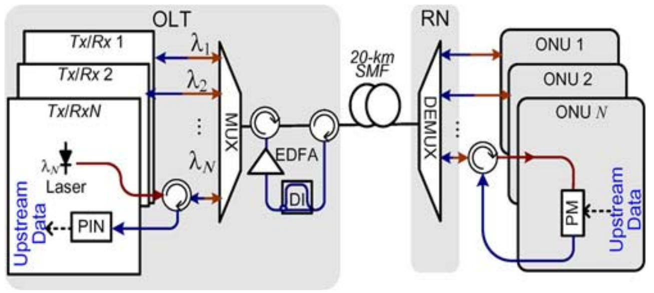

Fig. 1. Proposed loopback architecture using DPSK as the upstream modulation format to suppress Rayleigh noise. The downstream channels are omitted here for simplicity.

are generated by continuous-wave (CW) lasers at the OLT, and then multiplexed by an AWG. After the transmission in a 20-km single-mode fiber (SMF), the optical carriers from the OLT are wavelength routed toward different ONUs, by another AWG at the remote node (RN). At the ONU, the CW light is modulated by an optical phase modulator, driven by differentially precoded upstream data, before being sent back to the OLT. Due to the DI's periodic frequency response, all the upstream DPSK channels could be simultaneously demodulated by a common DI at the OLT [11], [12]. Athermal DIs, with $C+L$-band coverage by a single device, are commercially available. The demodulated DPSK signals are preamplified by a shared erbium-doped fiber amplifier (EDFA) before direct detection.

III. Experiment Demonstration

We first investigated the effectiveness of the destructive port of the DI on RBS suppression based on the setup shown in Fig. 2(a). The 20-km SMF used in the setup was properly terminated by an optical terminator. The relationship between the average reflection power (P_r) and the average power of the input CW light to the 20-km SMF $(P_{\rm in})$ was measured, as shown in Fig. 2(b). Two cases, with or without using the destructive port of the DI to suppress the RBS, are depicted. The extinction ratio of the DI is 22 dB. With the assistance of DI, for any given $P_{\rm in}$, the corresponding P_r was significantly reduced by more than 15 dB. The proposed scheme is actually based on the substantial difference in the insertion loss for the RBS noise (~15 dB) and the upstream DPSK signal (~3.8 dB). P_r increases significantly when $P_{\rm in}$ is over 7 dBm, due to stimulated Brillouin scattering. The solid line in the inset of Fig. 2(b) shows the measured spectrum (resolution bandwidth $= 0.06$ nm) of the RBS without using the destructive port of the DI to suppress the RBS. For comparison, the dashed line in the inset shows the substantially suppressed spectrum measured at the destructive port of the DI, demonstrating its effectiveness for RBS suppression. The RBS suppression will be enhanced for a DI with a higher extinction ratio as well as for a CW light with narrower linewidth.

We then conducted a proof-of-concept experiment to demonstrate the proposed loopback scheme, based on the architecture shown in Fig. 1. At the OLT, CW light at 1553.5 nm with a power of 3.5 dBm was fed into an AWG (4-dB insertion loss) with a channel spacing of 0.8 nm and a 3-dB bandwidth of 0.35 nm through a circulator (0.5-dB insertion loss). After propagating through another two circulators following the AWG, the CW light was coupled into a 20-km SMF (4-dB insertion loss) followed by another AWG (4-dB insertion loss) at the RN, with a channel spacing of 0.8 nm and a 3-dB bandwidth of 0.6 nm. At the ONU, through a circulator the CW light was fed into a polarization controller (0.8-dB insertion loss) followed by an optical PM (3.5-dB insertion loss). The PM was driven by a 10-Gb/s $2^{31}-1$ pseudorandom binary sequence (PRBS) as the upstream data. Following the PM, another polarization controller was used to assure that the system performance was investigated for the worst RBS interference scenario. After transmitting back to the OLT, the upstream DPSK data were demodulated by a DI with 94-ps relative delay and preamplified to -8 dBm by a shared EDFA. The amplified signal transmitted through the AWG, the circulator and a tunable optical attenuator (for BER measurement) at the OLT, before being detected by a 10-Gb/s p-i-n receiver.

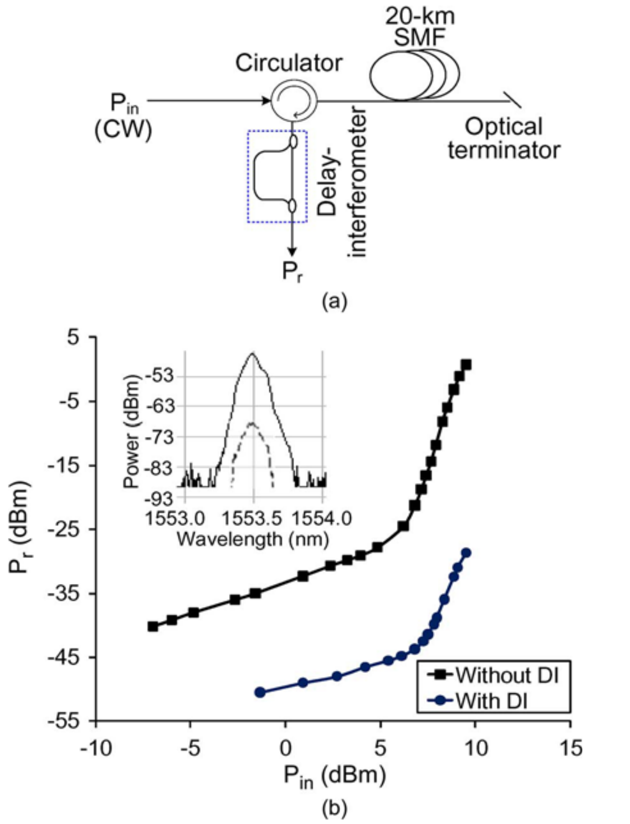

Fig. 2. (a) Experimental setup. (b) The relationship between the average reflection power (P_r) and the average power of the input CW light to the 20-km SMF $(P_{\rm in})$. Inset: measured spectrum of the RBS with (the dashed line) or without (the solid line) using the destructive port of the DI to suppress the RBS.

Fig. 3 depicts the eye diagrams of the detected upstream DPSK signals in both back-to-back (B2B) and transmission cases. In the transmission case, the eye of the upstream DPSK signal demodulated by the destructive port of the DI is clearly open, as shown in Fig. 3(b). Compared with the eye in the B2B case, shown in Fig. 3(a), only slight distortion, mainly due to the accumulated chromatic dispersion, is observed.

Although the two output ports of DI are generally equivalent in DPSK signal demodulation [Fig. 3(a) and (c)], using the destructive port of DI to demodulate the upstream DPSK signal is essential to suppress the RBS of the optical carrier. That is because the notch filter-like frequency response of destructive port of DI can effectively suppress the RBS of the optical carrier with a very narrow spectral width. On the contrary, the DPSK signal

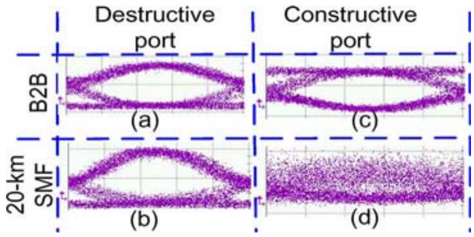

Fig. 3. Eye diagrams of the detected upstream DPSK signal by a 10-Gb/s p-i-n receiver in both back-to-back (a) and (c), and transmission case (b) and (d). Time scale: 20 ps/div.

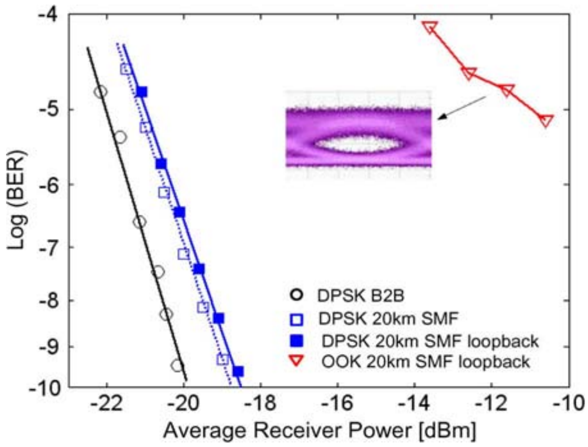

Fig. 4. BER measurements. The received signal power was measured before the p-i-n receiver. Inset: eye diagram of the detected upstream OOK signal. Time scale: 20 ps/div.

demodulated by the constructive port of the DI is vulnerable to RBS, due to the low-pass frequency response of the constructive port which is complementary to that of the destructive port. Therefore, it cannot prevent the RBS entering the upstream receiver. For comparison, the much degraded eye diagram of the upstream DPSK signal demodulated by the constructive port of the DI is shown in Fig. 3(d).

The BER measurement result for the upstream DPSK signal in the transmission case based on the architecture in Fig. 1 is shown in Fig. 4. Compared with the BER curve of the B2B DPSK signal, around 1.5-dB power penalty at BER of 10^{-9} is observed. To prove that such power penalty was mainly due to the accumulated chromatic dispersion rather than the RBS, the BER curve of the DPSK signal after 20-km SMF transmission was also measured. Compared to that, less than 0.2-dB power penalty at BER of 10^{-9} is shown for the upstream DPSK signal. Such a small power penalty demonstrates that the proposed loopback scheme is very robust to the interferometric crosstalk induced by the RBS. We also compared the proposed scheme with the on–off keying (OOK) modulation case. We replaced the PM in Fig. 1 by an optical intensity modulator and utilized OOK as the upstream modulation format. The BER measurement result for the upstream OOK signal after 20-km SMF transmission is also shown in Fig. 4. An error floor above 10^{-6} and a much degraded eye diagram are observed for the upstream OOK signal, due to the interferometric crosstalk caused by the beating between the signal and the RBS.

By placing the tunable optical attenuator before the shared EDFA, the preamplified receiver sensitivity ($\mathrm{BER} = 10^{-9}$) of the upstream DPSK signal after 20-km transmission in SMF, was measured to be -34.7 dBm. The received upstream power before the shared EDFA was around -28.4 dBm, implying $\sim$6-dB system margin.

IV. Conclusion

We have proposed a novel loopback scheme for carrier-distributed WDM-PONs to enhance system tolerance to RBS induced interferometric crosstalk. By using DPSK as the upstream modulation format, the destructive port of the DI used for upstream DPSK demodulation could simultaneously suppress the RBS of the optical carrier. Error-free operation of the 10-Gb/s upstream signals is achieved after the transmission of 20-km SMF with less than 0.2-dB power penalties induced by Rayleigh noise.

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